Tracking Studies for the Upgrade 2 of the LHCb Experiment

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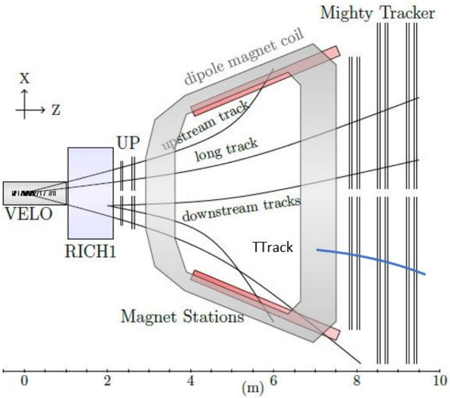
Introduction

- Improving precision for physics analysis → increase in luminosity
  → **higher pileup and occupancy**
- New complex detector setup for handling high occupancy and radiation damage
- Need to check/develop tracking reconstruction algorithms for new detector layout
  → **robust tracking performance needed**

Aim: Study effect of tracking design on performance

Detector Setup for Tracking in Upgrade 2

Magnetic field: $4\,\mathrm{T\,m}$
Wanted p resolution: $\frac{\sigma_p}{p} \sim 0.4 - 0.5\,\%$



[adapted from LHCB-TDR-023]

Velo (TV):

- Pixels, new *lighter* RF-foil
- Pitch size: $55\text{x}55\,\mu\mathrm{m}^2$

Upstream Tracker (UP):

- 4 layers of pixels
- Pitch size: $50\text{x}150\,\mu\mathrm{m}^2$

Mighty Tracker (MT):

- Fiber Tracker (FT)
  - 12 layers of scintillating fibers
  - Similar to Run3 config (x-u-v-x layout)
- Mighty Pixel (MP)
  - 6 pixel layers
  - Pitch size: $50\text{x}150\,\mu\mathrm{m}^2$

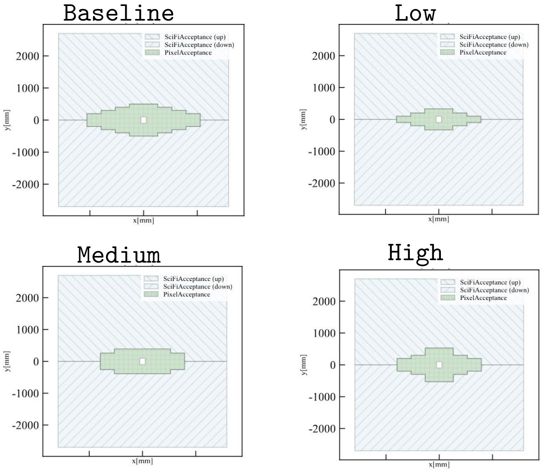
Geometry Options for the Mighty Tracker

Hybrid Tracker:

- Pixels placed at the z pos. where fiber x layers located
- Acceptance covered by pixels removed from fibers (also in u, v layers)
- Beam hole: 260 mm x 260 mm

Total Pixel Area Coverage:

- Baseline: $\sim 18\,\mathrm{m}^2$
- Low: $\sim 8\,\mathrm{m}^2$
- Medium: $\sim 13\,\mathrm{m}^2$
- High: $\sim 13\,\mathrm{m}^2$



Optimization of geometry with regards to cost, occupancy, and performance

Setups for the Mighty Tracker

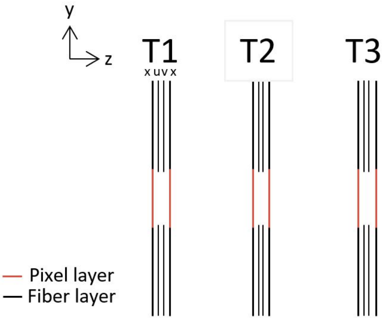
Default MT Setup:

- Pixel and fiber x layers at equal z position

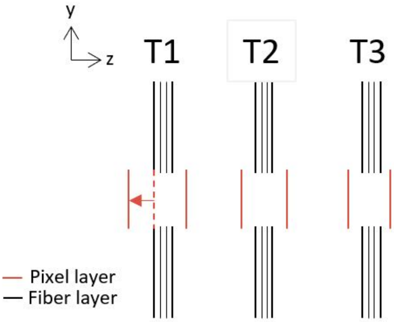
Shifted MT Setup:

- Pixel layers shifted in z from position of fiber x layer

Default Setup



Shifted Setup



Utilized Frameworks

Weight Matrix Formalism

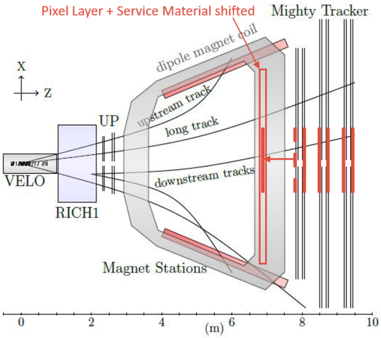
- Parametrically propagates uncertainty matrix along meas. planes
- Both forward and backward propagation possible
- Multiple Scattering taken into account
- Run 5 detector configuration

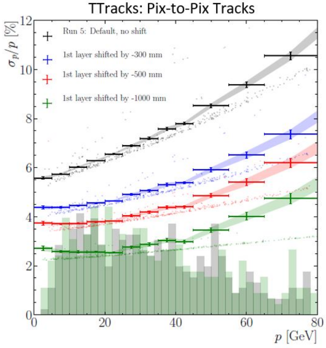
MP Placement Validation Studies

- Shift 1st MP layer towards magnet $\rightarrow \frac{\sigma_p}{p}$ improvement?
- Validation of modified Run 3 simulation results [C. Langenbruch, L. Uecker, A. Guenther]

Validation Study:

- Shift 1st MP layer ($\frac{X}{X_0} \sim 1.74\,\%$) **with** surrounding services ($\frac{X}{X_0} \sim 2\,\%$)
- p resolution checked for shifts of $\Delta z = 30\,\text{cm}, 50\,\text{cm}, 100\,\text{cm}$





Utilized Frameworks

Weight Matrix Approach

- Parametrically propagates uncertainty matrix along meas. planes
- Both forward and backward propagation possible
- Multiple Scattering taken into account
- Run 5 detector configuration

Pattern Recognition Framework

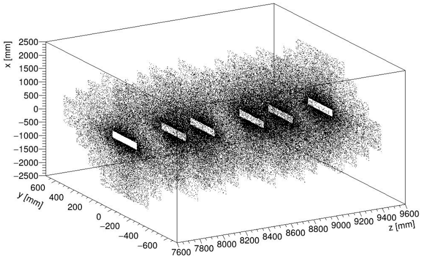
- Python-based offline reconstruction tool
- Custom hit digitization
- Includes prototypes of TTrack reconstruction algorithms:
  - Pixel to Pixel Algorithm
  - Fiber to Fiber Algorithm
  - Pixel to Fiber Algorithm

Utilized Upgrade 2 Simulation

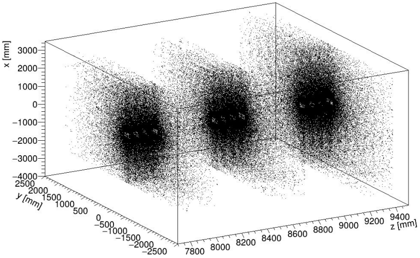
First time full-acceptance MT reconstruction run over Upgrade 2 simulation:

- minBias sample
- Luminosity working point: $\mathcal{L} = 1.5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
- Includes both MP and full FT acceptance
- Default setup: only FT hits used, hits for MP taken from FT
- Shifted setup: MP Hits used, hits in MP acceptance removed from FT

MP Acceptance



Full FT Acceptance



Reconstructing Pixel-Fiber Tracks

Contribution of migrating tracks to reconstructible tracks:

- Geometry dependent
- Long Recoble: $\sim 10\,\%$
- TTracks: $\sim 15\,\%$

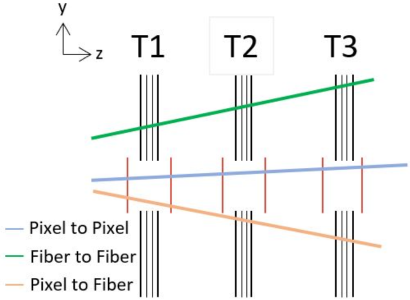
$\rightarrow$ non-negligible amount of migrating tracks

Reconstructing migrating tracks more complex, but:

- (Probably) Important for internal alignment considerations
- Important for FT-hole size design and overlapping region studies

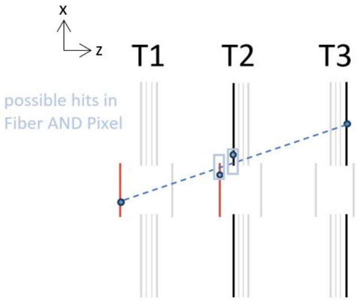
TTrack Types:

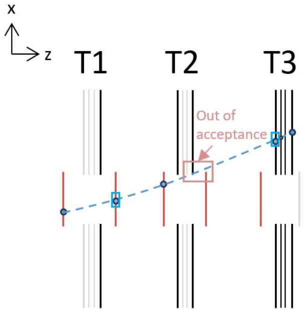
- Pixel to Pixel
- Fiber to Fiber
- Pixel to Fiber (migrating)



Effect of MP Placement on Pix-Fib Reconstruction

- Hits in both pixel and fiber part of same layer possible
  $\rightarrow$ cannot be treated as unique layer anymore: effectively 12 instead of 6 x layers
- Track might not hit pixel or fiber part
  $\rightarrow$ loosened reconstruction requirement: 5 hits over all x layers needed





Efficiencies for the TTrack Reconstruction Algorithms

- TTrack reconstruction algorithm efficiencies for Baseline geometry
- Efficiencies evaluated for tracks with $p > 5\,\mathrm{GeV}$, $2 < \eta < 5$ and w/o electrons

Setup		PixPix [%]	FibFib [%]	**PixFib [%]**	Overall [%]
Default	Eff. ε	97.93	92.36	**89.76**	96.21
	Ghost	2.53	6.89	**30.72**	7.51
Shifted	Eff. ε	98.20	92.95	**91.28**	96.67
	Ghost	2.03	6.89	**21.72**	5.93

- Ghost rate evaluated in each of the track containers separately
- Nb: PixPix efficiencies given for 3 hit finding routine included

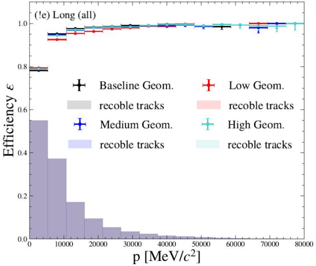
$\rightarrow$ for shifted setup modified algorithms perform well in both efficiency and ghost rate

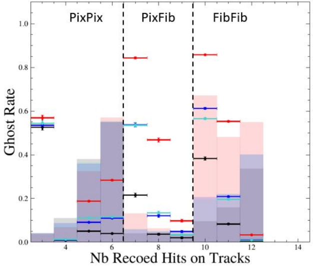
Results for Shifted Setup

- Overall Efficiencies evaluated for different MP geometries in shifted setup
- Efficiencies evaluated for tracks with $p > 5\,\text{GeV}$, $2 < \eta < 5$ and w/o electrons

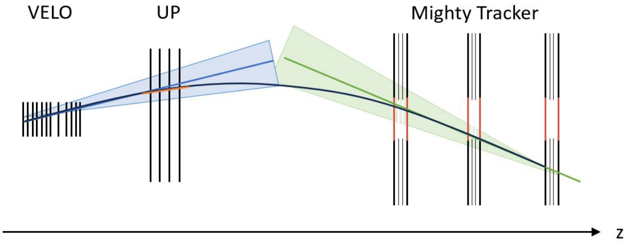
Geom.	Baseline [%]	Low [%]	Medium [%]	High [%]
Eff. ε	96.67	94.52	96.21	96.18
Ghost	5.93	31.68	13.08	13.03

- Ghost rate driven by higher occupancy in fiber
- Efficiencies similar to Run 3





Reconstructing Long Tracks: Matching



- Run existing prototype of matching algorithm using cheated Velo (TV) segments and full acceptance reconstructed TTracks
- High matching efficiencies ($\varepsilon > 90\,\%$) observed but high ghost rate ($\sim 60\,\%$)
  $\rightarrow$ Retrained BDT, but: improvement in ghost rate leads to significant efficiency losses

Next step: **How can we collect the correct UP hits?**

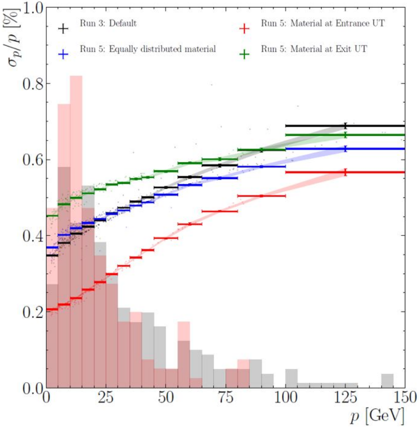
- Idea: given Velo and TTrack state parameters on found matches, predict and constrain parameters for the local UP track model
- UP hits selection based on best χ^2 matching criteria

Momentum Resolution Dependency on UP Material Studies

- Overall material budget for UP layers and cooling boxes: 10 %
- Scenarios of material placement:
  - equally distributed
  - mostly at entrance of UP
  - mostly at exit of UP
- Performance tested for long tracks

	material x/x_0		
	equal distrib.	entrance	exit
Cooling Box (Entrance)	1 %	4.8 %	0.1 %
UT layer 1	2 %	4.8 %	0.1 %
UT layer 2	2 %	0.1 %	0.1 %
UT layer 3	2 %	0.1 %	0.1 %
UT layer 4	2 %	0.1 %	4.8 %
Cooling Box (Exit)	1 %	0.1 %	4.8 %

Using FT Hits only



→ **Optimization of material budget at EXIT of UP can potentially lead to significant p resolution improvement**

Conclusion

Conclusions from carried-out tracking studies:

- First time running full MT reconstruction over Upgrade 2 simulation sample
  $\rightarrow$ efficiency similar to Run 3
- Inclusion of UP in pattern recognition crucial for matching performance
  $\rightarrow$ more work needed here
- UP material repartition has significant impact on p resolution

What I hope to finish in the remaining time:

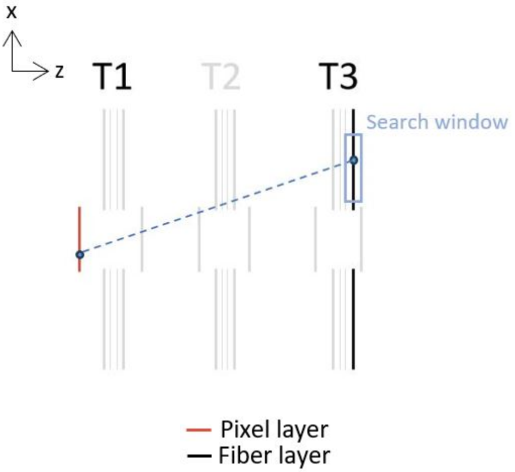
- Building parameterization of UP track motion
- First checks on UP hit collection

Backup

The Pixel Fiber Algorithm I

Two Hit Combination:
p.ex. Pair `T1_1x`, `T3_2x`

- From `T1_1x` predict x pos. of hit in `T3_2x` with a straight line
- Line parameters determined on truth sample
- Open search window of 1400 mm around the predicted position



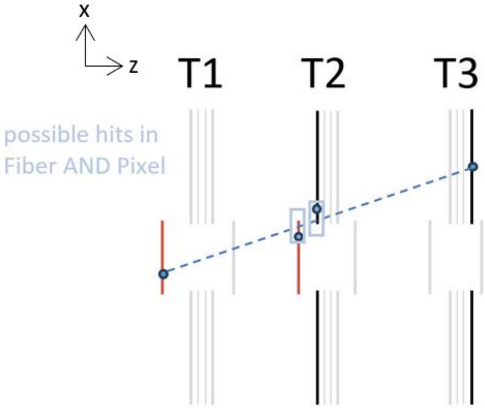
The Pixel Fiber Algorithm II

Three Hit Combination:

p.ex. `T1_1x`, `T2_1x`, `T3_2x`

- Predict x pos. in `T2_1x` using straight line from `T1_1x` to `T3_2x`
- Open search window around predicted position
- Correct for infinite momentum assumption
- Select hits in window of max. 3 mm
- Correction and window tuned on truth sample

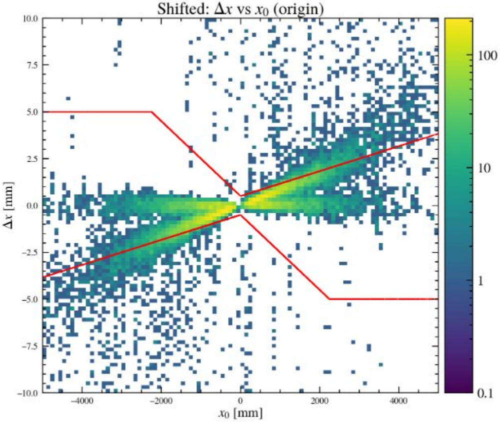
Shifted Acceptance: Can have both fiber and pixel hit in same layer!



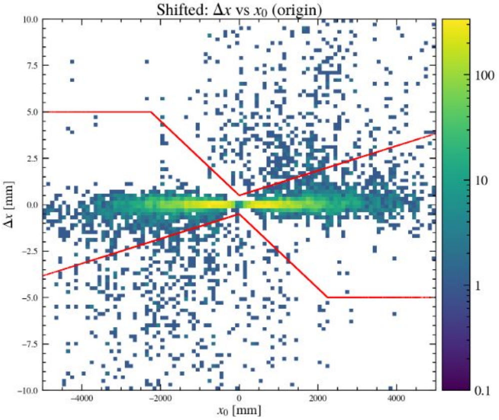
Three Hit Truth Window and Correction

Corrections shown here for Low geometry:

Old Correction



New Correction

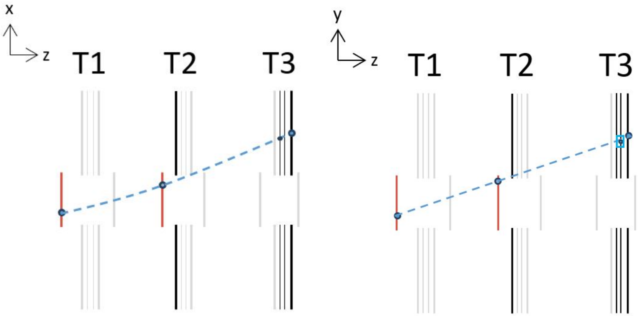


- plotted with old search window → new search window: 3

The Pixel Fiber Algorithm III

Hit collection in T3_u/v layers:

- With 3-hit combination: parabolic fit in xz, line fit in yz
- From predicted x and u/v hit information calculate y prediction
- Open window in y in `T3_u/v`:
  - if hit in T2 was in Pixel layer: 8 mm
  - if hit in T2 was in Fiber layer: 15 mm

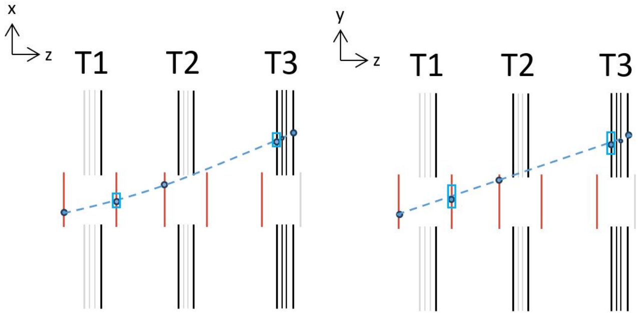


The Pixel Fiber Algorithm IV

Hit collection in remaining x layers:

- With T3_u/v hits: update yz line fit
- Predict from 3-hit combination x, from line fit y
- Open search window: 1 mm in x, 10 mm in y

Shifted Acceptance: Only 5 of 6 x layers required to have a hit!



Hit collection in remaining u/v layers;

- With all hits fit parabola in xz, line in yz to predict x, y in u/v layers

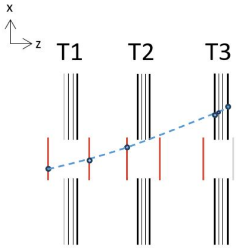
Case I:

- T1/2 hits in Pixel, no Hits in T1/2 u/v layers
- Cut on χ^2_{ndof} of fit: $\chi^2_{ndof} < 15$

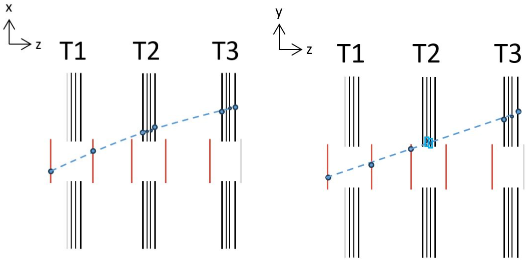
Case II:

- 5 mm window in y for hit selection
- Cut on χ^2_{ndof} of fit with all hits: $\chi^2_{ndof} < 5$

Case I



Case II



Effect of MP Placement on Pix-Fib Reconstruction (detailed)

For Default Acceptance:

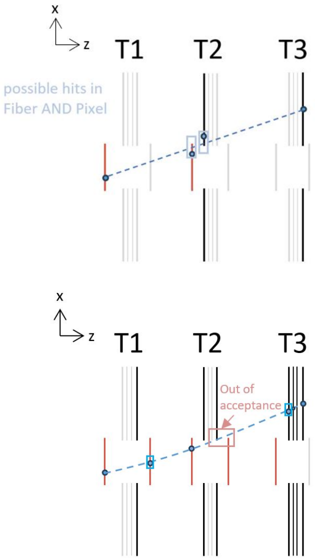
- Hit found either in pixel or fiber part of the same x layer
- Require hit in every x layer

For Shifted Acceptance:

- Hits can be found in both pixel and fiber acceptance of the same x layer
- Track might not leave hit in all 6 x layers

Changes made to the Pixel-Fiber algorithm:

- Track with either the pixel or the fiber hit of the same x layer
- In reconstruction requirement: track has to leave at least 5 hits in the 6 x layers



TTrack Reconstruction Algorithms

Pixel to Pixel Algorithm:

- Requires minimum of 3 hits in track (enabled 3 hit tracking)
- Hits in T1, T2 and T3 required (for 3 hit tracking disabled: 2 in T2 req.)

Fiber to Fiber Algorithm:

- Logic similar to Run 3
- Adapted for increased reco speed with slight drop in efficiency

Hit Flagging:

- Pixel to Pixel and Fiber to Fiber algorithm run first
- Hits utilized in PixPix algorithm flagged
- Pixel to Fiber algorithm run with remaining unflagged hits

Definition Efficiency and Ghost Rate

Definition Efficiency:

$$\text{efficiency} = \frac{\#\ \text{reconstructed tracks}}{\#\ \text{reconstructible tracks}}$$

- reconstructed tracks used here: clones and fakes removed from consideration
- reconstructible track:
  - hasVelo (from TVHits) ≥ 3
  - hasUP (from UPHits) ≥ 2

Definition Ghost Rate:

$$\text{rate} = \frac{\#\ \text{fake tracks}}{\#\ \text{reconstructed tracks}}$$

- fake track: $< 70\,\%$ of hits are associated to same MCP key

Efficiency and Ghost Rate: Default Setup

Geometry		PixPix [%]	FibFib [%]	PixFib [%]	Overall [%]
Baseline	Eff. ε	97.93	92.36	89.76	96.21
	Ghost	2.53	6.89	30.72	7.51
Low	Eff. ε	98.02	89.92	90.56	94.27
	Ghost	3.14	36.81	66.63	34.81
Medium	Eff. ε	97.93	91.93	90.46	95.85
	Ghost	2.70	15.68	47.03	15.37
High	Eff. ε	97.92	91.95	89.77	95.80
	Ghost	2.71	14.93	47.66	15.90

- Efficiency given for: $2 < \eta < 5$ and $p > 5\,\mathrm{GeV}$, w/o electrons
- for PixPix algorithm: 3 hit tracking included
- Best overall efficiency and ghost rate for FTDR geometry

Efficiency and Ghost Rate: Shifted Setup

Geometry		PixPix [%]	FibFib [%]	PixFib [%]	Overall [%]
Baseline	Eff. ε	98.20	92.95	91.28	96.67
	Ghost	2.03	6.89	21.72	5.93
Low	Eff. ε	98.34	90.18	89.76	94.52
	Ghost	2.67	36.97	57.43	31.68
Medium	Eff. ε	98.24	92.12	91.75	96.21
	Ghost	2.30	15.80	37.00	13.08
High	Eff. ε	98.24	92.00	91.00	96.18
	Ghost	2.27	14.84	36.79	13.03

- Efficiency given for: $2 < \eta < 5$ and $p > 5\,\text{GeV}$, w/o electrons
- for PixPix algorithm: 3 hit tracking included
- Best efficiency and ghost rate for FTDR geometry

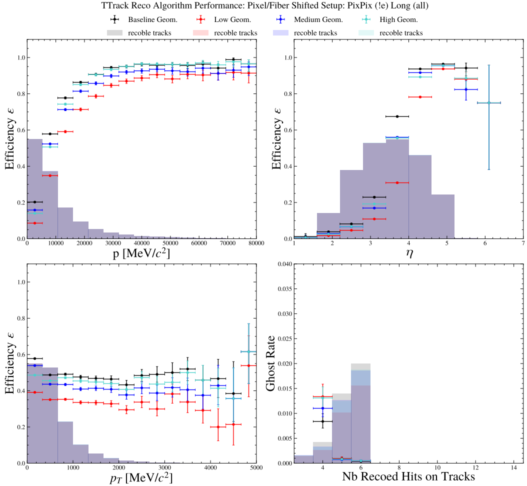
TTrack Reconstruction Algorithm Efficiencies II

Efficiencies for tracks with $p > 5\,\text{GeV}$, $2 < \eta < 5$ and w/o electrons:

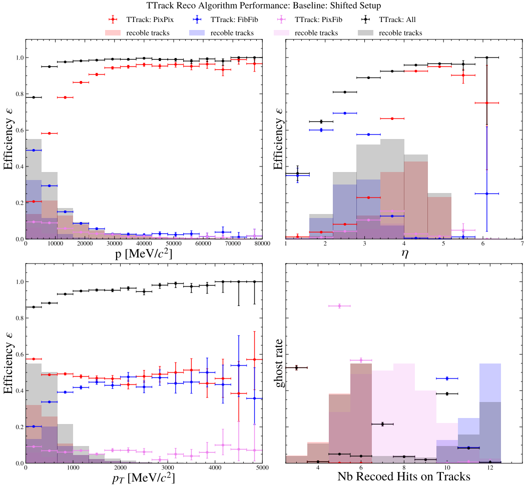
Geometry	Setup		PixPix [%]	FibFib [%]	**PixFib [%]**
Medium	Default	Eff. ε	97.93	91.93	90.46
		Ghost	2.70	15.68	47.03
	Shifted	Eff. ε	98.24	92.12	91.75
		Ghost	2.30	15.80	37.00
High	Default	Eff. ε	97.92	91.95	89.77
		Ghost	2.30	15.80	37.00
	Shifted	Eff. ε	98.24	92.00	91.00
		Ghost	2.27	14.84	36.79

Efficiency/Ghost Rate Plots

PixPix Algorithm: Shifted Setup: All Geometries



Baseline: All TTrack Reco Algorithms



Nb. of Long Reconstructible Tracks [p > 5 GeV]

Default Acceptance [p > 5 GeV]

Geometry	Nb. Recoble Tracks	Pixel [%]	Fiber [%]	Mixed [%]
Baseline	28323	20634 [72.9 %]	5949 [21.0 %]	1740 [6.1 %]
Low	28267	15321 [54.2 %]	10463 [37.0 %]	2483 [8.8 %]
Medium	28277	19128 [67.6 %]	7463 [26.4 %]	1686 [6.0 %]
High	28297	19325 [68.3 %]	6715 [23.7 %]	2257 [8.0 %]

Shifted Acceptance [p > 5 GeV]

Geometry	Nb. Recoble Tracks	Pixel [%]	Fiber [%]	Mixed [%]
Baseline	28154	20659 [73.4 %]	5951 [21.1 %]	1544 [5.5 %]
Low	28077	15394 [54.8 %]	10434 [37.2 %]	2249 [8.0 %]
Medium	28135	19140 [68.0 %]	7458 [26.5 %]	1537 [5.5 %]
High	28112	19379 [68.9 %]	6707 [23.9 %]	2026 [7.2 %]

- Overall nb. of long-recoble tracks drops slightly for shifted acc.
- higher percentage of Pixel tracks for shifted acc.

Nb. of Long Reconstructible Tracks

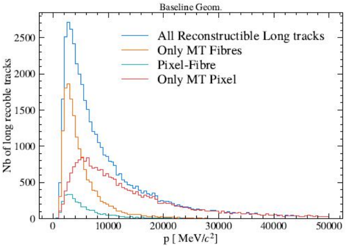
Default Setup

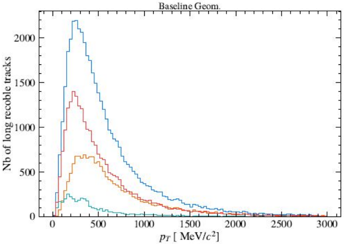
Geometry	Nb. Recoble Tracks	Pixel [%]	Fiber [%]	Mixed [%]
Baseline	44810	24523 [54.7 %]	16312 [36.4 %]	3975 [8.9 %]
Low	44760	16808 [37.6 %]	24033 [53.7 %]	3919 [8.8 %]
Medium	44776	22005 [49.1 %]	18968 [42.4 %]	3803 [8.5 %]
High	44786	21850 [48.8 %]	18569 [41.5 %]	4367 [9.8 %]

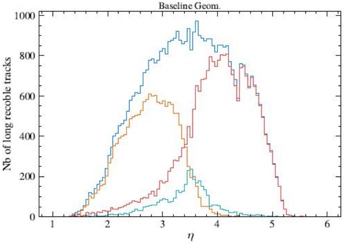
Shifted Setup

Geometry	Nb. Recoble Tracks	Pixel [%]	Fiber [%]	Mixed [%]
Baseline	44688	24784 [55.5 %]	16310 [36.5 %]	3594 [8.0 %]
Low	44604	17006 [38.1 %]	24008 [53.8 %]	3590 [8.0 %]
Medium	44646	22210 [49.7 %]	18972 [42.5 %]	3464 [7.8 %]
High	44640	22117 [49.5 %]	18566 [41.6 %]	3957 [8.9 %]

Nb. Recoble Tracks Plots: Baseline Geom

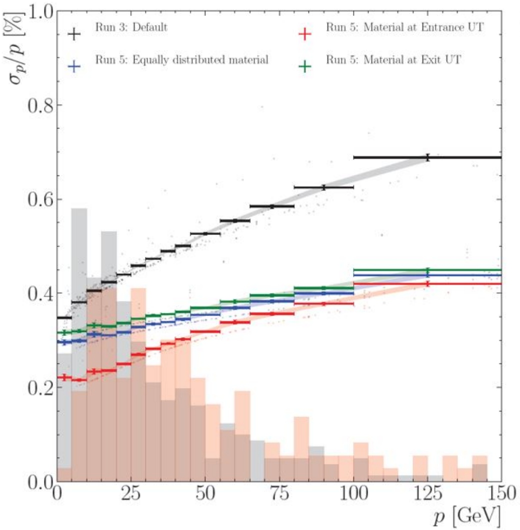




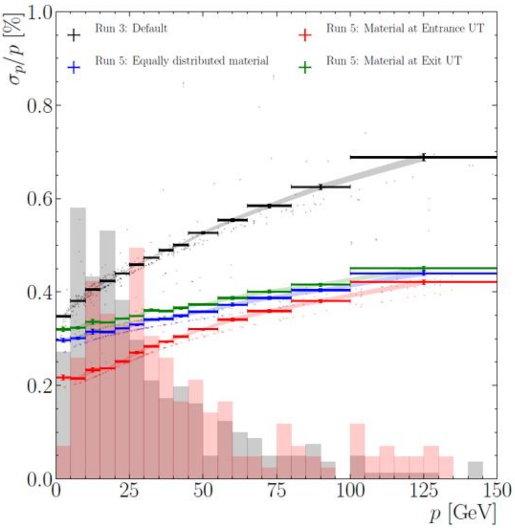


UP Material Placement Studies: Pixel and Migrating Track Results

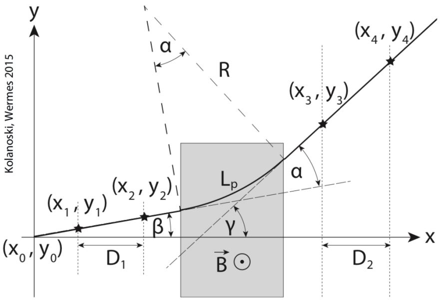
Using MP Hits only

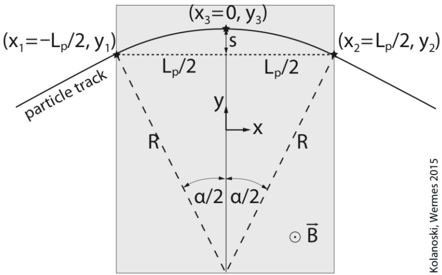


Using Hits from Migrating Tracks



Mathematics behind Momentum Resolution Improvement





Long Tracks:

- Curvature measured before and after mag. field
- $\left(\frac{\sigma_{p_T}}{p_T}\right) = \frac{\sigma_{\text{meas}} p_T}{0.3|z|L_p B\mathbf{D}} \sqrt{\frac{24(N-1)}{N(N+1)}}$
- shift increases lever arm

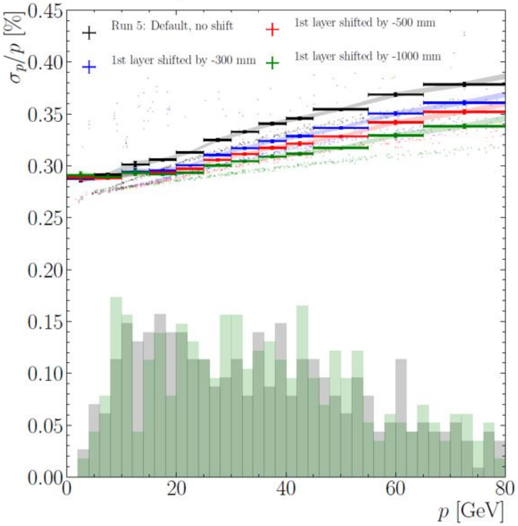
[C. Langenbruch], [Kolanoski, Wermes 2015]

TTracks:

- Curvature measured "in" mag. field
- $\left(\frac{\sigma_{p_T}}{p_T}\right) = \frac{\sigma_{\text{meas}} p_T}{0.3|z|\boldsymbol{L_p^2 B}} \sqrt{\frac{720}{N+4}}$
- shift influences B and L_p^2

Validation Study: Downstream and Long Track Results

Long Tracks: Pix-to-Pix Tracks



Downstream Tracks: Pix-to-Pix Tracks