# LHCb Upgrades

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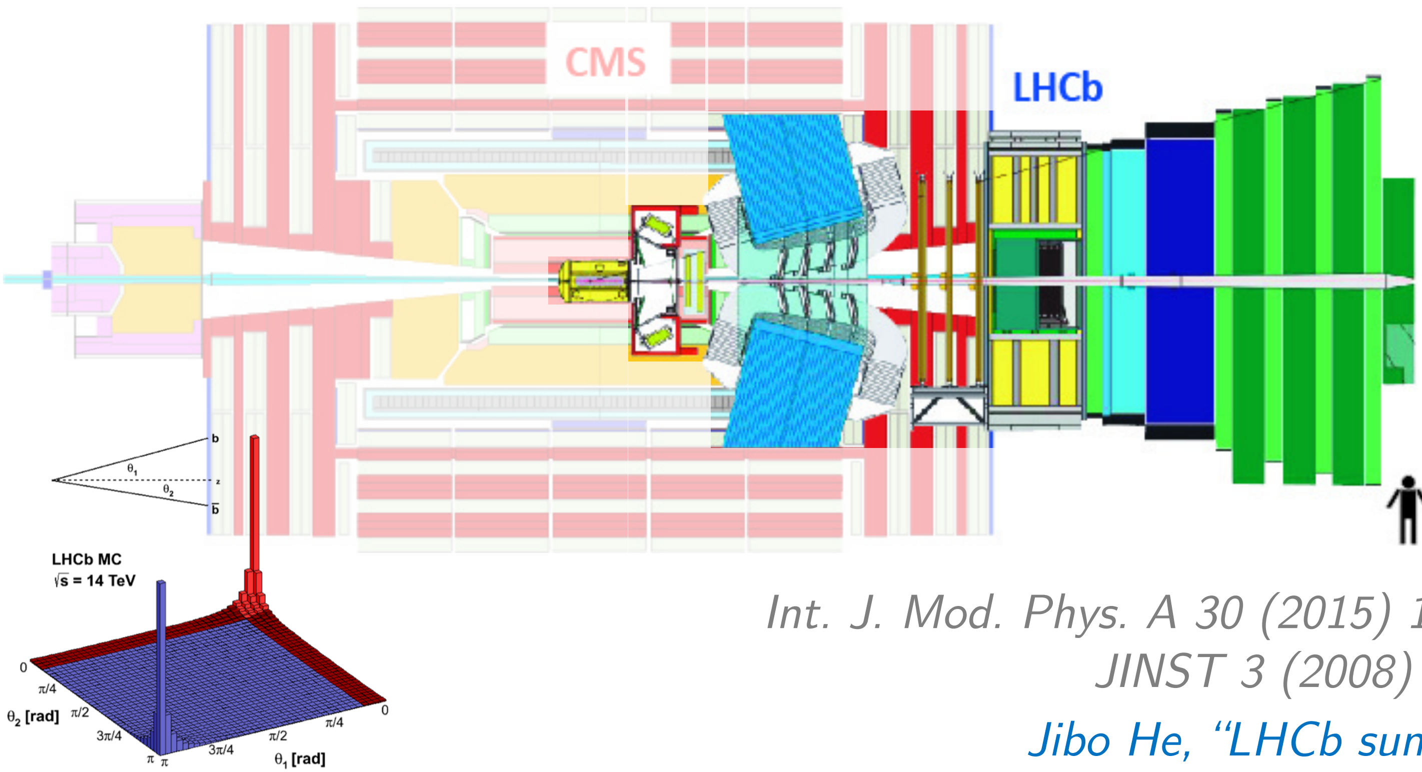
The 6th China LHC Physics Workshop, 9 Nov 2020

# Content

- Motivation of upgrade
- Plan and status of upgrade I
- Prospect of Upgrade II

# LHCb experiment

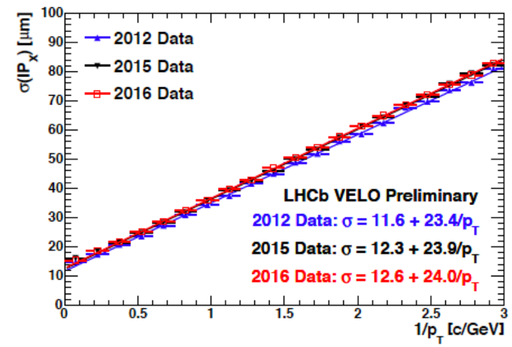
- Single-armed forward spectrometer
  - Designed for heavy flavor studies: probing new physics in rare SM processes
  - A general-purpose detector in the forward region

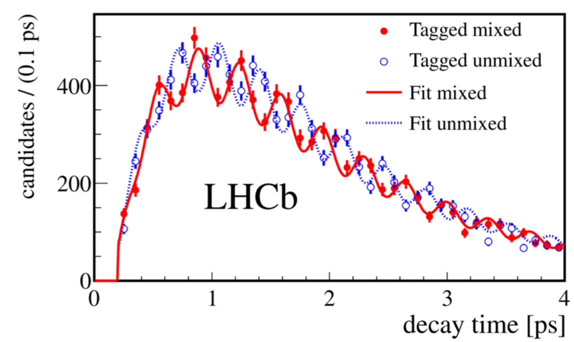


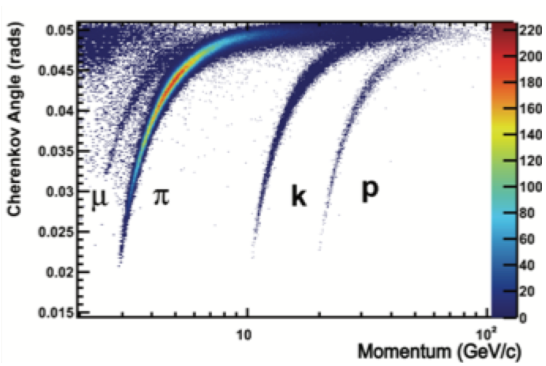

*Int. J. Mod. Phys. A 30 (2015) 1530022*
*JINST 3 (2008) S08005*
*Jibo He, "LHCb summaries"*

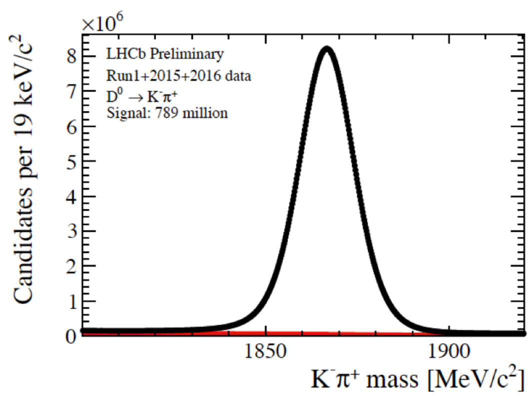
# Excellent detector performance

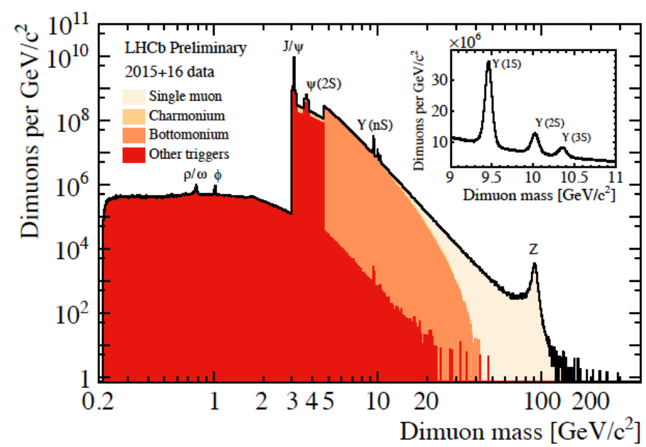
| | |
|---|---|
| Vertex res. | $\sigma_{\mathrm{IP}} = 20\ \mu\mathrm{m}$ |
| Time res. | $\sigma_\tau = 45\ \mathrm{fs}$ for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$ |
| Momentum res. | $\Delta p/p = 0.4 \sim 0.6\%\ (5 - 100\ \mathrm{GeV}/c)$ |
| Mass | $\sigma_m = 8\ \mathrm{MeV}/c^2$ for $B \to J/\psi X$ |
| Hadron ID | $\varepsilon(K \to K) \sim 95\%$ mis-ID $\varepsilon(\pi \to K) \sim 5\%$ |
| Muon ID | $\varepsilon(\mu \to \mu) \sim 97\%$ mis-ID $\varepsilon(\pi \to \mu) \sim 1 - 3\%$ |
| ECAL res. | $\Delta E/E = 1\% \oplus 10\%/\sqrt{E\ (\mathrm{GeV})}$ |



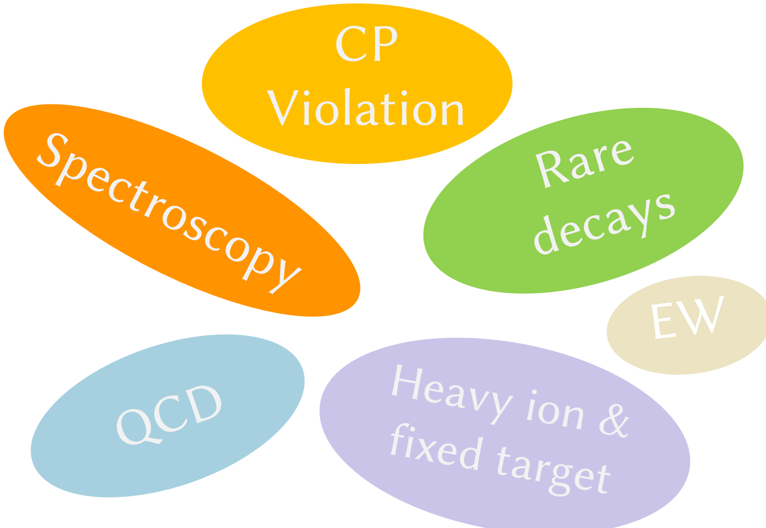



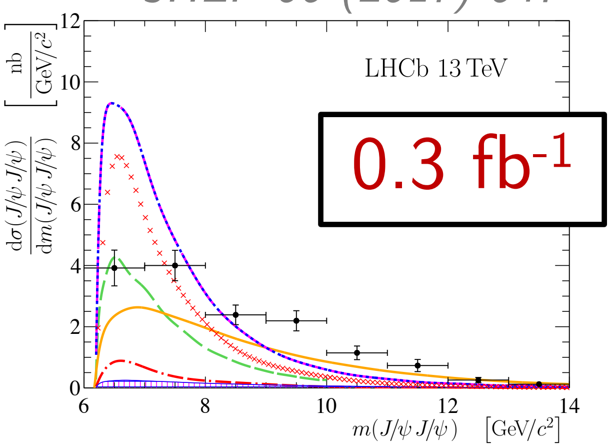



# Fruitful physics output – powered by statistics

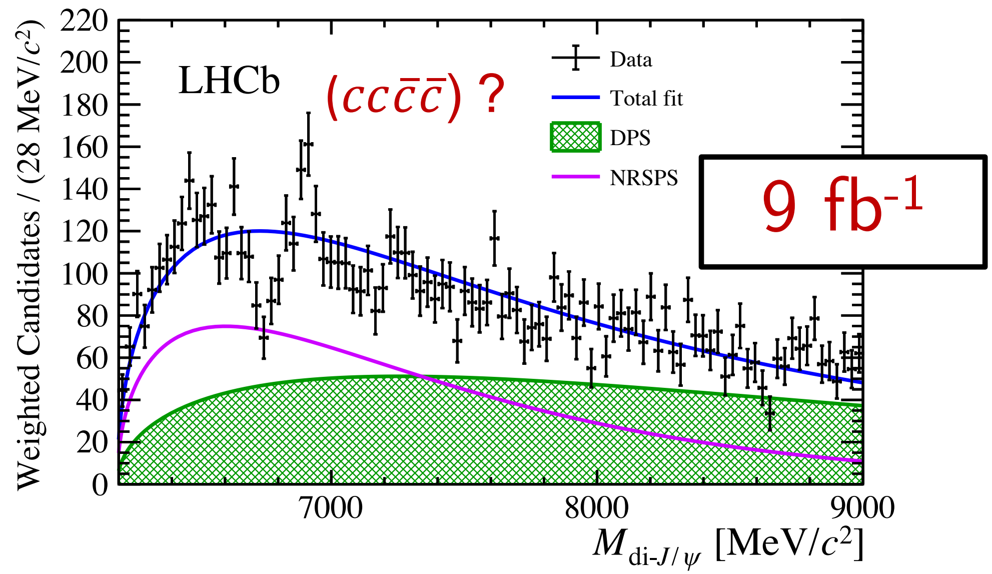



*Liming Zhang, "Exotic hadrons at LHCb"*
*Yanxi Zhang, "Heavy flavour production at LHCb"*
*Wenbin Qian, "CPV and rare decays at LHCb"*
*+ 11 talks @ Heavy Flavour parallel sessions*

*JHEP 06 (2017) 047*

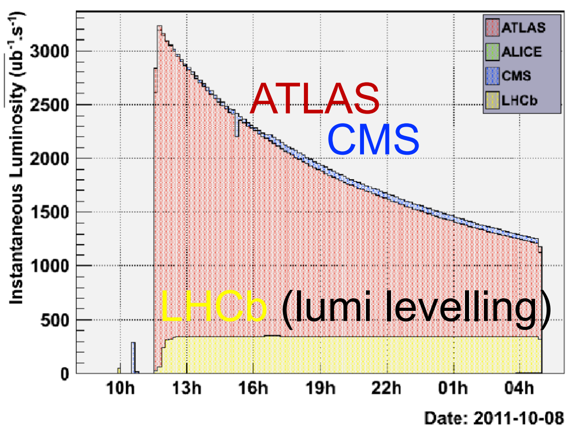


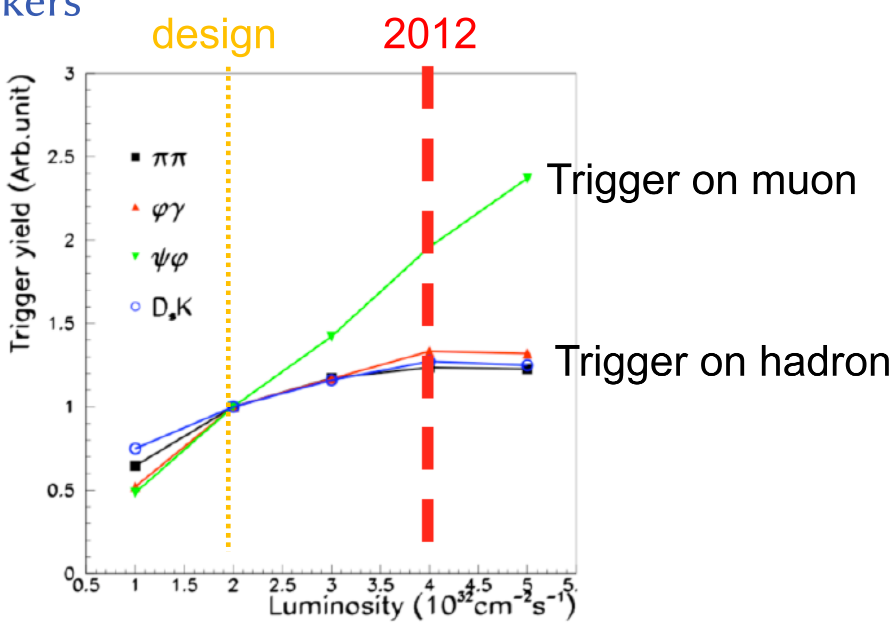

*Science Bulletin, arXiv:2006.16957*



# Motivation of detector upgrade

- More data, higher discovery potential!
- Why cannot fully exploit what LHC offers?
  - Saturation of hadronic trigger at higher lumi due to 1MHz hardware trigger
  - Performance degradation with increase of detector occupancy
  - Limited radiation hardness of trackers



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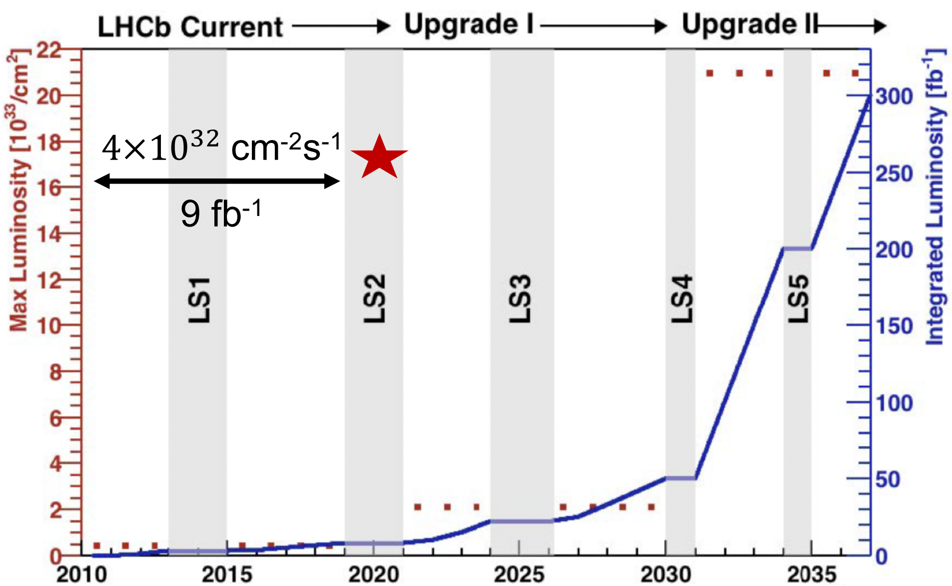
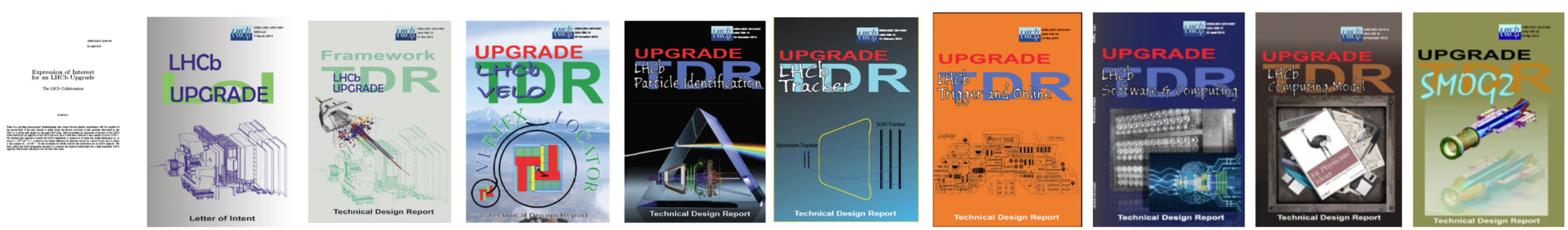
- Increase the instantaneous lumi to $2 \times 10^{33}$ $cm^{-2}s^{-1}$ a factor of 5 increase
- Remove the 1 MHz hardware trigger
  - All detectors read out @ 40MHz ⇒ new FE electronics & readout network
  - Flexible software trigger entirely on a CPU/GPU farm
- Sub-detectors work at higher lumi
  - High granularity for higher occupancy
  - Radiation tolerance

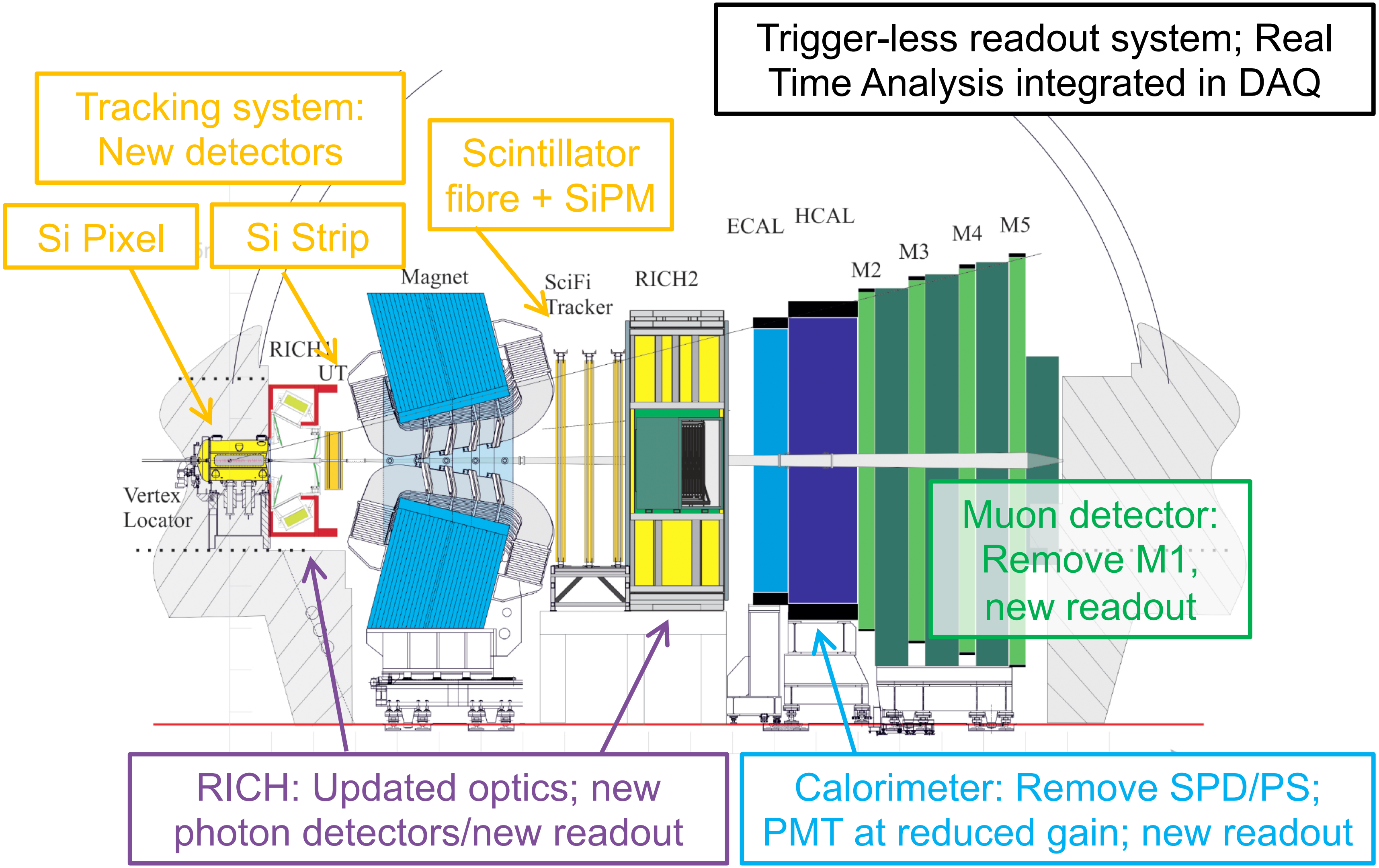
# Goal of LHCb upgrade I




- $\mathcal{L}_{inst} \rightarrow 2 \times 10^{33}\ cm^{-2}s^{-1}$ ($\times$ 5)
  - $\mathcal{L}_{int} \sim 50\ fb^{-1}$ by LS4
- Read out at 40 MHz
- Maintaining/improving previous performance

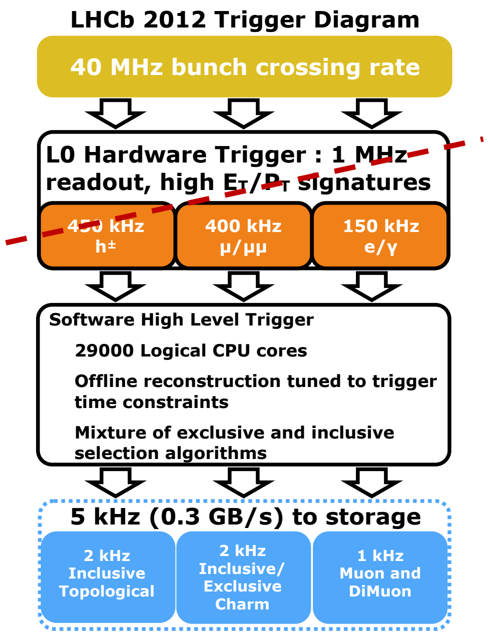


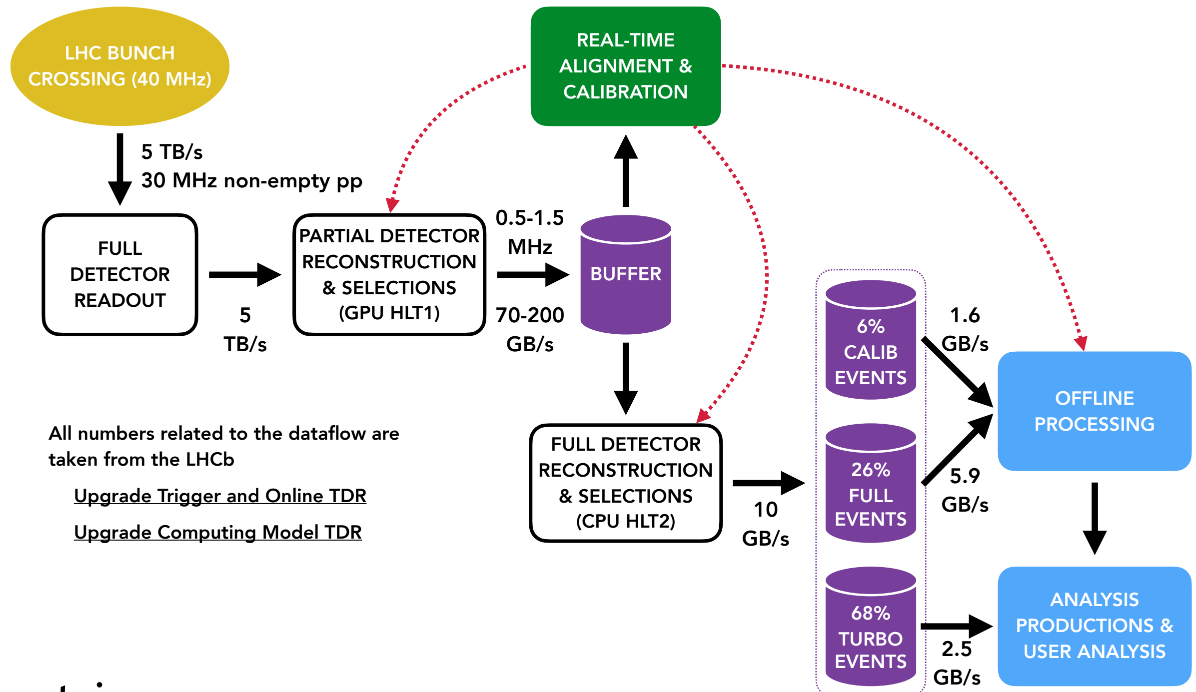
# Overview of Upgrade I



# Readout system

*Comput. Softw. Big Sci 4, 7 (2020)*



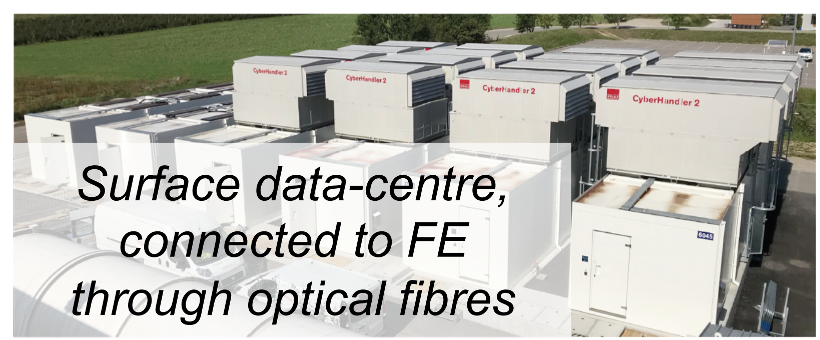




All numbers related to the dataflow are taken from the LHCb

Upgrade Trigger and Online TDR

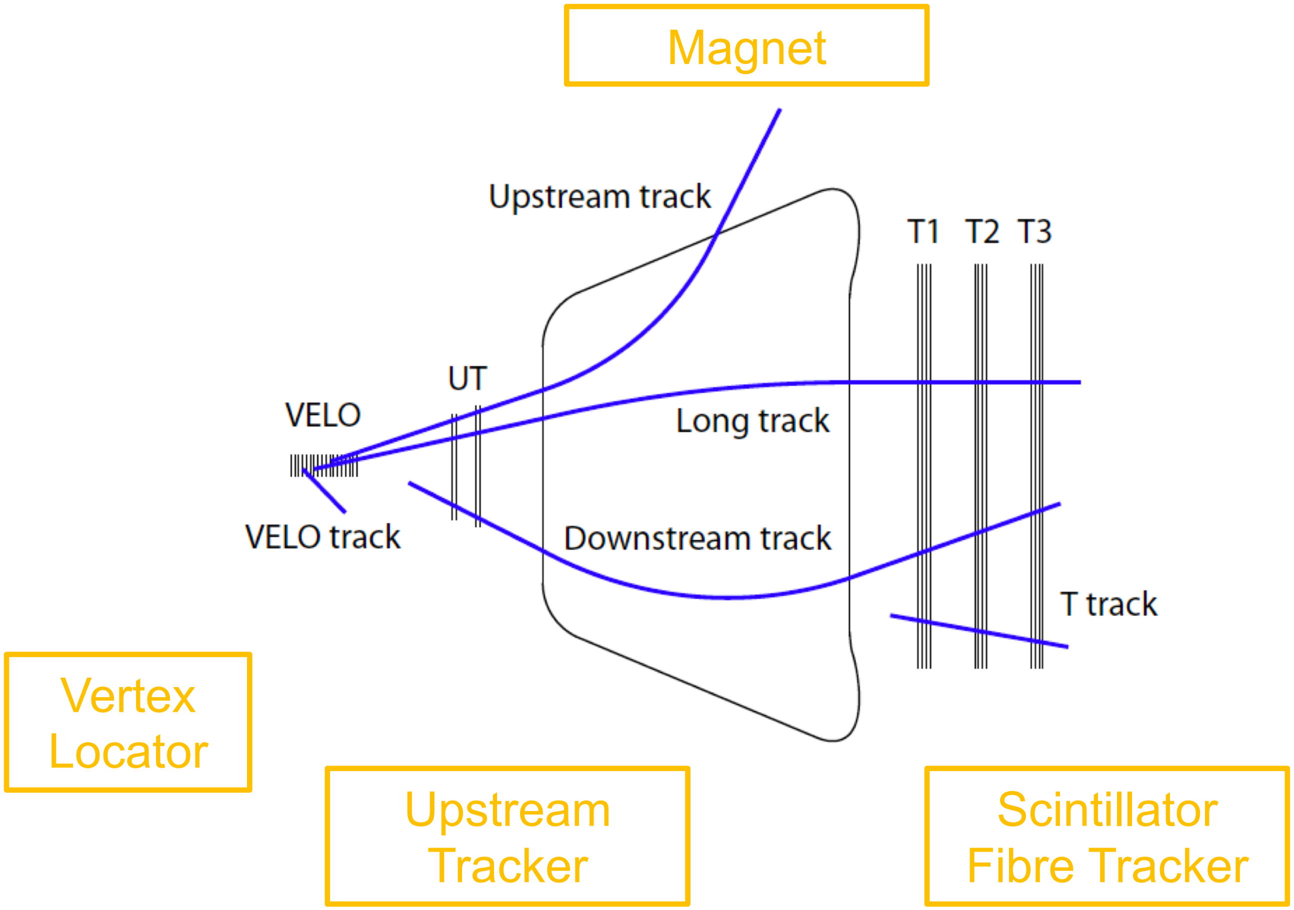
Upgrade Computing Model TDR

- Removal of L0 hardware trigger
- Event building using GPU
- Real Time Analysis
  - Realtime Align./calib.
  - Physics objects from HLT2
- Chinese contribution in many aspects



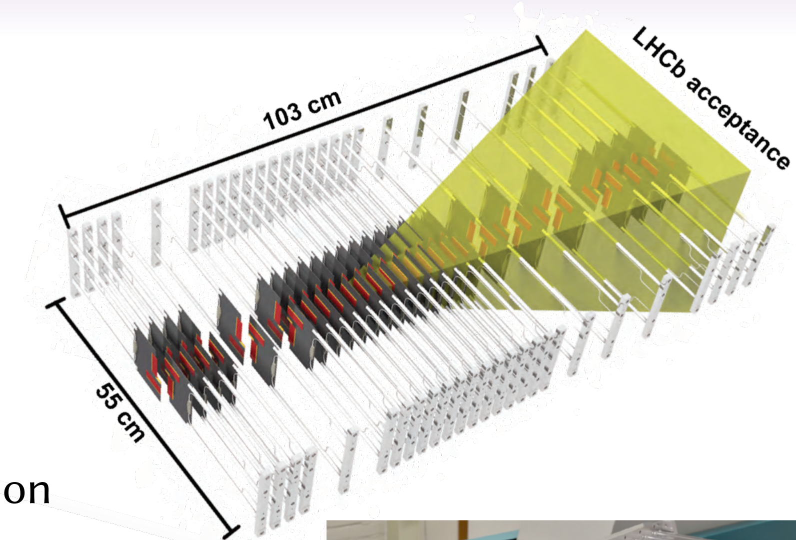

*Miroslav Saur, "Status of the Real Time Analysis project at LHCb"*

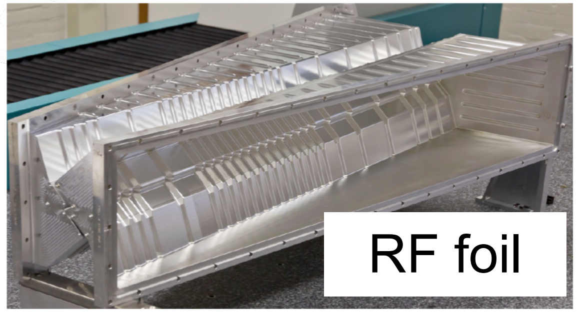
# Tracking system



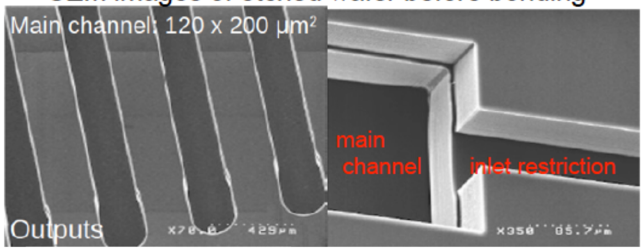
# VELO

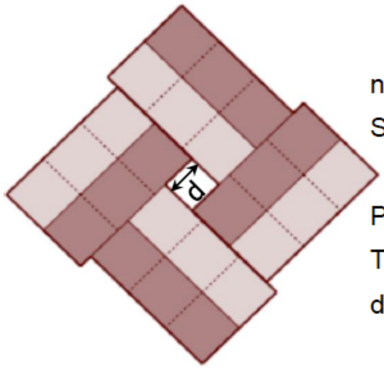
- Retractable two-halves
- Enclosed in secondary vacuum
  - Aluminum foil only 150um thick
- Hybrid pixel detector
  - Low occupancy, easy pattern recognition
- Closest beam approach: 8.2mm → 5.1mm
  - Better IP resolution
  - Severe radiation in innermost part
- Microchannels in silicon substrate for evaporative $CO_2$ cooling



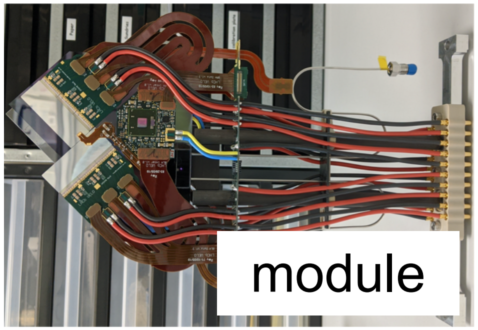

SEM images of etched wafer before bonding



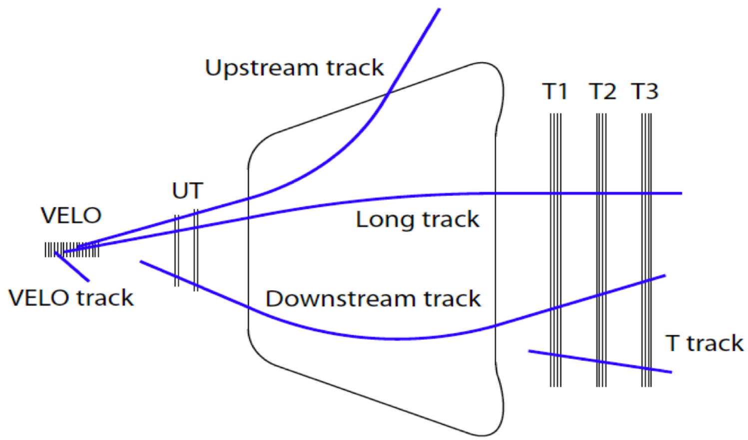




n-in-p sensor
Size ~43×15 mm²

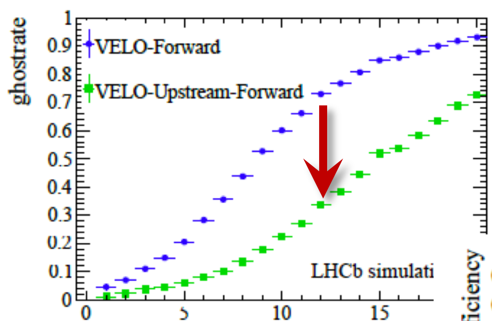
Pixel size 55×55 µm²
Thickness = 200 µm
d/2 = 5.1 mm



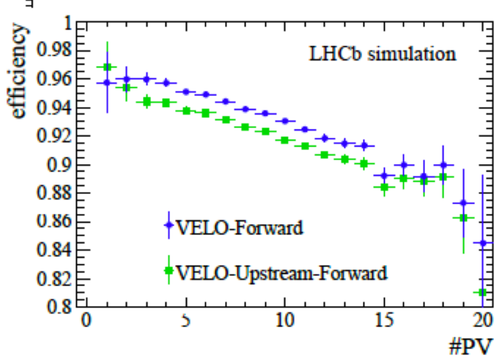
# Role of Upstream Tracker (UT)




- High tracking efficiency
  - Crucial for efficient reconstruction of particles decaying after VELO: $K_S, \Lambda$ when combined with SciFi



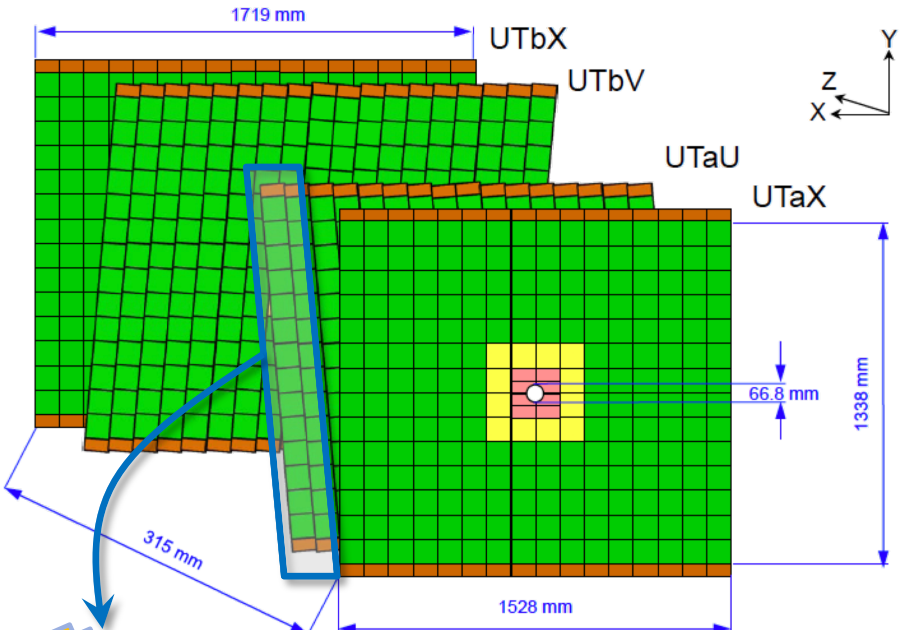

Ghost rate reduction by requiring UT hit

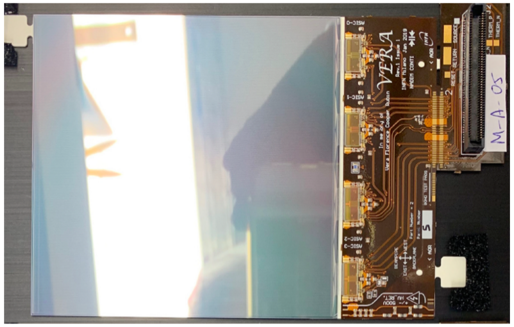


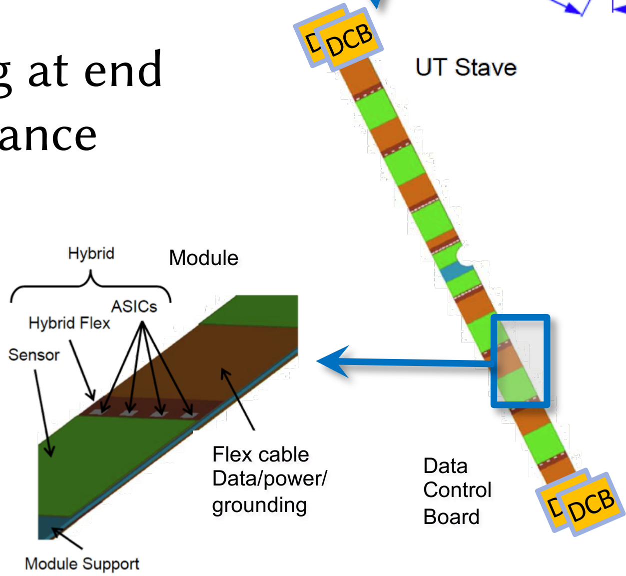

- Fast tracking algorithm
  - Reduction of 'ghost' tracks, speed up up- & downstream matching, allowing a more performant tracking and triggering algorithms

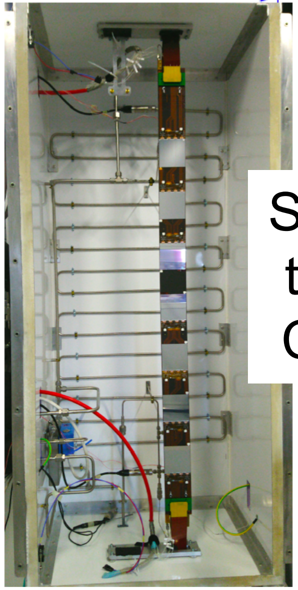
# UT

- Four layers of silicon strip det.
  - Strips along y (or $\pm 5°$)
- Improved coverage/granularity wrt current TT
- Radiation hard sensor $\Phi_{max} \sim 5 \times 10^{14}\, n_{eq}\mathrm{cm}^{-2}$
- Dedicated FE (SALT) for readout at 40 MHz near sensor
- More digital processing at end of stave outside acceptance



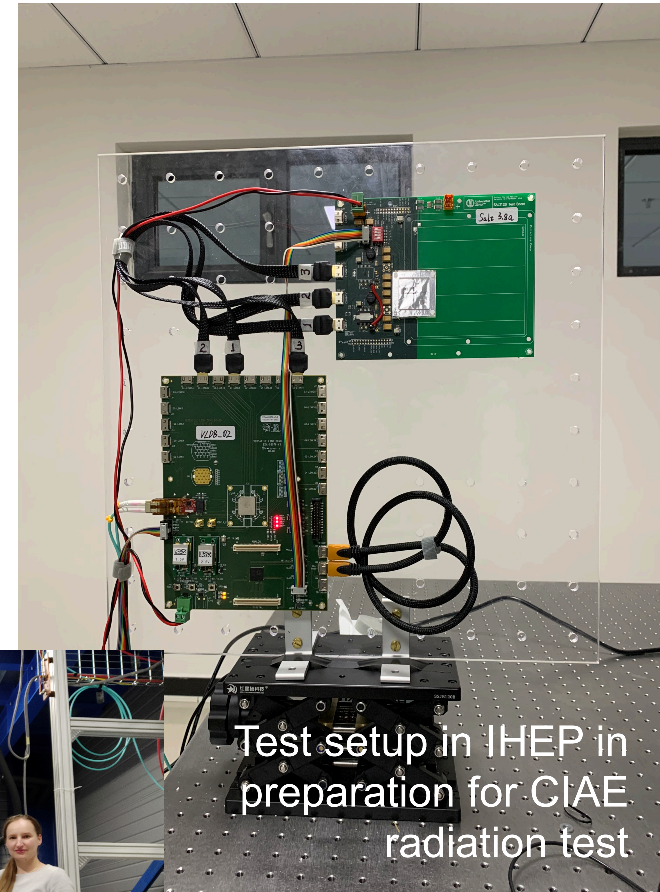


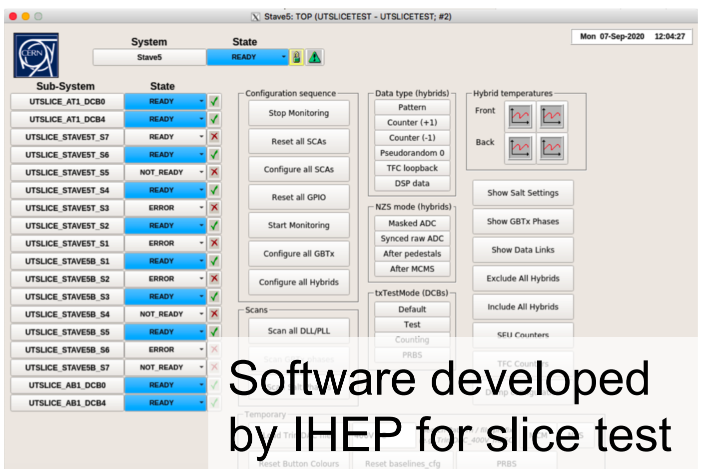
System test at CERN

# UT – Chinese contribution

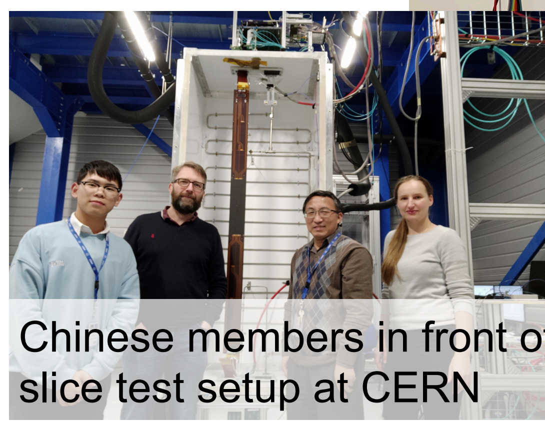
- IHEP play leading role in several testbeam campaigns to validate SALT radiation hardness
  - Fermilab, MGH, PSI in 2019
  - Planned test at CIAE Beijing
- IHEP, Hunan U and Tsinghua involved in system test, detector installation and control software development at CERN



Test setup in IHEP in preparation for CIAE radiation test




Software developed by IHEP for slice test

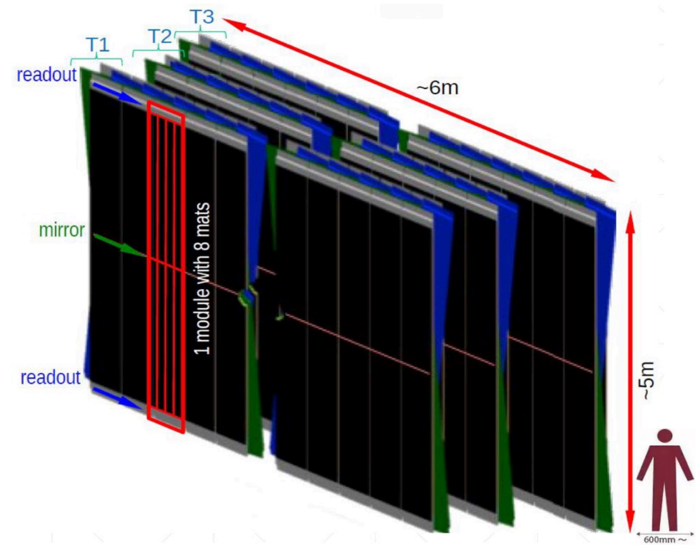


Chinese members in front of slice test setup at CERN

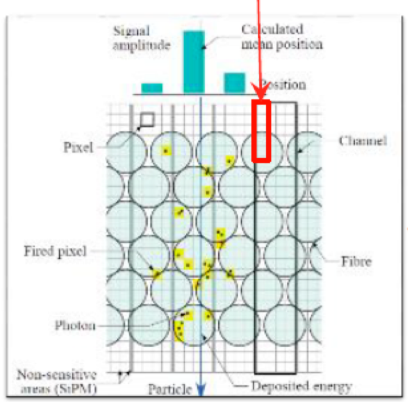
*Ina Carli, "Status of LHCb upstream tracker"*

# Scintillating Fibre Tracker (SciFi)

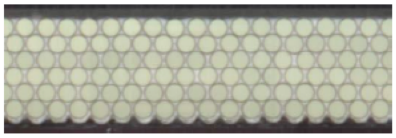
- 3-station scintillating fiber detectors
- 340 m$^2$ sensitive area
- Readout with 4096 SiPMs + custom made PACIFIC ASIC.
  - A total of ~ 0.5 M SiPM channels!
- Spatial resolution ~70 um in X
- Single hit efficiency ~99%



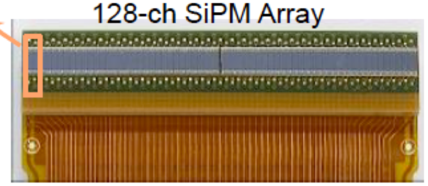

1 SiPM Channel




6 layers staggered Ø250 μm fiber mats

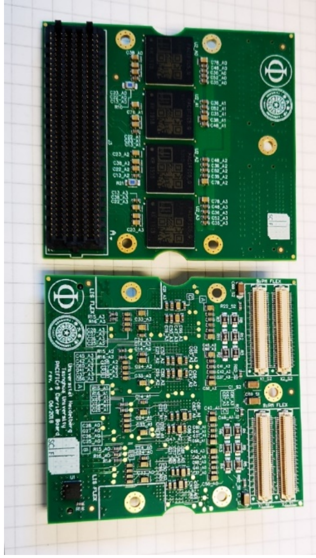


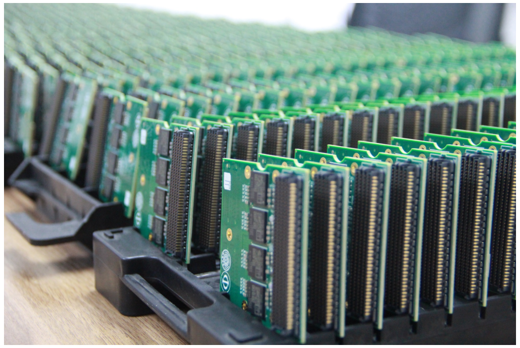
128-ch SiPM Array

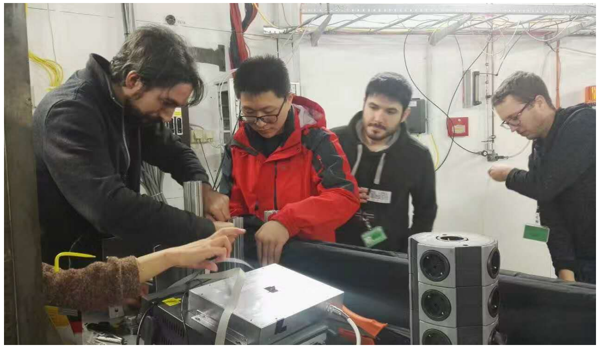


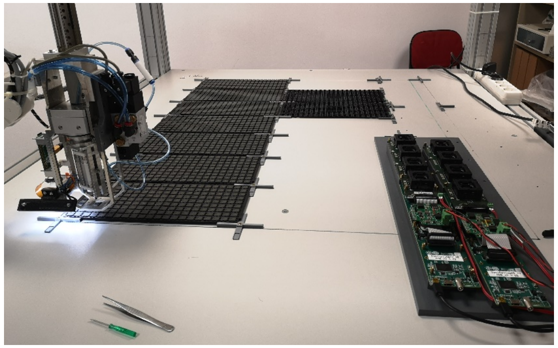
# SciFi – Chinese contribution

- Tsinghua played crucial part in FE electronics
  - Co-designed the PACIFIC board
  - Manufactured all (2300) boards with high quality
  - Set up QA system (a total of 11 setups)
  - Developed software to process SciFi testbeam data
- Contribution to SciFi readout test and commissioning from Tsinghua, UCAS and CCNU







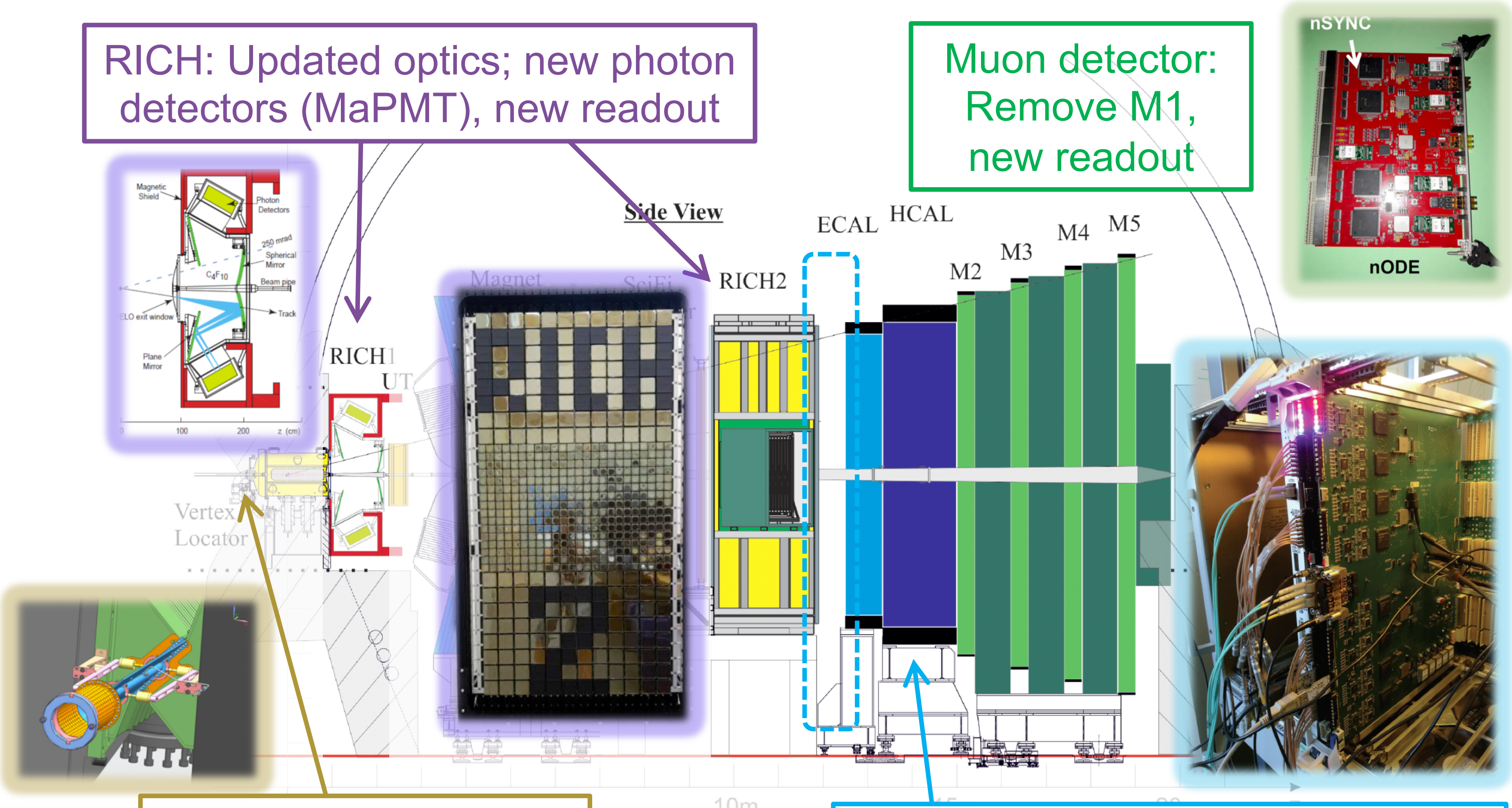


*Zhiyu Xiang, "Test of LHCb SciFi readout electronics"*

# Other sub-system in Upgrade I

RICH: Updated optics; new photon detectors (MaPMT), new readout

Muon detector: Remove M1, new readout

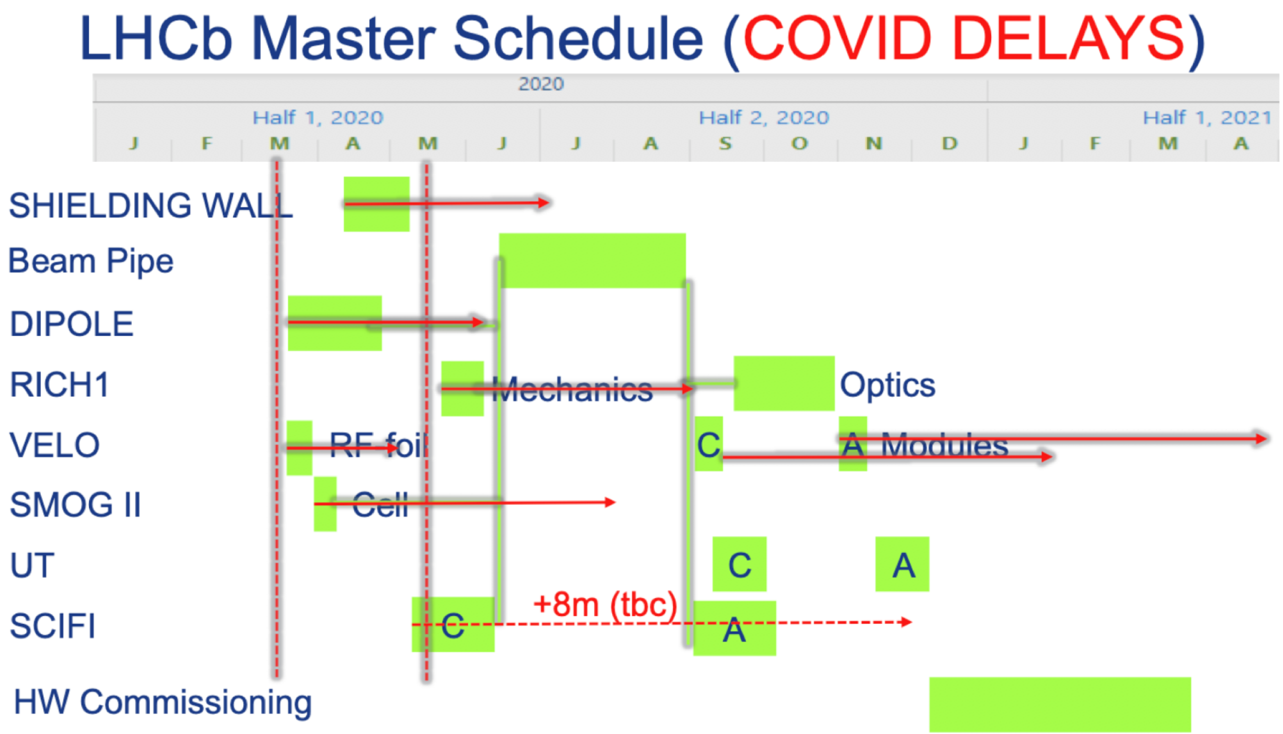



SMOG II
Inject noble gas
for fixed target study

Calorimeter: Remove SPD/PS;
PMT at reduced gain; new readout

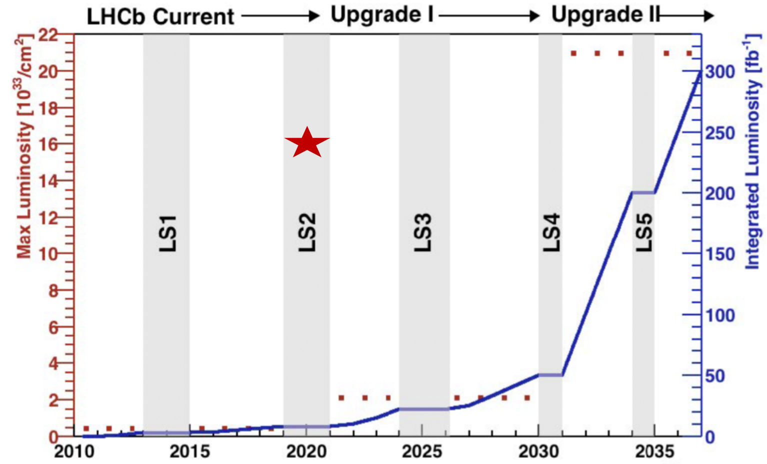
# Status and Timeline

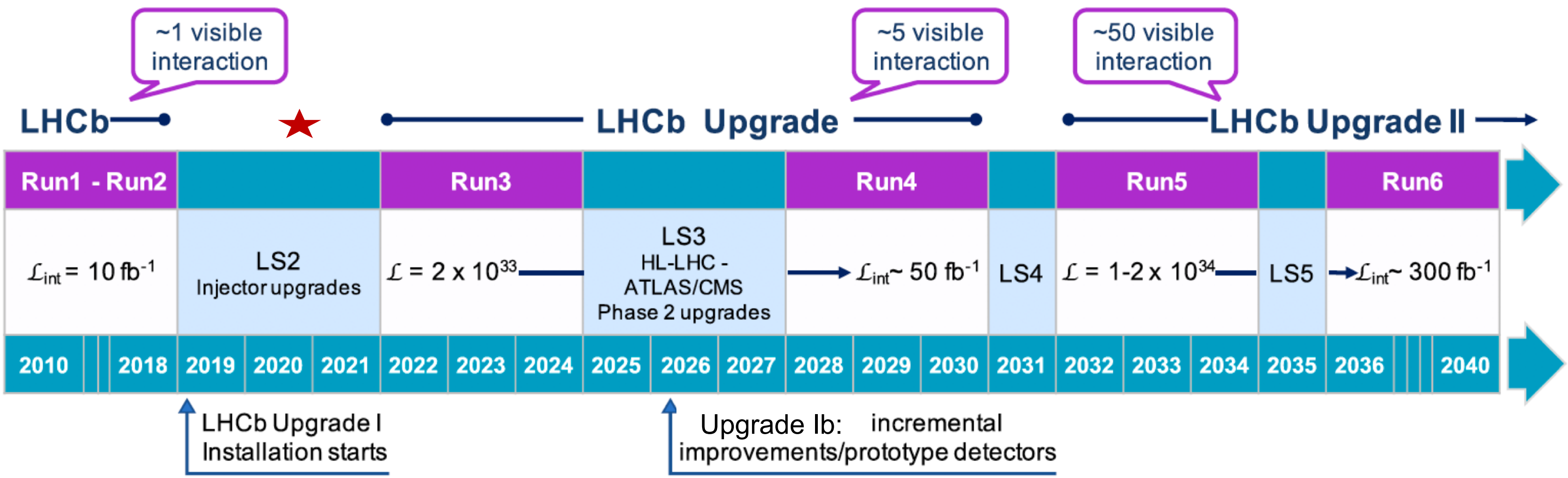
- Delays and uncertainties due to Covid-19, nonetheless:
  - Installation resumed since May, important milestones achieved. Bulk of infrastructure and detector services completed.
  - Ready for LHC commissioning as early as Nov 2021



# LHCb Upgrade II

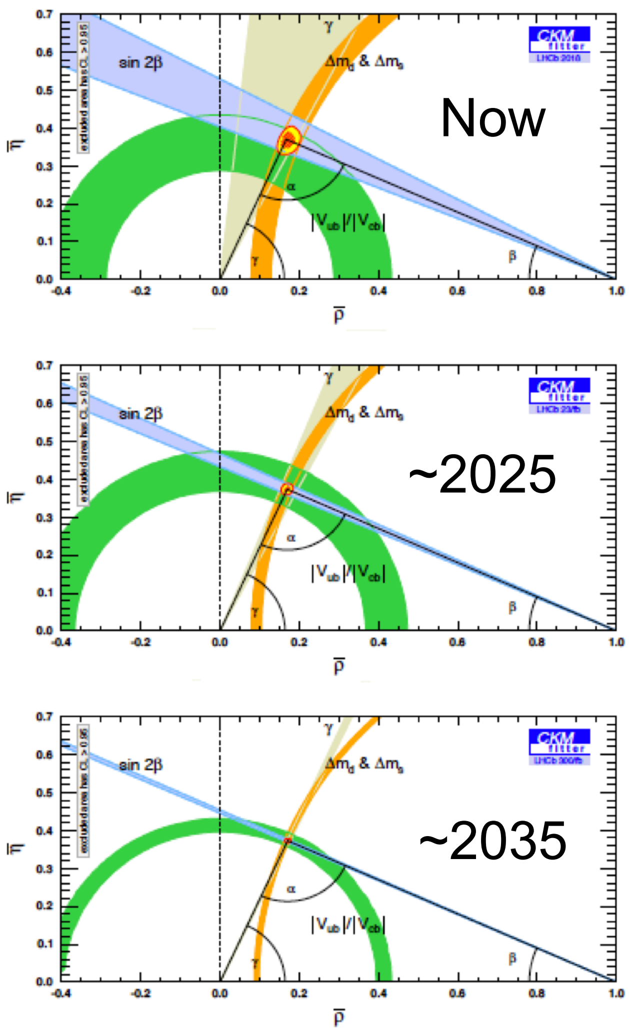
- A new detector in Run 3 assumed
- How to better exploit HL-LHC upgrade?
- LHCb Upgrade Ib+II
  - Increase lumi by an order of magnitude
  - Accumulate 300 $fb^{-1}$




Expression of Intent [CERN-LHCC-2017-003]; Physics Case for an LHCb Upgrade II [arXiv:1808.08865]

# Physics potential



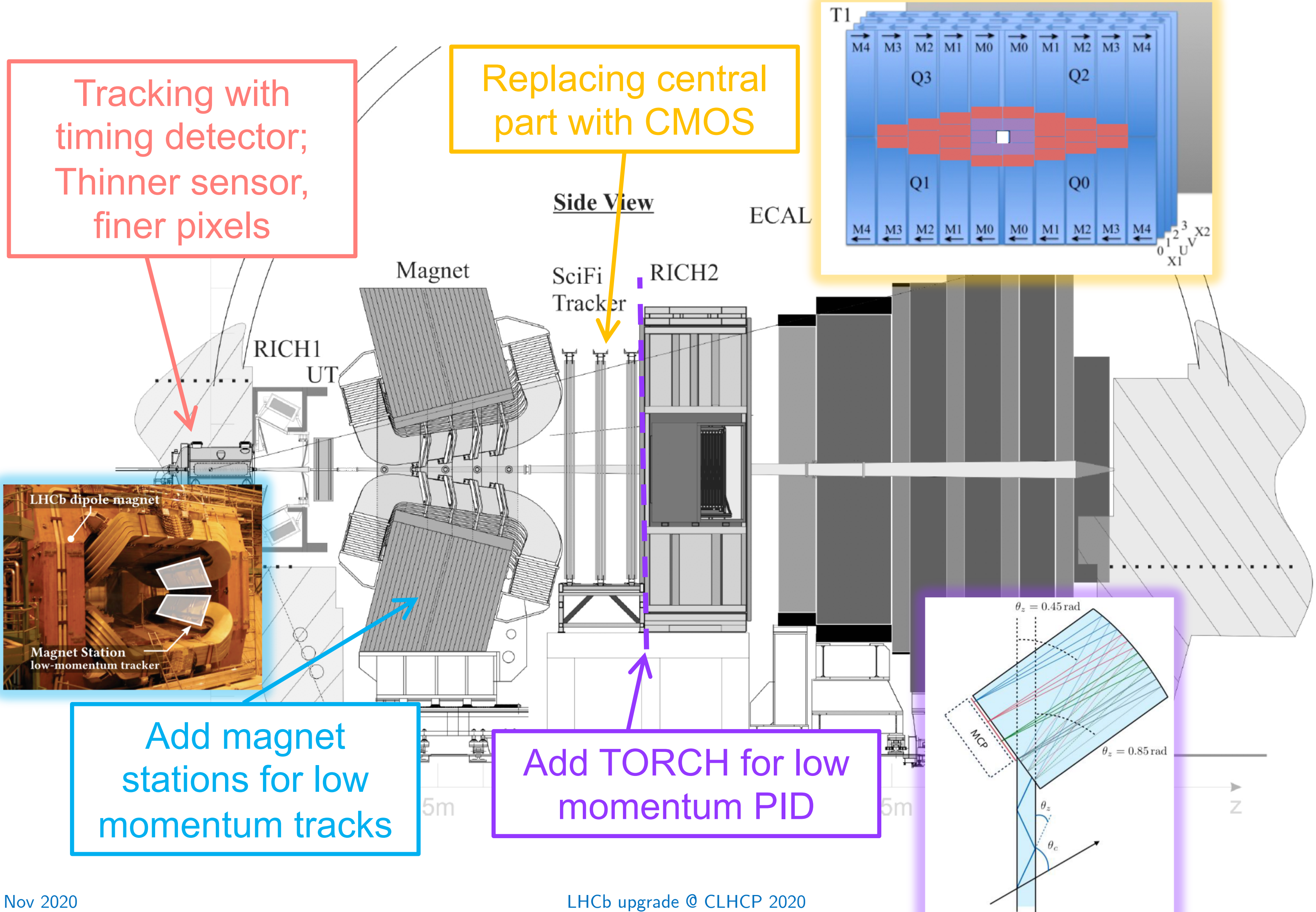

| | $R_K$ [%] | $R(D^*)$ [%] | $\frac{\mathcal{B}(B^0\to\mu^+\mu^-)}{\mathcal{B}(B^0_s\to\mu^+\mu^-)}$ [%] | LHCb |
|---|---|---|---|---|
| Current (LHCb) | ±10.0 | ±2.6 | ±90 | Current |
| 2025 (Belle II) | ±3.6 | ±0.50 | | Belle II |
| 2025 (LHCb) | ±2.2 | ±0.72 | ±34 | ATLAS/CMS, LHCb, 2025 |
| HL-LHC (ATLAS/CMS) | | | ±21 | |
| HL-LHC (LHCb) | ±0.70 | ±0.20 | ±10 | HL-LHC |

| | $a^s_{sl}$ | $\gamma$ [°] | $\phi_s$ [mrad] | $A_\Gamma$ | LHCb |
|---|---|---|---|---|---|
| Current (LHCb) | $\pm 33.0\times10^{-4}$ | ±5.4 | ±49 | $\pm 28.0\times10^{-5}$ | Current |
| 2025 (Belle II) | | ±1.5 | | $\pm 35.0\times10^{-5}$ | Belle II |
| 2025 (LHCb) | $\pm 10.0\times10^{-4}$ | ±1.5 | ±14 | $\pm 4.3\times10^{-5}$ | ATLAS/CMS, LHCb, 2025 |
| HL-LHC (ATLAS/CMS) | | | ±22 | | |
| HL-LHC (LHCb) | $\pm 3.0\times10^{-4}$ | ±0.35 | ±4 | $\pm 1.0\times10^{-5}$ | HL-LHC |

# Upgrade possibilities at UIb/II

Tracking with timing detector; Thinner sensor, finer pixels

Replacing central part with CMOS

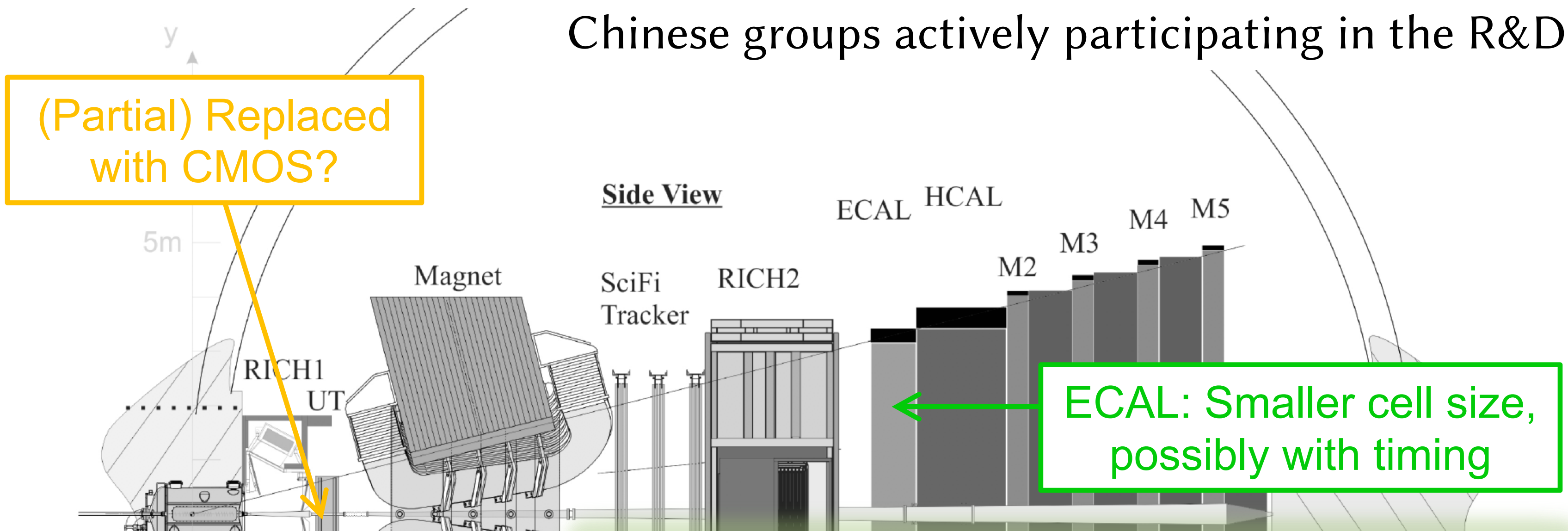



Add magnet stations for low momentum tracks

Add TORCH for low momentum PID

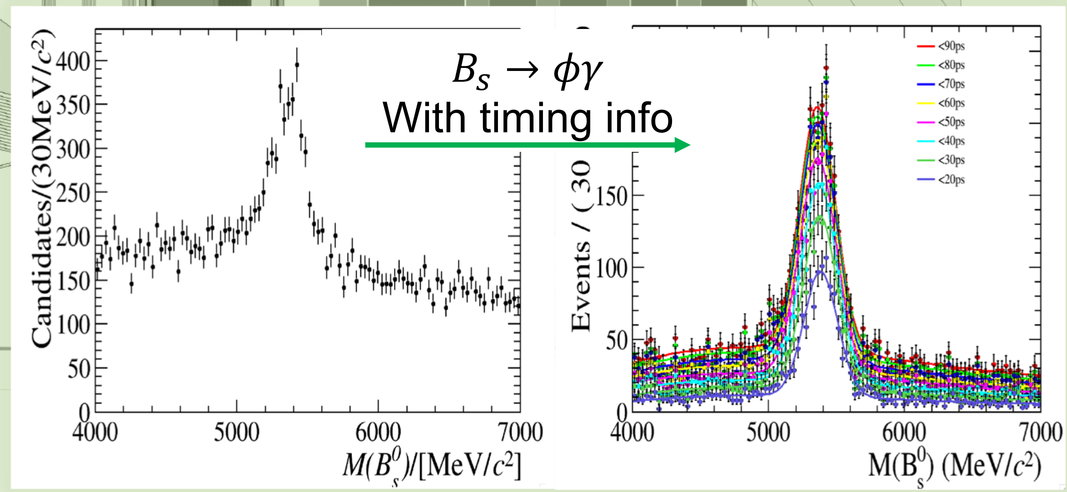
# Upgrade possibilities at UIb/II

Chinese groups actively participating in the R&D




Channel occupancy [%]

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 0.42 | 0.45 | 0.47 | 0.49 | 0.52 | 0.54 | 0.57 | 0.60 | 0.60 |
| 0.46 | 0.49 | 0.52 | 0.56 | 0.59 | 0.63 | 0.68 | 0.74 | 0.77 |
| 0.53 | 0.58 | 0.62 | 0.68 | 0.73 | 0.83 | 0.89 | 1.00 | 1.06 |
| 0.64 | 0.70 | 0.77 | 0.86 | 0.96 | 1.10 | 1.26 | 1.48 | 1.63 |
| 0.78 | 0.88 | 0.97 | 1.13 | 1.27 | 1.54 | 1.81 | 2.34 | 2.72 |
| 0.96 | 1.10 | 1.23 | 1.45 | 1.68 | 2.05 | 2.63 | 2.84 | 3.87 |
| 1.28 | 1.45 | 1.54 | 1.81 | 2.04 | 2.57 | 3.42 | 4.48 | 3.95 5.13 |



# Summary

- Installation for an upgraded LHCb ongoing
  - Despite the difficulty amid the pandemic
  - To deliver a luminosity 5 times higher in coming Run3
  - Chinese groups making substantial contributions

- Planning for upgrade II started
  - Physics potential to be exploited
  - Ideas & development for new technology on the way