The simulation and reconstruction studies on LHCb UP detector for Upgrade II

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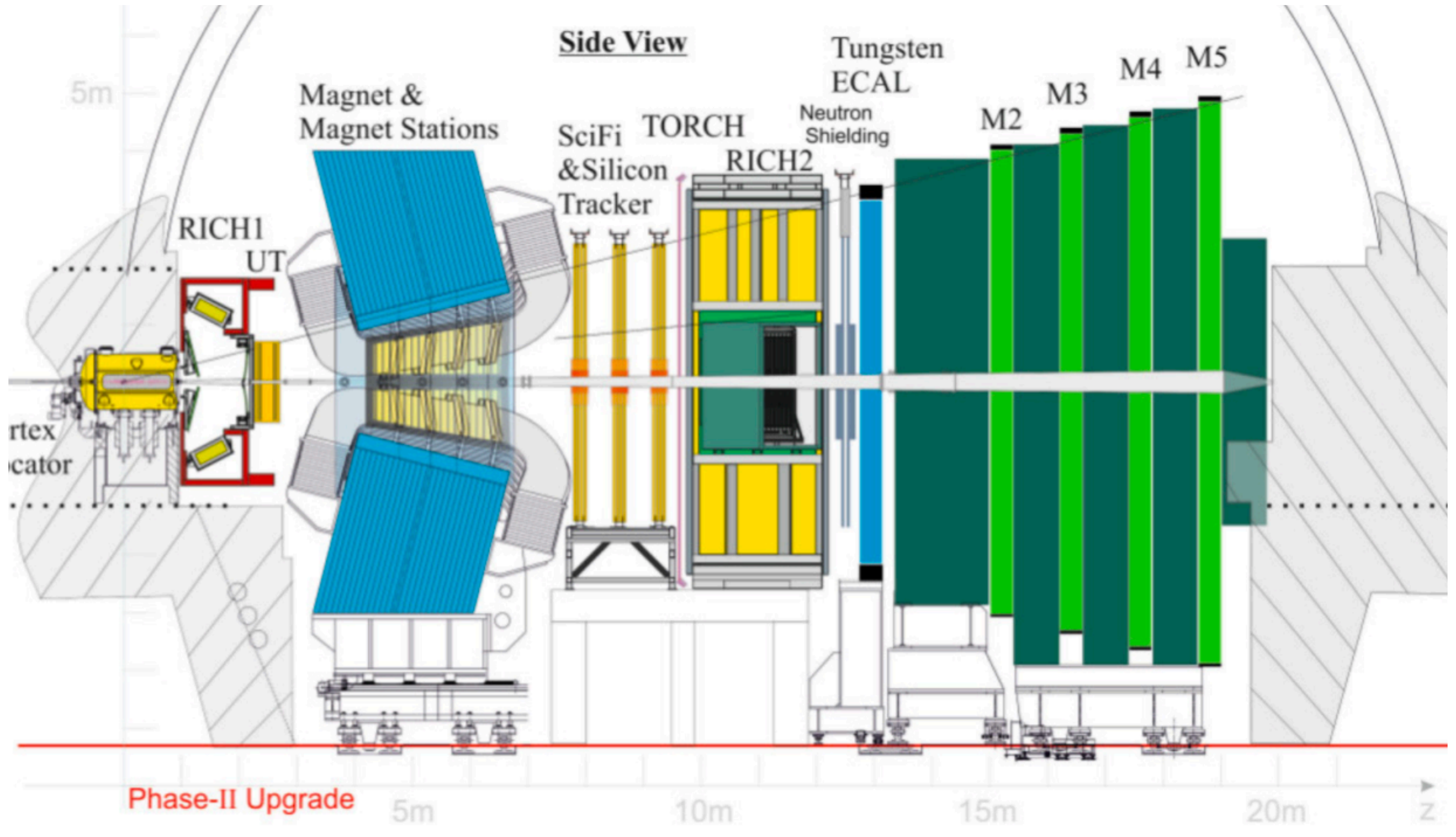
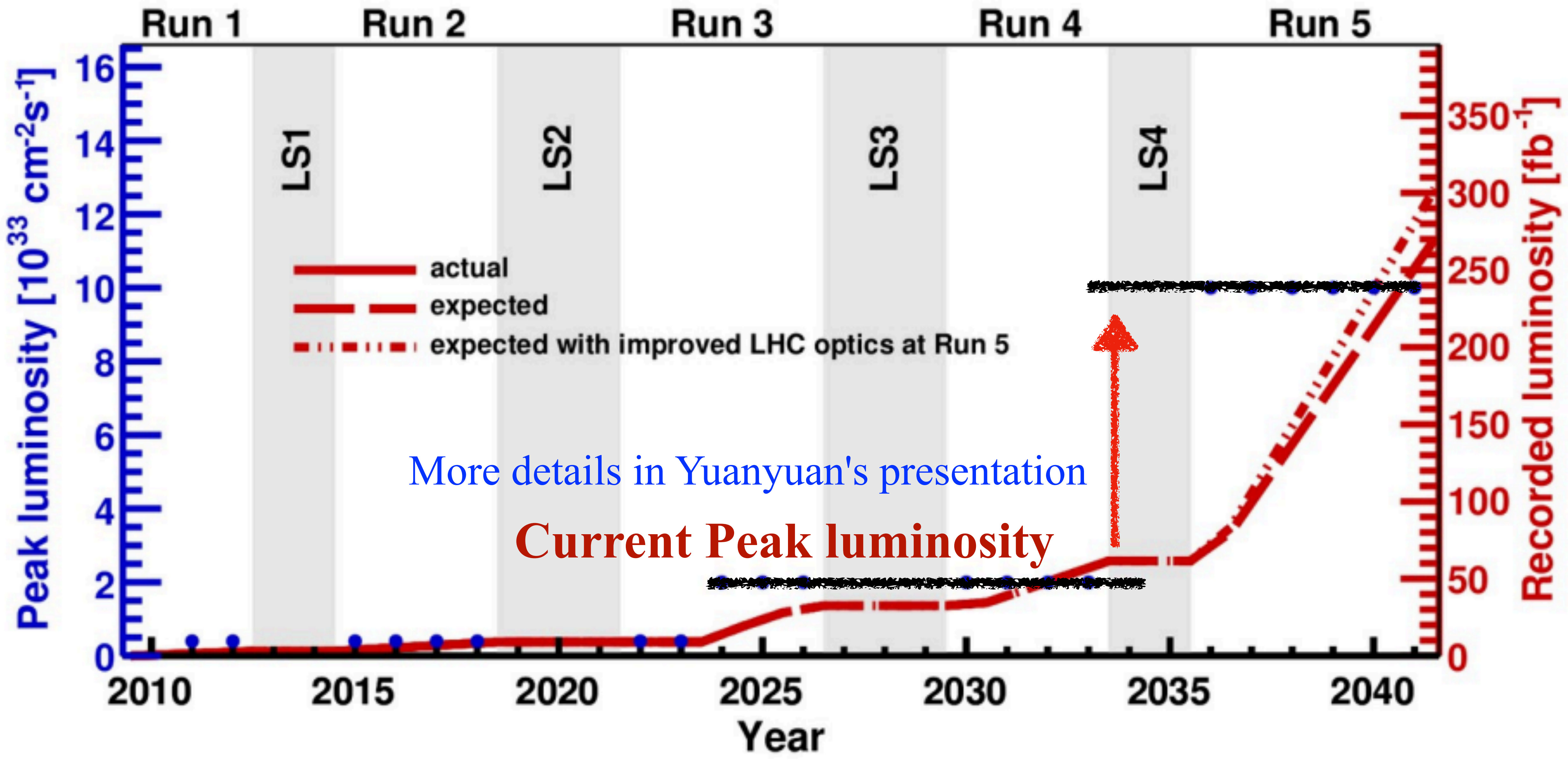
第十一届中国LHC物理会议

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)
    - $\mathscr{L}_{peak} = 4 \times 10^{32} cm^{-2}s^{-1}$, $\mathscr{L}_{Int} = 9\,fb^{-1}$
    - Achieved remarkable results in flavour physics, providing key tests of the SM
    - Need to measurement with much higher precision to further deepen understanding
  - Upgrade I (Run3 & Run4)
    - $\mathscr{L}_{peak} = 2 \times 10^{33} cm^{-2}s^{-1}$, $\mathscr{L}_{Int} = 50\,fb^{-1}$
    - The data-taking rate has increased dramatically
  - Upgrade II (Run5)
    - Peak luminosity increased by a factor of 5
      - Baseline: $\mathscr{L}_{peak} = 1.0 \times 10^{34} cm^{-2}s^{-1}$, $\mathscr{L}_{Int} = 240\text{ - }300\,fb^{-1}$
    - Sub-detector upgrade





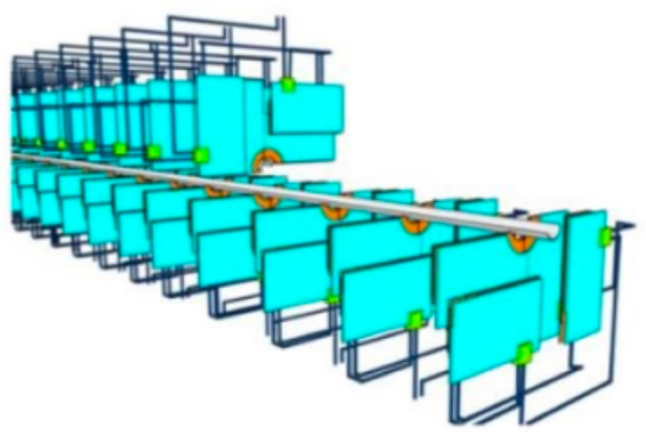
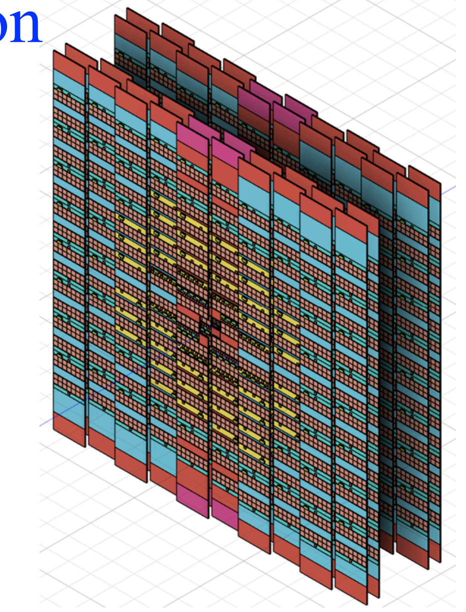
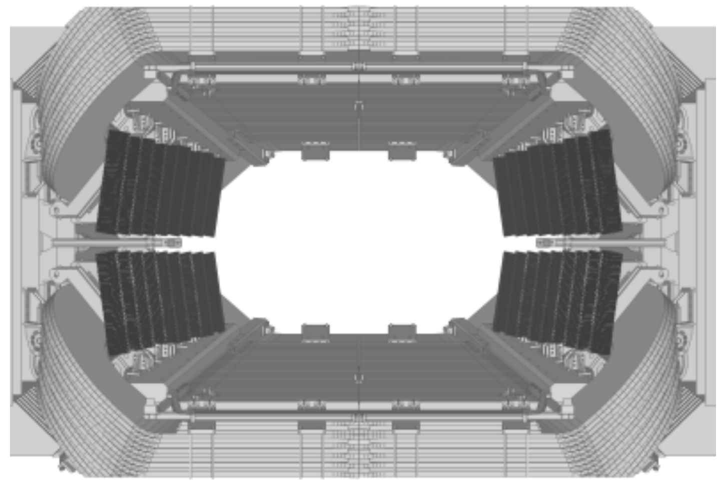
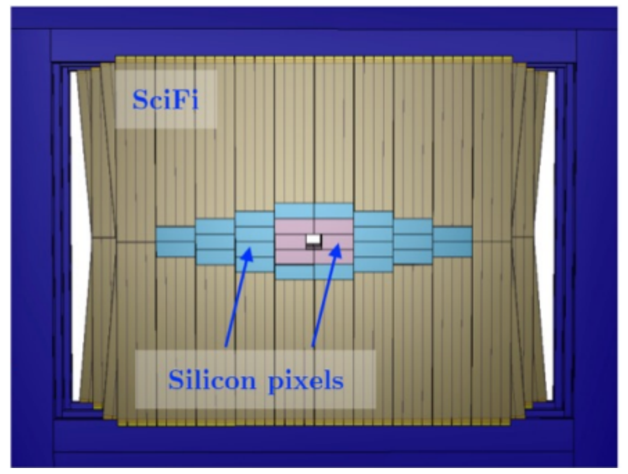
More details in Hengne Li's presentation

UP plays a key role in LHCb tracking system

- Fast estimates momentum for trigger system
- Improve momentum resolution
- Reduce ghost rate in track
- Increase reconstruction efficiency for Λ_0 K_S^0…

LHCb Track Type

- Long track: TV - **UP** - MT
- Upstream: TV - **UP**
- Downstream: **UP** - MT

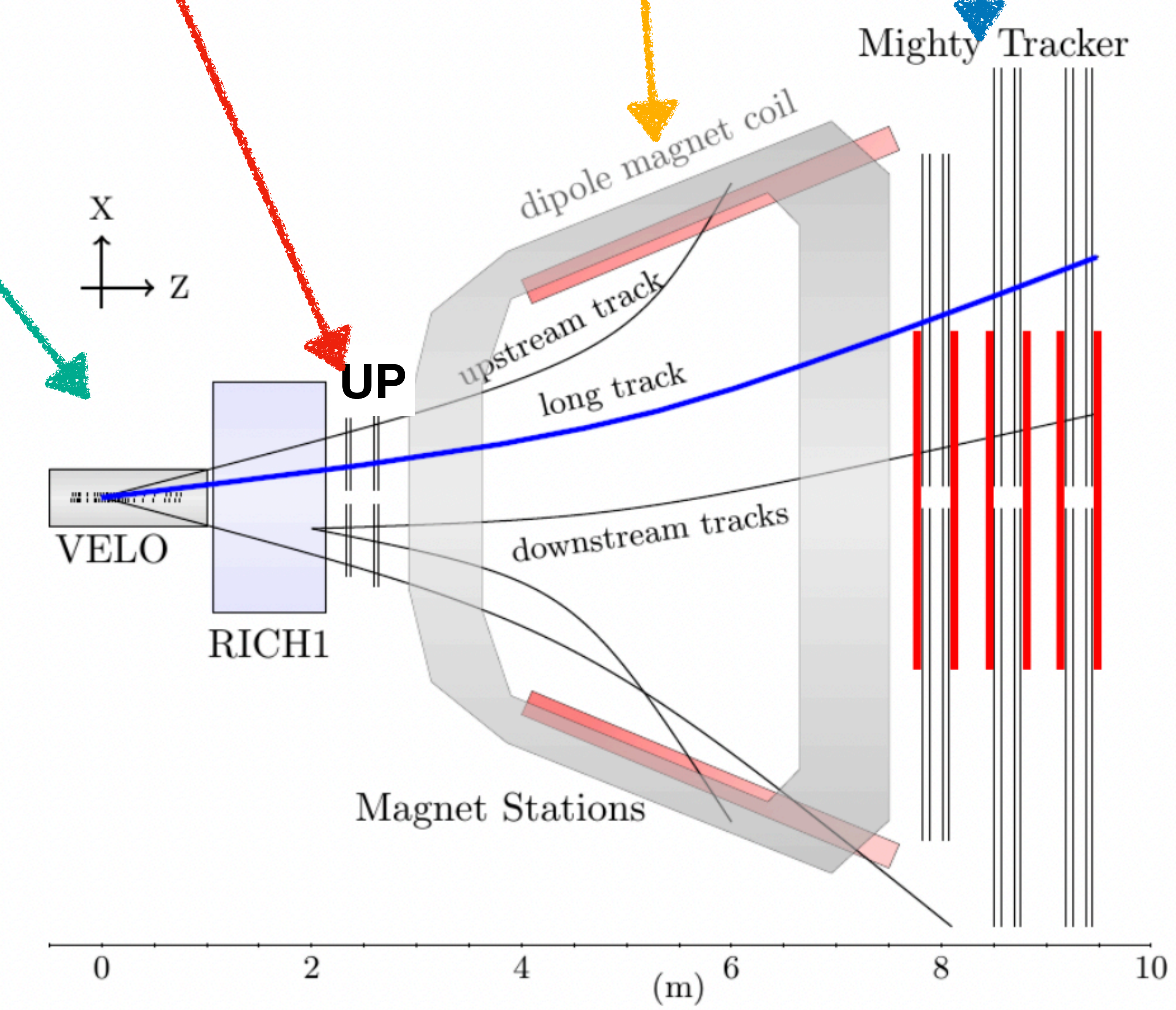





VELO Pixels with Timing (**TV**)

Upstream Pixel Tracker (**UP**)

Magnet Station(**MS**)

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



LHCb Tracking System

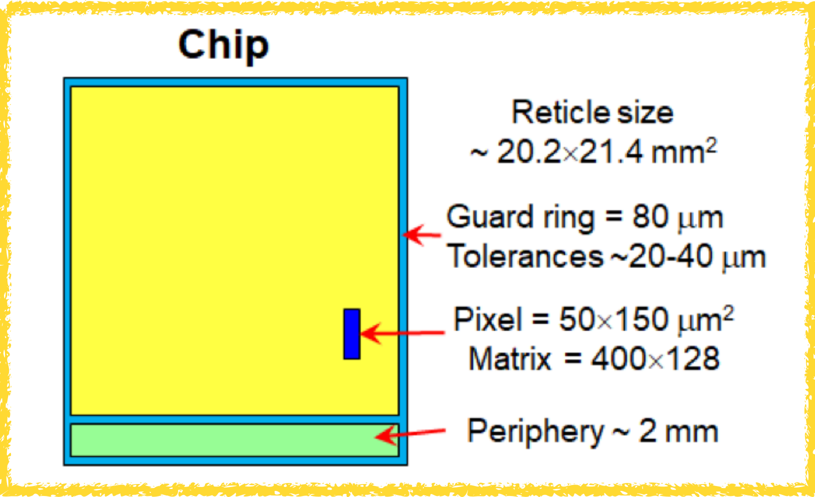
Upstream Pixel Tracker (UP): FTDR design

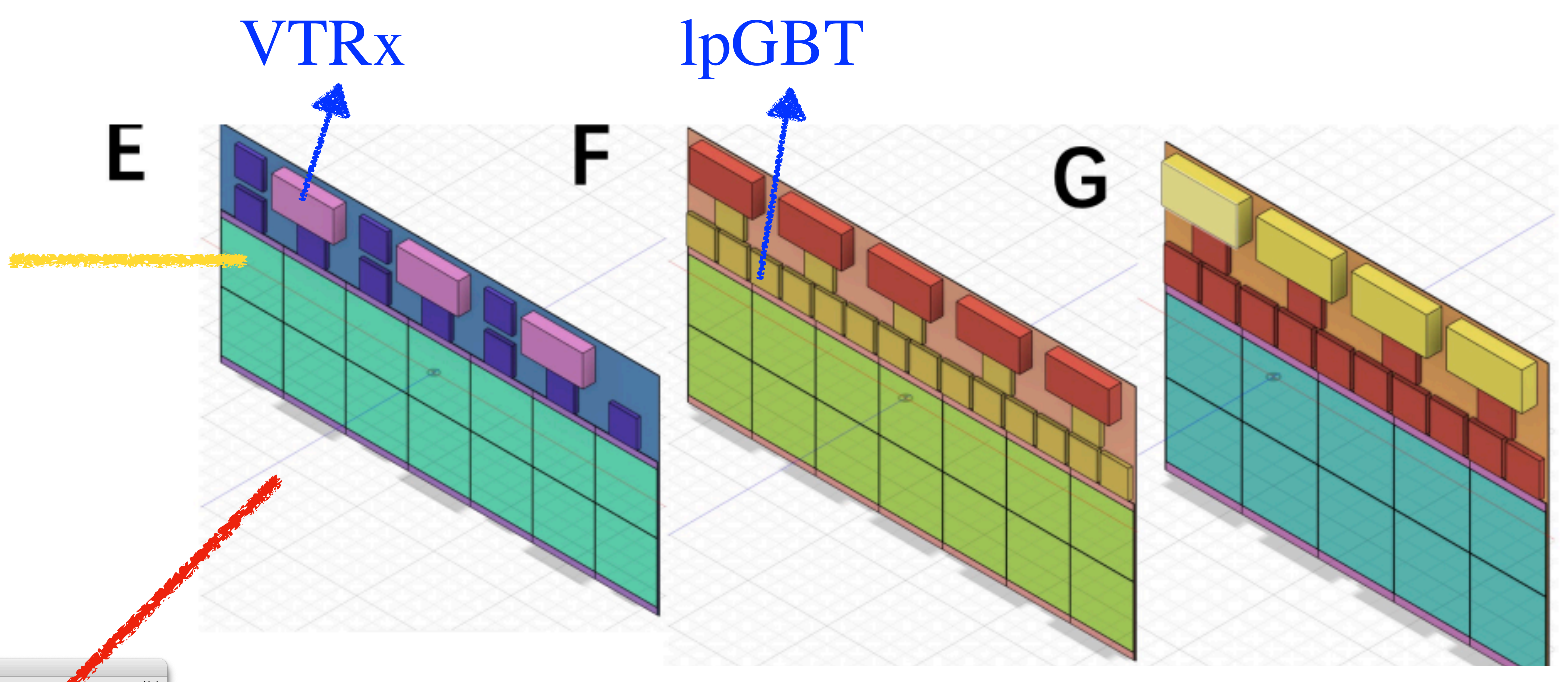
Silicon Strip (UT) → Silicon Pixel (UP)

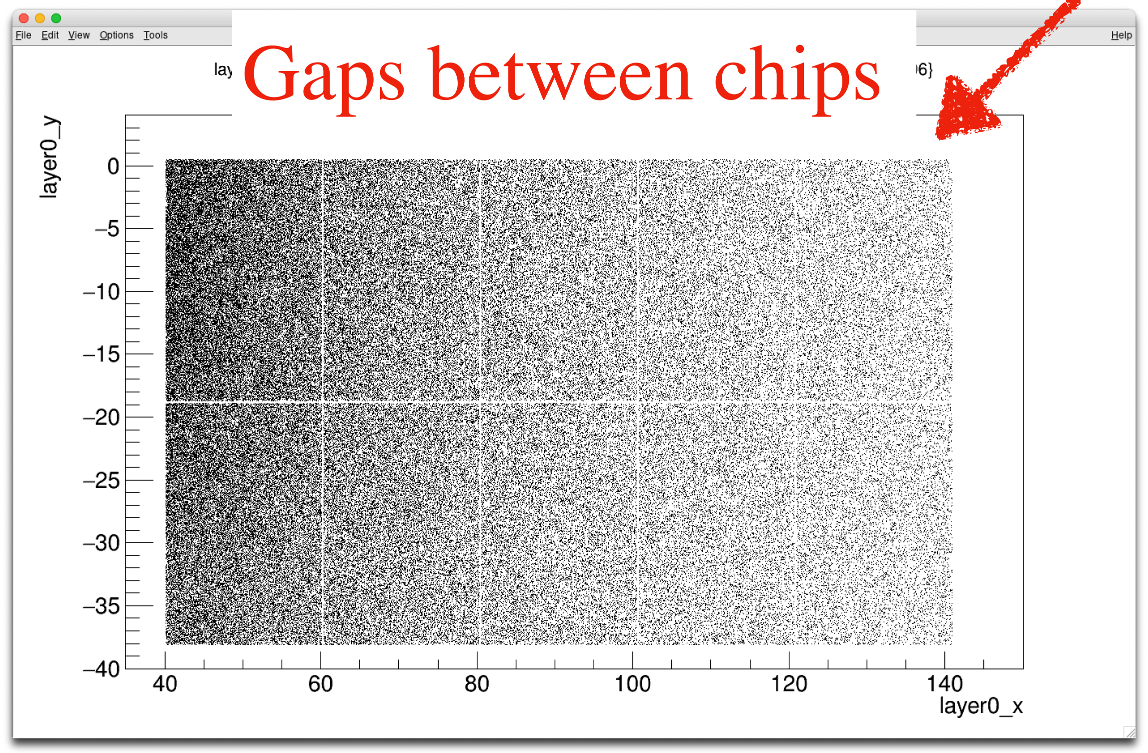
- Higher data rate and irradiation intensity…

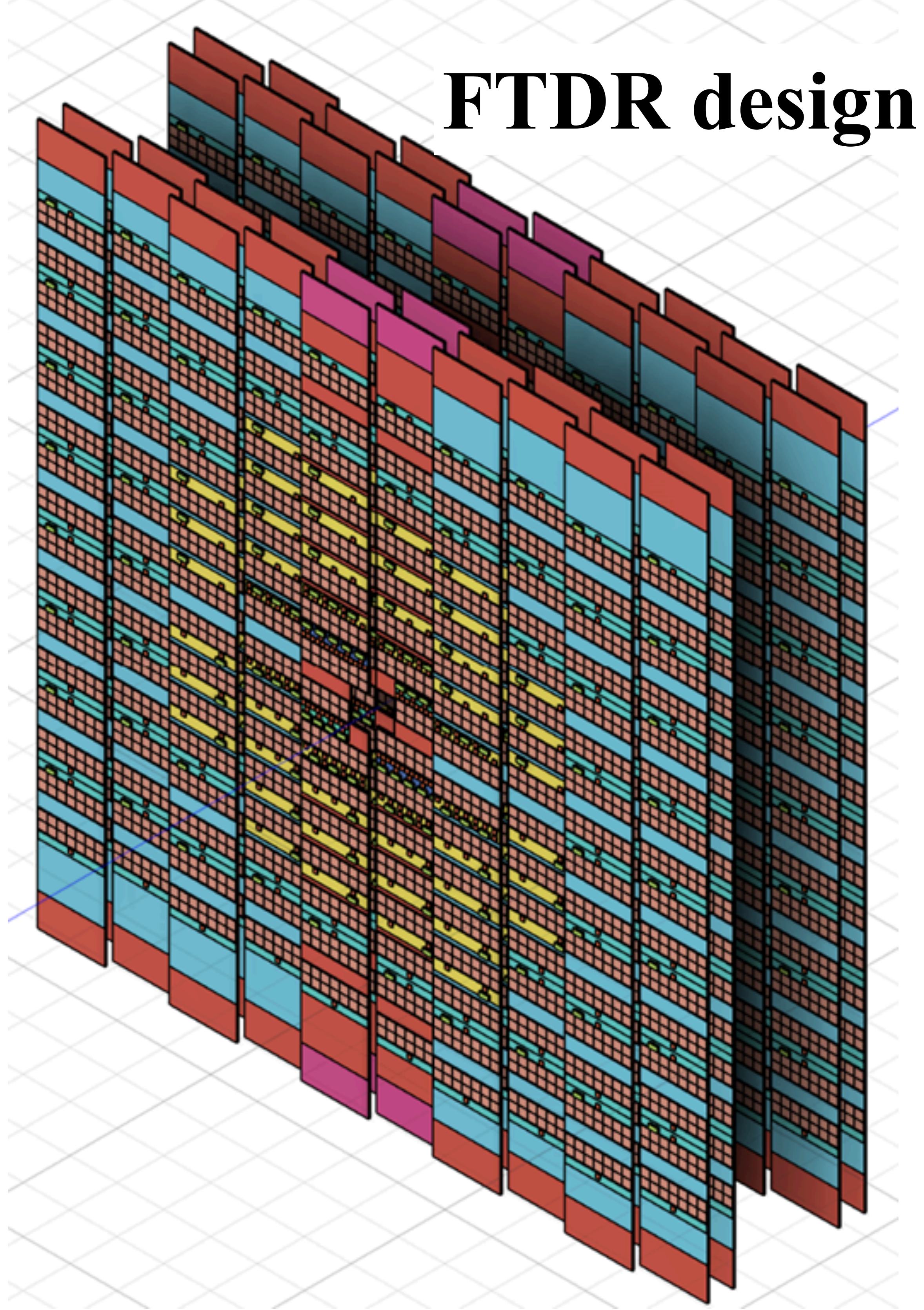
Chinese group led the R&D

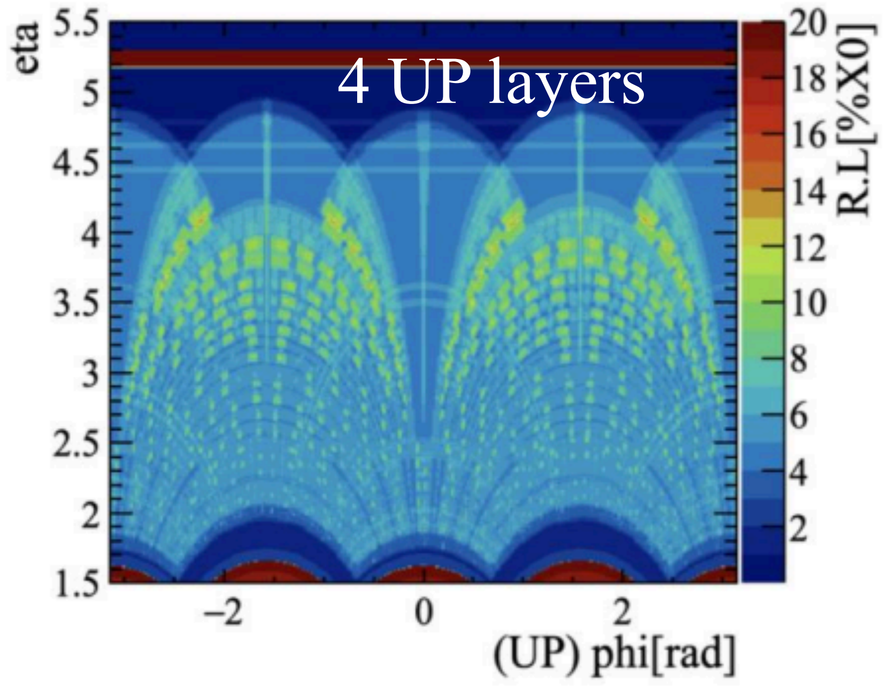
- 4 Layers, 10 Staves per Layer, 32 Modules per Stave, 14/10 Chips per Module
  - **lpGBT and VTRx at the FE**
    - Data can be sent out directly via optical fibers from the stave
    - Eliminating the need for a bulky data flex circuit
  - Coving ~ 1407 mm in X, ~ 1204 mm in Y
  - Central hole (beam pipe) ~ (± 39 mm) × (± 37mm)
- Material budget ~ 1.2%X0 per layer
- ~ 0.8mm guard ring per chip → gaps between chips
- A new detector layout design required for better performance

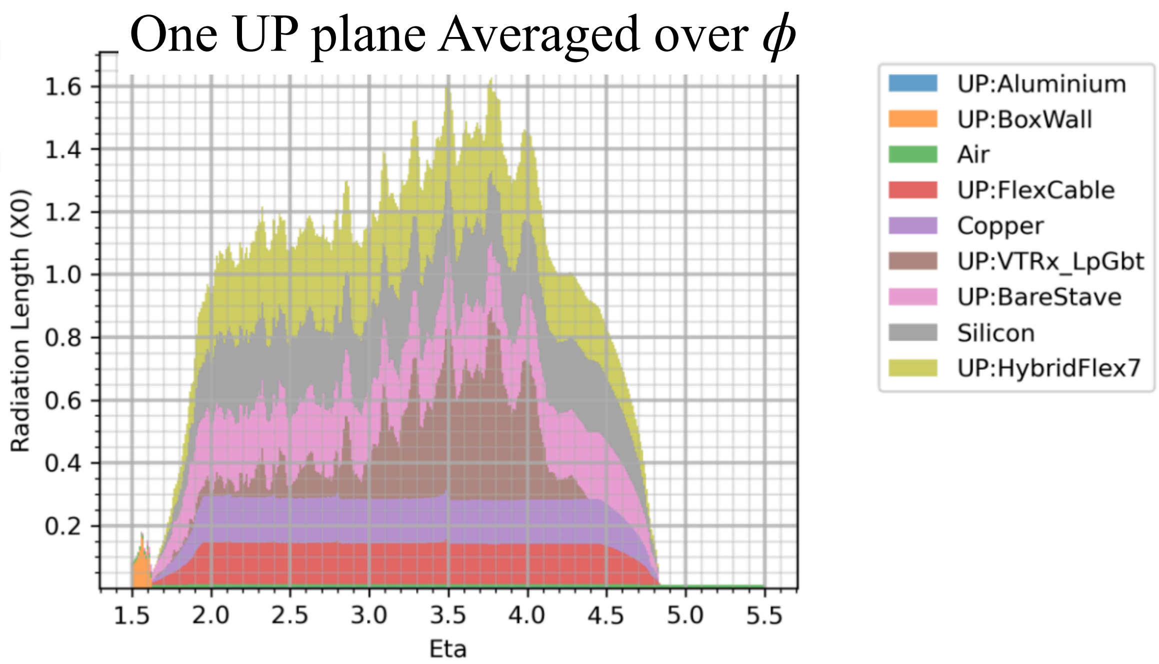










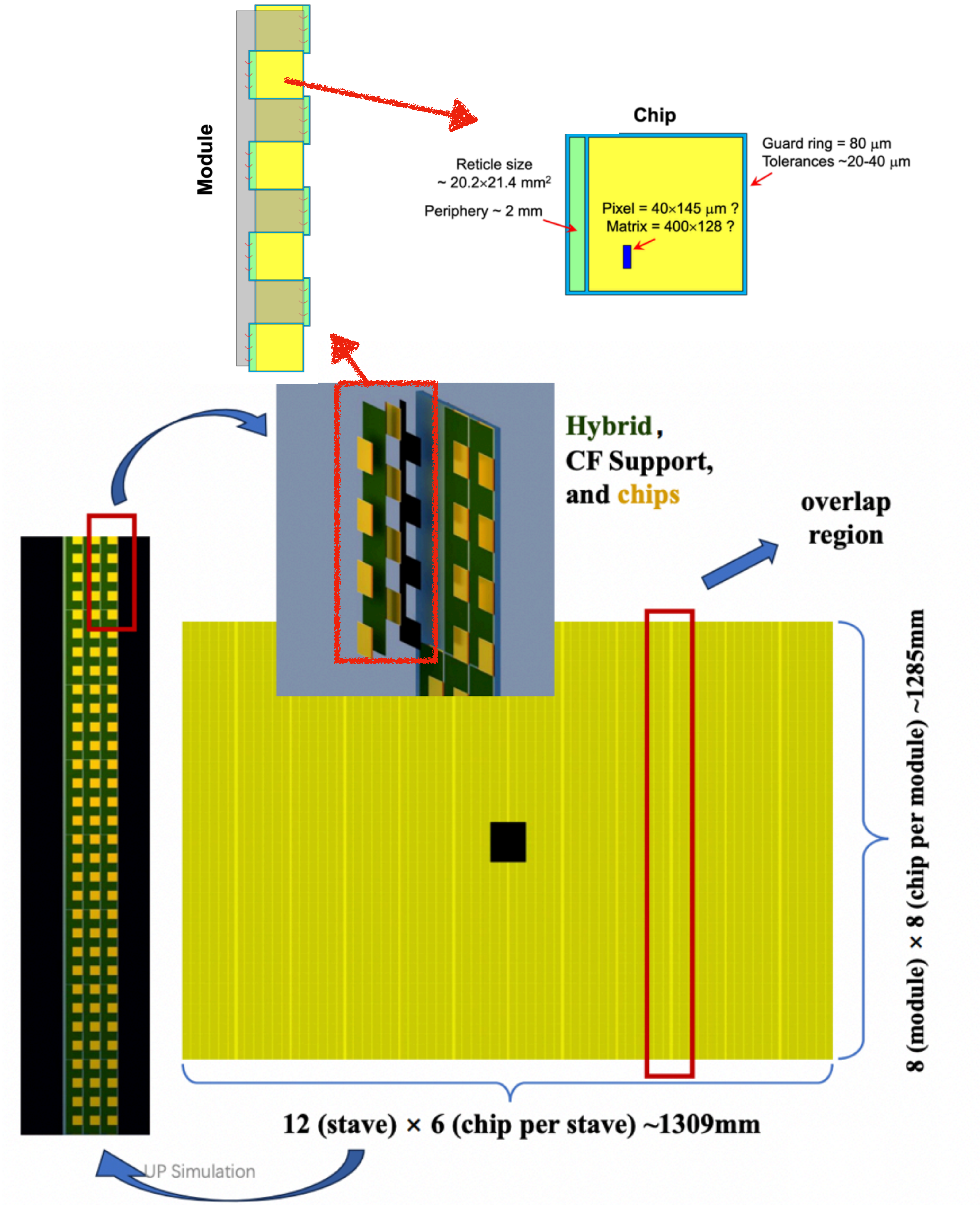


R.L distribution

Upstream Pixel Tracker (UP): Gapless design

UP new design → Gapless design

- 4 Layers, 12 Staves per Layer, 48 Modules per Stave, 8/6 Chips per Module
  - Coving ~ 1309 mm in X, ~ 1285 mm in Y
  - Central hole (beam pipe) ~ (± 35 mm) × (± 37mm)
  - Chip size ~ $2 \times 2\ cm^2$
- **2x4 chips amounted on both face of Hybrid**



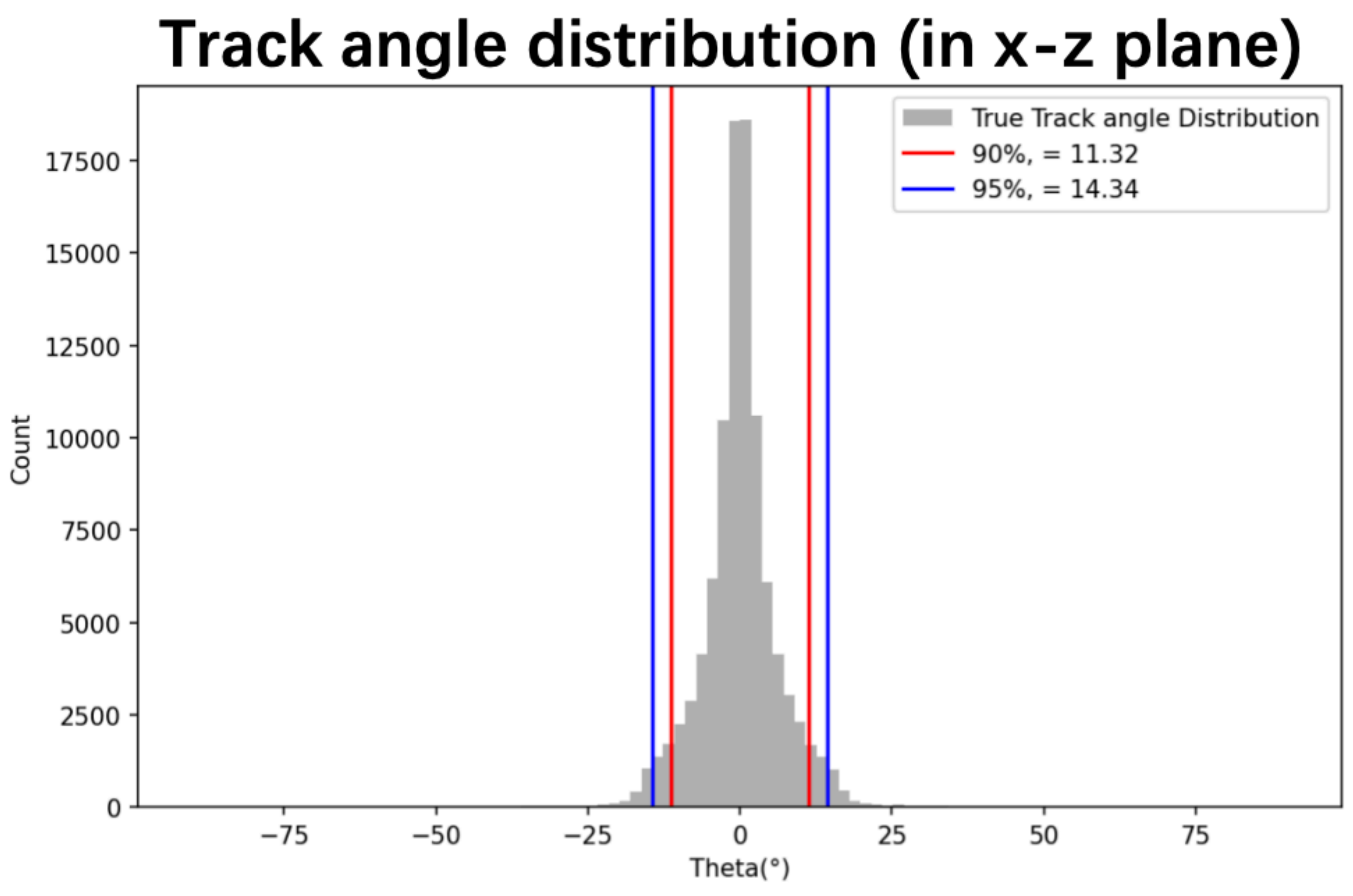
Upstream Pixel Tracker (UP): Gapless design

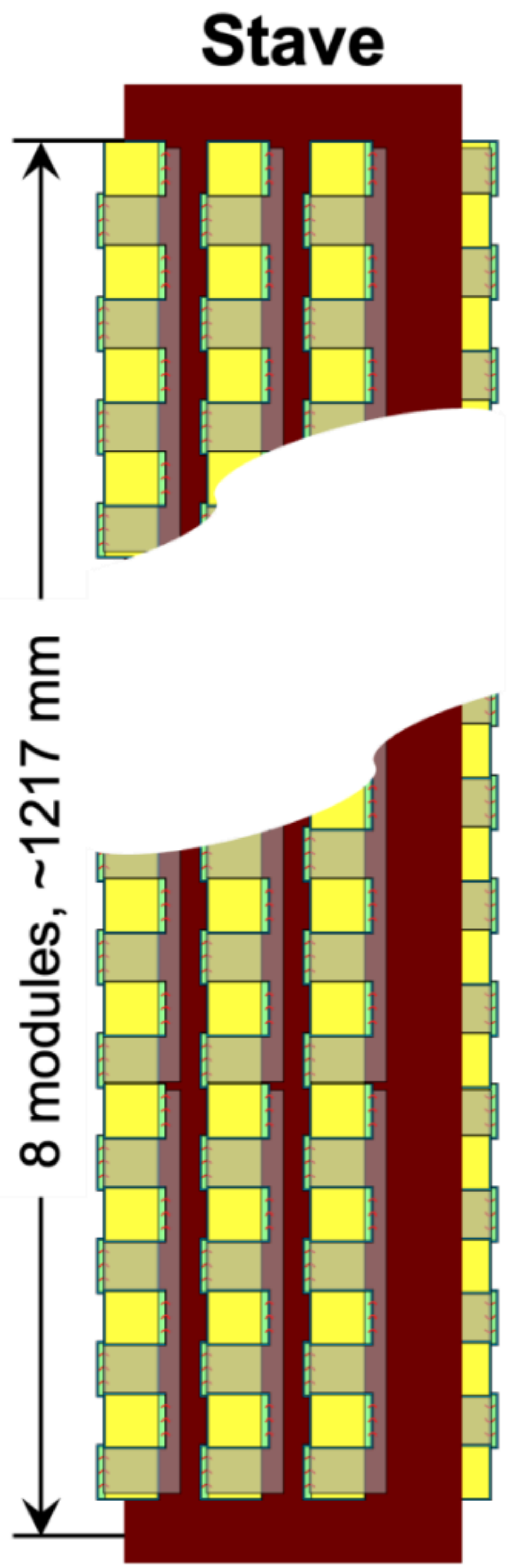
2x3 (x8) modules amounted on both face of Stave

Overlap setting for module and stave

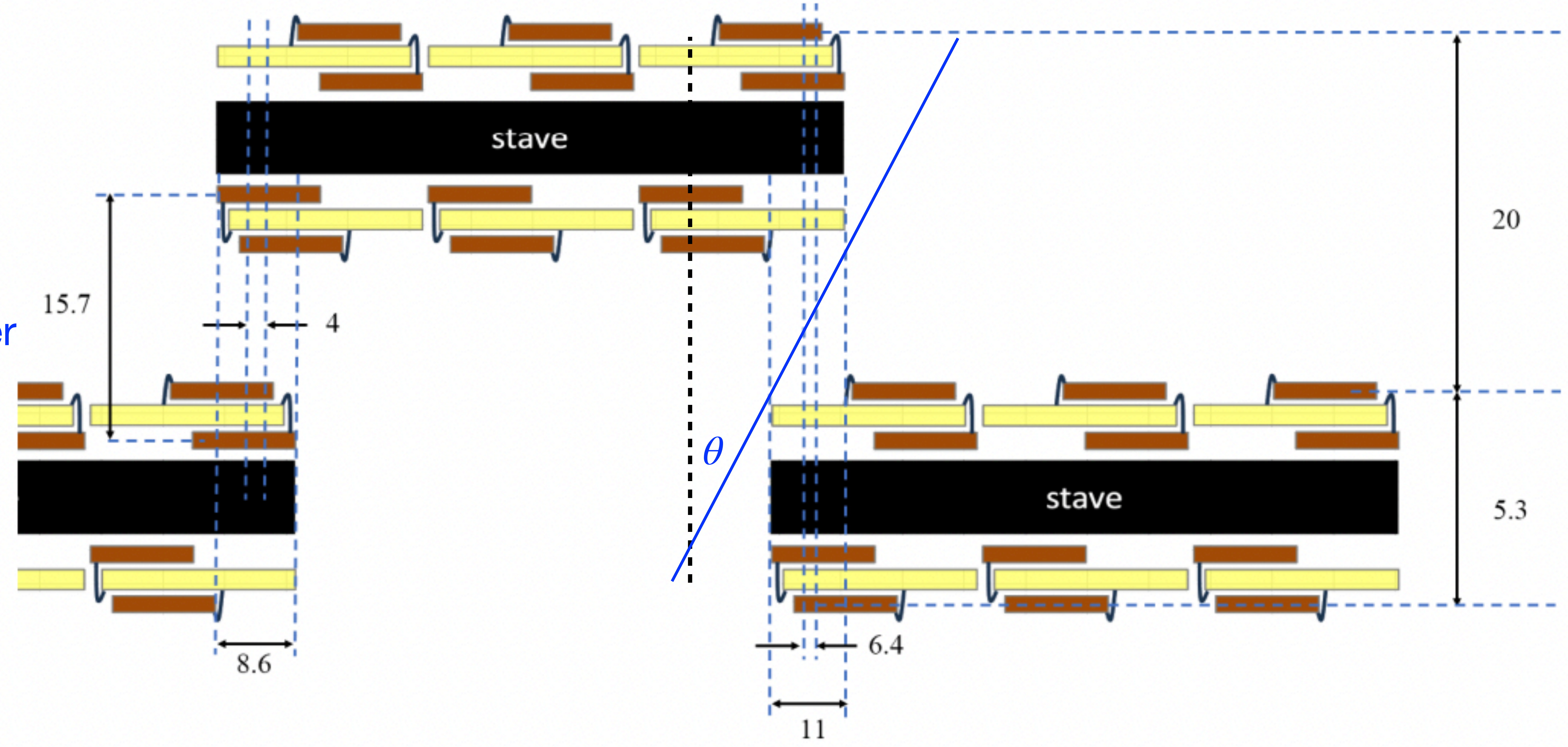
- $d_{overlap} = dz \times tan\theta$
- $\theta \sim 14°$ → Ensure 95% of track not loss hit in UP

Gap covered by setting overlap for all Chip, Module and Stave





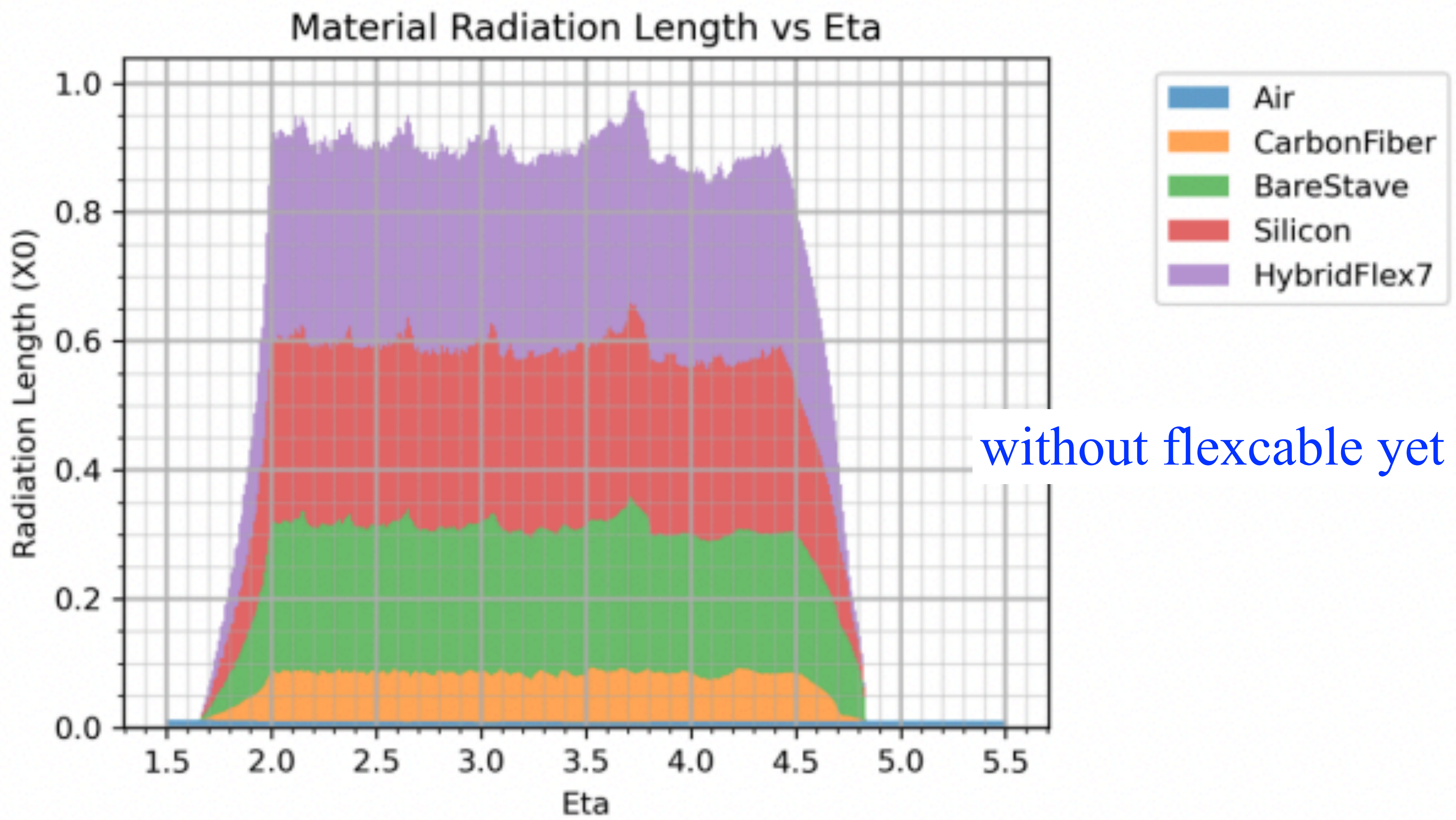
Staggered structure for UP layer



Upstream Pixel Tracker (UP): Gapless design

Material Budget

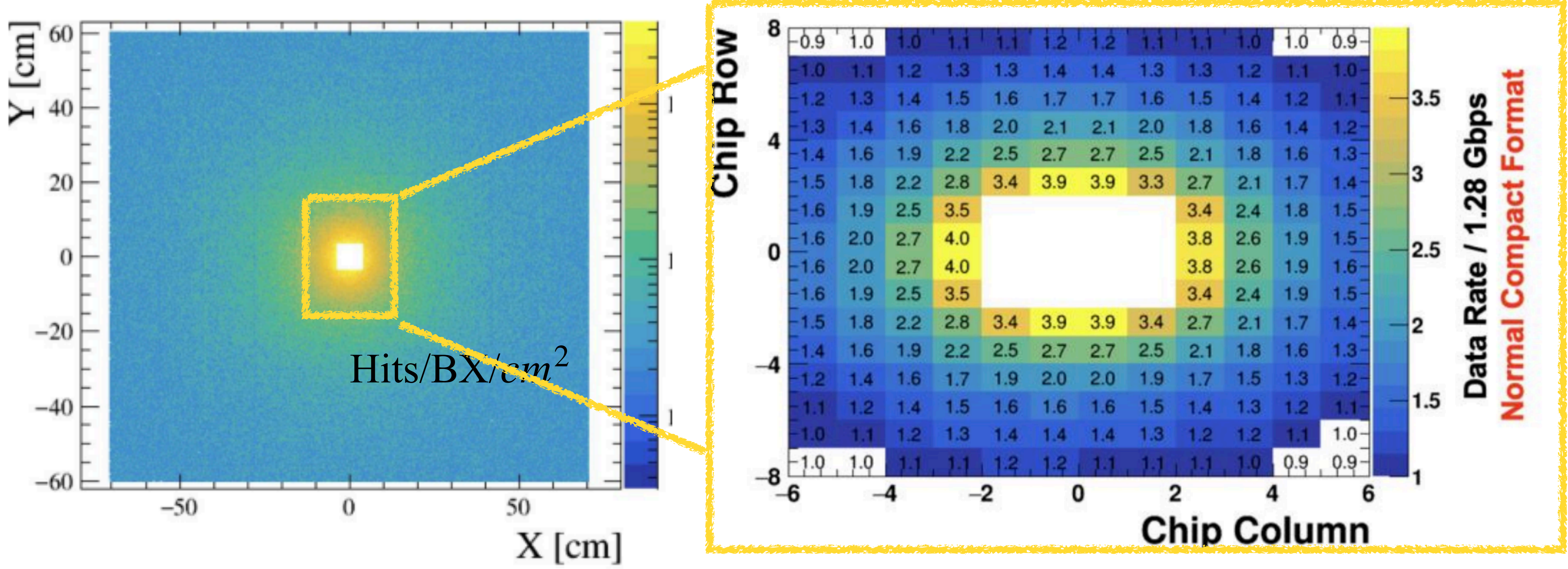
- The readout system was moved to both ends of the stave
- Radiation length under 1%X0
- The flexcable material to be decided



Hit density and data rate

- Mini-bias simulated events at LHCb upgrade II beam condition and studies at 1.0, 1.3, 1.5 $\times 10^{34} cm^{-2}s^{-1}$ performed
- Hit rate for pp at X = 4 cm ~ 74 MHits/s/cm^2
- According to preliminary data format in HV-CMOS chips and with x1.2 save factor and 1.2 cluster size contributions
  - Outer region with lower hit density, where 4x chips can be daisy chained and for each module 2 x 1.28Gbps elink needed
  - Inner region with high hit density, most busy chip need 4x 1.28Gbps per e-link
- The high hit density and data rate for UP in LHCb upgrade II results in a challenge for the tracking reconstruction

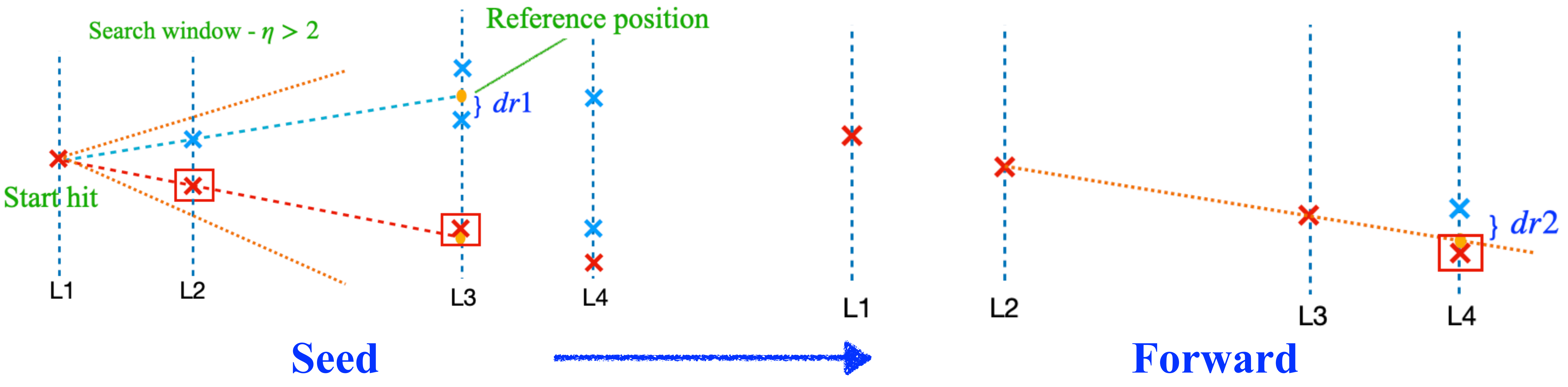
more details in ChengZeng' presentation

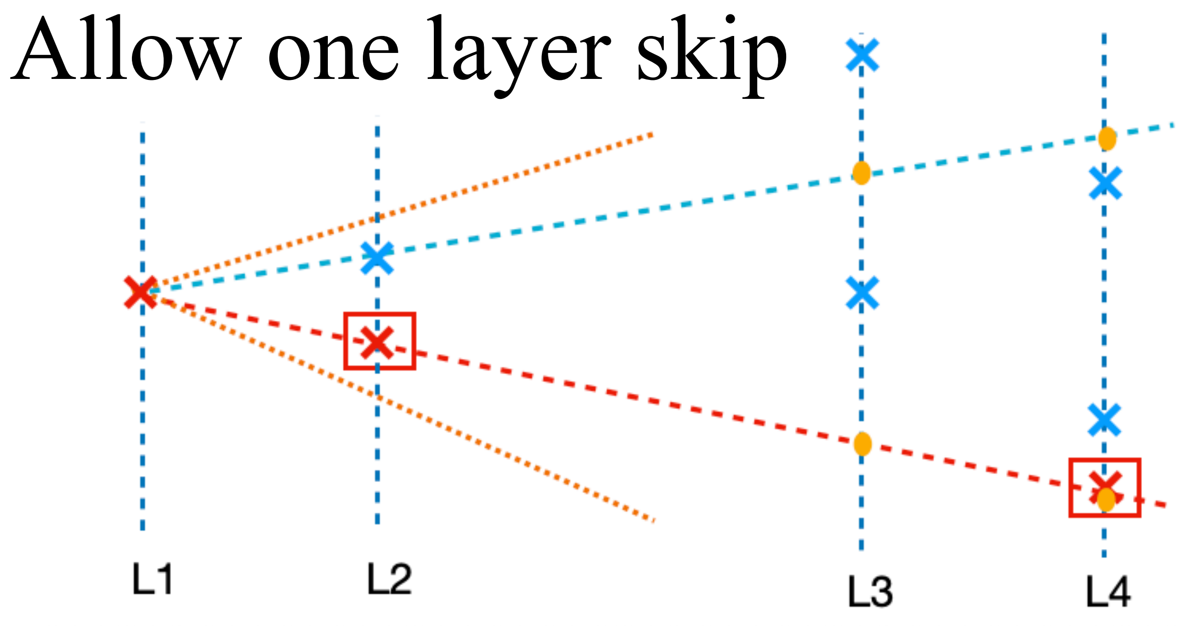


Hits map & Data rate @ (UP layer1, $\mathscr{L}$=1.0 $\times 10^{34}$ $cm^{-2}s^{-1}$, pp at 30MHz)

UP Standalone (v1)

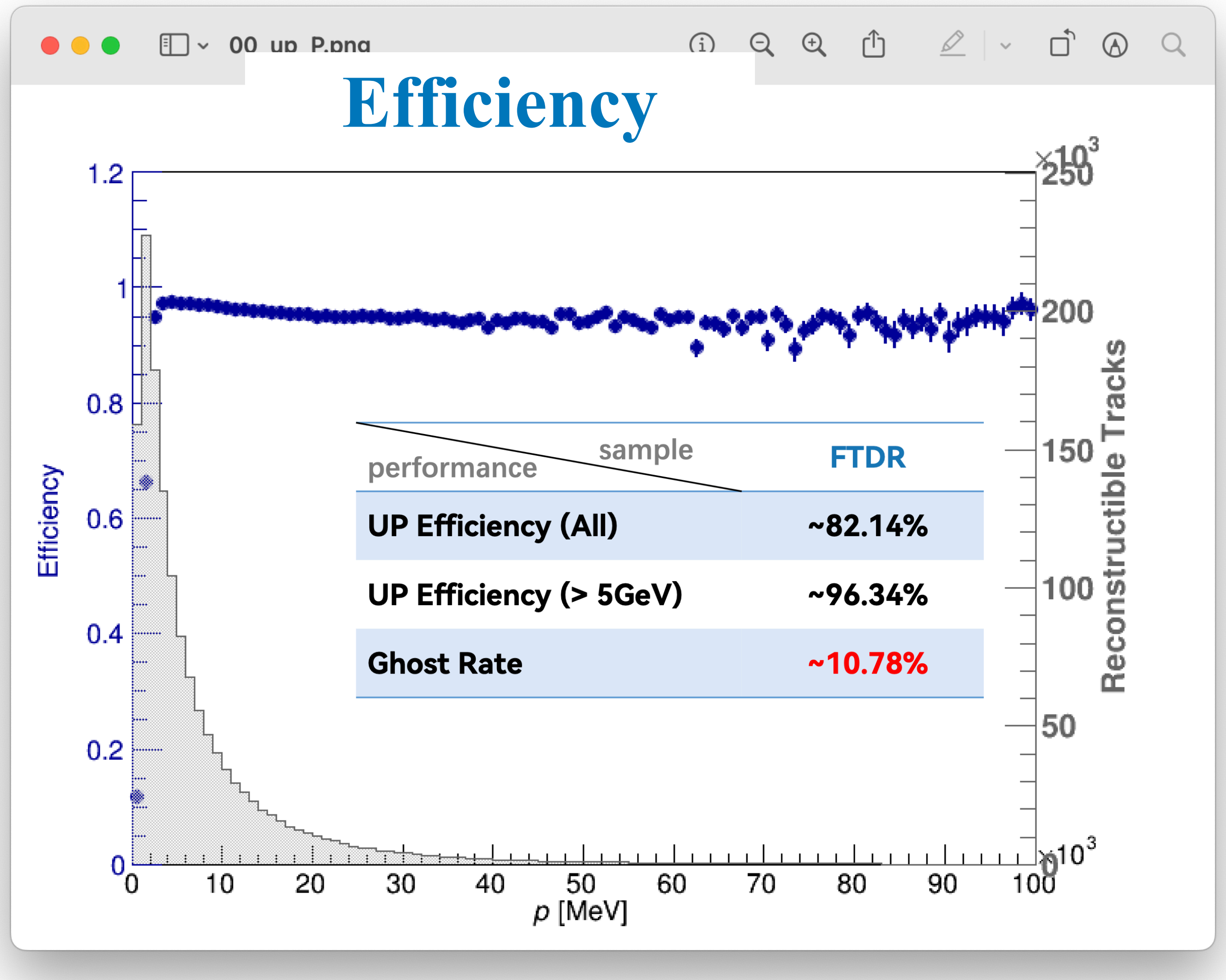
- Pixel HV COMS chips supply better resolution for particle hits positions both in X and Y direction
- Different from the current UT detector, in upgrade II, the UP detector can reconstruct the UP standalone track, and also can expect the improvement for the tracking performance in the future





At least have three layers with hit in each track

- Seed: Find three hits with $dr1$
- Forward: extrapolate from L2&L3, find best hit on L4 with $dr2$
- Mask Hits if $dr1\&dr2$ are small enough to reduce the clone rate
- Several iterations covering all possible combinations



performance \ sample	FTDR
UP Efficiency (All)	~82.14%
UP Efficiency (> 5GeV)	~96.34%
Ghost Rate	~10.78%

UP Standalone algorithm optimization

- Efficiency, especially in low momentum region, still has the improving space
- Ghost rate >10%, polluting the matching algorithm in next step

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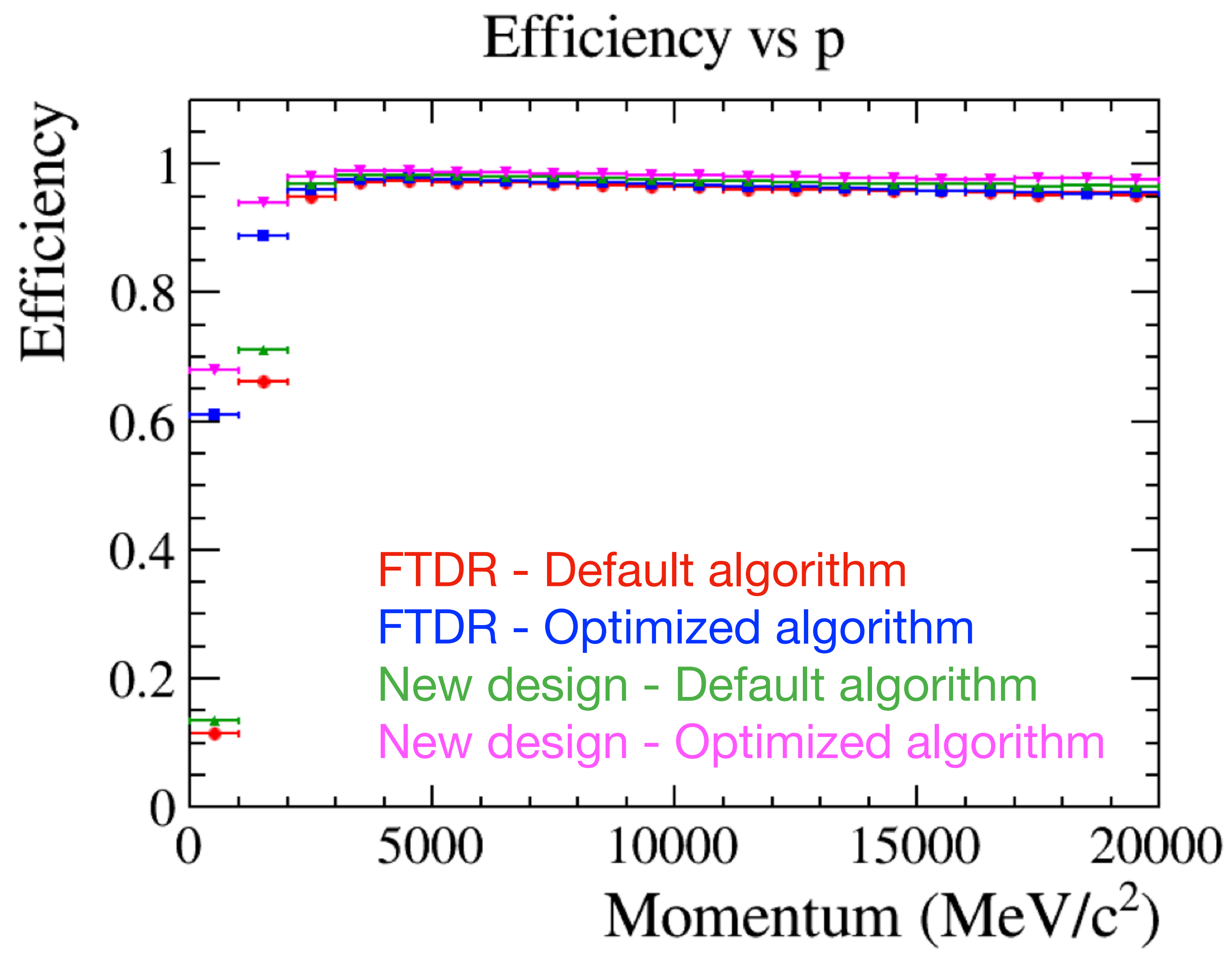
	FTDR		UP gapless design	
	Default Algorithm	**Optimized algorithm**	**Default Algorithm**	**Optimized algorithm**
UP Efficiency (All)	**~82.14%**	**~91.53%**	**~84.08%**	**~94.26%**
UP Efficiency (> 5GeV)	**~96.34%**	**~96.58%**	**~97.42%**	**~98.11%**
Ghost Rate	**~10.78%**	**~4.07%**	**~12.32%**	**~3.47%**

The algorithm is upgraded

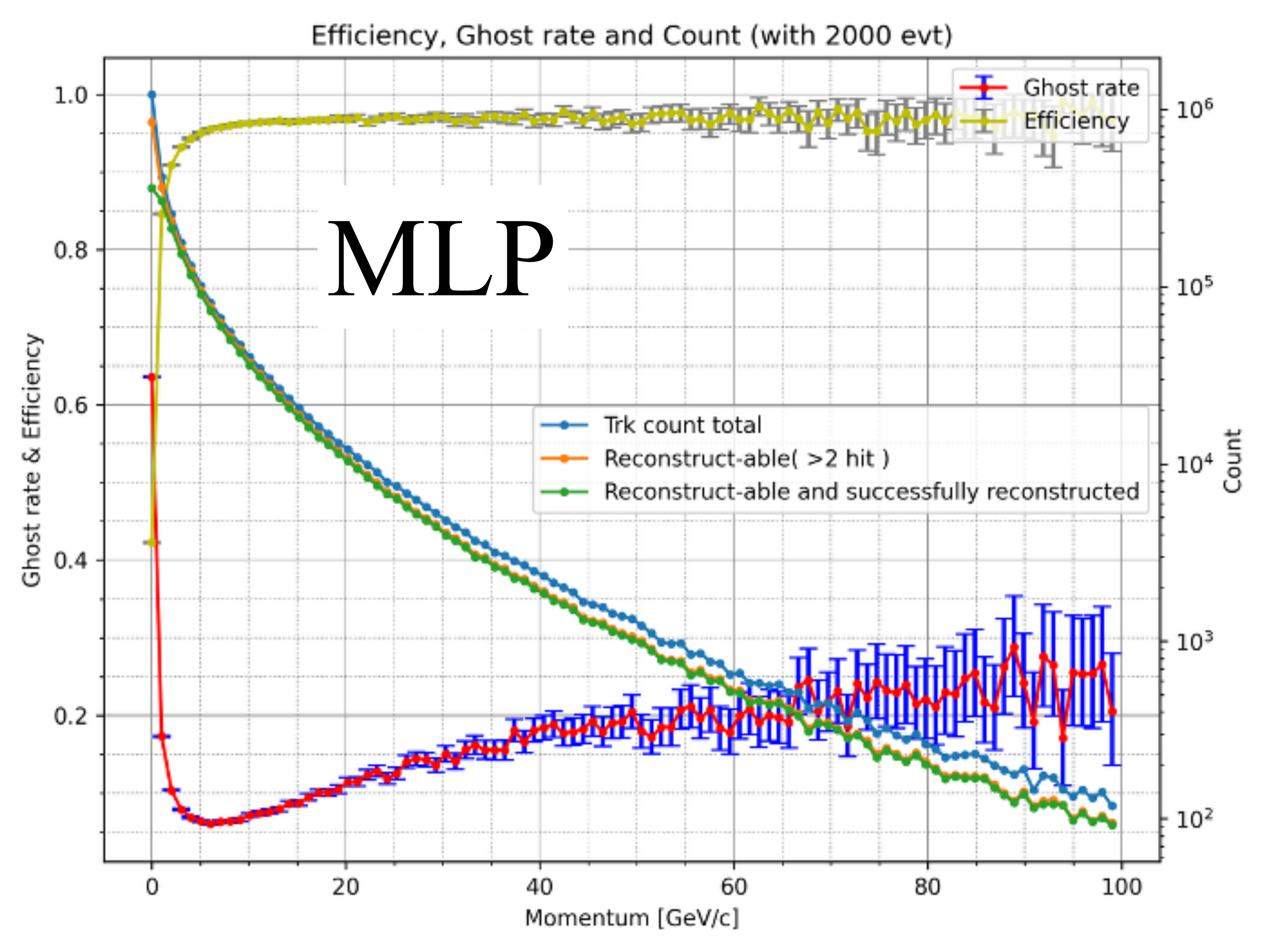
- Addhits: once a UP track reconstructed, other hits with small enough DOCA considered also belong to this track and masked —no use for other track reconstruction
- Track-by-track analysis shows most of ghost tracks in UP are with 3 hits. Therefore once a hit can be selected for two tracks with 3-hits OR 4-hits, we put this hit into the 4-hits track container

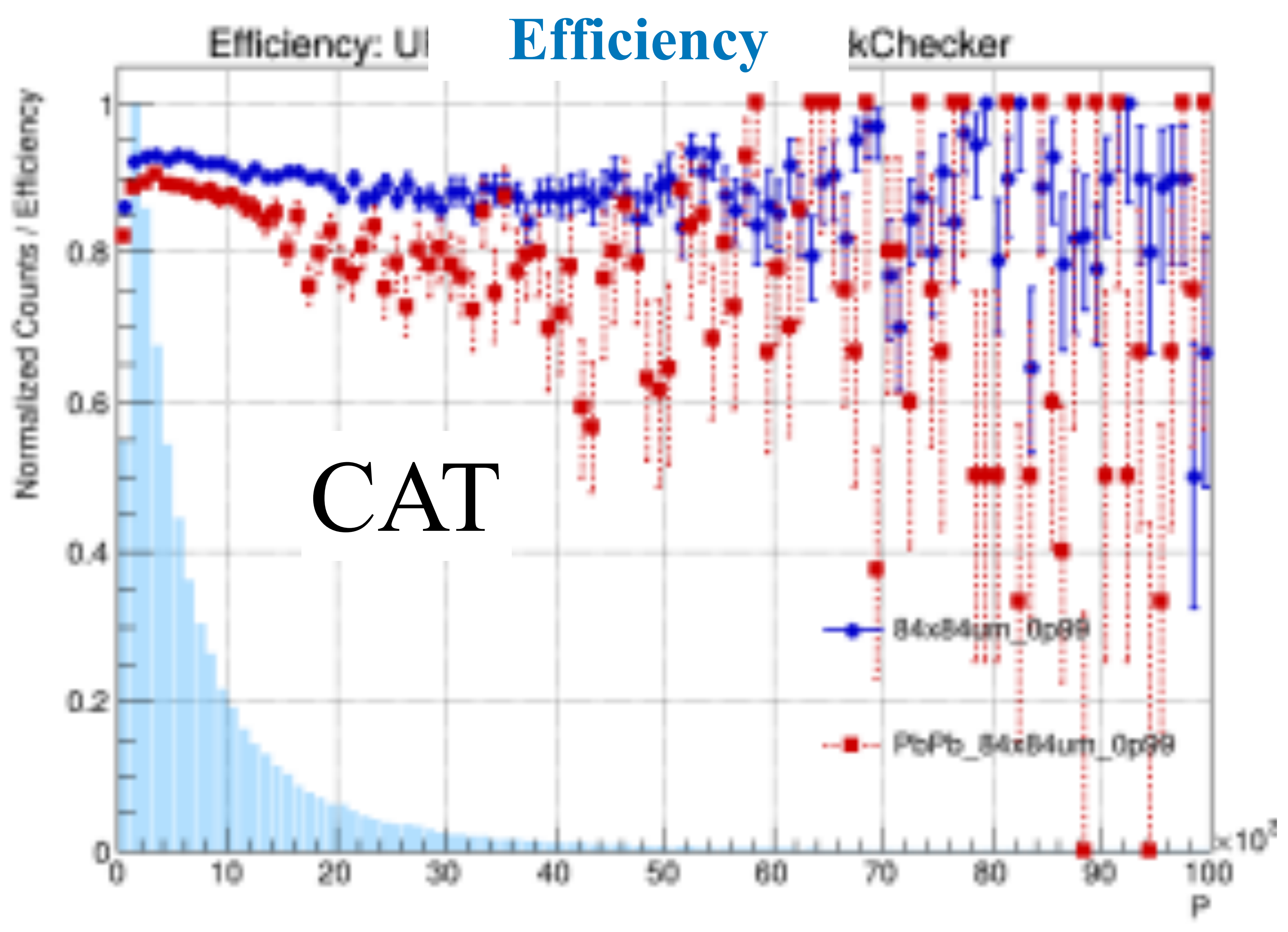


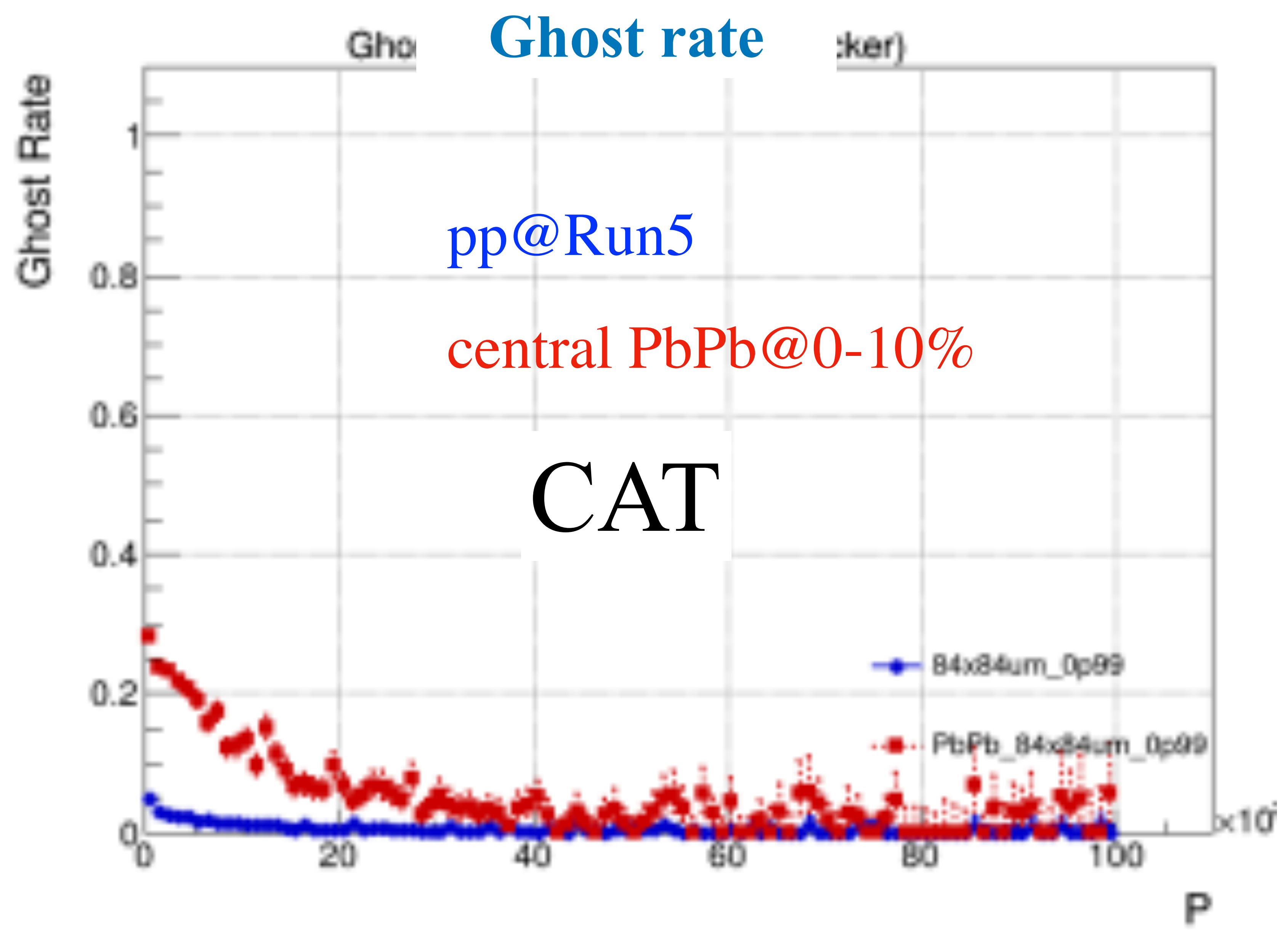
MLP/CAT algorithm for UP standalone track

Machine learning-based algorithms are also under development

- Compared to traditional algorithms, it shows no significant advantage in terms of efficiency and ghost rate



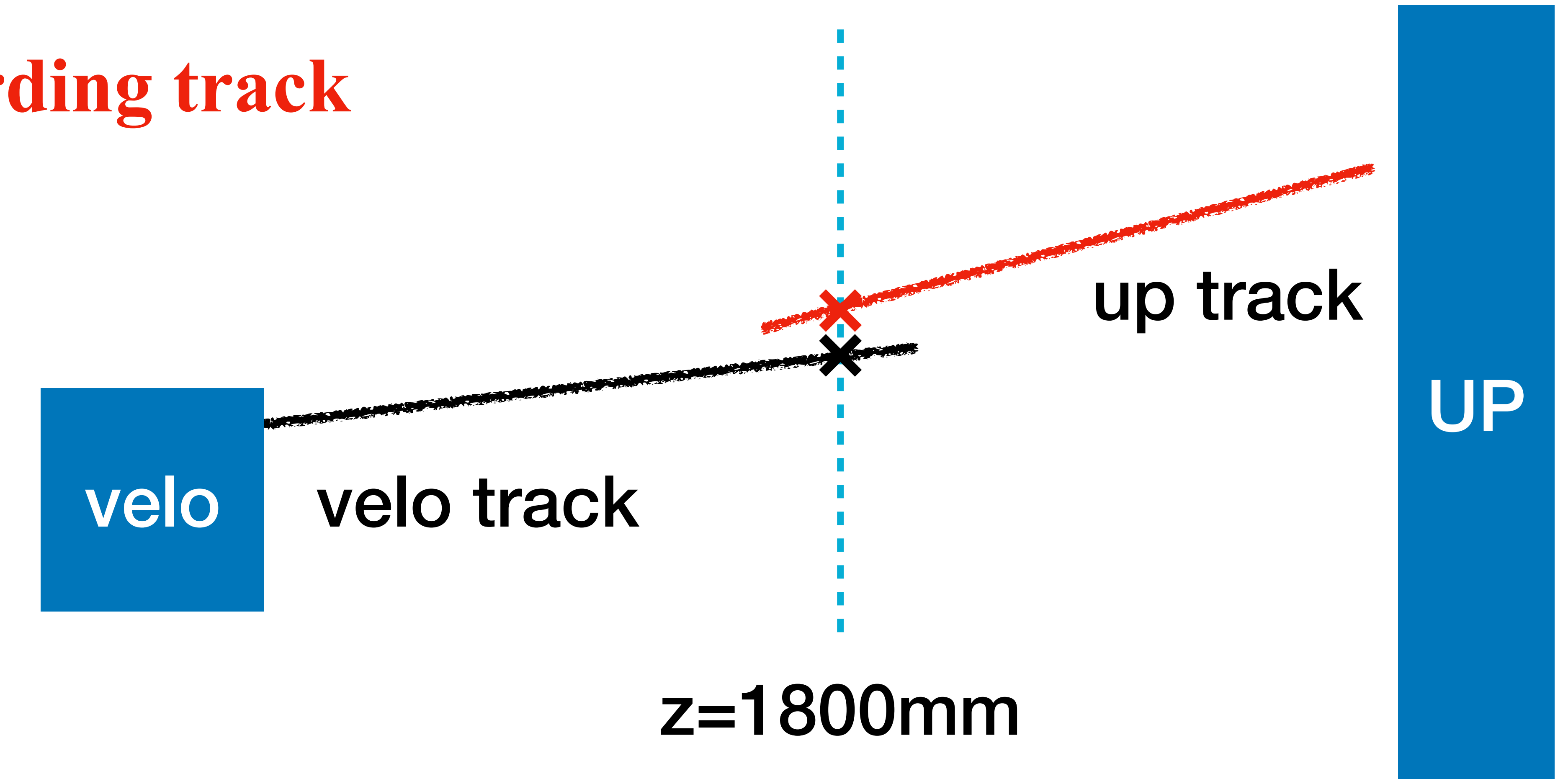


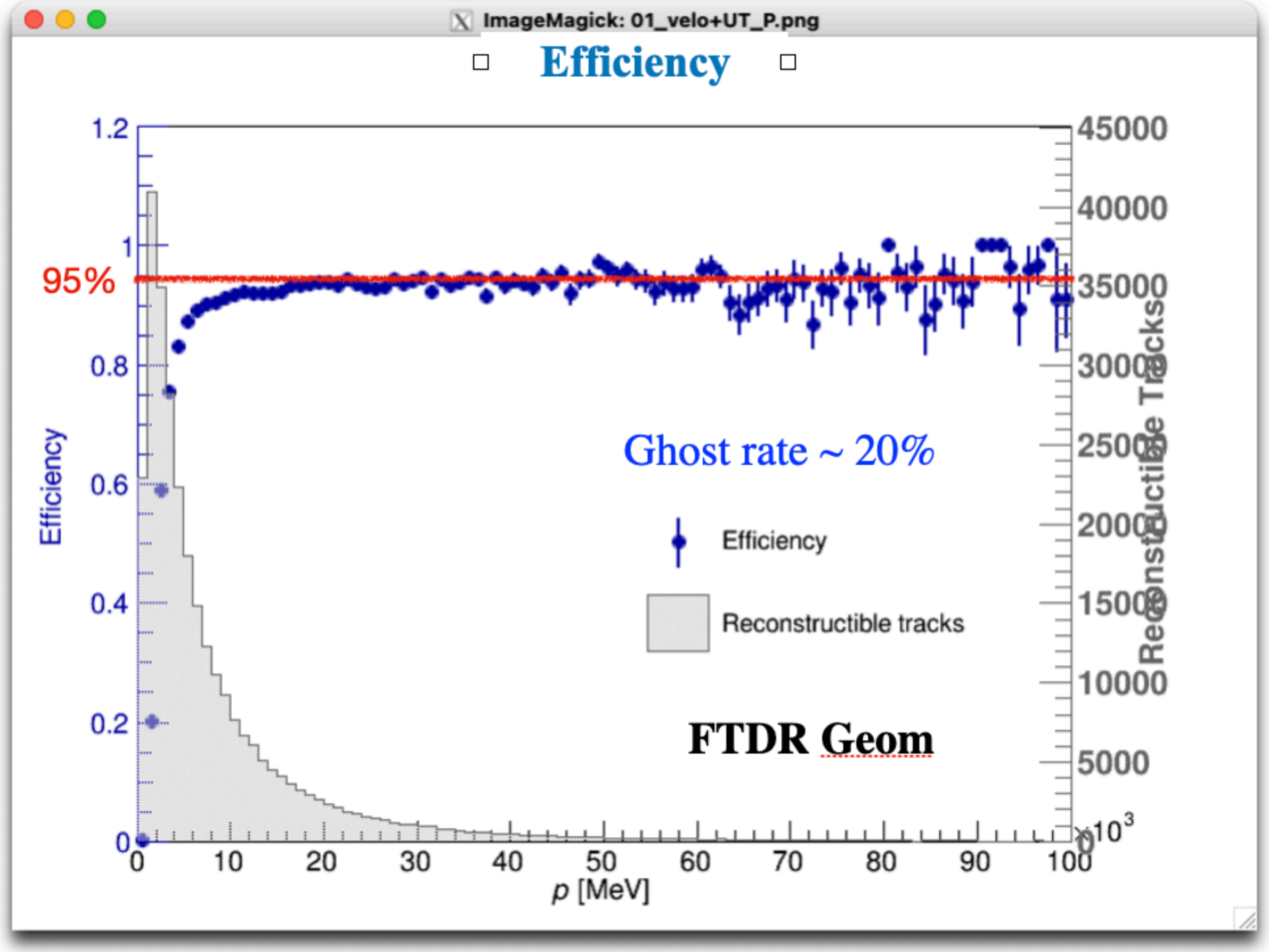


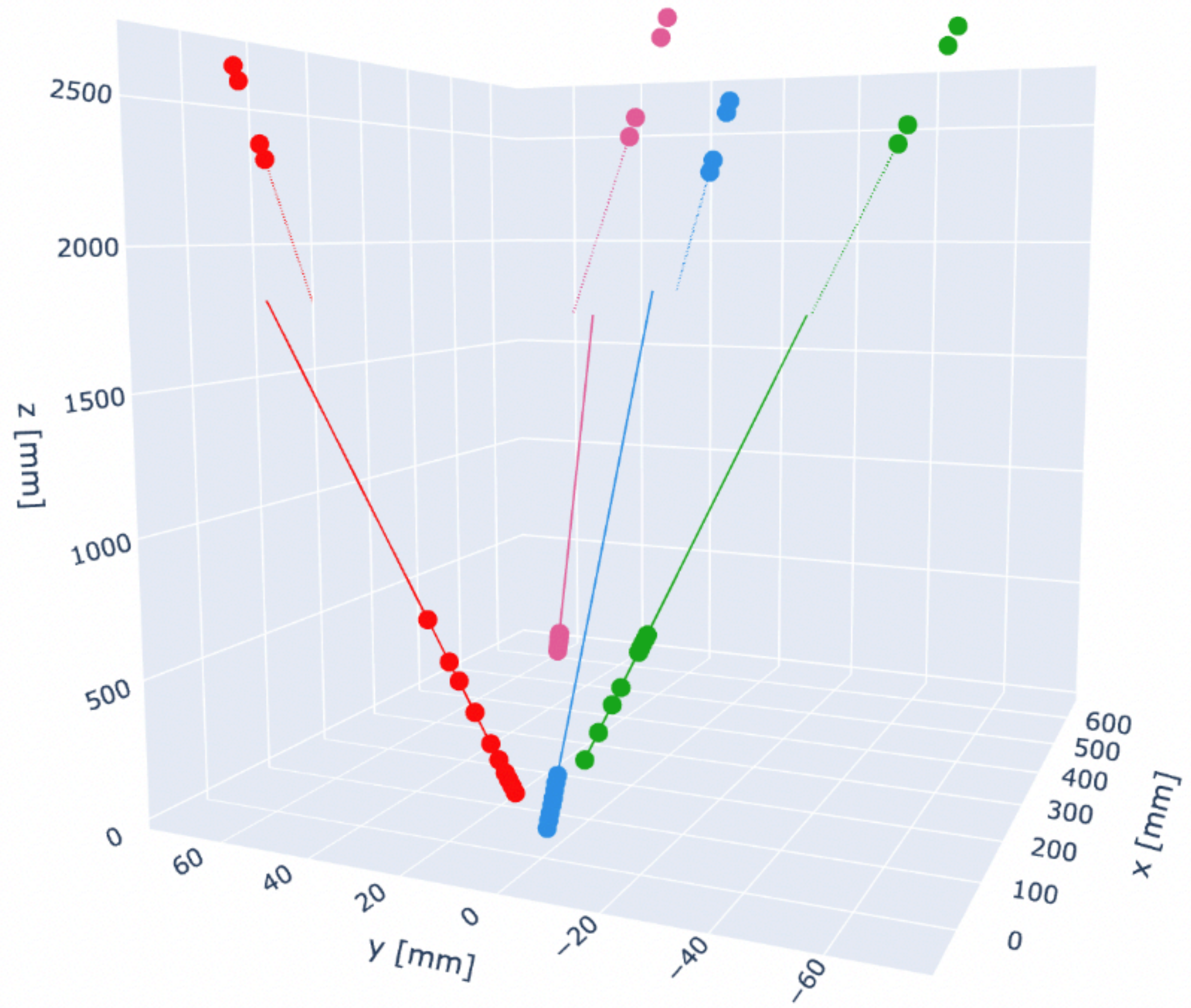
FTDR Geom

Upstream with UP Tracks

- **Forward Upstream (VELO-UP) tracks to match MT tracks → Forwarding track**
- **Key method for long track reconstruction in Upgrade II**
- **Upstream tracks are essential**
- **Match TV and UP Track**
    - Cut on *dx, dy, dtx, dty, dθ*
    - Choose the best track with *dr*

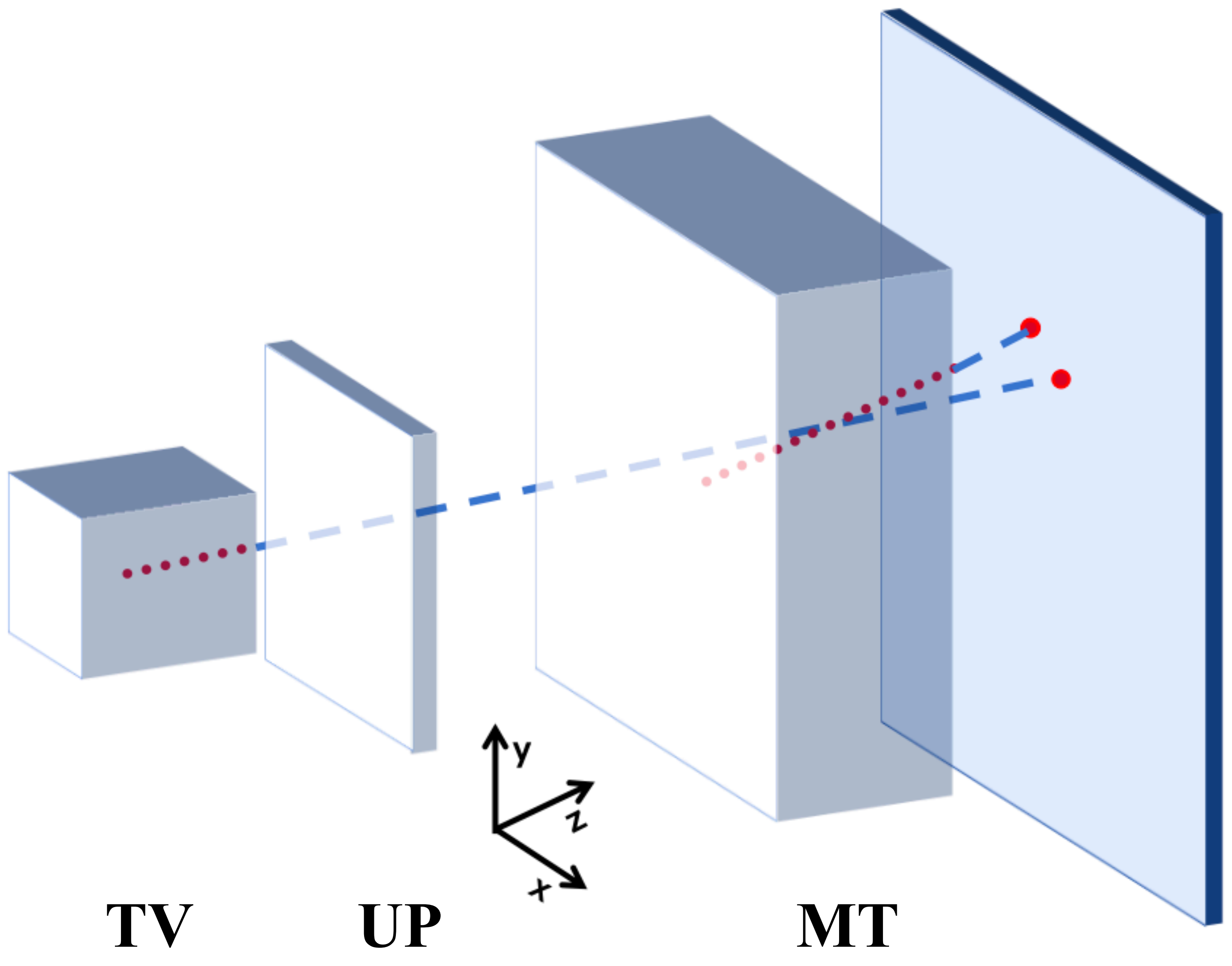


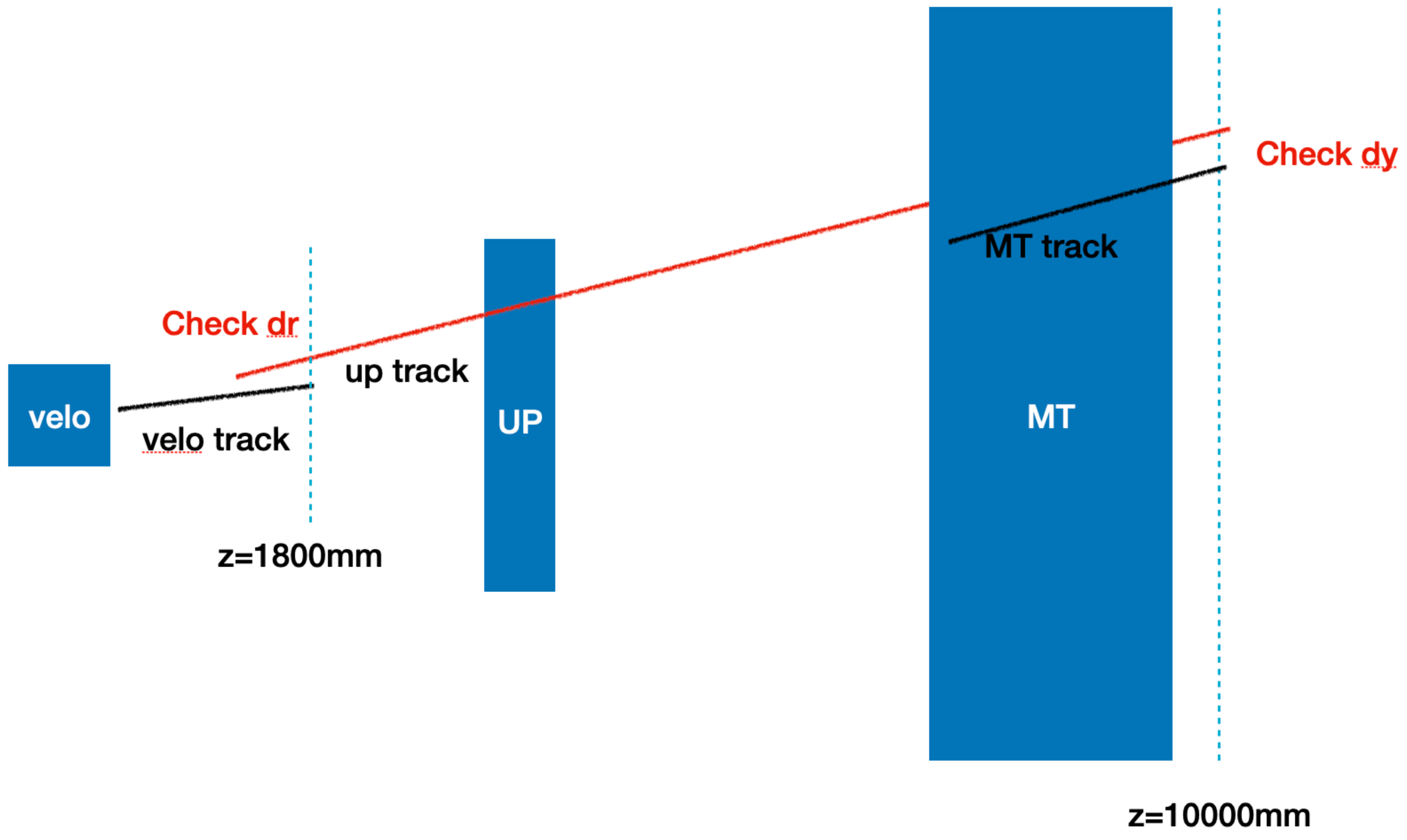




Long Track

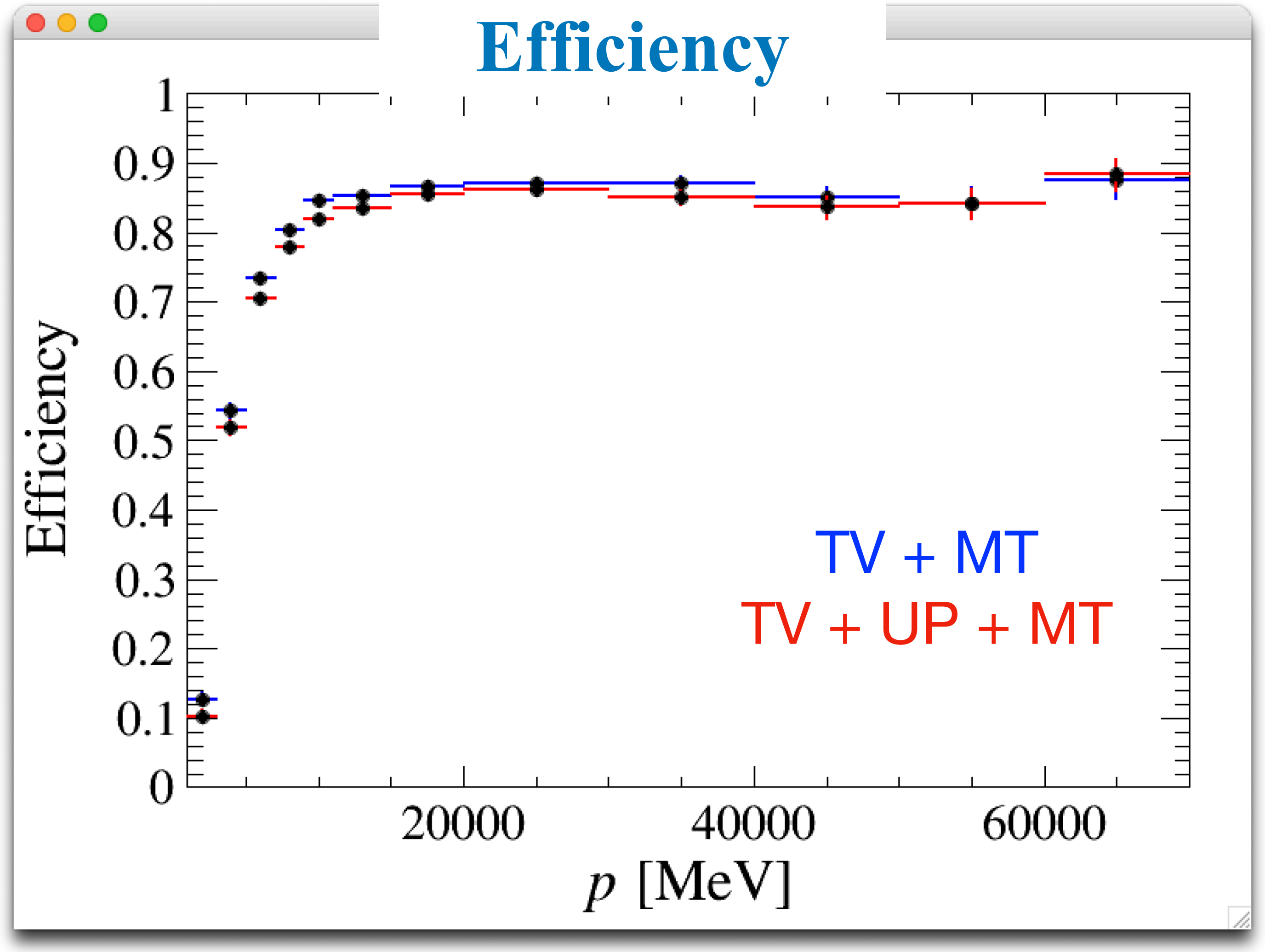
- **Combine the Velo and MT track firstly, then looking for the best matching UP tracks → similar as current LHCb reconstruction**
- **Matching TV tracks and MT tracks**
  - Extrapolate TV and MT tracks to a common Z-plane
  - Fast Pre-Filter: Discard candidates with large Y-mismatches
  - Precision 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 into matched TV-MT tracks**
  - TV-UP requirement: *dx, dy, dtx, dty, dθ*
  - UP-MT requirement: *dy*
  - Choose the track with the smallest TV-UP *dr*
- **Apply Kalman Filter for better performance**

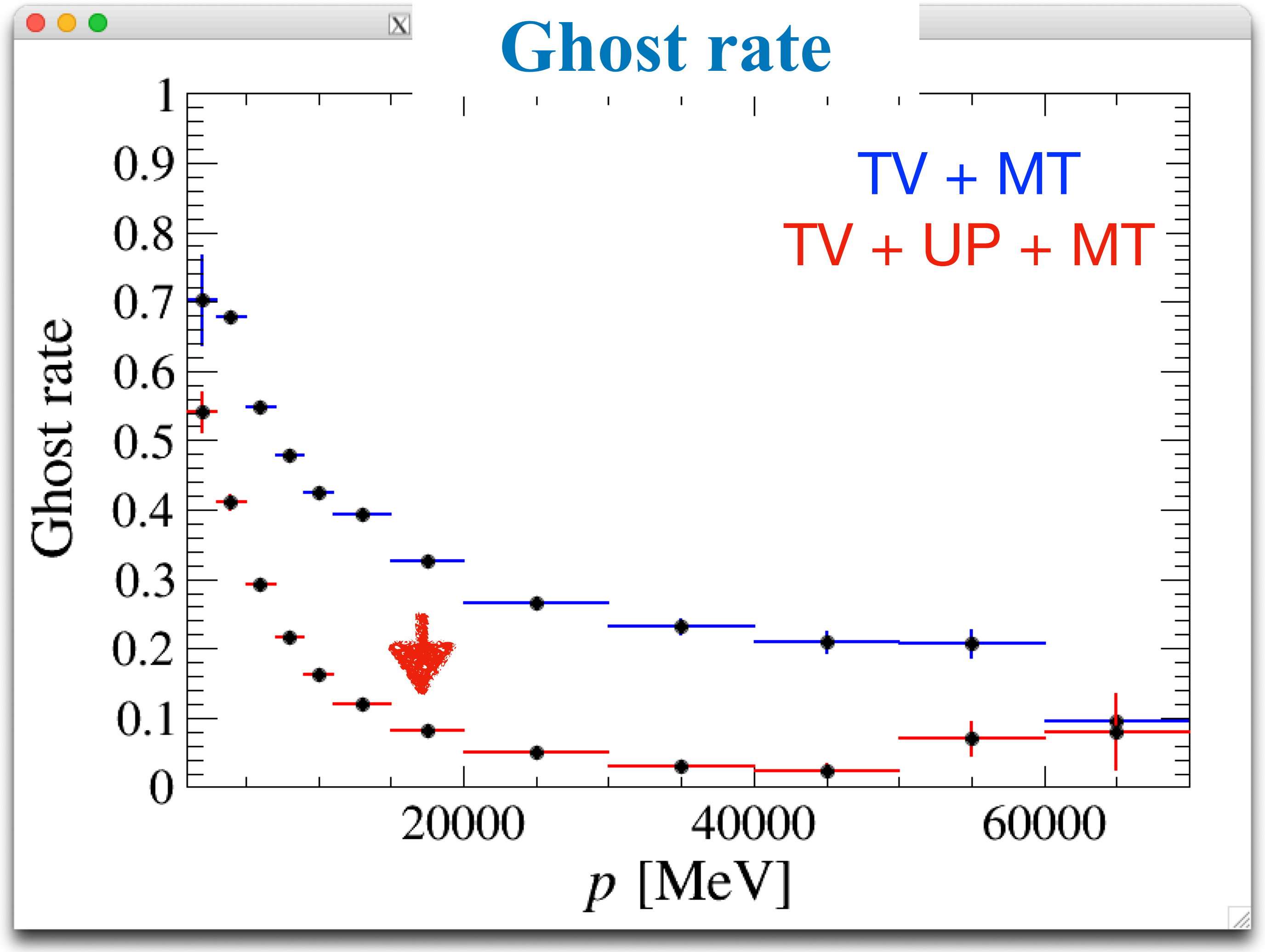


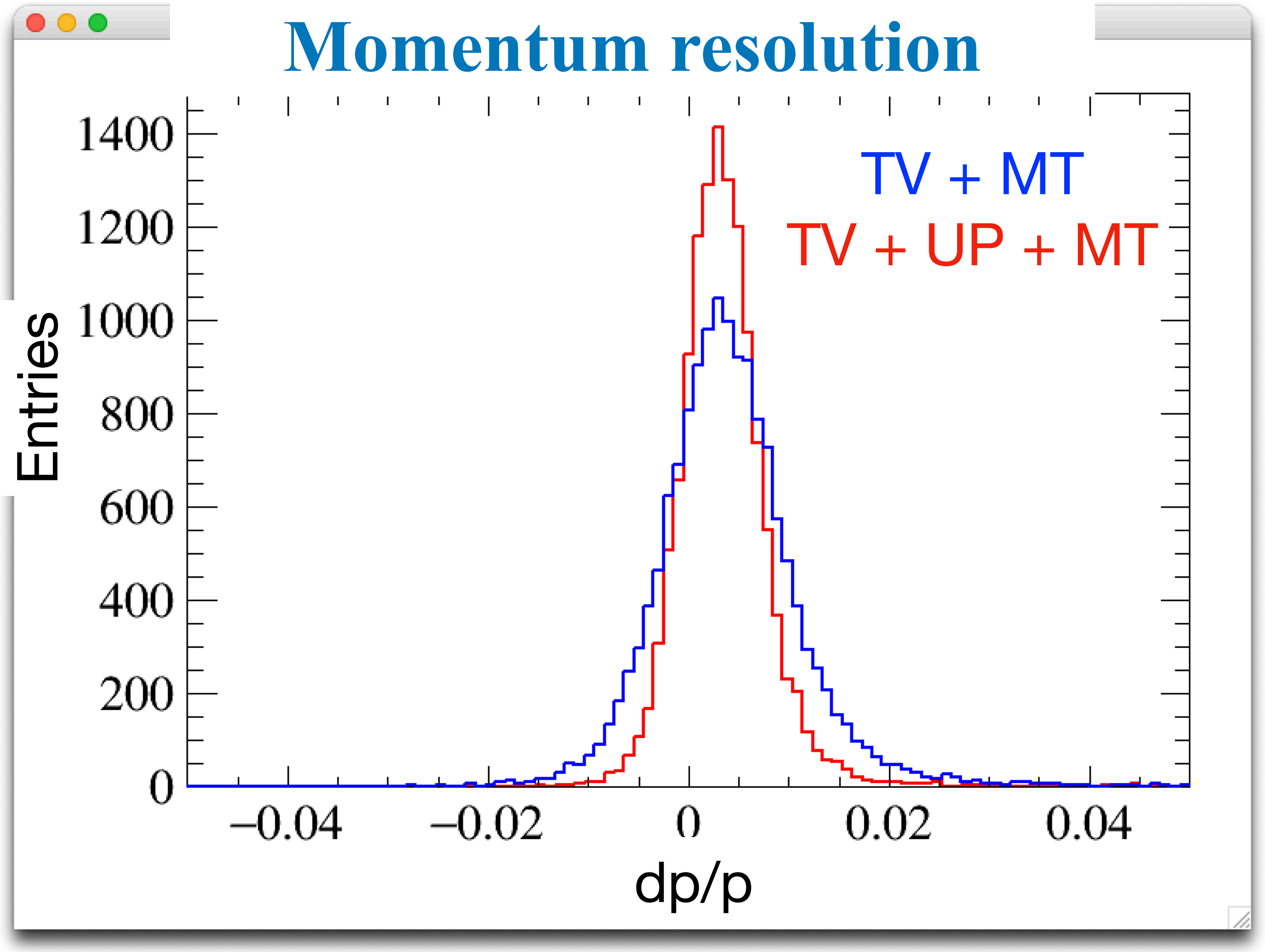


Long Track with UP

- Ghost rate reduced significantly
- Momentum resolution improved







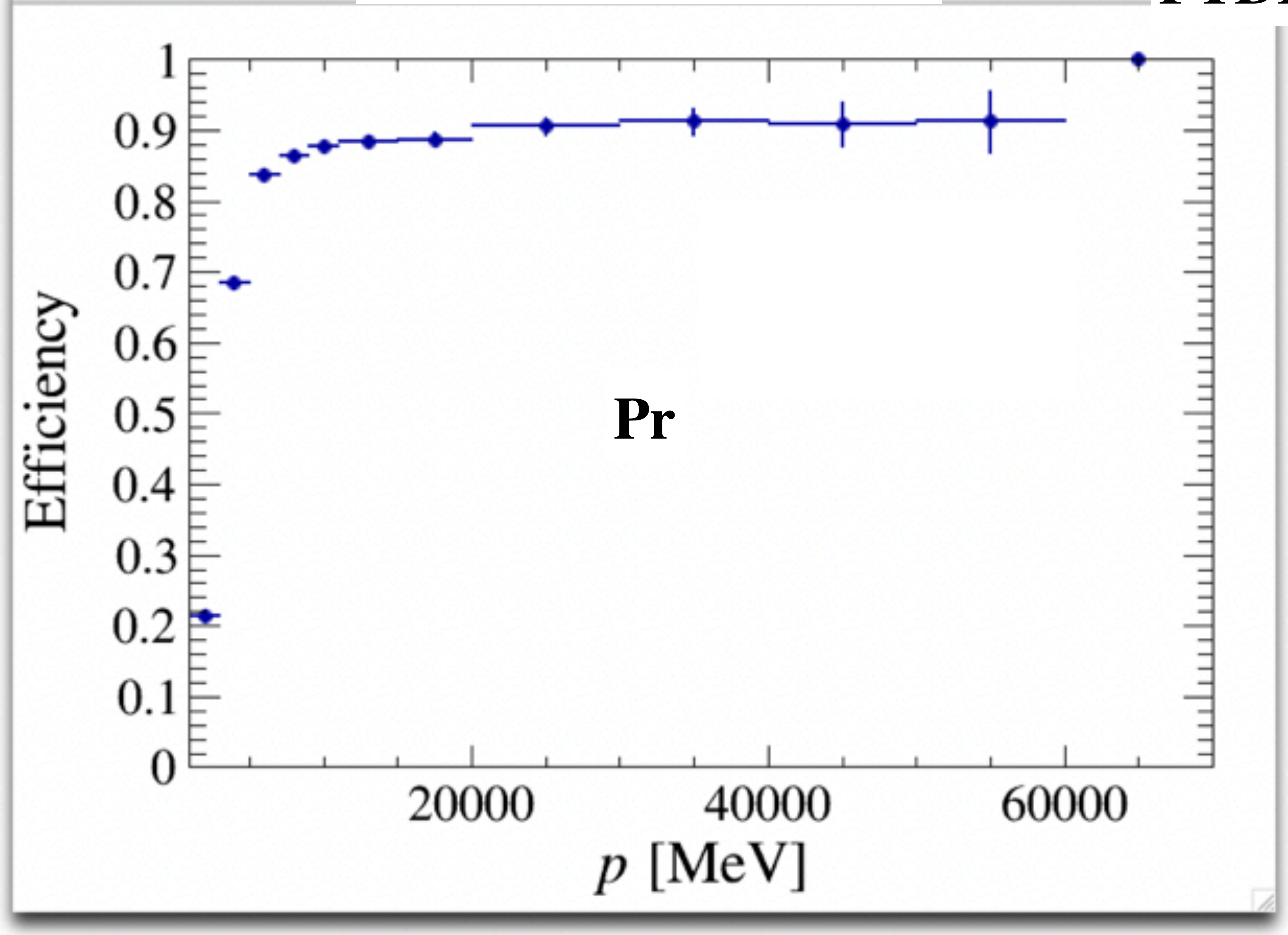
FTDR Geom

Downstream Track

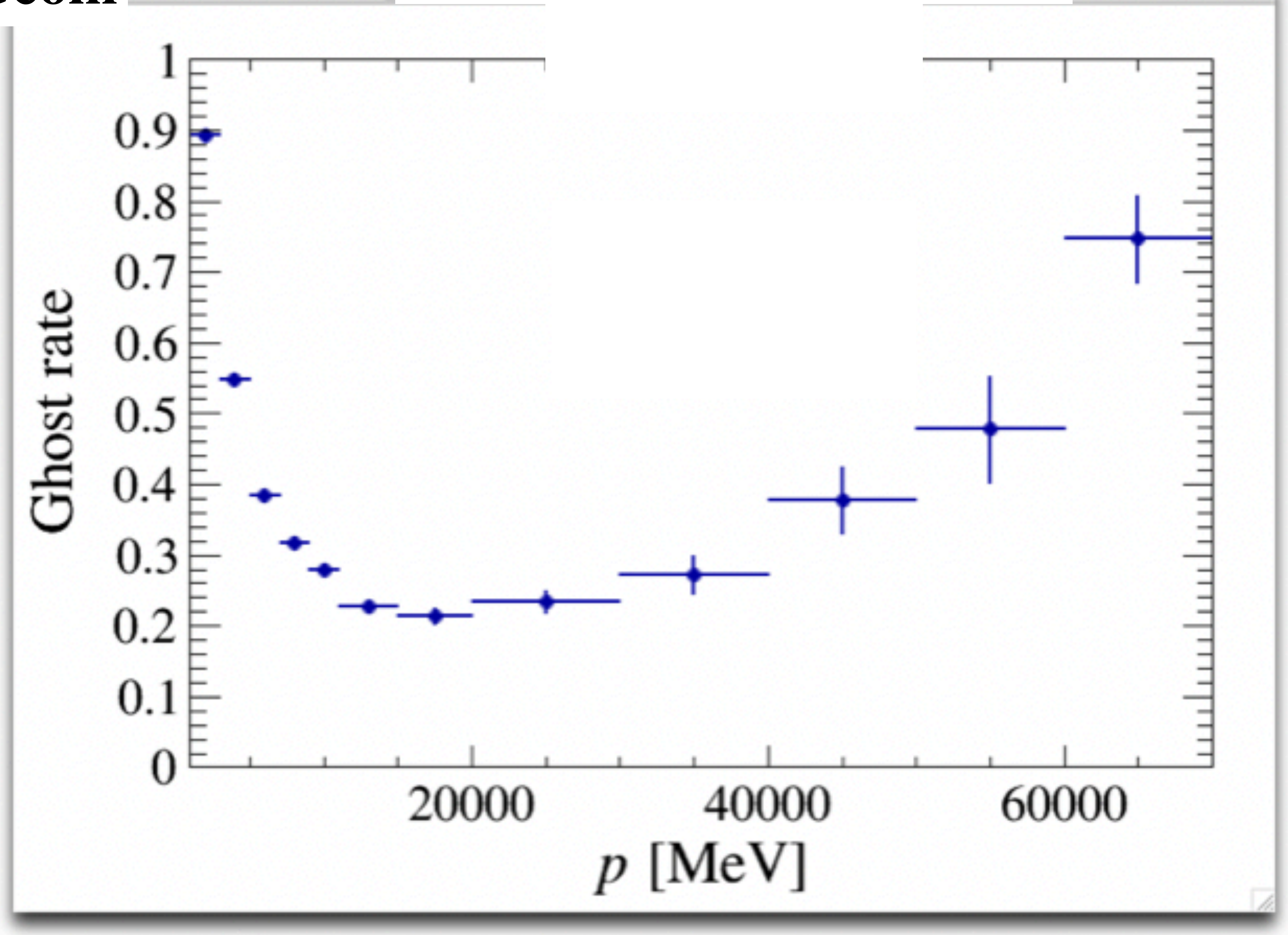
- **Downstream tracks is crucial for the long lived particles like K_s and Λ_0, those decays outside of the Velo**
- **Flavor physics studies with K_s or Λ_0 particles strongly rely on the downstream tracking performance**
- **Same algorithm as TV-MT Matching (UP + MT)**
  - Fast Pre-Filter: Discard candidates with large Y-mismatches
  - Precision Matching: cut on χ^2 and MLP score

FTDR Geom

Efficiency



Ghost rate



Upstream with UP Hits

Tracking based on UP Hits still considered as backup

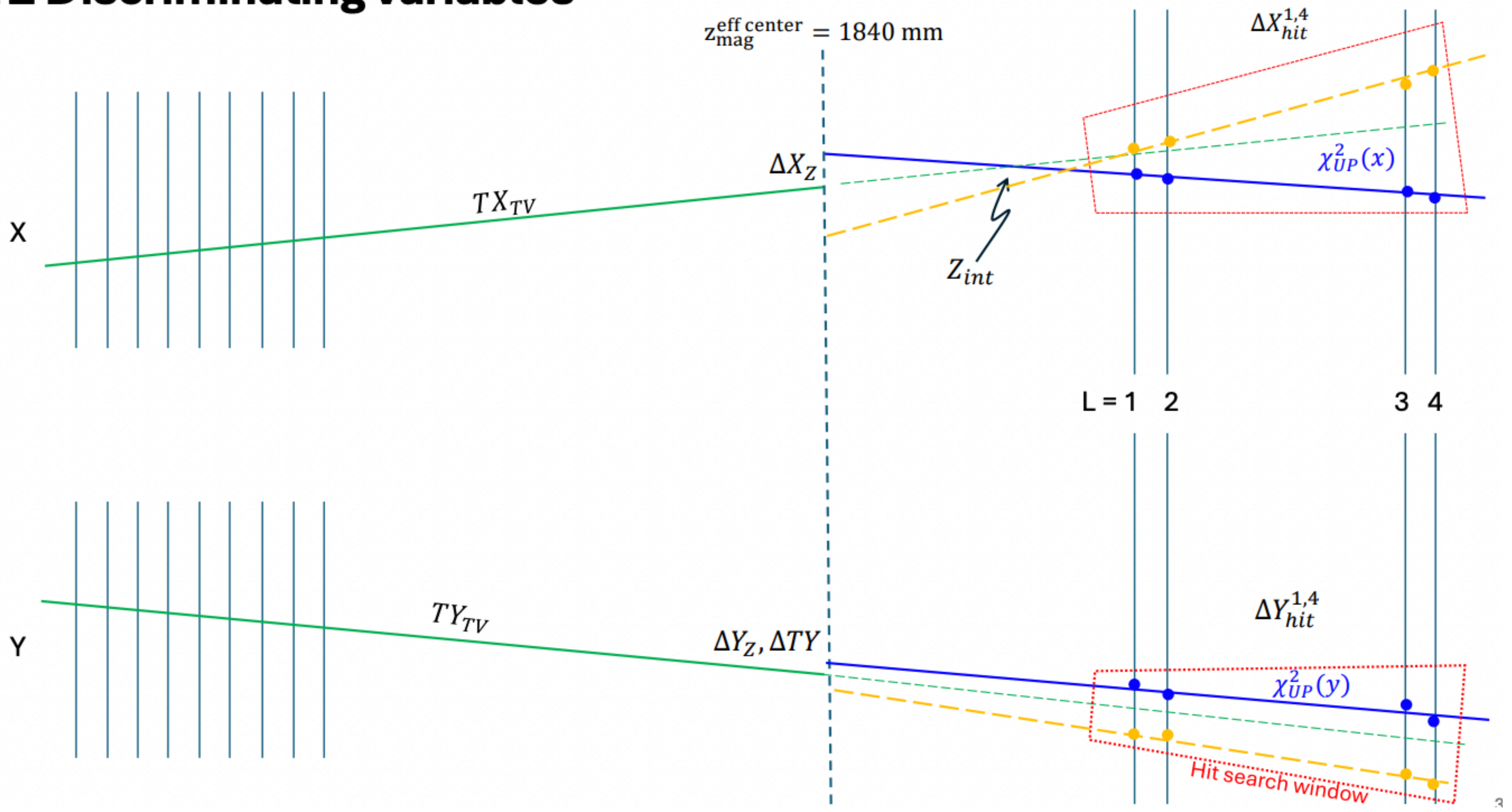
Match TV and UP Hits

Two FOMs

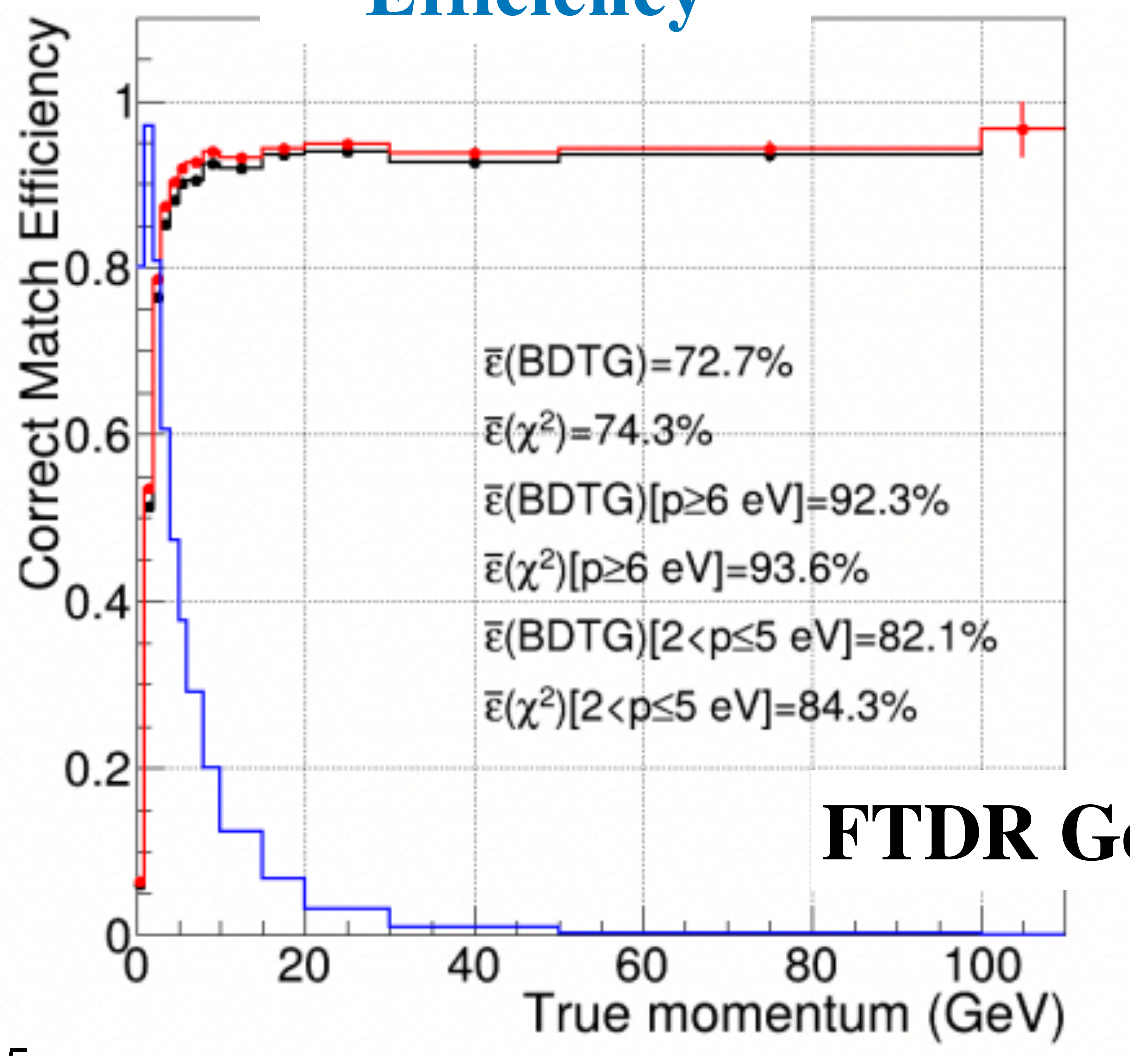
- $\chi^2 = \chi^2_{UP}(y) + (\frac{\Delta TY}{\sigma(\Delta TY)})^2 + (\frac{\Delta Y}{\sigma(\Delta Y)})^2 + (\frac{\Delta X}{\sigma(\Delta X)})^2$
  - $\sigma(\Delta TY) = 0.7\mathbf{mrad}, \sigma(\Delta Y) = 0.67\mathbf{mm}, \sigma(\Delta X) = 1.0\mathbf{mm}$

- **A gradient boosted BDT (using TMVA)**
  - **12 discriminating variables**
  - **Signal**: All used UP hits match to the correct MC particle
  - **Background**: 0 hits matched to the correct MC particle

12 Discriminating variables

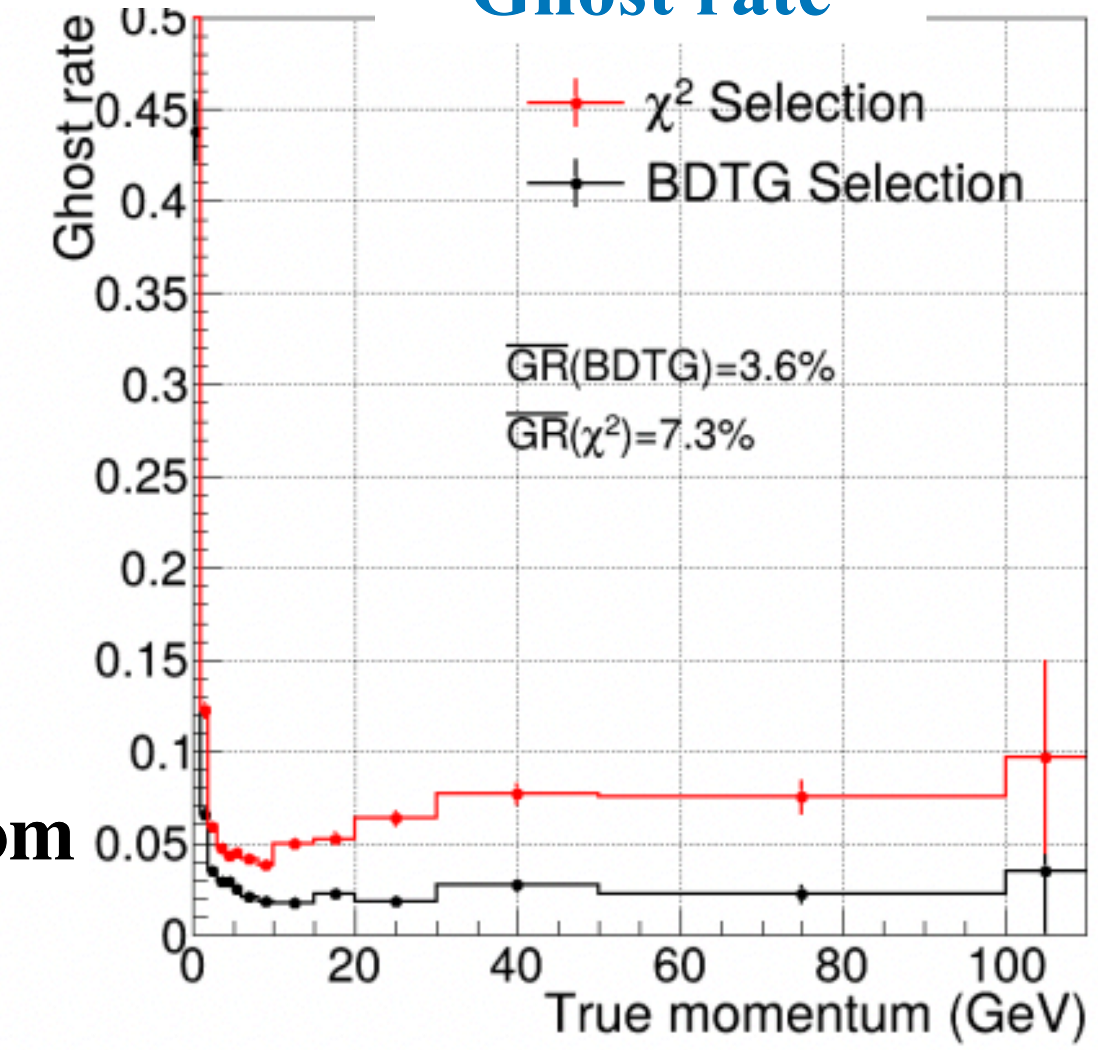


Efficiency



FTDR Geom

Ghost rate



Summary

- The upstream pixel tracker in Upgrade II will be redesigned due to the increase of luminosity
  - From silicon strip (UT) → silicon pixel (UP)
- Geometry versions are implemented under the LHCb framework
  - Compare the Material Budget between two UP designs
  - Study the hit density and data rate under the LHCb Upgrade II beam condition to guide UP design
- The UP performance study is ongoing
  - The development of all UP-related track reconstruction systems is developed
  - UPTracks-based algorithm and UPHits-based algorithm are developed in parallel
  - Tracking Algorithm Optimization in Progress

Thanks for your attention!

Backup

UP Standalone updates

- Efficiency, especially in low momentum region, still has the improving space
- Ghost rate >10%, polluting the matching algorithm in next step
- Once we check the simulation from UP.E design, with no-gap structure, the increase of the ghost rate is also observed
  - More hits detected, but the performance is worse?

performance \ sample	FTDR	UP.E.v2
UP Efficiency (All)	**~82.14%**	**~84.08%**
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Ghost Rate	**~10.78%**	**~12.32%**

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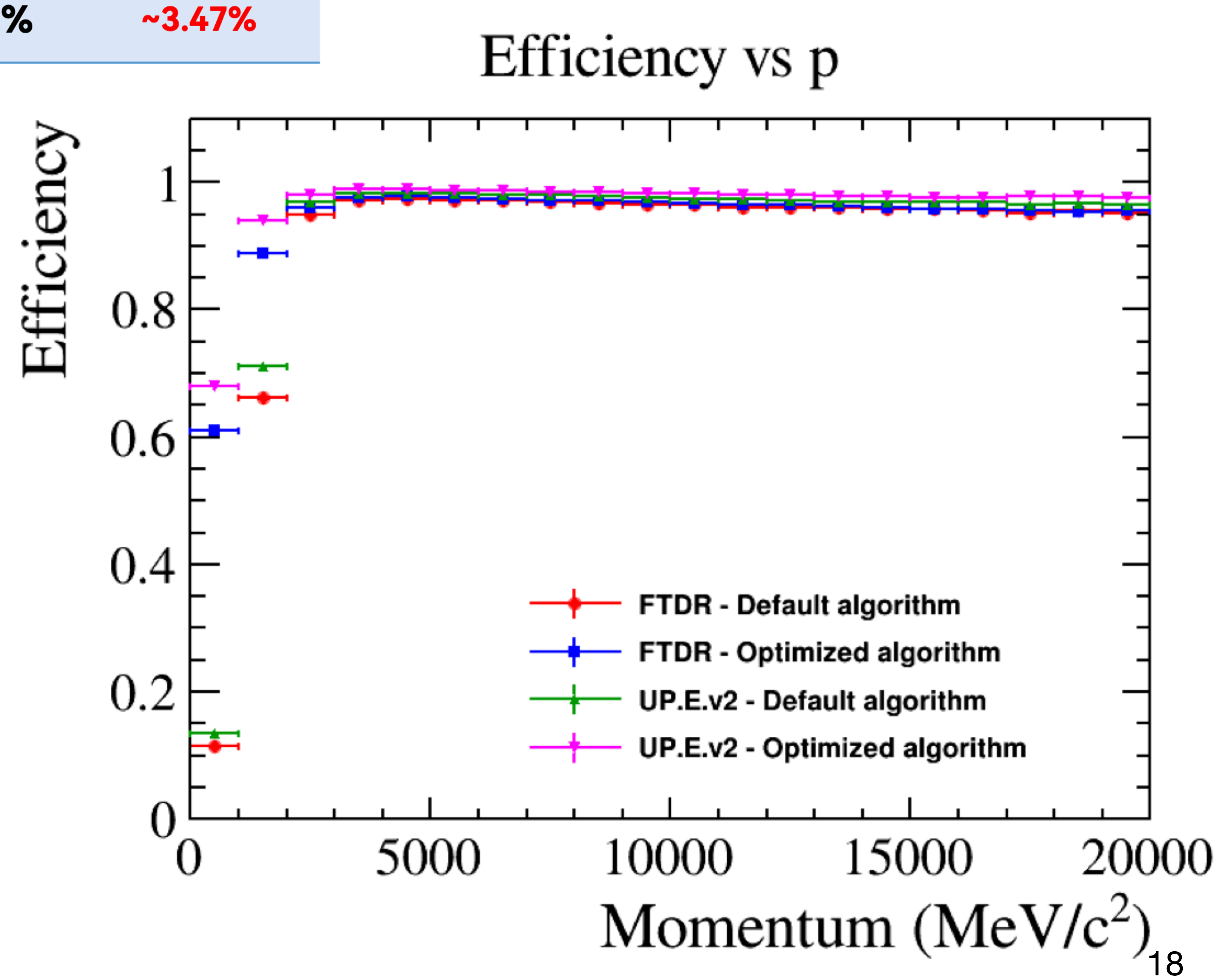
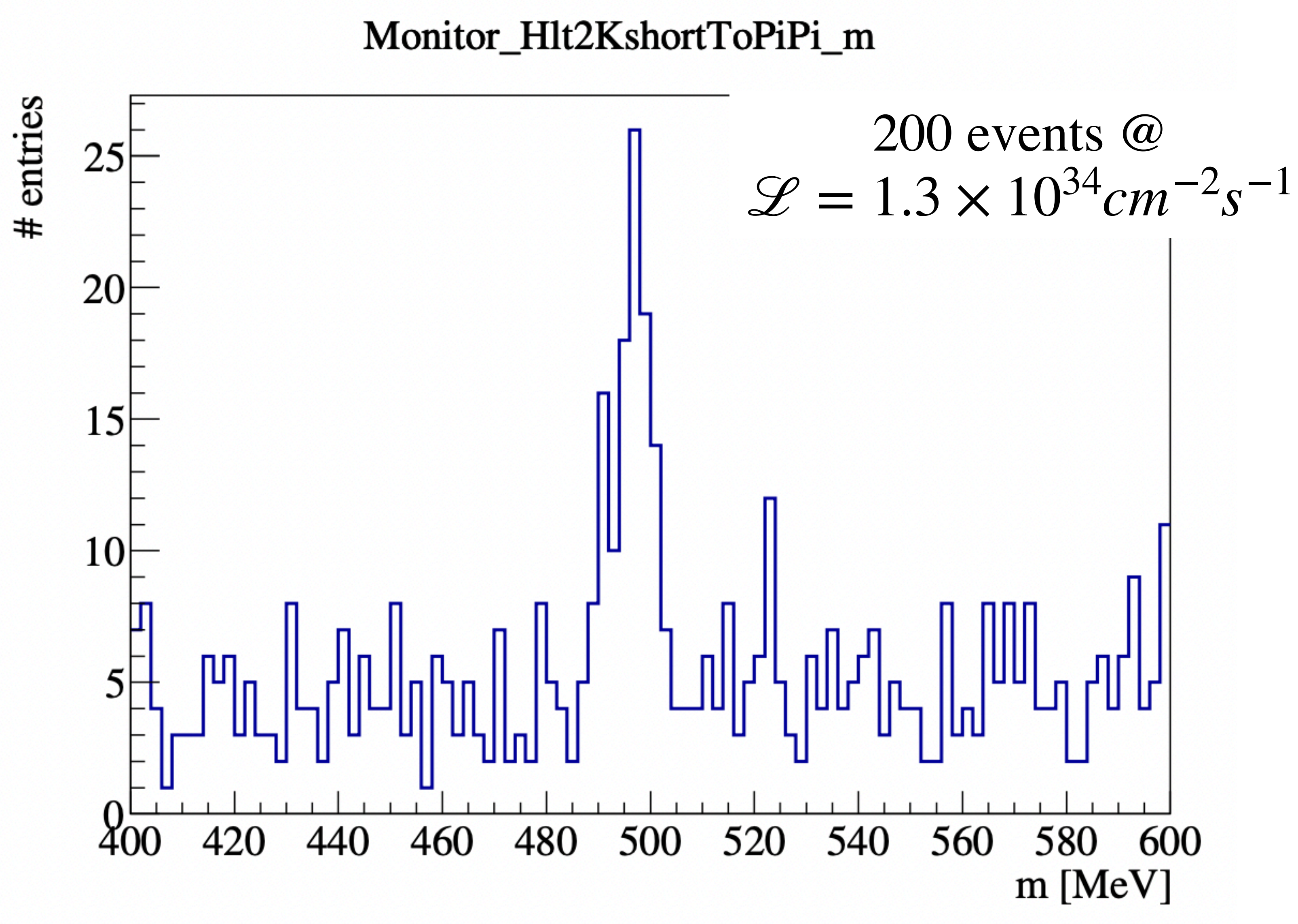


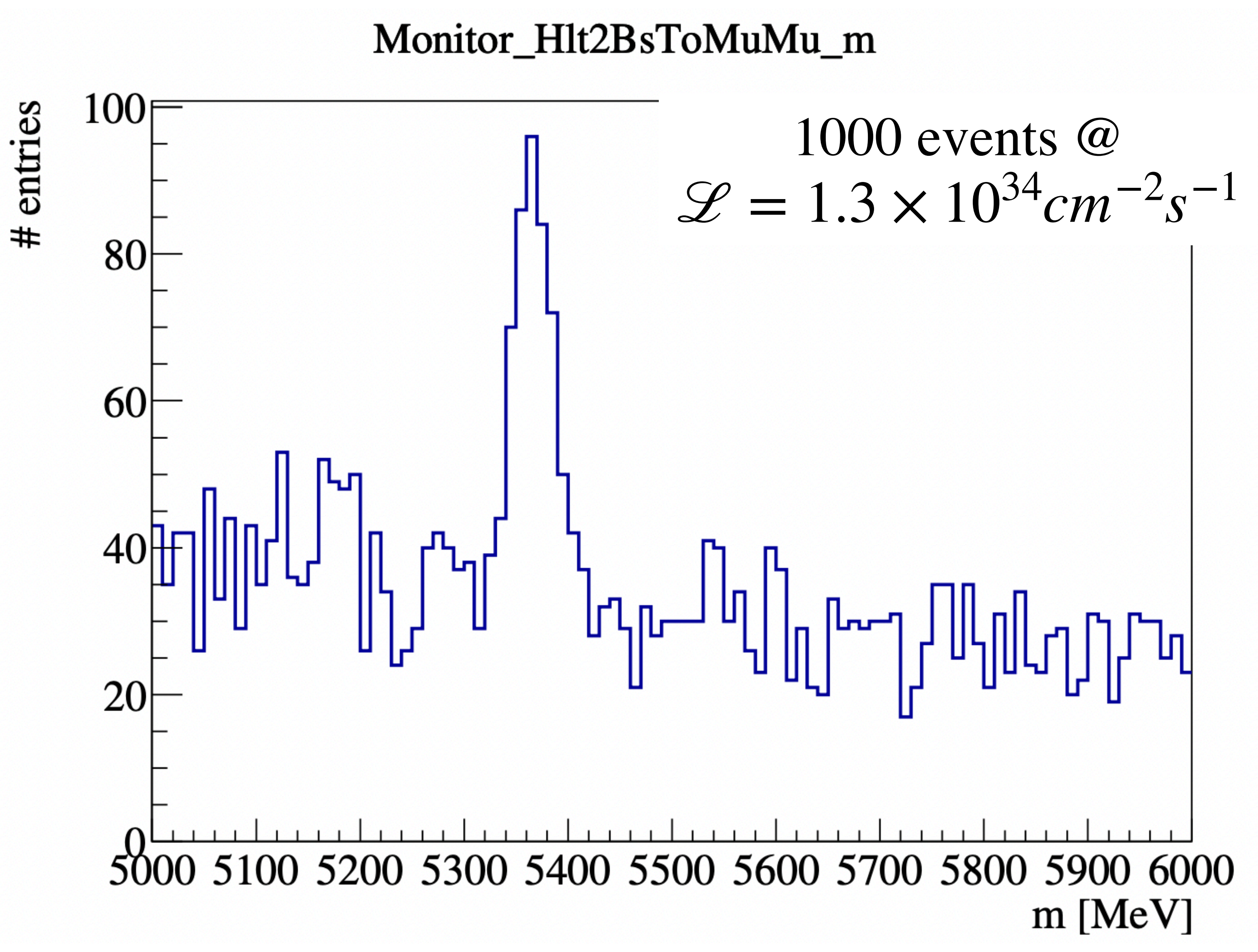
Reconstruction of physics decays

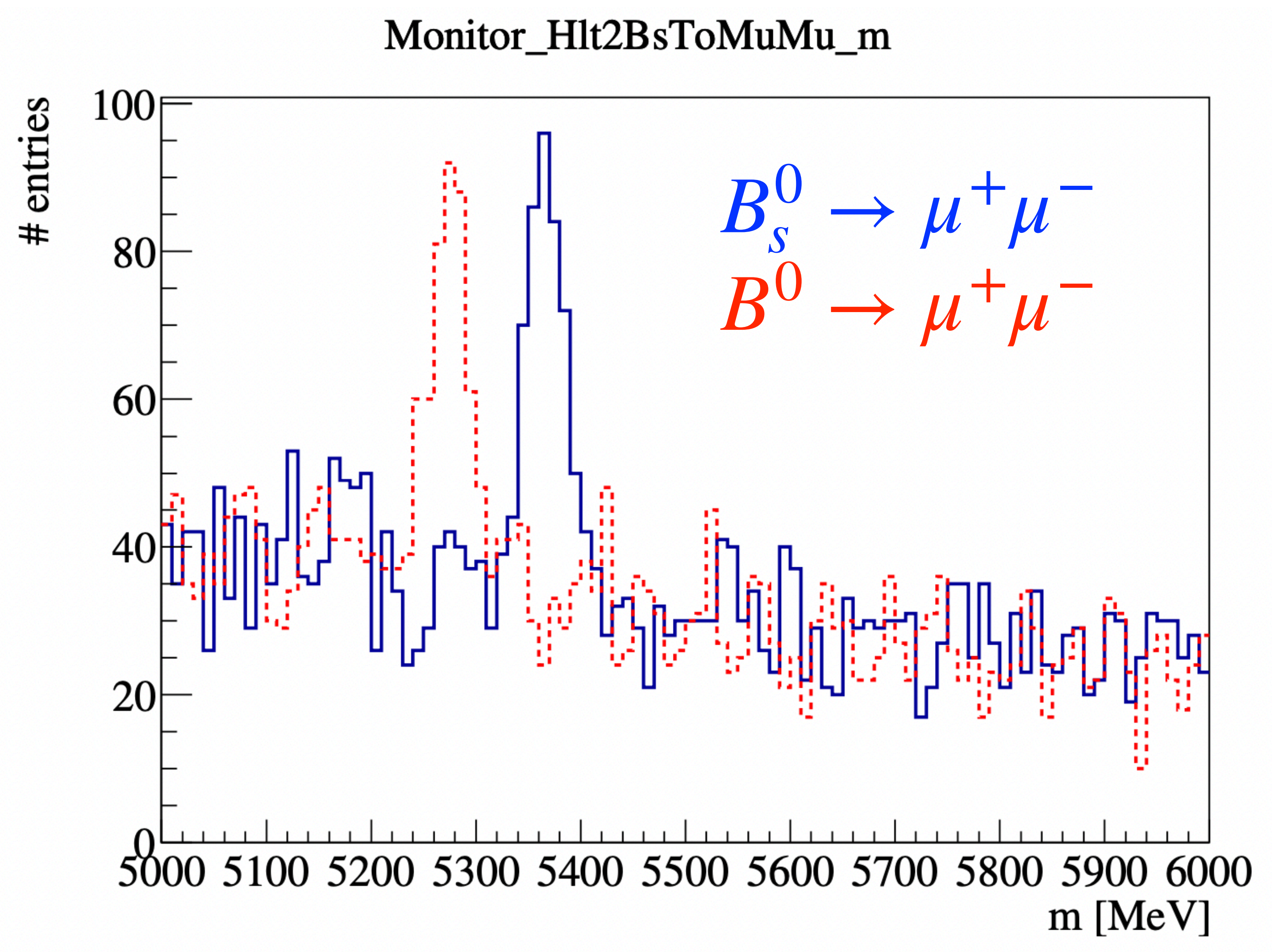
Reconstruct tracks on Upgrade2 simulation — Use Long Track

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



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





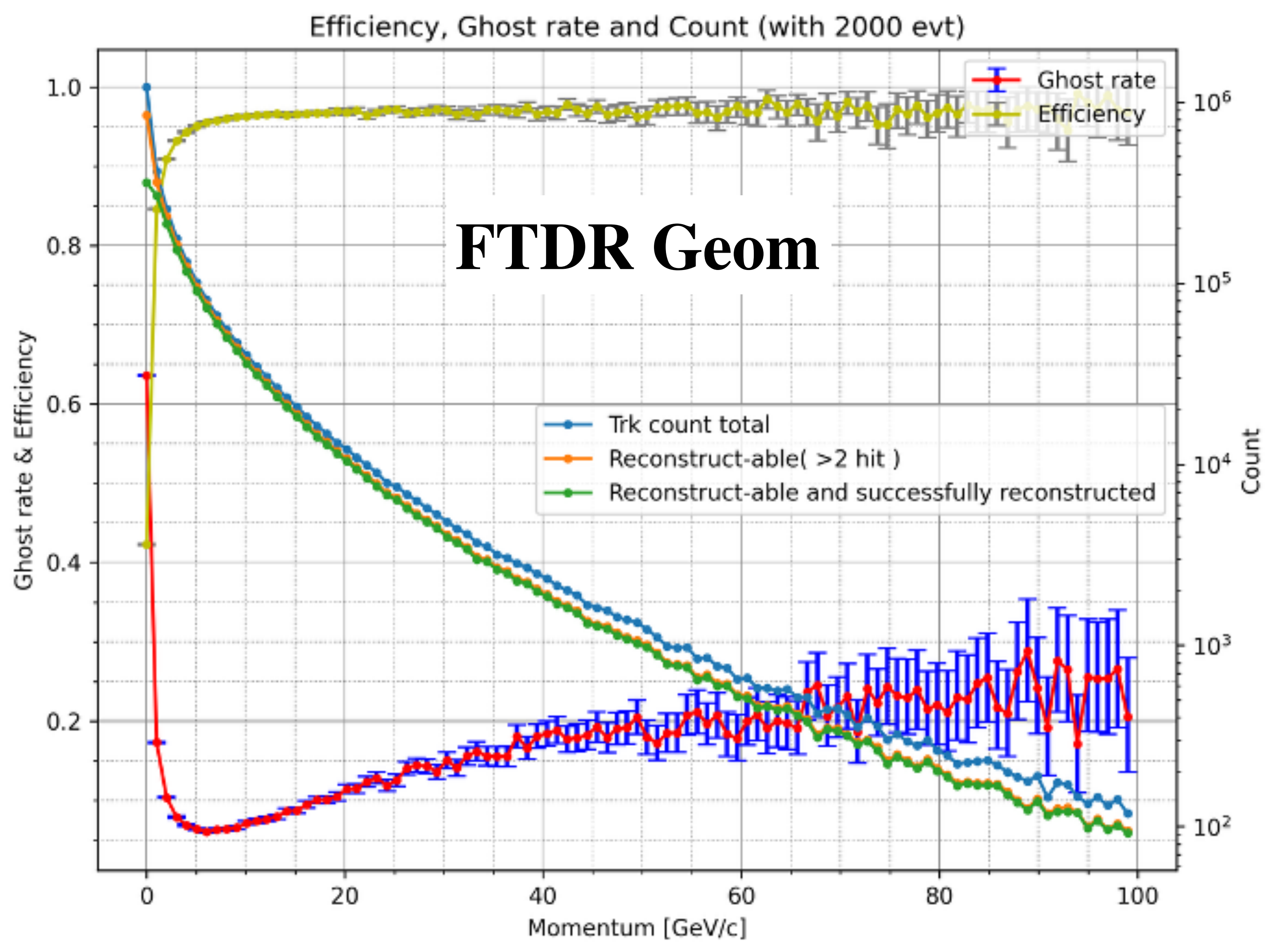
- Clear mass peak visible
- Well separated for $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

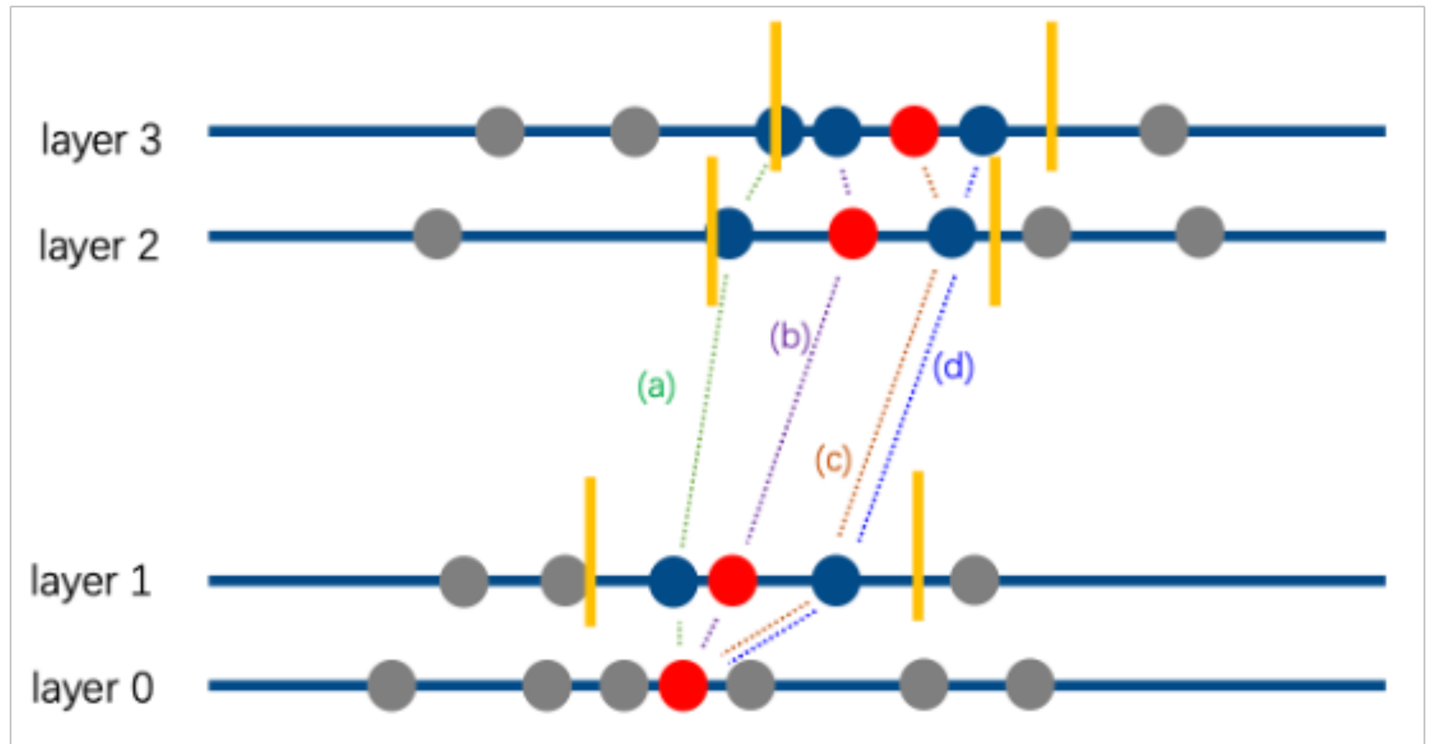
MLP target

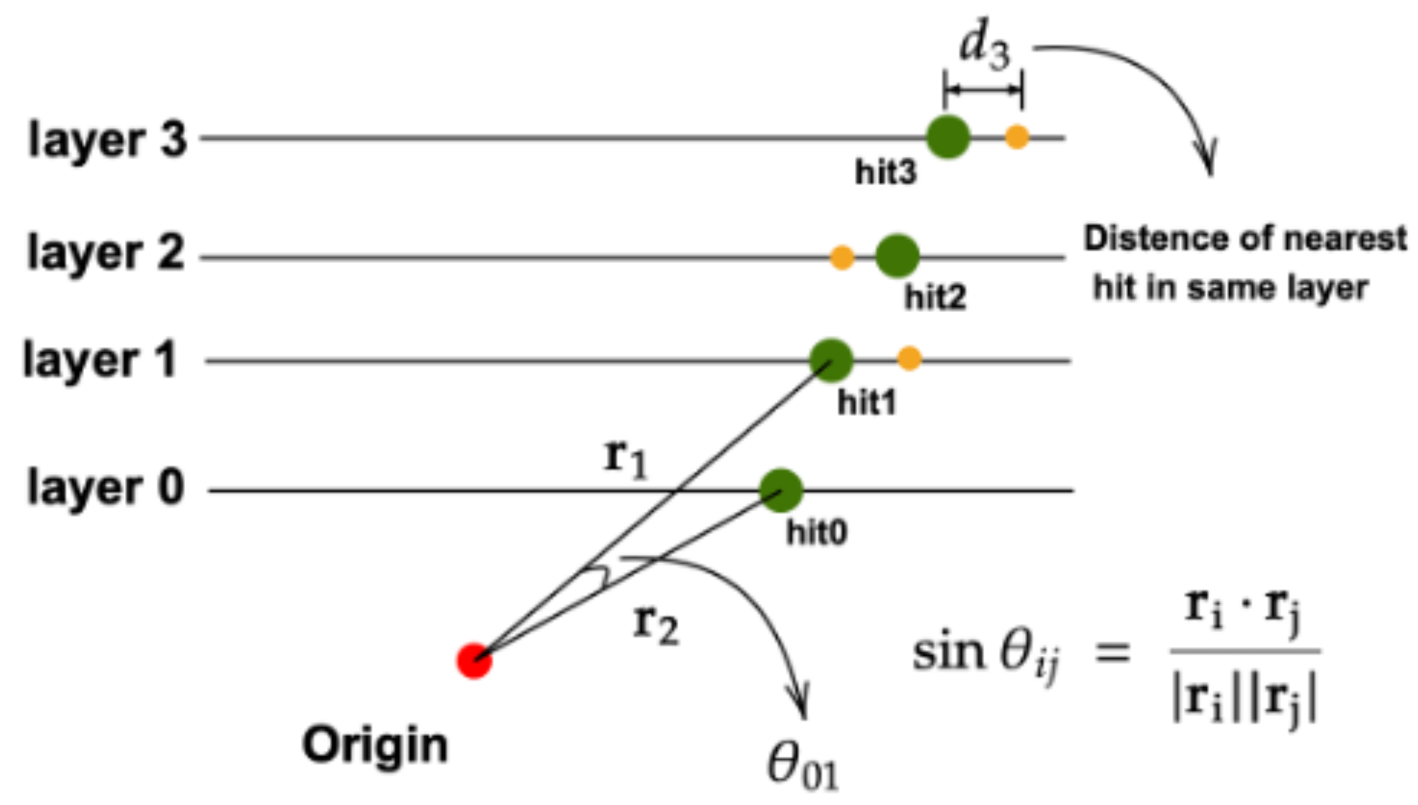
- To find the best track candidate for each reference hit by evaluating global hit combinations using an MLP model.

MLP Strategy

- Pickup a hit in Layer_0 as reference hit (h0)
- Build a track set combining all selected hits in other layers within a search window
- The best matches for h0 found by MLP after several iterations







Training variables

$\theta_{01}, \theta_{02}, \theta_{03}, \theta_{12}, \theta_{13}, \theta_{23}$
d_1, d_2, d_3

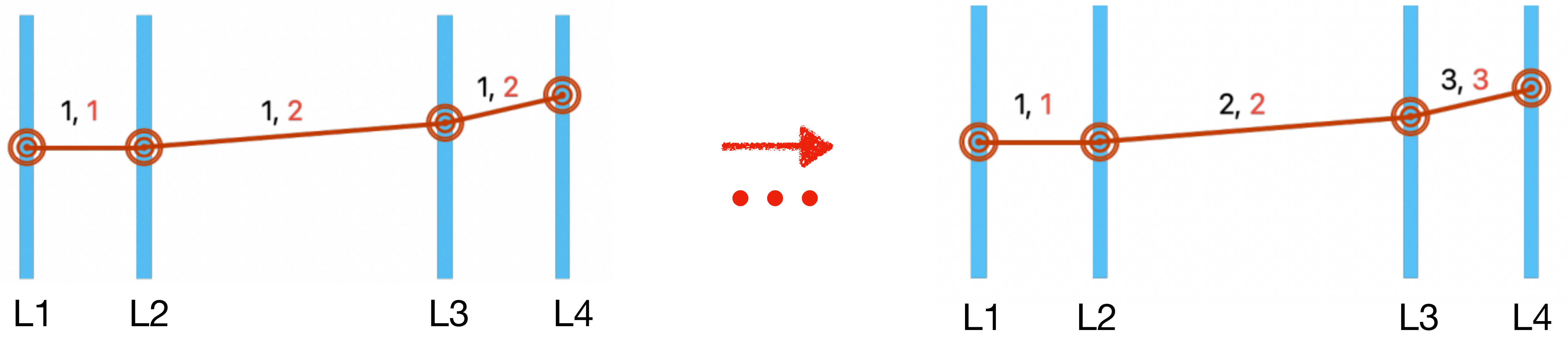
CAT for UP standalone track

CAT Target

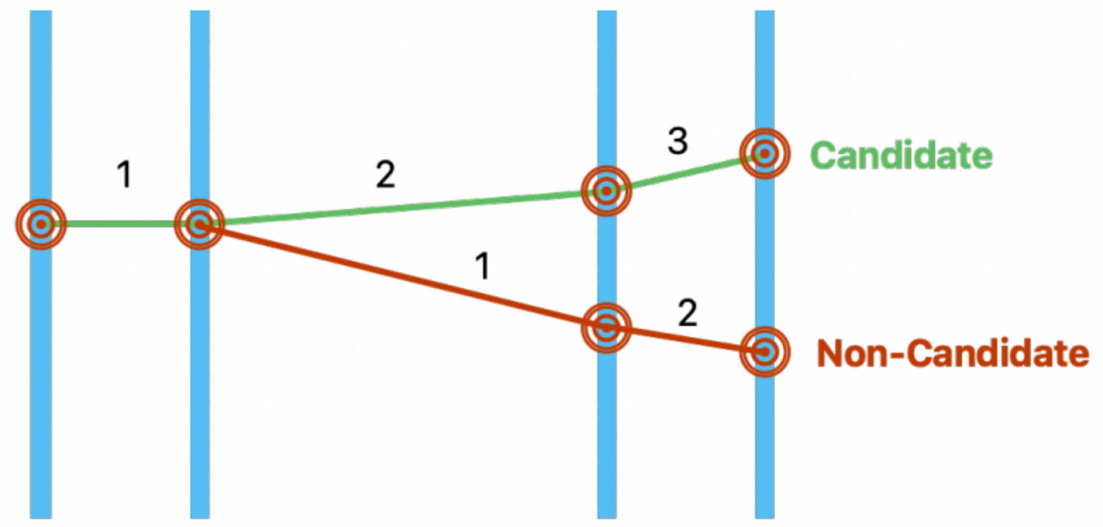
- To build the best track candidate by locally extending hit connections using Cellular Automaton evolution rules

CAT Strategy

- Construct doublets using geometry constraints
  - $\Delta\phi_x, \Delta\phi_y, \phi = \sqrt{(\Delta\phi_x^2 + \Delta\phi_y^2)}$
  - Allowing one layer skip

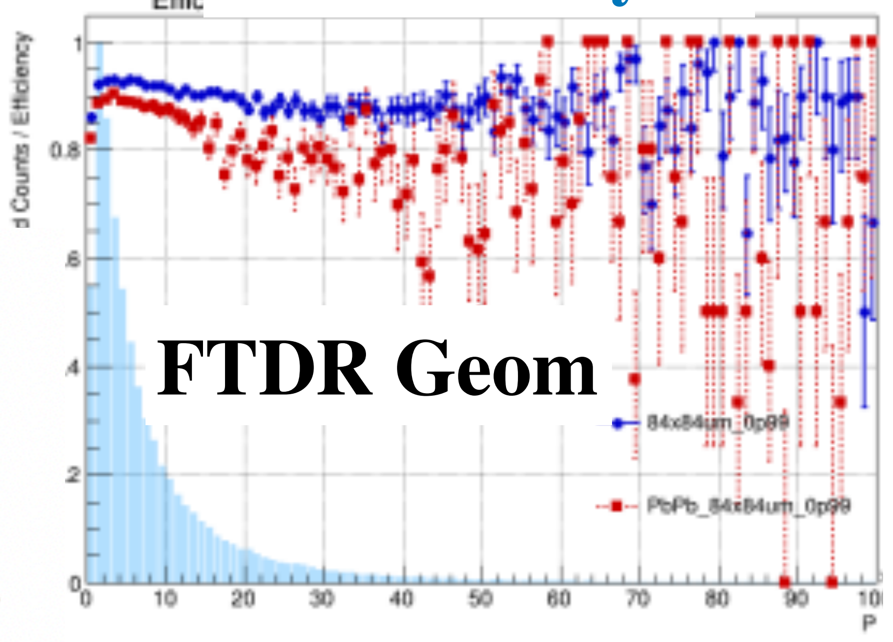


- Expand into tracklets
- Evolution score propagation under breaking angle ϕ_{max}
- Backward search for best-scored tracklet chain
  - $J = N - \gamma \sum_{j=1}^{N-1} \frac{\phi(L_{j+1}, L_j)}{z_{j+1,R} - z_{j,L}}$

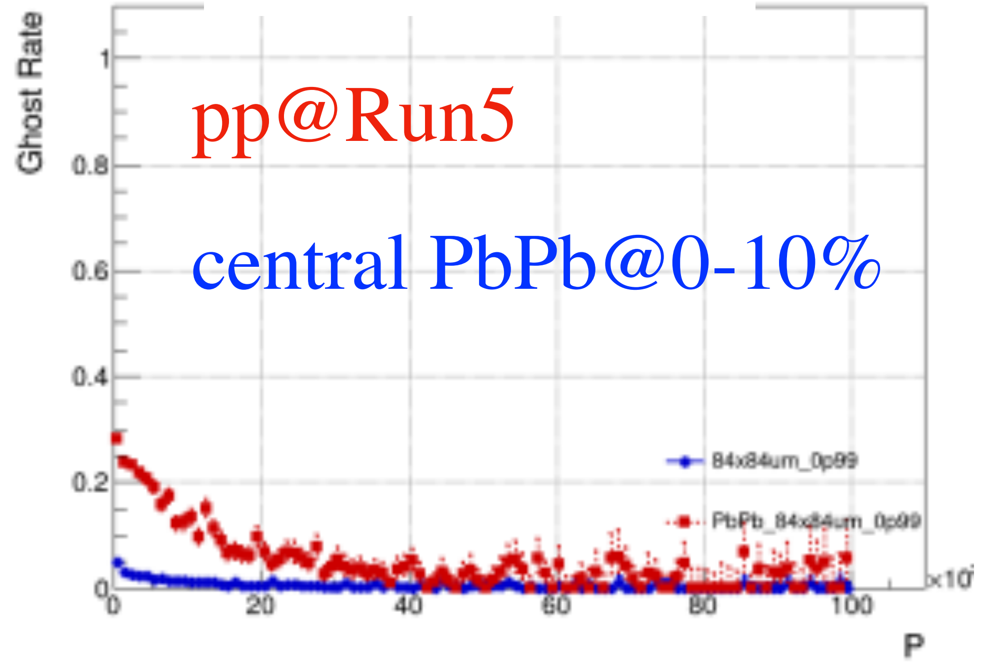


- Simple track fit + clone/ghost suppression

Efficiency



Ghost rate



- Good for low momentum tracks
- Low ghost rate (<5%)