Towards a global optimisation of the tracker layout: new tools and ideas

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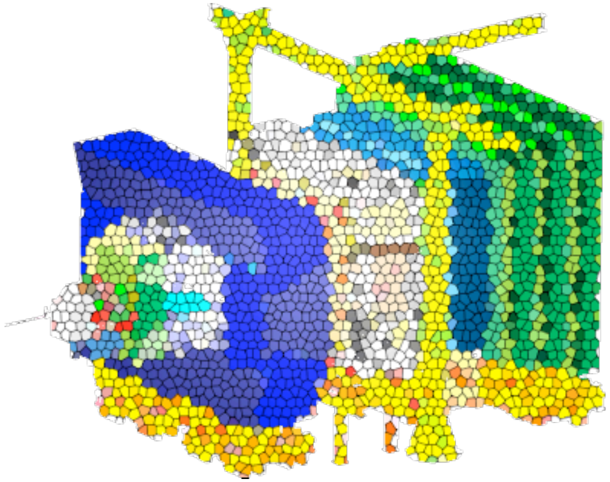
[with input from: M. De Cian, L. Dufour, R. Forty, V. V. Gligorov, M. Merk]

6th Workshop on LHCb Upgrade II
29 March 2023



Why a new tracker optimisation?

- What drives the optimal tracker geometry and size?
  - acceptance (driven by physics: lifetime, rapidity & momentum spectra)
  - running conditions (luminosity → pile-up → occupancies)
  - performance (detector technologies)
  - cost

    ⇒ is the original 9m-long tracker still optimal for $\mathscr{L} = 1.5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$?
- High luminosity
  - strips don't scale well with luminosity (⇒ need for inner tracker)
  - pixels are more "natural" candidates
- Magnet
  - can the LHCb magnet be operated until ≥ 2040?

    (structural integrity, cost of electricity)
  - if replaced, is a new superconducting magnet an option?

⇒ LHCb could consider a reoptimisation of the tracker/detector

Path to re-optimisation

- Define the target tracker characteristics:
  - fully pixel tracker
  - smaller tracker dimensions (factor 3 in this study)
  - new superconducting magnet ($\int \vec{B} \cdot d\vec{\ell} = 4\,\mathrm{Tm}$)
  - remove RICH1 to minimise material budget
    ($\Rightarrow$ PID optimisation will be needed: RICH/CALO/MUON)

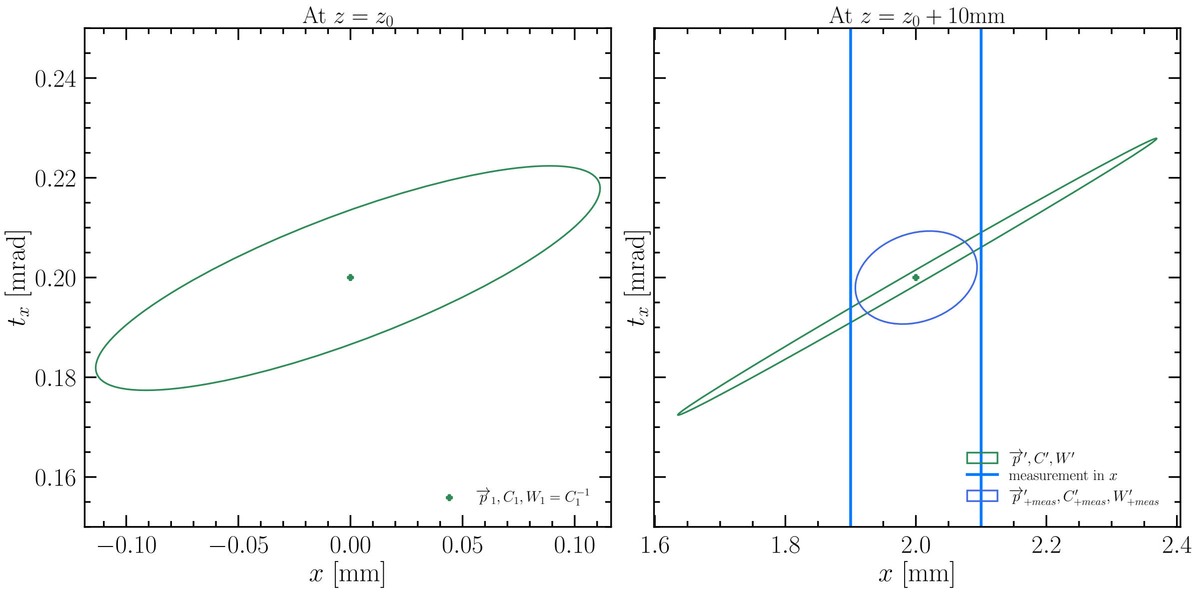
$\}\rightarrow$ MiniLHCb

- Tool development:
  - use momentum resolution, dp/p, as figure of merit
    - not studied here: efficiency, ghosts, occupancy (and impact on PID detectors)
  - flexible ***standalone*** code to evaluate dp/p for various geometries
    - developed and implemented by Renato Quagliani
    - based on the "Weight matrix formalism" proposed by Pierre Billoir at the 6th LHCb computing workshop, 2015
- Toy studies:
  1. Run 3 geometries, for validation of the tools
  2. Run 5 (FTDR, and variations), to define the benchmark
  3. Run 5 (MiniLHCb)

Method and basic principle

- Weight matrix formalism (by Pierre Billoir)
- Add multiple scattering as noise around unaffected reference trajectory
- Build the Kalman Filter to obtain the sensitivity on the fitted parameters for each measurement, given the previous measurements

1. *Use barycenter with matrices* ($W = C^{-1}$) *as measurement weights*
2. *Propagation along z induces "rotation-elongation" of the ellipse*
3. *New measurement of weight* W_{meas} *is added to the propagated state*
4. *Noise from multiple scattering added to* W^{-1} *at boundaries of material layers*
5. *Invert W after the last measurement to obtain the expected* σ_p



Full details in talk by Renato Quagliani, "Upgrade2 studies, Mini LHCb" at RTA WP6 meeting, 23 March 2023

Layer description

Ingredient 1: a measurement is added at given z $(+W_{meas})$

A measurement at a given z is introduced with flexible information on z,σ,α,*thick*

- What is the contribution to the fit assuming no misalignment and track pass exactly through a reference trajectory? $W_{meas} = \begin{bmatrix} \frac{\cos^2(\alpha)}{\sigma^2} & \frac{\cos(\alpha)\sin(\alpha)}{\sigma^2} & 0 & 0 & 0 \\ \frac{\cos(\alpha)\sin(\alpha)}{\sigma^2} & \frac{\sin^2(\alpha)}{\sigma^2} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$
- Where σ is derived from the pitch size of the measurements (Run3 detectors):
  1. `Velo` : $\sigma = \frac{56\ \mu\text{m}}{\sqrt{12}} = 16\ \mu\text{m}$
  2. `UT` : $\sigma = \frac{196\ \mu\text{m}}{\sqrt{12}} = 56\ \mu\text{m}$, corrected for $|x, y| < 200$mm to be $\frac{96}{\sqrt{12}}\mu m$
  3. `SciFi` : $\sigma = \frac{250\ \mu\text{m}}{\sqrt{12}} = 80\ \mu\text{m}$ (rounded to $100\ \mu\text{m}$ as baseline)[1]
- Where α is a *stereo* angle:
  1. Pixel-like: duplicate contribution with $\alpha = 0(90)$ at same z
  2. x-u-v-x measurements : $\alpha = 0/+5^\circ/-5^\circ/0$ (SciFi & UT)
- *thick* is δ_z/X_0 of the measurement layer. Noise for measurements made dimensionless (thin-layer approximation).

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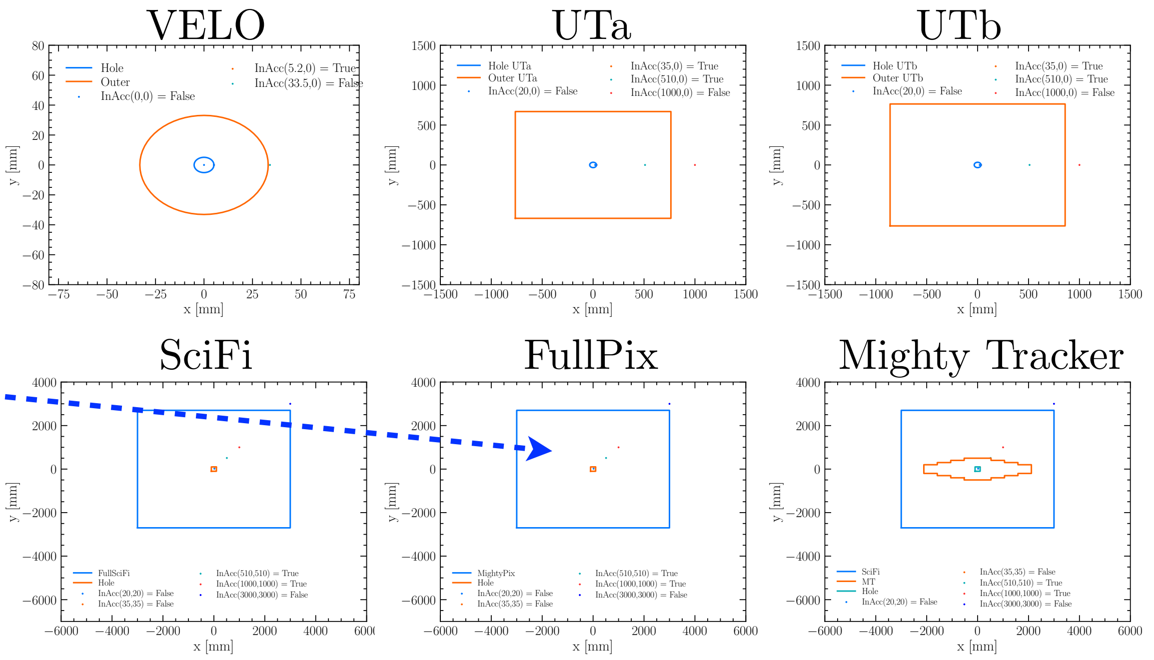
[1] No dependency on track slope and 1.2mm thickness of SciFi so far in toy-model, only rough assumption.

cf. talk by Renato Quagliani, "Upgrade2 studies, Mini LHCb"

at RTA WP6 meeting, 23 March 2023

Detector geometries and magnetic field

VELO layer:
$X/X_0 = 1\,\%$
$r_{\text{in}} = 5.1\,\text{mm}$
$r_{\text{out}} = 32\,\text{mm}$

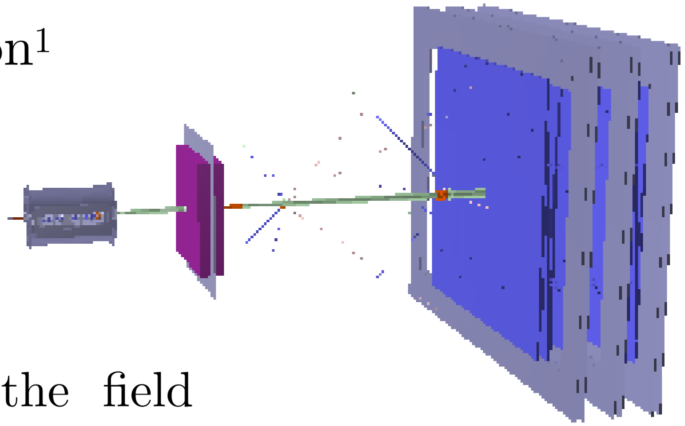


UT layer:
$X/X_0 = 2\,\%$ (Run3)
$X/X_0 = 1\,\%$ (Run5)
Pixel size:
$50 \times 150\,\mu\text{m}^2$
or $30 \times 30\,\mu\text{m}^2$

FullPix scale by 1/3
for miniLHCb geometry

Mighty Tracker
pixel size:
$50 \times 150\,\mu\text{m}^2$

- GDML file loaded for material budget navigation[1]
  - removed RICH1 and replaced with air
- Magnetic field:
  - default LHCb field map
  - parabolic extrapolator to propagate the tracks in the field
  - emulated miniLHCb magnet by increasing the field and shorten the lever arm by the same factor (=3 in this study)



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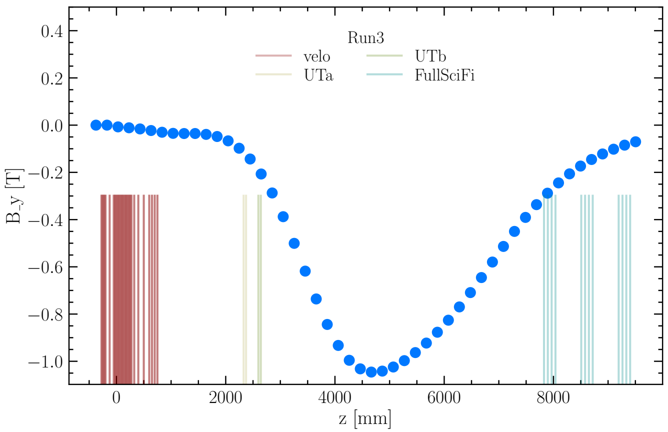
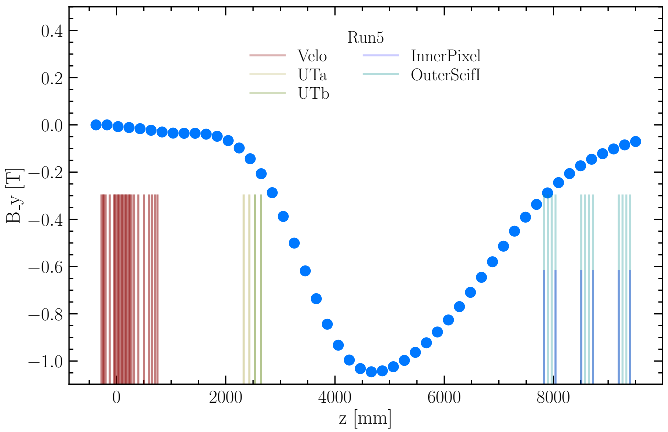
[1] GDML dump and navigation from Ben Couturier

Examples of simulated geometries

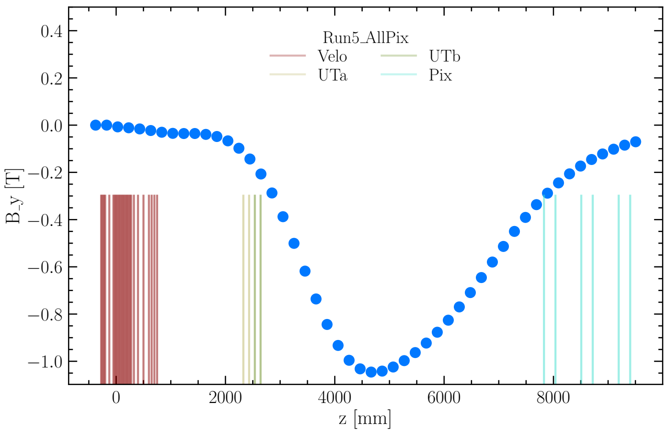
Run3



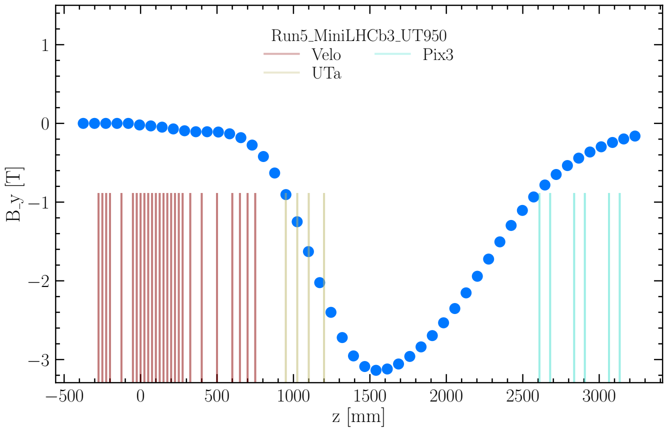
Run5 (UT4Pix, Pix/SciFi mix)



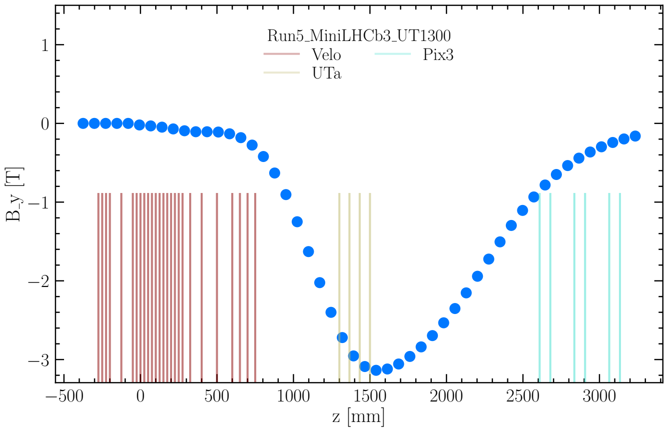
Run5 (UT4Pix, Pix)



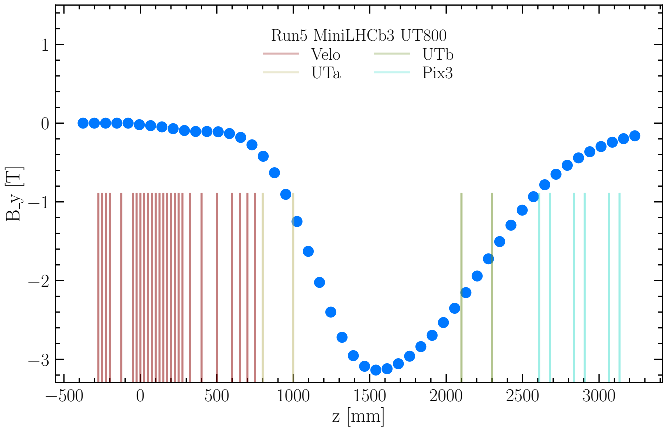
MiniLHCb (UT4Pix950, Pix)



MiniLHCb (UT4Pix1300, Pix)

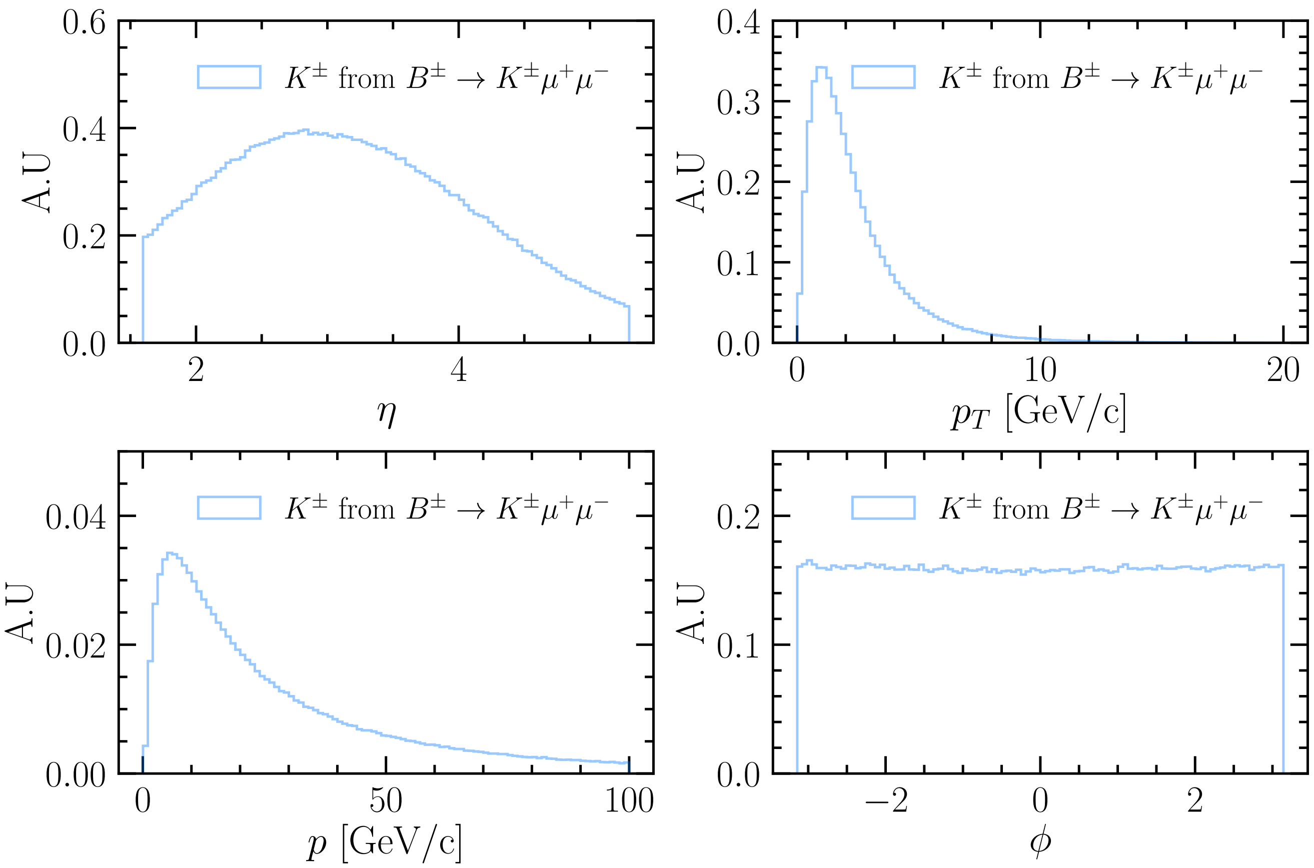


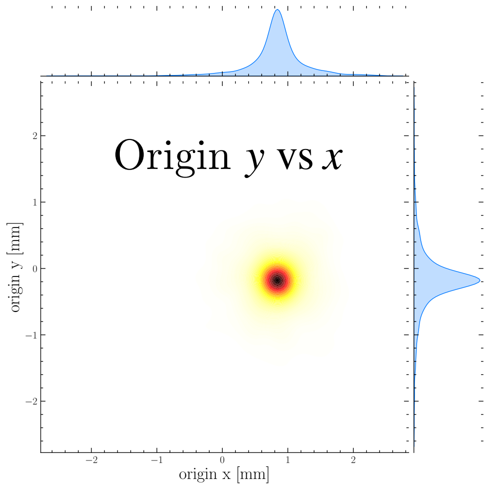
MiniLHCb (UT4Pix800, Pix)

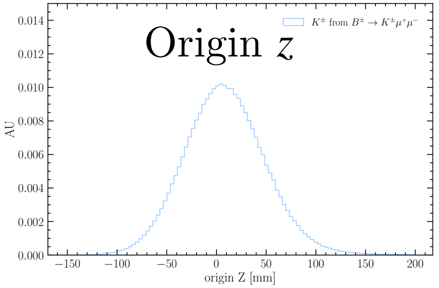


Sample of tracks

- Generate xgen file of $B^{\pm} \to K^{\pm}\mu^{+}\mu^{-}$ decays
- Use the $K^{\pm}$ kinematics for the study (10k events)
- Emulate K_S^0 by linear extrapolation of $K^{\pm}$ from origin to fixed z_{decay}, then start propagation with charge from z_{decay}



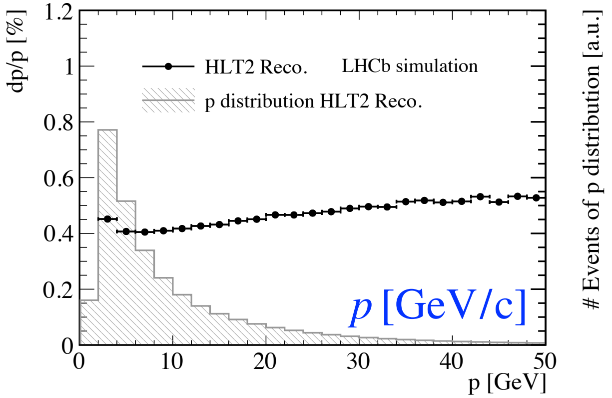




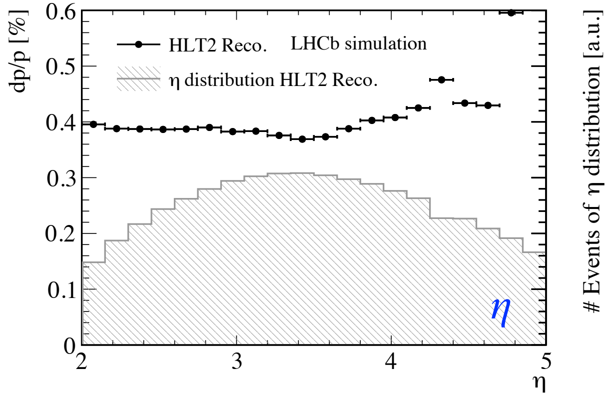
Run 3 resolution (for tool validation)

- Predicted resolution in Run 3, compared with HLT2 Kalman fit
  - results are in agreement with the expectation
  - dependence on η not perfectly reproduced

(LHCB-FIGURE-2021-003)



(LHCB-FIGURE-2021-003)



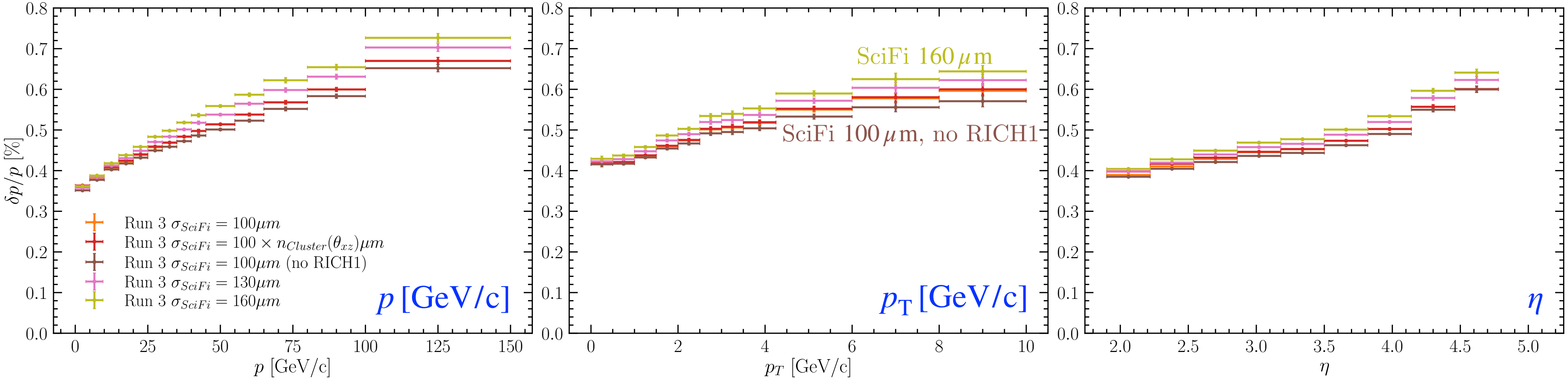
Run 3 $\sigma_{SciFi} = 100\mu m$

Run 3 $\sigma_{SciFi} = 100 \times n_{Cluster}(\theta_{xz})\mu m$

Run 3 $\sigma_{SciFi} = 100\mu m$ (no RICH1)

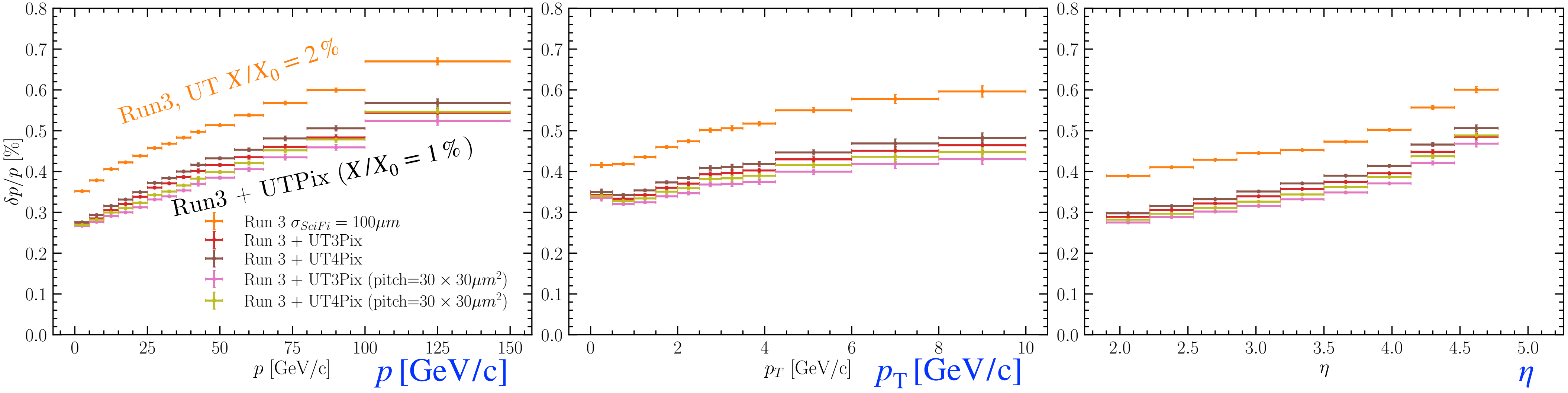
Run 3 $\sigma_{SciFi} = 130\mu m$

Run 3 $\sigma_{SciFi} = 160\mu m$

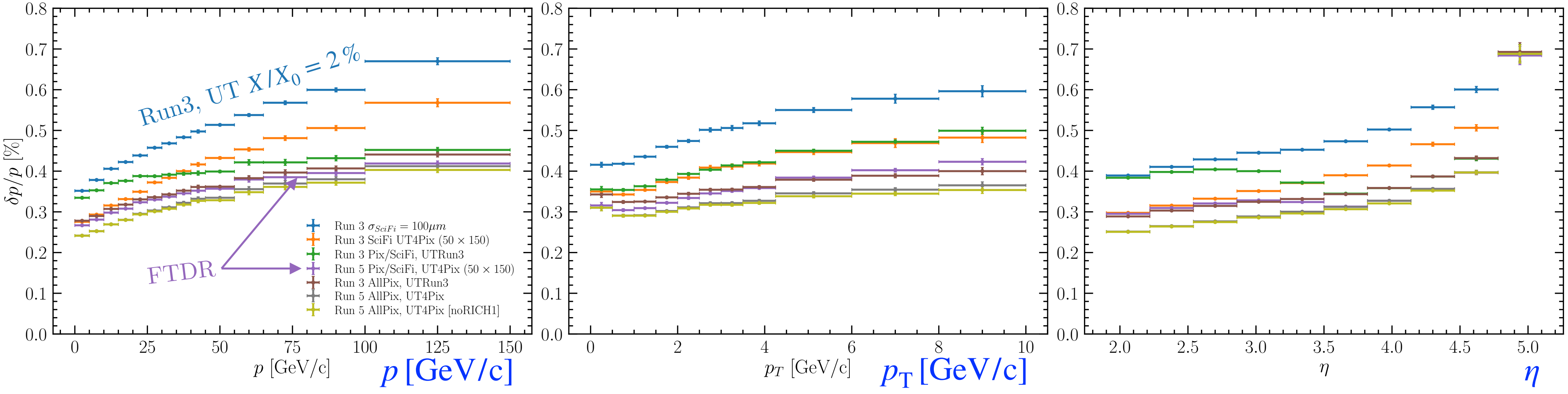


From Run 3 to Run 5

Run3 + UT pixel (3 or 4 layers, $50 \times 150\,\mu\mathrm{m}^2$ or $30 \times 30\,\mu\mathrm{m}^2$)

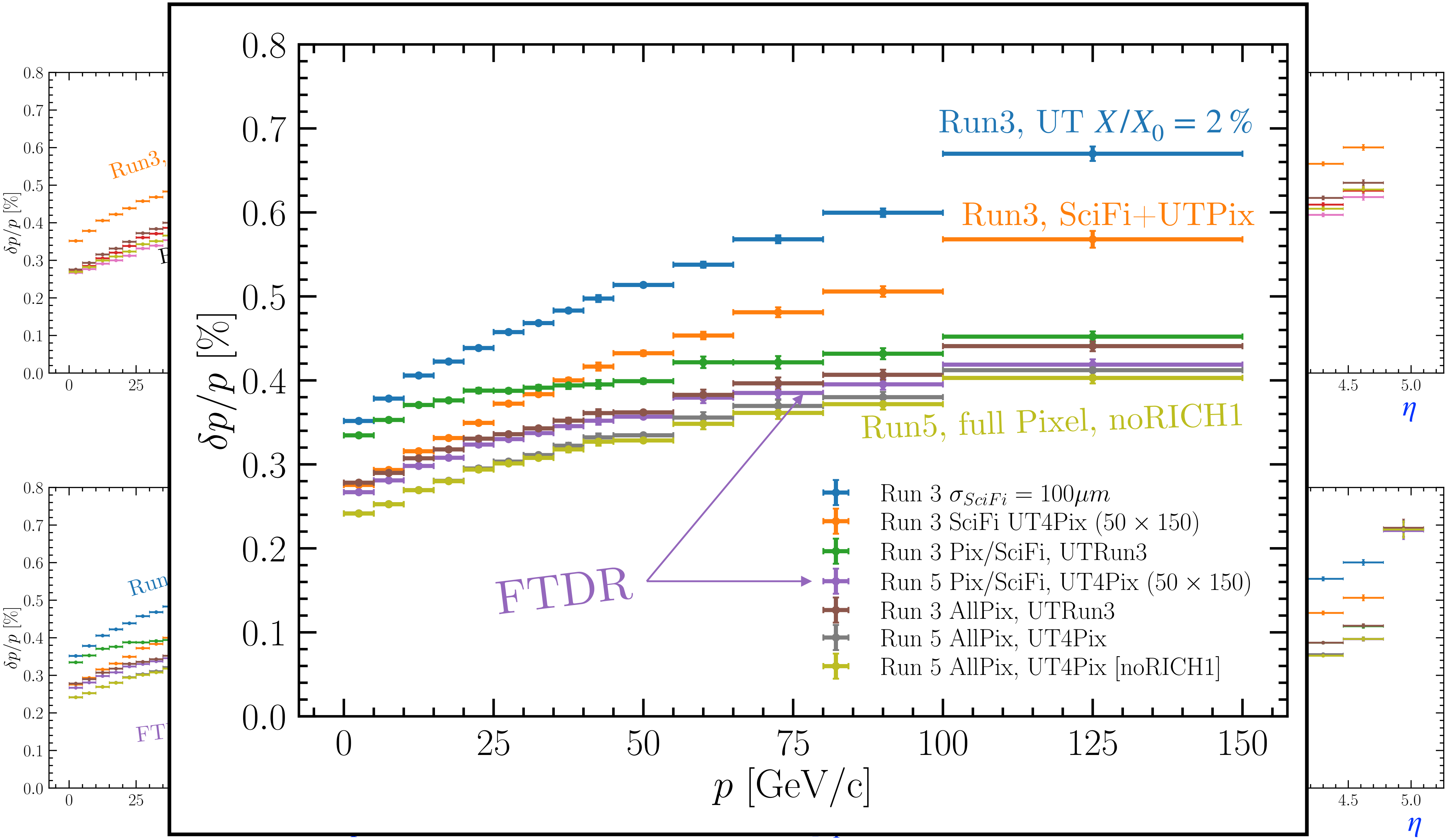


Run3 + SciFi/Pix + UT pixel (variations)



→ Gain from low UTPix material budget, and from downstream pixels

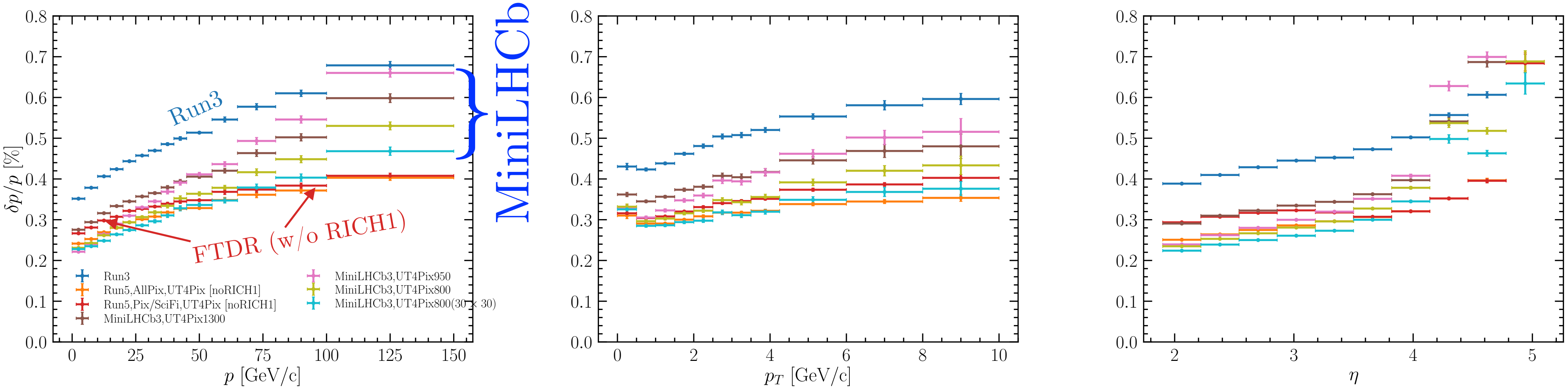
From Run 3 to Run 5



→ Gain from low UTPix material budget, and from downstream pixels

MiniLHCb Tracker

- Shorter lever arm has a visible impact on momentum resolution
- Sensitivity to the location of the measurements
  → impact on long-lived particles
- Performance can be better than FTDR at low p, worse at high p



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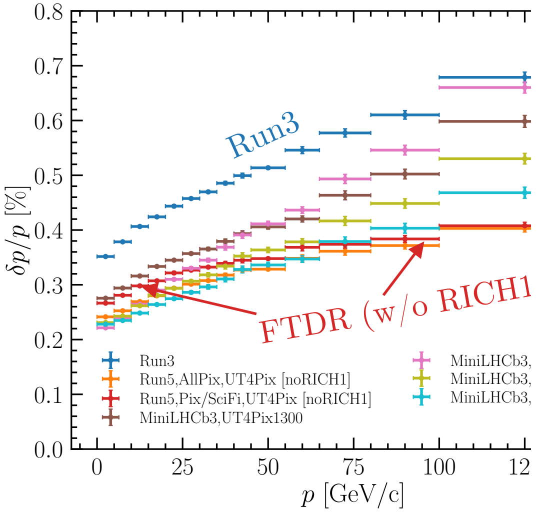
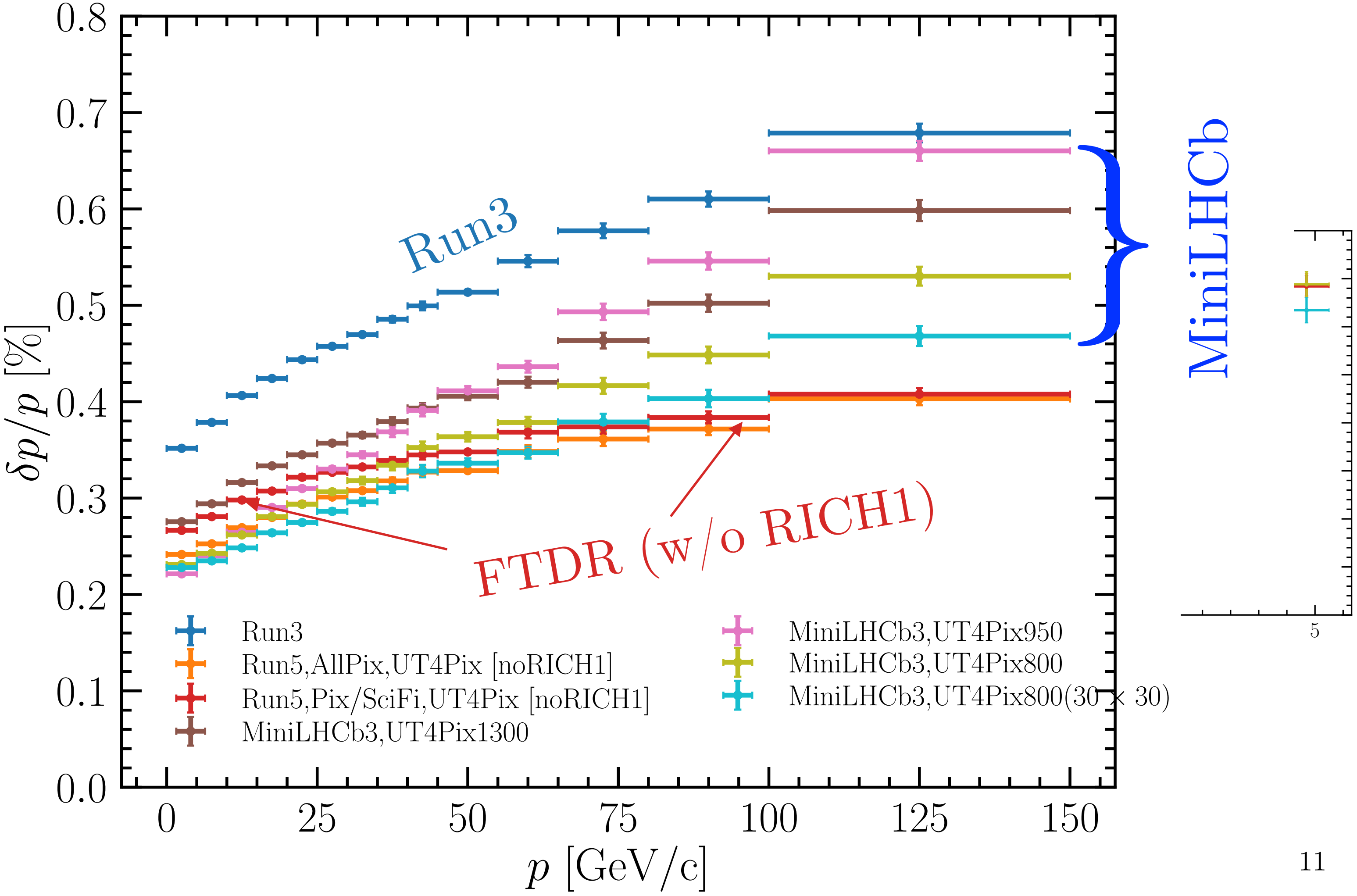
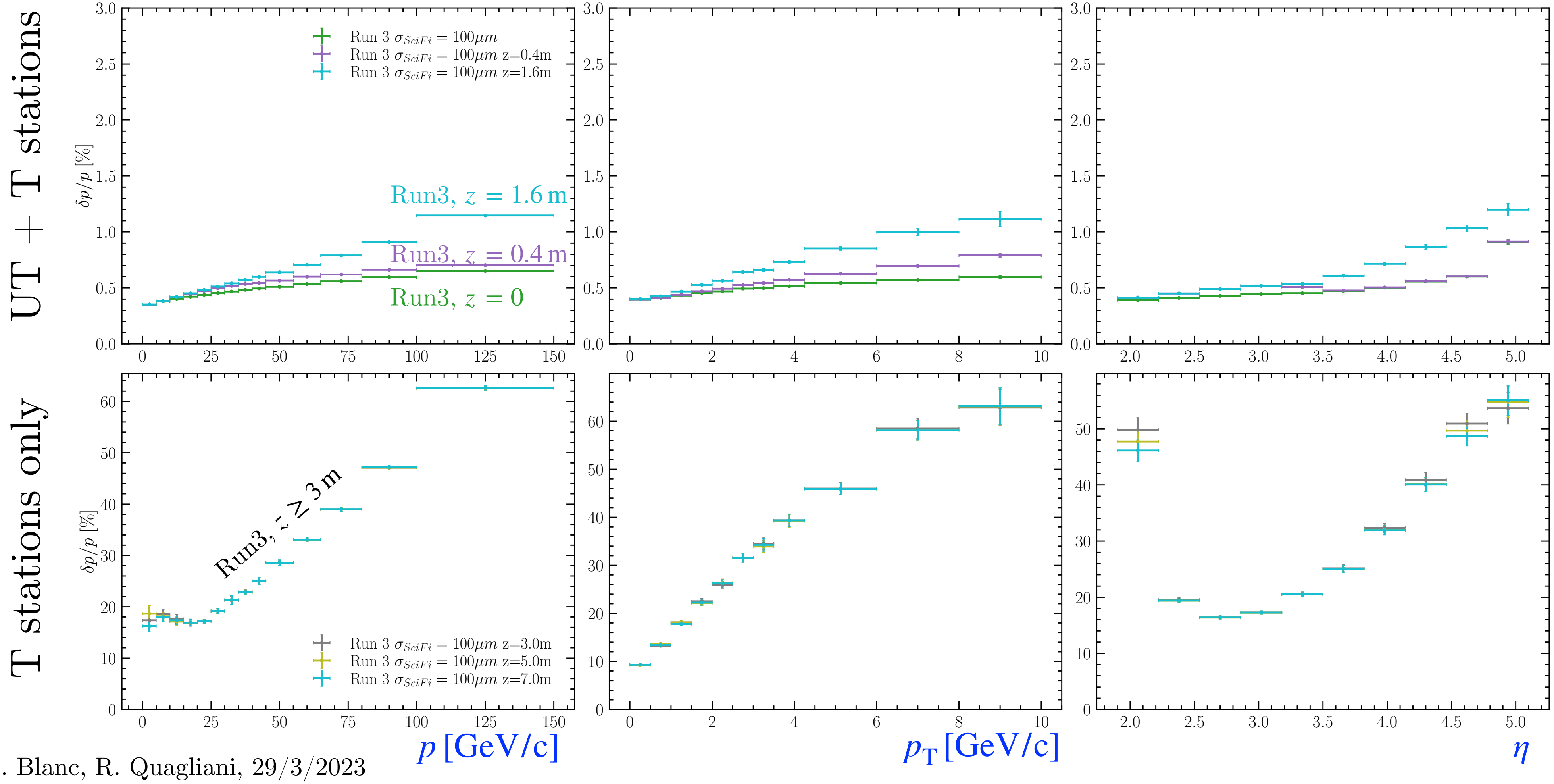




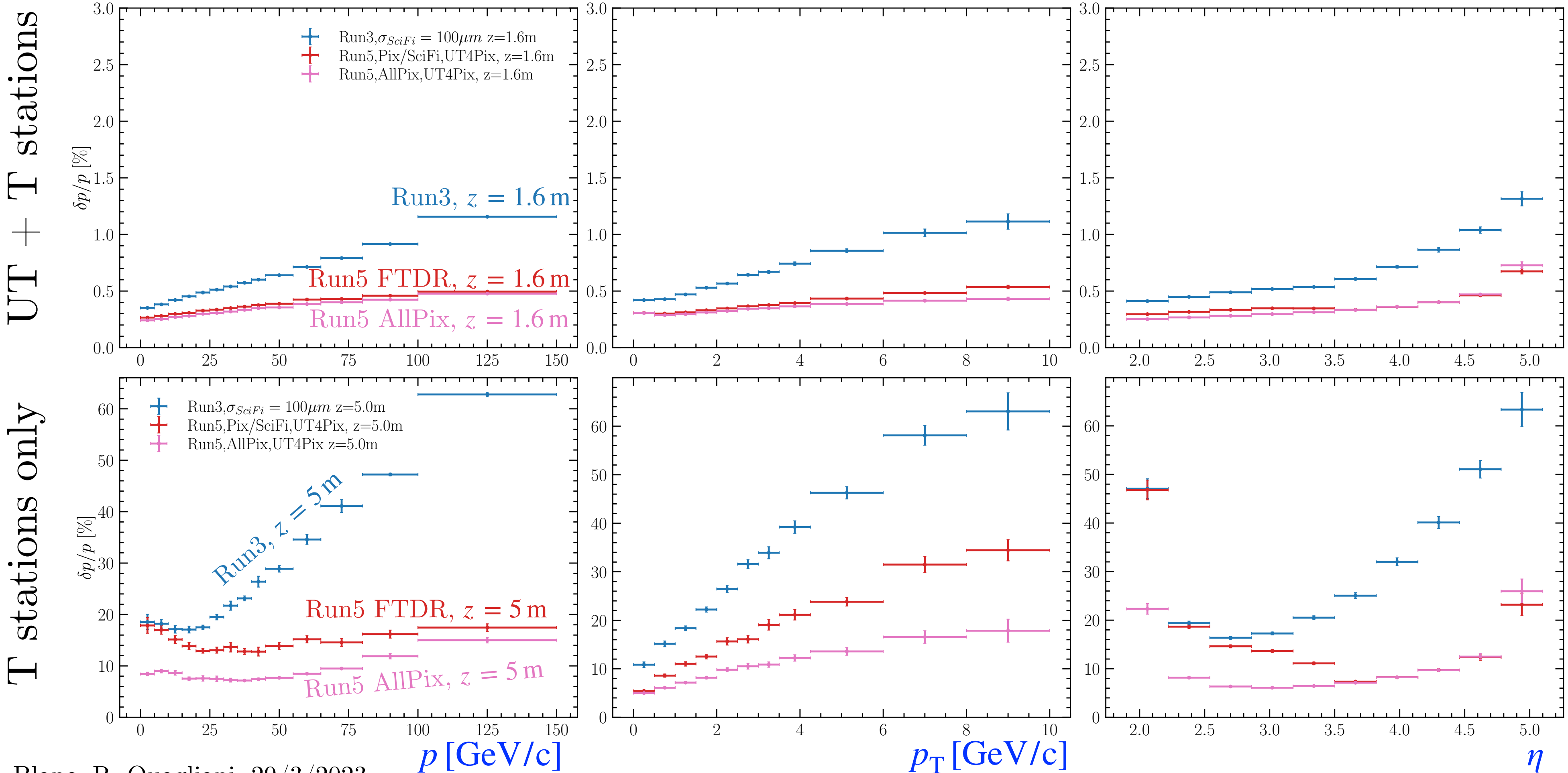
Long-lived particles in Run3

- Emulating K_S^0 with K^+ track
- Top: have measurement in UT, decay before magnet region
- Bottom: no measurement in UT, decay in magnet region



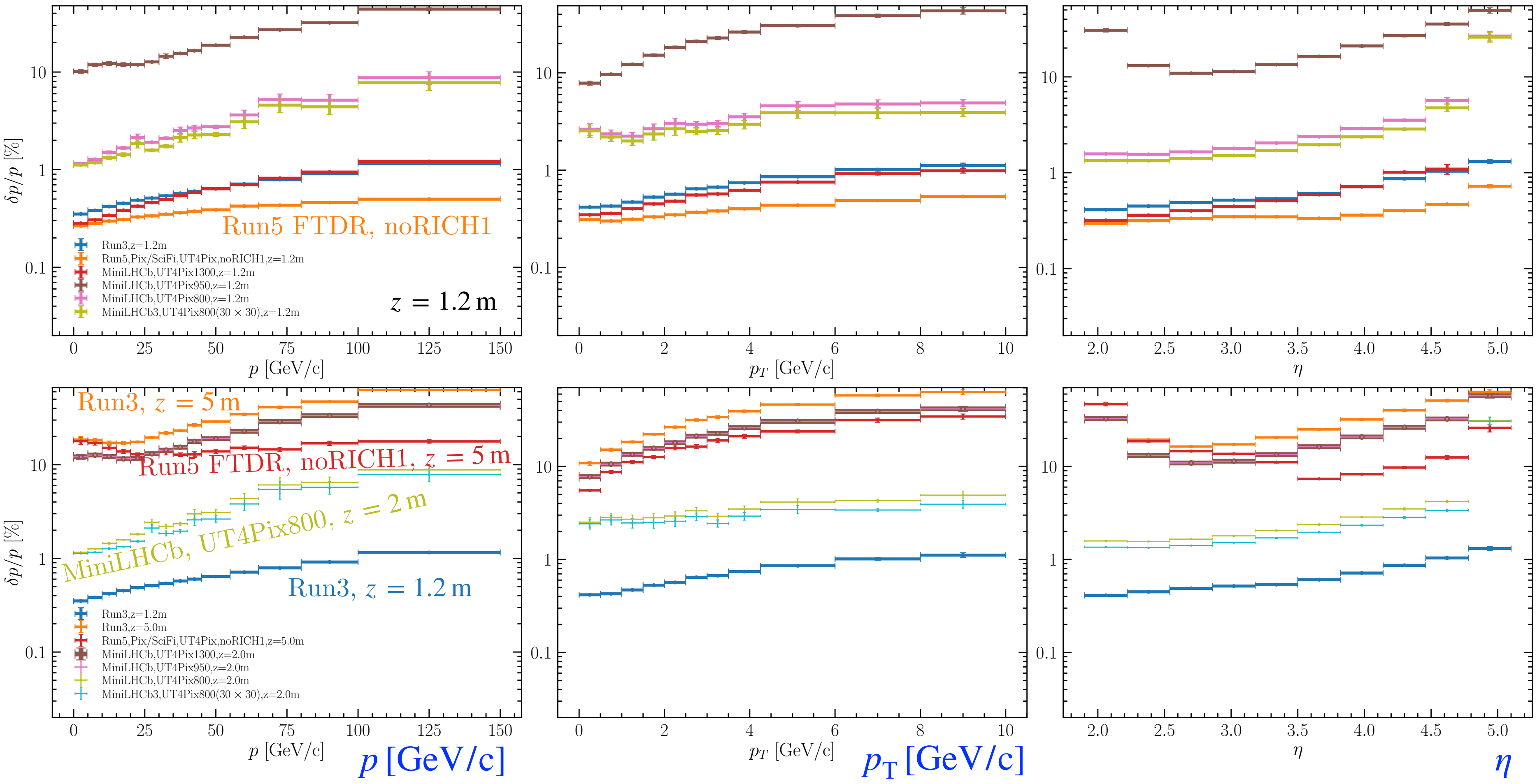
Long-lived particles: from Run3 to Run5

- Changing SciFi for SciFi/Pix or full-Pix, and changing UT
- Top: no VELO measurements, only UT+Downstream
  $\rightarrow$ major improvement from pixels for $z < 2.4\,\mathrm{m}$
- Bottom: pixels are powerful in fringe field tails



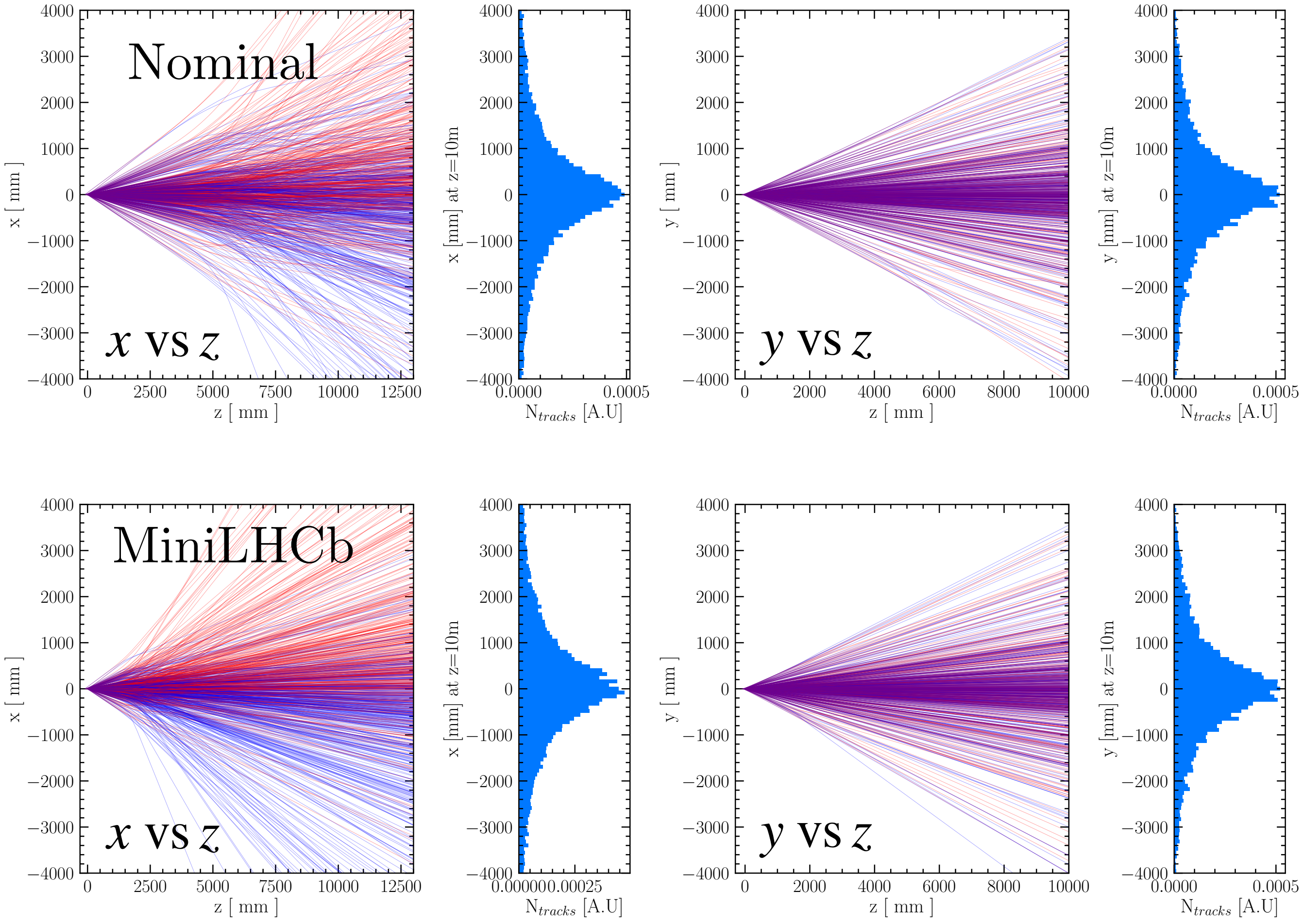
Long-lived particles: miniLHCb

- With MiniLHCb, 1% – 10 % resolution up to $z_{\mathrm{decay}} = 2.3\,\mathrm{m}$
- Clear acceptance effect, can be partly recovered from UT and downstream stations in the ***B*** field tail
- Long-lived particles are neutral → maybe gain in acceptance at low p



Track distribution in CALO region

- Consider a $8\mathrm{m} \times 8\mathrm{m}$ detector at 10 (13) meters
- Kaons with $p > 2.5\,\mathrm{GeV}$ from $B \to K\mu\mu$ are in acceptance
  - 97.5 (93.4) % of the time in the nominal magnetic field
  - 95 (90) % of the time in the $B \times 3$ setup (MiniLHCb)



Summary

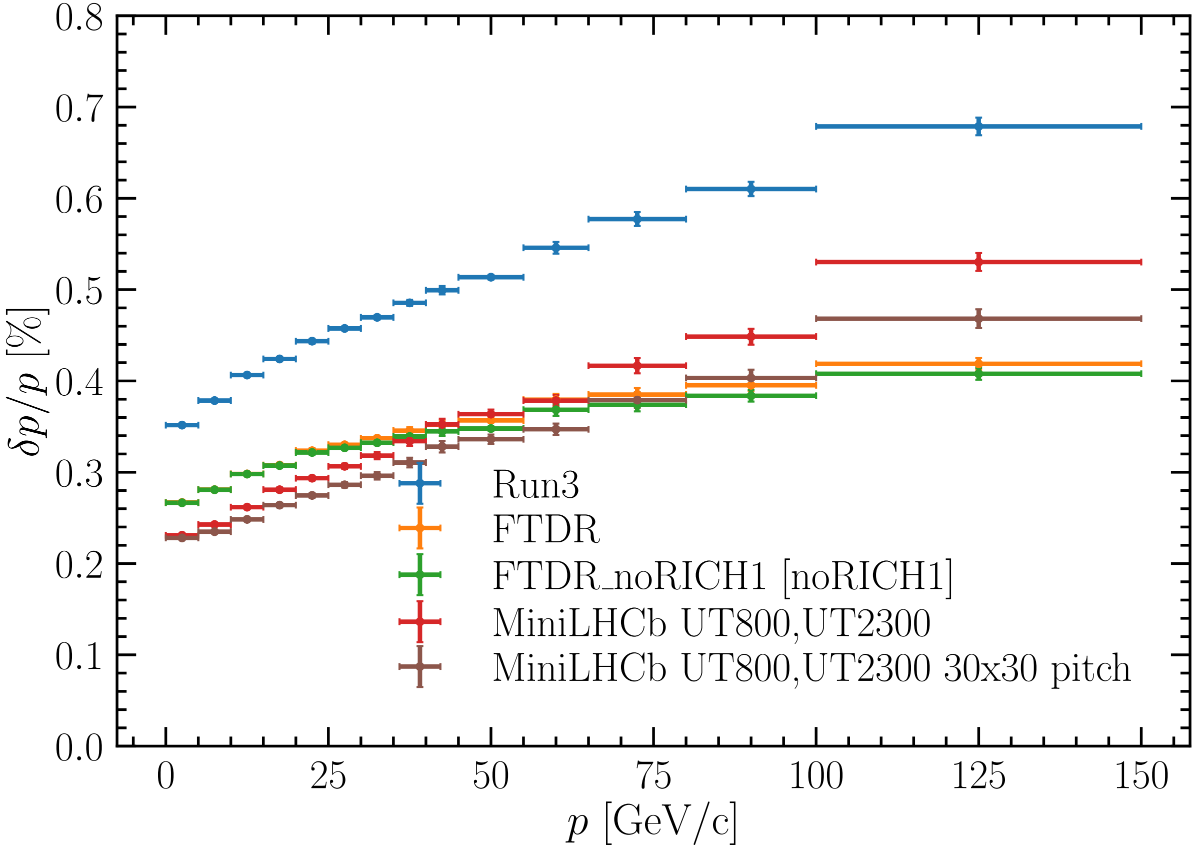
- Momentum resolution improves from using
  - fully pixel tracker (resolution)
  - lower material budget (multiple scattering)
  - placing tracking stations in the tail of the $\overrightarrow{\boldsymbol{B}}$ field

- The MiniLHCb setup looks interesting:
  - full downstream pixel detector with $9\times$ smaller area
  - lower material budget (UT, no RICH1, less air), i.e. fewer secondaries
  - $\overrightarrow{\boldsymbol{B}}$ field map and detector size/geometry can be further tuned for performance
  - some impact on long-lived physics programme, but room for improvement

- Global optimisation:
  - must include RICH, CALO, MUON (and VELO?)
  - can include beam pipe design to minimise secondaries
  - resolution, occupancy, efficiency, ghosts, ...

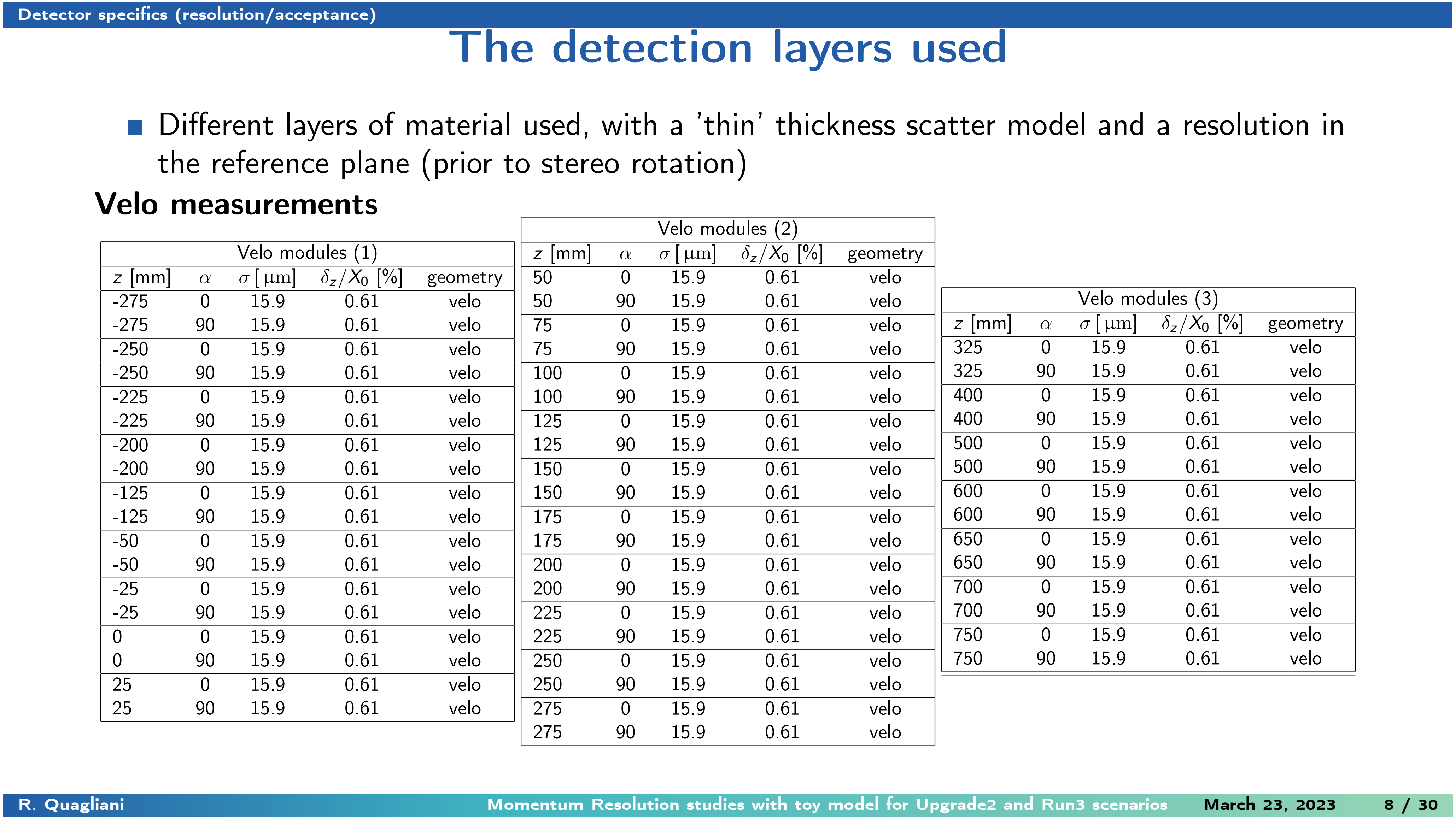
Conclusion

- A small-size tracker can provide FTDR-like momentum resolution
- Global reoptimisation of the detector geometry/technology may provide a descoping option with reduced loss of physics reach
- A tool is available for studying the momentum resolution for various geometries; can be extended to study IP resolution, impact of misalignments



Backup

VELO model



Detector specifics (resolution/acceptance)

The detection layers used

- Different layers of material used, with a 'thin' thickness scatter model and a resolution in the reference plane (prior to stereo rotation)

Velo measurements

Velo modules (1)				
z [mm]	α	$\sigma\,[\mu m]$	δ_z/X_0 [%]	geometry
-275	0	15.9	0.61	velo
-275	90	15.9	0.61	velo
-250	0	15.9	0.61	velo
-250	90	15.9	0.61	velo
-225	0	15.9	0.61	velo
-225	90	15.9	0.61	velo
-200	0	15.9	0.61	velo
-200	90	15.9	0.61	velo
-125	0	15.9	0.61	velo
-125	90	15.9	0.61	velo
-50	0	15.9	0.61	velo
-50	90	15.9	0.61	velo
-25	0	15.9	0.61	velo
-25	90	15.9	0.61	velo
0	0	15.9	0.61	velo
0	90	15.9	0.61	velo
25	0	15.9	0.61	velo
25	90	15.9	0.61	velo

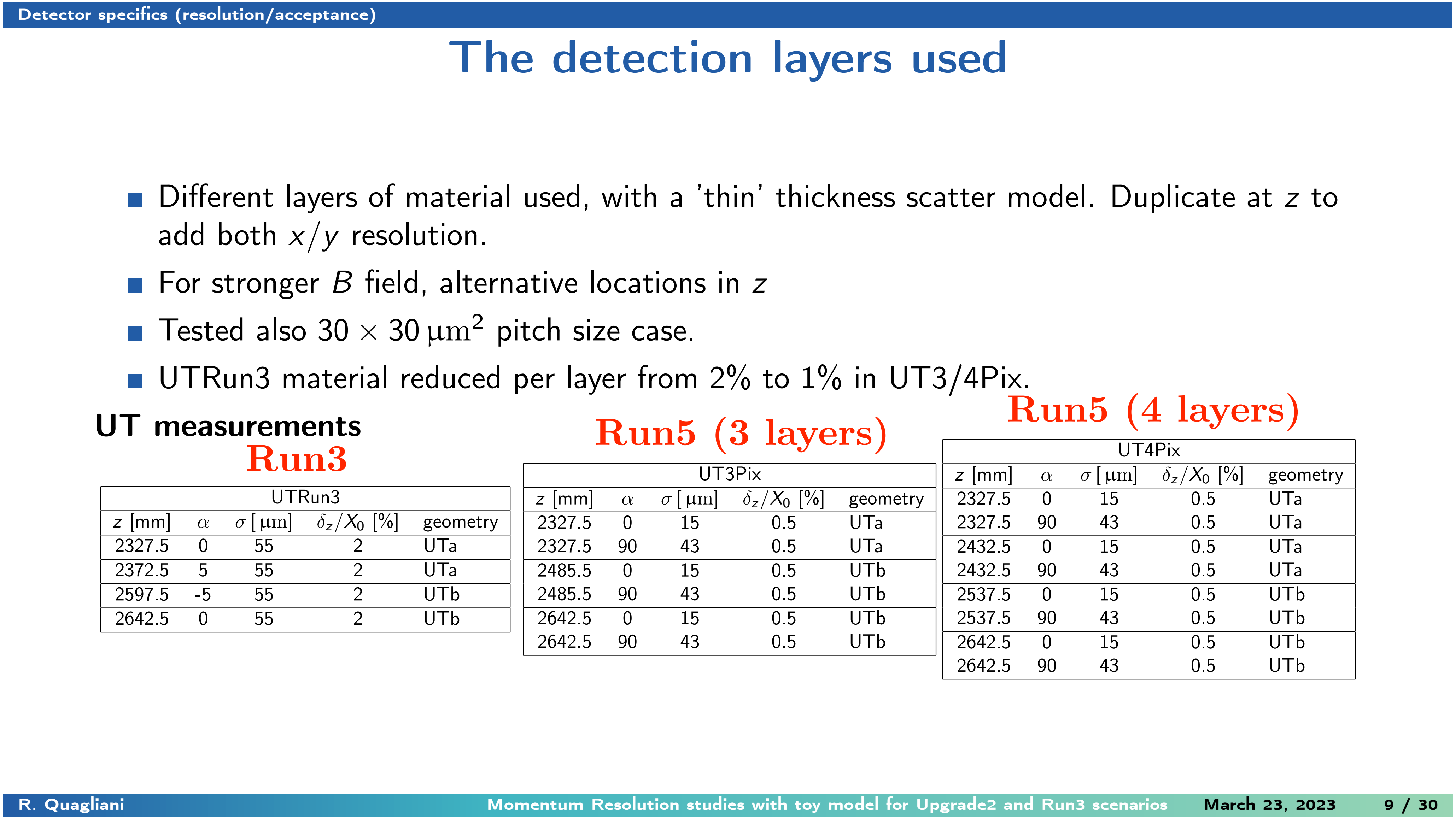
Velo modules (2)				
z [mm]	α	$\sigma\,[\mu m]$	δ_z/X_0 [%]	geometry
50	0	15.9	0.61	velo
50	90	15.9	0.61	velo
75	0	15.9	0.61	velo
75	90	15.9	0.61	velo
100	0	15.9	0.61	velo
100	90	15.9	0.61	velo
125	0	15.9	0.61	velo
125	90	15.9	0.61	velo
150	0	15.9	0.61	velo
150	90	15.9	0.61	velo
175	0	15.9	0.61	velo
175	90	15.9	0.61	velo
200	0	15.9	0.61	velo
200	90	15.9	0.61	velo
225	0	15.9	0.61	velo
225	90	15.9	0.61	velo
250	0	15.9	0.61	velo
250	90	15.9	0.61	velo
275	0	15.9	0.61	velo
275	90	15.9	0.61	velo

Velo modules (3)				
z [mm]	α	$\sigma\,[\mu m]$	δ_z/X_0 [%]	geometry
325	0	15.9	0.61	velo
325	90	15.9	0.61	velo
400	0	15.9	0.61	velo
400	90	15.9	0.61	velo
500	0	15.9	0.61	velo
500	90	15.9	0.61	velo
600	0	15.9	0.61	velo
600	90	15.9	0.61	velo
650	0	15.9	0.61	velo
650	90	15.9	0.61	velo
700	0	15.9	0.61	velo
700	90	15.9	0.61	velo
750	0	15.9	0.61	velo
750	90	15.9	0.61	velo

R. Quagliani Momentum Resolution studies with toy model for Upgrade2 and Run3 scenarios March 23, 2023 8 / 30

VELO description identical in all geometries

UT models



The detection layers used

- Different layers of material used, with a 'thin' thickness scatter model. Duplicate at z to add both x/y resolution.
- For stronger B field, alternative locations in z
- Tested also $30 \times 30\,\mu\text{m}^2$ pitch size case.
- UTRun3 material reduced per layer from 2% to 1% in UT3/4Pix.

UT measurements

Run3

UTRun3

z [mm]	α	σ [µm]	δ_z/X_0 [%]	geometry
2327.5	0	55	2	UTa
2372.5	5	55	2	UTa
2597.5	-5	55	2	UTb
2642.5	0	55	2	UTb

Run5 (3 layers)

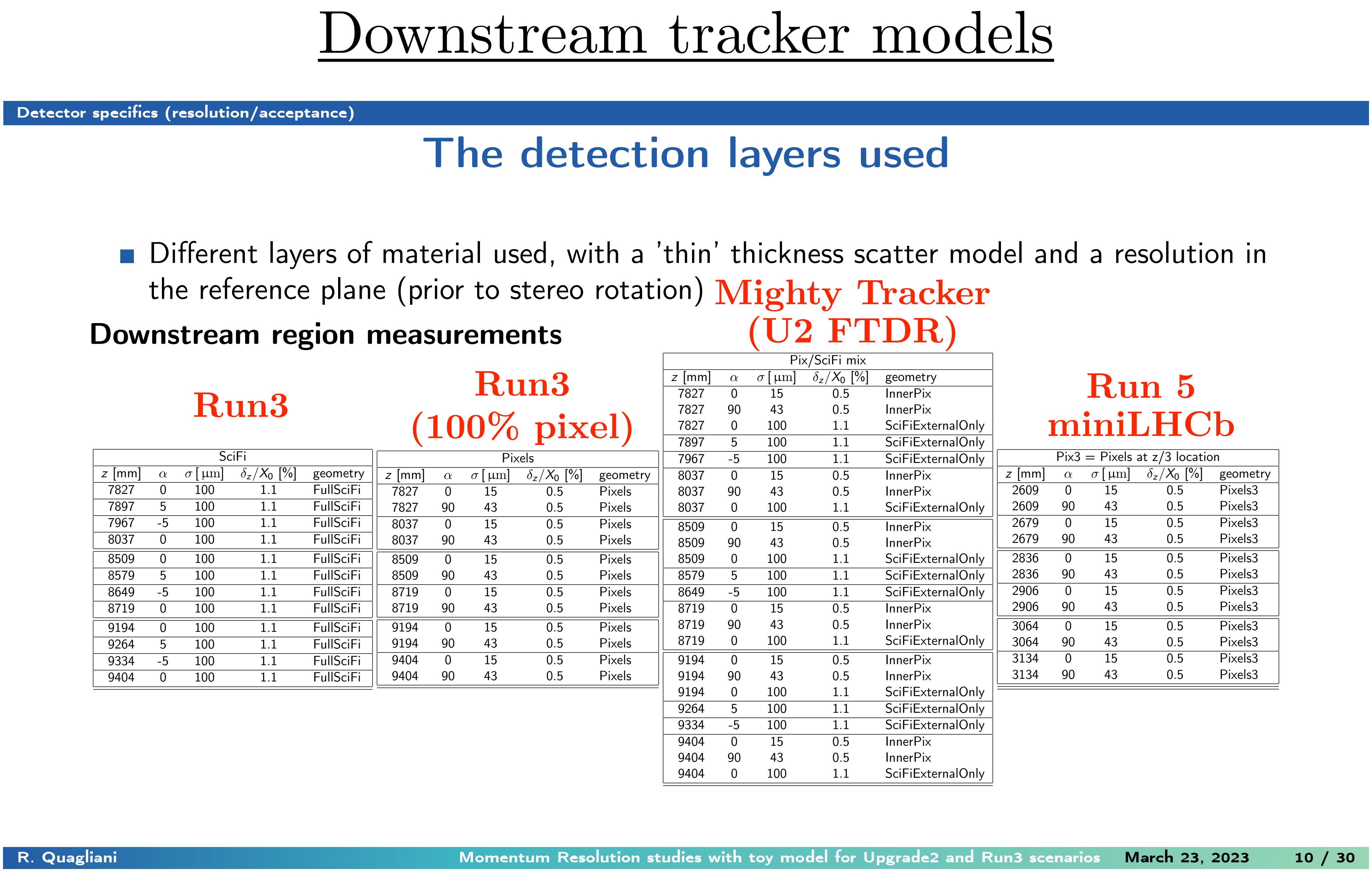
UT3Pix

z [mm]	α	σ [µm]	δ_z/X_0 [%]	geometry
2327.5	0	15	0.5	UTa
2327.5	90	43	0.5	UTa
2485.5	0	15	0.5	UTb
2485.5	90	43	0.5	UTb
2642.5	0	15	0.5	UTb
2642.5	90	43	0.5	UTb

Run5 (4 layers)

UT4Pix

z [mm]	α	σ [µm]	δ_z/X_0 [%]	geometry
2327.5	0	15	0.5	UTa
2327.5	90	43	0.5	UTa
2432.5	0	15	0.5	UTa
2432.5	90	43	0.5	UTa
2537.5	0	15	0.5	UTb
2537.5	90	43	0.5	UTb
2642.5	0	15	0.5	UTb
2642.5	90	43	0.5	UTb



Downstream tracker models

Detector specifics (resolution/acceptance)

The detection layers used

- Different layers of material used, with a 'thin' thickness scatter model and a resolution in the reference plane (prior to stereo rotation)

Downstream region measurements

Run3

SciFi				
z [mm]	α	σ [μm]	δ_z/X_0 [%]	geometry
7827	0	100	1.1	FullSciFi
7897	5	100	1.1	FullSciFi
7967	-5	100	1.1	FullSciFi
8037	0	100	1.1	FullSciFi
8509	0	100	1.1	FullSciFi
8579	5	100	1.1	FullSciFi
8649	-5	100	1.1	FullSciFi
8719	0	100	1.1	FullSciFi
9194	0	100	1.1	FullSciFi
9264	5	100	1.1	FullSciFi
9334	-5	100	1.1	FullSciFi
9404	0	100	1.1	FullSciFi

Run3 (100% pixel)

Pixels				
z [mm]	α	σ [μm]	δ_z/X_0 [%]	geometry
7827	0	15	0.5	Pixels
7827	90	43	0.5	Pixels
8037	0	15	0.5	Pixels
8037	90	43	0.5	Pixels
8509	0	15	0.5	Pixels
8509	90	43	0.5	Pixels
8719	0	15	0.5	Pixels
8719	90	43	0.5	Pixels
9194	0	15	0.5	Pixels
9194	90	43	0.5	Pixels
9404	0	15	0.5	Pixels
9404	90	43	0.5	Pixels

Mighty Tracker (U2 FTDR)

Pix/SciFi mix				
z [mm]	α	σ [μm]	δ_z/X_0 [%]	geometry
7827	0	15	0.5	InnerPix
7827	90	43	0.5	InnerPix
7827	0	100	1.1	SciFiExternalOnly
7897	5	100	1.1	SciFiExternalOnly
7967	-5	100	1.1	SciFiExternalOnly
8037	0	15	0.5	InnerPix
8037	90	43	0.5	InnerPix
8037	0	100	1.1	SciFiExternalOnly
8509	0	15	0.5	InnerPix
8509	90	43	0.5	InnerPix
8509	0	100	1.1	SciFiExternalOnly
8579	5	100	1.1	SciFiExternalOnly
8649	-5	100	1.1	SciFiExternalOnly
8719	0	15	0.5	InnerPix
8719	90	43	0.5	InnerPix
8719	0	100	1.1	SciFiExternalOnly
9194	0	15	0.5	InnerPix
9194	90	43	0.5	InnerPix
9194	0	100	1.1	SciFiExternalOnly
9264	5	100	1.1	SciFiExternalOnly
9334	-5	100	1.1	SciFiExternalOnly
9404	0	15	0.5	InnerPix
9404	90	43	0.5	InnerPix
9404	0	100	1.1	SciFiExternalOnly

Run 5 miniLHCb

Pix3 = Pixels at z/3 location				
z [mm]	α	σ [μm]	δ_z/X_0 [%]	geometry
2609	0	15	0.5	Pixels3
2609	90	43	0.5	Pixels3
2679	0	15	0.5	Pixels3
2679	90	43	0.5	Pixels3
2836	0	15	0.5	Pixels3
2836	90	43	0.5	Pixels3
2906	0	15	0.5	Pixels3
2906	90	43	0.5	Pixels3
3064	0	15	0.5	Pixels3
3064	90	43	0.5	Pixels3
3134	0	15	0.5	Pixels3
3134	90	43	0.5	Pixels3