Searches for ultra long-lived particles with MATHUSLA

Emma Torró, for the MATHUSLA Collaboration

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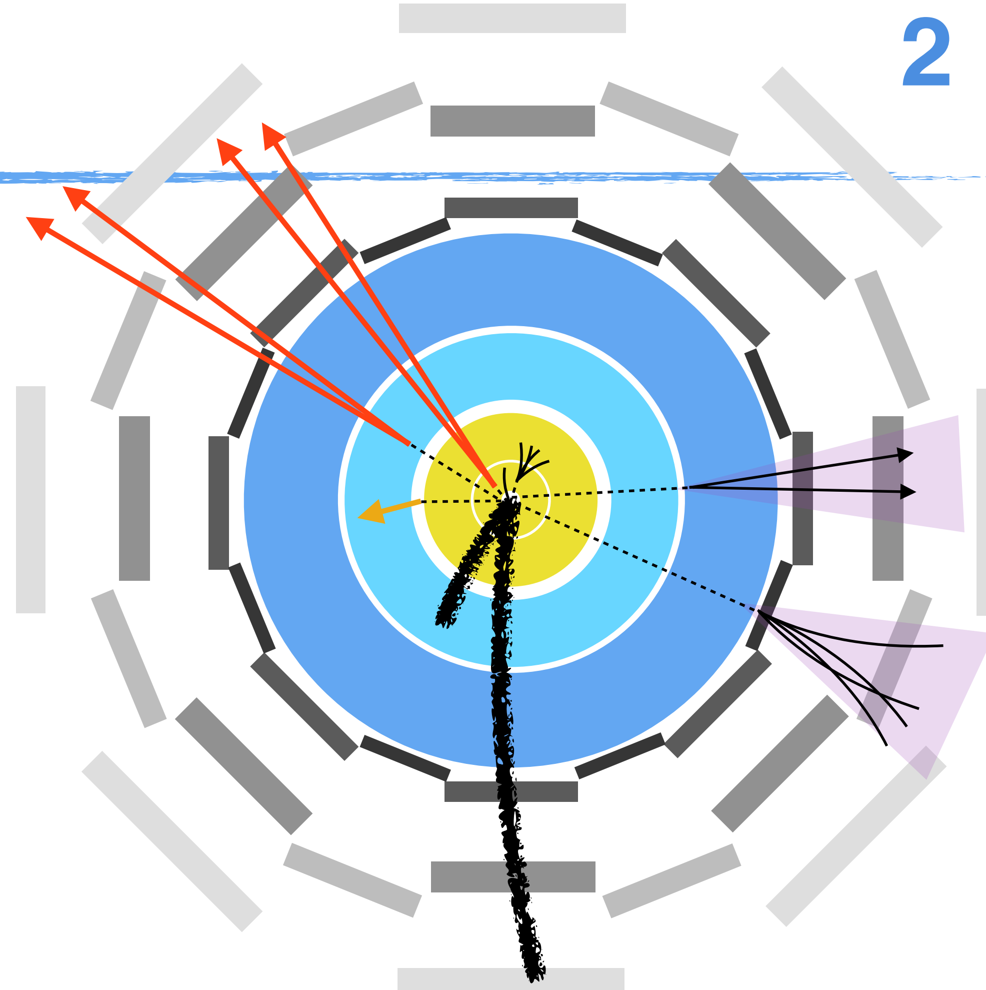
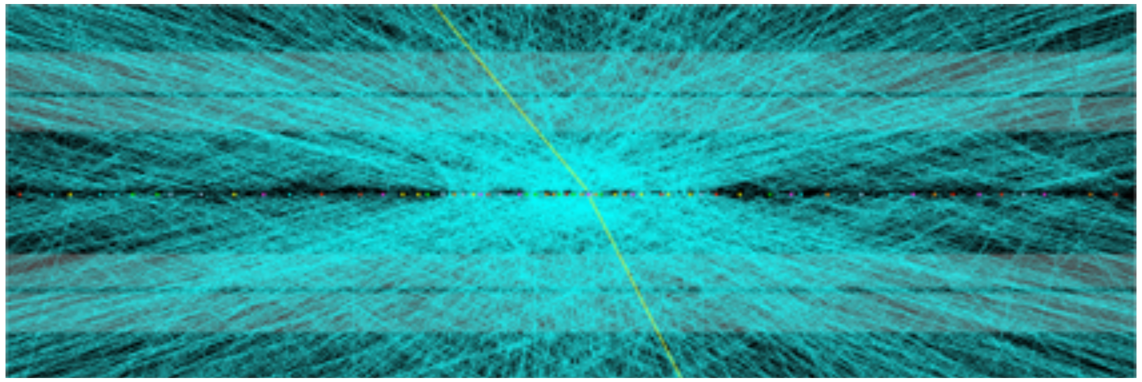
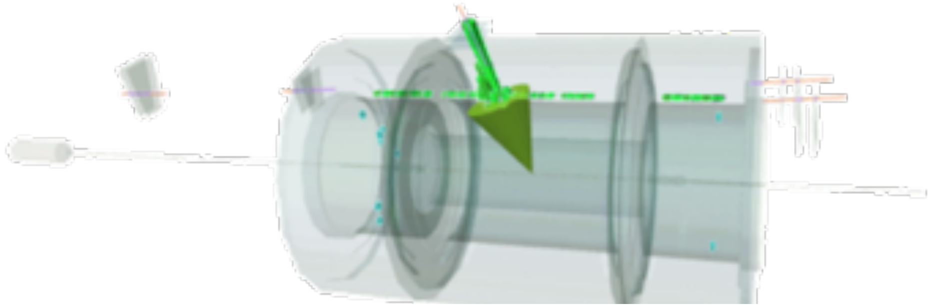
Why MATHUSLA?



- ATLAS, CMS, LHCb have a wide program to search for LLPs
- However these searches are limited by a number of factors:
  - triggers
  - backgrounds from collisions (including pileup)
  - backgrounds from the beam
  - cosmics
  - the size of the detector



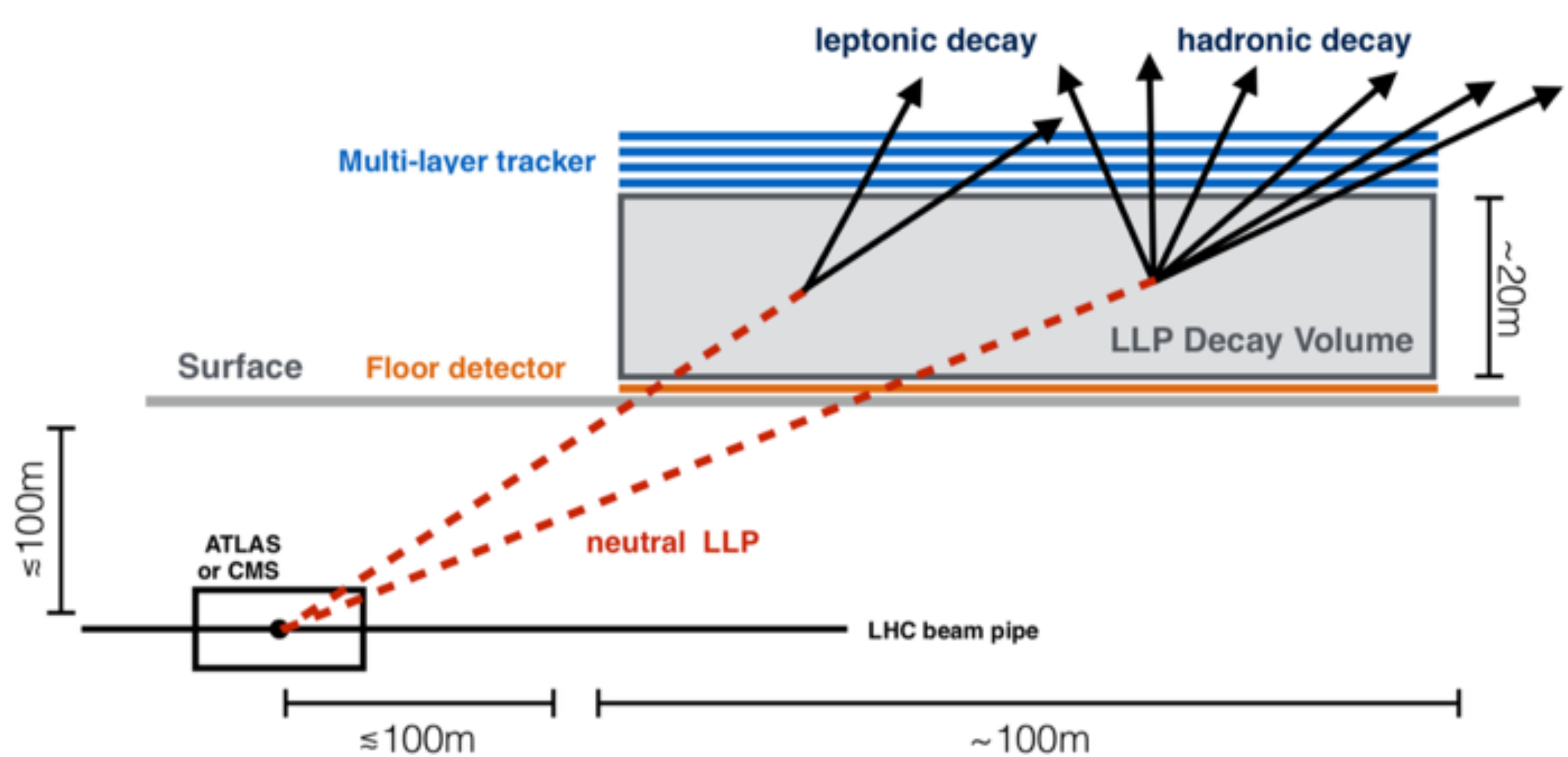


- A detector working in a clean **background-free** environment would increase the sensitivity
- **MATHUSLA is designed to be such detector**

MATHUSLA concept

- **MATHUSLA: MAsive Timing Hodoscope for Ultra Stable neutraL pArticles**
- Going to Big Bang Nucleosynthesis (BBN) limit (10^7 - 10^8 m) lifetime, need to suppress SM backgrounds
- Dedicated detector placed on the surface above CMS or ATLAS detectors LHC:

  O(90) meters of rock takes care of problem ☺
- Large volume filled with air as decay volume with several detector layers for tracking



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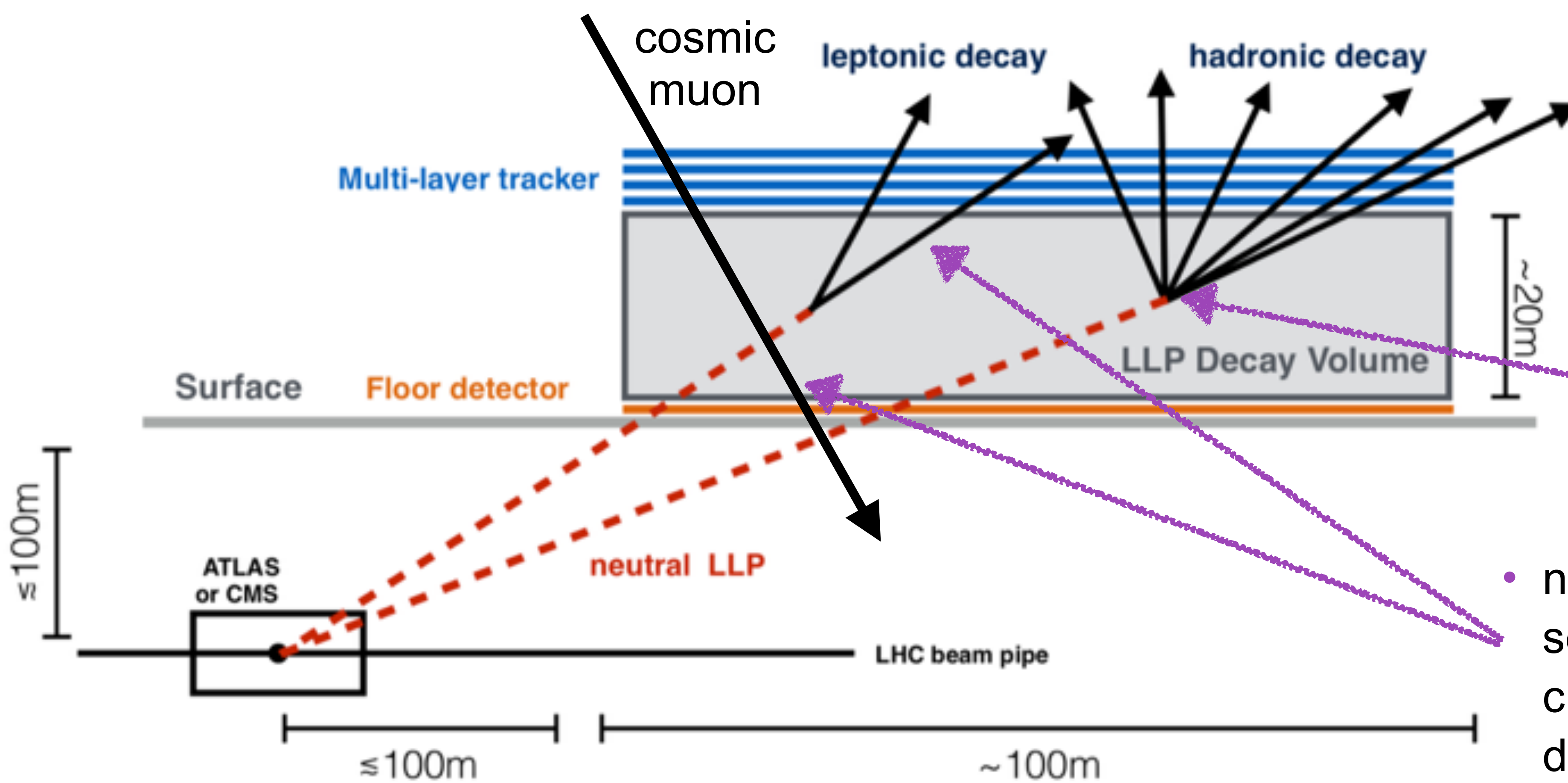

- need robust tracking for vertex reconstruction
- need good timing for separating upward going charged particles from downward going cosmic muons.

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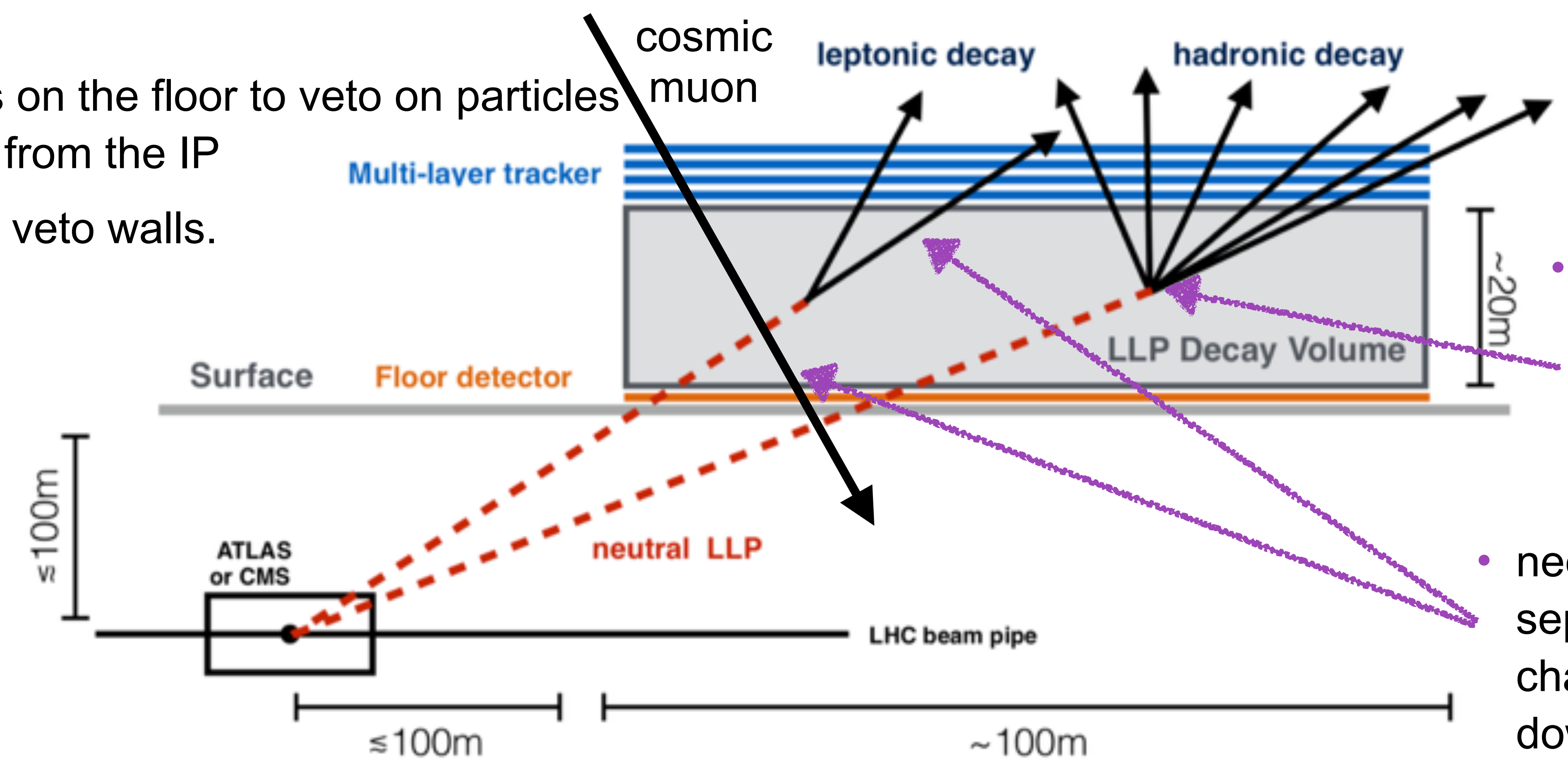
- 5 layers for robust tracking (originally RPCs, currently scintillators are being considered)
- 2 layers on the floor to veto on particles coming from the IP
- No side veto walls.



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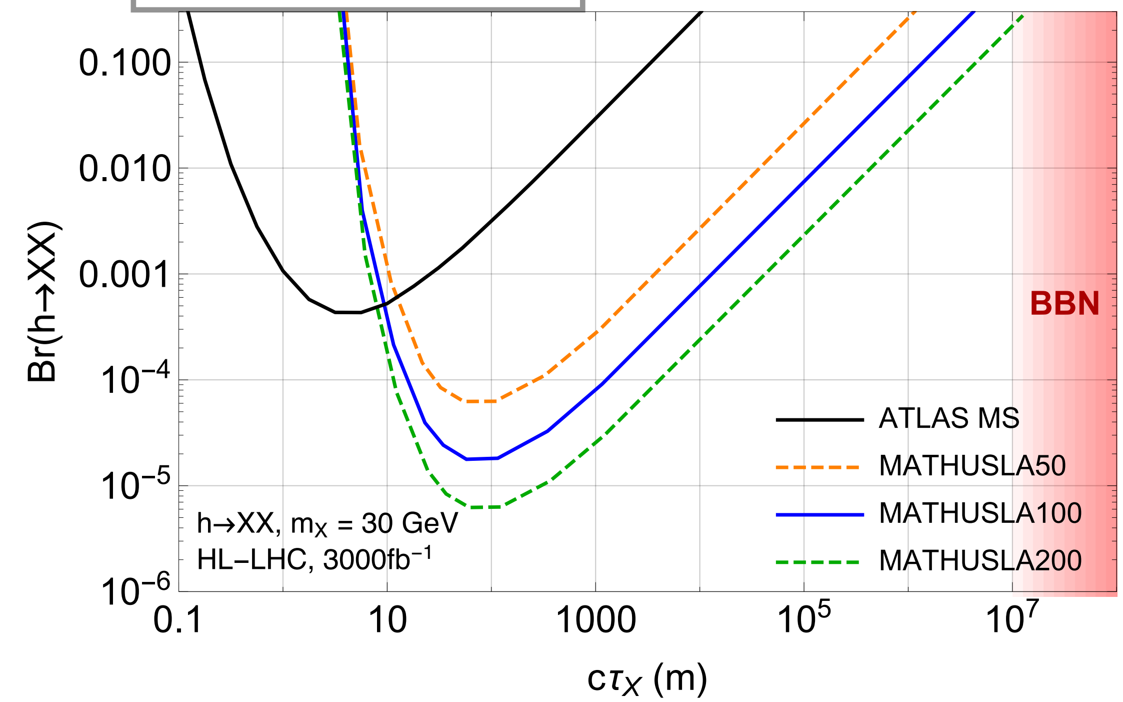
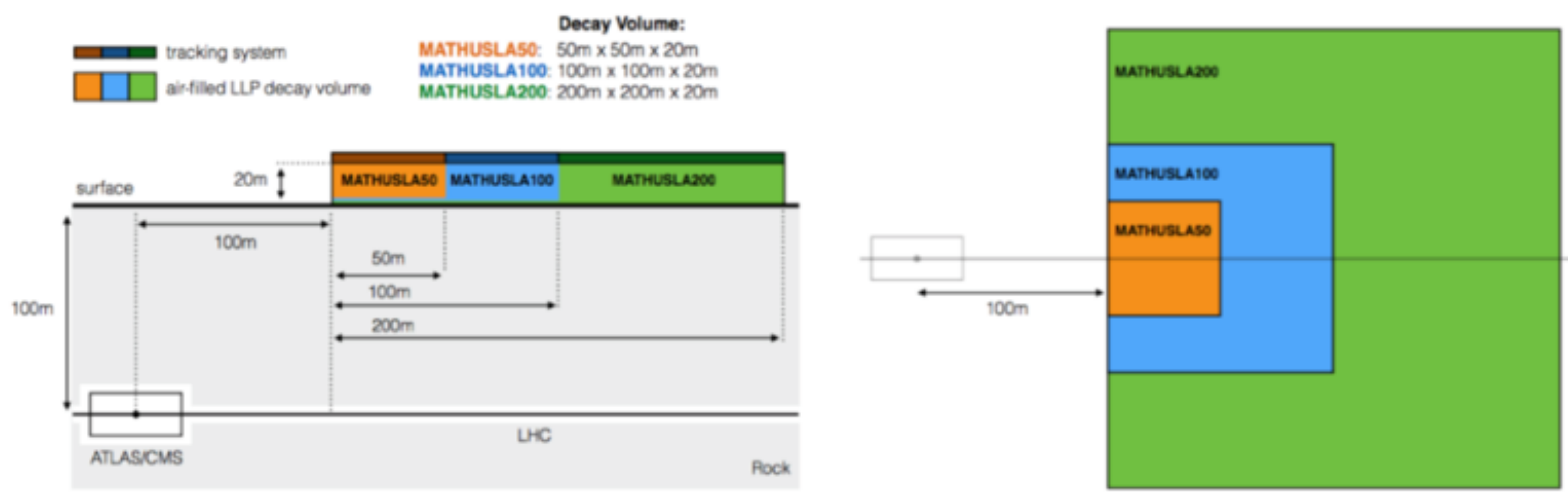
MATHUSLA concept

- Original design gives sensitivity to neutral LLPs with lifetime up to the Big Bang Nucleosynthesis (BBN) limit (10^7 - 10^8 m):

arXiv 1811.00927



- Requires large footprint (area) and large decay volume (height) for good acceptance: three benchmarks were studied:
  - 20 m high
  - surface of 50x50 m^2, 100x100 m^2, 200x200 m^2
  - with increasing sensitivity



side view

aerial view

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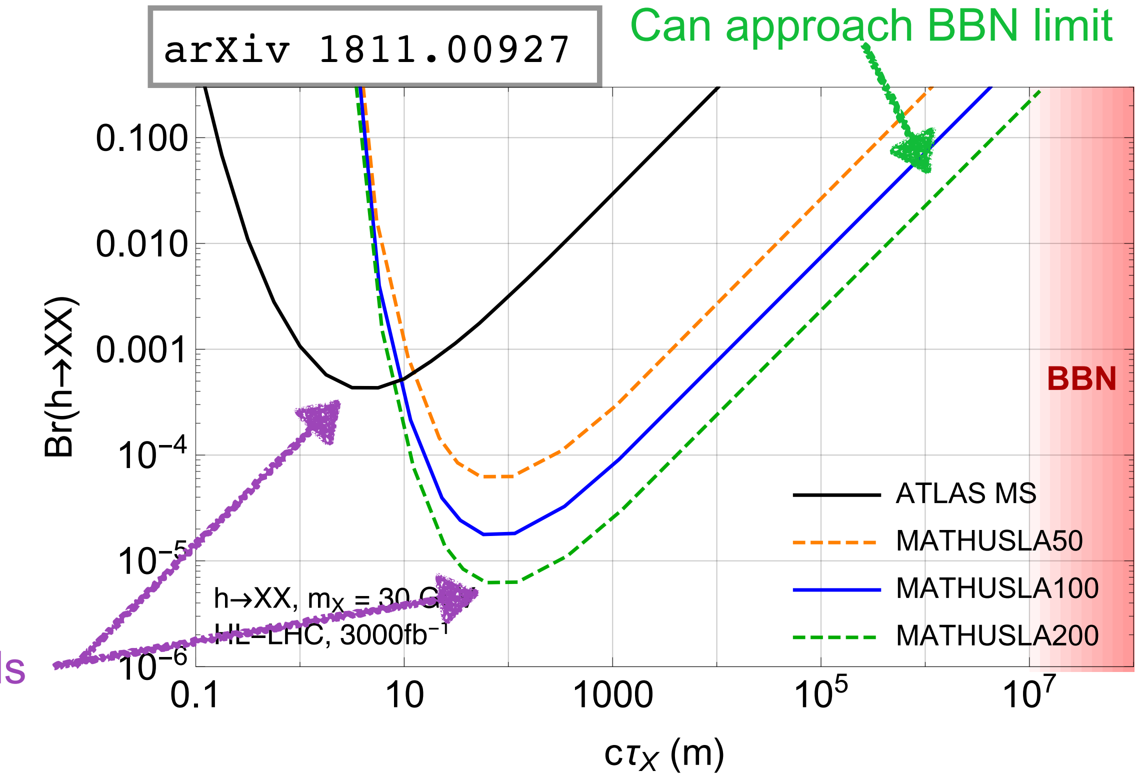
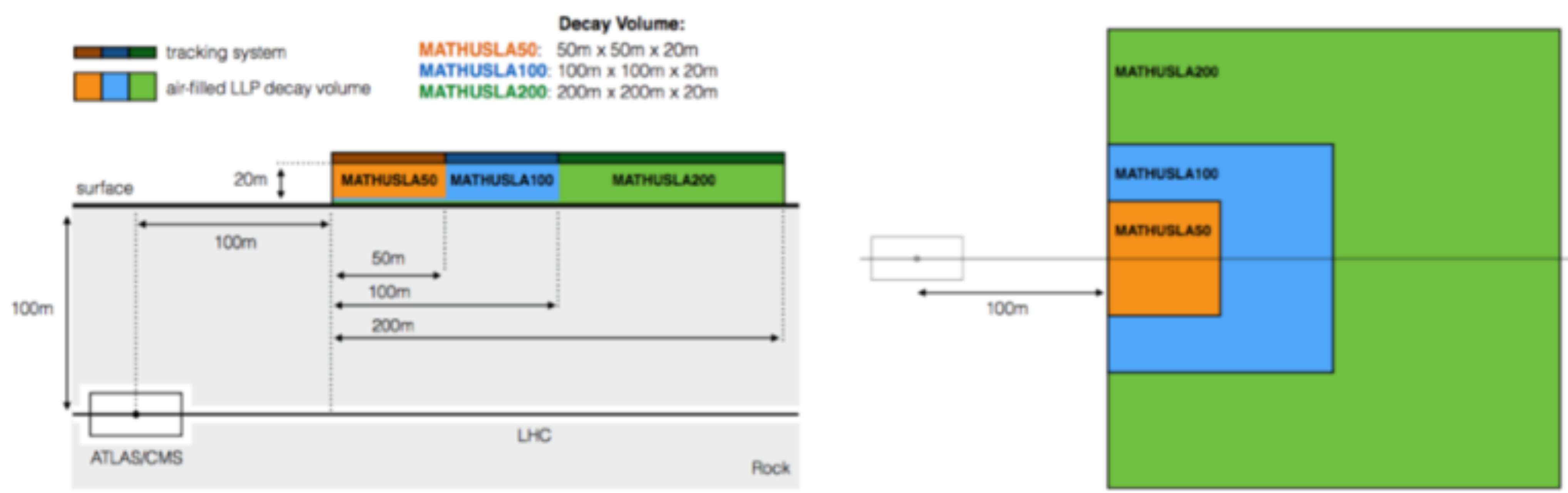


Mathusla has no SM backgrounds
→ sensitivity gain wrt ATLAS



side view *aerial view*

MATHUSLA Documentation

- **MATHUSLA: MA**sive **T**iming **H**odoscope for **U**ltra **S**table neutra**L** p**A**rticles
- Designed to accomplish excellent background rejection and robust tracking
- Original idea: J-P Chou, D. Curtin, H. Lubatti [arXiv 1606.06298]
- Mathusla Physics case - theory white paper to be published in Physics Reports: [arxiv: 1806.07396]
- Letter of Intent submitted to LHCC in November 2018: [MATHUSLA LoI: arXiv 1811.00927]
- Input to European Strategy for Particle Physics: [arxiv 1901.04040]

v1 [physics.ins-det] 2 Nov 2018

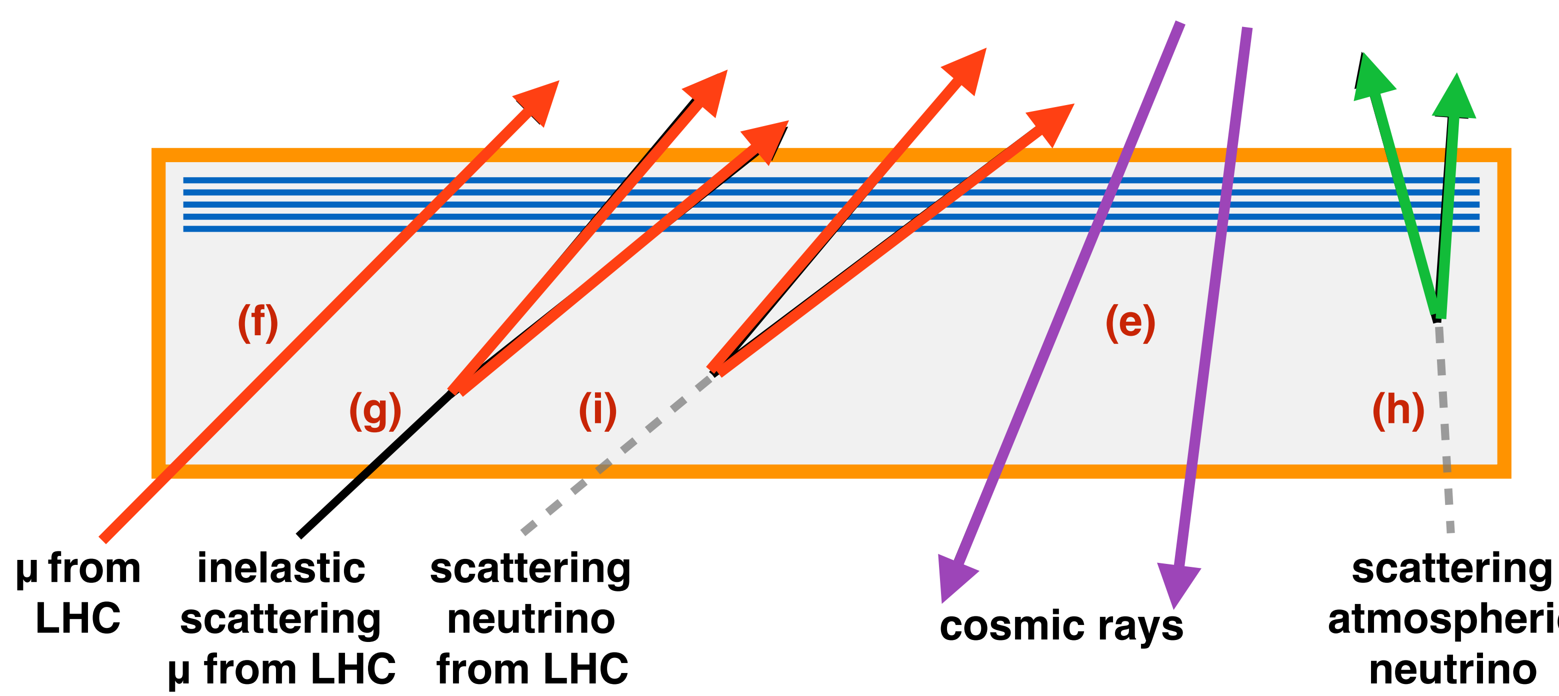
A Letter of Intent for MATHUSLA: a dedicated displaced vertex detector above ATLAS or CMS

Cristiano Alpigiani,[a] Austin Ball,[o] Liron Barak,[c] James Beacham,[ah] Yan Benhammo,[c] Tingting Cao,[c] Paolo Camarri,[f,g] Roberto Cardarelli,[f] Mario Rodríguez-Cahuantzi,[h] John Paul Chou,[d] David Curtin,[b] Miriam Diamond,[e] Giuseppe Di Sciascio,[f] Marco Drewes,[x] Sarah C. Eno,[u] Erez Etzion,[c] Rouven Essig,[q] Jared Evans,[v] Oliver Fischer,[w] Stefano Giagu,[k] Brandon Gomes,[d] Andy Haas,[l] Yuekun Heng,[z] Giuseppe Iaselli,[aa] Ken Johns,[m] Muge Karagoz,[u] Luke Kasper,[d] Audrey Kvam,[a] Dragoslav Lazic,[ae] Liang Li,[a,f] Barbara Liberti,[f] Zhen Liu,[y] Henry Lubatti,[a] Giovanni Marsella,[n] Matthew McCullough,[o] David McKeen,[p] Patrick Meade,[q] Gilad Mizrachi,[c] David Morrissey,[p] Meny Raviv Moshe,[c] Karen Salomé Caballero-Mora,[j] Piter A. Paye Mamani,[ab] Antonio Policicchio,[k] Mason Proffitt,[a] Marina Reggiani-Guzzo,[ad] Joe Rothberg,[a] Rinaldo Santonico,[f,g] Marco Schioppa,[ag] Jessie Shelton,[t] Brian Shuve,[s] Martin A. Subieta Vasquez,[ab] Daniel Stolarski,[r] Albert de Roeck,[o] Arturo Fernández Téllez,[h] Guillermo Tejeda Muñoz,[h] Mario Iván Martínez Hernández,[h] Yiftah Silver,[c] Steffie Ann Thayil,[d] Emma Torro,[a] Yuhsin Tsai,[u] Juan Carlos Arteaga-Velázquez,[i] Gordon Watts,[a] Charles Young,[e] Jose Zurita.[w,ac]

- Planned to start working for the HL-LHC

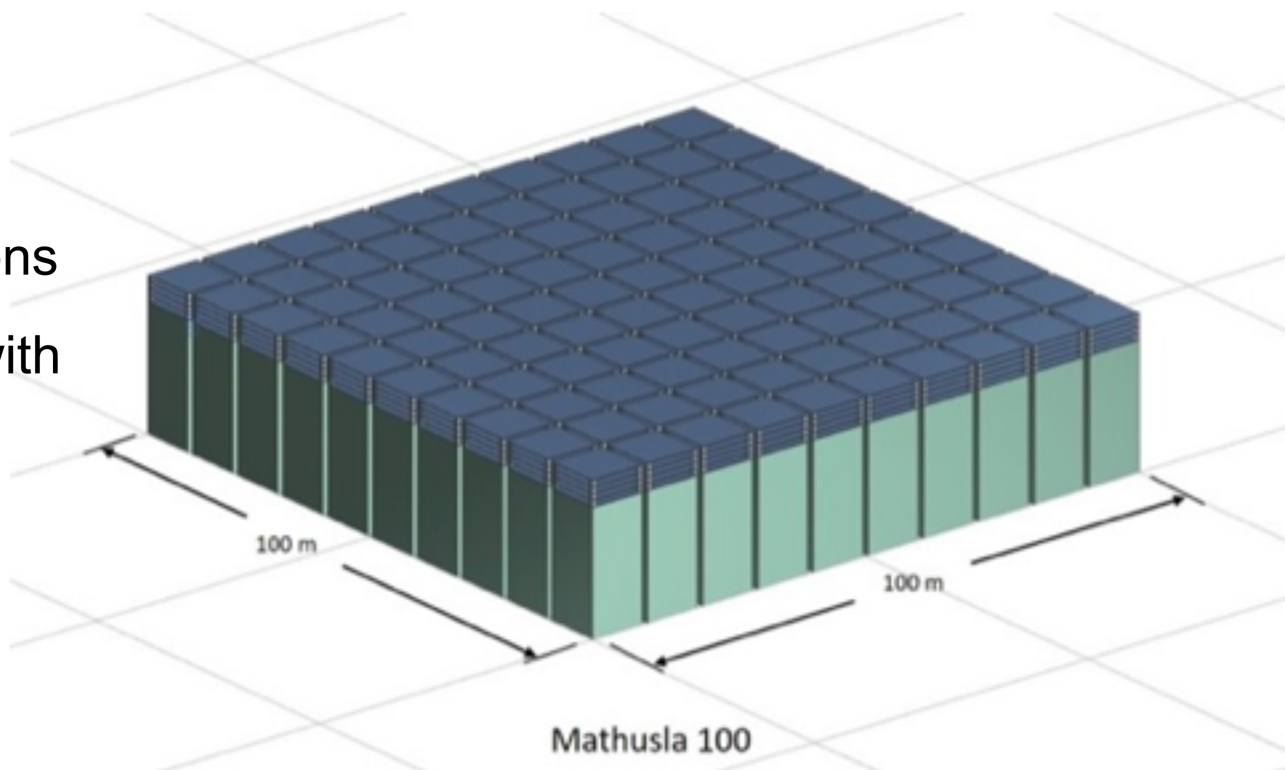
MATHUSLA backgrounds

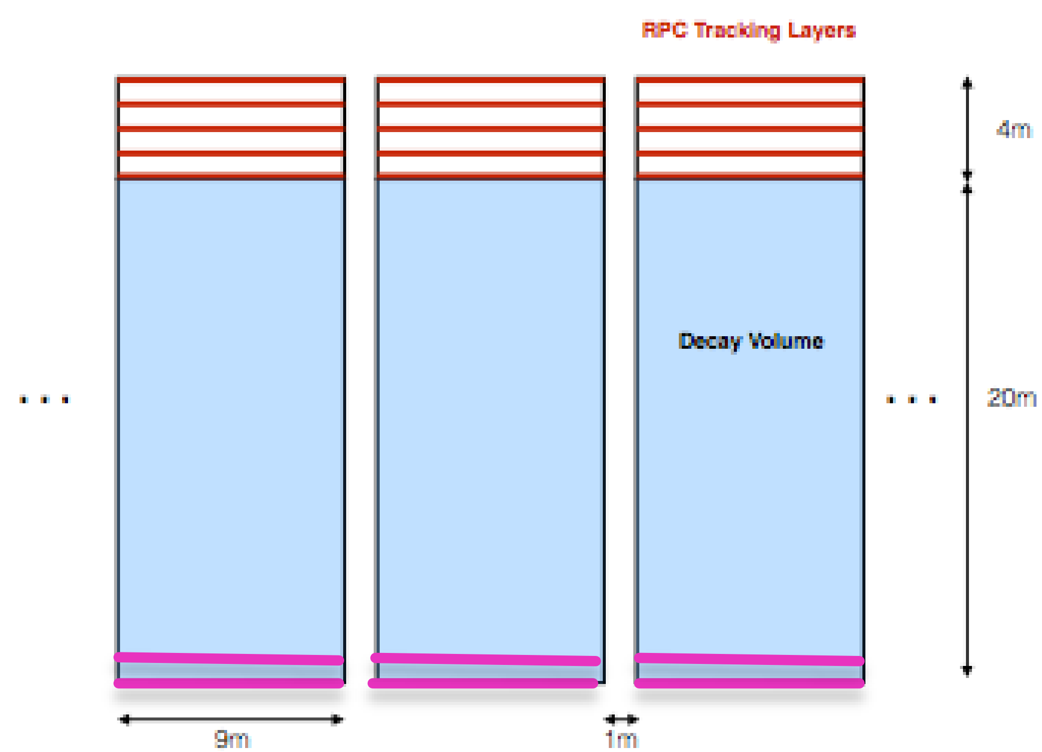
- LHC collision backgrounds (muons): low rate O(1) Hz, reject with timing and entrance hit position
- Exposed to cosmic rays and atmospheric neutrinos…☹
  - Cosmic rays: 1.7 MHz (7 MHz) for 100x100 m^2 (200x200 m^2) detector
    - Requires veto of downward going cosmic rays (good timing)
    - In 5 m (top layers), Δt(top,bottom) ≈ 16 ns
  - Upward atmospheric neutrinos that interact in air decay volume
    - Estimate Low rate ~ 10-100 per year above 300 MeV
    - Most have low momentum proton (~ 300 MeV - reject with time of flight)



Modular concept

- Need to cover a wide surface with detector material
- Current design considers a modular configuration
  - Easy to adapt to available land / specific site conditions
  - Allows for modular construction, staged integration with incremental ramp-up
  - 9mx9m modules
  - 5 tracking/timing layers on top
  - 20 - 25 m air decay volume
  - 2 veto layers on the bottom
  - Studies conclude scintillator veto surrounding entire volume is not need.



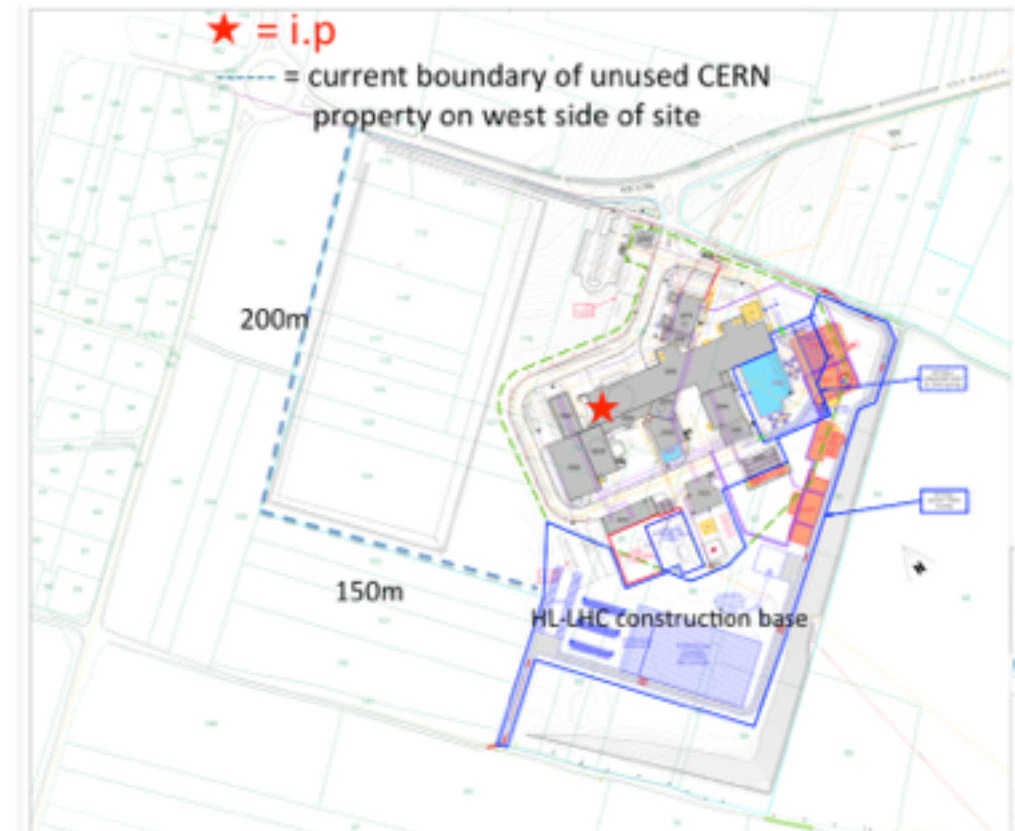


side view

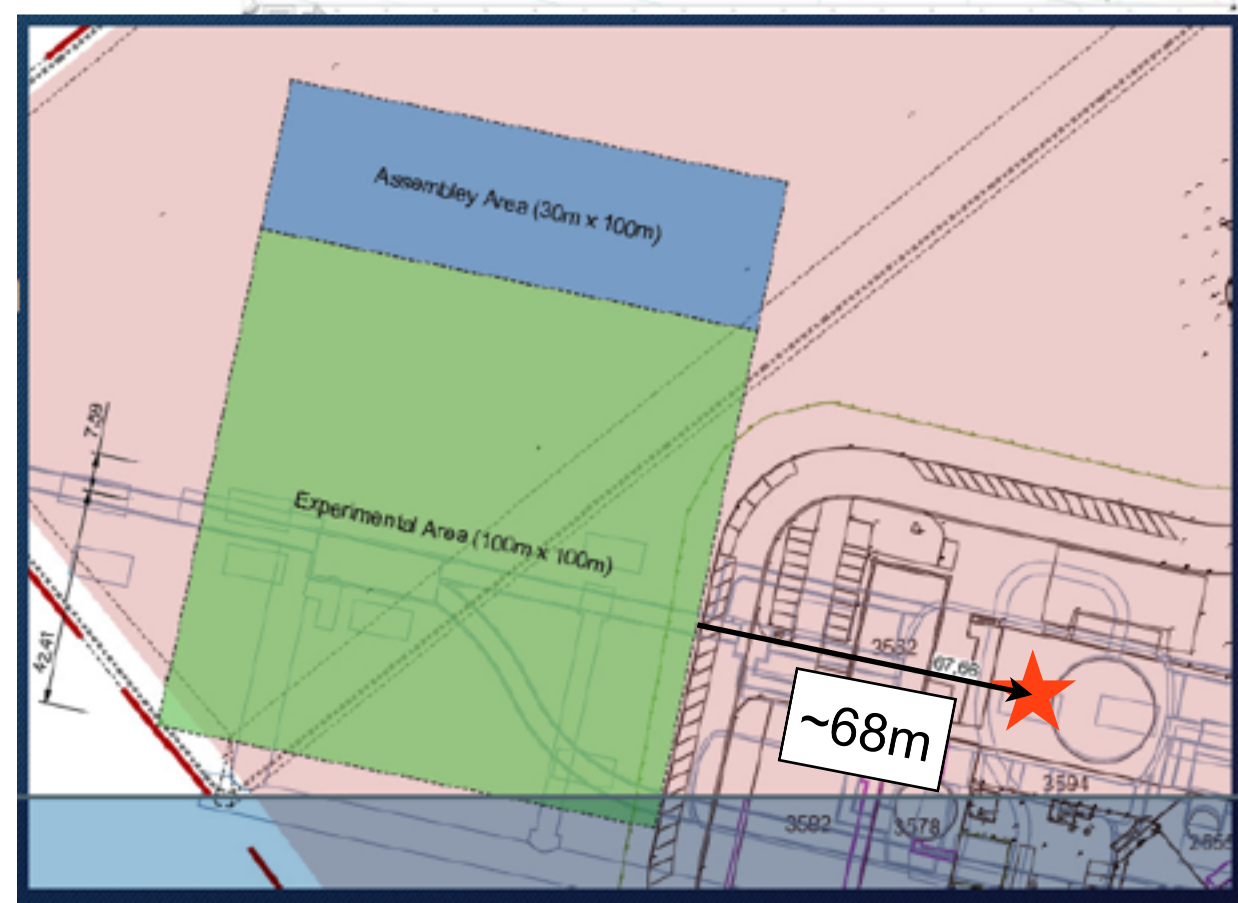
- Trigger unit: 3 x 3 modules is the baseline.
  - Choice based on largest inclination angle for 200 m X 200 m detector and very safe for 100 m X 100 m detector.

MATHUSLA Detector on the surface of CMS

- Working with Civil Engineers from CERN to define building and the layout of MATHUSLA at P5.
  - Must fit on CERN owned land at P5, restricted by existing structures
  - **excavating** below surface
    - increases solid angle wrt surface option
    - sensitivity is comparable to the original 200x200 m^2
    - repects landscape

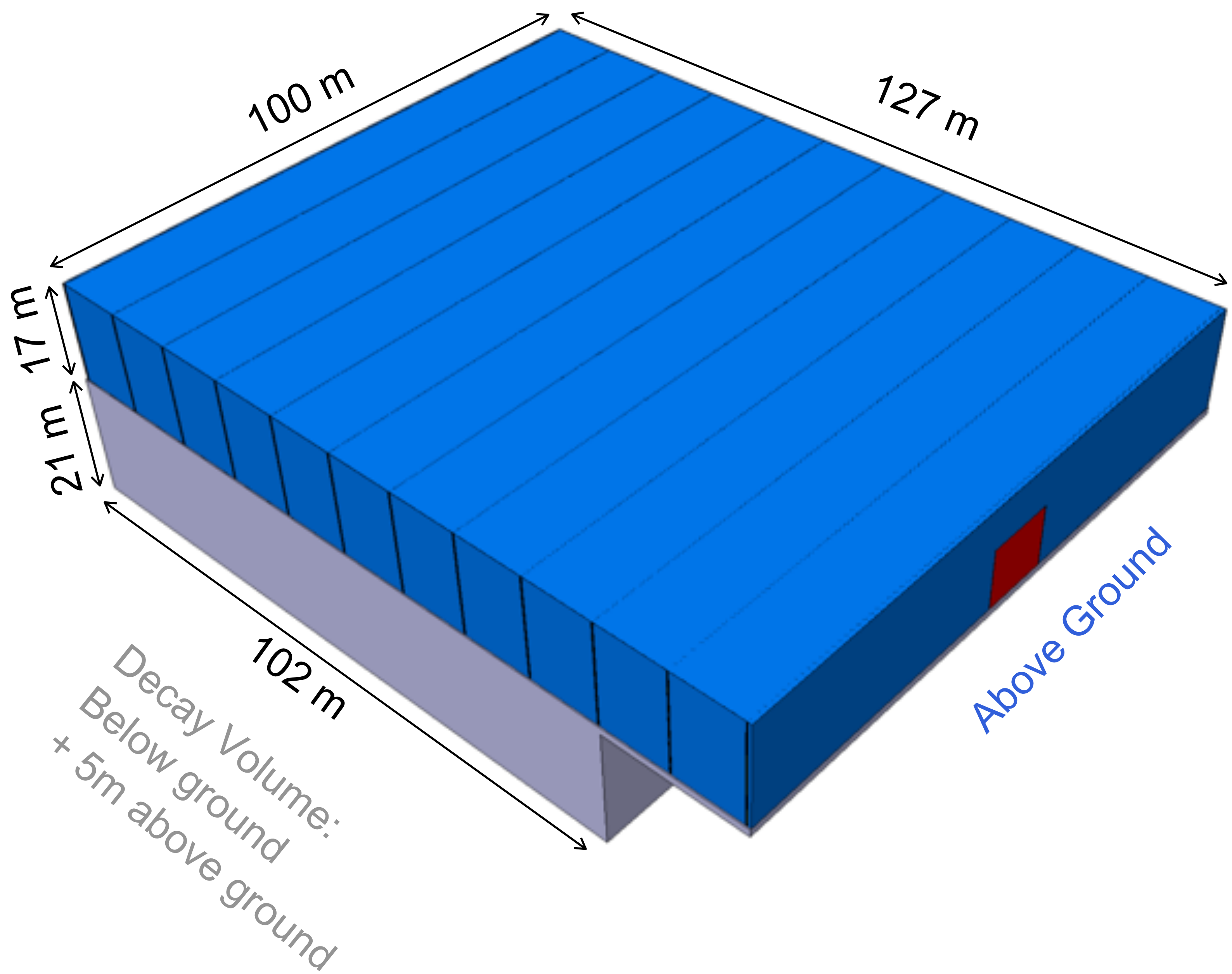


- The current MATHUSLA concept is **100x100 m^2 experimental area located at the surface of CMS**
  - 30m x 100m adjacent detector assembly area.
  - Crane coverage from assembly area to detector building
  - Enclosed building for experimental and assembly areas with cranes
  - ~7.5m offset to center of beam
  - ~68m to IP on surface and IP ≈ 80m below surface
  - gain of 1.5 wrt detector at 100 m and IP 100 m below

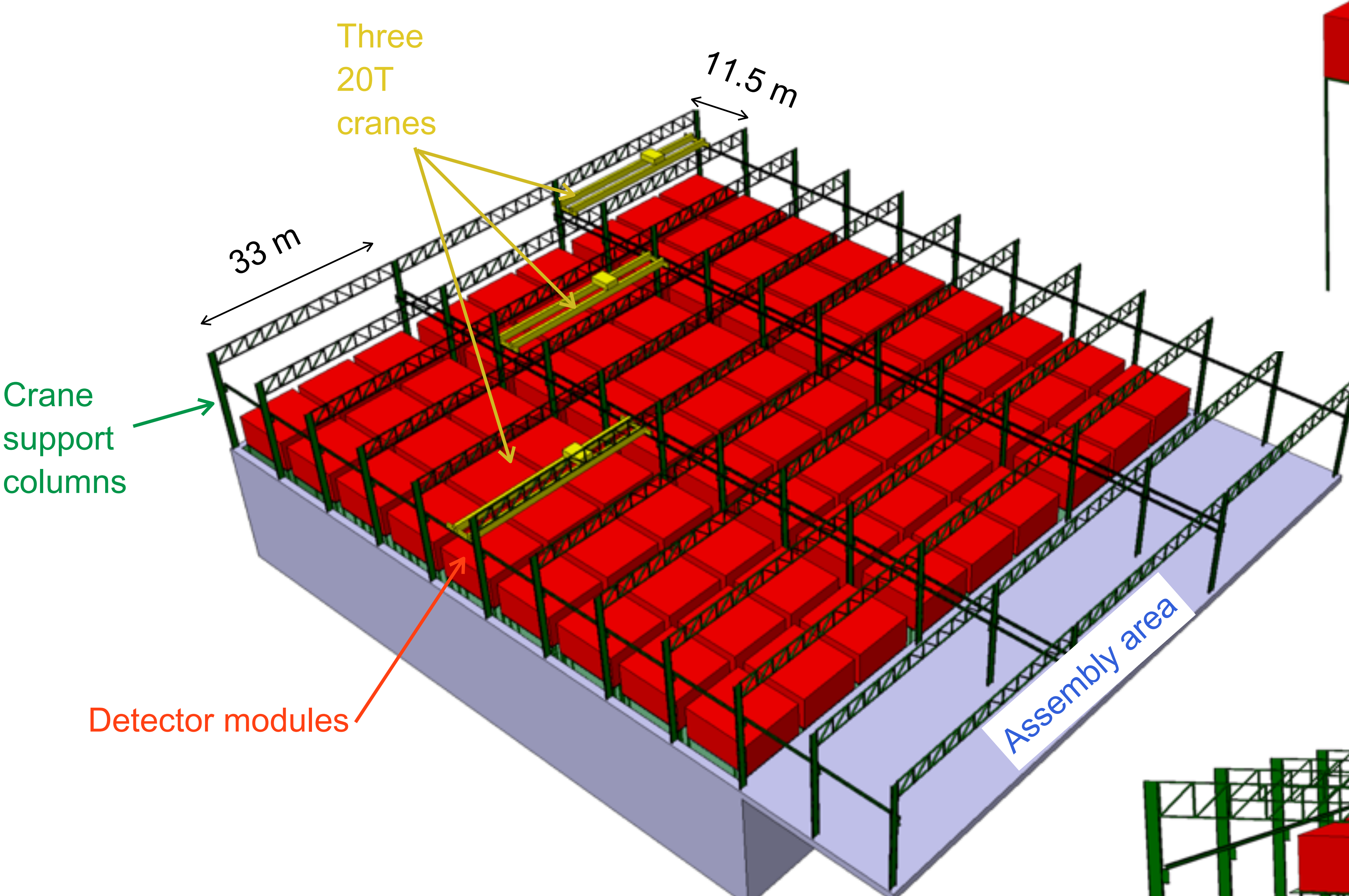


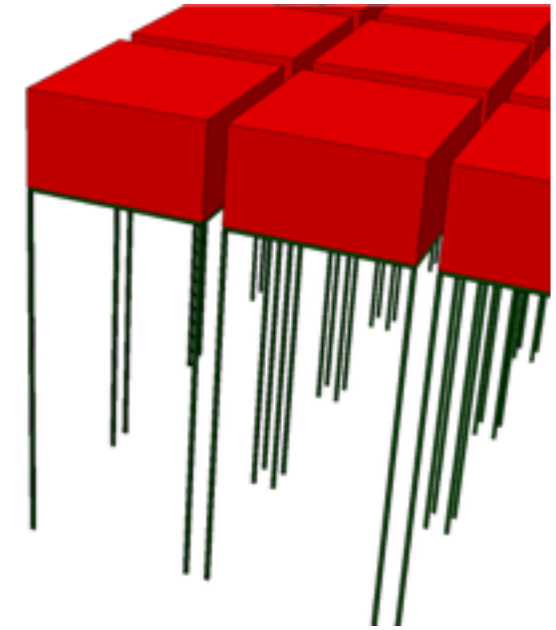
Preliminary layout

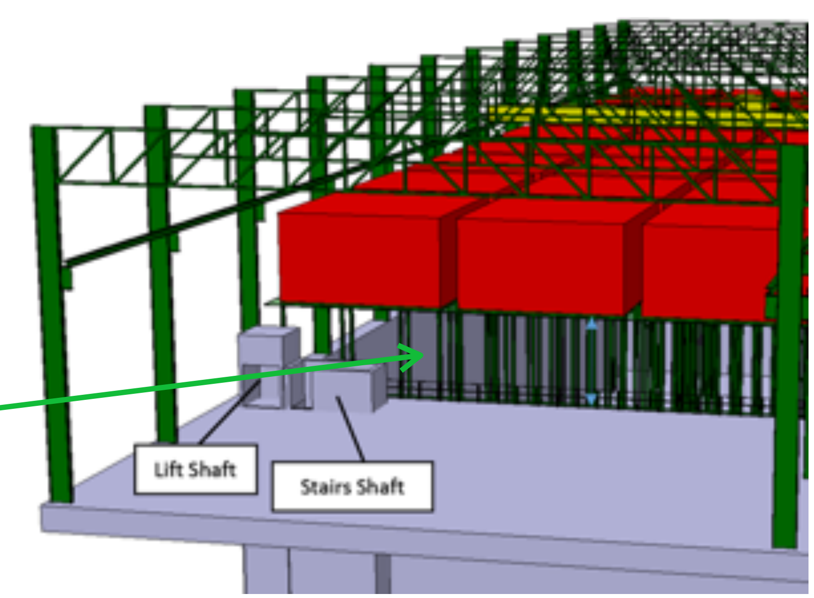
- A 3-d model of detector building and basic structures exists and will continue to evolve.



Preliminary layout







possibility: extra 5m decay volume

increase sensitivity closer to 200mx200m benchmark

MATHUSLA technology

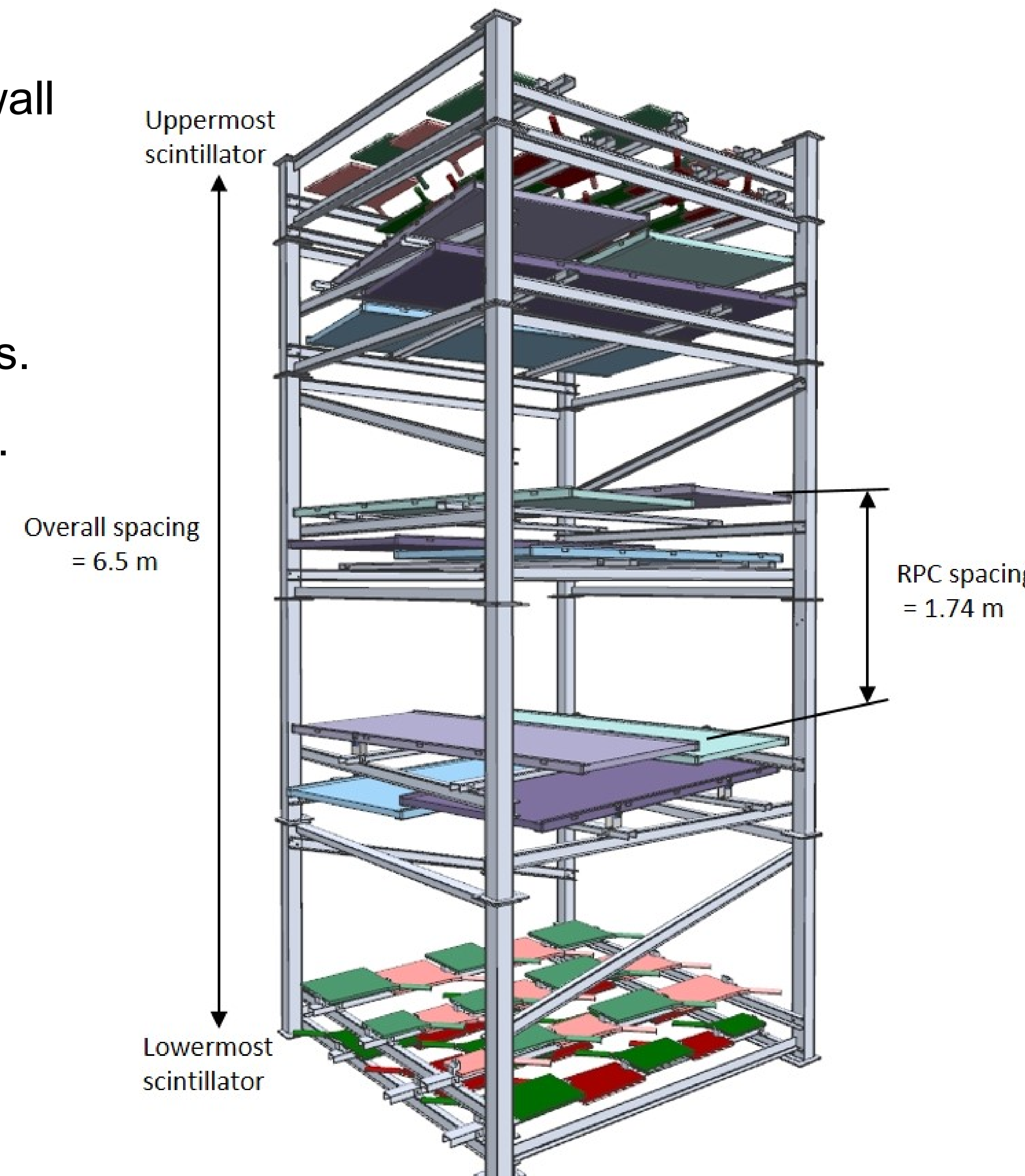
- Two technologies being evaluated that provide good time/space resolution needed for cosmic ray rejection and vertex reconstruction.

- **RPCs planes are used in many LHC detectors.**
  - THE GOOD☺
    - Proven technology with good timing and spatial resolution.
    - Costs per area covered are low.
  - The Less GOOD ☹
    - Require HV ~10 KV
    - Gas mixture used for ATLAS and CMS has high Global Warming Potential (GWP) and will not be allowed for HL-LHC.
    - RPC experts are attempting to find a replacement gas with lower GWP.

- **Extruded scintillators coupled to SiPMs**
- THE GOOD
  - SiPMs operate at low-voltage (25 to 30 V).
  - No gas involved.
  - Timing resolution can be competitive with RPCs.
  - Cost wise competitive with RPCs.
- General concept: **scintillator bar ~ 5mx4cmx2cm with wave-length shifting fiber readout at both ends**.
  - Transverse resolution $\sigma = 4\text{cm}/\sqrt{12} \approx 1$ cm.
  - Time difference between two ends gives longitudinal resolution (aiming for ~ 1 cm)

Test stand above the ATLAS IP

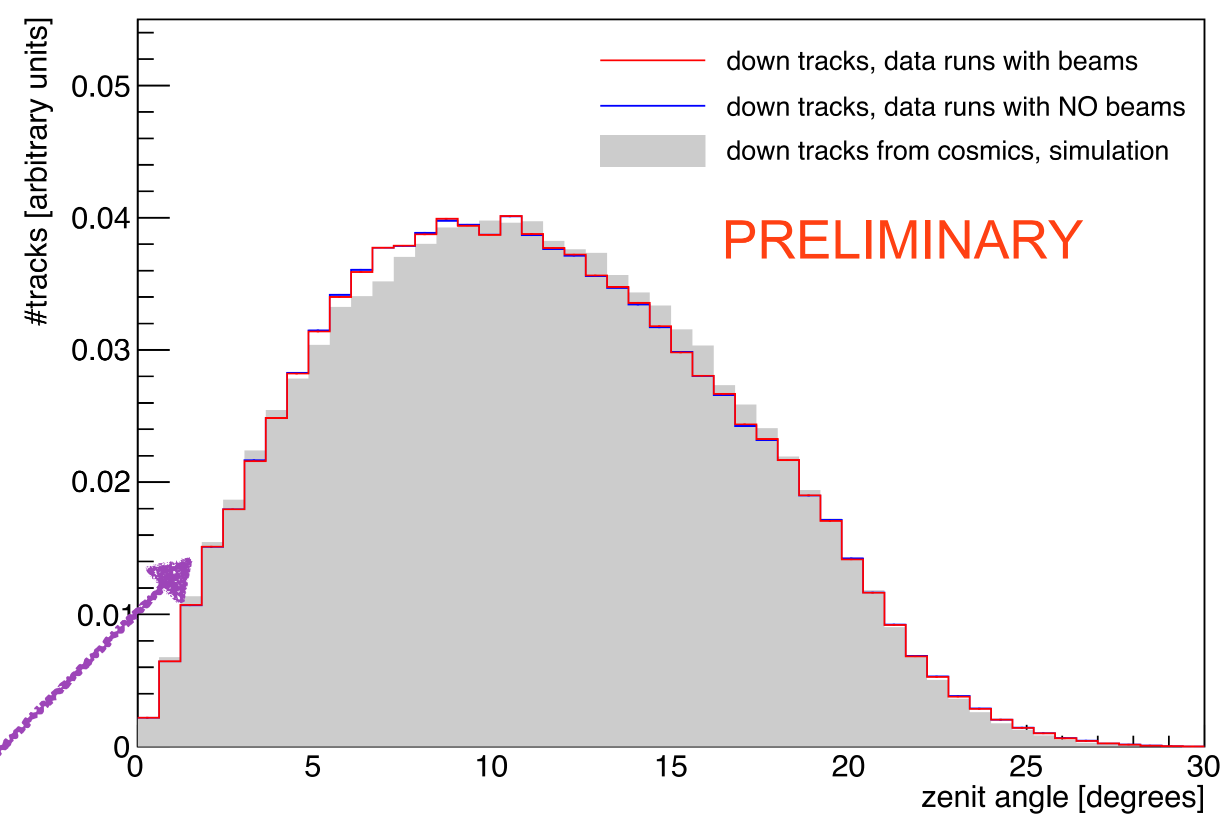
- To help guide background studies and understand LHC collision backgrounds we built a TEST STAND
- Goal to get some idea of upward LHC backgrounds
- 2.5x2.5x6 m^3 test stand with three layers of RPCs and top and bottom scintillator layers
  - RPCs – spares from ARGO experiment
  - Scintillators - recycled from D0 forward muon trigger wall



- RPCs and scintillators have timing resolution of $\sigma \sim 2.5$ ns.
- With a total length of ~ 6 m, Δt(top,bottom) $\approx$ 20 ns or 8 σ.
- Two triggers running simultaneously.
  - Downward trigger for cosmic rays
  - Upward trigger for tracks from IP
- Took data in 2018 to end of Run-2.

Test stand preliminary results

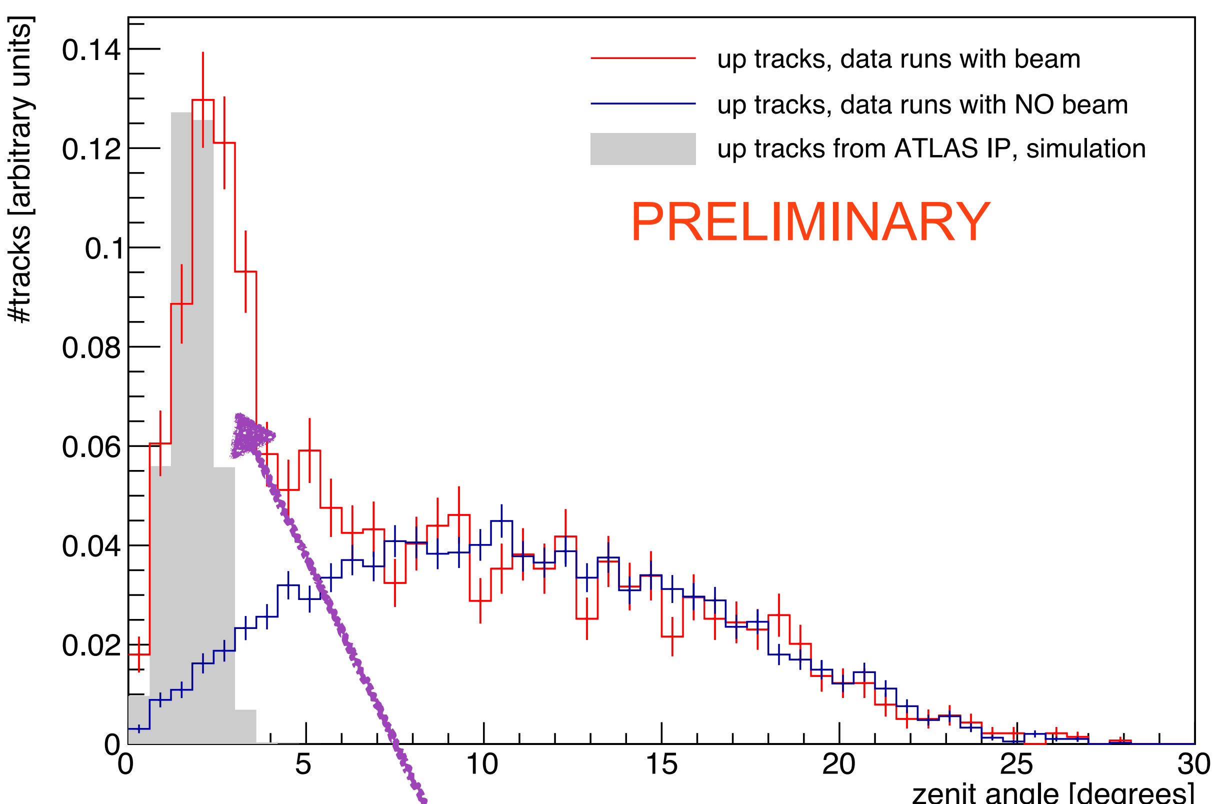
- Took data in different LHC conditions: with beam and without beam
- MC simulation has been implemented for cosmic muons and for particles generated at the ATLAS IP
- **Preliminary results – MC not corrected for efficiency or multiple scattering**
- Angular distribution for down tracks (cosmic muons) match very well expected from MC
- Arbitrary normalization



Data with and w/o beam show exact same shape for downwards tracks (cosmics) ✔

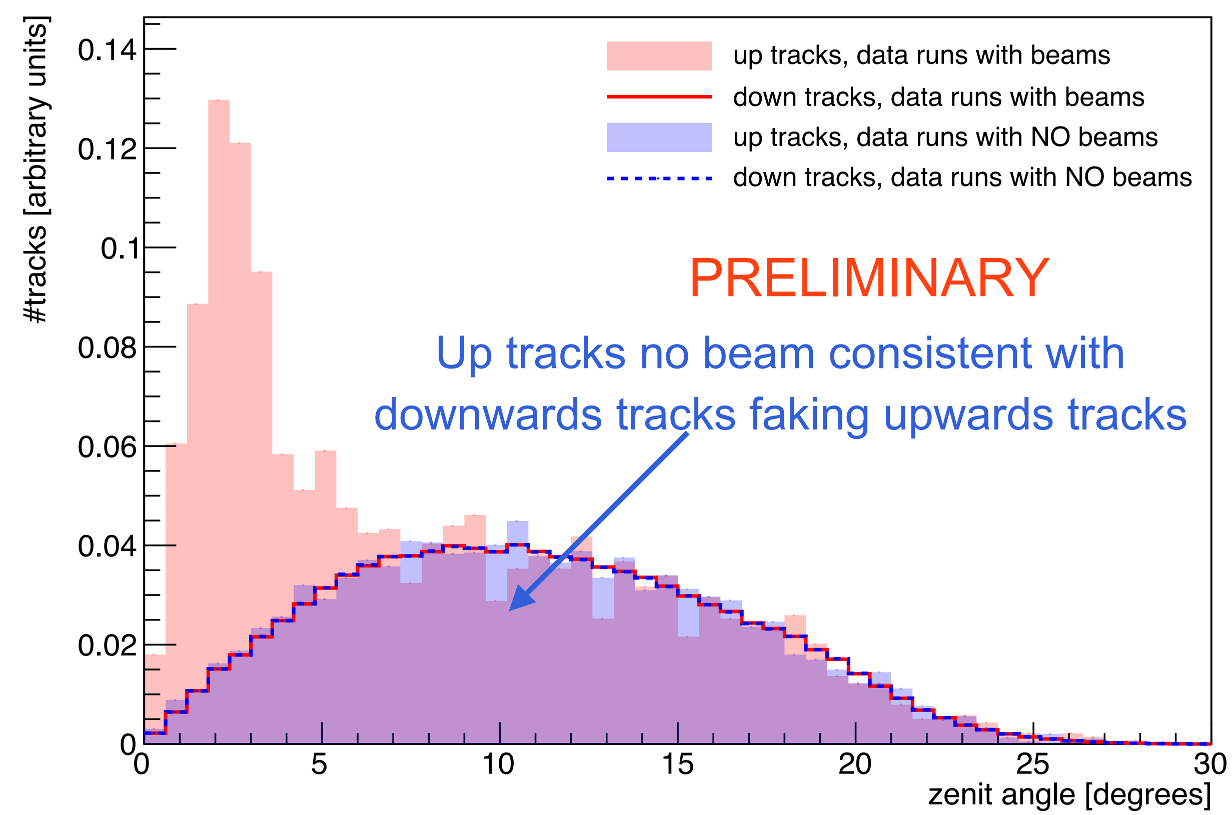
Test stand preliminary results

- Took data in different LHC conditions: with beam and without beam
- MC simulation has been implemented for cosmic muons and for particles generated at the ATLAS IP
- **Preliminary results – MC not corrected for efficiency or multiple scattering**
- Accumulation for zenith angle $< \sim 4°$ consistent with upward going tracks from IP when collisions occur
- Arbitrary normalization



Observed peak of up tracks at small angles in runs with beam consistent with particles from IP

Test stand data



Up tracks no beam consistent with downwards tracks faking upwards tracks

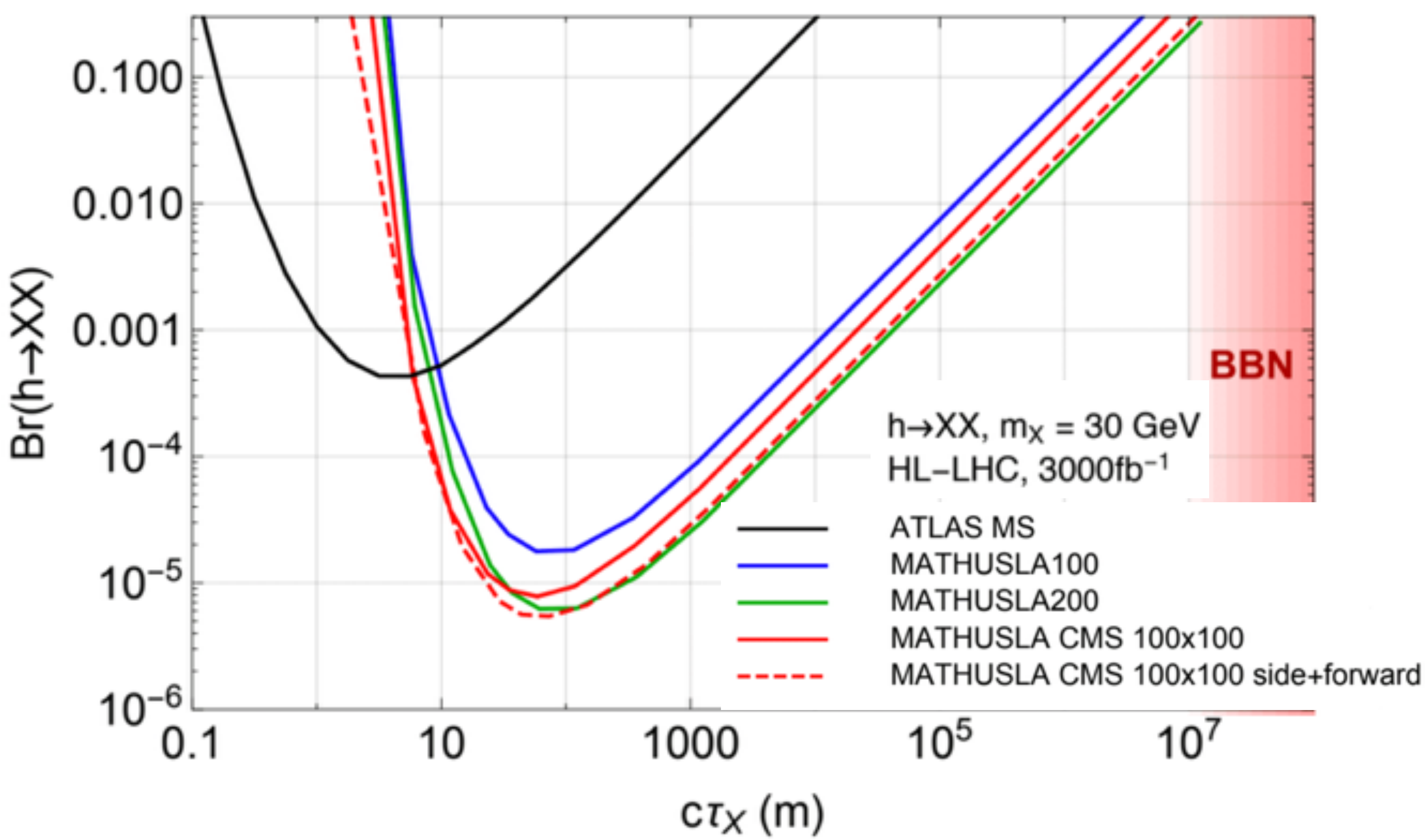
Going forward

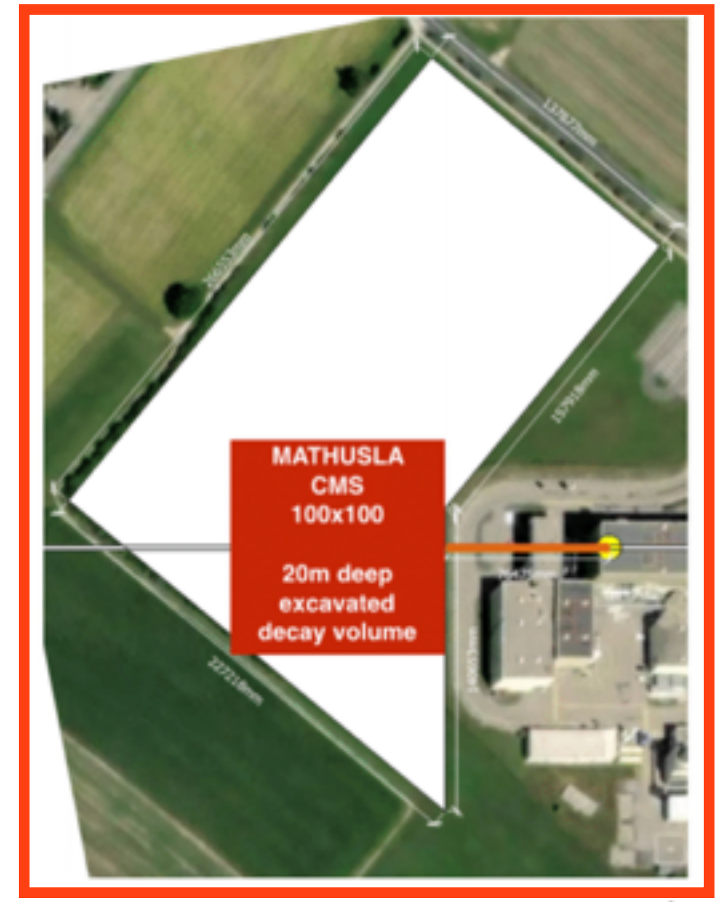
- Detector footprint at CMS to be finalized
- Building details coming together and goal is to have a preliminary cost estimate this year.
- Goal is to make tracker technology choice early next year.
- Open items to be fixed include:
  - Frontend electronics
  - Trigger details
  - Tracking chamber support structure
  - Installation procedures
- Complete Technical Design Report (TDR) by end 2020.
- Finalising the preliminary results from the Test Stand to obtain reliable up tracks rate

backup

Current configuration

- **100x100 m² buried a few meters deep** has several advantages:
  - getting closer to the IP, increases solid angle wrt surface option
  - sensitivity is comparable to the original 200x200 m², used as benchmark in the LoI
  - repects landscape





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- Going to BBN lifetime limit need to suppress SM backgrounds
- Dedicated detector placed on the surface above CMS or ATLAS detectors LHC: O(90) meters of rock takes care of problem ☺
- Requires large footprint (area) and large decay volume (height) for good acceptance.

> HL-LHC → order of N_h = 1.5 x 10^8 Higgs boson produced

> Observed decays:

$$N_{\mathrm{obs}} \sim N_h \cdot \mathrm{Br}(h \to \mathrm{ULLP} \to \mathrm{SM}) \cdot \boxed{\epsilon_{\mathrm{geometric}} \cdot \frac{L}{b c \tau}}$$

ϵ = geometrical acceptance along ULLP

L = size of the detector along ULLP direction

$b \sim m_h /(n \cdot m_X) \leq 3$ for Higgs boson decaying to n = 2, $m_X \geq 20$ GeV

❖ To collect a few ULLP decays with $c\tau \sim 10^7$ m require a 20 m detector along direction of travel of ULLP and about 10 % geometrical acceptance

$$L \sim (20\ \mathrm{m}) \left(\frac{b}{3}\right) \left(\frac{0.1}{\epsilon_{\mathrm{geometric}}}\right) \frac{0.3}{\mathrm{Br}(h \to \mathrm{ULLP})}$$

slide from Cristiano Alpigiani

- Large volume filled with air as decay volume with several detector layers for tracking