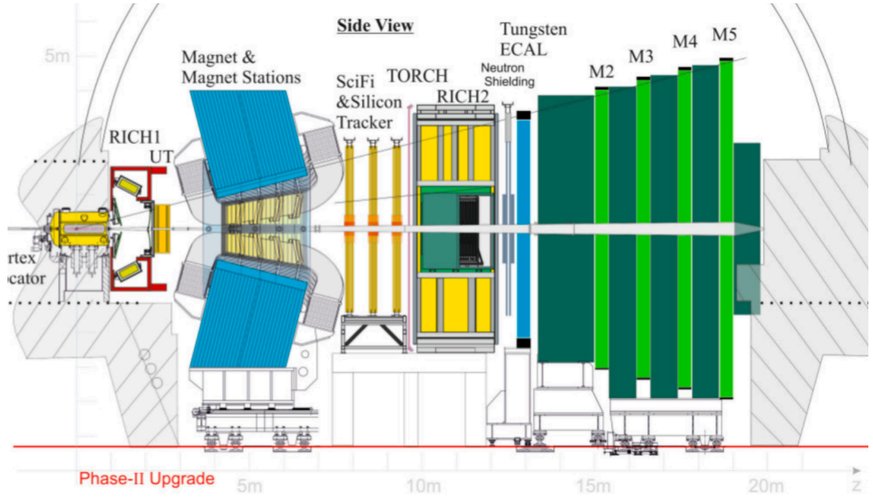
The simulation and reconstruction studies on LHCb UP detector for Upgrade II

Mingjie Feng (冯铭婕, 中国科学院高能物理研究所)

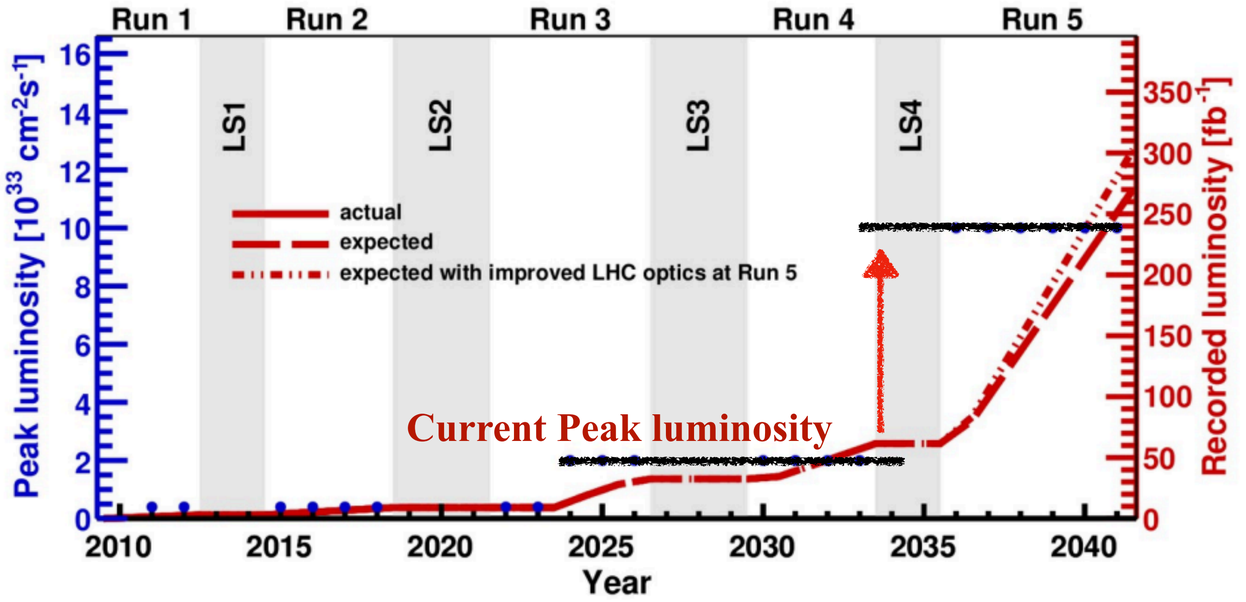
25/10/29-25/11/02, Xinxiang
第十一届中国LHC物理会议

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)
    - $\mathscr{L}_{peak} = 4 \times 10^{32} cm^{-2} s^{-1}$, $\mathscr{L}_{Int} = 9\, fb^{-1}$
  - 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

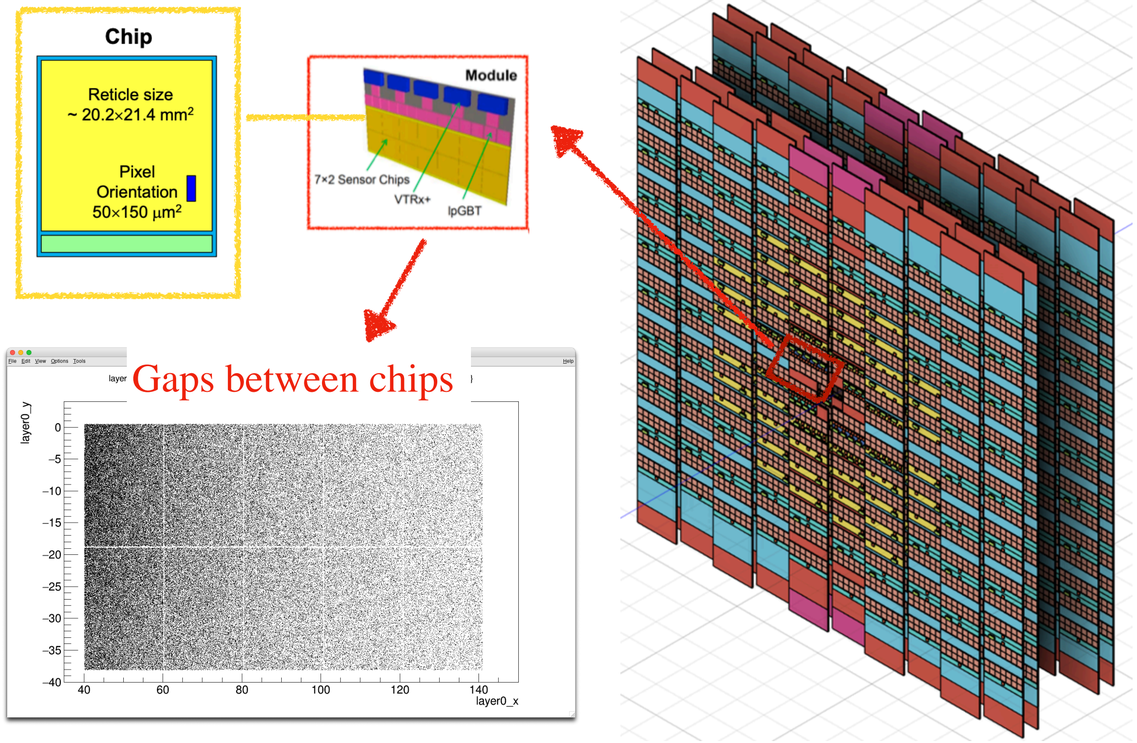


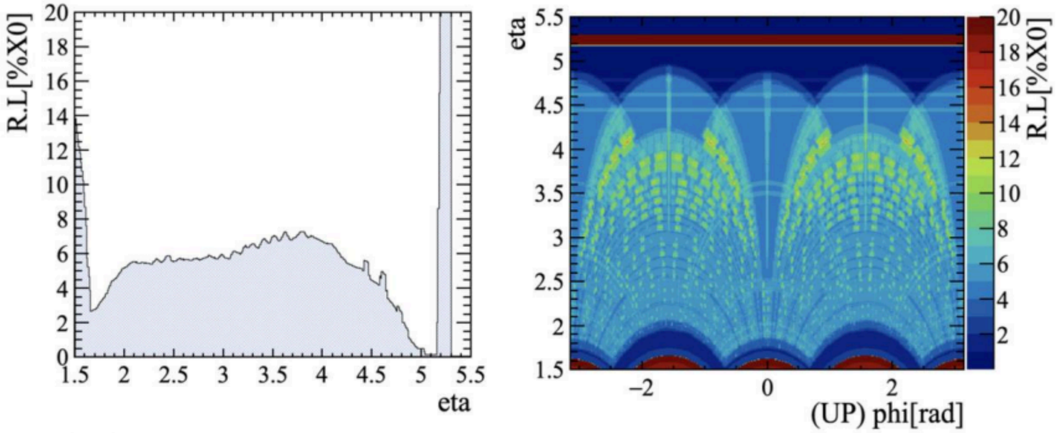
Upstream Pixel Tracker (UP)

Chinese group contributes significantly

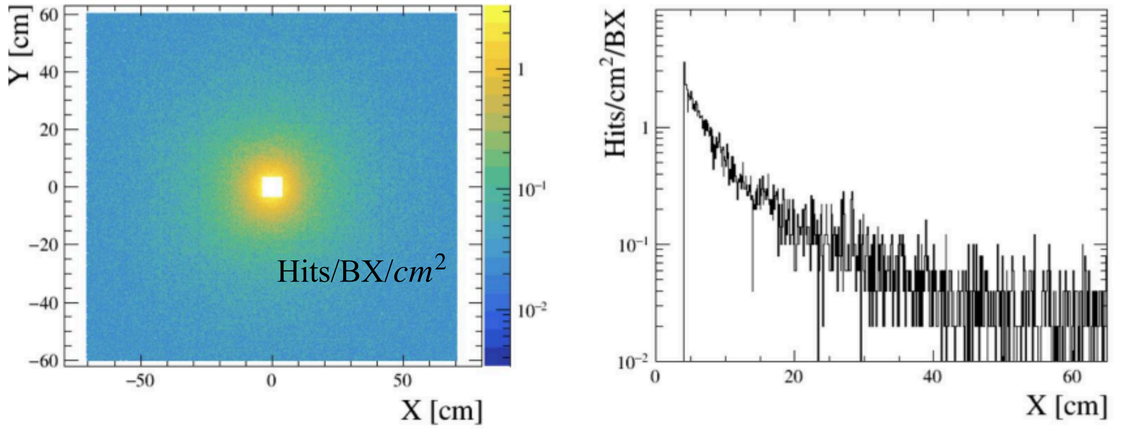
FTDR design

- 4 Layers, 10 Staves per Layer, 32 Modules per Stave, 14/10 Chips per Module
  - Coving ~ 1407 mm in X, ~ 1204 mm in Y
  - Central hole (beam pipe) ~ (± 39 mm) × (± 37mm)
  - Chip size ~ $2 \times 2\ cm^2$
- Material budget ~ 1.2% per layer
- Hit rate for pp at X = 4 cm ~ 74 MHits/s/cm^2





R.L distribution (4 UP layers)

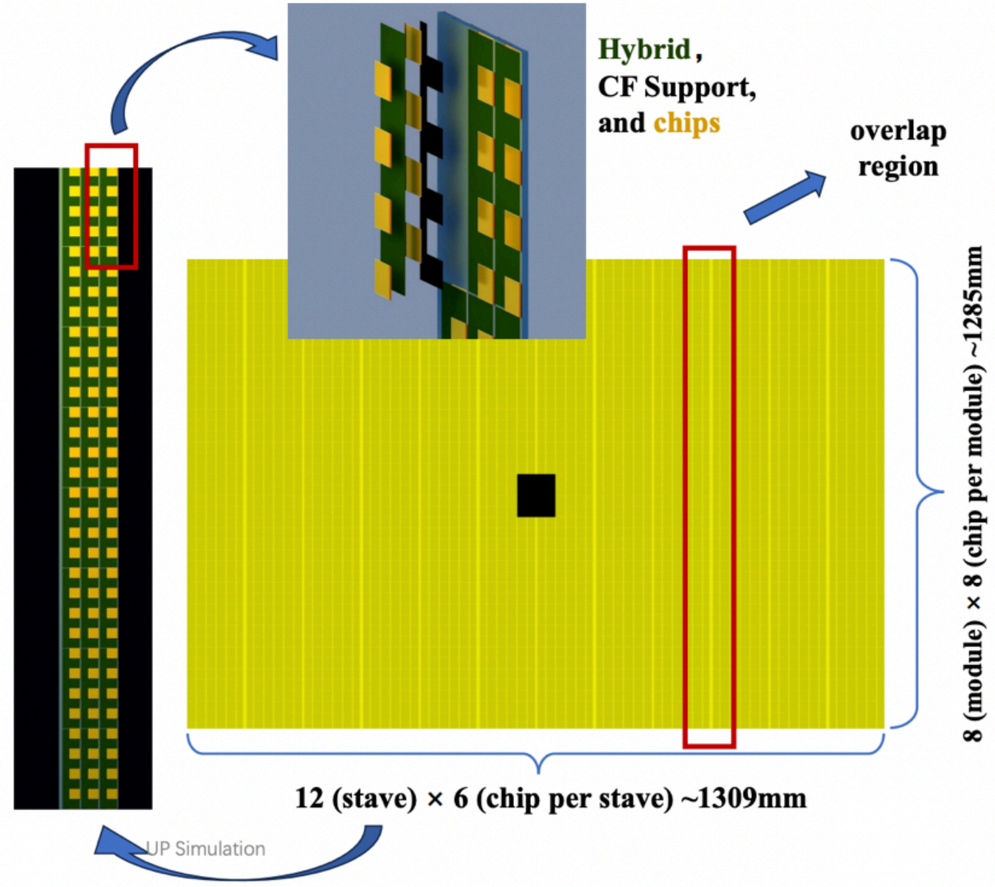


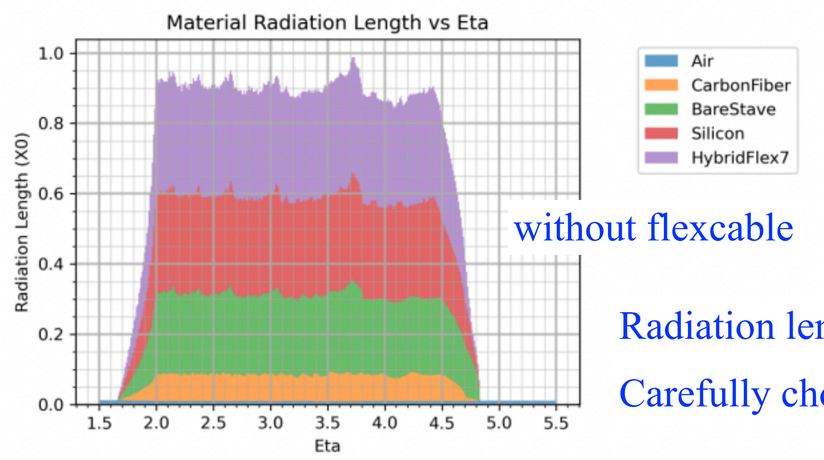
Hits map @ (UP layer1, $\mathscr{L}$=$1.0 \times 10^{34}\ cm^{-2}s^{-1}$, pp at 30MHz)

Upstream Pixel Tracker (UP)

UP .E.v2 design → cover gaps

- 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 ~ $2 \times 2\ cm^2$
- **Gap covered by setting overlap for all Module and Stave**
  - Less missing hit
  - Higher Efficiency and Lower Ghost rate

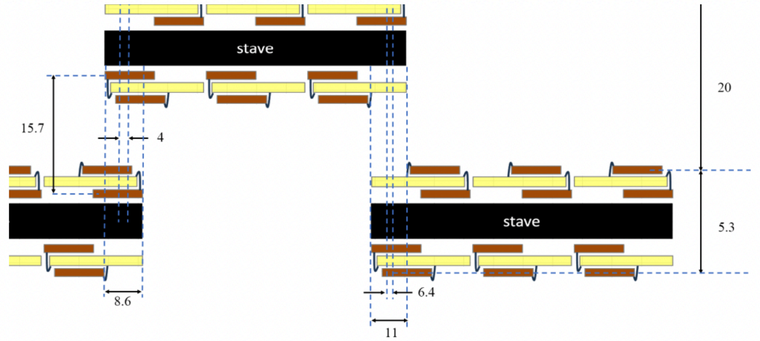




without flexcable

Radiation length under 1% without flexcable

Carefully choose the flexcable material



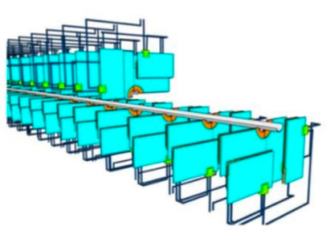
LHCb Tracking System

UP plays a key role in LHCb tracking system

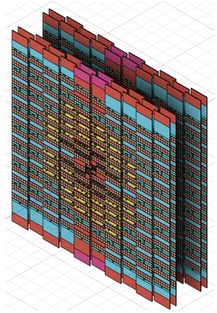
- Fast estimates momentum for trigger system
- Improve momentum resolution
- Reduce ghost rate in track
- Increase reconstruction efficiency for Λ_0 K_S^0…

UP tracking performance

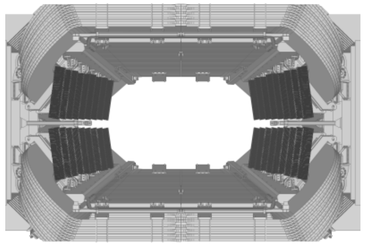
- Simulation events generate at $\mathscr{L} = 1.3 \times 10^{34} cm^{-2} s^{-1}$
- TV, UP, FT, MP: all baseline geometry



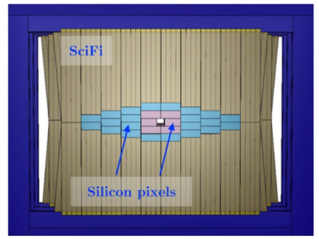
VELO Pixels with Timing (**TV**)



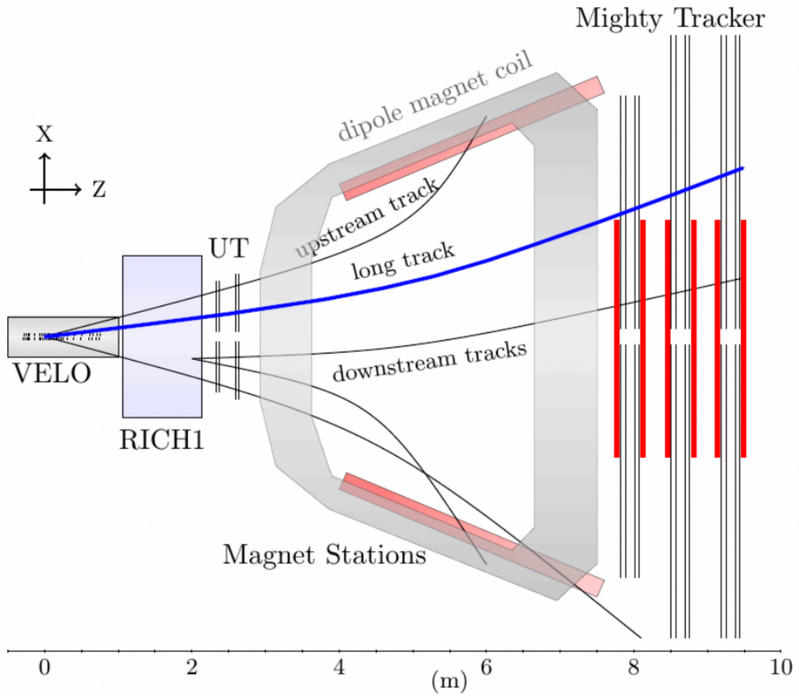
Upstream Pixel Tracker (**UP**)



Magnet Station(**MS**)



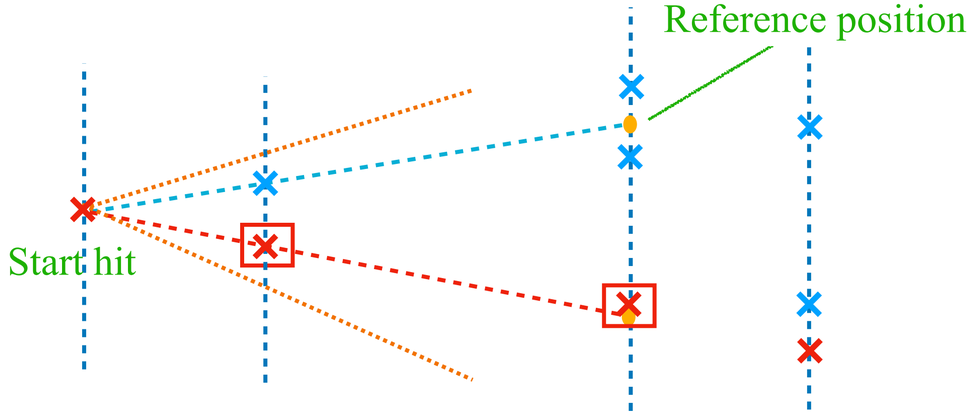
Mighty tracker (**MT**)
- MAPS CMOS pixel (inner, **MP**)
- SciFi (outer, **FT**)

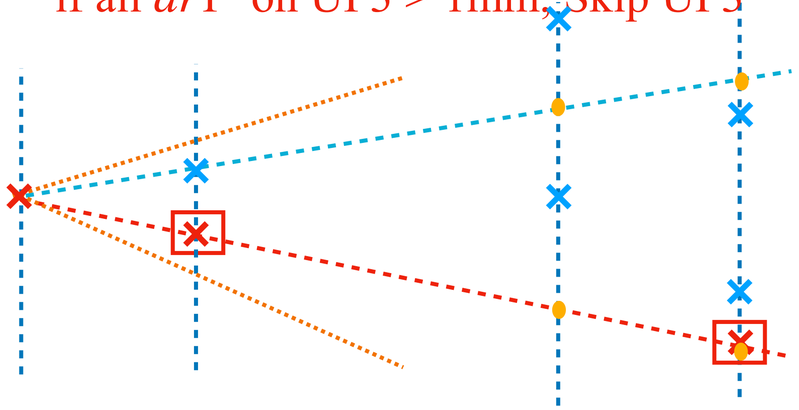


LHCb Tracking System

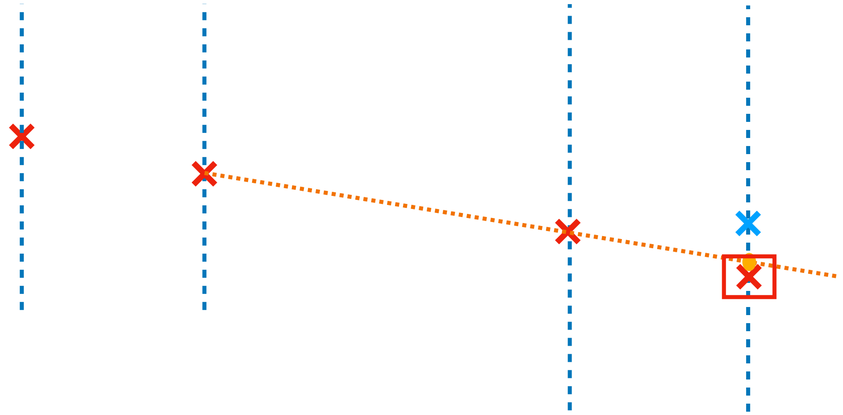
UP Standalone (v1)

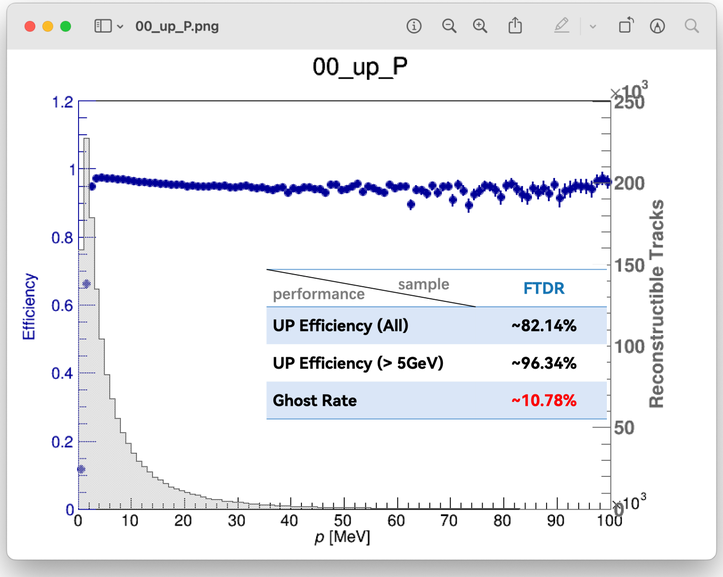
At least have three layers with hit in each track





Step1 Seed: Find three hits with the smallest $dr1^2$ $(dx^2 + dy^2)$ && $dr1^2 < 1$mm





Step2 Forward: extrapolate from layer2&3, find best hit on layer4 with the smallest $dr2^2$ && $dr2^2 < 1$mm

Step3: Mask Hits if $dr1^2$ || $dr2^2 < 0.01$mm and $dr1^2$ && $dr2^2 < 0.5$ to reduce clone rate

Start hit will loop in all 4 layers to covering all possible combinations

UP Standalone updates

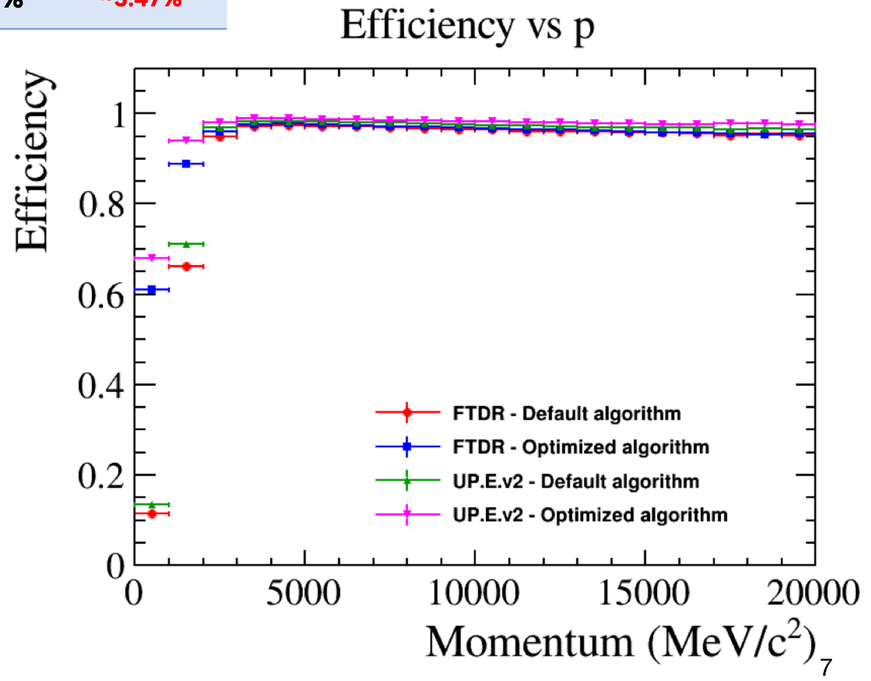
- Efficiency, especially in low momentum region, still has the improving space
- Ghost rate >10%, polluting the matching algorithm in next step
- Once we check the simulation from UP.E design, with no-gap structure, the increase of the ghost rate is also observed
  - More hits detected, but the performance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

performance \ sample	FTDR	UP.E.v2
UP Efficiency (All)	~82.14%	~84.08%
UP Efficiency (> 5GeV)	~96.34%	~97.42%
Ghost Rate	~10.78%	~12.32%

	FTDR		UP.E.v2	
	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



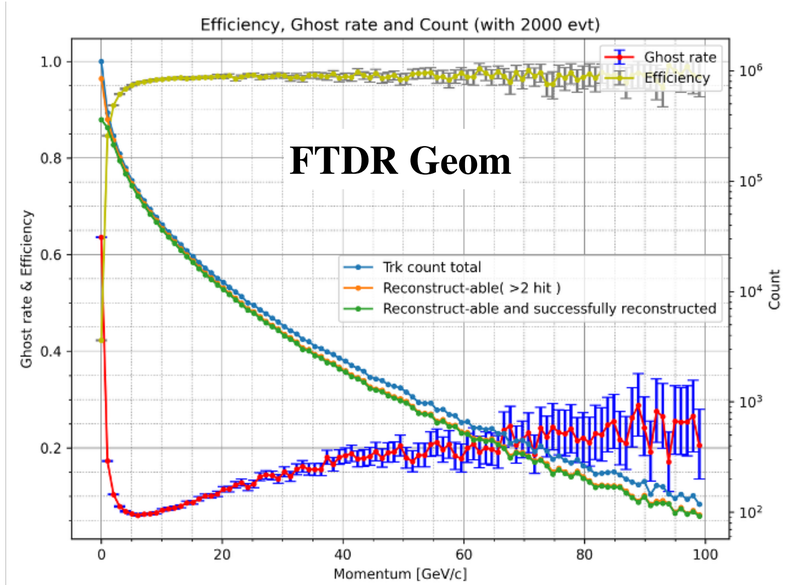
MLP for UP standalone track

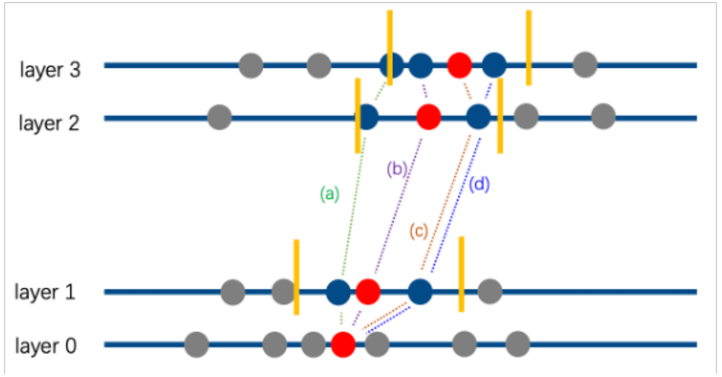
MLP target

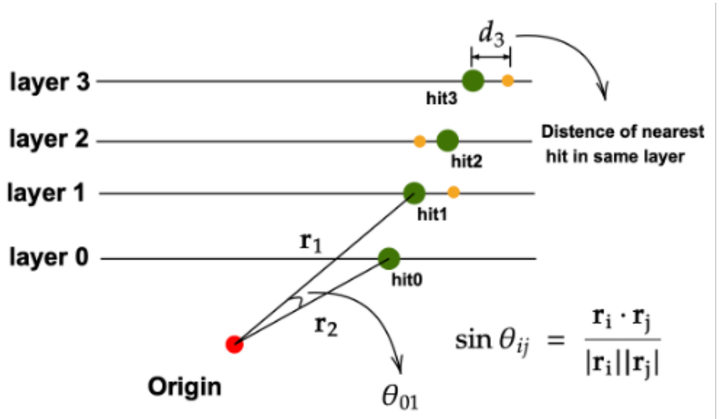
- To find the best track candidate for each reference hit by evaluating global hit combinations using an MLP model.

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

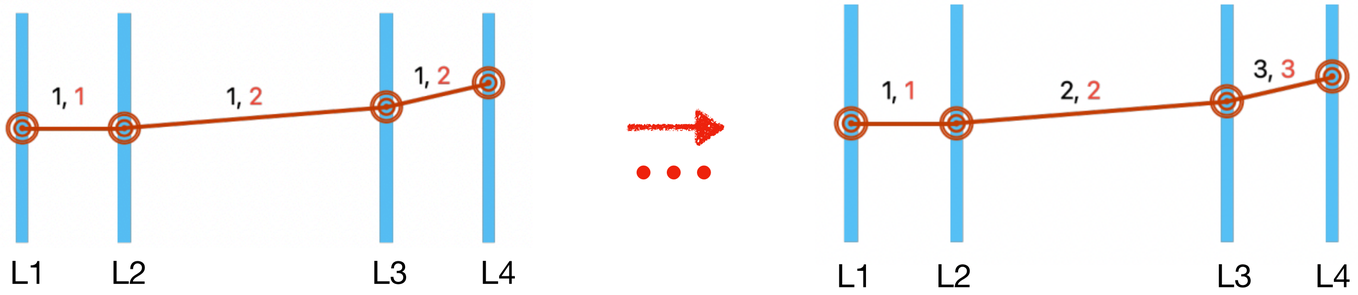
CAT for UP standalone track

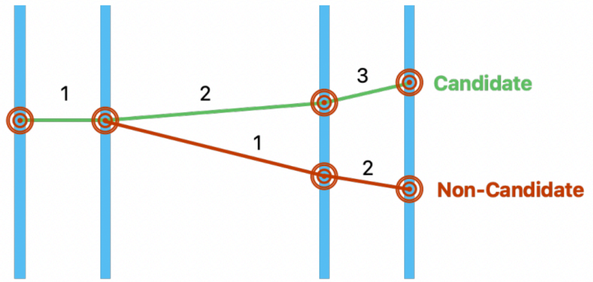
CAT Target

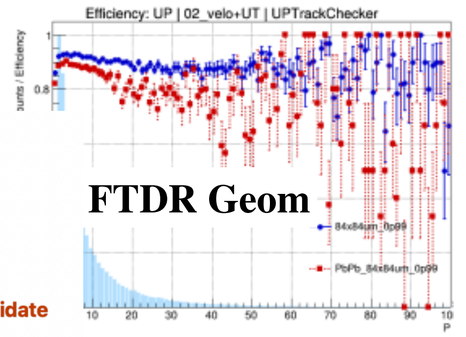
- To build the best track candidate by locally extending hit connections using Cellular Automaton evolution rules

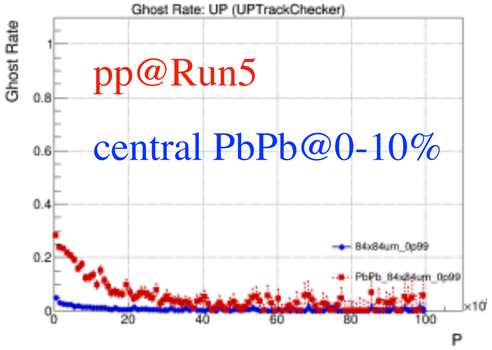
CAT Strategy

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









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

Upstream with UP Hits

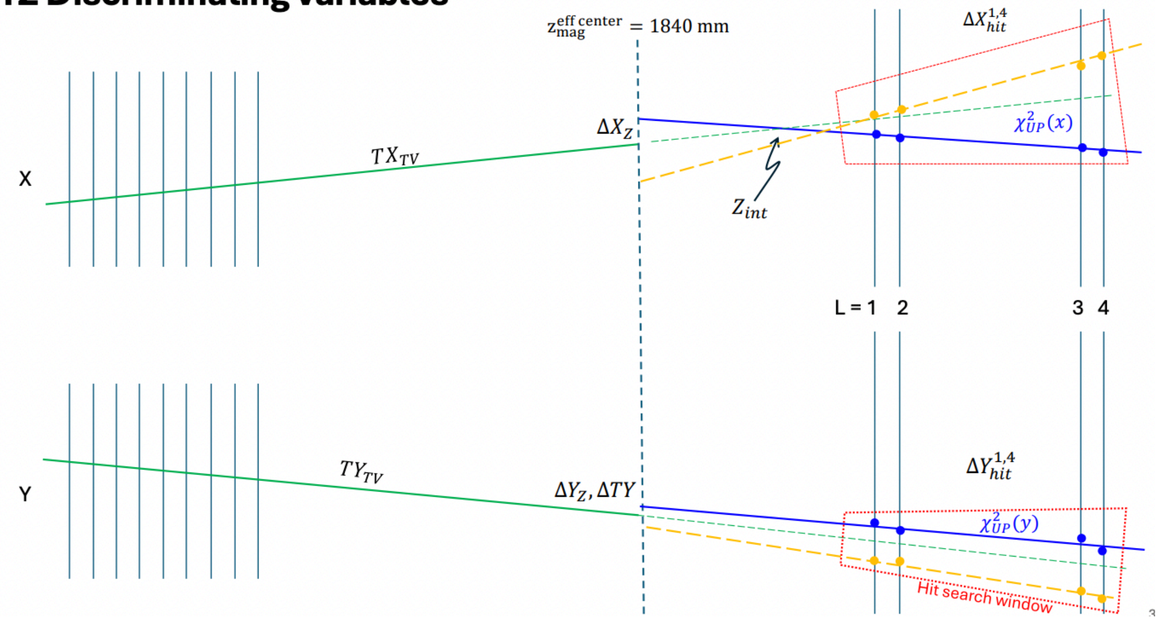
Match TV and UP Hits

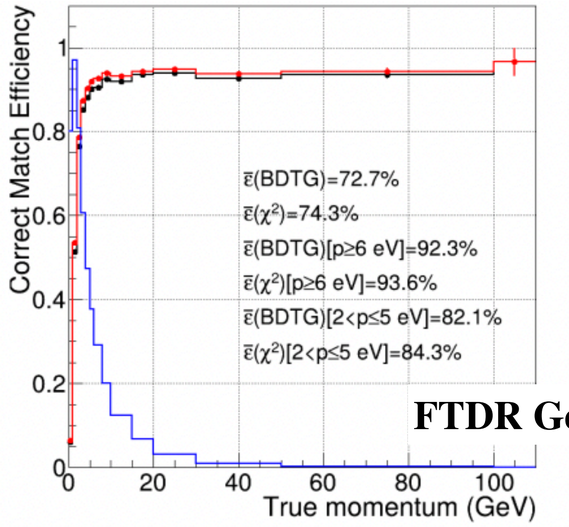
Two FOMs

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

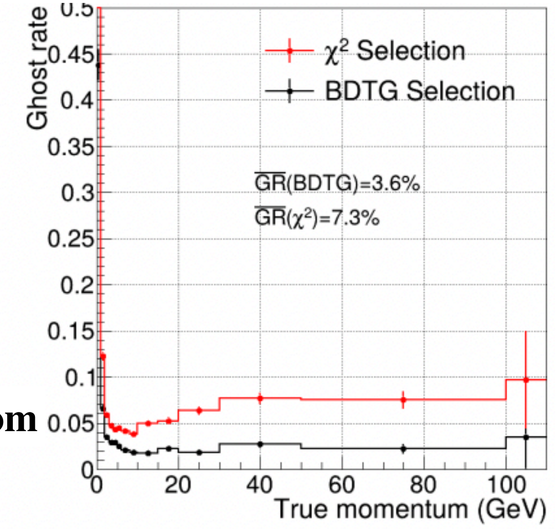
- **A gradient boosted BDT (using TMVA)**
  - **12 discriminating variables**
  - **Signal**: All used UP hits match to the correct MC particle
  - **Background**: 0 hits matched to the correct MC particle

12 Discriminating variables





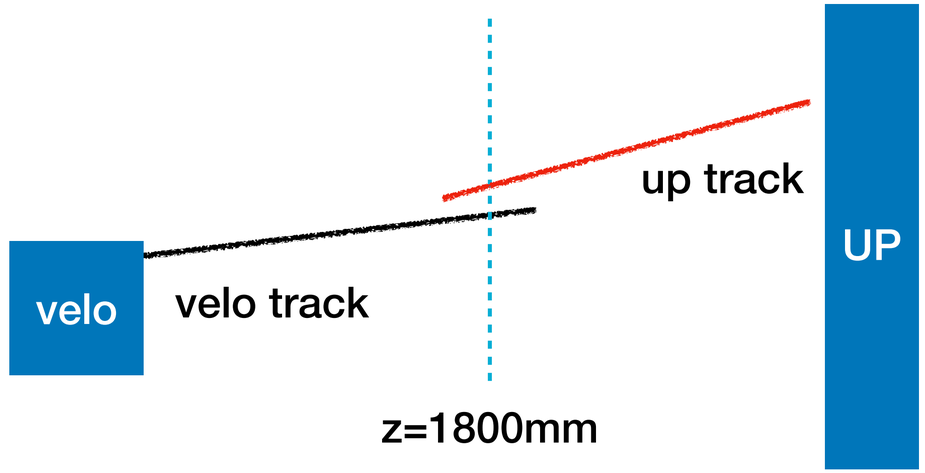
FTDR Geom

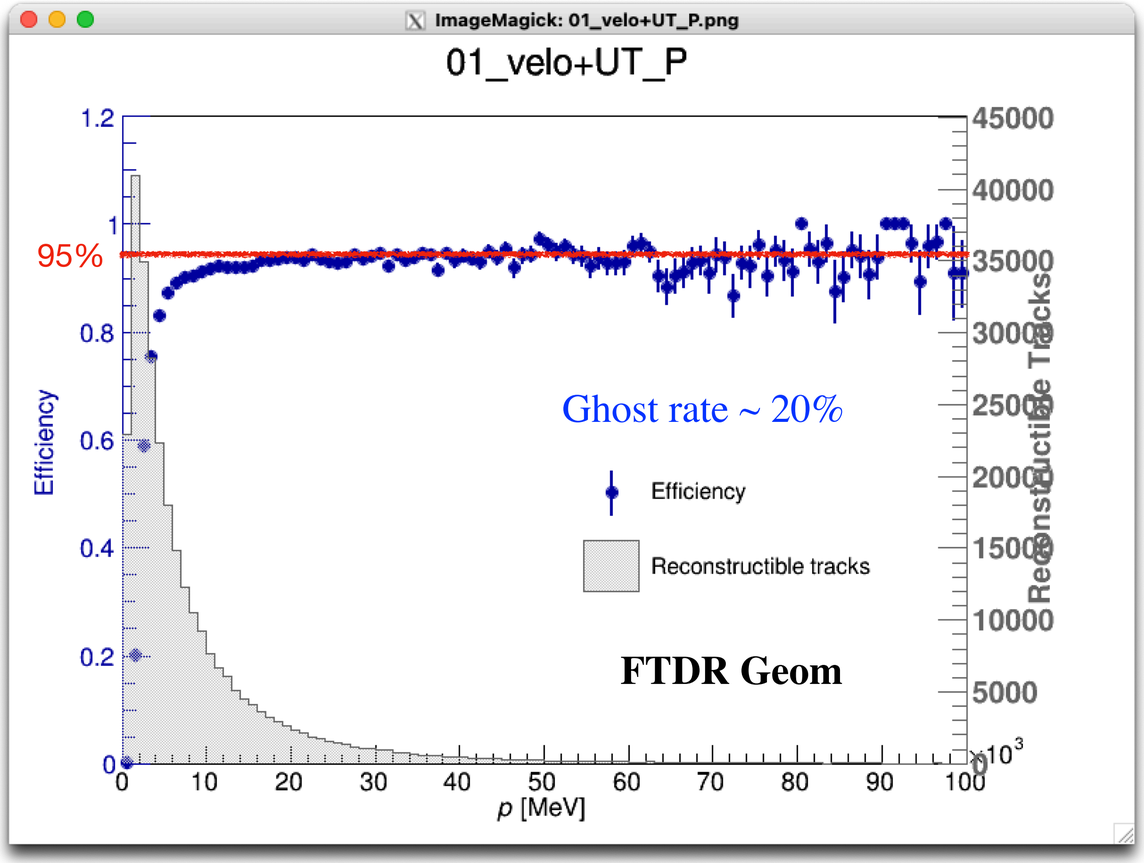


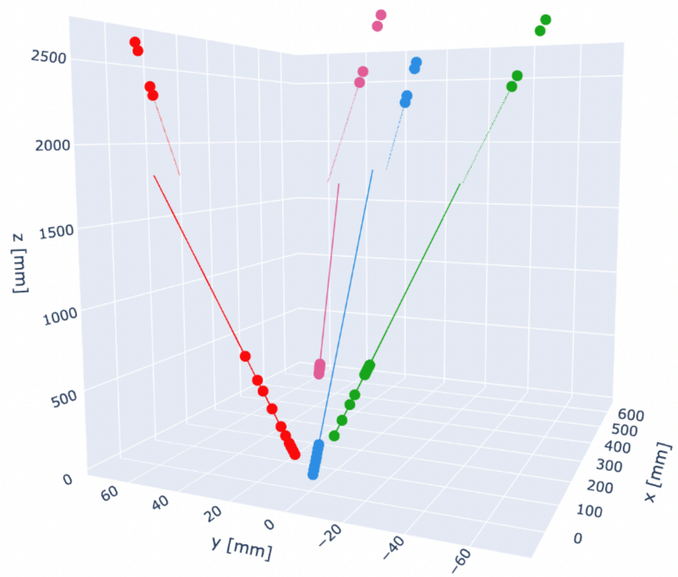
Upstream with UP Tracks

Match TV and UP Track

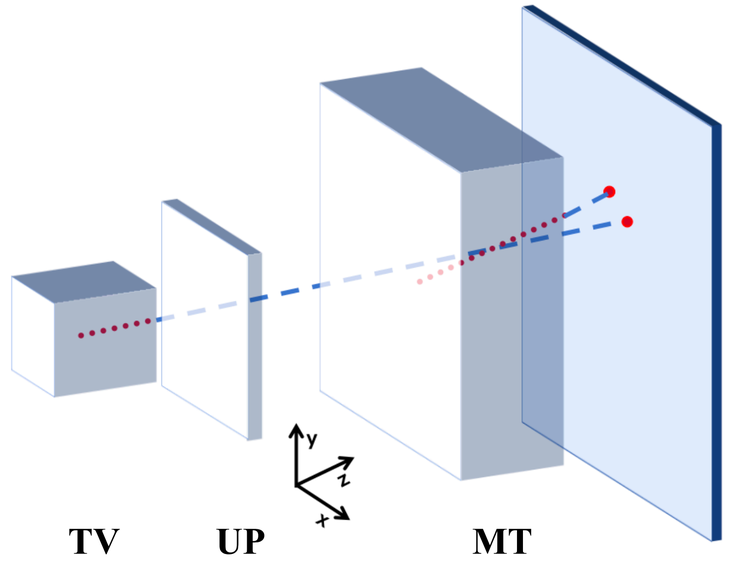
- Cut on *dx, dy, dtx, dty, dθ*
- Choose the best track with *dr*

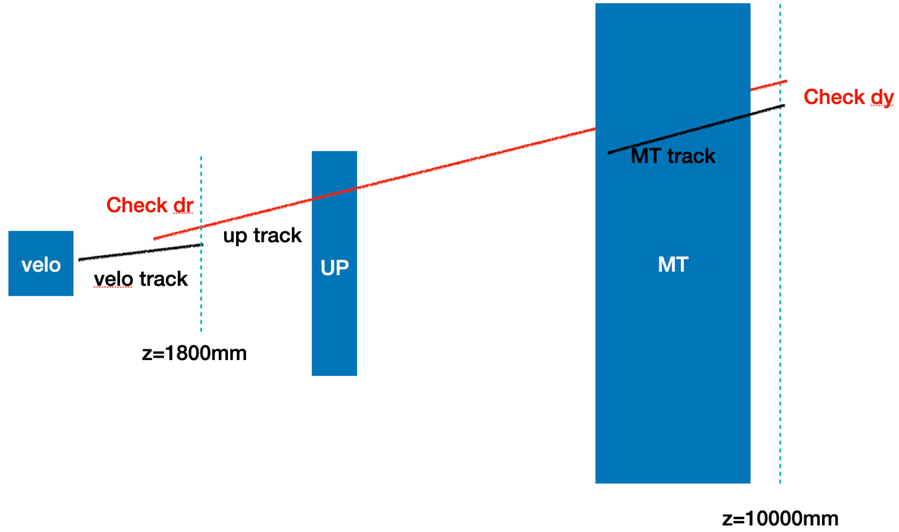






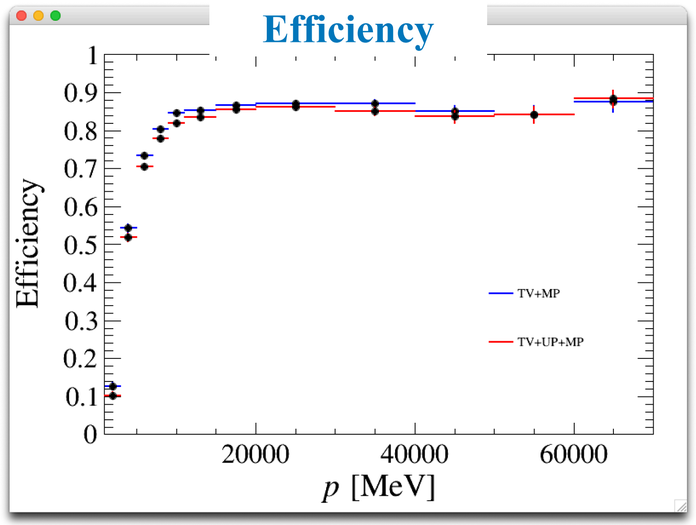
- **Matching TV tracks and MT tracks**
  - Extrapolate TV and MT tracks to a common Z-plane
  - Fast Pre-Filter: Discard candidates with large Y-mismatches
  - Precision Matching: cut on χ^2 and MLP score
    - Compute χ^2 from position/angle differences, with dynamic error scaling
      - $\chi^2 = (\Delta X^2/tolX) + (\Delta Y^2/tolY) + (\Delta Ty^2 \times 625)$
    - 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 best track with TV-UP *dr*
- **Apply Kalman Filter for better performance**

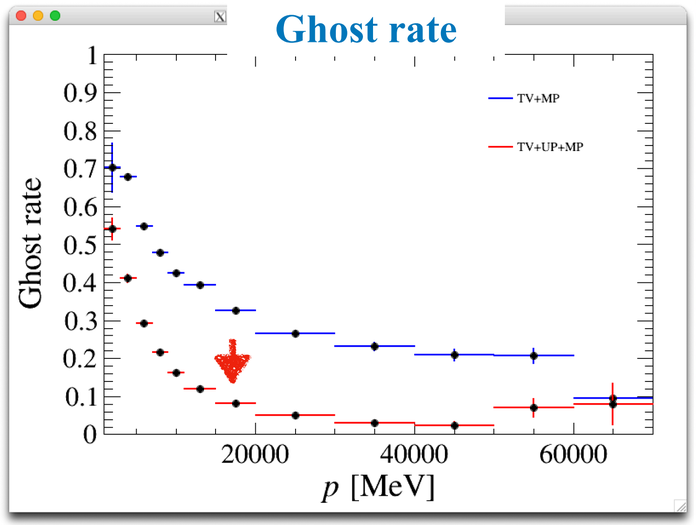


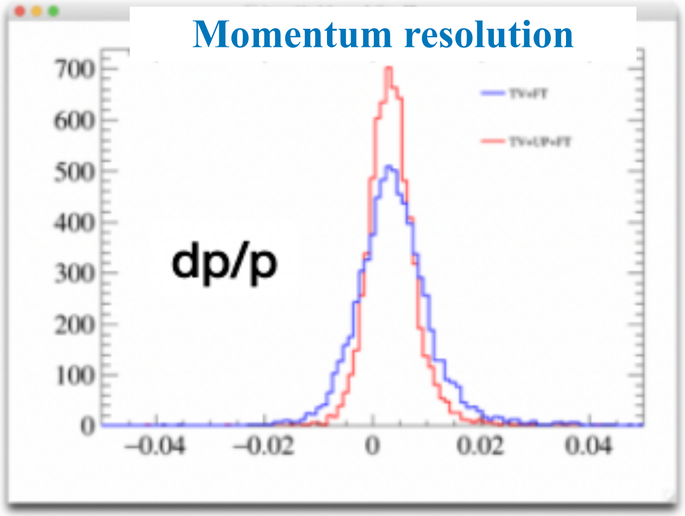


Long Track with UP

- Tracking efficiency have’t effected a lot
- Ghost rate reduced
- Momentum resolution improved





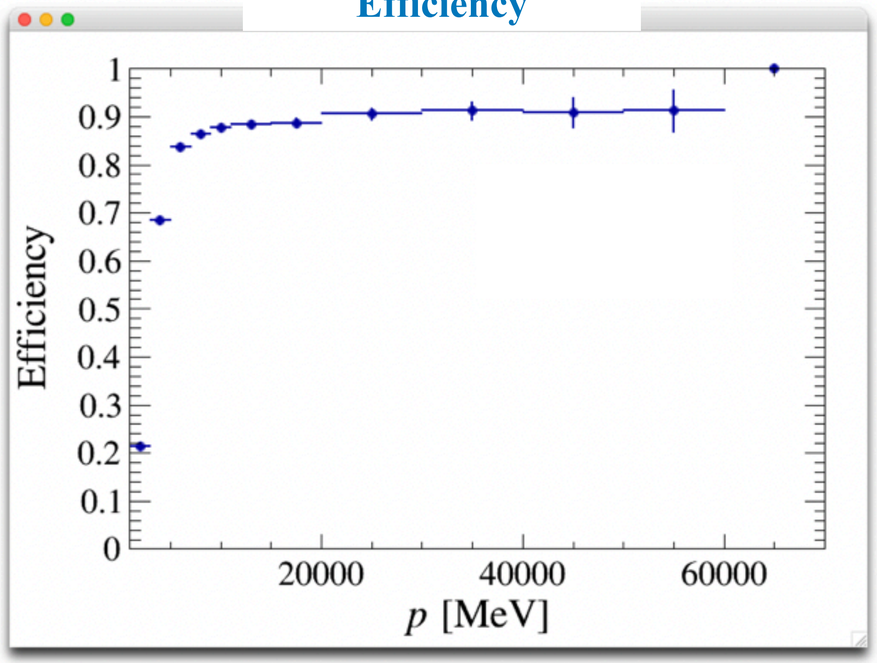


FTDR Geom

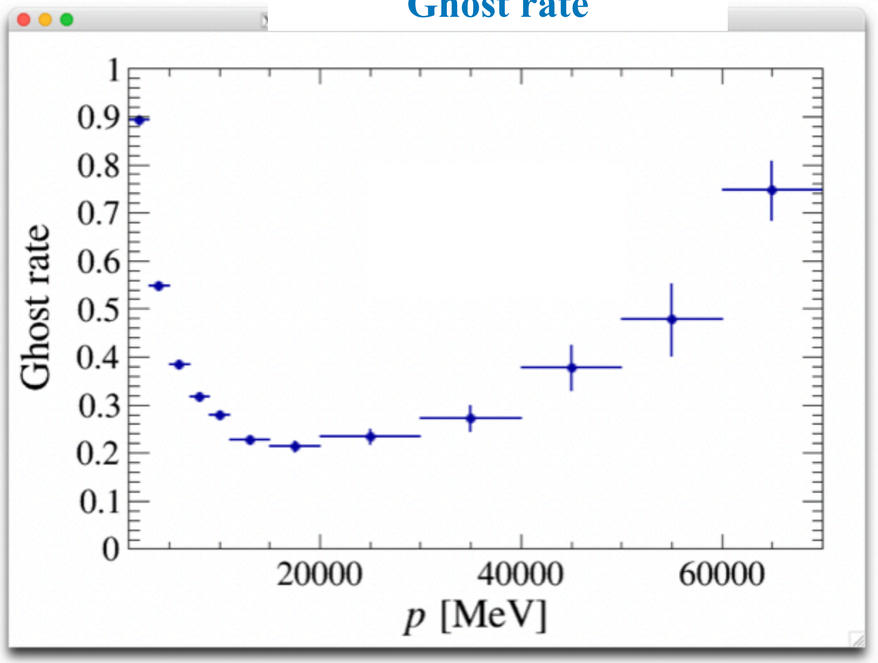
Same algorithm as TV-MT Matching (UP + MT)

- Fast Pre-Filter: Discard candidates with large Y-mismatches
- Precision Matching: cut on χ^2 and MLP score

Efficiency



Ghost rate



FTDR Geom

Summary

- The upstream pixel tracker in Upgrade II will be redesigned due to the increase of luminosity
  - From silicon strip (UT) → silicon pixel (UP)

- Multiple geometry versions implement under DD4HEP framework
  - New no-gap geometry design (UP .E.v2) is under development

- The UP performance study is ongoing
  - The development of all UP-related track reconstruction systems is largely complete
  - Tracking Algorithm Optimization in Progress

Backup

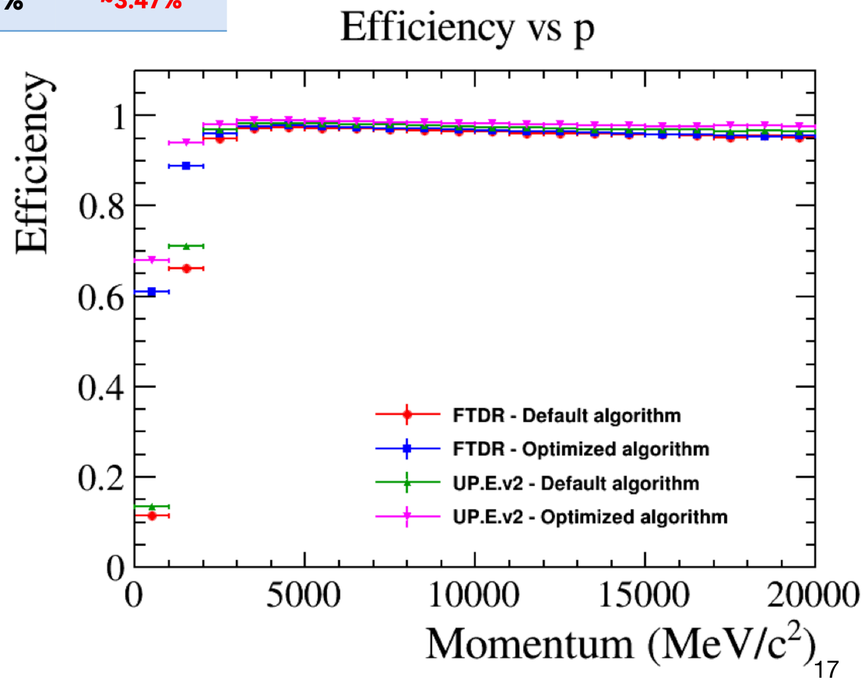
UP Standalone updates

- 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%
UP Efficiency (> 5GeV)	~96.34%	~97.42%
Ghost Rate	~10.78%	~12.32%

	FTDR		UP.E.v2	
	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%

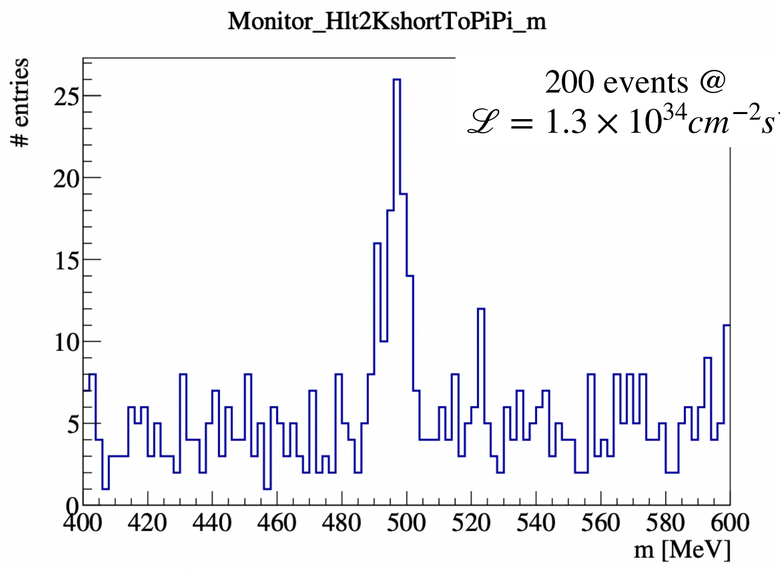
- The algorithm is upgraded
  - Addhits: once a UP track reconstructed, other hits with small enough DOCA considered also belong to this track and masked —no use for other track reconstruction
  - Track-by-track analysis shows most of ghost tracks in UP are with 3 hits. Therefore once a hit can be selected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



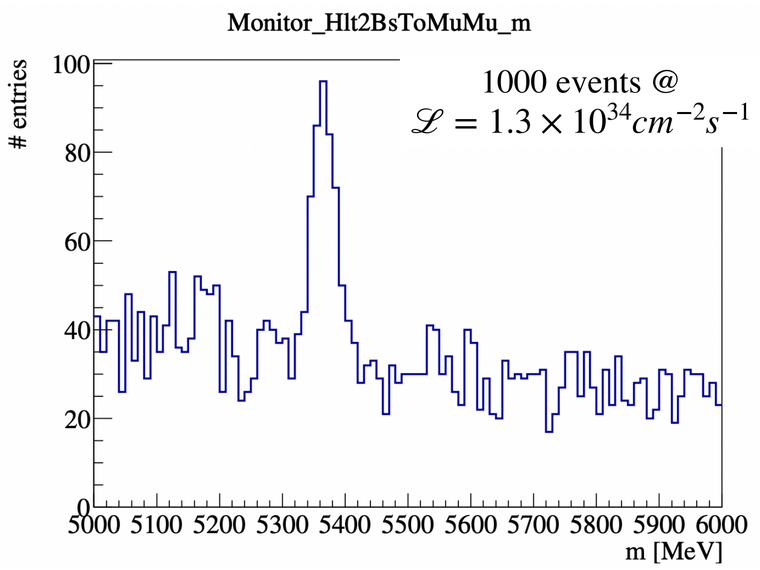
Reconstruction of physics decays

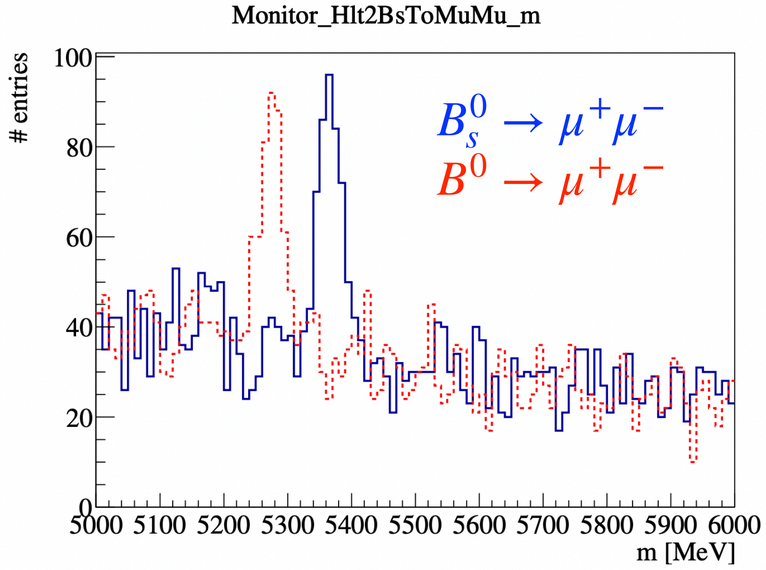
Reconstruct tracks on Upgrade2 simulation — Use Long Track

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



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





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