

# ICHEP 2020 | PRAGUE

40<sup>th</sup> INTERNATIONAL CONFERENCE  
ON HIGH ENERGY PHYSICS

**VIRTUAL  
CONFERENCE**

**28 JULY - 6 AUGUST 2020**

PRAGUE, CZECH REPUBLIC

## Exploring the lifetime frontier with the proposed MATHUSLA experiment

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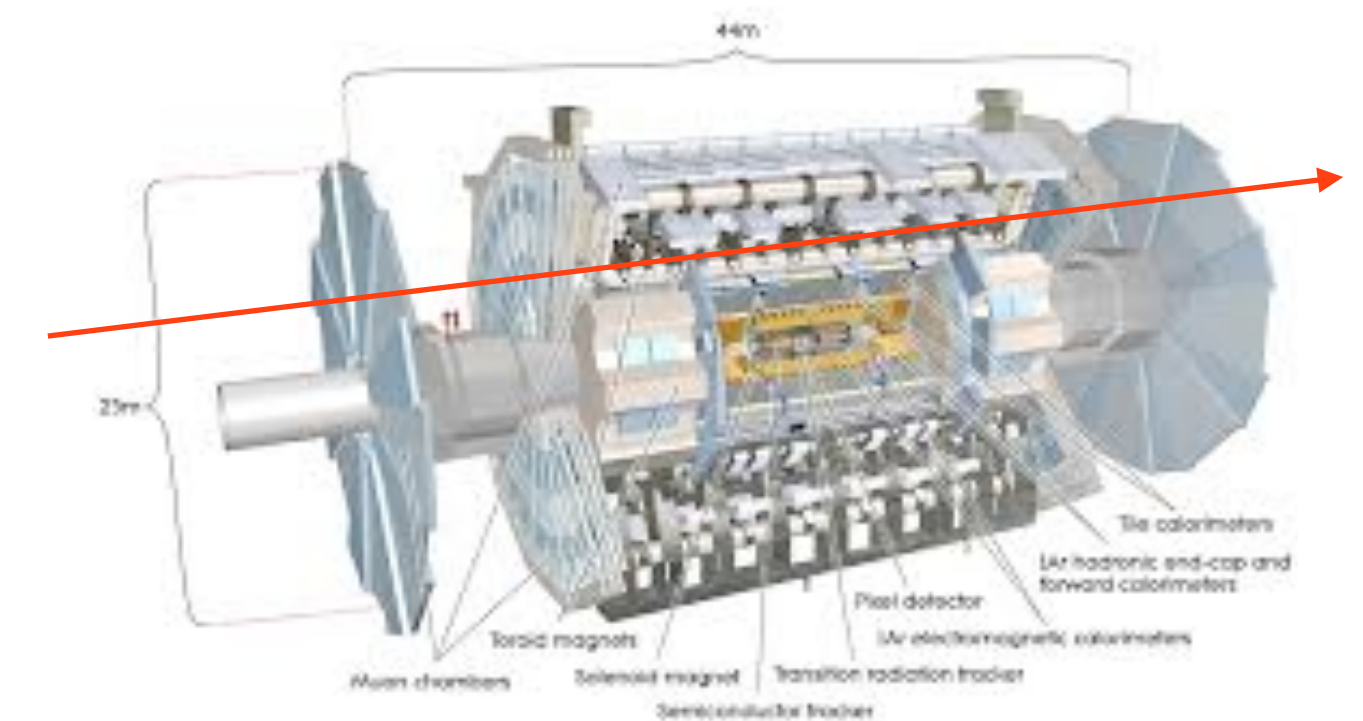
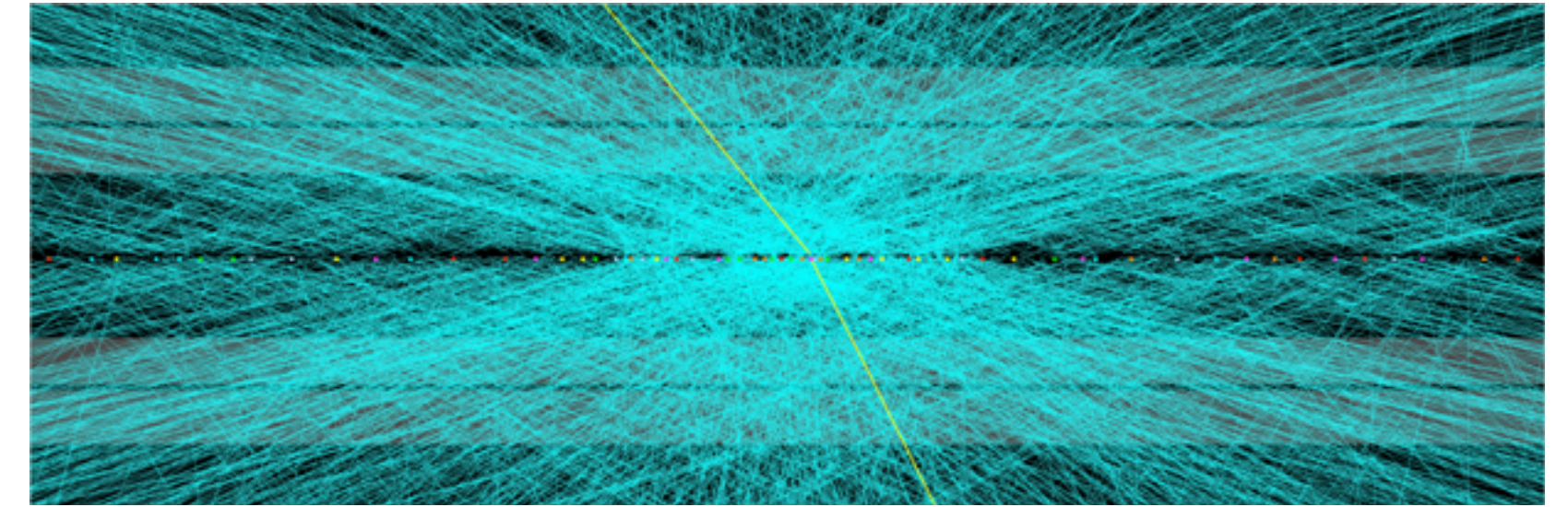


**ICHEP 2020**  
Prague (online)  
31 July 2020

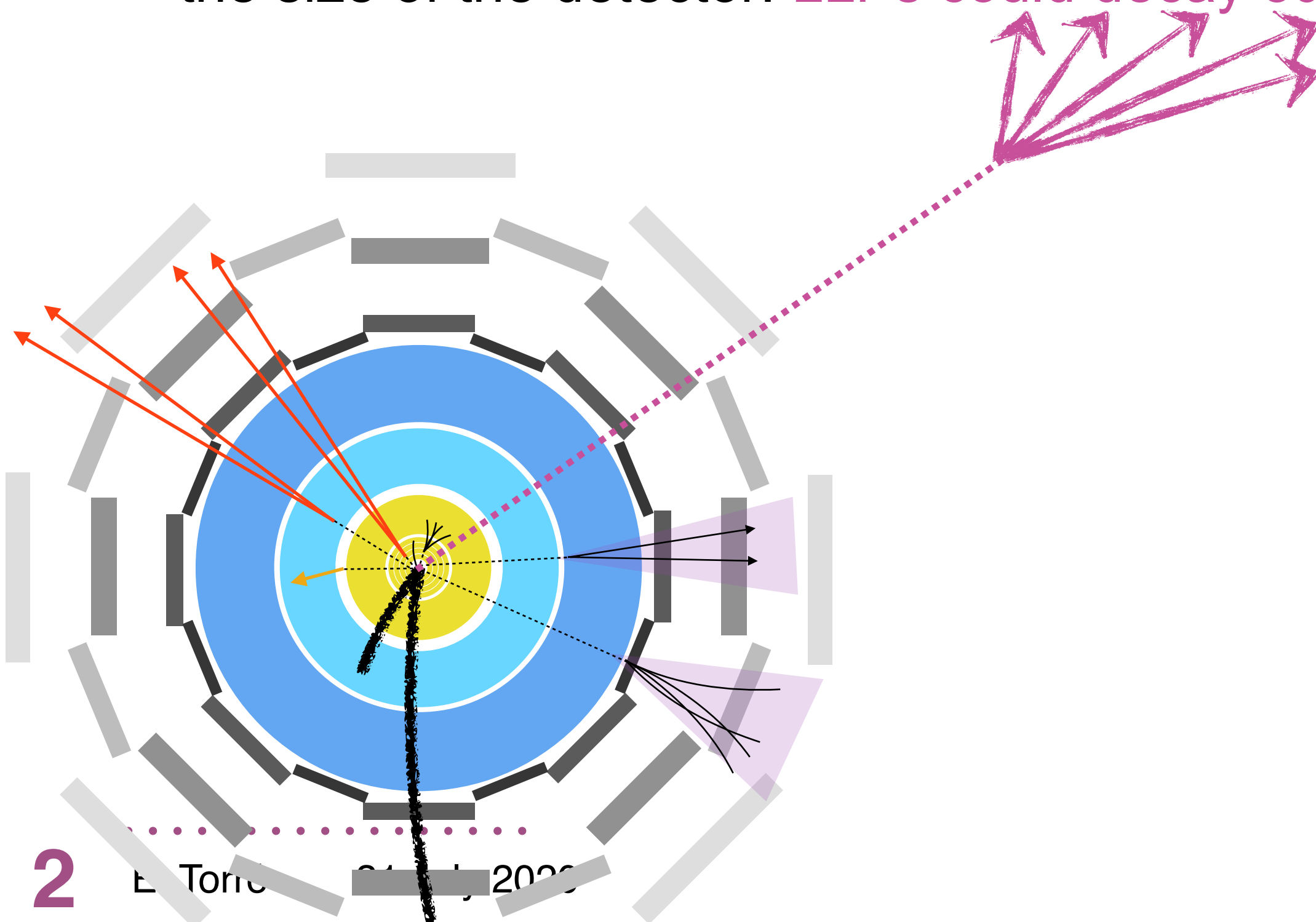
# MATHUSLA

# Why MATHSULA?

- 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: **LLPs could decay outside!**



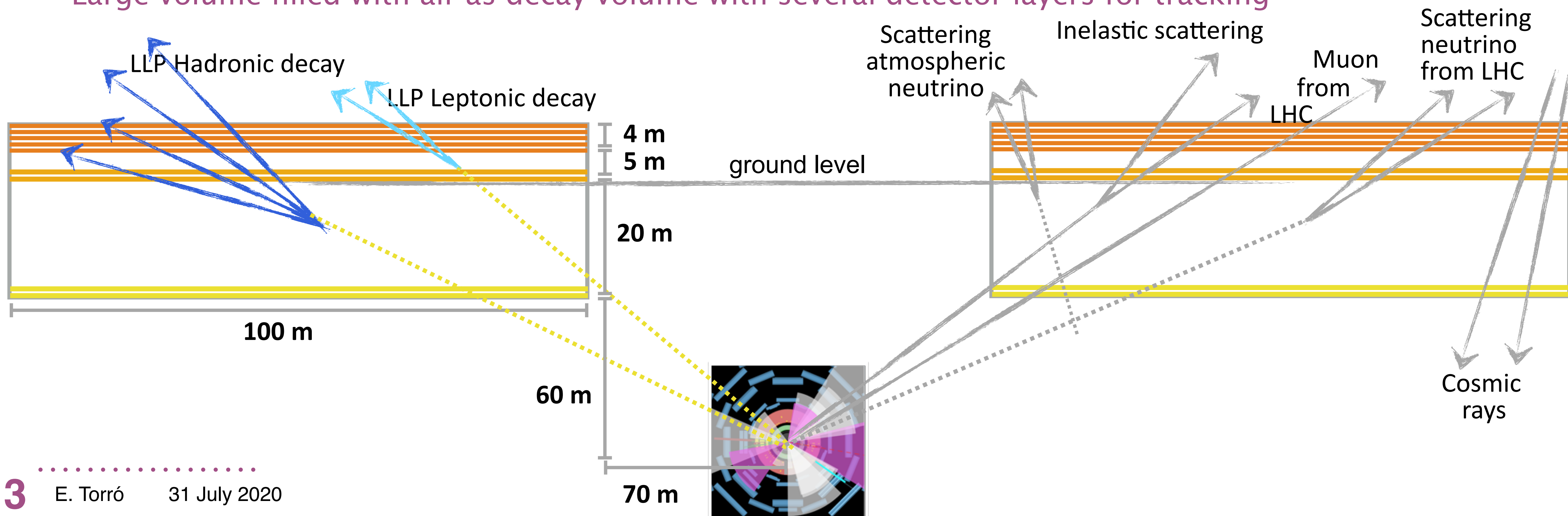
beam halo muons



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

# MATHUSLA concept

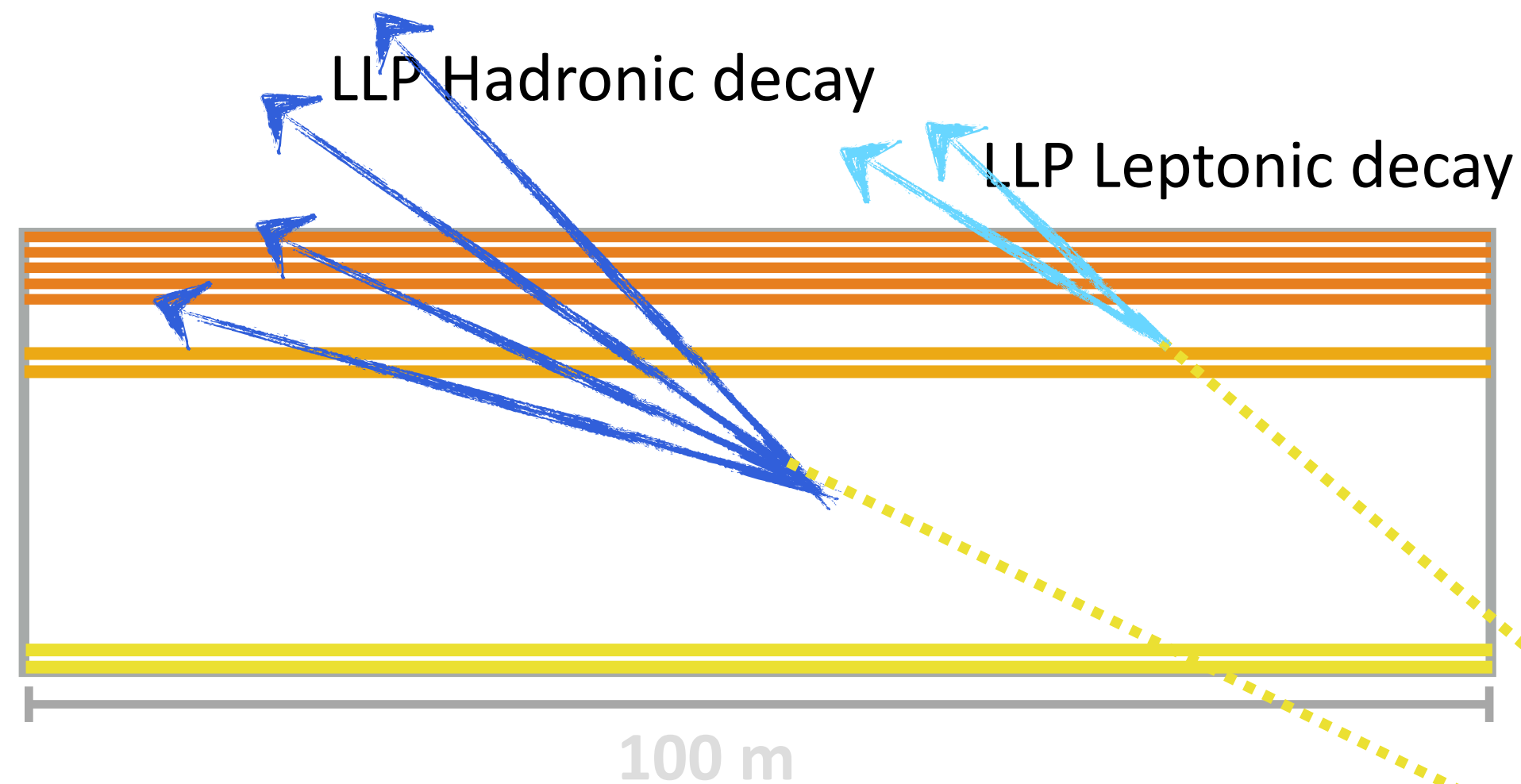
- **MATHUSLA: M**Assive **T**iming **H**odoscope for **U**ltra **S**table neutral **p**Articles
- Aiming to reach to Big Bang Nucleosynthesis (BBN) limit ( $c\tau \sim 10^7 - 10^8$  m) lifetime
  - need to suppress LHC backgrounds
- Dedicated detector placed on the surface above CMS during HL-LHC:
  - O(60) meters of rock suppress most backgrounds
- Large volume filled with air as decay volume with several detector layers for tracking



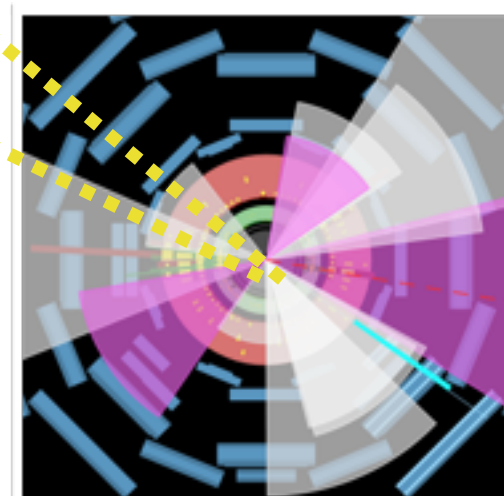
# MATHUSLA concept

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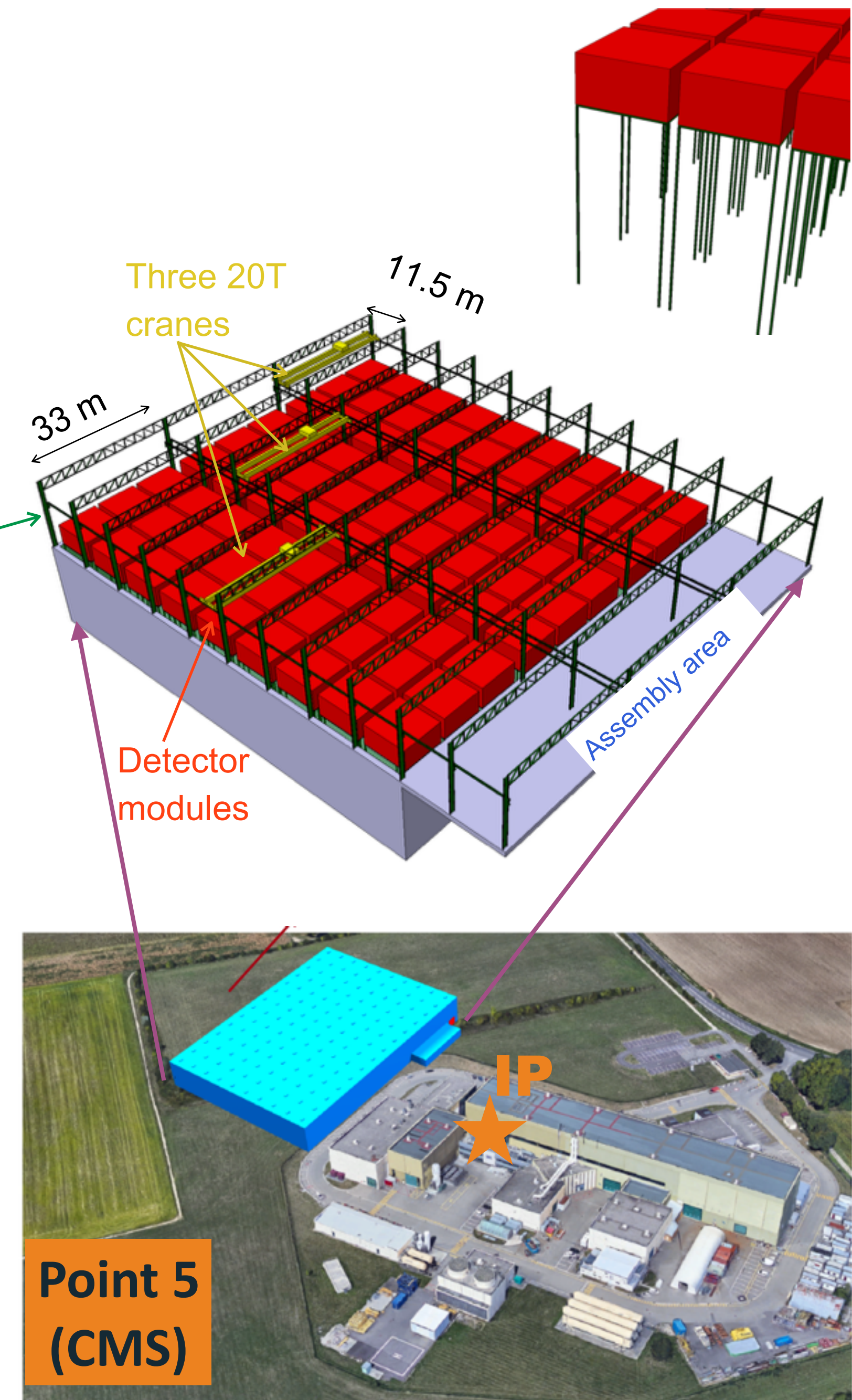
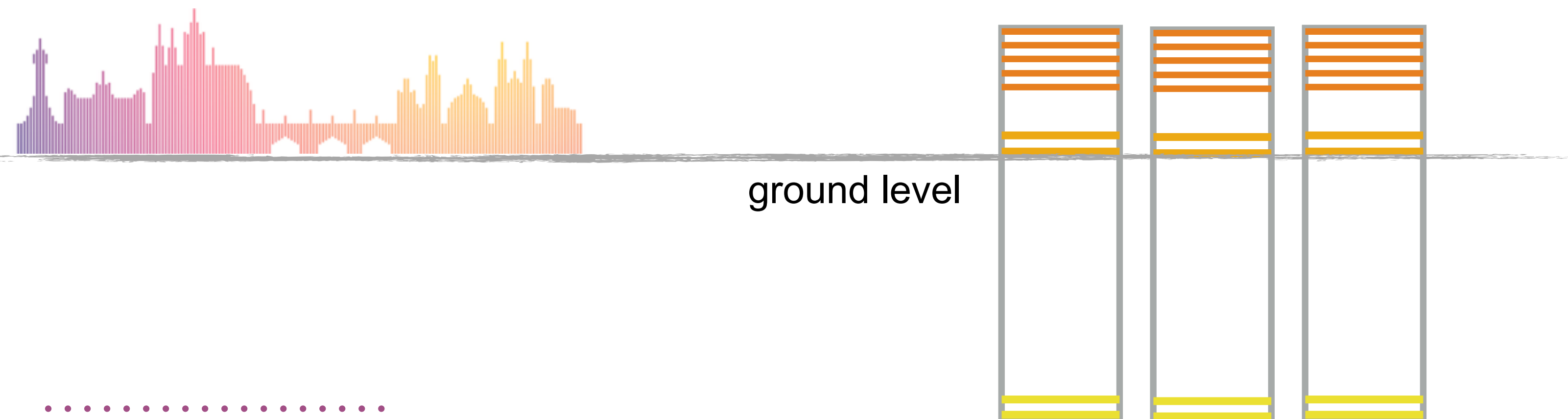


- need **robust tracking** for **vertex reconstruction**
- need **good timing** to separate upward going charged particles from downward going cosmic muons



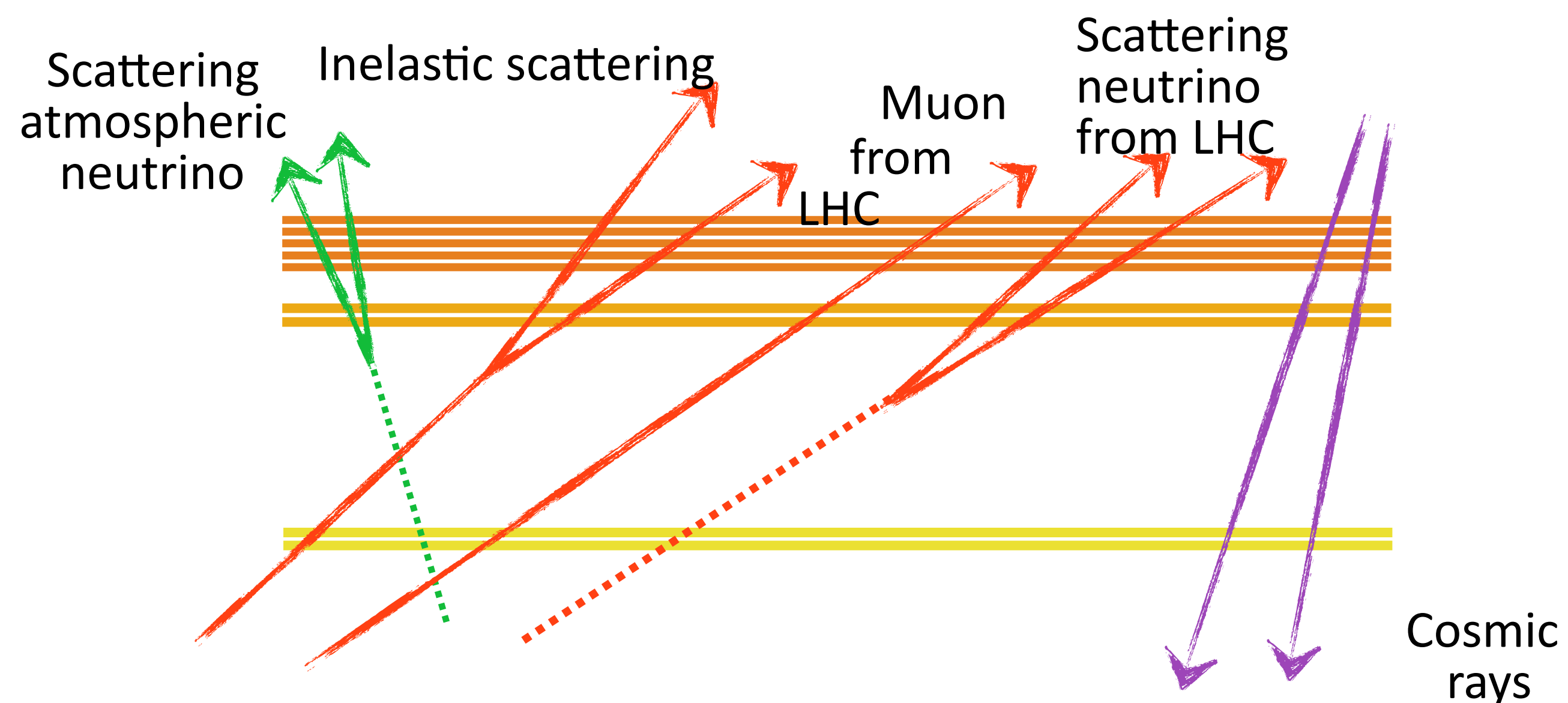
# Baseline detector design

- 100 x 100 m<sup>2</sup> x 25m high, on the surface above CMS
- Modular configuration:
  - easy to adapt to available land on site
  - Allows for modular construction, staged integration, incremental ramp-up
  - 10 m x 10 m modules
- Three sets of tracking detectors:
  - **Floor detectors**: two layers, to flag charged particles from the LHC
  - **Top detectors**: five layers with 1m-spacing, above the decay volume
  - **Intermediate detectors**: two layers, 5m below the top detectors to optimize performance



# MATHUSLA backgrounds

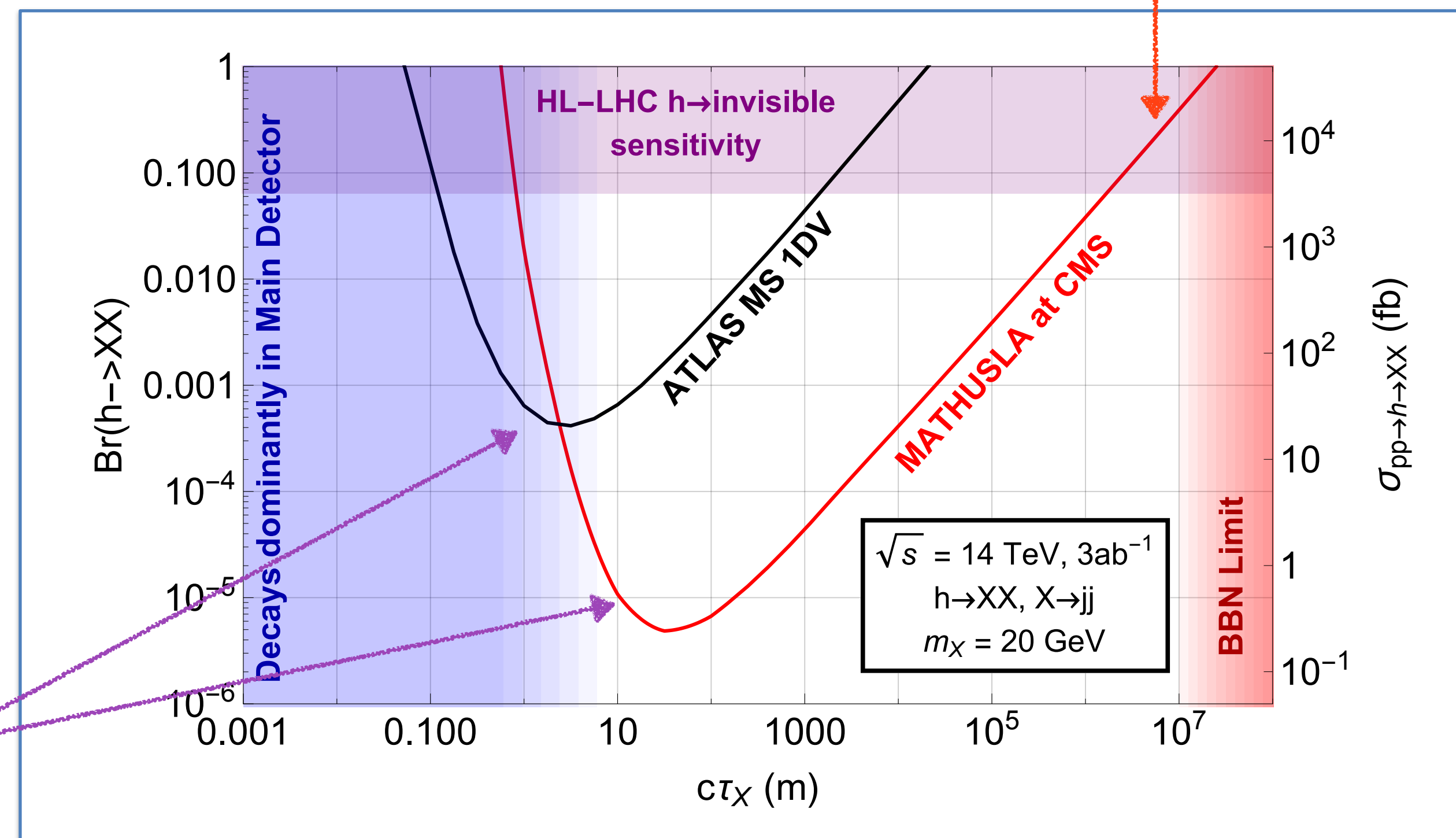
- **LHC collision backgrounds** (muons): low rate  $O(1)$  Hz, reject with timing and entrance hit position
- Exposed to cosmic rays and atmospheric neutrinos
  - **Cosmic rays**: 1.7 MHz (7 MHz) for  $100 \times 100 \text{ m}^2$  ( $200 \times 200 \text{ m}^2$ ) detector
    - Requires veto of downward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



# Baseline sensitivity

- Aim for near zero background in analysis
- Comparison of LLP sensitivity between ATLAS and baseline MATHUSLA design via exotic Higgs decays
- The sensitivity of this design is similar to that of the original benchmark (200 x 200 m<sup>2</sup> x 20m), by bringing the detector closer to the Interaction Point:
  - vertically: excavating 20m
  - horizontally: placing the detector at 70m instead of 100m

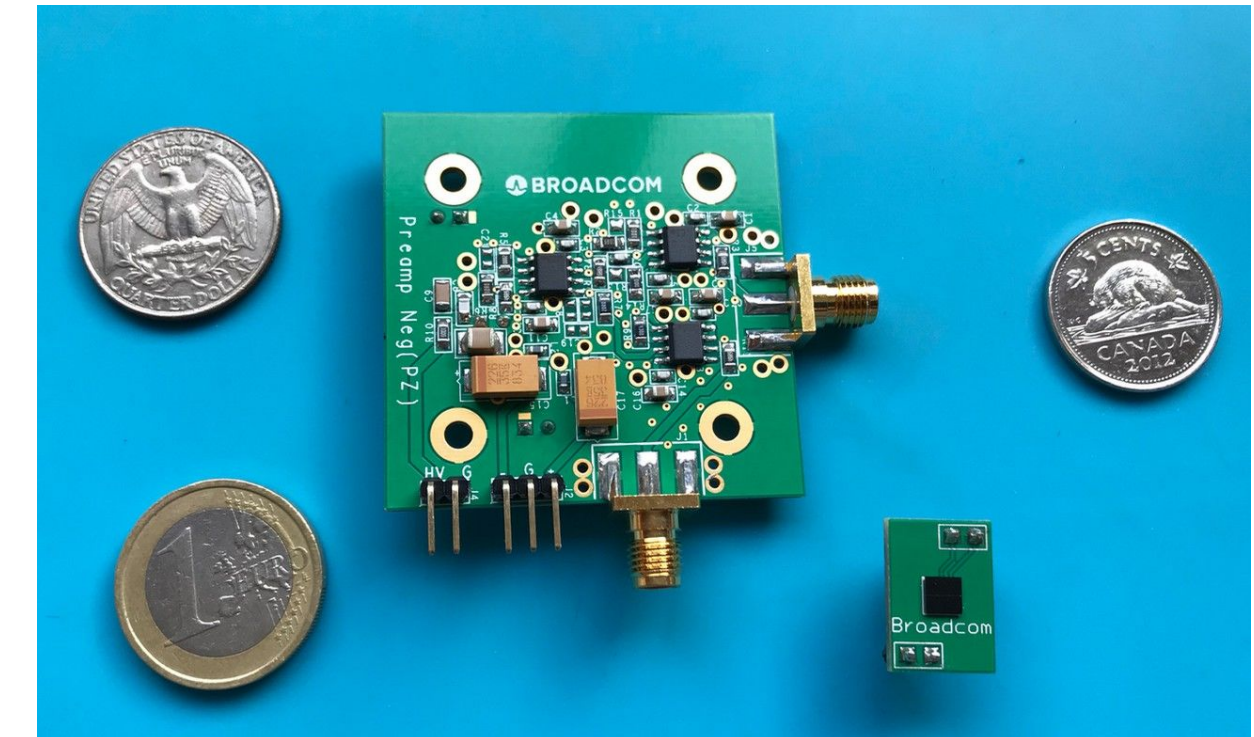
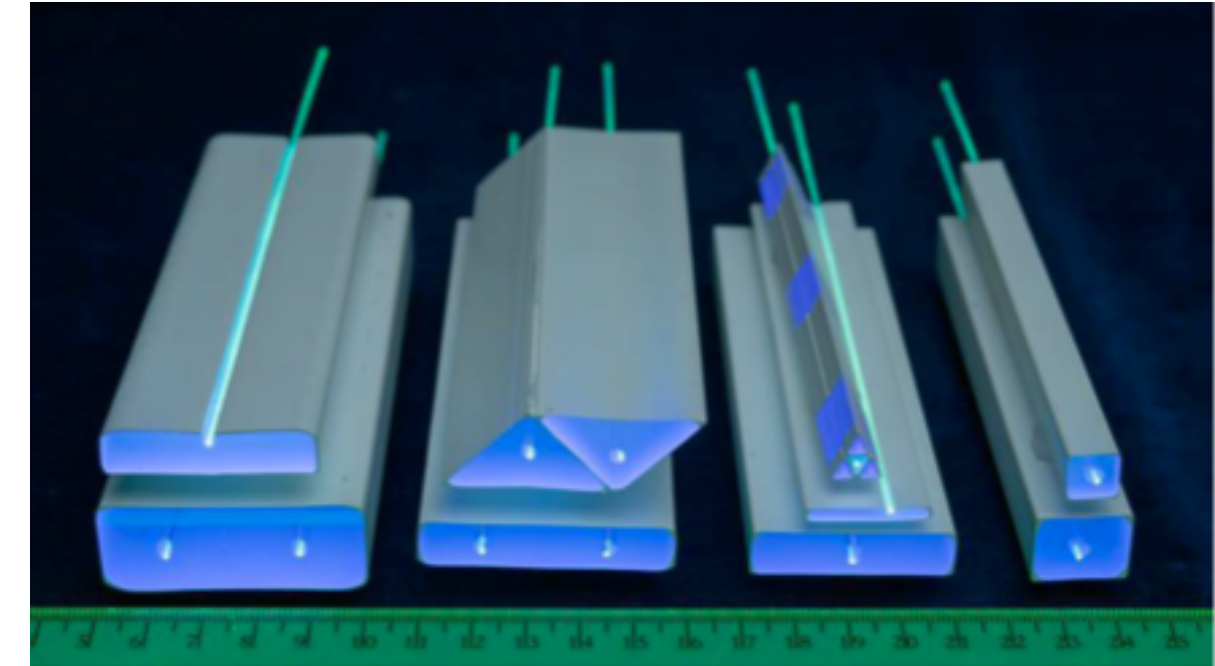
Mathusla has no SM backgrounds  
→ sensitivity gain wrt ATLAS



# Detector hardware

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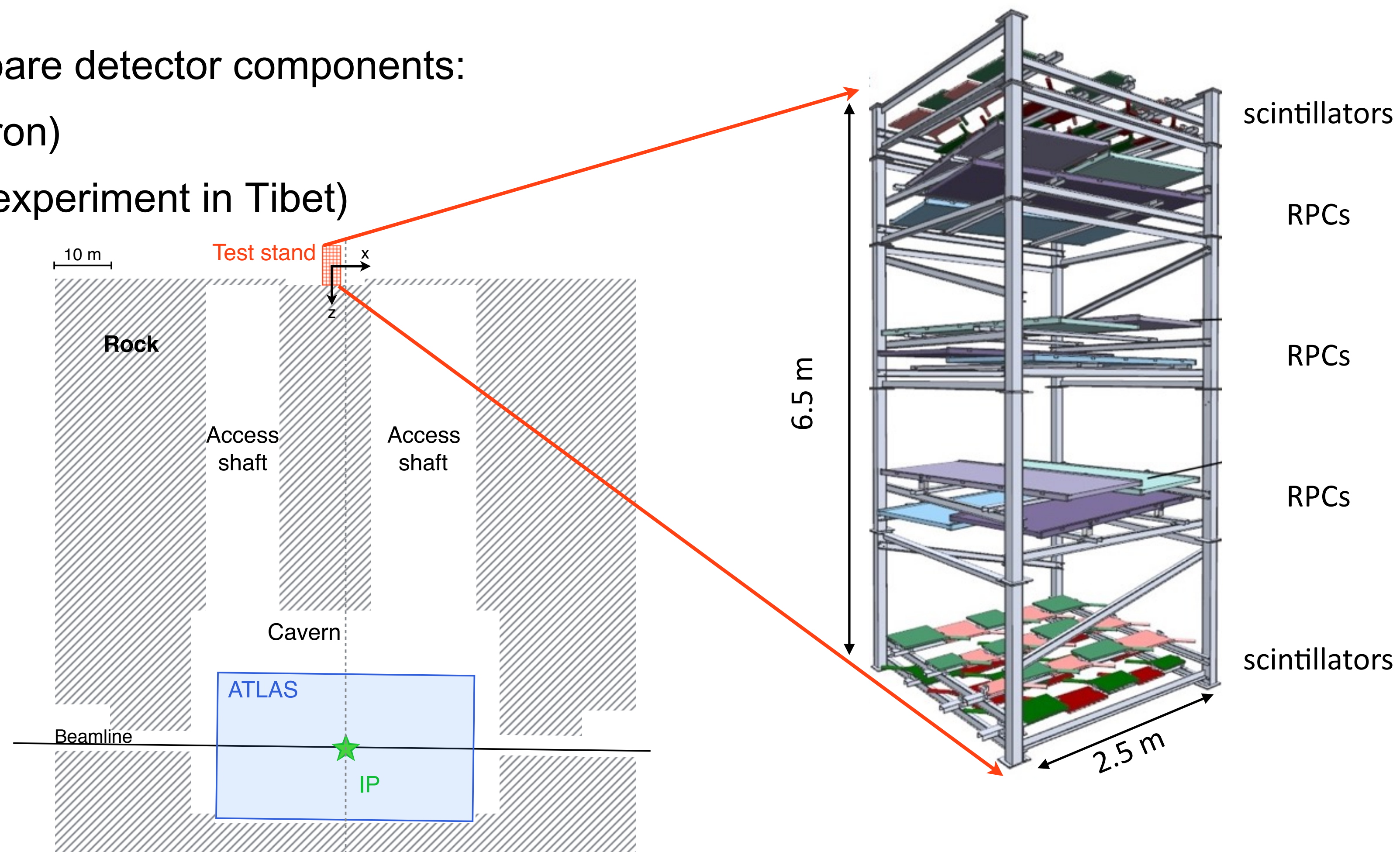
- Plan to use extruded scintillators for tracking with wavelength shifting (WLS) fibers.
- Fiber read out on both ends using silicon photomultipliers (SiPMs)
- Time difference gives longitudinal position
- Some advantages over RPCs:
  - don't require high voltage or gas systems
  - relatively stable with temperature and pressure changes



# The MATHUSLA Test Stand Description

<https://arxiv.org/abs/2005.02018>

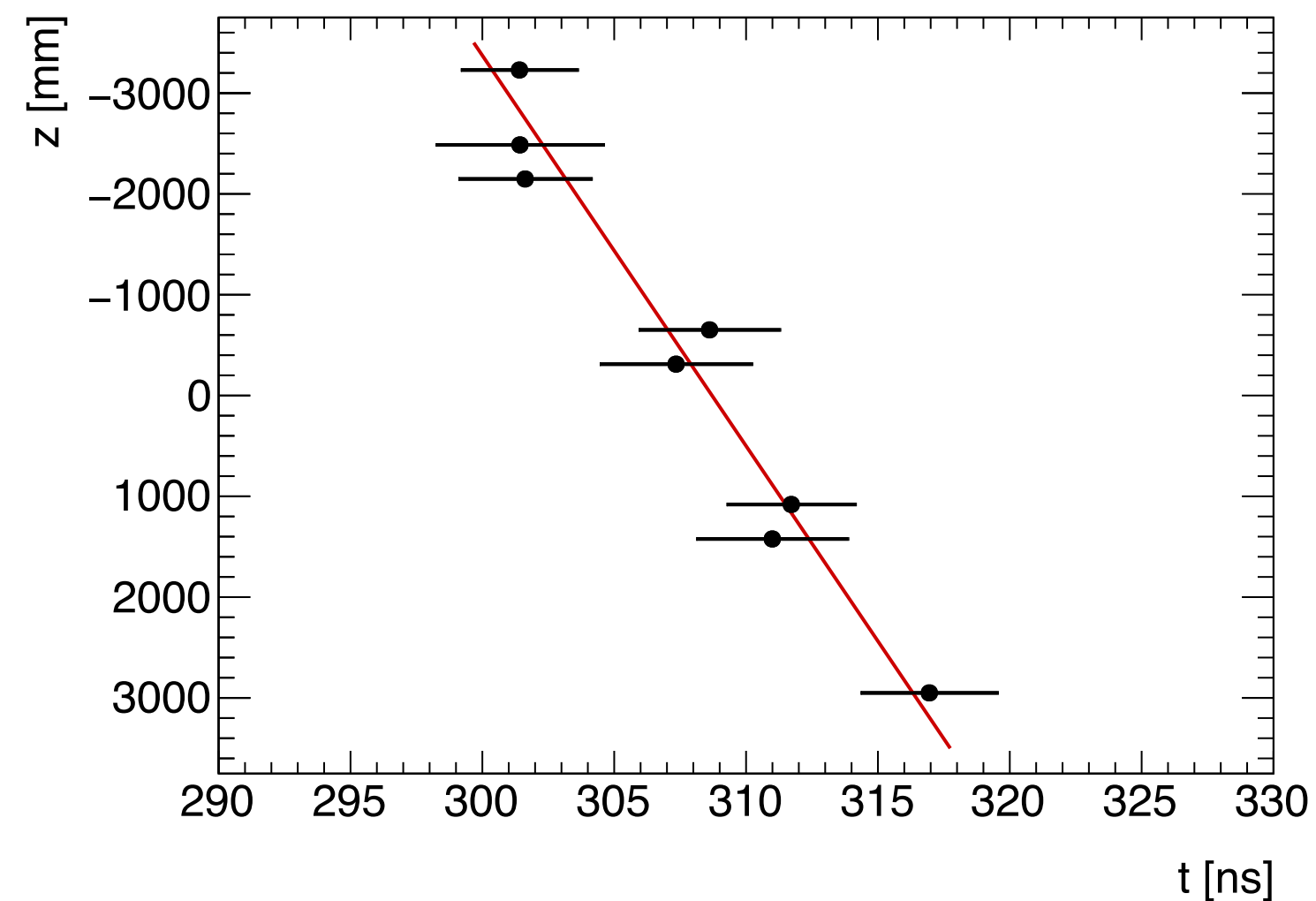
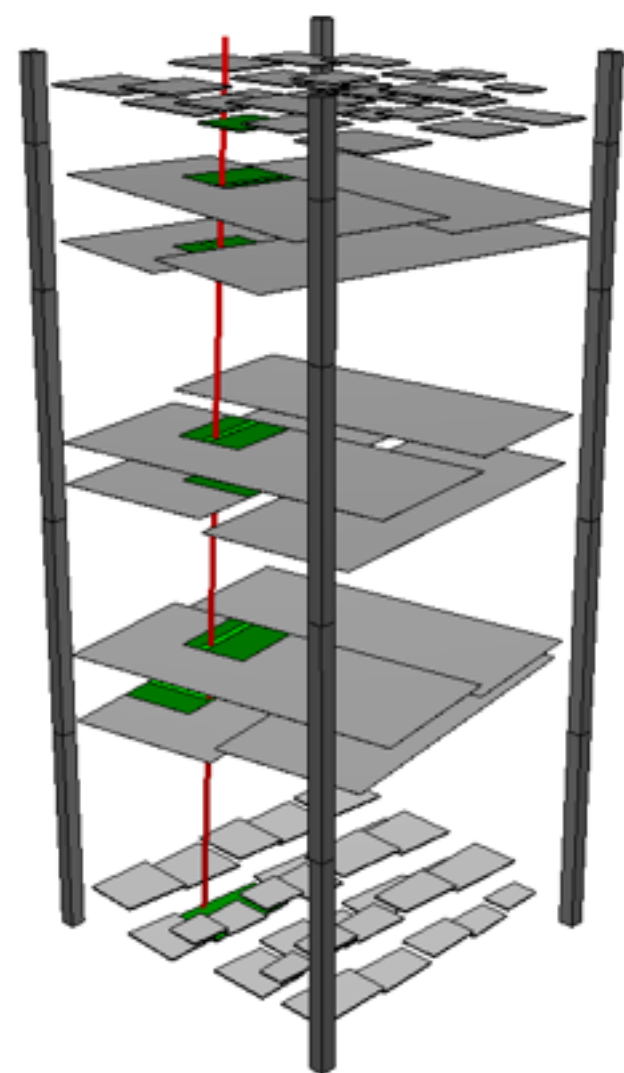
- The MATHUSLA Test Stand is a small-scale experiment, built on the surface above the ATLAS detector
- It collected data during 2018, both with LHC pp collisions and when the LHC was not colliding protons.
- $2.5 \times 2.5 \times 6$  m<sup>3</sup> active area composed of spare detector components:
  - 59 scintillation counters from D0 (Tevatron)
  - 12 RPCs from ARGO-YBJ (cosmic ray experiment in Tibet)



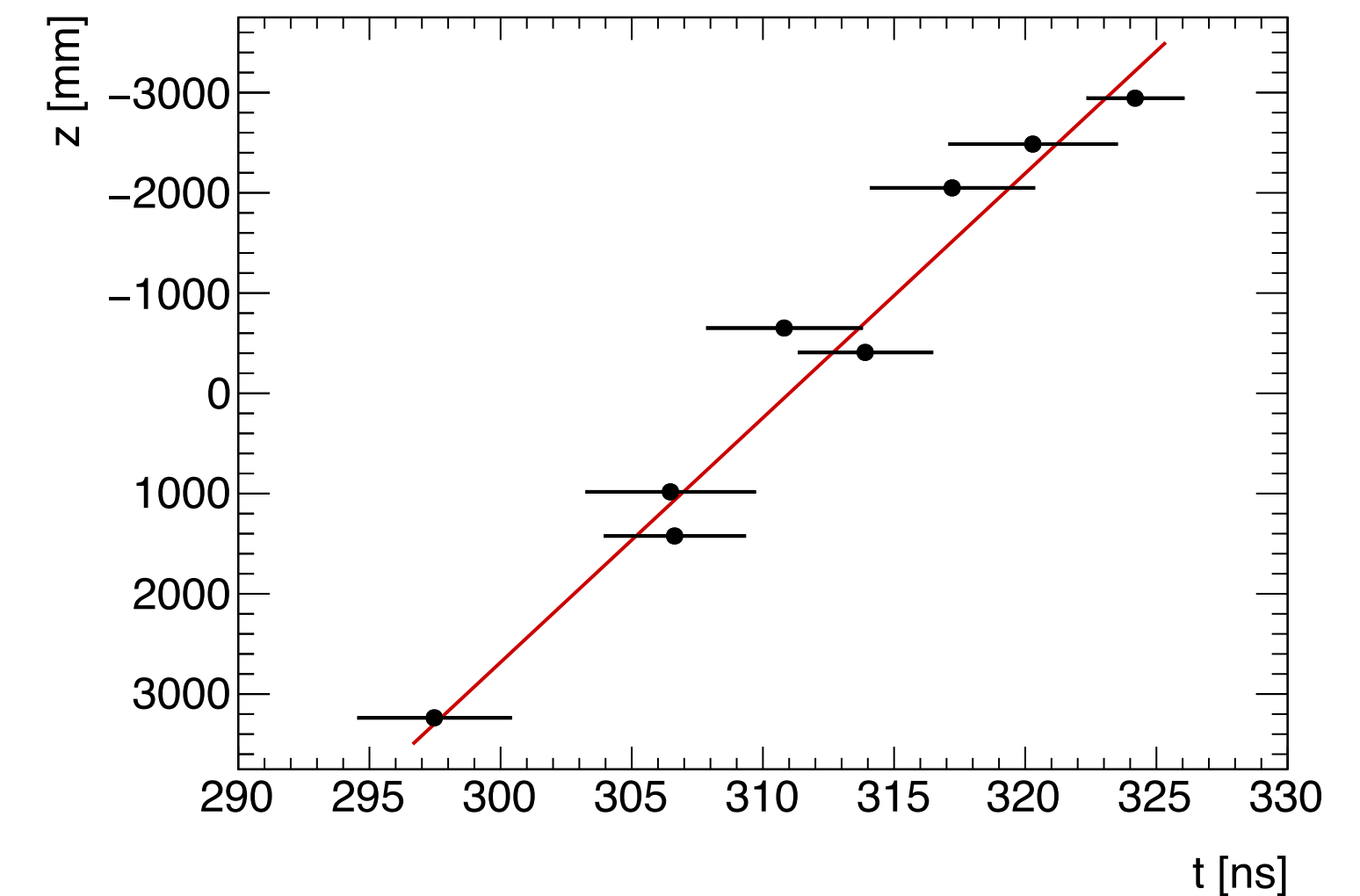
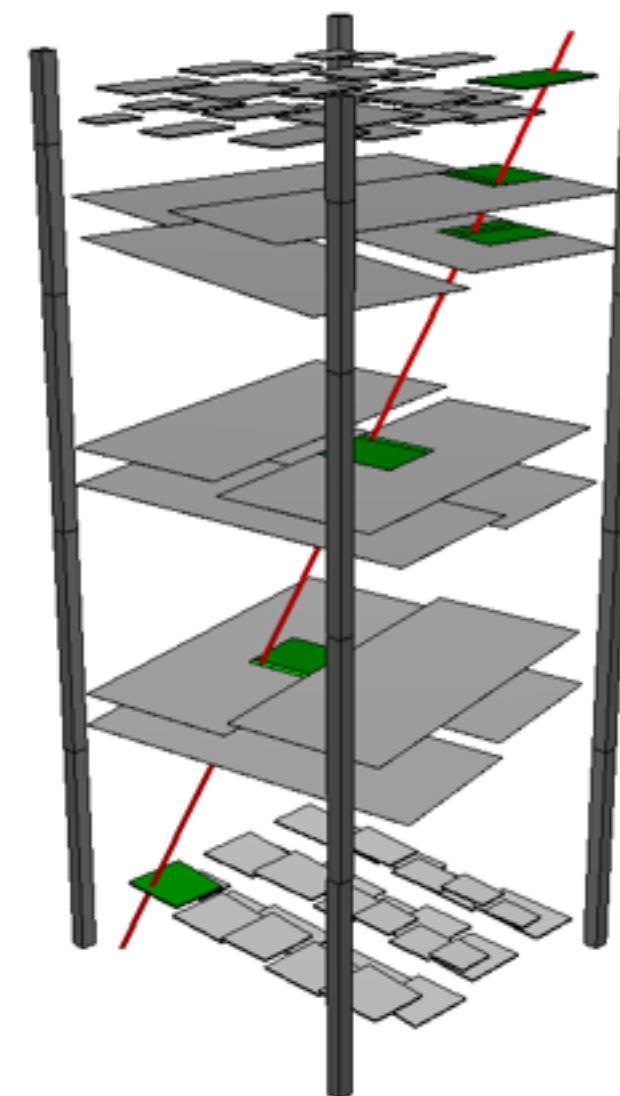
# Test Stand Tracking

- Coincidences of top-bottom scintillator planes for two triggers running simultaneously
  - Downward trigger for cosmic rays
  - Upward trigger for tracks from IP
- Tracks were reconstructed using scintillator and RPC information
- Upward and downward directions were distinguished with timing
- RPCs and scintillators have timing resolution  $\sigma \sim 2 - 3$  ns

Downward-going track

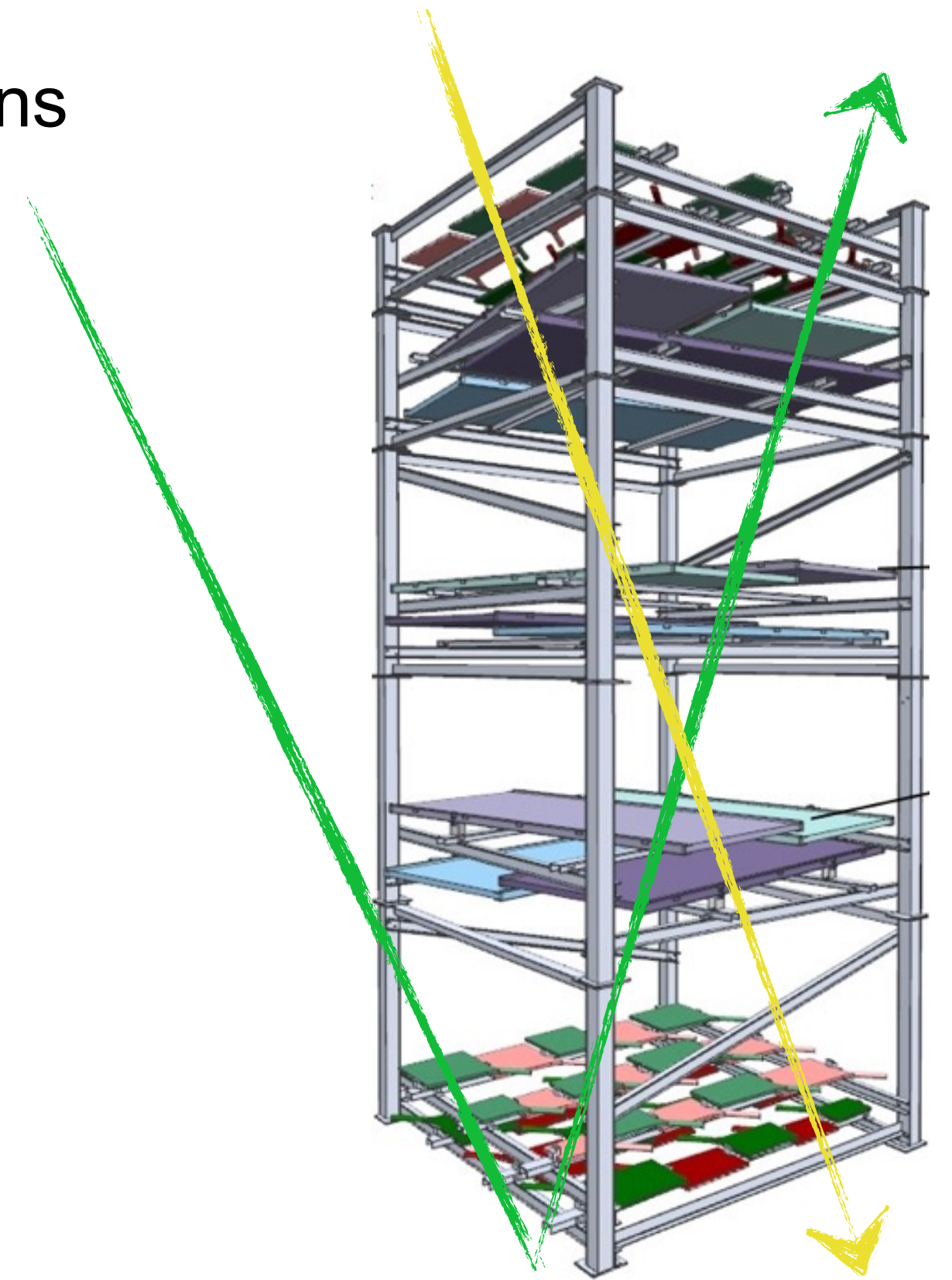
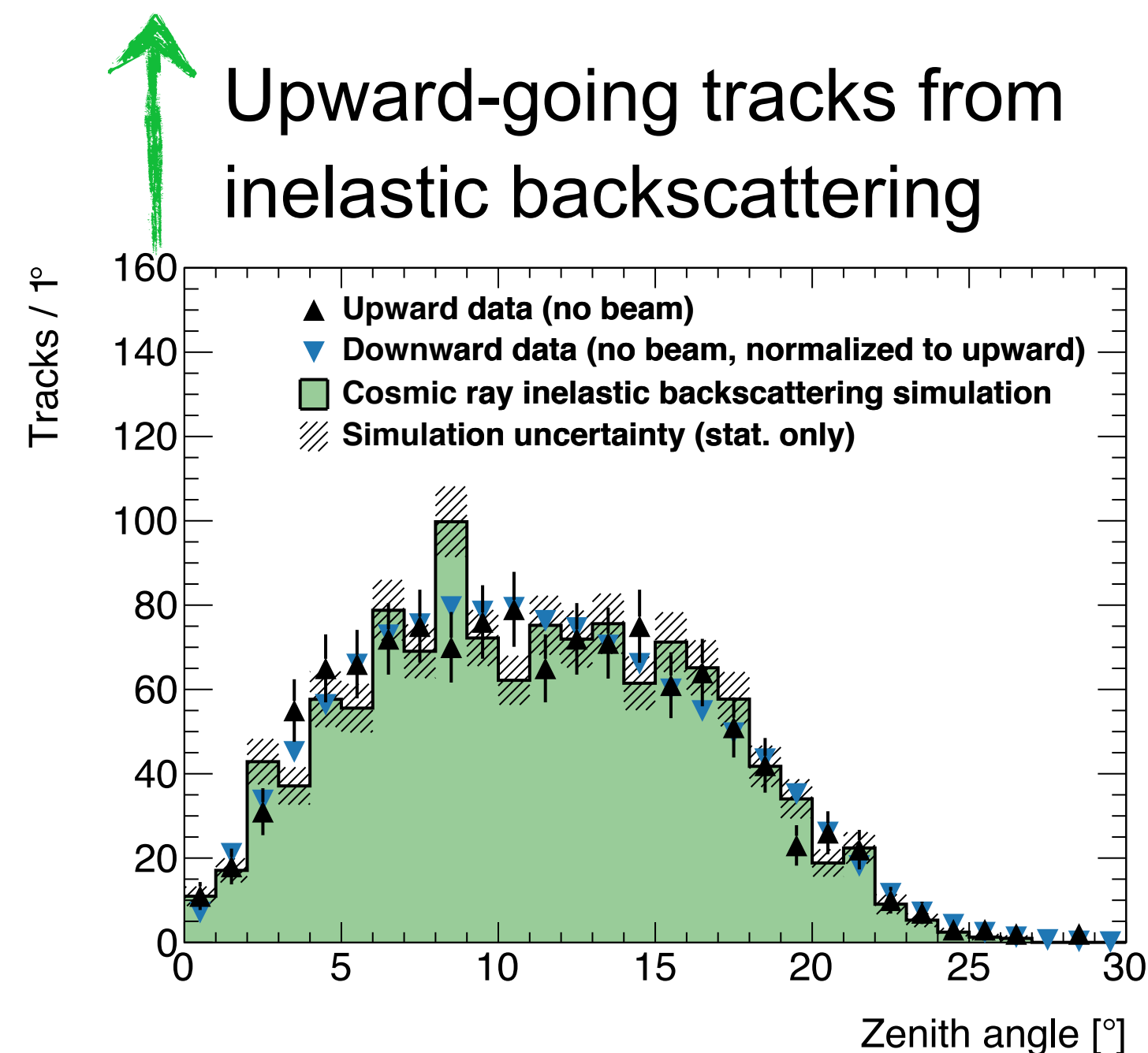
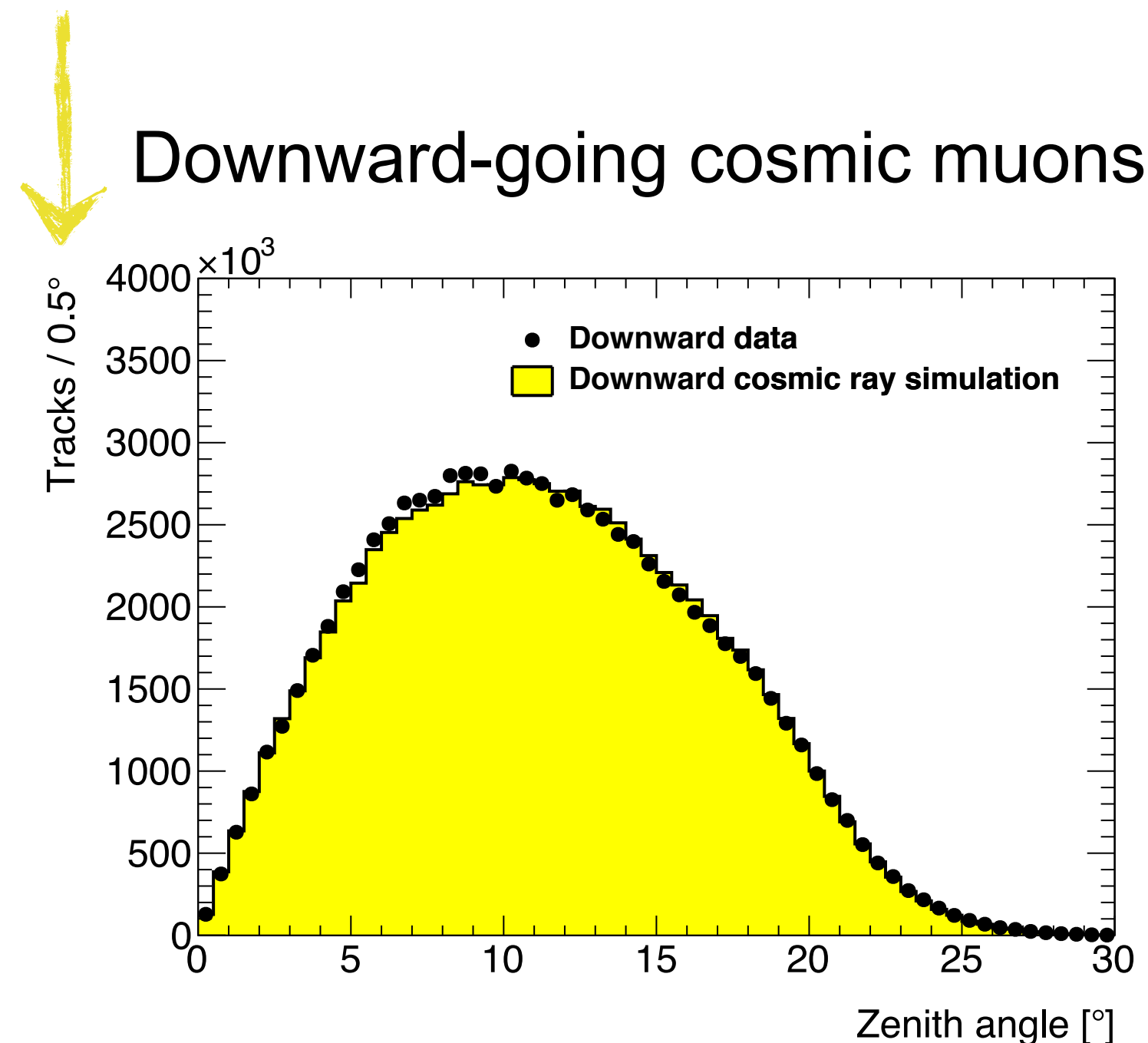


Upward-going track



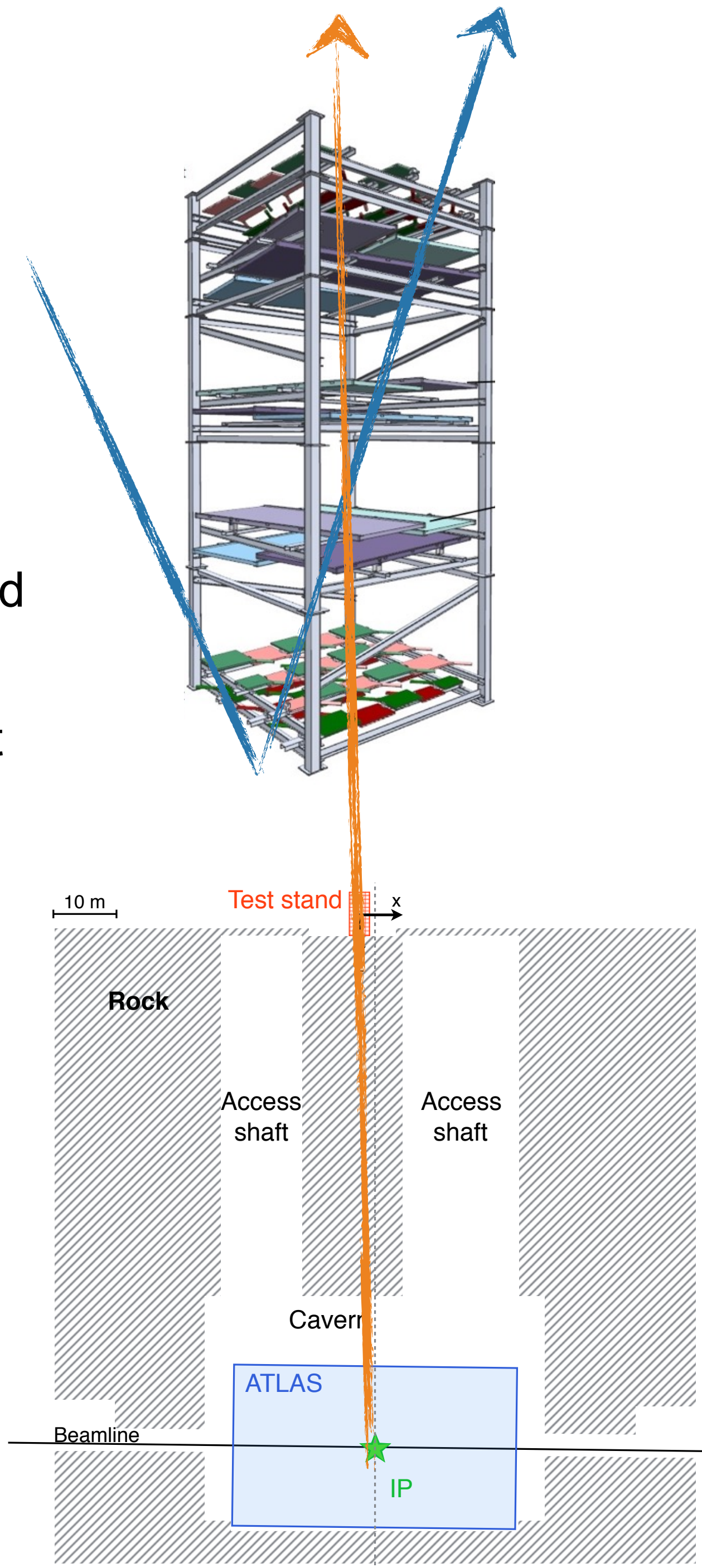
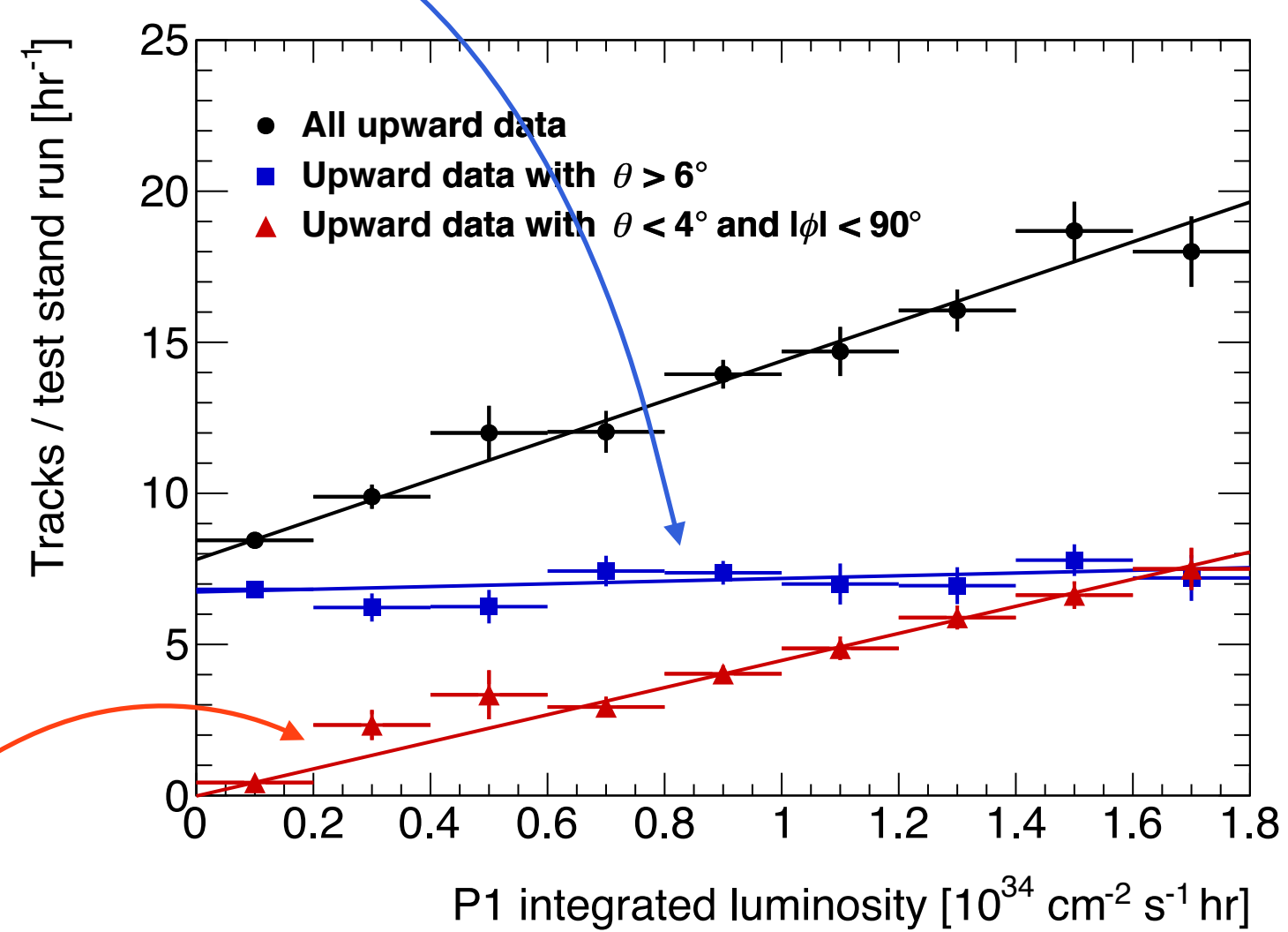
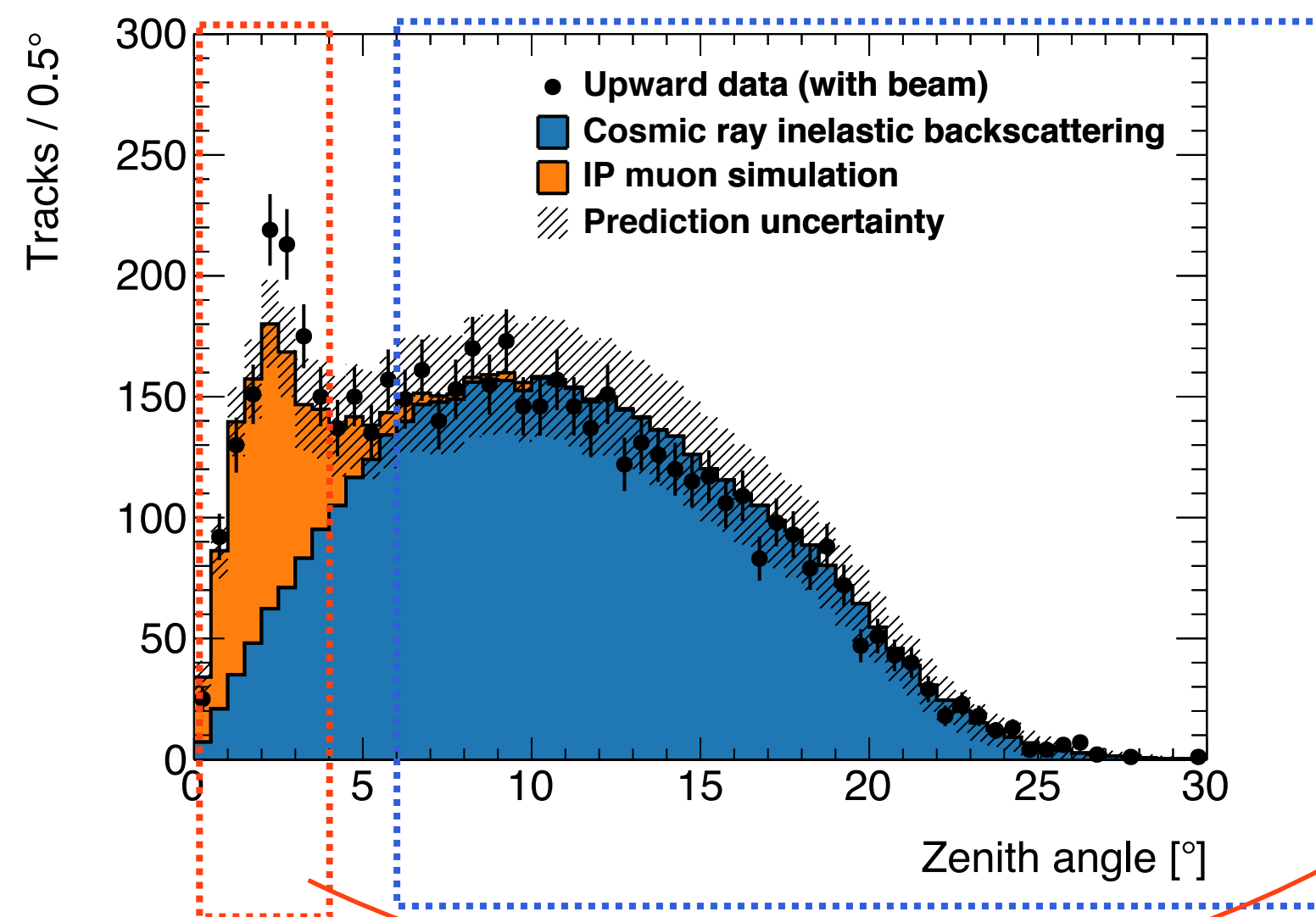
# Test Stand Results without beam

- When LHC has no beams running, data in the test stand correspond to cosmic muons
  - Downward-going tracks from incident downward cosemics
  - Upward-going tracks are created by inelastic backscattering of incident downward cosmic rays
- Test stand data compared to simulated cosmic rays and backscattering



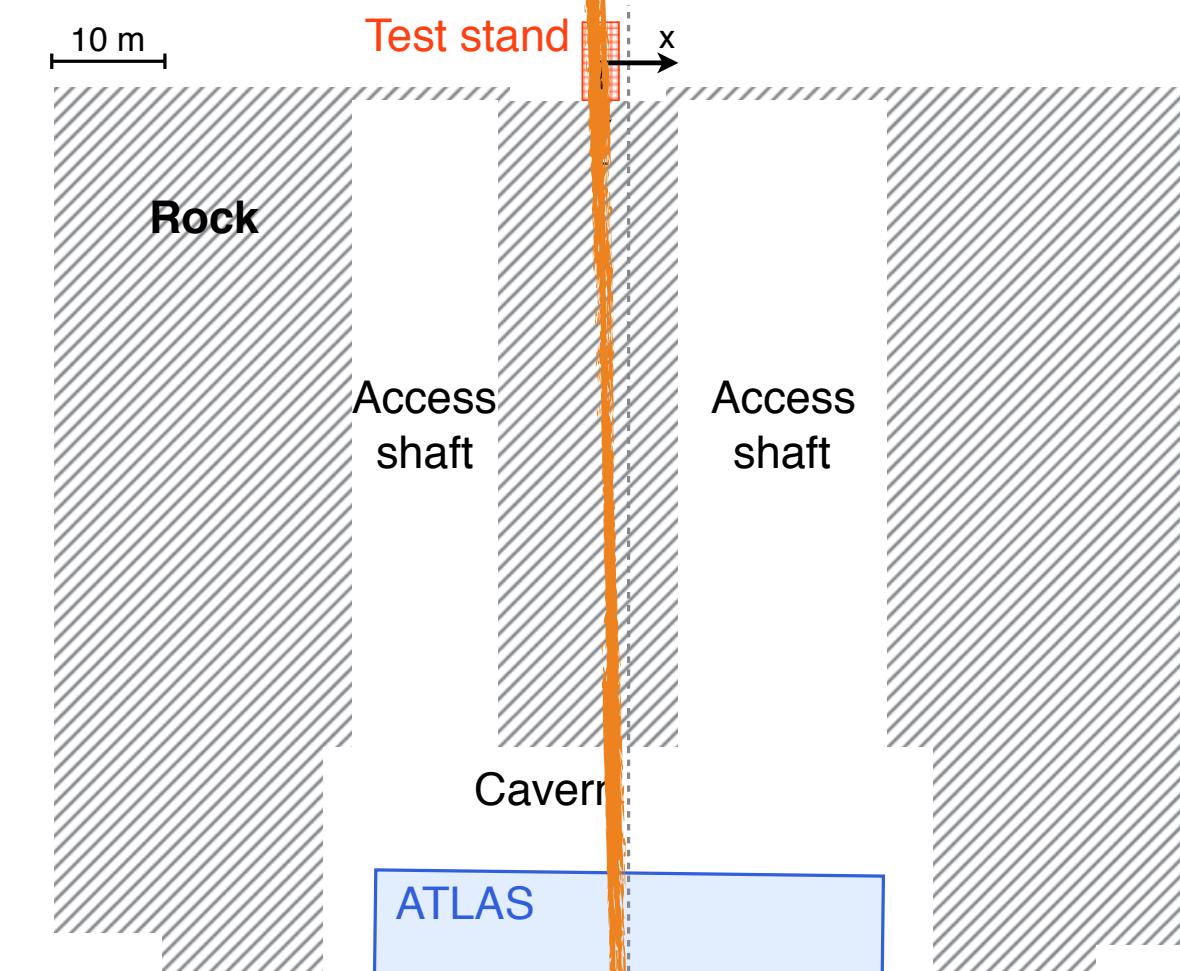
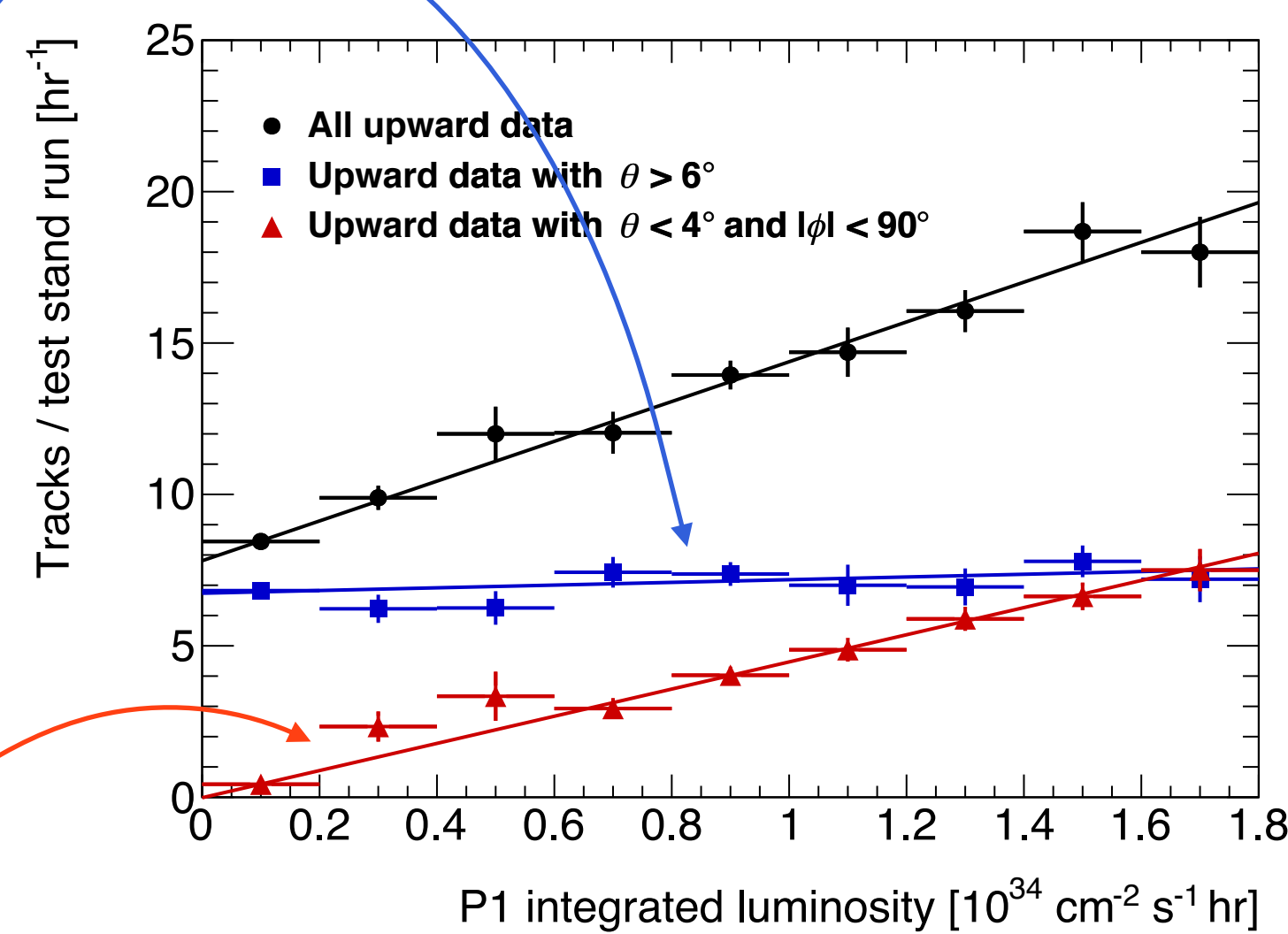
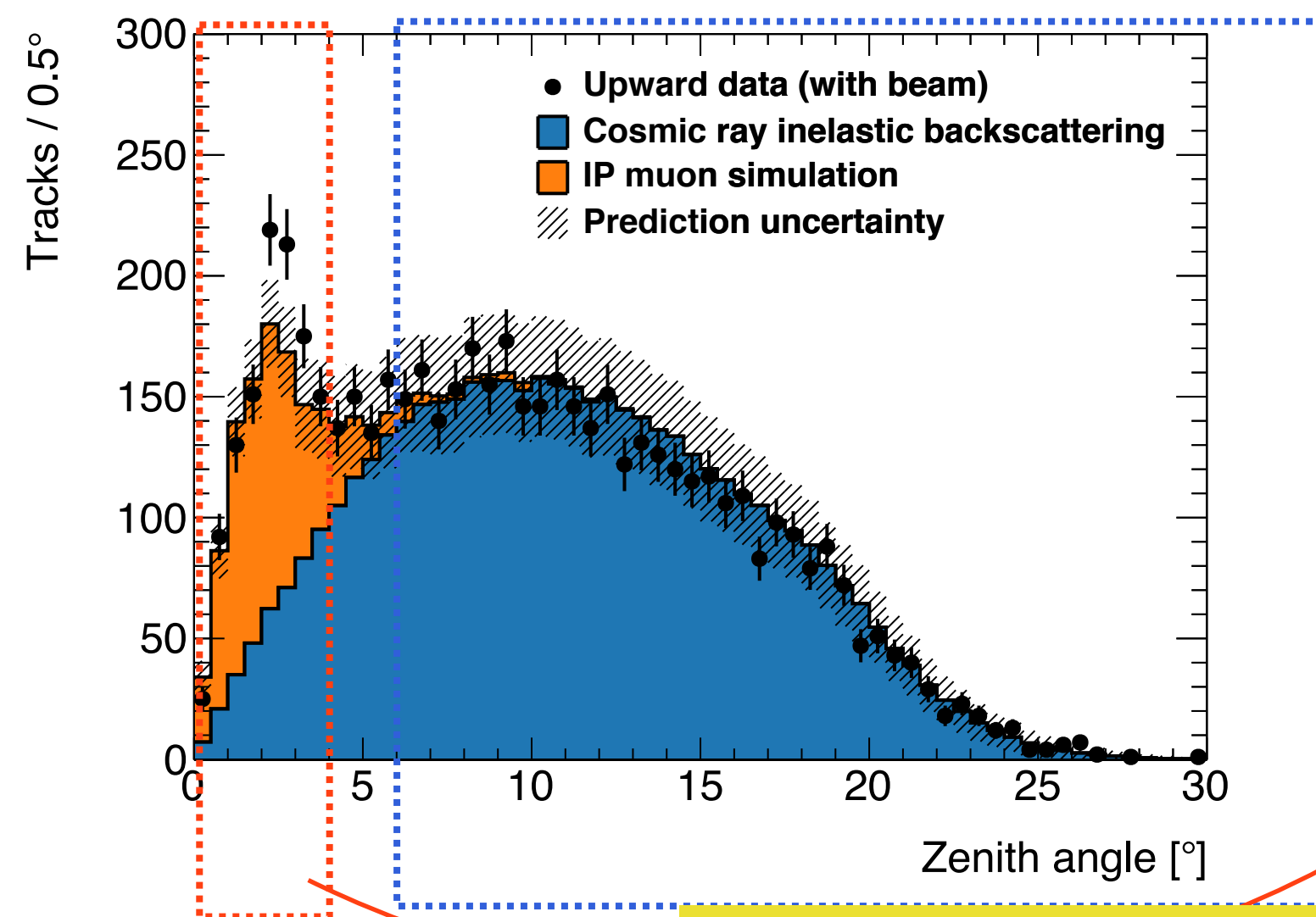
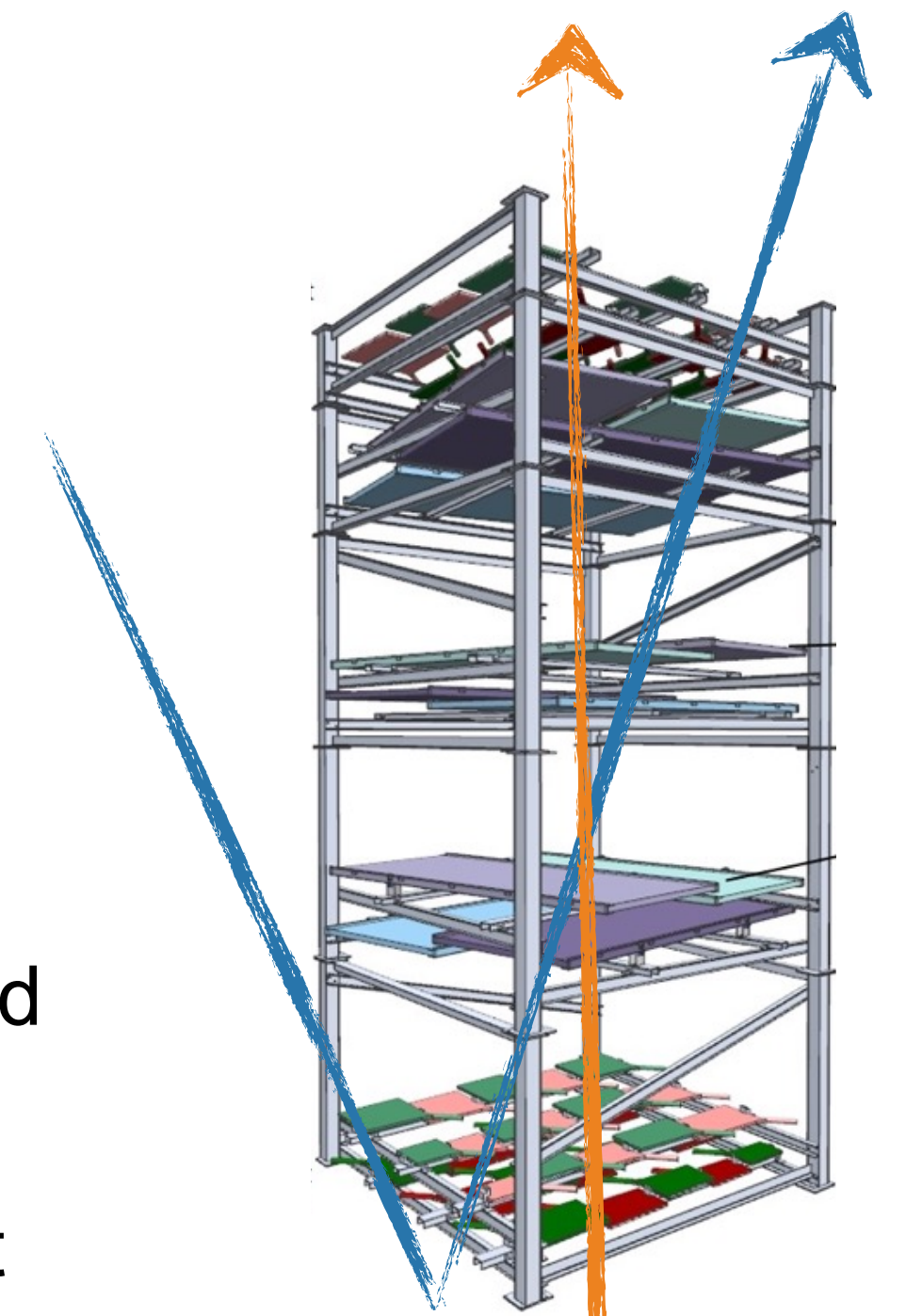
# Test Stand Results from LHC collisions

- In runs with LHC collisions, upward tracks in data correspond to two sources:
  - inelastic backscattering from cosmic rays
    - rate of upward-going tracks at large zenith angles is constant with luminosity
    - wide angular distribution
  - muons from LHC pp collisions reaching the surface
    - narrow angular distribution determined by the small solid angle subtended by the test stand
    - the rate of muons from the IP scales linearly with luminosity
    - consistent with MC simulated rates from decays of W and Z bosons and b- and c-quark jet



# Test Stand Results from LHC collisions

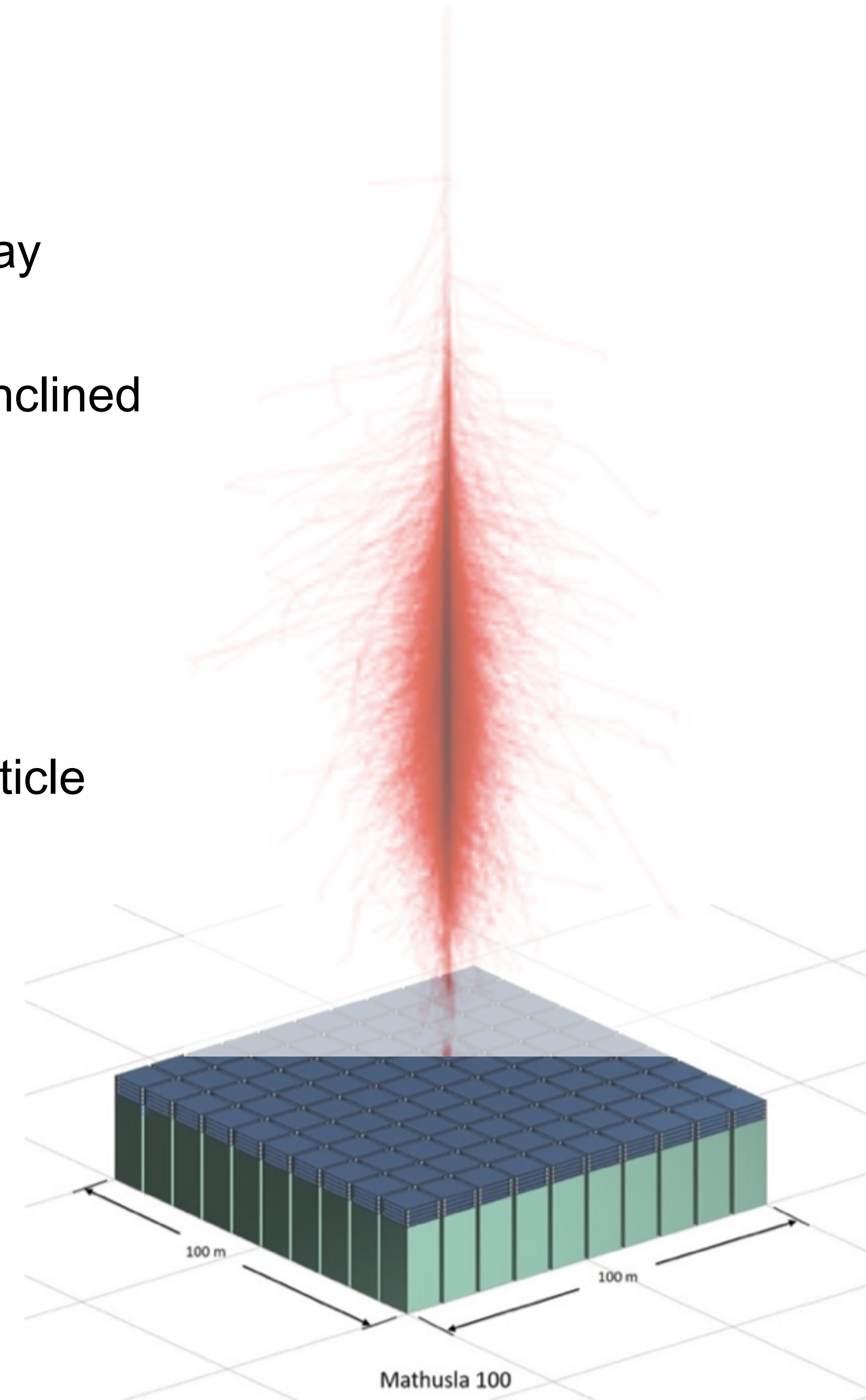
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**The test stand results confirm the background assumptions in the MATHUSLA proposal and give confidence in the MATHUSLA projected physics reach.**

# Cosmic ray physics

- Position on the surface and large area makes MATHUSLA perfect for cosmic ray measurements
- Baseline detector can already provide useful energy spectrum information for inclined cosmic ray showers (>70° zenith angle)
- Studies ongoing of how to expand cosmic ray physics potential
  - For Extensive Air Shower (EAS), densities of  $O(10^4)$  charged particles/m<sup>2</sup>
  - problem of signal saturation at the scintillator bars for more than 1 hitting particle
  - inclusion of an RPC layer would enhance EAS detection
- Collaborating with cosmic ray experts and looking to bring more of them!



# Summary

- Test stand data analysis complete and results public
  - <https://arxiv.org/abs/2005.02018> submitted to NIM
  - Results confirm background assumptions for MATHUSLA
- Full baseline detector design established
- Performing hardware tests on various scintillators, WLS fibers and SiPMs
- In addition to searching for LLPs, MATHUSLA can be competitive cosmic ray experiment — a guaranteed physics payoff!
  - working with cosmic ray experts to study how to take full advantage
- Currently updating letter of intent and planning to finish Technical Design Report



# MATHUSLA documentation

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- Original idea: J-P Chou, D. Curtin, H. Lubatti [arXiv 1606.06298](https://arxiv.org/abs/1606.06298)
- Mathusla Physics case - theory white paper to be published in Physics Reports: [arxiv: 1806.07396](https://arxiv.org/abs/1806.07396)
- Letter of Intent submitted to LHCC in November 2018: [MATHUSLA LoI: arXiv 1811.00927](https://arxiv.org/abs/1811.00927)
- Input to European Strategy for Particle Physics: [arxiv 1901.04040](https://arxiv.org/abs/1901.04040)
- Test stand paper: <https://arxiv.org/abs/2005.02018>
- Mathusla webpage: <https://mathusla-experiment.web.cern.ch/>



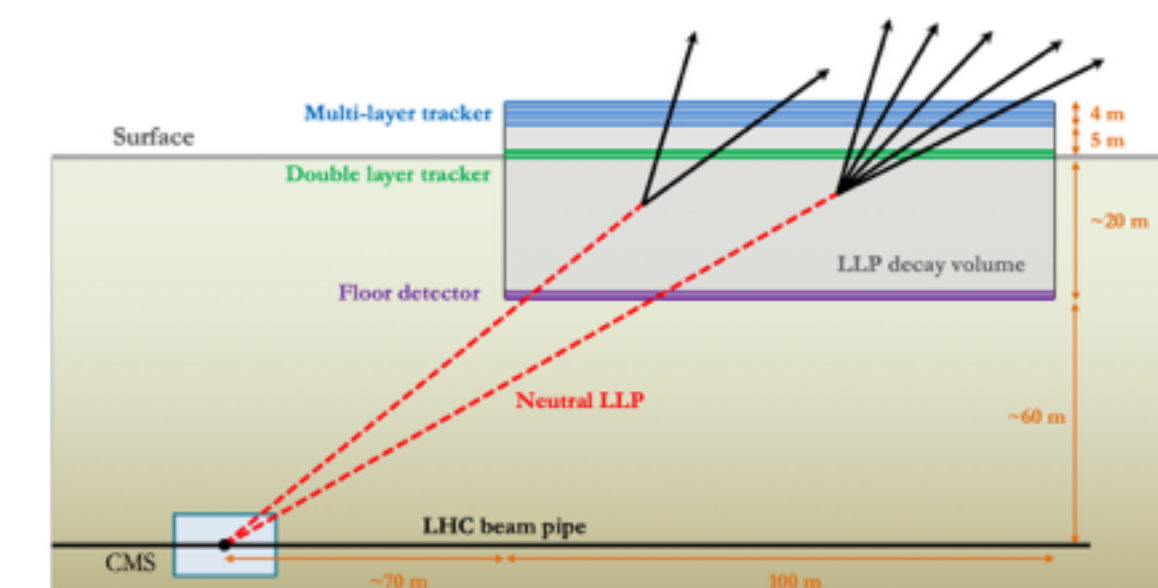
## The MATHUSLA experiment

MATHUSLA (Massive Timing Hodoscope for Ultra Stable neutral pArticles) is a proposed detector at CERN with the aim of going online with the HL-LHC upgrade to the Large Hadron Collider in ~2026.

Many extensions of the Standard Model (SM) include particles that are neutral, weakly coupled, and long-lived that can decay to final states containing several SM particles. Missing energy (MET) searches at ATLAS and CMS are undoubtedly crucial in probing new physics giving rise to more than several hundred GeV of MET, but the sensitivity drastically drops for softer signals. Searches for long-lived particles (LLP) in the LHC detectors have set significant exclusion limits from a few centimetres to tens of meters, but the detection reach of the LHC detectors is limited by trigger and background difficulties. Therefore, even if an LLP was already produced at the LHC, it might have been inevitably missed.

No existing or proposed search strategy will be able to observe the decay of neutral LLPs with masses above ~GeV and lifetimes up to the limit set by Big Bang Nucleosynthesis (ct  $\sim 10^{-4} - 10^{-8}$  s).

MATHUSLA is a large-scale (100x100 m<sup>2</sup>), relatively simple detector for the HL-LHC that can detect the decay of neutral LLPs produced in proton-proton (pp) collisions at the LHC. Its location on the surface shields it from backgrounds that constrain the ability of the main detectors, like ATLAS and CMS, to look for many of these kinds of particles, and provides MATHUSLA with a background free environment and no trigger limitations. Moreover, the large size of MATHUSLA would also allow it to act as a cosmic ray (CR) telescope.



# Backup

# MATHUSLA technology

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- 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  $\sigma = 4\text{cm}/\sqrt{12} \approx 1 \text{ cm}$ .
- Time difference between two ends gives longitudinal resolution (aiming for ~ 1 cm)