Explore the Lifetime Frontiers with MATHUSLA

Cristiano Alpigiani

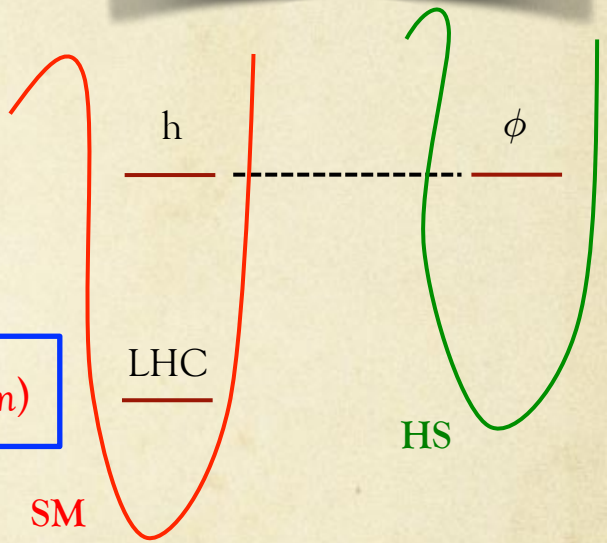
on behalf of the MATHUSLA Collaboration

28th July 2017

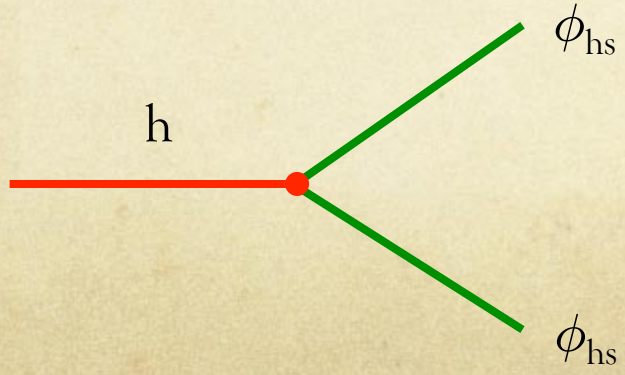
LPC @ Fermilab

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 $\mathcal{O}(m/km)$

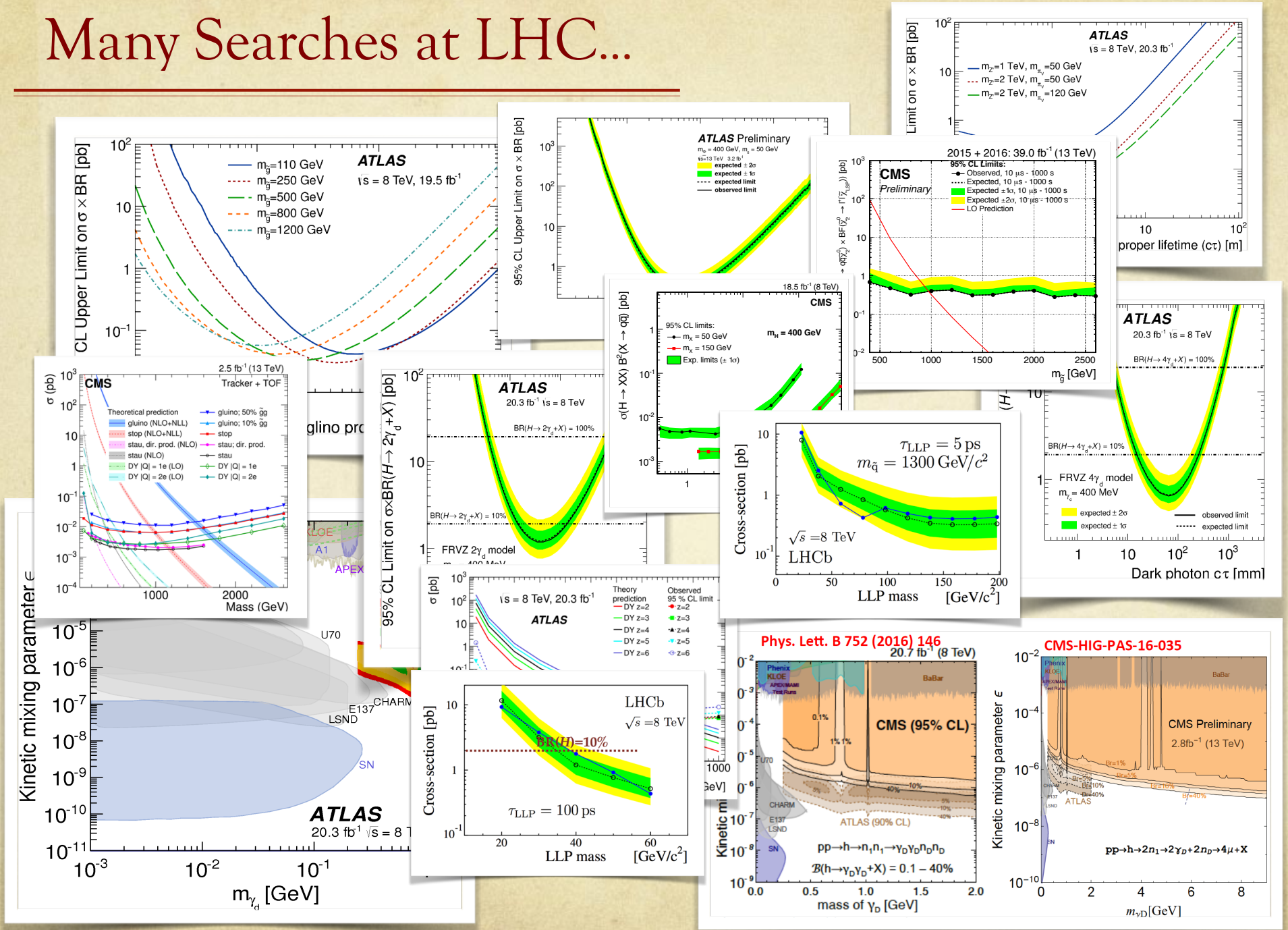


The mixing of Higgs with HS results in a Higgs like particle decaying into LLPs:

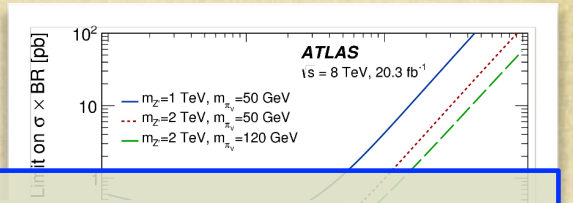
small coupling → long lifetimes [Phys. Lett. B6512 374-379, 2007]

~ 10^8 Higgs boson @ HL-LHC

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 → MAssive **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 x 10^8** Higgs boson produced
- Observed decays:

$$N_{\text{obs}} \sim N_h \cdot \text{Br}(h \to \text{ULLP} \to \text{SM}) \cdot \epsilon_{\text{geometric}} \cdot \frac{L}{bc\tau}$$

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**

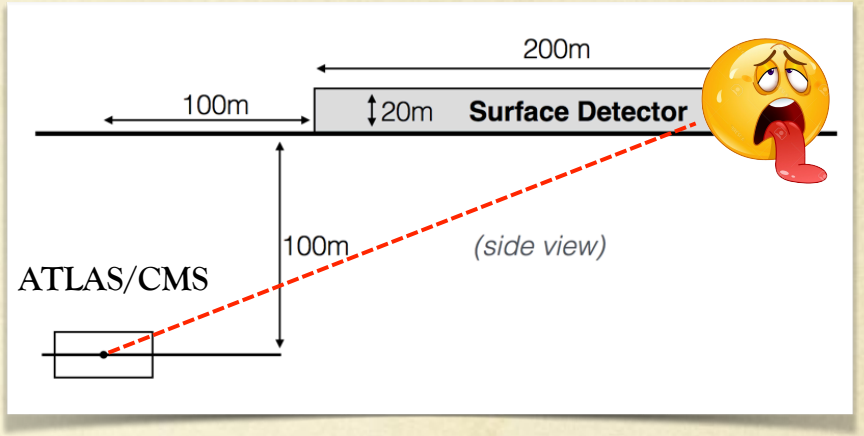
$$L \sim (20\text{ m}) \left(\frac{b}{3}\right) \left(\frac{0.1}{\epsilon_{\text{geometric}}}\right) \frac{0.3}{\text{Br}(h \to \text{ULLP})}$$

MATHUSLA

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

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

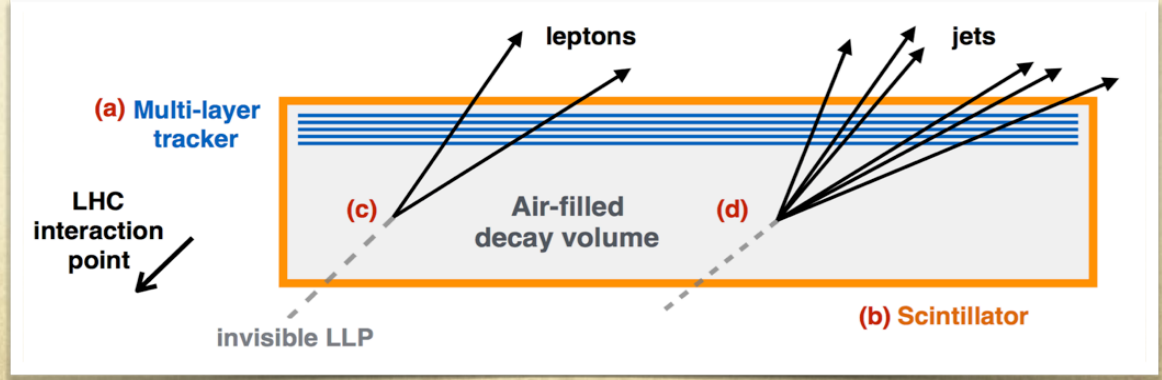
- Large area **surface detector (200 x 200 m^2)** above an LHC p-p IP dedicated to detection of ultra long-lived particles
- Air decay volume with **tracking chambers surrounded by scintillators**



- **Need robust tracking**
- **Excellent background rejection**

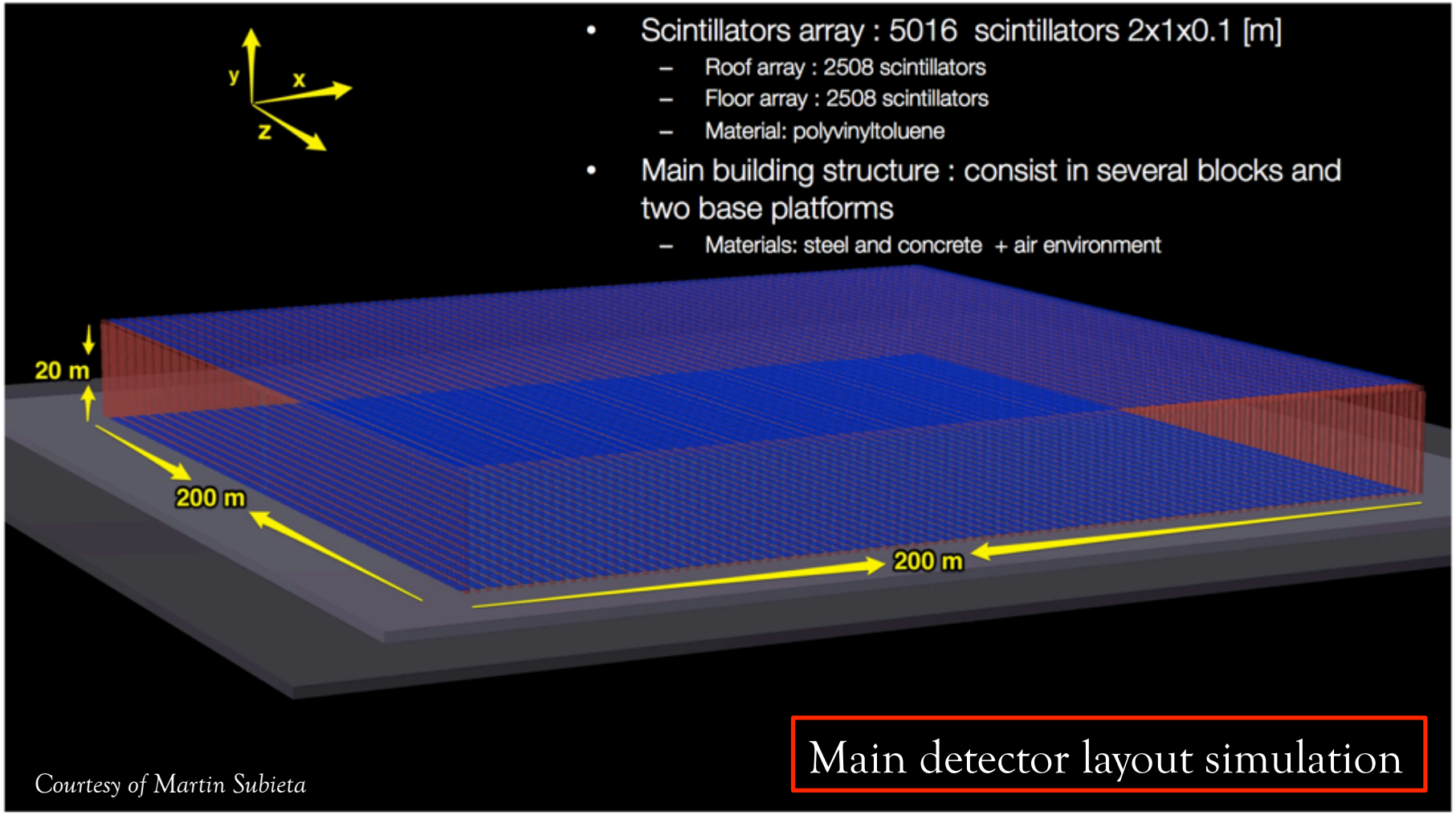
→ **RPCs** planes are an attractive choice (**good space and time resolution** for vertex reconstruction and cosmic ray rejection)

→ **Scintillator** planes for redundant background rejection - timing



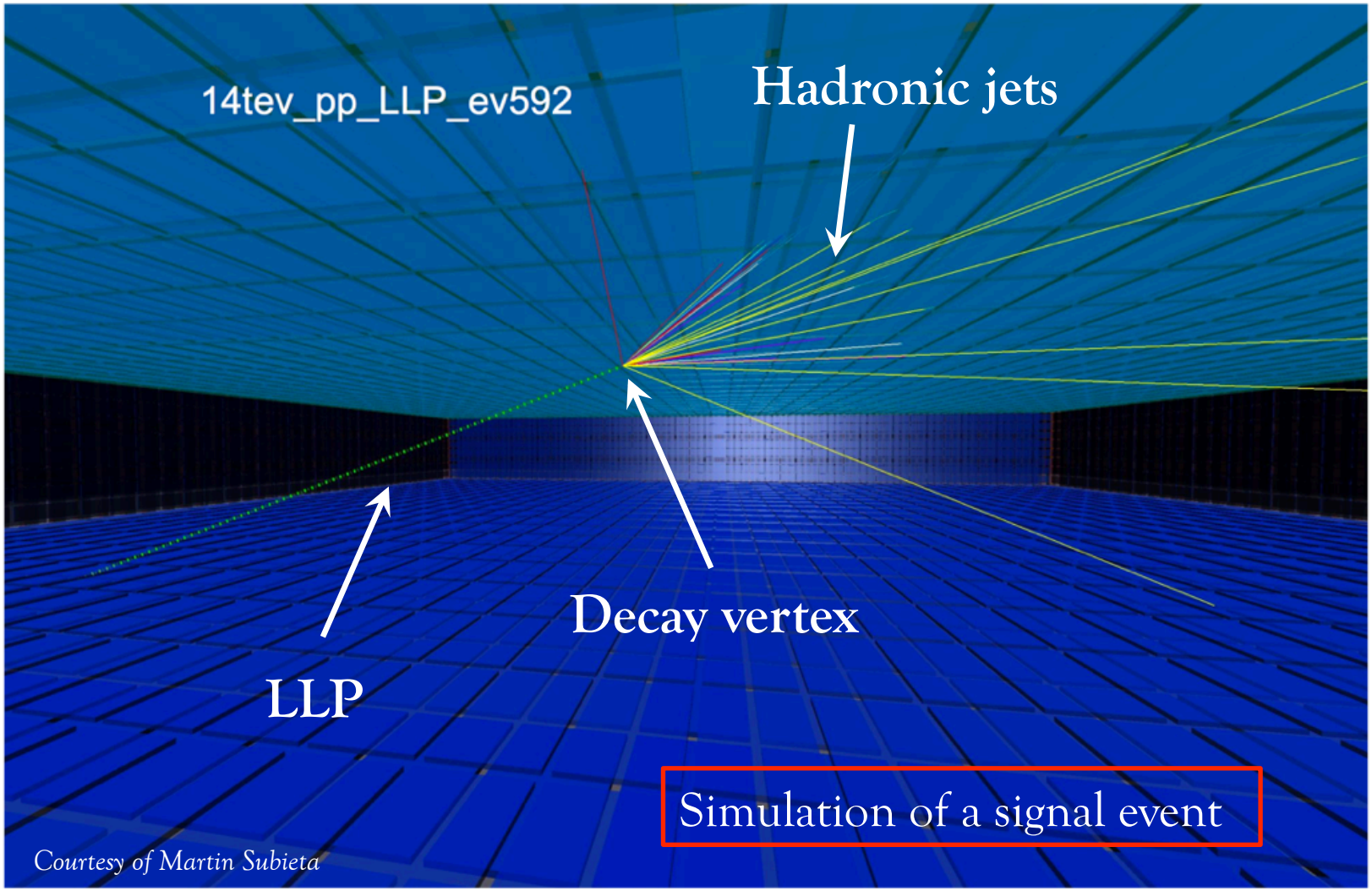
MATHUSLA – Main Detector

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



MATHUSLA – Signal Simulation

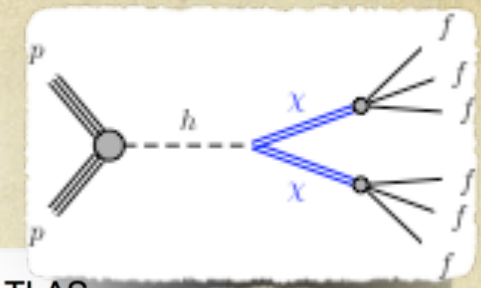
MATHUSLA detector → **MA**ssive **T**iming **H**odoscope for **U**ltra **S**table neutra**L** p**A**rticles

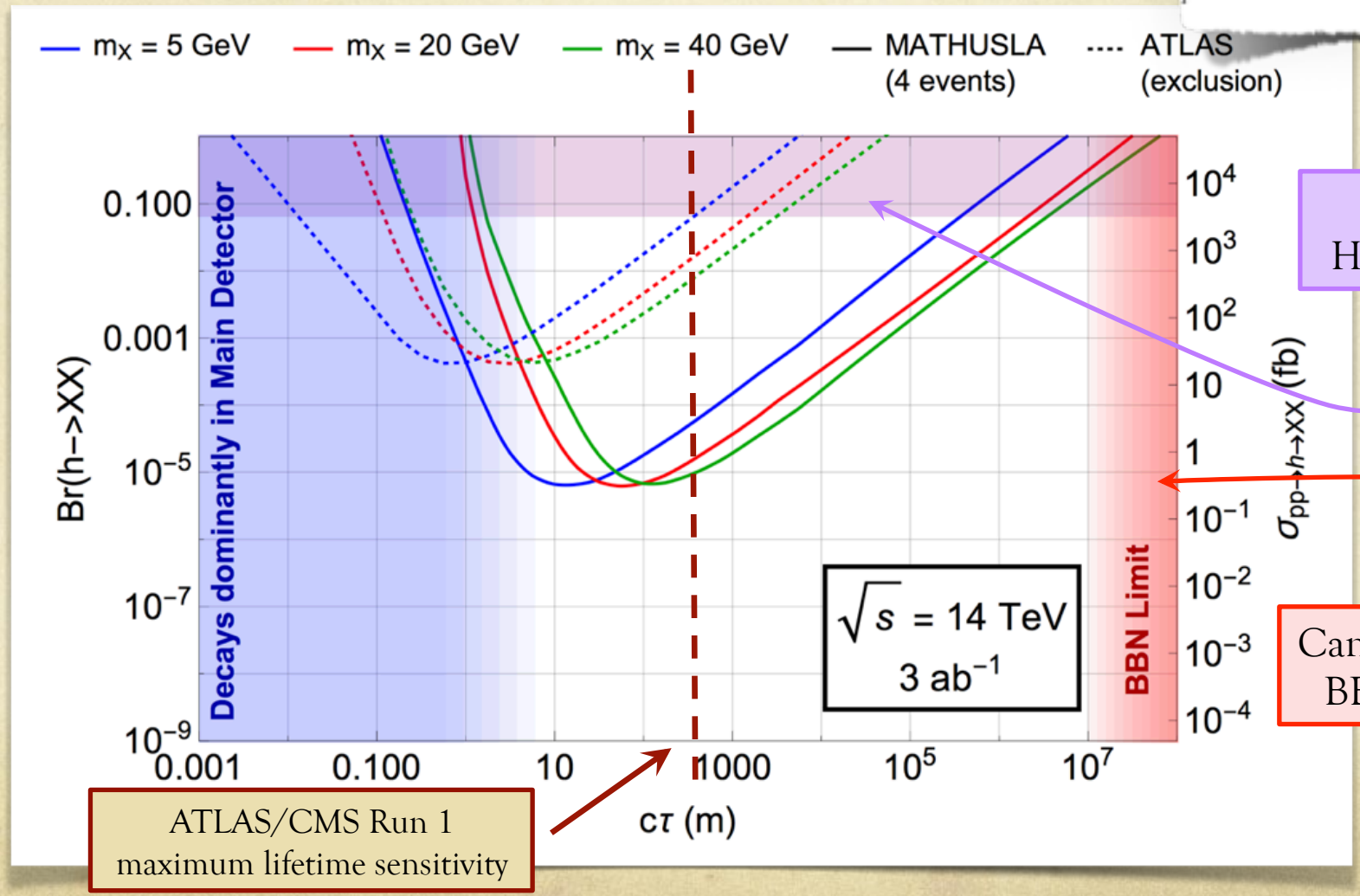


HL-LHC Sensitivity Estimate

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





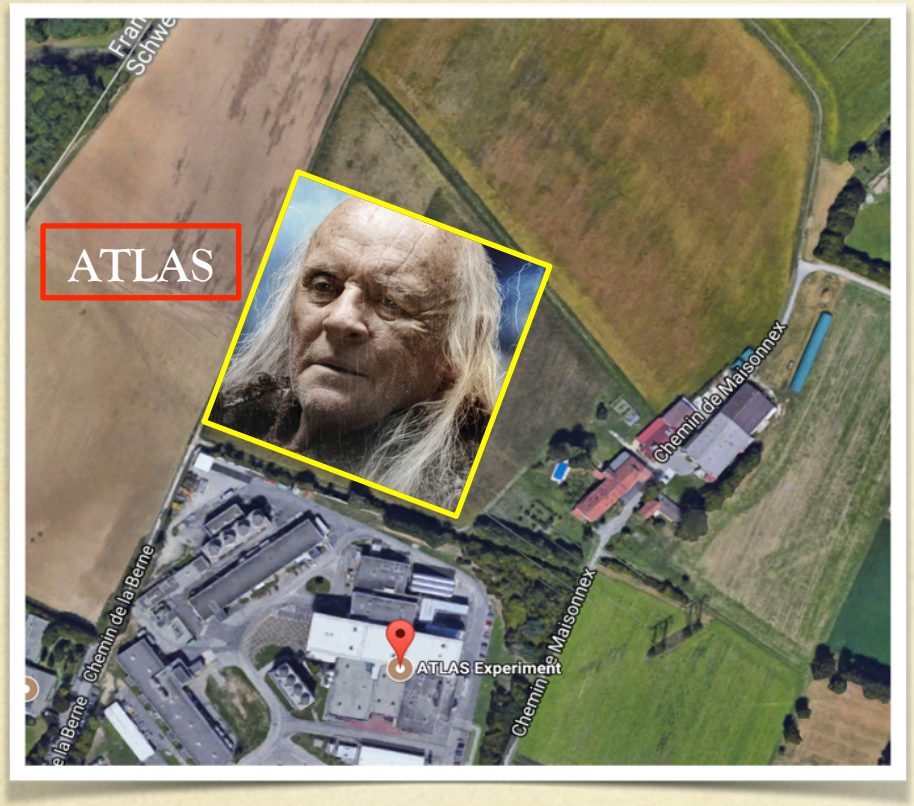
h → inv HL-LH limit

Can approach BBN limit!

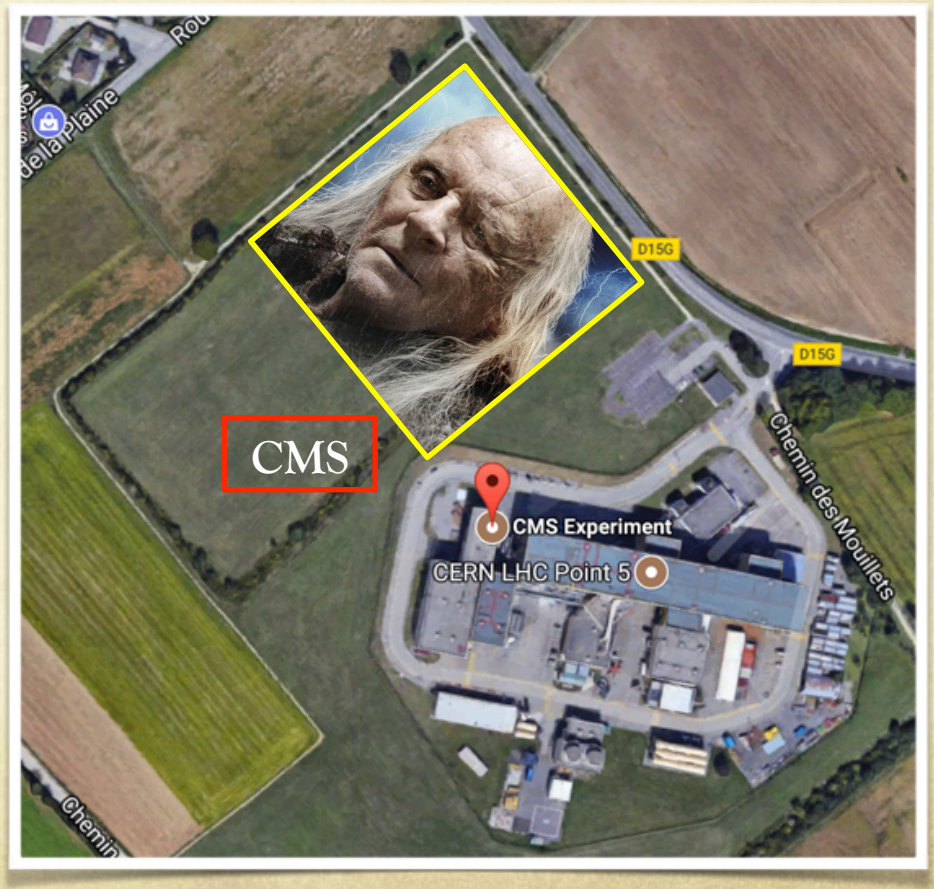
ATLAS/CMS Run 1 maximum lifetime sensitivity

Where MATHUSLA could be located?

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

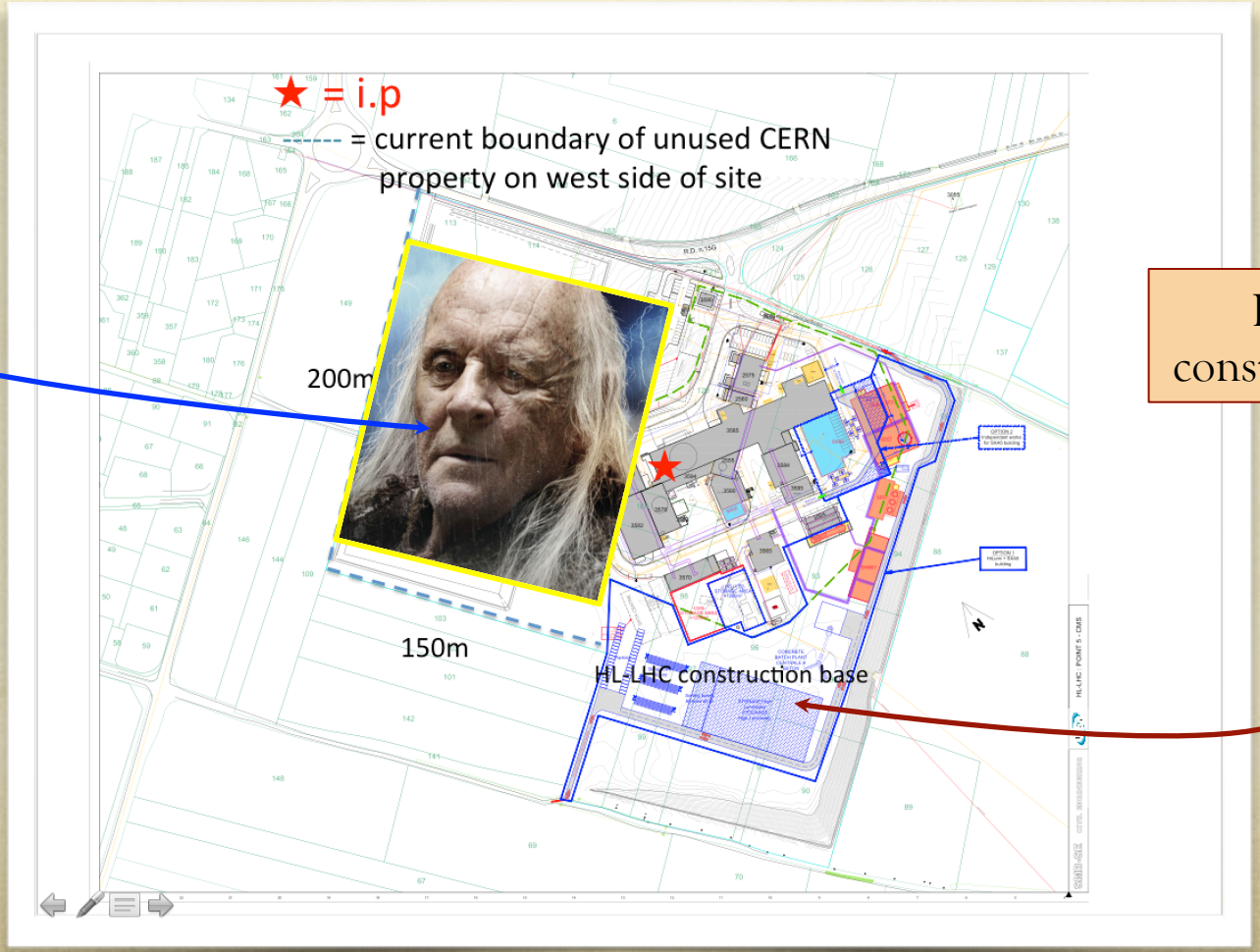


MATHUSLA could be located above either ATLAS (P1) or CMS (P2)



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

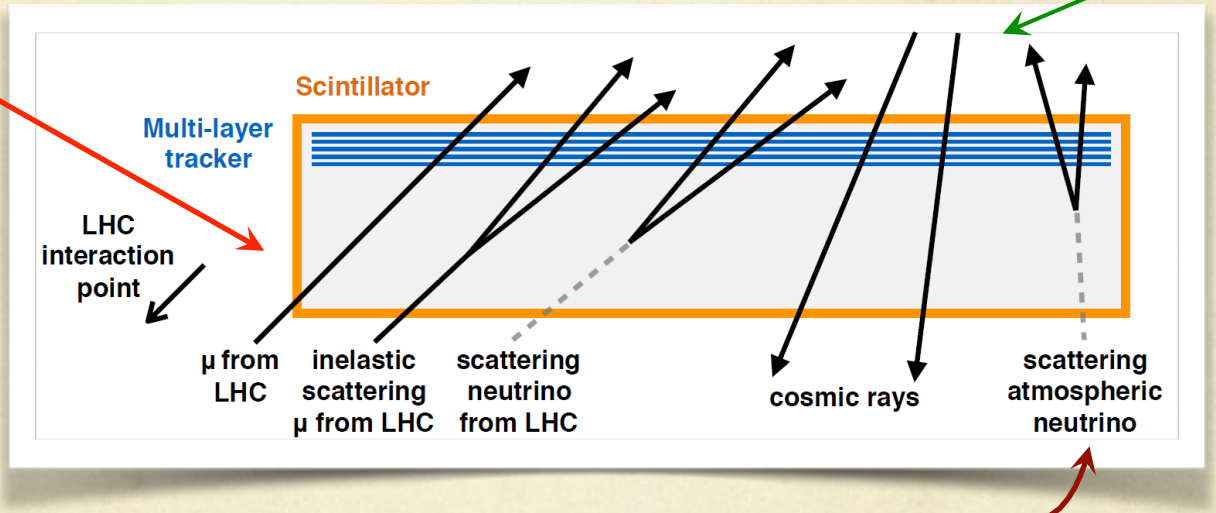
MATHUSLA - Backgrounds

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



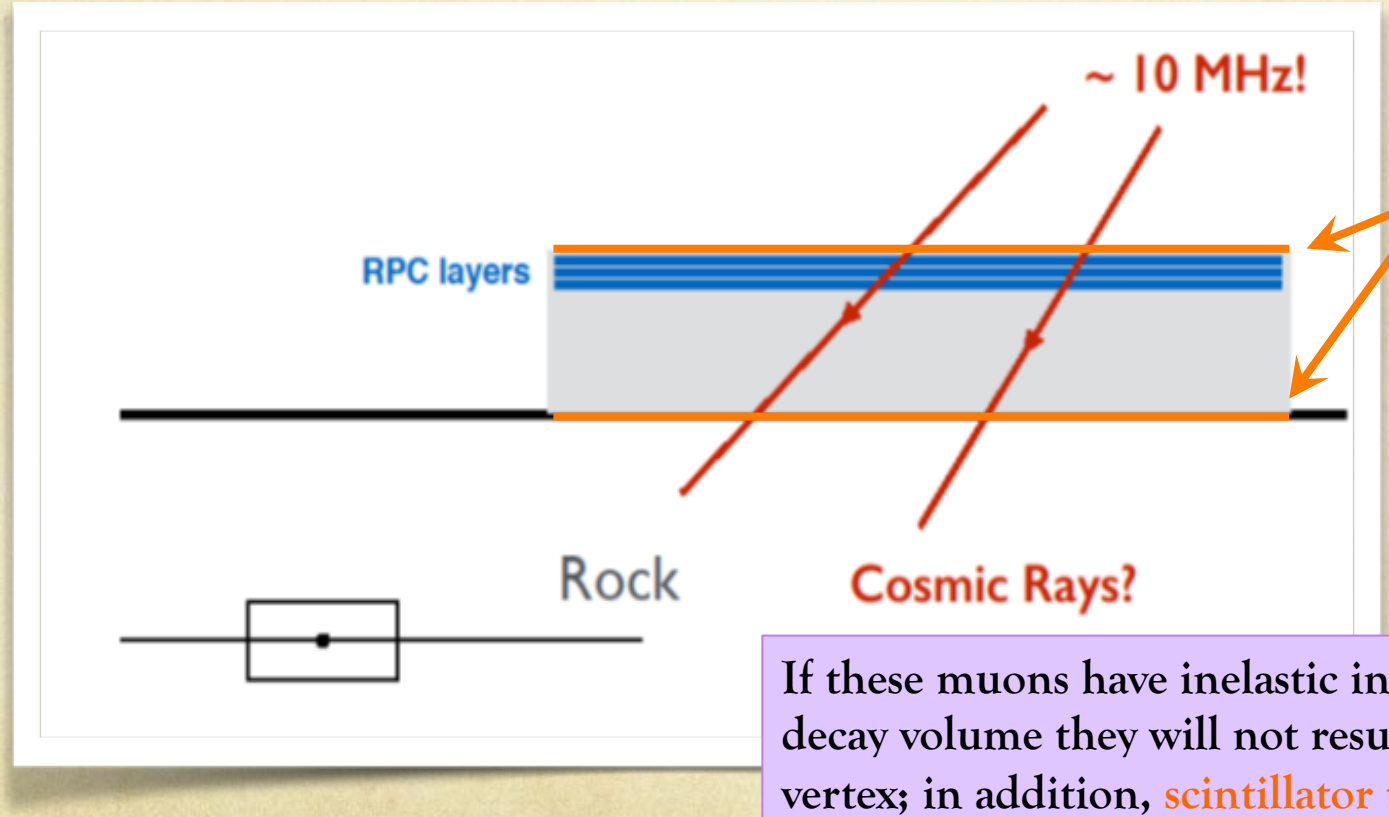
- Upward atmospheric neutrinos that interact in air decay volume
  - ✓ Estimate Low rate ~ 10-100 per year above 300 MeV
  - ✓ Most have low momentum proton - reject with time of flight

Goal is a background-free MATHUSLA!

MATHUSLA – Cosmic Muon Background

No LHC Background, BUT…

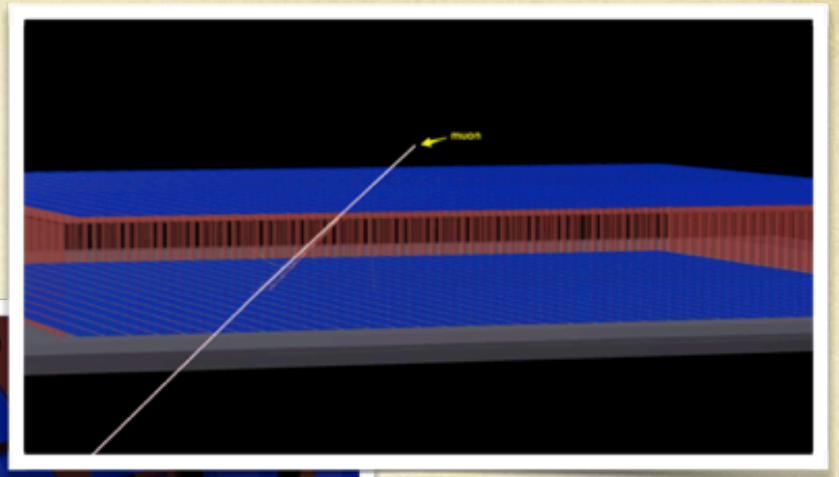
- Cosmic muon rate or order 10 MHz (200 m^2)
- Scintillators 1.5 ns timing resolution in 20 m have $\Delta t \approx 70$ ns top to bottom

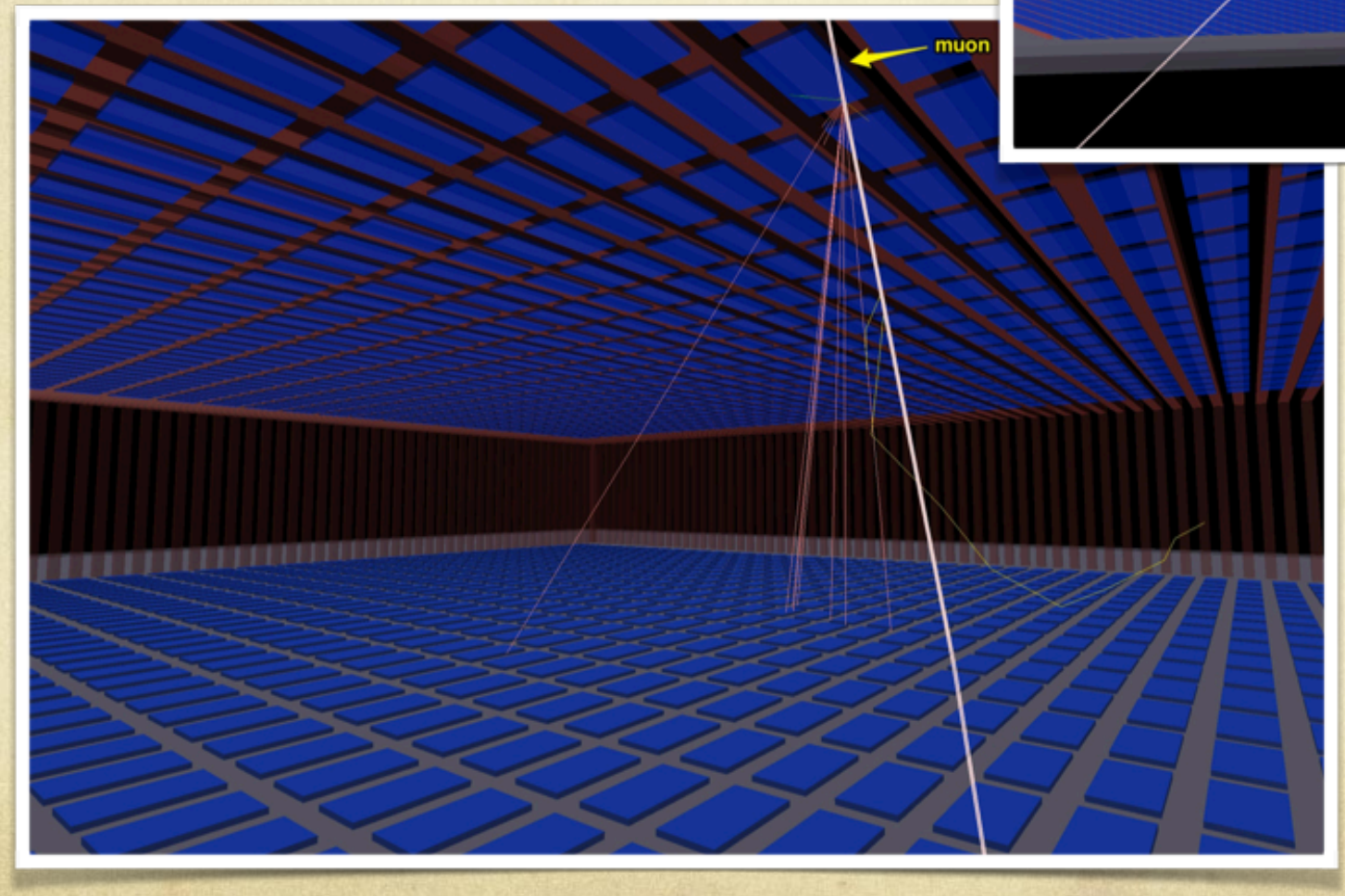


scintillators 1.5 ns time resolution

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

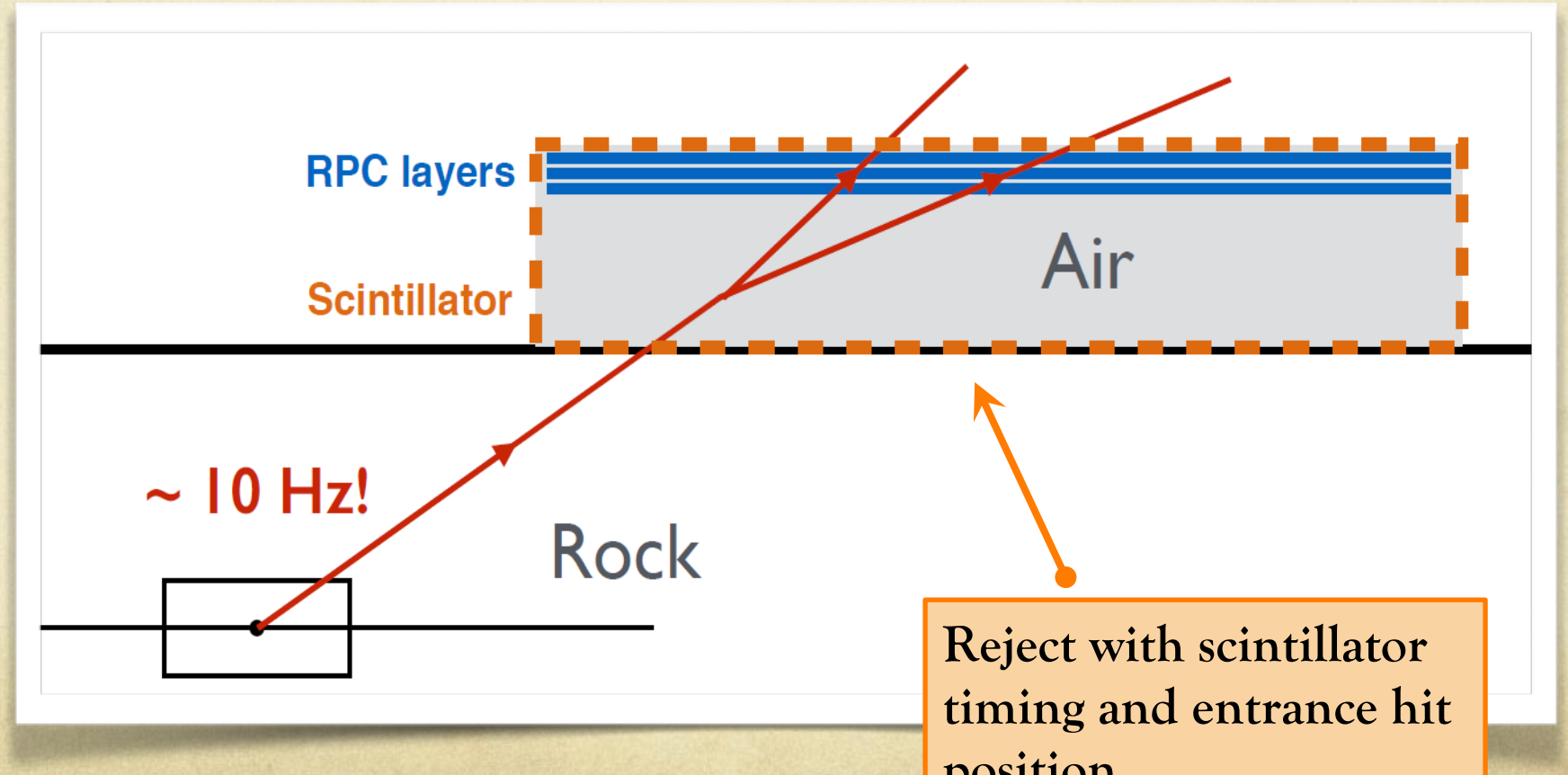




MATHUSLA – LHC Muon Background

No LHC Background, BUT…

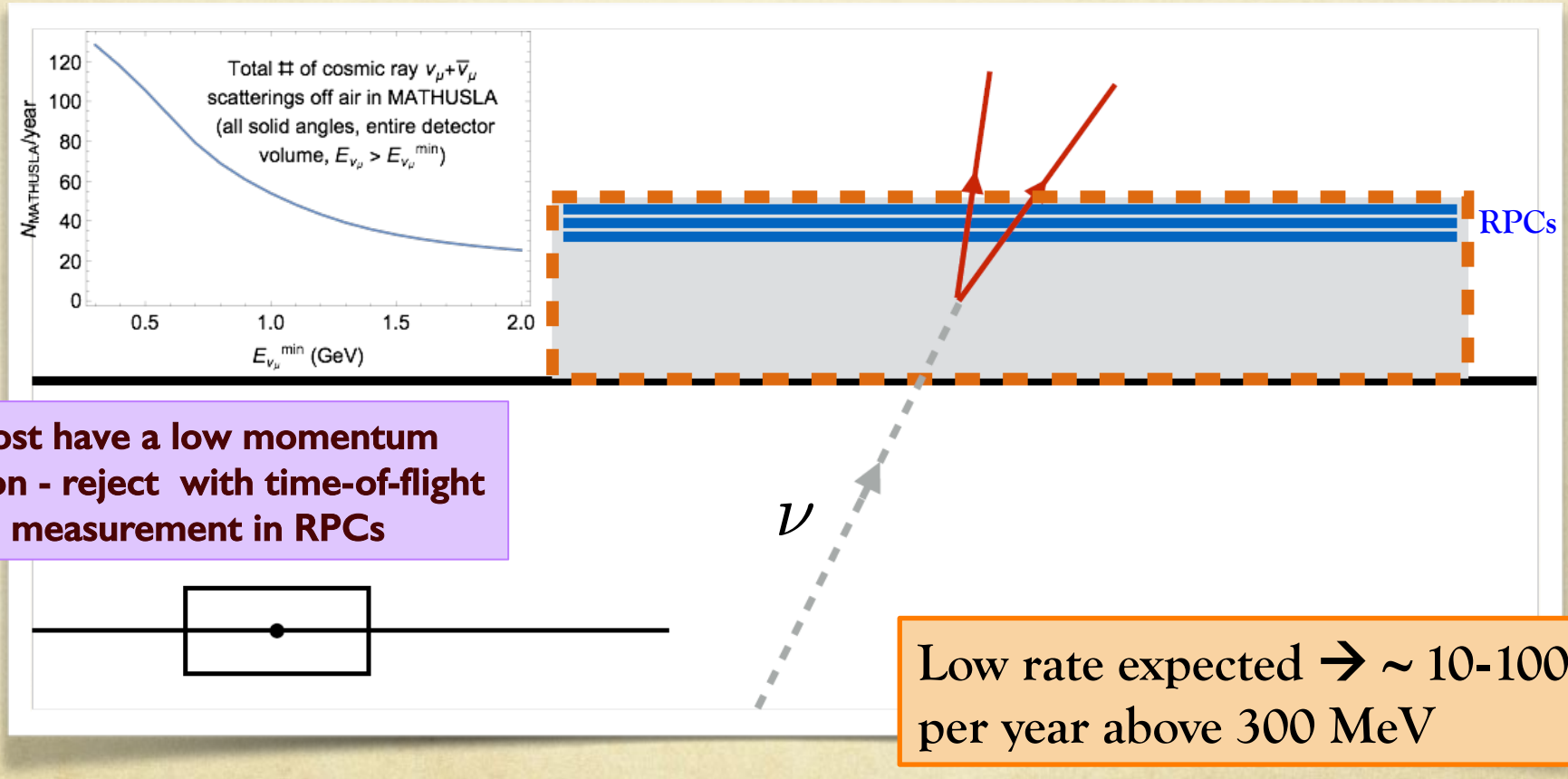
- Upward going muons from LHC with inelastic interaction (10 Hz)
- Scintillators 1.5 ns timing resolution in 20 m have $\Delta t \approx 70$ ns top to bottom



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

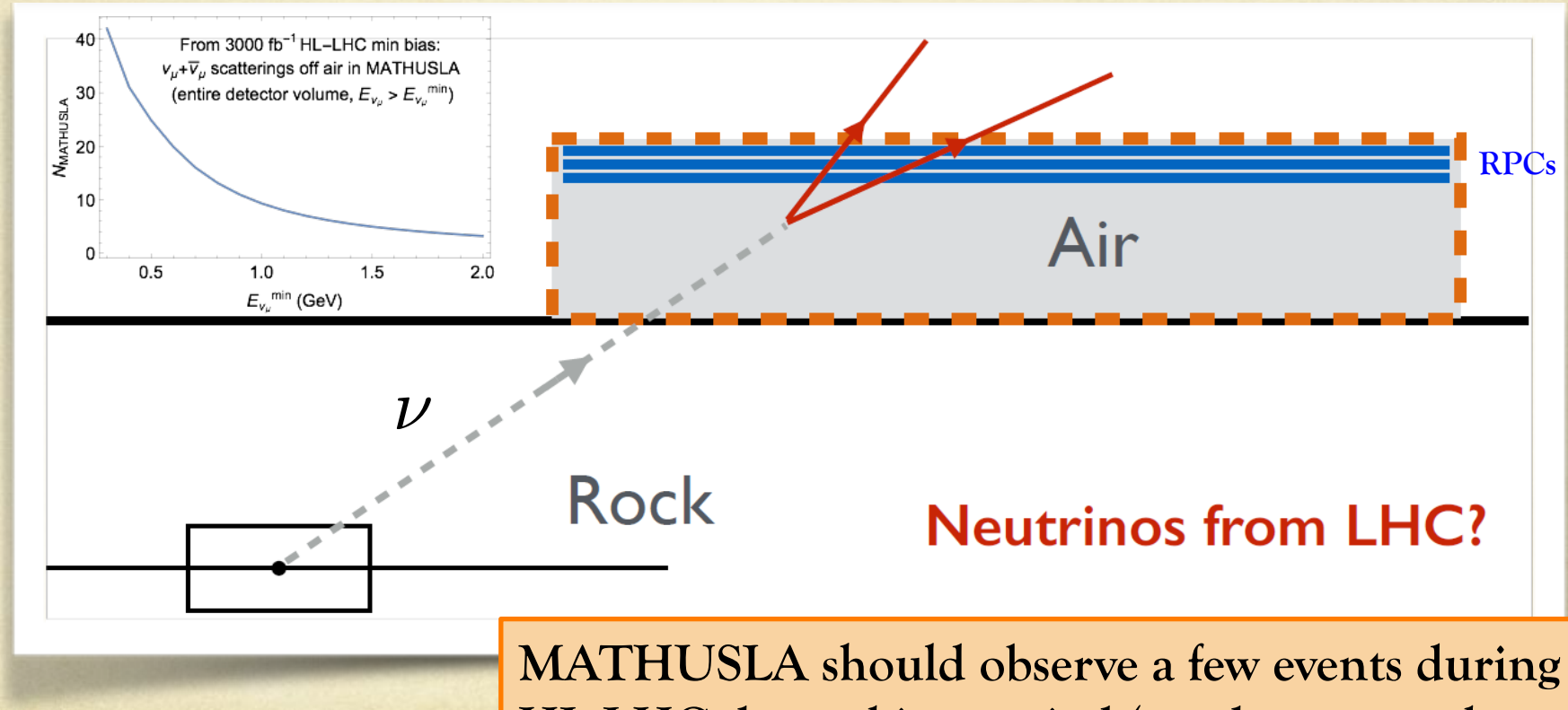
Low rate expected → ~ 10-100 per year above 300 MeV

- 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**

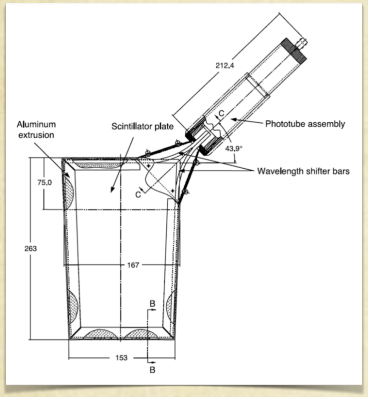
…we need a

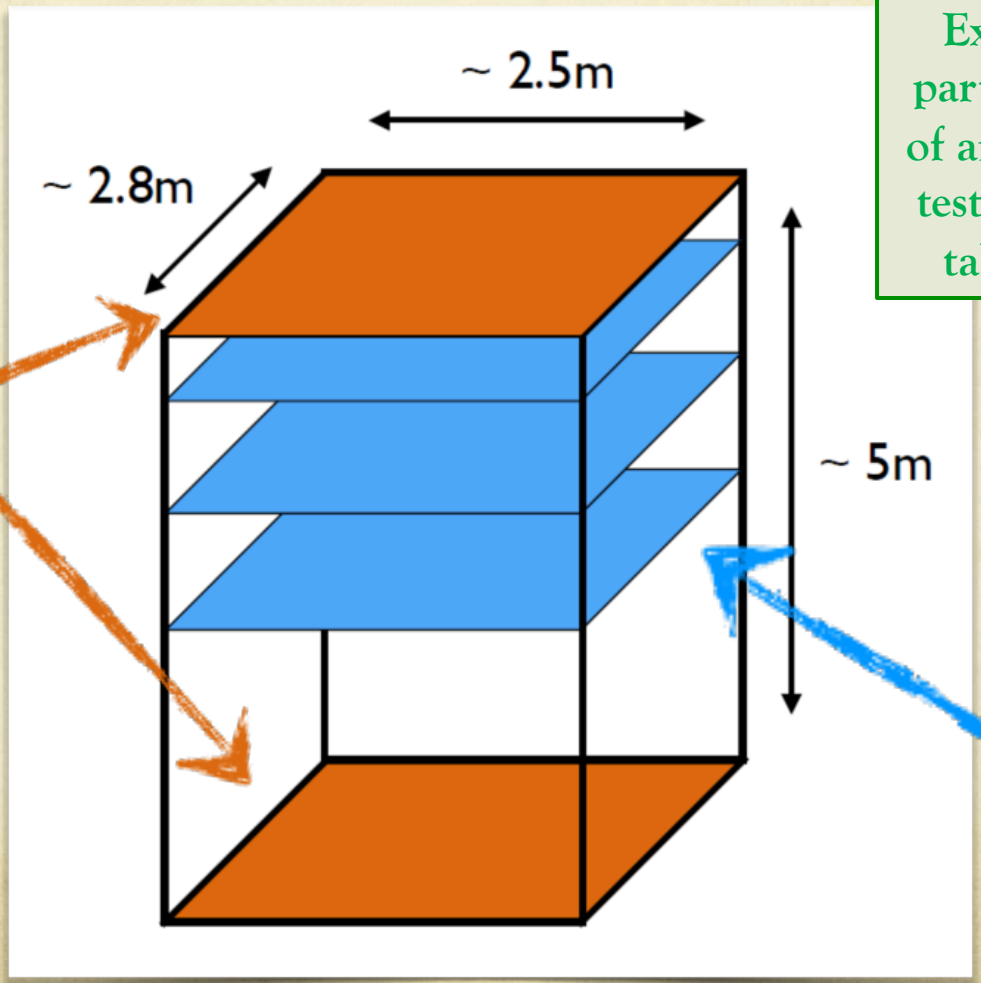
TEST MODULE

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



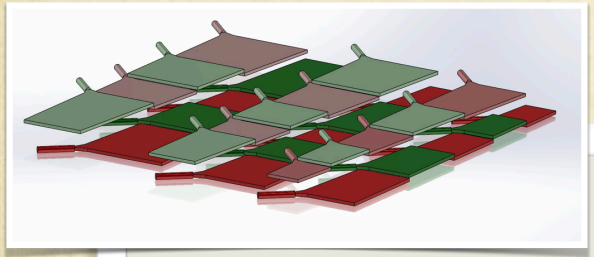


Excellent for students participation at all stages of an experiment: design, test components, install, take data and analysis

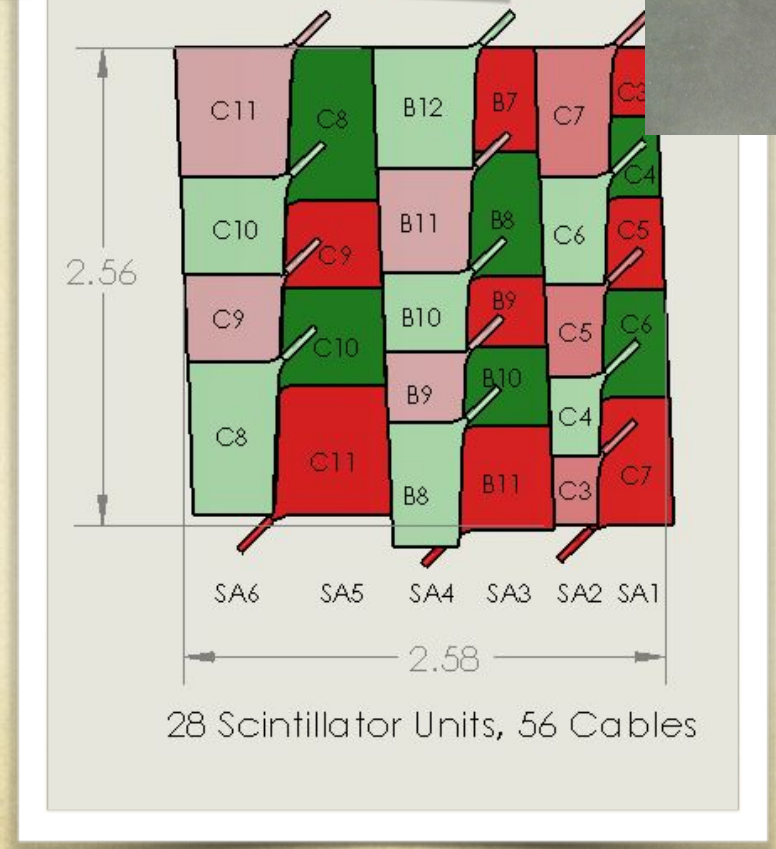
3 layers of RPCs provided by University of Tor Vergata (Rome) by Rinaldo Santonico

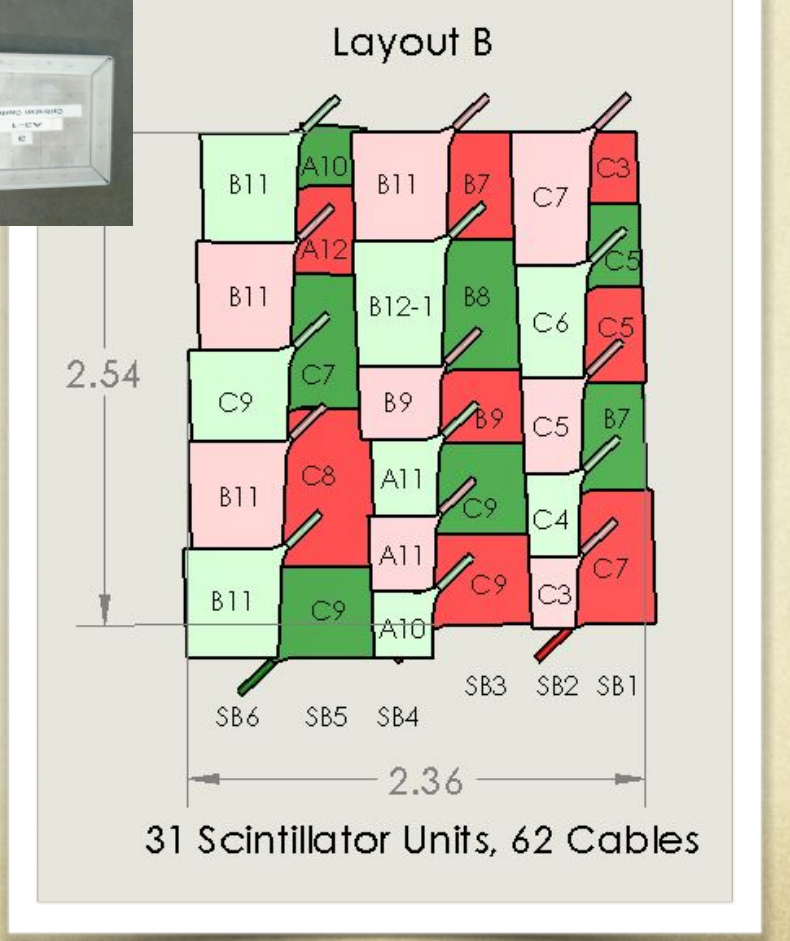
MATHUSLA Test Module: Scintillator Planes

- Possible layout for the 2 scintillator planes



D0 forward MUON Trigger scintillator





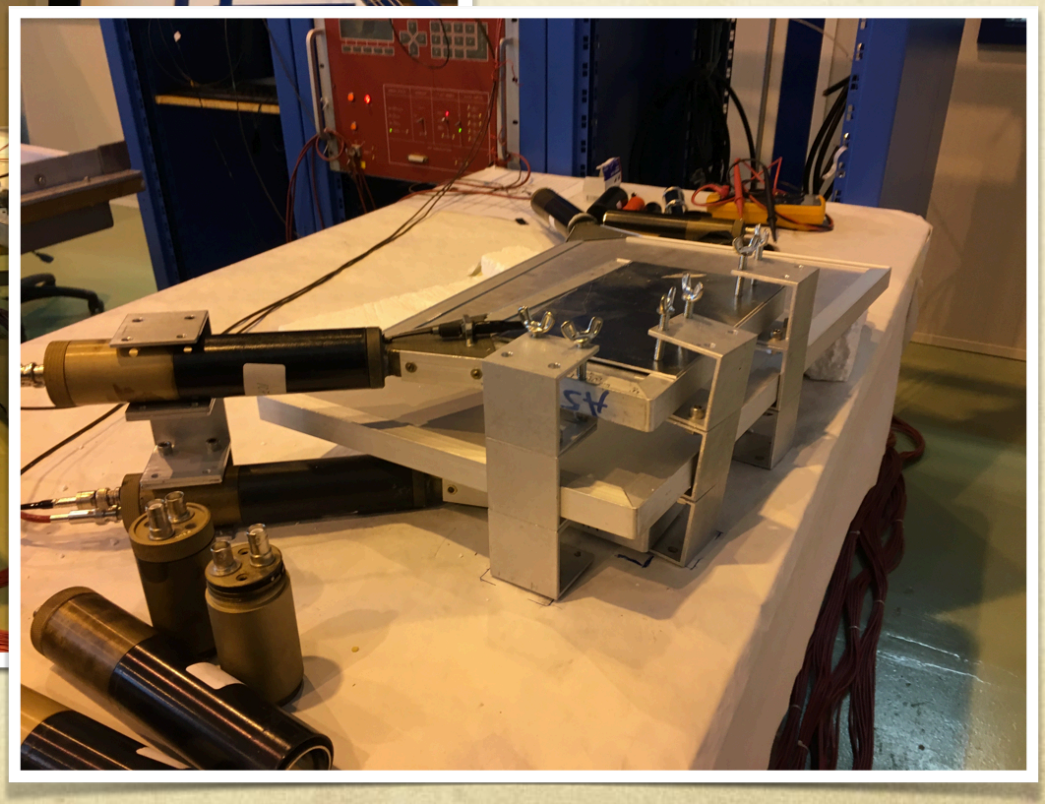
MATHUSLA Test Module Status

- Scintillators at CERN and undergoing certification to establish HV setting, noise rates and efficiency (**expected to finish next week**)
  - ✓ 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 August
  - ✓ **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 Planes

- On-going commissioning @ CERN in building 175



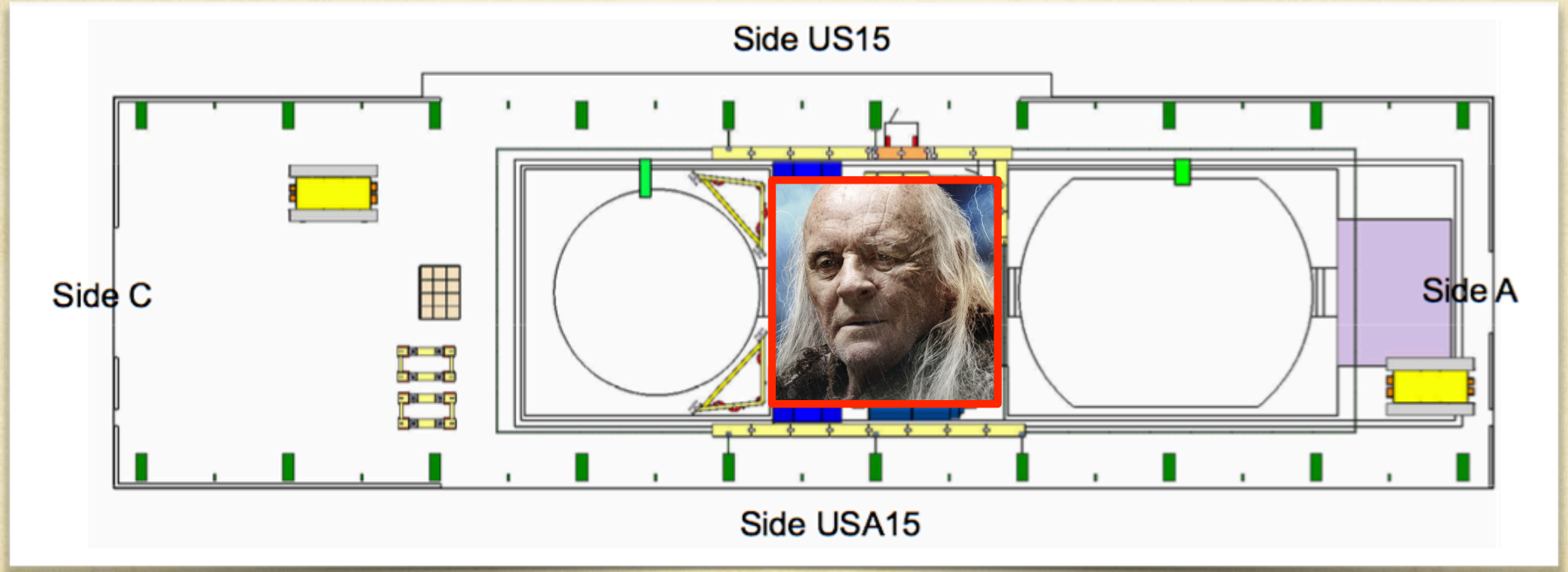
MATHUSLA Test Module: RPCs

- RPCs from Tor Vergata Rome

Pictures from Rinaldo Santonico

Installation in ATLAS P1

- 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

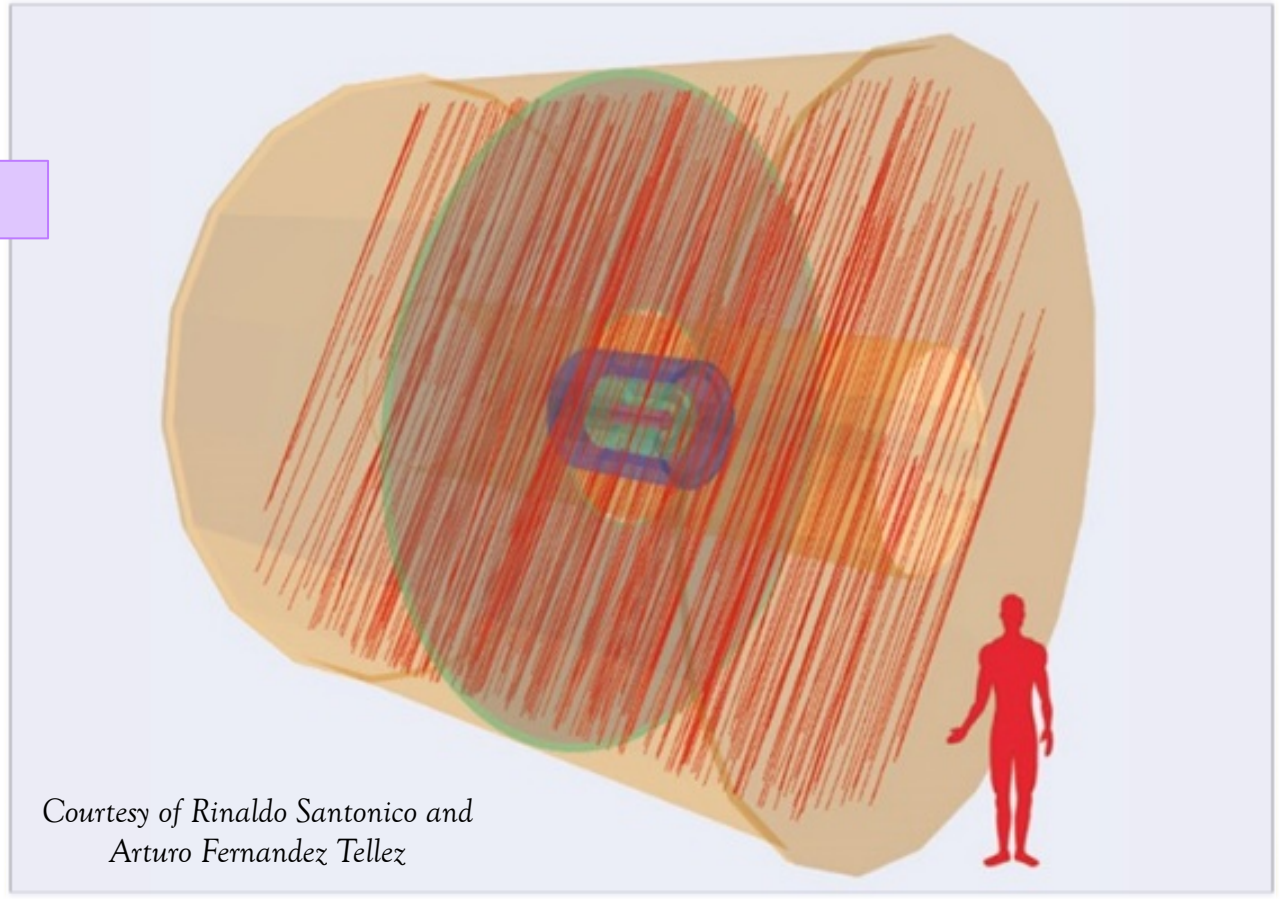


❖ Measurement fundamental for future background simulations!

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

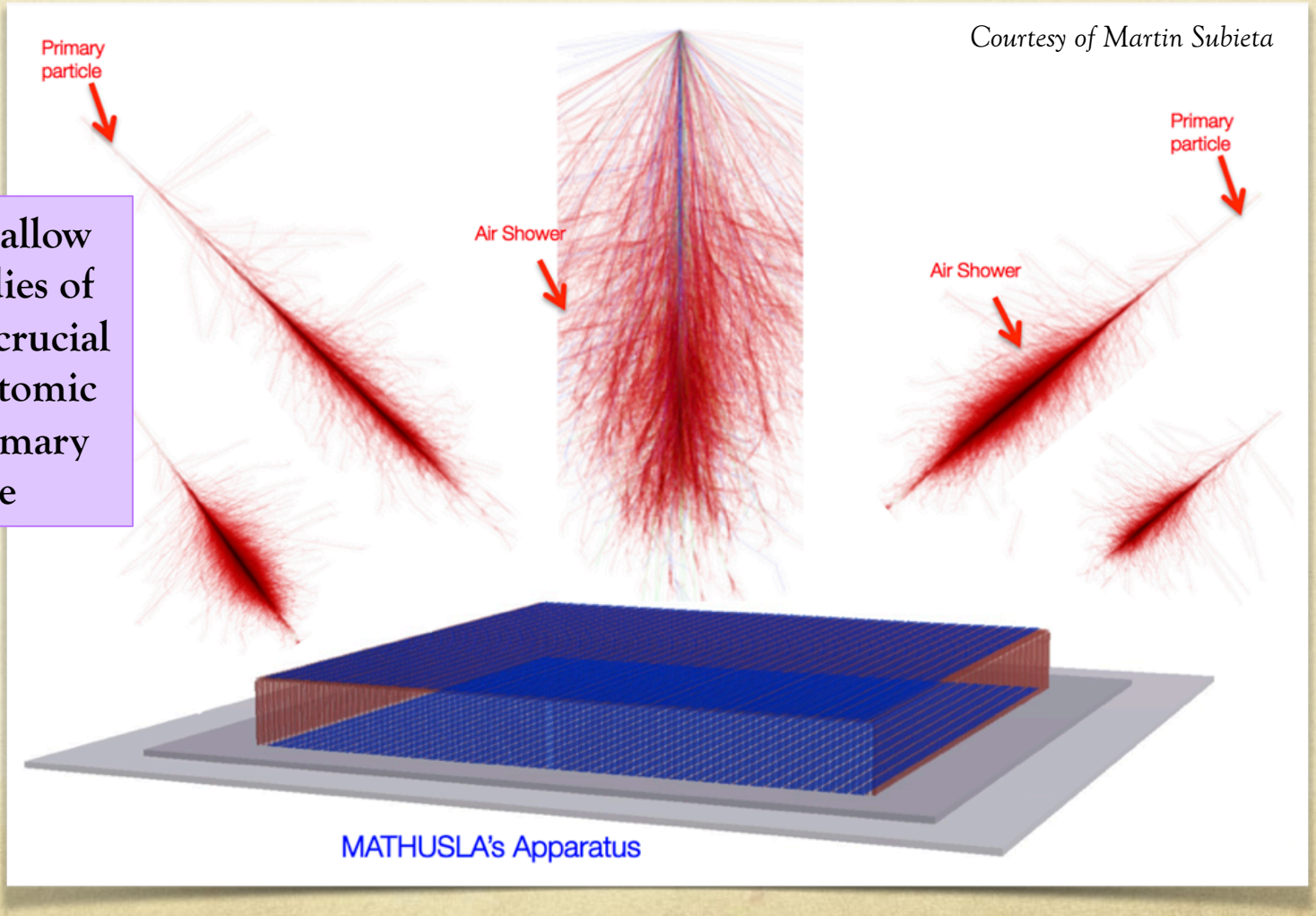


Courtesy of Rinaldo Santonico and Arturo Fernandez Tellez

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

University of Washington Seattle, FNAL, Tel Aviv University, University of Michigan, University of Maryland, Autonomous University of Puebla, Rutgers State University of New Jersey, SLAC, Università di Tor Vergata, Università della Calabria, Sapienza Università di Roma and CERN

Mario Rodriguez Cahuantzi	mario.rodriguez.cahuantzi@cern.ch	Autonomous University of Puebla
Martin Hentschinski	martin.hentschinski@gmail.com	Autonomous University of Puebla
Mario Ivan Martinez Hernandez	Mario.Martinez.Hernandez@cern.ch	Autonomous University of Puebla
Guillermo Tejeda Munoz	Guillermo.Tejeda.Munoz@cern.ch	Autonomous University of Puebla
Arturo Fernandez Tellez	Arturo.Fernandez.Tellez@cern.ch	Autonomous University of Puebla
Martin Alfonso Subieta Vasquez	martin.alfonso.subieta.vasquez@cern.ch	Autonomous University of Puebla
John Paul Chou	john.paul.chou@cern.ch	Rutgers, State University of New Jersey
Luke Kasper	lukekasper25@gmail.com	Rutgers, State University of New Jersey
Amitabh Lath	Amitabh.Lath@cern.ch	Rutgers, State University of New Jersey
Steffie Ann Thayil	steffie.ann.thayil@cern.ch	Rutgers, State University of New Jersey
Charlie Young	young@slac.stanford.edu	SLAC
Robert Arthur Mina	robmina@stanford.edu	SLAC
Paolo Camarri	paolo.camarri@cern.ch	Università di Tor Vergata
Roberto Cardarelli	roberto.cardarelli@roma2.infn.it	Università di Tor Vergata
Rinaldo Santonico	santonic@roma2.infn.it	Università di Tor Vergata
Barbara Liberti	barbara.liberti@roma2.infn.it	Università di Tor Vergata
Roberto Iuppa	roberto.iuppa@cern.ch	Università di Tor Vergata
Luca Pizzimento	luca.pizzimento@cern.ch	Università di Tor Vergata
Antonio Policicchio	Antonio.Policicchio@cern.ch	Università della Calabria
Marco Schioppa	Marco.Schioppa@cern.ch	Università della Calabria
Stefano Giagu	Stefano.Giagu@cern.ch	Sapienza Università di Roma
Cristiano Sebastian	Cristiano.Sebastiani@cern.ch	Sapienza Università di Roma
Austin Ball	Austin.Ball@cern.ch	CERN
Ce Zhang	ce.zhang@cern.ch	CERN (Summer Student)

Giovanni Marsella	giovanni.marsella@cern.ch	INFN Lecce e Universita del Salento
Cristiano Alpigiani	Cristiano.Alpigiani@cern.ch	University of Washigton - Seattle
Akaxia Danae Cruz	a.cruz@cern.ch	University of Washigton - Seattle
Audrey Katherine Kvam	audrey.katherine.kvam@cern.ch	University of Washigton - Seattle
Henry Lubatti	lubatti@u.washington.edu	University of Washigton - Seattle
Mason Louis Proffitt	mason.louis.proffitt@cern.ch	University of Washigton - Seattle
Joseph Rothberg	Joseph.Rothberg@cern.ch	University of Washigton - Seattle
Rachel Christine Rosten	rachel.rosten@cern.ch	University of Washigton - Seattle
Gordon Watts	gwatts@uw.edu	University of Washigton - Seattle
Emma Torró Pastor	emma.torro.pastor@cern.ch	University of Washigton - Seattle
Nina Anikeeva	nina.anikeeva@gmail.com	University of Washigton - Seattle
Sunna Banerjee	Sunanda.Banerjee@cern.ch	Fermi National Accelerator Laboratory
Yan Benhammou	Yan.Benhammou@cern.ch	Tel Aviv University
Meny Ben Moshe	Menyb@post.tau.ac.il	Tel Aviv University
Tingting Cao	Tingting.cao@cern.ch	Tel Aviv University
Erez Etzion	Erez.Etzion@cern.ch	Tel Aviv University
Tamar Garbuz	tgarbuz137@gmail.com	Tel Aviv University
Gilad Mizrahi	giladmiz01@gmail.com	Tel Aviv University
Yiftah Silver	yiftahsi@gmail.com	Tel Aviv University
Abi Soffer	Abner.Soffer@cern.ch	Tel Aviv University
Dan Levin	dslevin@umich.edu	University of Michigan
David Curtin	david.r.curtin@gmail.com	University of Maryland
Andy Haas	Andy.haas@nyu.edu	New York University

MATHUSLA White Paper

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

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

Editors:
David Curtin[1], *Marco Drewes*[2], *Matthew McCullough*[3], *Patrick Meade*[4], *Rabindra Mohapatra*[1], *Michele Papucci*[5], *Jessie Shelton*[6], *Brian Shuve*[7]

Contributors: B. Batell, Timothy Cohen, Nathaniel Craig, Csaba Csaki, Yanou Cui, Francesco D'Eramo, B. Dev, Keith Dienes, Marco Drewes, Rouven Essig, Jared Evans, Marco Farina, Thomas Flacke, Claudia Frugiuele, Elina Fuchs, Dmitry Gorbunov, M. Graesser, Peter Graham, C. Hagedorn, Lawrence Hall, Philip Harris, J. Helo, M. Hirsch, Yonit Hochberg, Anson Hook, A. Ibarra, Seyda Ipek, Sunghoon Jung, S. King, Simon Knapen, Joachim Kopp, Gordan Krnjaic, Eric Kuflik, Salvator Lombardo, Rabindra Mohapatra, S. Moretti, Duccio Pappadopulo, Gilad Perez, David Pinner, Maxim Pospelov, Mattthew Reece, Rick S., Brian Shuve, Daniel Stolarski, Brooks Thomas, Yuhsin Tsai, Brock Tweedie, Stephen West, Y. Zhang, Kathryn Zurek, ...

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

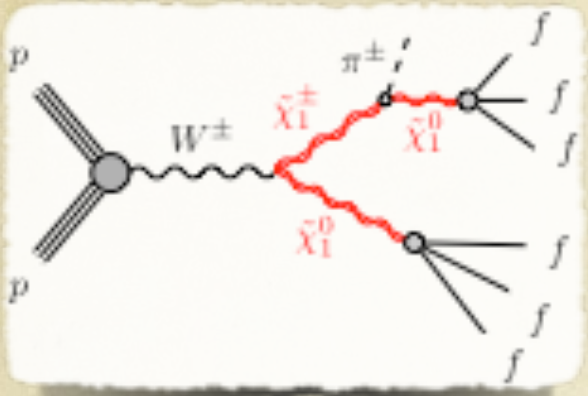
Signature Space of Displaced Vertex Searches

- 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 ⇒ generic searches

Neutral Long-lived particles

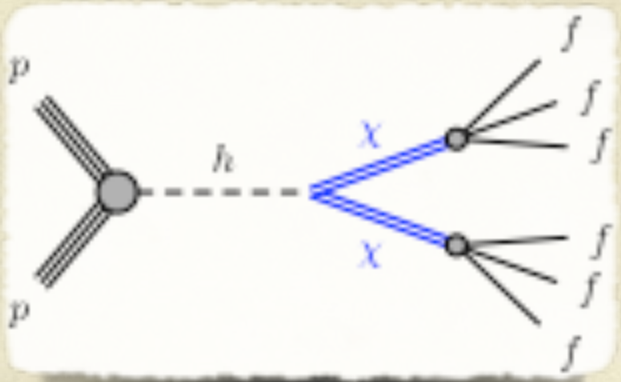
- Neutral LLPs lead to displaced decays with no track connecting to the IP, a distinguishing signature
  - **SM particles predominantly yield prompt decays (good news)**
  - **SM cross sections very large (eg. QCD jets) (bad news)**
- To reduce SM backgrounds many Run 1 ATLAS searches required two identified 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-$c\tau$)
- ATLAS search strategy for displaced decays - based on signature driven triggers that are detector dependent

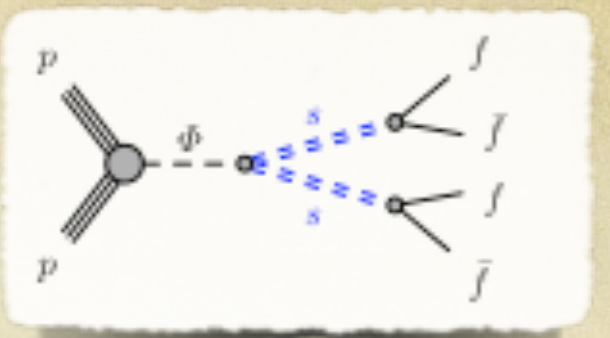
Some of the LLP Models



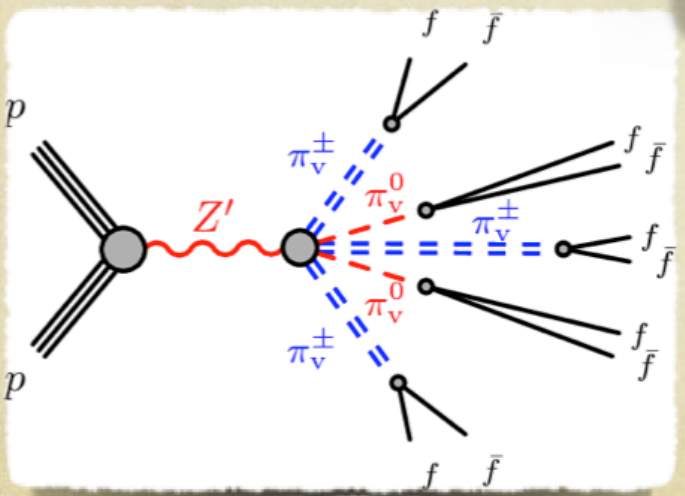
Baryogenesis
wino-like model

Baryogenesis
Higgs portal

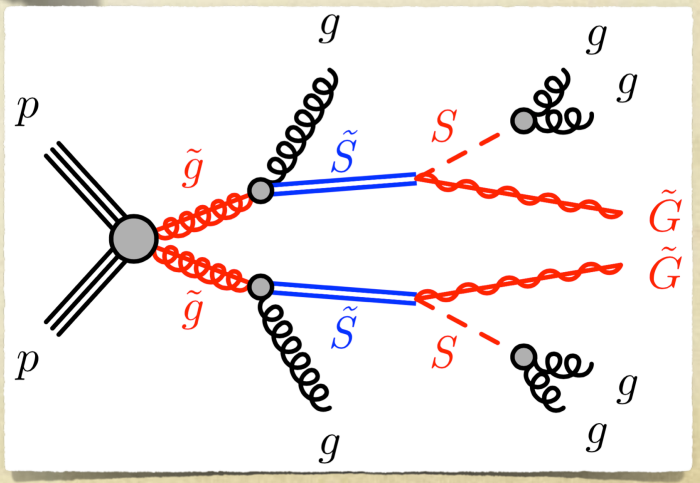




Low/high
mass bosons
to scalars



Z' models



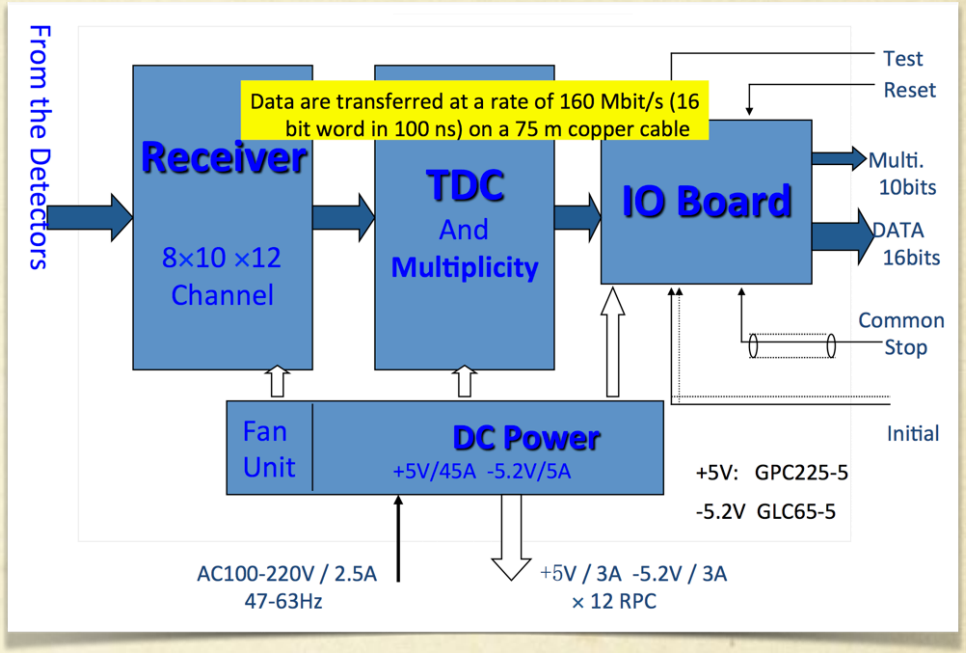
Stealth SUSY

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



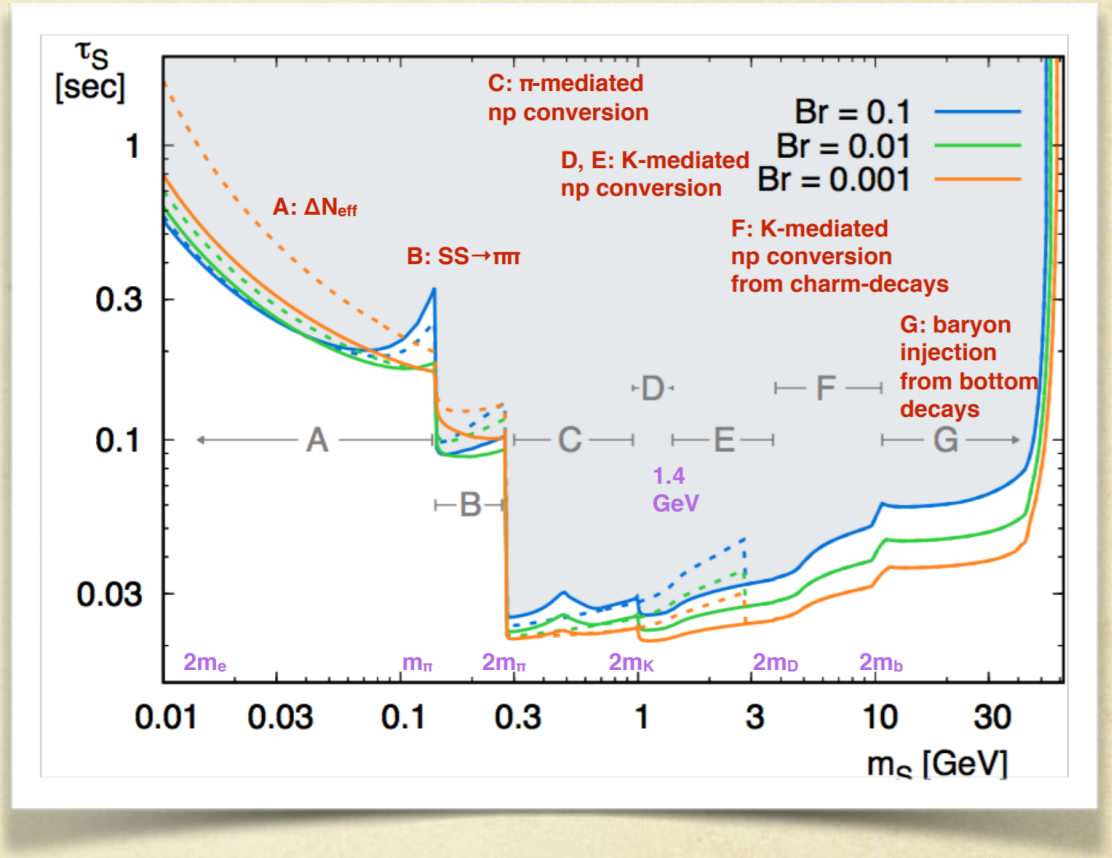
Test module trigger

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

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

MATHUSLA

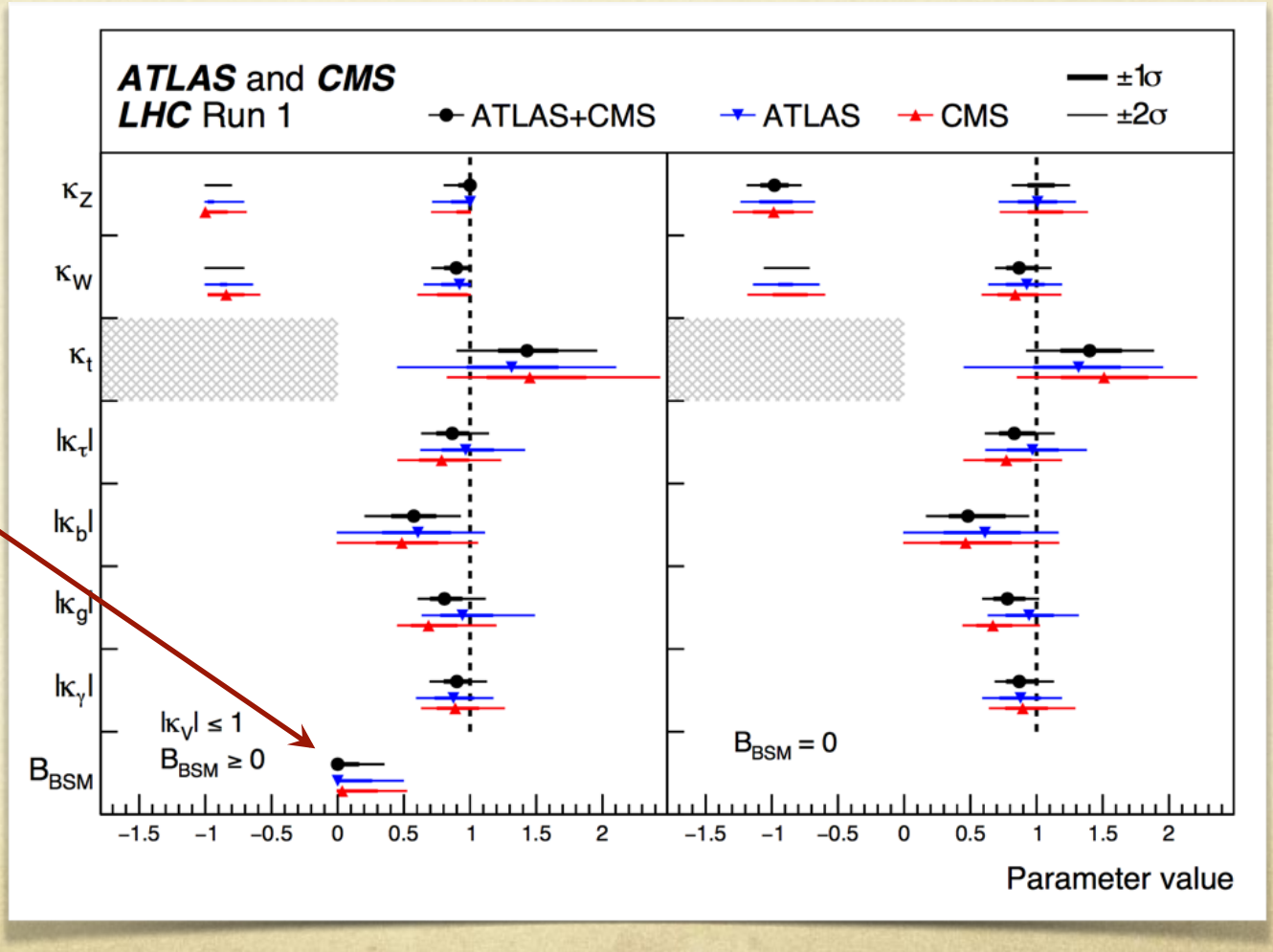
- A recent paper [A. Fradette and M. Pospelov, arXiv:1706.01920v1] examines the BBN lifetime bound on lifetimes of long-lived particles in the context of constraints on a scalar model coupled through the Higgs portal, where the production occurs via $h \rightarrow SS$, where the decay is induced by the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



Higgs Boson Decay Modes

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

BUT > 30% BSM allowed



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