

Explore the Lifetime Frontier with MATHUSLA

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on behalf of the MATHUSLA Collaboration



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UNIVERSITY of
WASHINGTON

4th Workshop of the LHC LLP Community

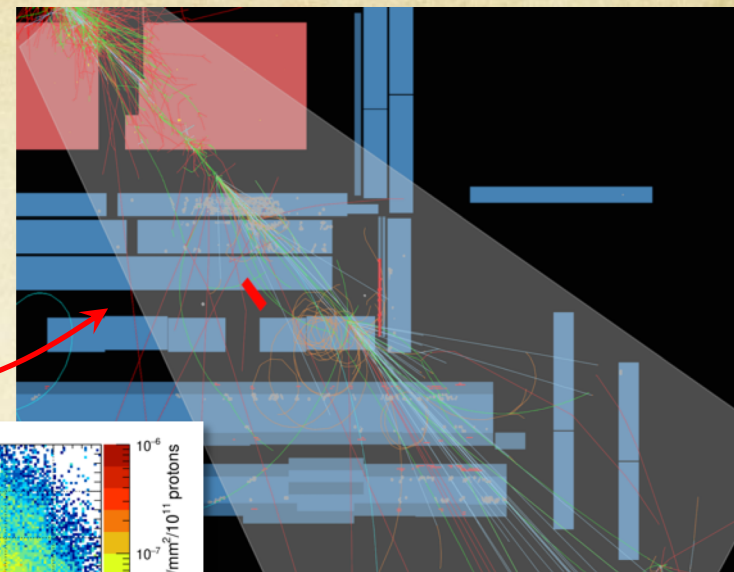
23th October 2018

NIKHEF, Amsterdam

MATHUSLA

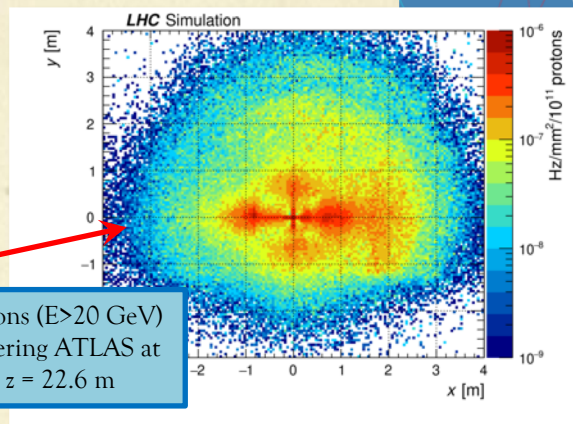
LHC LLP Search Limitations

LHC experiments are doing a wonderful job searching for LLPs



But LHC detector searches are limited by large backgrounds

- ✓ Large QCD jet production
- ✓ Pile-up problems
- ✓ Beam halo issues
- ✓ Cosmic background



Still room to improve background rejection in LHC detectors for HL-LHC (e.g. timing detectors)

At the HL-LHC one of the best possible sensitivity is coming from ATLAS displaced vertex search in the muon spectrometer (shielded and able to trigger on LLP at L1), but searches (1605.02742) suggest that punch through background of the order 100 fb

- In addition, strong dependence on the sub-detectors of ATLAS, CMS and LHCb
- And boost of LLP determines opening angle(s) and that affects trigger efficiencies

Need detector in a more clean environment that could also explore very long lifetimes

MATHUSLA detector → **MA**ssive **T**iming **H**odoscope for **U**ltra **S**table neutral **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:

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

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

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

MATHUSLA detector → **MA**ssive **T**iming **H**odoscope for **U**ltra **S**table neutral **p**Articles

➤ Large area **surface detector** above an LHC p-p IP dedicated to detection of ultra long-lived particles

➤ Air decay volume with **tracking chambers** **surrounded by scintillators**

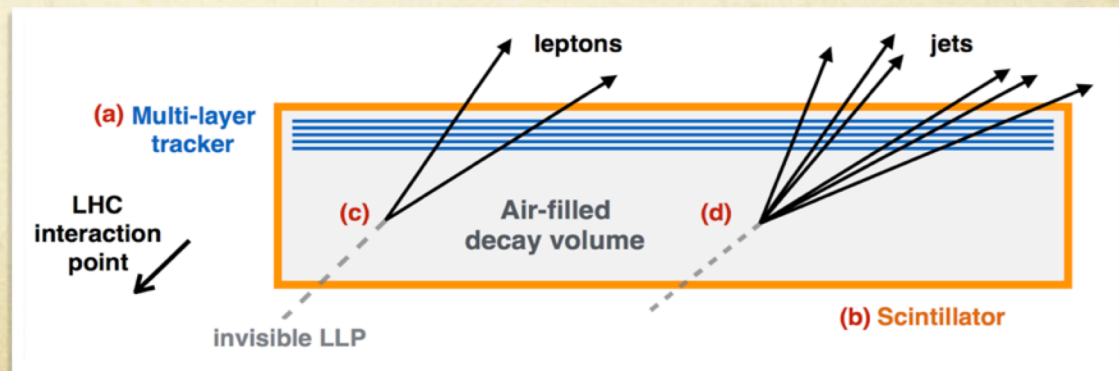
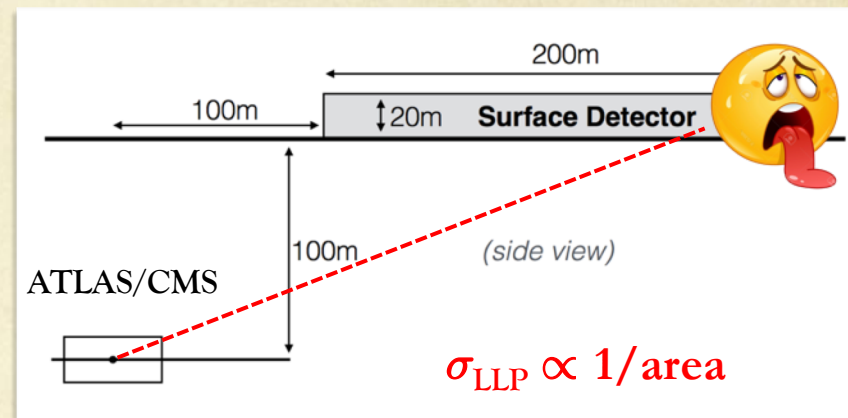
❖ Need robust tracking

❖ 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

But other technologies can be investigated for the main detector



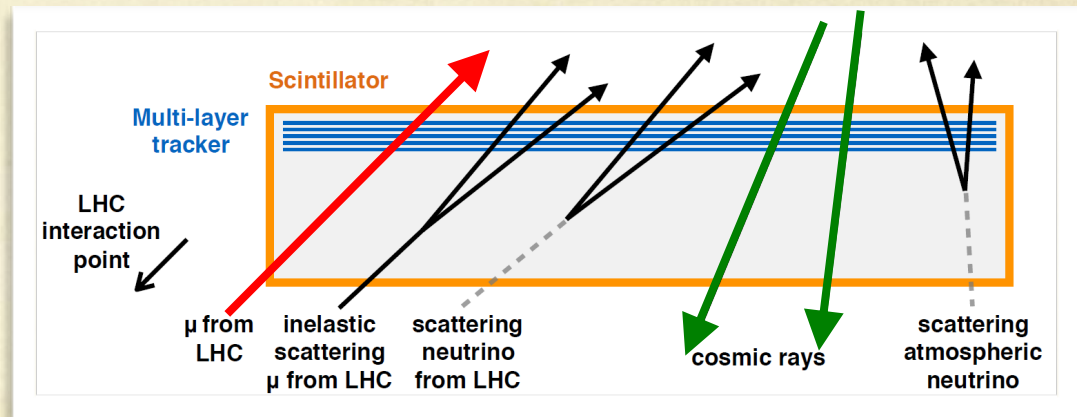
MATHUSLA - Backgrounds

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

Non-collision backgrounds
can be measured when no
LHC collisions

No LHC QCD background, BUT...

- **Cosmic muon** rate of about 10 MHz (200 m²)
→ rejected with scintillator timing (**1.5 ns timing resolution**)
- LHC collision backgrounds
 - ✓ **LHC muons** about 10 Hz
→ Reject with scintillator timing and entrance hit position



- ✓ **LHC neutrinos** (subdominant background) → MATHUSLA should observe a few events during HL-LHC data taking period

- **Upward atmospheric neutrinos** that interact in air decay volume
 - ✓ Estimate Low rate ~ 70 events per year above 300 MeV
 - ✓ Mostly “decay” to low momentum proton → reject with time of flight

Goal is a background-free MATHUSLA!

MATHUSLA - Muon Rates from LHC (new!)

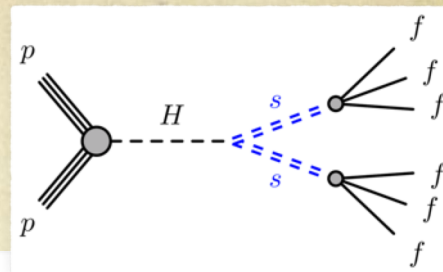
- Simulated muons coming from LHC and passing 100 m of rocks made of 45.3m of sandstone, 18.25m of marl (calcium and clay), 36.45m mix (marl and quartz)
- Minimum energy ~ 70 GeV
- What a muon can do inside the detector?
 - ✓ **Pass through** \rightarrow detected as a single upwards track
 - ✓ **Decay** \rightarrow entirely to $e\nu\nu$ (single e deflected wrt muon direction), but also to $eee + \nu\nu$ with BR $\sim 3 \times 10^{-5}$ (looks like a genuine DV decay, but rejected through floor layer veto or main trigger muon trigger)
 - ✓ **Inelastic scattering** \rightarrow off the air or the support structure (rejected using floor layer veto)
- ❖ **Over the entire HL-LHC run expected $\sim 10^6$ muons pass through MATHUSLA, corresponding to ~ 0.1 Hz**
 - 3000 muons** decaying to $e\nu\nu$ (electron deflected from original muon trajectory by angle $\sim 1/\text{muon boost}$ ($\sim 5-10$ degrees))
 - 0.1 muons** decaying to $eee + \nu\nu$
 - < 1 muon scattering off air**



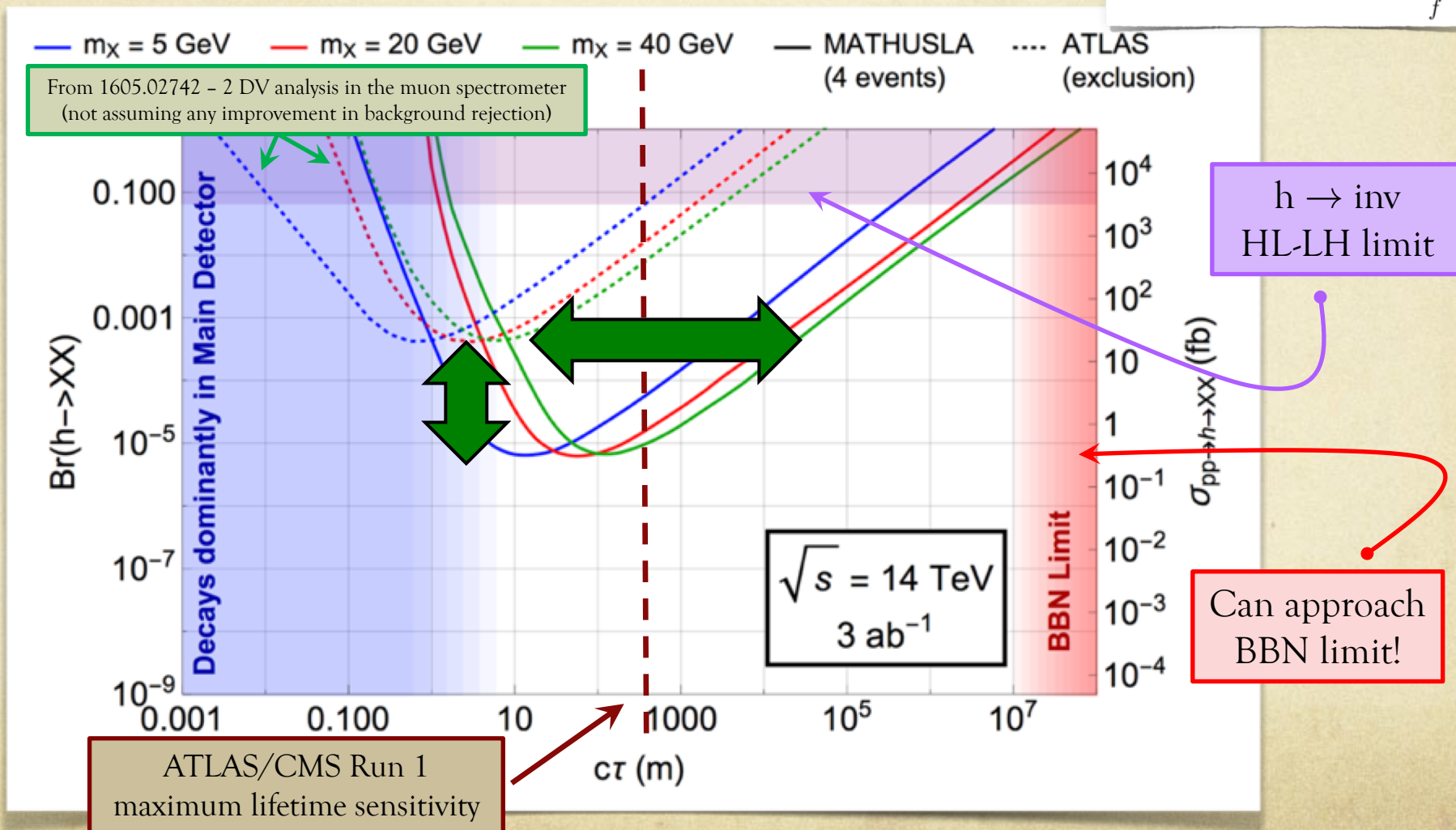
Looking at these results probably
the floor veto is not needed

HL-LHC Sensitivity Estimate

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

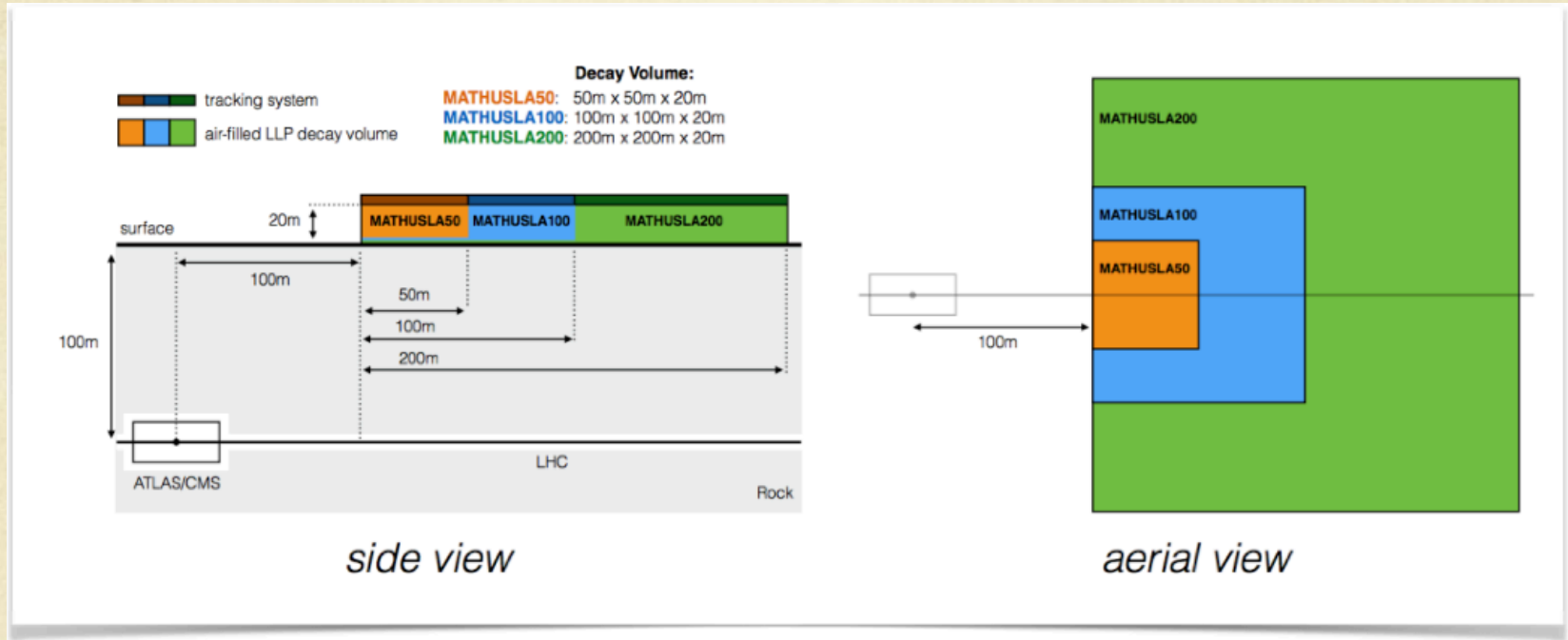


- Decay of Higgs boson to pair of scalars for different masses m_X
- No QCD background \rightarrow big sensitivity gain



MATHUSLA LoI Layouts

- Geometry discussed in LoI submitted to LHCC (July 2018)

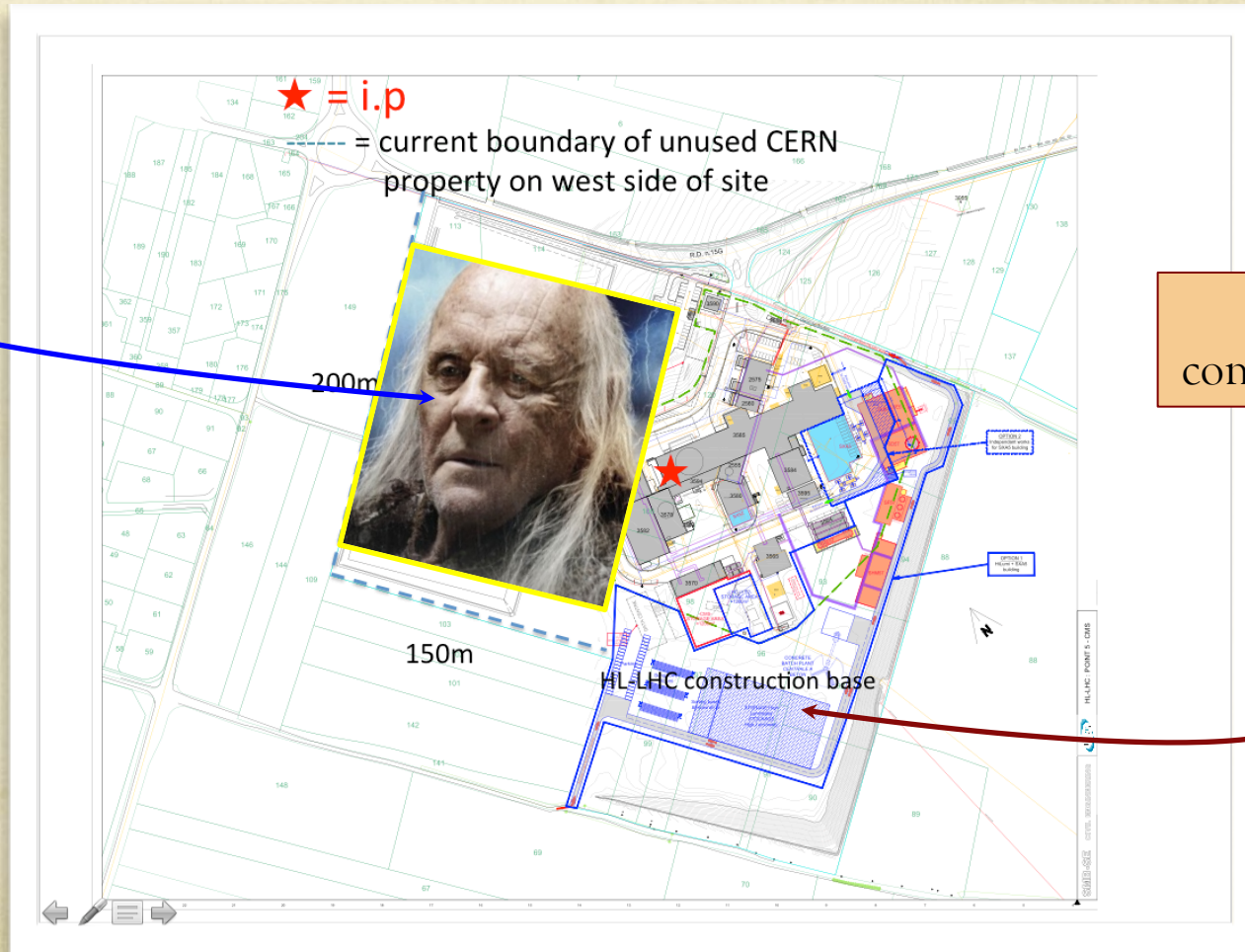


- **Current bench mark is 100m x 100m x 25m**

- 20 m decay volume
- 5 layers of tracking chambers (RPCs) separated by 1 m
- Bottom tracking layer not operated as a veto

Where MATHUSLA could be located?

- CMS site has a large area that is owned by CERN and there are no plans to occupy it in the future!

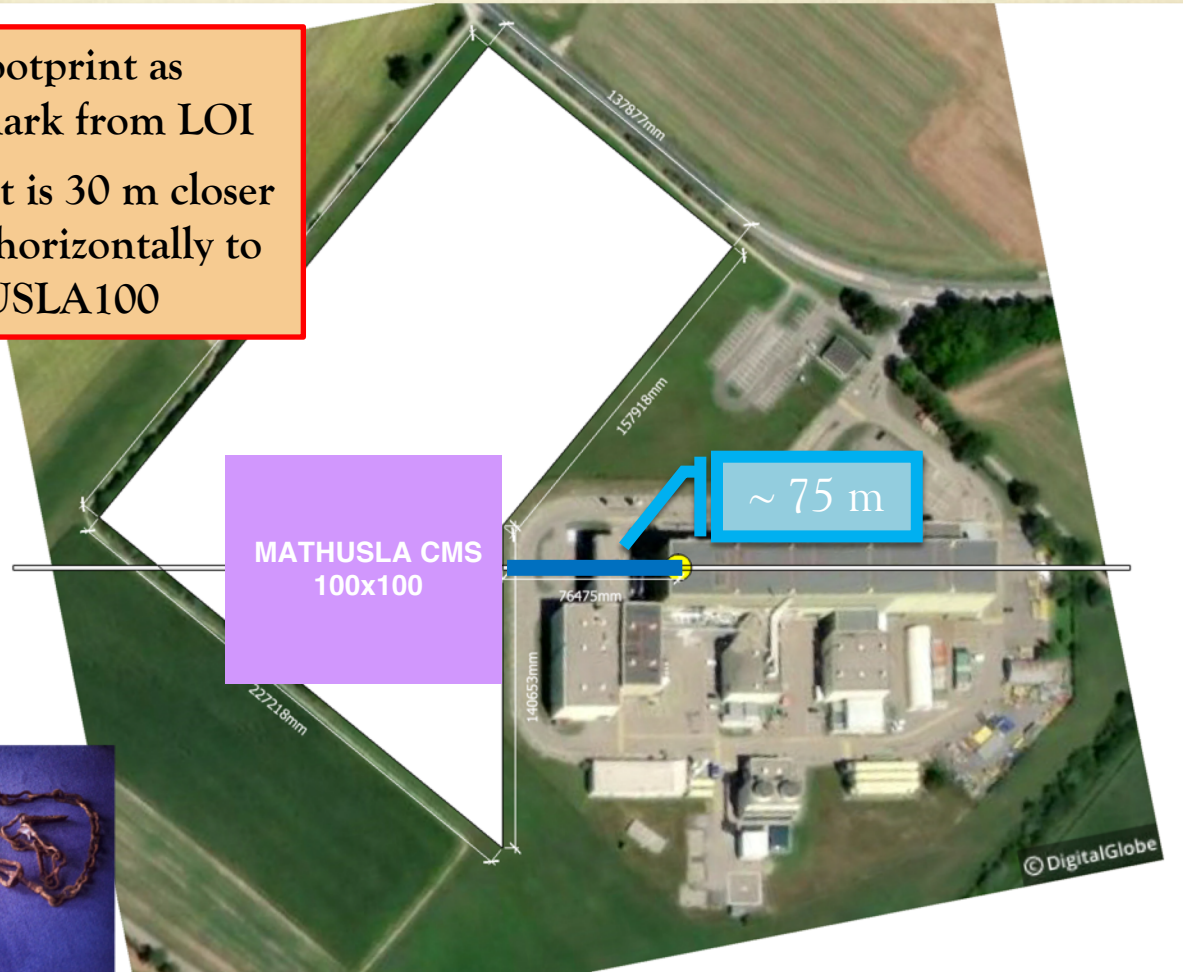


HL-LHC
construction base

Where MATHUSLA could be located?

- MATHUSLA 100x100 m closer to CMS

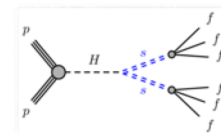
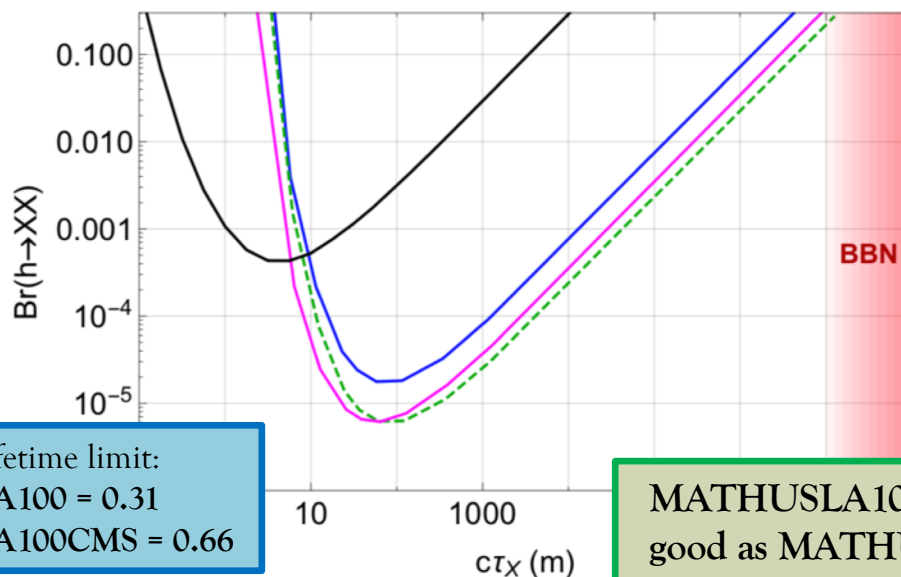
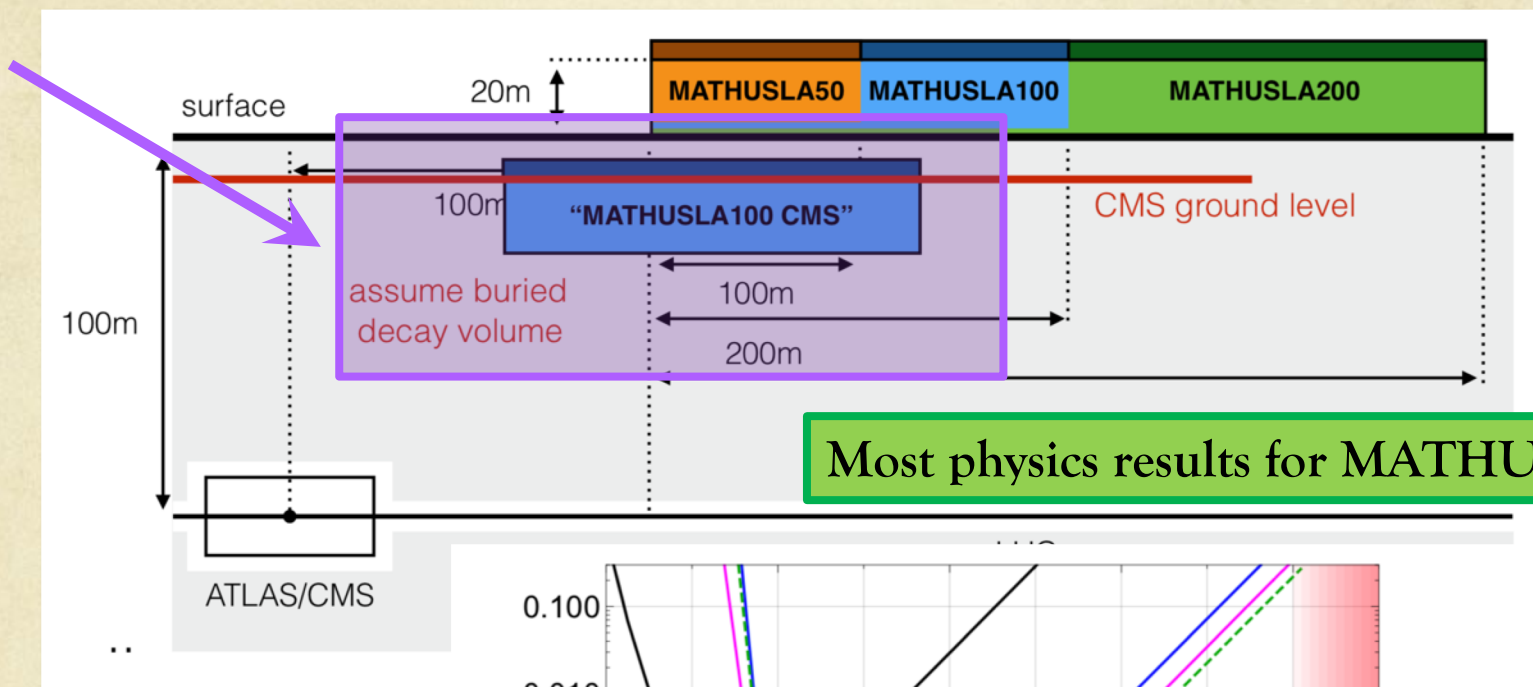
Same 100m x 100m footprint as MATHUSLA100 benchmark from LOI
If decay volume is **buried**, it is 30 m closer vertically and 25 m closer horizontally to the IP than MATHUSLA100



...but excavating around CMS might hold surprises...

Where MATHUSLA could be located?

- MATHUSLA 100x100 m closer to CMS



$h \rightarrow XX, m_X = 30 \text{ GeV}$
 HL-LHC, 3000 fb^{-1}
 — ATLAS MS
 — MATHUSLA100
 - - - MATHUSLA200
 — MATHUSLA100 CMS
 (50m distance, 20m buried)

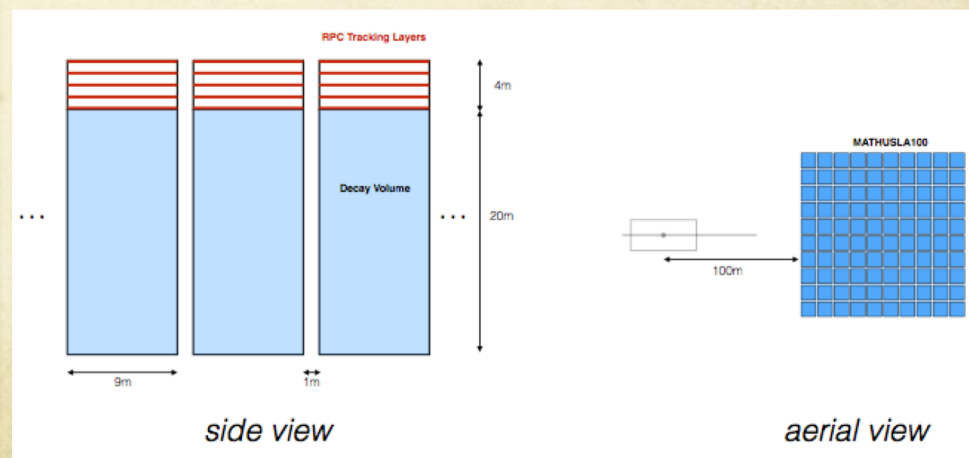
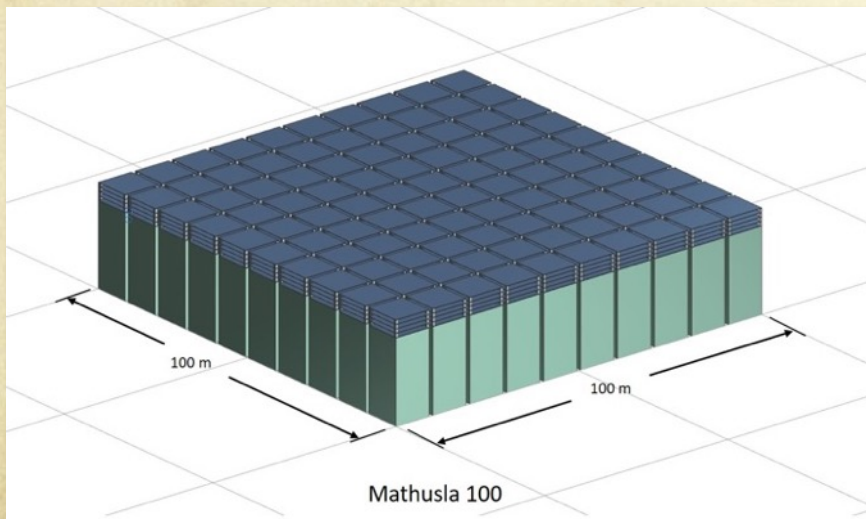
LLP acceptance ratios in long-lifetime limit:
 $\text{MATHUSLA200/MATHUSLA100} = 0.31$
 $\text{MATHUSLA200/MATHUSLA100CMS} = 0.66$

MATHUSLA100 CMS is almost as good as MATHUSLA200, and only uses part of available land near CMS!

Modular Concept



- One hundred individual **10 m X 10 m modules**
 - ✓ 5 tracking/timing planes at top of 20 m decay volume
 - ✓ **Easy to adapt** to site specific conditions (non square geometries)
 - ✓ Allows for modular construction, **staged installation** of modules and **incremental ramp-up**
- Allow for possibility of **adding material for particle identification** (e/μ in cosmic rays)
- Option to make detector volume weather tight or install modules in a large building
- **Trigger unit: 3 x 3 modules** is current baseline (choice based on largest inclination angle for 200 m X 200 m detector and very safe for 100 m X 100 m detector)



Modular Concept = Flexible Concept

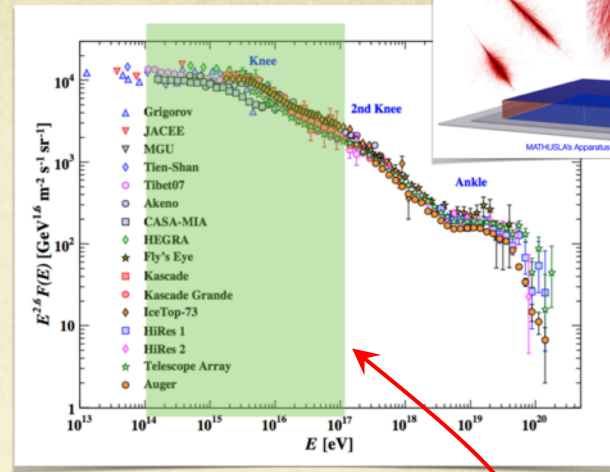
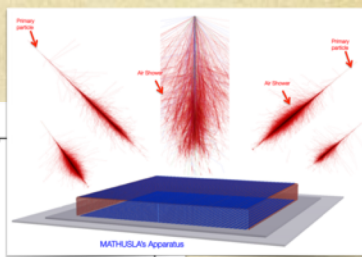
- In the limit where funding is not a consideration, we could **add detector modules to fill available site** to extend our sensitivity



Is MATHUSLA
only LLP?



MATHUSLA - Cosmic Rays



- **KASCADE** is currently a leading experiment in this energy range
 - ✓ Has larger area than MATHUSLA100 (40,000 m² vs 10,000 m²) but ~100 % detector coverage in MATHUSLA vs < 2 % in KASCADE will more than make up for it
- MATHUSLA could perform **cosmic rays studies at PeV energies**
- MATHUSLA has **better time, spatial and angular resolution**, and five detector planes
- Measurements of arrival times, number of charged particles, their spatial distributions allow for reconstruction of the **core**, the **direction of the shower** (zenith and azimuthal angles) and number of charged particles (the shape of the core is not well studied, and MATHUSLA could provide new information)
- MATHUSLA+CMS/ATLAS is uniquely able to analyse muon bundles going through both detectors. This is a **powerful probe of heavy primary cosmic ray spectra and astrophysical acceleration**
- Lots of time to connect MATHUSLA with CMS bunch crossing
 - ✓ CMS trigger at HL-LHC has 12 microsecond latency

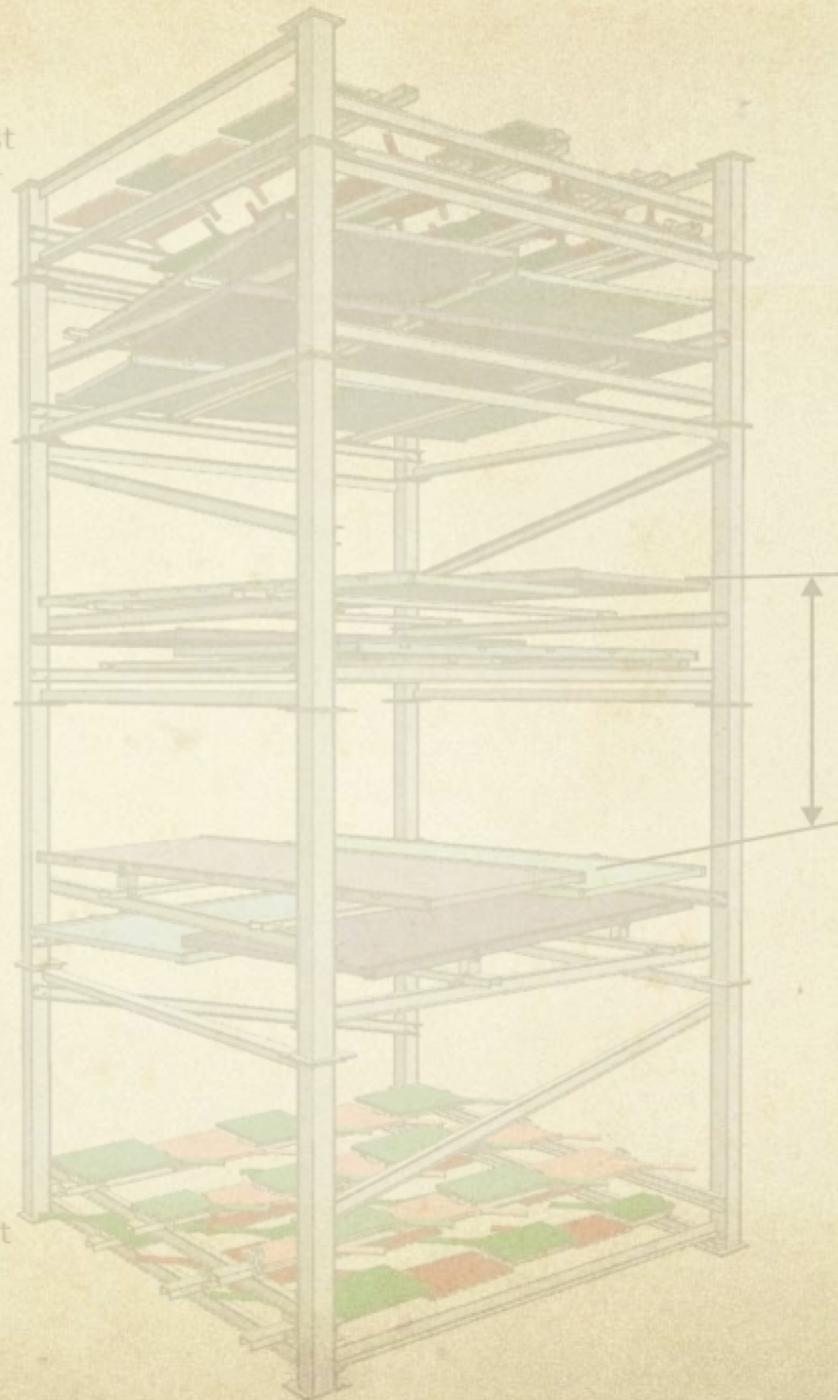
MATHUSLA test stand

Overall spacing
= 6.5 m

Uppermost
scintillator

Lowermost
scintillator

RPC spacing
= 1.74 m

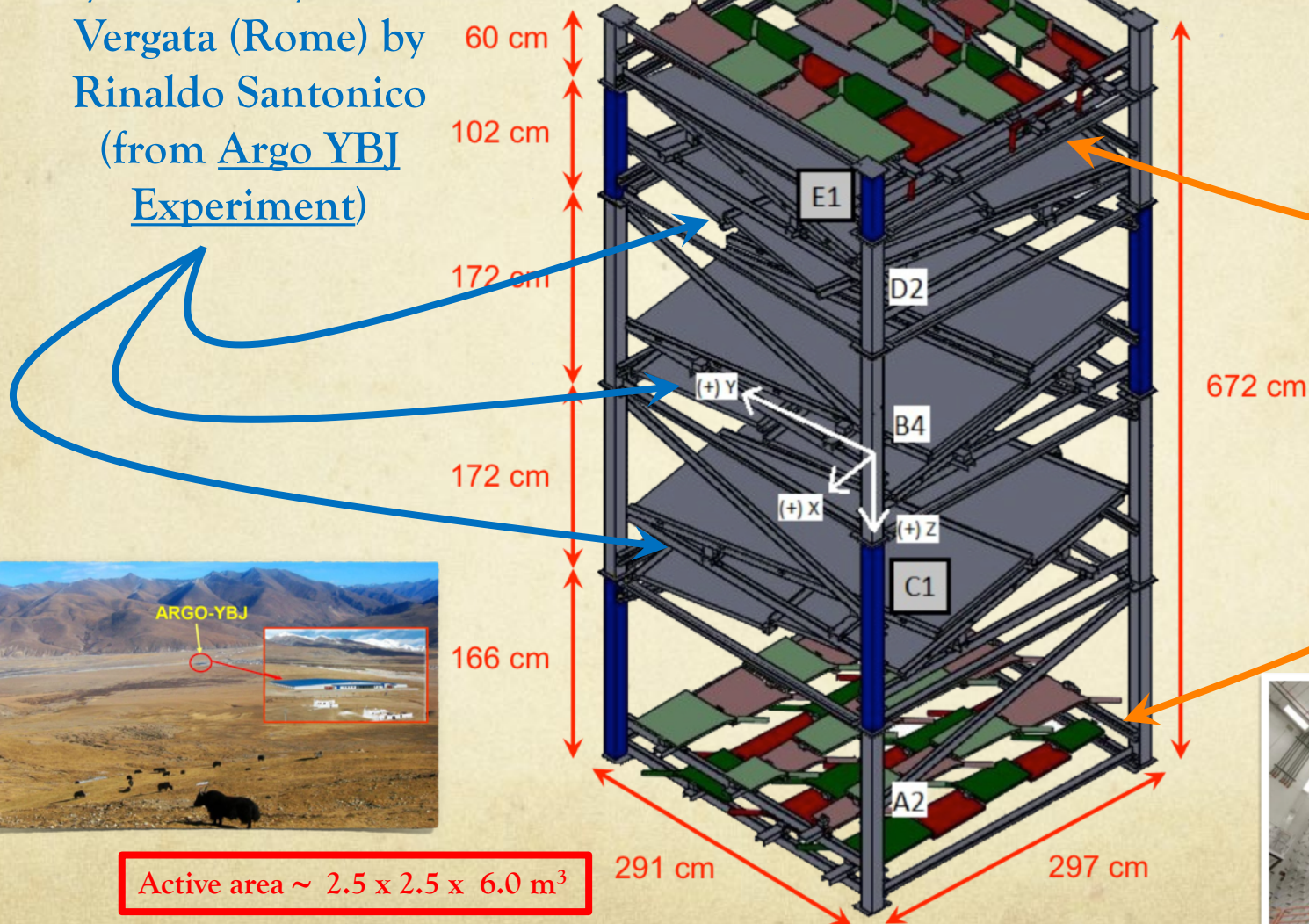


*MC background simulations need
data with LHC colliding protons
and also when the beam is off*

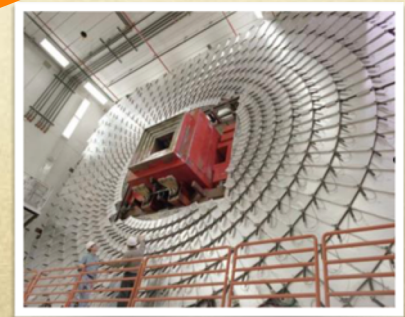
The MATHUSLA Test Stand

3 layers of RPCs provided by University of Tor Vergata (Rome) by Rinaldo Santonico (from Argo YBJ Experiment)

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

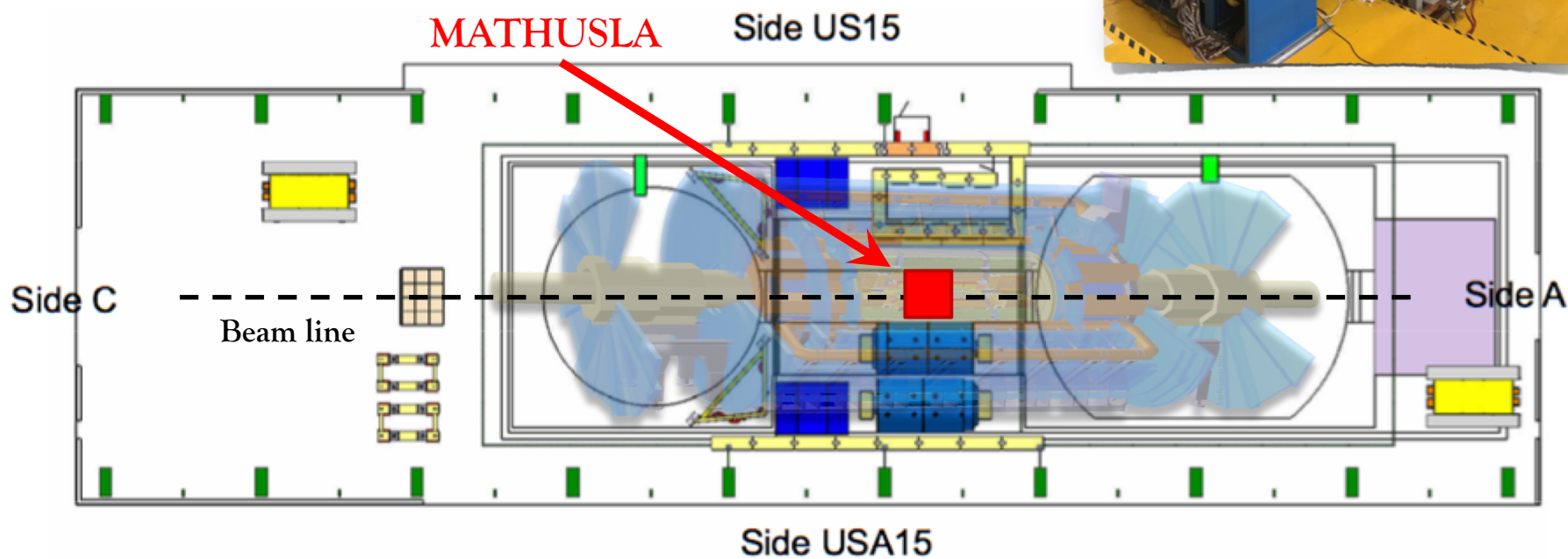


Active area ~ 2.5 x 2.5 x 6.0 m³



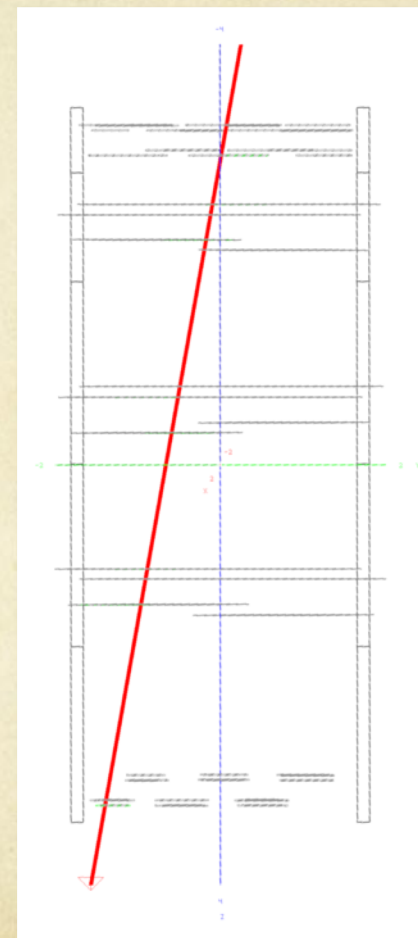
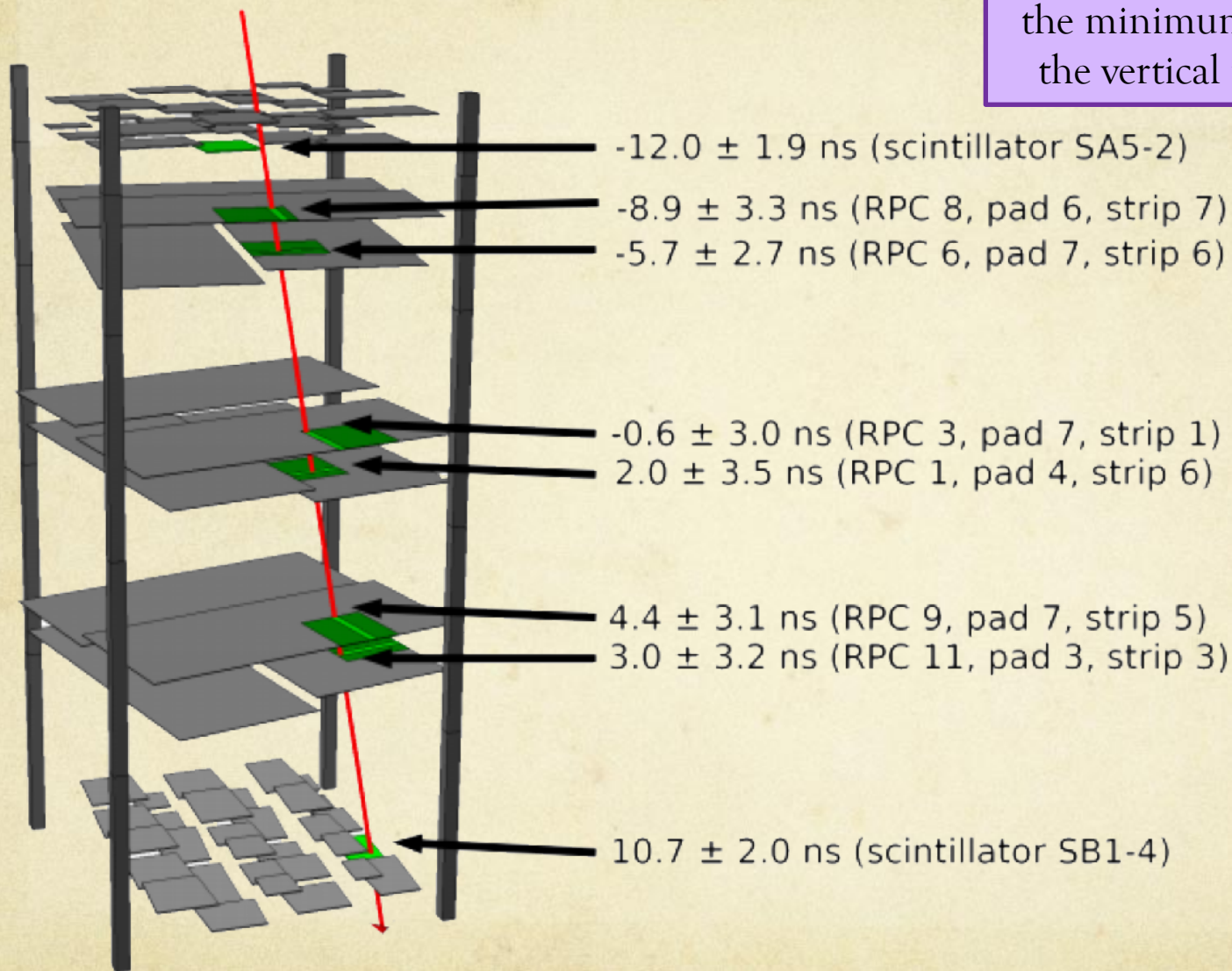
Installation in ATLAS P1

- Cosmic background (\sim) well understood
- Need to quantify the **background from ATLAS**
- Test stand installed in the (Buffer Zone) on the surface area above ATLAS (exactly above IP) in November 2017 (during ATLAS operations this space is empty)
 - ✓ Perform measurements with beam on and off



MATHUSLA downward track

Example of downward track hitting all detector layers. Times relative to the minimum χ^2 timing fit crossing the vertical midpoint of structure



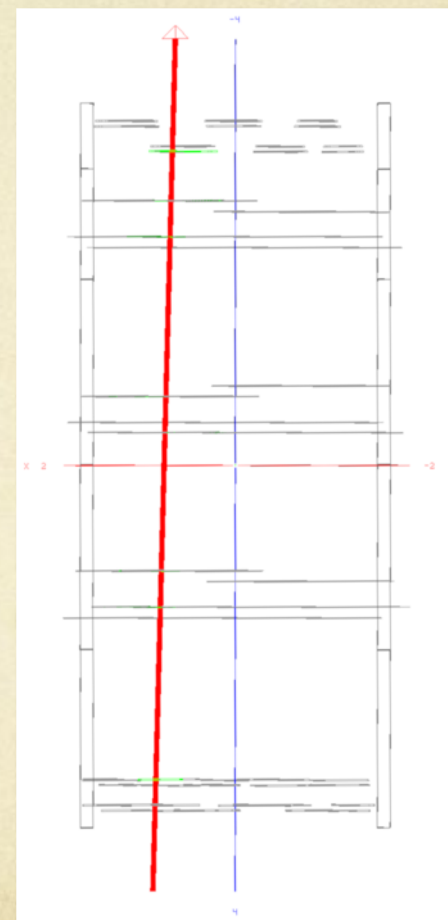
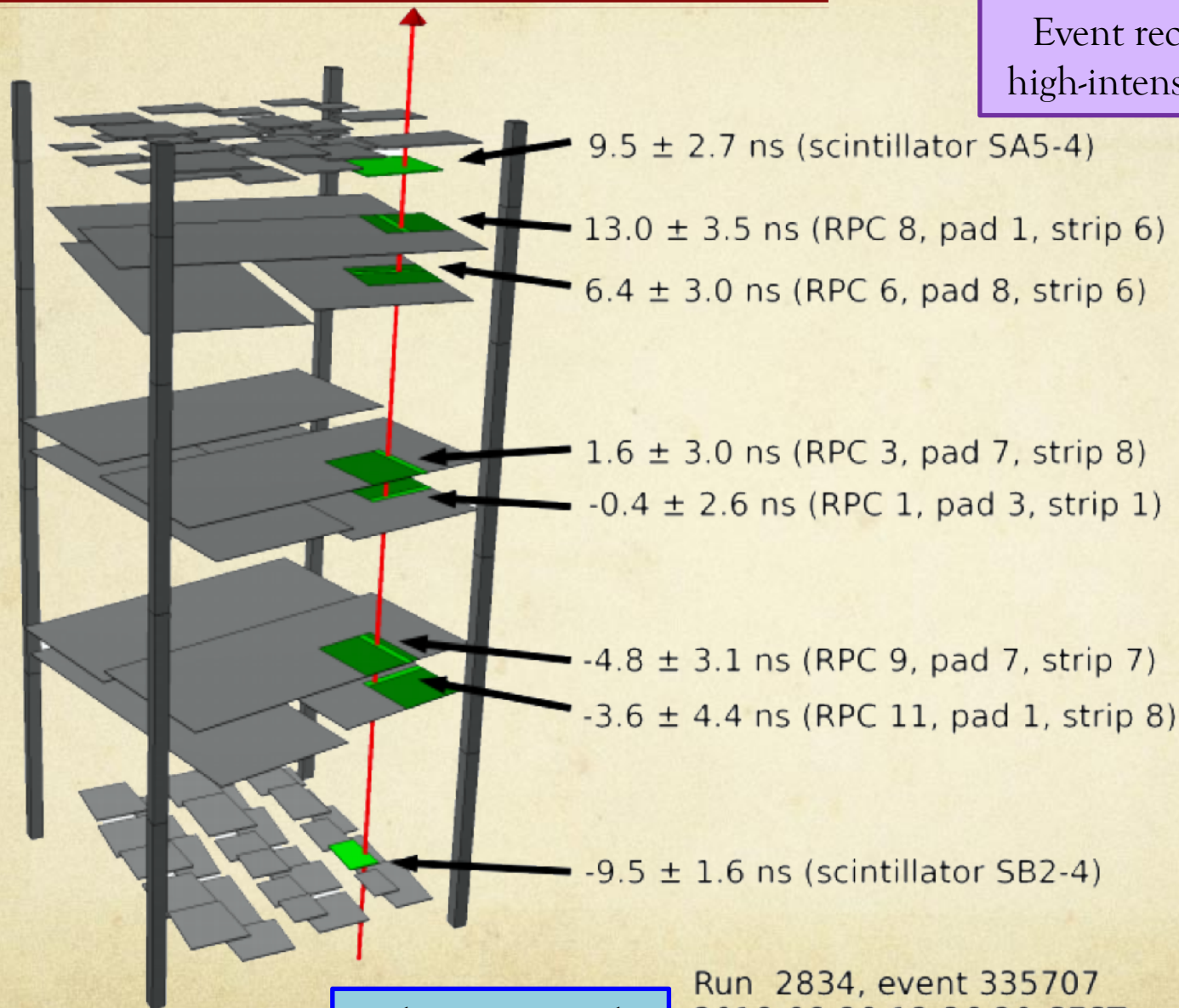
Preliminary results

Run 2834, event 870
2018-08-29 11:39:15 CEST

MATHUSLA upward track

Example of upward track hitting all detector layers

Event recorded during standard high-intensity ATLAS pp collisions



Preliminary results

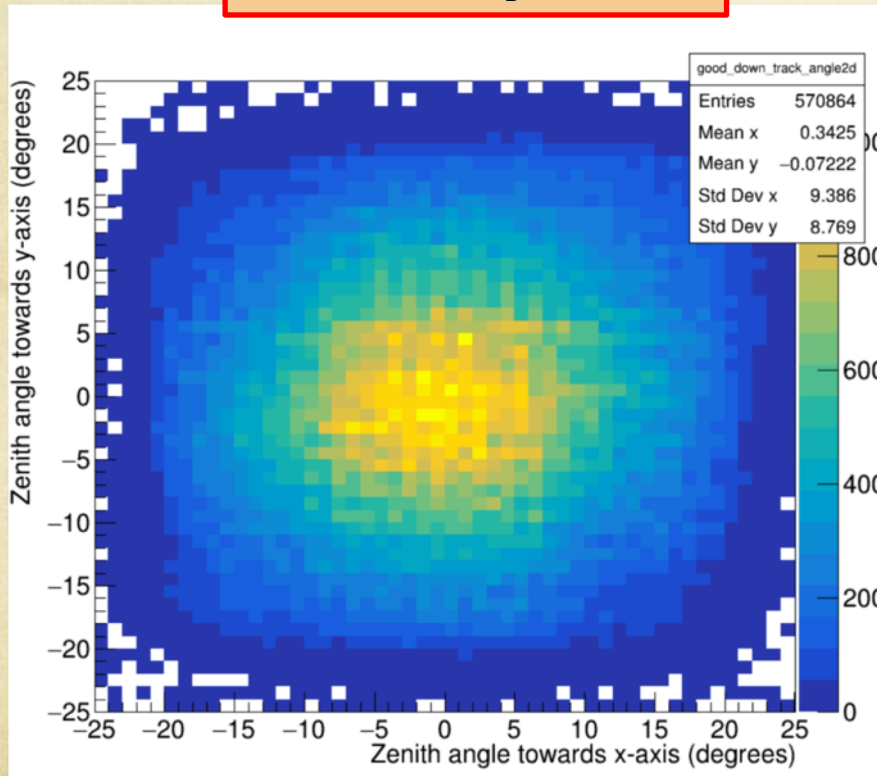
Run 2834, event 335707
2018-08-29 12:36:20 CEST

MATHUSLA tracking: upward and downward

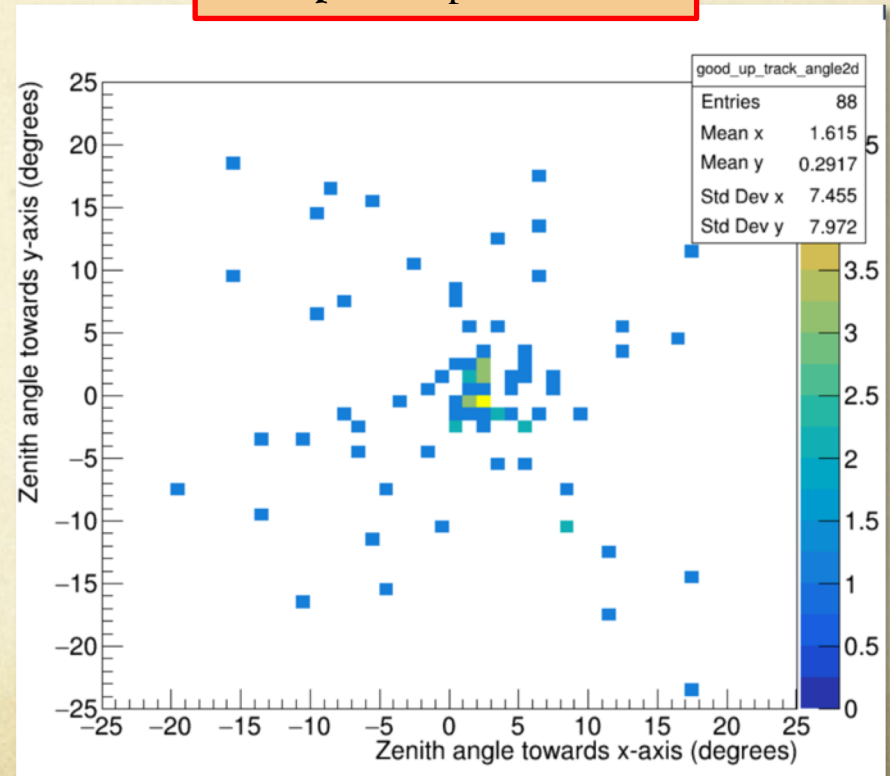


- Result from several hours with LHC beam on
- Preliminary results
- Some tuning still needed

Angle distribution for
downward particles



Angle distribution for
upward particles



Summary & Conclusions

- We are studying the feasibility of a large scale detector to measure LLPs with very long lifetimes
- A test module has been installed on the ATLAS surface area in November 2017 and it will continue taking data until the end of the year (end of LHC Run 2 operations)
 - ✓ Background tests will continue to prove MATHUSLA potential in rejecting background from LHC (and cosmic rays)
- A **letter of Intent** has been submitted to LHCC in July
- A workshop hosted by Simon Center for Geometry and Physics in Stony Brook at the end of last August helped improving the layout and the performance of the future
 - ✓ Lots of feedbacks from reviewers, lot of discussion
- **Finalising data taking and analysis for the next LHCC meeting (end of November)**

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Some of the MATHUSLA people at work...

Henry Lubatti Audrey Kvam Gordon Watts Charlie Young



Mason Louis Proffitt Cristiano Alpigiani David Curtin Nina Anikeeva



30 Oct 2017, 5pm

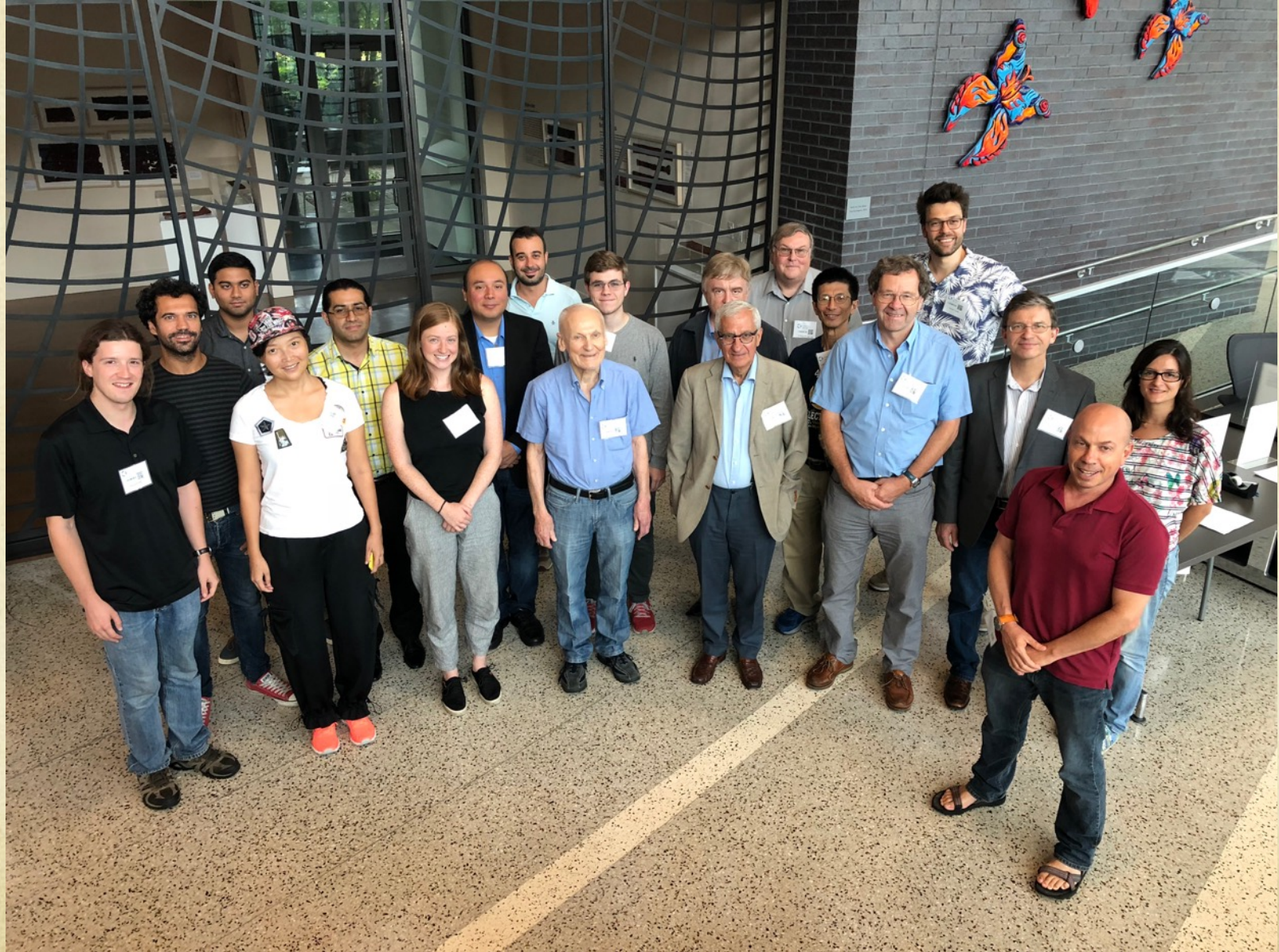
Henry Lubatti

Audrey Kvam

Cristiano Alpigiani



MATHUSLA Collaboration (~complete)+reviewers



BACKUP

The Hidden Sector

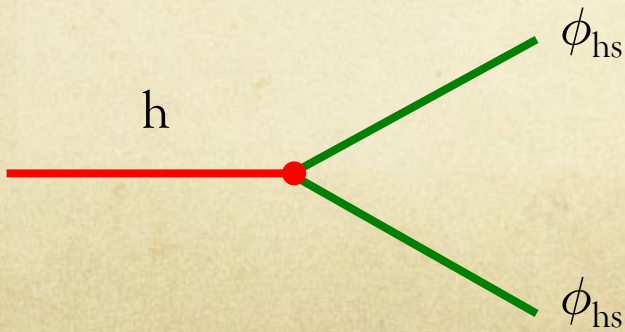
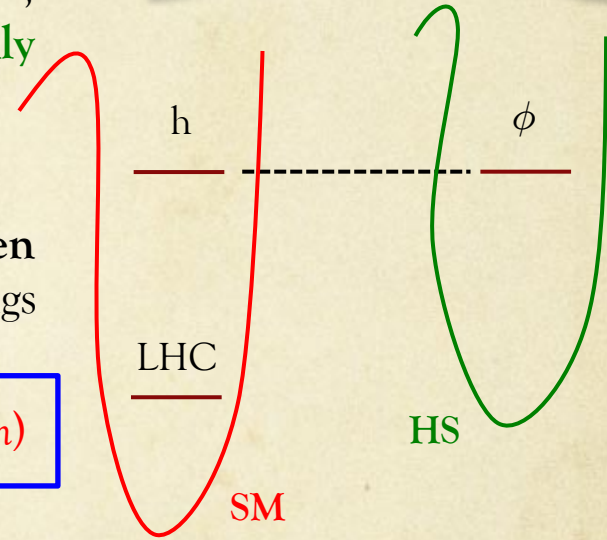


➤ The Standard Model (SM) is in amazing agreement with the experimental data, but **still some problems remain unsolved**: dark matter, neutrinos masses, hierarchy, matter-antimatter asymmetry...

➤ 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 \rightarrow long lifetimes [Phys. Lett. B6512 374-379, 2007]

$\sim 10^8$ Higgs boson @ HL-LHC

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- $c\tau$)
- ATLAS search strategy for displaced decays - based on signature driven triggers that are detector dependent

MATHUSLA - signal reconstruction example (2)

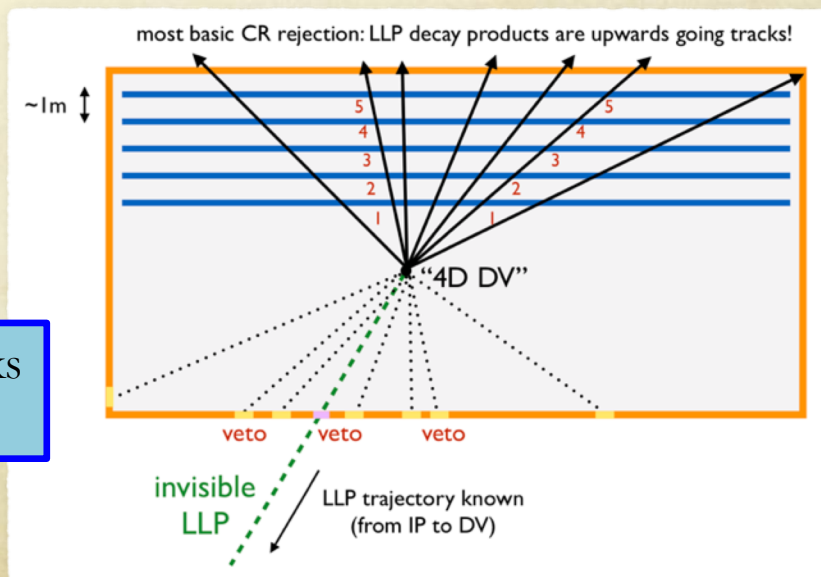
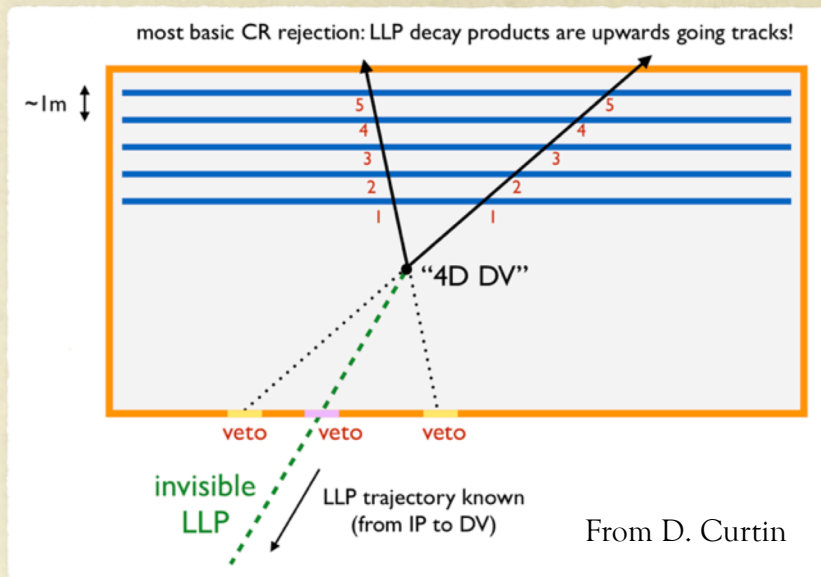
Hadronic decay of a LLP

➤ Δt between tracking layers $> \sim 3.5$ ns

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

Tracks are reconstructed in 3D and with detailed **timing** information at each layer, the DV is really a **4D DV**

More difficult to fake \rightarrow all tracks have to pass veto requirements



MATHUSLA - particle identification

D. Curtin, M. Peskin,
arXiv:1705.06327

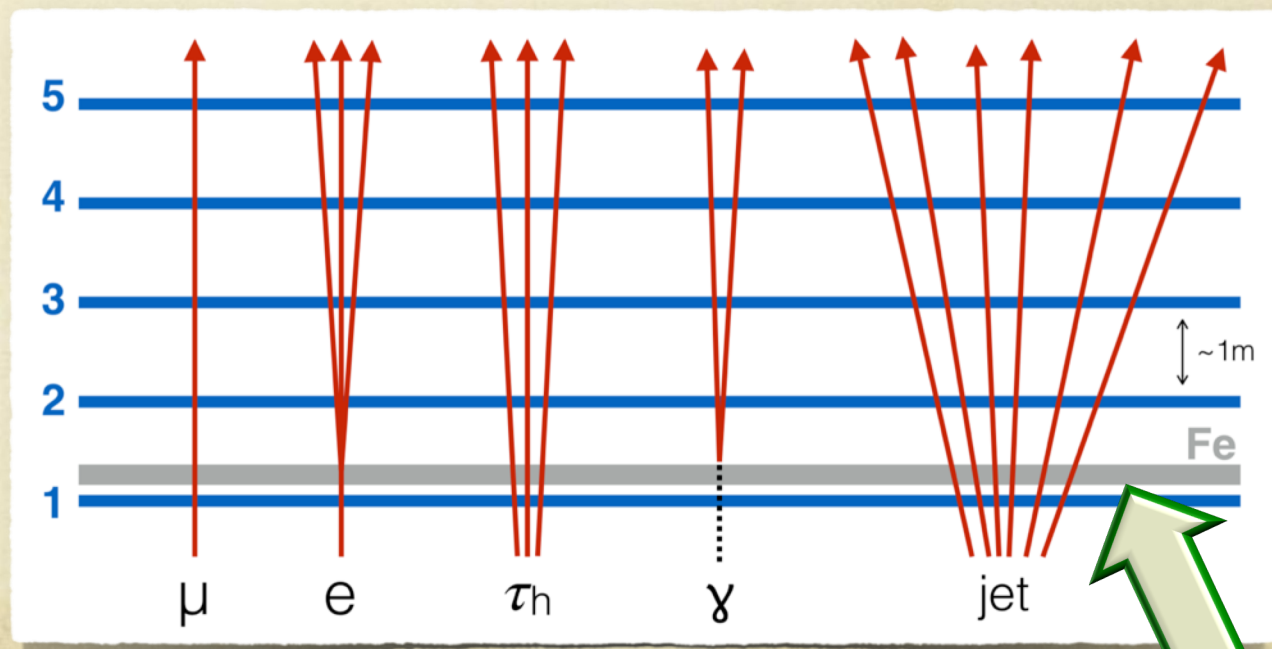
With the current detector design muons and electrons are undistinguishable, while photons are invisible



- **New idea:** insert a layer of iron few cm thick between the first and the second tracking layer
 - Provide 1-2 X_0 to convert electron and photons generating visible electromagnetic showers

No energy or momentum measurements, but allows to qualitatively distinguish the various particle types

Angle of the charged tracks w.r.t. tracking plane can be known with a precision of ~ 2 mrad



Details about location, material, thickness, etc. still under investigation

MATHUSLA - Any other “crazy” background?

Are we really taking into account all backgrounds?

- We are looking at very rare events, so we are very sensitive to less obvious backgrounds!
 - Horizontal cosmic rays hitting atoms below MATHUSLA in floor
 - Single K_L or neutron traveling upwards, decaying in MATHUSLA (exactly a LLP signal!)
 - ✓ Rate estimated to be very small, but...
 - Cosmic rays hitting material in detector, either floor or walls or support structures? and creating K_L or neutron?
 - ???

We are working on precisely estimating (and simulating, if possible) all these rare backgrounds!

Some preliminary detector cost estimate

Scintillators

Top and bottom are = $2 \times 200 \text{ m}^2 = 80\,000 \text{ m}^2$ + sides = $4 \times 200 \times 20 \text{ m}^2 = 16\,000 \text{ m}^2$

→ Total area = $96\,000 \text{ m}^2$

- Assume thickness = 1 cm, density = 1 gm/m^3
- Assume 3 USD / kg (low end of NO ν A estimates) excluding electronics

→ Total cost ~ 3M USD

RPCs

- Resistive electrode of high pressure laminate based on phenolic resin → 80 E/m^2
- Gas gap construction and procurement of all materials excluded the electrode laminate → 160 E/m^2
- Signal read out panels → 60 E/m^2
- Mechanical support panels (could be optimised, should be cheaper) → 200 E/m^2
- Front end electronics → 150 E/m^2
- Total/ m^2 → 650 E/m^2

→ Total for 10^5 m^2 → 65M E

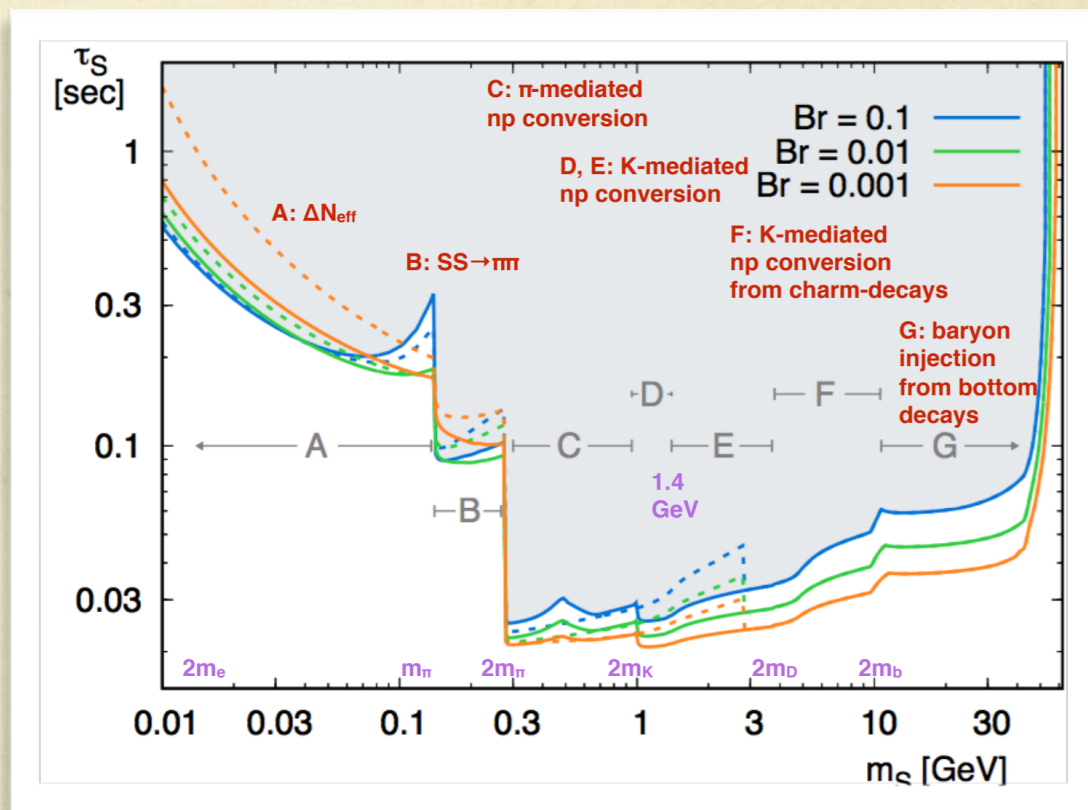
Not included: mounting of the FE electronics over the strip panels; power system (LV and HV); gas system; trigger and DAQ; cabling and piping.

Some preliminary building cost estimate

- Building 947 (FLEX building) is about the same footprint as MATHUSLA (90 m x 110 m), and ~10 m high. It costs ~10 MCHF.
- **MATHUSLA sized building is plausible for 16 MCHF:** twice the height and probably more support columns. This assumes a surface building.
- As another point of reference, Building 887 (neutrino platform) is smaller (roughly 70 m x 50 m) but involves a pit requiring excavation and lining. It costs 6 MCHF + 3M for metal shell over the pit.
- Building 947 has two rows of support columns in addition to the side walls to support the roof. These two rows of columns support two bridge cranes in addition to the roof. A similar design may work for MATHUSLA.

MATHUSLA - Scalar LLP Lifetime Constraints

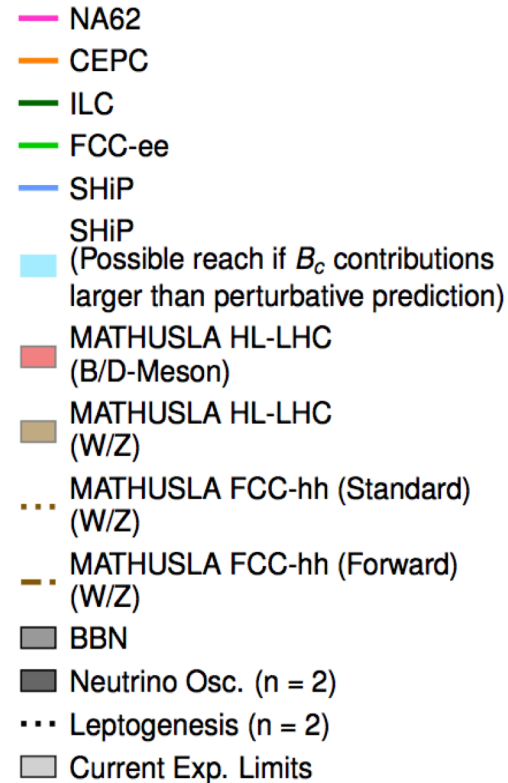
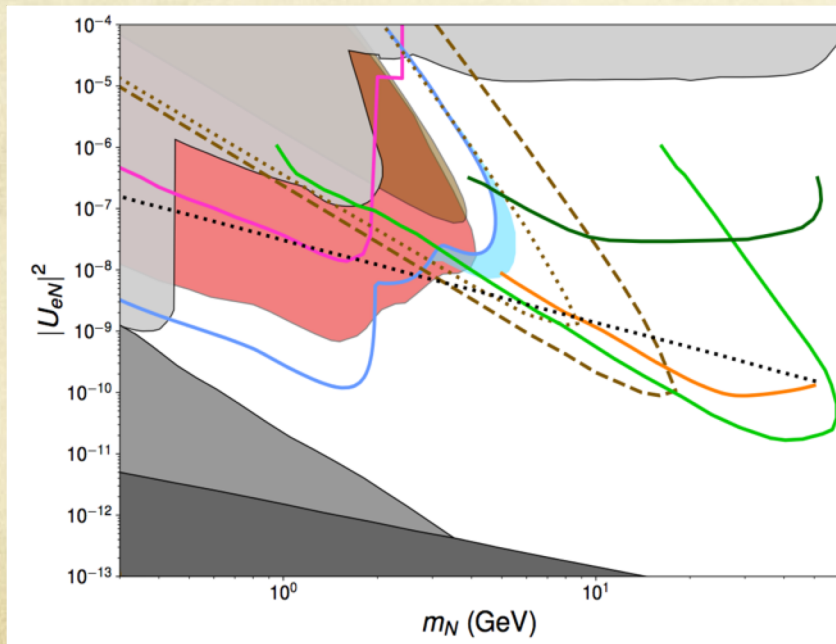
- A recent paper [A. Fradette and M. Pospelov, arXiv:1706.01920v1] examines the BBN lifetime bound on lifetimes of long-lived particles in the context of constraints on a scalar model coupled through the Higgs portal, where the production occurs via $h \rightarrow ss$, where the decay is induced by the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



MATHUSLA - SHiP Comparison

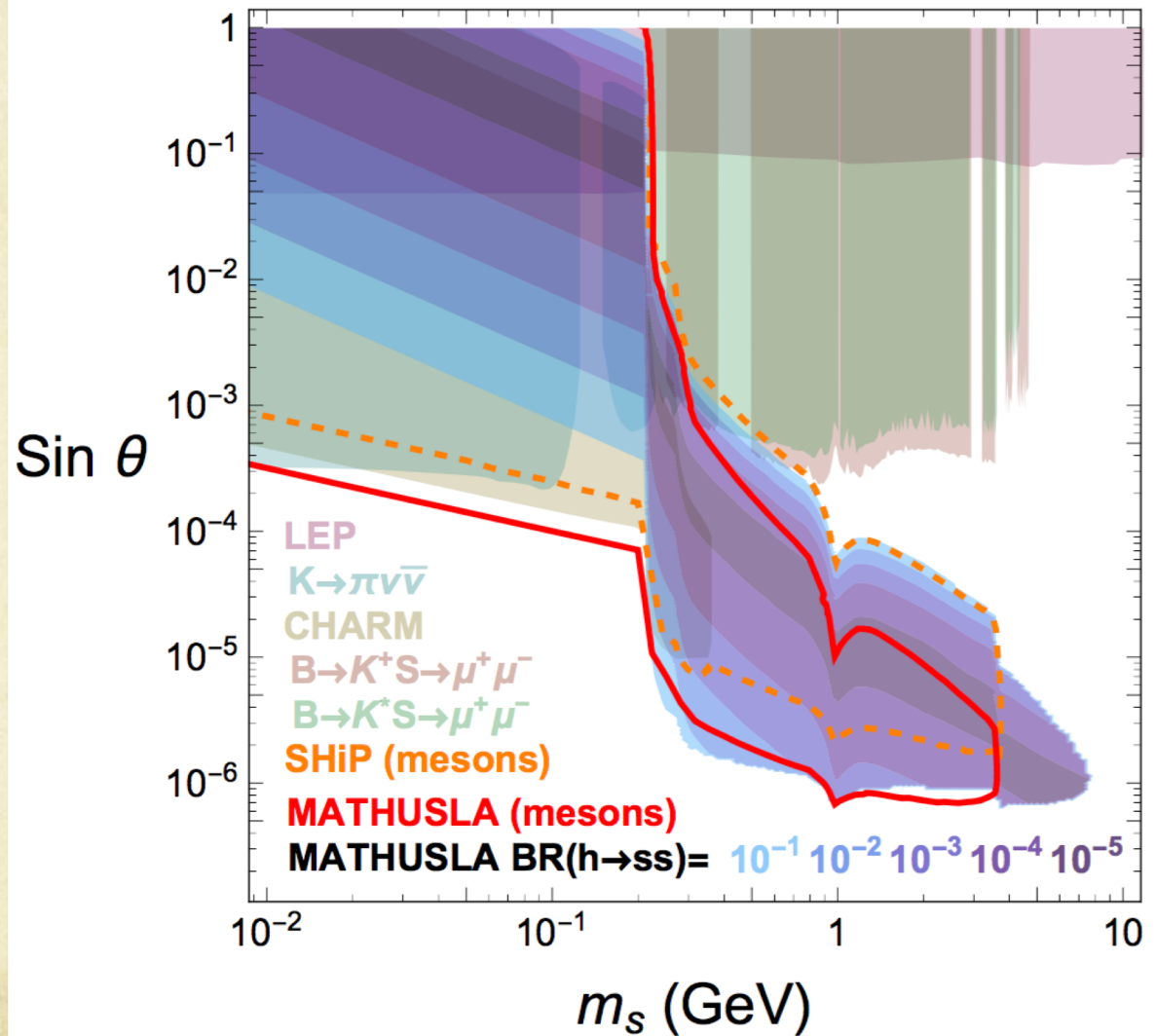
- SHiP is better for **shorter lifetimes** and **lower masses**
- MATHUSLA high-energy LHC collisions can probe LLPs at **GeV to TeV scale**
- MATHUSLA is better or competitive for mass scale **above ~ 5 GeV**, and for **lifetime $\gg 100$ m** even at low masses
- SHiP is limited by lower \sqrt{s} to probing masses of order a few GeV which limits new physics reach to low mass LLPs

“Heavy Neutral Leptons”



MATHUSLA - SHiP Comparison

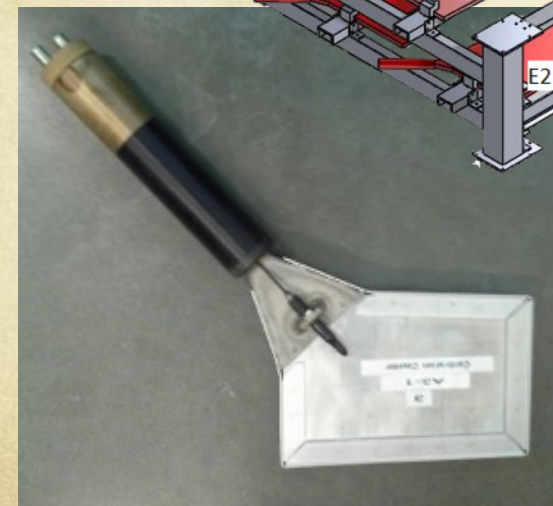
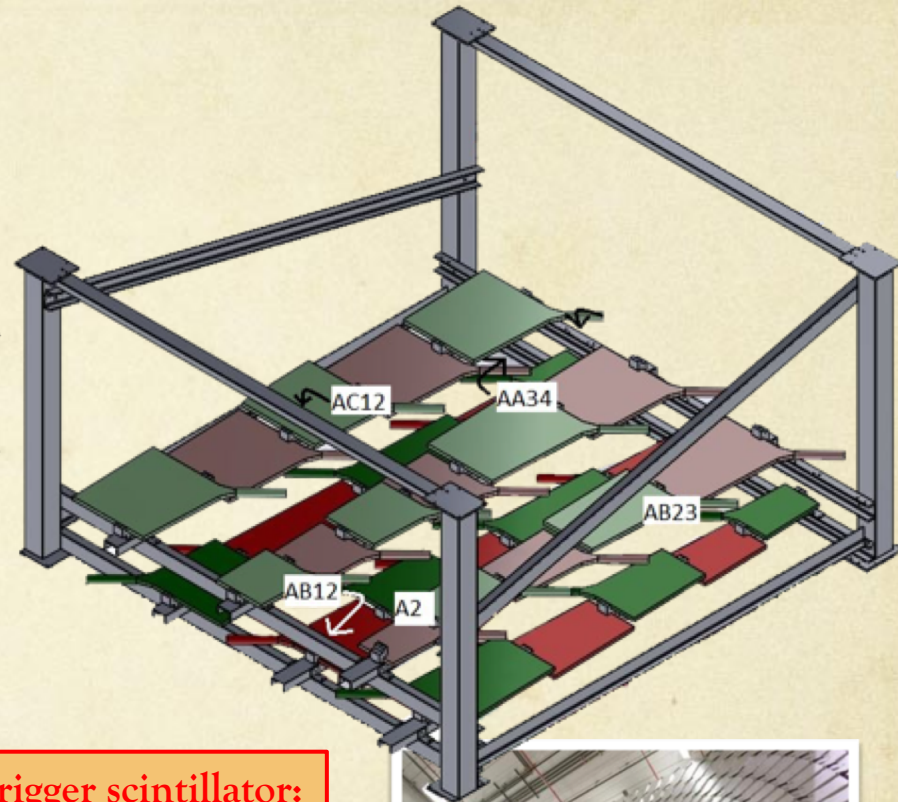
MATHUSLA has significant sensitivity for long lifetime



Test Stand Scintillator Details

Top - 31 scintillators

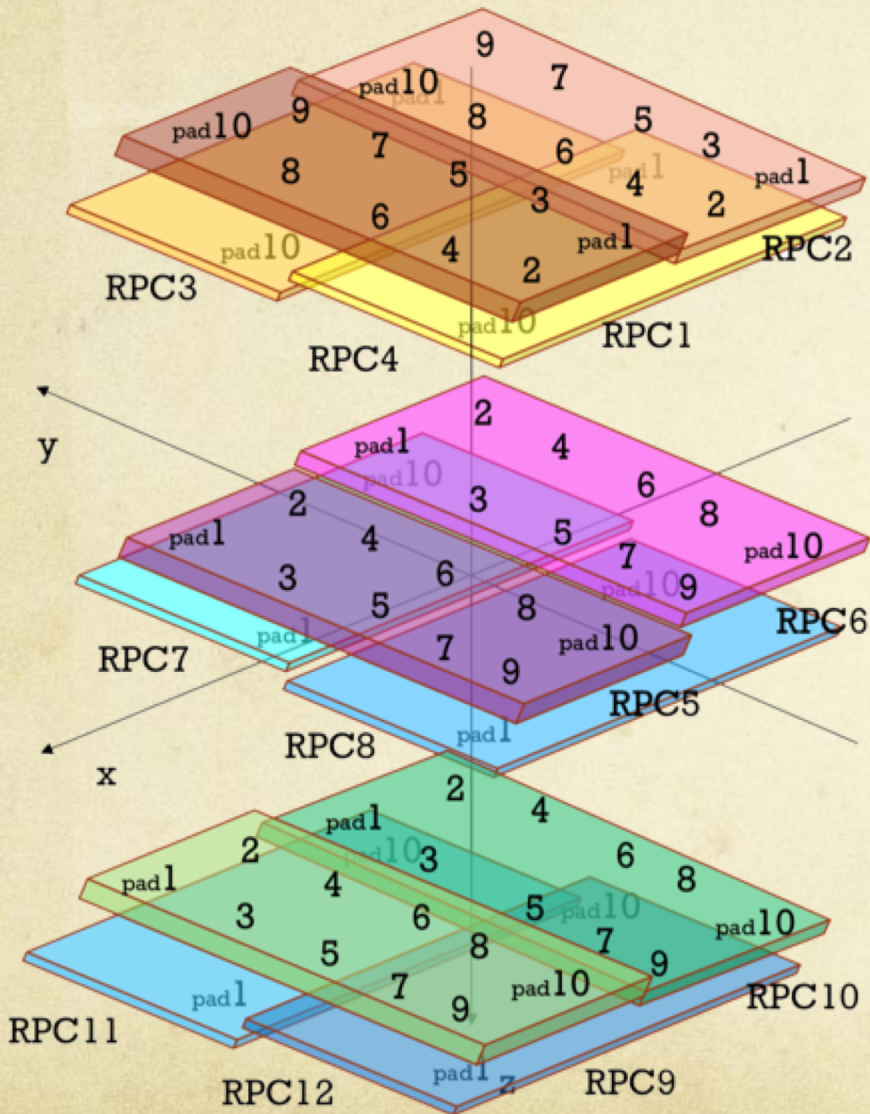
Bottom - 28 scintillators



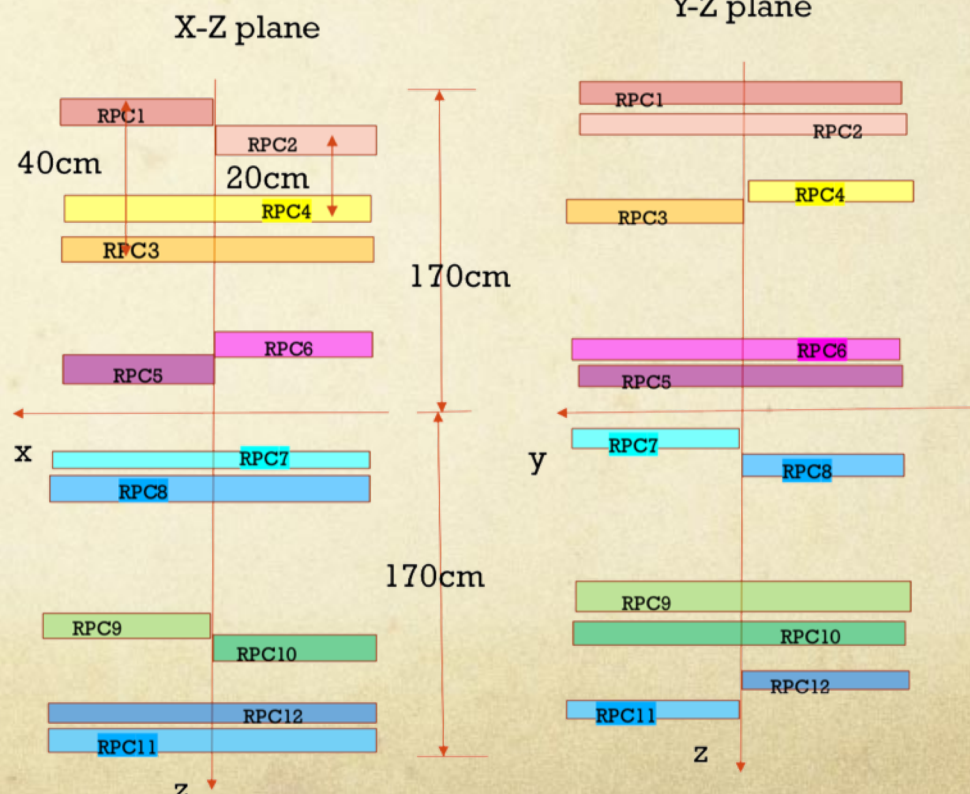
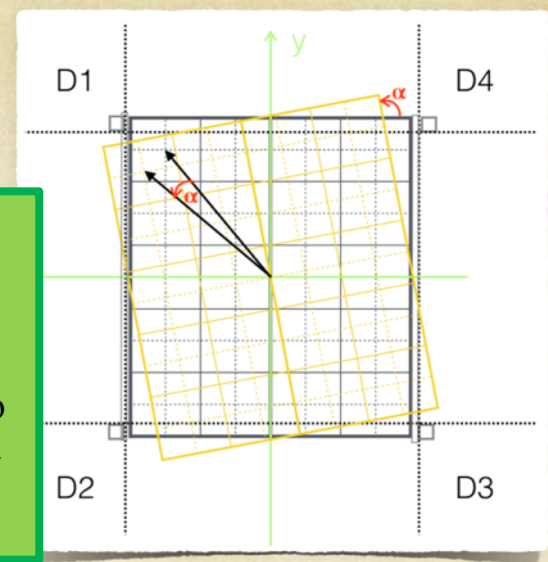
D0 forward MUON trigger scintillator:
12.8-mm-thick BICRON 404A of
trapezoidal shape + WLS bars for light
collection



Test Stand RPC Details

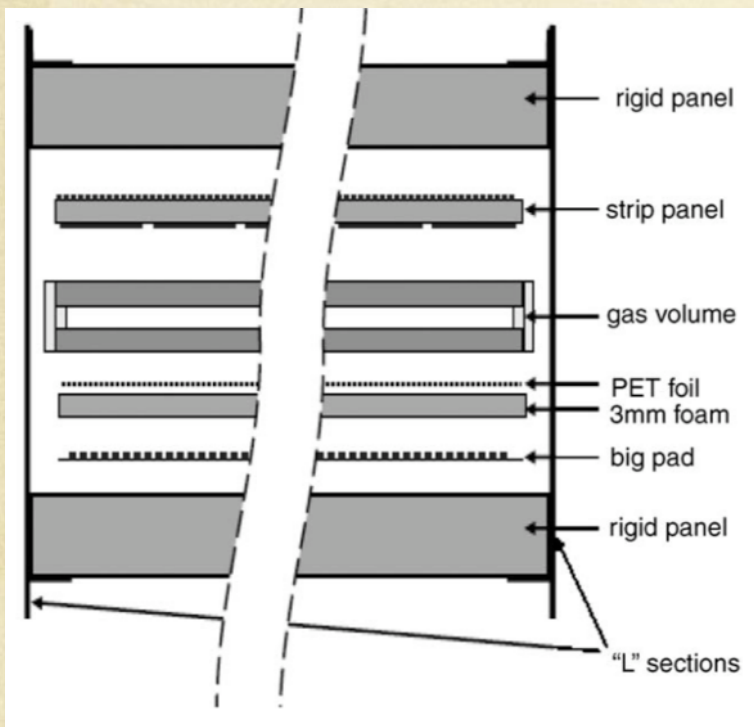


Small stereo rotation angle between the 3 tracking planes to reduce ambiguity and ghost hits



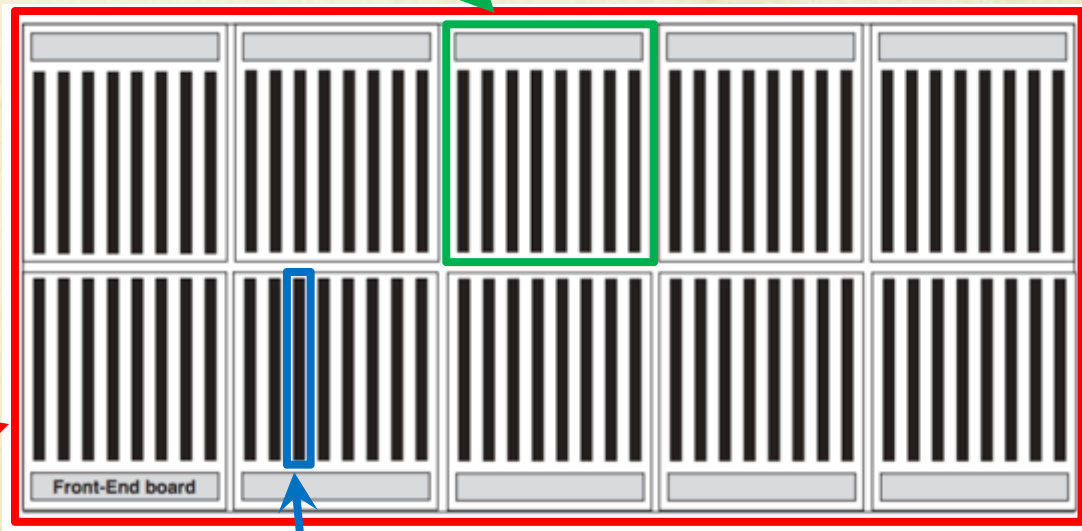
Test Stand RPC Details

- 12 RPCs from the prototype of ARGO YBJ cosmic ray shower experiment in Tibet



- ✓ Operating in streamer mode
- ✓ Ar + ATLAS RPC gas ($C_2H_2F_4$ /Iso- C_4H_{10} / SF_6 (94.7/5/0.3))

10 Pads ($55.6 \times 61.8 \text{ cm}^2$) for each RPC



Chamber size: $1.25 \times 2.80 \text{ m}^2$

8 Strips ($6.75 \times 61.8 \text{ cm}^2$) for each Pad

Test Stand DAQ and Trigger

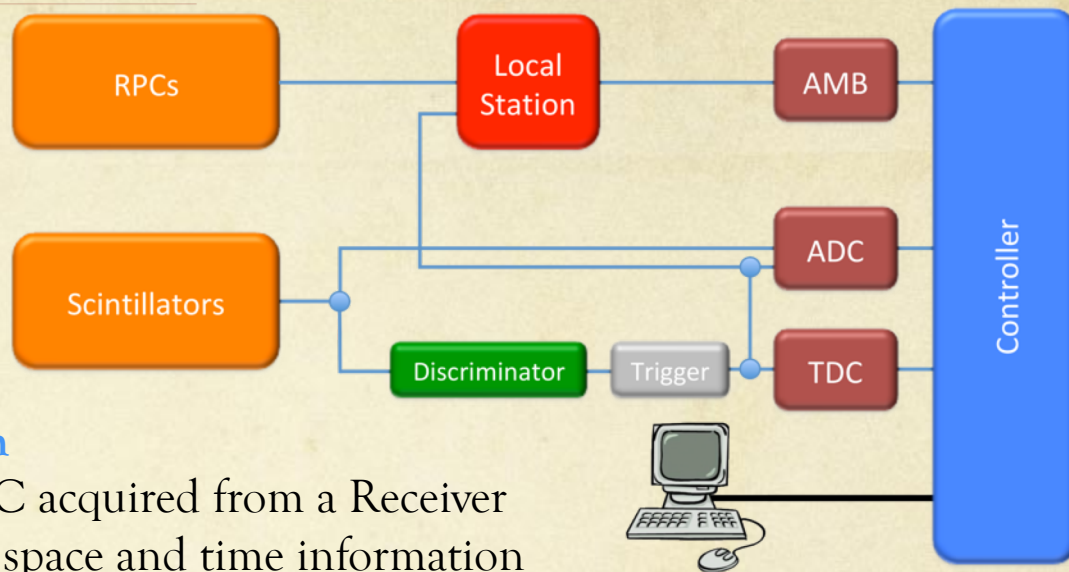
Test module DAQ

➤ Scintillators

PMTs interfaced with a VME CAEN module

➤ RPCs: Argo Experiment Local Station

(from Lecce, Italy). 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

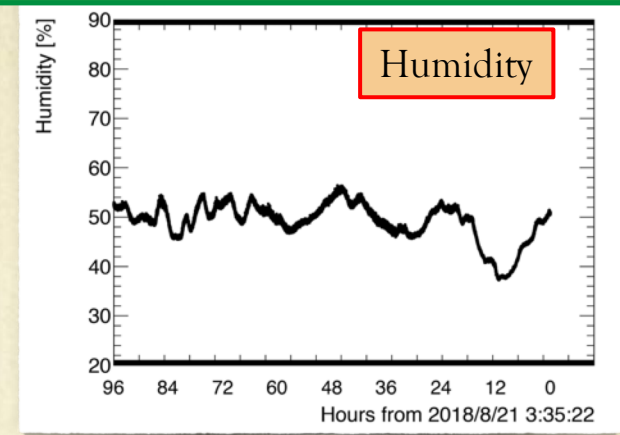
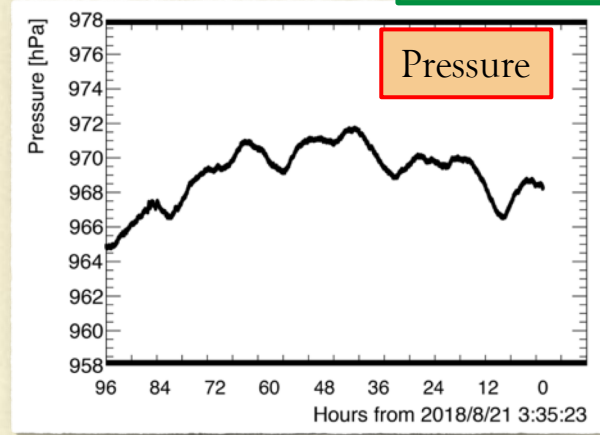
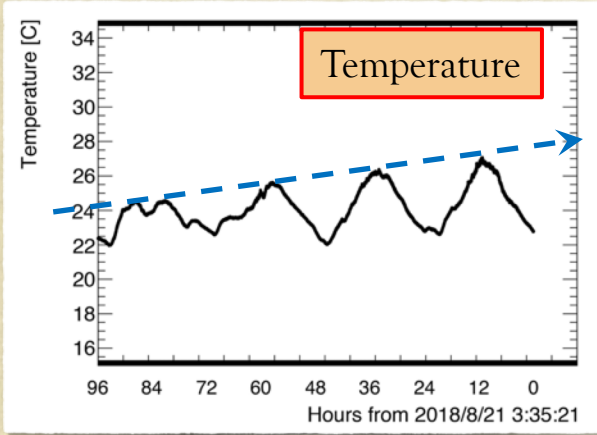
Two possible triggers: top and bottom scintillators in coincidence, with:

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

RPC Performance vs Environmental Conditions

➤ Environmental conditions

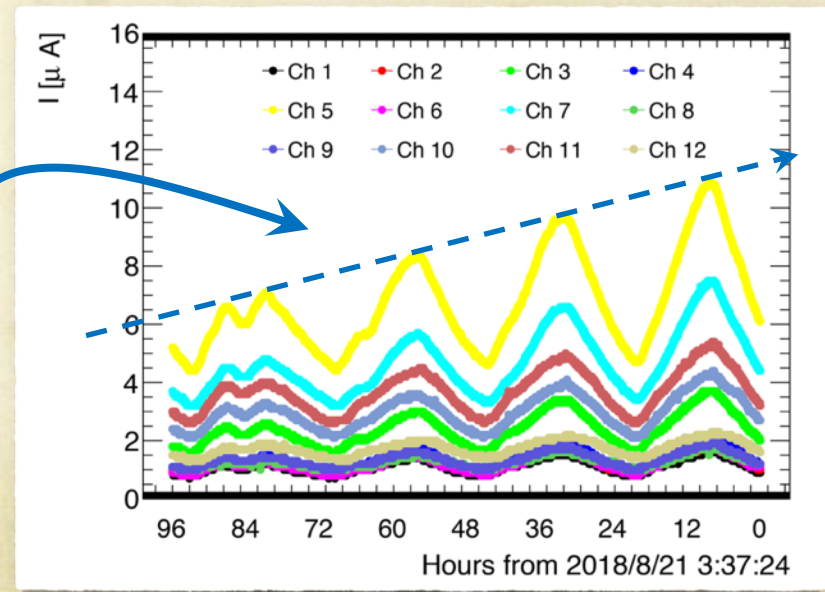
Monitoring system (realised with an **Arduino** and a **Bosch BME280**) installed in ATLAS SX1 building



...modify the RPC behavior/performance

[Operational features, monitoring and control for the RPCs in the Argo-YBJ experiment - P. Camarri, JINST 8 T03002]

Clear dependence of the currents absorbed by the chambers on the **temperature** (and also **pressure**)



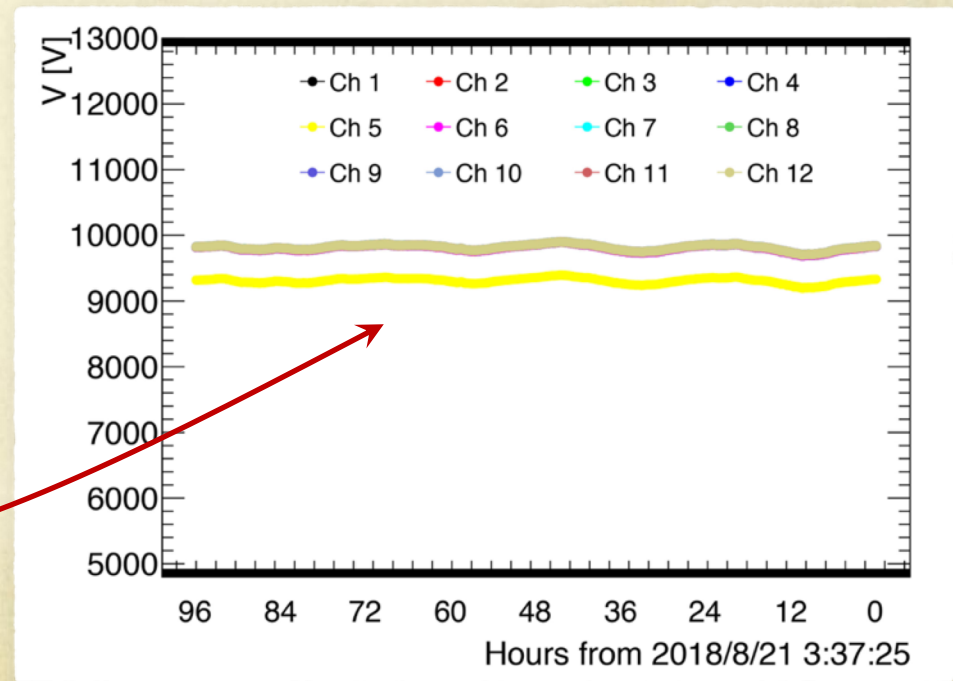
RPC HV Tuning

- The HV of each RPC depends on the **instantaneous pressure** and on the **1 hour delayed temperature**

$$V_{\text{eff}} = V_{\text{app}} \frac{T}{T_0} \frac{p_0}{p} \quad \Rightarrow \quad \text{We want to obtain a constant effective voltage} \quad \Rightarrow \quad V_{\text{app}}(t) = V_0 \frac{T_0}{p_0} \frac{p(t)}{T(t-1\text{h})}$$

[temperature] = K , [pressure] = Pa , [voltage] = V

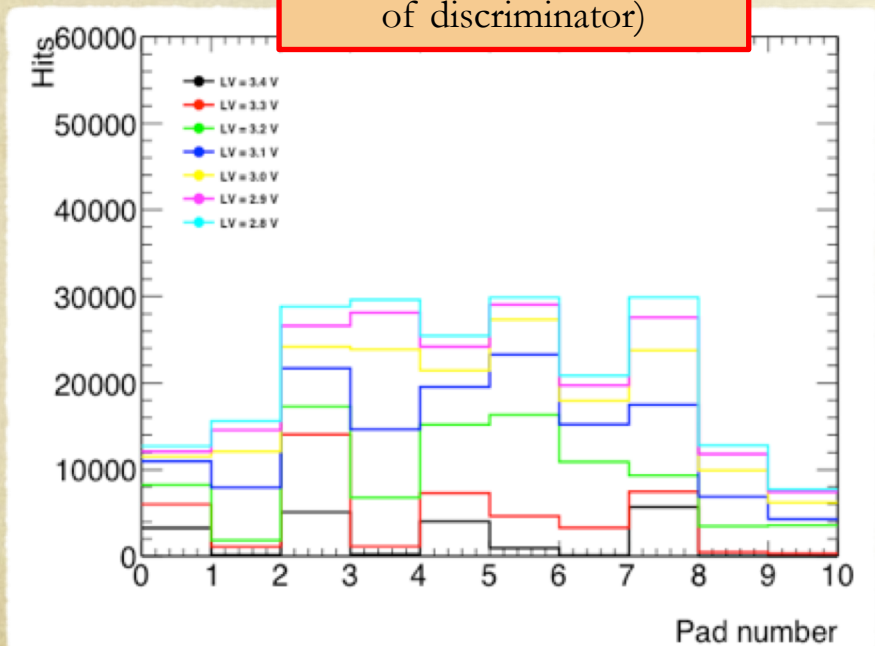
- Implemented an **automatic control system** that monitors temperature and pressure in SX1 and **changes the HV of each chamber accordingly**



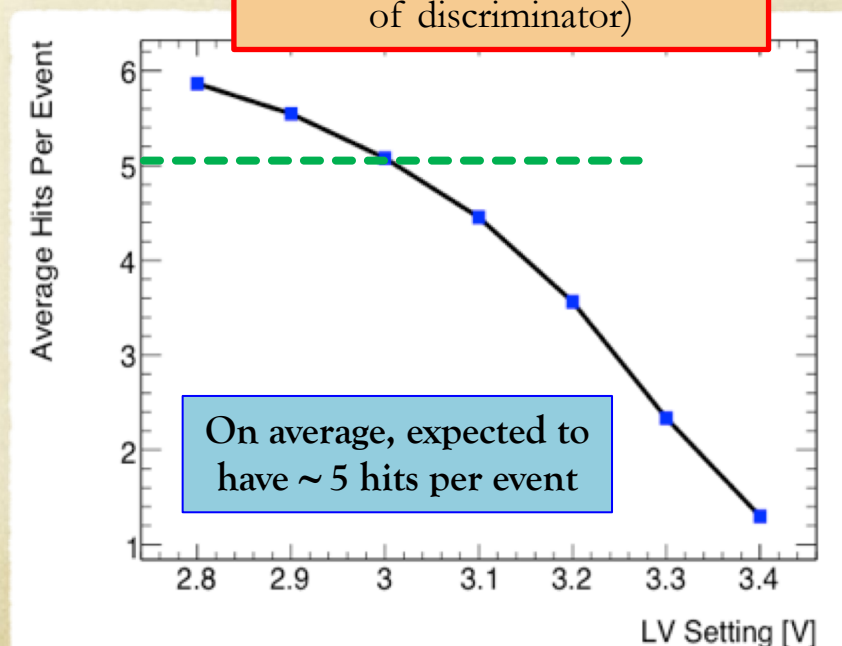
RPC Front-End Readout Tuning

- Front end electronics based on GaAs custom chip consisting of eight discriminator channels each with an output of single-ended ECL level
- Front end discriminator threshold need to be tuned
 - ✓ A too low threshold will increase the number of noisy (fake) hits

RPC pad occupancy
(tuning voltage threshold
of discriminator)



RPC average hits per event
(tuning voltage threshold
of discriminator)

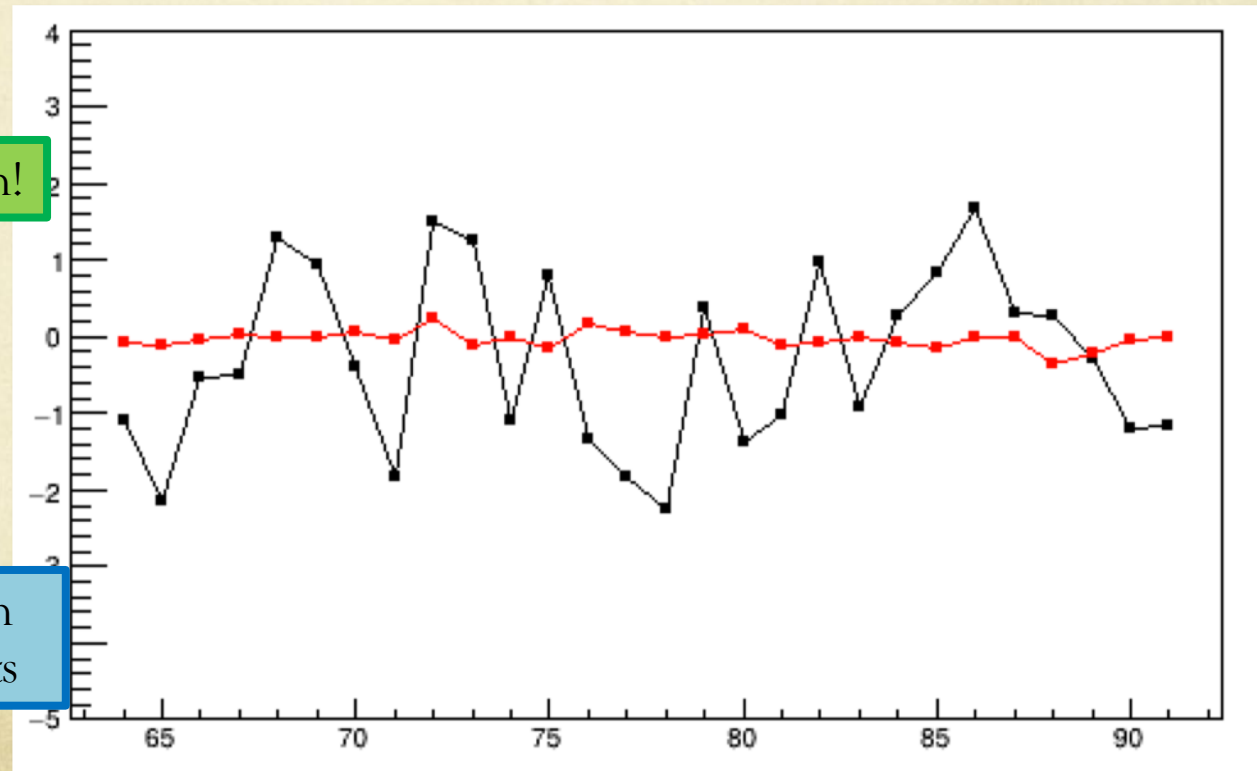


Scintillators Timing Corrections

- Signal propagation time from the scintillators to the TDC input channel is not zero
- Time is different from counter to counter and it depends on HV setting, counter size, etc...
- Delay is calculated for each scintillator (Gaussian fit of the distribution)
 - Time is corrected at hardware level w.r.t. a reference counter

Very good calibration!

...but still margin for improvements



Installation in ATLAS P1 (2)

Henry L. putting the last bolt



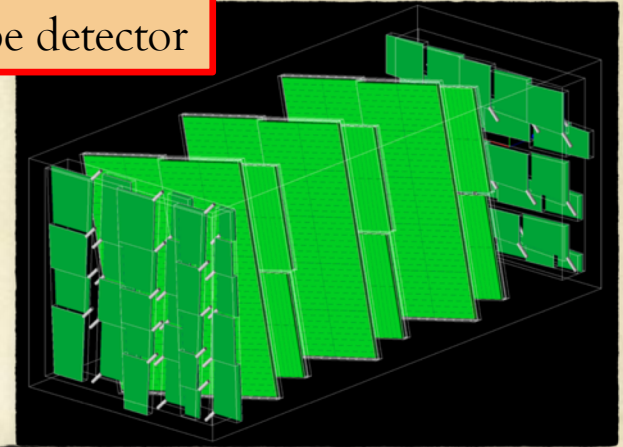
P1 data-taking lasted < 2 weeks

MATHUSLA - Background Simulations

Effort underway to develop simulations of all the sources of backgrounds

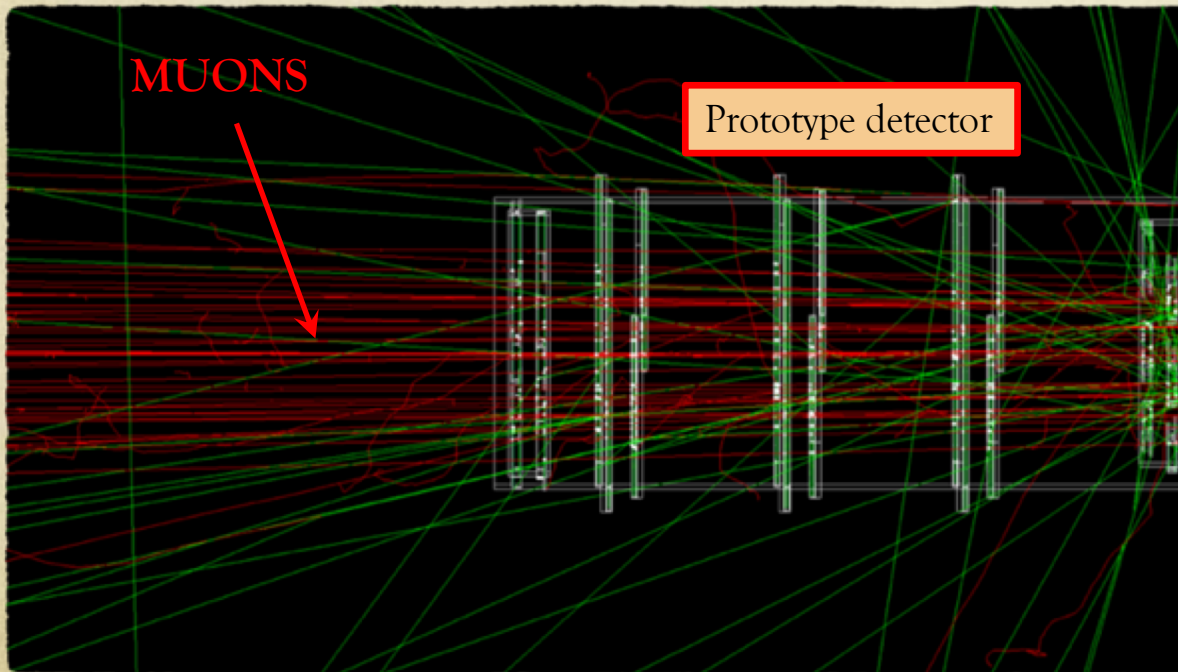
- Current plan to deal with **muons** and **neutrinos traveling upwards** is to create a “gun” that shoots particles into MATHUSLA
- Cosmic ray showers simulated using **CORSIKA** (work is well advance!)
- Atmospheric neutrinos simulated using **GENIE**

Prototype detector

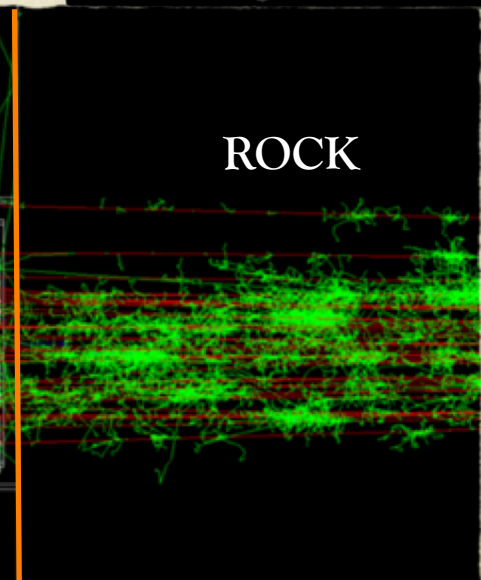


MUONS

Prototype detector



ROCK



ATLAS/CMS
IP

... but simulation need to be anchored to real data!

MATHUSLA White Paper and LoI

Long-Lived Particles at the Energy Frontier: The MATHUSLA Physics Case

1806.07396

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

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