Prospects of the Upgrade-II of LHCb

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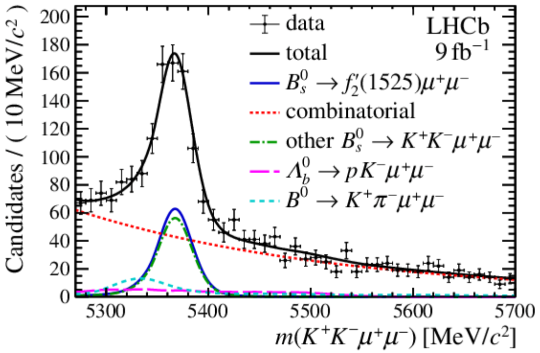
on behalf of the LHCb Collaboration

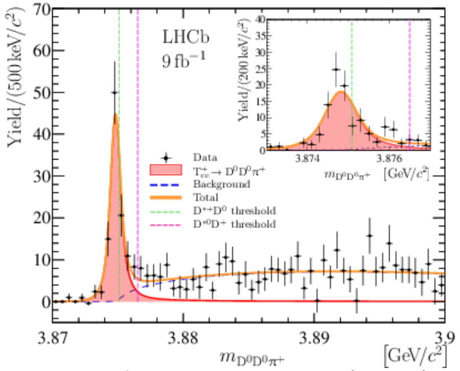
Highlights of LHCb

- Upcoming plans and upgrades build on the achievements of LHCb Run 1 and 2, many of which we obtained in pursue for BSM physics
  - Rare decay physics



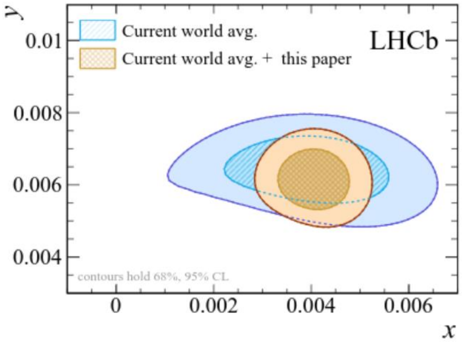
[Phys. Rev. D 05.1 (2022).]

  - Exotic hadrons



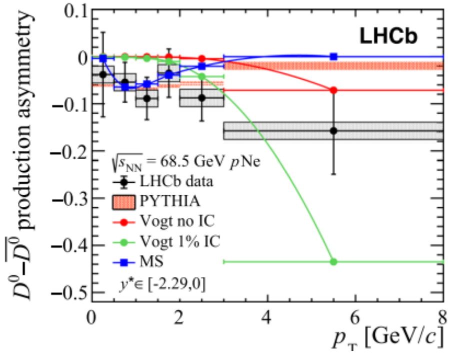
[*Nat. Phys.* **18**, 751–754 (2022).]

  - Charm physics



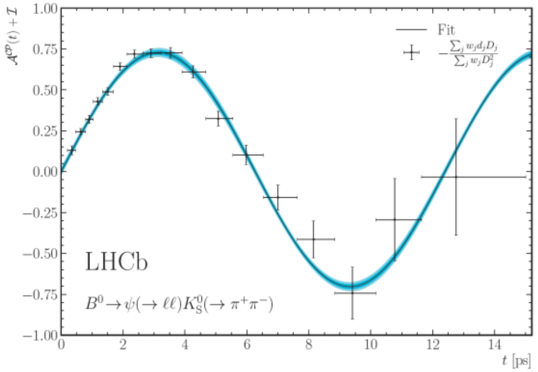
[*J. High Energ. Phys.* **2021**, 141 (2021).]

  - Fixed target physics



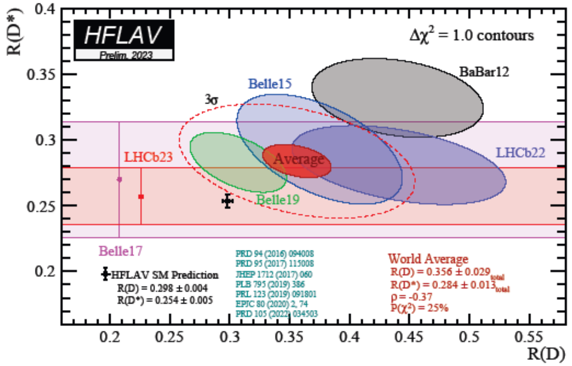
[*Eur. Phys. J. C* **83**, 541 (2023).]

  - Strong constraints on CKM



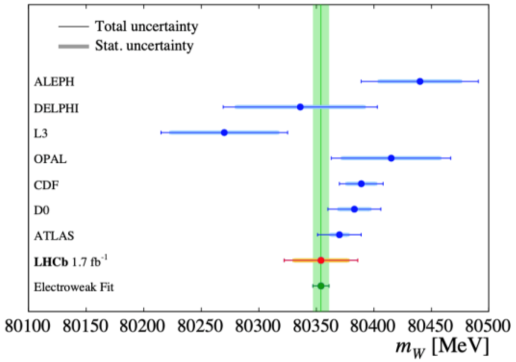
[*LHCb Talk @ FPCP2023*]

  - Tests of lepton universality



[*arXiv:2302.02886* (2023).]

  - Electroweak physics



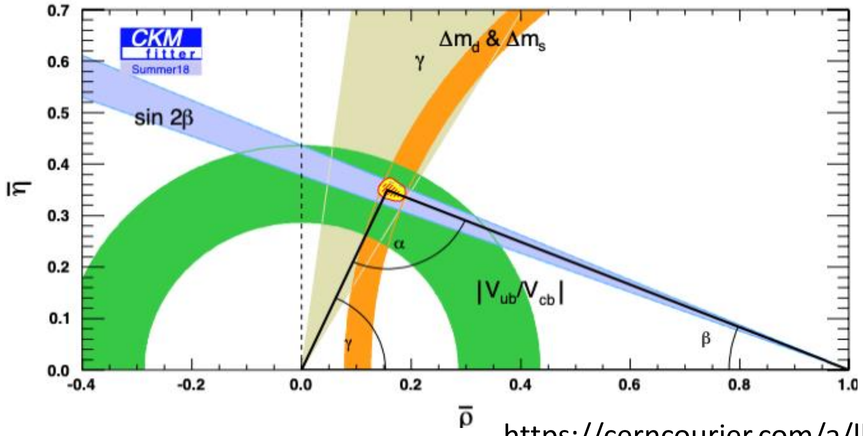
[*J. High Energ. Phys.* **2022**, 36 (2022).]

A lot of which you've learned from Pellian Li, Martin Tat, Irene Bachiller, Sara Celani, Davide Fazzini, Liming Zhang, Dominik Mitzel, Jike Wang, Federica Oliva

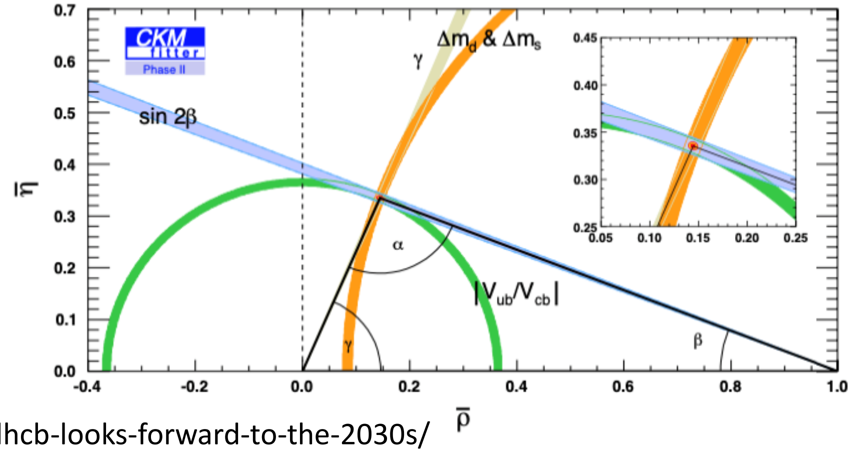
The Physics Case for Upgrade 2

- Absence of evidence for NP implies that it is either very heavy or highly complex
- Flavor physics can probe NP before it is observed directly, by looking at indirect effects in already accessible energy scale processes (e.g., B decays)
- LHCb has a unique chance to find new physics by doing precision flavor physics, testing lepton universality, measuring CPV in the charm sector, etc..

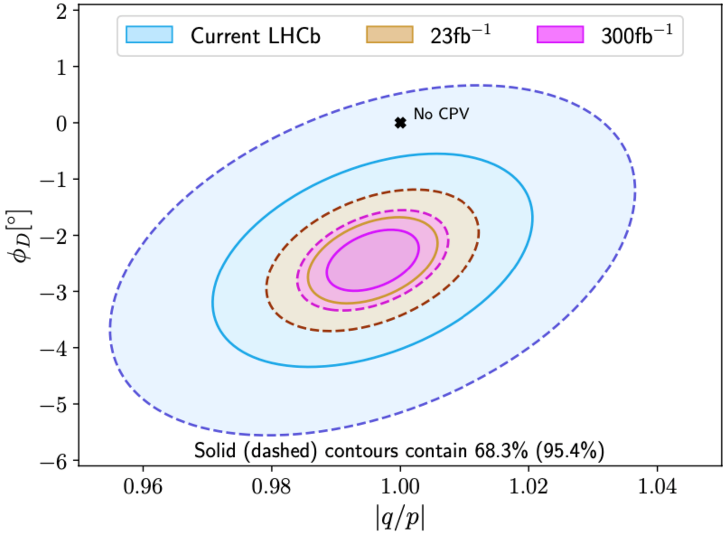
LHCb – end of Run 2



LHCb – Upgrade 2



https://cerncourier.com/a/lhcb-looks-forward-to-the-2030s/

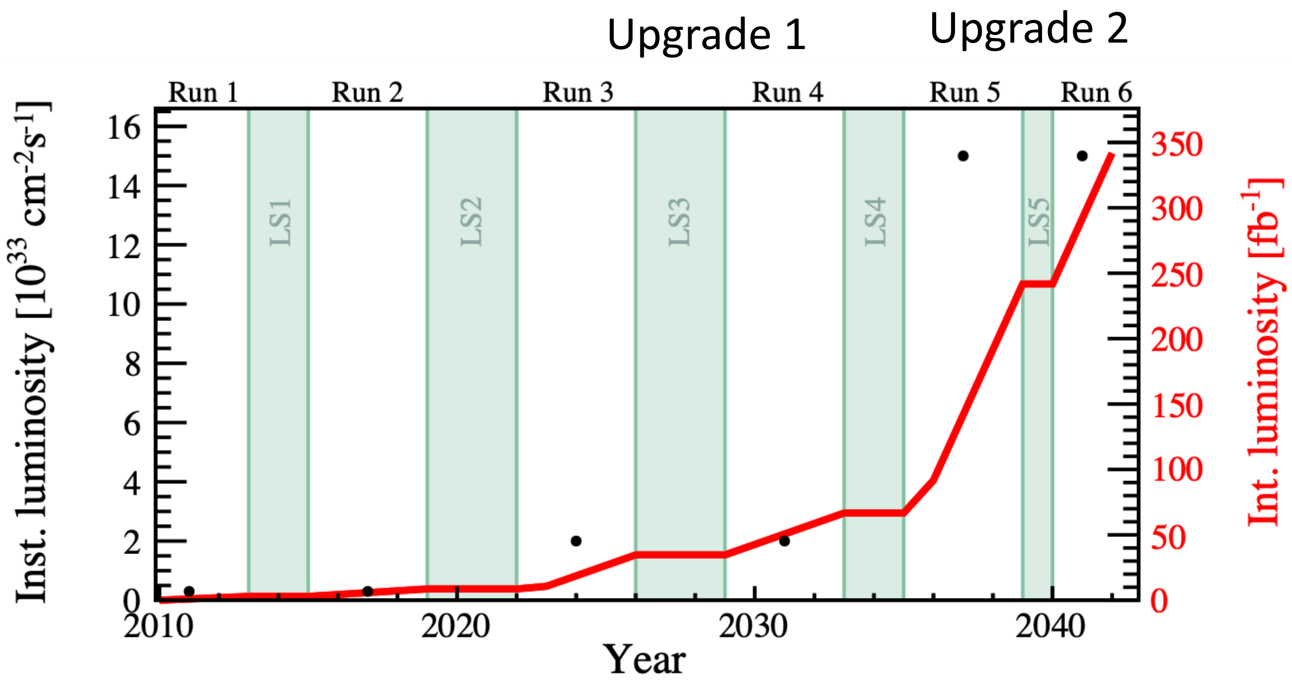


https://cds.cern.ch/record/2636441

- For all these efforts, we need huge statistics (high L), low systematics (very well-characterized detectors) and precise SM predictions

A Detector to exploit Upgrade 2

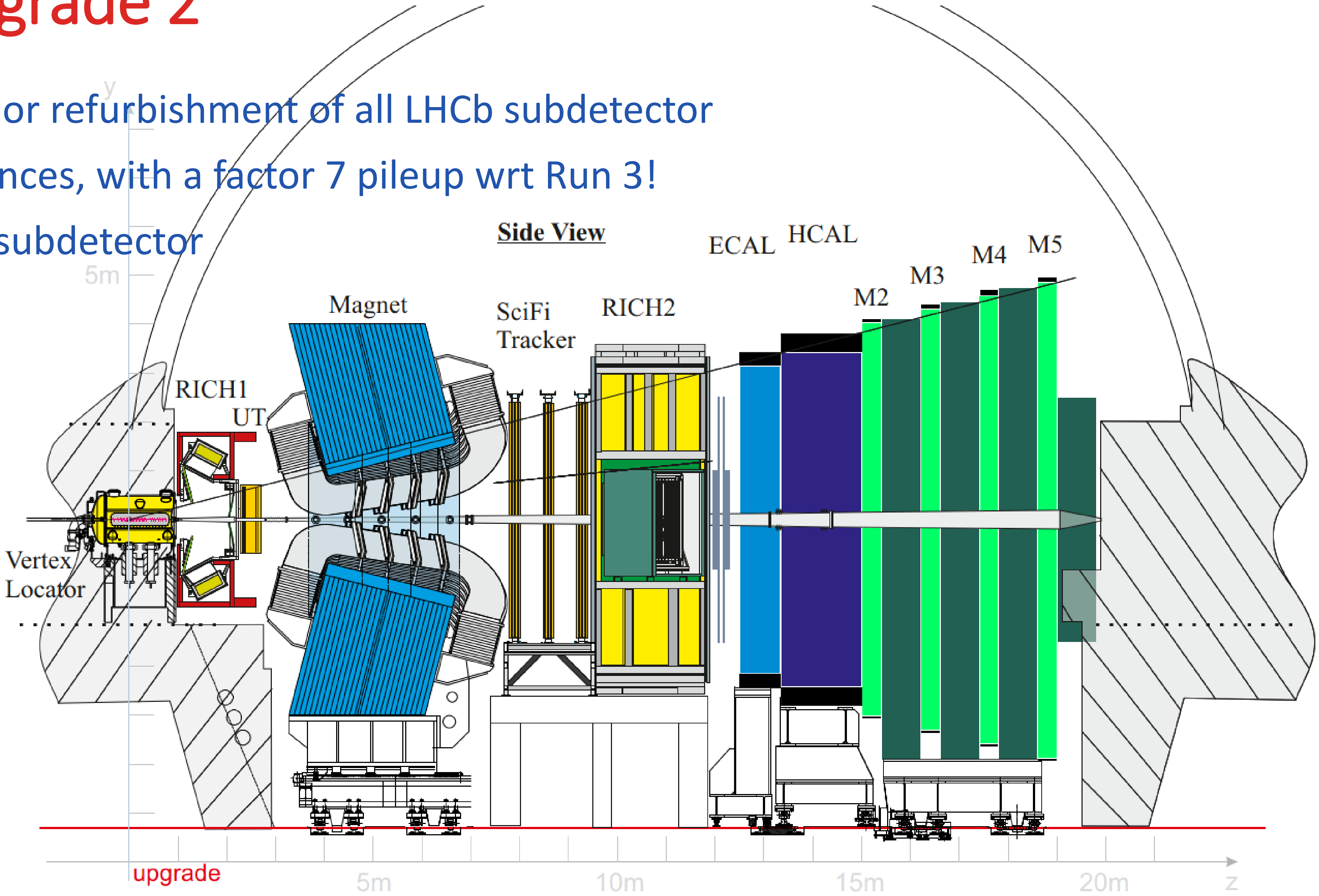
- With High Luminosity LHC (HL-LHC), providing ~50 fb^{-1}/year, and by retaining similar performances to current LHCb, we can achieve all that
- Upgrade 1
  - $L_{peak} = 2 \times 10^{33}\ cm^{-2}s^{-1}$
  - $L_{int} = 50\ fb^{-1}$ (Run 3 & 4)
  - Sinergy w/ Belle II
- Upgrade 2
  - $L_{peak} = 1.5 \times 10^{34}\ cm^{-2}s^{-1}$
  - $L_{int} = 300\ fb^{-1}$ (Run 5 & 6)
  - Potentially the only general flavor physics facility at this timescale



- Main challenges: high radiation (materials), event complexity (detector granularity & timing capabilities), data rate (fast decisions and data processing)
- These are the premises on which the success of Upgrade 2 is based on

What is LHCb Upgrade 2

- Same structure, with major refurbishment of all LHCb subdetector
- Maintain same performances, with a factor 7 pileup wrt Run 3!
- Key ingredients for each subdetector
    - Granularity
    - Fast timing
    - Radiation hardness
- Intensive R&Ds ongoing



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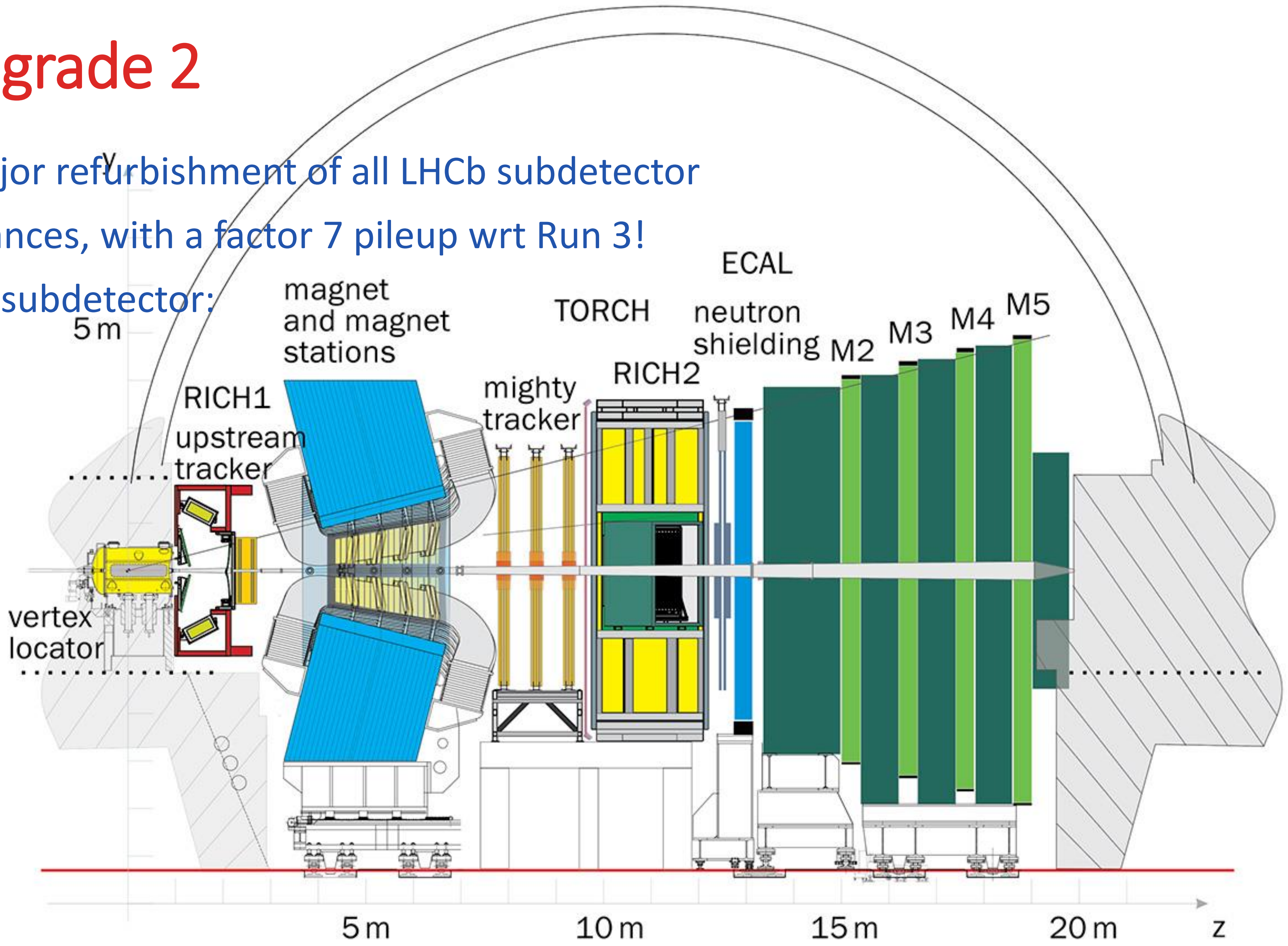
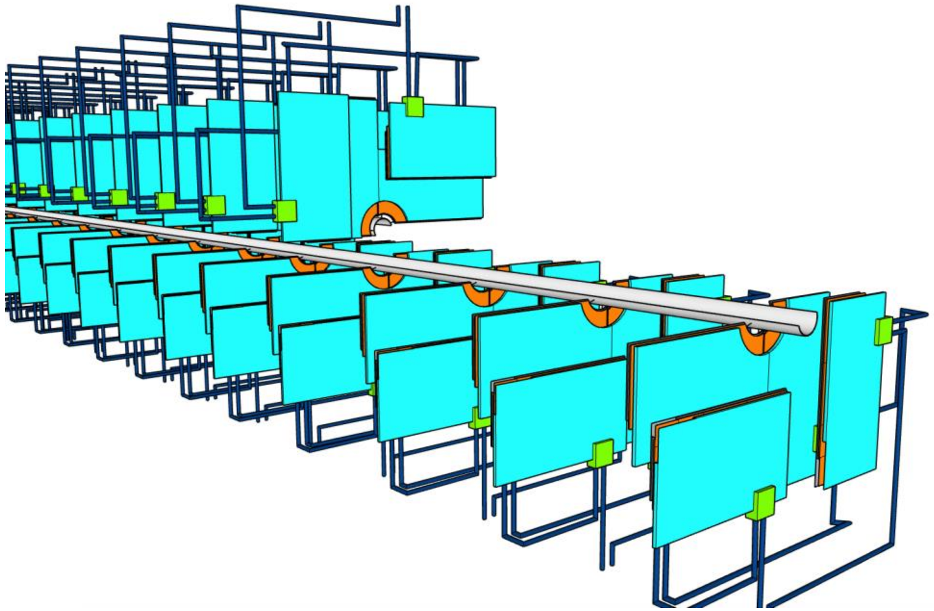
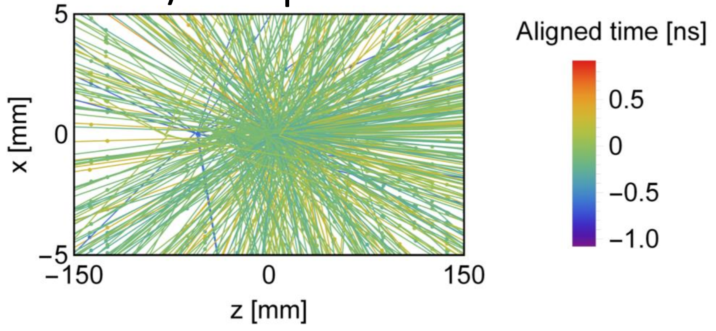


Vertex Locator (VELO)

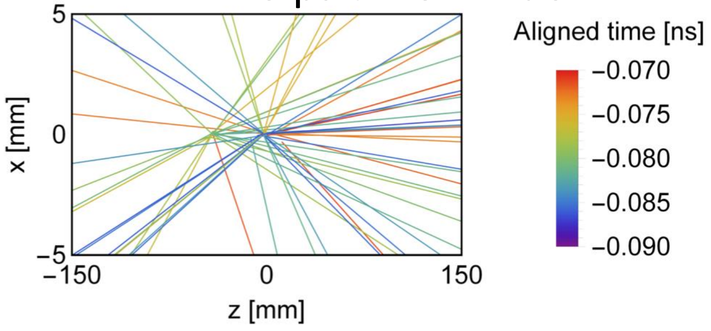


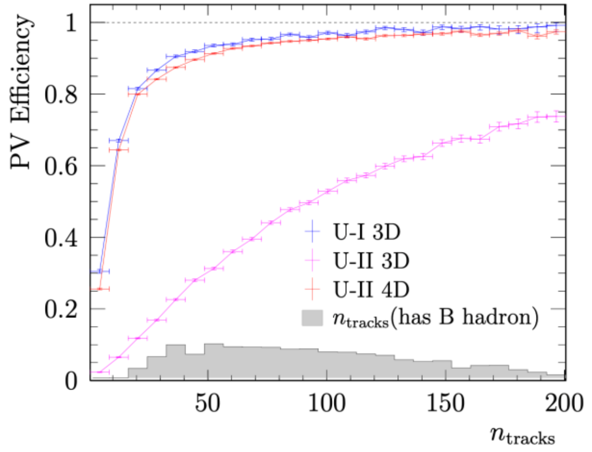
- L_{peak} = 1.5 X 10^{34} $cm^2 s^{-1}$ → ~42 interactions/crossing or ≈2k charged particles in VELO acceptance
- By adding timestamp similar performances as for Upgrade 1 are achieved
  - 50 ps per hit timestamp (i.e. 20 ps/track)
  - ASIC bandwidth > 250 Gb/s
  - X 6 radiation hardness wrt U1

w/o 20 ps time window



W 20 ps time window

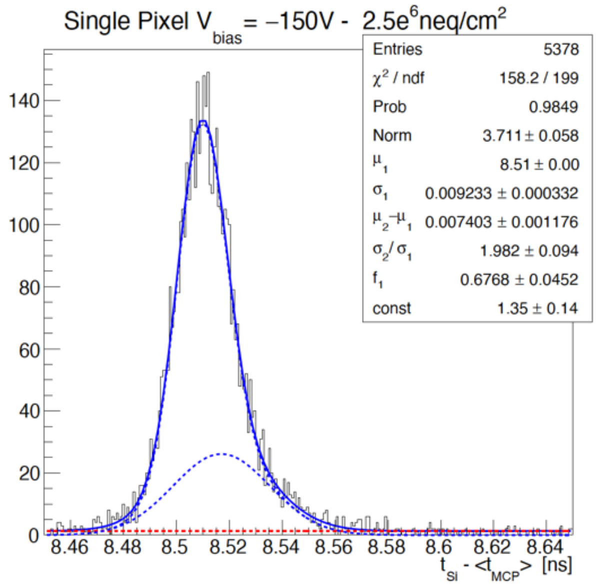




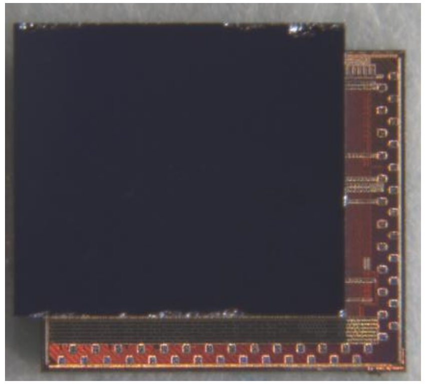
- Alternatively, we can reduce pixel size (40 µm), increase distance from the beam, and further optimize material budget (VELO mechanics, vacuum, cooling system)

VELO R&D

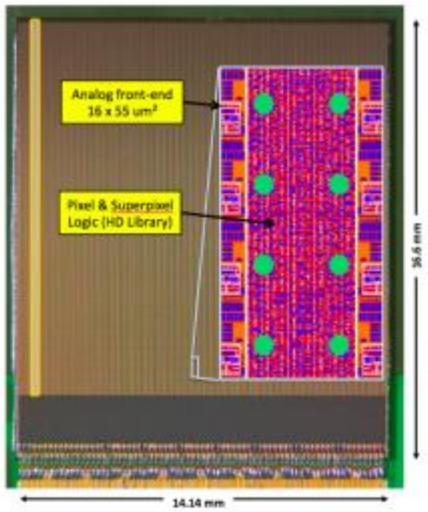
- Explored technologies to achieve full 4D reconstruction include LGADs, 3D-trench silicon sensors, ultra-fast planar silicon sensors
- FE electronics (ASIC) should match per-hit time measurement and pixel pitch of VELO
  - TIMESPOT demonstrator chips implemented in 28 nm CMOS to evaluate performances → excellent timing resolution (σ_{eff} = 10.3 ps @ 150 V) after irradiating w/ 2.5 X 10^{16} n_{eq}/cm^2
  - PicoPix design on track, similar pixel and chip size and can achieve 20-50 ps resolution



First 28 nm ASIC in HEP



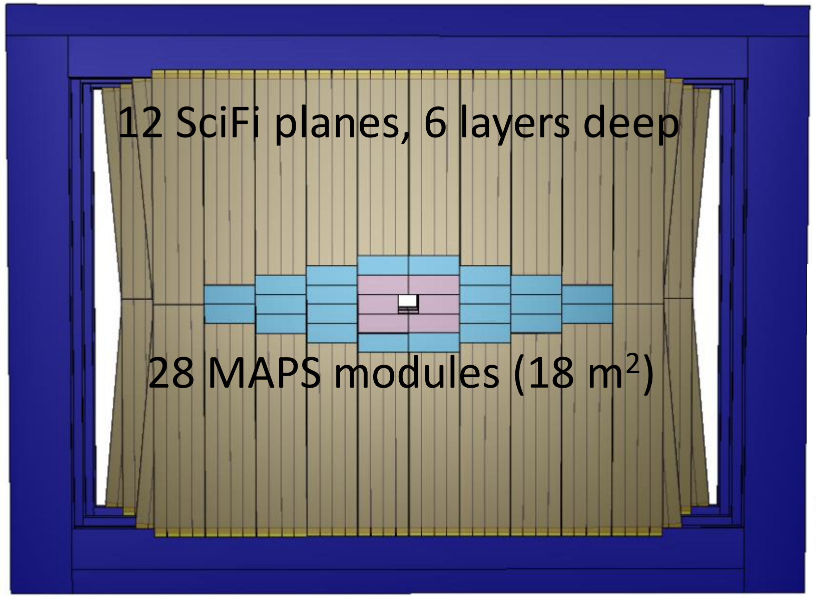
Hybridized Timespot1 ASIC, 32x32 pixels, $55\mu m$ pitch

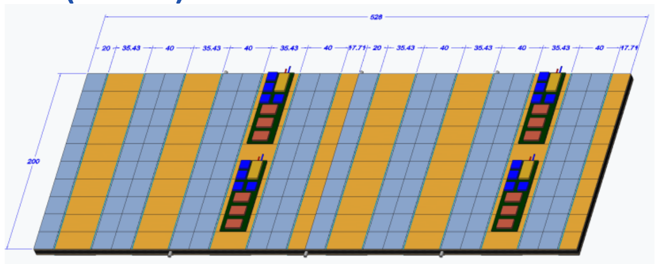


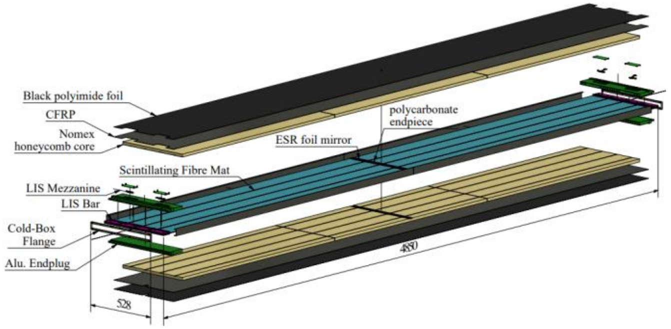
VeloPix ASIC

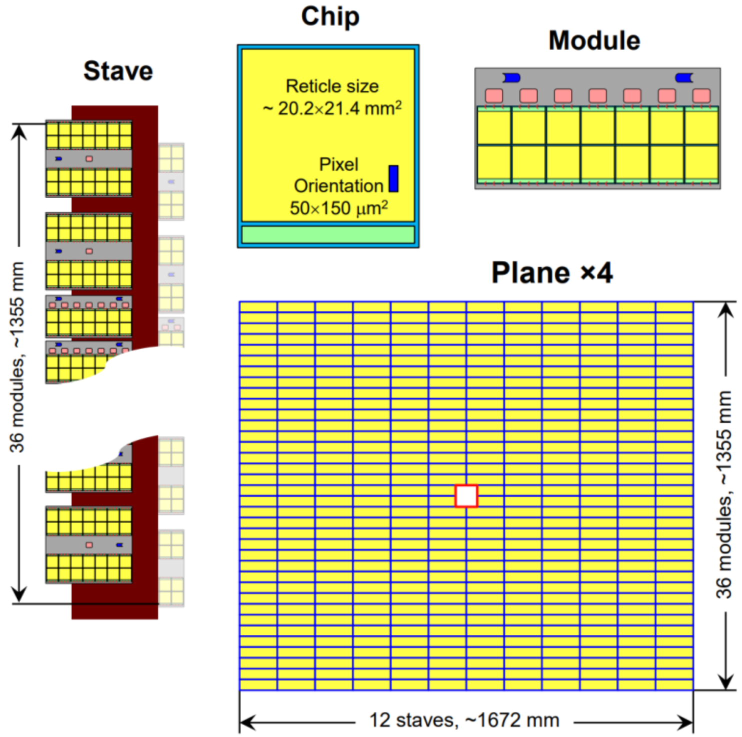
Upstream (UT) & Mighty Tracker (MT)

- Upgrade 2 high track density requires the usage of active pixel detectors both upstream (Upstream tracker, UT) and downstream (Mighty Tracker, MT) of the magnet
  - σ_{res} of few ns, material budget < 1% X_0, 6 X 10^{14} n_{eq}/cm^2 fluence for MT (3 X 10^{15} for UT)
- DMAPS are a promising cost/effective option for large-area pixel detectors (also LGADs, etc..)
- MT design (30 m^2 per layer, 3 layers):
  - MAPS in inner region w/ HV-CMOS electrode (AtlasPix, MightyPix)
  - Scintillating fibers in outer region (SciFi) & SiPMs
- UT design (4 planes):
  - MAPS detector (w/ AtlasPix)



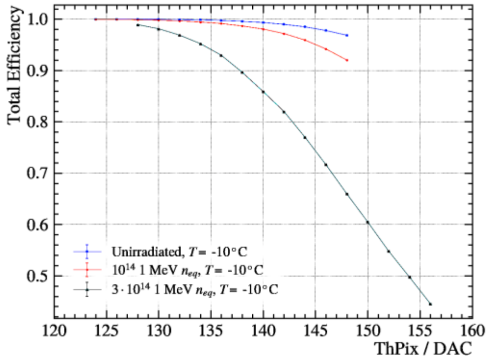


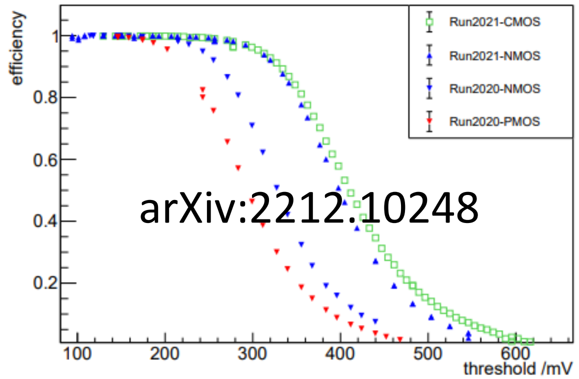




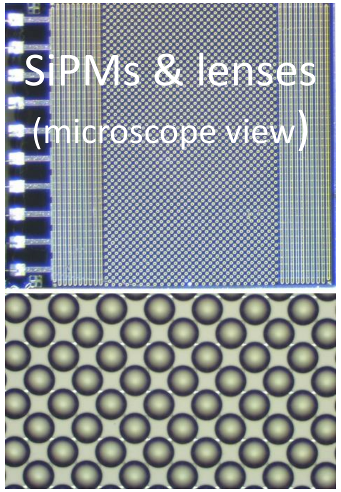
Trackers R&D

- MAPS R&D aimed at improving σ_{res} up to 3 ns w/ radiation hardness and w/o increasing consumption
  - Building from experience of Mu3e, ATLAS, ALICE
  - First prototypes prepared; thermal testing ongoing
  - Several approaches for cooling are being studied
  - Different Pixel prototype sensors tested

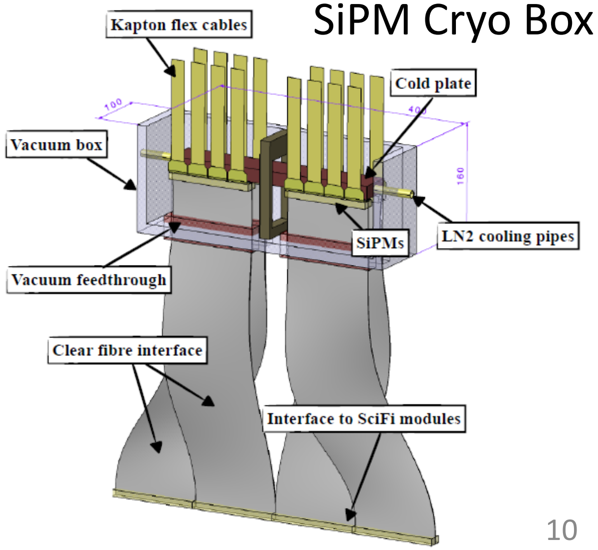




- SciFI R&D are aimed at containing SiPM noise and improve overall radiation hardness & durability
  - SiPMs have high dark count rate (DCR)
    - Micro-lenses (focus light) → improve light yield
    - Cooling to cryogenic T → reduce noise
    - Reduction of cluster size → same ε, less DCR
  - New NOL scintillator to reduce impact of radiation damage
    - Emits green-light, less susceptible to LY loss

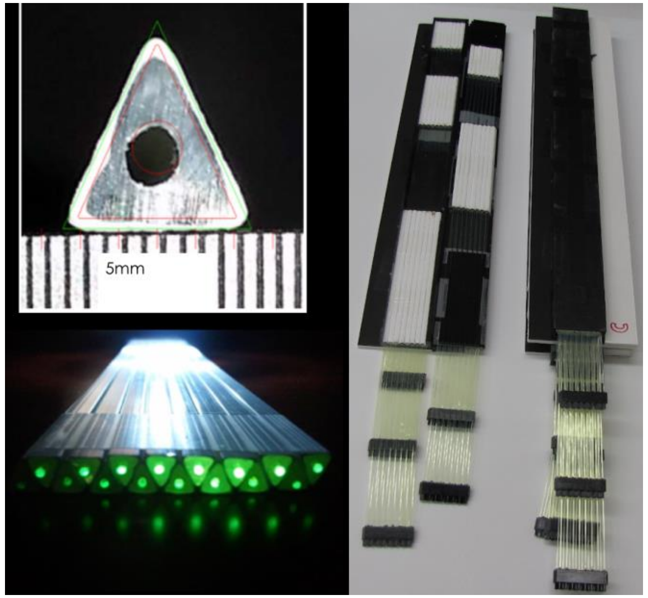


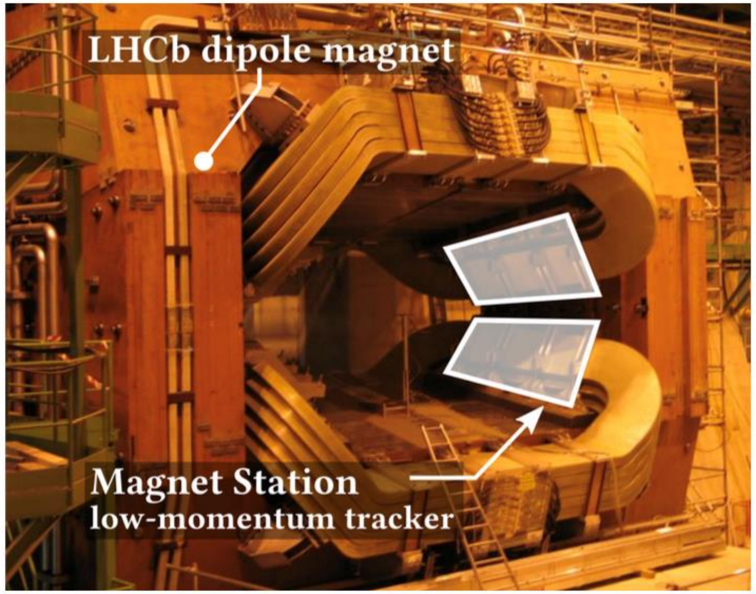
SiPM Cryo Box

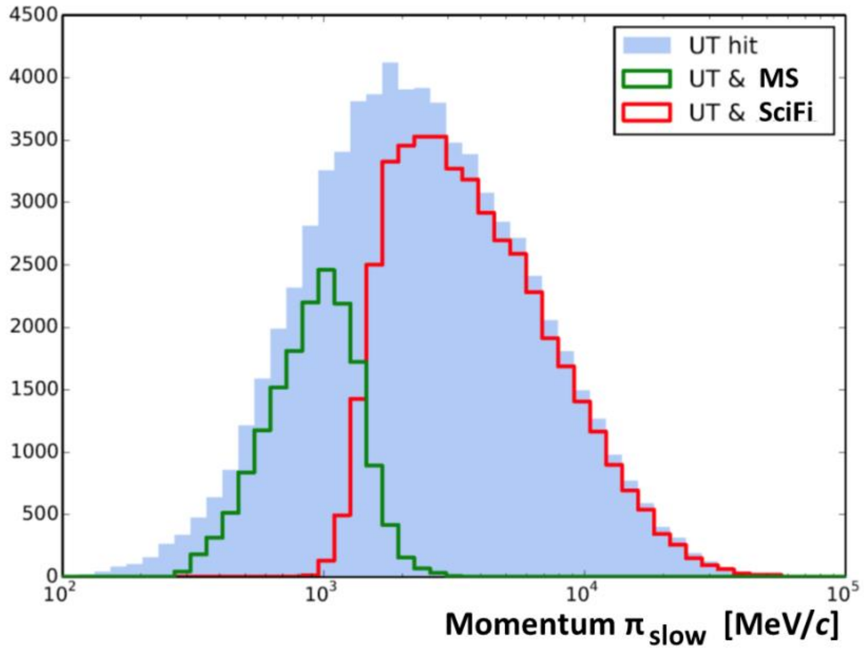


Magnet Station (MS)

- Scintillator-based tracking system to measure position/direction of particles hitting the magnet inner walls
  - New subsystem for Upgrade 2!
  - Improves momentum resolution of upstream tracks (<1%)
  - Significant increase in acceptance for low-momentum tracks (e.g. X2 for prompt D^{*+} w/ slow π)
- Triangular scintillating bars w/ 1mm WLS fibers and SiPM light readout (outside the magnet)

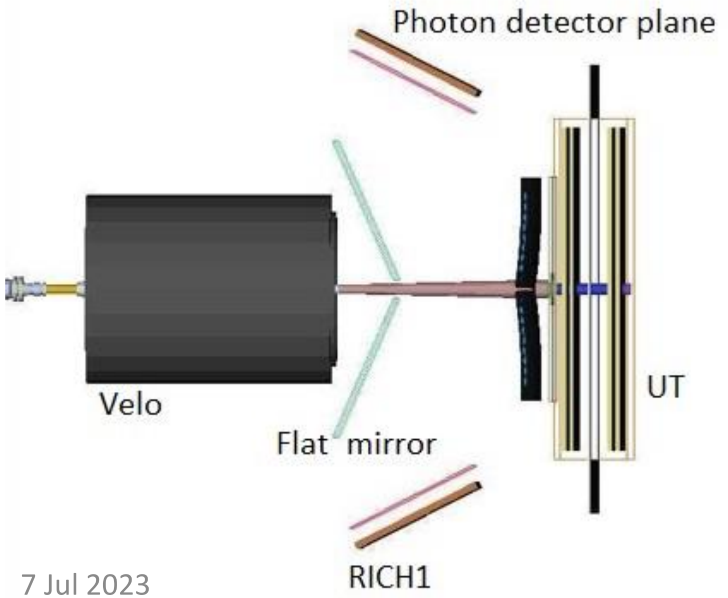


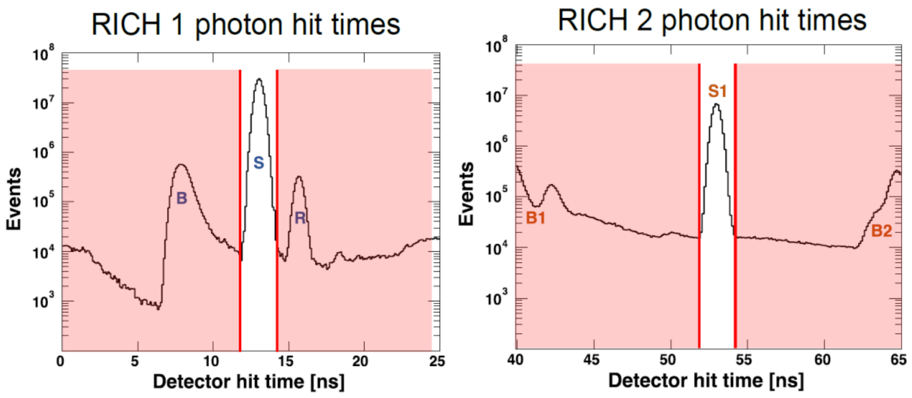


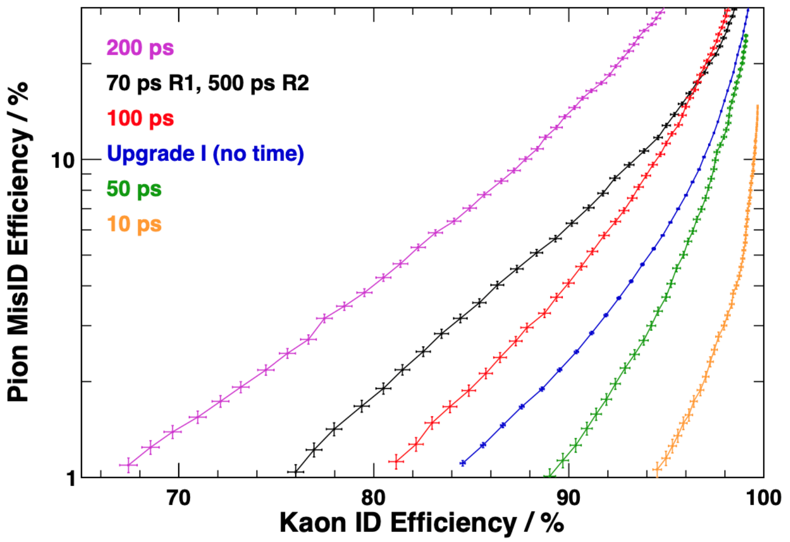


RICH Detectors

- Baseline plan: re-design RICH system w/ similar footprint to RICH1 & 2
- Luminosity is a challenge: need high-resolution timing, better θ_{Ch} resolution
  - Photon detectors w/ high radiation tolerance and good space & time resolution
  - Reduced tilt in mirrors to decrease chromatic abberration (flat placed within acceptance)
  - Better reconstruction software, fast and powerful readout
- Key specs: occupancy below 30%, single-γ σ_θ < 0.5 mrad (also dependent on tracking)
- Foreseen resolution: 0.22 (0.13) mrad for RICH1(2)

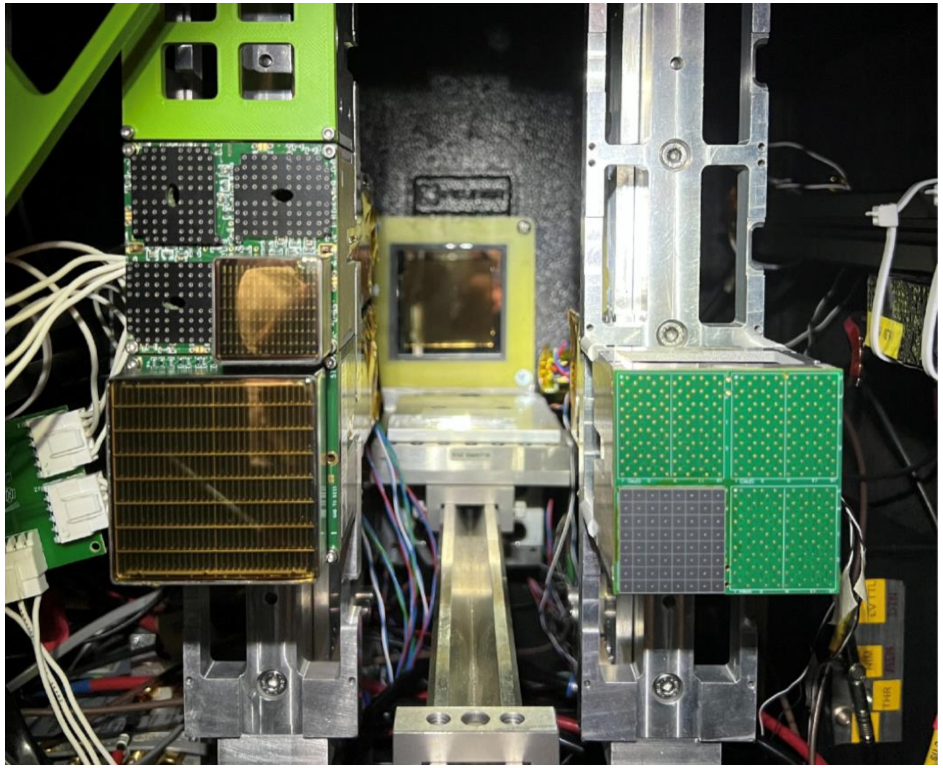




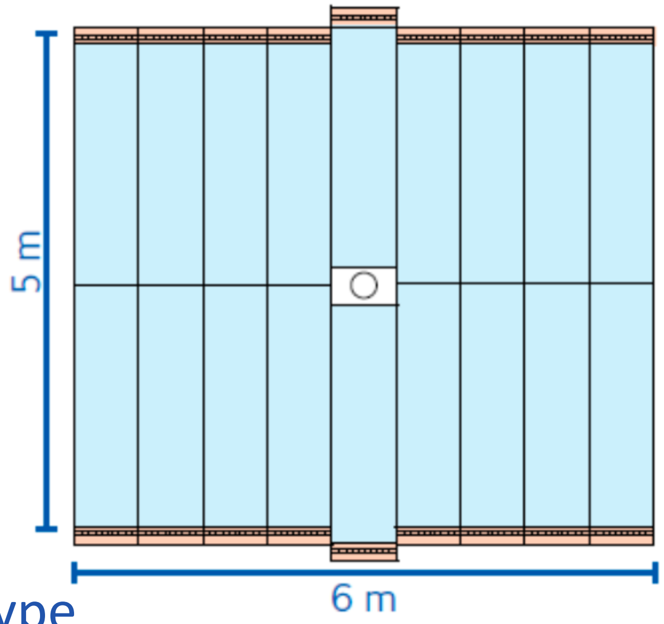


RICH R&D

- Current MaPMT photosensors can be used only in regions of low occupancy
  - SiPMs are a highly attractive option for high-occupancy regions
    - Better PDE, 1 mm^2 pixel, lower V, don't need B shielding but..
    - ~100ps σ_t and DCR < 100 kHz/mm^2 are required (requires cryogenic cooling, n-shielding)
    - Micro-lensing & FE time gate can reduce DCR
  - Microchannel-plate (MCP) also attractive
    - Exceptional σ_t (30 ps) and low DCR but smaller lifetime (improvements foreseen)
    - New designed w/ pixelated anode made of CMOS ASIC under study
- Testing new gas mixtures to improve angular precision
- Investigation on using meta-materials as radiators
- Massive R&D, simulation, and reconstruction effort, as well as prototyping

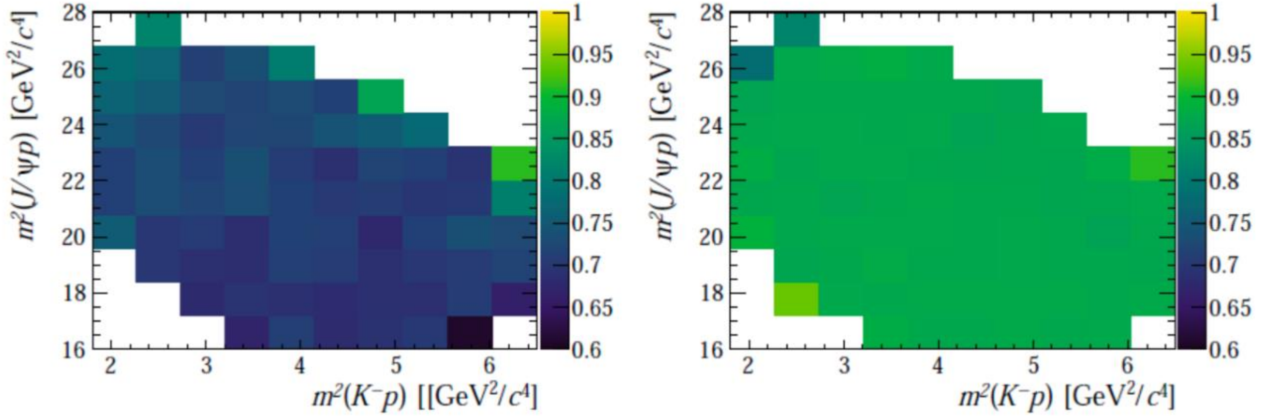


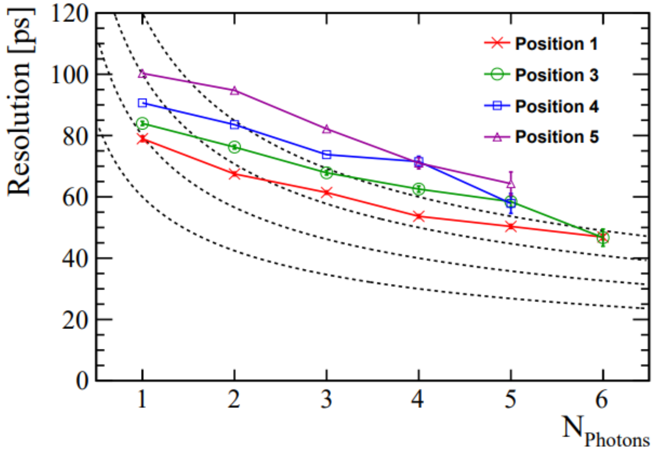
TORCH



- ToF detector w/ quartz planes read by MCP-PMTs in front of the RICH2
  - New to Upgrade 2!
  - 10-15 ps time resolution per track
  - Provides p/K (improves π/K) separation below 10 (5) GeV
- Clear physics benefits of low-momentum PID
  - Increased ε and bkg suppression in many channels
  - Improved flavor tagging with soft kaons (20-50%)
  - Improved uniformity in PID acceptance
- R&D w/ prototype
  - Measured photon yields compared w/ MC
  - Time resolution approaching 70 ps / photon

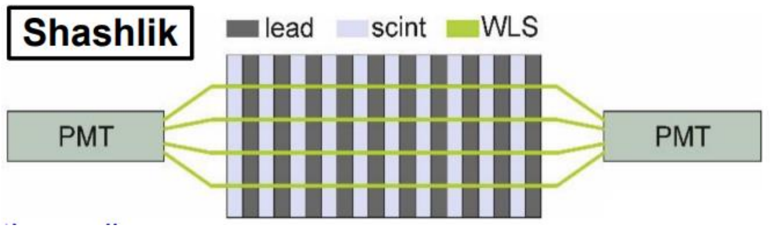
Dalitz plot efficiency for $\Lambda_b \to J/\psi p K^-$ w/o and with TORCH

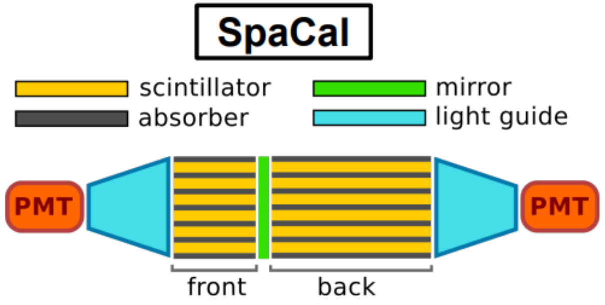


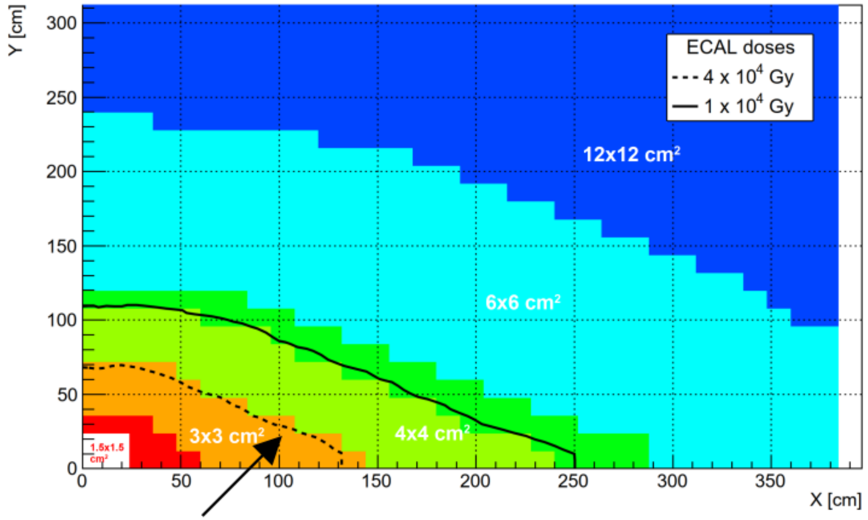


Electromagnetic Calorimeter (ECAL)

- Current ECAL optimized for π & γ identification in few-100 GeV region (radiation hard up to 40 kGy)
- Requirements for Upgrade 2:
  - Sustain radiation up to 1 MGy while retaining current σ(E)/E ≈ 10% √E + 1%
  - Pile-up mitigation via precise timing (O(10)ps) and increased granularity
- Occupancy map calls for a modular structure
  - SpaCal technology for the inner region
    - 40-200 kGy region modules (3x3 cm2 cells) w/ scintillating plastic fibers and Pb absorber
    - Innermost ≤1 MGy modules (1.5x1.5 cm2 cells) w/ scintillating crystals and tungsten absorber
  - Shashlik technology for outer region
    - 2k existing + 1.3k new modules
    - Timing w/ WLS fibers, double readout



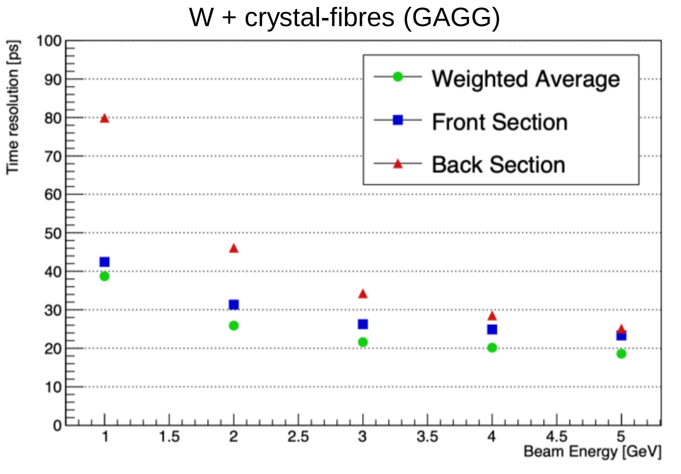


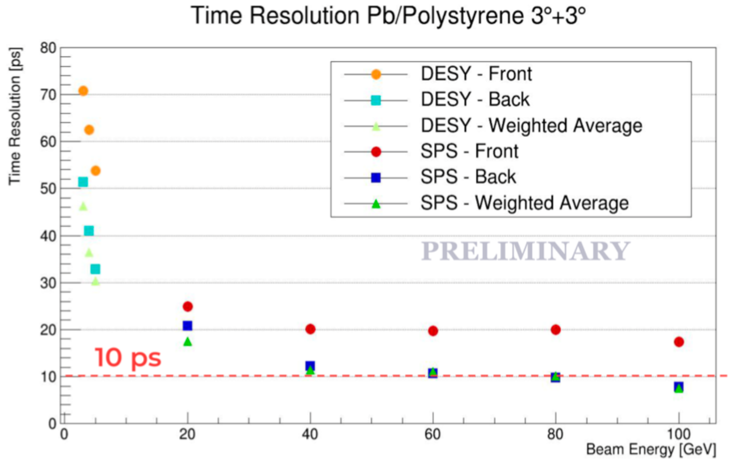


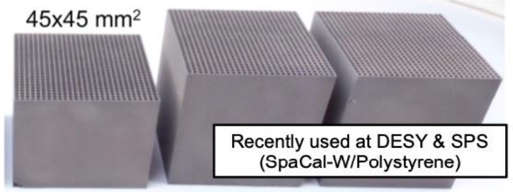
Radiation limit of current Shashlik technology

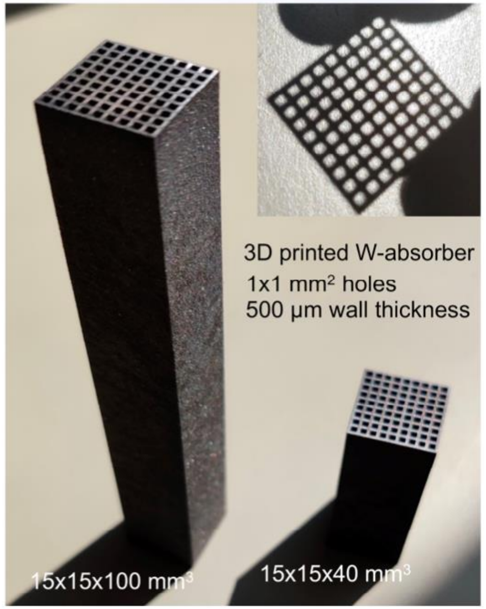
ECAL R&D

- Upgrade strategy foresees gradual implementation of SpaCal modules during LS3 & 4
- R&D on SpaCal σ_t shows excellent results for W + crystal fibers & Pb + polystyrene fibers
- R&D on Shashlik w/ timing also shows excellent σ_t (single vs double readout explored)
- Need radiation hard materials
  - R&D on different crystals & organic scintillators
  - 3D printed tungsten absorber prototypes w/ smooth surfaces



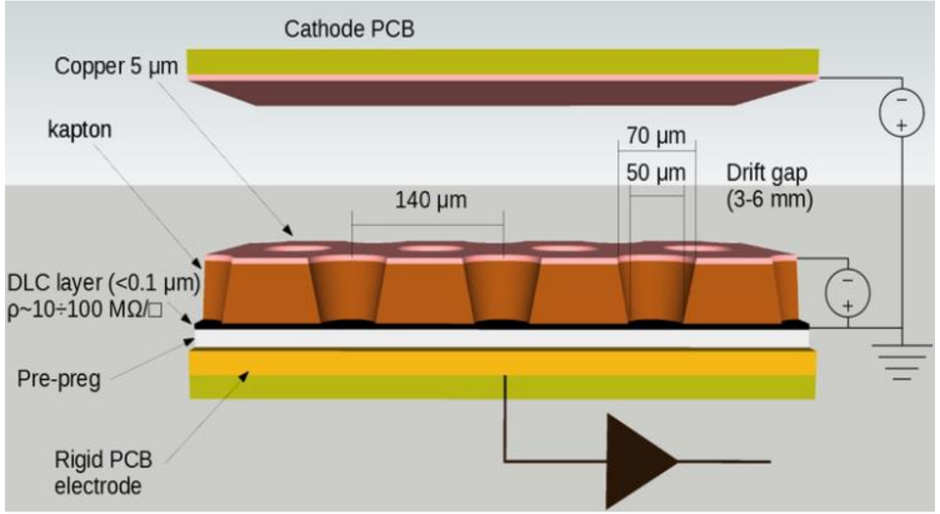


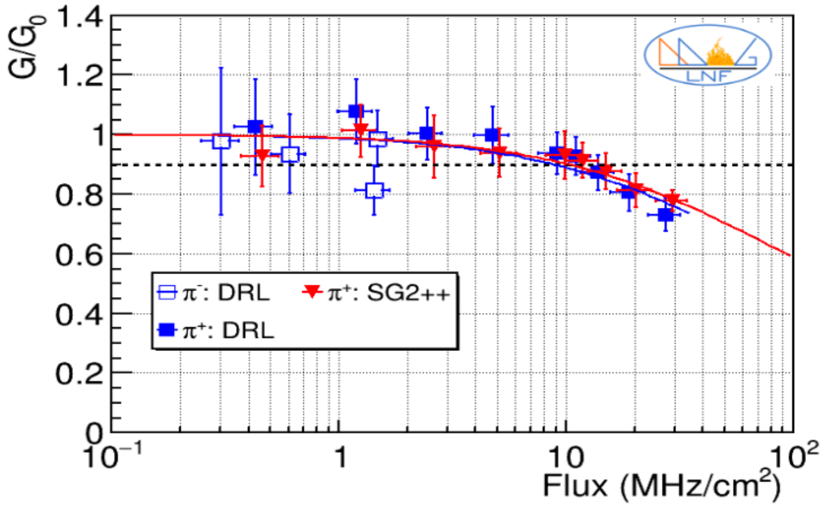




Muon Station

- Novel MPGD detectors (muRWELL) for the inner region (144 chambers)
  - Can stand several MHz/cm^2
- Keep present MWPCs chambers for outer region (880 reused + 80 new w/ higher granularity)
- Additional shielding (6 → 10 λ_I) will be installed in lieu of the HCAL
  - Factor 2 reduction of rate while maintaining same trigger and hadron reconstruction capabilities
- R&D focused on ageing studies at GIF++, FE electronics under development

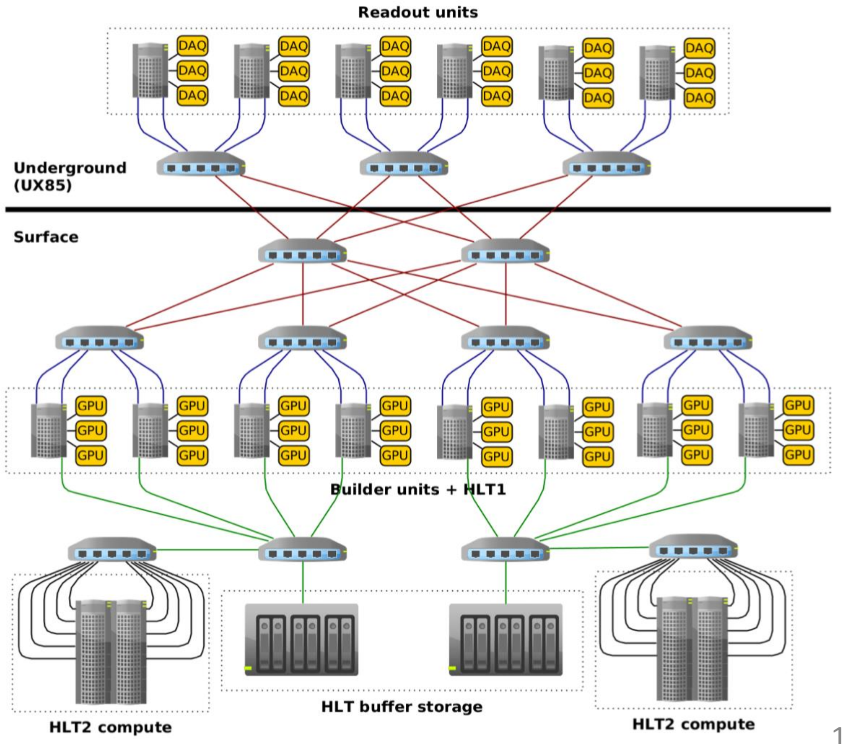




DLC sputtering machine for base material realization @CERN

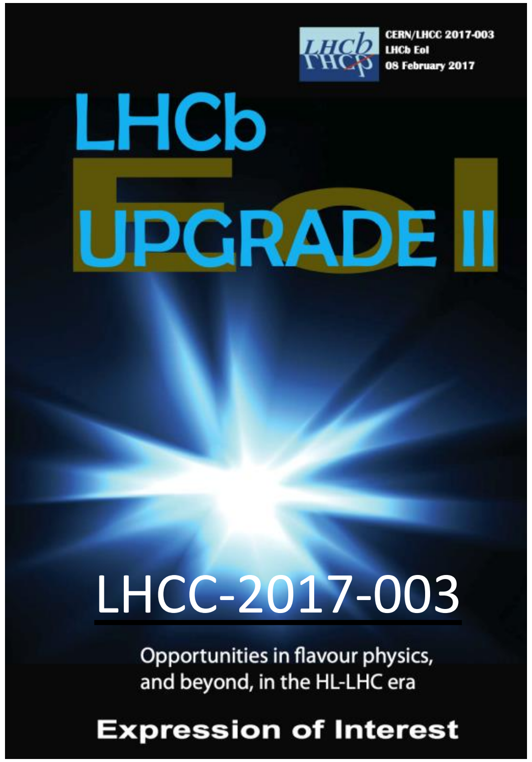
Trigger and Data Acquisition

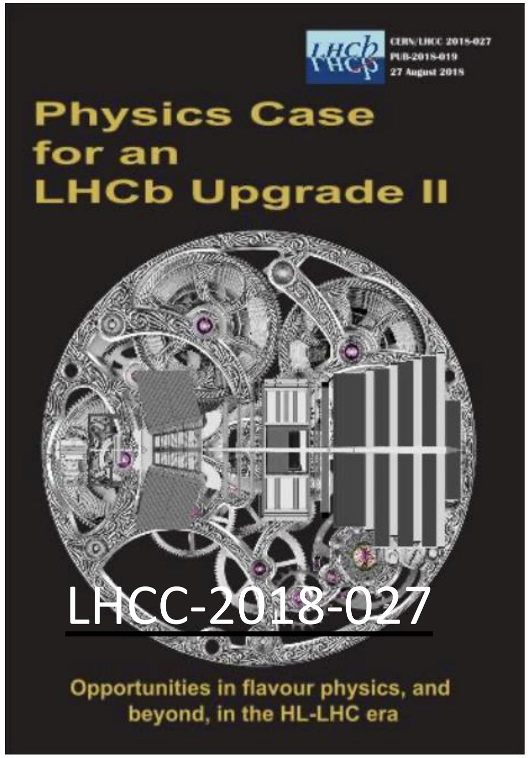
- Readout and DAQ should be reliable, scalable, cost-effective, flexible for heterogeneous compute elements (GPUs, CPUs, FPGAs, etc..)
- Architecture similar to Run 3: single-stage readout (single custom-made FPGA board) → event building (local network) → two-stage high-level trigger (HLT1 & HLT2)
- Full software trigger already implemented for Run3 (first time for a hadron collider)
  - HLT1 fully based on GPUs (~40 Tb/s of data processed)
- Upgrade 2 will upscale these numbers
  → need faster readout & improved algorithms
  - ~200 Tbits/s from detector
  - ~800 Gb/s on disk
  - Full event reconstruction (HLT1 & HLT2) based on GPUs
  - R&D investigating hybrid architecture (GPUs, FPGAs, ..)
- Testbed of new technologies in Run3 readout environment



Where we Stand Now

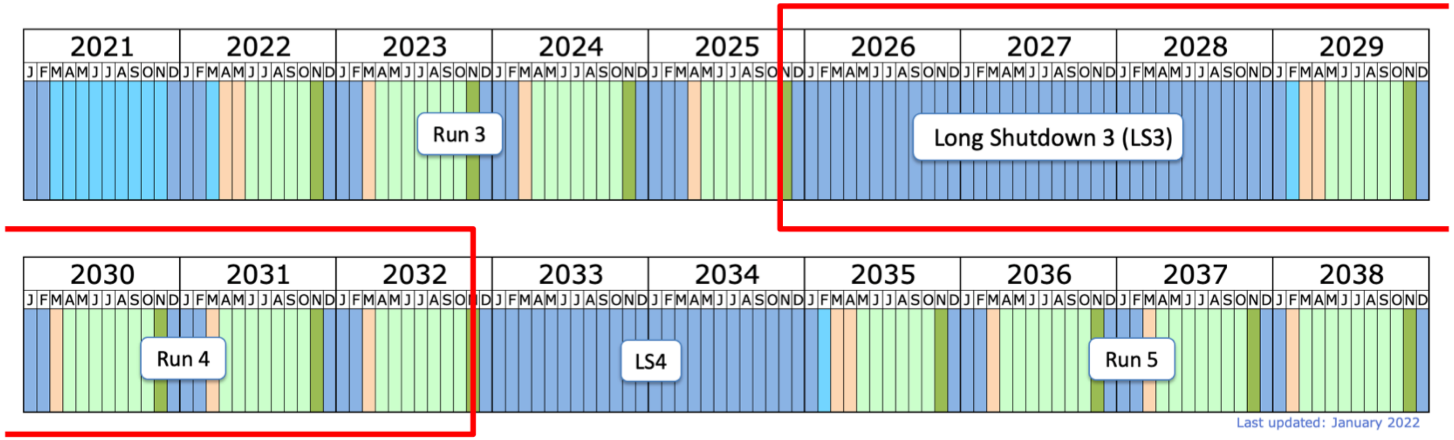
- After Expression of Interest (2017) & Physics Case (2018), Framework TDR approved in March 2022
- We need to complement it with more detailed plans / scoping scenarios, manpower and funds, before moving to sub-detector TDRs
- Target: produce the Scoping Document within 2024

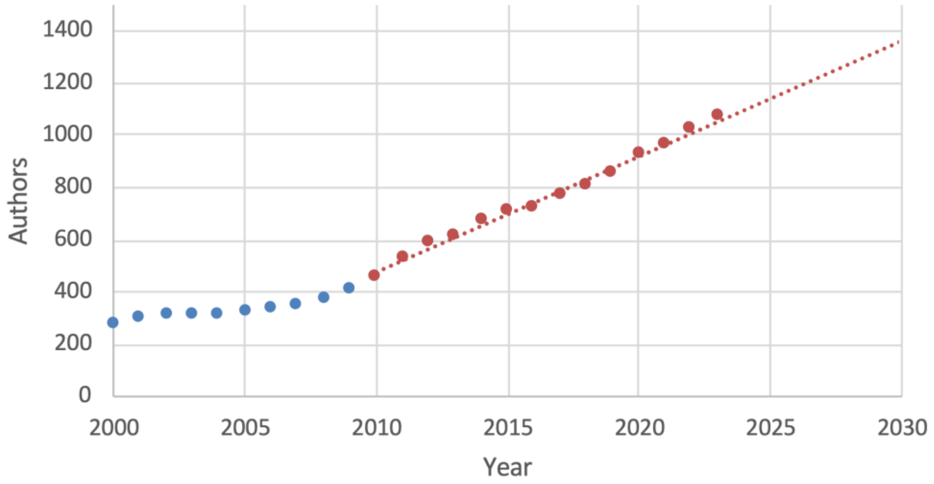




Timeline, Collaboration & Resources

- Priority of LHCb in the coming years is to exploit all physics potential of Upgrade 1 detector
- Planning for Upgrade 2 within the time constraints
  - R&D efforts will continue throughout Run 3, before sub-detector TDRs
  - Infrastructure preparation and detector construction should begin in LS3
  - Ready for Upgrade 2 installation only in LS4
  - LS3 is an opportunity to increase LHCb performances and lay basis for U2
- The project presented in FTDR is very ambitious, a larger collaboration is needed!
- Strong interest from the community in our physics case (X2 collaboration in the last decade) more people are welcome to keep the growth going





Summary

- LHCb as a general-purpose detector in the forward region has produced a wide range of compelling physics results, and has a unique potential to explore new physics with HL-HLC
- The harsh conditions of HL-HLC call for an intelligent remodeling the detector, adapting individual subsystems to the HL conditions without worsening (and possibly improving) performances
- An intense and attractive R&D program is ongoing, that really pushes the limit of existing technologies in HEP and explores new uncharted scenarios
- First approval steps fulfilled, following a clear strategy laid by LHCC (next: Scoping Document 2024)
- A clever usage of all time slots (e.g. preparation of installation of Upgrade 2 during LS3) is important to stay on schedule
- Upgrade 2 will ultimately give us the unique opportunity to fully exploit the great physics potential of HL-HLC
- **Upgrade 2 is an ambitious project, with excellent prospects for physics and for developing new technologies, new collaborators are welcome!**

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Thank you!