Discussion on MATHUSLA Conceptual Design

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SIMONS CENTER FOR GEOMETRY AND PHYSICS MATHUSLA **workshop**

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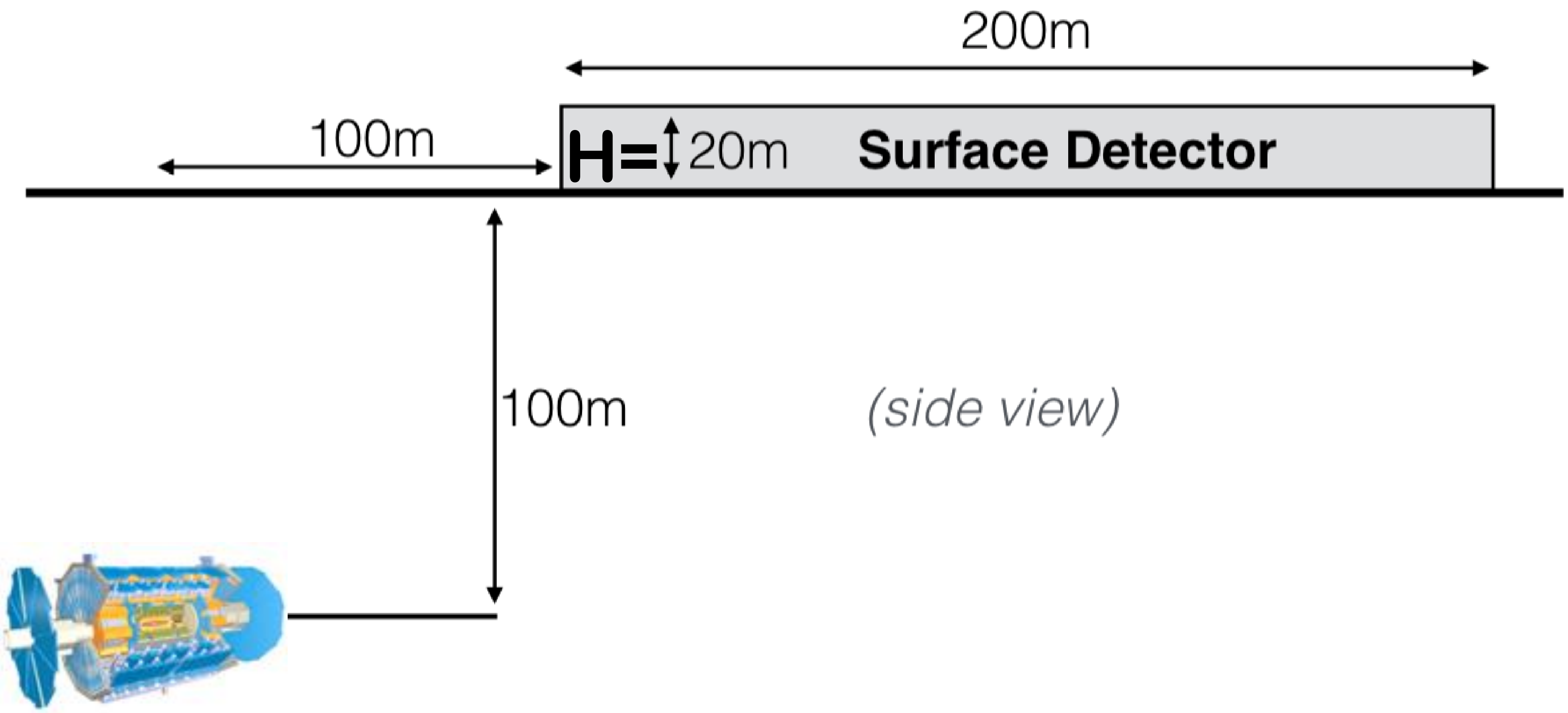
SLAC NATIONAL ACCELERATOR LABORATORY

TEL AVIV UNIVERSITY

MAssive Timing Hodoscope for Ultra-Stable NeutraL PArticles

- Assume ULLPs are produced in exotic Higgs decays with Br > 10%
- Assume a lifetime near the Big Bang nucleosynthesis (BBN) limit: $c\tau \sim 10^7$m
- The LHC makes a lot of Higgs bosons…
- A few of these LLPs will decay in ATLAS or CMS!
- Detection requires:
  - High production rate but also **Tiny** BG rate
    - Dedicated detector sensitive to neutral long-lived particles that have lifetimes up to the BBN limit (10^7– 10^8m) for the HL-LHC
    - A large-volume, air filled detector located on the surface above and somewhat displaced from ATLAS or CMS interaction points (IP)

Extension to the detectors for HL-LHC



- Surface detector (100m above the IP and displaced horizontally)
- H=20 m
- Geometrical acceptance of ~5% (200 m x 200 m = **40,000 m^2** per detector plane) to search for ULLP's during the HL-LHC run
- (R. Santonico's talk at RPC 2018: currently all RPC sensitive area Opera, ATLAS, CMS, Argo-YBJ is 25,000 m^2)

In The Beginning

- Five detector planes
- Each plane provides space point with ~1 cm resolution in each transverse direction and ~1 nsec time resolution

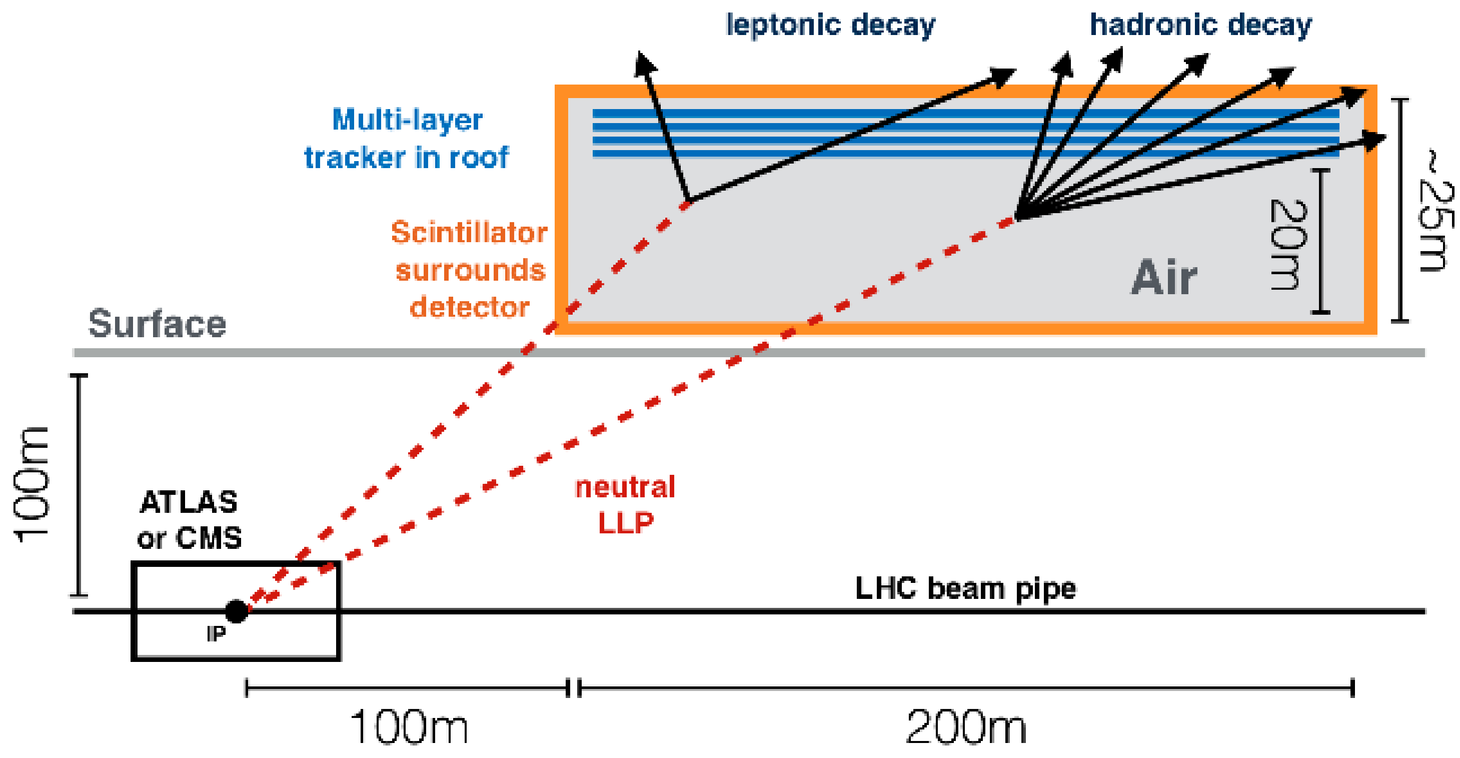
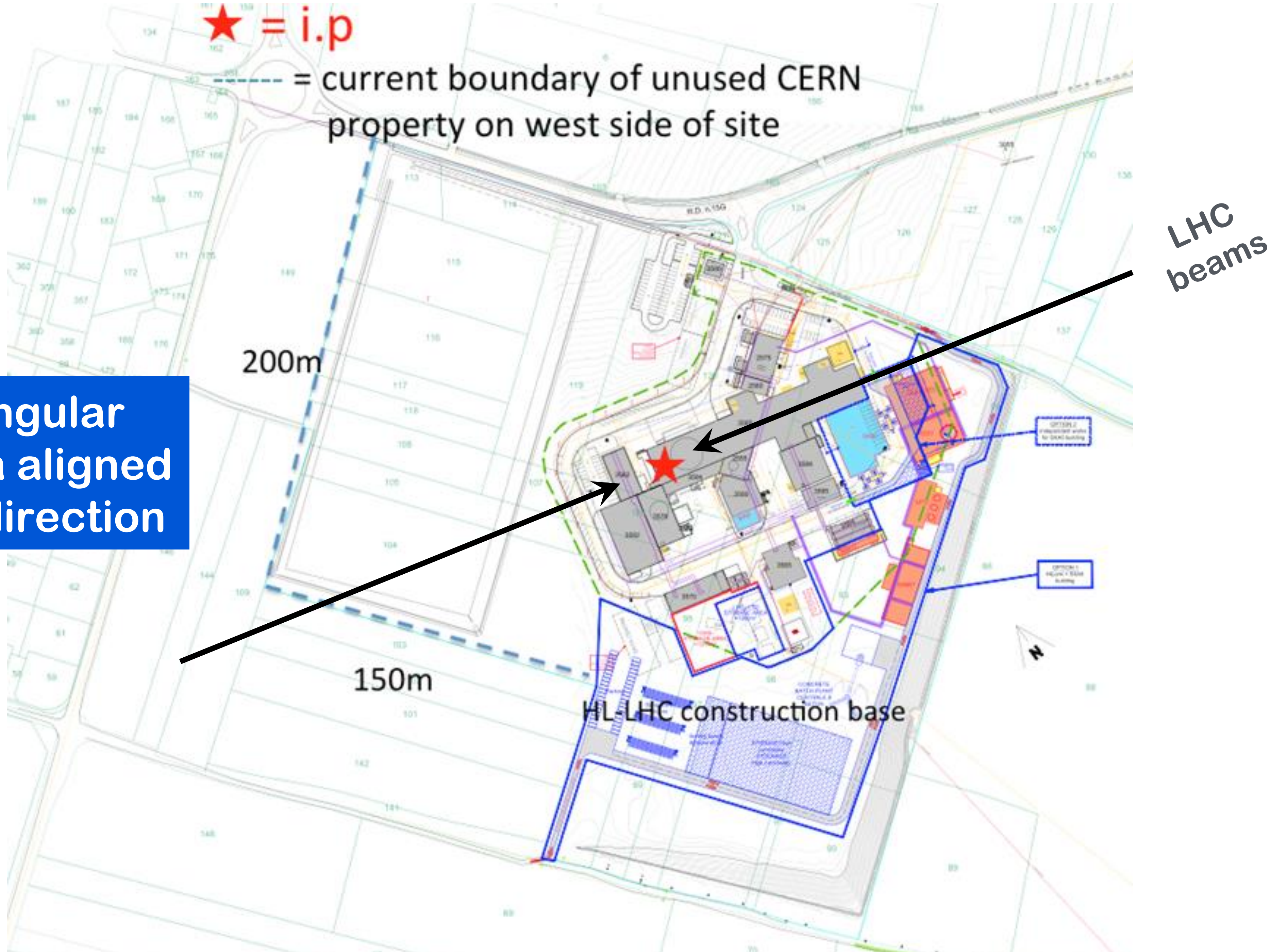


Fig. 1: Simplified detector layout showing the position of the 200 m × 200 m × 20 m LLP decay volume used for physics studies. The tracking planes in the roof detect charged particles, allowing for the reconstruction of displaced vertices in the air-filled decay volume. The scintillator surrounding the volume provides vetoing capability against charged particles entering the detector.

Potential locations

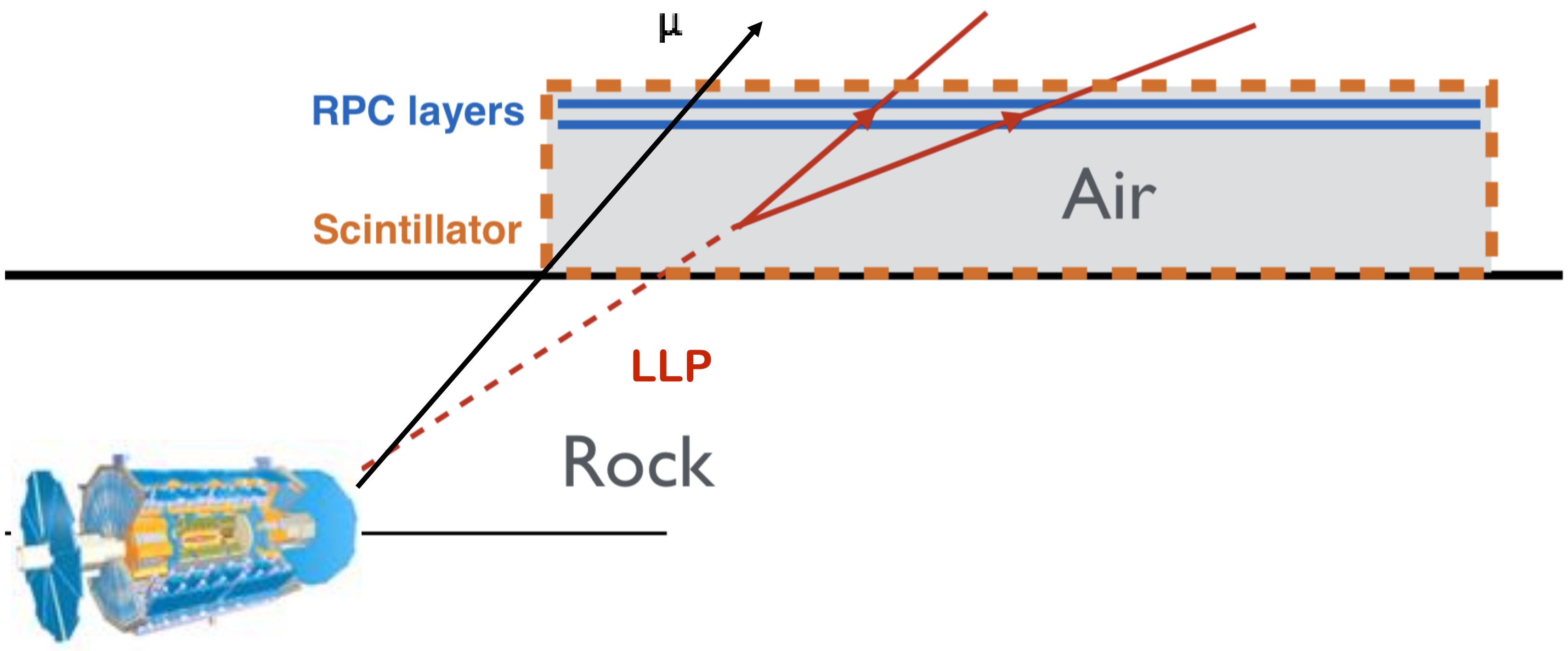
Potential location



Not rectangular shaped area aligned with beam direction

The relevant area is to the west of the IP and enclosed by the blue dashed lines. The LHC beam runs roughly east-west. This site could accommodate a detector layout similar to our MATHUSLA100 benchmark.

The signal characteristic

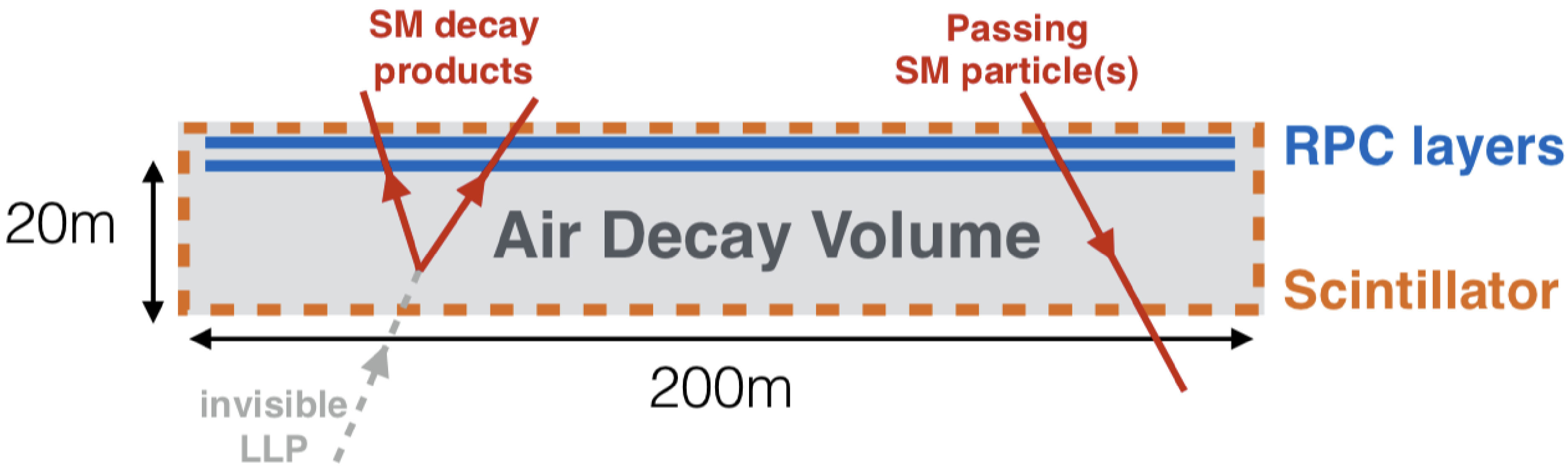


- Searching for upward going vertex in the detector volume
  - LLP may decay to jets or lepton pair, signal requires >= two
  - Particles reaching the ground should be relativistically boosted
  - The tracks point toward a common vertex
  - The vertex within a cone from the ATLAS/CMS IP
  - Veto charged particles from LHC based on bottom scintillator

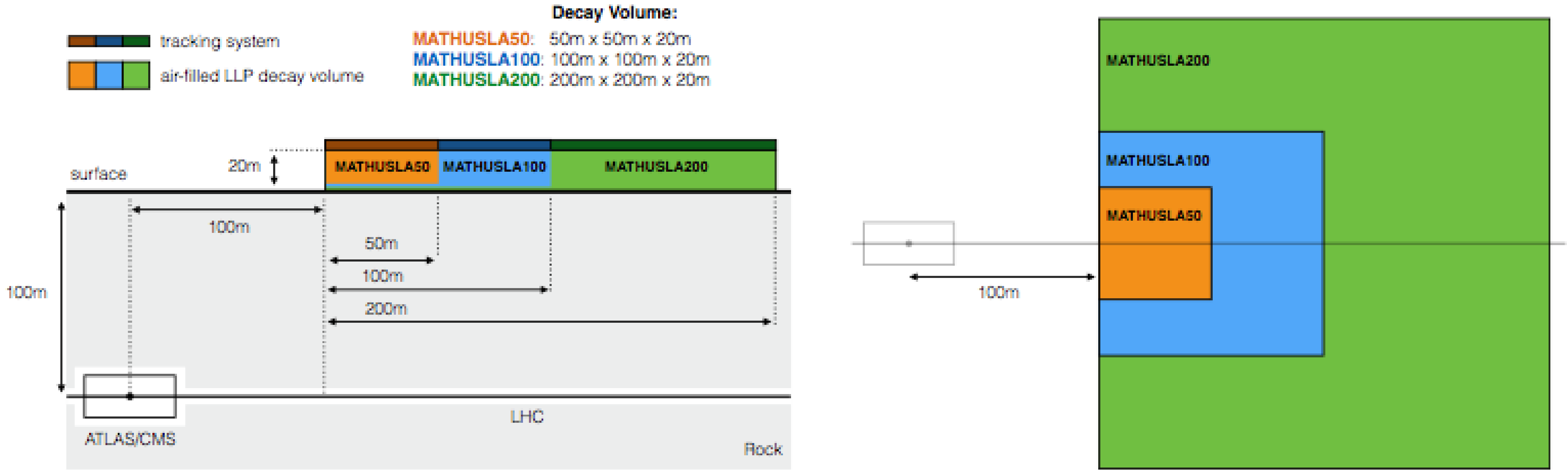
Size matters…

- Size versus cost ..

$$\textcolor{blue}{\text{Sensitivity} \propto \text{Volume}} \text{ while } \textcolor{red}{\text{Cost} \propto \text{Area}}$$



MATHUSLA Geometry

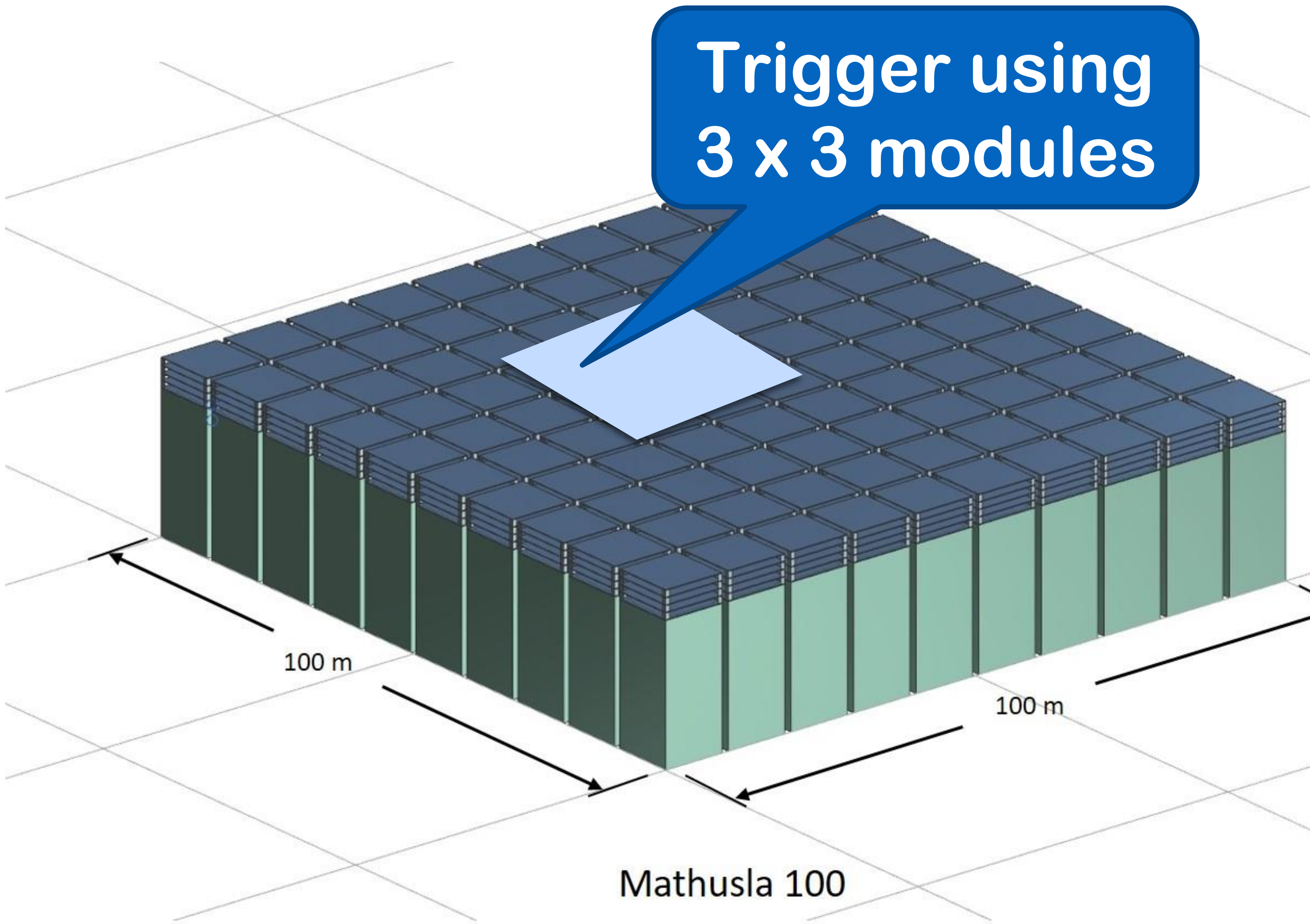


side view *aerial view*

- MATHUSLA200 - originally proposed and is the white paper benchmark point
- MATHUSLA100 - default LOI size
- MATHUSLA50 - scalable project ..

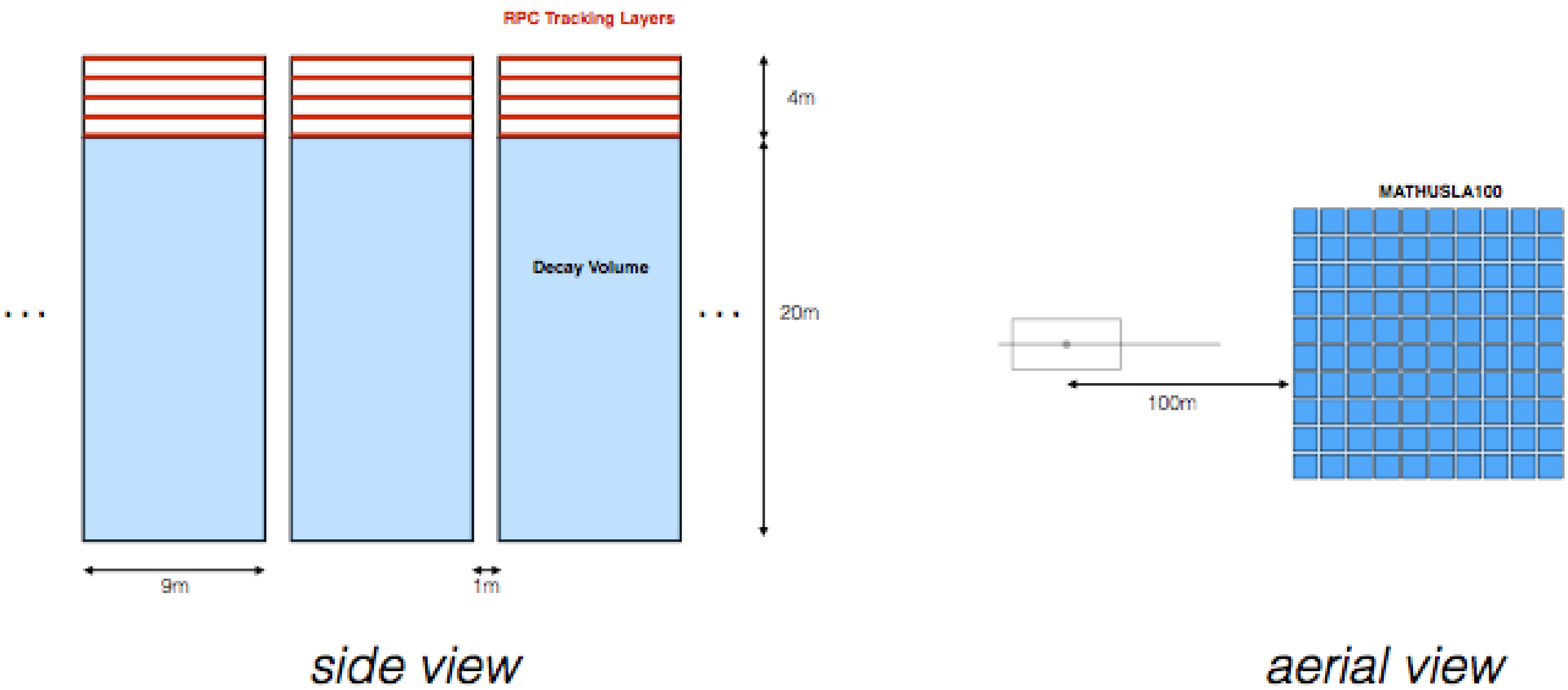
Layout - Modular structure

- Scalability - > modular nature
- 100 identical units
- Modular construction
- Modular operation
- Adjustable to site condition
- Incremental operation ramp-up
- Allows maintenance upgrades and improvements in steps
- Allows testing implementation in different technologies
- Allows improved tracking or adding material for partial particle ID in stages



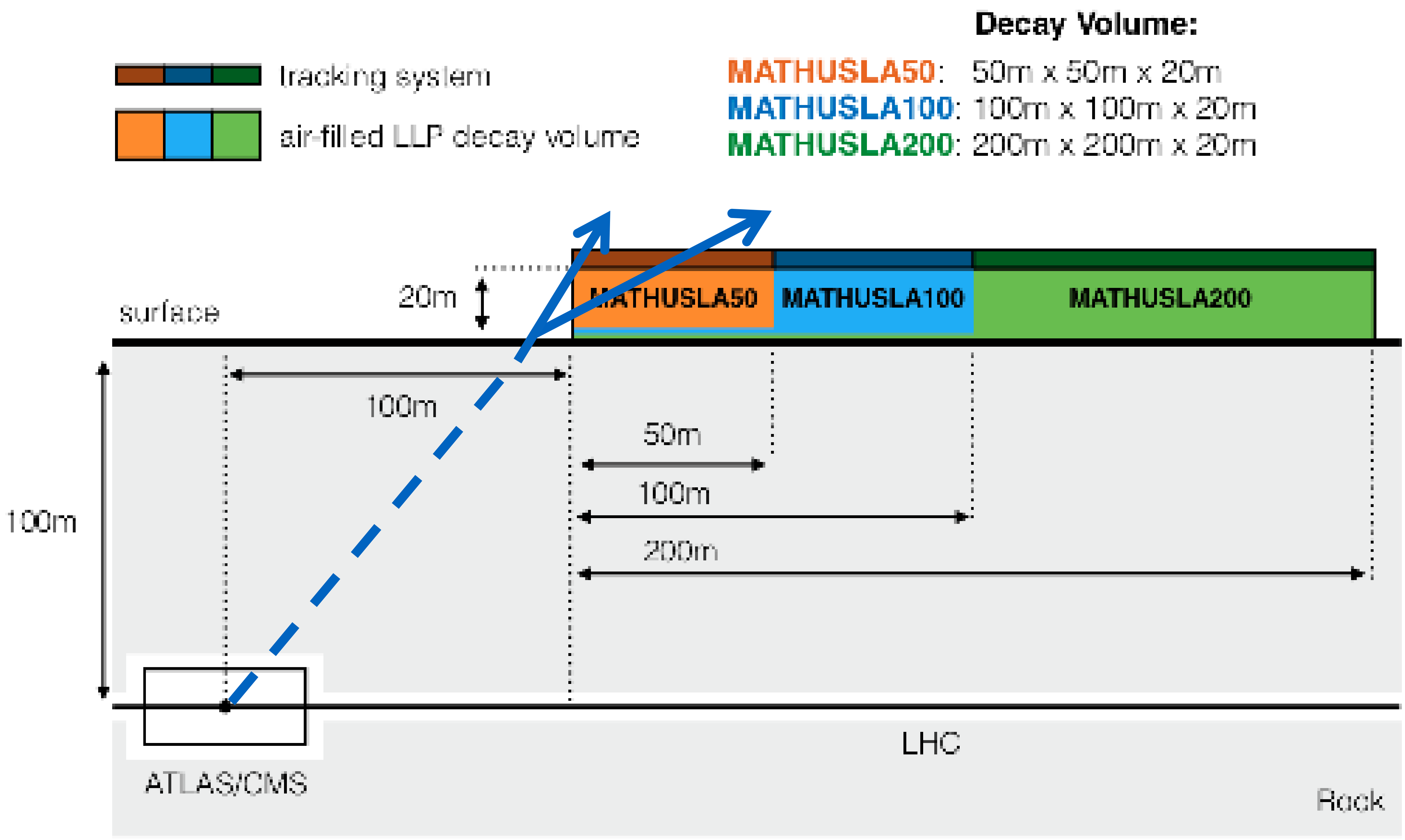
Identical 10 m x 10 m modules, each with five detector planes above 20 m decay volume

Layout guidelines



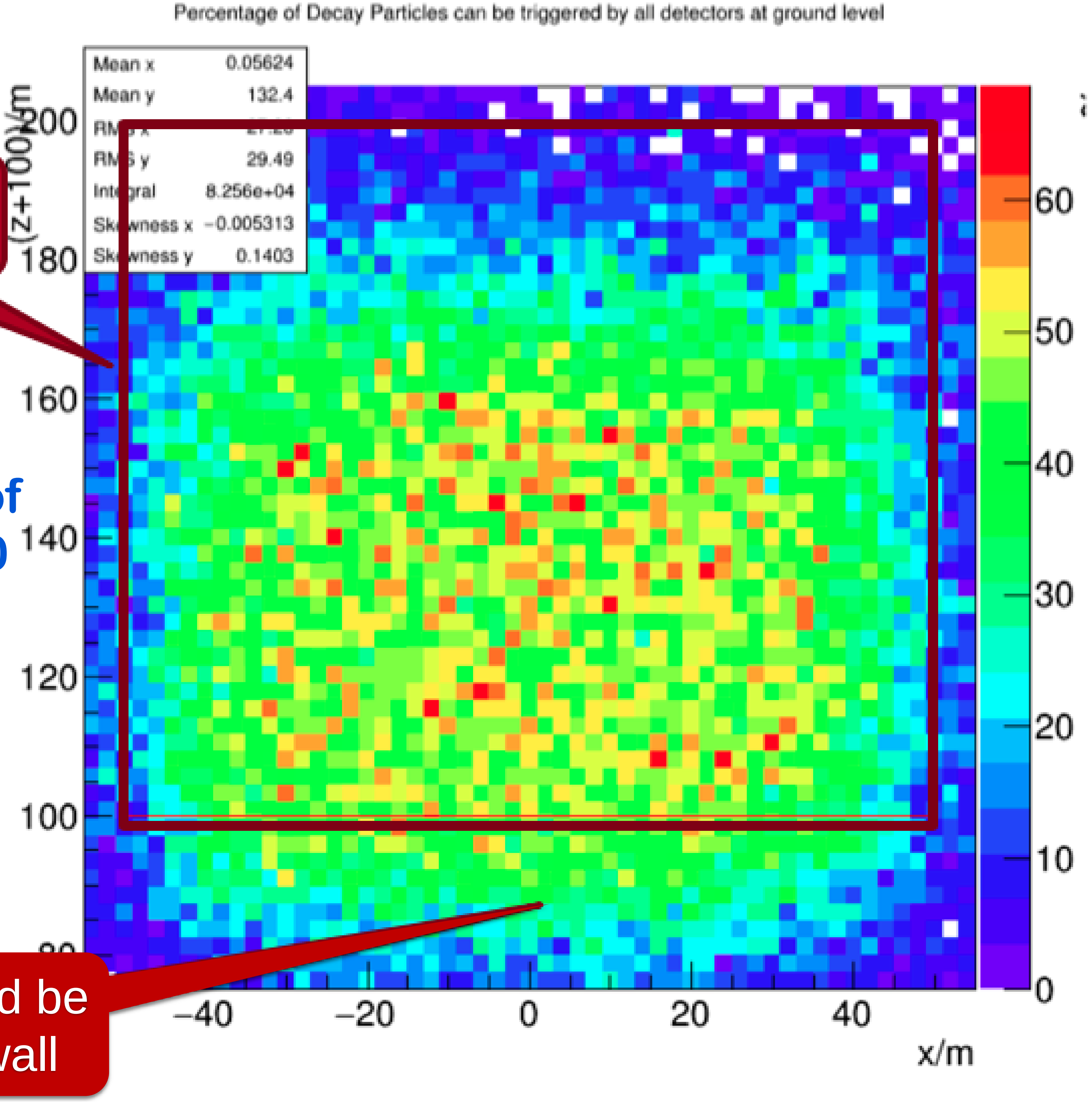
- Overall cosmic rate expected: O(2MHz)
- Cosmic shower can reach 10^4 m^{-2} in the core
- Each module is weather tight unit (Power, temperature, pressure, humidity, readout)

Front Veto Wall: Reduced Signal Acceptance



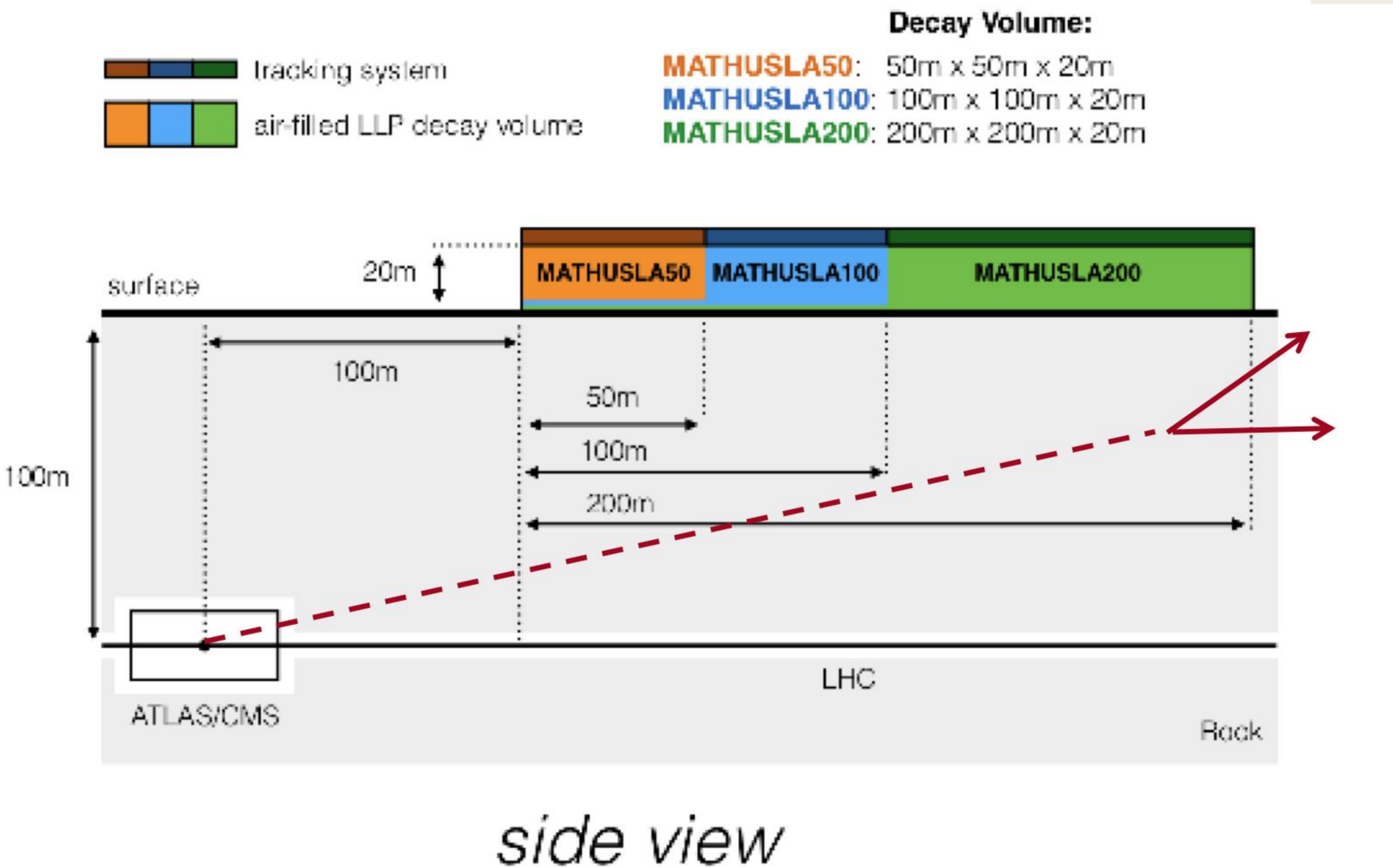
side view

Front Veto Wall: Reduced Signal Acceptance

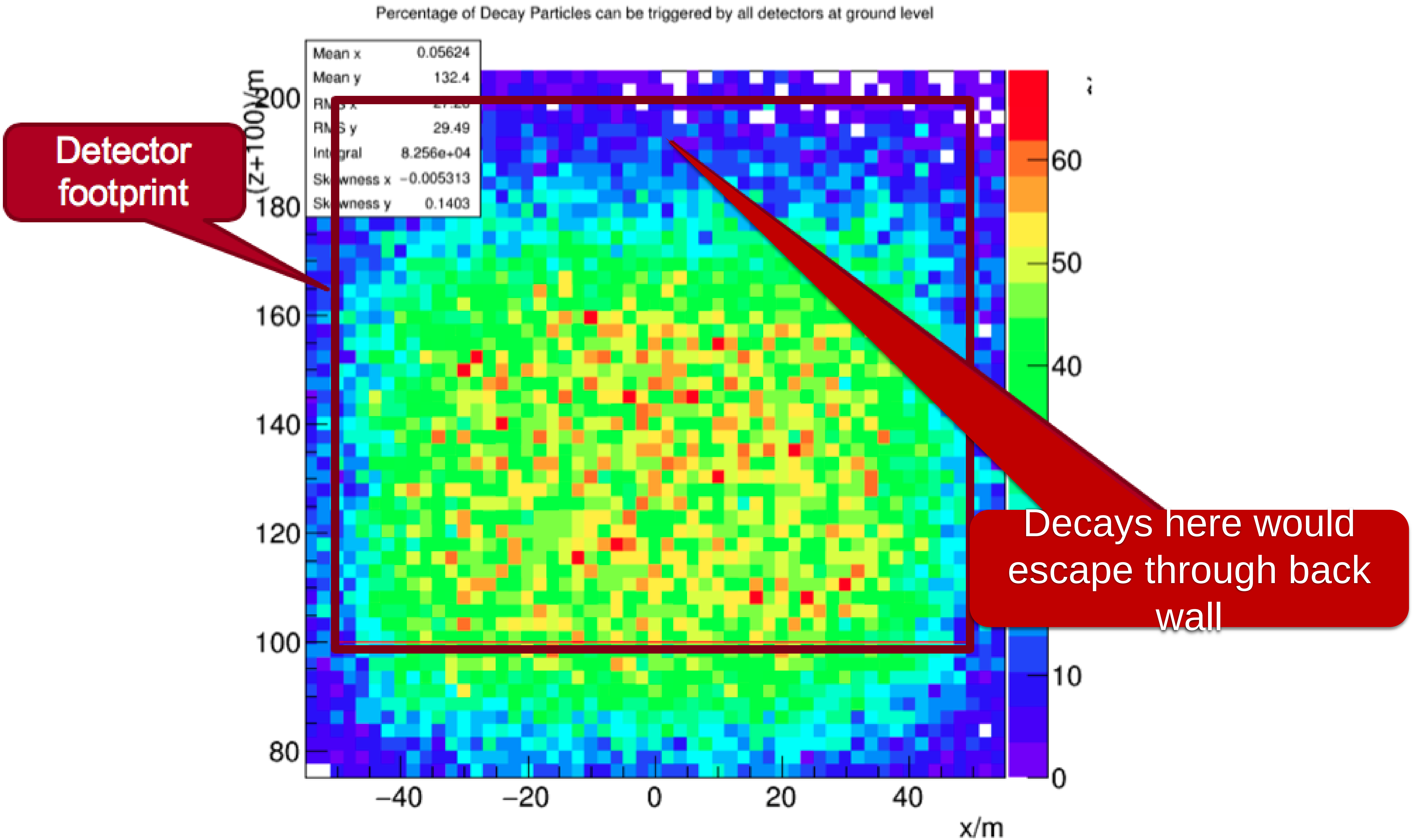


Trigger efficiency of the MATHUSLA100 for decays at the ground level

Back "Veto" Wall: Reduced Signal Acceptance



Back Veto Wall: Reduced Signal Acceptance



Current thinking on Veto Walls

- Remove all veto walls
- Add five tracking planes on back wall – for signal, not veto
  - Similar detector performance requirements as top tracker
  - Detector technology likely to be same
- Leave side walls uninstrumented (for now)
  - Side walls will also increase signal acceptance but less favorable cost-to-benefit ratio than back wall

Acceptance Comparisons

Description	Module Size (m)	Module Gap (m)	RPC Gap (m)
Default	9	1	1
Smaller module gap	9.5	0.5	1
Smaller RPC gap	9	1	0.5
Larger modules	19	1	1
Monolithic detector	100	0	1

	$X \to b\bar{b}$		$X \to \mu^+\mu^-$	
	$m_X = 15$ GeV	$m_X = 50$ GeV	$m_X = 15$ GeV	$m_X = 50$ GeV
Default geometry	0.72, 0.82	0.83, 0.93	0.17, 0.20	0.076, 0.080
Smaller module gap	0.79, 0.90	0.87, 0.98	0.33, 0.37	0.13, 0.14
Smaller RPC gap	0.80, 0.93	0.89, 1.0	0.27, 0.31	0.11, 0.11
Larger modules	0.79, 0.89	0.88, 0.99	0.36, 0.40	0.14, 0.15
Monolithic Detector	0.82, 0.93	0.90, 1.0	0.57, 0.63	0.21, 0.22

Table 3. Average LLP reconstruction efficiencies ϵ_{DV} for module configurations in Table. 2. The first (second) number in each entry corresponds to the tight (loose) search allowing only LLP decays in the decay volume (allowing decays outside), both normalized to the number of decays in the decay volume. Neighboring-module trigger except for Monolithic Detector. Note these efficiencies are normalized to the probability of decaying in decay volume under the RPCs.

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Reconstruction efficiency

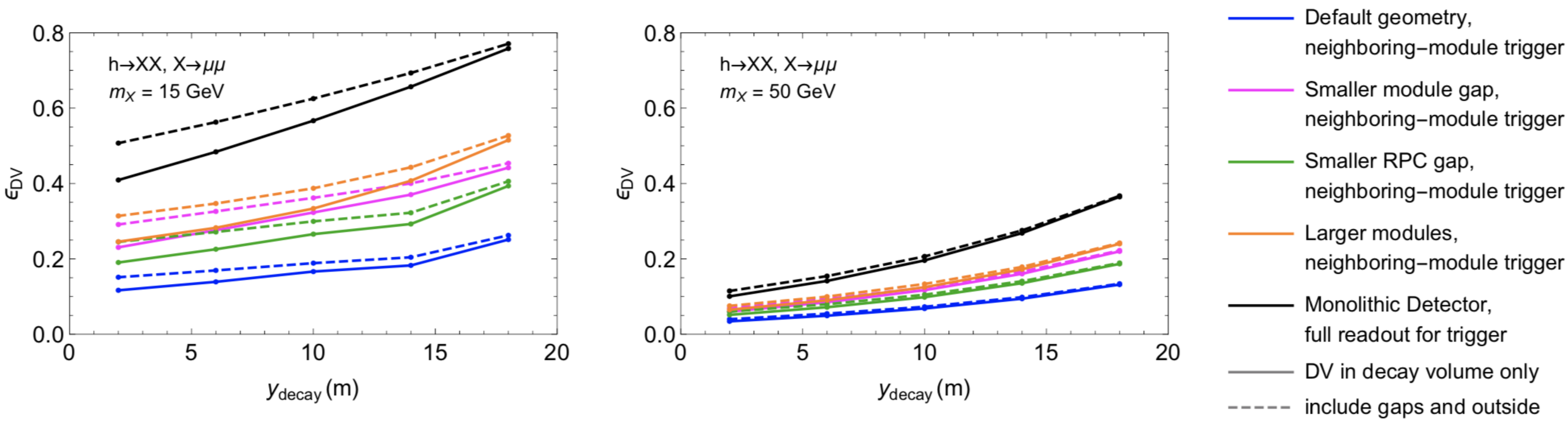


Figure 23. Same as Fig. 22 but for leptonic LLP decays.

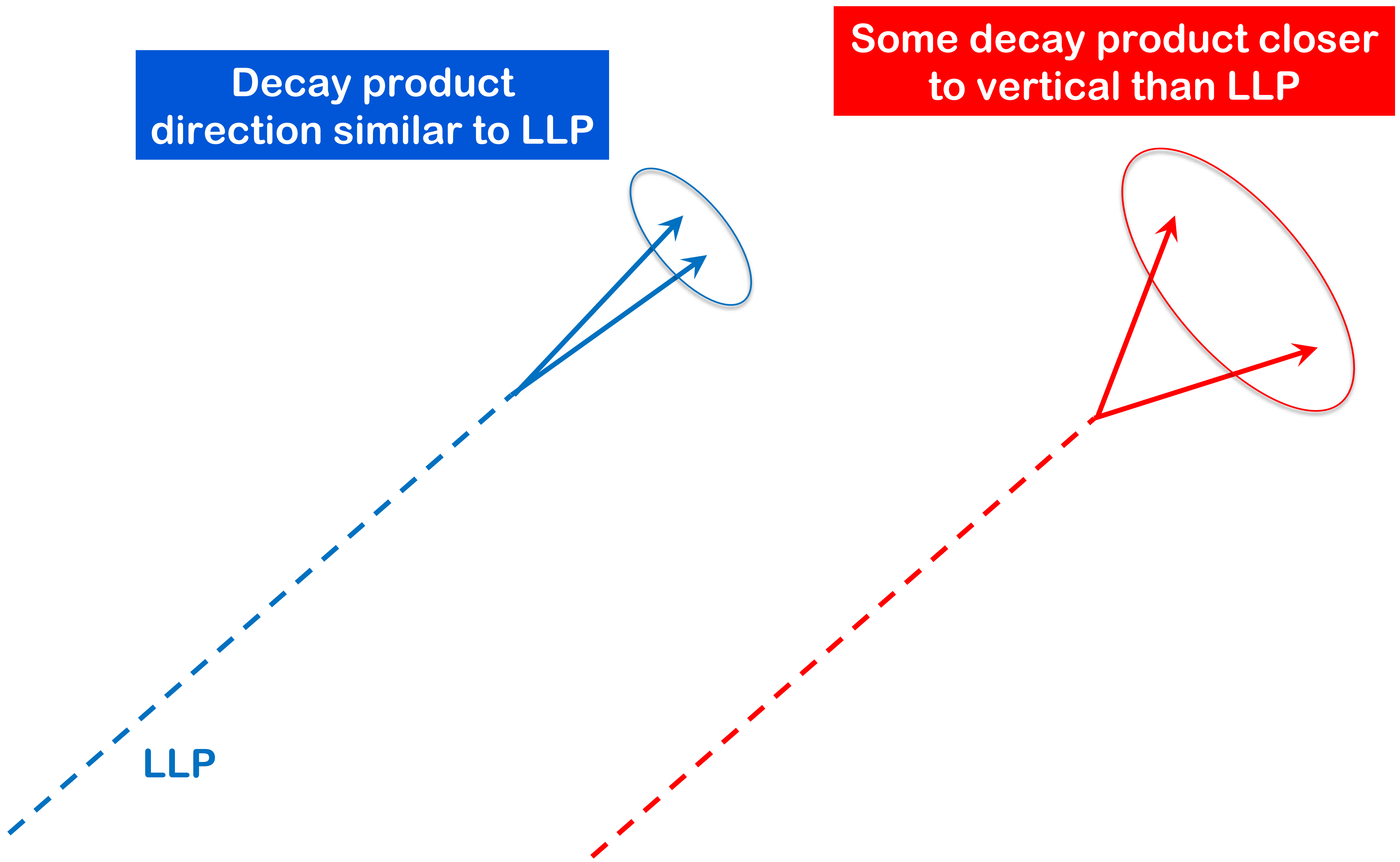
Figure 22. Reconstruction efficiencies for LLPs decaying hadronically a height y_{decay} above the ground in MATHUSLA100. The blue curve corresponds to the modular design of Fig. 17. The magenta, green and orange curves show the effect of changing the gap size between modules or RPC layers, or the module size, see Table. 2. The black curve represents a non-modular monolithic detector that can trigger with full readout, representing the theoretical maximum efficiency for this detector geometry with 5 RPC layers separated by 1 m.

Trigger

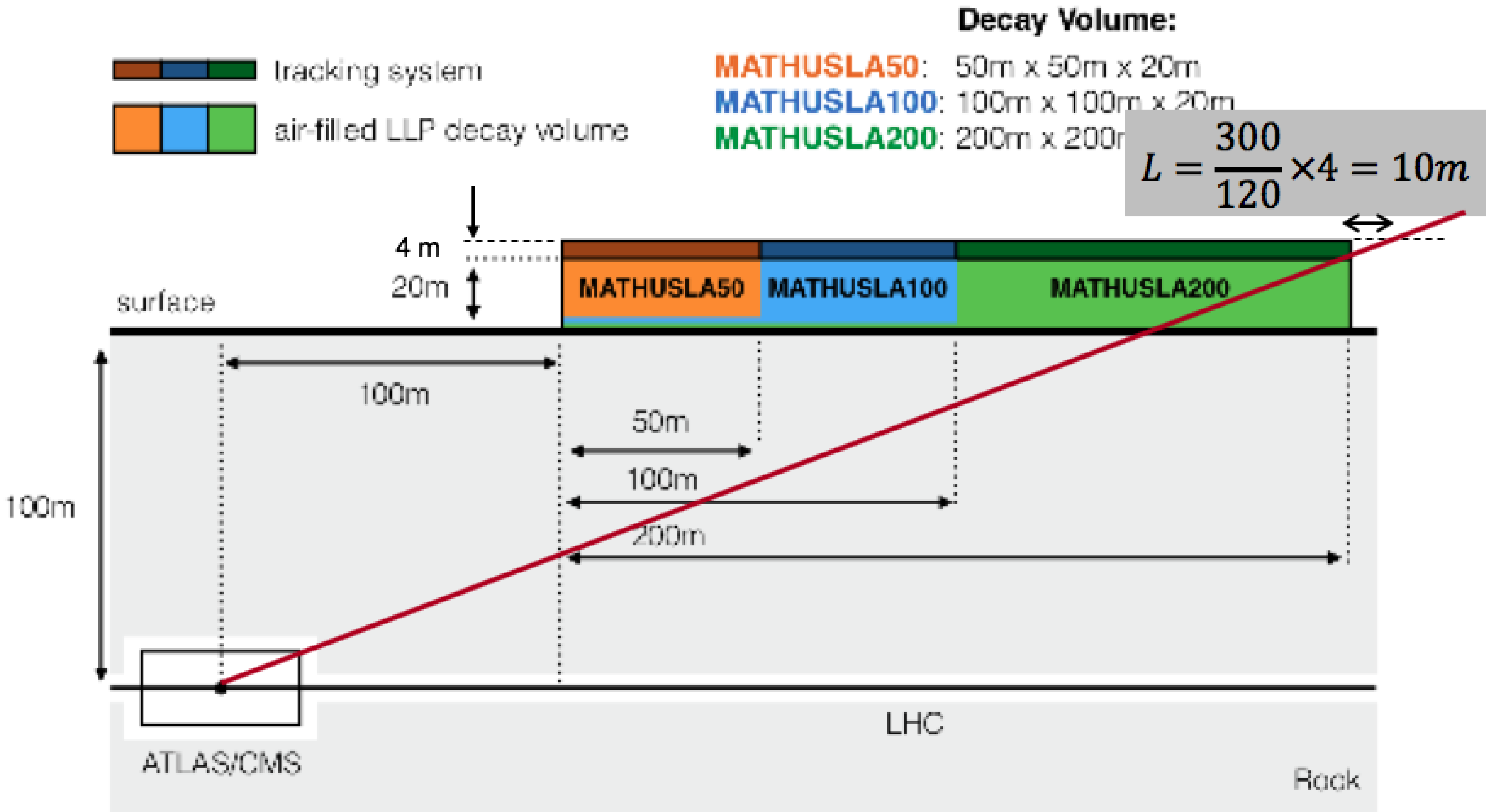
- Envision at least 3 out of 5 layers to define a track (to be insensitive to hit inefficiencies)
  - Studies here have no hit inefficiencies or inter-module gaps
  - Requires crossing all 5 layers
- Require at least one track to trigger

- How many modules required to define trigger tracks?
  - Fewer will be easier to implement - module size cannot be ignored!
  - Too fewer may be inefficient

Direction of Decay Products



Track Inclination

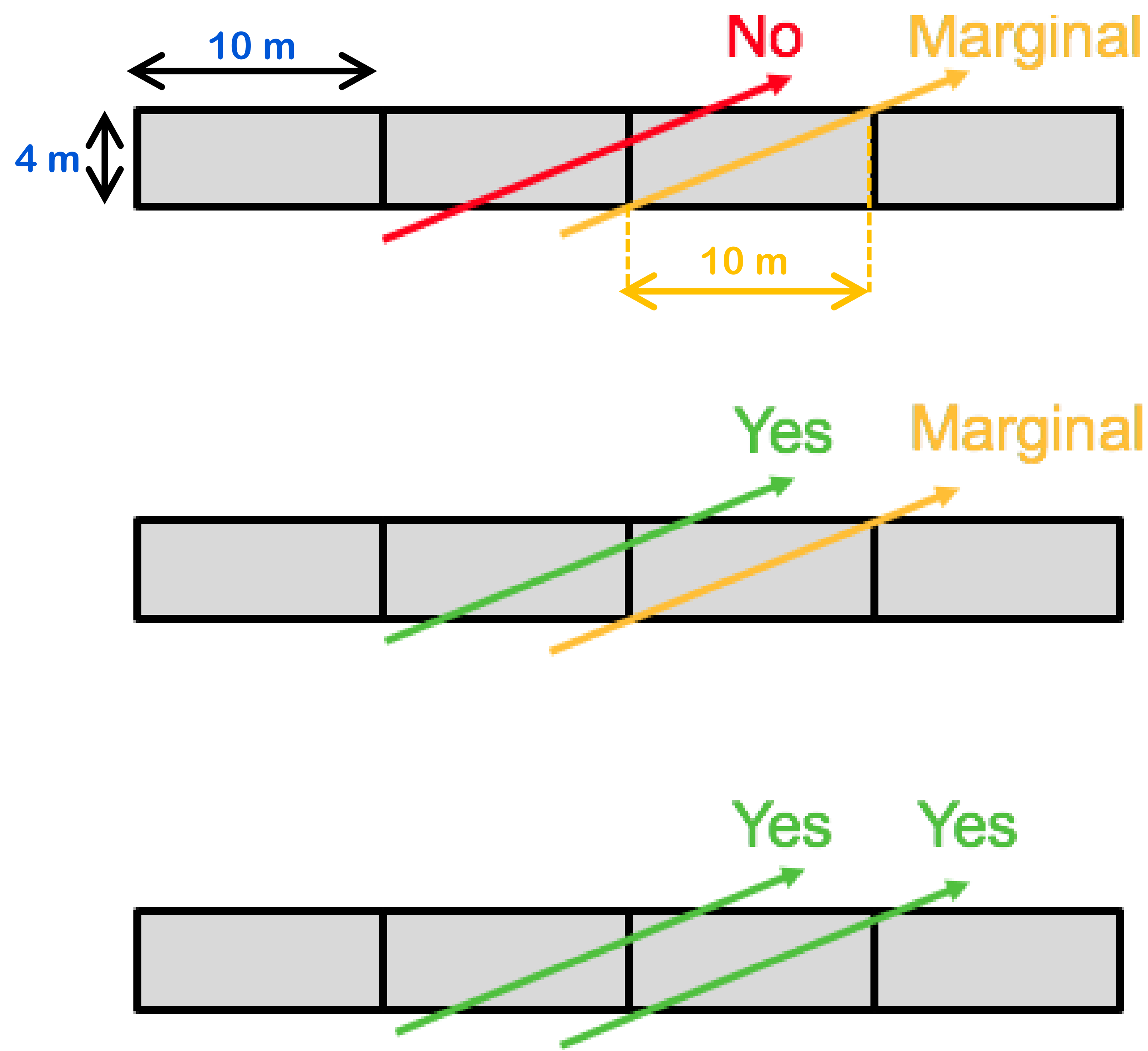


$$L = \frac{300}{120} \times 4 = 10m$$

side view

Number of modules per trigger tower

- 1 x 1
- 2 x 2
- 3 x 3

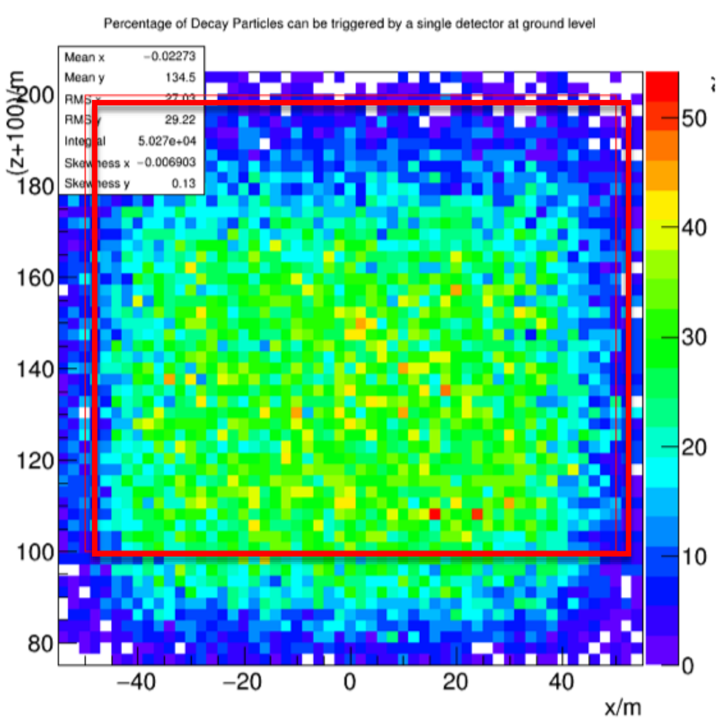


3x3 has safety margin against the largest inclination angle for 200m x 200m detector.

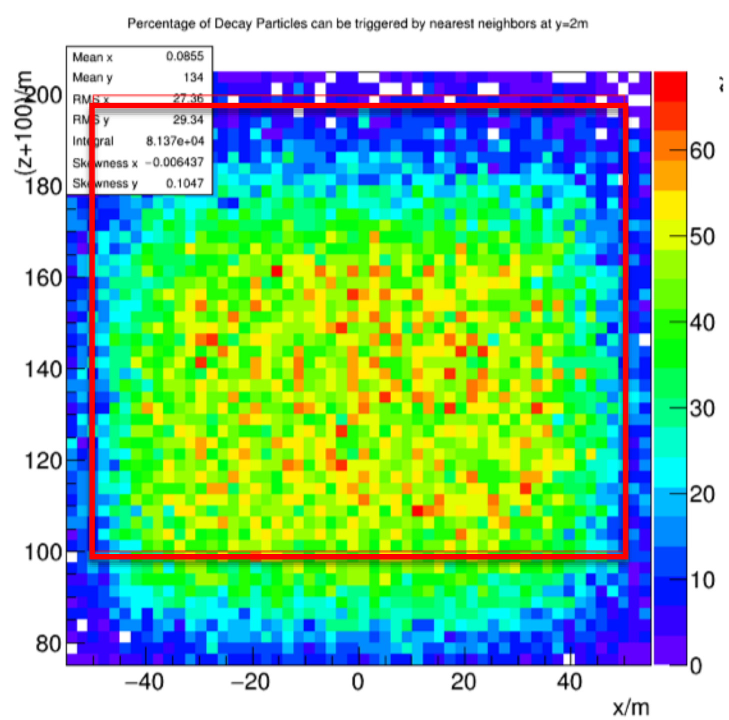
Trigger Efficiency studies

- Di-muon final state
- Decays at 2 m above ground level
- Trigger track to be contained in *n* x *n* modules
- Red outline is the footprint of the MATHUSLA100

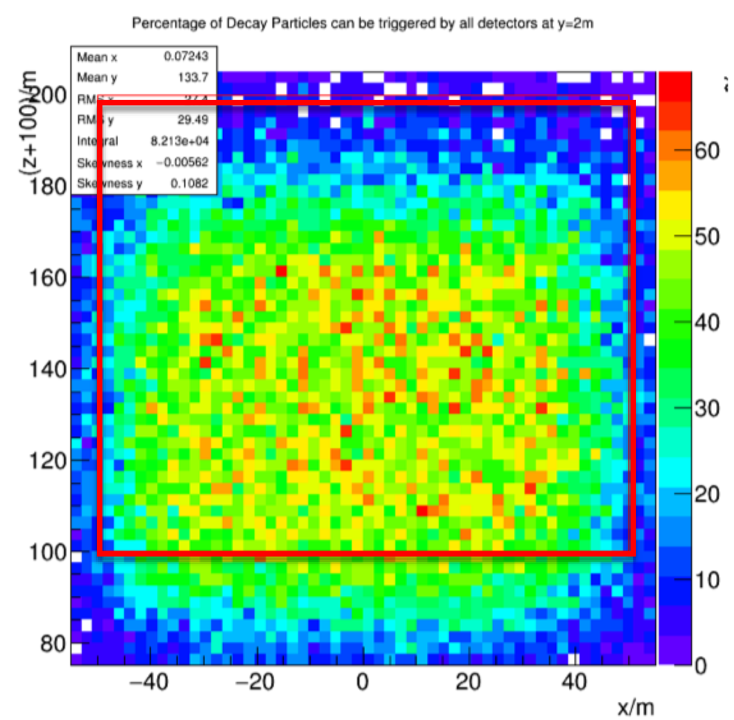
1 x 1 modules



3 x 3 modules

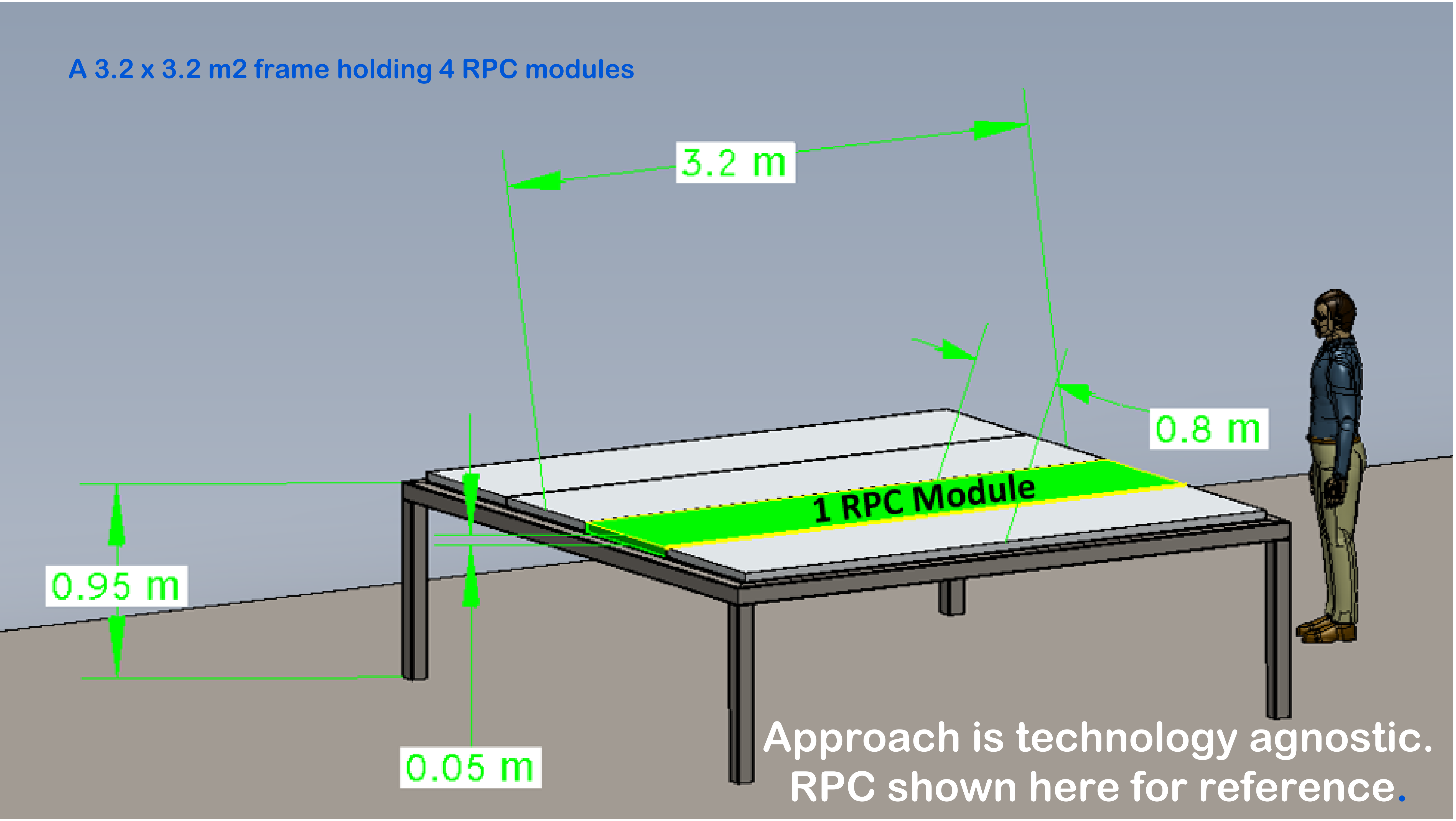


All modules

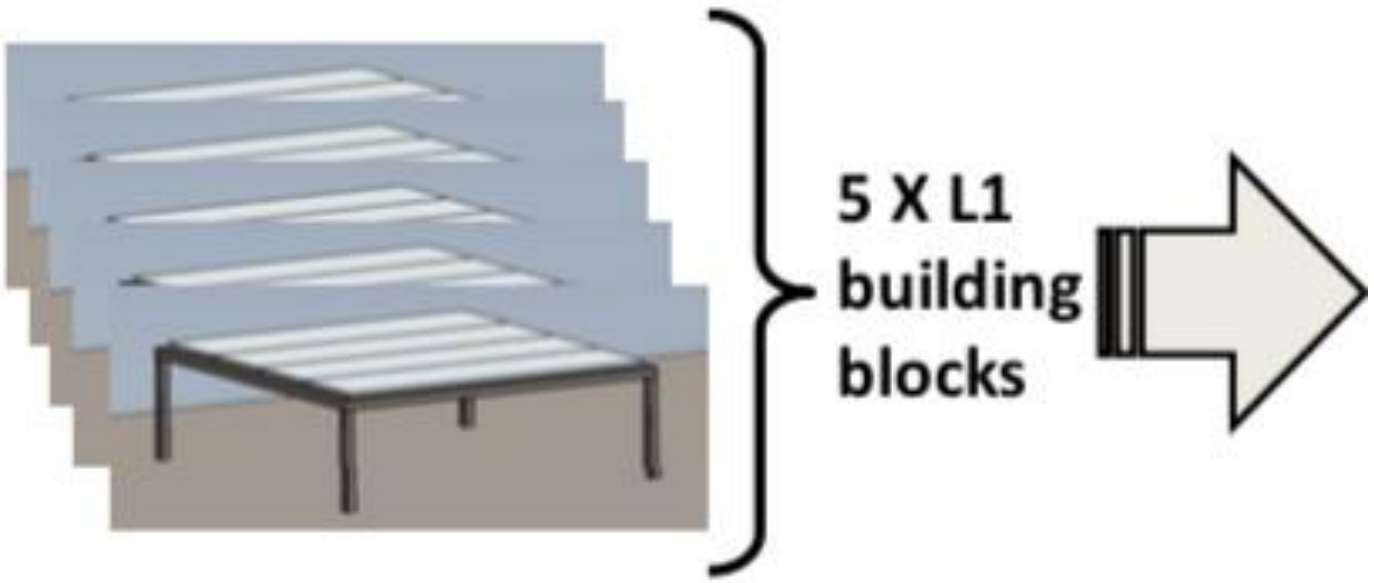


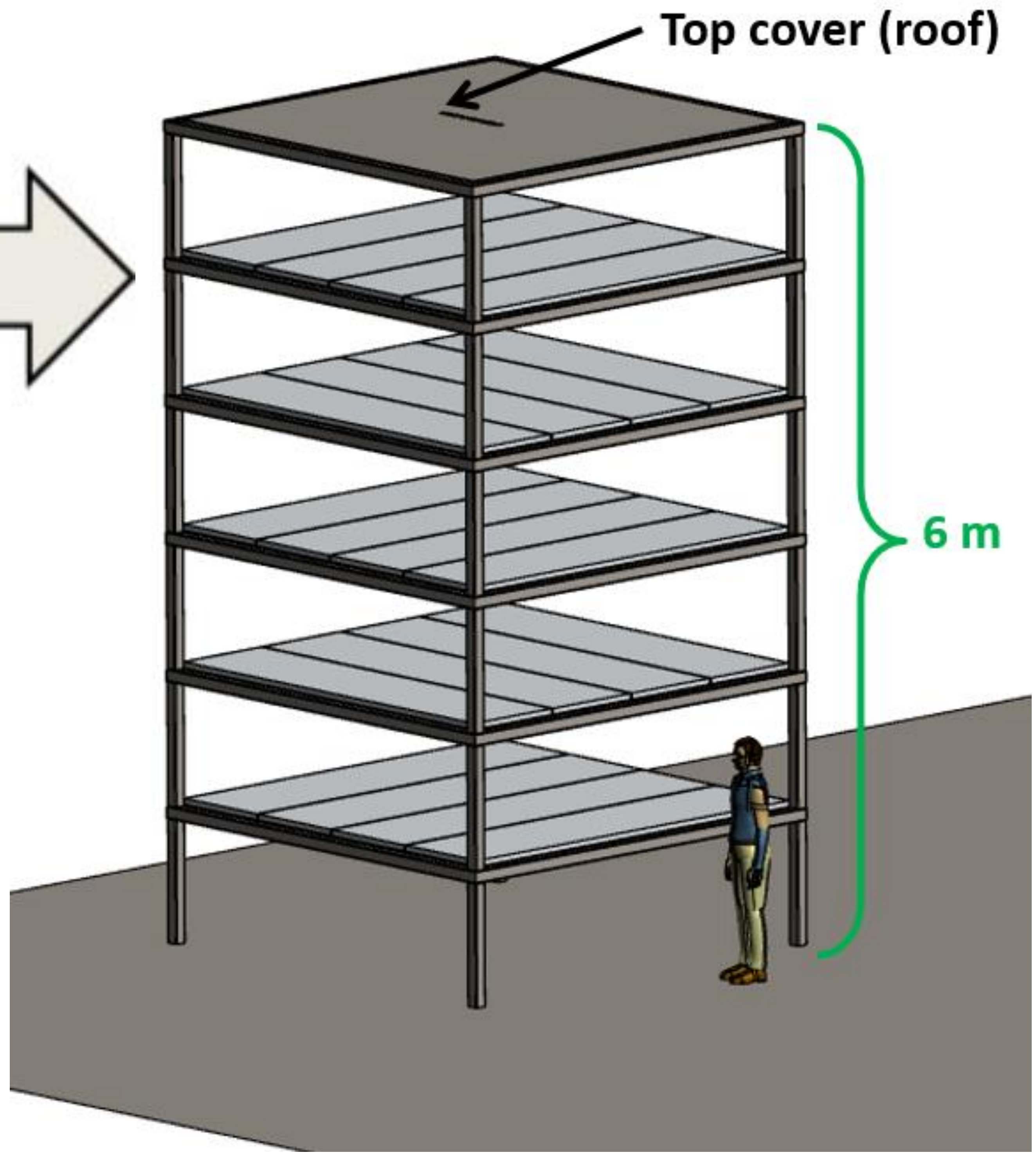
Engineering concepts

Basic (L1) building block



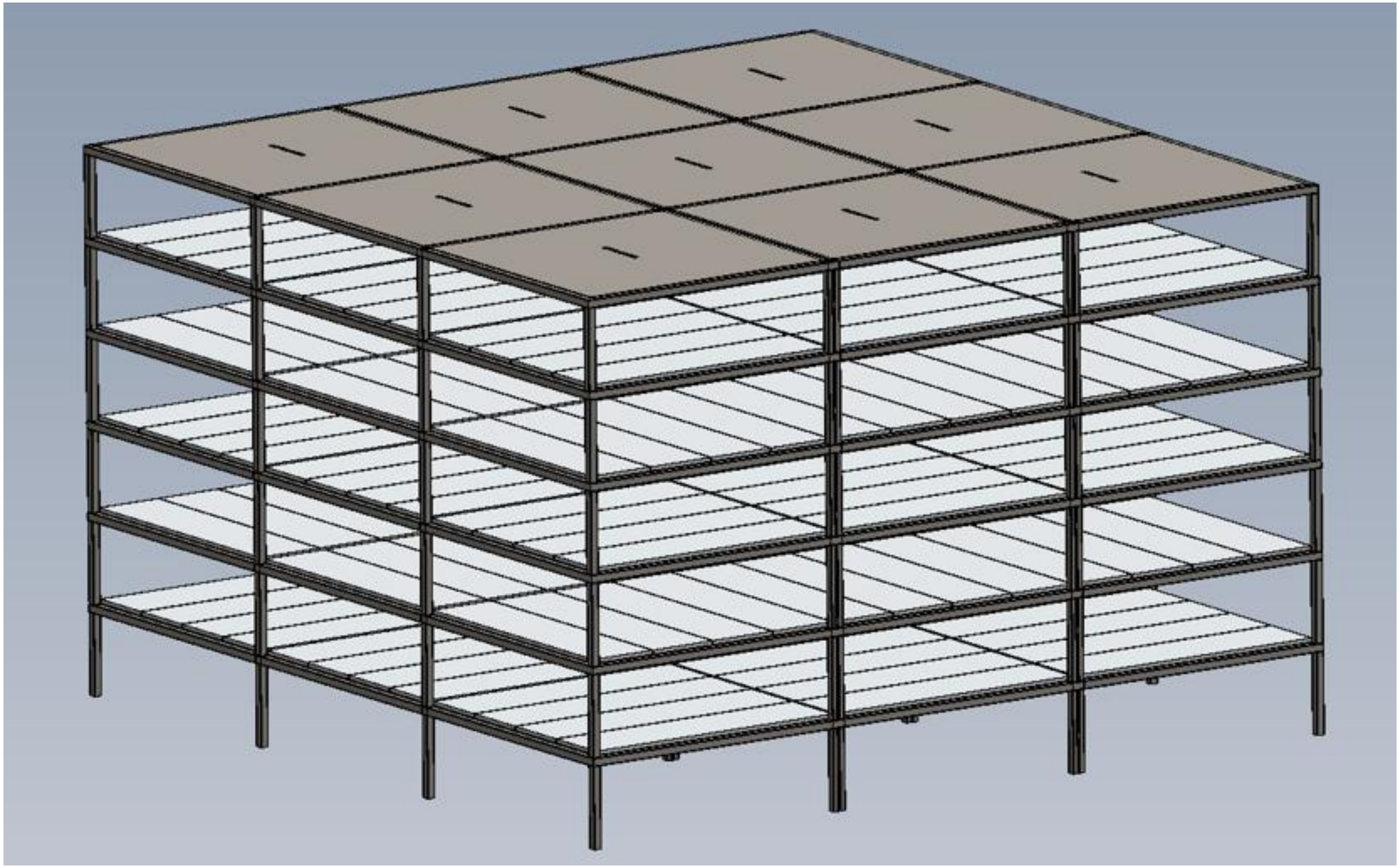
L2 building block





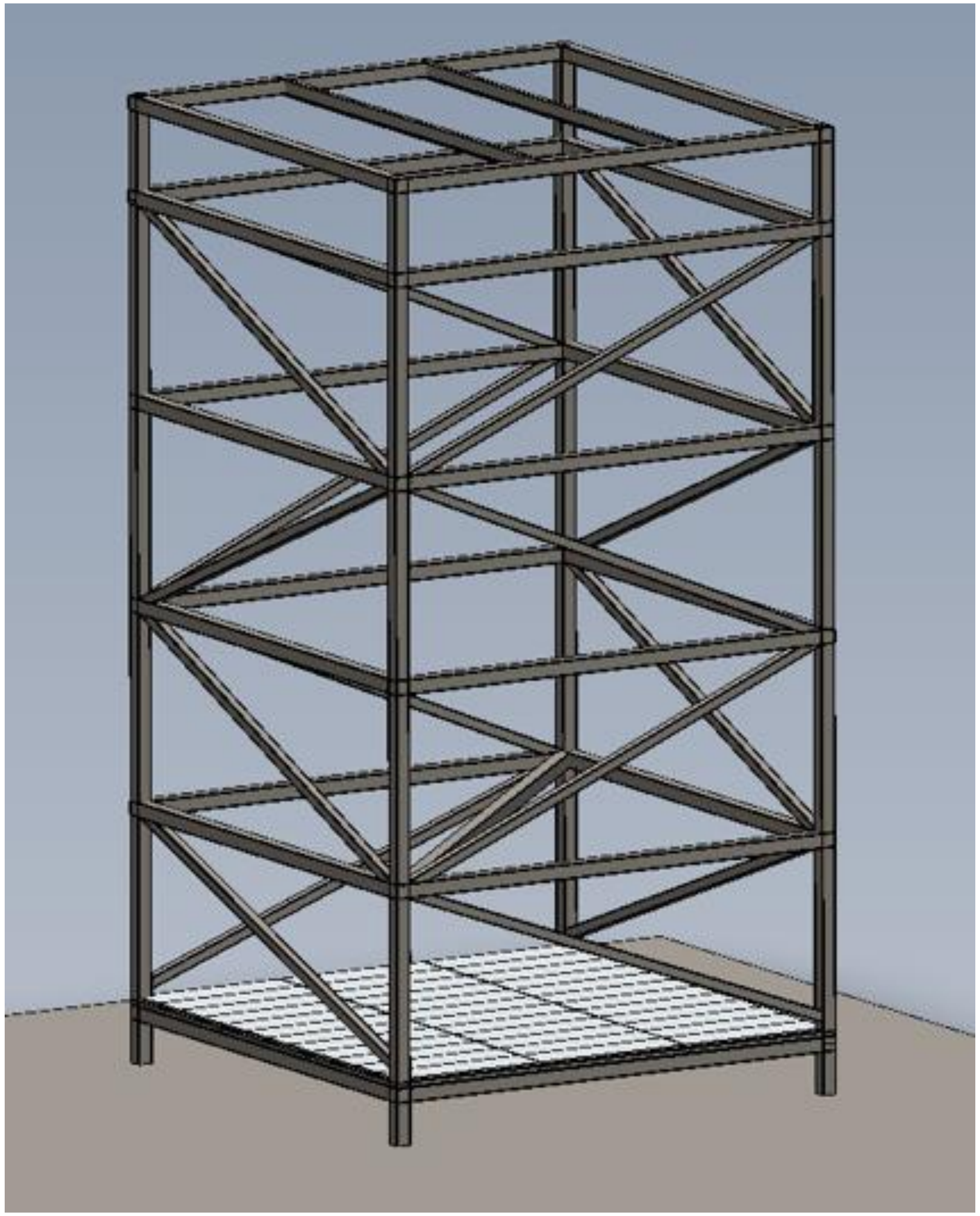
- 5 tracking layers
- Separation of 1 meter (3 ns)=>24 ns between upward and downward particles.
- Provide robust tracking for BG rejection and DV reconstruction

Top tracker - 3x3 Array of L2 blocks

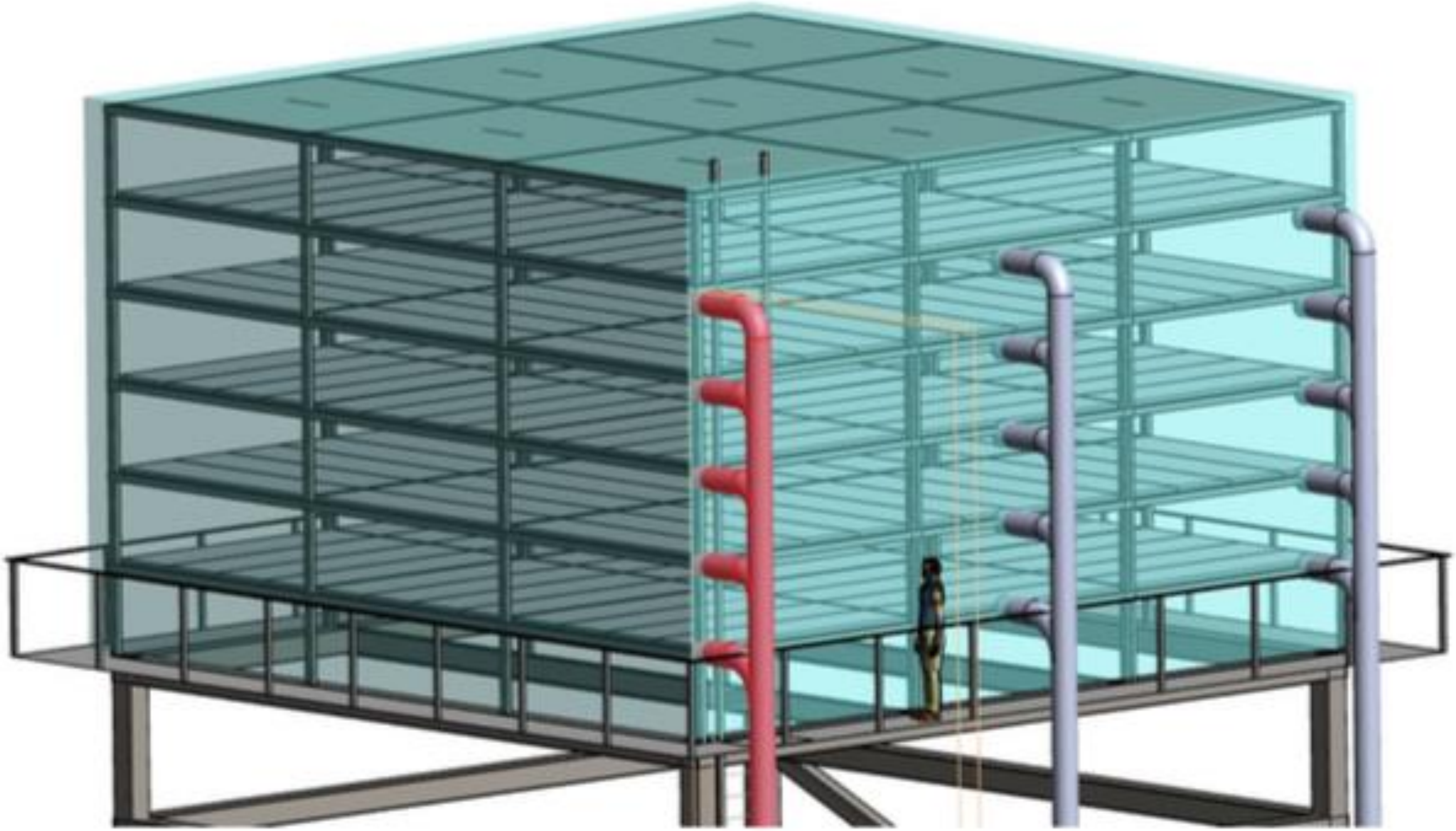


Bottom layer and construction

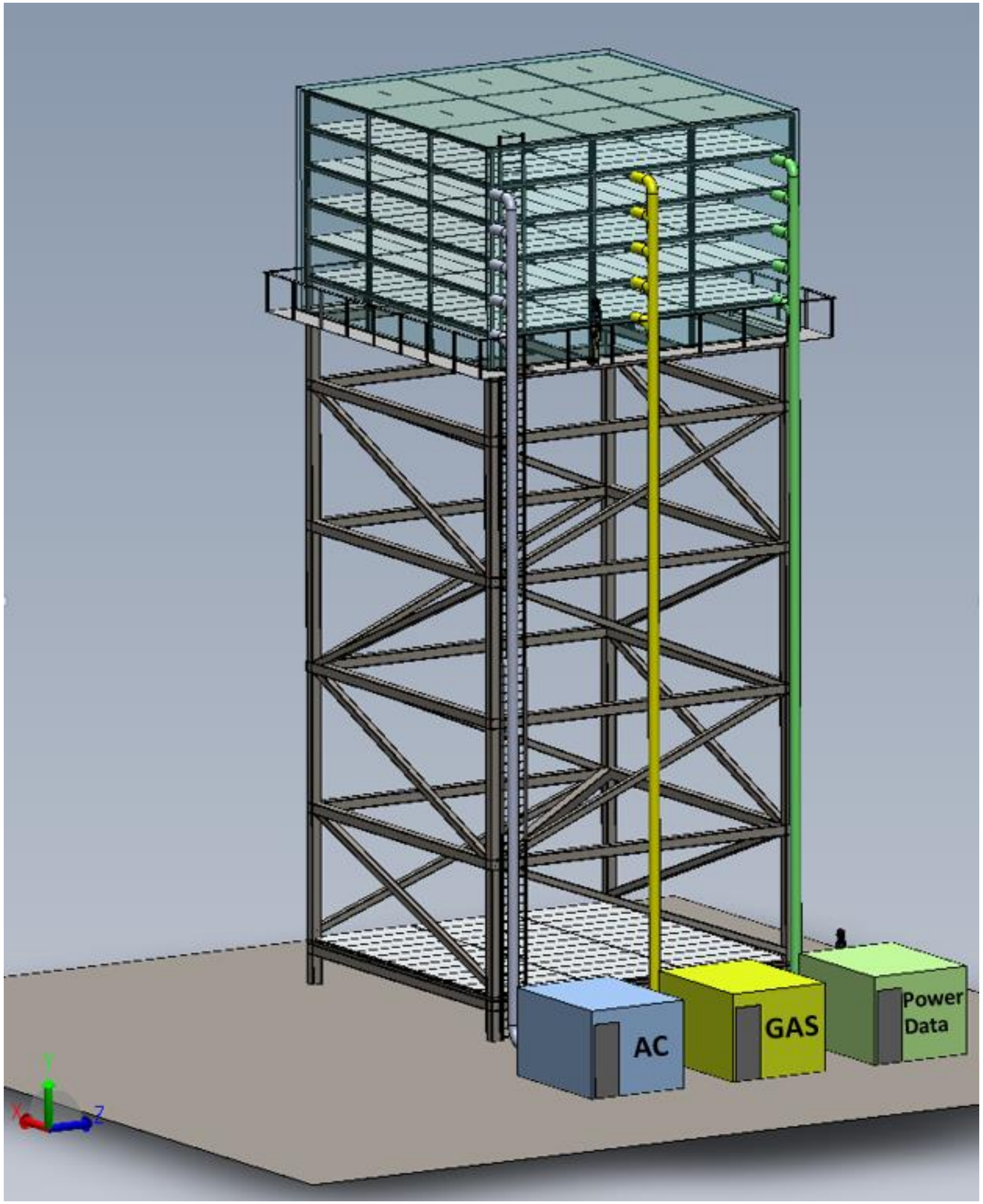
- Bottom layer is 3 x 3 array of L1 blocks
- Structure made of 30 cm x 30 cm rectangular steel profile



External walls (climate ..)

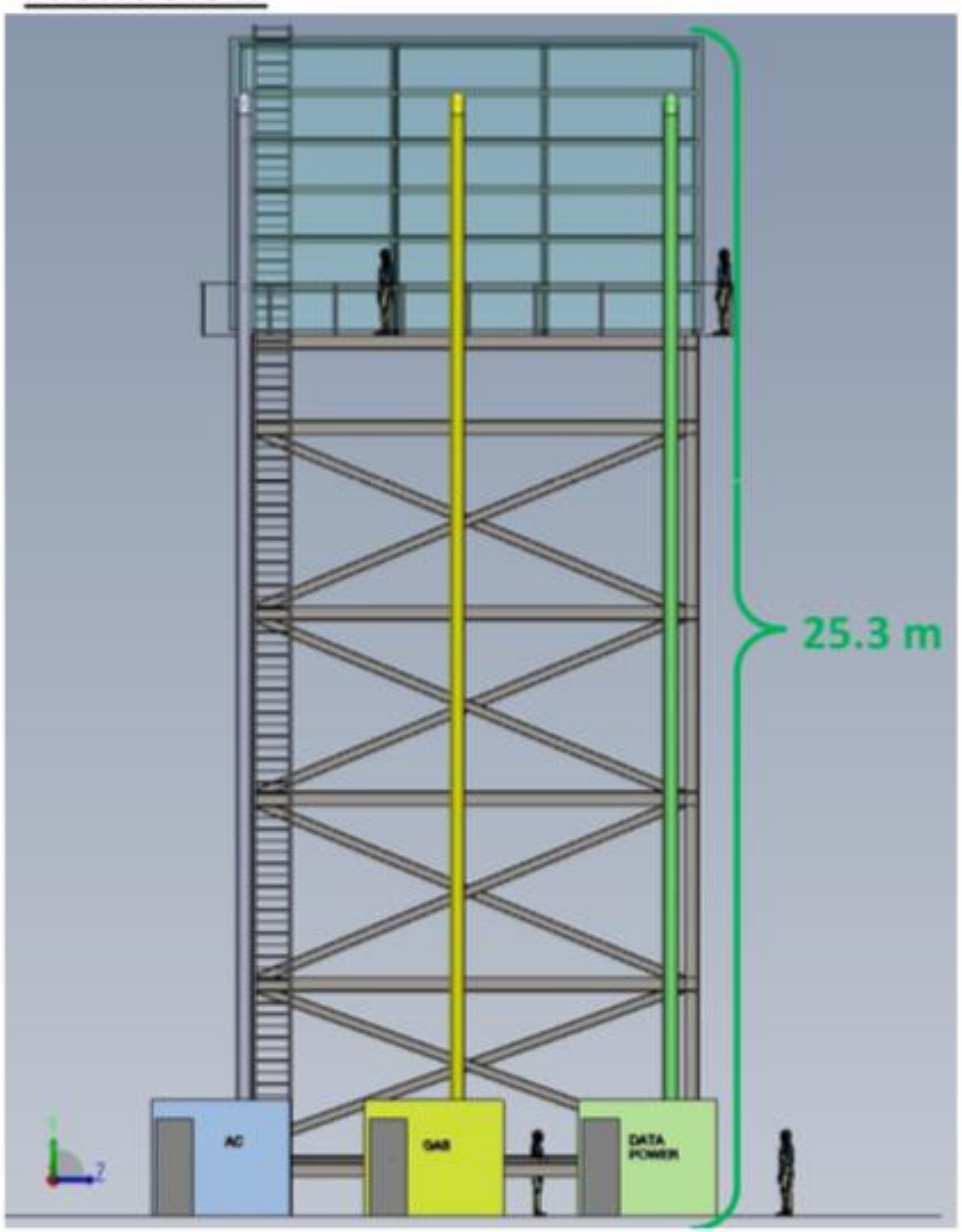


- Walking platform
- Climbing lader
- AC top tracker and lower level
- Gas mixing monitoring supply room
- Power / readout / control room

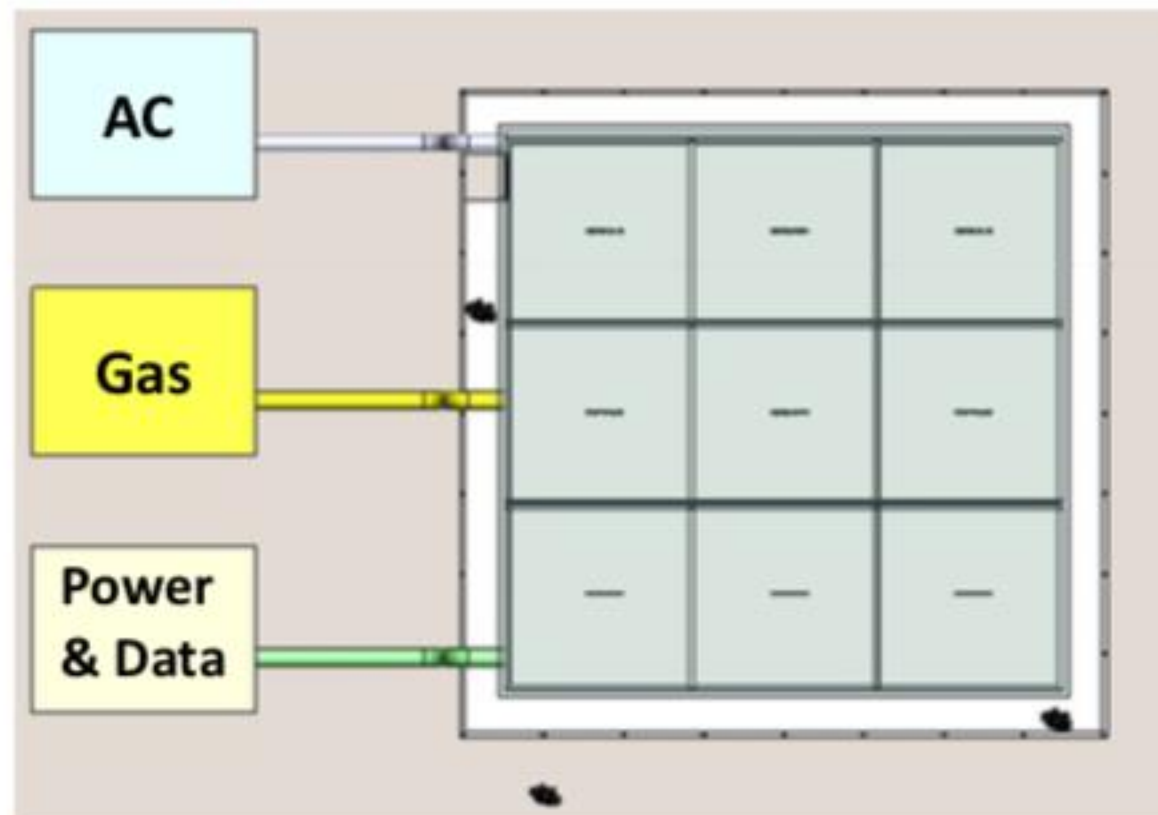


MATHUSLA 9.6²

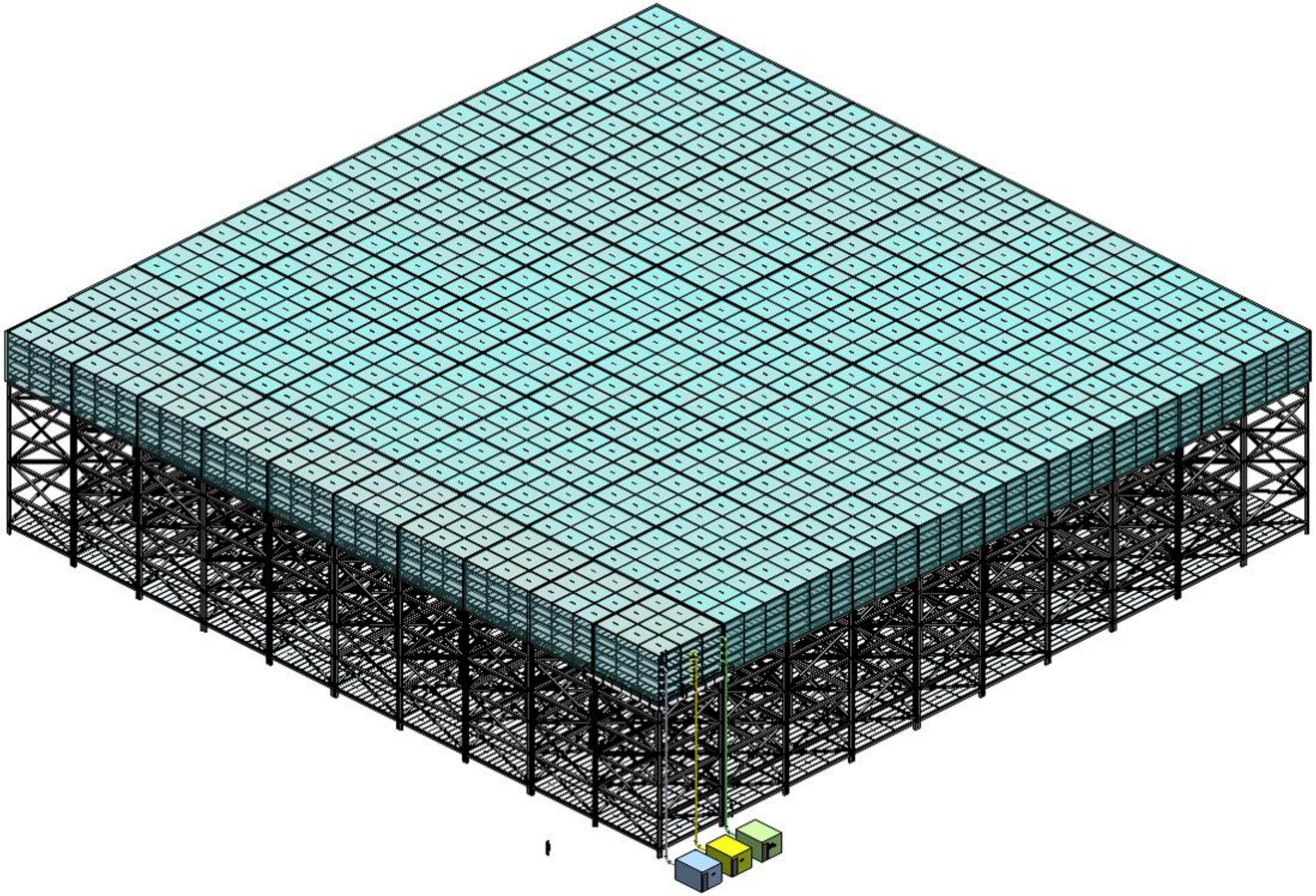
Front view



Top view



Fulll size MATHUSLA 100



- 105 x 105 x 25
- Inter module gap - 1m.

Summary

- Modular design
  - Each module independently functional
  - Each module weathertight
  - Fully tested before installation
  - Assembled to fit ultimate detector footprint
  - Staged installation as well as staged upgrade

- BACKUP

Sensitivity for LLP detection

- Characterisation of the signals:
  - Clean vertex of lepton pair
  - Vertex with two energetic jets, large angular separation
  - LLP decay length from microns to 10^8 m..
- Signal sensitivity
  - Geometrical acceptance
  - Detector efficiency
  - Decay volume .vs. the LLP decay length
  - Background rejection

Sensitivity for LLP detection

- Benchmark: **Higgs to LLP**, assuming $N_h = 1.5 \times 10^8$ Higgses for HL-LHC,
  and take the invisible Higgs with Br of 30%
- $N_{obs} \approx N_h \cdot Br(h \to LLP \to SM) \cdot Accept \cdot \frac{Length}{bc\tau}$
- b is the LLP Lorentz boost. If the Higgs is produced on threshold, and it decays to n LLP with M_x
  $b \approx \frac{m_h}{n \cdot M_X}$. For $M_x > 20$ GeV and $n = 2 \Rightarrow b \leq 3$
- Naive estimation:
  - A few events = discovery
  - Exclusive decay of LLP to SM
  - $c\tau = 10^7 m$
- $\Rightarrow L \approx (20m)(\frac{b}{3})(\frac{5\%}{Accept})(\frac{30\%}{Br(h \to LLP)})$
  The required dimensions are geometrical coverage of a few % and Length (height) of 20 m

Size matters…

- Physics reach scales with decay volume

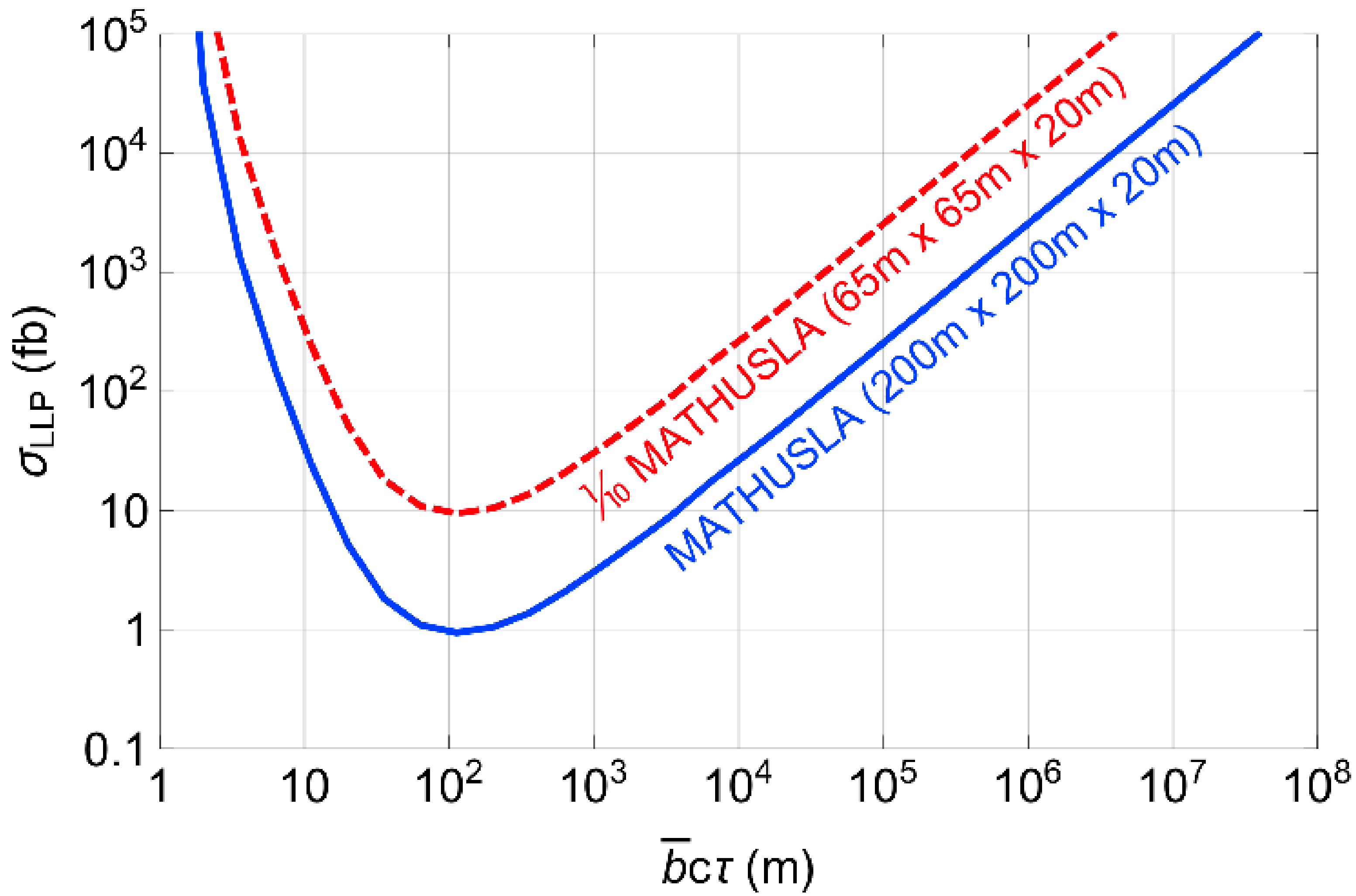
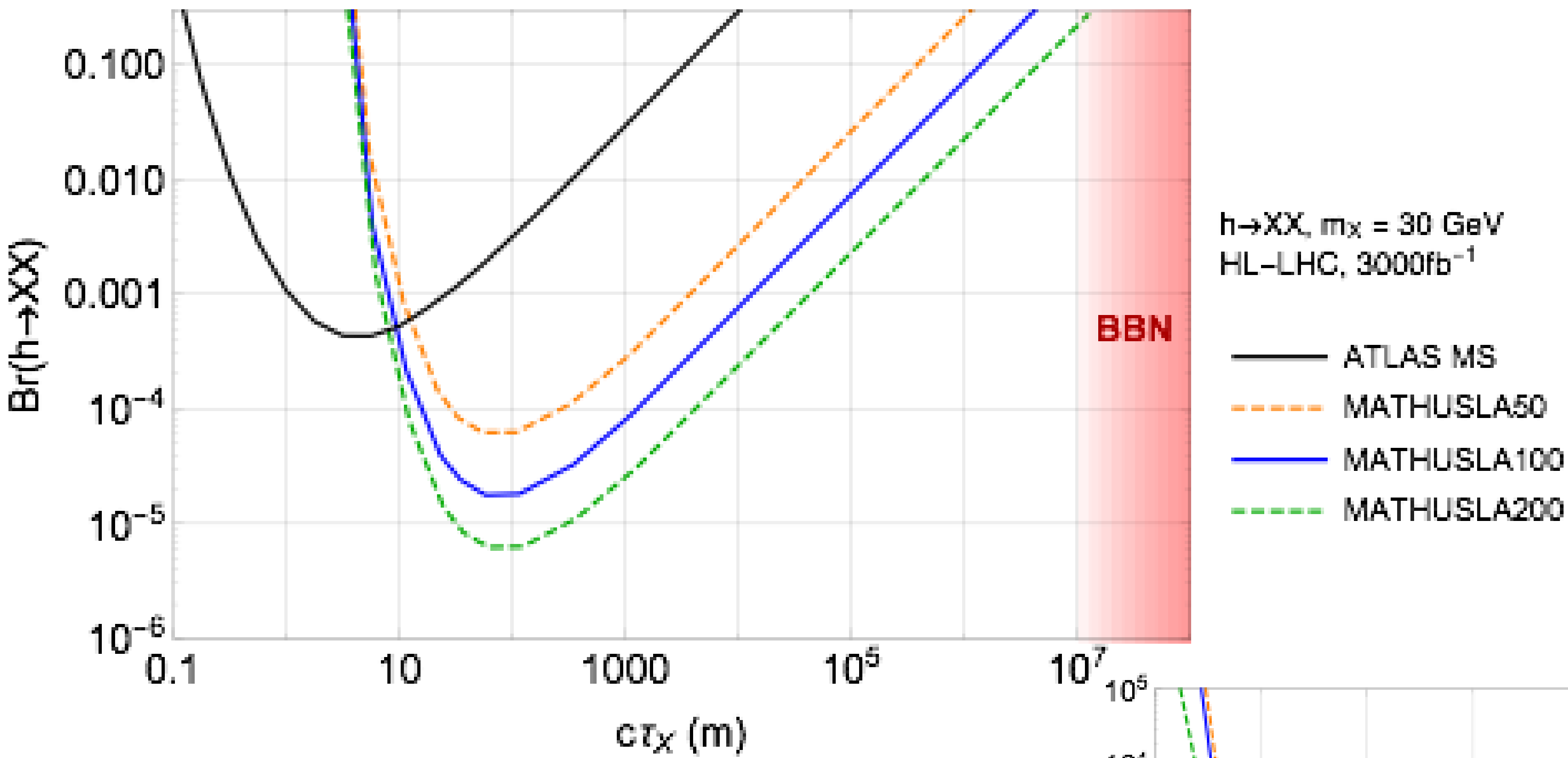
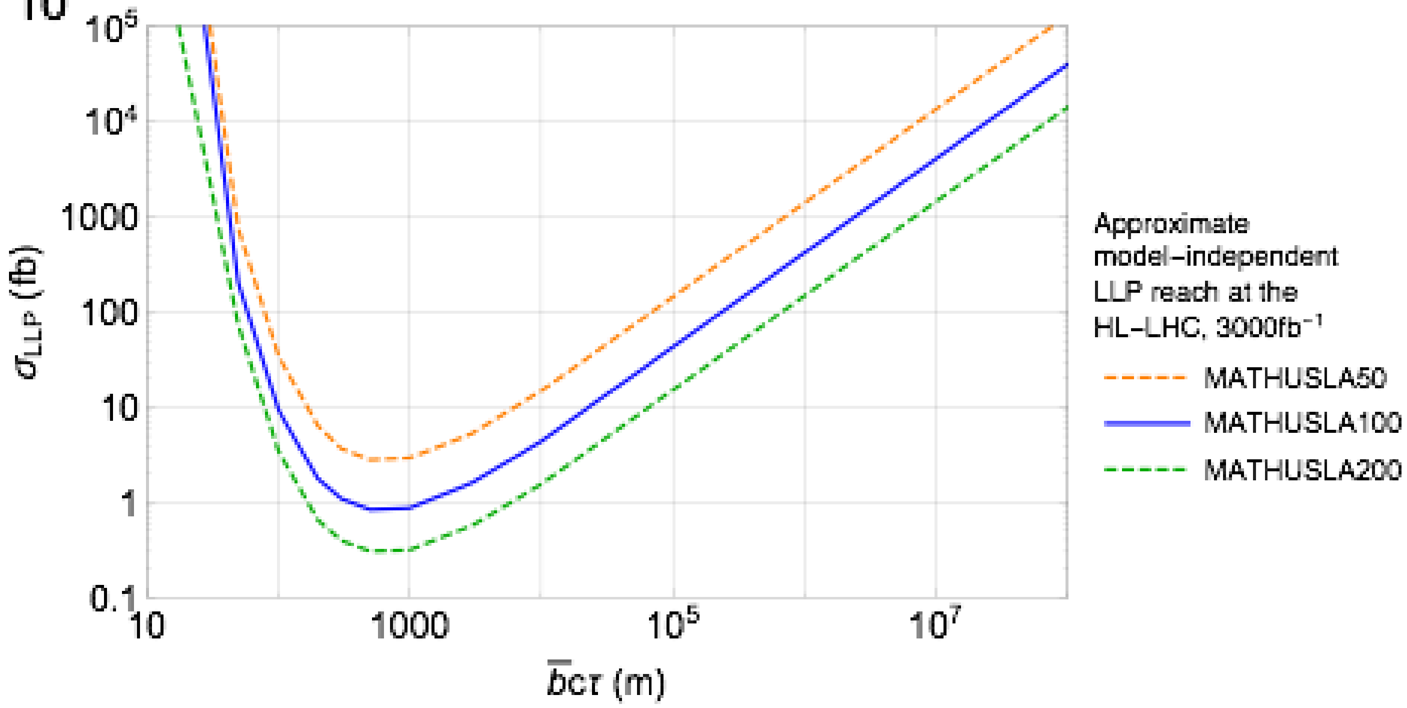


Fig. 7: Schematic order-of-magnitude sensitivity of MATHUSLA, assuming $\mathcal{O}(1)$ produced LLPs per production event at the HL-LHC. $\bar{b}$ is the mean boost of the produced LLPs. The shape of the exclusion/discovery region at short lifetimes depends on the detailed boost distribution, but for long lifetimes $\bar{b}c\tau \gg 200m$ depends only on the mean boost and is very model-independent up to an $\mathcal{O}(1)$ factor. Note that LLPs near the BBN lifetime limit of $c\tau \sim 10^7$m can be probed if they are produced with cross-sections in the pb range at the HL-LHC. To emphasize the scalability of the MATHUSLA design, we also show the reach achievable with a version of MATHUSLA with only $1/10$ the detector volume of the $200m \times 200m \times 20m$ benchmark geometry.

Sensitivity versus area

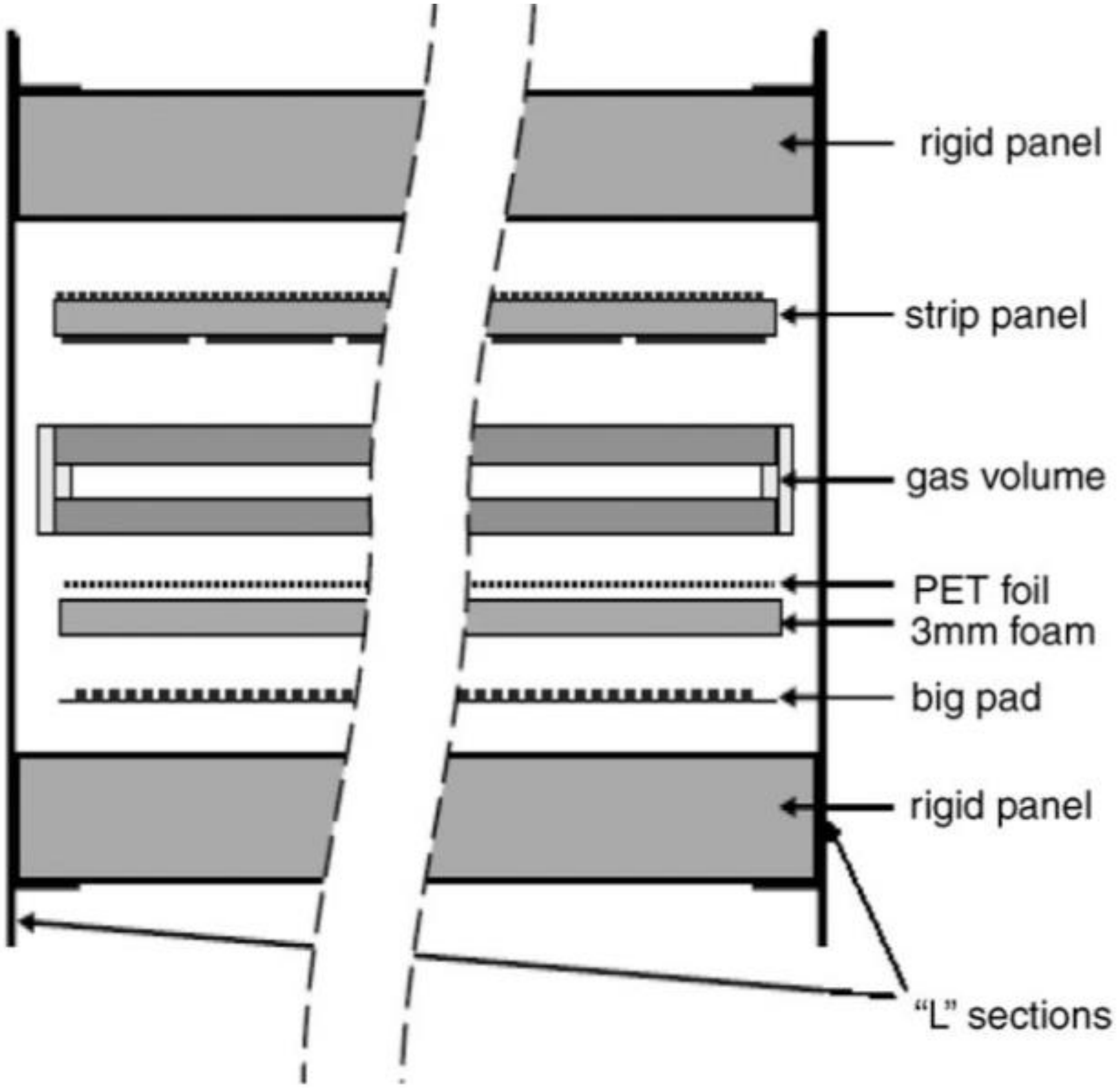




Mathusla sensitivity for LLP (H->xx)
Beta is the boost of LLP. Shown for
Various sizes of MATHUSLA

Modular structure

- Array of independent units of RPCs.
- Single RPC basic dimensions 3.2 x 0.8 x 0.05 meter
- Estimated weight 15 kg (detector) + 20 kg = 35 kg
- Each module connects to pass supply, dedicated HV line and readout lime.
- Assumptions:
  - Spatial Resolution 1cm
  - Timing 1 ns
  - Single hit efficiency 98%



Next steps