Searches for Ultra Long-Lived Particles with MATHUSLA

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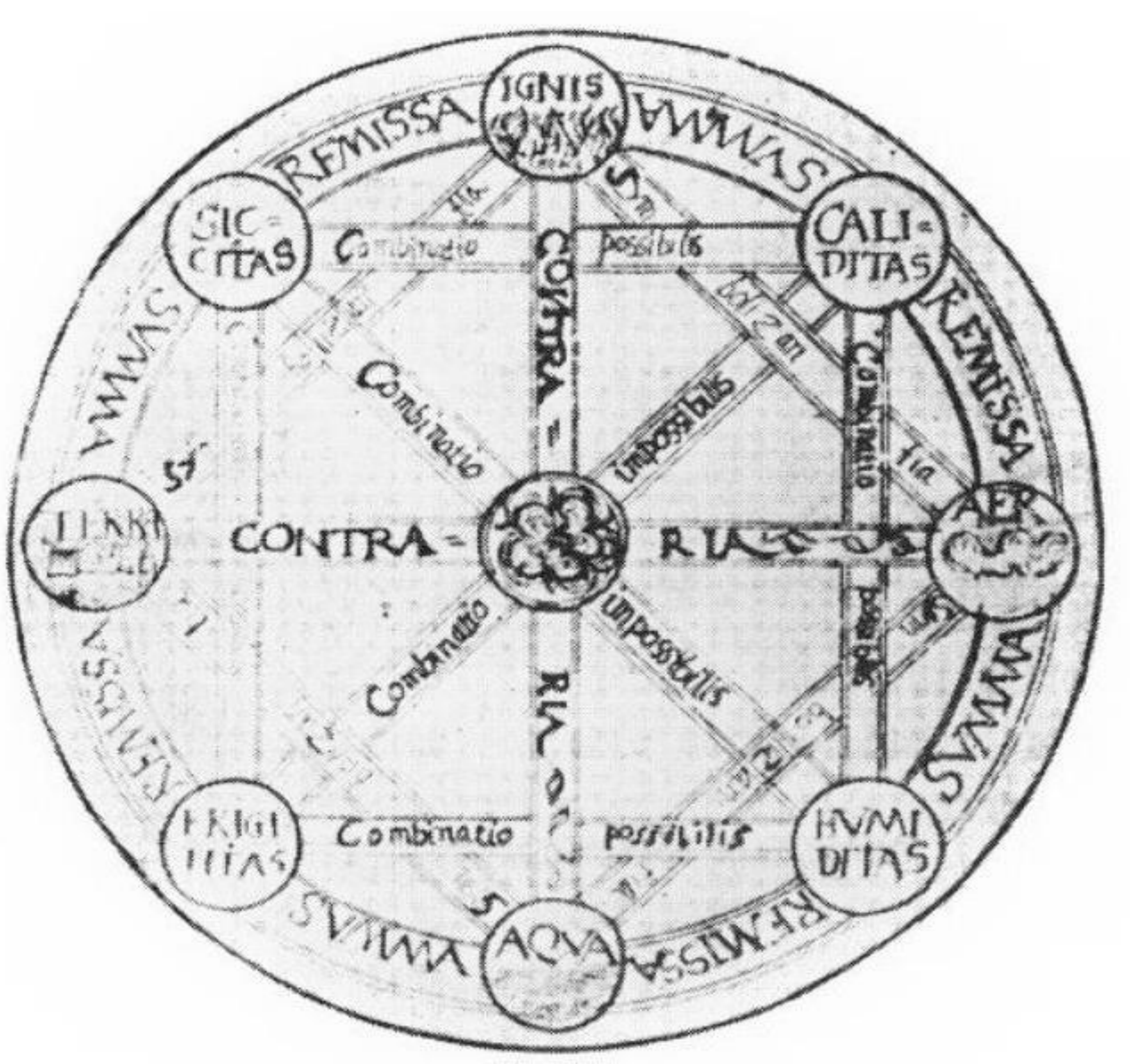
Outline

- Fundamental Motivations for Long Lived Particles
- LLP Searches at the Large Hadron Collider
- MATHUSLA
  - Basic Concept
  - LLP Sensitivity
  - Cosmic Ray Telescope
- Detector Design
  - Test Stand
- Next Steps & Opportunities

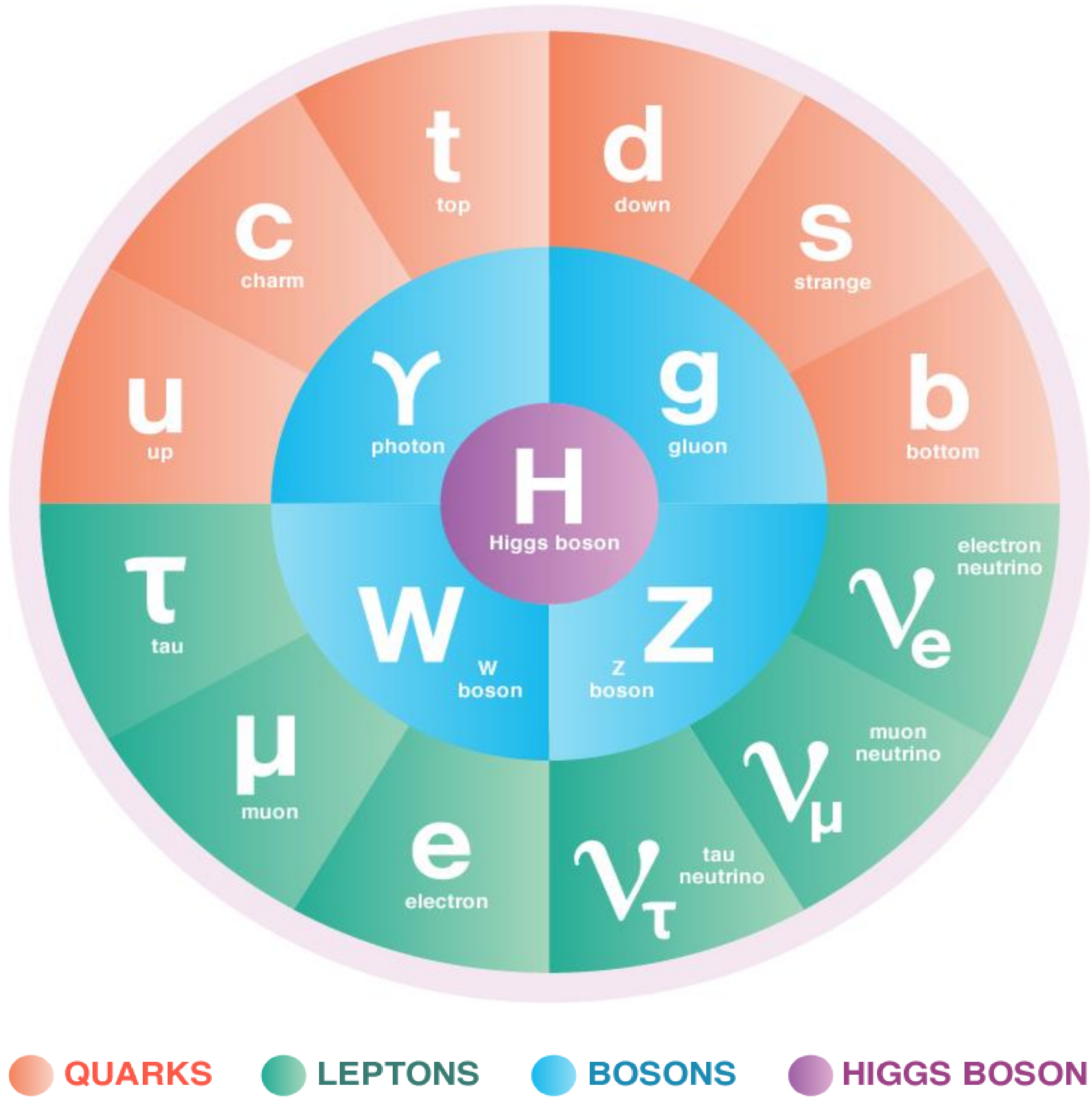
Fundamental Motivations for LLPs

The Standard Model …

2500 years ago



Today

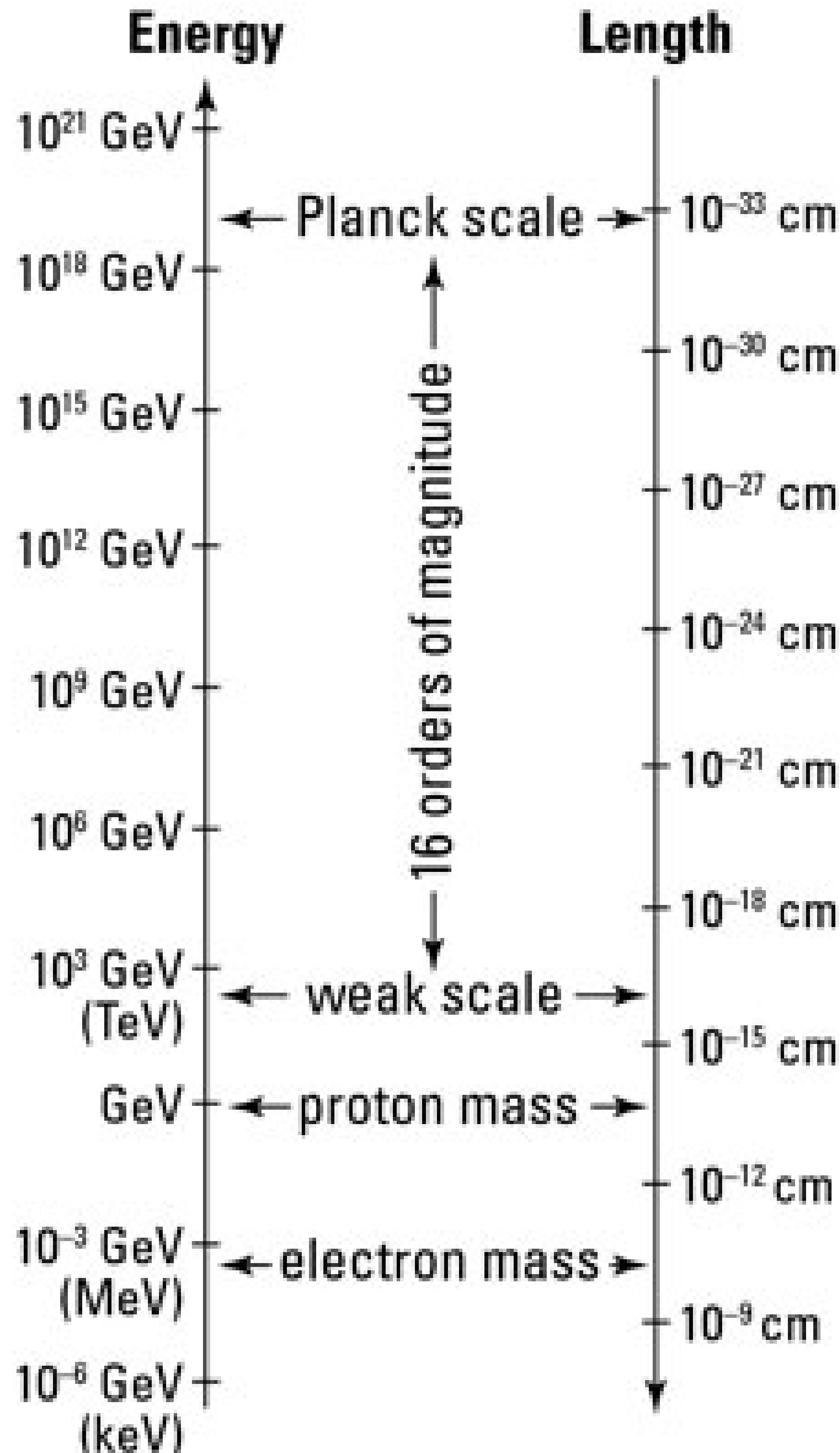


Symmetry Magazine: Sandbox Studio, Chicago

… is incomplete!

Hierarchy Problem & Naturalness: why is the Higgs Boson mass so low, and what stabilizes its mass?

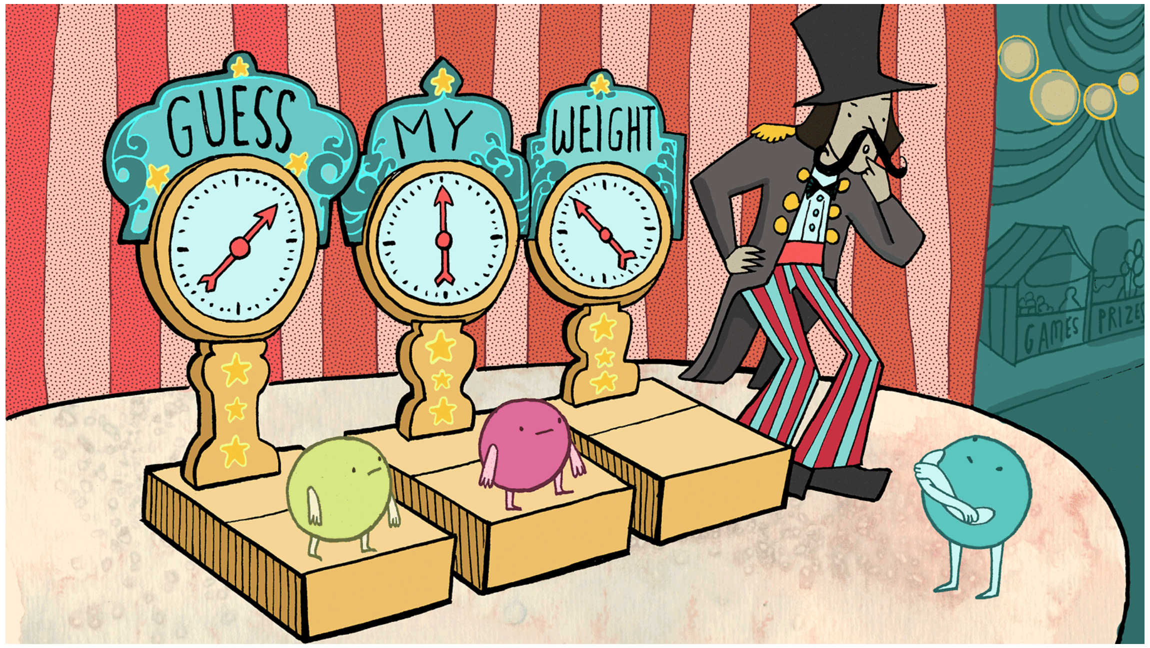
Quantum Diaries



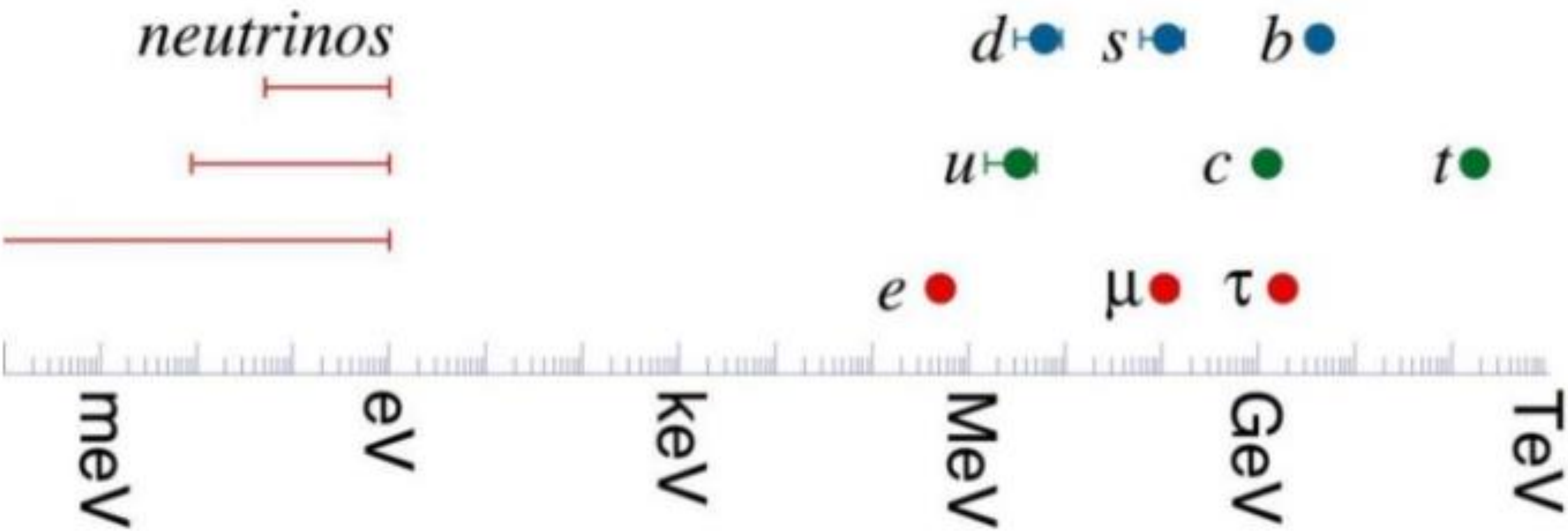
Lisa Randall

… is incomplete!

Neutrinos: where do their tiny masses come from?



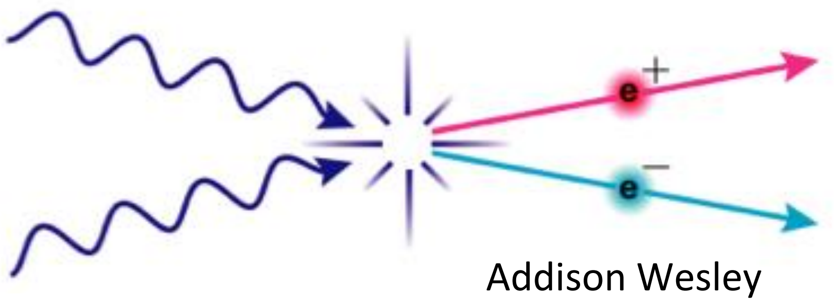
Symmetry Magazine: Sandbox Studio, Chicago with Corinne Mucha



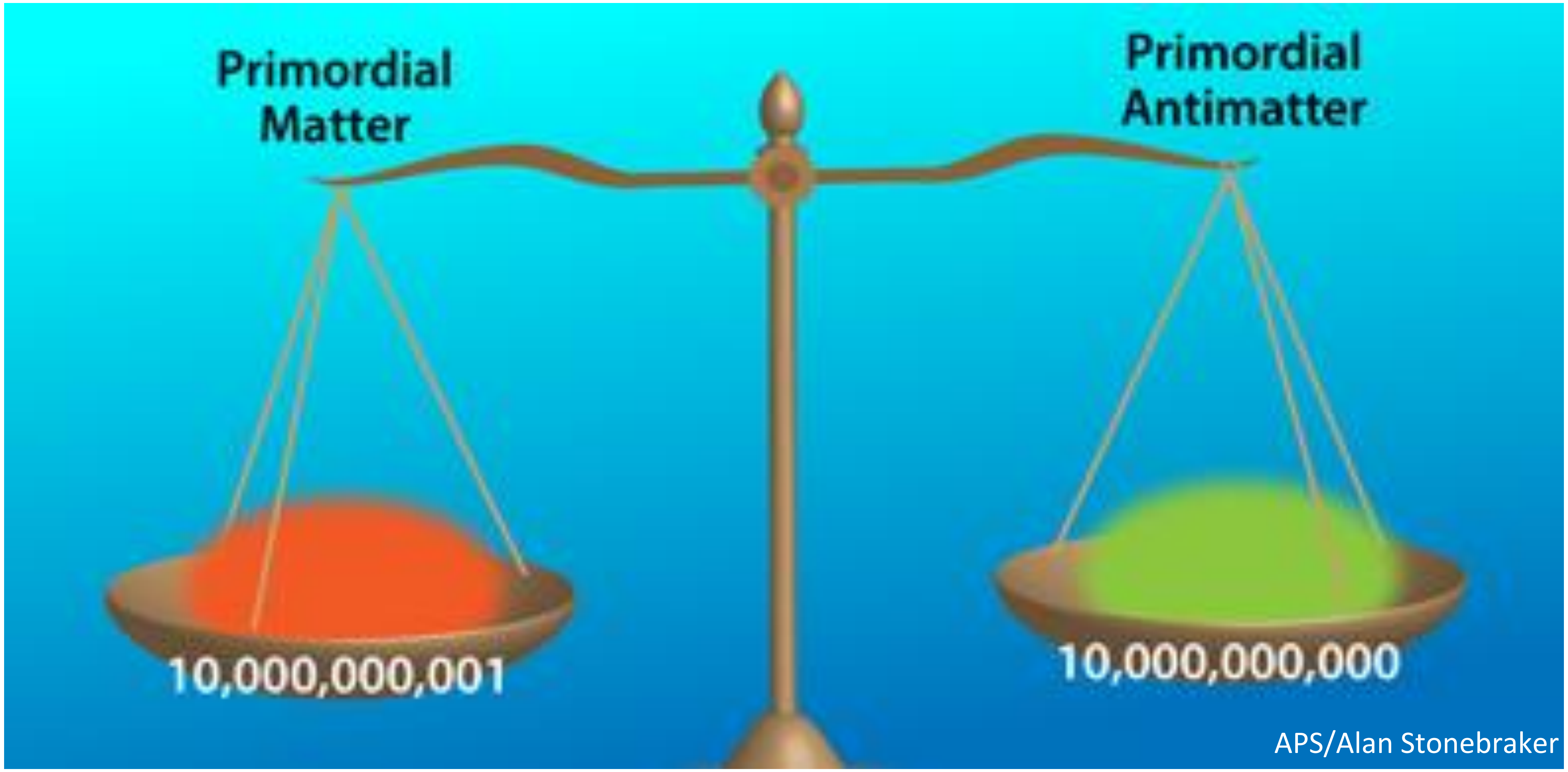
Hitoshi Murayama

… is incomplete!

Matter-antimatter asymmetry: How did the universe become matter-dominated?



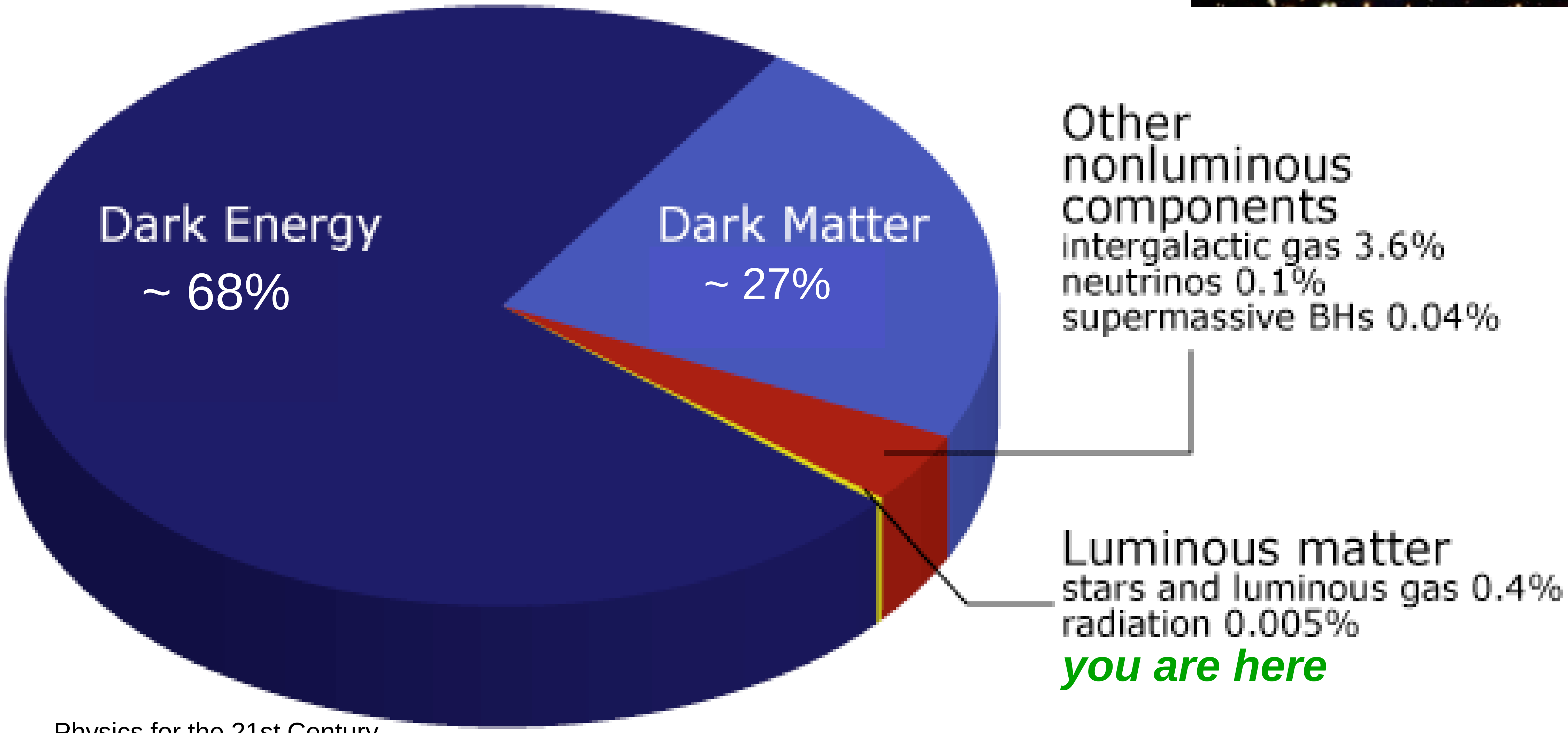
Addison Wesley



APS/Alan Stonebraker

… is incomplete!

Dark Matter: What is it, and what sets the relative amount of it in the universe?



Physics for the 21st Century

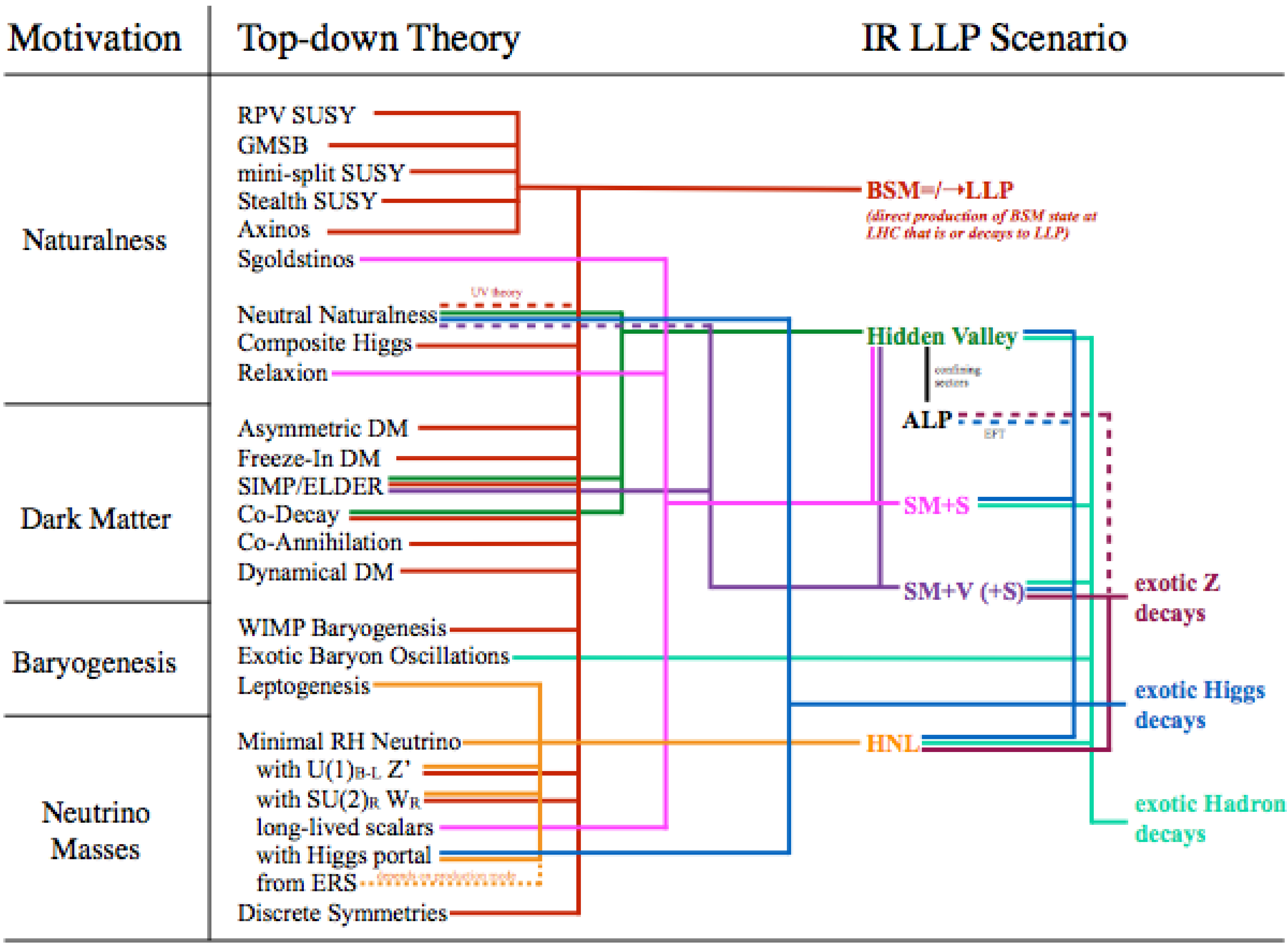
Theoretical motivation for LLPs

Seeking to go Beyond the Standard Model (BSM) motivates the possibility of so-far-undiscovered LLPs

"**Top-down**": Various BSM theories (e.g. supersymmetry) constructed to explain the Fundamental Mysteries naturally include new LLPs

"**Bottom-up**": LLPs occur in the SM (e.g. muons), and can occur via similar mechanisms when adding new particles to the model

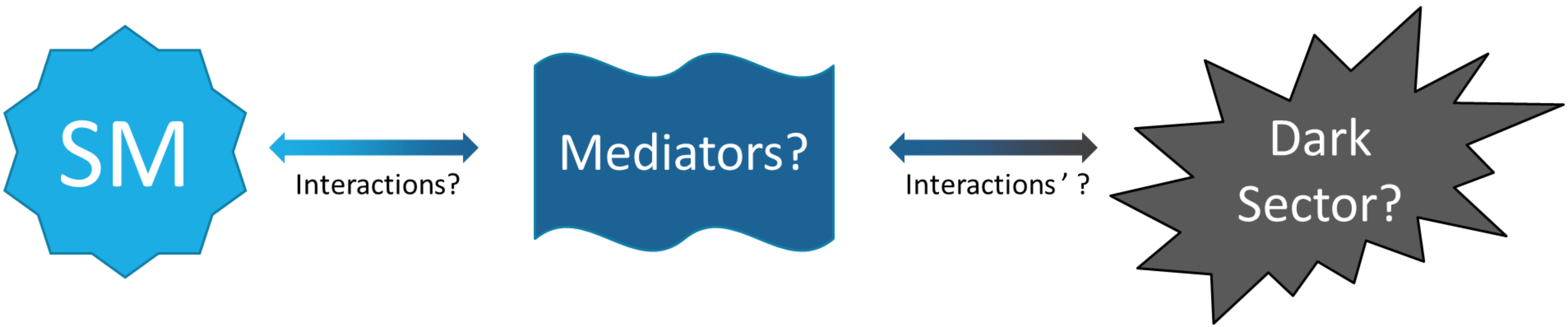
Top-down LLP motivation



Bottom-up LLP motivation

Example: "Hidden Sector" of BSM particles & forces not directly accessible to us

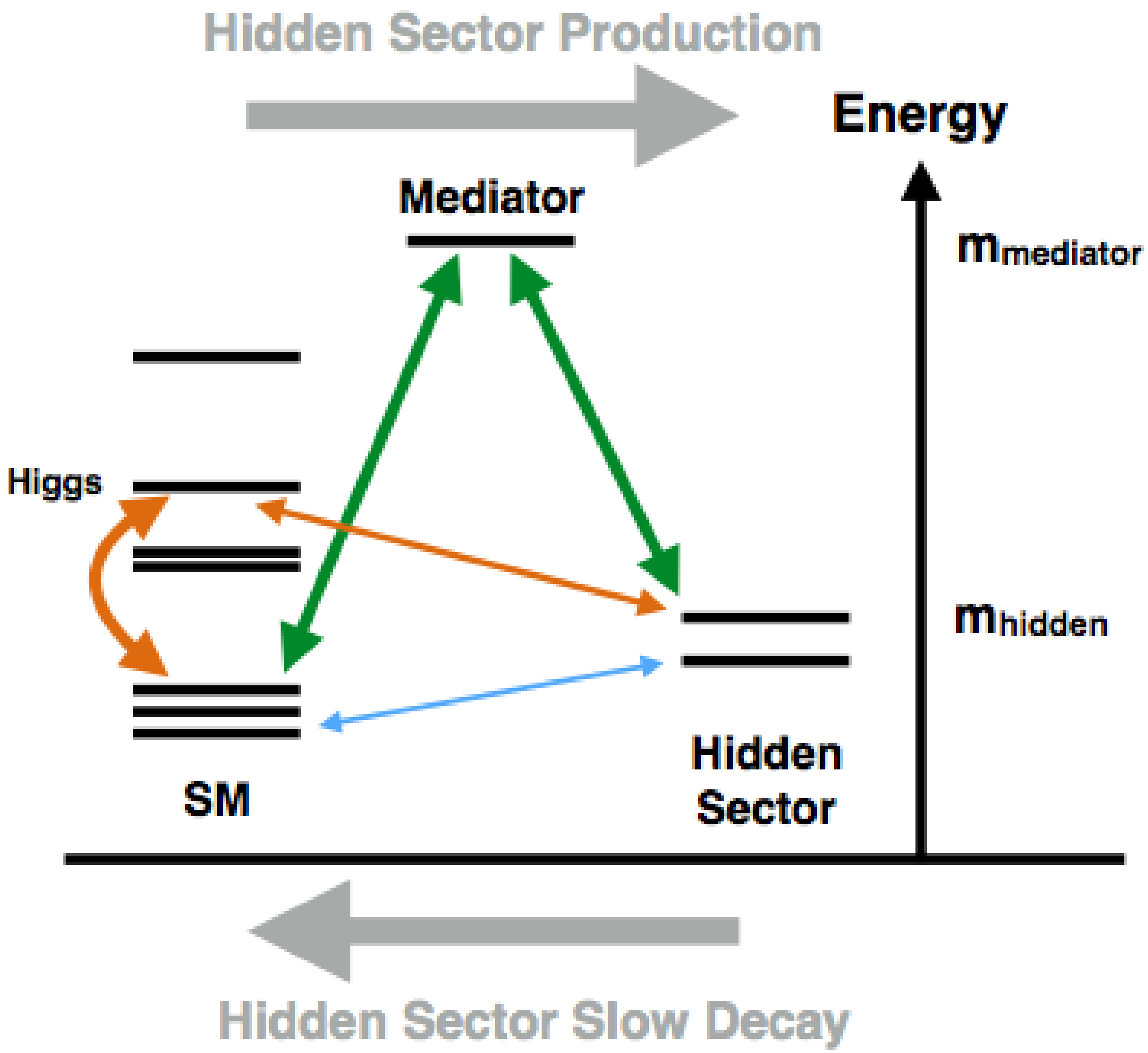
The Standard Model is only ~5% of the universe.
It includes 3 forces.
Why should the ~25% that is Dark Matter be any simpler?
Dark Forces?
How would DM interact with the SM?
Mediator particles?



Bottom-up LLP motivation

Dark Matter lives in the Hidden Sector

Metastable Hidden Sector states can only decay to SM via mediators (e.g. extra Higgs Bosons) with small couplings, so they are long-lived



LLP Searches at the HL-LHC

Large Hadron Collider at CERN

Probing the fundamental mysteries with 4 main detectors since 2010

Proton-proton collisions with 7, 8, then 13 TeV centre-of-mass energy
Announced the Higgs Boson discovery in July 2012
Currently in a shutdown period following “Run 2”

High-Luminosity Large Hadron Collider

Upgrading the world’s most powerful supercollider:
10x the original rate of particle collisions

Planned for mid-2020s, following “Run 3”

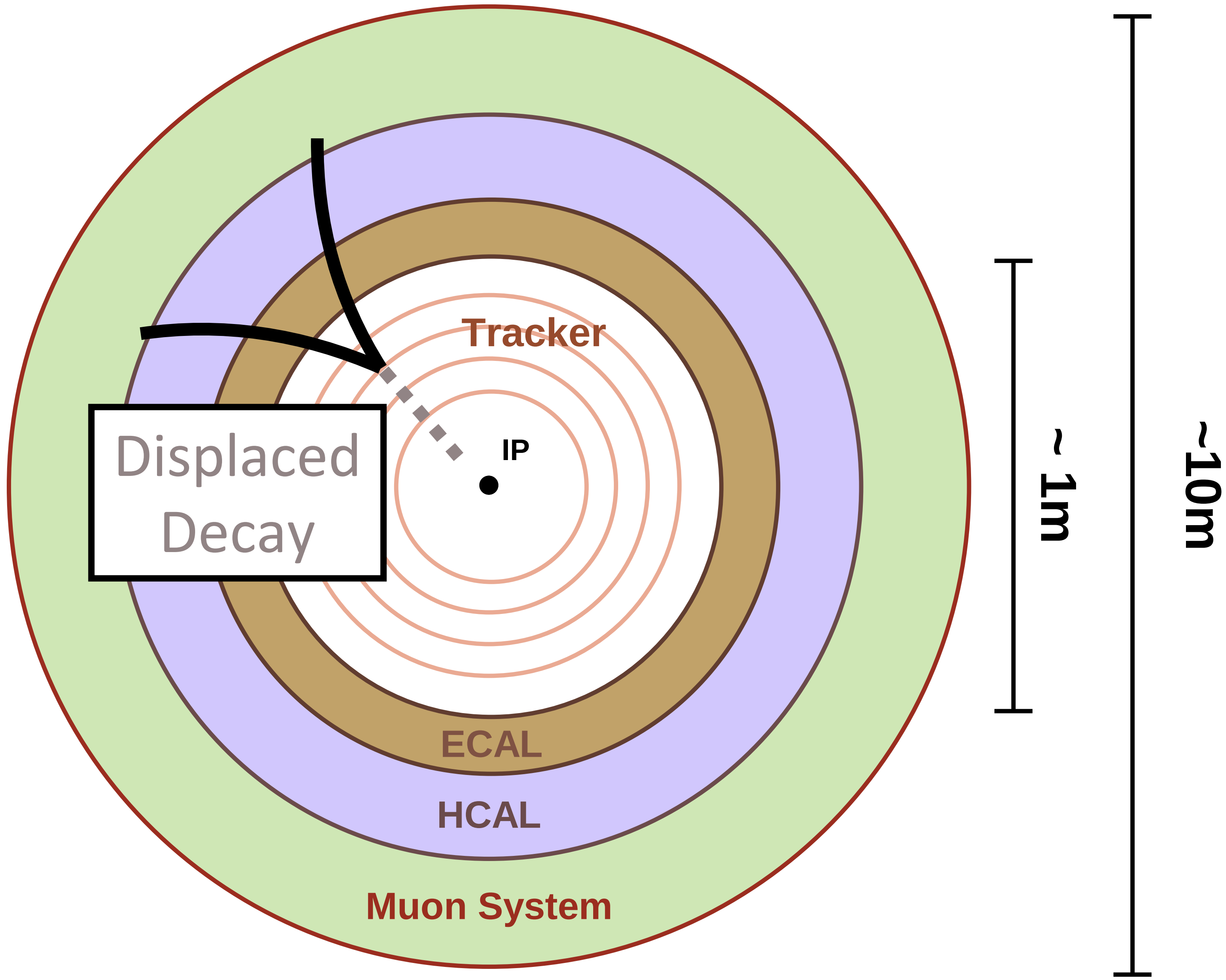
LLPs at the LHC

The problem of long lifetimes: LHC could be making LLPs that are invisible to its main detectors!

- **If the LLP has c · lifetime >> detector size, most escape the detector entirely**
- **Even LLPs that decay in the detector, but a significant distance away from the Interaction Point, are difficult to spot**
- **If the LLPs decay in the detector with only a tiny rate, they get swamped by backgrounds**

LLPs at the LHC

Neutral LLPs that decay in ATLAS or CMS are *spectacular* signatures that are missed by most standard searches, since **trigger** & **event reconstruction** are designed for decays near the Interaction Point



Comprehensive LLP search program at LHC has been ramping up over the past few years

Significant progress has been made, but LLP searches are very labour-intensive

Why search for LLPs at HL-LHC at all?

Searches at other facilities have also been proposed, but HL-LHC has many advantages:

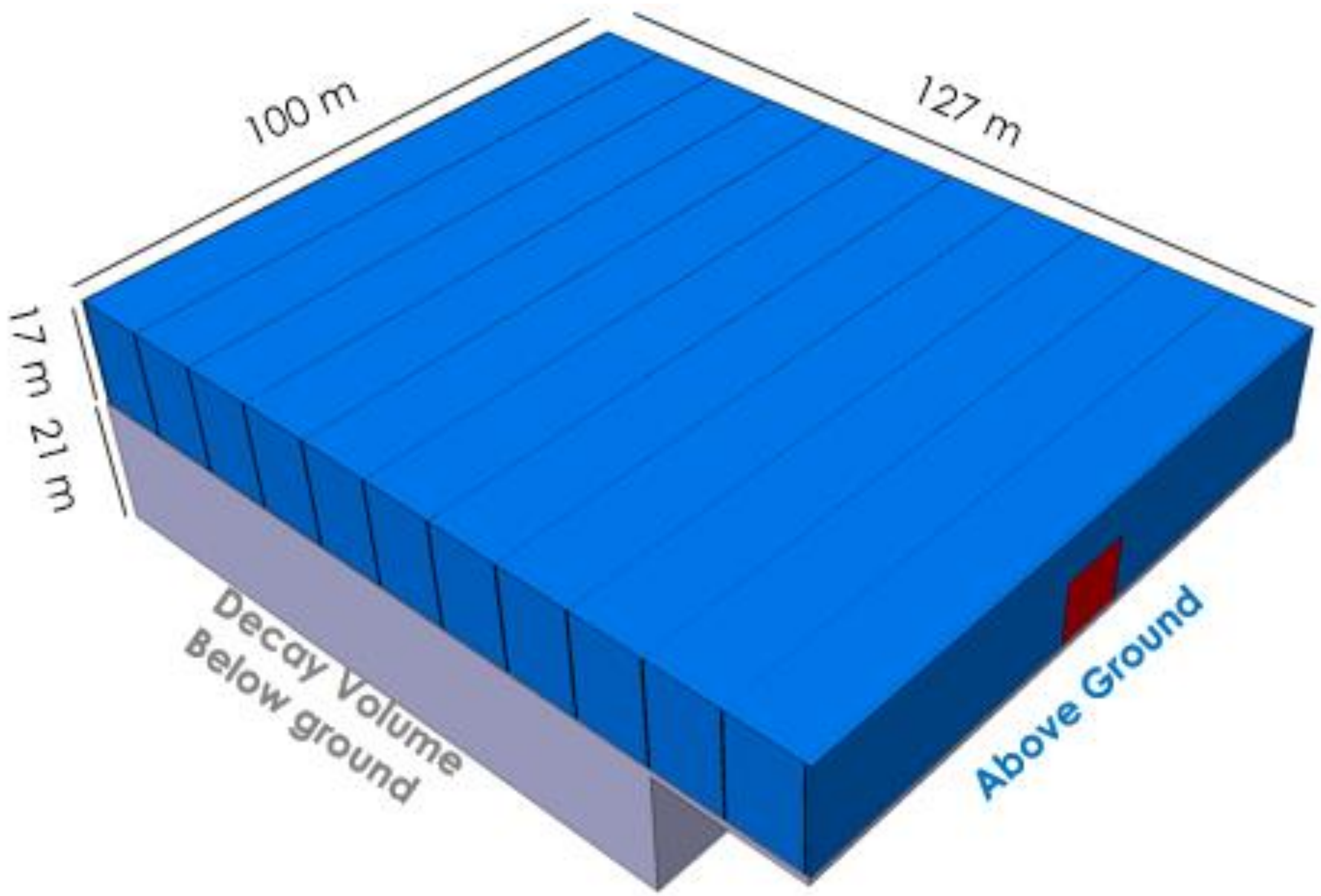
- High center of mass energy gives access to heavy states that may be coupled to LLPs (e.g. Higgs) not easily produced at lower energies
- Large data sample
- Enormous existing investment in machine and experiments

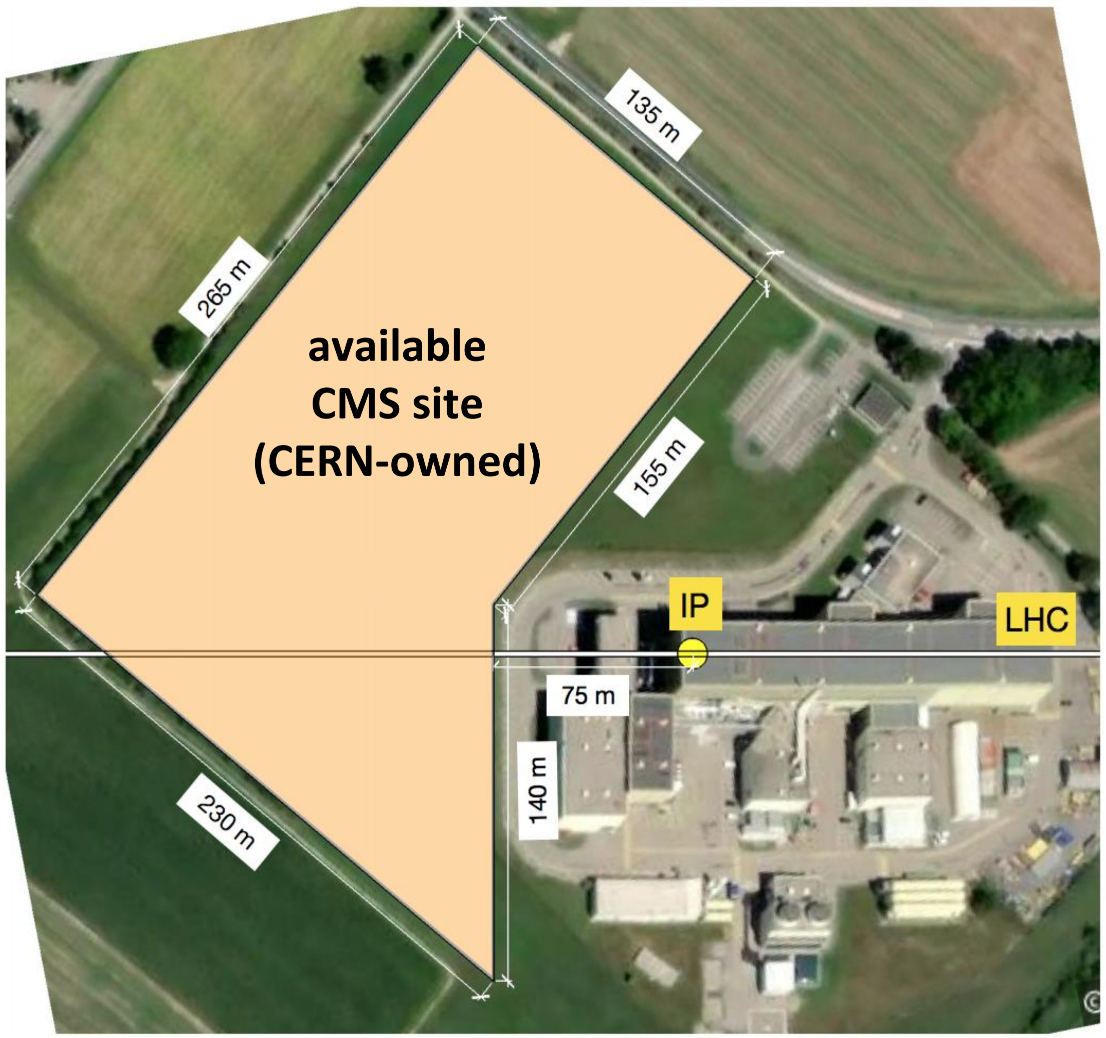
LLP searches have been identified by the [HL-]LHC community as a growing priority

The Concept of

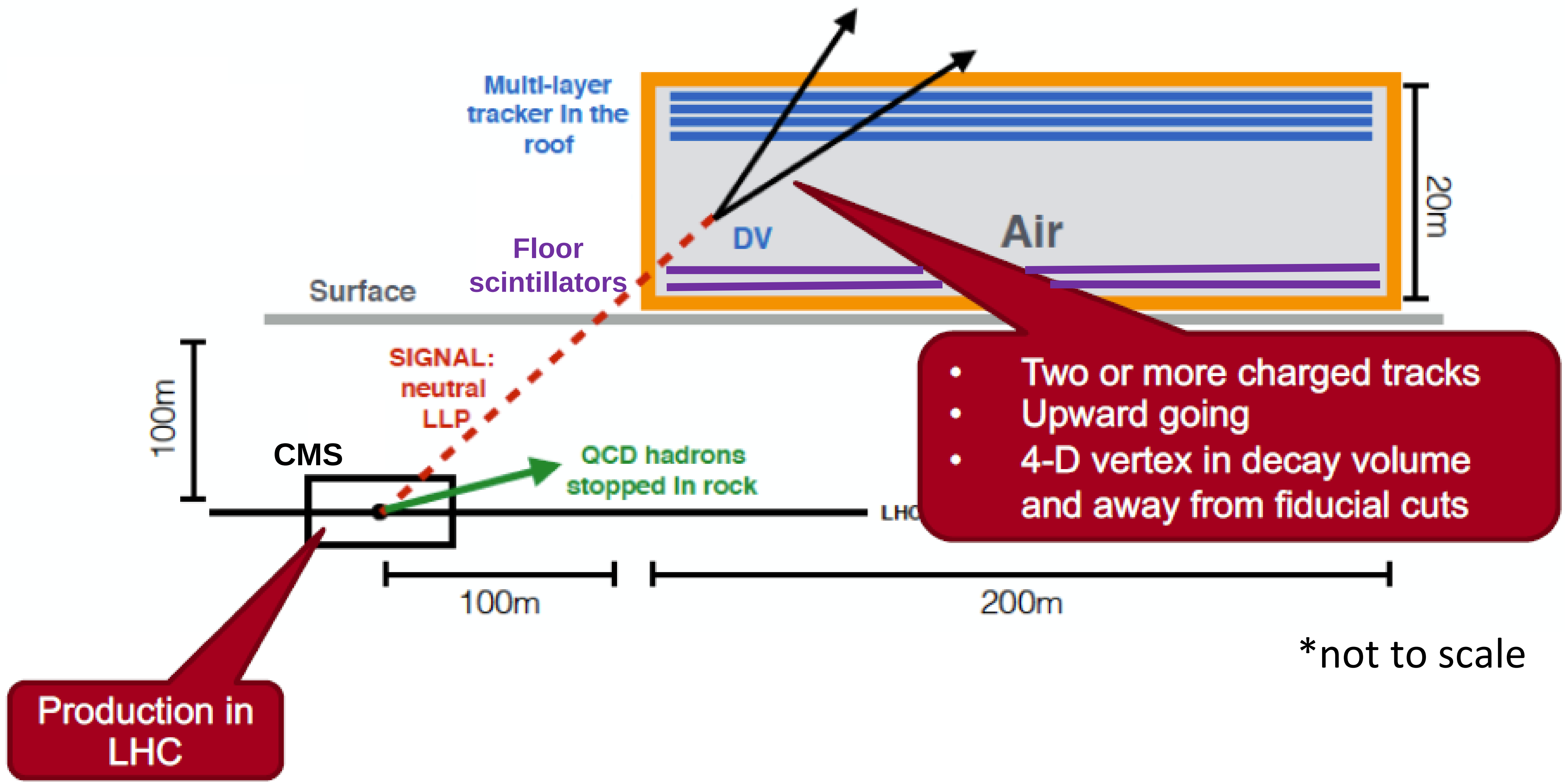
MATHUSLA

An external LLP detector for HL-LHC





An external LLP detector for HL-LHC

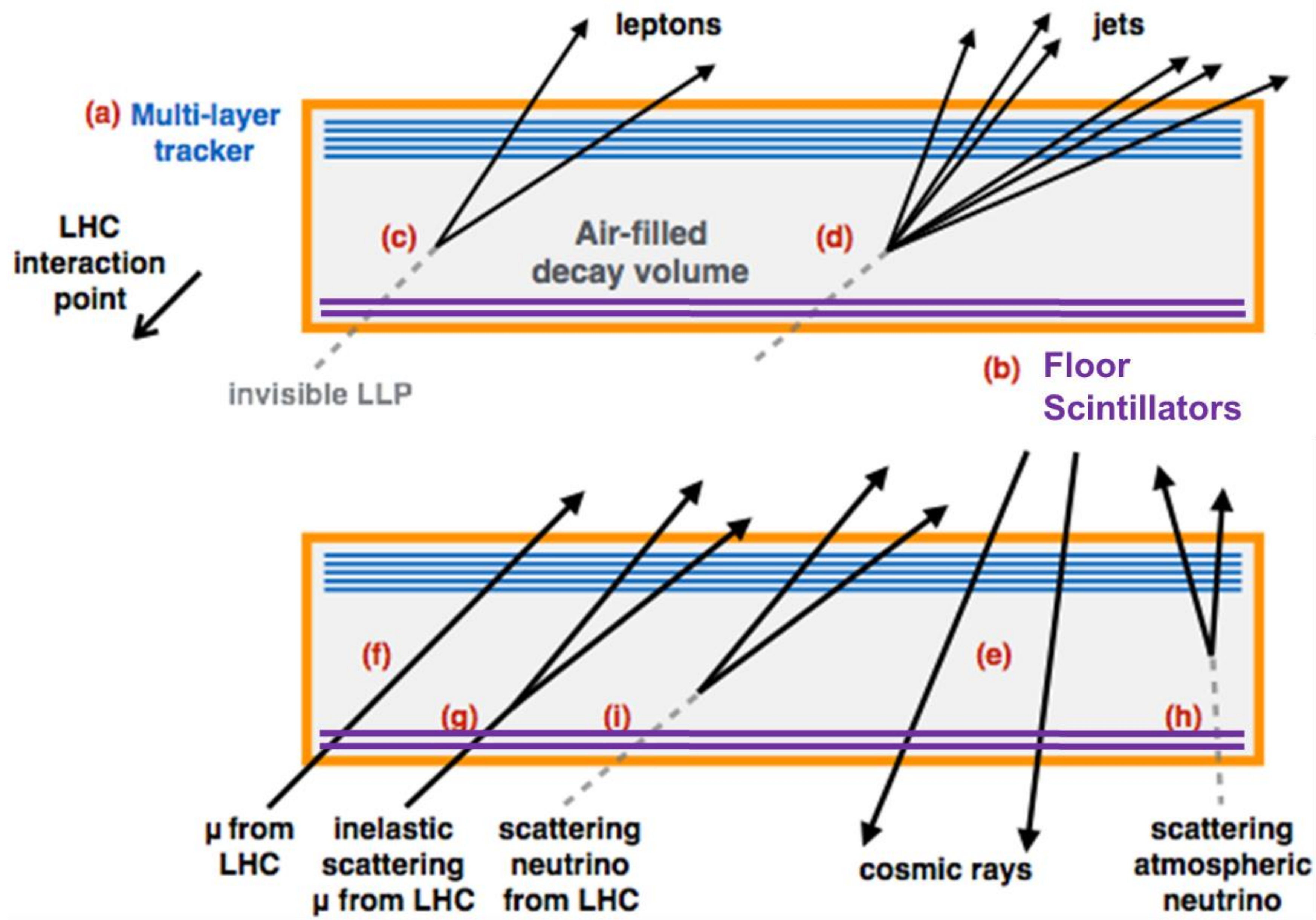


*not to scale

LLP identification with MATHUSLA

- Strict geometry & timing cuts will achieve near-zero backgrounds for neutral LLP decays!

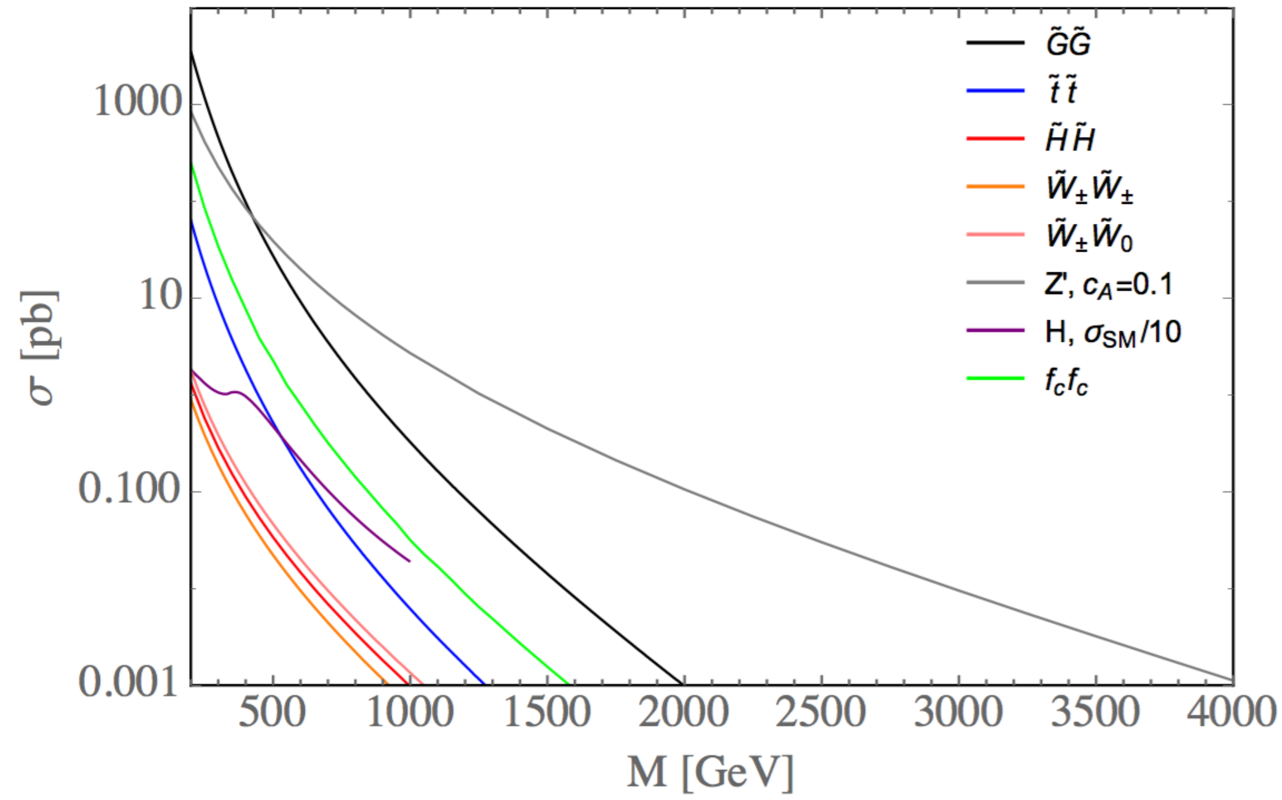
- Integration into CMS trigger system will associate CMS detector activity with MATHUSLA LLP candidate events



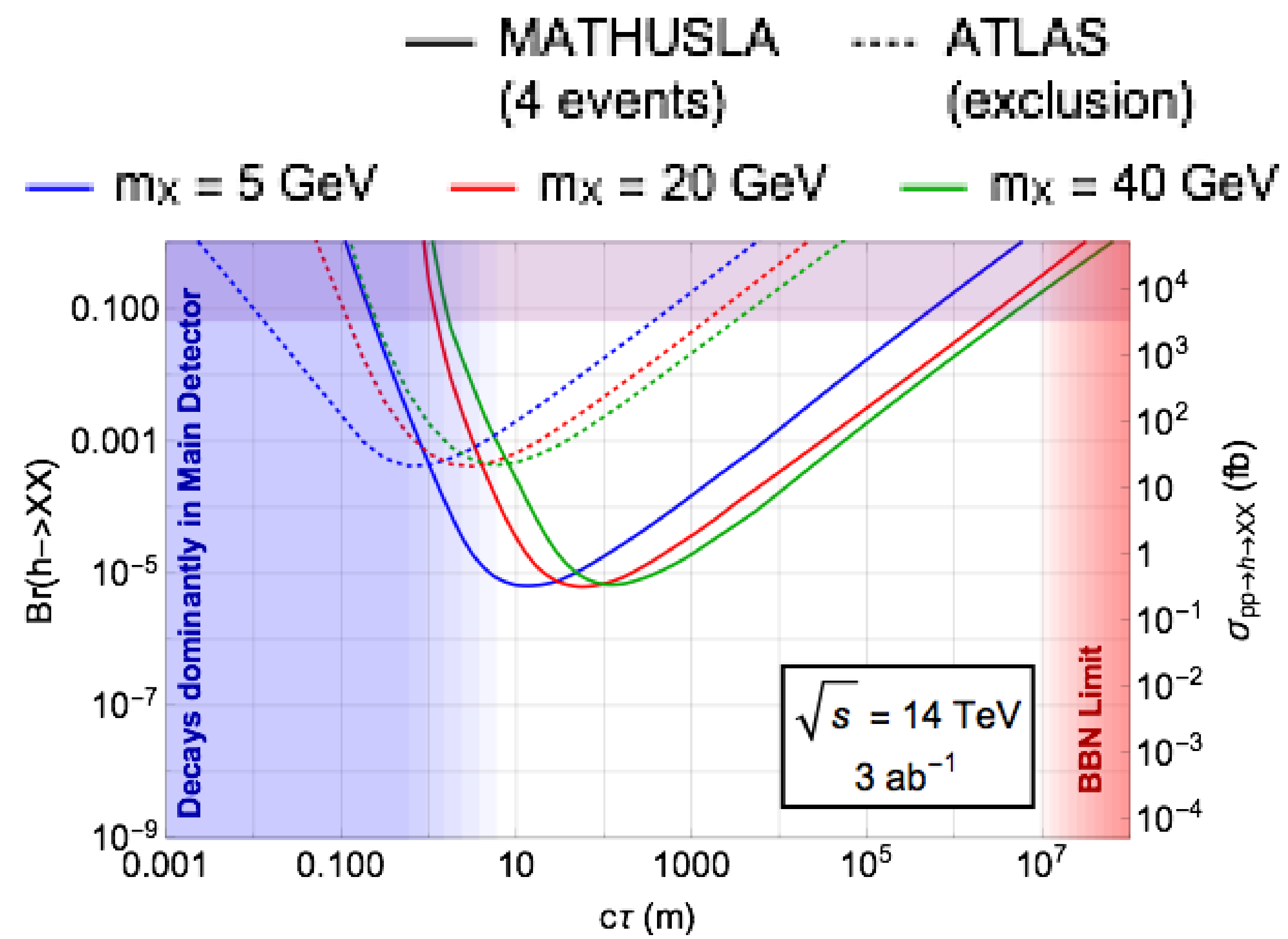
- MATHUSLA standalone: Determination of LLP decay mode and boost
- MATHUSLA + CMS: Also LLP production mode, mass range and spin

LLP sensitivity

- Sensitivity to any LLP production process with σ > fb

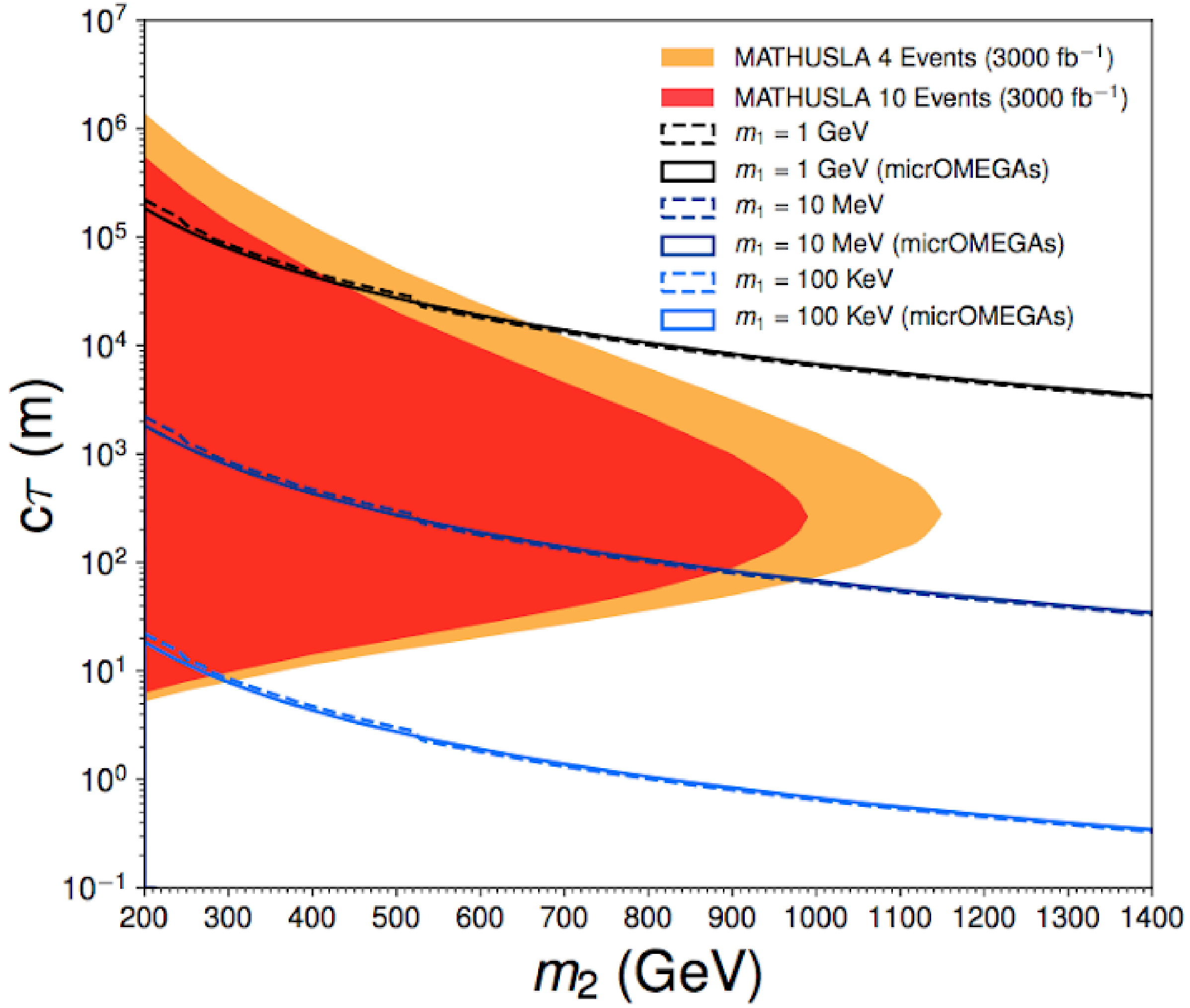


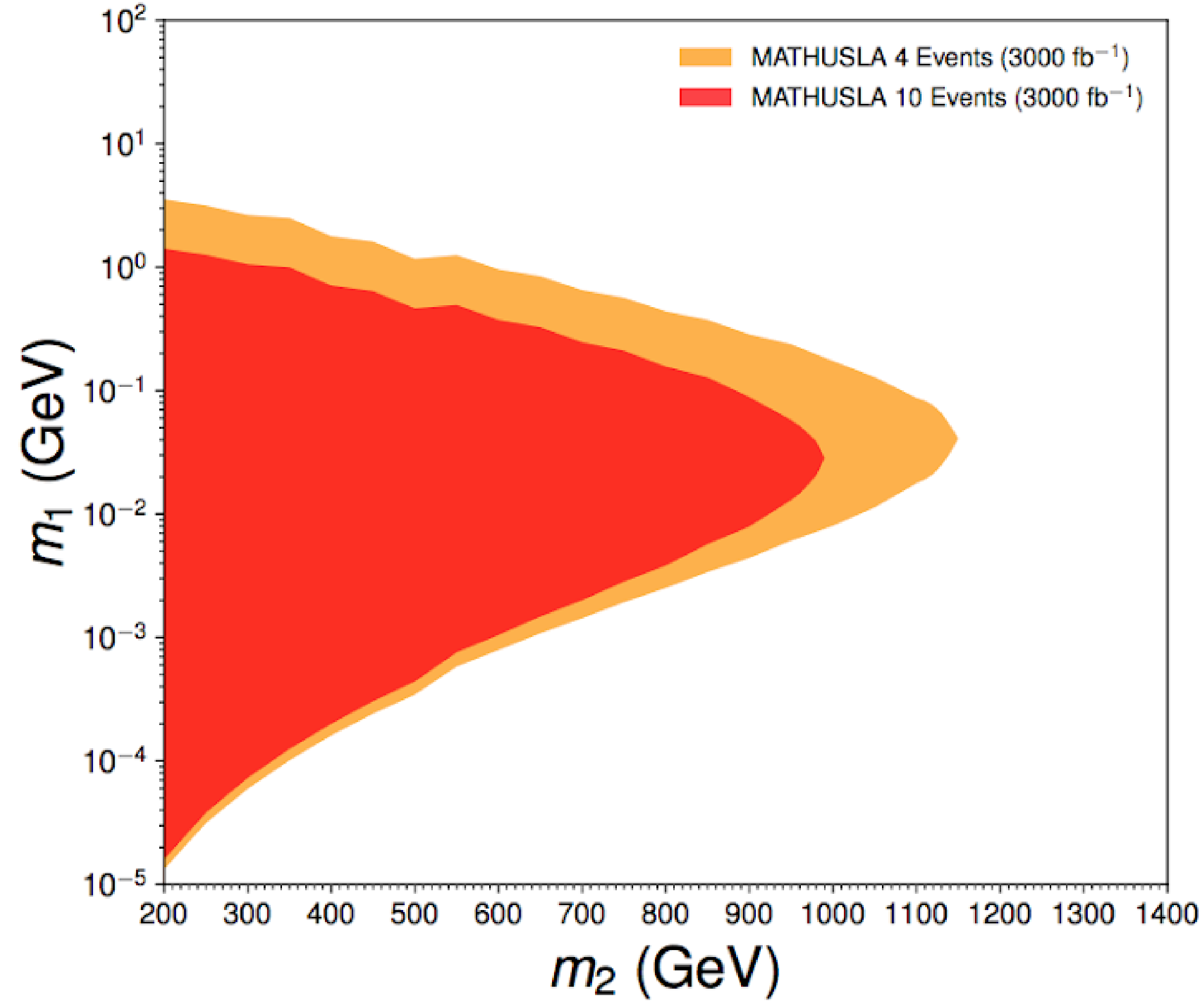
- Can probe scales from >TeV all the way down to GeV
- Scenarios include:
  - Exotic Higgs decay (up to 1000x better sensitivity than LHC main detectors)
  - Heavy sterile neutrinos
  - Dark photons
  - Axions



LLP sensitivity

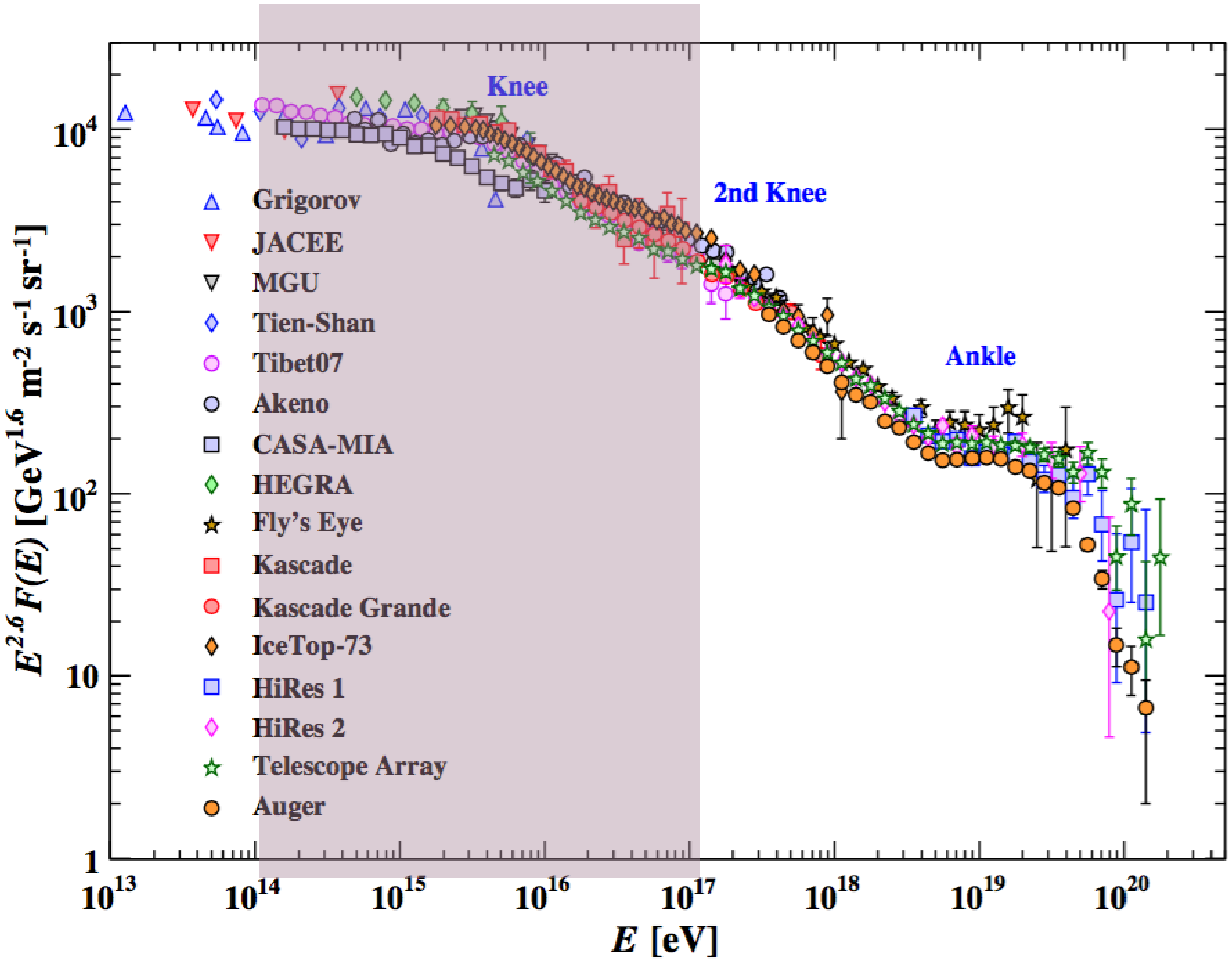
- Scenarios where LLP → DM + SM decay is the only way to see the DM
- e.g. model with BSM (χ_1, χ_2) where DM candidate χ_1 is very difficult to see due to low mass and possibly very small coupling. We look for LLP χ_2 which eventually decays to χ_1





(lines yield observed DM relic density)

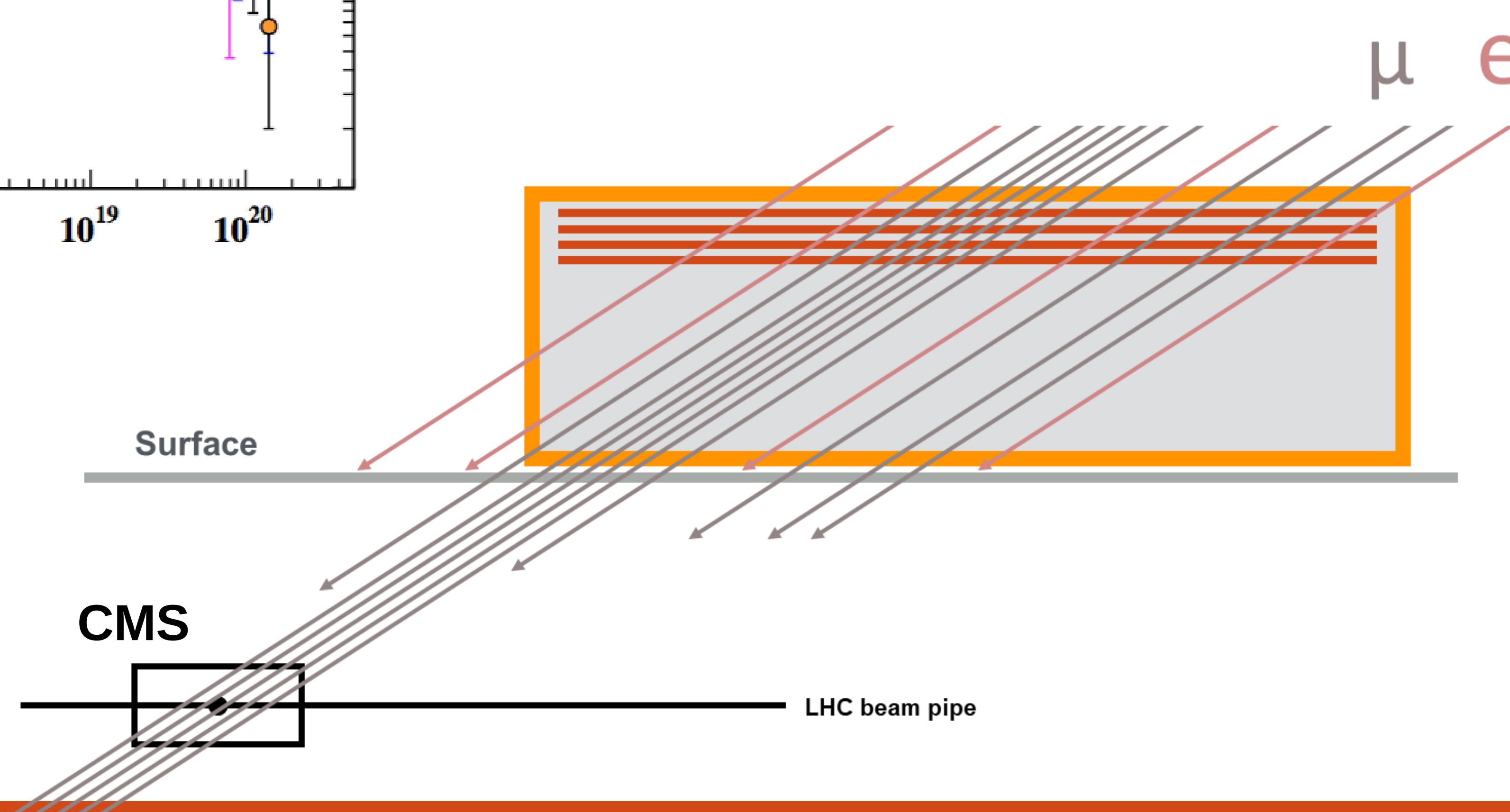
MATHUSLA as a Cosmic Ray Telescope



"Guaranteed Physics Return"

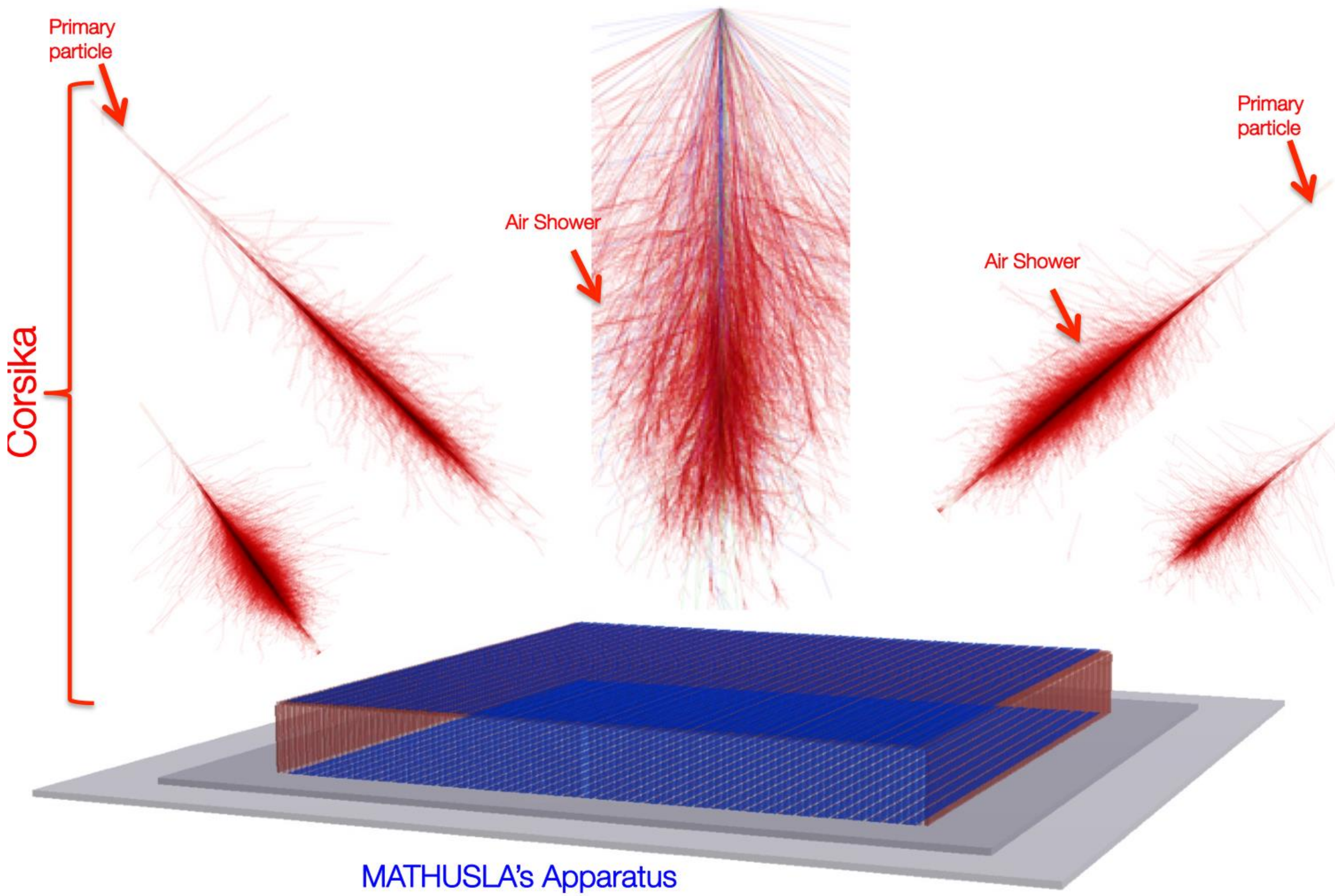
Unique abilities in CR experimental ecosystem (precise resolution, directionality, large-area coverage)

Probes highly interesting region of CR spectrum



MATHUSLA as a Cosmic Ray Telescope

Standalone: reconstruction of shower core, direction, total # charged particles, slope of radial particle density distribution

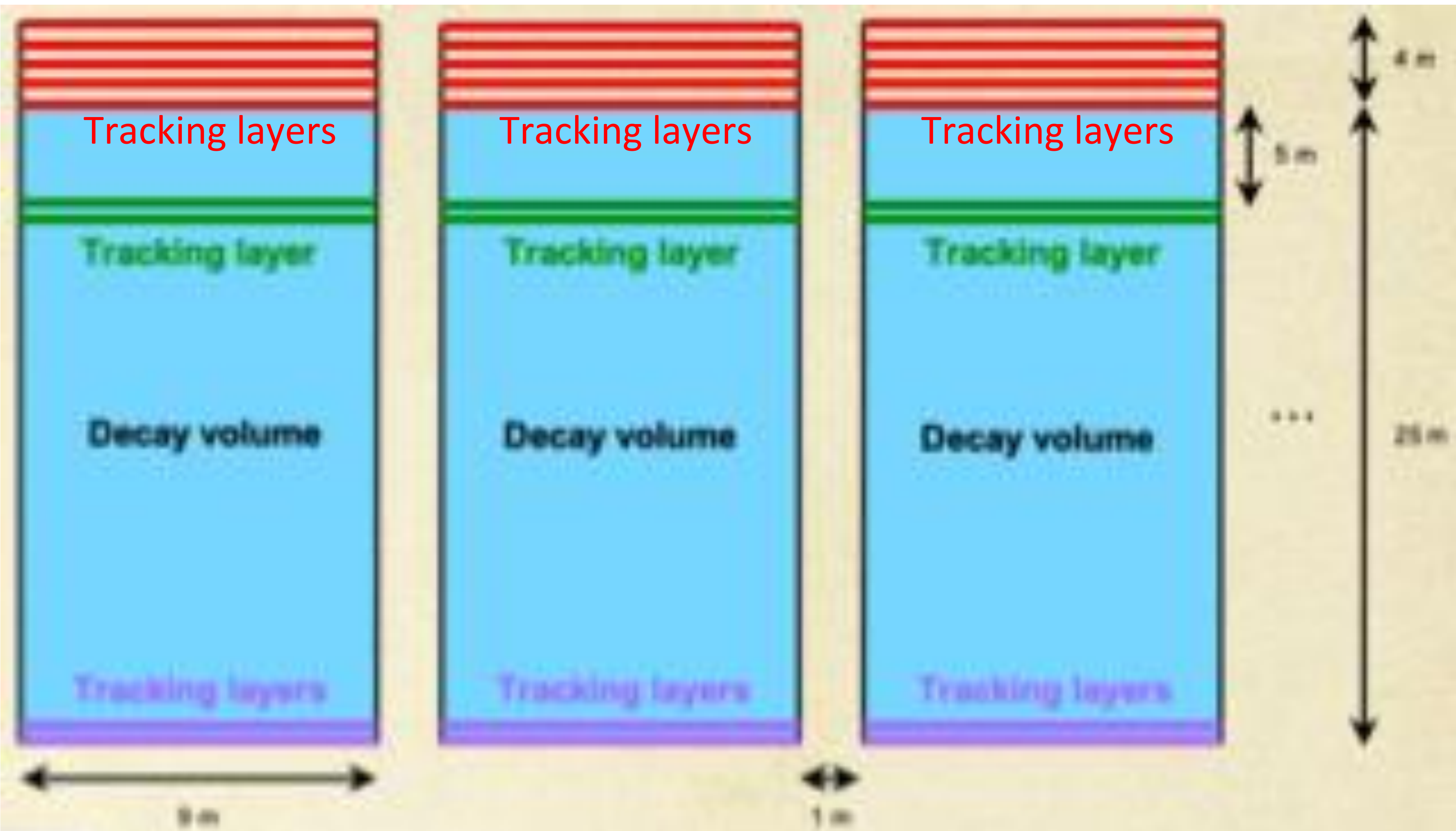


+ CMS: analysis of muon bundles traversing both detectors, probing heavy primary CR spectra and astrophysical acceleration mechanisms

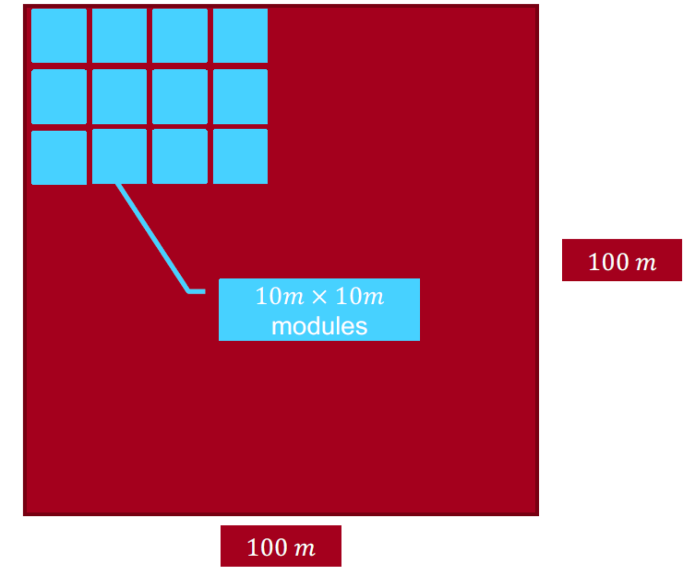
MATHUSLA
Detector Design

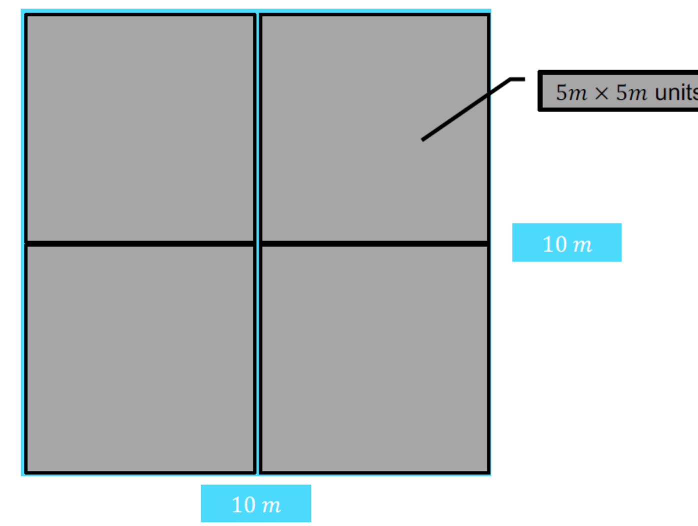
Detector design

Modular design facilitates staged construction and commissioning



Each module has 5 tracking layers on top + 2 floor layers + 2 mid-level layers

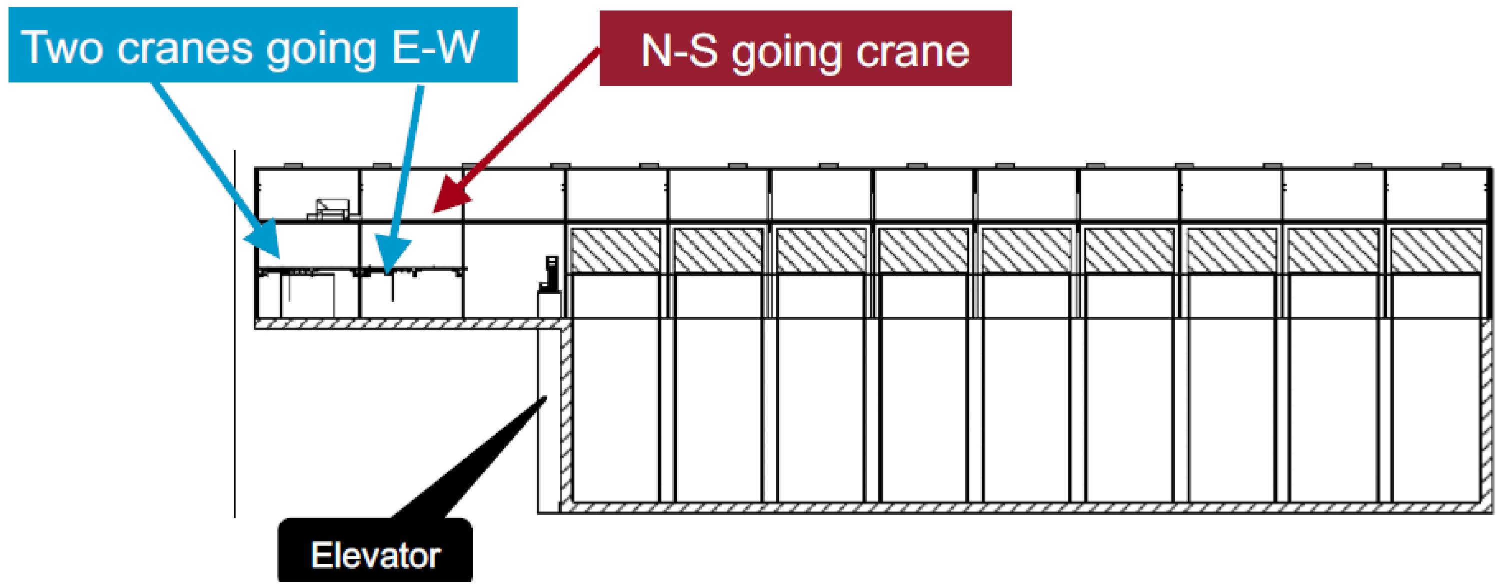


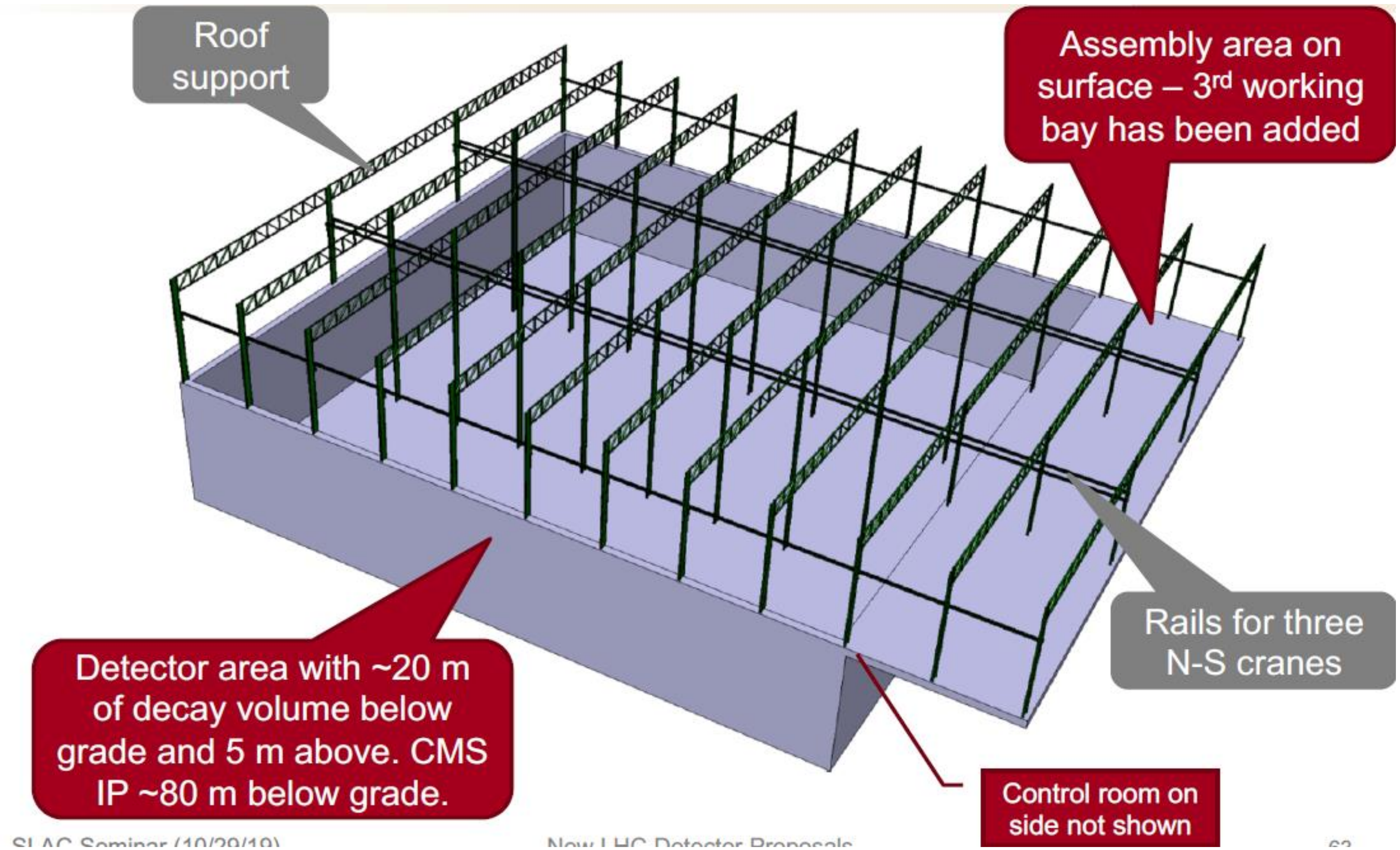


100 Modules in $\mathbf{100}\boldsymbol{m} \times \mathbf{100}\boldsymbol{m}$ Footprint

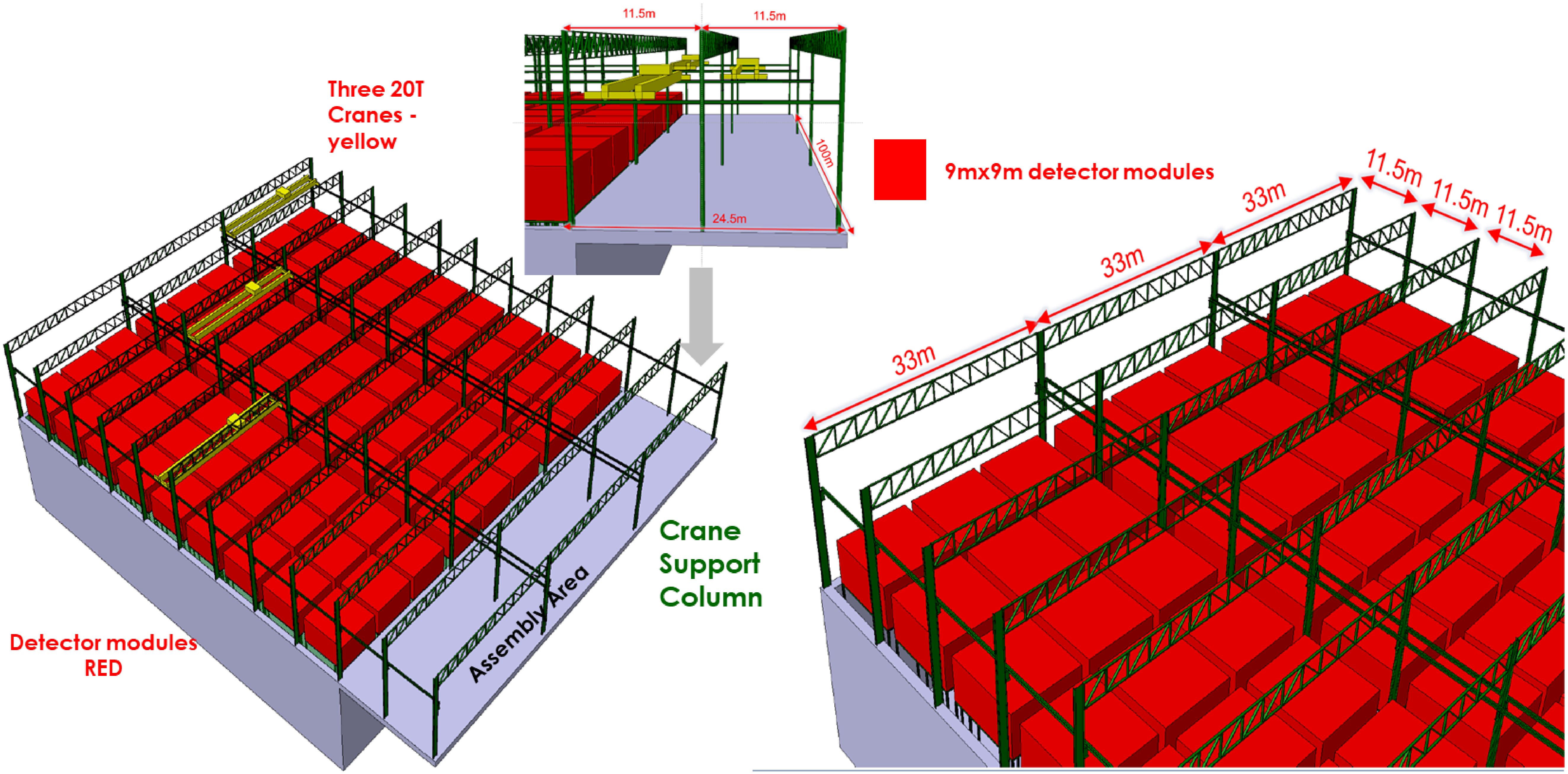
4 Detector Units per Module Plane

Detector design

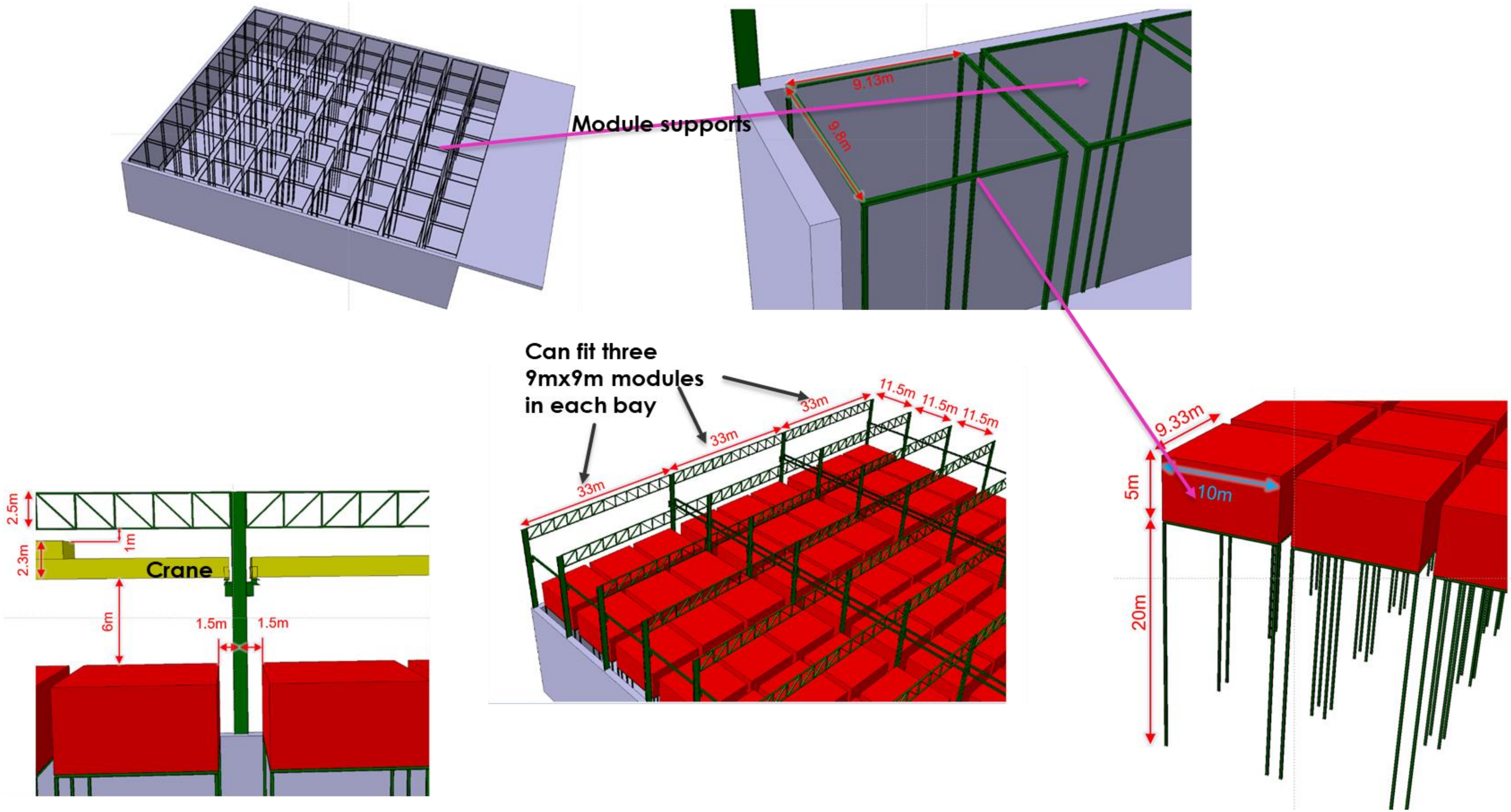




Detector design



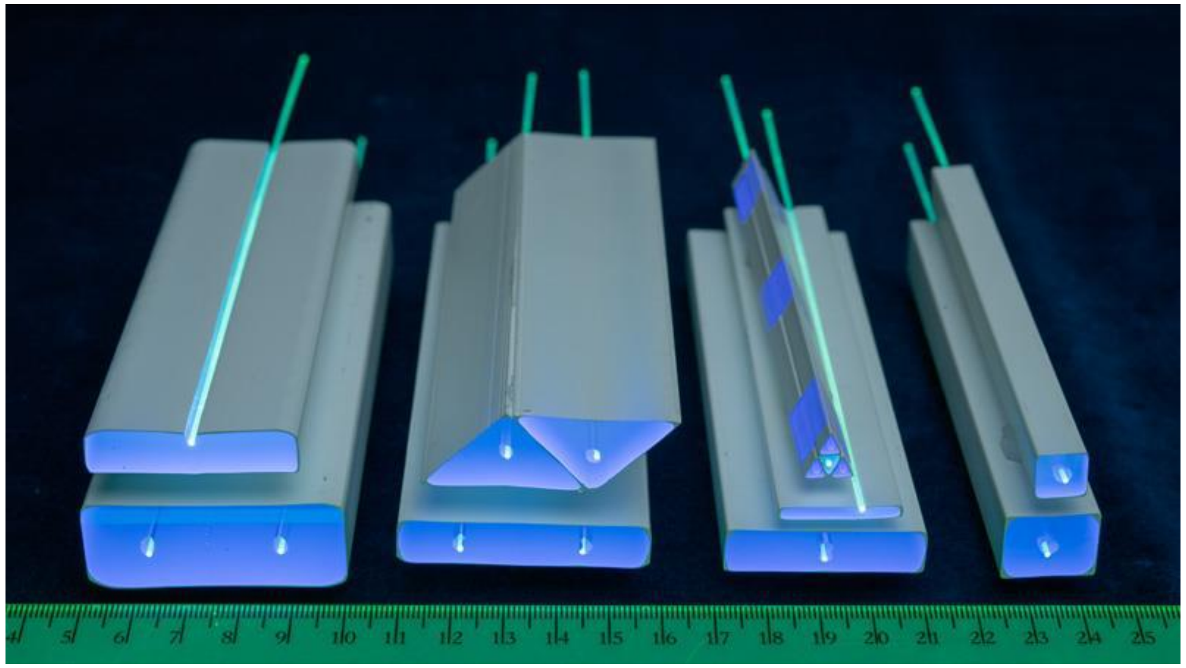
Detector design



Trackers, readout & trigger

Tracker layers: Composed of extruded scintillator bars with wavelength-shifting fibers coupled to Silicon Photo Multipliers

- Possibility of adding Resistive Plate Chamber layers



Each scintillator bar ~ 5m x 4cm x 2cm, with readout at both ends

- Transverse resolution $\sigma \approx 1$ cm
- Δt between two ends gives longitudinal resolution: need sub-ns precision

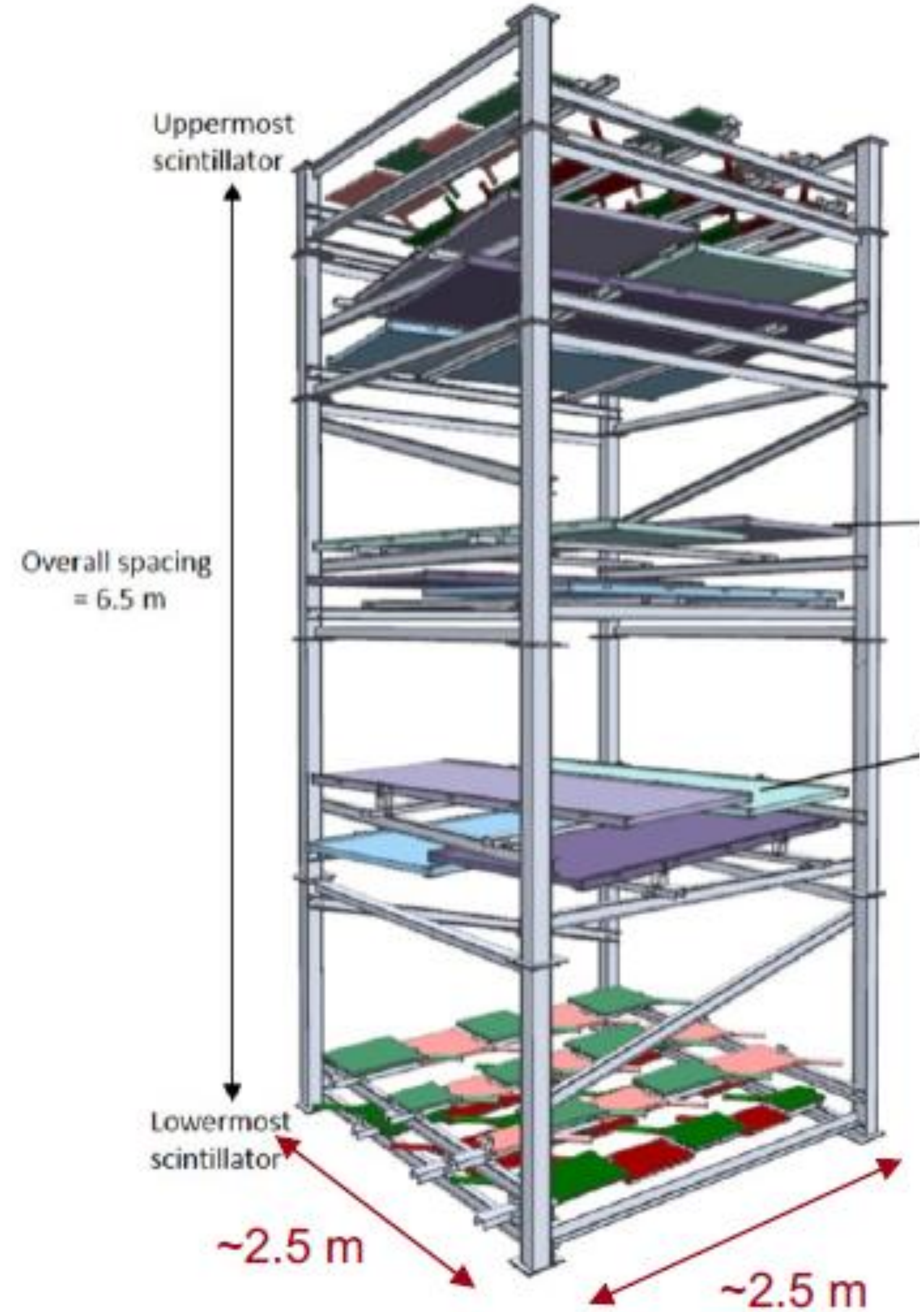
Collect all hits with no trigger selection; separately record trigger data and associate it with CMS bunch crossings

- Cosmic ray rate ~2MHz

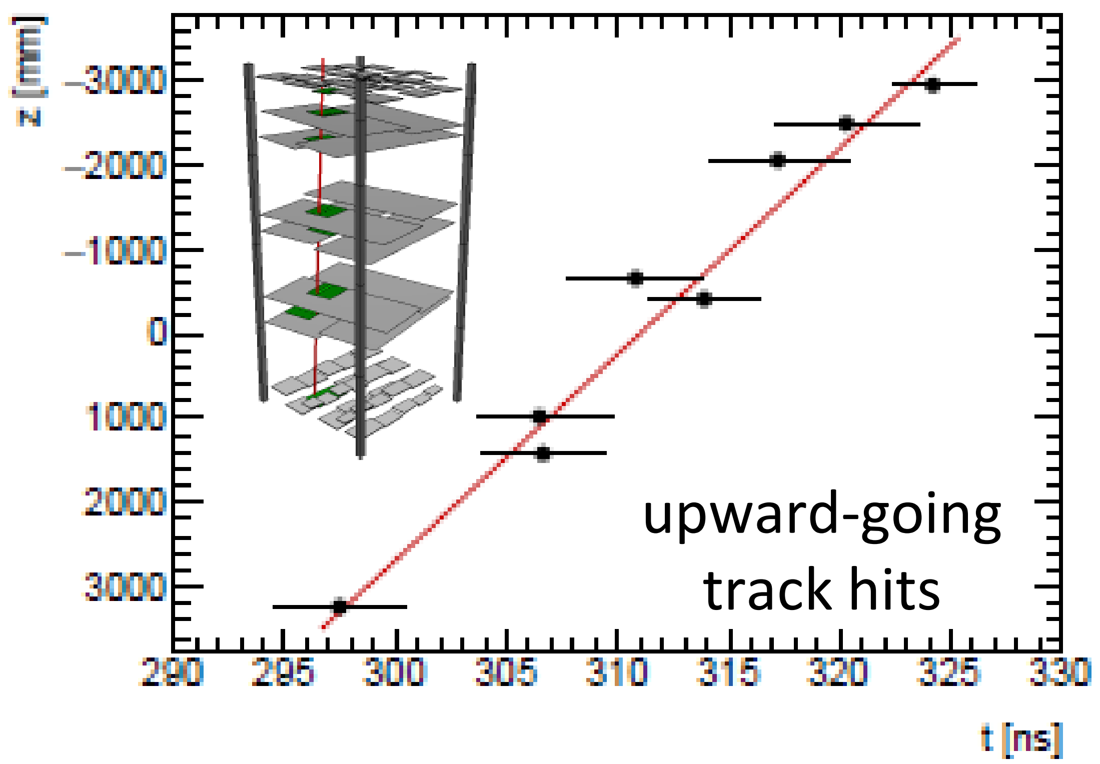
Test Stand

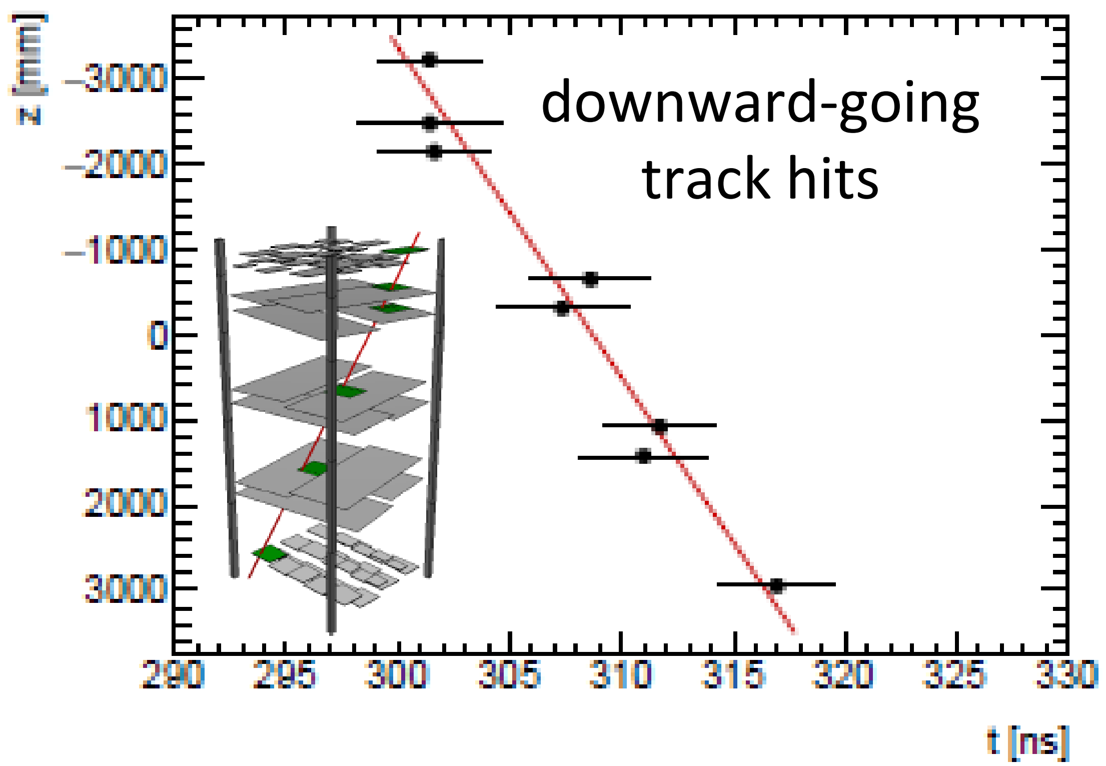
- To understand LHC collision backgrounds (e.g. upward-going muons), built a test stand
- ~2.5 x 2.5 x 6 m^3
- Two triggers running simultaneously:
  - Downward trigger for cosmic rays
  - Upward trigger for tracks from IP

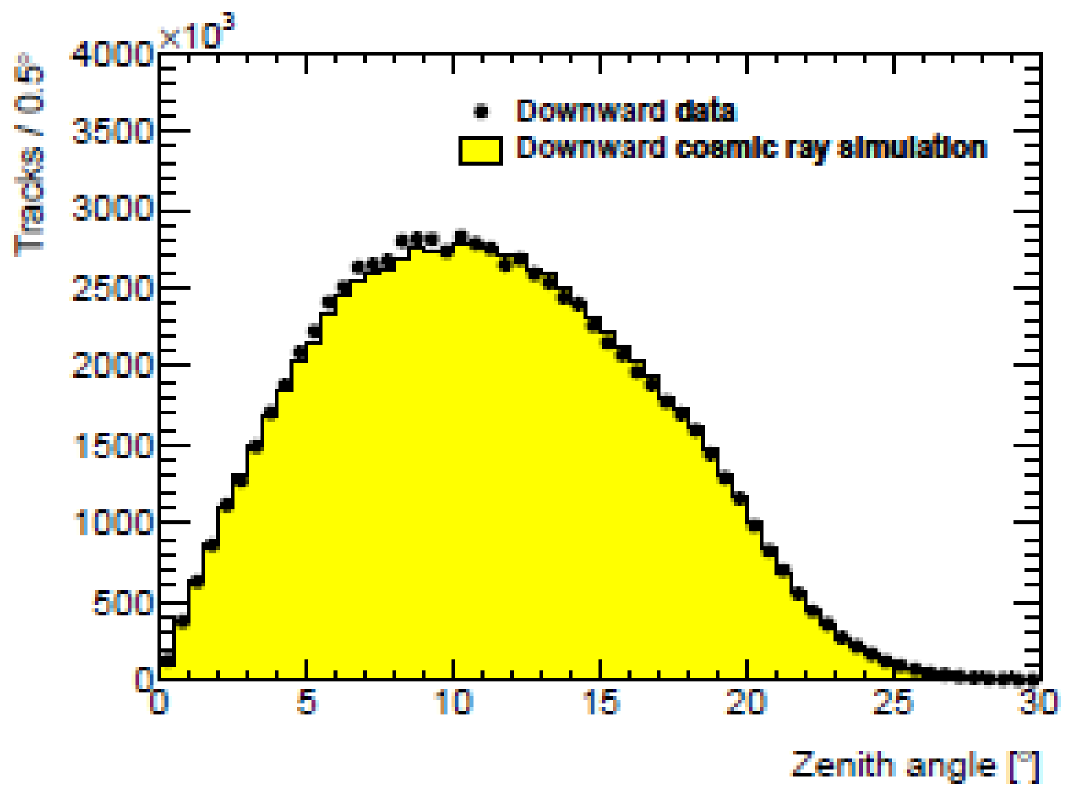
Took data above the ATLAS IP in 2018

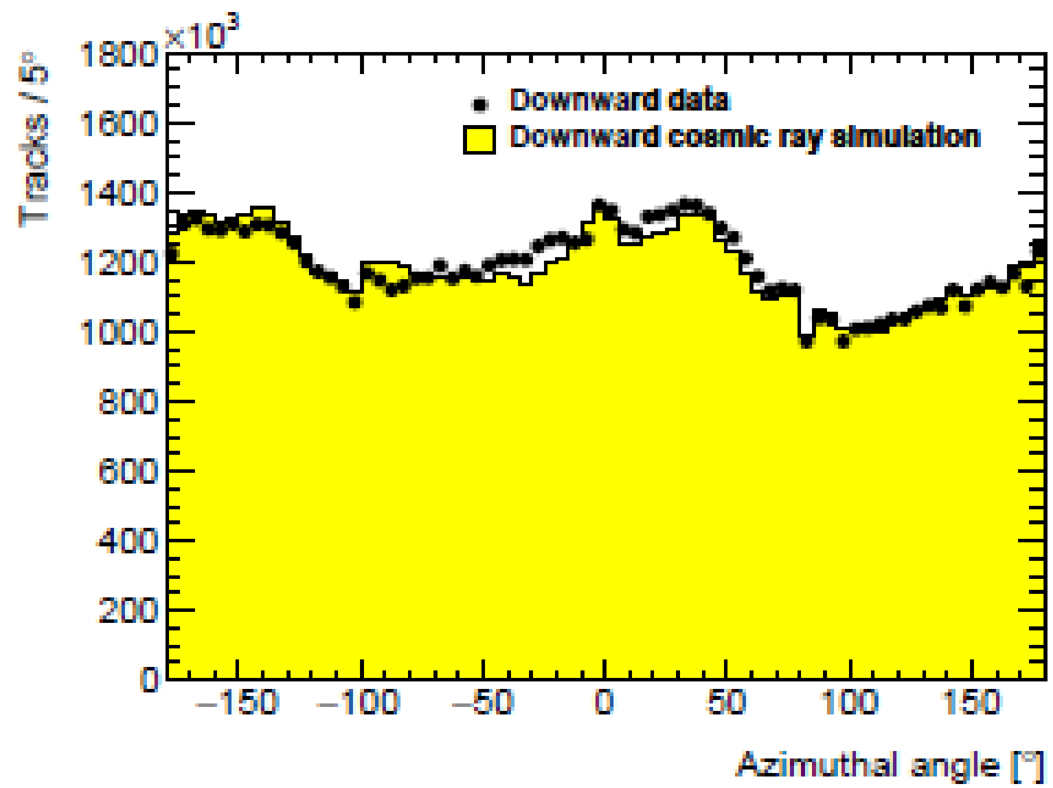


Test Stand

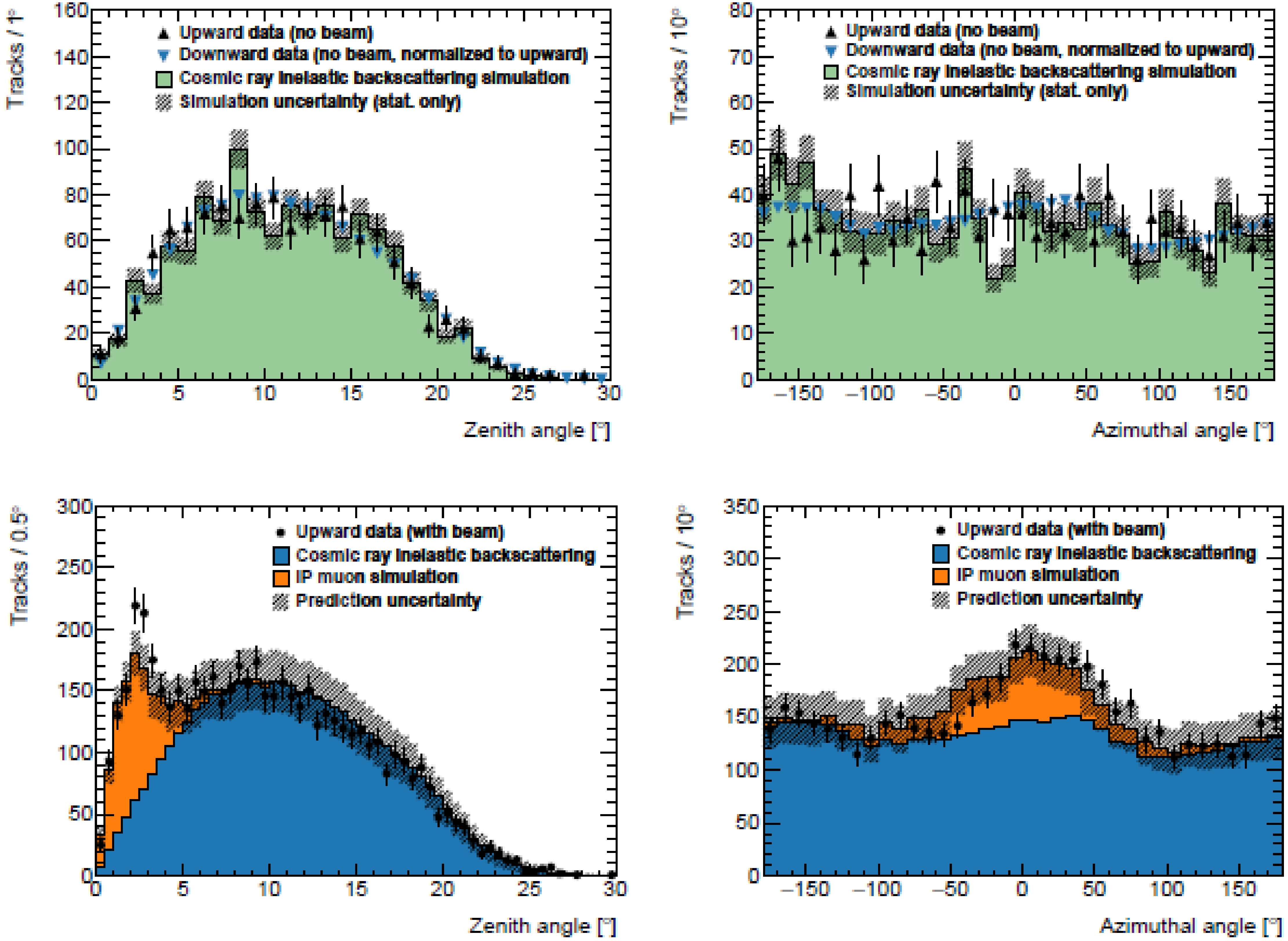

z [mm]
t [ns]
upward-going
track hits


z [mm]
t [ns]
downward-going
track hits


Tracks / 0.5°
Downward data
Downward cosmic ray simulation
Zenith angle [°]


Tracks / 5°
Downward data
Downward cosmic ray simulation
Azimuthal angle [°]

Test Stand



Upward data (no beam)
Downward data (no beam, normalized to upward)
Cosmic ray inelastic backscattering simulation
Simulation uncertainty (stat. only)
Tracks / 1°
Zenith angle [°]
Tracks / 10°
Azimuthal angle [°]
Upward data (with beam)
Cosmic ray inelastic backscattering
IP muon simulation
Prediction uncertainty
Tracks / 0.5°
Zenith angle [°]
Tracks / 10°
Azimuthal angle [°]

MATHUSLA

Next Steps

R&D plan

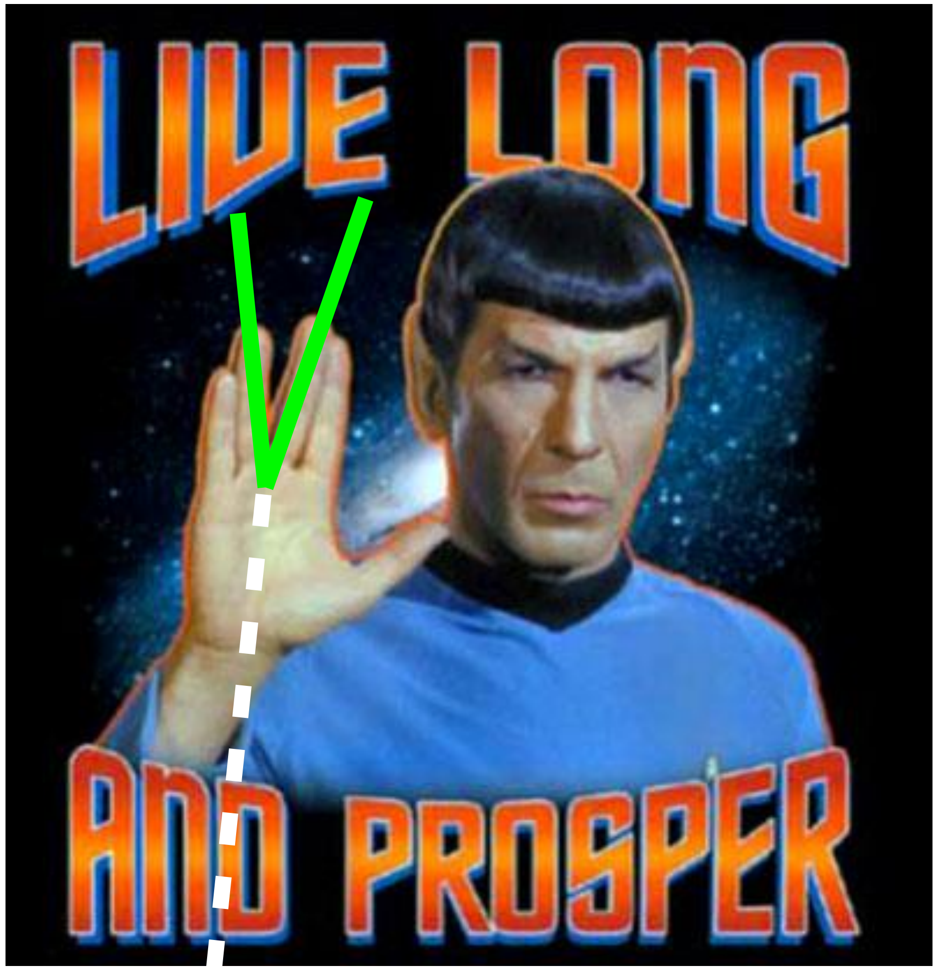
For MATHUSLA to go online ~2026, R&D required over the next few years includes:

- Front-end electronics design
- Trigger development (simple concept, nontrivial implementation)
- Detector design details (module parameters, tracking chamber support structure, installation procedures…)
- Cost optimization of detector components (scintillator, WLS, SiPMs)

Opportunities

Exploration of the Lifetime Frontier will be central to the future of the LHC program to discover new physics

MATHUSLA is the best way to probe deep into the LLP lifetime parameter space for a wide range of masses



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LLPs at LHC:

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