Explore the Lifetime Frontier with MATHUSLA

Cristiano Alpigiani

on behalf of the MATHUSLA Collaboration

UNIVERSITY of WASHINGTON

The Future of Particle Physics: a Quest for Guiding Principles

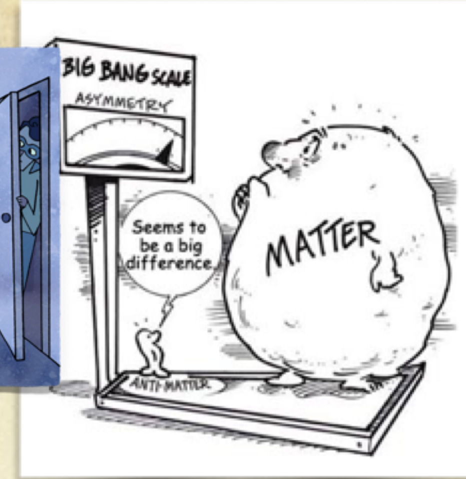
1st October 2018

KIT, Karlsruhe

MATHUSLA

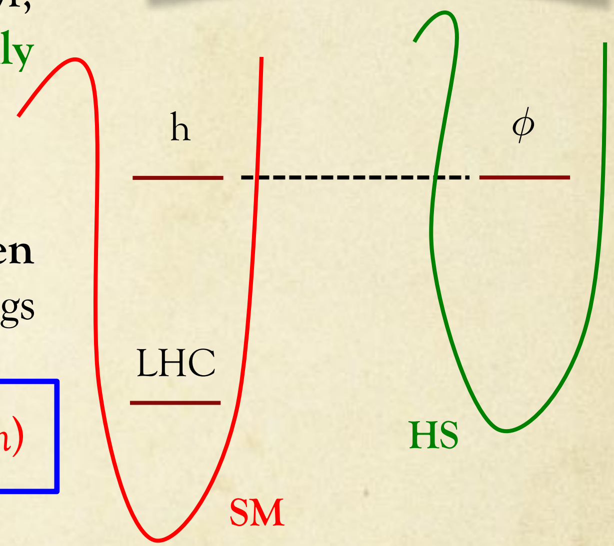
The Hidden Sector

- 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…

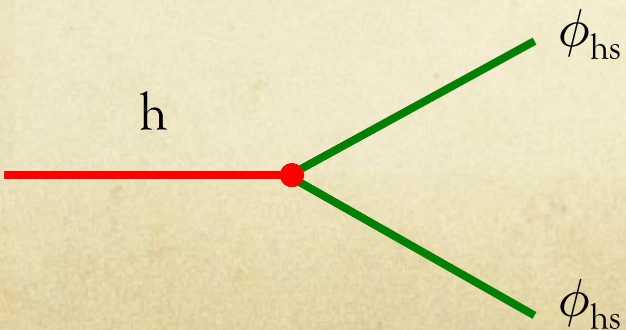


- Many extensions of the SM (Hidden Valley, Stealth SUSY, 2HDM, baryogenesis models, etc) include particles that are **neutral**, **weakly coupled**, and **long-lived** that can decay to final states containing several hadronic jets

- 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)

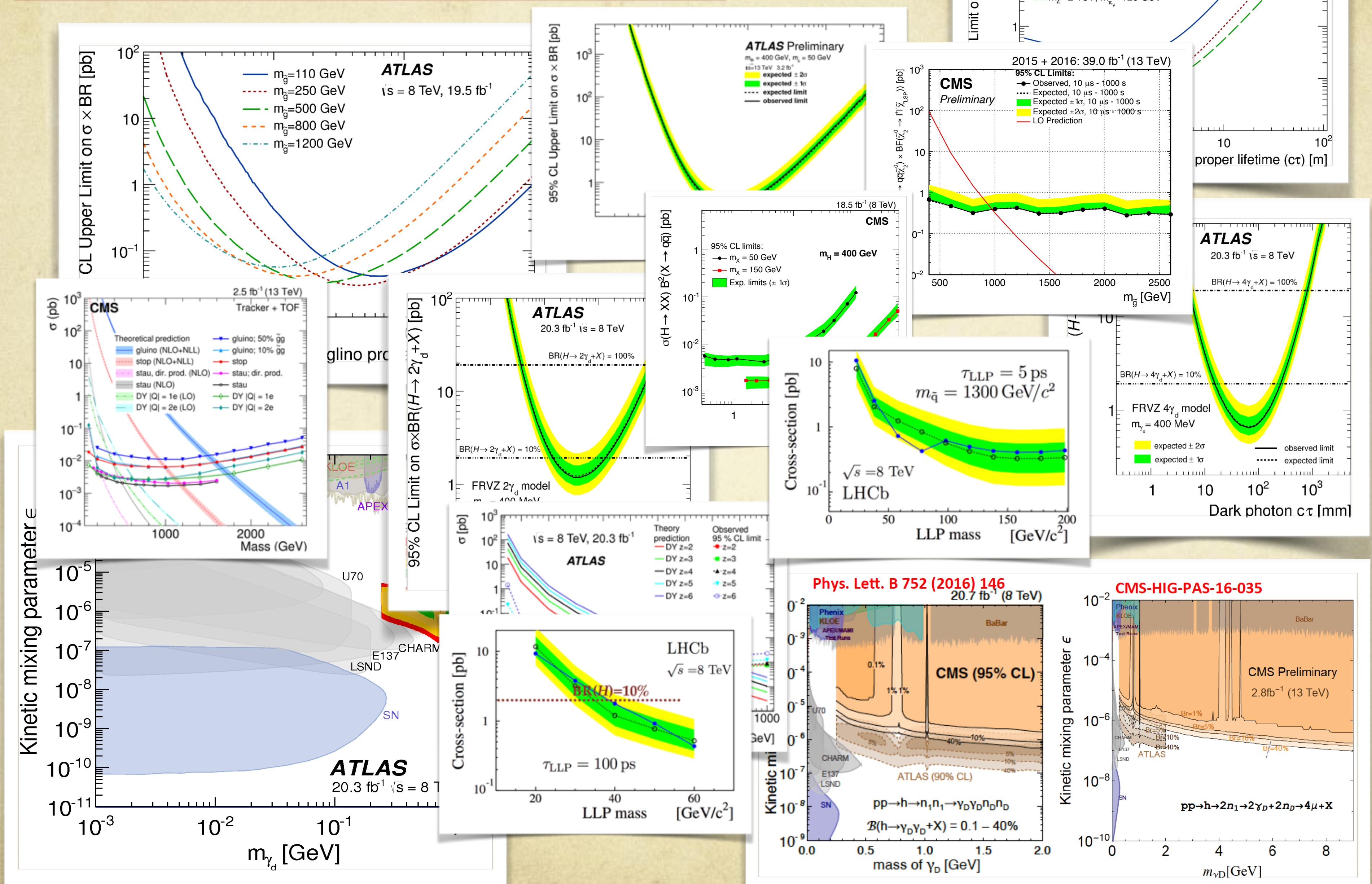


The mixing of Higgs with HS results in a Higgs like particle decaying into LLPs:

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

~ 10^8 Higgs boson @ HL-LHC

Many Searches at LHC…



Many Searches at LHC…

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

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

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**

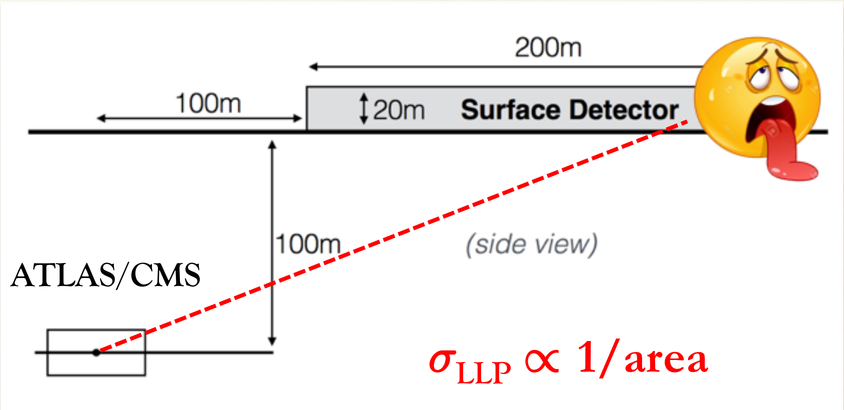
$$L \sim (20\ {\rm m}) \left(\frac{b}{3}\right) \left(\frac{0.1}{\epsilon_{\rm geometric}}\right) \frac{0.3}{{\rm Br}(h \to {\rm ULLP})}$$

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

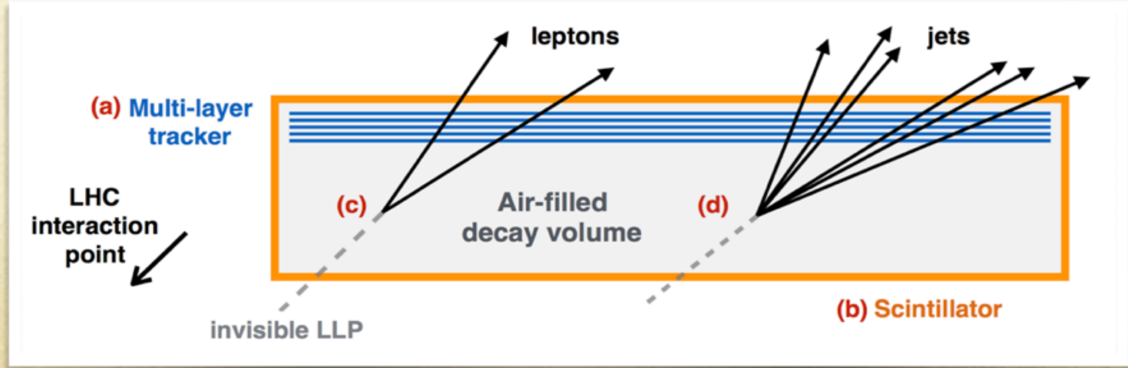
❖ **Need robust tracking**

❖ **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

But other technologies can be investigated for the main detector



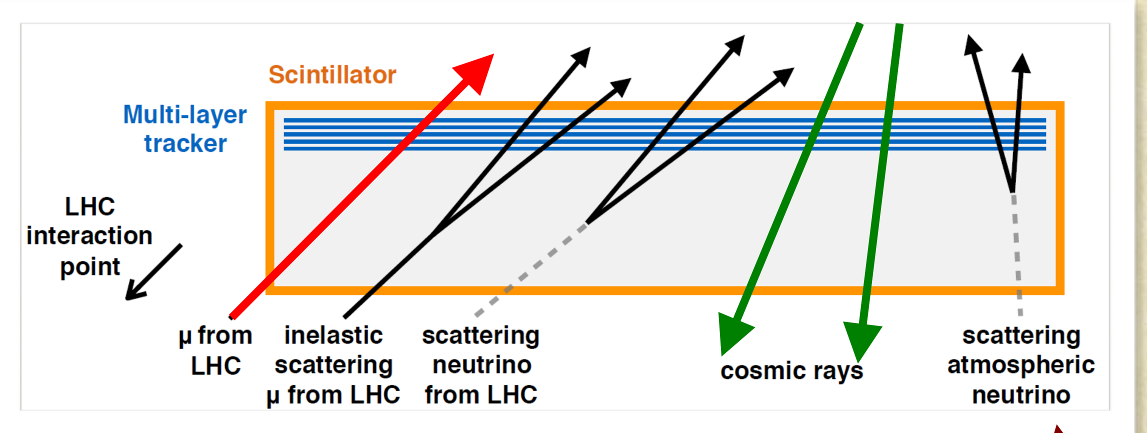
MATHUSLA - Backgrounds

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 m^2)
  → 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**

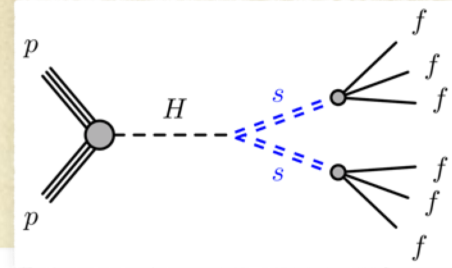


- **Upward atmospheric neutrinos** that interact in air decay volume
  - ✓ Estimate Low rate ~ **70 events per year above 300 MeV**
  - ✓ Mostly "decay" to low momentum proton → reject with time of flight

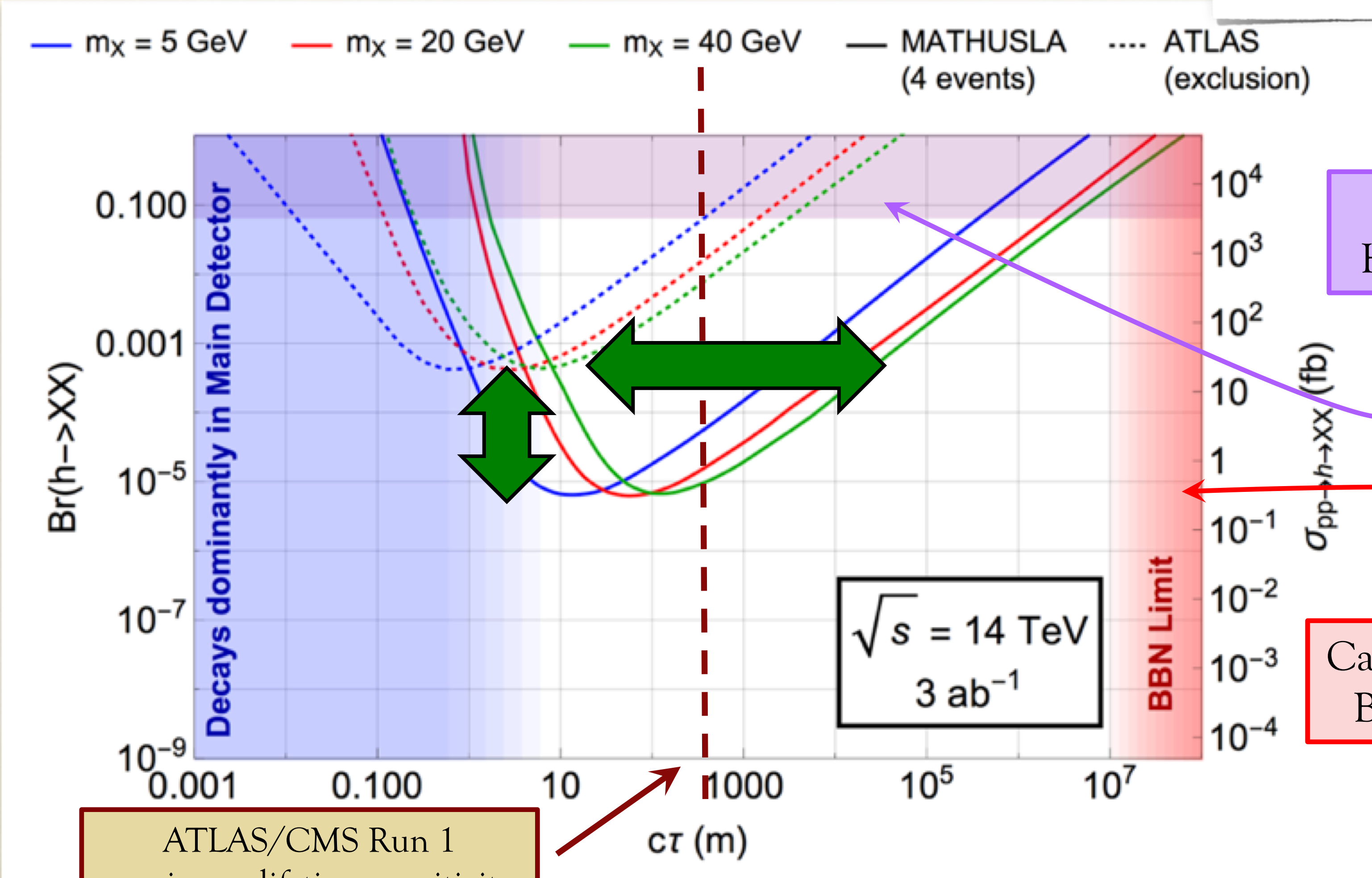
Goal is a background-free MATHUSLA!

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



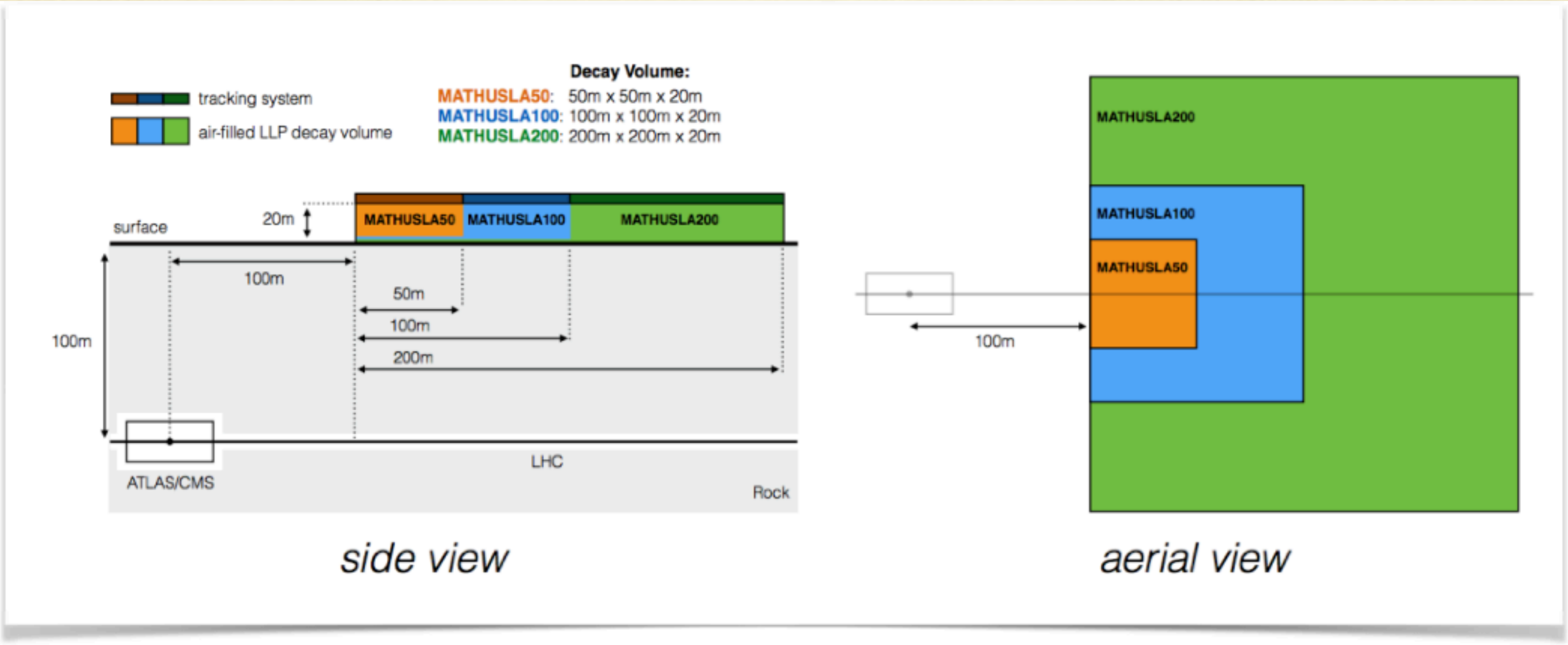
h → inv
HL-LH limit

Can approach
BBN limit!

ATLAS/CMS Run 1
maximum lifetime sensitivity

MATHUSLA LoI Layouts

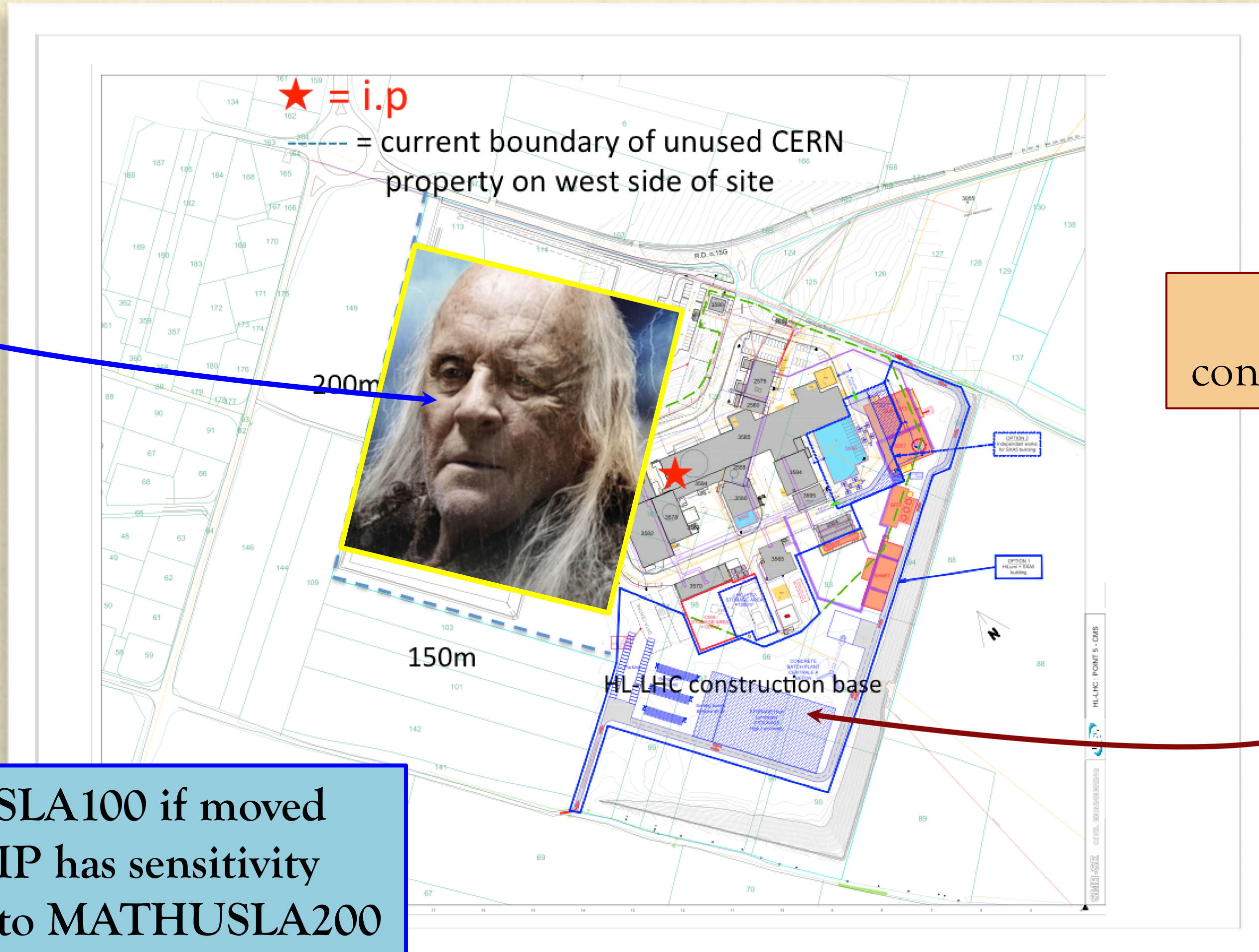
- Geometry discussed in LoI submitted to LHCC



- **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!**

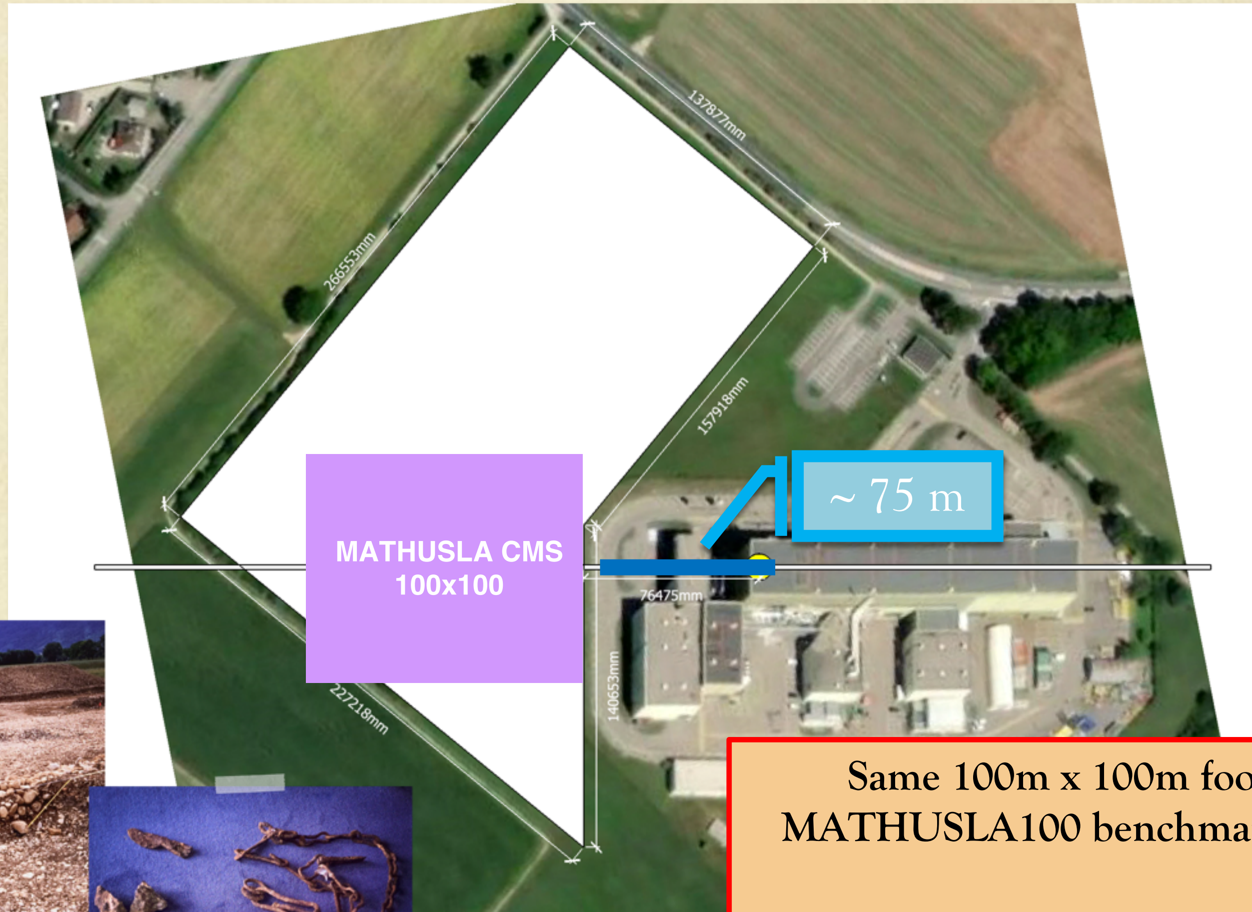


HL-LHC construction base

MATHUSLA100 if moved closer to IP has sensitivity comparable to MATHUSLA200 proposed in 1606.06298

Where MATHUSLA could be located?

- MATHUSLA 100x100 m closer to CMS



Same 100m x 100m footprint as MATHUSLA100 benchmark from LOI

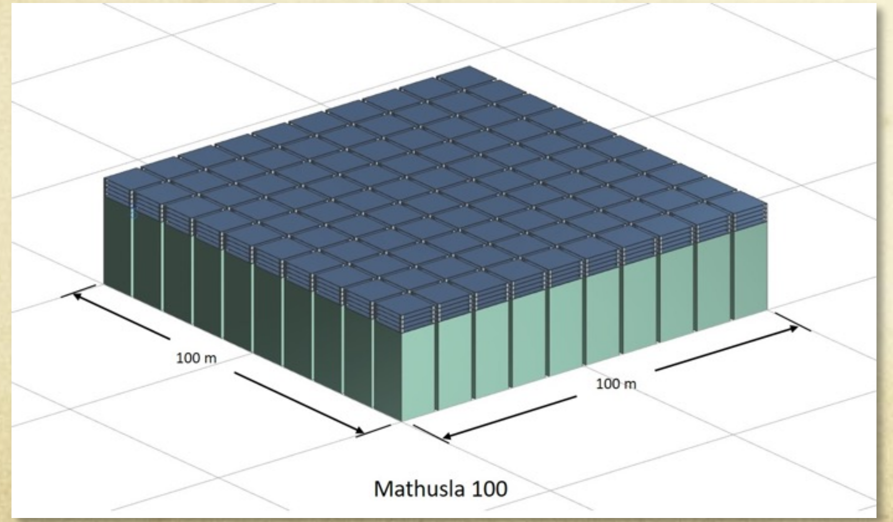
If decay volume is buried, it is 30 m closer vertically and 25 m closer horizontally to the IP than MATHUSLA100

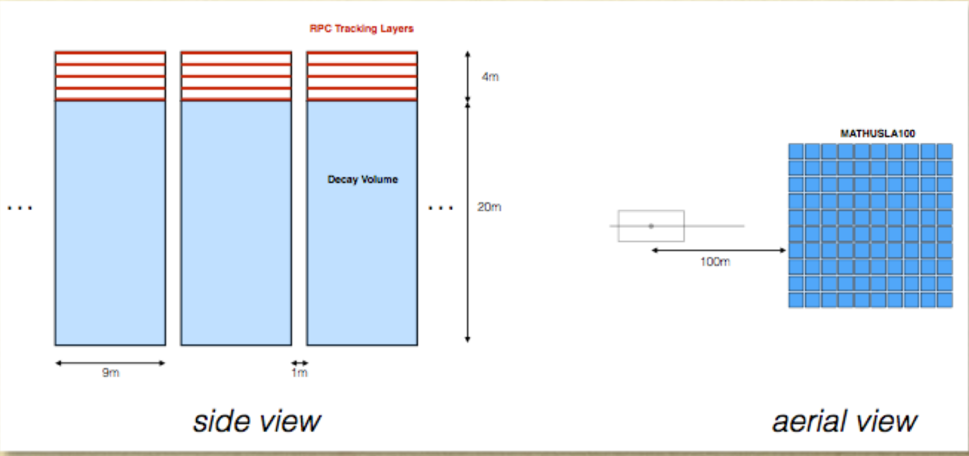
Where MATHUSLA could be located?

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

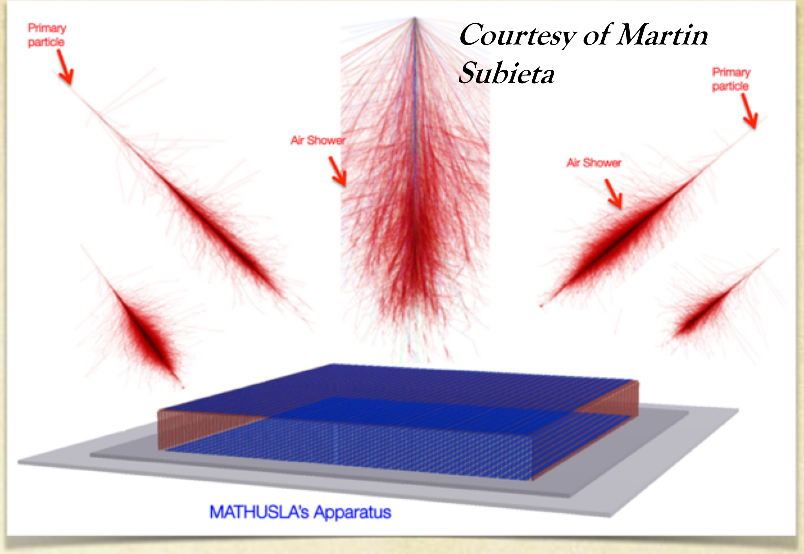
Modular Concept

- 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



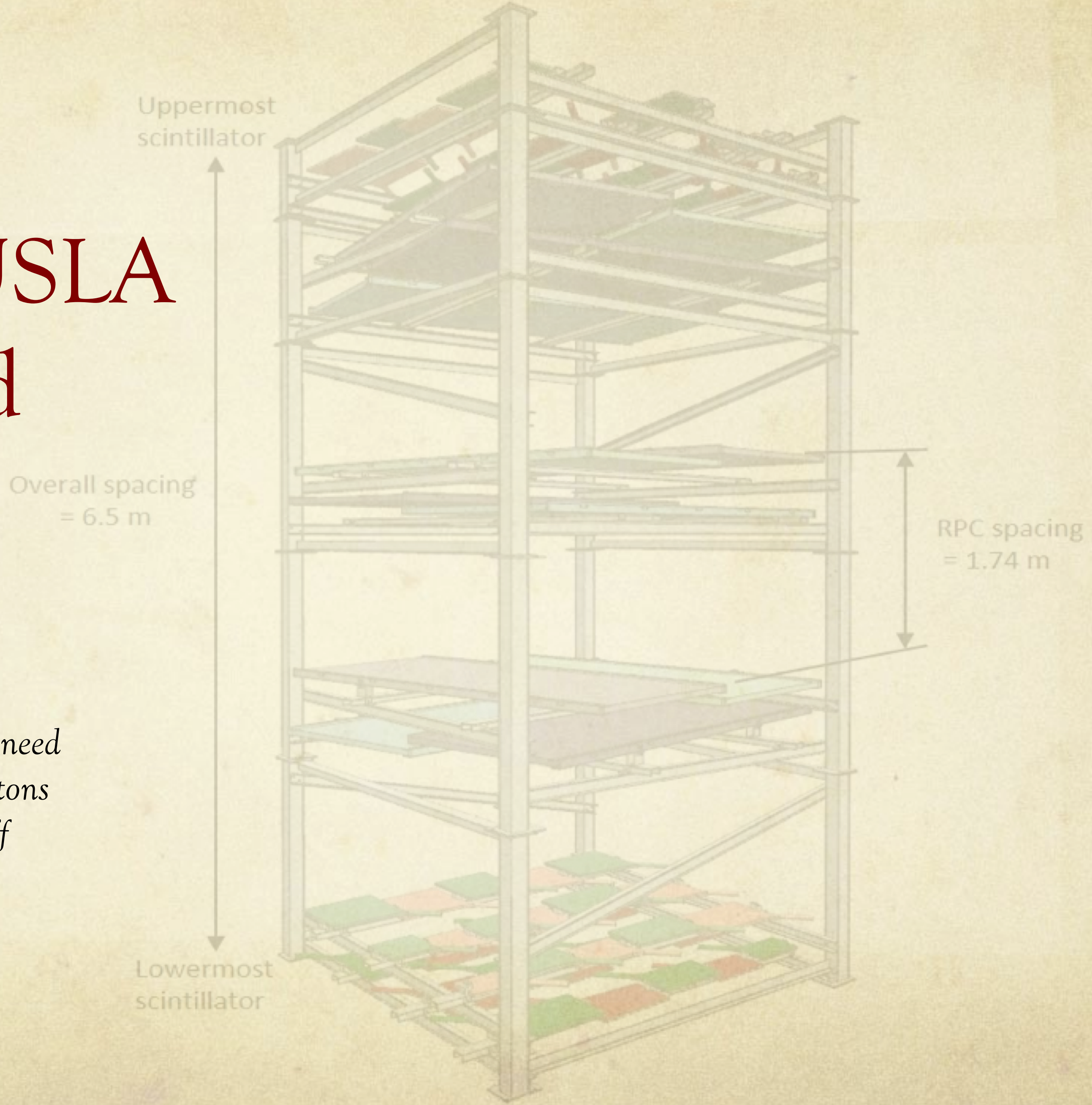


MATHUSLA - Cosmic Rays



- **KASCADE** is currently a leading experiment in this energy range
- Has larger area than MATHUSLA100 (40,000 m^2 vs 10,000 m^2) 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. For example, **the shape of the core is not well studied, and MATHUSLA could provide new information**
- MATHUSLA+CMS 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

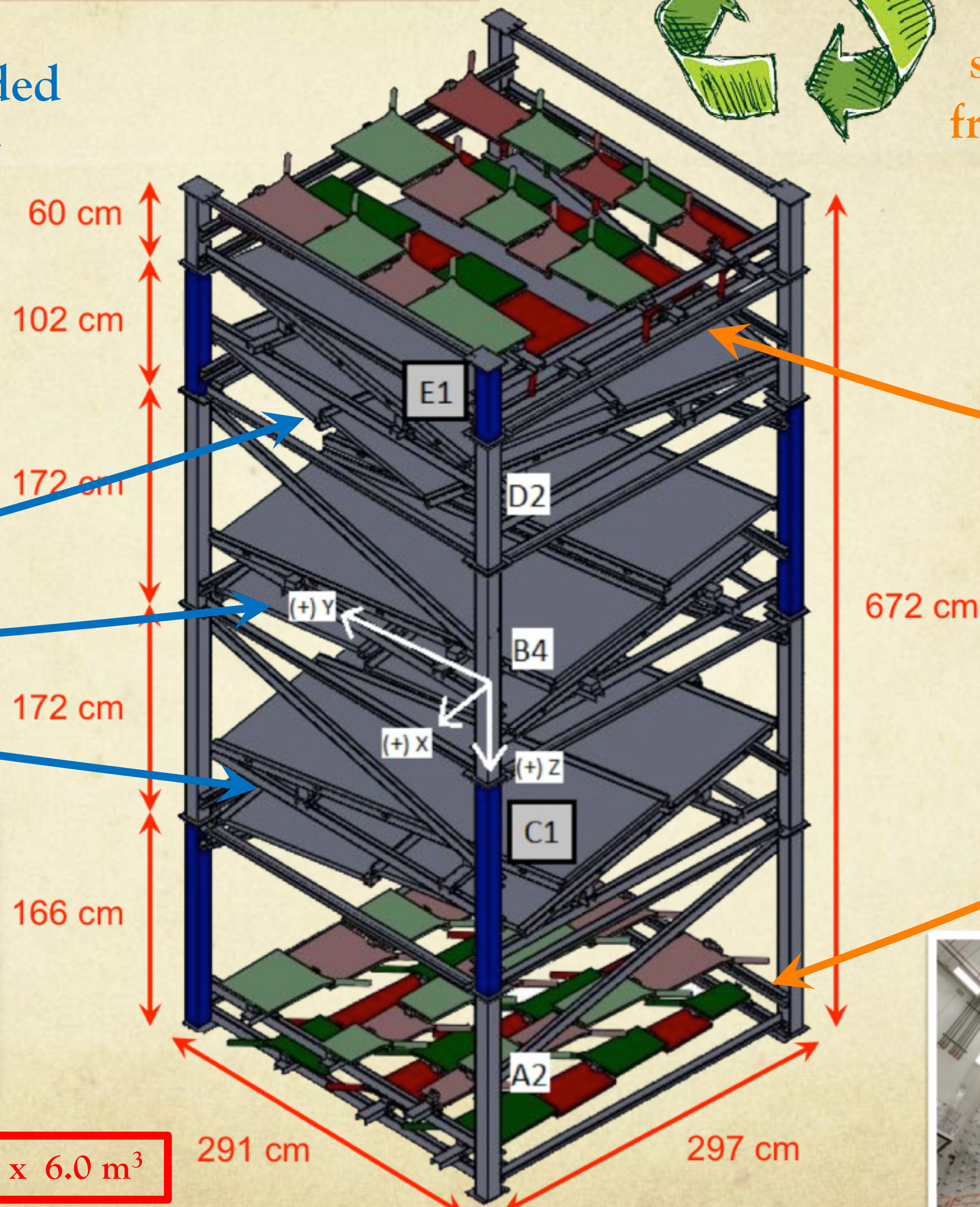


MC background simulations need data with LHC colliding protons and also when the beam is off

The MATHUSLA Test Stand

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

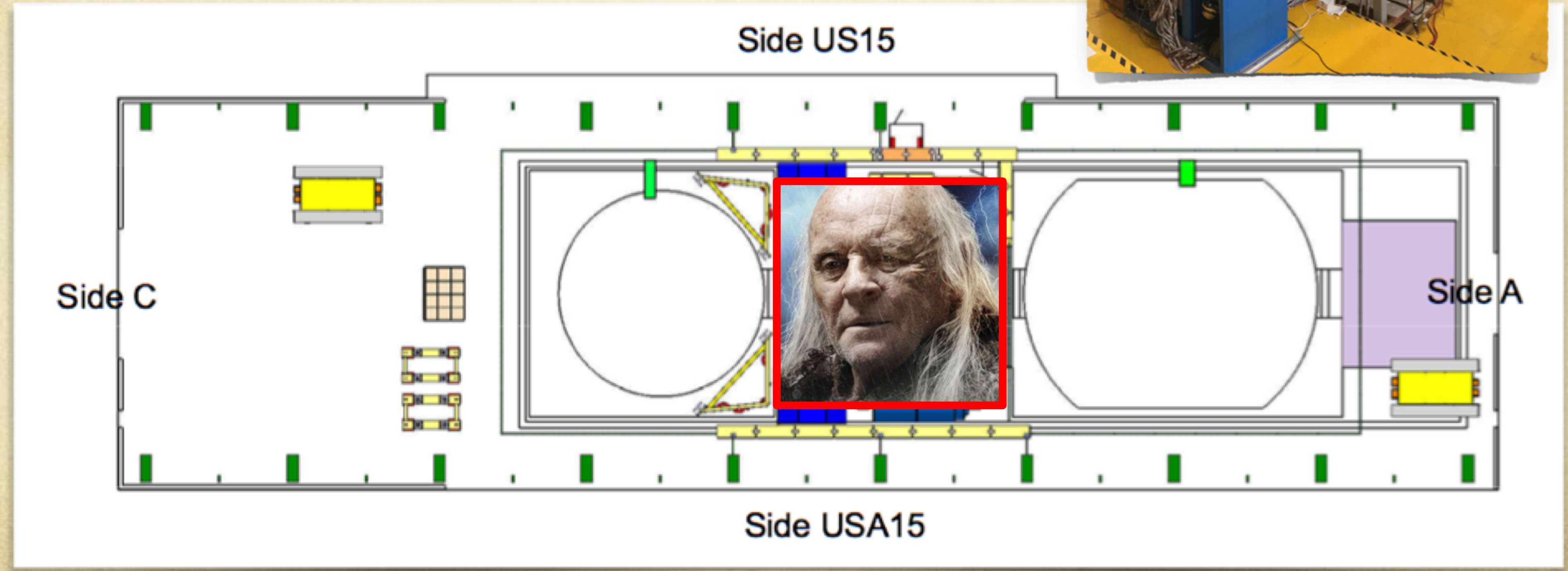
Active area ~ 2.5 x 2.5 x 6.0 m^3



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

Installation in ATLAS P1

- Cosmic background (~) 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**

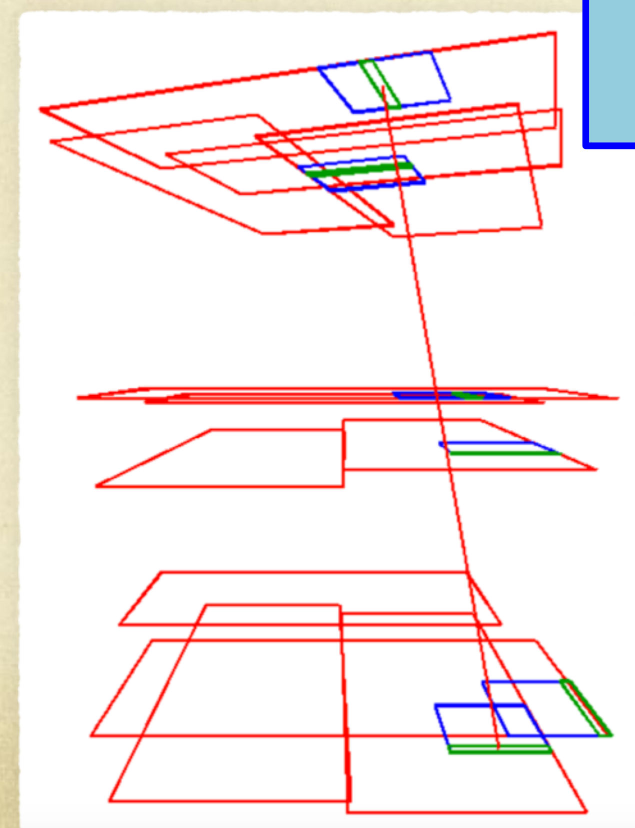


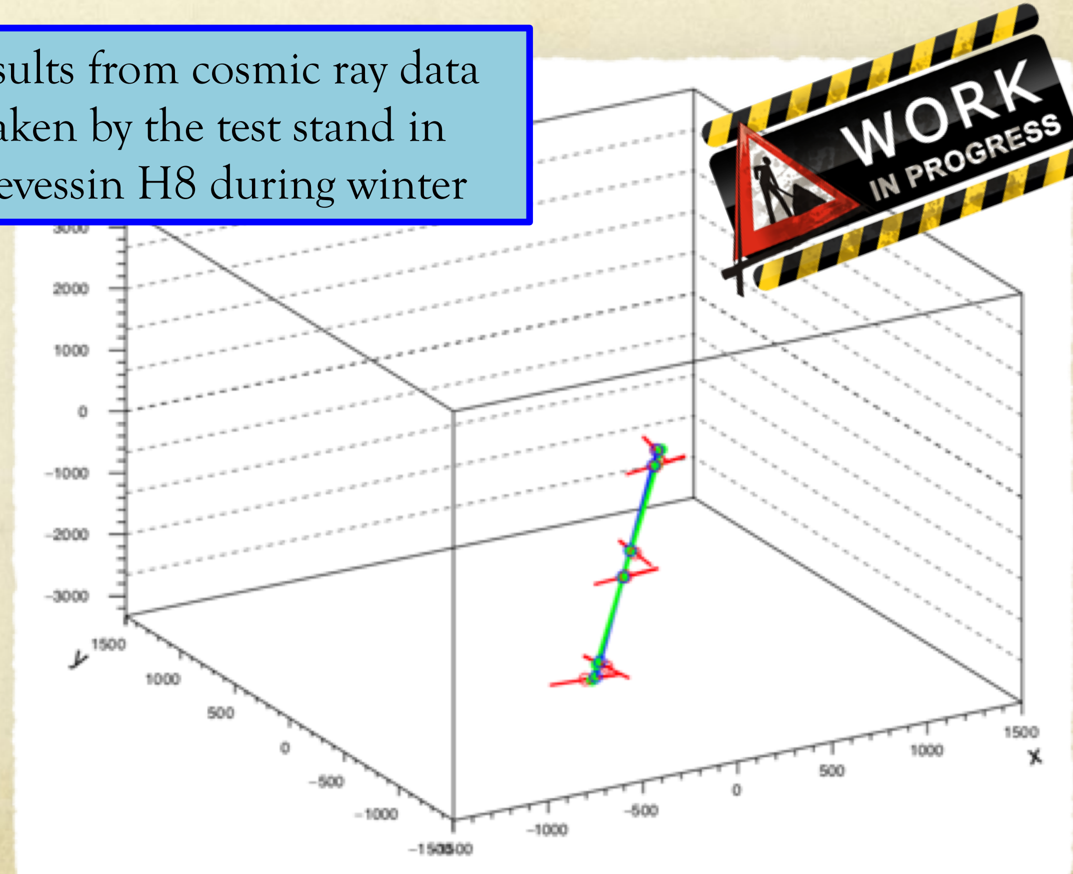
MATHUSLA tracking

- On-going effort
- Very simple track reconstruction, χ^2 fit

$$\Delta\chi^2 = \left[(\vec{x}_{hit} - \vec{x}_{track}) \cdot \hat{L}/\sigma_L\right]^2 + \left[(\vec{x}_{hit} - \vec{x}_{track}) \cdot \hat{W}/\sigma_W\right]^2$$

- **Preliminary results**



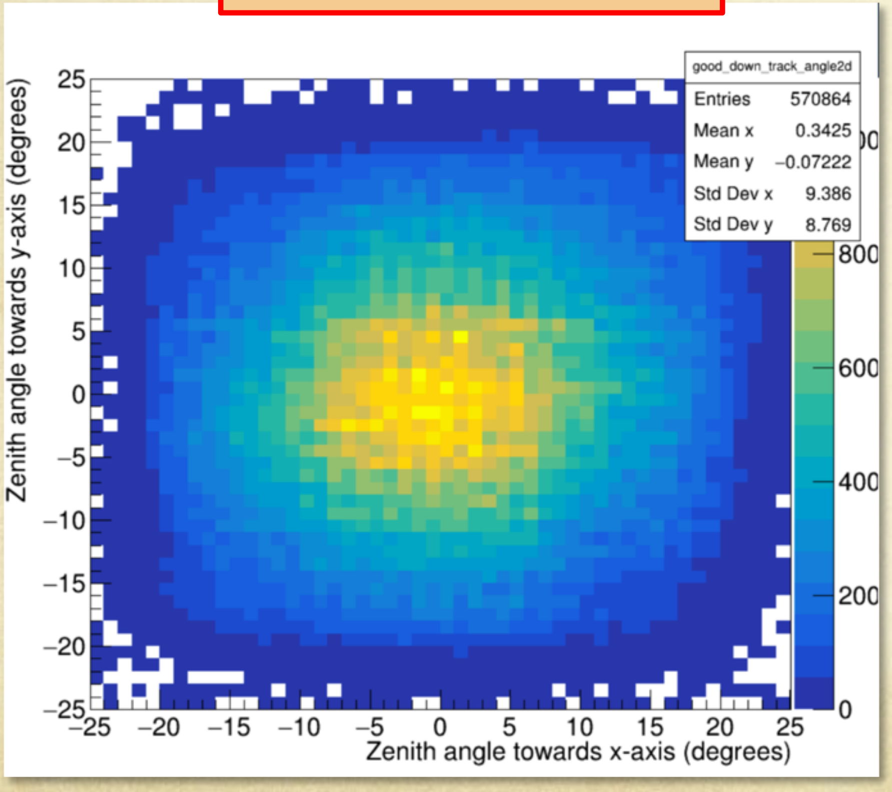


Results from cosmic ray data taken by the test stand in Prevessin H8 during winter

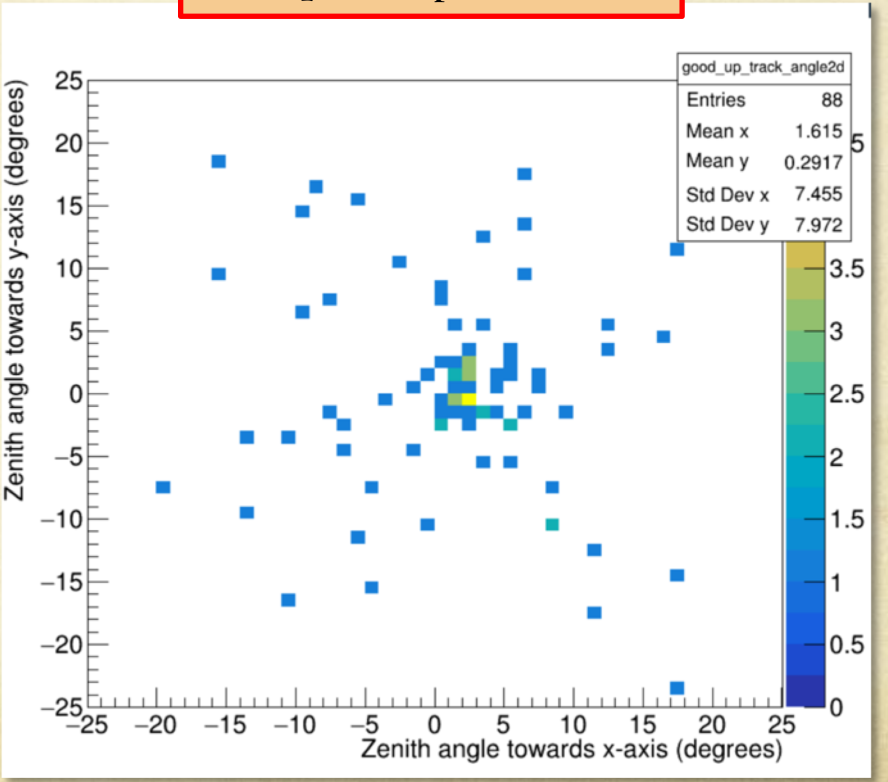
MATHUSLA tracking: upward and downward

- Result from several hours with LHC beam on
- Preliminary results

Angle distribution for **downward** particles



Angle distribution for **upward** particles



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 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 cosmics)
- A **letter of Intent** has been submitted to LHCC in July
- Workshop hosted by Simon Center for Geometry and Physics in Stony Brook at the end of last August
  - ✓ Lots of feedbacks from reviewers, lot of discussion
- Finalising data taking and data analysis

- Cristiano.Alpigiani@cern.ch
- mathusla.experiment@cern.ch

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-cτ)
- 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 **>~** 3.5 ns

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J-P Chou, D. Curtin, H. Lubatti
arXiv 1606.06298
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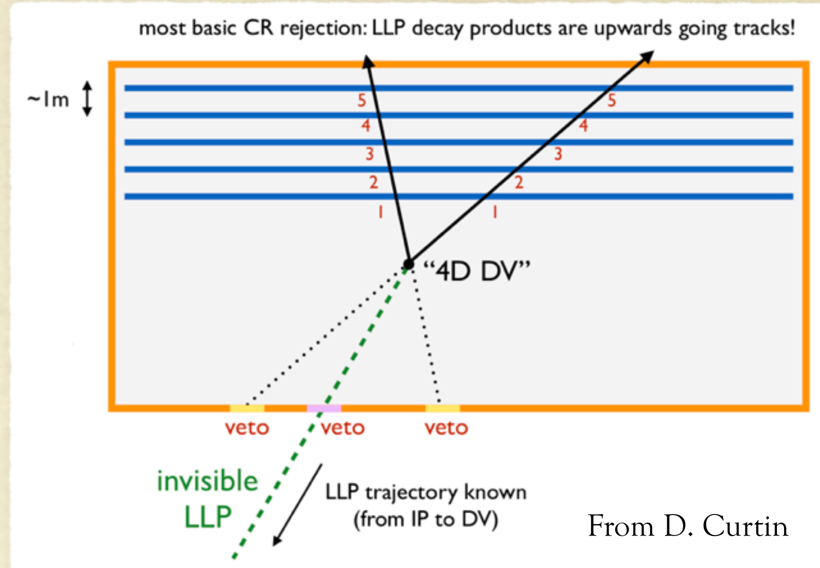
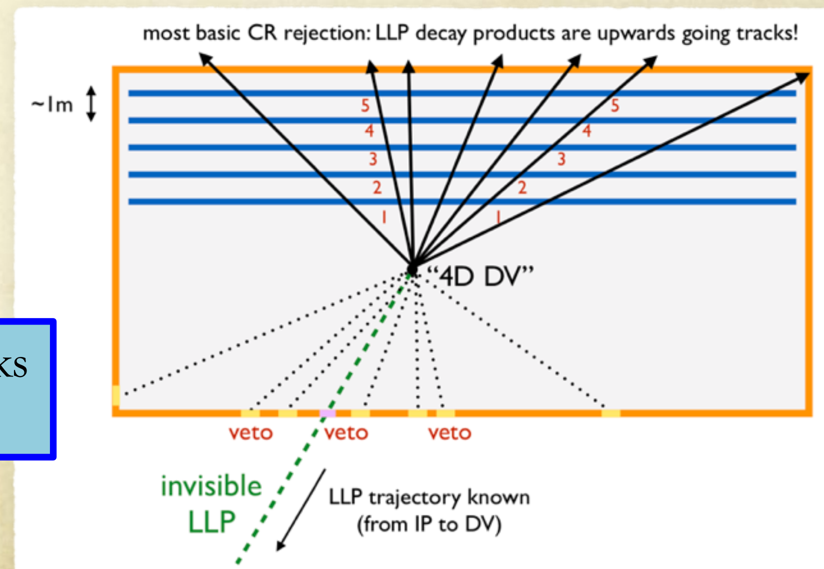
Tracks are reconstructed in **3D** and with detailed **timing** information at each layer, the DV is really a **4D DV**

More difficult to fake → all tracks have to pass veto requirements



From D. Curtin



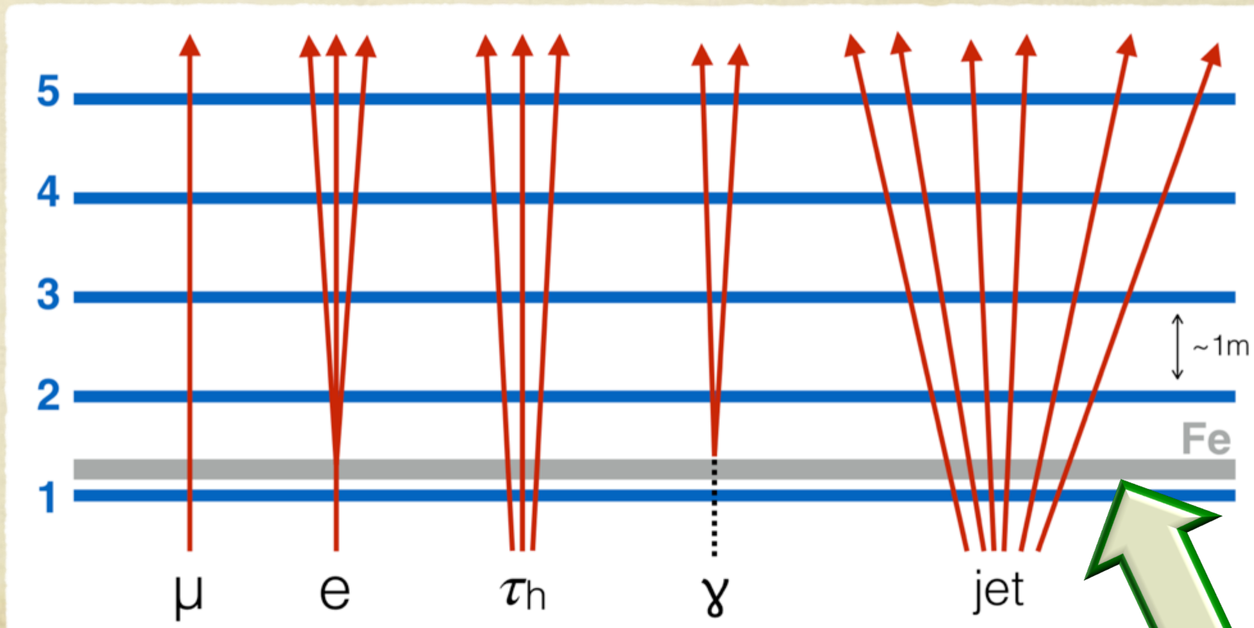
MATHUSLA – particle identification

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. trcking plane can be know 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 x 200 m^2 = 80 000 m^2 + sides = 4 x 200 x 20 m^2 = 16 000 m^2

→ Total area = 96 000 m^2

- Assume thickness = 1 cm, density = 1 gm/m^3
- Assume 3 USD / kg (low end of NOνA 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 optmised, 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.

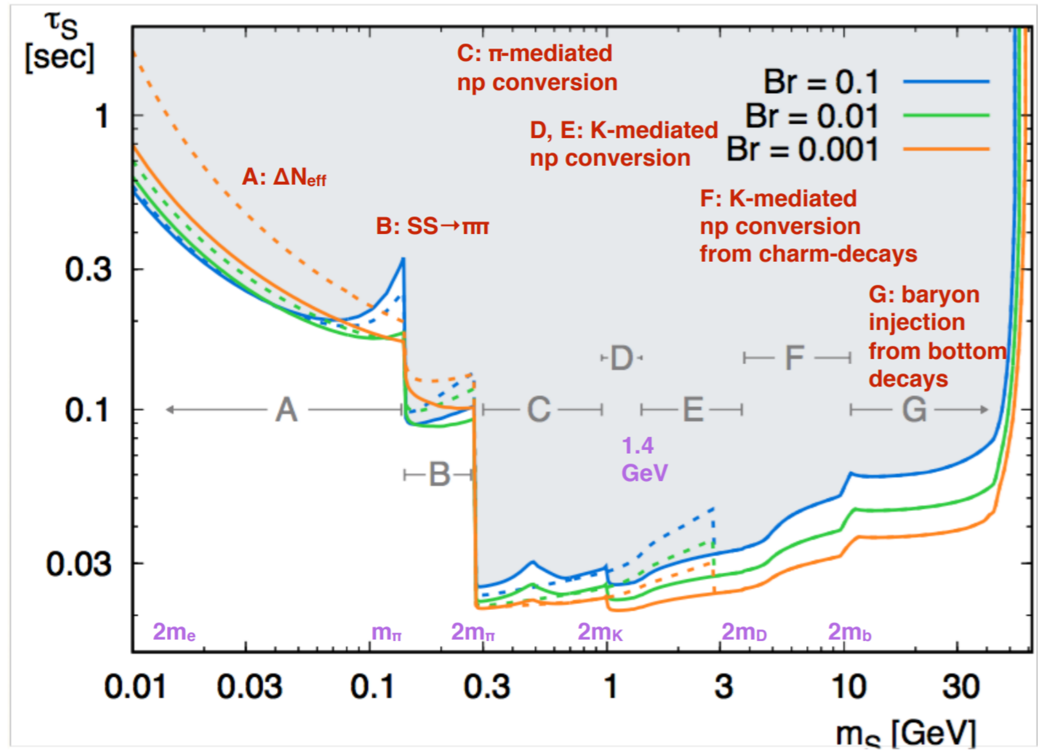
- **MATHUSLA sized building is plausible for 16 MCHF**: twice the height and probably more support columns. This assumes a surface building.

- 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.

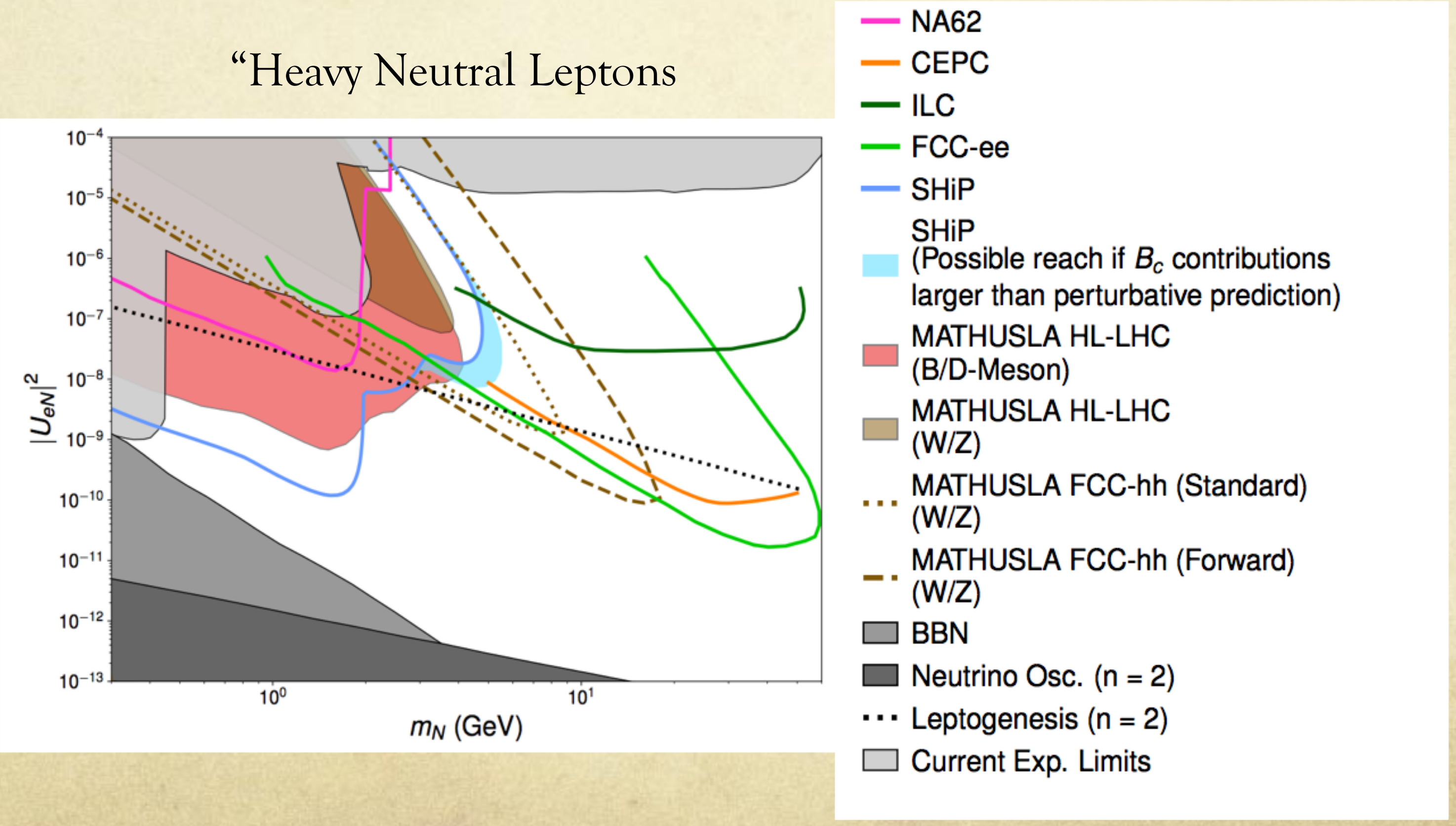


- For $m_s > m_\pi$ the lifetime $\tau < 0.1$ s.
- Conclusion does not depend strongly on BR($h \rightarrow ss$)

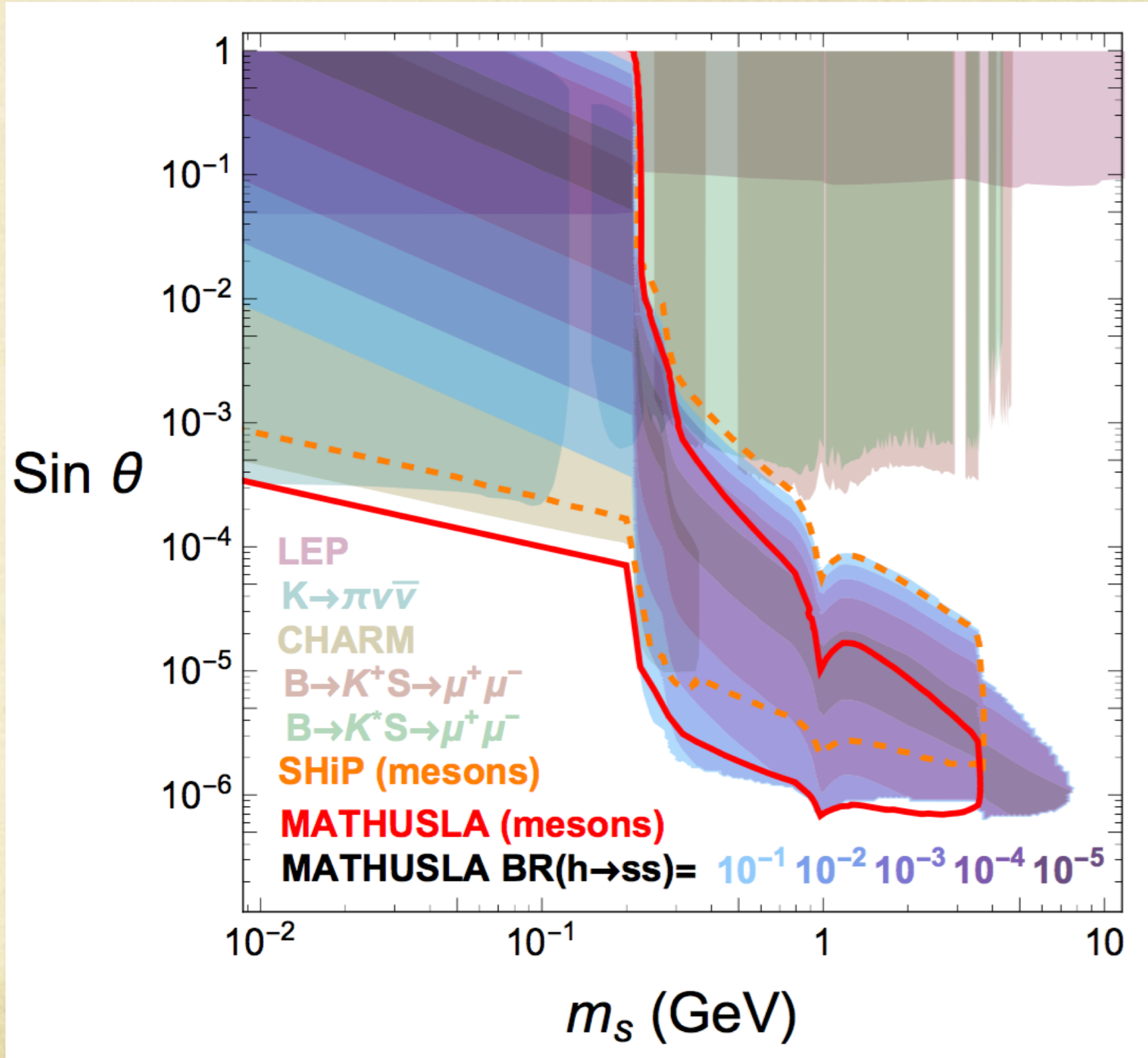
MATHUSLA – SHiP Comparison

- **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 >> 100** m even at low masses
- SHiP is limited by lower √s to probing masses of order a few GeV which limits new physics reach to low mass LLPs

"Heavy Neutral Leptons



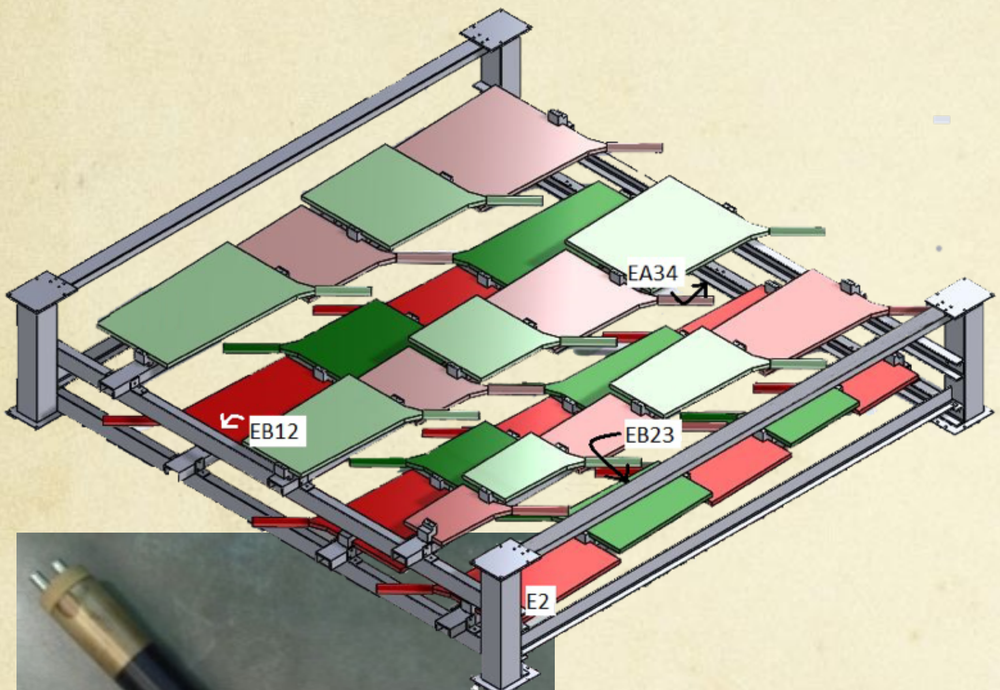
MATHUSLA – SHiP Comparison



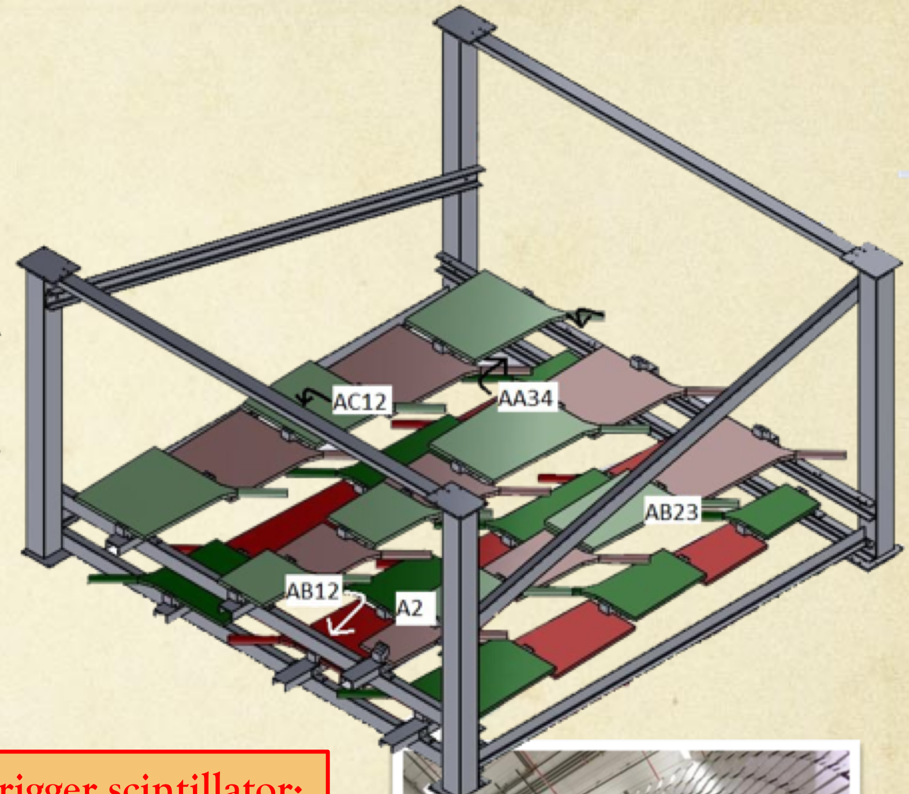
MATHUSLA has significant sensitivity for long lifetime

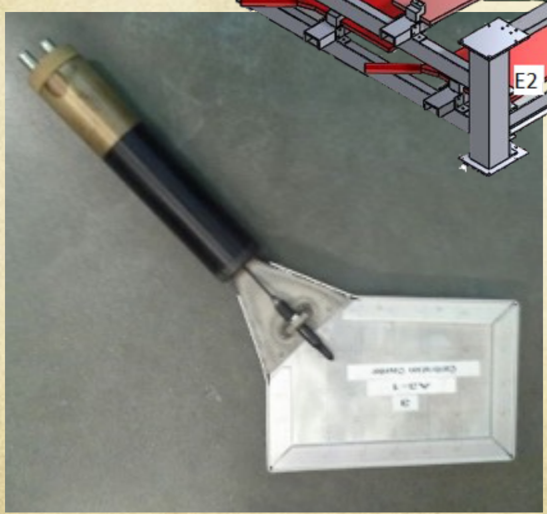
Test Stand Scintillator Details

Top – 31 scintillators



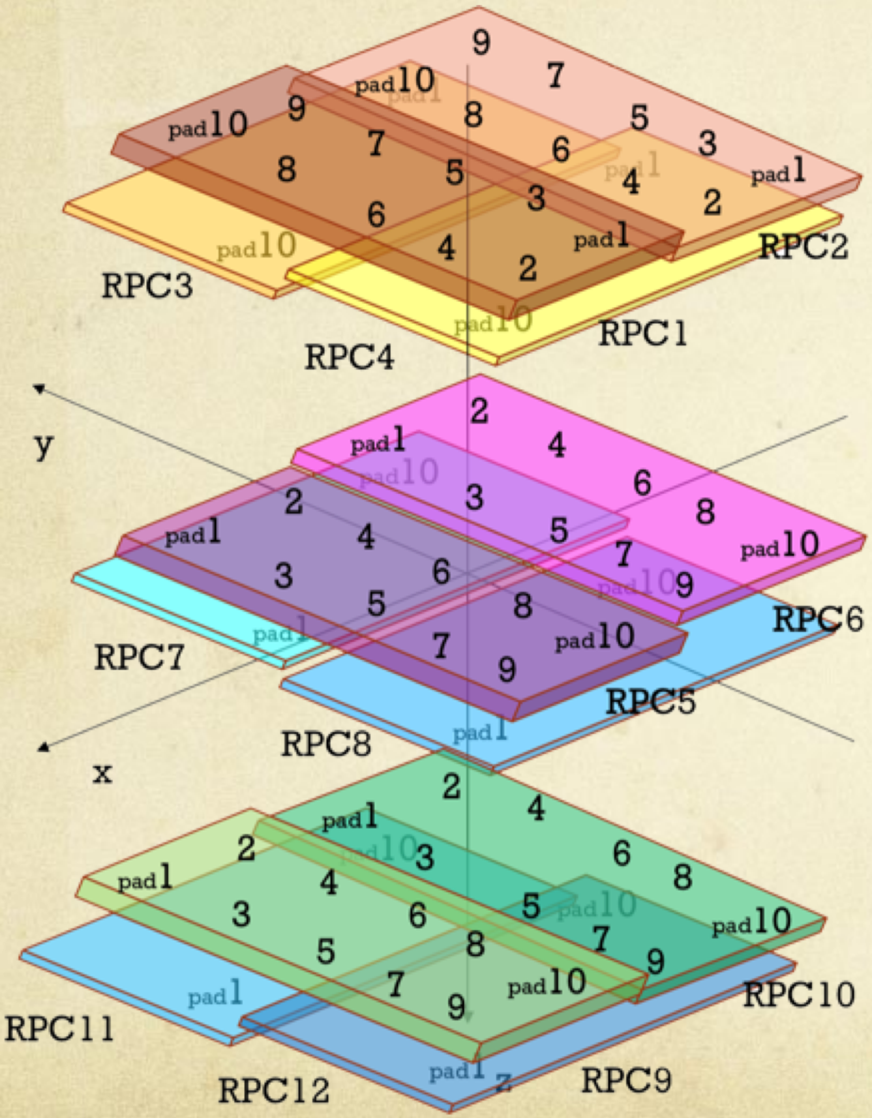
Bottom – 28 scintillators



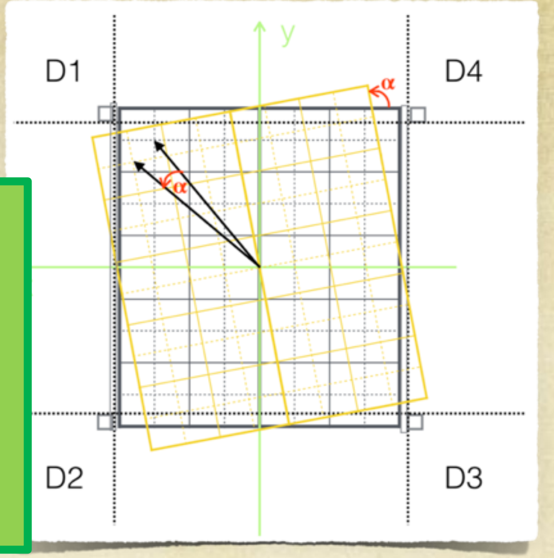


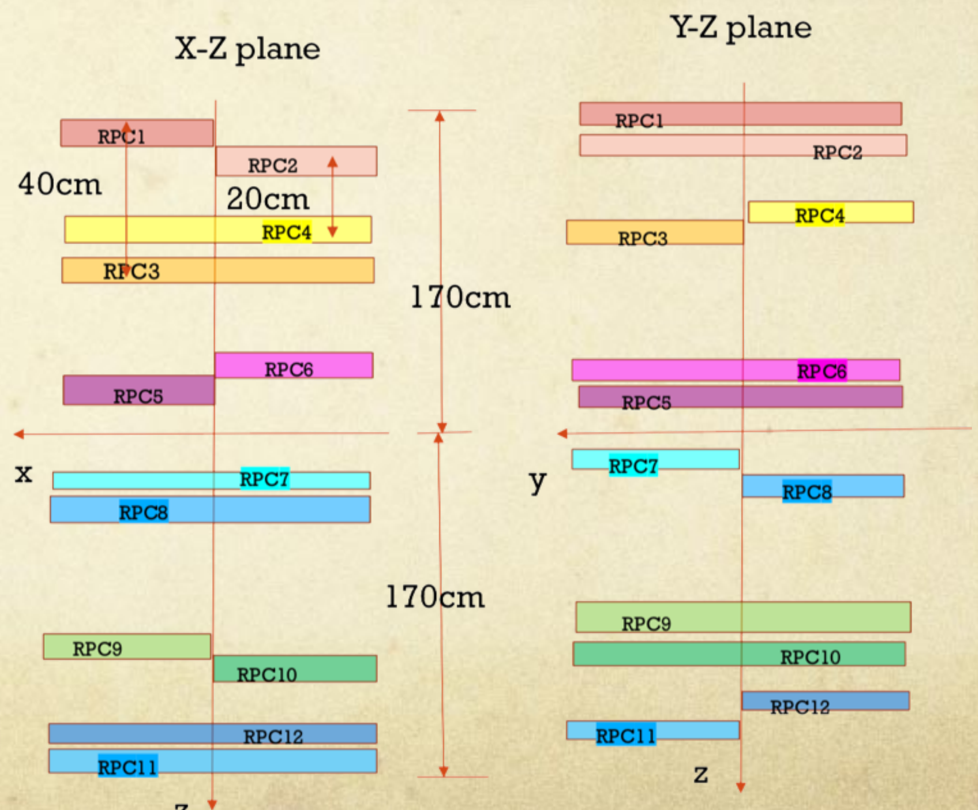
D0 forward MUON trigger scintillator: 12.8-mm-thick BICRON 404A of <u>trapezoidal</u> shape + WLS bars for light collection

Test Stand RPC Details



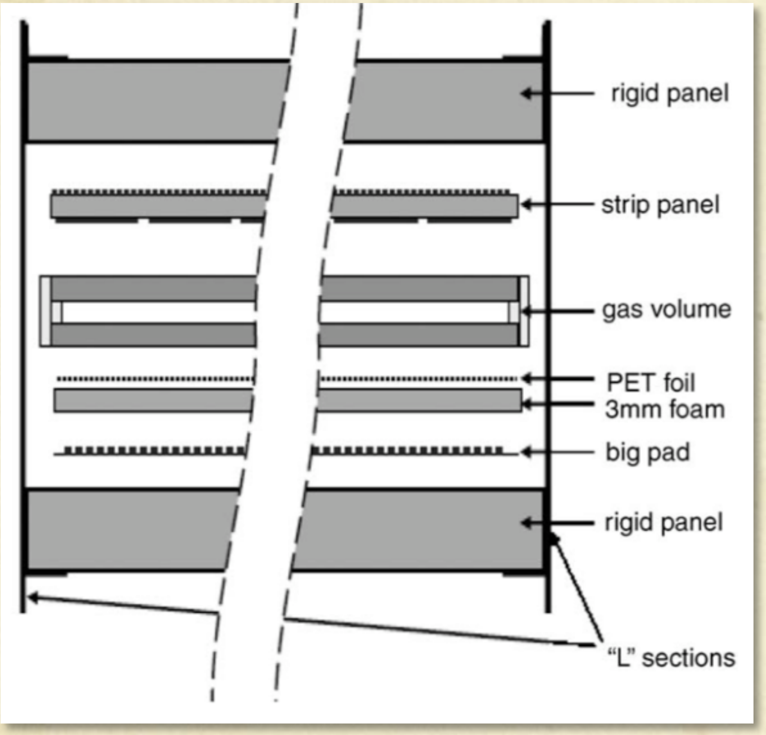
Small stereo rotation angle between the 3 tracking planes to reduce ambiguity and ghost hits





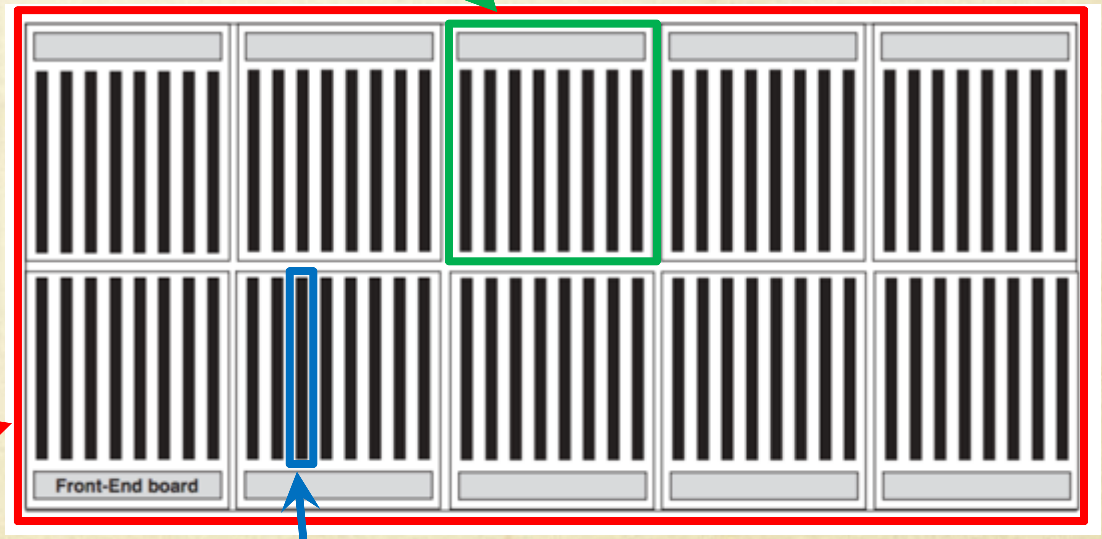
Test Stand RPC Details

- 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)**

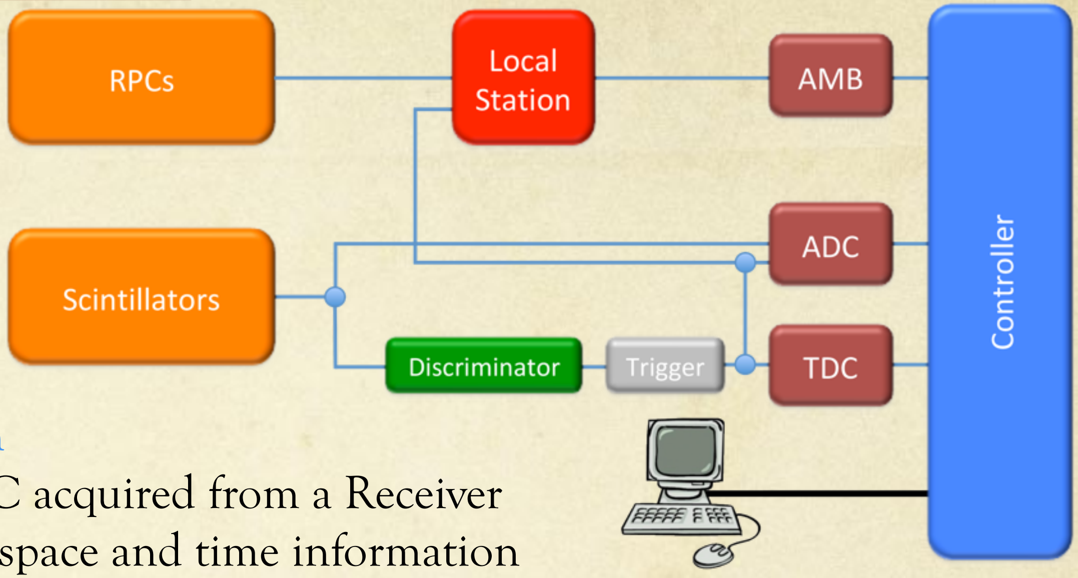
10 Pads (55.6 x 61.8 cm^2) for each RPC



Chamber size: 1.25 x 2.80 m^2

8 Strips (6.75 x 61.8 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

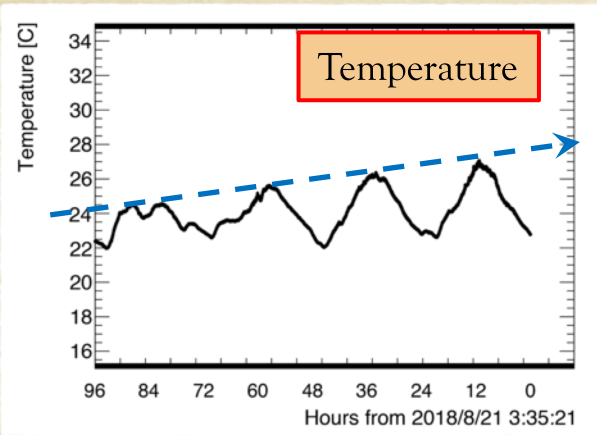
Two possible triggers: top and bottom scintillators in coincidence, with:

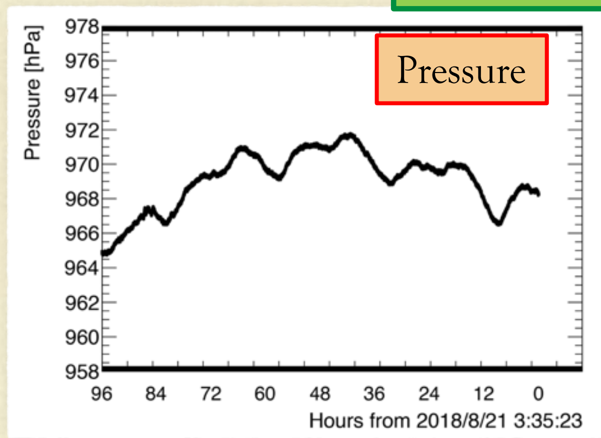
1. **Timing appropriate for downward going particle** (cosmic ray events can be used for space and time alignment)
2. **Timing appropriate for upward going particle**

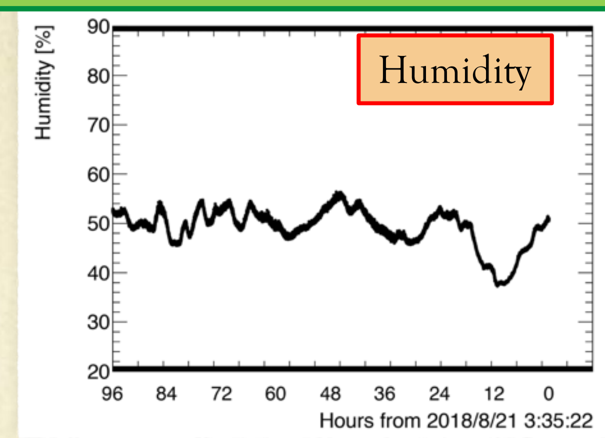
RPC Performance vs Environmental Conditions

- Environmental conditions

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



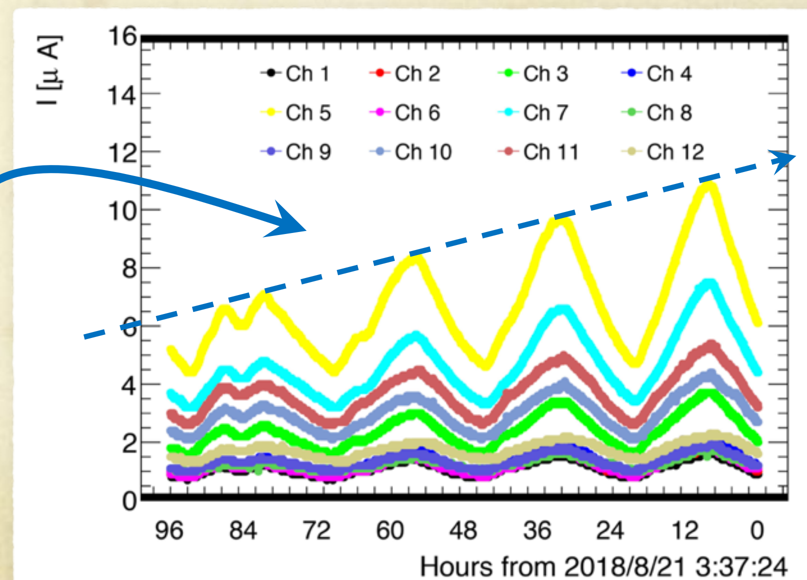




...modify the RPC behavior/performance

[*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**

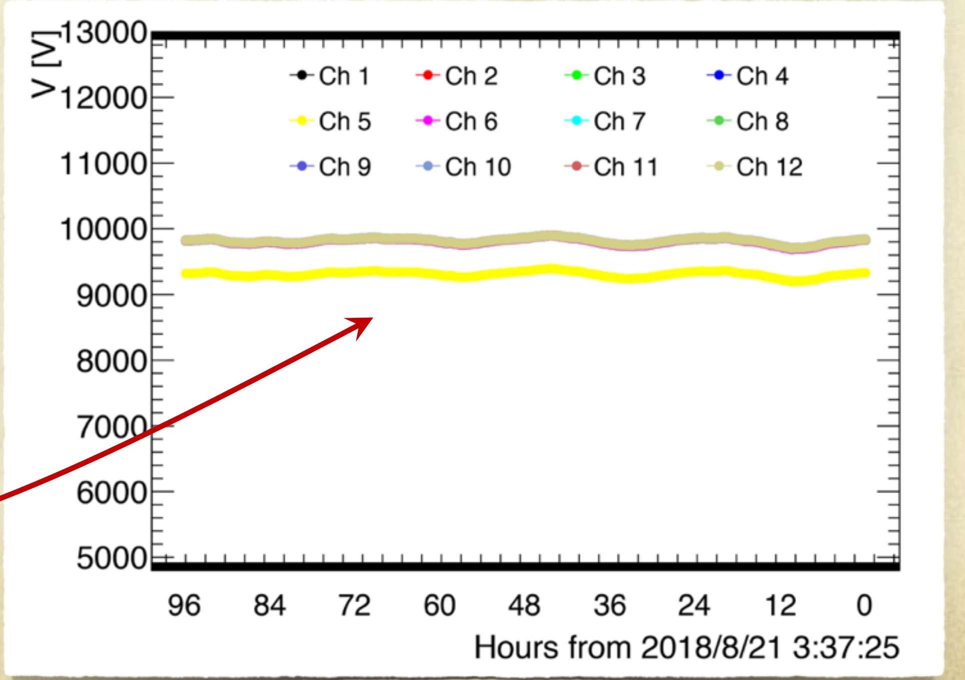
$$V_{\text{eff}} = V_{app} \frac{T}{T_0} \frac{p_0}{p}$$

→ **We want to obtain a constant effective voltage** →

$$V_{app}(t) = V_0 \frac{T_0}{p_0} \frac{p(t)}{T(t - 1\text{h})}$$

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

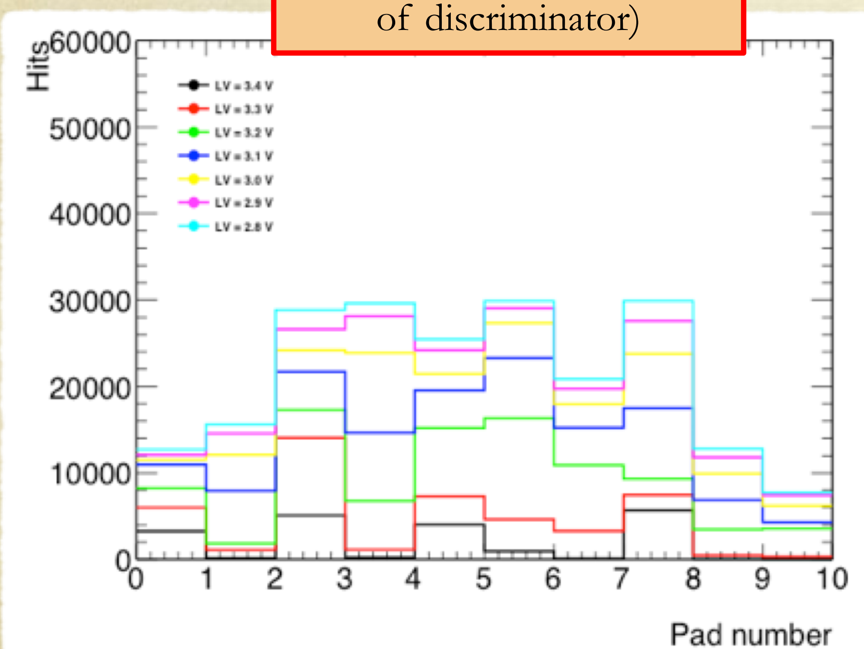
- Implemented an **automatic control system** that monitors temperature and pressure in SX1 and **changes the HV of each chamber accordingly**



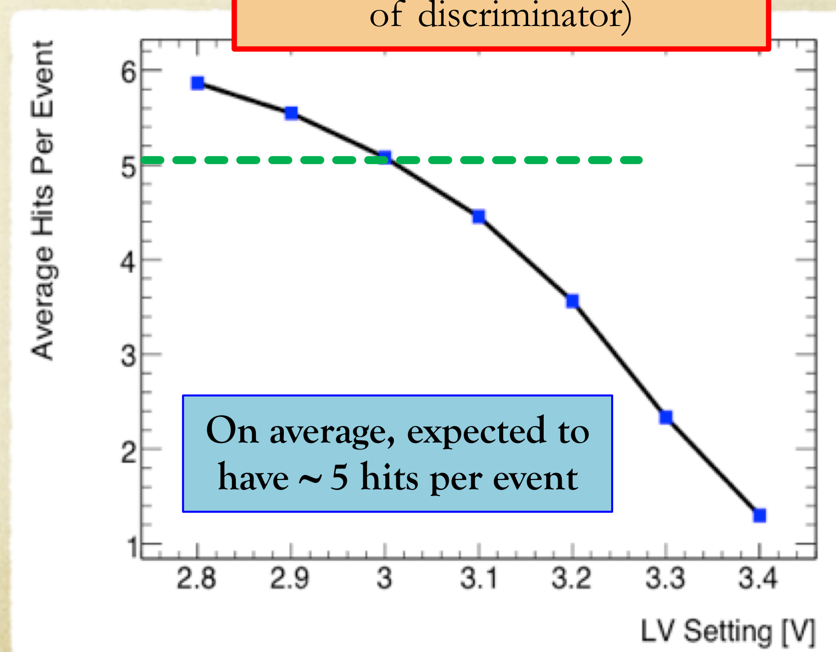
RPC Front-End Readout Tuning

- 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)



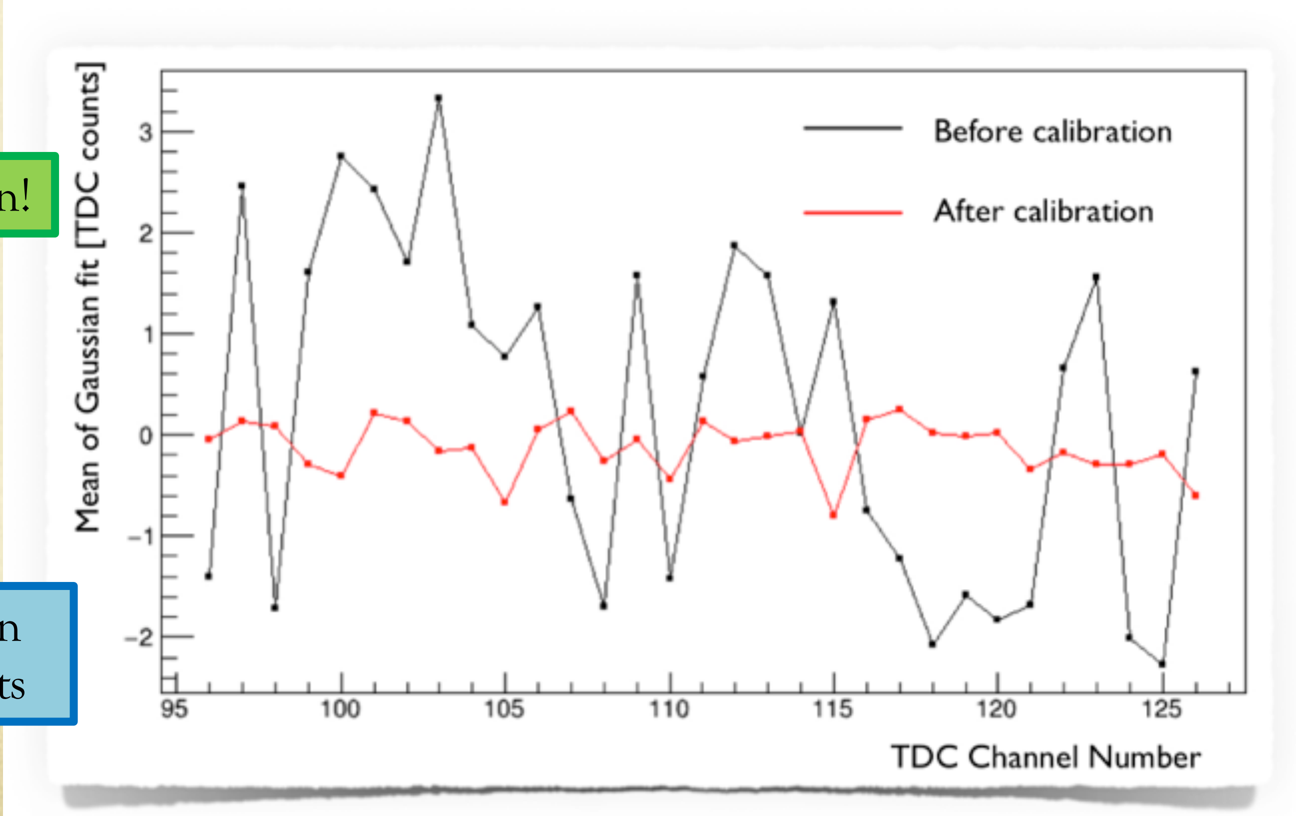
On average, expected to have ~ 5 hits per event

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

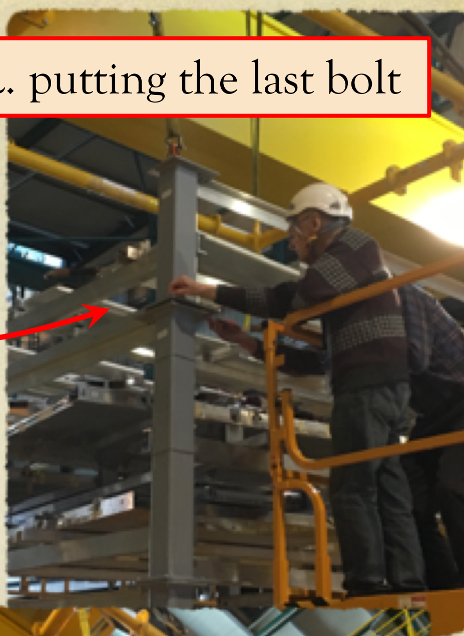
Very good calibration!

…but still margin for improvements



Installation in ATLAS P1 (2)

Henry L. putting the last bolt



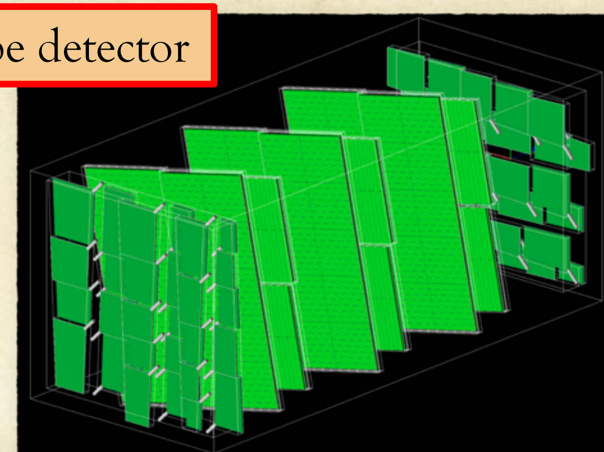
P1 data-taking lasted < 2 weeks

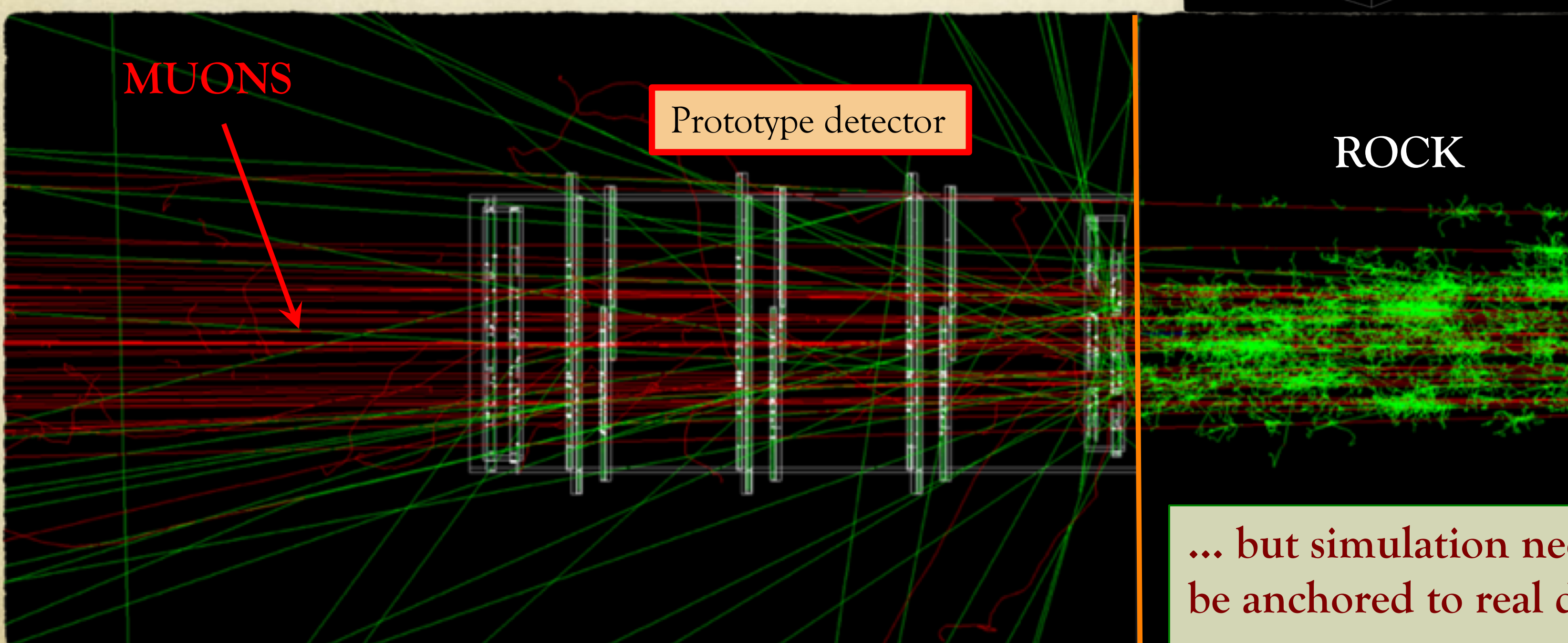
MATHUSLA - Background Simulations

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





ATLAS/CMS IP

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

...so we need a...

MATHUSLA White Paper and LoI

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

1806.07396

Editors:
David Curtin[1], Marco Drewes[2], Matthew McCullough[3], Patrick Meade[4], Rabindra Mohapatra[5], Jessie Shelton[6], Brian Shuve[7,8].

Contributors:
Elena Accomando[9], Cristiano Alpigiani[10], Stefan Antusch[11], Juan Carlos Arteaga-Velázquez[12], Brian Batell[13], Martin Bauer[14], Nikita Blinov[8], Karen Salomé Caballero-Mora[15,16], Jae Hyeok Chang[4], Eung Jin Chun[17], Raymond T. Co[18], Timothy Cohen[19], Peter Cox[20], Nathaniel Craig[21], Csaba Csáki[22], Yanou Cui[23], Francesco D'Eramo[24], Luigi Delle Rose[25], P. S. Bhupal Dev[26], Keith R. Dienes[27,5], Jeff A. Dror[28,29], Rouven Essig[4], Jared A. Evans[30,6], Jason L. Evans[17], Arturo Fernández Tellez[31], Oliver Fischer[32], Thomas Flacke[33], Anthony Fradette[34], Claudia Frugiuele[35], Elina Fuchs[35], Tony Gherghetta[36], Gian F. Giudice[3], Dmitry Gorbunov[37,38], Rick S. Gupta[39], Claudia Hagedorn[40], Lawrence J. Hall[28,29], Philip Harris[41], Juan Carlos Helo[42,43], Martin Hirsch[44], Yonit Hochberg[45], Anson Hook[5], Alejandro Ibarra[46,17], Seyda Ipek[47], Sunghoon Jung[48], Simon Knapen[29,28], Eric Kuflik[45], Zhen Liu[49], Salvator Lombardo[22], Henry Lubatti[10], David McKeen[50], Emiliano Molinaro[51], Stefano Moretti[9,52], Natsumi Nagata[53], Matthias Neubert[54,22], Jose Miguel No[55,56], Emmanuel Olaiya[52], Gilad Perez[35], Michael E. Peskin[8], David Pinner[57,58], Maxim Pospelov[59,34], Matthew Reece[57], Dean J. Robinson[30], Mario Rodríguez Cahuantzi[31], Rinaldo Santonico[60], Matthias Schlaffer[35], Claire H. Shepherd-Themistocleous[52], Andrew Spray[33], Daniel Stolarski[61], Martin A. Subieta Vasquez[62,63], Raman Sundrum[5], Andrea Thamm[3], Brooks Thomas[64], Yuhsin Tsai[5], Brock Tweedie[13], Stephen M. West[65], Charles Young[8], Felix Yu[54], Bryan Zaldivar[55,66], Yongchao Zhang[26,67], Kathryn Zurek[29,28,3], José Zurita[32,68].

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

Cristiano Alpigiani,[a] Austin Ball,[e] Liron Barak,[c] James Beacham,[ah] Yan Benhammo,[c] Tingting Cao,[c] Paolo Camarri,[f,g] Roberto Cardarelli,[f] Mario Rodríguez-Cahuantzi,[h] John Paul Chou,[d] David Curtin,[b] Miriam Diamond,[e] Giuseppe Di Sciascio,[f] Marco Drewes,[z] Sarah C. Eno,[u] Erez Etzion,[c] Rouven Essig,[q] Jared Evans,[v] Oliver Fischer,[w] Stefano Giagu,[k] Brandon Gomes,[d] Andy Haas,[l] Yuekun Heng,[z] Giuseppe Iaselli,[aa] Ken Johns,[m] Muge Karagoz,[u] Luke Kasper,[d] Audrey Kvam,[a] Dragoslav Lazic,[ae] Liang Li,[a,f] Barbara Liberti,[f] Zhen Liu,[y] Henry Lubatti,[a] Giovanni Marsella,[n] Matthew McCullough,[o] David McKeen,[p] Patrick Meade,[q] Gilad Mizrachi,[c] David Morrissey,[p] Meny Raviv Moshe,[c] Karen Salomé Caballero-Mora,[j] Piter A. Paye Mamani,[ab] Antonio Policicchio,[k] Mason Proffitt,[a] Marina Reggiani-Guzzo,[ad] Joe Rothberg,[a] Rinaldo Santonico,[f,g] Marco Schioppa,[ag] Jessie Shelton,[t] Brian Shuve,[s] Martin A. Subieta Vasquez,[ab] Daniel Stolarski,[r] Albert de Roeck,[o] Arturo Fernández Téllez,[h] Guillermo Tejeda Muñoz,[h] Mario Iván Martínez Hernández,[h] Yiftah Silver,[c] Steffie Ann Thayil,[d] Emma Torro,[a] Yuhsin Tsai,[u] Juan Carlos Arteaga-Velázquez,[i] Gordon Watts,[a] Charles Young,[e] Jose Zurita.[w,ac]

CERN-LHCC-2018-025