Tracking System Upgrades for LHCb Phase-II

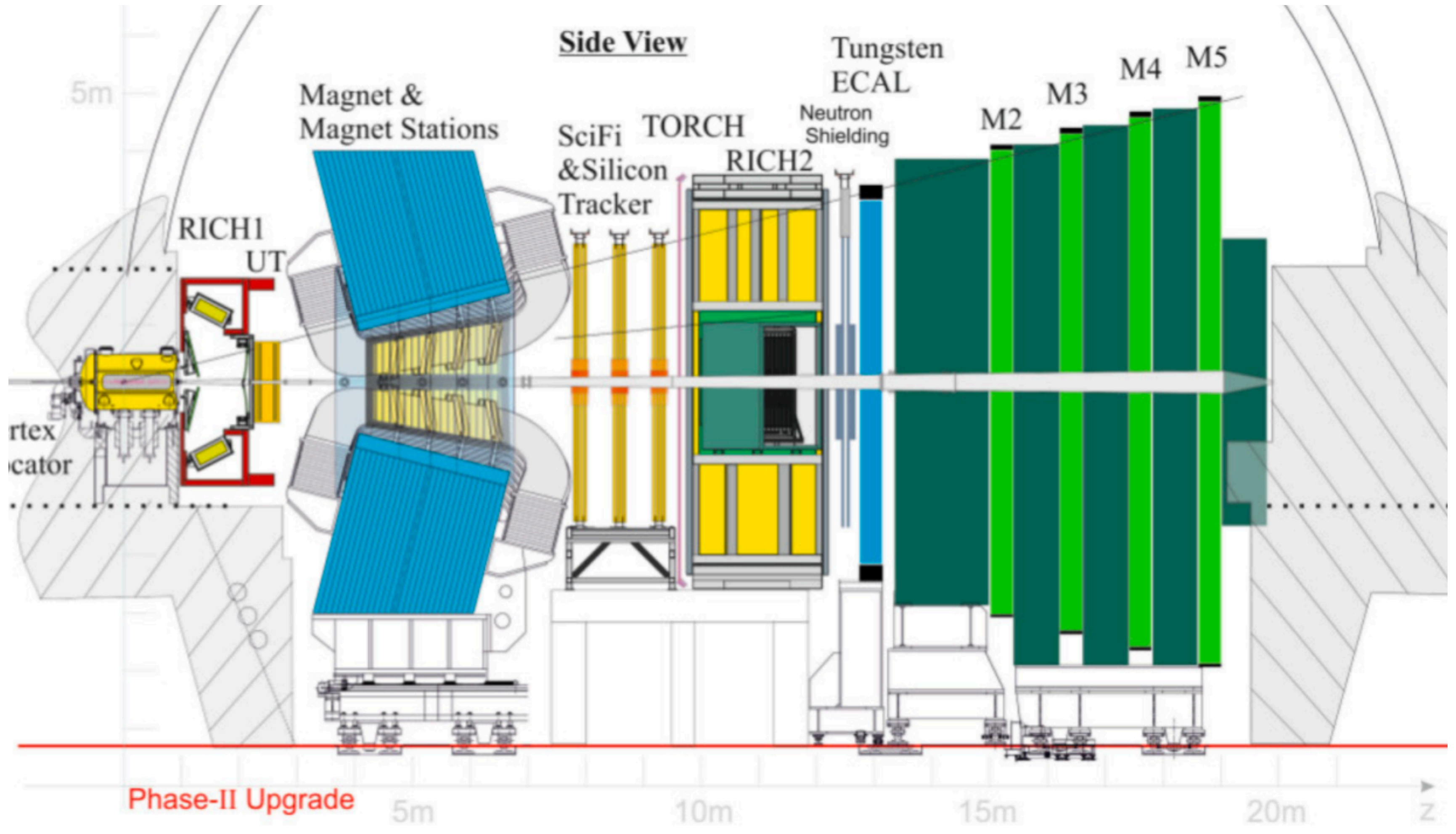
Mingjie Feng (冯铭婕, 中国科学院高能物理研究所)

21-23, July, Huizhou

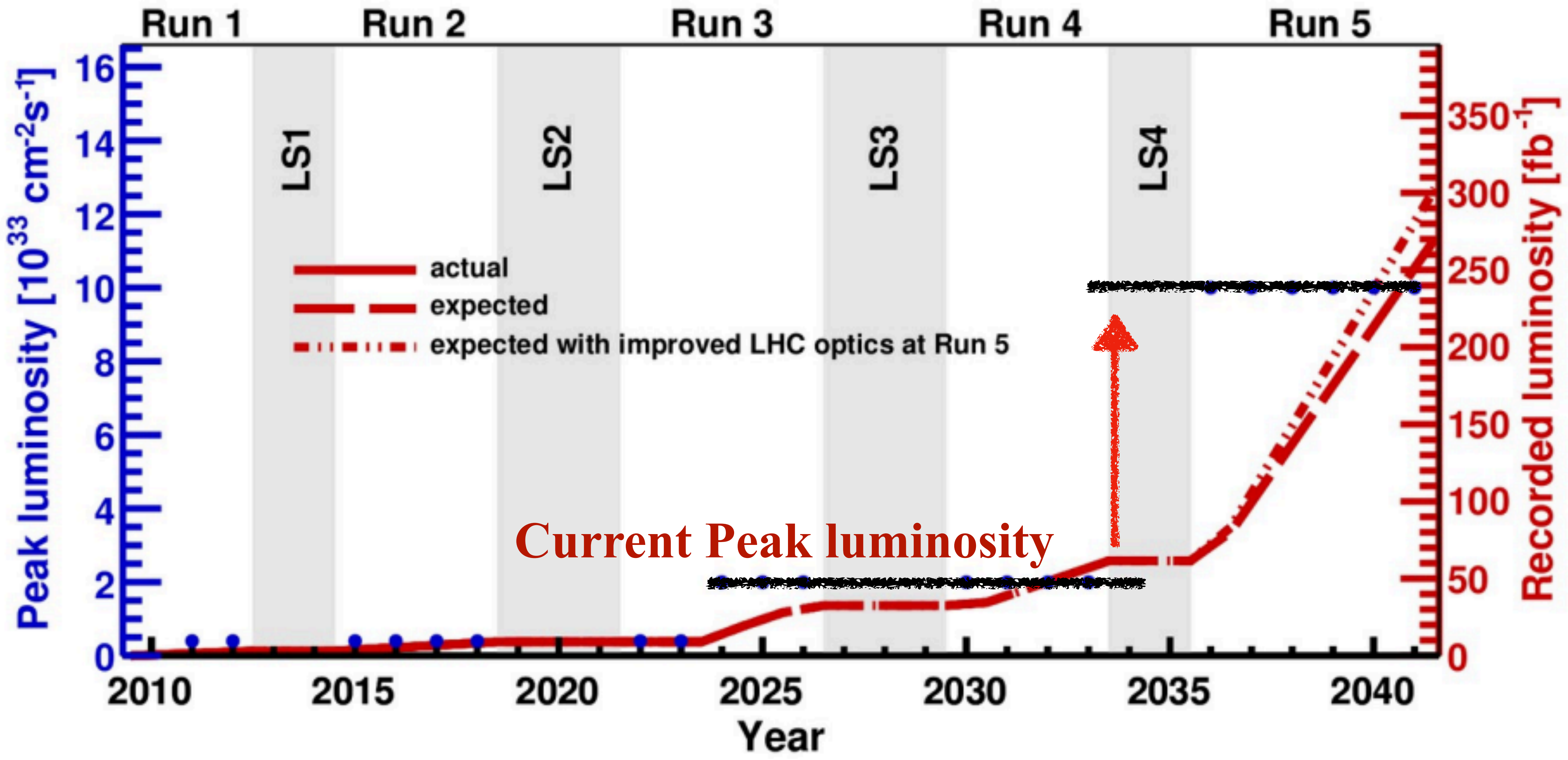
第二届粒子物理实验径迹重建研讨会

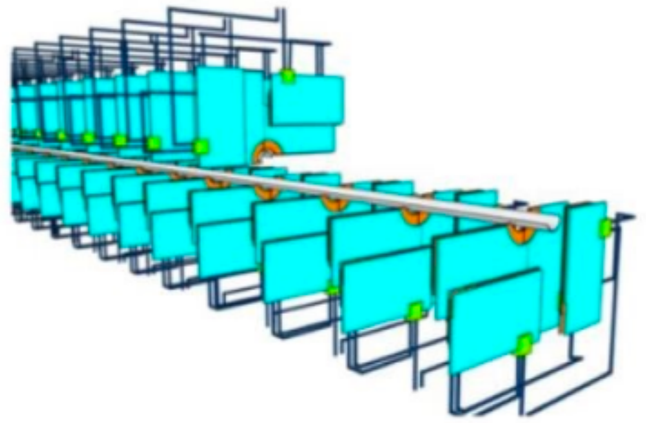
LHCb Detector

- Single arm forward spectrometer (2<η<5)
  - Designed to study CP violation and rare decays in hadrons containing b- and c-quarks

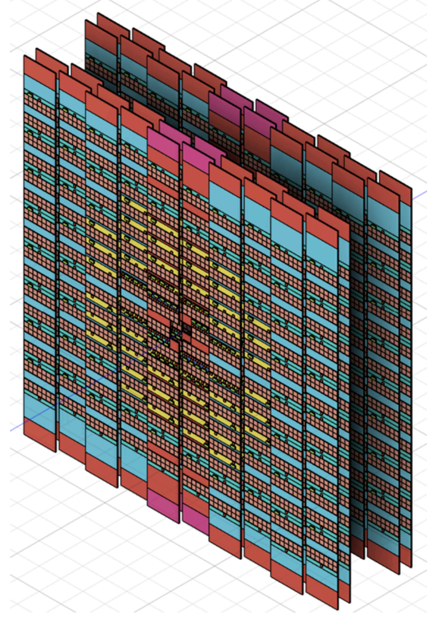


- Evolution of LHCb
  - Pre-Upgrade (Run1, Run2)
    - $\mathscr{L}_{peak} = 4 \times 10^{32} cm^{-2}s^{-1}$, $\mathscr{L}_{Int} = 9\,fb^{-1}$
  - Upgrade I (Run3 & Run4)
    - $\mathscr{L}_{peak} = 2 \times 10^{33} cm^{-2}s^{-1}$, $\mathscr{L}_{Int} = 50\,fb^{-1}$
  - Upgrade II (Run5)
    - Peak luminosity increased by a factor of 5
      - Baseline: $\mathscr{L}_{peak} = 1.0 \times 10^{34} cm^{-2}s^{-1}$, $\mathscr{L}_{Int} = 270\,fb^{-1}$
      - Other scenario: $\mathscr{L}_{peak} = 1.3 \times 10^{34} cm^{-2}s^{-1}$
    - Sub-detector upgrade

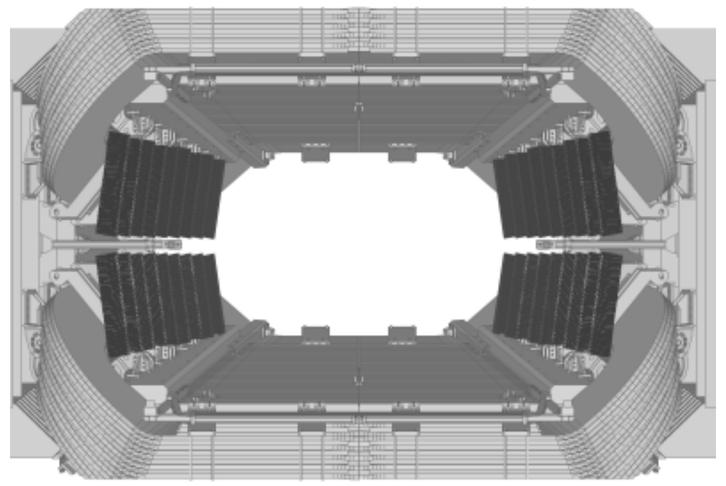




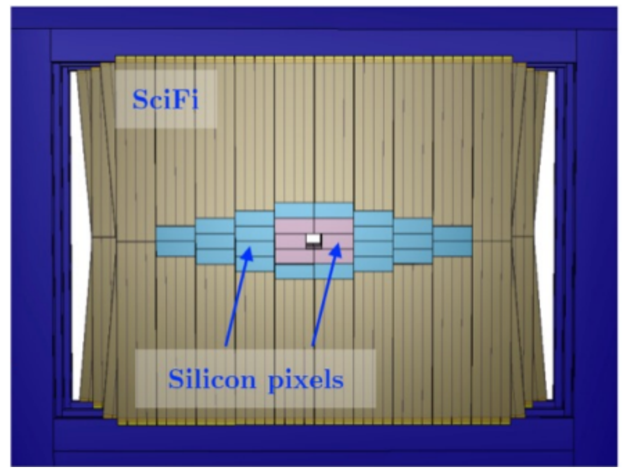
VELO Pixels with Timing (**TV**)



Upstream Pixel Tracker (**UP**)



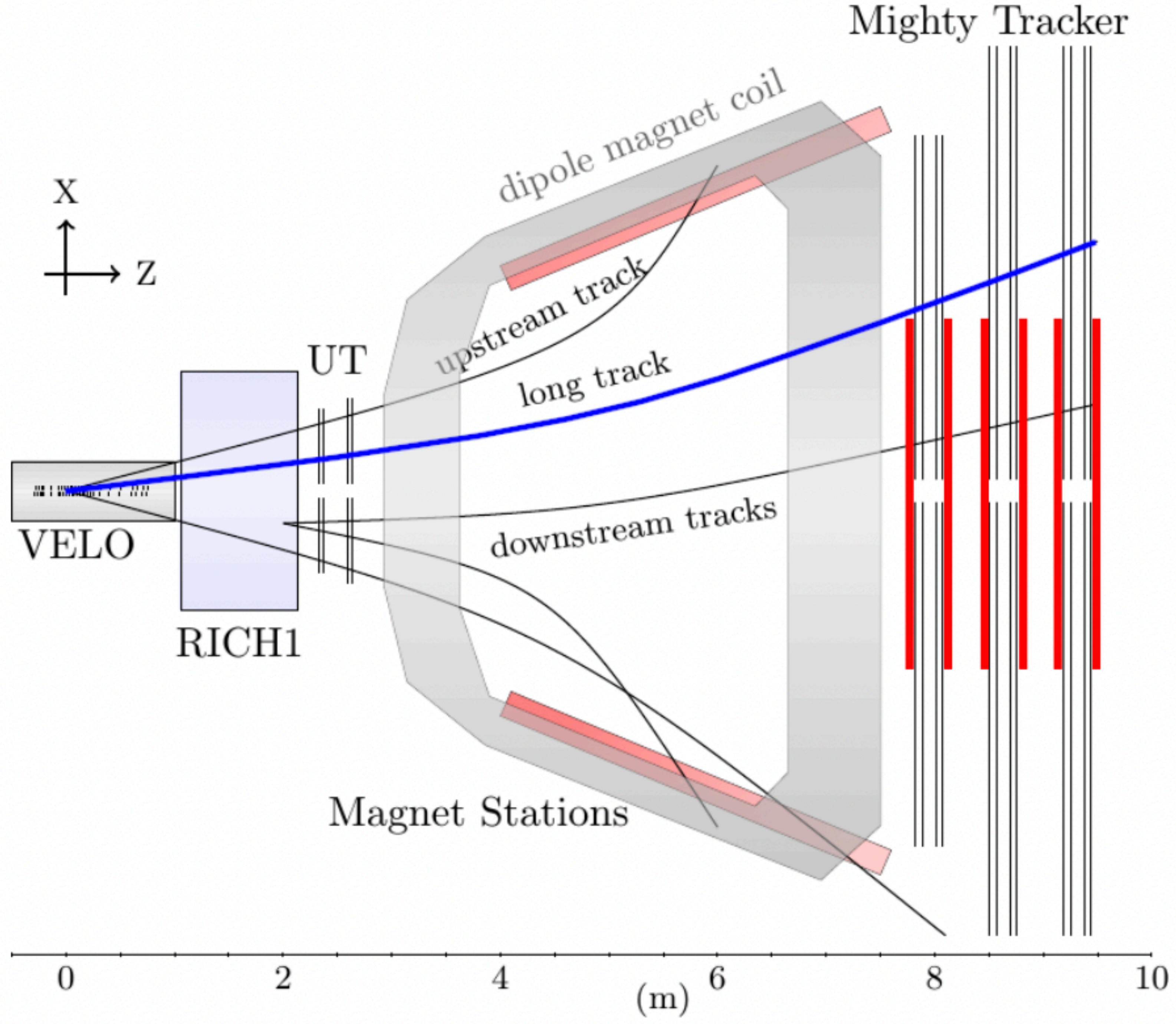
Magnet Station(**MS**)



Mighty tracker (**MT**)
- MAPS CMOS pixel (inner, **MP**)
- SciFi (outer, **FT**)

Status of LHCb UII tracking system

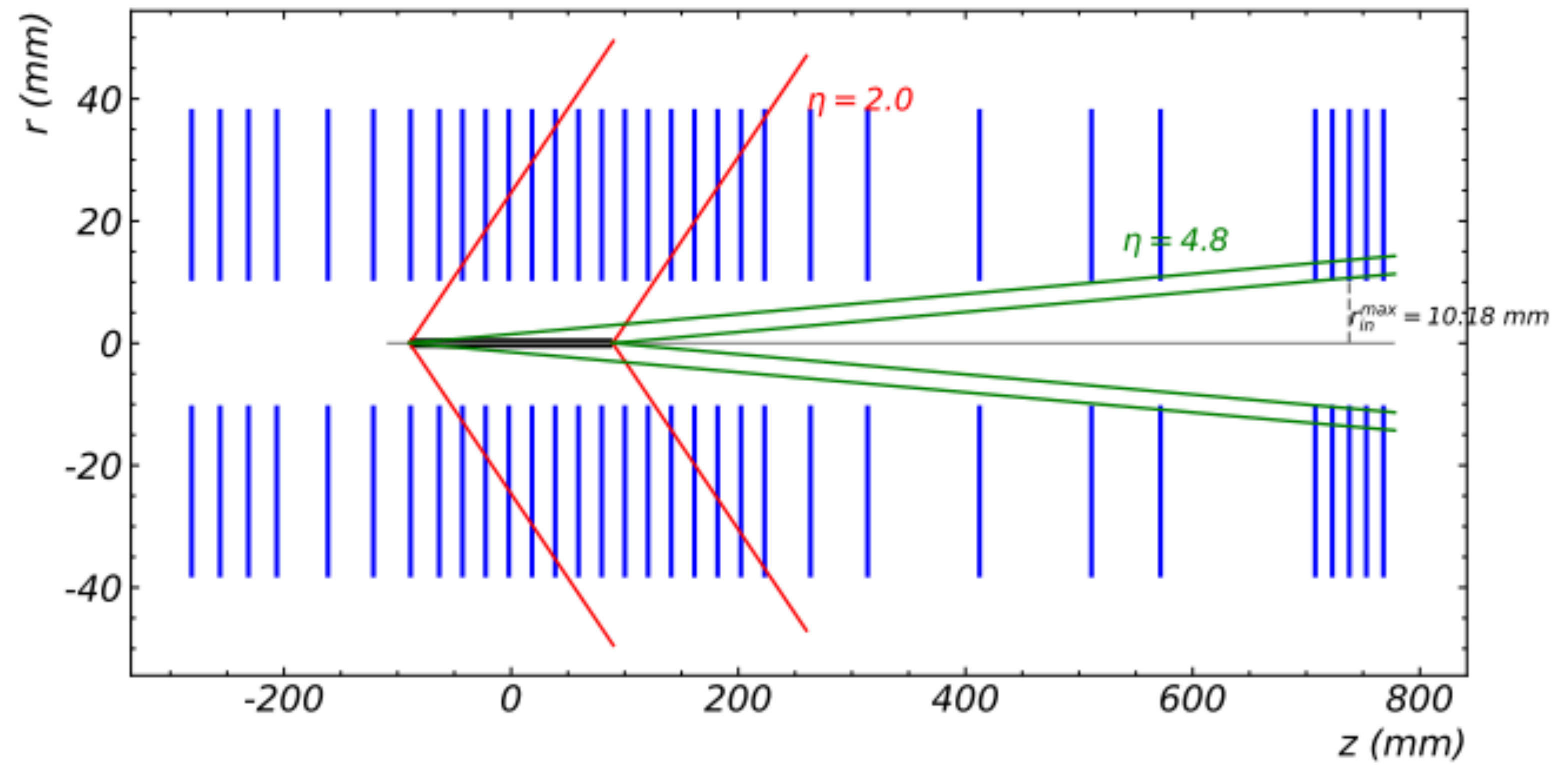
- **Standalone tracks**
  - 4D reconstruction for TV track
  - New algorithm for UP track and MP track
  - Run3 algorithm reused for Scifi track
- **Long tracks**
  - Matching: TV tracks + MT tracks + UP tracks/UP hits
  - Forward: TV Tracks → UP → MT (ongoing)
- **Upstream tracks**
  - TV tracks + UP hits (UP tracks)
  - TV tracks + UP hits/UP tracks + Magnet hits (ongoing)
- **Downstream tracks**
  - MT tracks + UP tracks (UP hits)

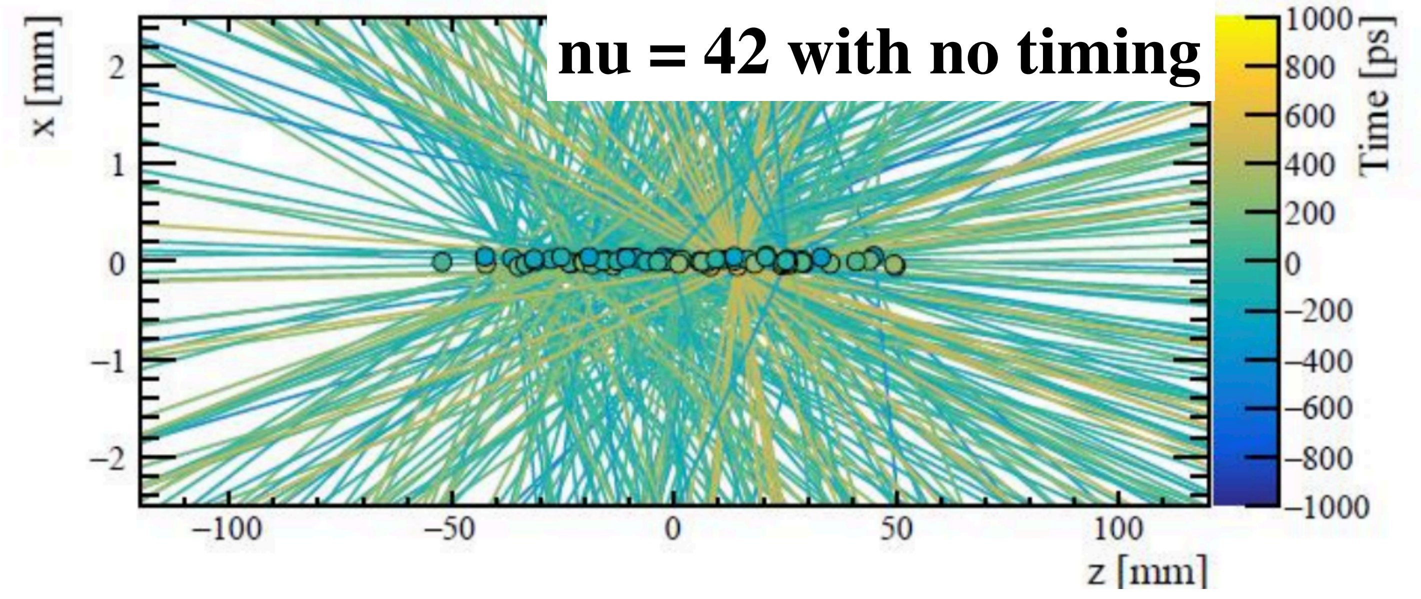


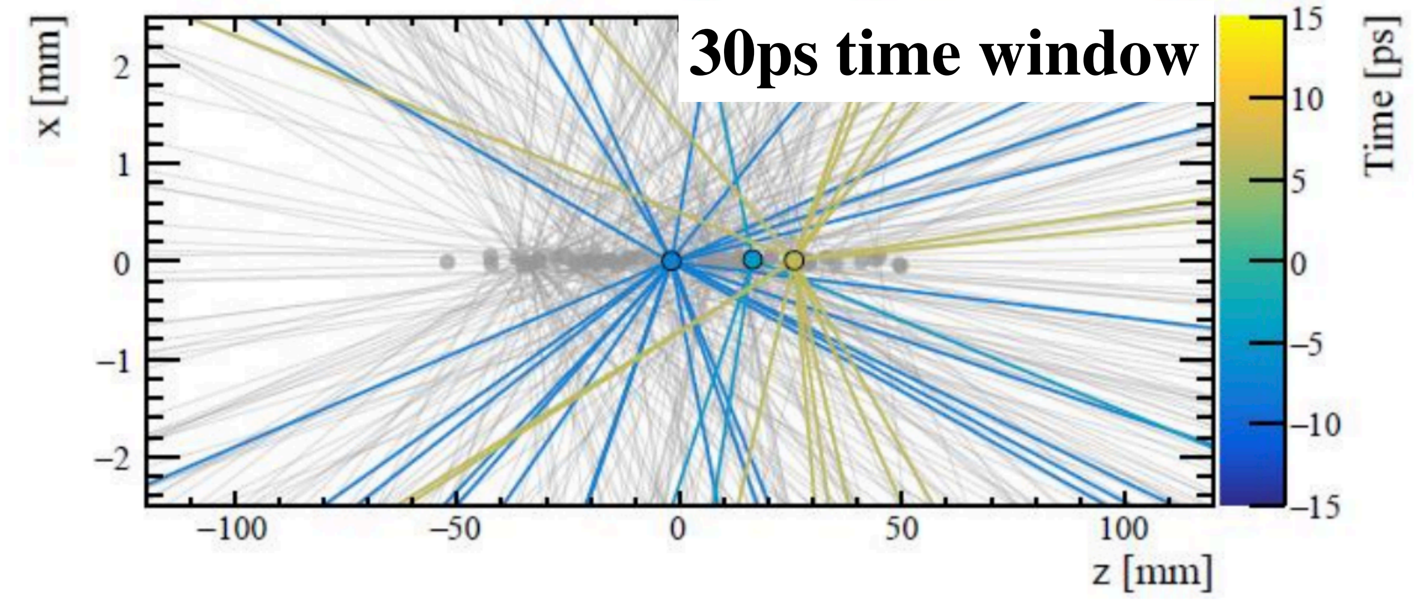
LHCb Tracking System

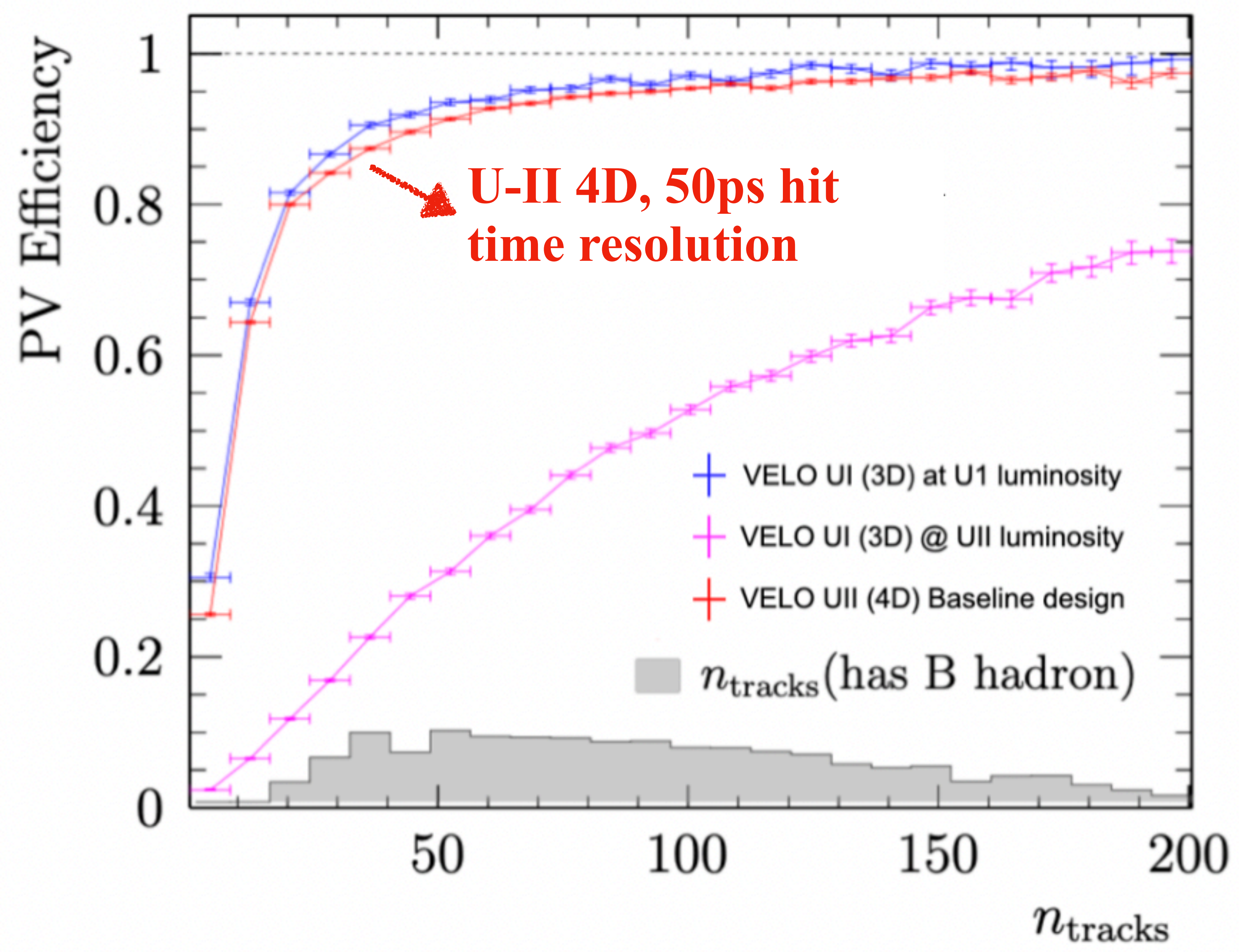
VELO Pixels with Timing (TV)

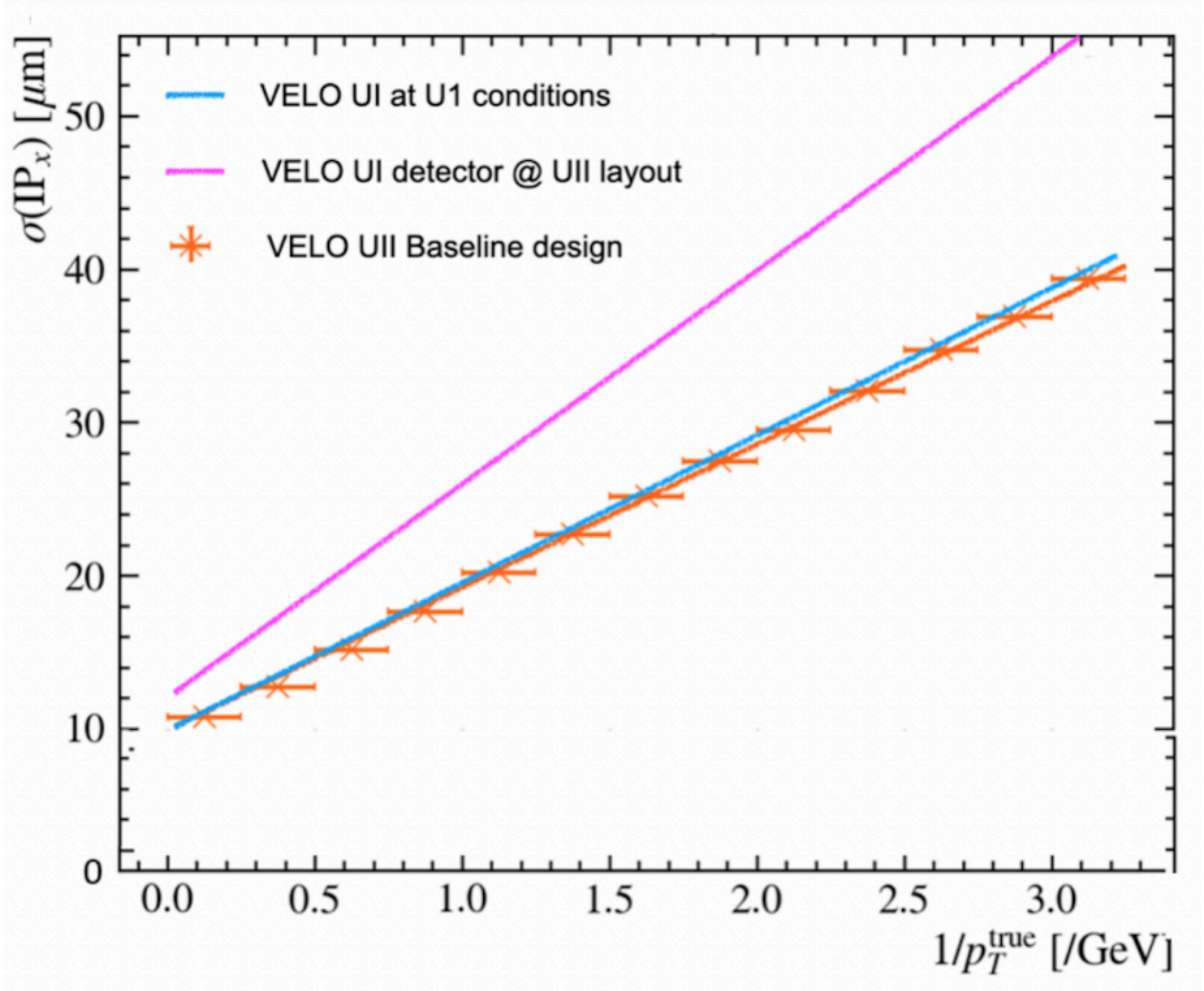
- 32 layers of silicon pixels detector
- 150 µm thick sensors with 10 µm spatial resolution
- **Recover UI performance at UII conditions**
  - An additional 50ps time resolution per hit for PV reconstruction
  - Reduce material and improve spatial resolution for IP resolution





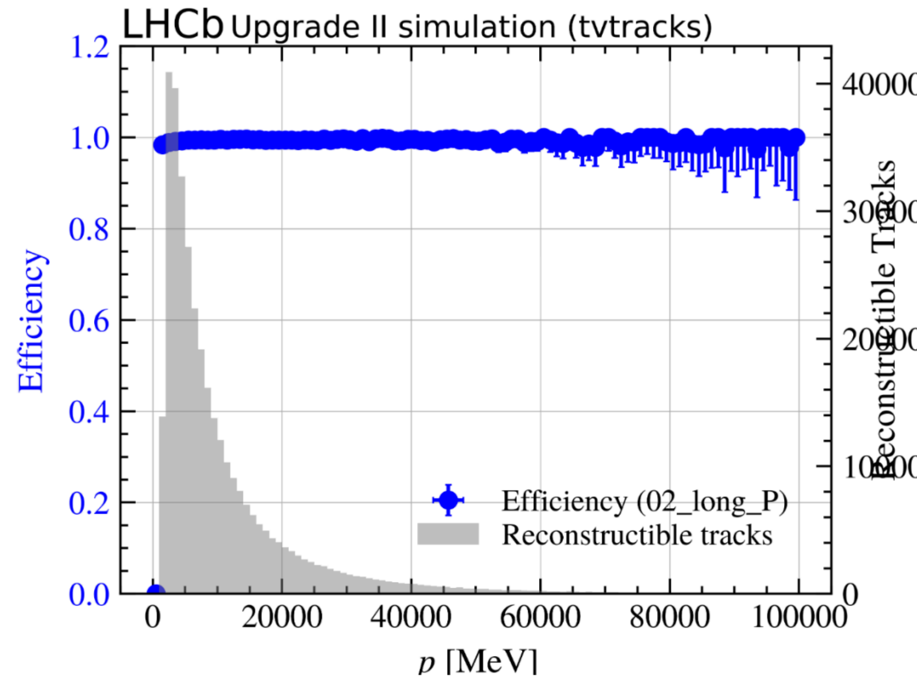


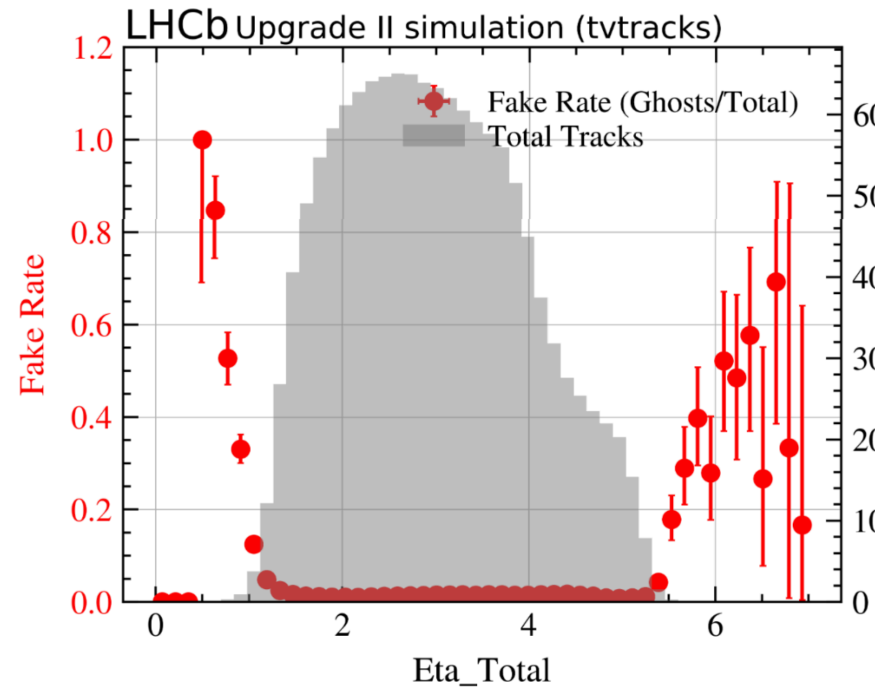


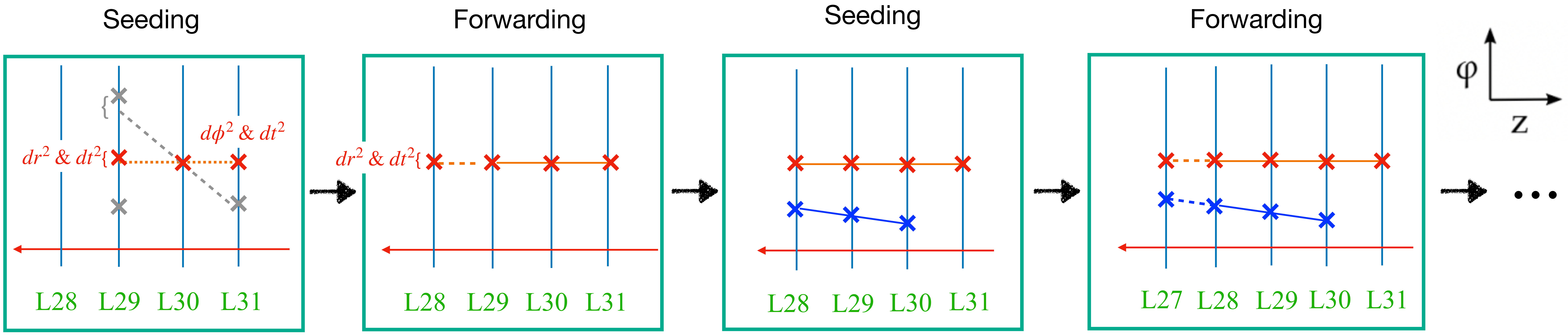


4D tracking algorithm

- Use seeding - forwarding algorithm to get the best tracking candidate
  - Make 3 hits seed on consecutive 3 layers
  - Extrapolate seed to next layer
  - Choose hits based on $d\phi$, dr^2 and dt^2
- Fit tracks and update results (position, direction, time and state covariance matrix)

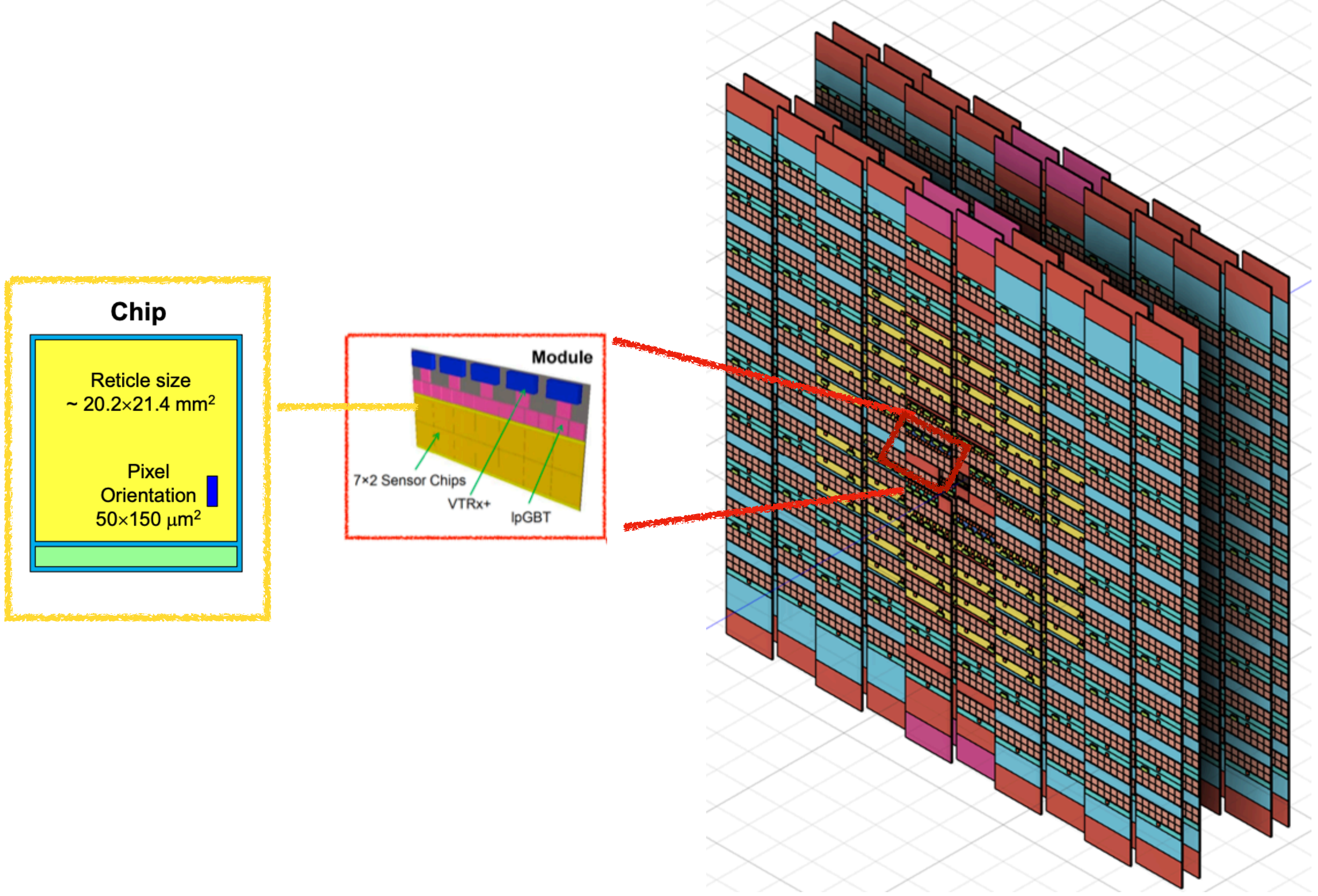


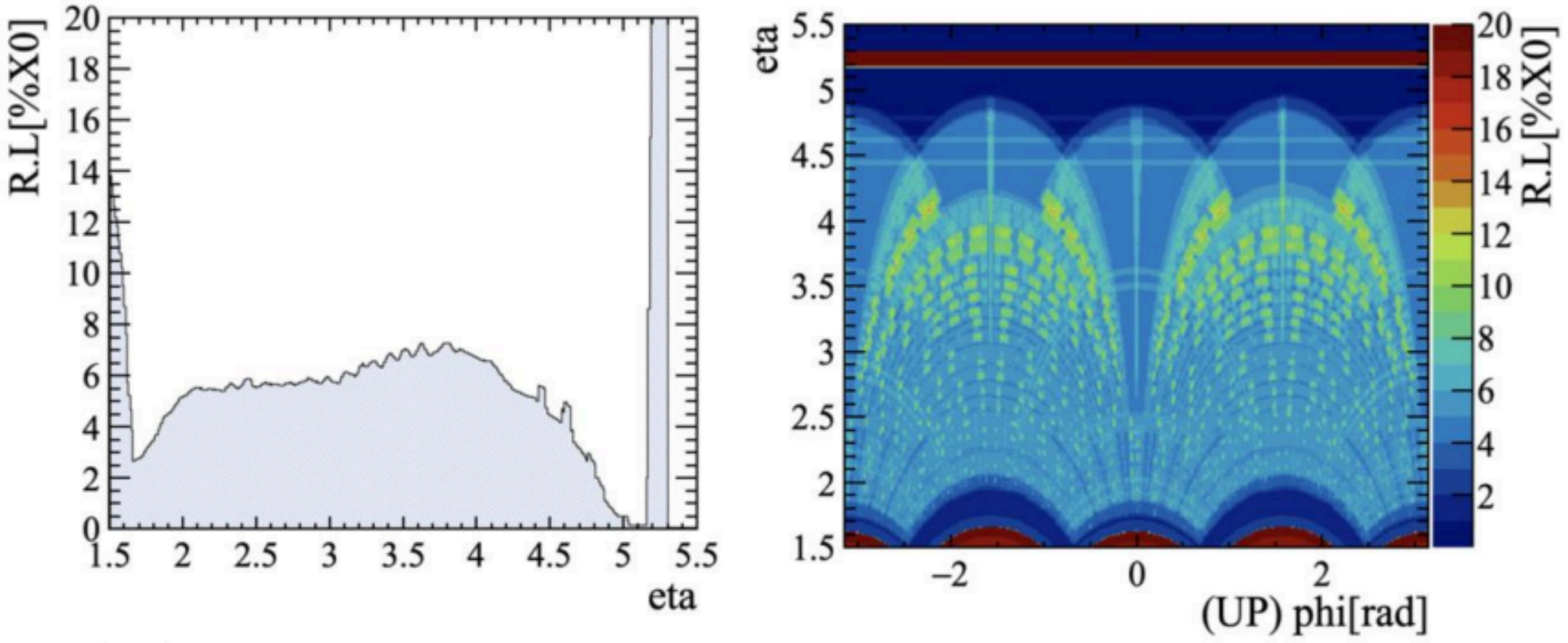




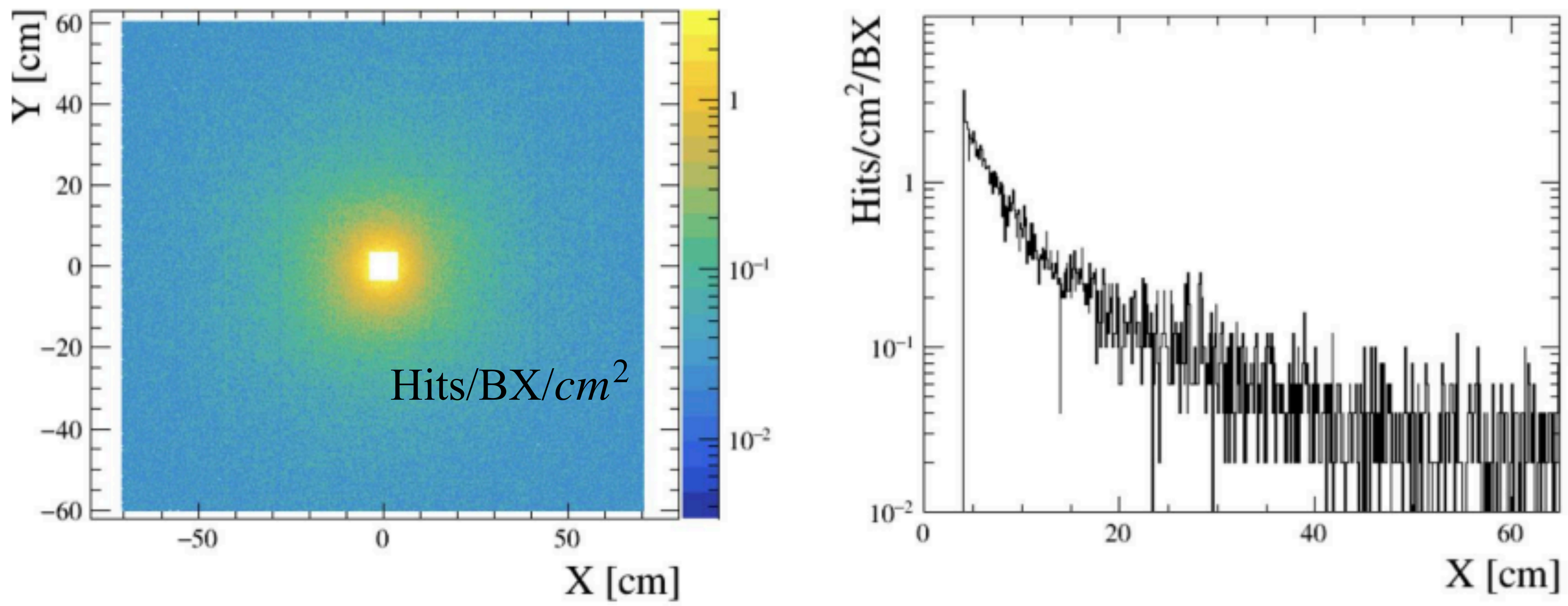
Upstream Pixel Tracker (UP)

- **Chinese group contributes significantly**
- 4 layers MAPS-based pixel detector
- Material budget ~ 1.2% per layer
- Hit rate for pp at X = 4 cm ~ 74 MHits/s/cm^2
- **UP plays a key role in LHCb tracking system**
  - Fast estimates momentum for trigger system
  - Essential to reconstruct long lived particles, e.g. K_S^0, Λ





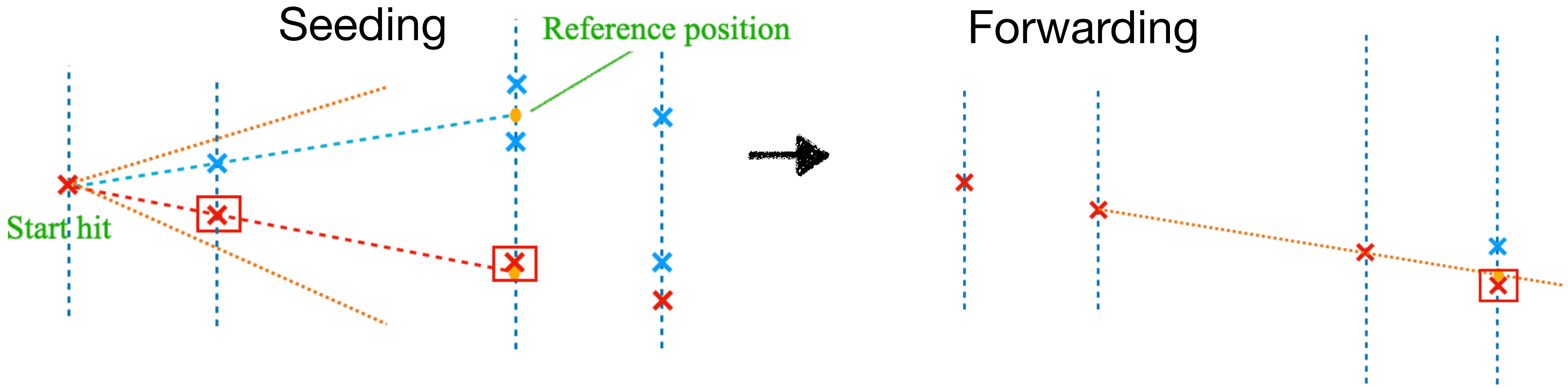
R.L distribution (4 UP layers)

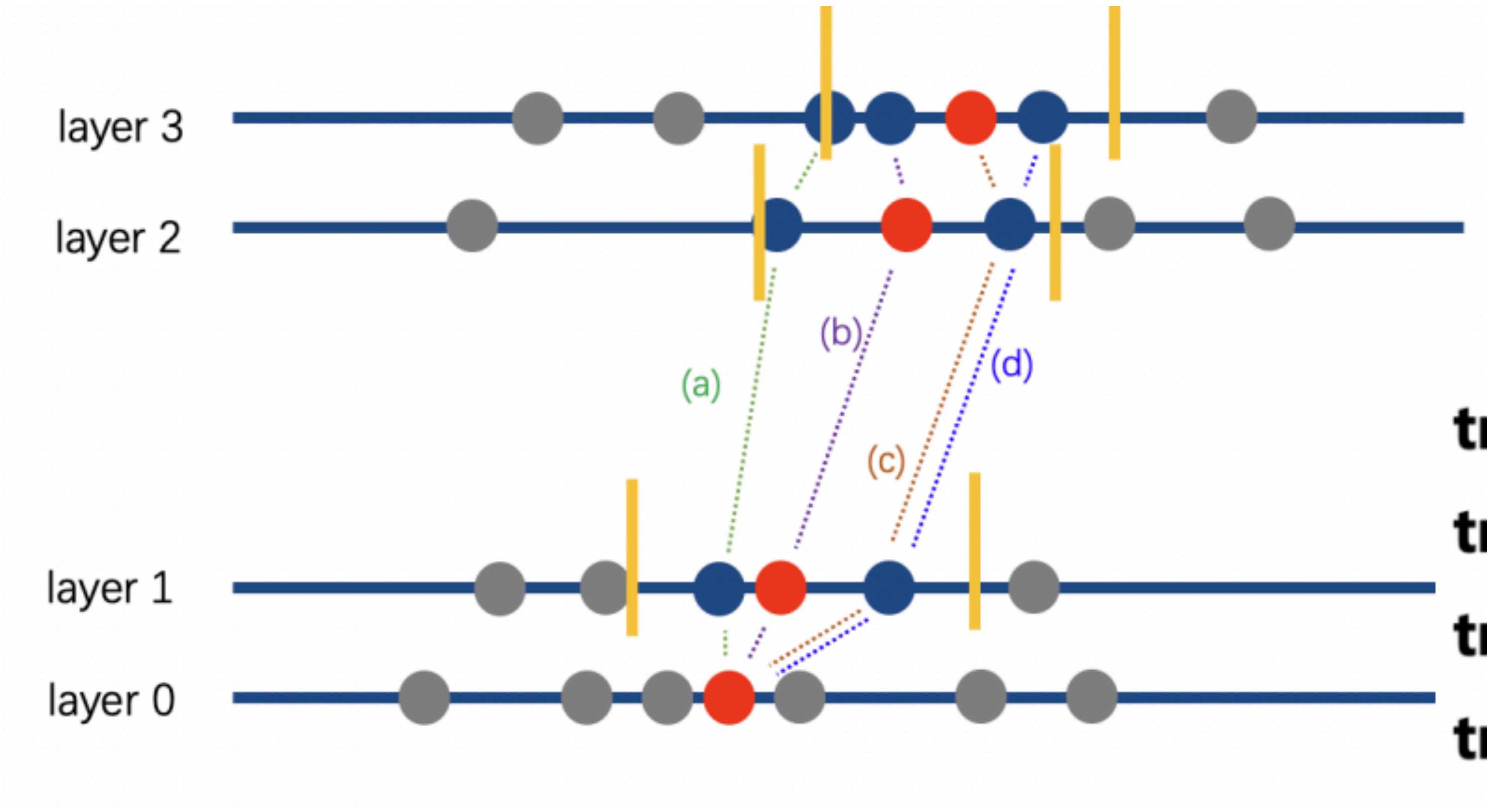


Hits map @ (UP layer1, $\mathscr{L}$=1.0 × 10^{34} $cm^{-2}s^{-1}$, pp at 30MHz)

At least 3 UP layers with hit in each UP standalone track

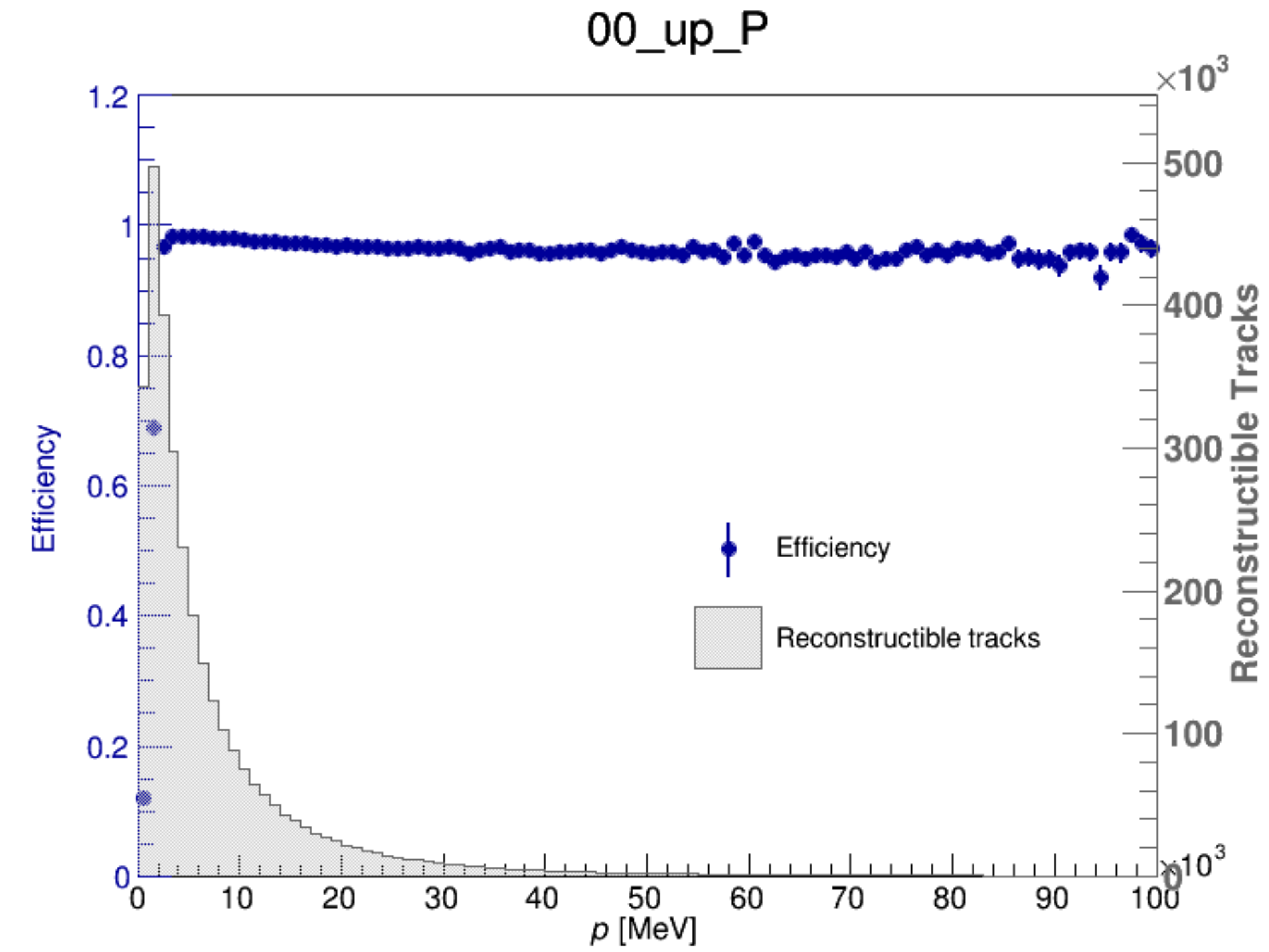
- **Traditional algorithm in LHCb U2 framework**
  - Similar seed-forward algorithm with TV
- **Several works ongoing, covering the MLP, CAT or GNN**

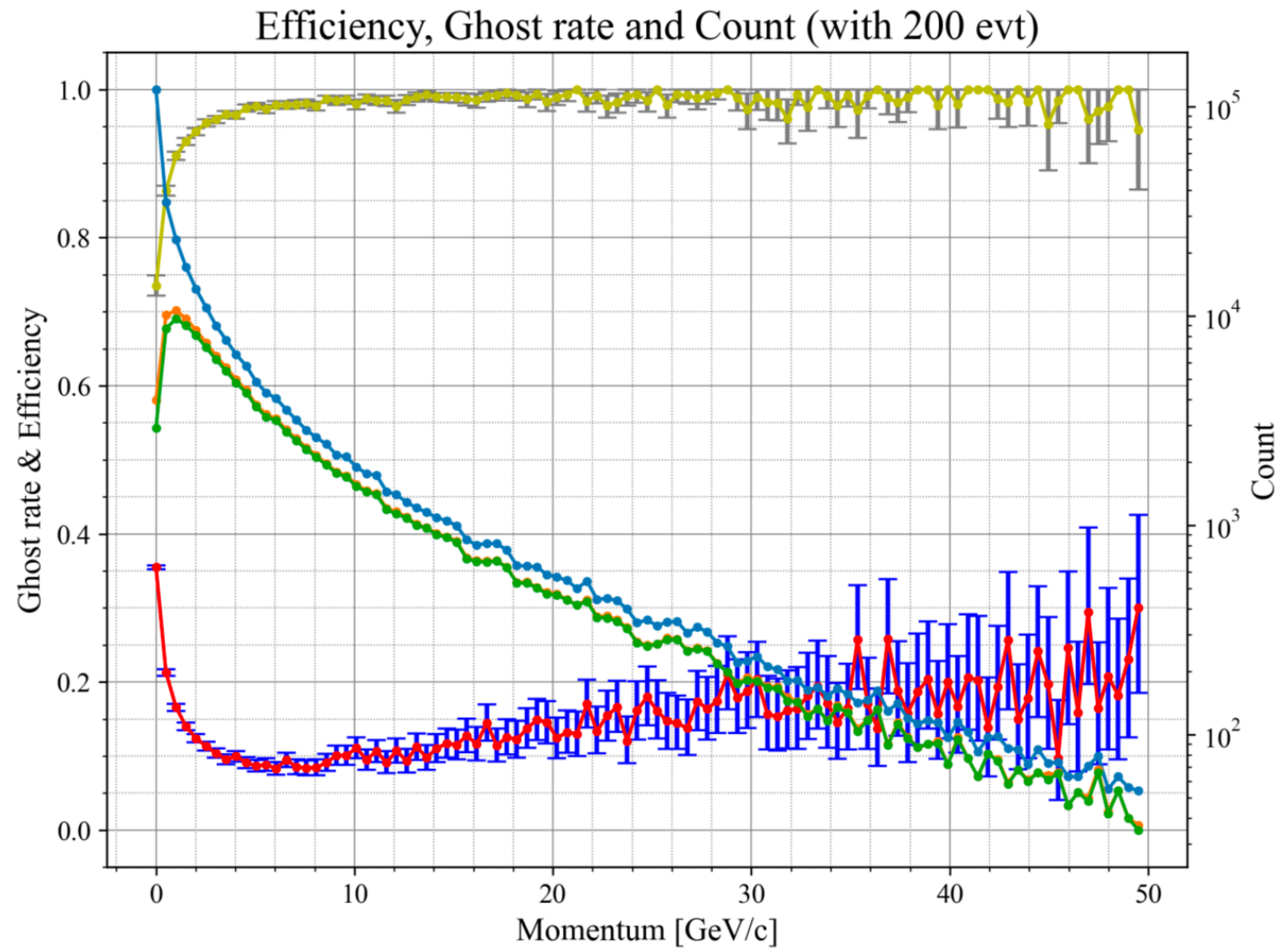




track (a) should classified as [1, 0, 0, 0],
track (b) should classified as [1, 1, 1, 0],
track (c) should classified as [1, 0, 0, 1],
track (d) should classified as [1, 0, 0, 0],

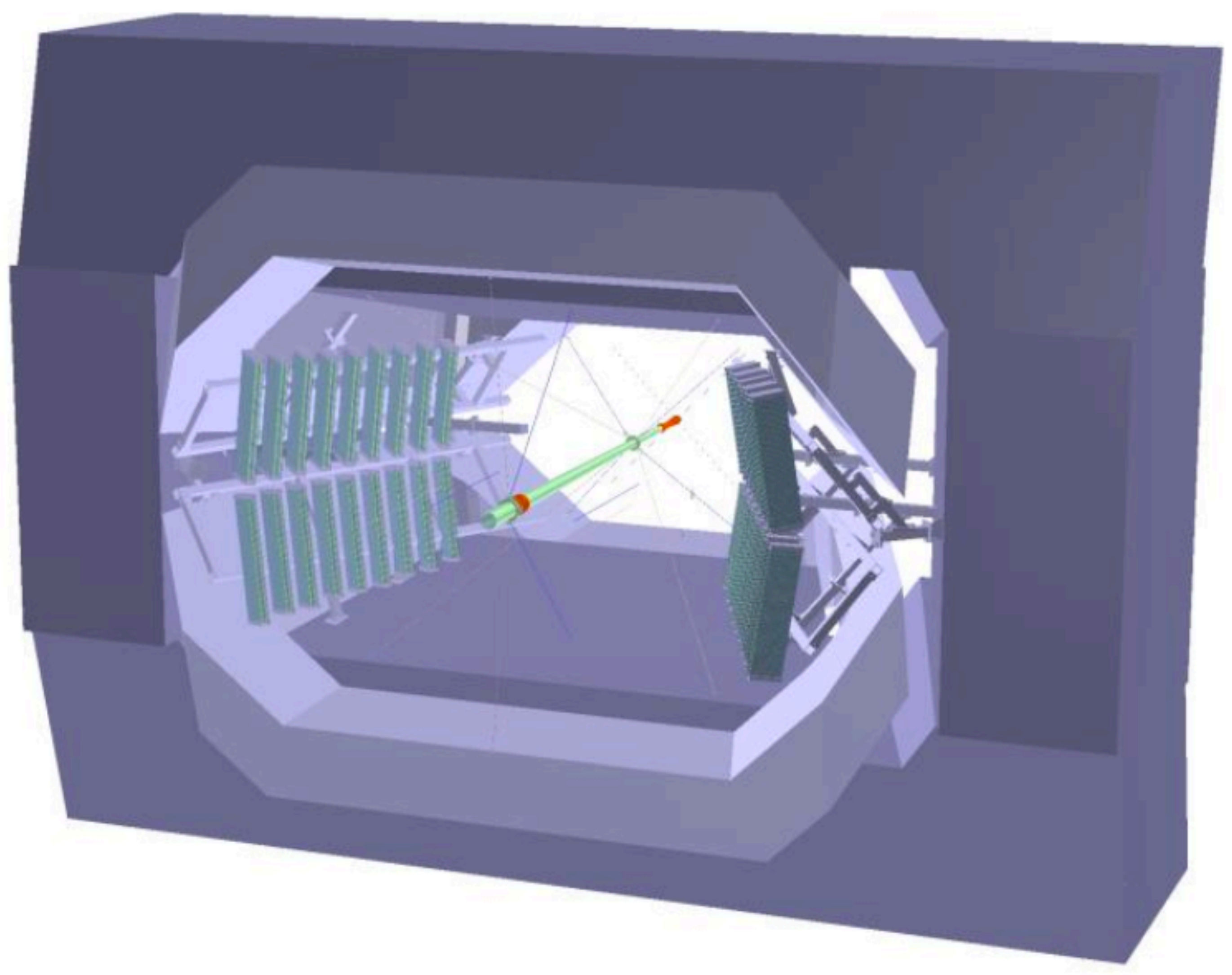
In MLP, transformed into a classification problem

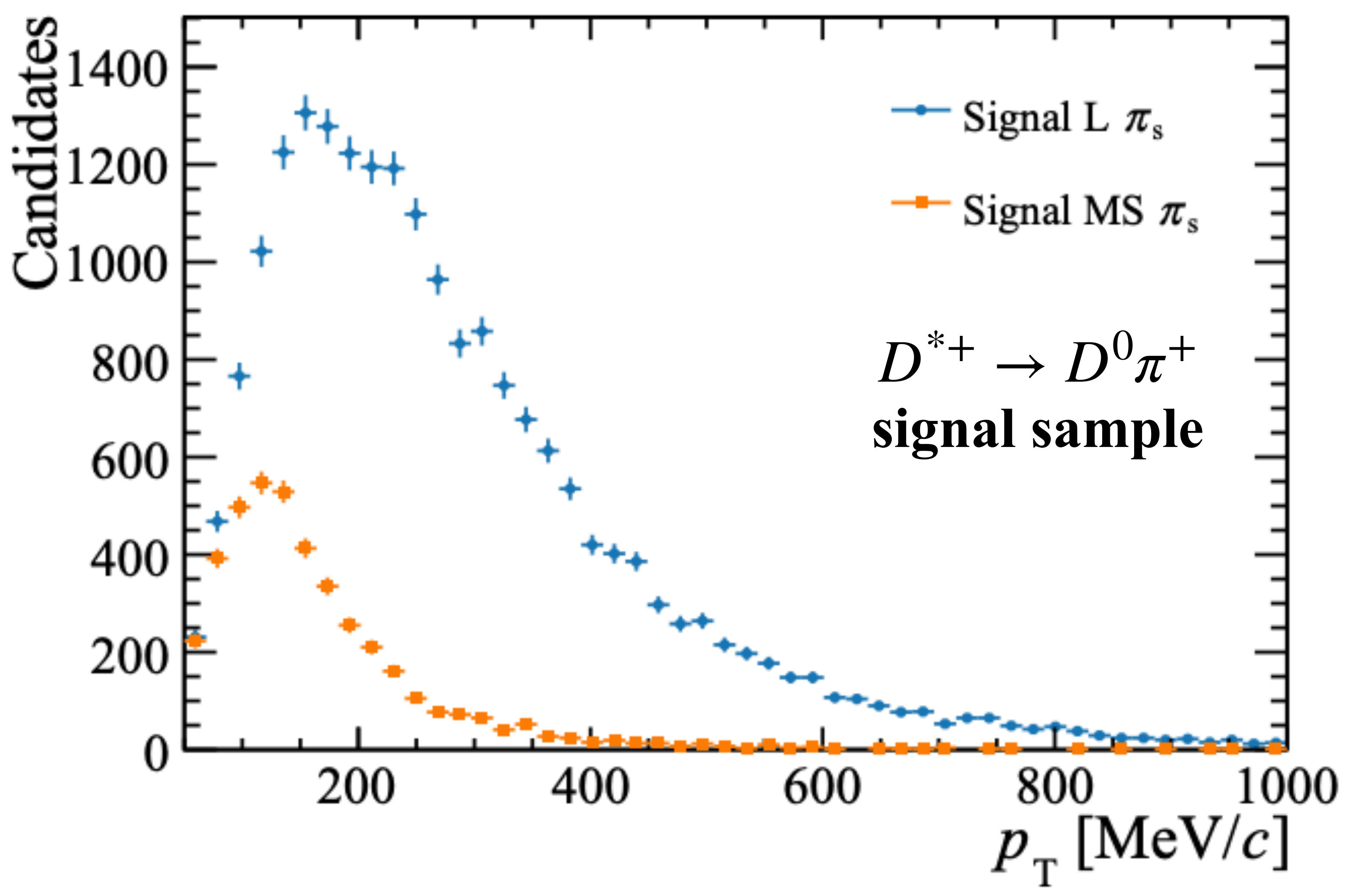


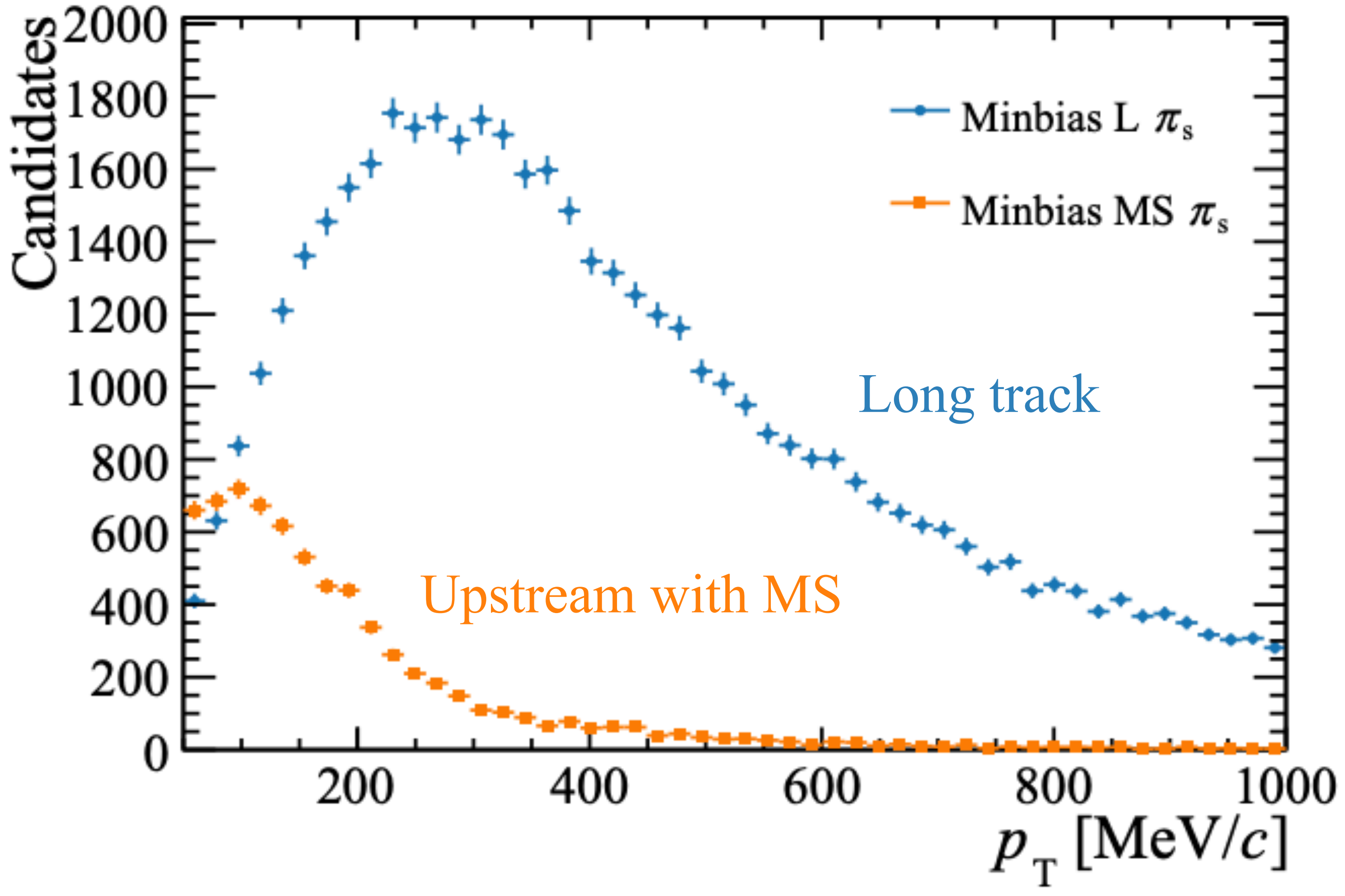


Magnet Station (MS)

- New sub-detector for UII
- Scintillating-based tracker located inside the magnet to provide measurements of the positions and directions of particles hitting the magnet side walls
- **Improves momentum resolution of upstream tracks (~10-20% →~1%)**
- **Significant gains for modes with soft tracks (eg. $D^{*+} \to D^0\pi^+$)**

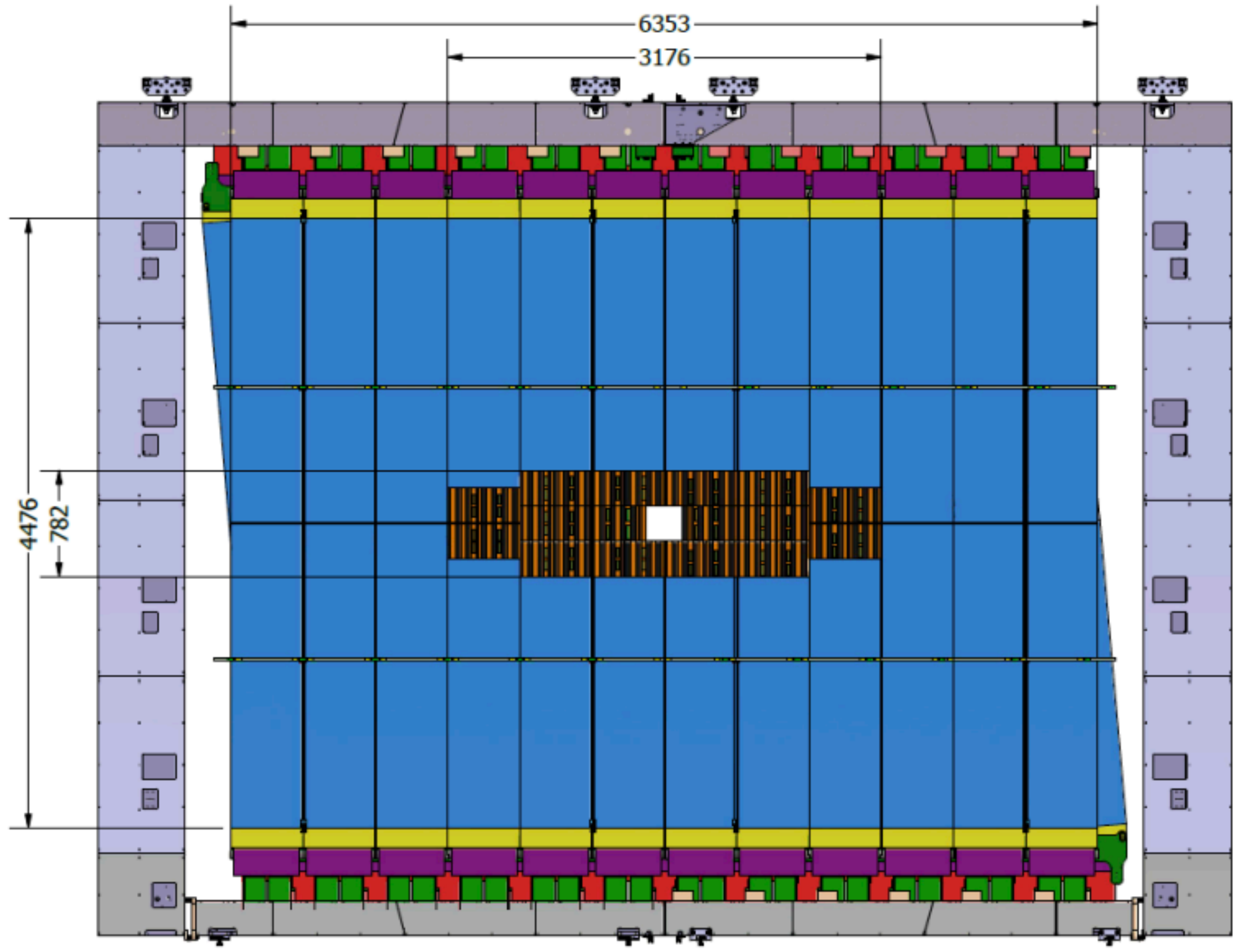






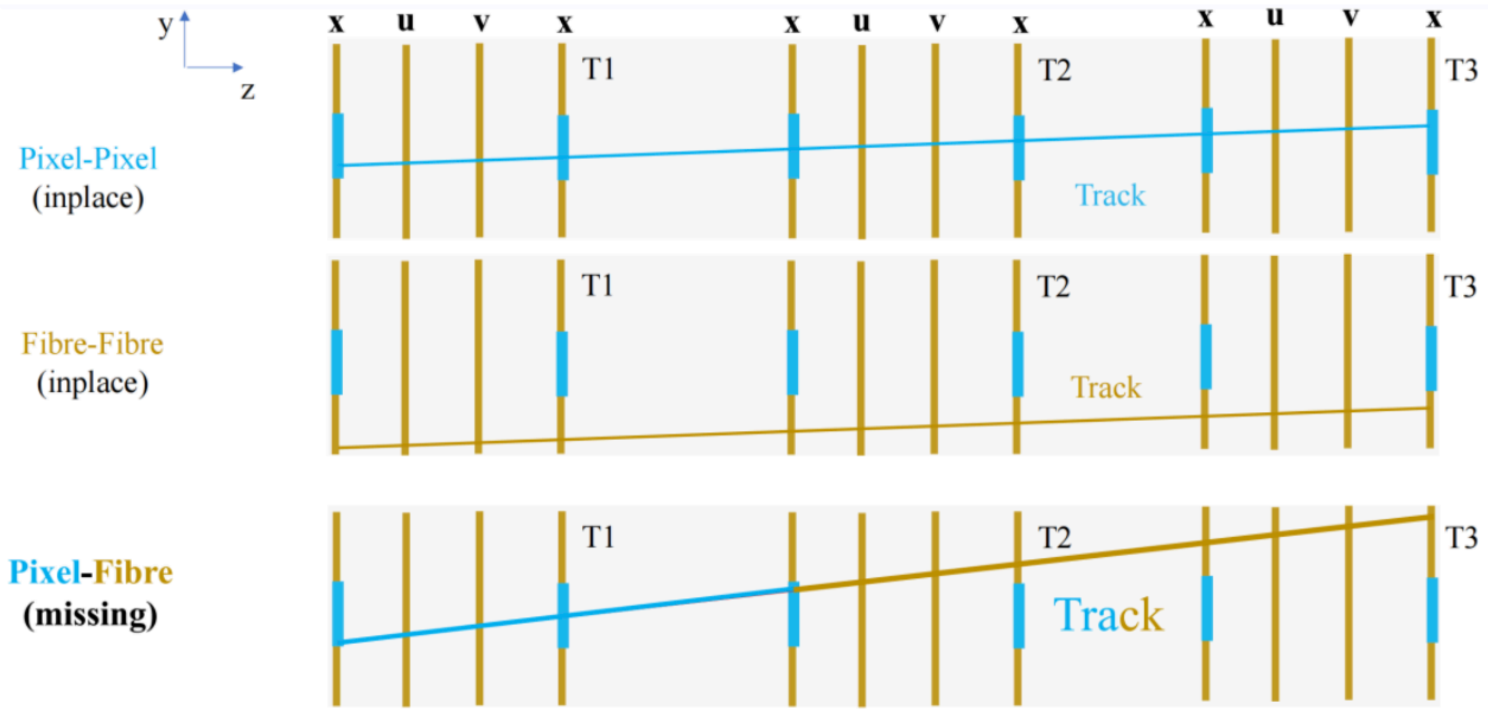
Mighty-SciFi

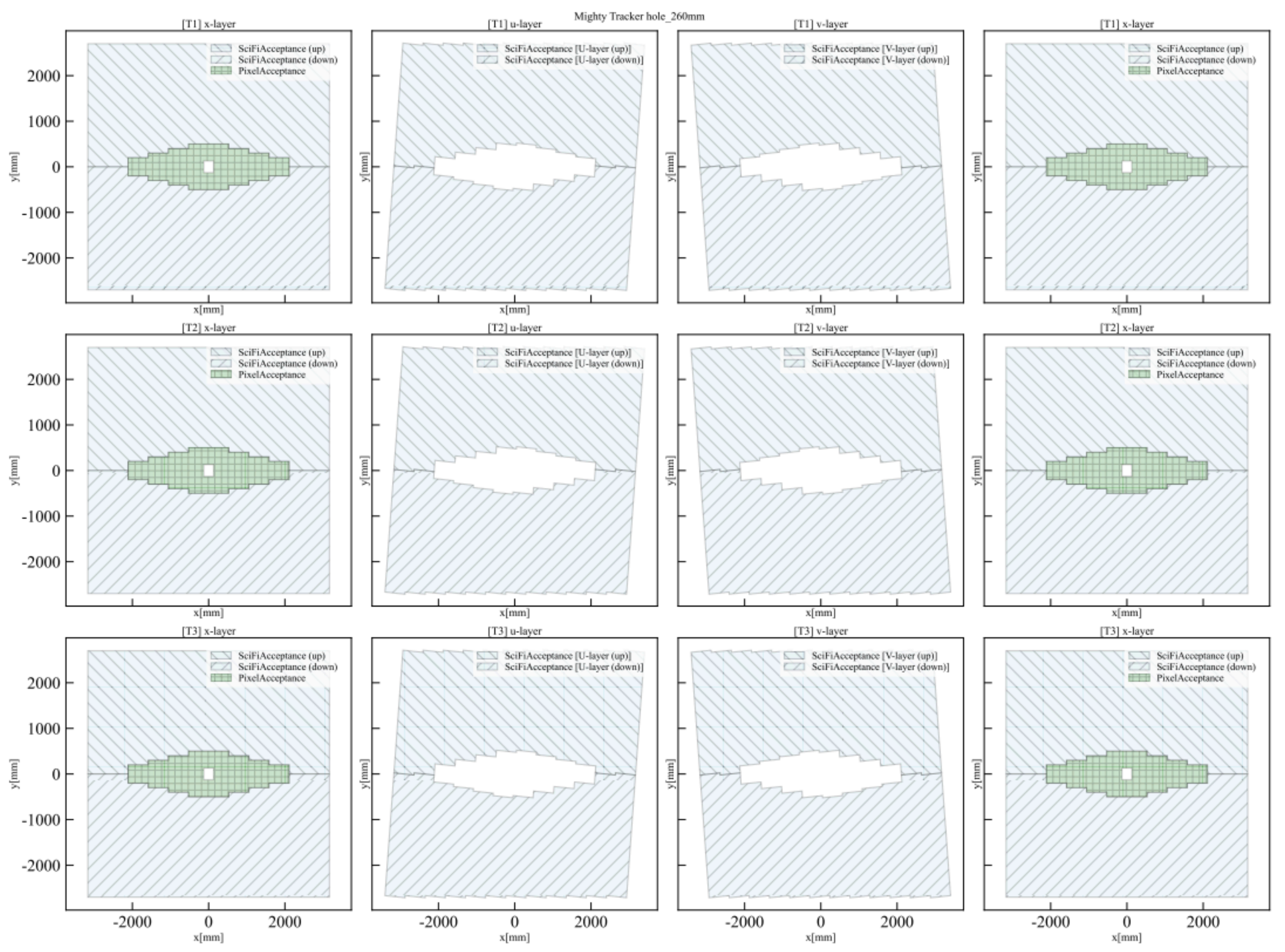
- Twelve layers of scintillating fibres with SiPM readout
- Keep UI SciFi design at outer region but with significant improvements
  - Improve light collection using micro-lens (μLens) enhanced detectors.
  - Reduce SiPM noise by cryogenic cooling for SiPM: -40°C => -120°C



Mighty-Pixel

- 6 layers of silicon pixel (HV-CMOS MAPS)
- Spatial resolution: pixel size < 100 × 300 μm
- Time resolution: ~ 3ns
- High radiation hardness





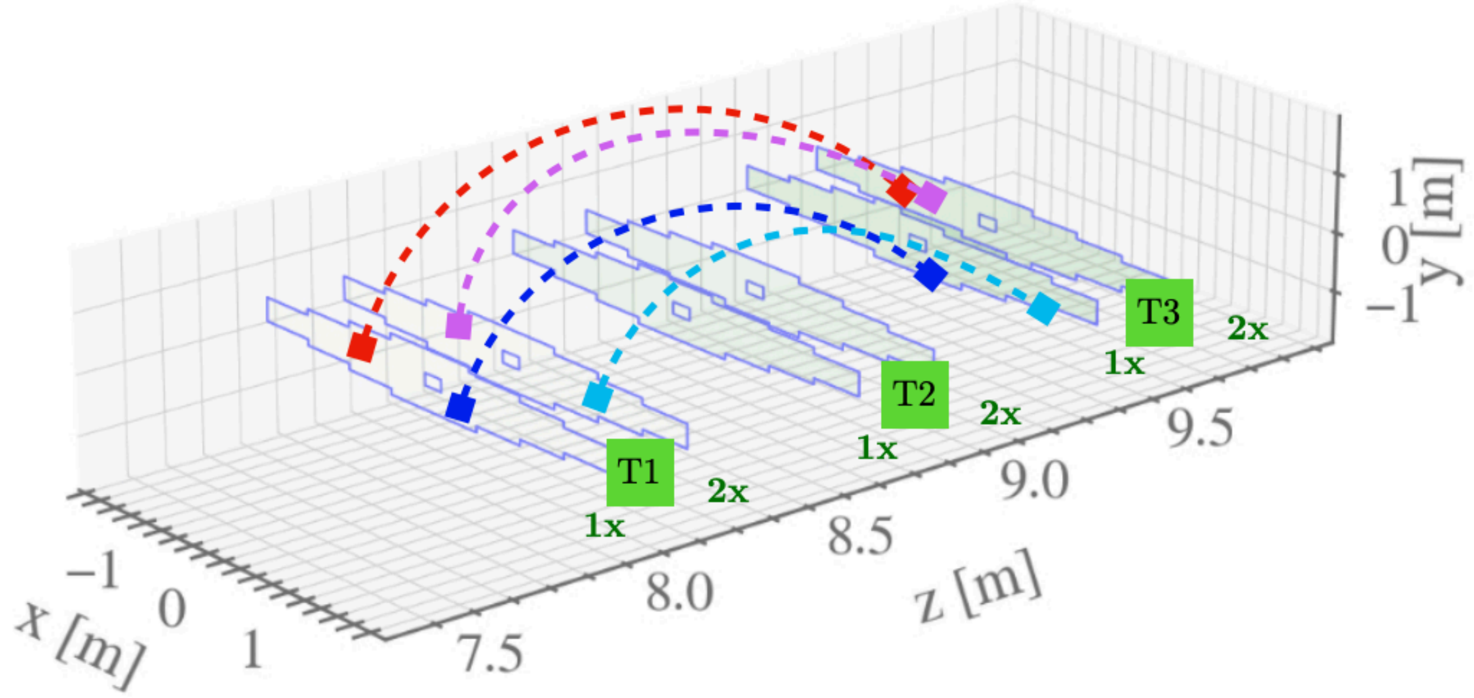
Mighty Tracker

- Run3 algorithm reused for Scifi track
- MP track reconstruction
  - Combine T1T3 lines, then open search windows in T1, T2, T3
  - Collecting hits in remaining layers for each T1T3 pair
  - Fit & select track, select one with best $\chi^2/NDOF$
  - Use clone killer to reduce clone rate

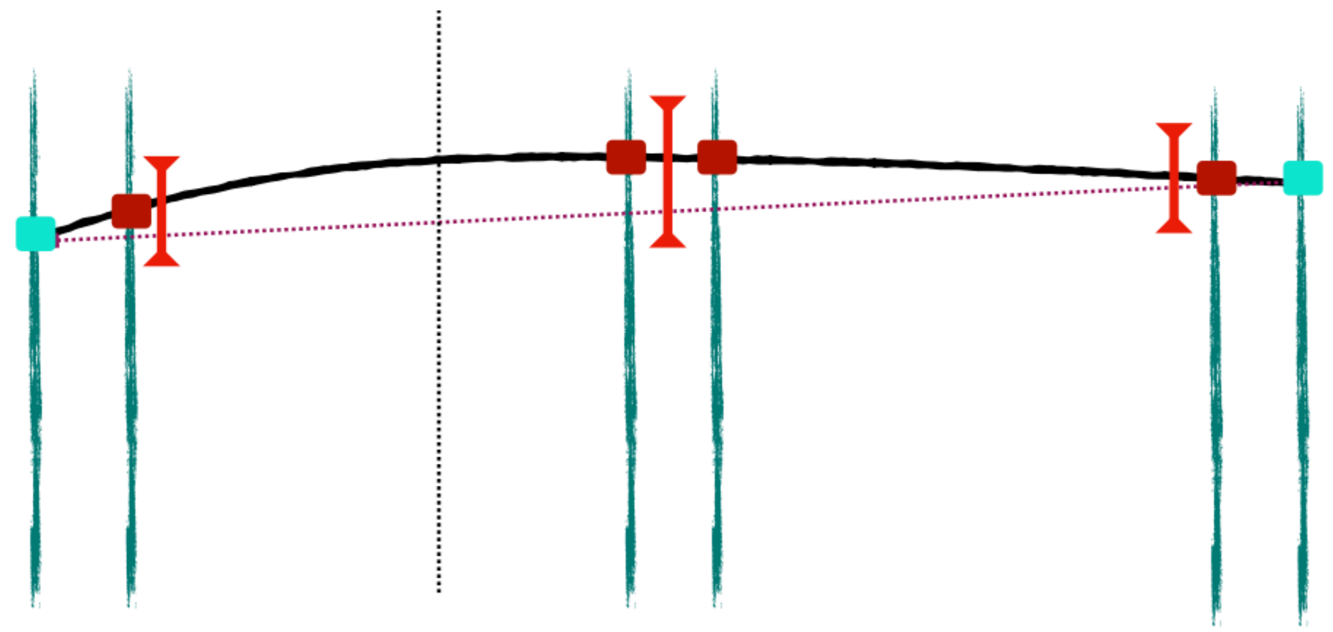
Case 0 → **Case 1** → **Case 2** → **Case 3**

- For each T1 hit
  - For each T3 hit in window
    - T1-T3 Line
    - Collect hits in other planes
    - All combinations for same T1 hit
    - Fit & select track
  - Select among combination the one with best chi2/NDOF
  - Clone kill tracks, keep highest Nhits , or smaller chi2/ndof
  - Flag all hits on tracks

Fake rate found extremely small:
hits can be removed for a next search to find what the previous combination was not able to find



Case	T1 layer	T3 layer
0	1x	2x
1	2x	2x
2	1x	1x
3	2x	1x

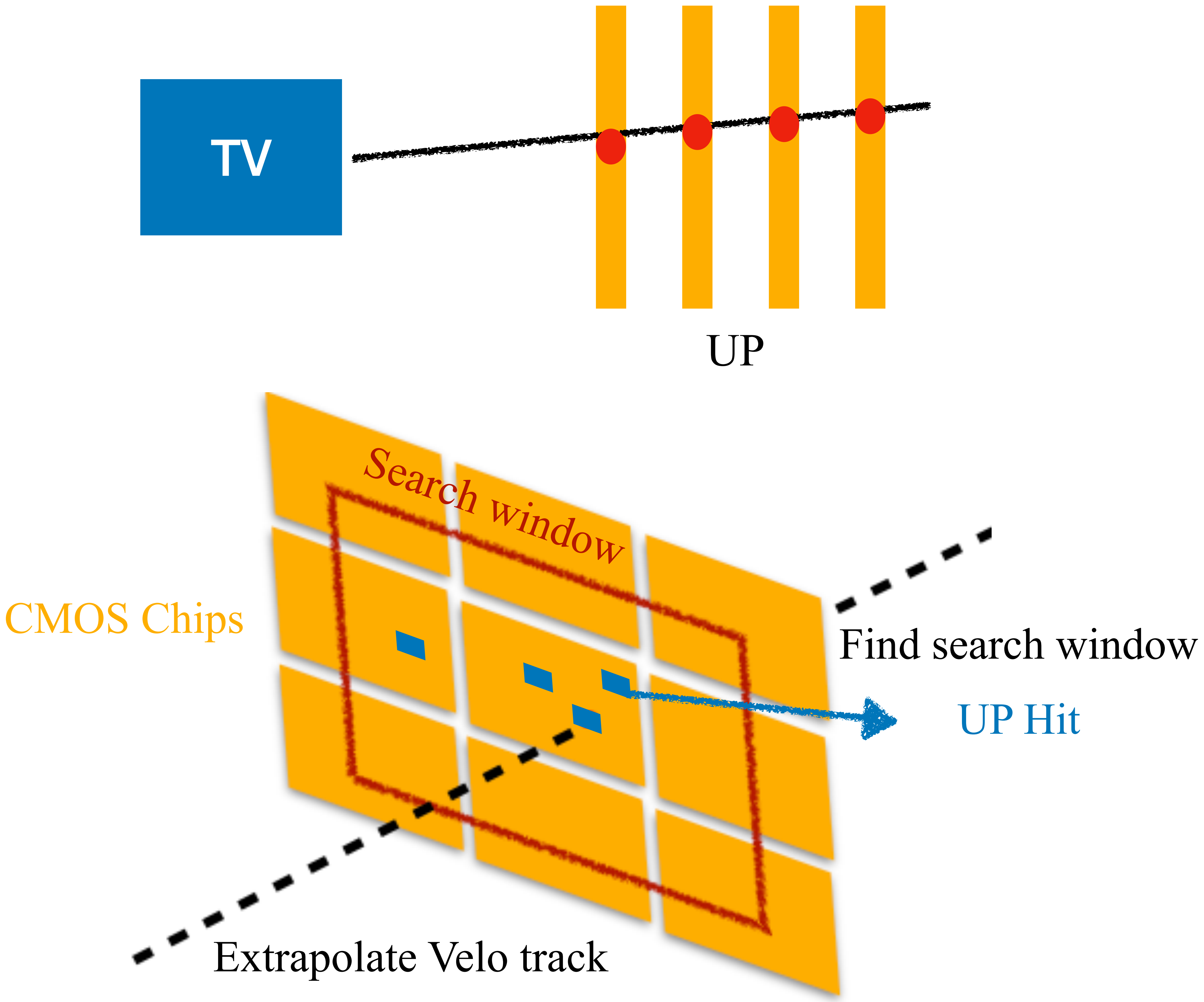


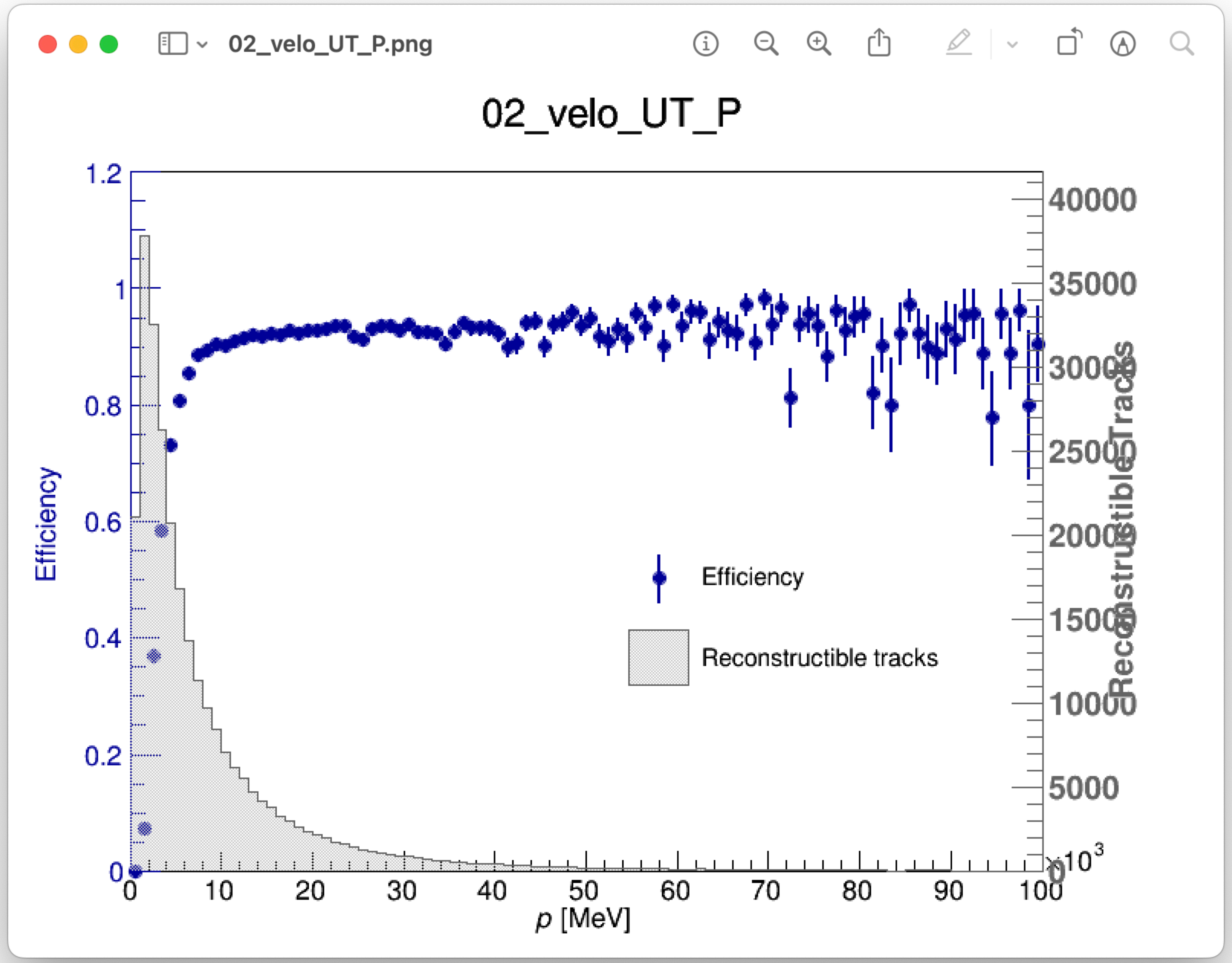
$$x(z) \sim a + b \cdot z + c \cdot z^2(1 + Dz)$$

$$y(z) \sim a + b \cdot z$$

Upstream Track

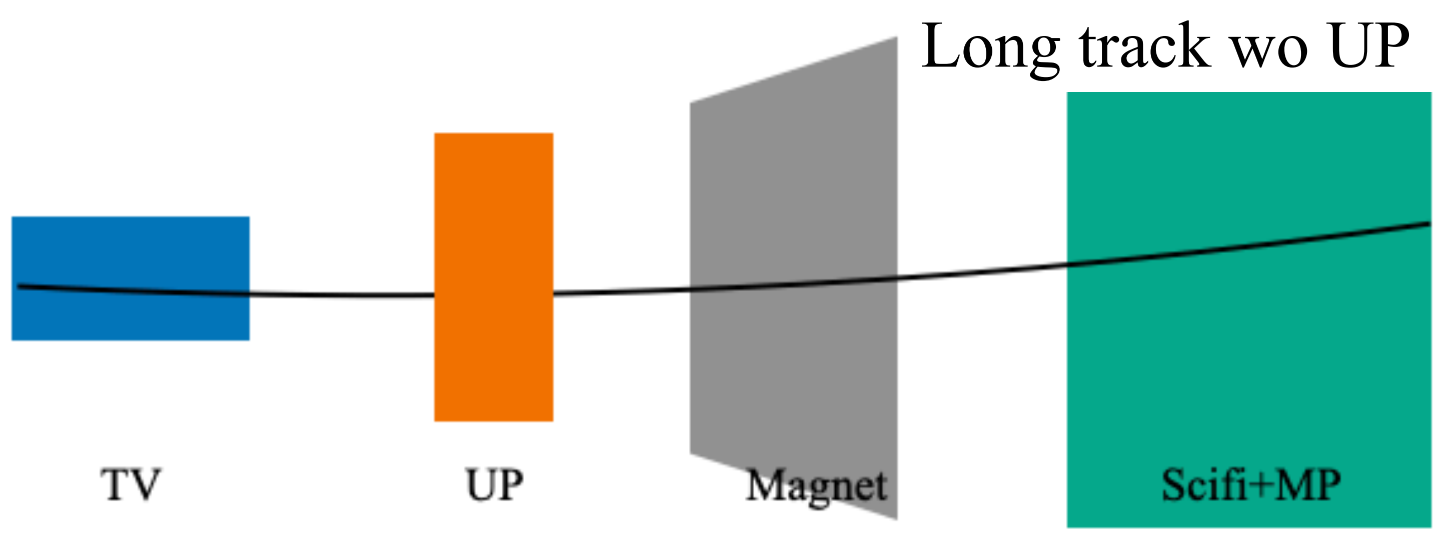
- Extrapolate TV Tracks to find search window of each UP layer (2×2 chips, 40×40 mm)
- Loop all the hits in search windows and fit with linear model to get the best track candidate

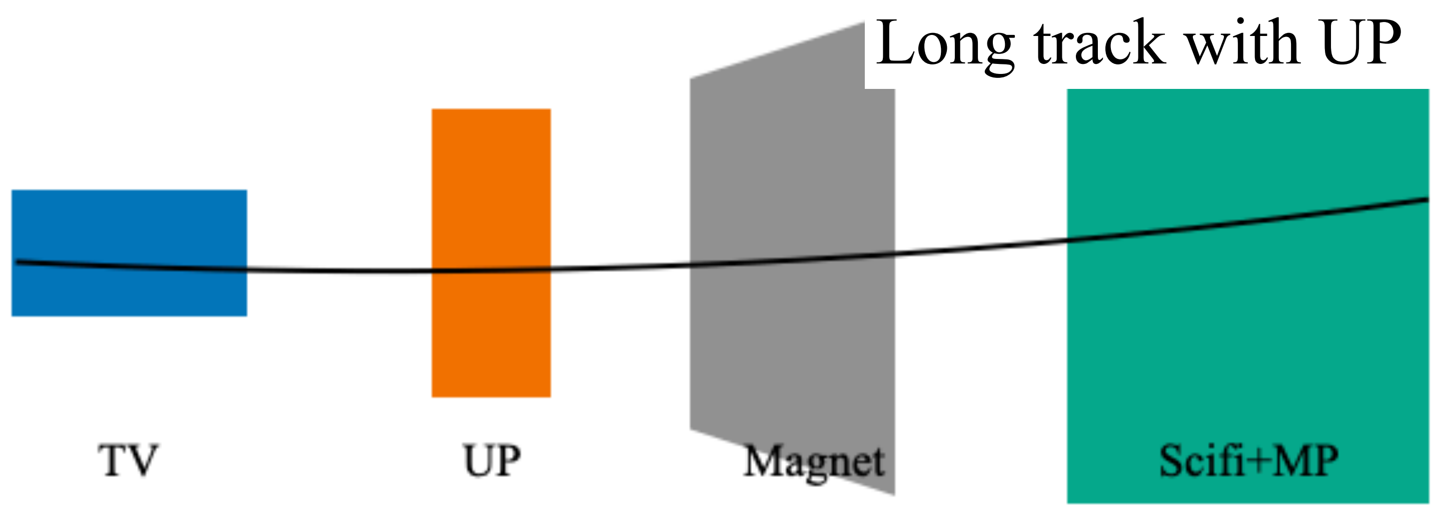


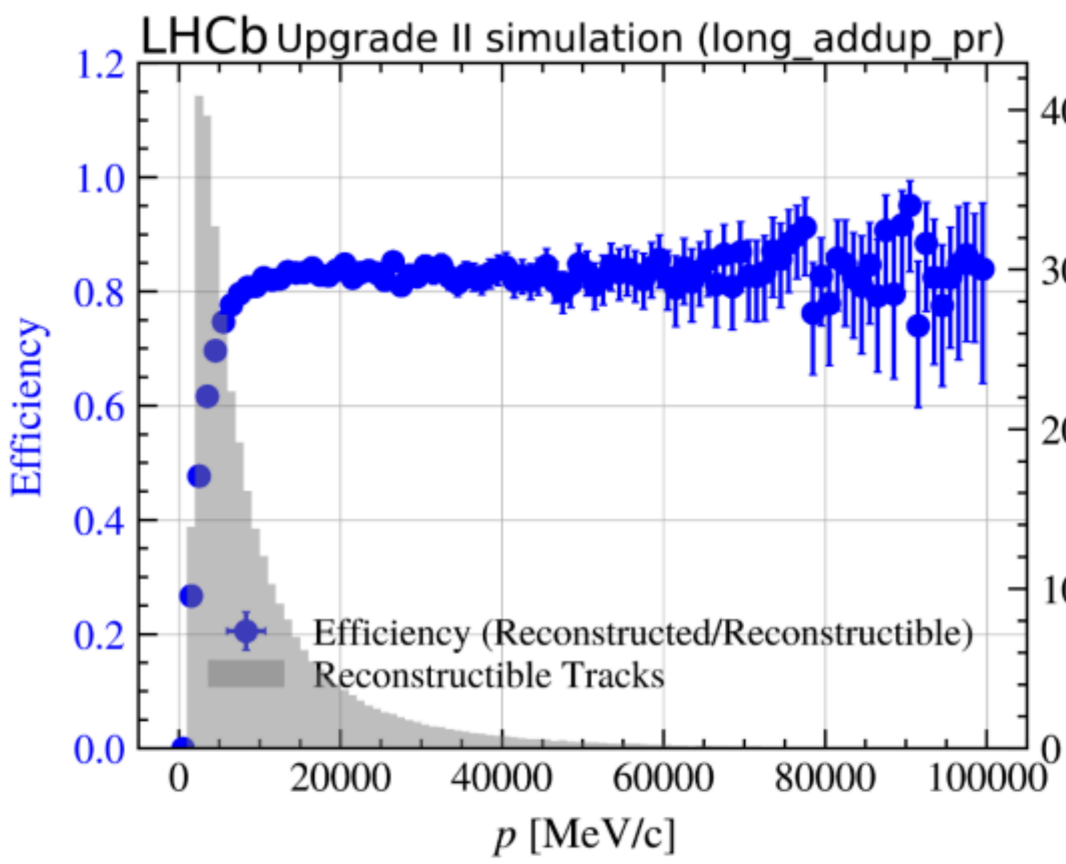


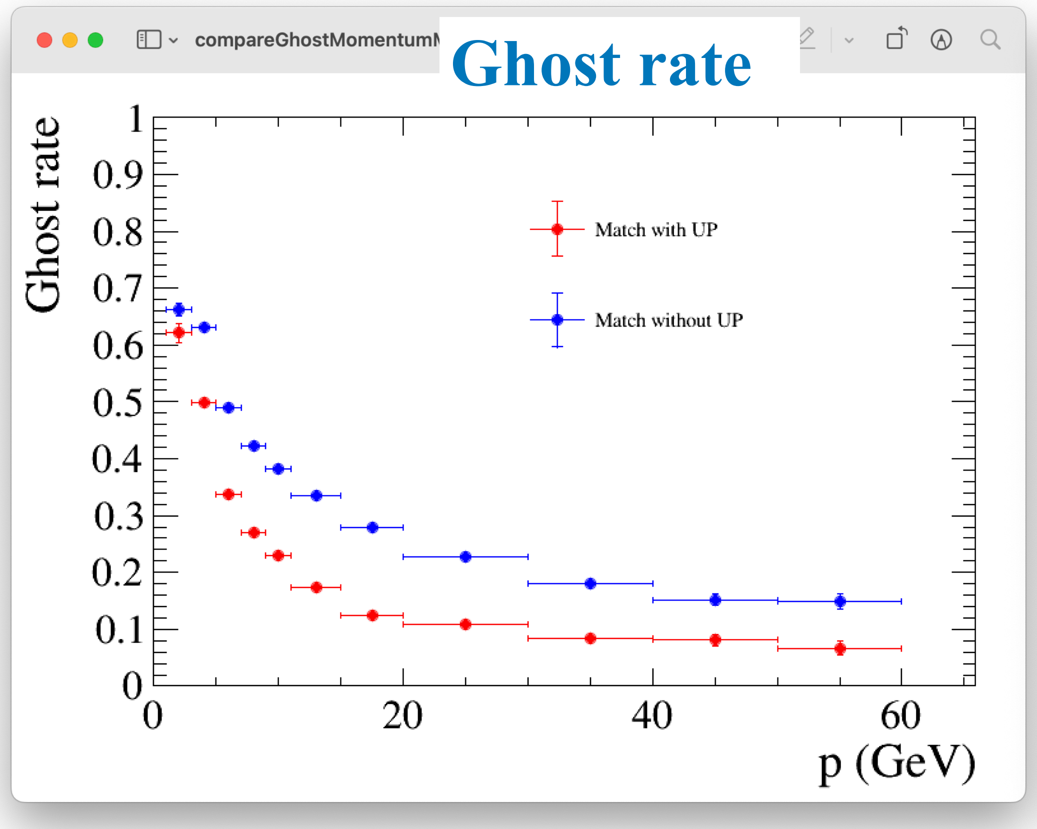
Long Track

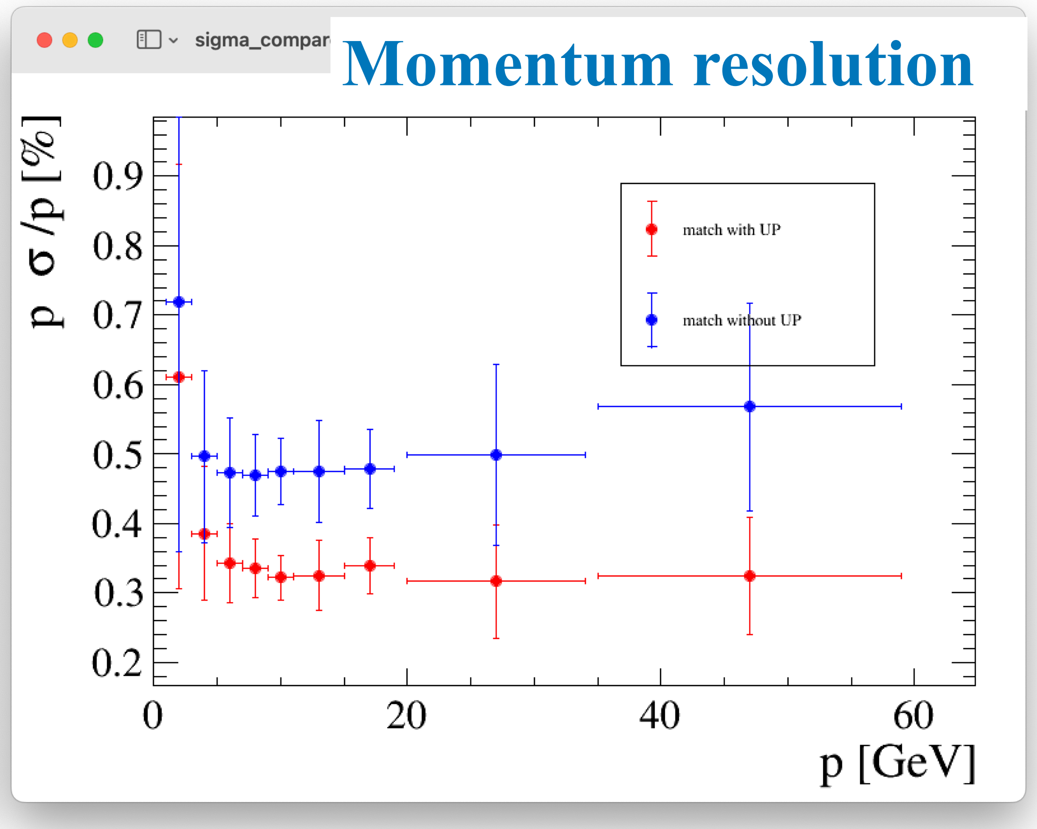
- **Matching TV tracks and MT tracks**
  - Extrapolate TV and MT tracks to a common Z-plane
  - Fast Pre-Filter: Discard candidates with large Y-mismatches
  - Precision Matching: cut on χ^2 and MLP score
    - Compute χ^2 from position/angle differences, with dynamic error scaling
      - $\chi^2 = (\Delta X^2/tolX) + (\Delta Y^2/tolY) + (\Delta Ty^2 \times 625)$
    - Evaluate match quality via MLP (6 inputs → mlp score)
      - Inputs: $\Delta X, \Delta Y, \Delta Tx, \Delta Ty, \chi^2$, TV $tx^2 + ty^2$
- **Add UP tracks/UP hits into matched TV-MT tracks**
  - Similar with upstream track — extrapolate from TV

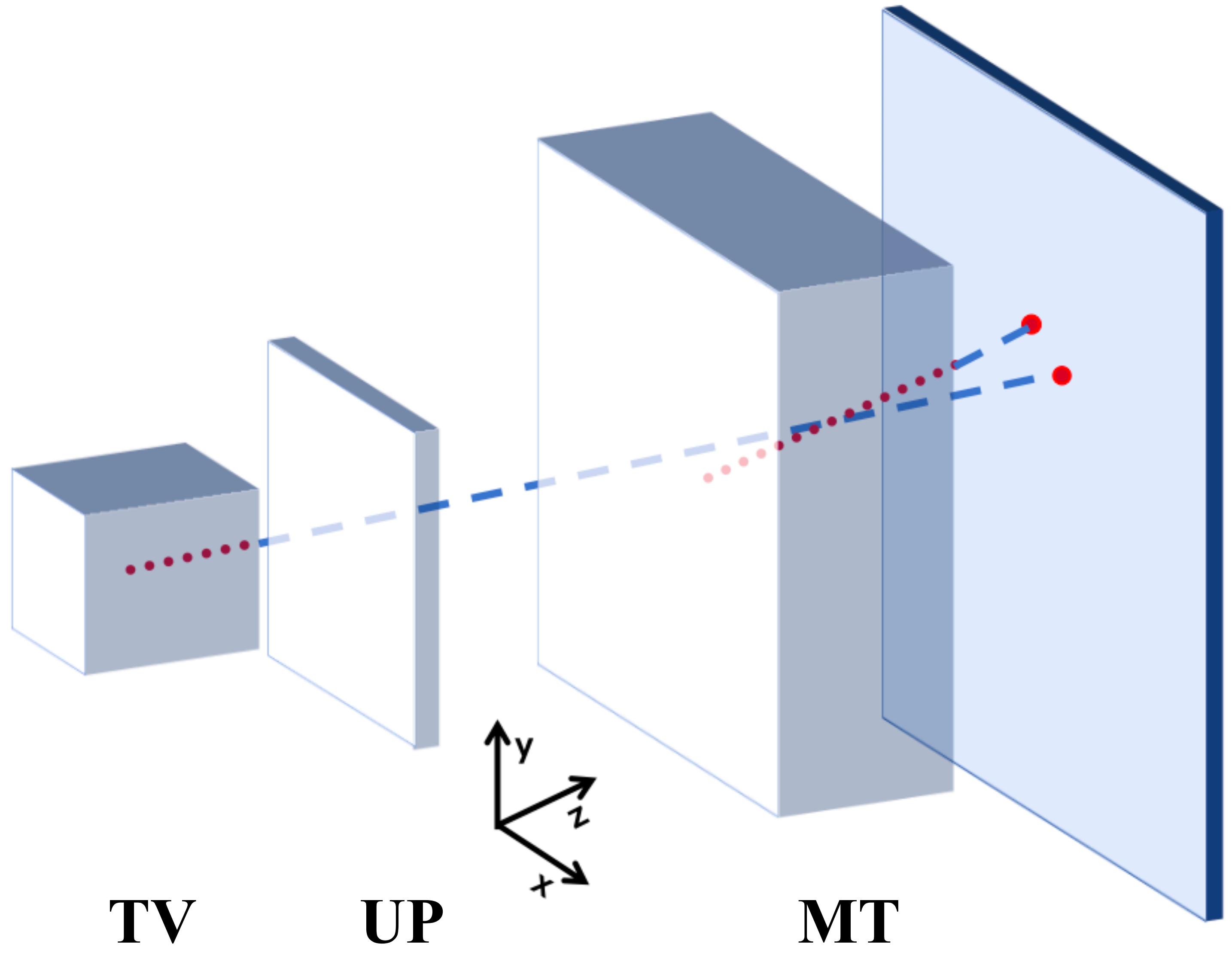




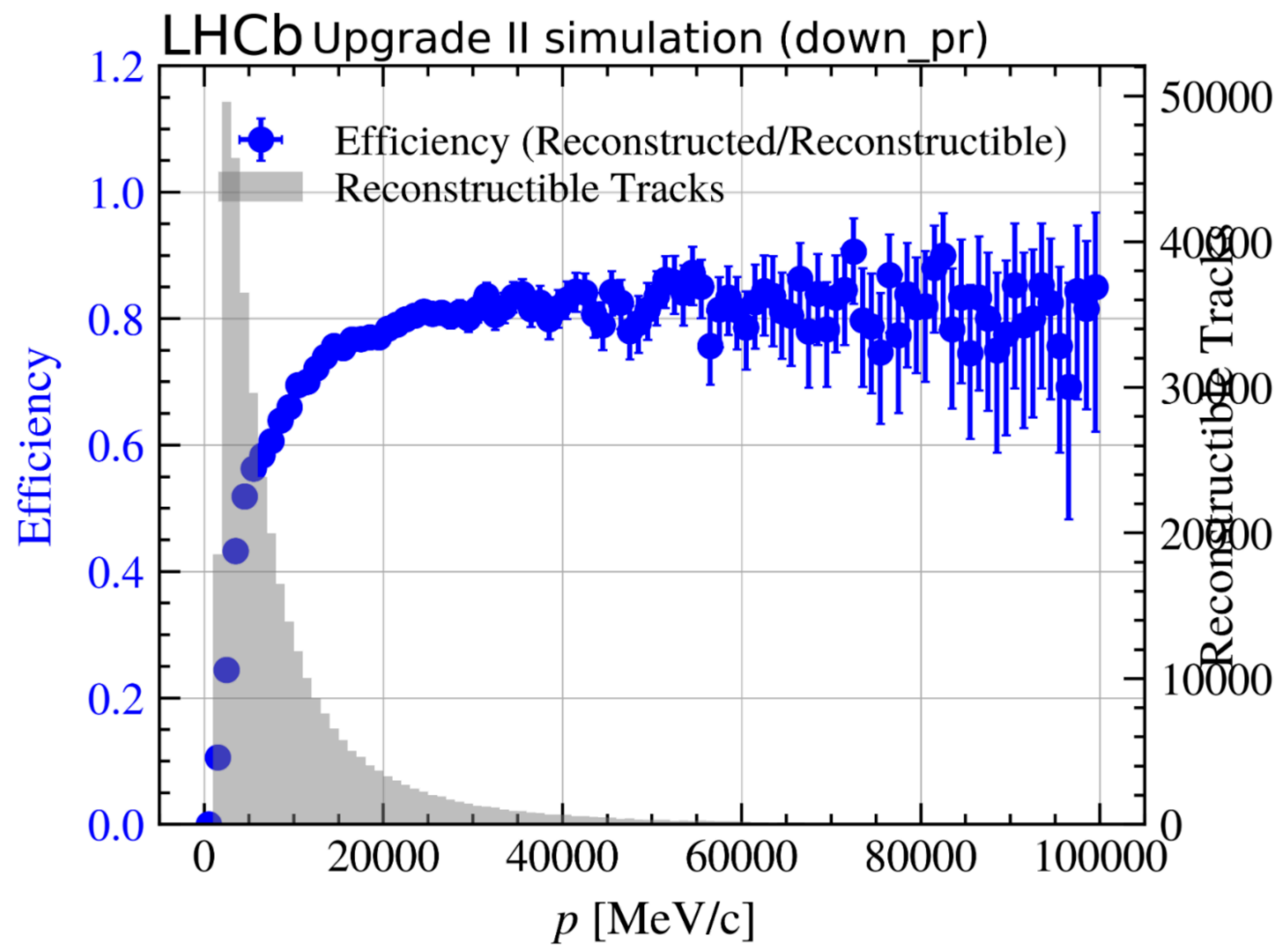


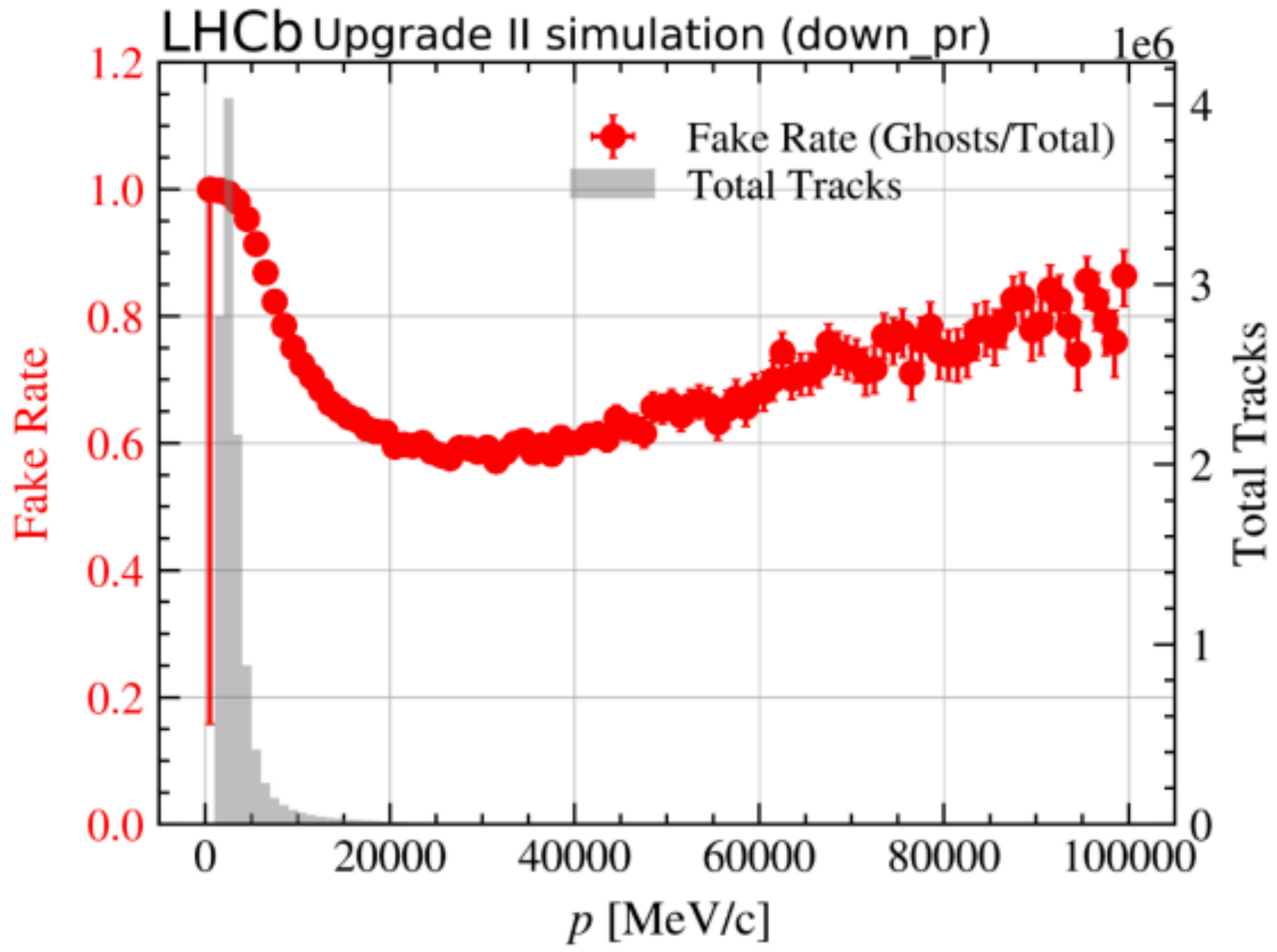






- Matching UP tracks and MT tracks
- Same algorithm with TV-MT matching, MT tracks matched UP tracks instead of TV tracks
- Without Kalman filter yet, the fake rate will reduce significantly with KF

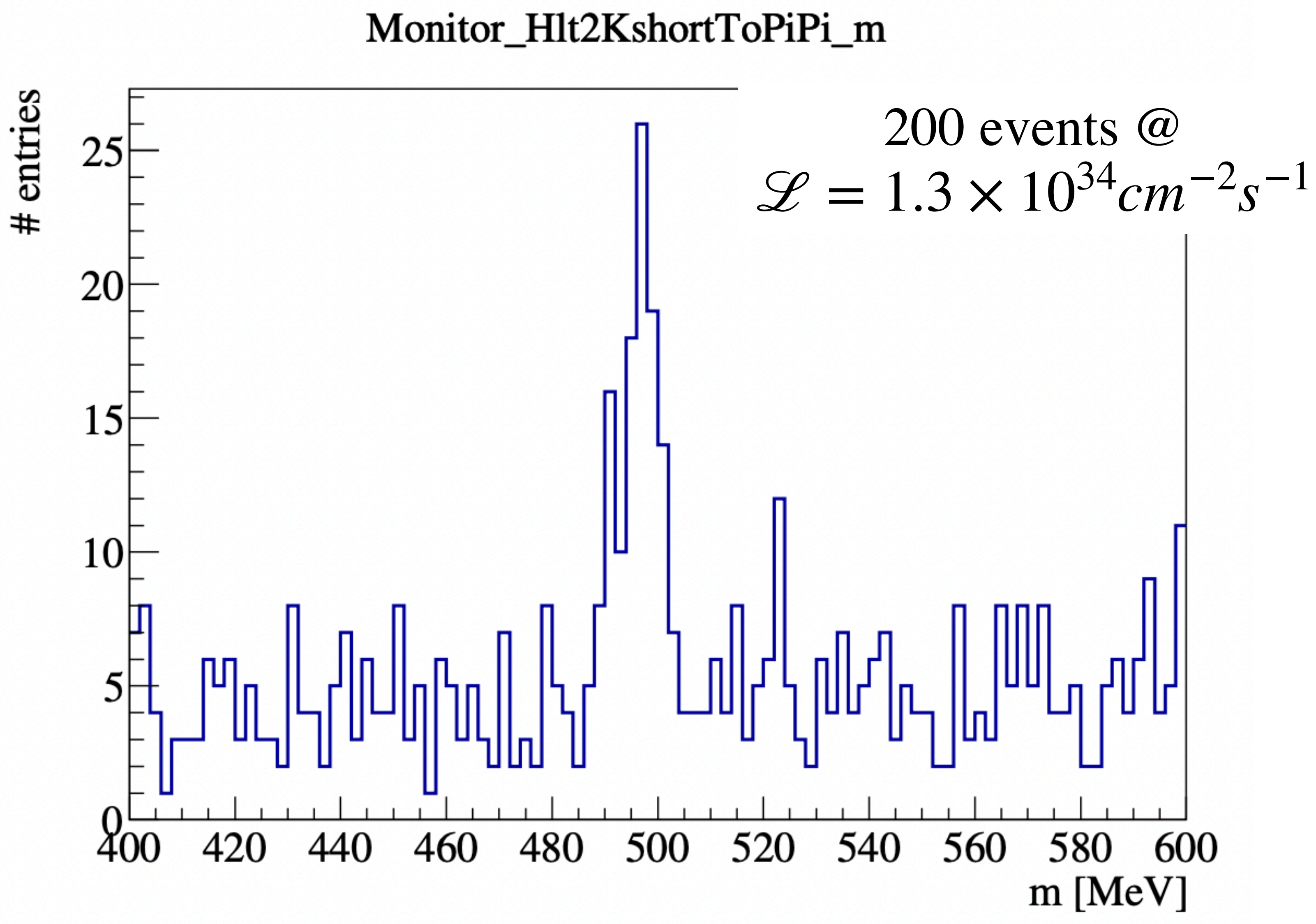




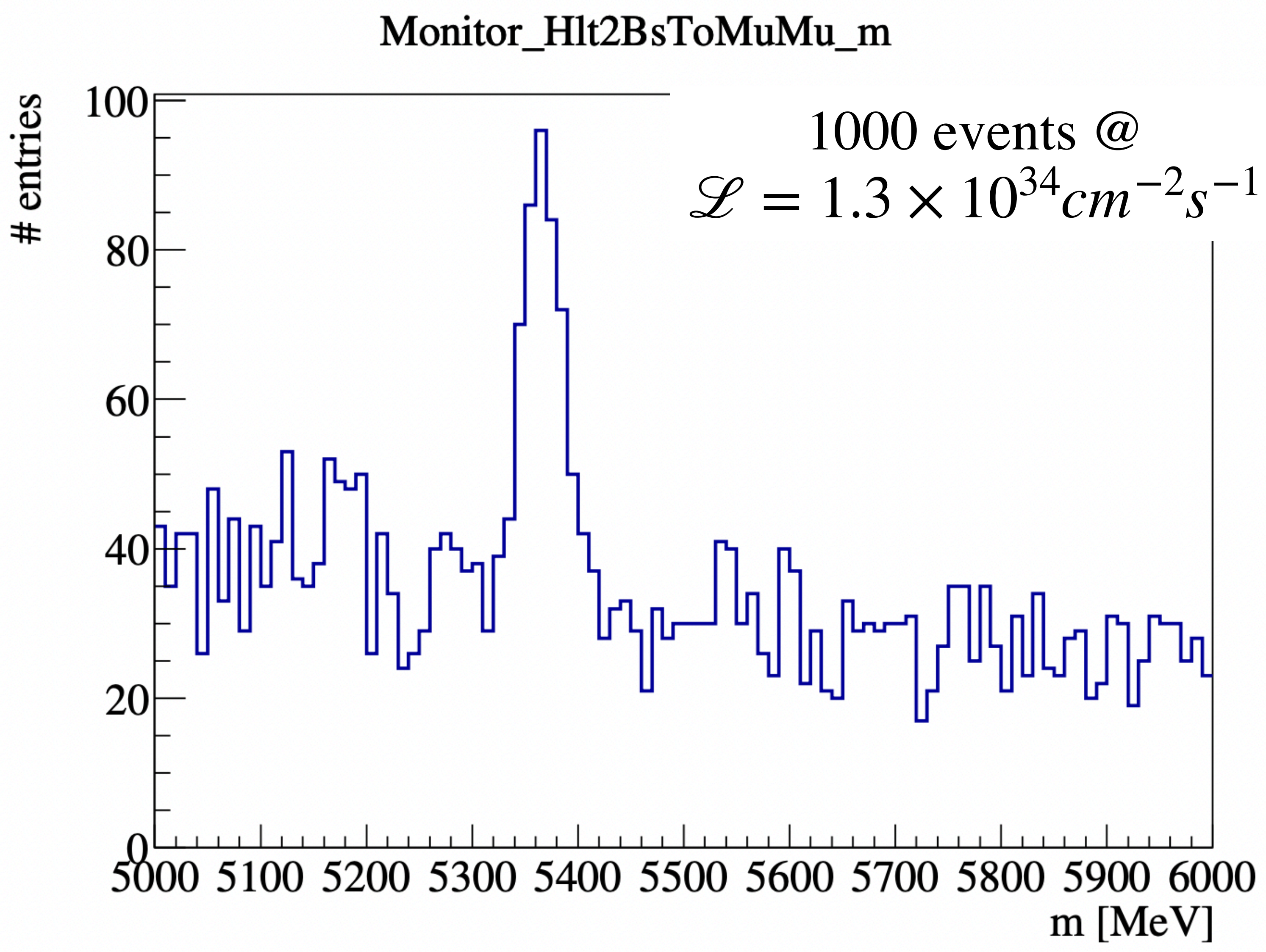
Reconstruction of physics decays

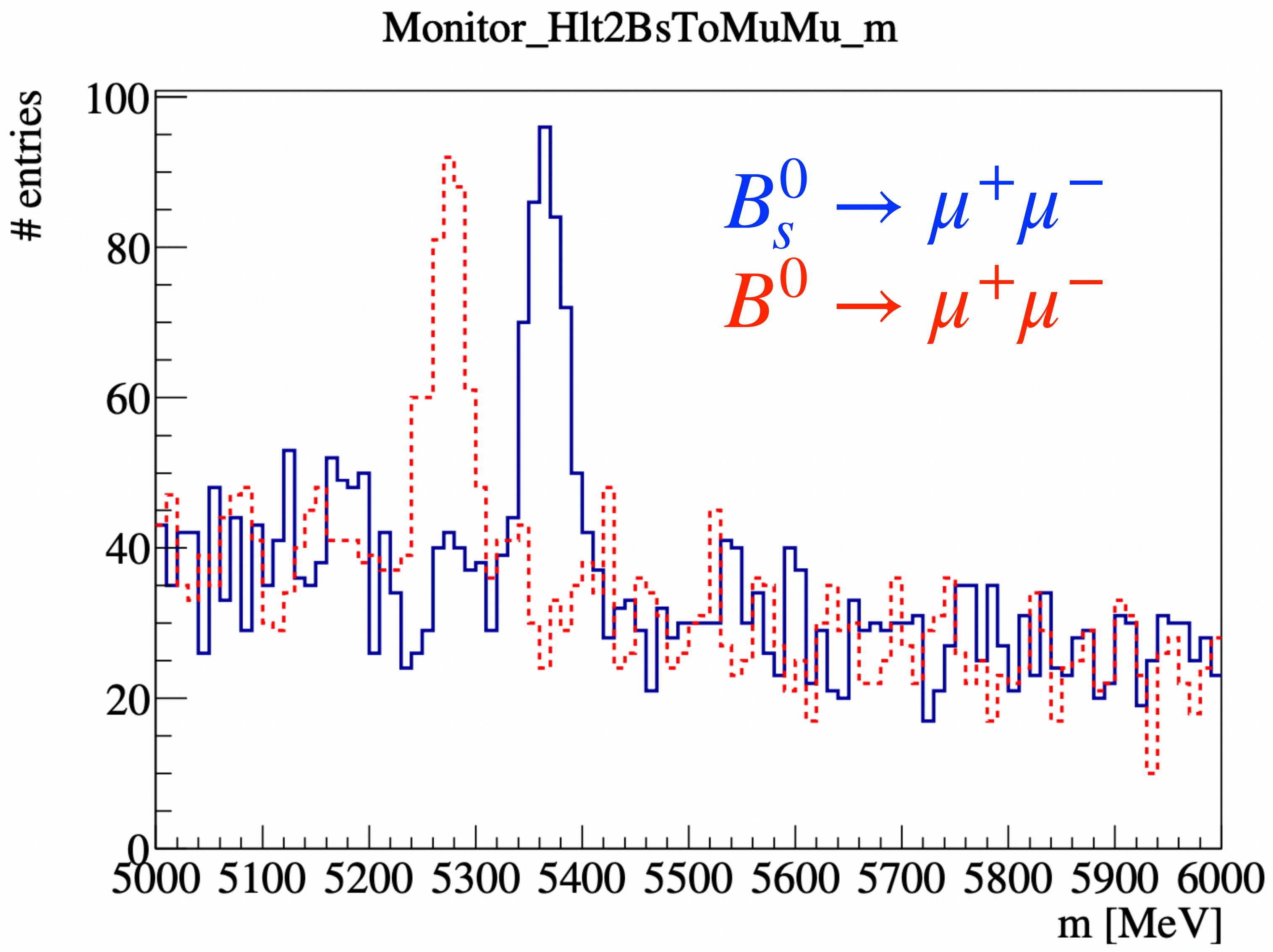
Reconstruct tracks on Upgrade2 simulation — Use Long Track

$K_s^0 \rightarrow \pi^+\pi^-$ mass peak



$B_s^0 \rightarrow \mu^+\mu^-$ mass peak





- Clear mass peak visible
- Well separated for $B_s^0 \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$

Summary

- All the sub-detectors of LHCb tracking system will upgrade in UII
- Nearly the entire tracking system will be constructed using high-resolution silicon pixel detectors
- The goals for UII is keep or improve detector performance as in UI
- The reconstruction algorithm development for UII is still ongoing

Backup

COFFEE development

Team:

IHEP, CAS / KIT / Zhejiang U / Hunan U / Shandong U / NPU / Dalian Minzu U ···

CMOS SENSOR IN FIFTY-FIVE NM PROCESS

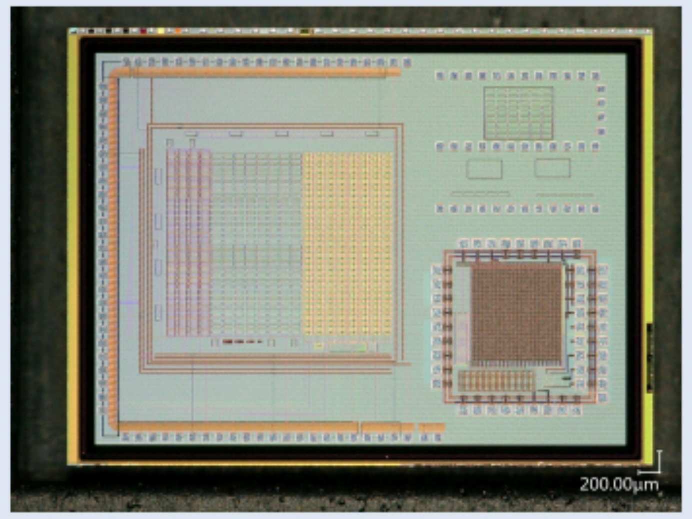
Goal: Full-size full functioning sensor chip ~2027

··· | 2022 | 2023 | 2024 | 2025 | ...

COFFEE 2

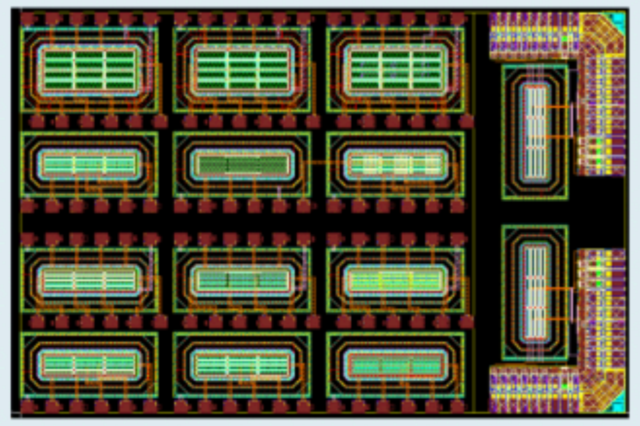
First HVCMOS 55nm prototype chip

- Breakdown at -70V
- Responsive to laser, X-ray and beta-ray sources



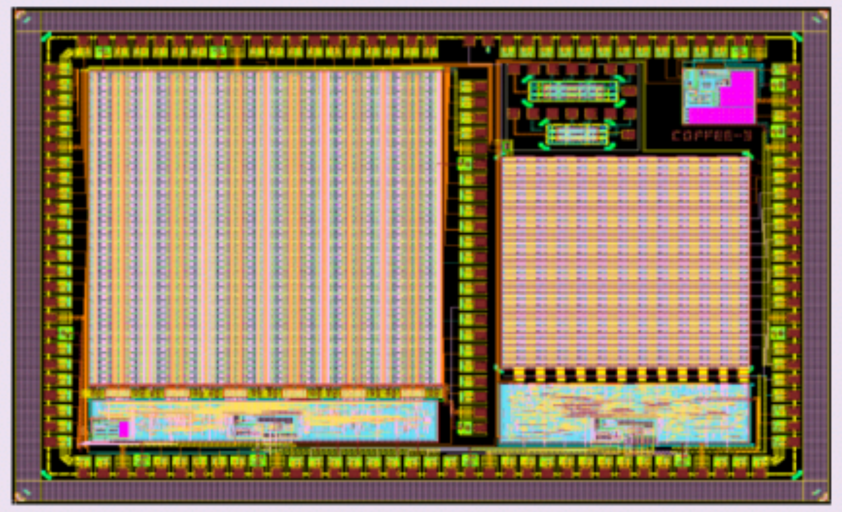
COFFEE1

- Prototype in LL process
- Validation of deep N-well structure
- Breakdown at -9V



COFFEE3

- Two pixel arrays with data-driven readout
- Designed for good timing resolution and moderate power consumption

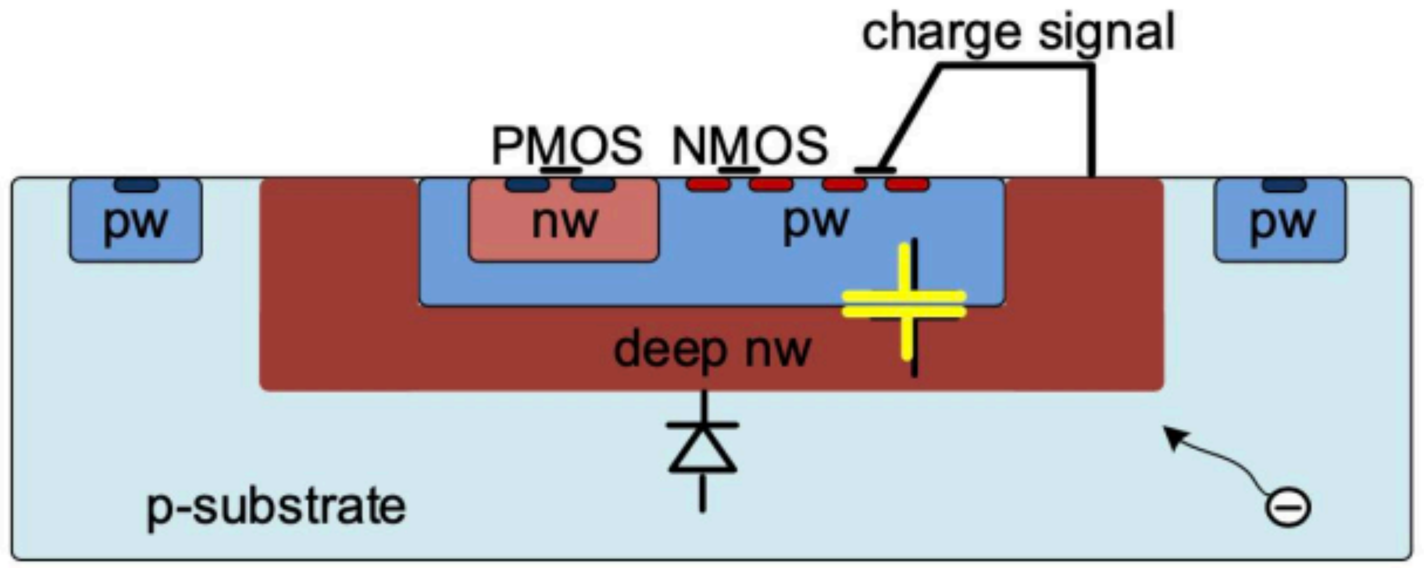


Possible MAPS solutions

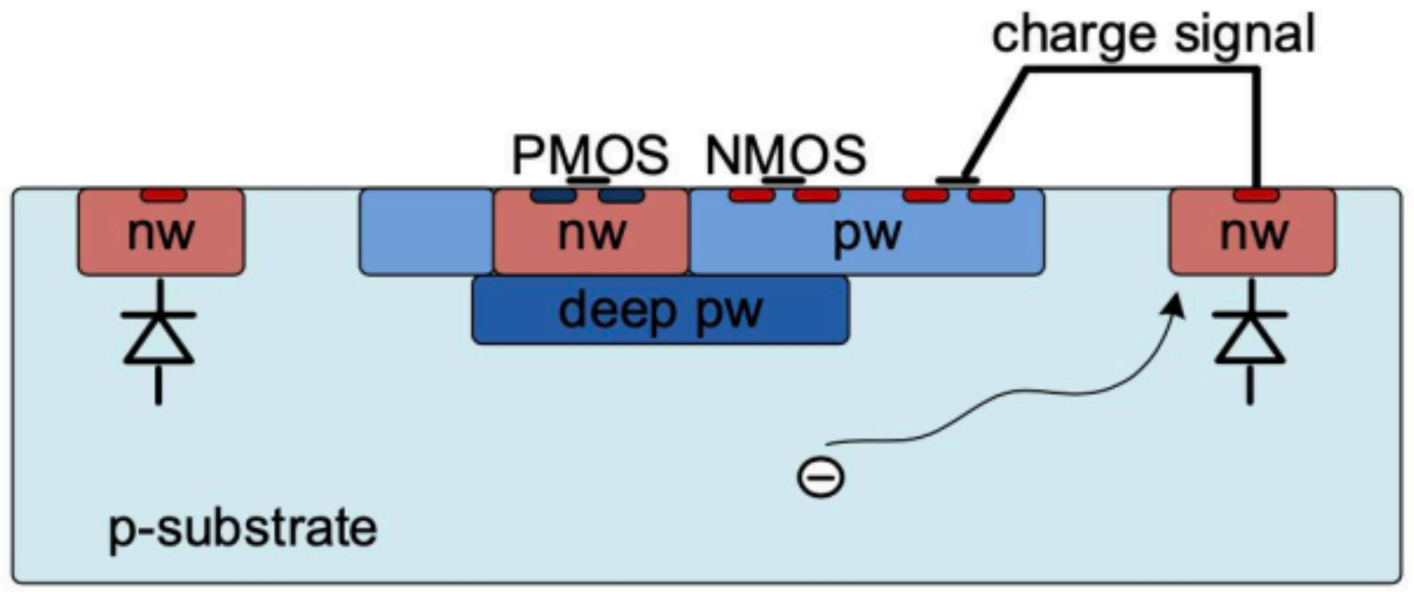
- **UP Sensor requirements**
  - Good spatial resolution especially in horizontal
  - High radiation hardness: $3 \times 10^{15} n_{eq}/cm^2$
  - Frontend design provide good timing resolution: 3-5 ns
- **Candidate technologies: HV- or LV-CMOS**

Technology	HV-CMOS	LV-CMOS	Sensor
AMS/TSI 180nm	✓		MightyPix
TowerJazz 180nm		✓	MALTA
LF 150nm	✓		RadPix
TPSCo 65nm		✓	SPARC
SMIC 55nm	✓		COFFEE

Parameter	UP Specification
Pixel size in x	$\leq 100\mu m$
Pixel size in y	$\leq 100\mu m$
Substrate thickness	$< 200\mu m$
Pixel orientation	Central sym.
Max. Particle Rate (R_{part})	74 (34) MHz/cm^2
Max. Hit Rate	150 Mhit $s^{-1}cm^{-2}$
Max. Length of the data word	32
Overall efficiency	> 96%
In-time efficiency	> 99% within 25ns
Noise rate (End of life)	$\leq$ 400kHz/cm^2
Transmission rate	N×1.28 Gbit/s
NIEL	$3 \times 10^{15} n_{eq}/cm^2$
TID	240 MRad
Power Consumption	$\leq$ 300 mW/cm^2



Large collection electrode



Small collection electrode

UP Specification