Explore the Lifetime Frontier with MATHUSLA

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on behalf of the MATHUSLA Collaboration

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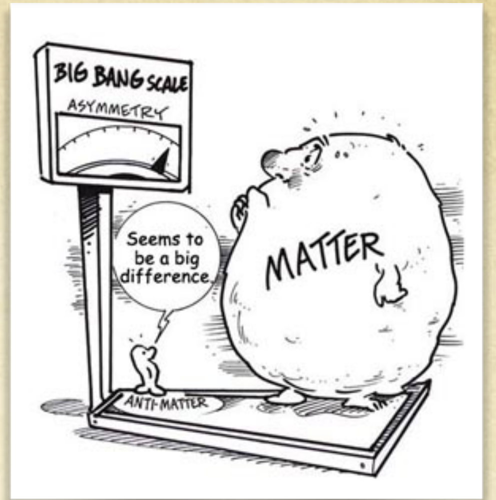
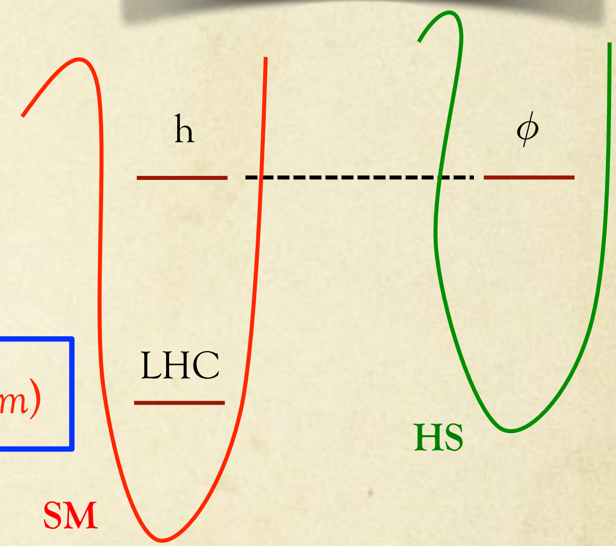
UNIVERSITY of WASHINGTON

MATHUSLA

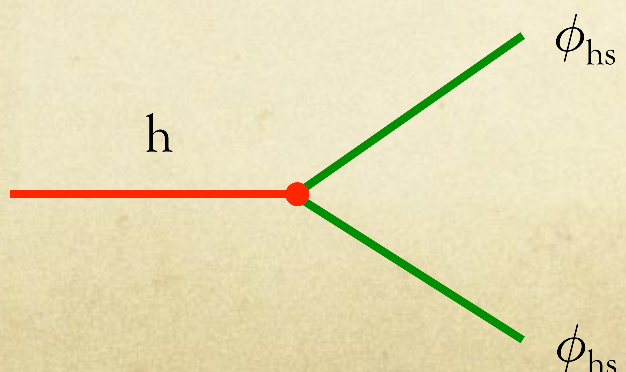
The Hidden Sector



- The Standard Model (SM) is in amazing agreement with the experimental data, but **still some problems remain unsolved**: dark matter, neutrinos masses, hierarchy, matter-antimatter asymmetry…
- Many extensions of the SM (Hidden Valley, Stealth SUSY, 2HDM, baryogenesis models, etc) include particles that are **neutral**, **weakly coupled**, and **long-lived** that can decay to final states containing several hadronic jets
- Long-lived particles (LLPs) occur naturally in **coupling to a hidden sector (HS)** via small scalar (Higgs) or vector (γ, Z) portal couplings



❖ Wide range of possible lifetimes from $\mathcal{O}$(mm) up to $\mathcal{O}$(m/km)



The mixing of Higgs with HS results in a Higgs like particle decaying into LLPs:

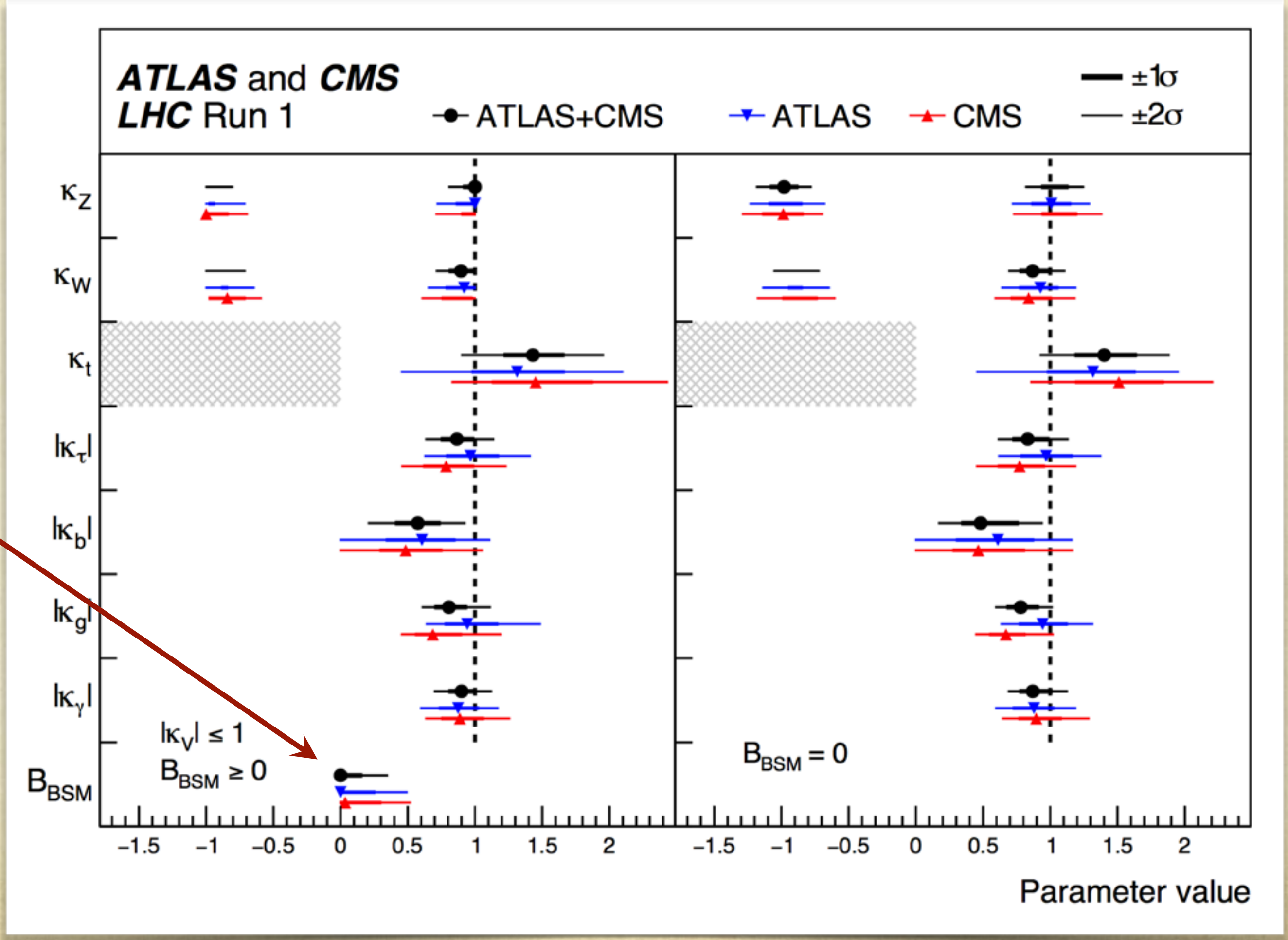
small coupling → long lifetimes [Phys. Lett. B6512 374-379, 2007]

~ 10^8 Higgs boson @ HL-LHC

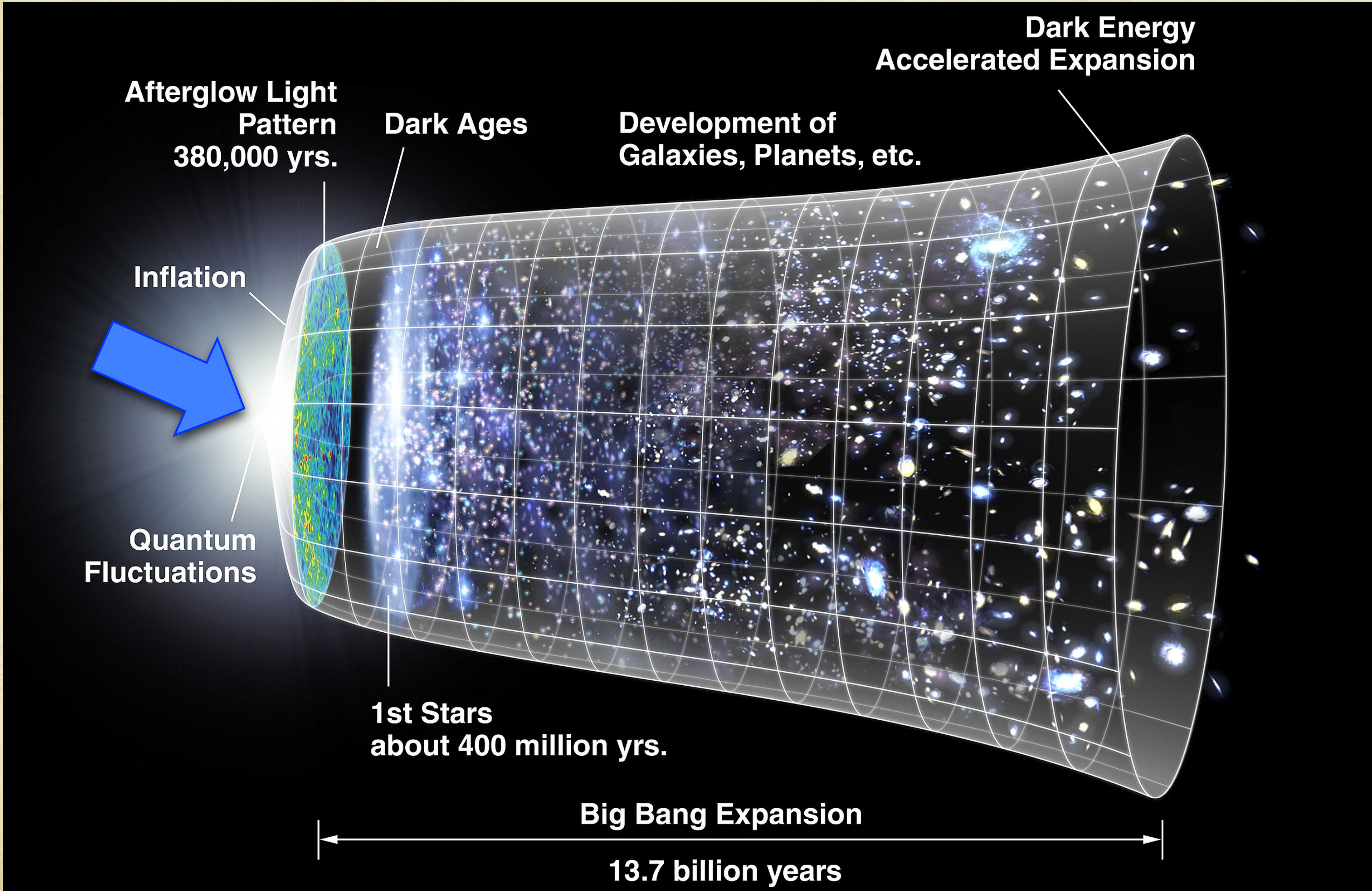
Higgs Boson Decay Modes

- Combined ATLAS-CMS Run 1 results w.r.t. standard model expectations
- Good agreement with SM…BUT…

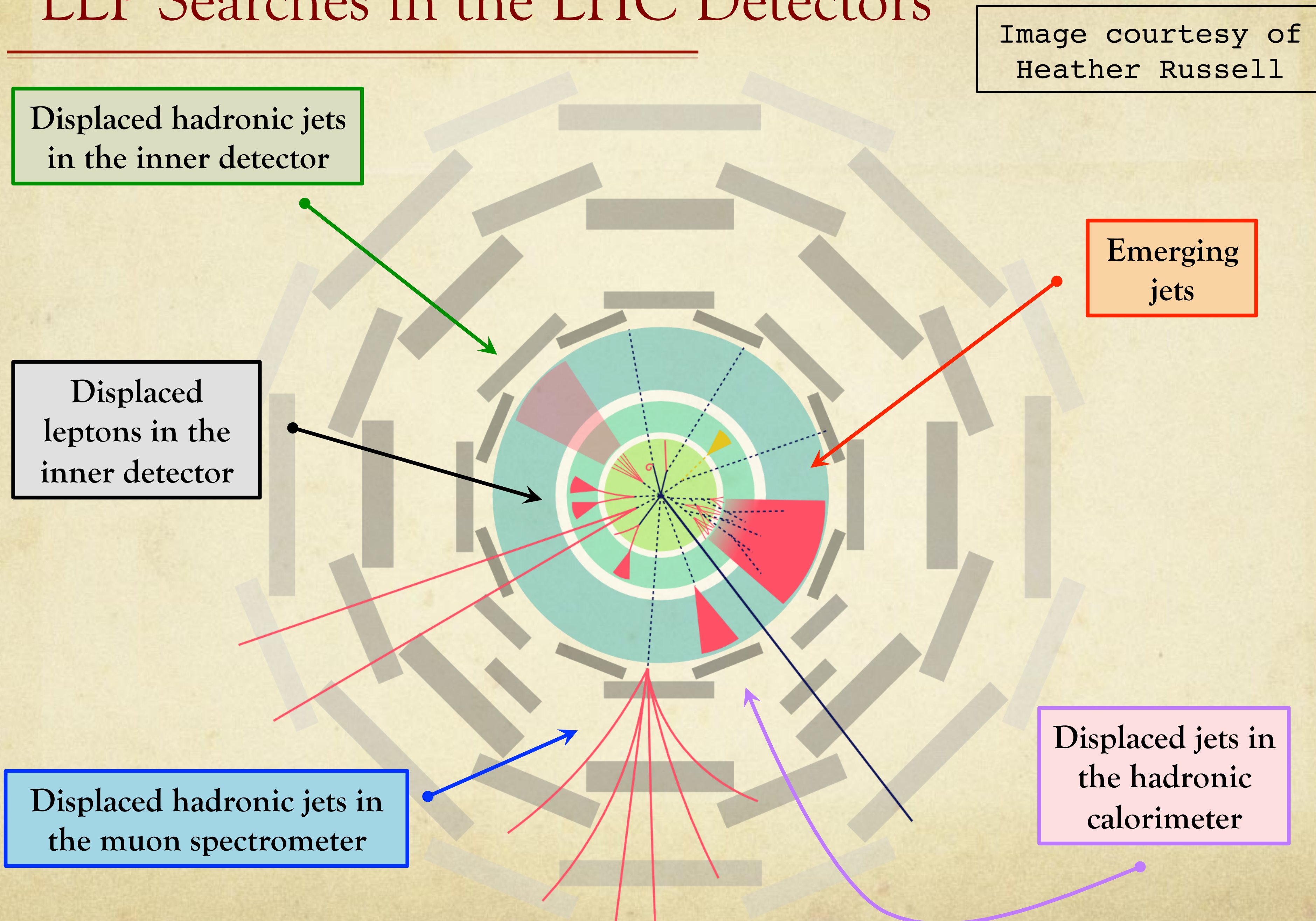
BUT > 30% BSM allowed



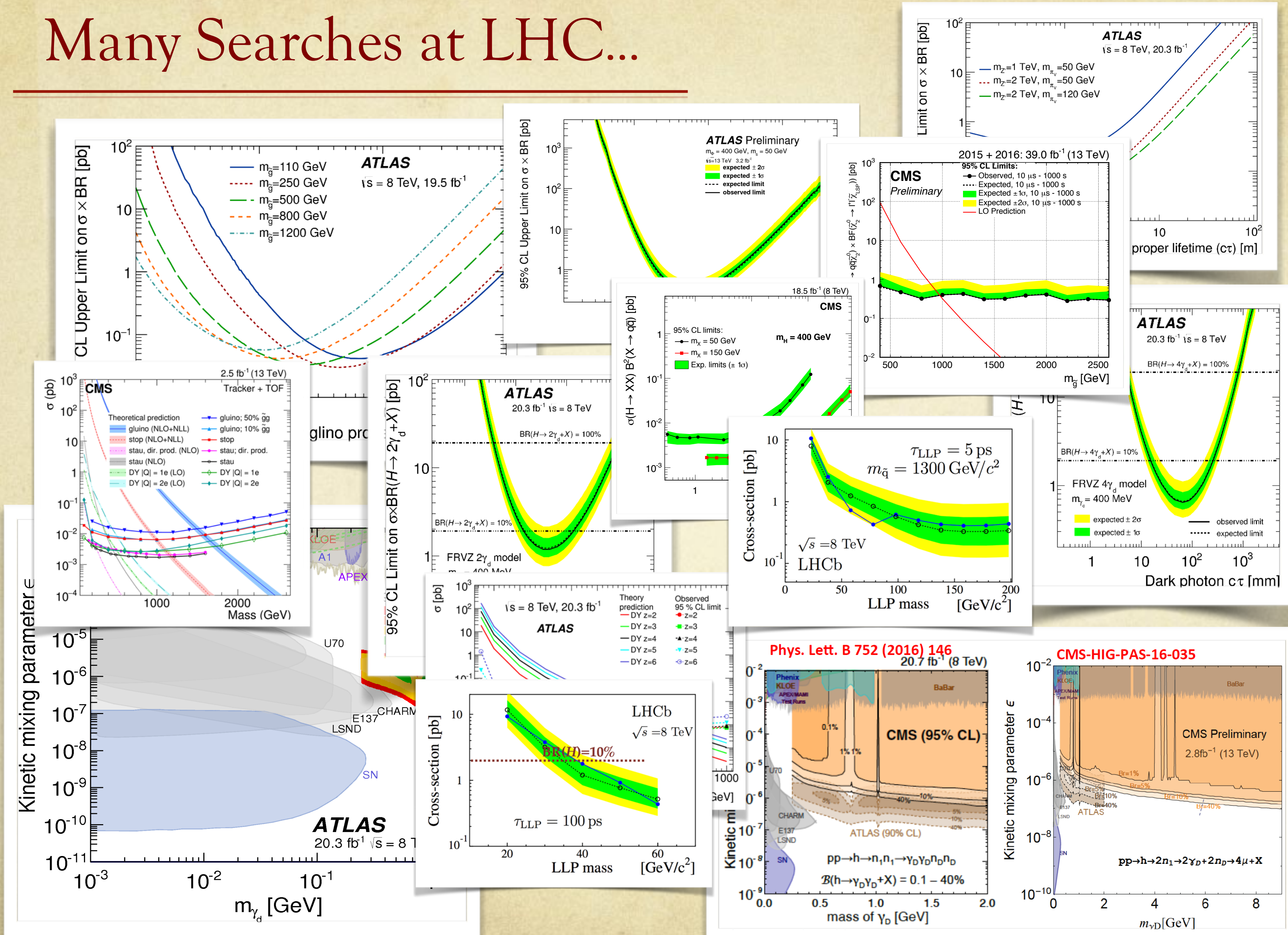
How Long Lived Can Particles Be?



LLP Searches in the LHC Detectors



Many Searches at LHC…



Many Searches at LHC…but…

- Strong dependence on the sub-detectors of ATLAS, CMS and LHCb
- Detector signature depends of production and decay operators of a given model

- LHC detector searches limited by large backgrounds
  - ✓ Large QCD jet production
  - ✓ Pile-up problems
  - ✓ Beam halo issues
  - ✓ …

→ **Need a background-free detector!**

…and who ya gonna call?


MATHUSLA!

MATHUSLA

J-P Chou, D. Curtin, H. Lubatti
arXiv 1606.06298

MATHUSLA detector → **MA**ssive **T**iming **H**odoscope for **U**ltra **S**table neutra**L** p**A**rticles

- Dedicated detector **sensitive to neutral long-lived particles that have lifetime up to the Big Bang Nucleosynthesis** (BBN) limit (10^7 – 10^8 m) for the HL-LHC
- **Large-volume, air filled detector located on the surface** above and somewhat displaced from ATLAS or CMS interaction points
- HL-LHC → **order of $N_h = 1.5 \times 10^8$** Higgs boson produced
- Observed decays:

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

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

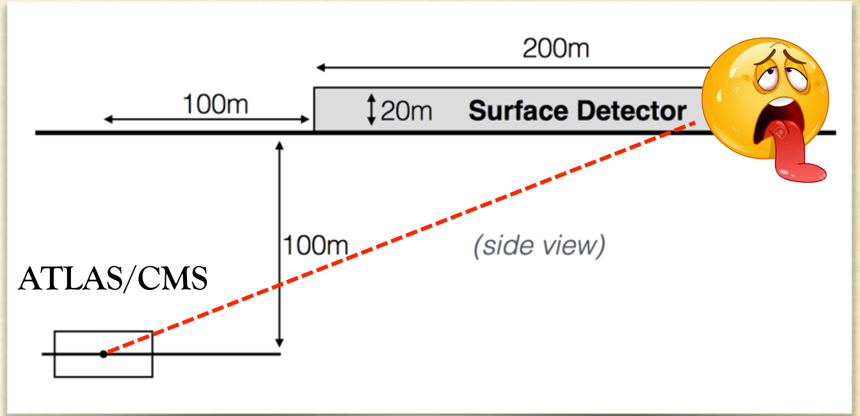
$$L \sim (20\ {\rm m}) \left(\frac{b}{3}\right) \left(\frac{0.1}{\epsilon_{\rm geometric}}\right) \frac{0.3}{{\rm Br}(h \to {\rm ULLP})}$$

MATHUSLA

J-P Chou, D. Curtin, H. Lubatti
arXiv 1606.06298

MATHUSLA detector → MAssive Timing Hodoscope for Ultra Stable neutraL pArticles

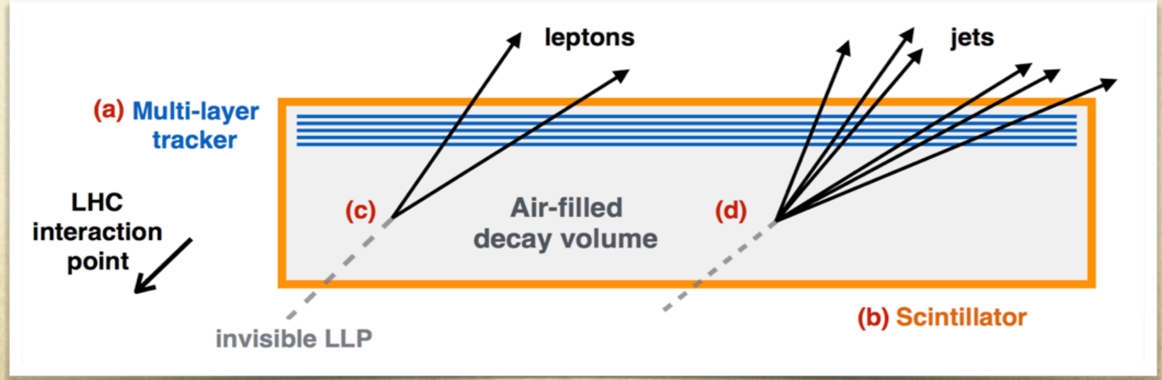
- Large area surface detector (200 x 200 m^2) above an LHC p-p IP dedicated to detection of ultra long-lived particles
- Air decay volume with tracking chambers surrounded by scintillators



- Need robust tracking
- Excellent background rejection

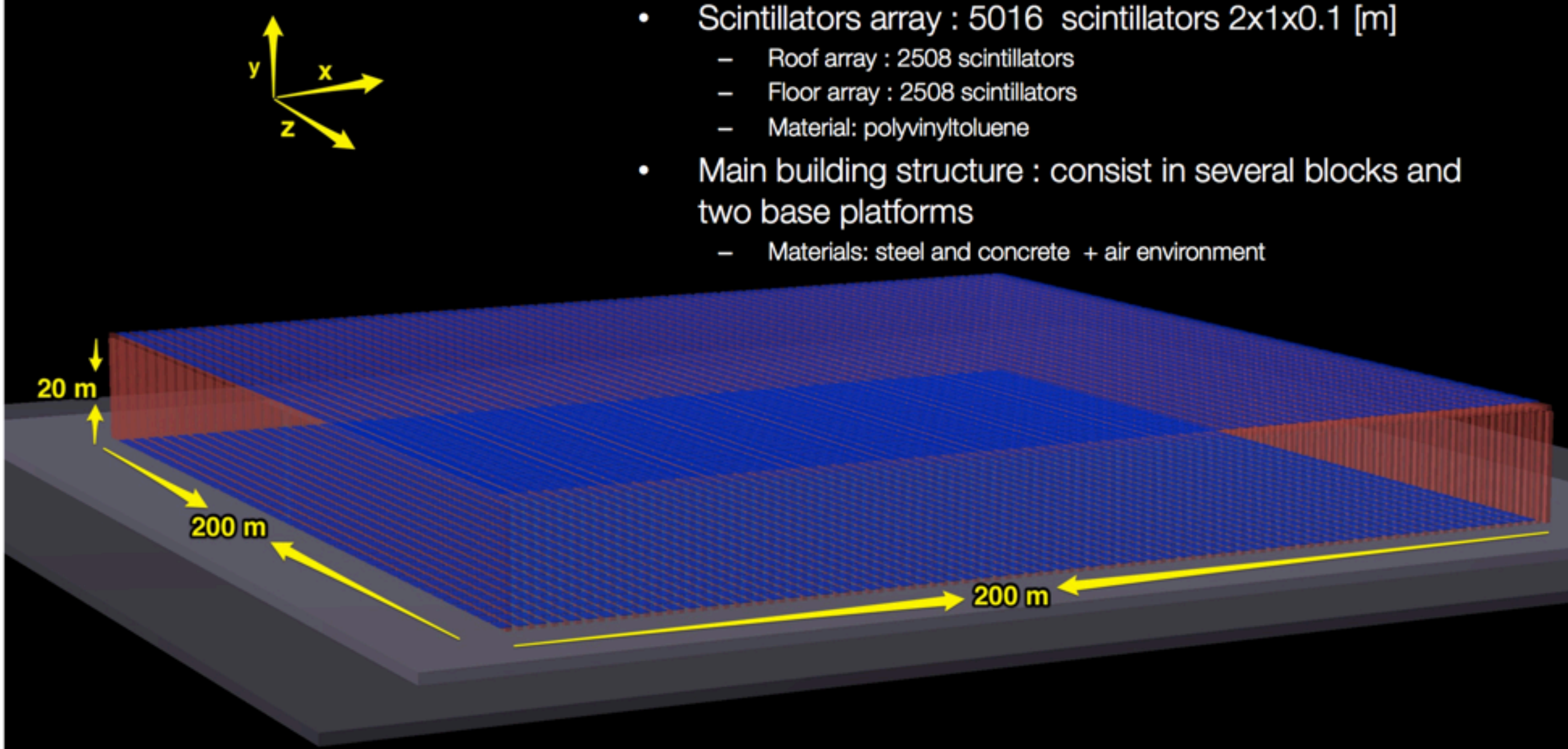
→ RPCs planes are an attractive choice (good space and time resolution for vertex reconstruction and cosmic ray rejection)

→ Scintillator planes for redundant background rejection - timing



MATHUSLA – Main Detector

MATHUSLA detector → **MA**ssive **T**iming **H**odoscope for **U**ltra **S**table neutra**L** p**A**rticles



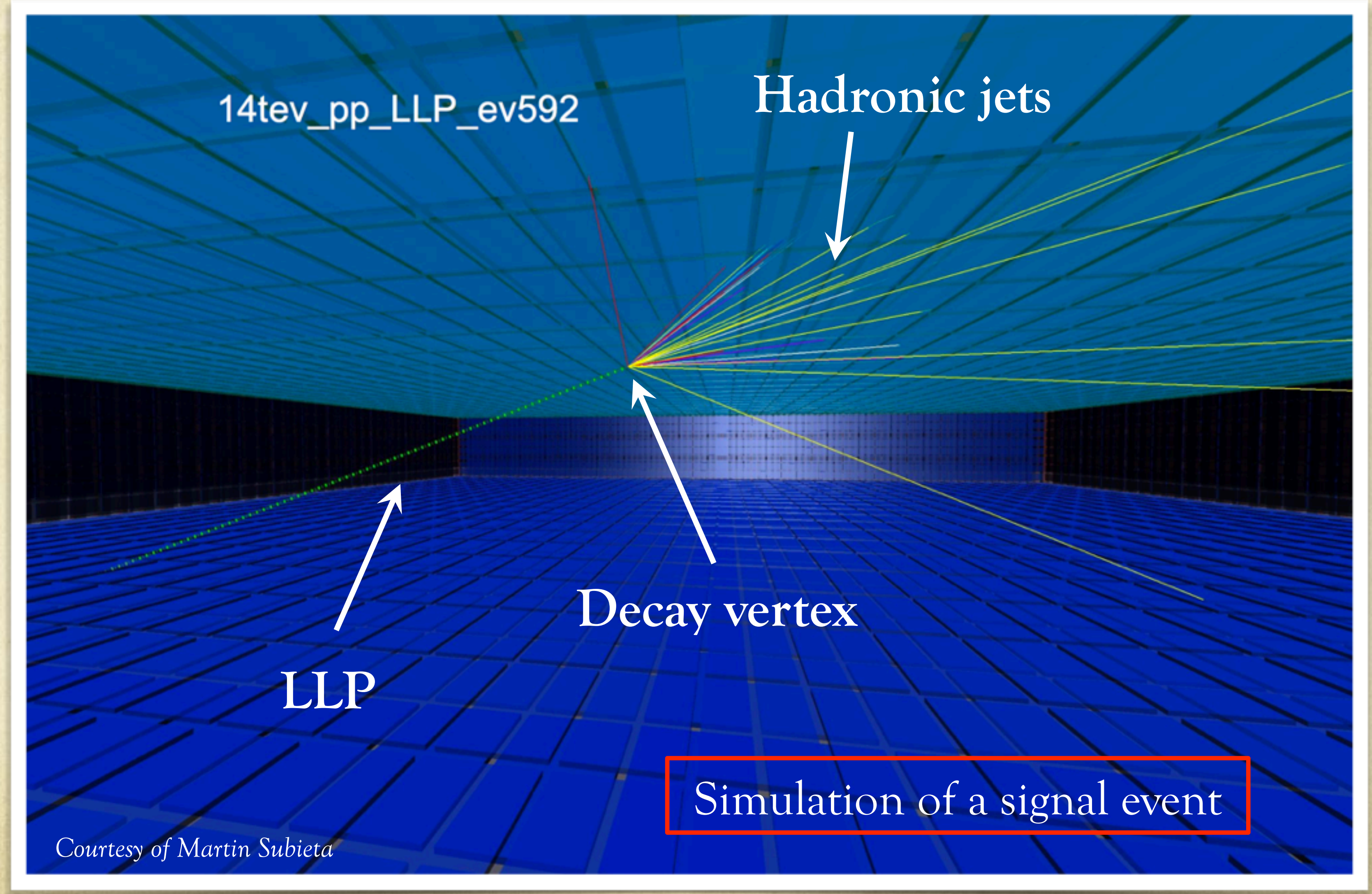
- Scintillators array : 5016 scintillators 2x1x0.1 [m]
  - Roof array : 2508 scintillators
  - Floor array : 2508 scintillators
  - Material: polyvinyltoluene
- Main building structure : consist in several blocks and two base platforms
  - Materials: steel and concrete + air environment

Main detector layout simulation

Courtesy of Martin Subieta

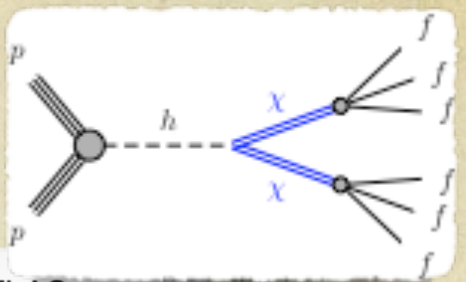
MATHUSLA – Signal Simulation

MATHUSLA detector → **MA**ssive **T**iming **H**odoscope for **U**ltra **S**table neutra**L** p**A**rticles

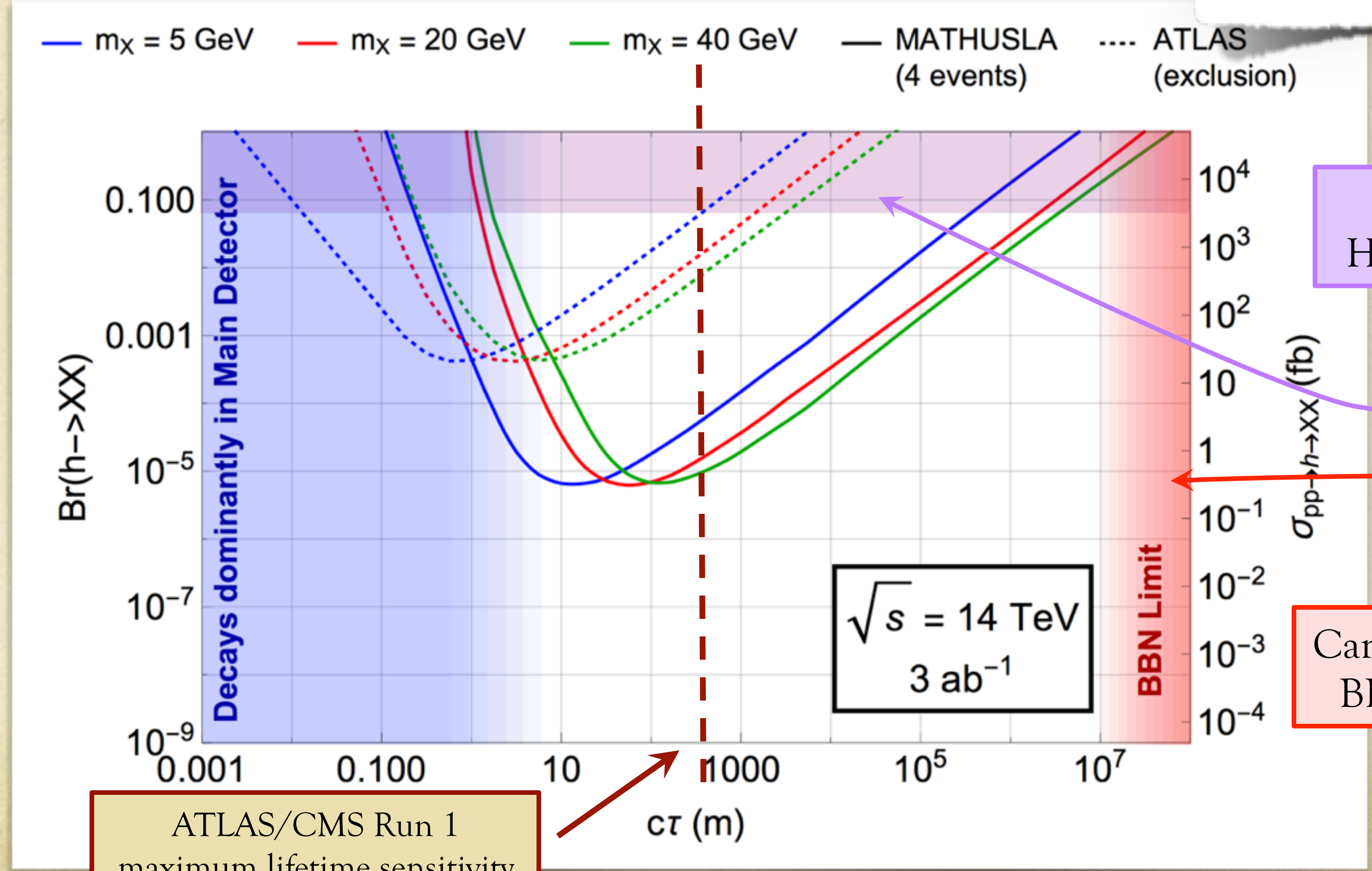


HL-LHC Sensitivity Estimate

J-P Chou, D. Curtin, H. Lubatti
arXiv 1606.06298



- Decay of Higgs boson to pair of scalars for different masses m_X
- No QCD background → big sensitivity gain



h → inv
HL-LH limit

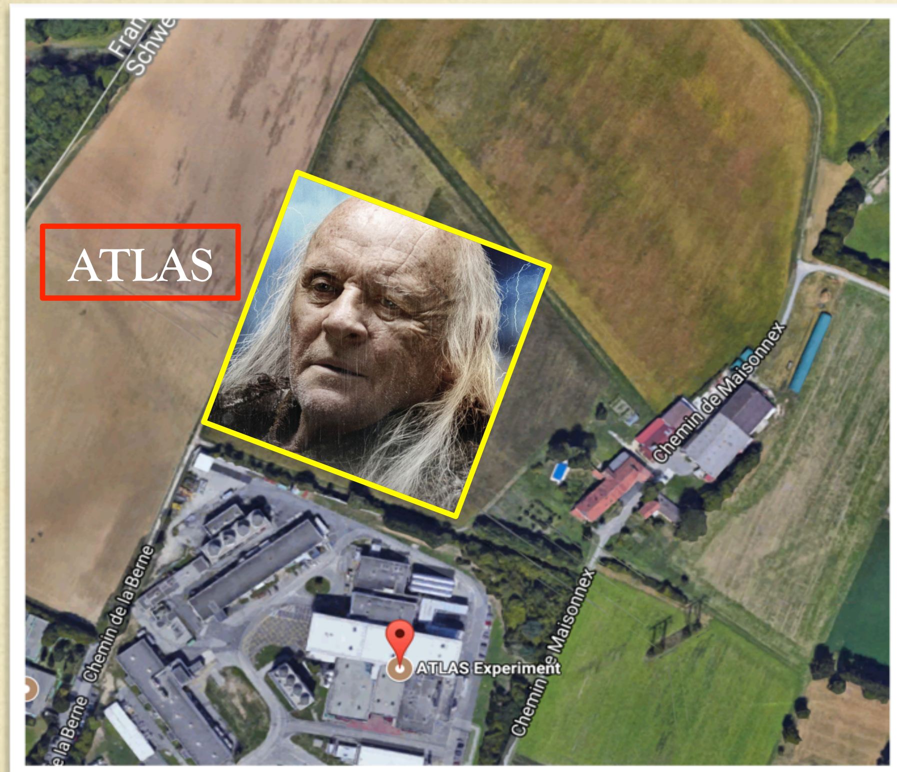
Can approach BBN limit!

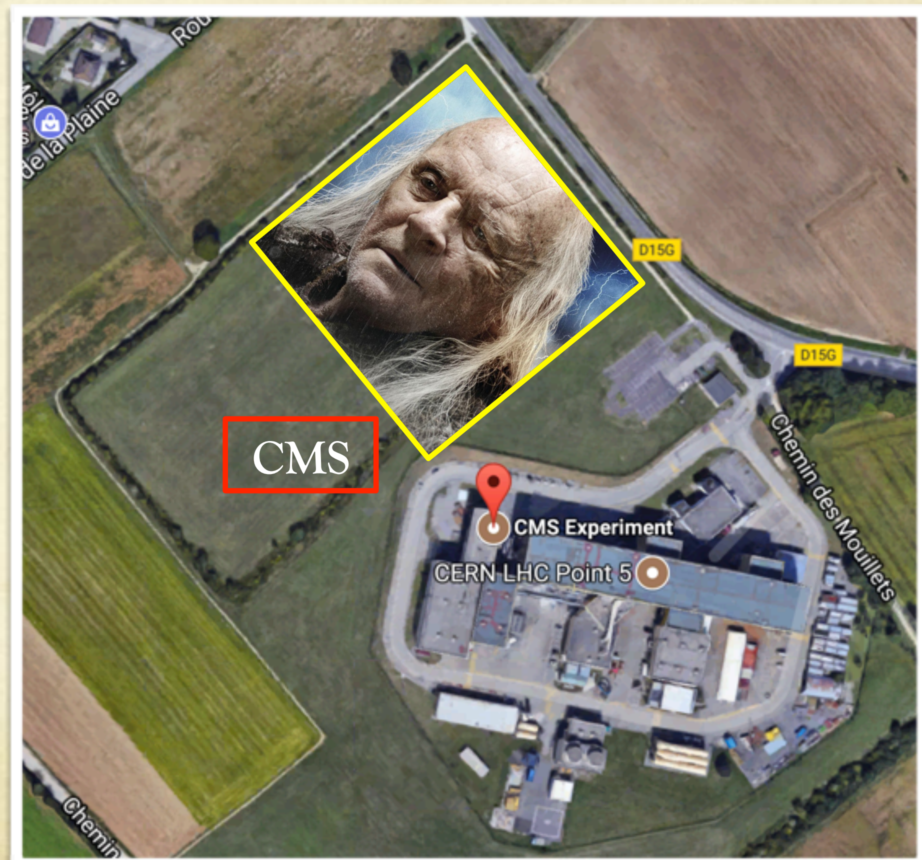
ATLAS/CMS Run 1
maximum lifetime sensitivity

Where MATHUSLA could be located?

- We need a large surface close to a p-p interaction point (IP)

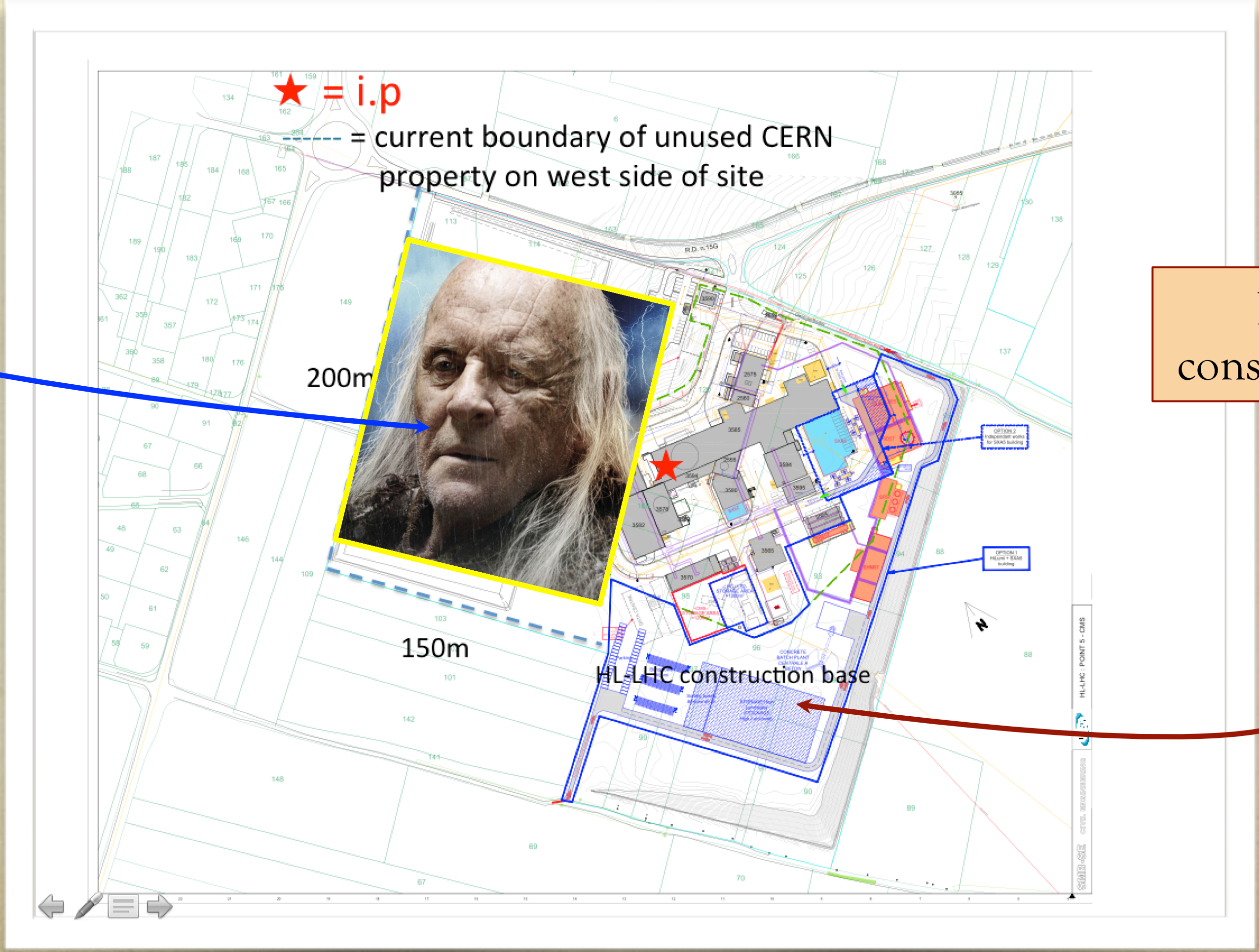
MATHUSLA could be located above either ATLAS (P1) or CMS (P2)





Where MATHUSLA could be located?

- ...not sure there is enough space around ATLAS...
- But **CMS site has a large area that is owned by CERN and there are no plans to occupy it in the future!**



HL-LHC construction base

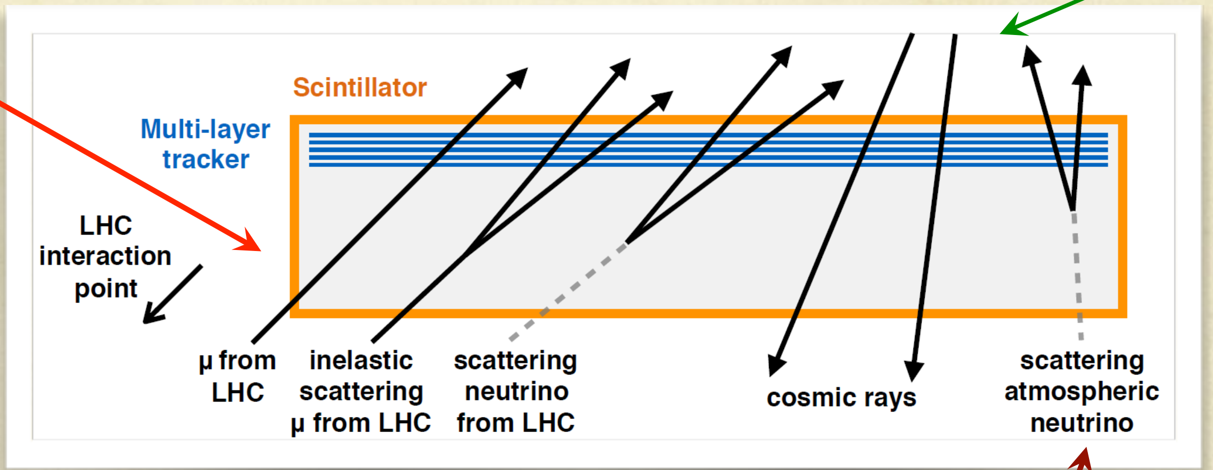
MATHUSLA - Backgrounds

J-P Chou, D. Curtin, H. Lubatti
arXiv 1606.06298

No LHC Background, BUT…

- **Cosmic muon** rate of about **10^6 Hz**
- LHC collision backgrounds
  - ✓ **LHC muons** about **10 Hz**

Non-collision backgrounds can be measured when no LHC collisions



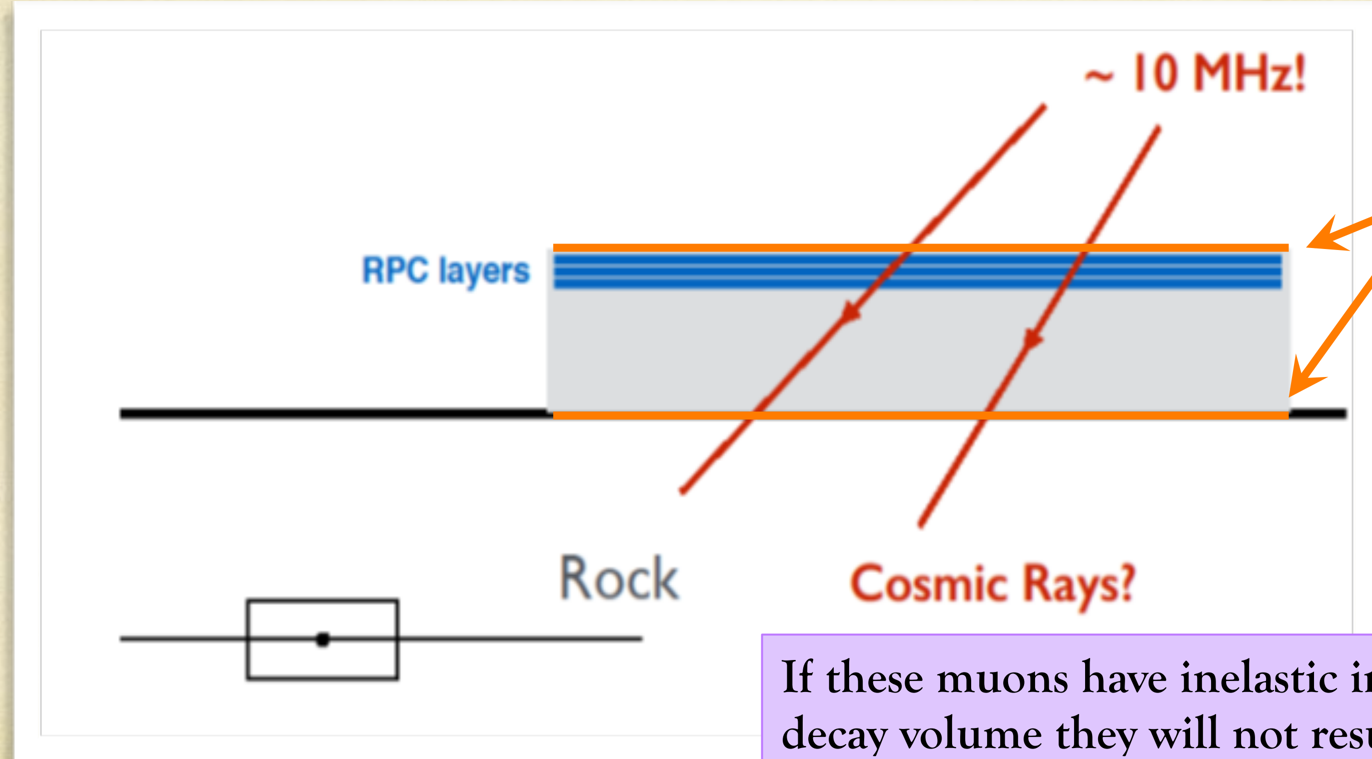
- **Upward atmospheric neutrinos** that interact in air decay volume
  - ✓ Estimate Low rate ~ **10-100 per year above 300 MeV**
  - ✓ Most have low momentum proton - reject with time of flight

Goal is a background-free MATHUSLA!

MATHUSLA – Cosmic Muon Background

No LHC Background, BUT…

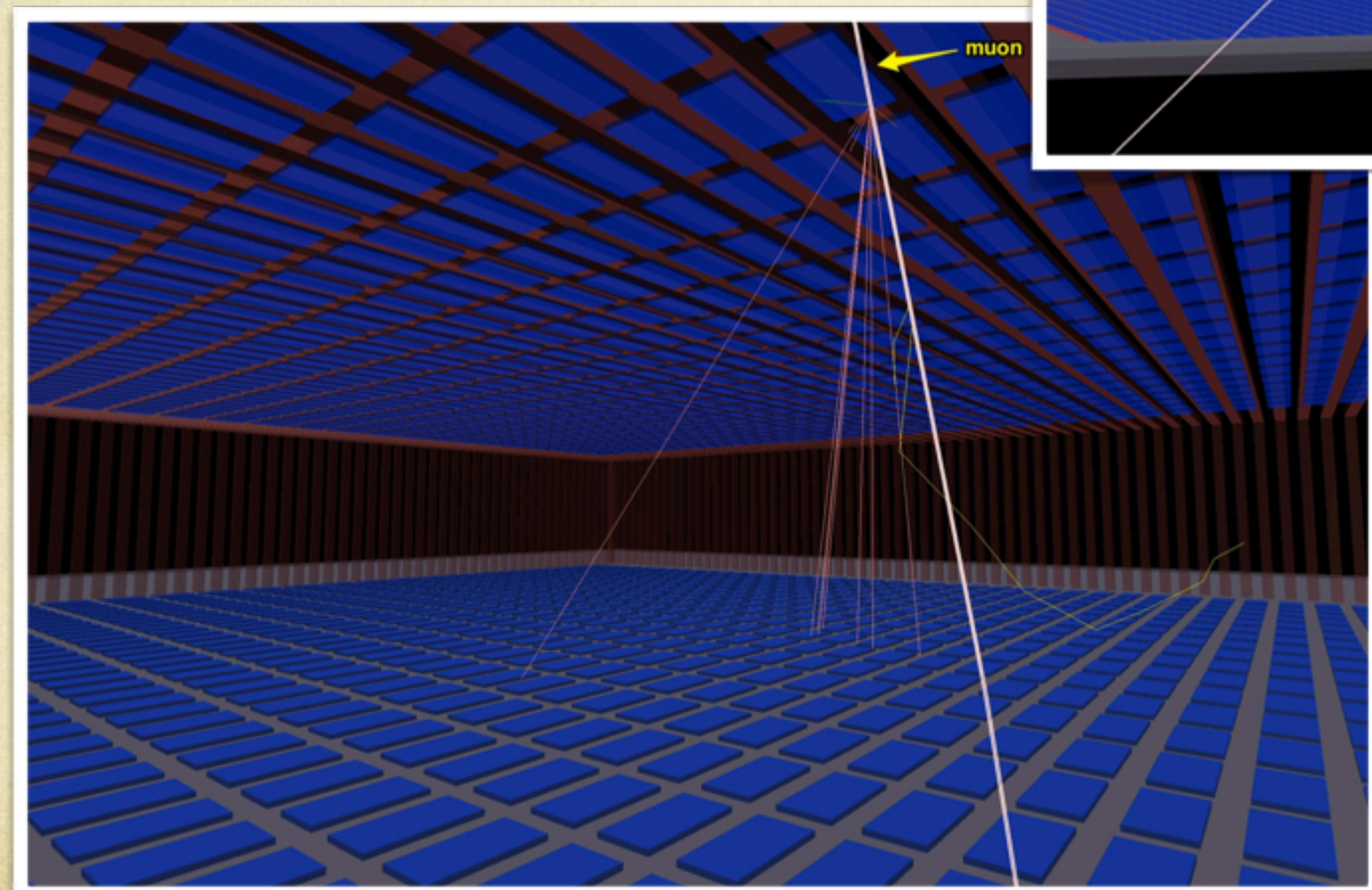
- Cosmic muon rate or order 10 MHz (200 m^2)
- Scintillators 1.5 ns timing resolution in 20 m have $\Delta t \approx 70$ ns top to bottom

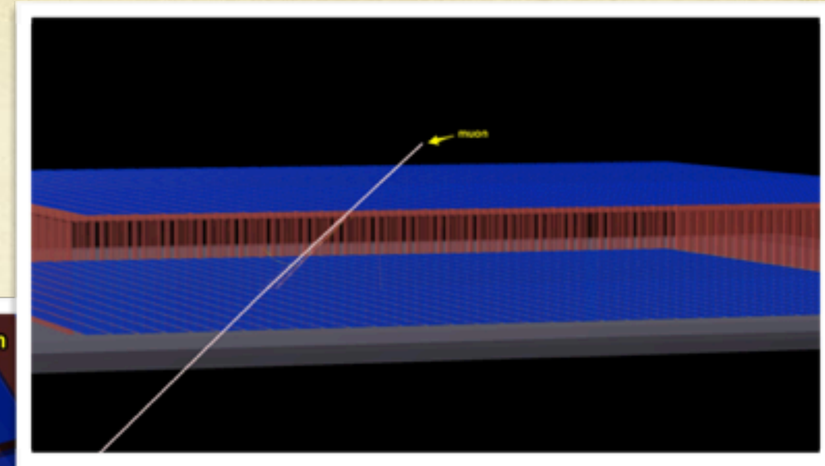


scintillators 1.5 ns time resolution

If these muons have inelastic interaction in air decay volume they will not result in a reconstructed vertex; in addition, scintillator timing also can be used to reject

MATHUSLA – Cosmic Muon Background Event

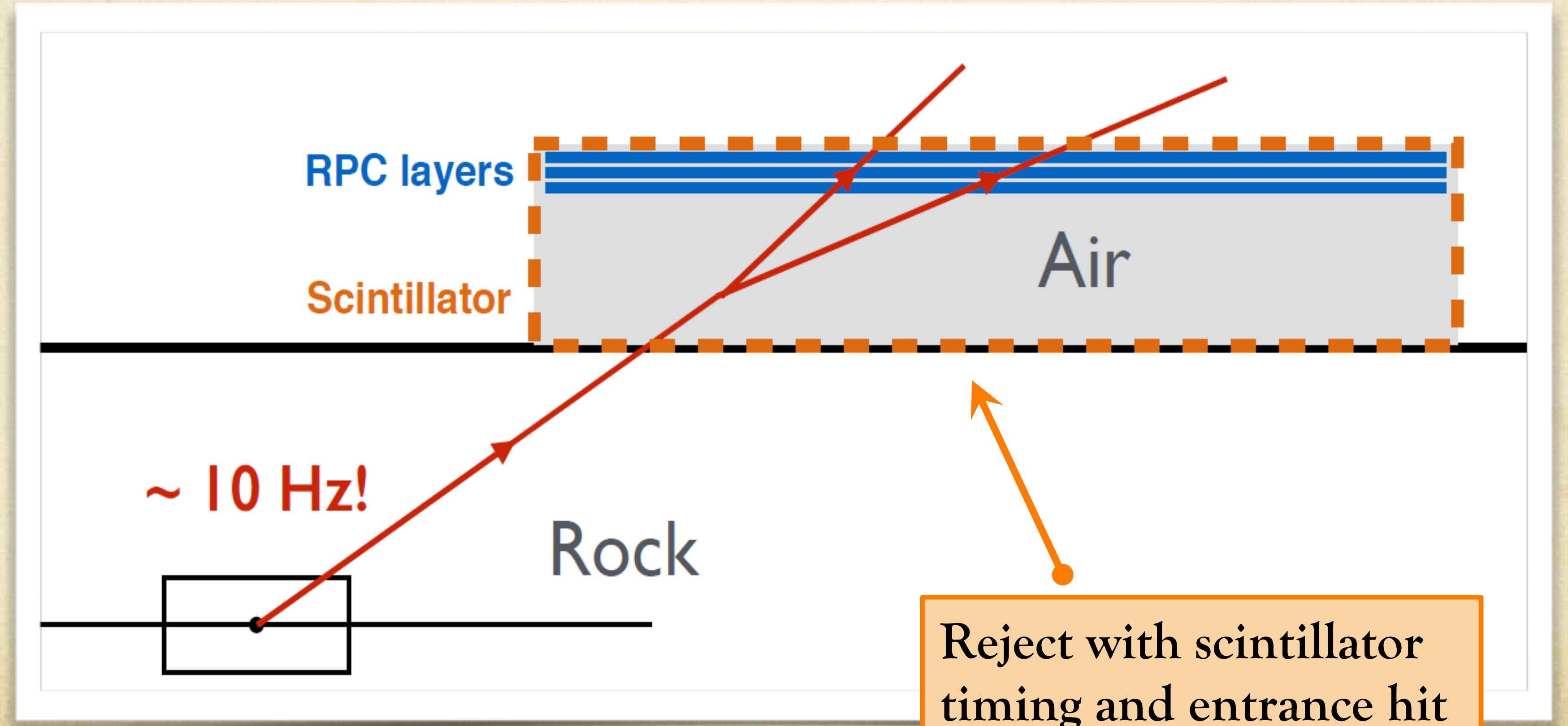




MATHUSLA – LHC Muon Background

No LHC Background, BUT…

- Upward going muons from LHC with inelastic interaction (10 Hz)
- Scintillators 1.5 ns timing resolution in 20 m have $\Delta t \approx 70$ ns top to bottom

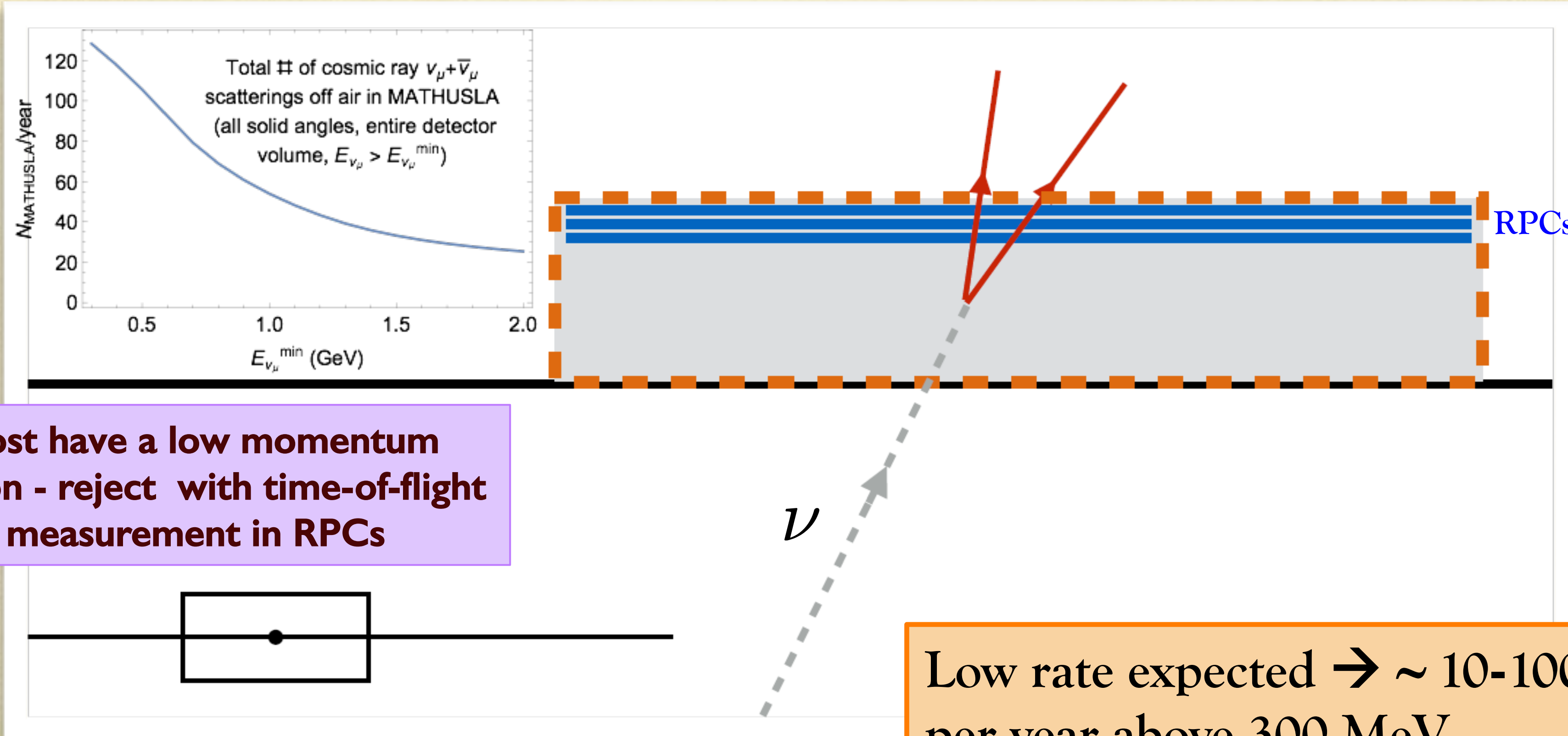


Reject with scintillator timing and entrance hit position

MATHUSLA – Cosmic Neutrinos Background

No LHC Background, BUT…

- Cosmic neutrinos traveling upwards that have inelastic interactions in the decay volume



Most have a low momentum proton - reject with time-of-flight measurement in RPCs

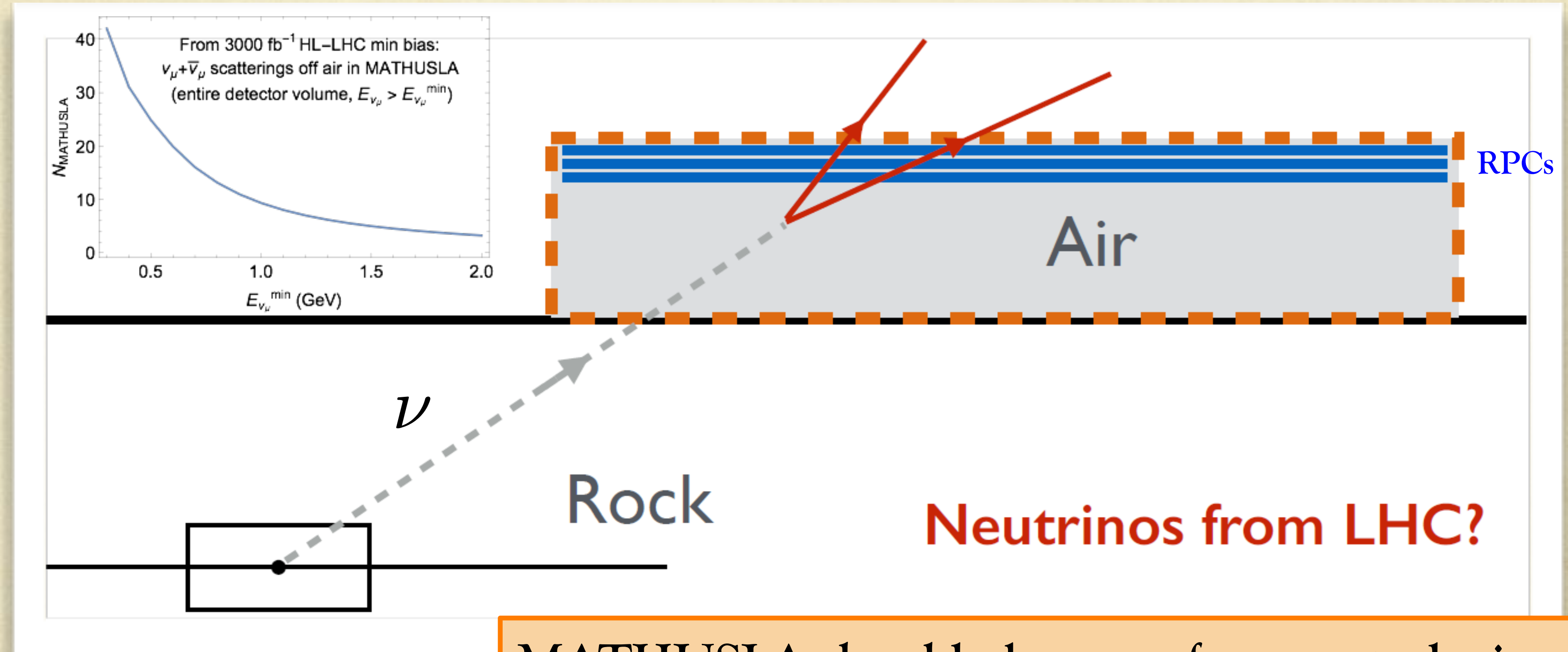
Low rate expected → ~ 10-100 per year above 300 MeV

❖ This background can be measured when there is no beam in the LHC!

MATHUSLA – Cosmic Neutrinos Background

No LHC Background, BUT…

- Neutrino from LHC interactions (subdominant background)



MATHUSLA should observe a few events during HL-LHC data taking period (need more work, but the effect should be subdominant)

MATHUSLA Background Simulations

Effort underway to develop GEANT simulations of the backgrounds discussed above

- Current plan to deal with **muons** and **neutrinos traveling upwards** is to create a "gun" that shoots particles into MATHUSLA
- For cosmic muons from above plan to use standard cosmic muon simulation code
- **Simulation/data anchor with LHC colliding protons and also when there are no pp collisions in LHC – beam OFF**

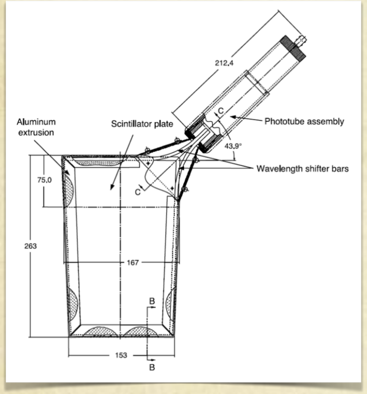
…we need a

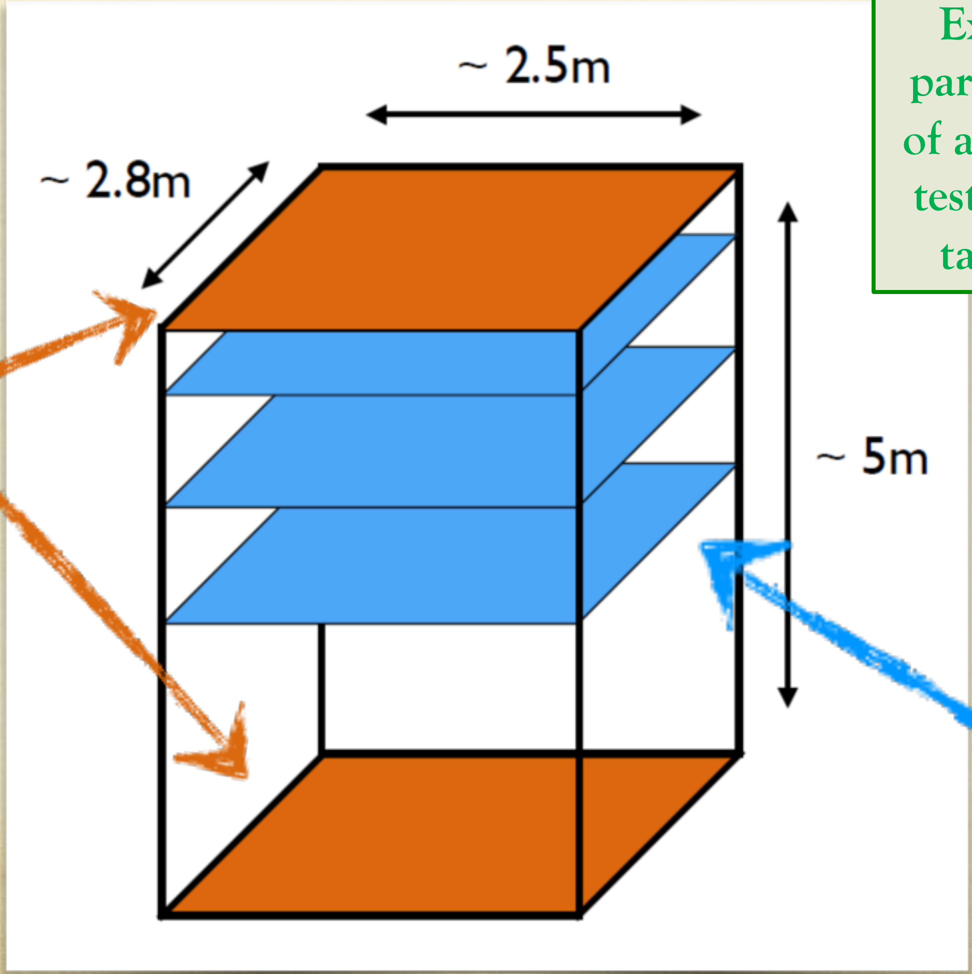
TEST MODULE

MATHUSLA Test Module

- MC simulations need data with LHC colliding protons and also when the beam is off → need a **TEST module**!
- **On-going assembling of a test detector at CERN**

Top and bottom scintillator layers from Tevatron DØ provided by Dmitri Denisov



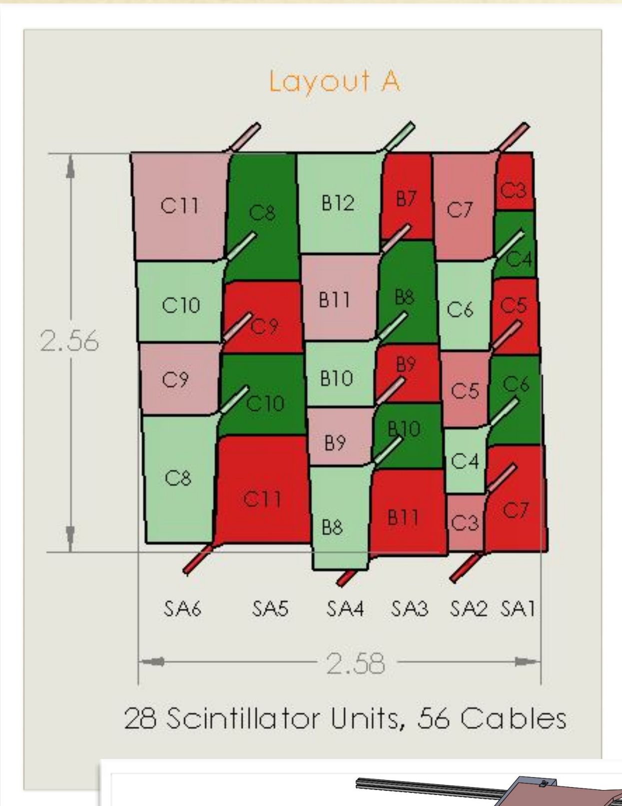


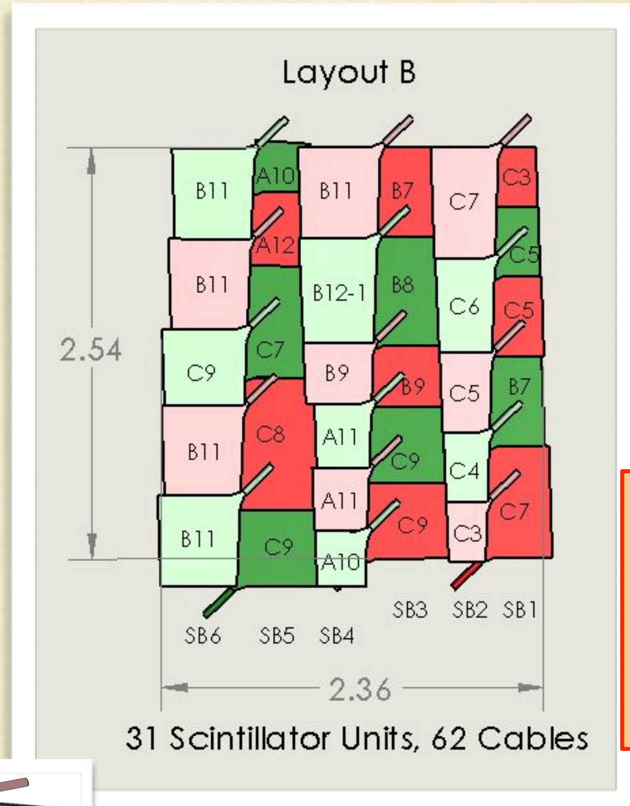
Excellent for students participation at all stages of an experiment: design, test components, install, take data and analysis

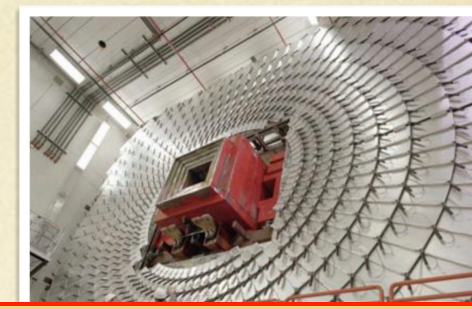
3 layers of RPCs provided by University of Tor Vergata (Rome) by Rinaldo Santonico

MATHUSLA Test Module: Scintillator Planes

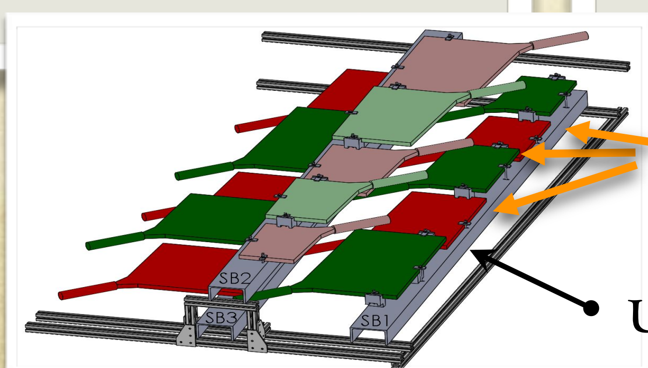
- Possible layout for the 2 scintillator planes







D0 forward MUON Trigger scintillator: 12.8-mm-thick BICRON 404A of trapezoidal shape + WLS bars for light collection



Clamps

U-Channel

Will test of assembly Procedures/tooling with short U-channel section and two scintillators

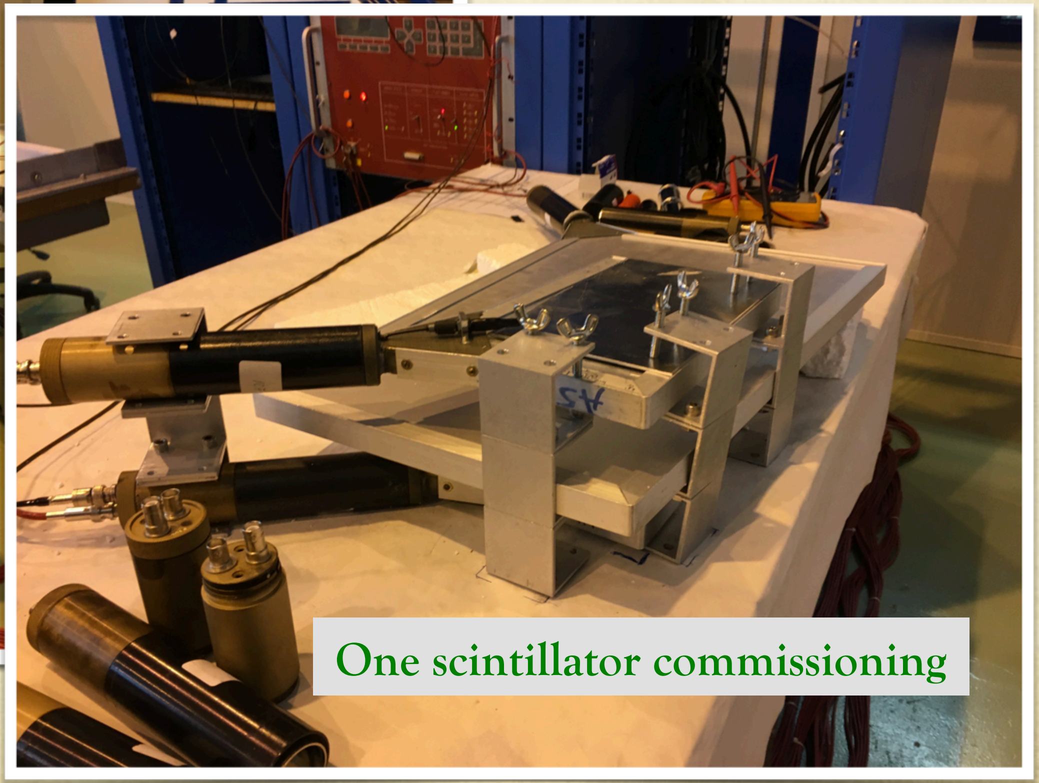
MATHUSLA Test Module Status

- Scintillators at CERN have finished certification to establish HV setting, noise rates and efficiency
  - ✓ Will be assembled into two planes shown on previous slide
- RPCs provided by R. Santonico University of Rome, Tor Vergata to be shipped to CERN early September
  - ✓ **Twelve RPC** chambers **1.25 m X 2.8 m** (spares from ARGO experiment) measure one coordinate
  - ✓ For test module will have 3 RPC planes composed of 4 RPCs

❖ **RPCs and scintillator planes will be assembled into the test module and transported and installed on the surface above the ATLAS detector**

MATHUSLA Test Module: Scintillator Tests

- Scintillator commissioning @ CERN in building 175



MATHUSLA Test Module: Scintillator Tests

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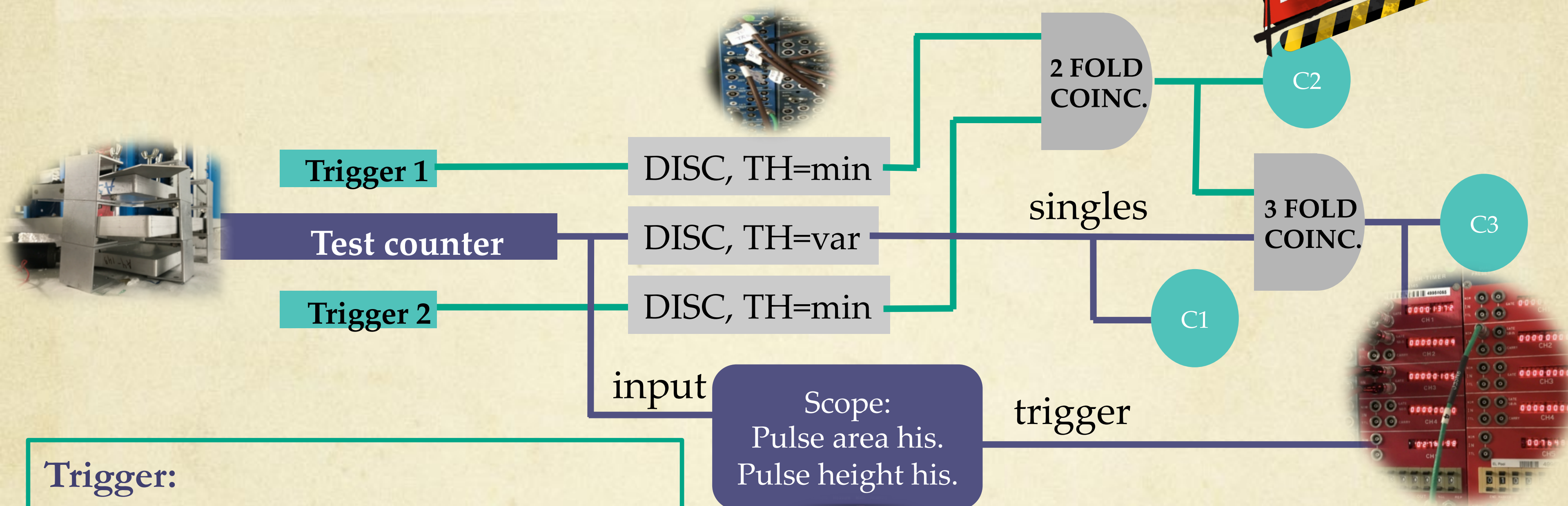
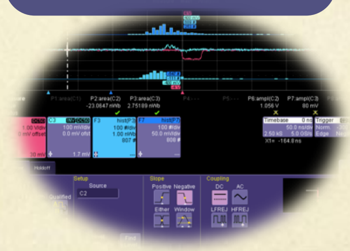


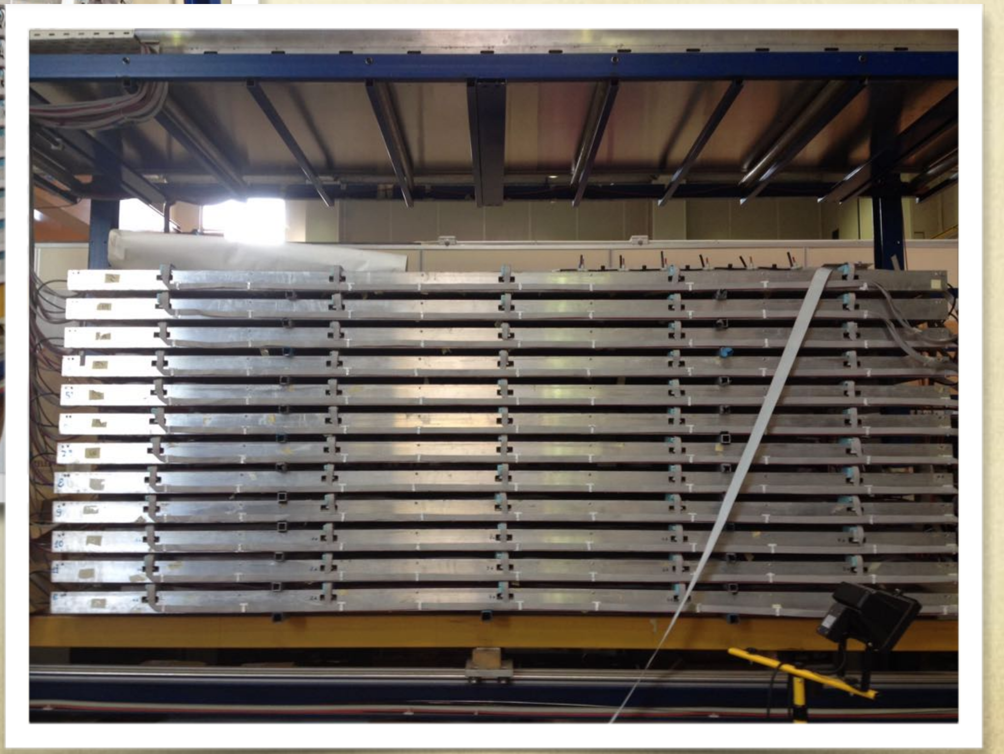


Trigger:
- Trigger1 and trigger2 are small counters used to form a cosmic ray trigger
- Operated at a high supply voltage(1.9kV) and minimum discriminator threshold(30mV)
- Trigger counters are set up at corner of test counter furthest from PMT

Counting:
- C1 counts single hits on the test counter
- C2 counts 2-fold coincidence C3 counts 3-fold coincidence
- C3/C2 measures efficiency of the test counter for cosmic ray

MATHUSLA Test Module: RPCs

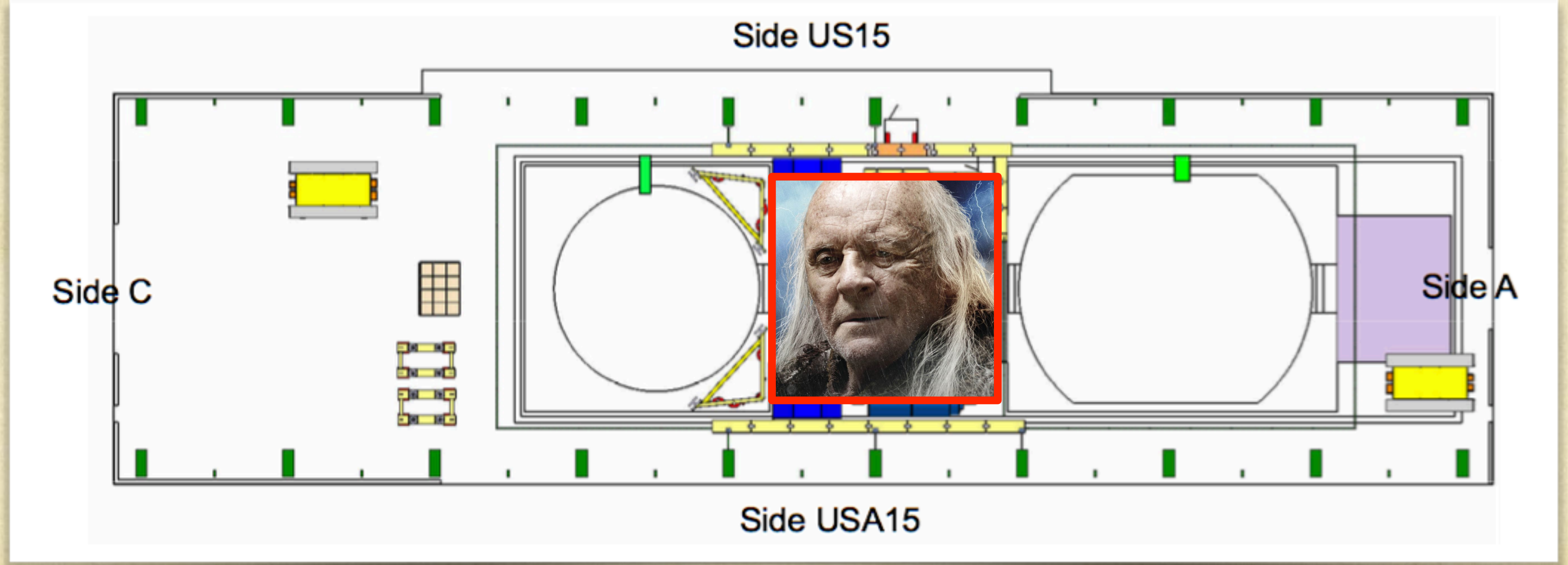
➢ RPCs from Tor Vergata Rome



Pictures from Rinaldo Santonico

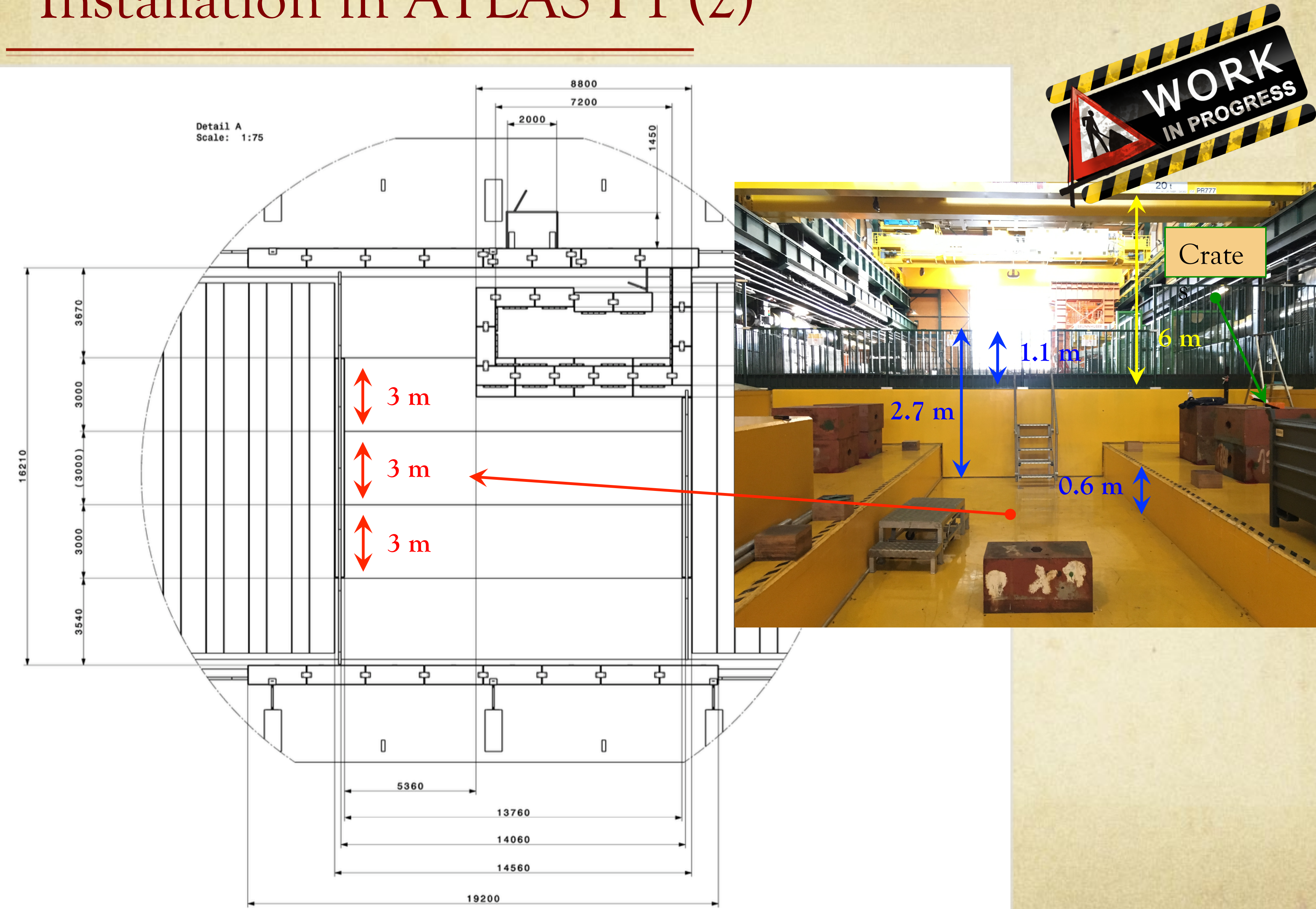
Installation in ATLAS P1 (1)

- Cosmic background well understood
- Need to quantify the **background from ATLAS**
- Test detector will be installed in the surface area above ATLAS in September
  - ✓ **Perform measurements with beam on and off**



❖ **Measurement fundamental for future background simulations!**

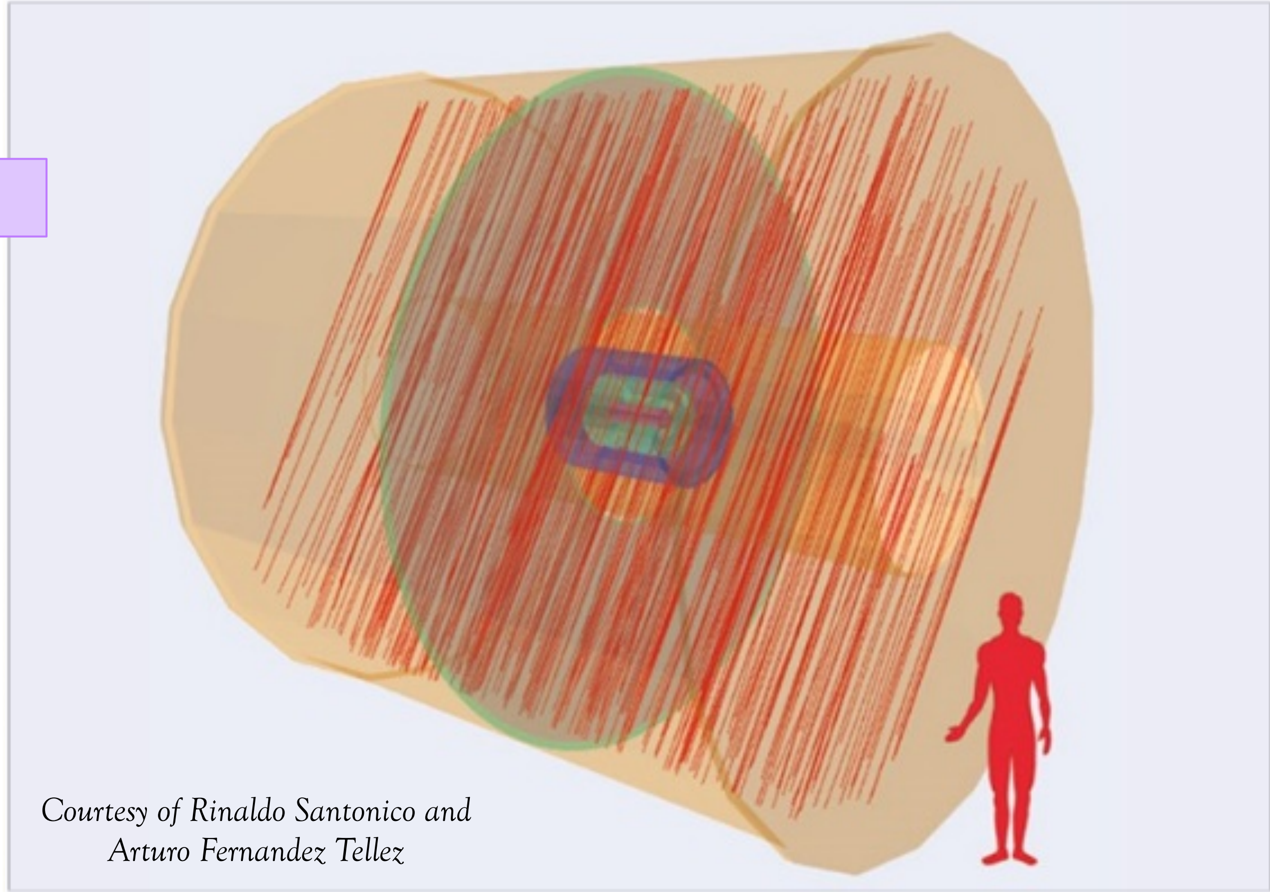
Installation in ATLAS P1 (2)



MATHUSLA and Cosmic Rays

- The combination of a **large area detector** of atmospheric showers (e and μ meas.) with a **LHC detector** (only μ meas.) provides a more complete picture of air showers

Muon bundles at LHC

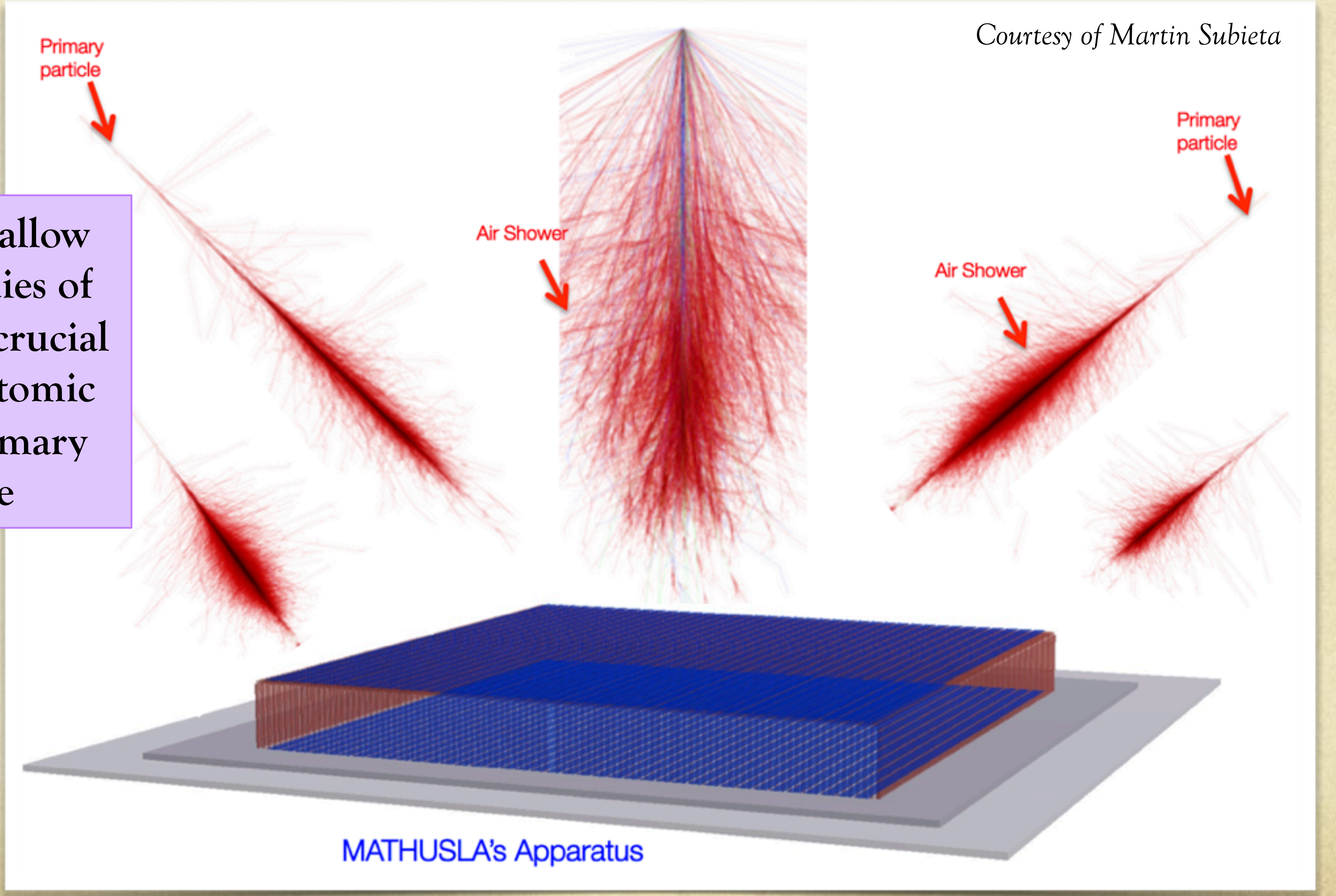


Courtesy of Rinaldo Santonico and Arturo Fernandez Tellez

MATHUSLA and Cosmic Rays

- The combination of a **large area detector** of atmospheric showers (*e* and μ meas.) with a **LHC detector** (only μ meas.) provides a more complete picture of air showers

MATHUSLA can allow more detailed studies of the core structure, crucial to determine the atomic number of the primary cosmic particle



MATHUSLA Collaboration

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MATHUSLA White Paper

- Collaboration of 70+ theorists
- Aiming for publication in 2017

Detecting Ultra-Long-Lived Particles: The MATHUSLA Physics Case

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Conclusions

- We are studying the feasibility of a large scale detector to measure LLPs with very long lifetimes
- Several studies have already been performed
- A test module is under installation and commissioning at CERN
- Background tests above ATLAS will start in September
- Aiming to prepare a letter of intent for the future main detector

BACKUP

LHC Detector Signatures

- Strong dependence on the sub-detectors of ATLAS, CMS and LHCb.
  - Inner detectors, calorimeters an muon systems not the same in the three detectors
  - All LHC detectors need to overcome obstacles
- Boost of LLP determines opening angle(s) and that affects trigger efficiencies.
  - Efficiencies can also depend on trigger algorithm and subsystem readout at trigger level
  - Presents a challenge for generic, model independent searches

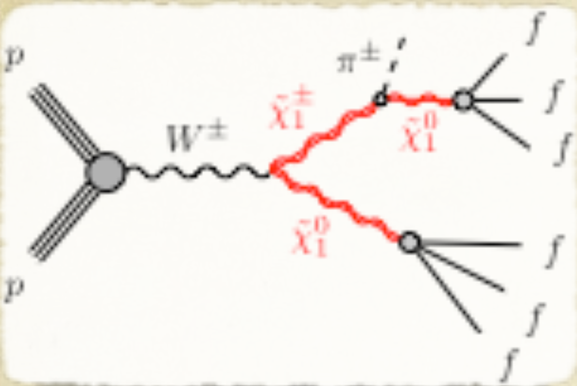
Signature Space of Displaced Vertex Searches

- Detector signature depends of production and decay operators of a given model
  - Production determines cross section and number and characteristics of associated objects
  - Decay operator coupling determines life time, which is effectively a free parameter
- Common Production modes
  - Production of single object - with No associated objects (AOs)
    - Higgs-like scalar Φ that decays to a pair of long-lived scalars, ss, that each in turn decay to quark pairs – Hidden Valley, Neutral Naturalness, …
    - Vector (γ_{dark},Z') mixing with SM gauge bosons – kinetic mixing
  - Production of a single object P with an AO – Many SUSY models
    - AO jets if results from decay of a colored object
    - AO leptons if LLP produced via EW interactions with SM
- Common detector signatures $\Rightarrow$ generic searches

Neutral Long-lived particles

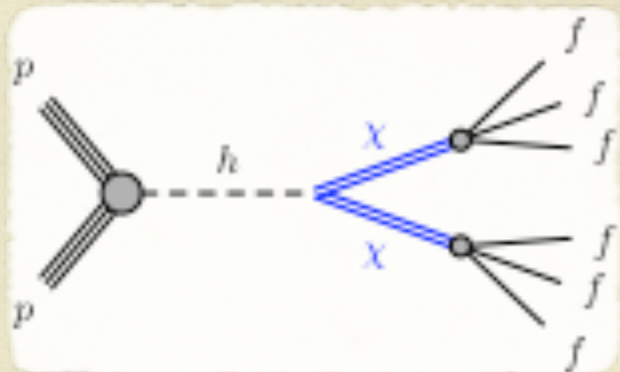
- Neutral LLPs lead to displaced decays with no track connecting to the IP, a distinguishing signature
  - **SM particles predominantly yield prompt decays (good news)**
  - **SM cross sections very large (eg. QCD jets) (bad news)**
- To reduce SM backgrounds many Run 1 ATLAS searches required two identified displaced vertices or one displaced vertex with an associated object
  - **Resulted in good rejection of rare SM backgrounds**
  - **BUT limited the kinematic region and/or lifetime reach**
- None the less, these Run 1 searches were able to probe a broad range of the LLP parameter space (LLP-mass, LLP-cτ)
- ATLAS search strategy for displaced decays - based on signature driven triggers that are detector dependent

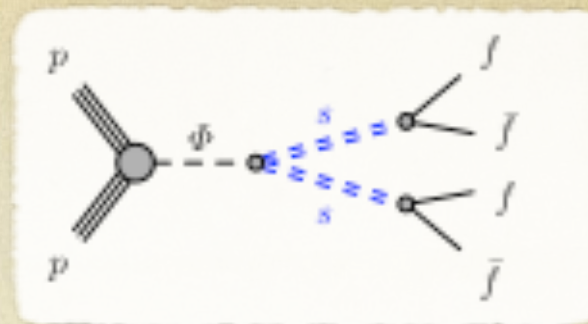
Some of the LLP Models



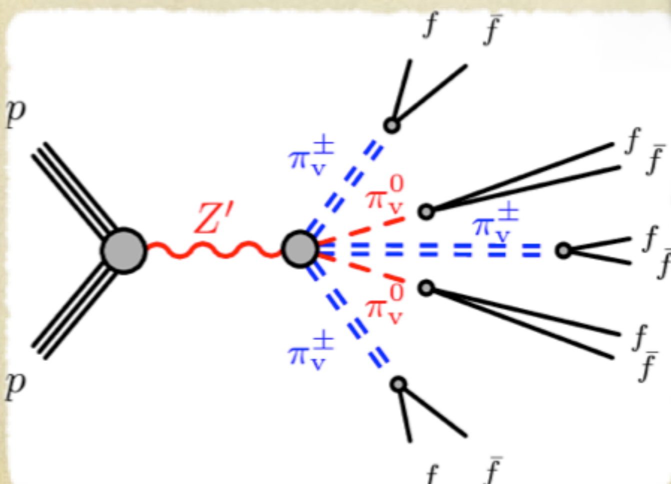
Baryogenesis
wino-like model

Baryogenesis
Higgs portal

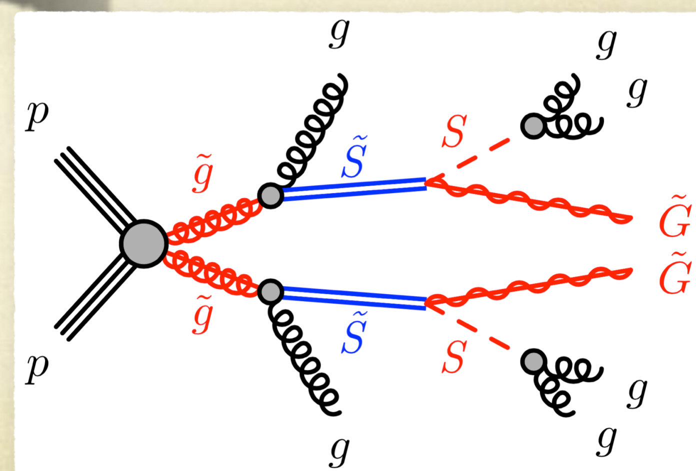




Low/high
mass bosons
to scalars



Z' models



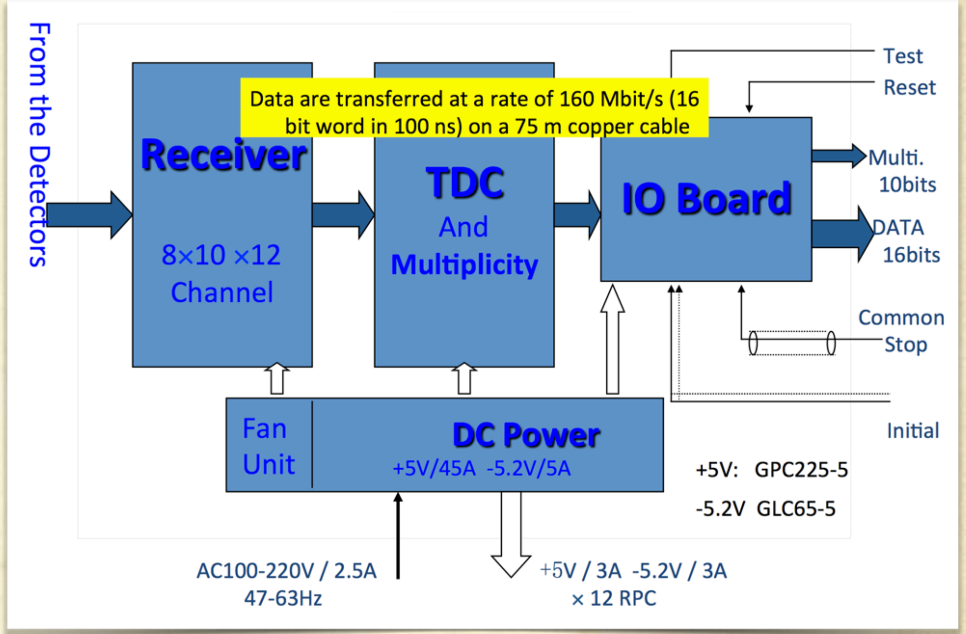
Stealth SUSY

MATHUSLA – DAQ and Trigger

Test module DAQ

- **Scintillators:** PMTs interfaced with a VME crate connected to a PC

- **RPCs: Argo Experiment Local Station** (from Lecce). Data from each RPC acquired from a Receiver Card which reads out and digitises the space and time information from 10 pick-up pads and gives out the pad multiplicity for trigger purposes. On trigger occurrence the Local Station sends the collected data to the PC

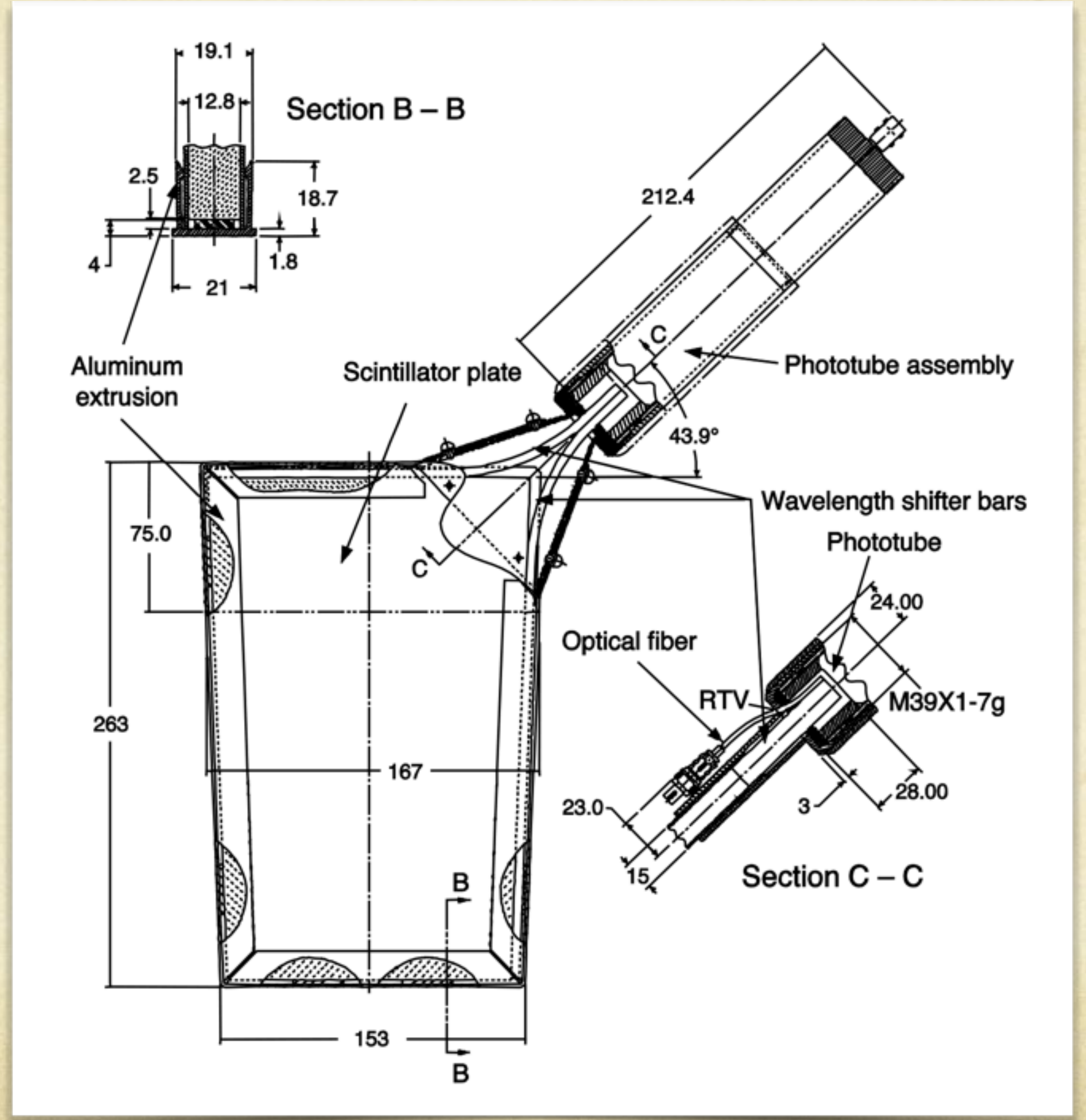


Test module trigger

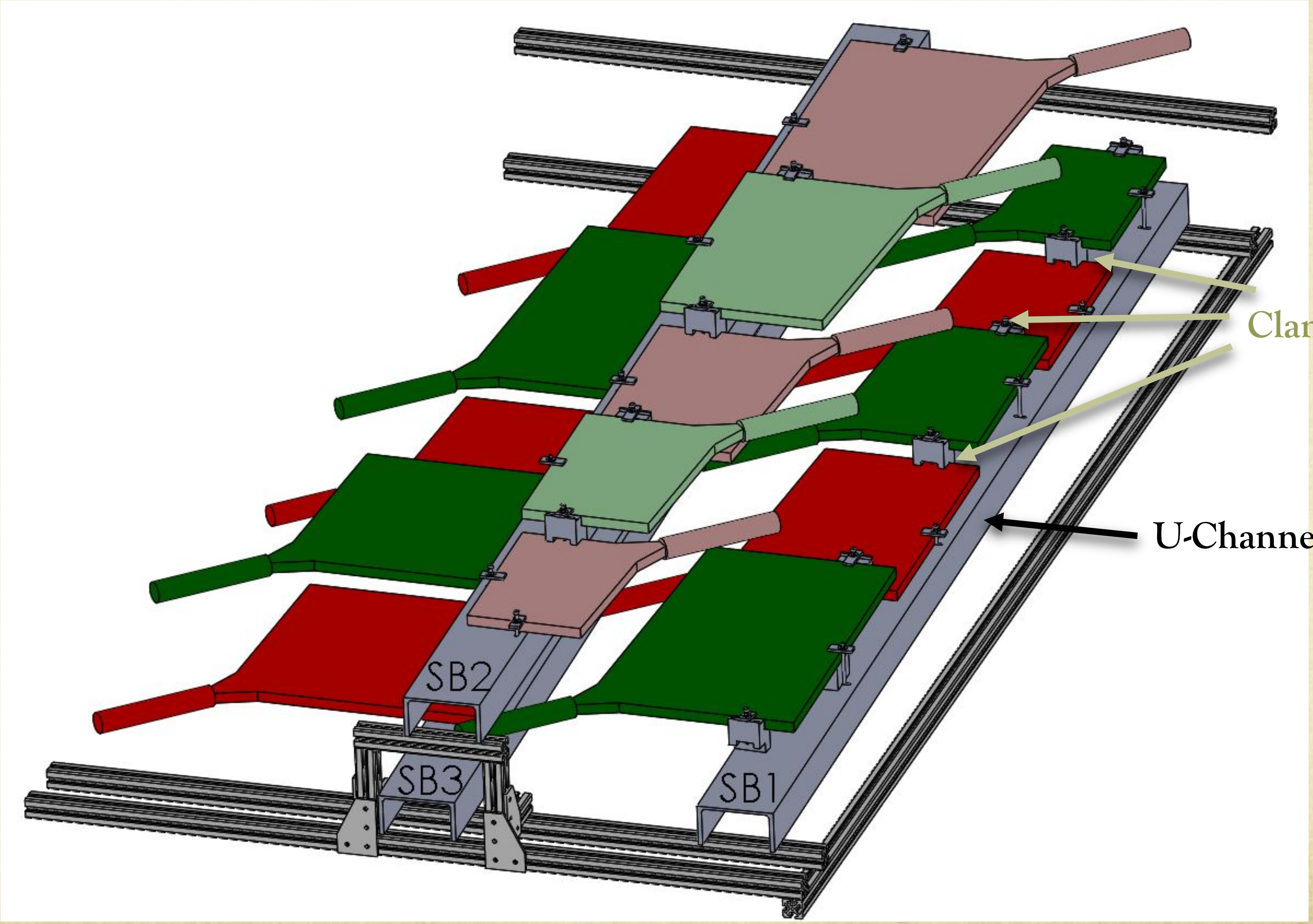
Two possible triggers: top and bottom scintillators in coincidence, with:

1. **Timing appropriate for downward going particle** (cosmic ray events can be used for space and time alignment)
2. **Timing appropriate for upward going particle**

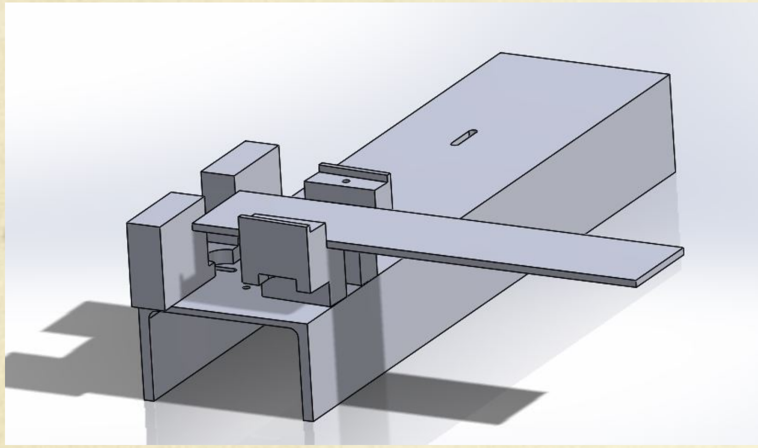
MATHUSLA – Scintillators Details



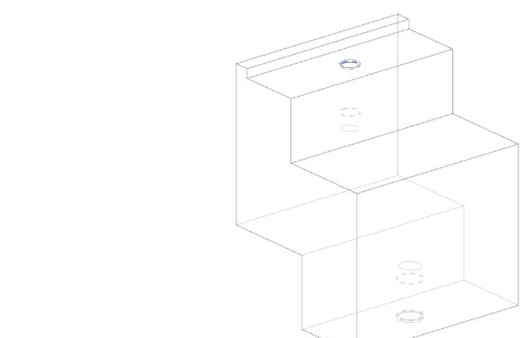
MATHUSLA – Scintillators Support Details (1)



MATHUSLA – Scintillators Support Details (2)



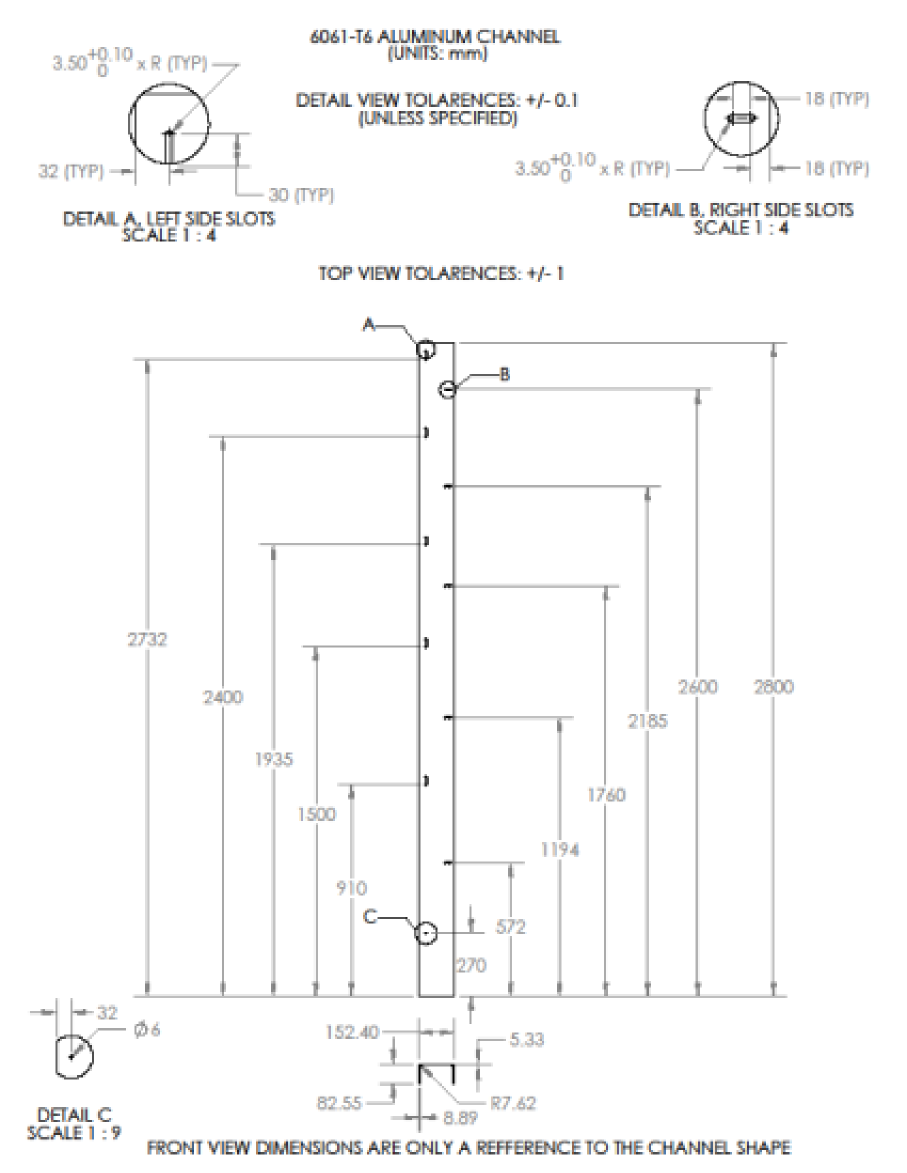
- Tapped holes not through holes.
- Soft rubber spacers between the shim and detector to evenly distribute the clamping force.
- Working on eliminating the side clamps entirely - requires a different alignment.
- Assembly test with two small scintillators this week.
- Will tweak some of the shim dimensions based on our assembly test.



Shim simple design

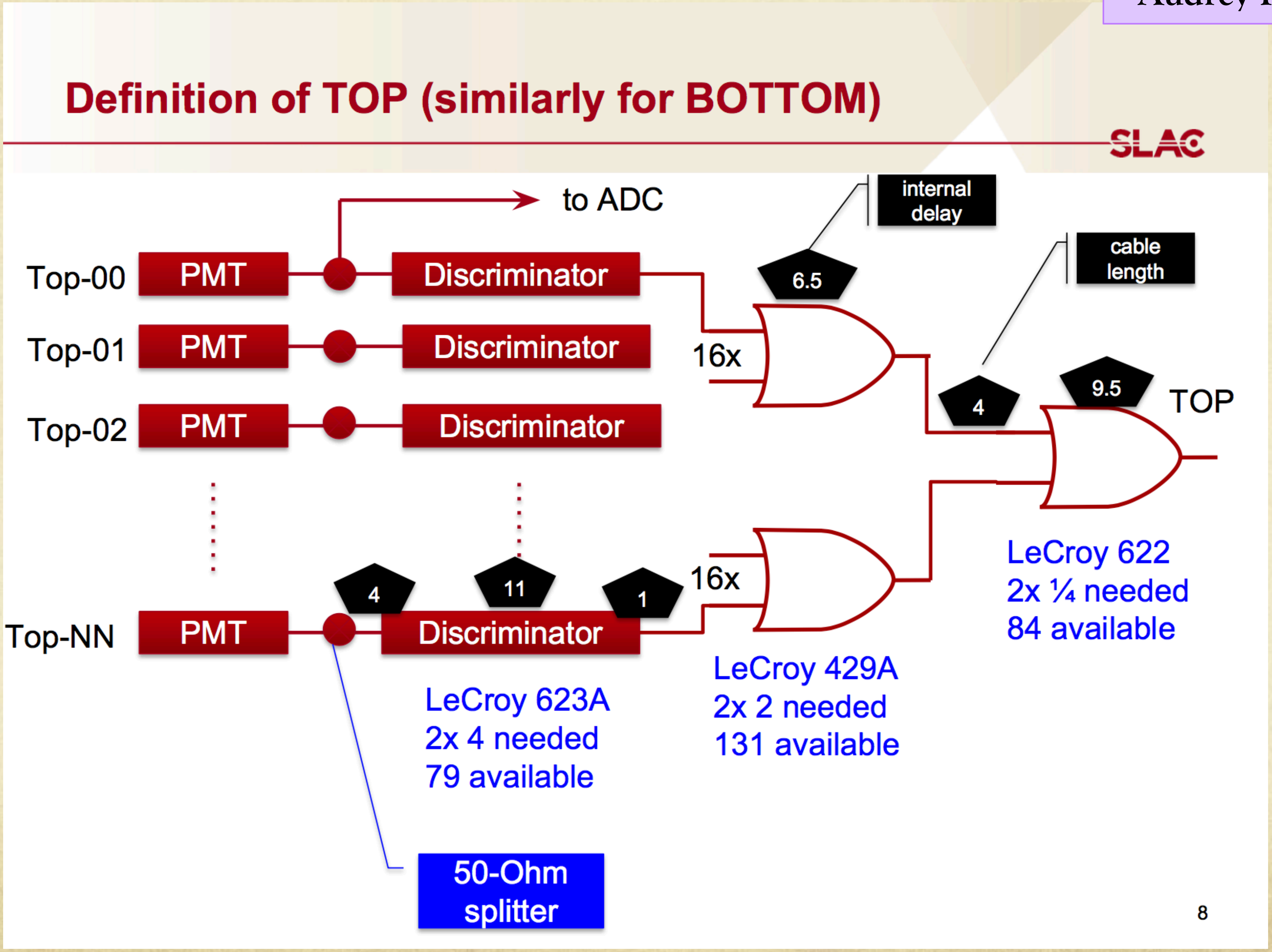
MATHUSLA – Scintillators Support Details (3)

- **Preliminary- NOT FINAL**
- **Options to explore**
  - **Get –channel at CERN and add slots**
  - **Do in US but then have shipping costs**
  - **To be continued**



MATHUSLA – Trigger Development (1)

Courtesy of Audrey Kvam

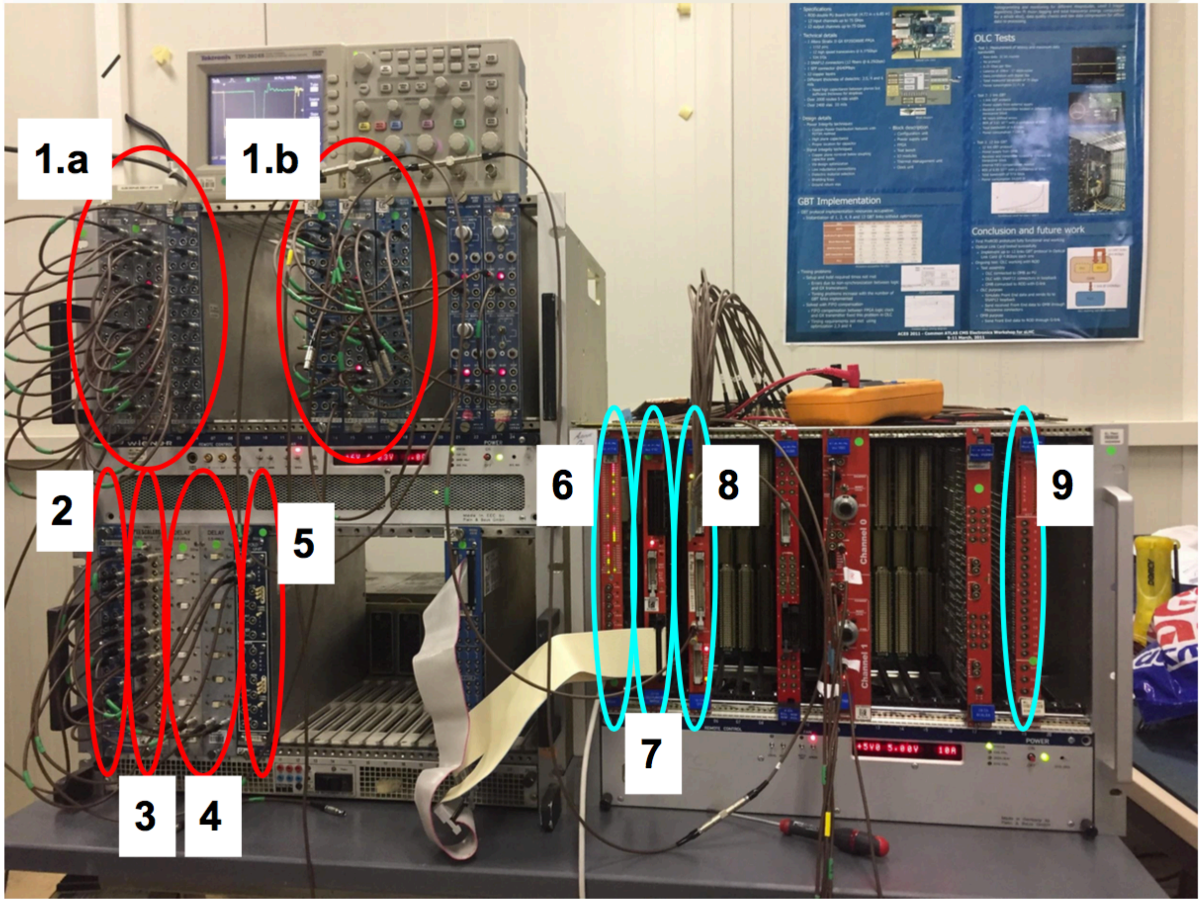


MATHUSLA – Trigger Development (1)

Courtesy of Audrey Kvam

Putting together (some of) trigger in 175

SLAC

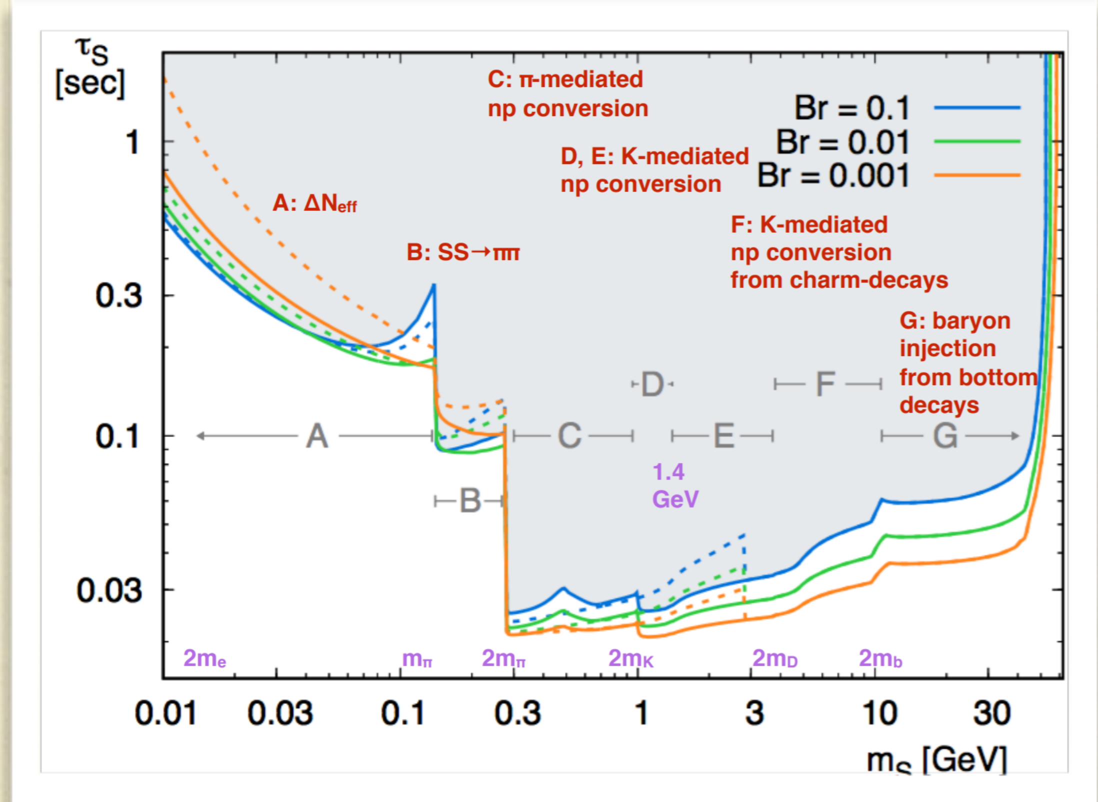


1. Disc + first level OR logic
   a. TOP
   b. BOTTOM
2. Second level OR + AND between TOP & BOTTOM
3. Prescaler
4. Delay boxes
5. OR for 4 triggers
6. Controller
7. TDC
8. ADC
9. Input Register

6

MATHUSLA

- A recent paper [A. Fradette and M. Pospelov, arXiv:1706.01920v1] examines the BBN lifetime bound on lifetimes of long-lived particles in the context of constraints on a scalar model coupled through the Higgs portal, where the production occurs via $h \rightarrow SS$, where the decay is induced by the small mixing angle of the Higgs field h and scalar S.



- For $m_S > m_\pi$ the lifetime $\tau <$ 0.1 s.
- Conclusion does not depend strongly on $BR(h \rightarrow SS)$

MATHUSLA White Paper - Organisation

1. Foreword
2. Introduction
3. Summary of MATHUSLA experiment
4. Letters of Support
5. LLPs at the LHC and MATHUSLA
6. Theory Motivation for ULLPs: Naturalness
7. Theory Motivation for ULLPs: Dark Matter
8. Theory Motivation for ULLPs: Baryogenesis
9. Theory Motivation for ULLPs: Neutrinos
10. Theory Motivation for ULLPs: Bottom-Up Considerations
11. Signatures
12. Cosmic Ray Physics prospects with MATHUSLA
13. Conclusions