LHCb Upgrade II – Tracking System

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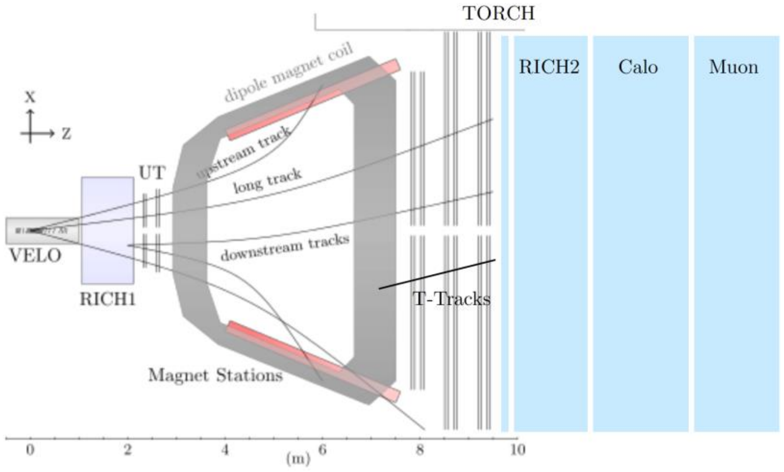
第4届LHCb前沿物理研讨会@烟台

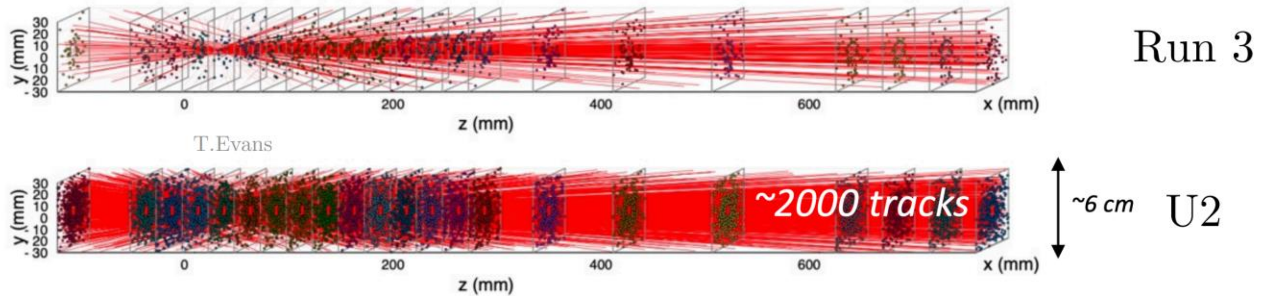
LHCb Upgrade II

2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042

LS 2 | Run 3 | LS 3 | Run 4 | LS4 | Run 5 | LS5 | Run6

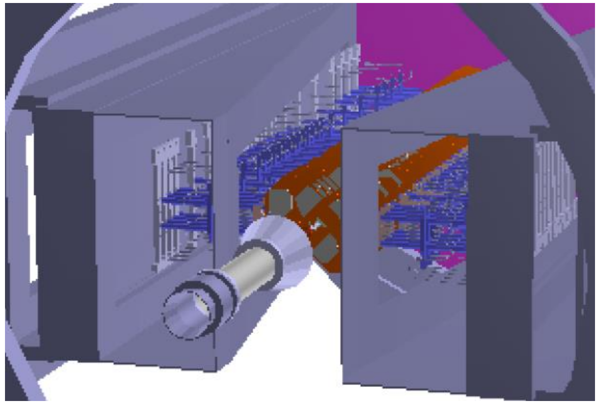
- LHCb upgrade II: Intend to run at $5\times\sim7\times$ higher instantaneous luminosity ($\sim10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$) and provide massive physical program output, maintaining or exceeding the performance of Run3
  - Estimate ~40 pile-up, ~ $O(200)\mathrm{Tb/s}$ data readout
- Essentials: efficient charged particles reconstruction, vertices reconstruction and association, mass (momentum) resolution, signal versus background separation
  - Higher granularity, faster timing, lighter material, radiation resistant ⟹ tracking system
  - Efficient track reconstruction (software trigger) >96%
  - Ghost rate for long+downstream tracks <10%
  - Vertexing capabilities ~σ(IP) ≈25μm, tracking timing ~20ps

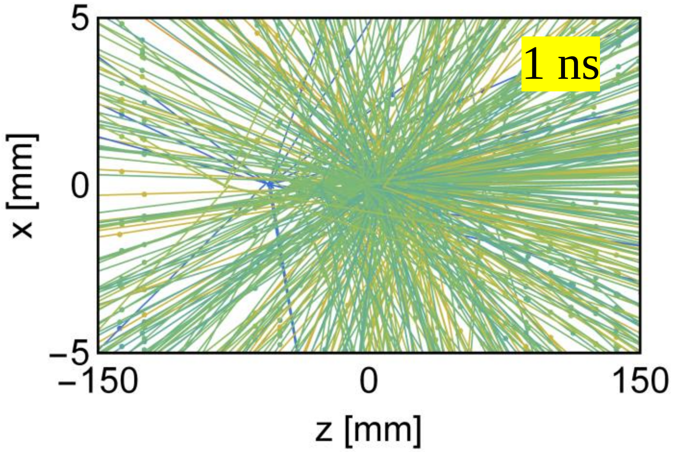


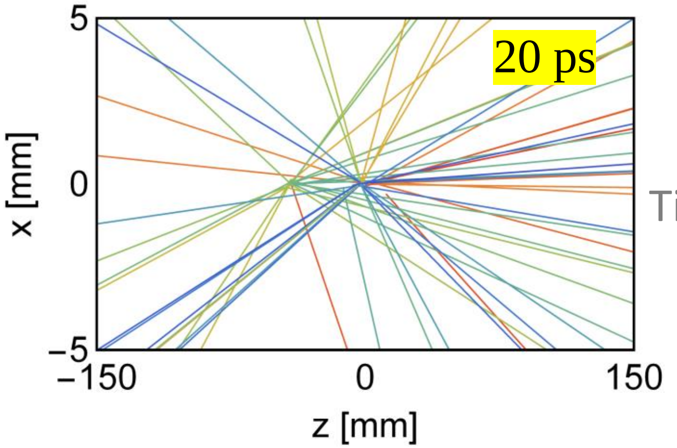


Velo (TV) detector: 4-D tracking

- Challenge: data rates, high hit/track/vertex density, high non-uniform radiation dose
- Hit timing: necessary to distinguish PVs and reject out of time hits in pattern recognition.
- Design for several different scenarios, performance studies are mostly based on scenario A:
  - Geometry remains the same as Run3; Hit timestamp with precision ~50 ps





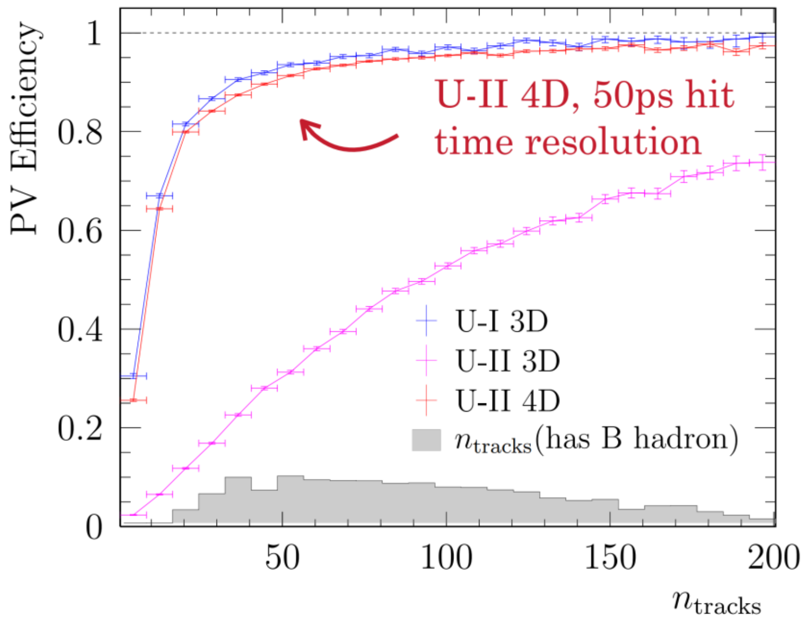


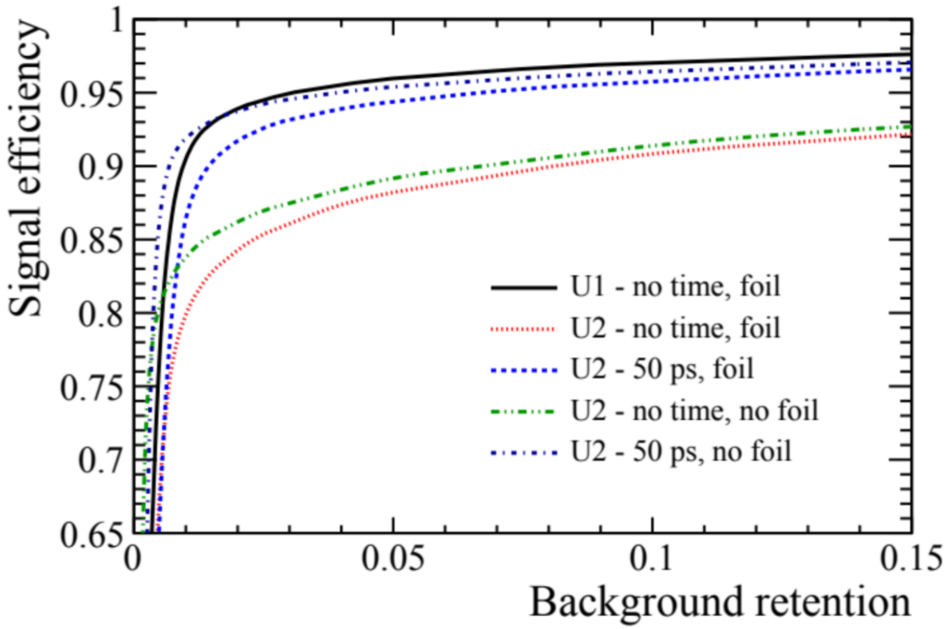
Tim's

  - Alternative scenarios:
    - Scenario B: increase inner radius to mitigate radiation damage/ hit rate per pixel
    - Scenario D: aggressive cost reduction by limiting the technological choices (65 nm & planar sensor)
    - Scenario X: designed at the limits of radiation damage for the duration of Runs 5 and 6, 28nm & 3D sensor
    - Scenario H: cost saving option considering ACCEPTANCE CUT, heavier cooling substrate and overall module construction ⇒ EQUALLY HIGH DAQ RATES

Velo (TV) detector: 4-D tracking

- Addition of 50ps time resolution per hit recovers Run3 performance almost entirely for reconstruction of tracks and vertices
- Discriminating power of χ^2_{IP} can also be largely recovered using hit timestamp
  - e.g. separating tracks of a b-hadron from those promptly produced, time information help improved





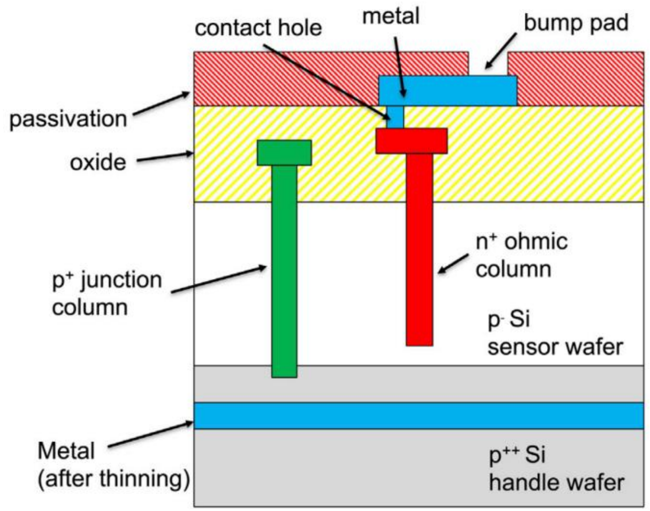
Tim's

Velo (TV) : possible technology & layout

- A lot of R&D needed on sensor + ASIC
  - Radiation hardness, deadtime, bandwidth

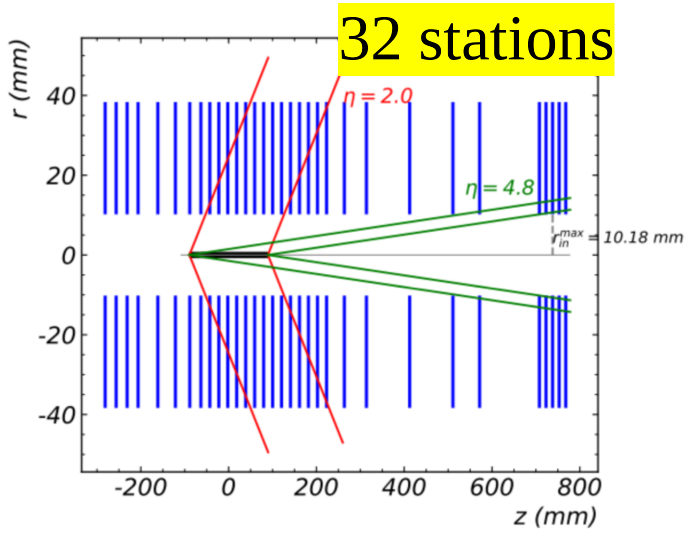
- 3D sensors: best candidate sensor technology, e.g. ATLAS 3D
  - Fabricated in the 65 nm CMOS technology, target 28nm?
  - At limited hit efficiency due to electronics

ATLAS 3D Pixel Sensors



- Minimum amount of hits is 3 to be able to reconstruct a track
- Naive interpretation: increase number of stations (and detector material) by 20%
  - 2**σ** luminous region
  - At least 5 planes in acceptance
  - Eta max of 4.8 for 100% acceptance

- Also assuming that we can achieve ~10 μm spatial resolution
  - smaller pitch implied

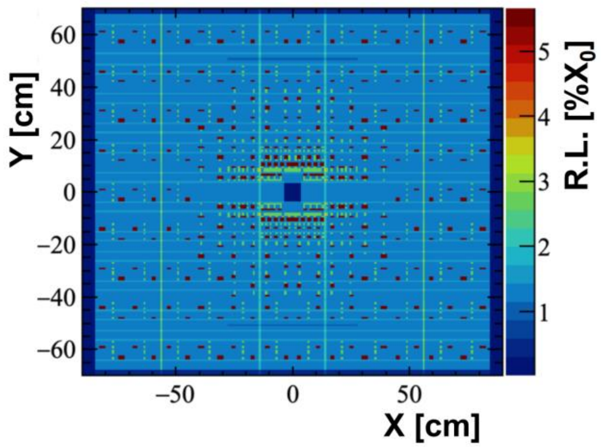


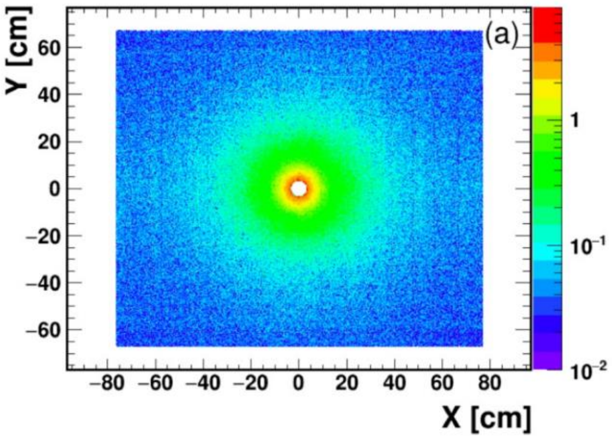
Kazu's

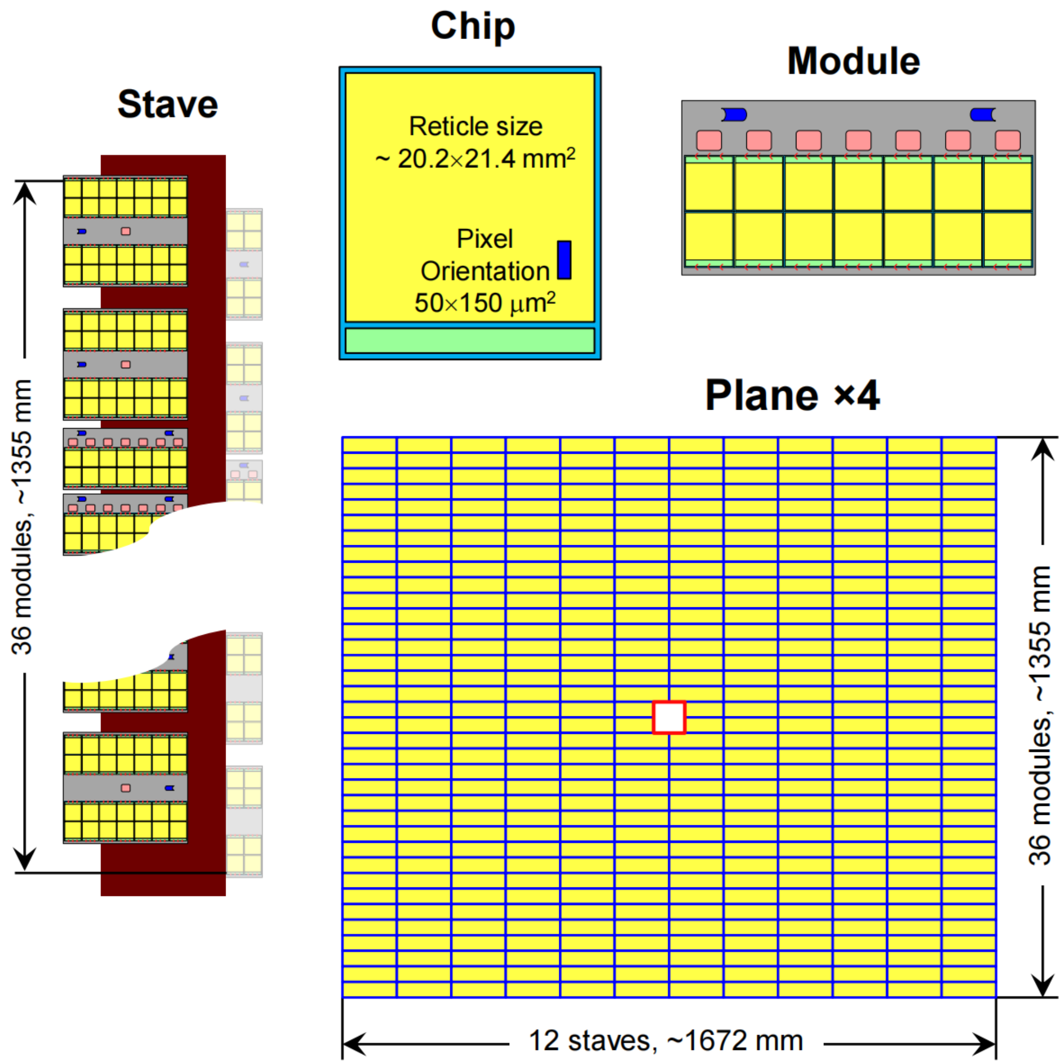
Upstream Tracker (UP)

- UP (UT) provides a fast track momentum estimate and plays a critical role in trigger strategy
- Essential to reconstruct long lived particles, e.g. K_S^0, Λ
- A MAPS-based pixel detector
- Certain features of the current UT may be kept
  - e.g. stave structure, and strip / long pixel orientation
  - Reduction to 3 layer need to be study
- Material budget aimed to be at/ below 1% level per layer
- Due to higher data rate , more electronics in the inner part leading to more material

Xuhao's

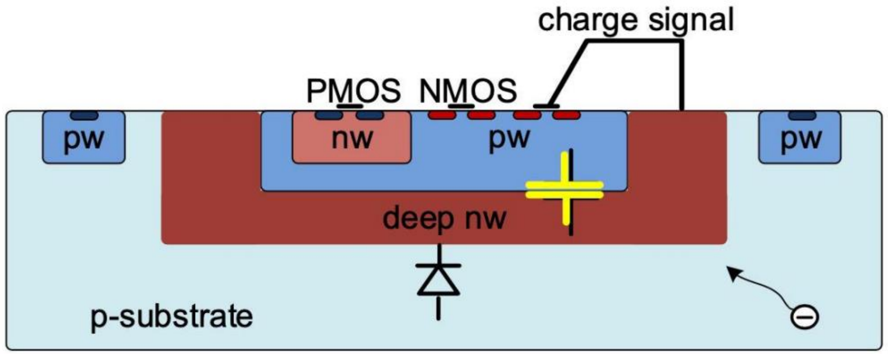


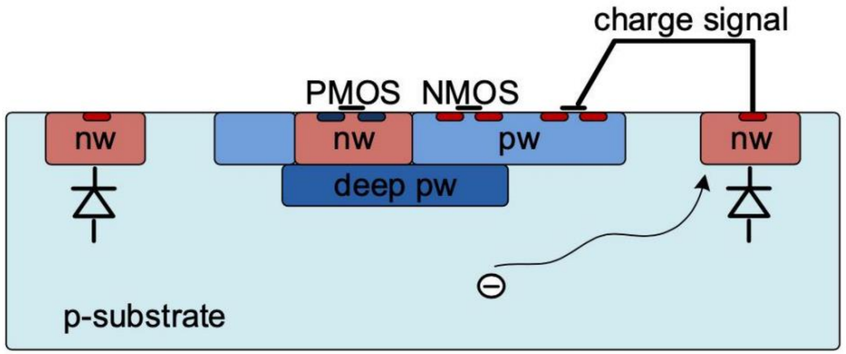




Chinese group contributes significantly

UP: MAPS technologies

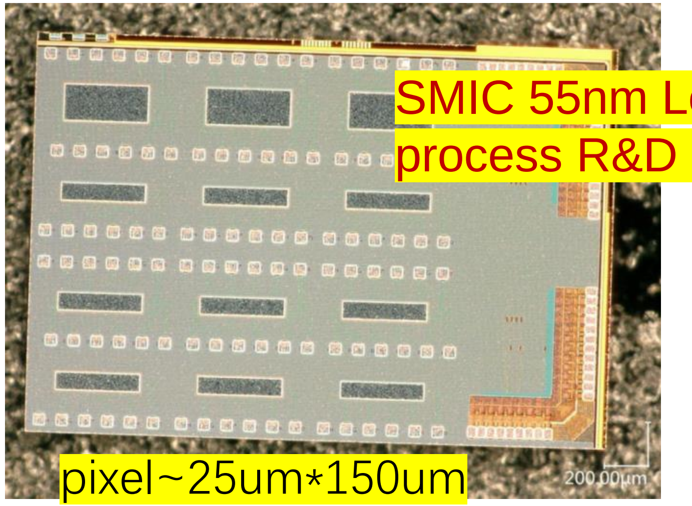




JC's

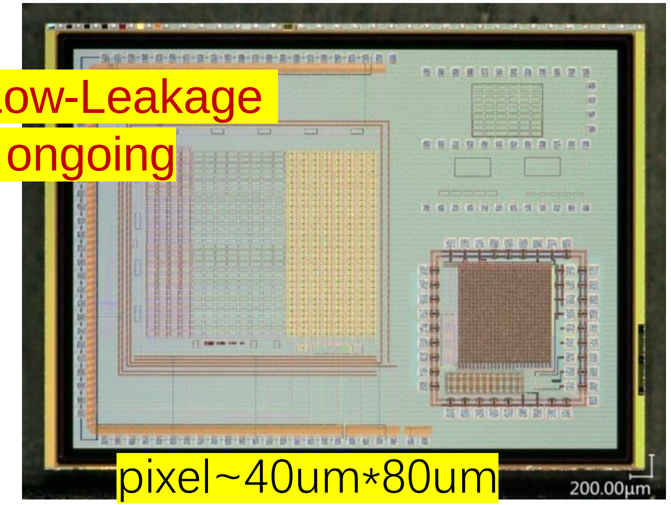
Large collection electrode
- Circuitry inside the charge collection well
- Large uniform electric field
- On average shorter drift path
- Better radiation hardness (less trapping)
- Very large sensor capacitance (both pw and dnw)

Small collection electrode
- Circuitry outside the charge collection well
- Optimization of little low-field regions
- On average longer drift path
- Radiation hardness needs process modifications
- Very small sensor capacitance

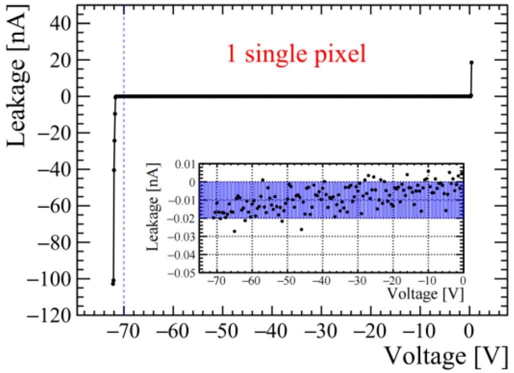


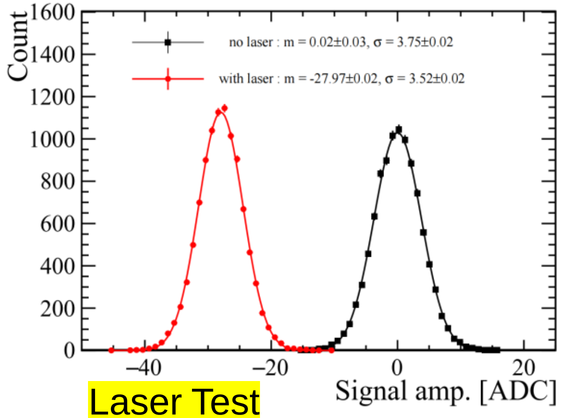
pixel~25um*150um

SMIC 55nm Low-Leakage process R&D ongoing



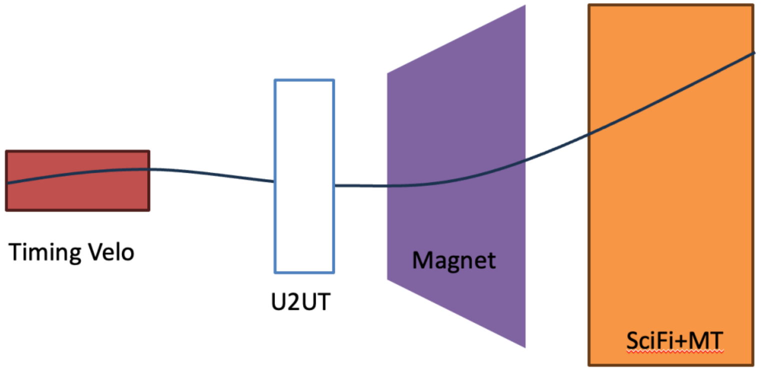
pixel~40um*80um



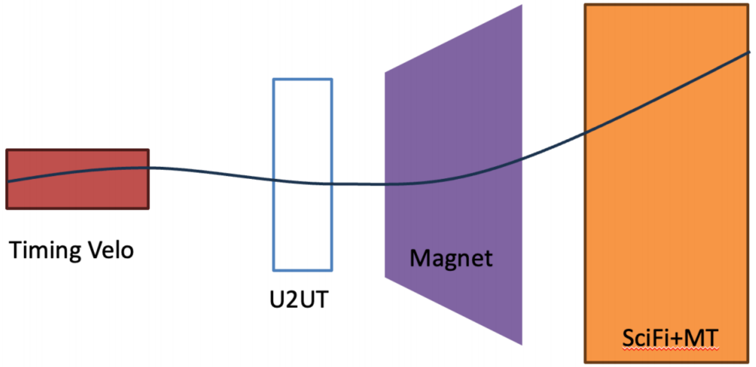


Laser Test

UP: role in long track system



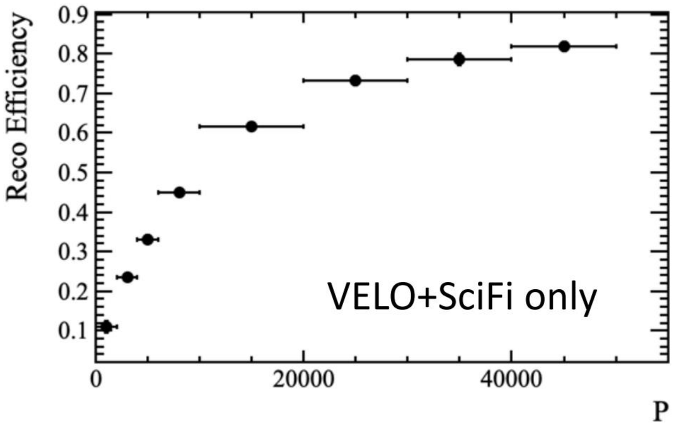
VELO-SciFi tracks w/o UT

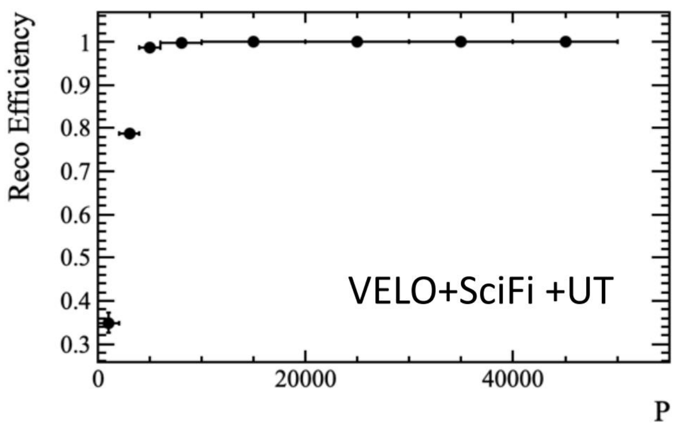


VELO-SciFi tracks w/ UT tracks

- Long tracks reconstructed by fitting in both XZ and YZ plane
  - In XZ plane, a 4th-order polynomial used for magnet effects
  - In YZ plane, a linear func. used

- Quick test studied with Kaon tracks under Run3 condition
  - VELO+SciFi only: total efficiency ~50% and the "ghost rate" ~34%
  - VELO+SciFi +UT: total efficiency ~94% and the "ghost rate" ~4.5%



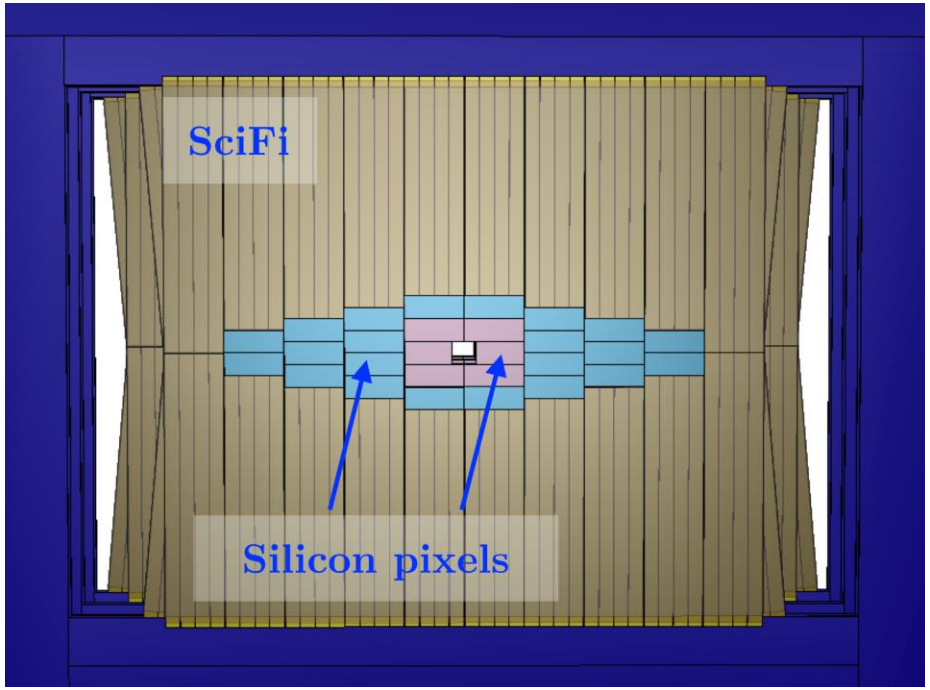


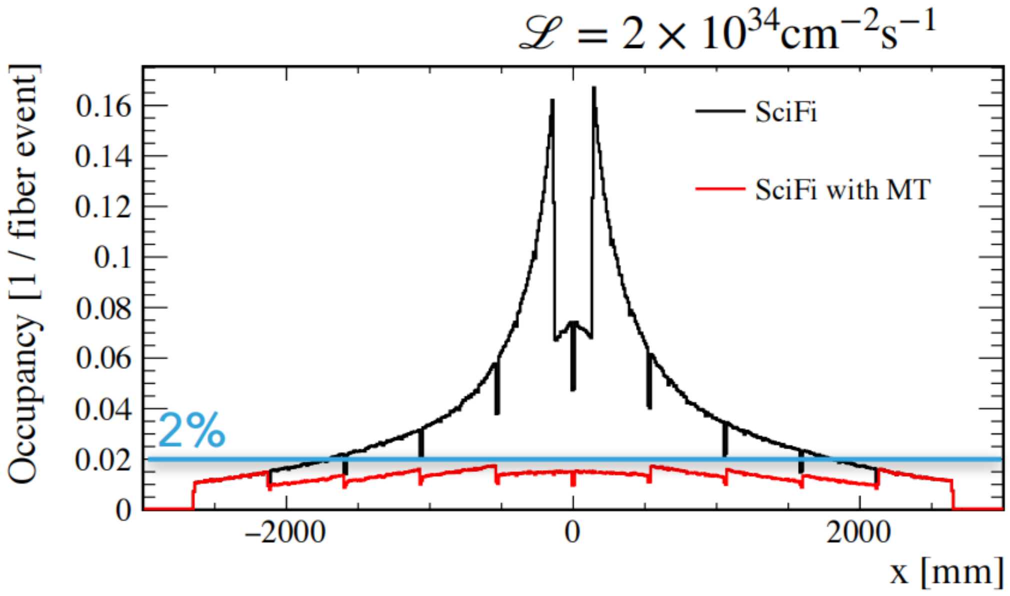
Xuhao's

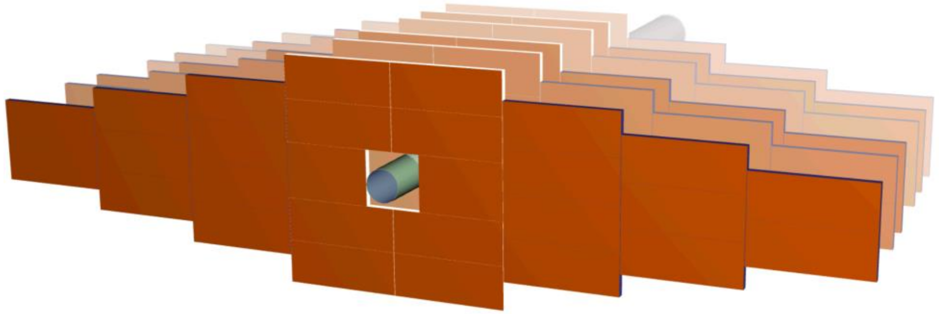
Downstream tracker: Mighty Tracker (MP+FT)

- HV-CMOS sensors for highest track density region, Scintillating Fibre (+SiPM) in outer region
- Initial layout from FTDR:
  - 6 layers of HV-CMOS pixels. Each layer 3 m^2 (18 m^2 in total)
  - Each layer divided into 28 modules 54 x 20 cm^2
  - 50 x 150 μm^2 (100 x 300 μm^2 pixels already ok for physics)

- Initial design driven by SciFi radiation damage and occupancies
  - Assumed SciFi as U1 (no gains for better SiPMS or cooling)



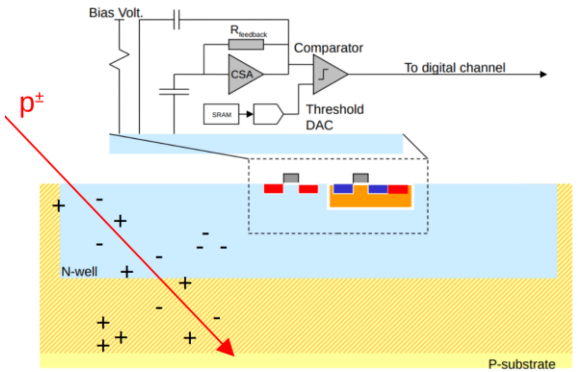


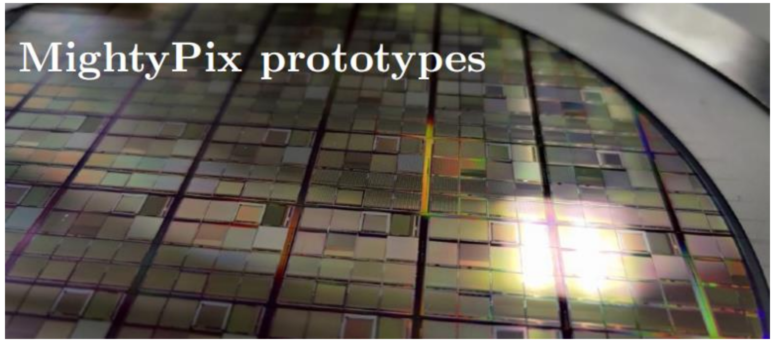


MT: MightyPix technologies

- Challenges:
  - In Time Efficiency ; Power Consumption; Radiation Tolerance
- MPix1 R&D Chip, time resolution ~3ns:
  - Timing and Fast Control (TFC)
  - Configuration register interface
  - Clock:40MHz external from lpGBT
  - Triggerless readout also supported

- MightyPix1 design has been verified with Test Beam, bug found:
  - Large x-talk in the chip due to shielding traces not tied down
- To be submitted in 2025 with MightyPix2, using 180nm





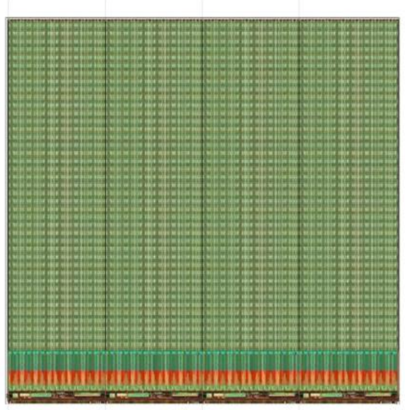
¼ size MightyPix1

Chip size: 5 x 20 mm^2
Pixel matrix: 29 x 320
Pixel: 50 x 165 μm^2

Black's

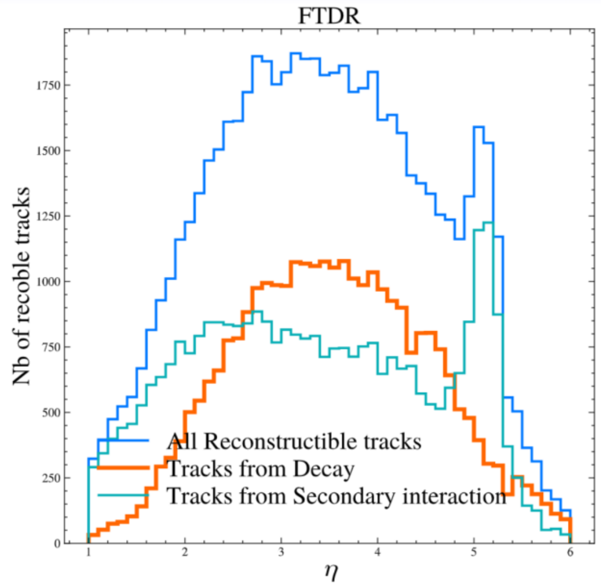
MightyPix2 & 3

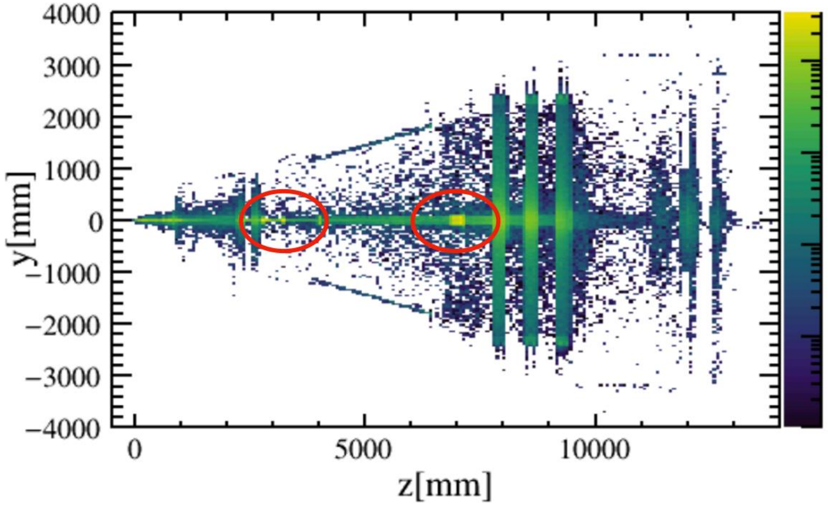
full size

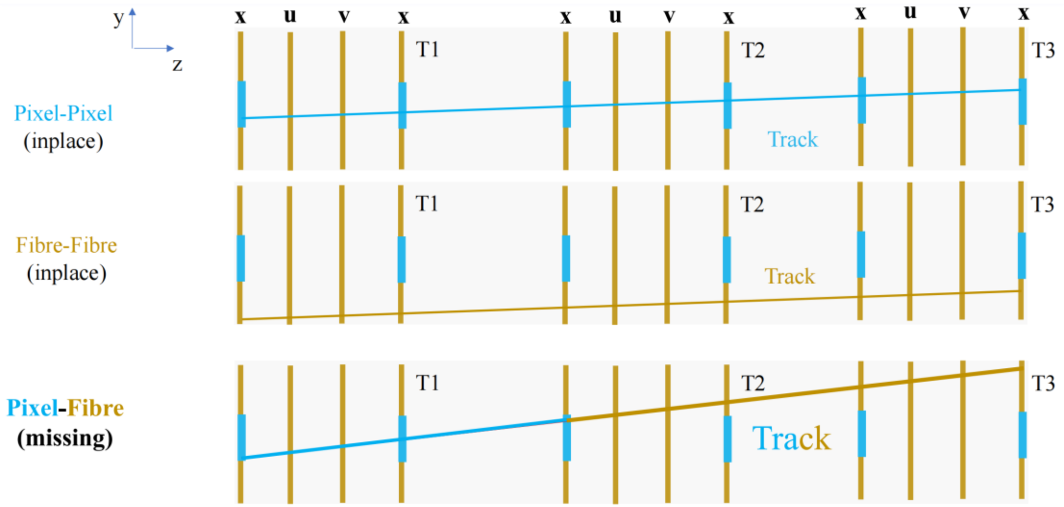


MT: tracks flavours

- Large fraction of tracks from secondary interactions



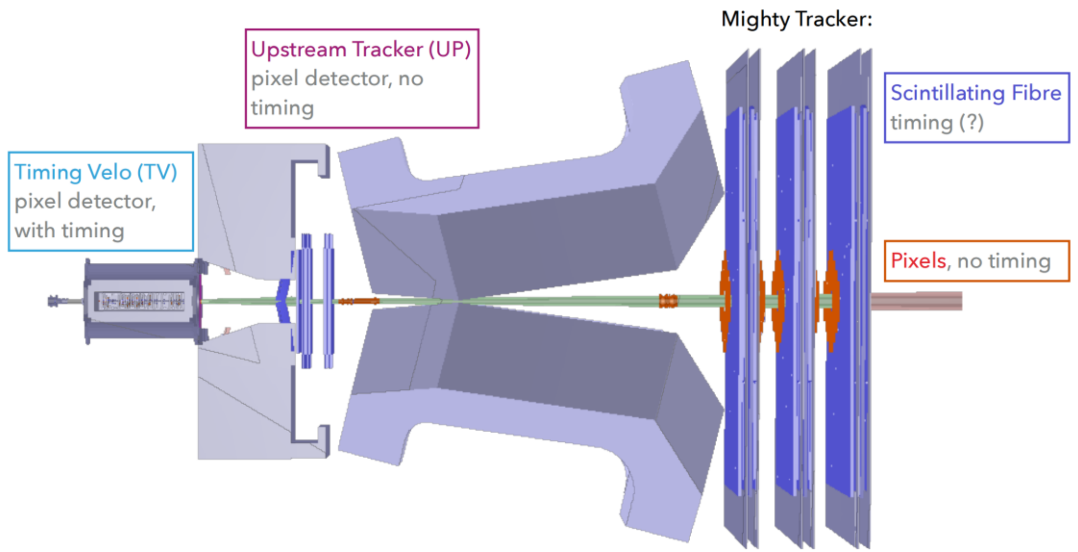


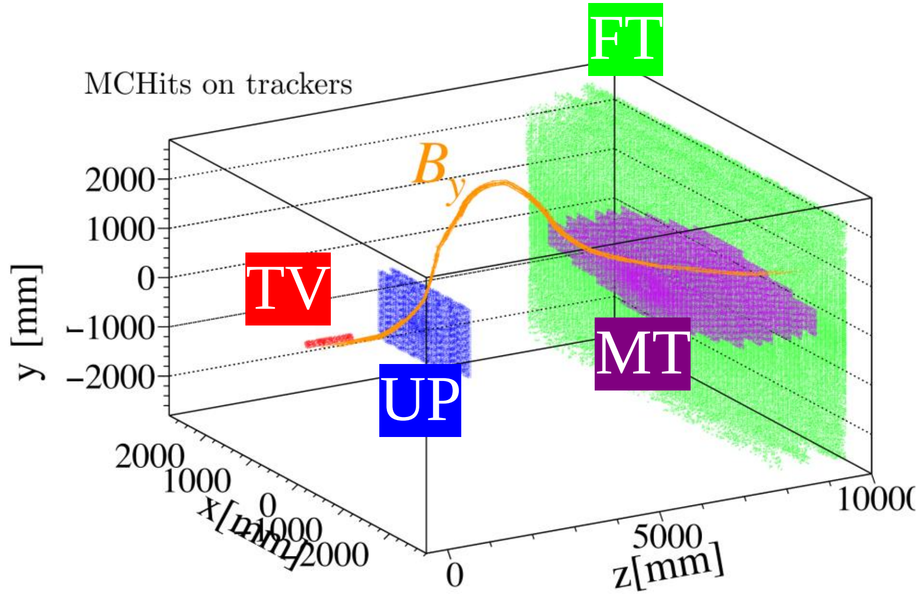


Mathad's

- Standalone-TTracks: increasing tracking efficiency and clone killing
  - To increase efficiency, each time excluding the hits that have already been used
  - Clone killing: Out of two tracks that are close and have more than 30% (pixel) or 20% (fibre) hit overlap, only one is kept based on nHits or track quality
  - Additionally to decrease the clone rate, we remove all the hits used in building Pixel-Pixel tracks in MT

Tracking simulating in U2

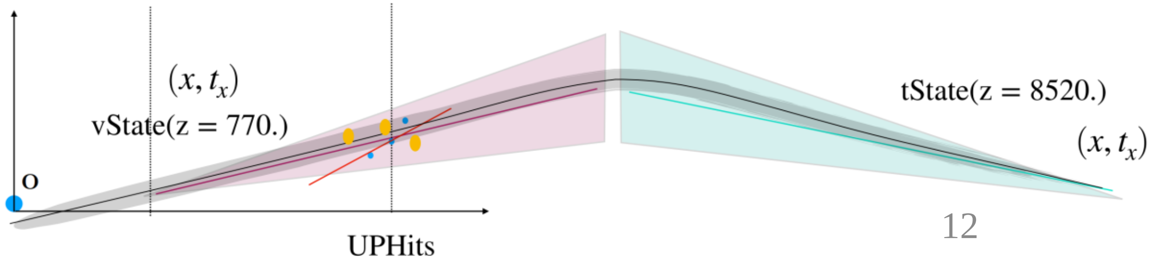




Renato's

- TV : pixel with timing : (x,y,z,t), pitch ~45μm
- UP : pixel no timing : 4 layers (x,y,z), pitch ~30/50 × 150 μm
- MP : pixel no timing : 6 layers (x,y,z), pitch ~50 × 150 μm
- FT : Sci-Fi no timing (?): 12 layers (x,z), pitch ~250 μm

- Pattern recognition : recent development, even reconstruct tracks we want for physics?
- Constructing from TV, UP and MP cheated track
  - Long tracks minTVHits=3, minMPHits=4
  - Downstream tracks minUPHits=3, minMPHits=4
  - Upstream tracks minTVHits=3, minUPHits=3

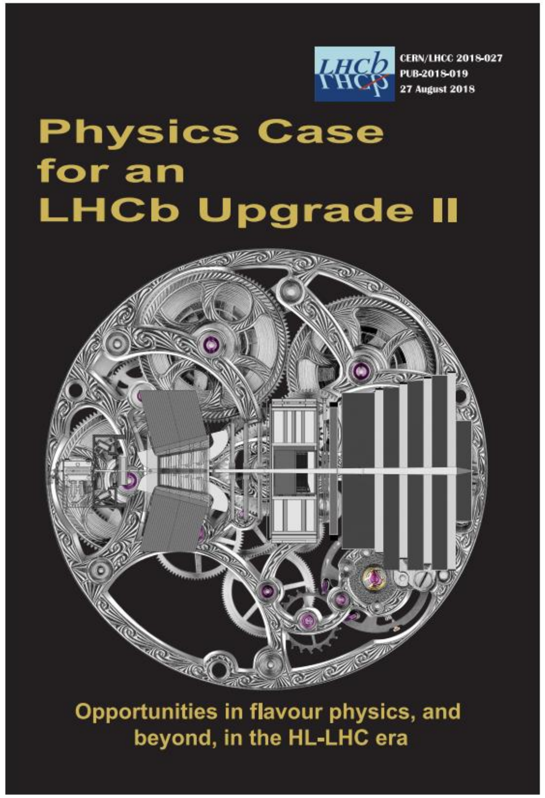


Tracking requirements for physics

- The rule of thumb: "Same or better" detector performance as in Upgrade I

- Key tracking parameters
  - - momentum resolution
  - - vertexing (primary and secondary decays)
    - - beauty, charm, lepton, flavour tagging
    - - but also for spectroscopy, fixed target, medium-to-long lived particles
  - ghost rejection
    - high segmentation (pixels where needed)
    - keeping (very) low material budget

- Quantification of the requirement must come from simulation



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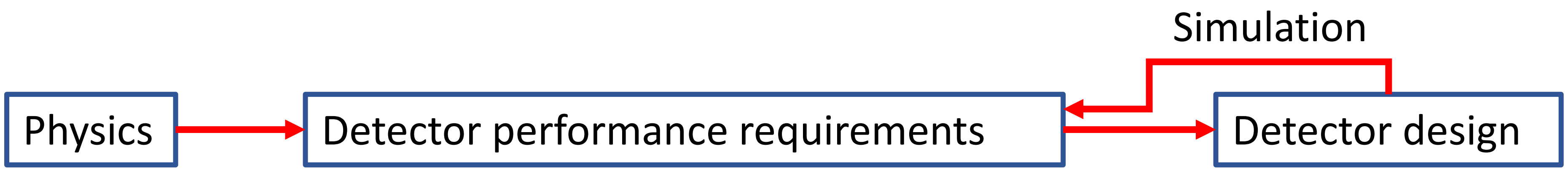
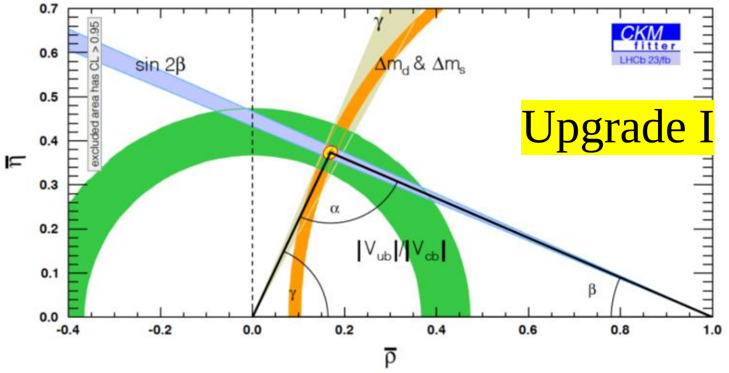
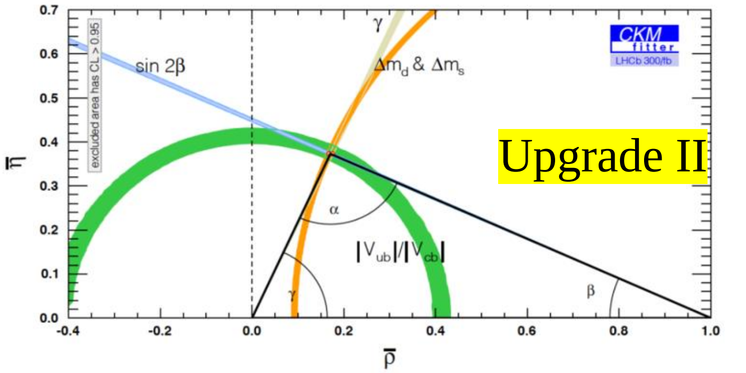


U2 physics: e.g. CP violation and rare deca

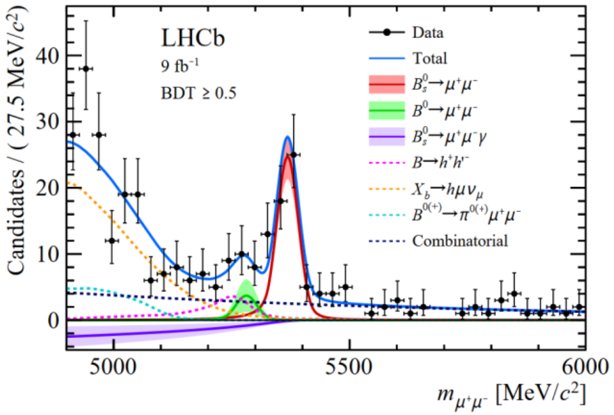
- CKM phases:
  - CPV in B mixing
  - Angle γ in time integrated decays
  - or even CPV in b baryons

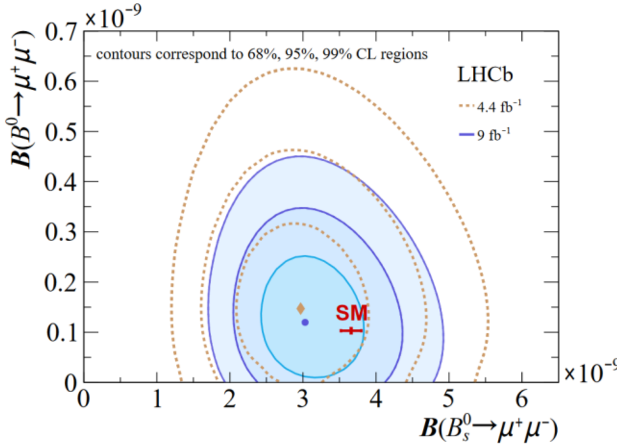




- Rare decays:
  - $B^0_{(s)} \to \mu^+\mu^-$
  - $b \to s\ell^+\ell^-$ $(\ell = e, \mu, \tau)$, need $\tau^\pm$ reconstruction capability

- Need control syst. when it close to the stat.



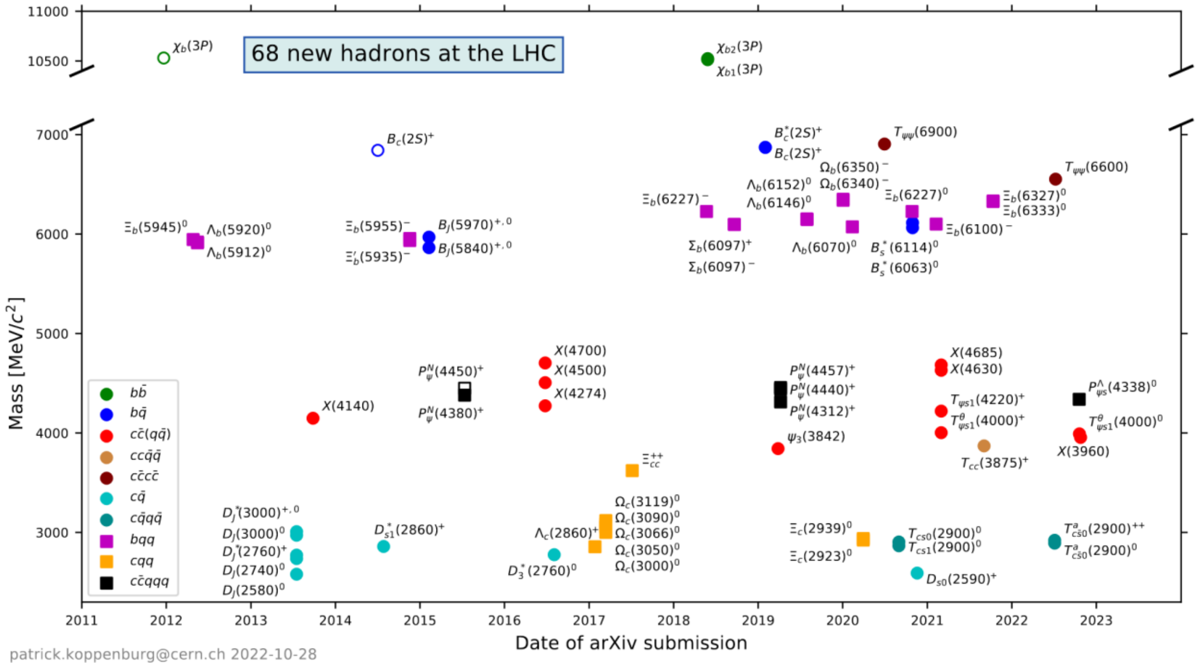


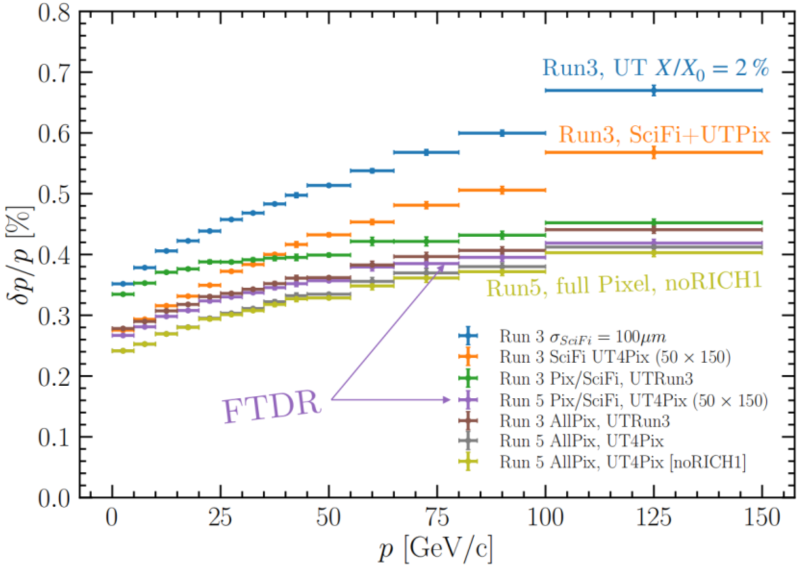
- Requirements ("usual suspects")
  - Vertexing capabilities
  - Tracking, momentum resolution
  - PID (RICH, MUON, CALO), leptons
  - Flavour tagging classifiers:
    - Pileup, PIDs, IP resolution, correct PV association efficiency, ghost rate, timing

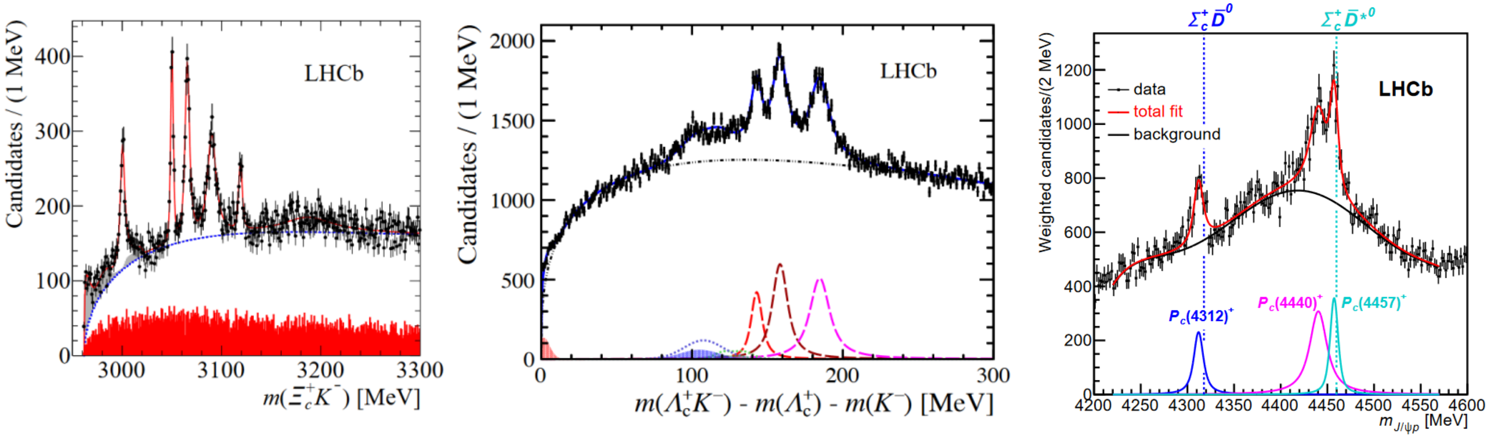
U2 physics: e.g. Spectroscopy

- Search for new hadrons
- Measure hadron properties
  - exotic states (tetra- penta-quarks)
  - double-heavy baryons ($\tau \sim 0.1$ ps)

- TV performance is essential to:
  - Reduce the background level
  - Measure short lifetimes
- UP would improve $\Delta p/p$ for spectrum precision





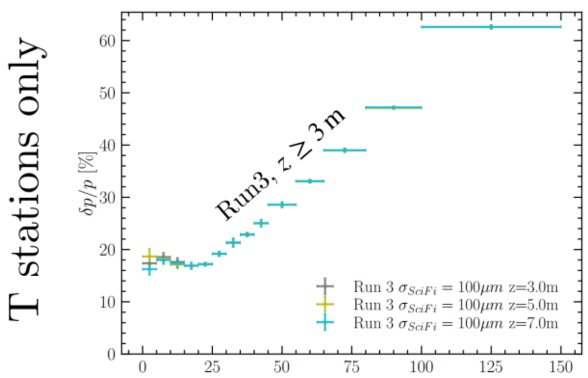


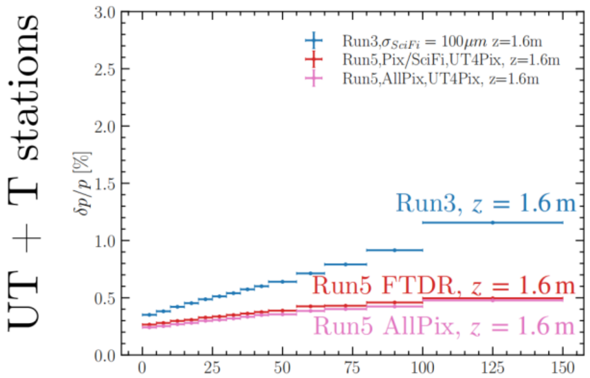
Fred's

U2 physics: e.g. long-lived particle

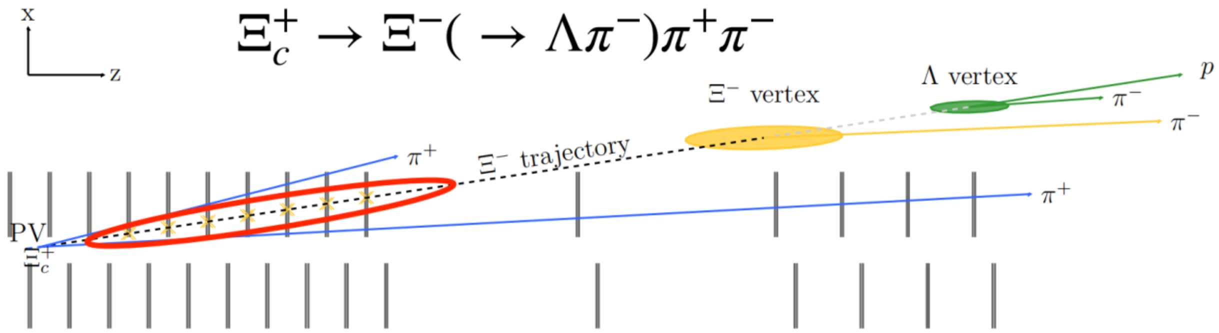
Renato's

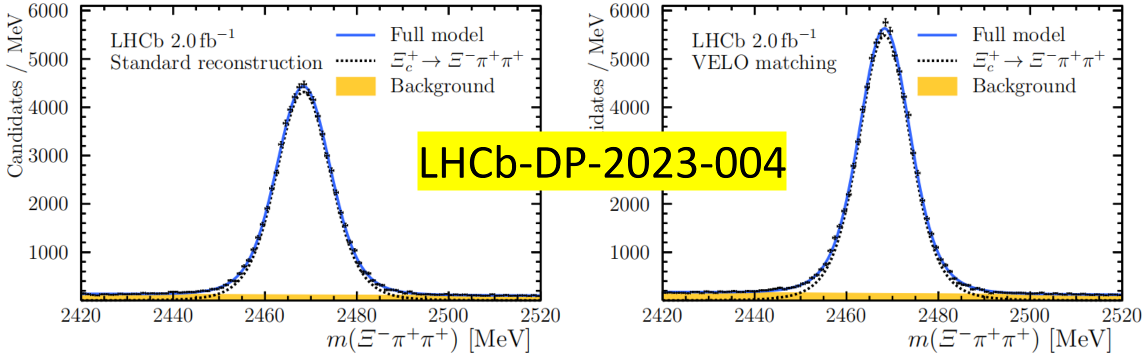
- Long lifetime particles essential input to much physics, e.g. $K_S^0 \to \pi^+\pi^-, \Lambda \to p\pi^-$
  - Emulating K_S^0 with $K^\pm$ track, linear extrapolation to fixed z_{decay}, then propagation with charge





- Charged hyperon decaying in the VELO
  - Track hyperons in the VELO, improve signal selection





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Conclusion

- The tracking system will be built almost entirely on high granularity silicon pixel detectors
- The simulation of U2 forming can be used for reliable performance estimation/inspection of the entire tracking system
- Timestamp is crucial for the possibility of track reconstruction and data process
- For Upgrade II, aiming to “same or better" detector performance as in Upgrade I
- Still many R&D issues or open questions, we need you!