Exploring the Lifetime and Cosmic Frontier with MATHUSLA

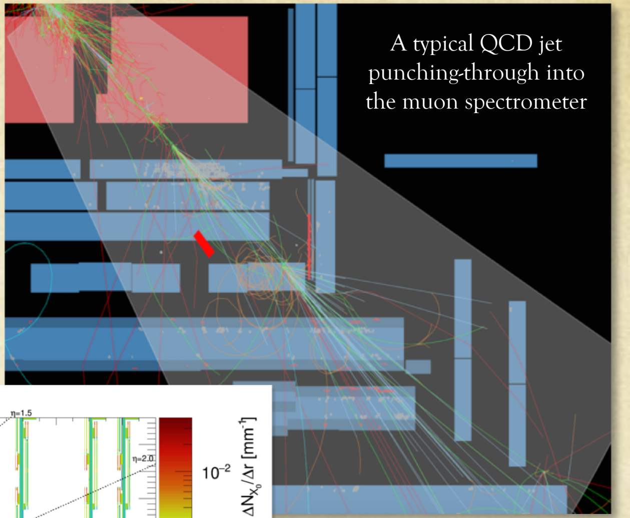
Cristiano Alpigiani

ICHEP 2022 Bologna, 9th July 2022

UNIVERSITY of WASHINGTON

MATHUSLA

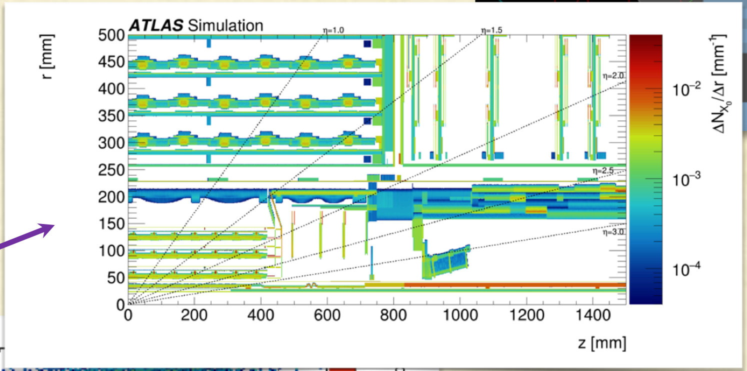
LLP Challenges @ Colliders

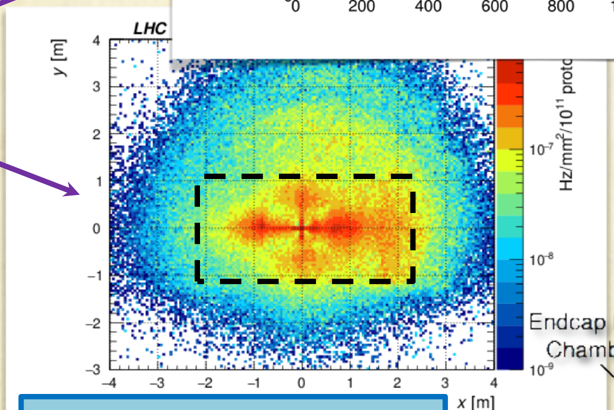


LHC detectors are optimised to detect prompt SM particles

➢ BSM particles can produce **final states** that might be **very difficult to study** due to complicated backgrounds

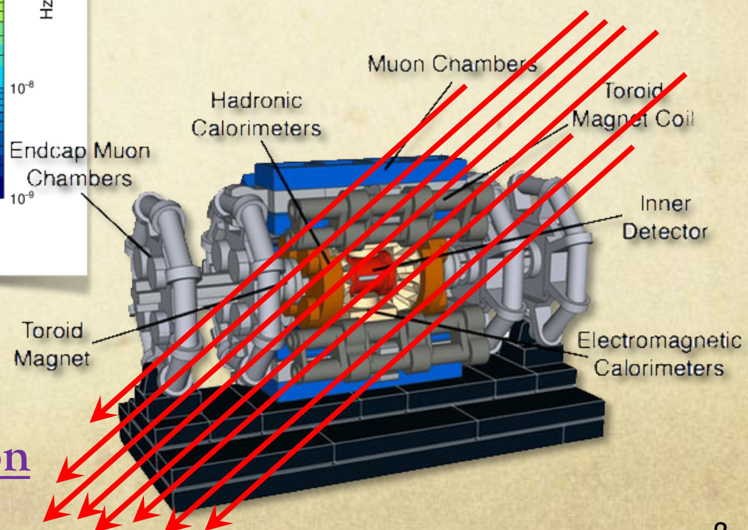
- ✓ Instrumental backgrounds
- ✓ Large QCD jet production
- ✓ Pile-up problems
- ✓ Material interaction
- ✓ Beam induced background (BIB)





muons (E>20 GeV) entering ATLAS at z=22.6 m [arXiv:1810.04450]

✓ Cosmic background



❑ Need to develop

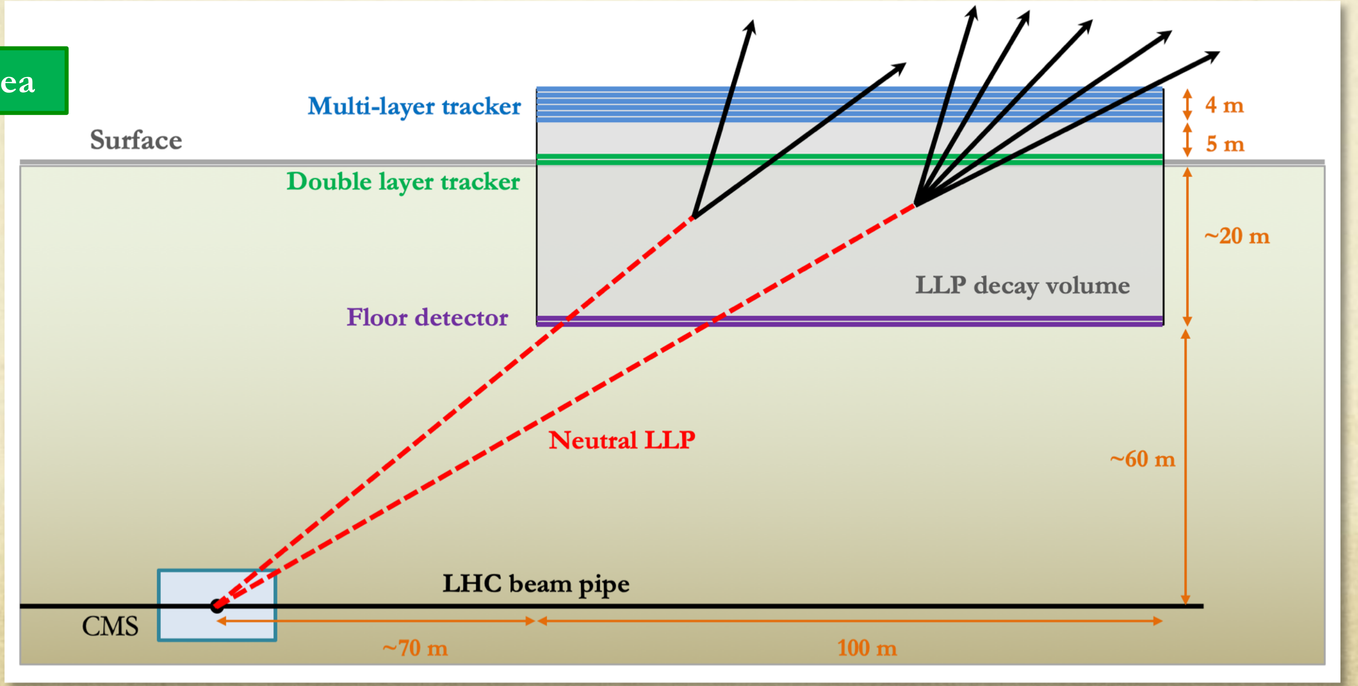
- Dedicated triggers
- Custom reconstruction tools
- Very robust background modelling and rejection

MATHUSLA - Layout

- arXiv 1606.06298
- arXiv 1806.07396
- CERN-LHCC-2018-025

- 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
- Proposed a large area surface detector located above CMS
  - ✓ Need robust tracking
  - ✓ Need excellent background rejection
  - ✓ Need a floor detectors to reject interactions occurring near the surface
  - ✓ Extruded scintillators + SiPMs are considered for tracking (good time/space resolution)

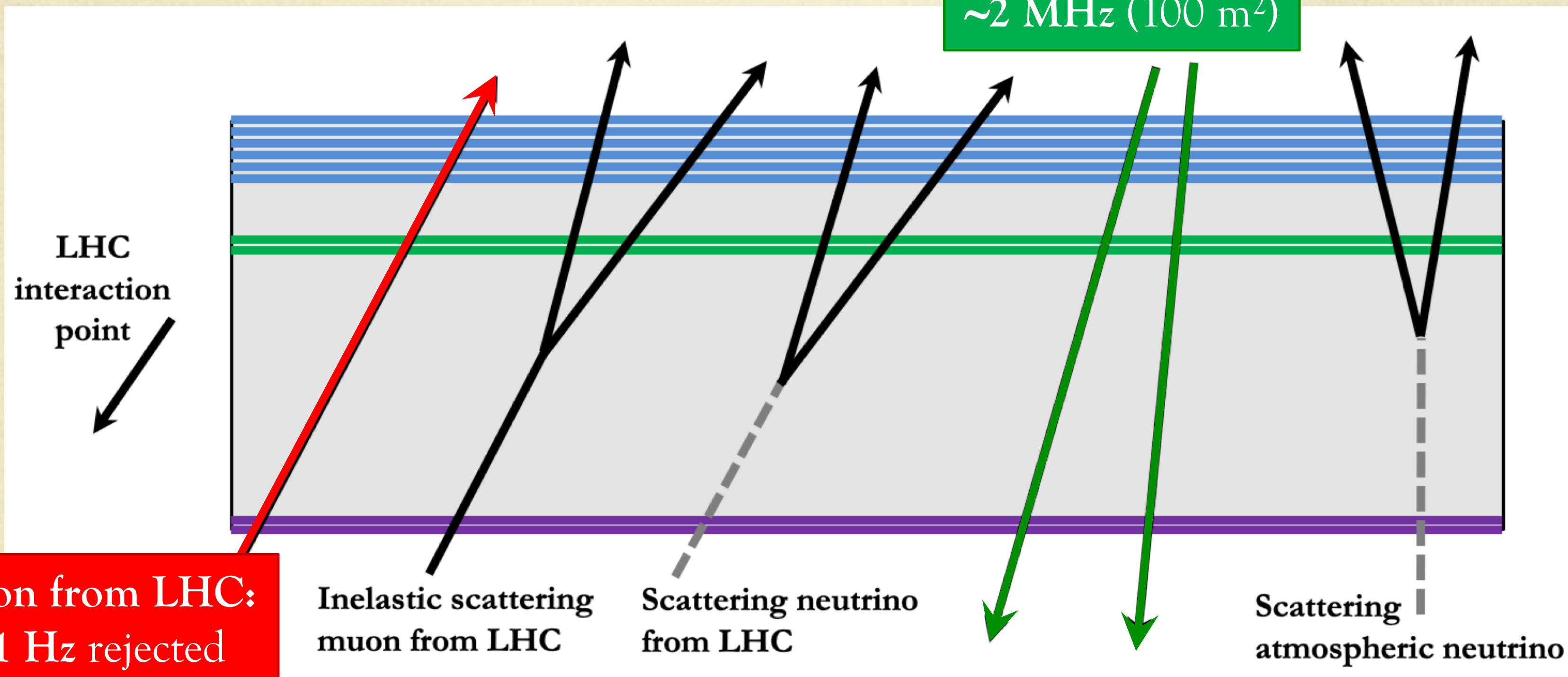
$\sigma_{LLP} \propto 1/\text{area}$



MATHUSLA - Backgrounds

Main backgrounds…

Cosmic rays
~2 MHz (100 m²)



Muon from LHC: 0.1 Hz rejected with veto layer

LHC neutrinos: expected **0.1 events** from high-E neutrinos (W, Z, top, b), **~1 events** from low-E neutrinos (π/K) over the entire HL-LHC run

Upward atmospheric neutrinos that interact in the decay volume (**70 events per year above 300 MeV**) "decaying" to low momentum proton (reject by timing and geometrical constraints)

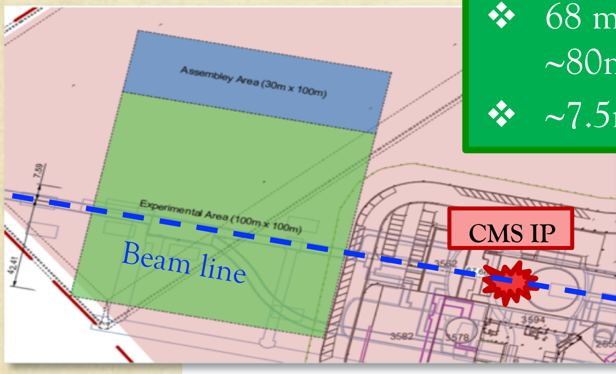
Detector layout

Recent Progress and Next Steps for the MATHUSLA LLP Detector [arXiv:2203.08126 [hep-ex]]

MATHUSLA @ P5

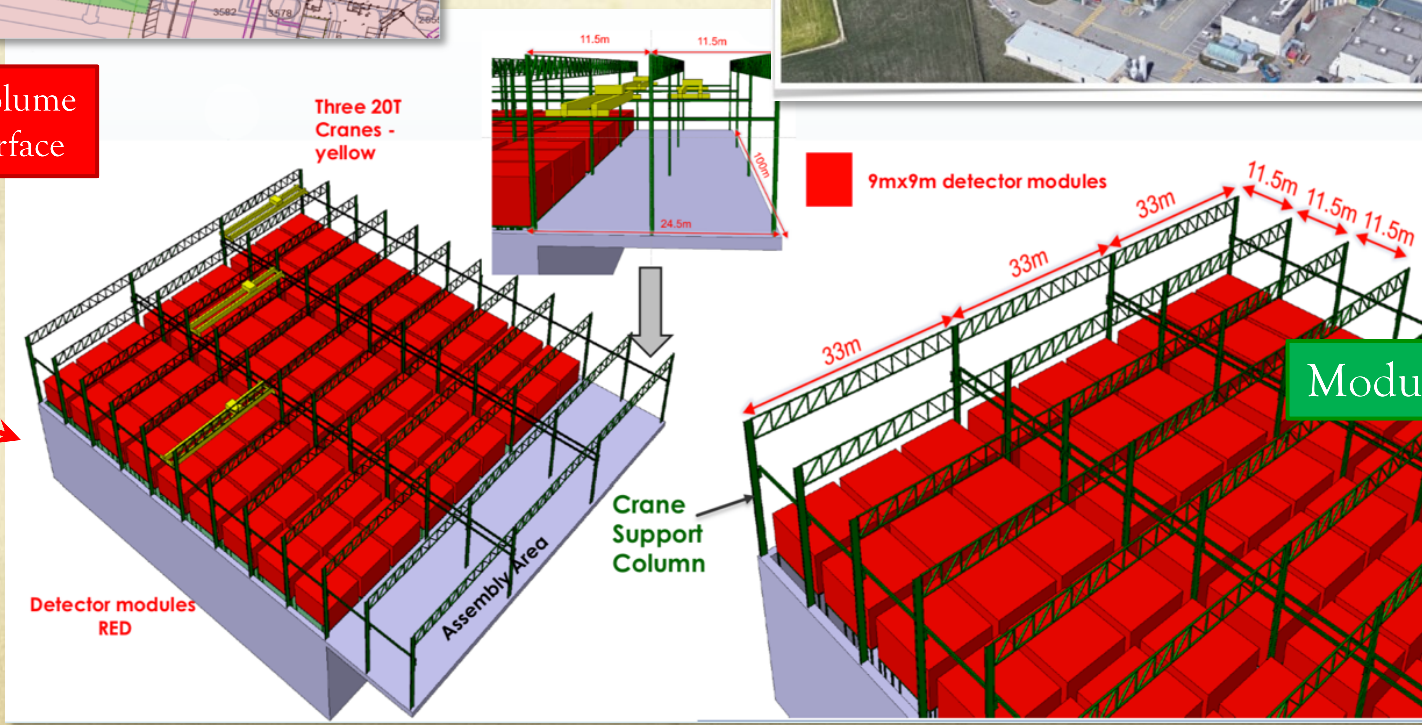
Worked with Civil Engineers to define the **building and the layout of MATHUSLA at P5**

➢ **Layout restricted by existing structures** based on current concept and engineering requirements



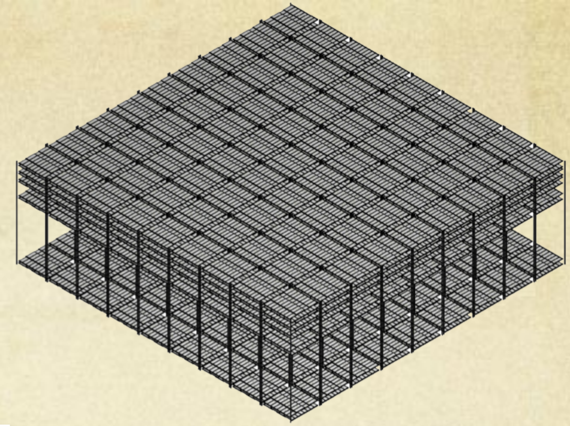
- 68 m to IP on surface and IP ~80m below surface
- ~7.5m offset to the beam line

20 m decay volume
Below the surface



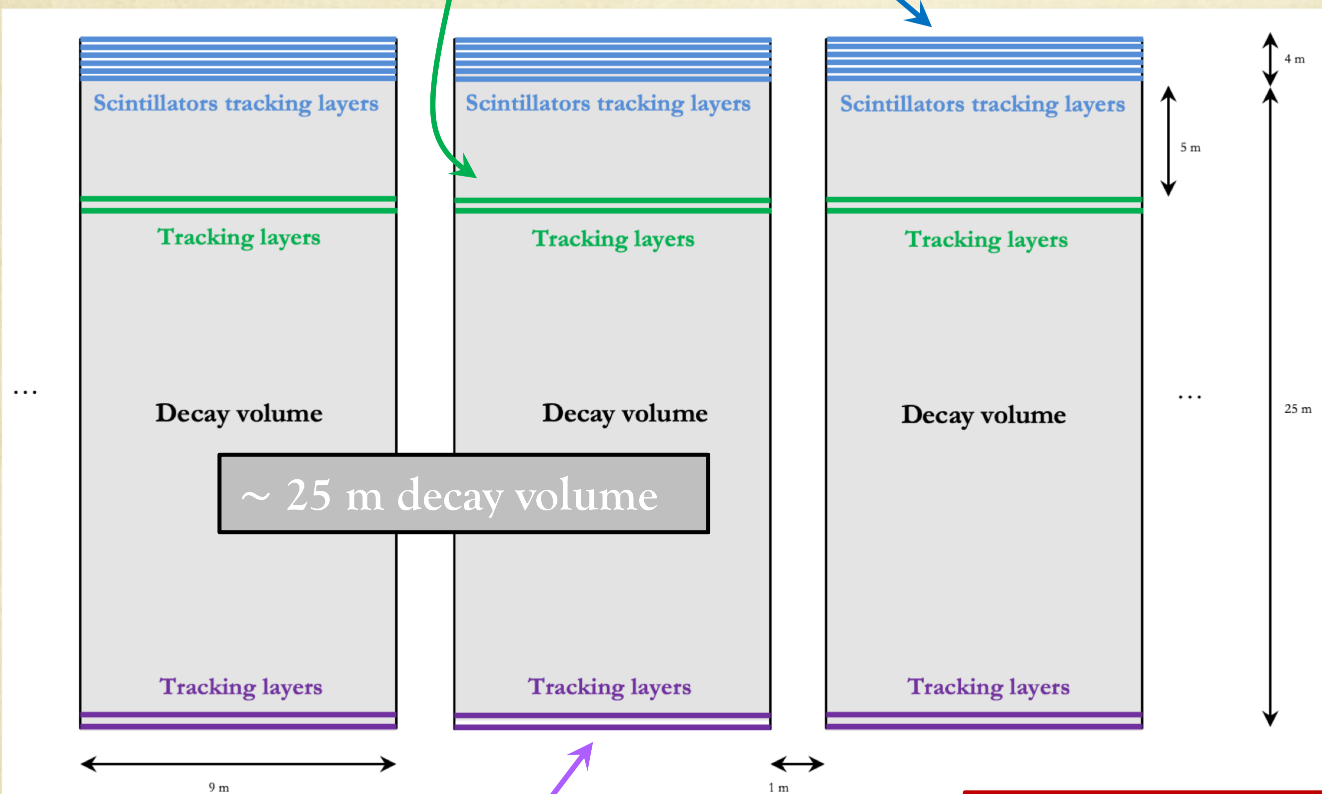
Modular concept

Modules Layout



Modular concept allows to stage the construction (scalable detector)

- 6 layers of tracking/timing detectors separated by 80 cm
- Additional **tracking/timing layer 5m**

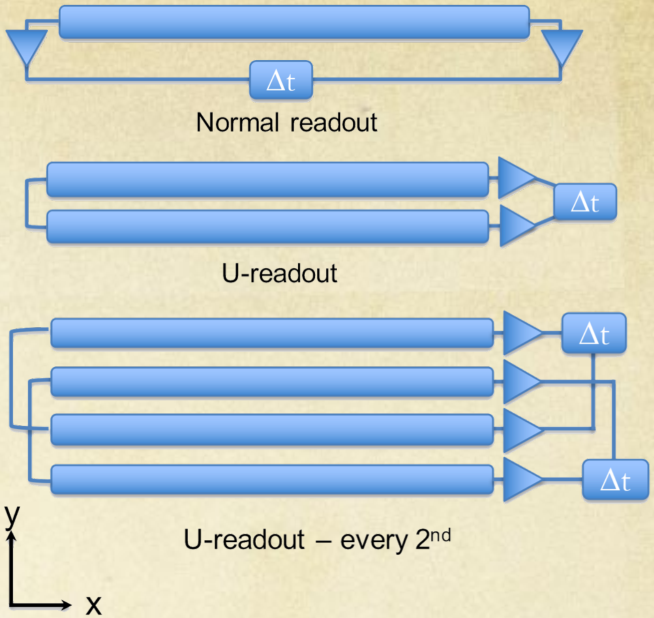


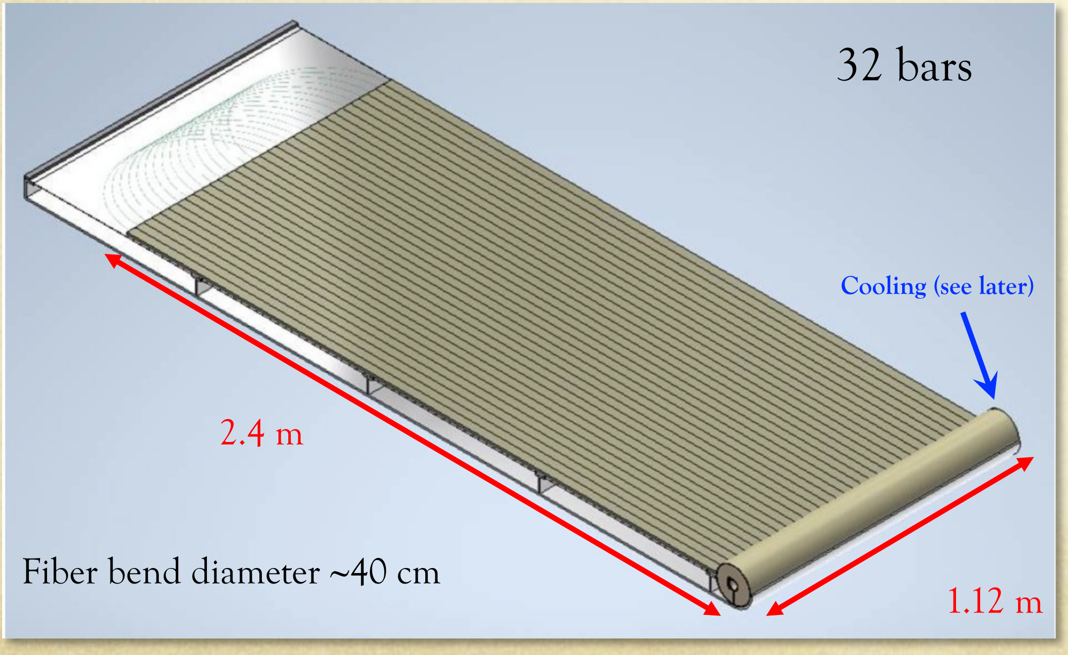
- Double layer floor detector (tracking/timing)

Individual detector units 9 x 9 x 30 m^3

Detector Plane Layout Studies

- Studying possible layouts for scintillating detector planes
  - ✓ Layout option where all SiPM connections are on one side of layer with **2.4 m extruded bars**
  - ✓ Looking at options that have **number of bars that are multiples of 16** (may be convenient for DAQ)
- **128 bars of dimensions result in 2.4 x 4.48 m^2** units (8 units to cover ≈ 9x9 m^2 with overlaps)





Main advantages

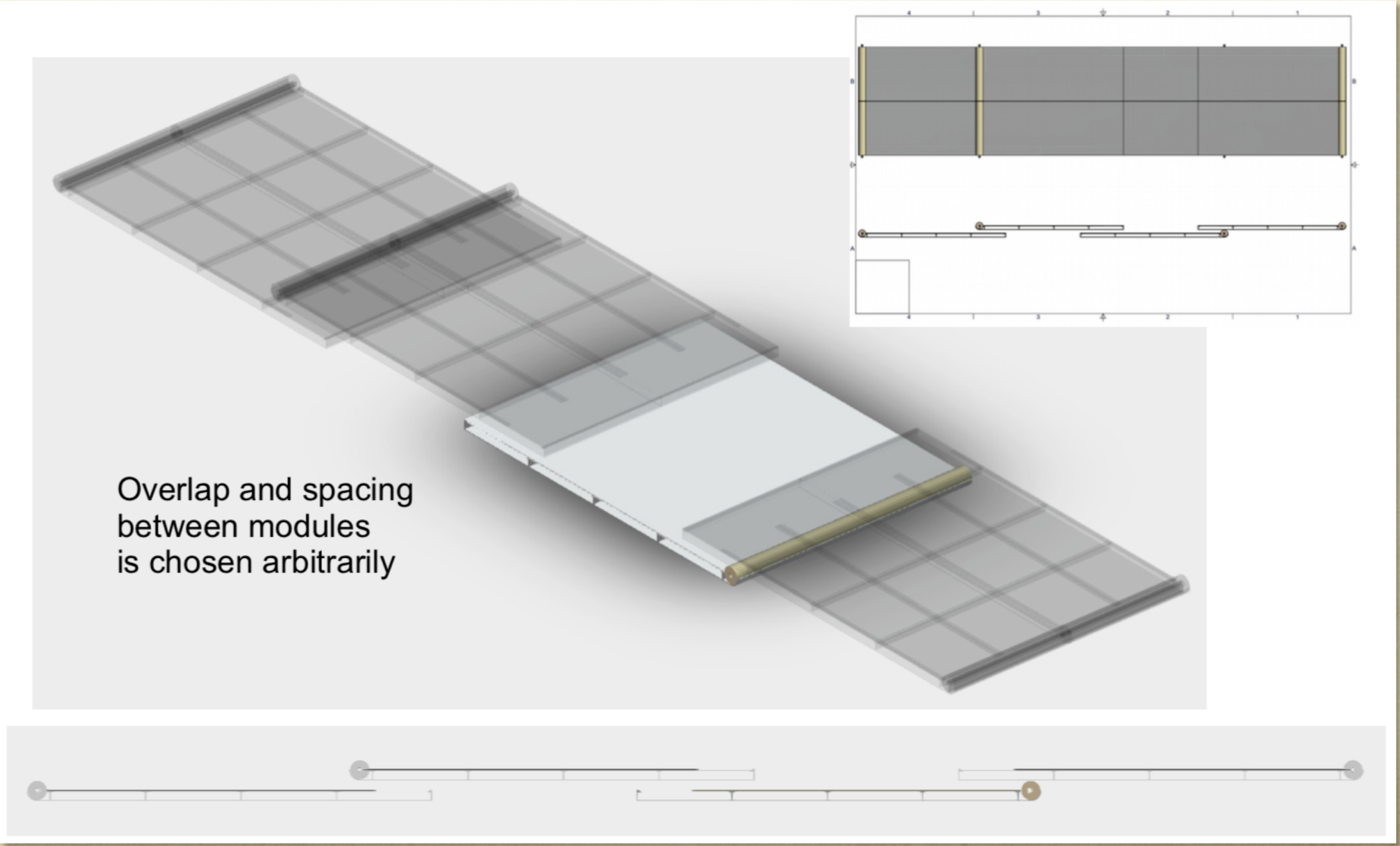
- SiPMs on same side simplifies DAQ read out
- Cooling, insulation all in one unit on one side

Complications

- Assembly of WLS fiber and higher probability of damaging fiber during installation
- Requires protective cover on WLS fibers

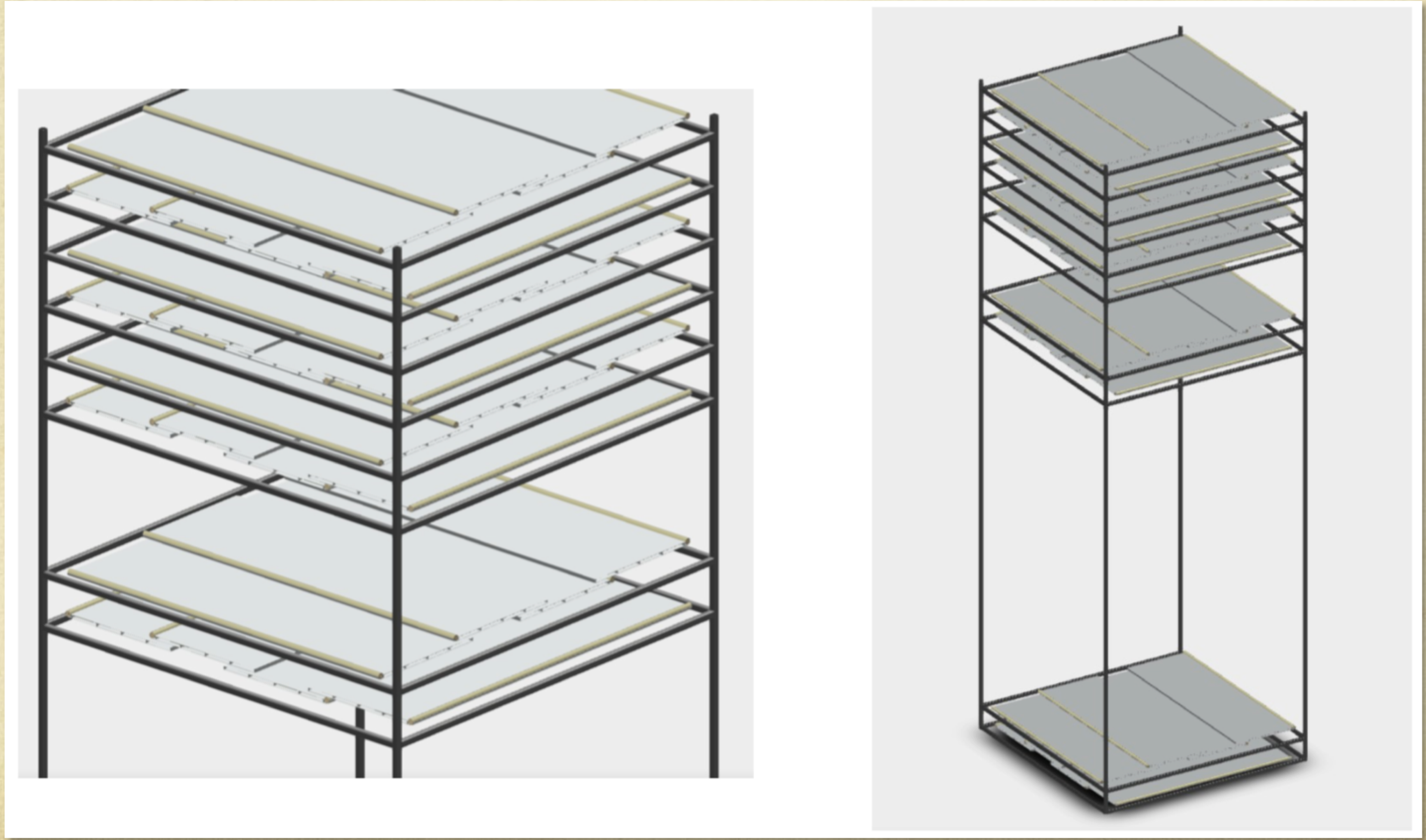
Detector Plane Layout Studies

- Module overlap



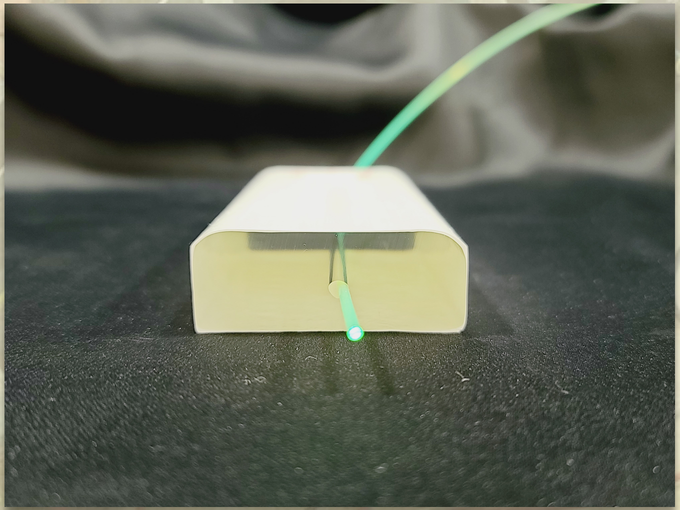
Detector Plane Layout Studies

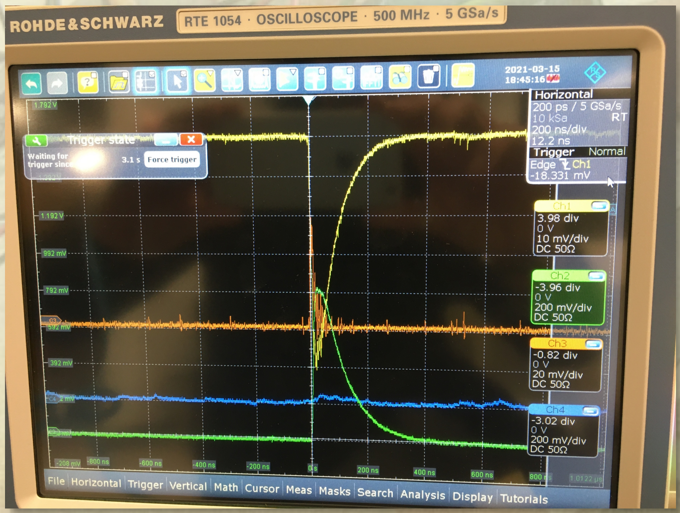
- Tower layout



Detector Technology

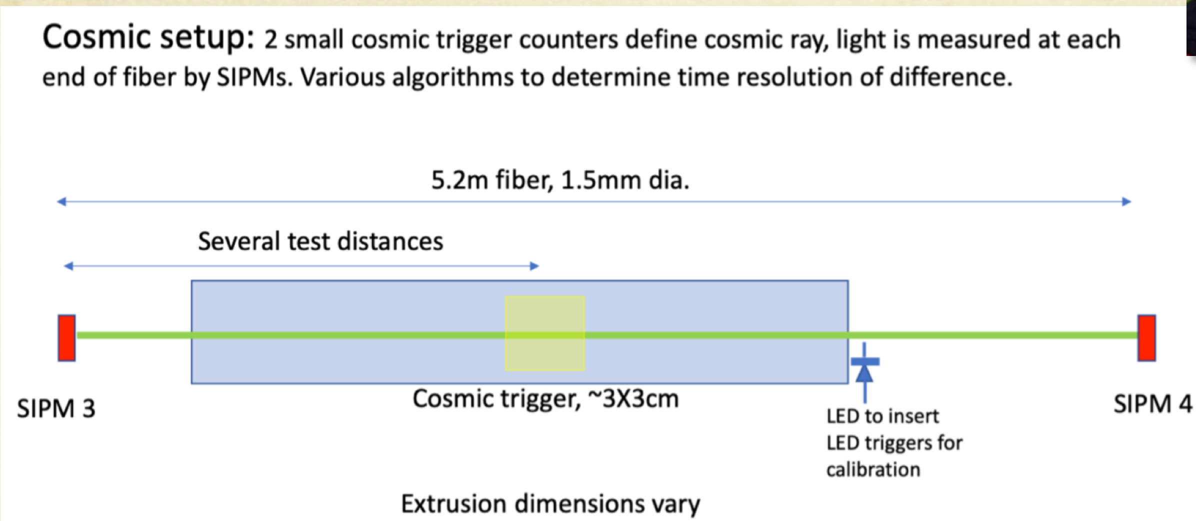
Extruded scintillator bars with wavelength shifting fibers coupled to SiPMs (tested extrusion facilities - ***FNAL*** and Russia)





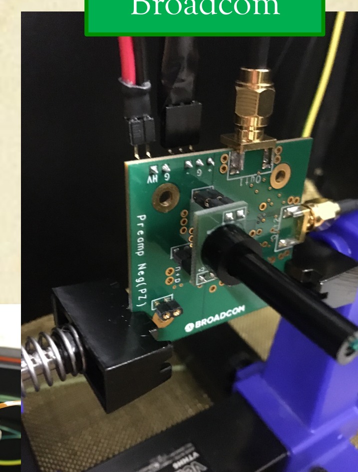
Scintillator Timing and Testing

Target timing resolution is ~1 ns (15 cm RMS) with >15 photoelectrons (PE) per end of the fiber

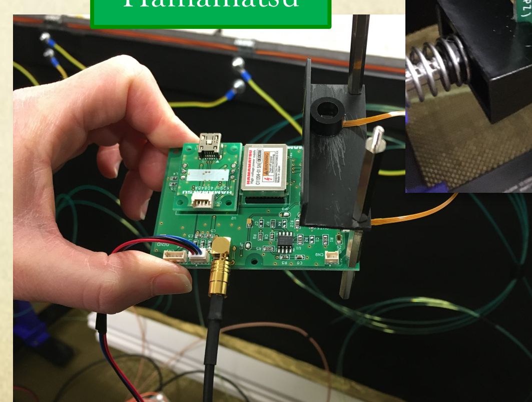


- Average noise subtracted from each event
- Filter signal to reduce jaggedness

Broadcom



Hamamatsu

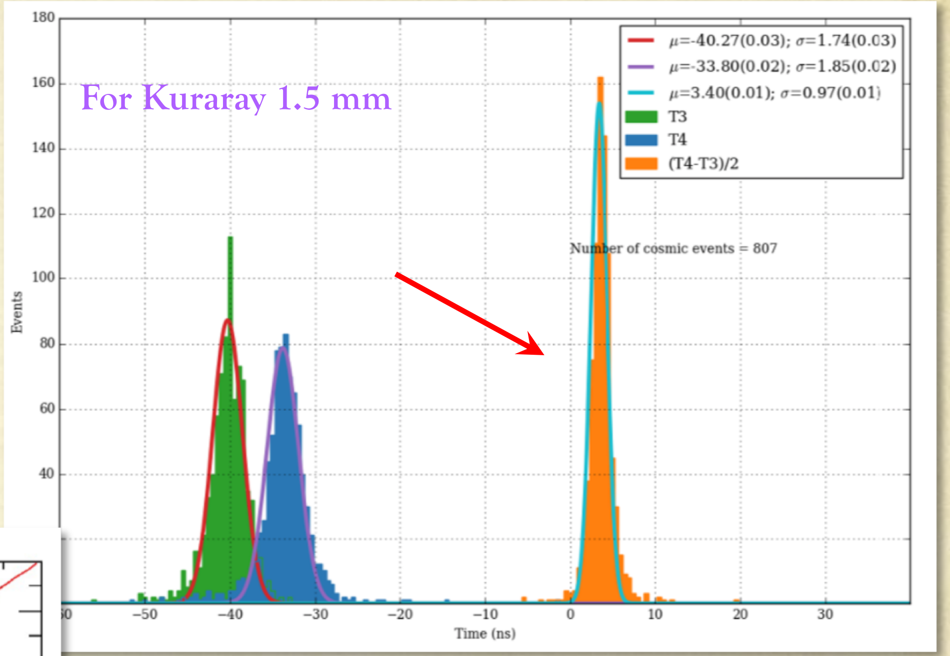


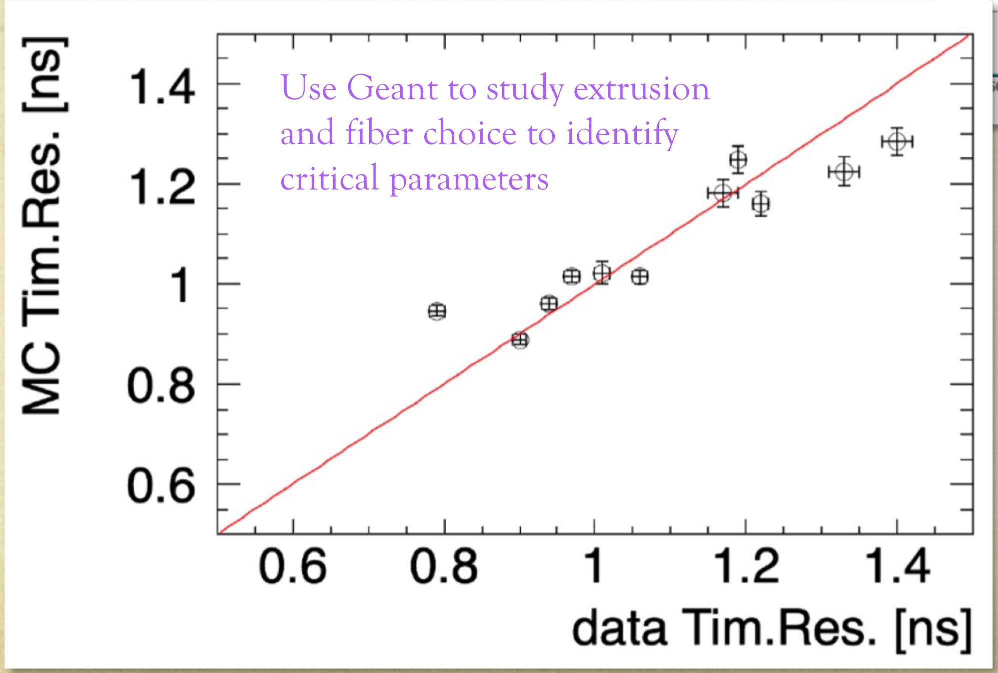
- ➢ **Use difference in arrival time between separate measurements at two ends**
- ➢ Critical feature of the detector design
  - ✓ Separates downwards from upwards going tracks
  - ✓ Reject low beta particles from neutrino QIS
  - ✓ 4D tracking and vertexing reduces fakes/combinatorics
- ➢ On-going studies on dark current and SiPM cooling

Scintillator Timing and Testing

- Timing measurement for a 5 m long fiber through a 1 x 4 cm^2 extrusion located at the center of the fiber

- **Timing resolution of 0.538 ns** (i.e. 9 cm RMS position resolution) well within MATHUSLA requirement
- **Worst case light-yield was 23 PE**



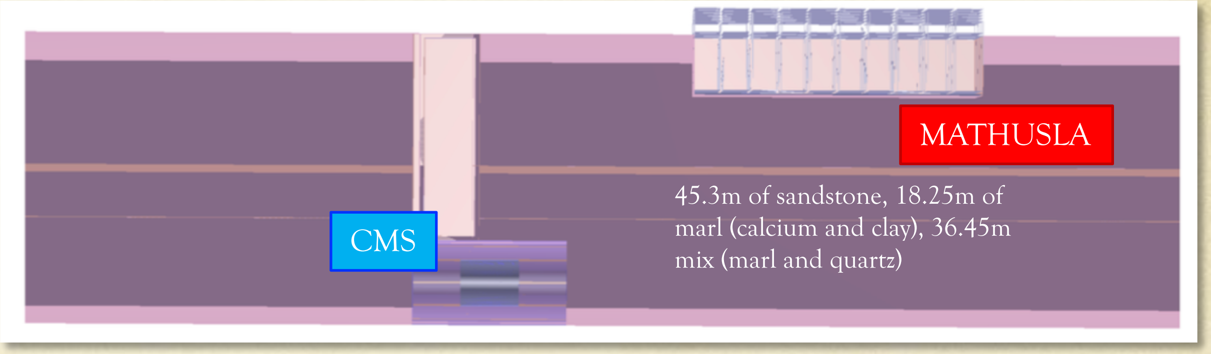


Currently testing

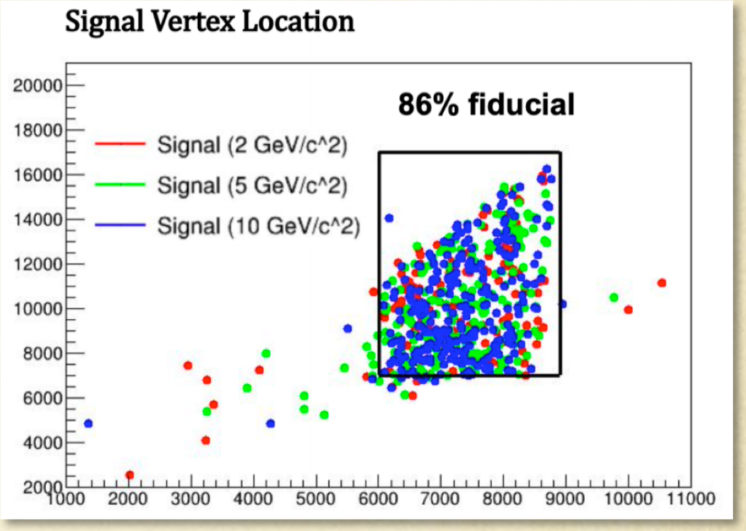
- Different extrusion thickness
- Different fiber diameters
- Different fiber lengths
- Different fiber vendors (Kuraray, Saint Gobain, ...)

Background Simulation

Use Geant to model particle interactions in matter



- Backgrounds under study:
  - ✓ **Upwards going muons** from collisions (Pythia8)
    - → Can create vertices in a few different ways
      - Delta-rays
      - Induce EM Showers
      - 5-body decay in flight
  - ✓ **Backscatter** from downwards going cosmic rays **(Parma)**
  - ✓ Neutrino interactions **(Genie3)**

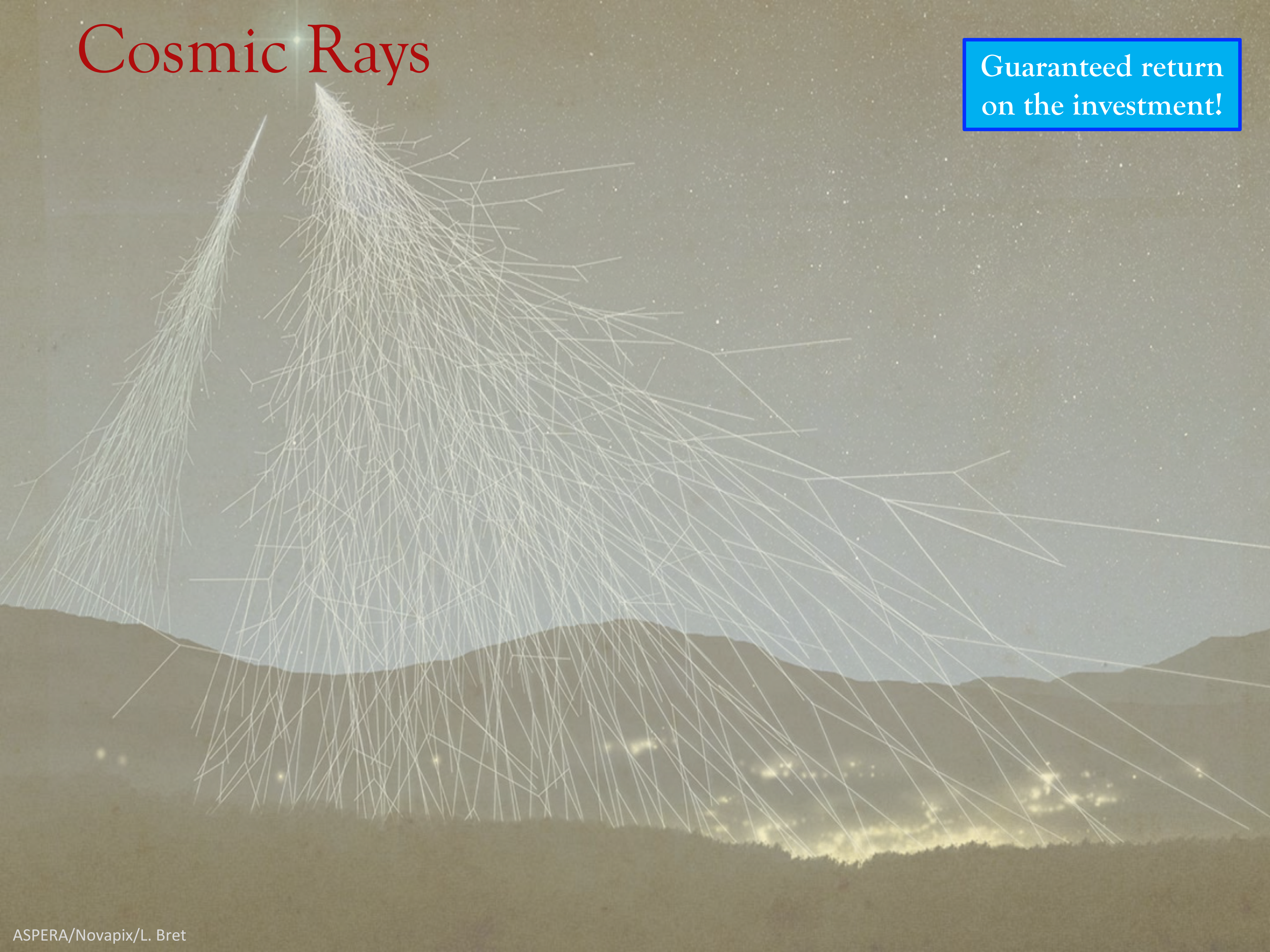


Analysis software uses Kalman Filtering to reconstruct tracks and form 4D vertices

Backgrounds rejected with a high-coverage floor veto + topological constraints on the vertices

Cosmic Rays

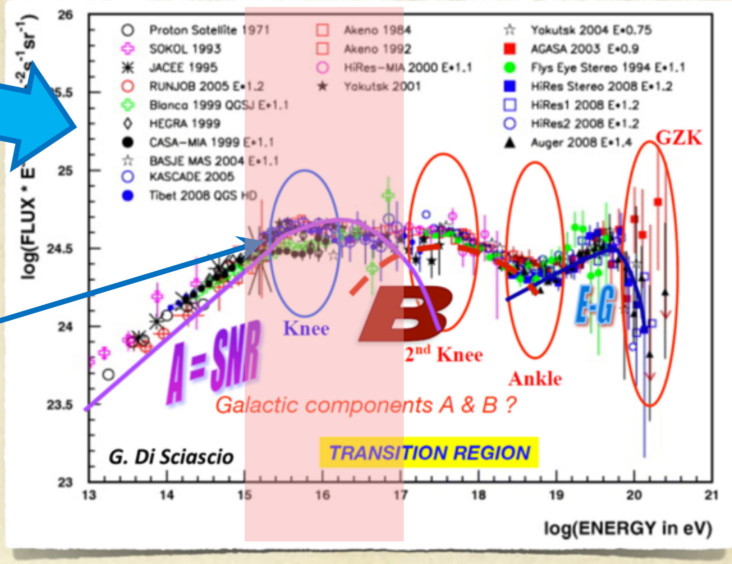
Guaranteed return on the investment!



ASPERA/Novapix/L. Bret

MATHUSLA - Cosmic Rays – Energy Spectrum

Several structures in the current measurements



- Good measurements in the energy range 10^{15}-10^{17} eV is crucial to understand the **transition** from **galactic to extragalactic cosmic rays**

- Understanding the **knee** may be the **main open problem in cosmic ray physics** (requires high statistic and good measurements)

- The full coverage of **MATHUSLA100** will allow a **lower energy threshold** (~ 100 GeV) than KASCADE (~ 1 PeV)
  - ✓ Lower threshold allows **comparison with satellite measurements** (CREAM, Calet, HERD)

- With the ability to measure several different parameters it should be possible to **separate** with decent statistics **p+He**, **intermediate mass nuclei** and **Fe** up to 10^{16} eV

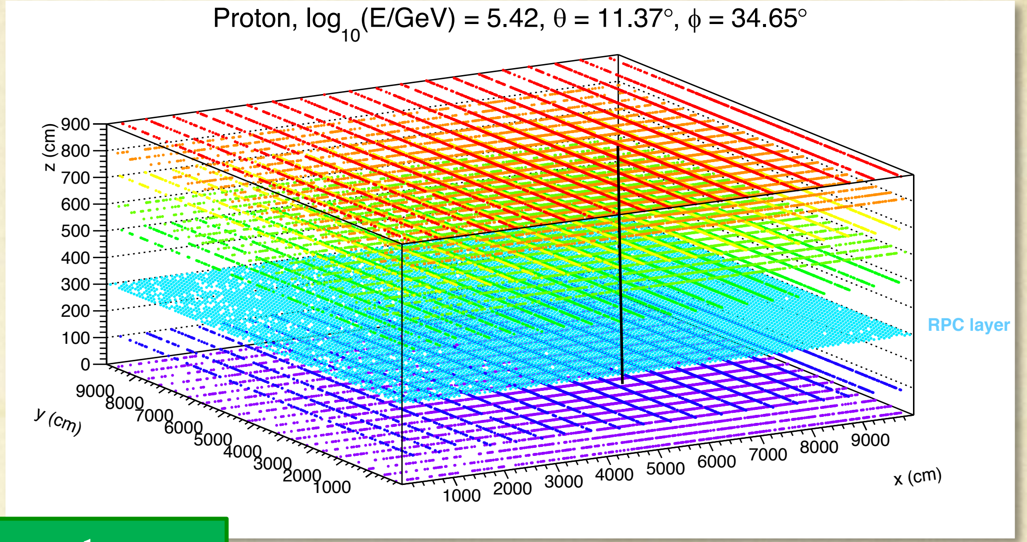
- MATHUSLA **multiple tracking layers** may help to **understand the energy spectrum**

- Extending the linearity of analog measurements by a factor of 10 greater than ARGO-YBJ MATHUSLA may be able to **measure shower energies above a PeV** (~10^{17} eV)

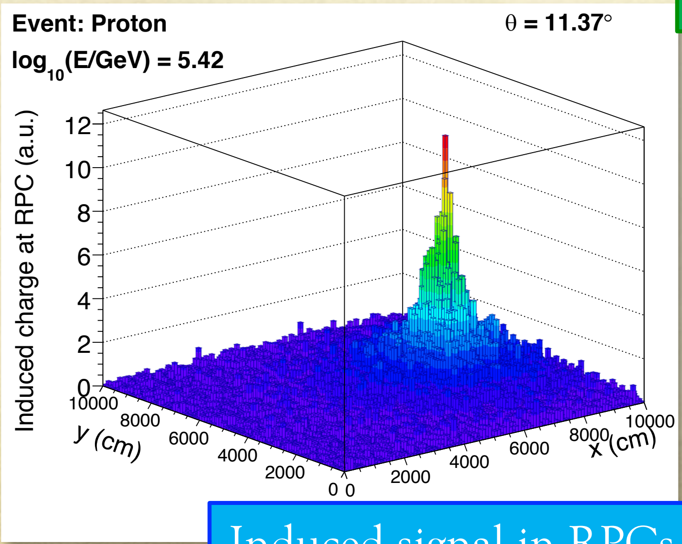
EAS Studies with Scintillators and RPC

These studies are considering 5 tracking layers on top

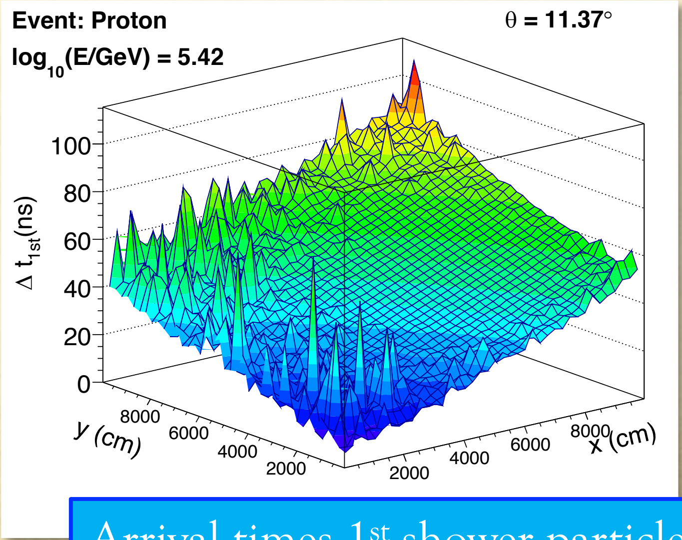
- MATHUSLA has good performance for inclined (>60˚) air showers induced by **Fe/H nuclei**
- Studying the possibility of adding a layer of RPC to improve the performance for vertical EAS
- For these tests considered **4 cm x 5 m** scintillator bars. **Coordinate of the hit = center of the bar**



Vertical event



Induced signal in RPCs



Arrival times 1st shower particles

Summary, Conclusions & Plans

- MATHUSLA is a complementary detector
  - ✓ Can make the LHC **LLP search program more comprehensive**
  - ✓ Can have the potential to significantly **enhance and extend the new physics reach** and capabilities of the current LHC detectors
- **Many ongoing studies** to define the (almost) final detector technology and layout
- ❑ Goal to complete the Technical Design Report (TDR) by end of Summer 2022
- ❑ Planning to build a demonstrator ~9 m^2 made up of a **few construction units** to validate the design and construction procedure of individual units

- Several cosmic ray studies
  - ✓ Simulations showed good performance for inclined EAS (quite good angular resolution)
  - ✓ MATHUSLA can do nice and competitive measurements for very inclined showers
- ❑ Physics case for the additional layer of RPC will be made public soon

BACKUP

The MATHUSLA Collaboration

Fermilab

University of Victoria

Universidad San Francisco

University of Toronto

Tel Aviv University

Università di Roma Tor Vergata

CERN

McGill University

University of Washington 1861

Rutgers The State University of New Jersey 1766

SLAC National Accelerator Laboratory

Università degli Studi di Palermo

The University of Arizona

UNACH Universidad Autónoma de Chiapas

Universitas Major Pacensis Divi Andreæ

INFN Bologna

Benemérita Universidad Autónoma de Puebla 1578

Universidad Michoacana de San Nicolás de Hidalgo

Universidad Andrés Bello

Escuela Nacional de Ciencias de la Tierra

University of Rochester 1850 Meliora

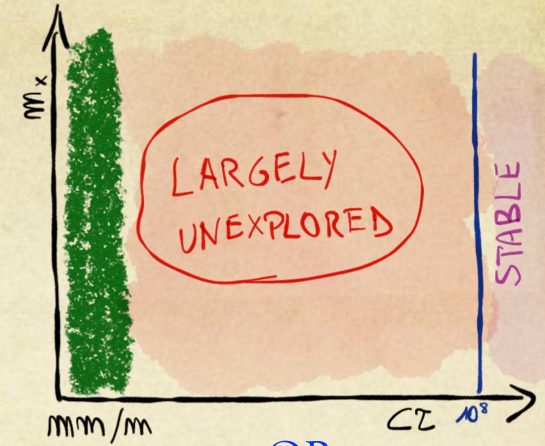
ESG

Warsaw University of Technology

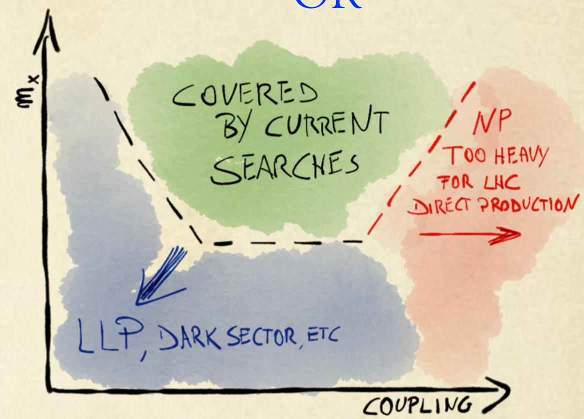
Why Long Lived Particles?

Most new physics searches focus on production and prompt decays at the p-p interaction point

- **Impressive agreement with SM expectations**
- **Naturalness does not seem to be a guiding principle of Nature**
- Why this lack of any evidence of new phenomena?
  - New **particles** might be more likely **labelled as background**

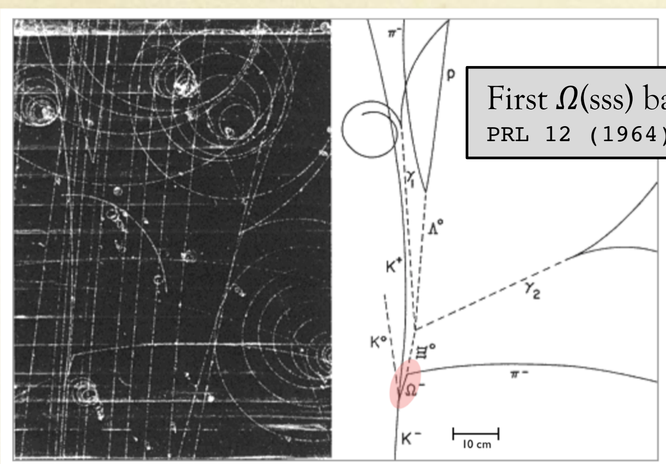


OR

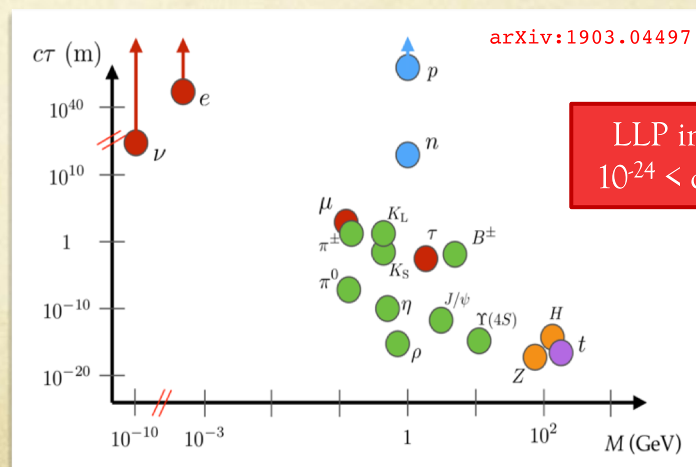


Nature is plenty of particles with macroscopic detectable decay lengths

→ Not surprising that long-lived particles (LLP) might exist also beyond the SM



First Ω(sss) baryon
PRL 12 (1964) 204-206



LLP in the SM
$10^{-24} < c\tau < 10^{41}$ s

What Makes the Lifetime Longer?

Start with Γ=0 and break something…

1. **Approximate symmetry**

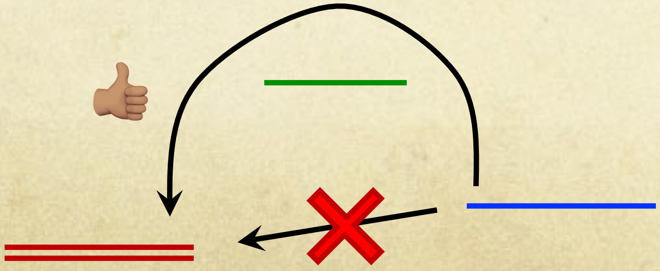
Multiplet of particles prevented from decaying by symmetry (e.g. isospin, baryon number, …)

Symmetry is <u>slightly</u> broken with small order parameter ϵ, but still a good approximation for most dynamics

$$\Gamma \propto \varepsilon\, m \ll m$$

2. **Heavy mediator** (virtual intermediate state)

Particle is stable, except for possible transition that can only proceed by exciting a heavy intermediate particle from the vacuum

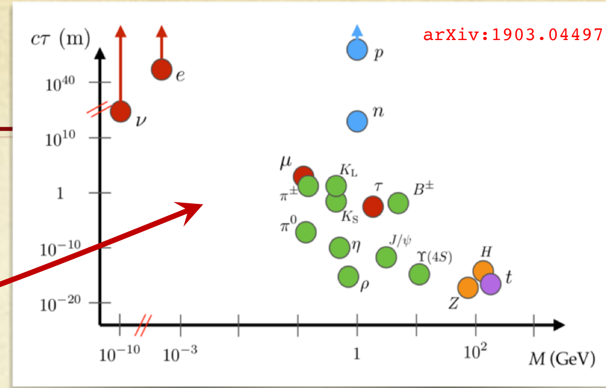


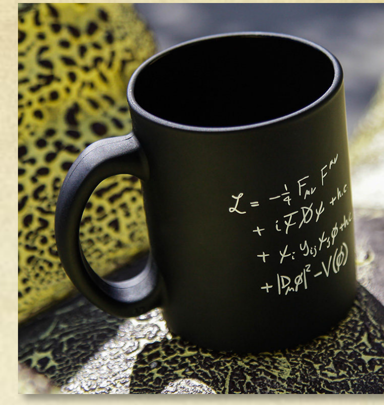
Heisenberg uncertainty principle
→ borrowing energy is "expensive"

$$\Gamma \propto \frac{m^5}{M_{med}^4} \ll m$$

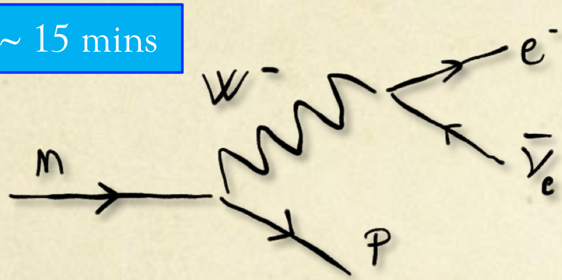
LLP in the SM

Many example of LLP in the SM…



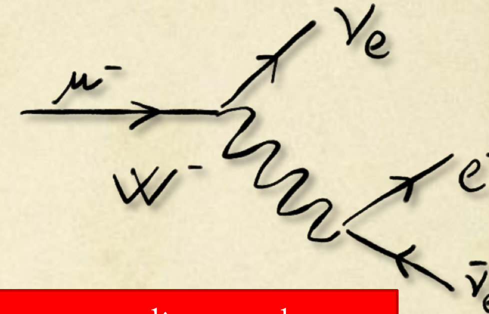


Neutron: $c\tau$ ~ 15 mins



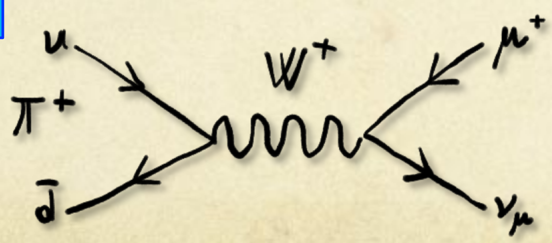
- Phase space suppression of weak decay to p and ℓ
- Heavy mediator
- Approximate symmetry (isospin)

Muon: $c\tau$ ~ 2.2 μs



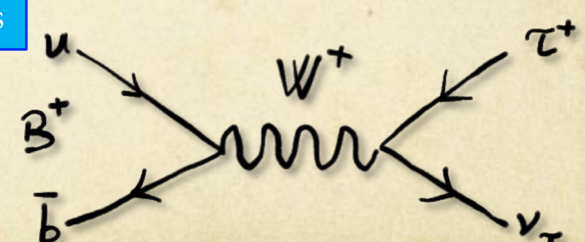
- Small coupling corresponding to a large dimensionful scale (Fermi constant G_F) , arising due to the high mass of the W

Pion: $c\tau$ ~ 10 ns



- Heavy mediator

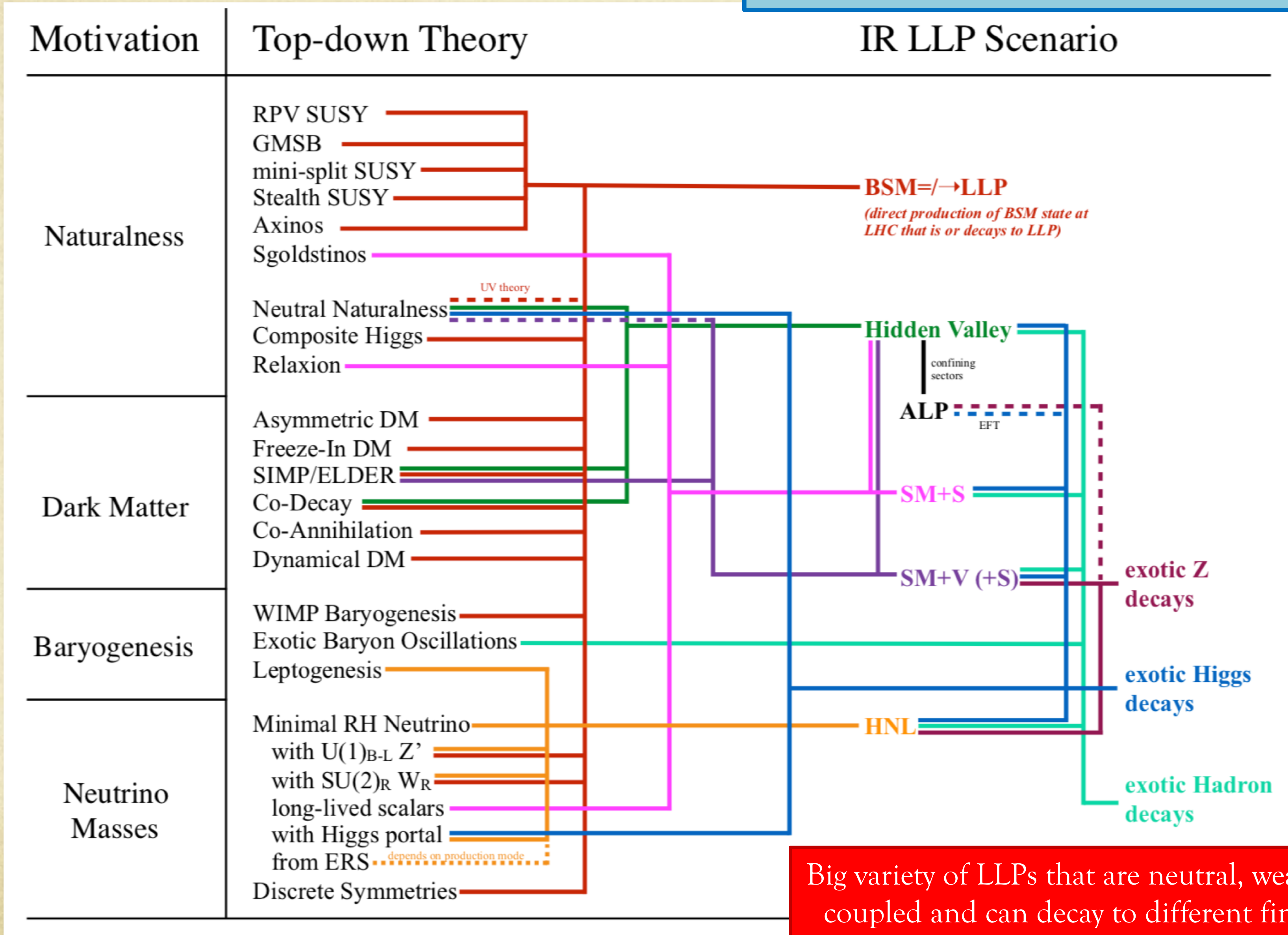
b-quark: $c\tau$ ~ 1 ps



- Phase space suppression
- Approximate flavor symmetry
- Large dimensionful scale in the decay

LLP in BSM - Top-down Theoretical Motivations

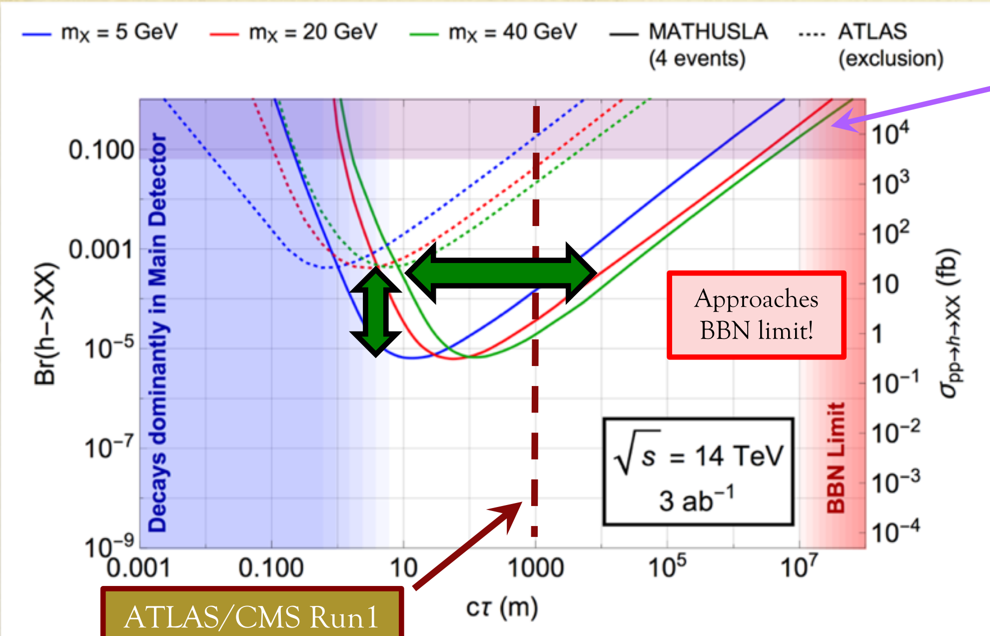
From the MATHUSLA White Paper arXiv:1806.07396



Big variety of LLPs that are neutral, weakly coupled and can decay to different final states (hadrons, leptons, photons, etc)

MATHUSLA – Physics Reach

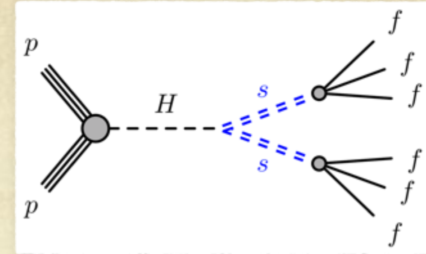
arXiv:1806.07396 [hep-ph]



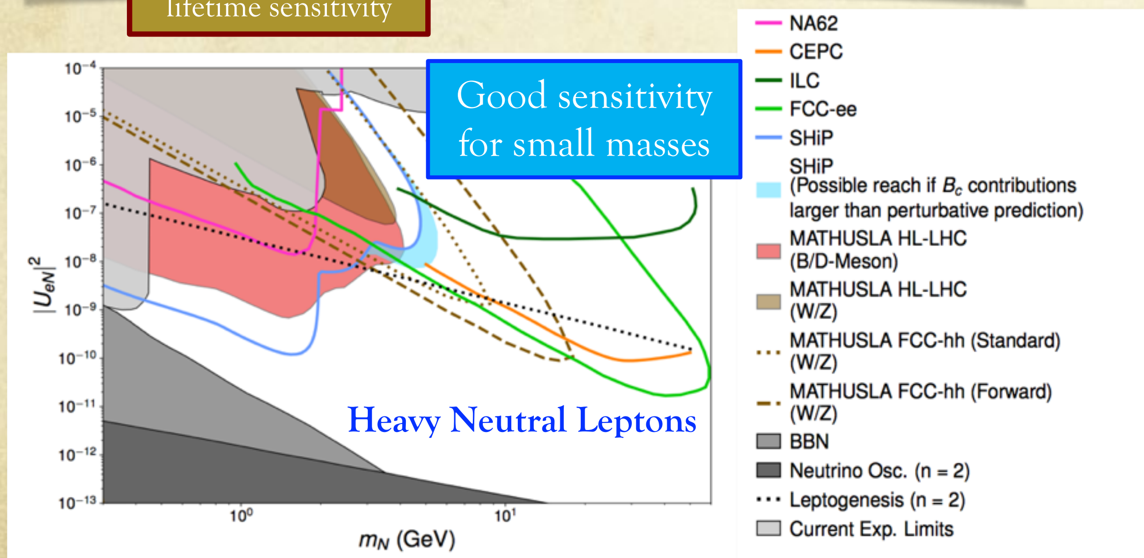
h → inv HL-LH limit

Approaches BBN limit!

ATLAS/CMS Run1 lifetime sensitivity

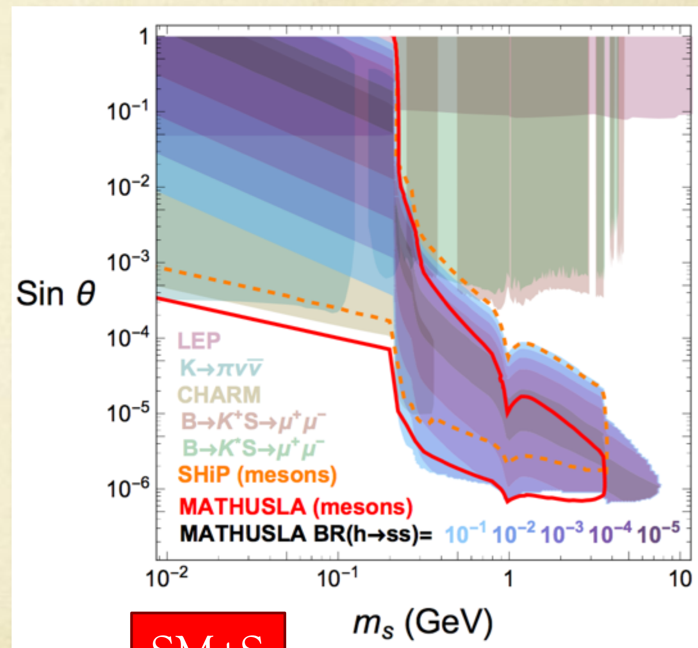


- **Can** probe LLPs at **GeV to TeV**
- **Good sensitivity** for mass scale **above ~ 5 GeV**, and for **lifetime >> 100** m even at low masses



Good sensitivity for small masses

Heavy Neutral Leptons



SM+S

Higher sensitivity for long lifetimes

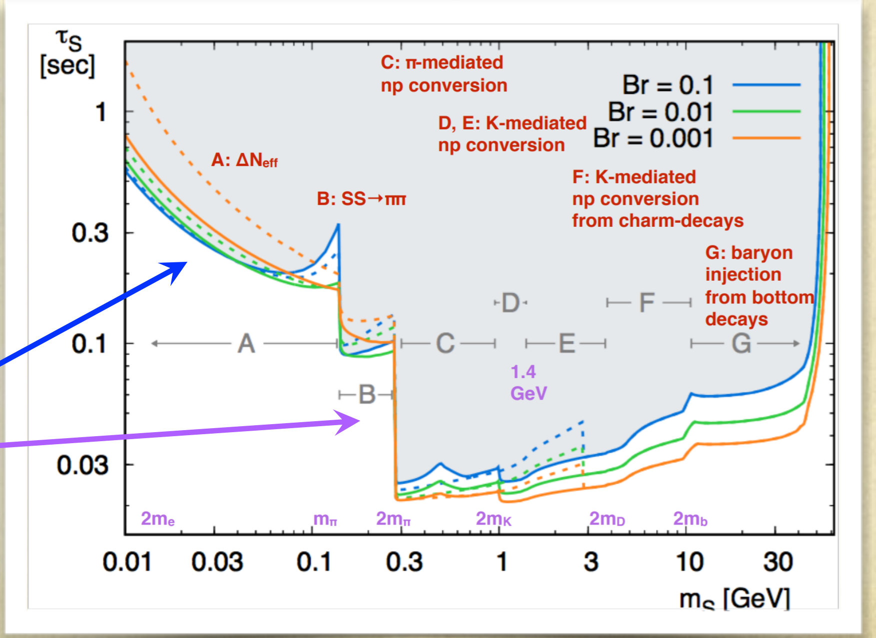
But How Much Long?

arXiv:1706.01920v1

The lifetime of metastable particles can be limited by cosmology, in particular by the Big Bang Nucleosynthesis (BBN)

- BBN very well understood within SM physics and well constrained
  - ✓ Happened in an interval between ~10 s – 15 mins after the Big Bang
  - ✓ The LLP lifetime should be smaller of that limit or the **n/p ratio** should have been **raised by nucleonic and mesonic decays of the LLP** spoiling the final light nuclei abundances

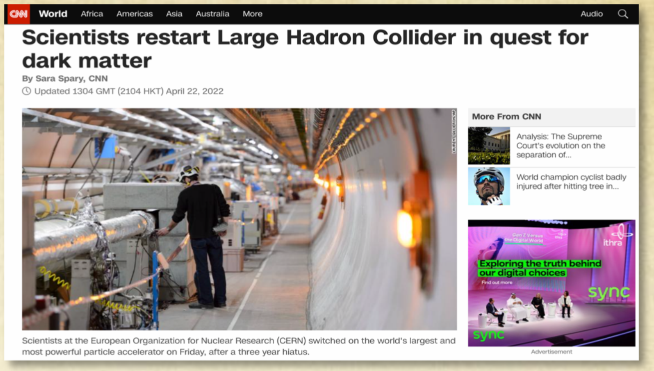
- Constraint studied on a **scalar model** coupled through the Higgs portal ($h \to ss$); decay induced by the **small mixing angle of the Higgs field h and scalar s**
  - For $m_s < 2m_\mu$ the lifetime τ can go up to 1 s
  - For $2m_\mu < m_s < m_h/2$ the lifetime $\tau < 0.1$ s



- Conclusion does not depend strongly on $BR(h \to ss)$

Dark Matter and LLP

link


World Africa Americas Asia Australia More Audio

Scientists restart Large Hadron Collider in quest for dark matter

By Sara Spary, CNN

Updated 1304 GMT (2104 HKT) April 22, 2022

Scientists at the European Organization for Nuclear Research (CERN) switched on the world's largest and most powerful particle accelerator on Friday, after a three year hiatus.

More From CNN

Analysis: The Supreme Court's evolution on the separation of...

World champion cyclist badly injured after hitting tree in...

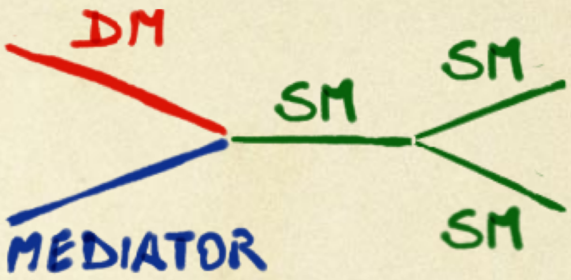
Exploring the truth behind our digital choices

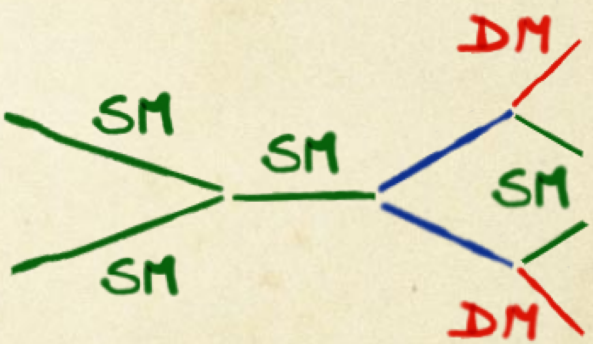
sync

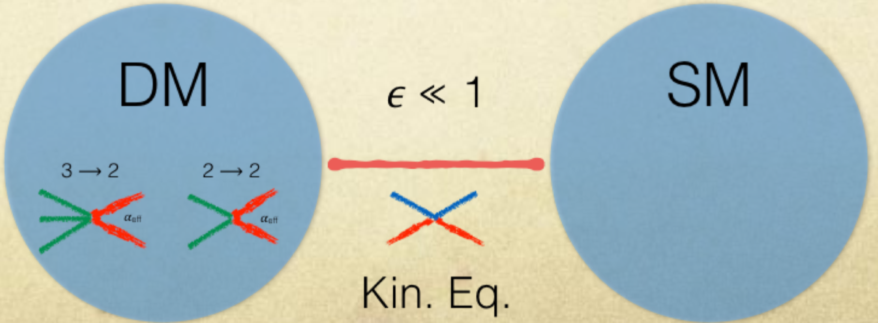
Several DM models require new BSM states in addition to DM

➢ Mechanisms giving a particle a long lifetime are naturally realised in well-motivated DM models

- Small phase space → WIMPs co-annihilate with an additional particle in the early universe (small mass splitting between DM and co-annihilating partner)
- Decays suppressed by high mass scales → theories of asymmetric DM
- Small coupling → SIMP: dark sector consists of DM which annihilates via a 2-3 → 2 process. Small couplings to the visible sector allow for thermalization of the two sectors, thereby allowing heat to flow from the dark sector to the visible one



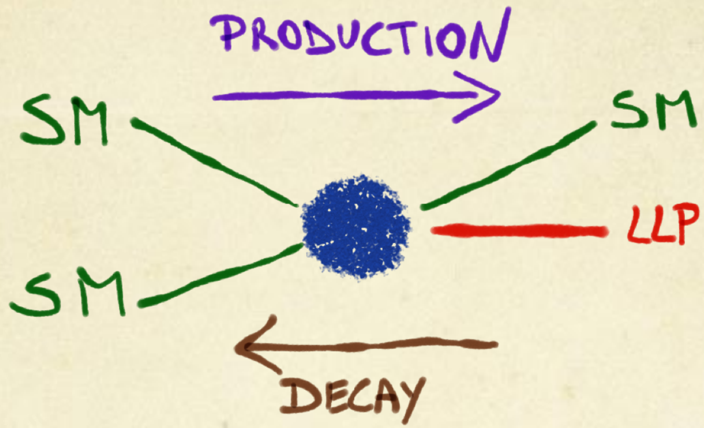




LLP Production and Decay

Simple model

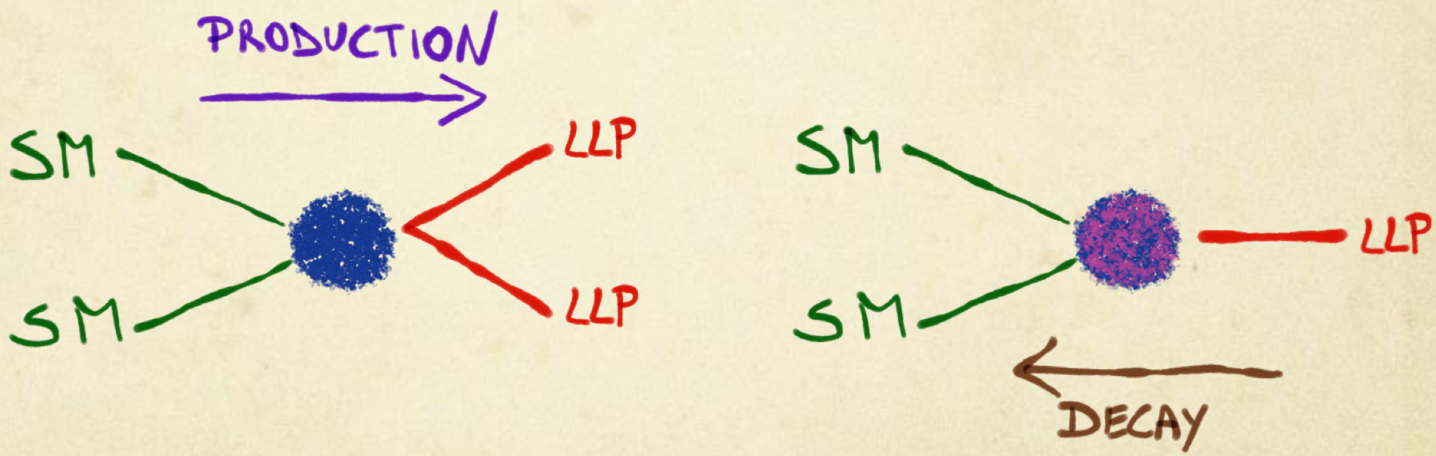
One effective coupling



Difficult to have a sufficient rate and to keep a long lifetime!

Ideal model

Production and decay are separated – pair production



Best sensitivity achieved with **models where the production and decay occur due to <u>different coupling constants</u>**, and the particle lifetime defines the probability of decay within a detector

LLP Geometrical Acceptance

What shapes the sensitivity vs lifetime?

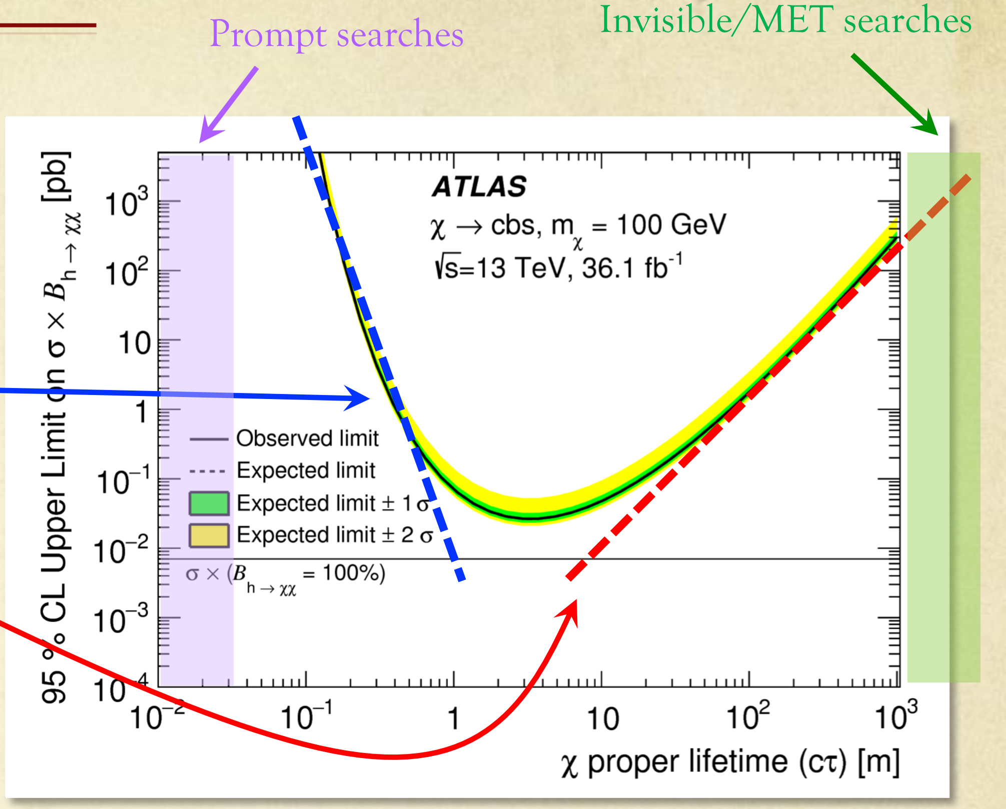
- P = geometrical acceptance

$$P = \frac{1}{4\pi}\int_{\Delta\Omega} d\Omega \int_{L_1}^{L_2} dL \frac{1}{d} e^{-\frac{L}{d}}$$

$$\approx \frac{\Delta\Omega}{4\pi}\, e^{-\frac{L_1}{d}}\, \frac{L_2 - L_1}{d}$$

Solid angle

- $L_2 - L_1$ = detector length
- d = average LLP decay length in lab frame



❖ Good solid angle coverage → lifetime independent

❖ For smaller lifetimes → need high efficiency close to the IP

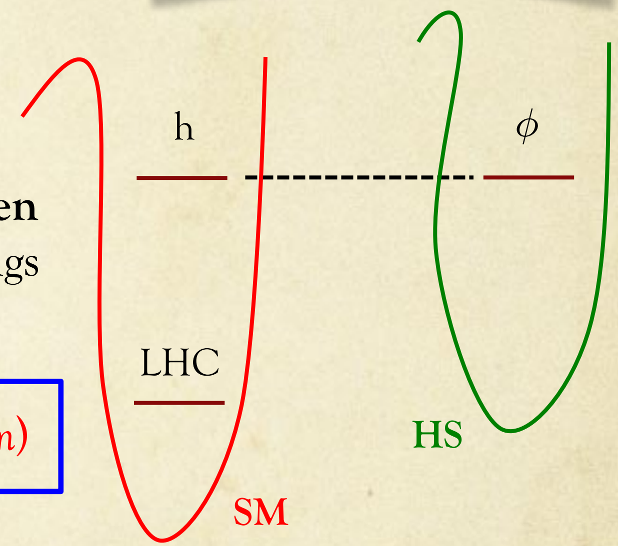
❖ For larger lifetimes → longer detector

The Hidden Sector

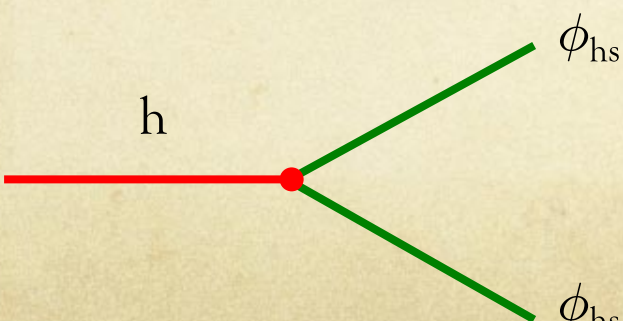
- The Standard Model (SM) is in amazing agreement with the experimental data, but **still some problems remain unsolved**: dark matter, neutrinos masses, hierarchy, matter-antimatter asymmetry…

- 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

LLP in BSM

Examples of LLP in different BSM models…

		Small coupling	Small phase space	Scale suppression
SUSY	GMSB			✓
	AMSB		✓	
	Split-SUSY			✓
	RPV	✓		
NN	Twin Higgs	✓		
	Quirky Little Higgs	✓		
	Folded SUSY		✓	
DM	Freeze-in	✓		
	Asymmetric			✓
	Co-annihilation		✓	
Portals	Singlet Scalars	✓		
	ALPs			✓
	Dark Photons	✓		
	Heavy Neutrinos			✓

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:

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

ϵ = geometrical acceptance along ULLP

L = size of the detector along ULLP direction

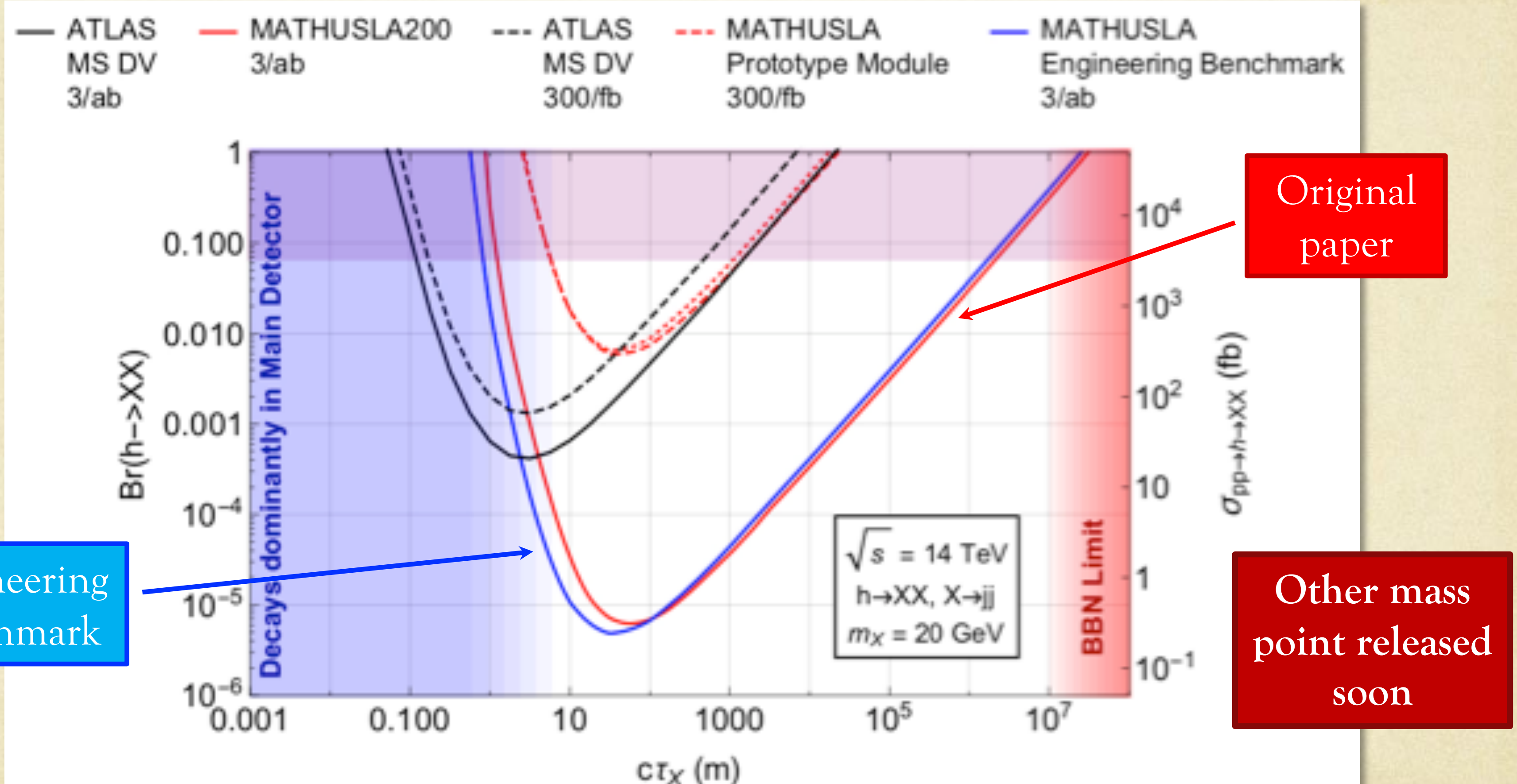
$b \sim m_h/(n \cdot m_X) \leq 3$ for Higgs boson decaying to n = 2, $m_X \geq 20$ GeV

❖ **To collect a few ULLP decays with $c\tau \sim 10^7$ m requires 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 @ P5

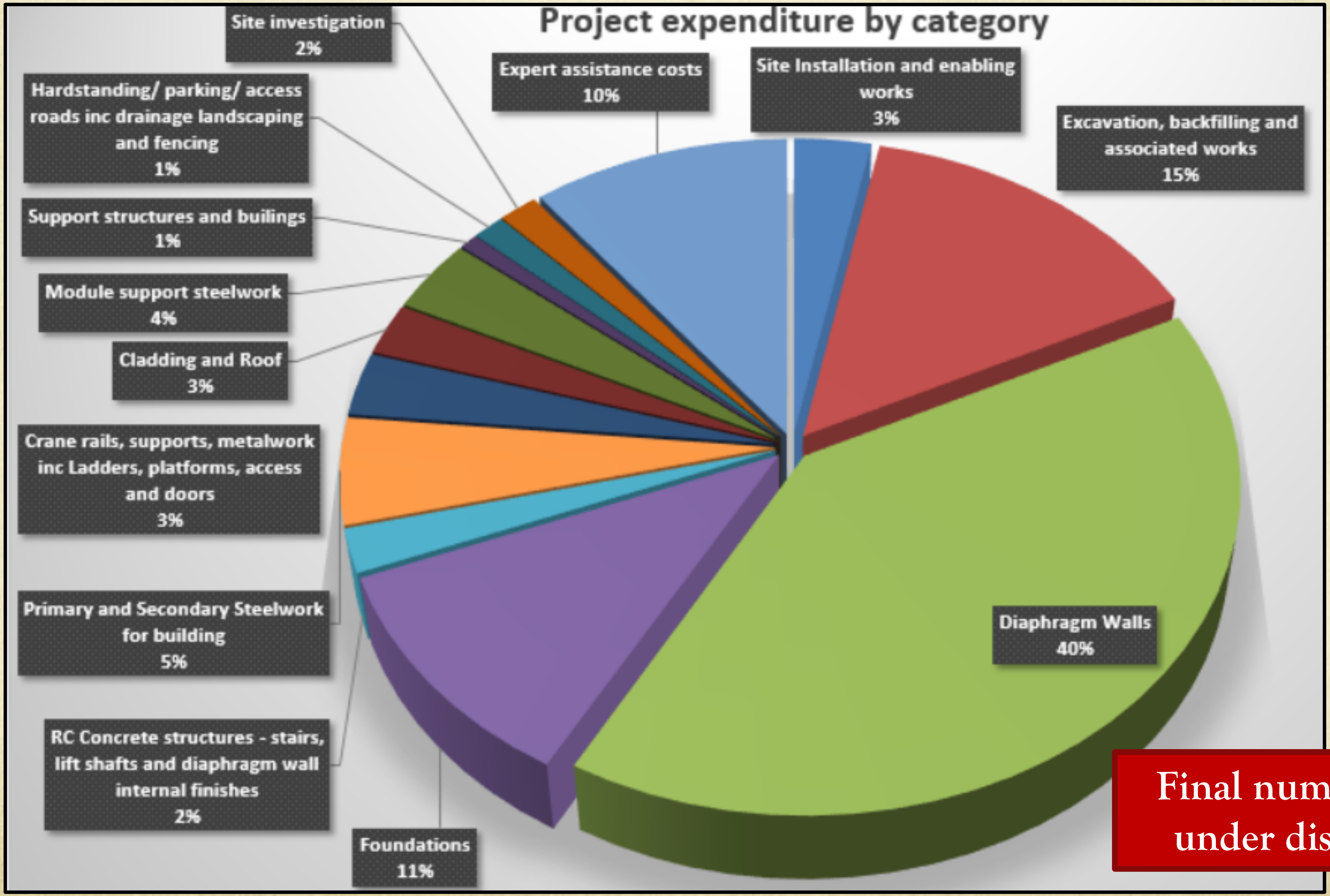
- Worked with Civil Engineers to define the **building and the layout of MATHUSLA at P5**
- **Layout restricted by existing structures** based on current concept and engineering requirements



More details on the comparison MATHUSLA200/Engineering benchmark in Imran Alkhatib thesis, "*Geometric Optimization of the MATHUSLA Detector*" - arXiv:1909.05896

MATHUSLA @ P5

- Worked with Civil Engineers to define the building and the layout of MATHUSLA at P5
- **Layout** restricted by existing structures based on current concept and engineering requirements

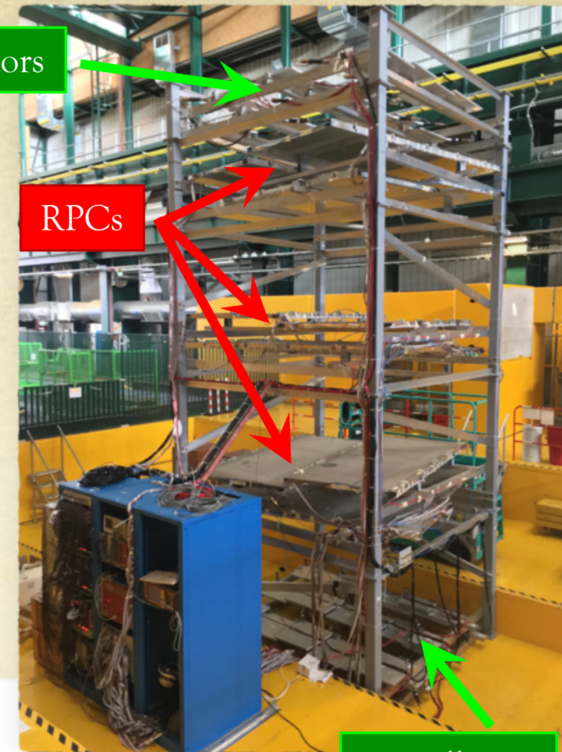


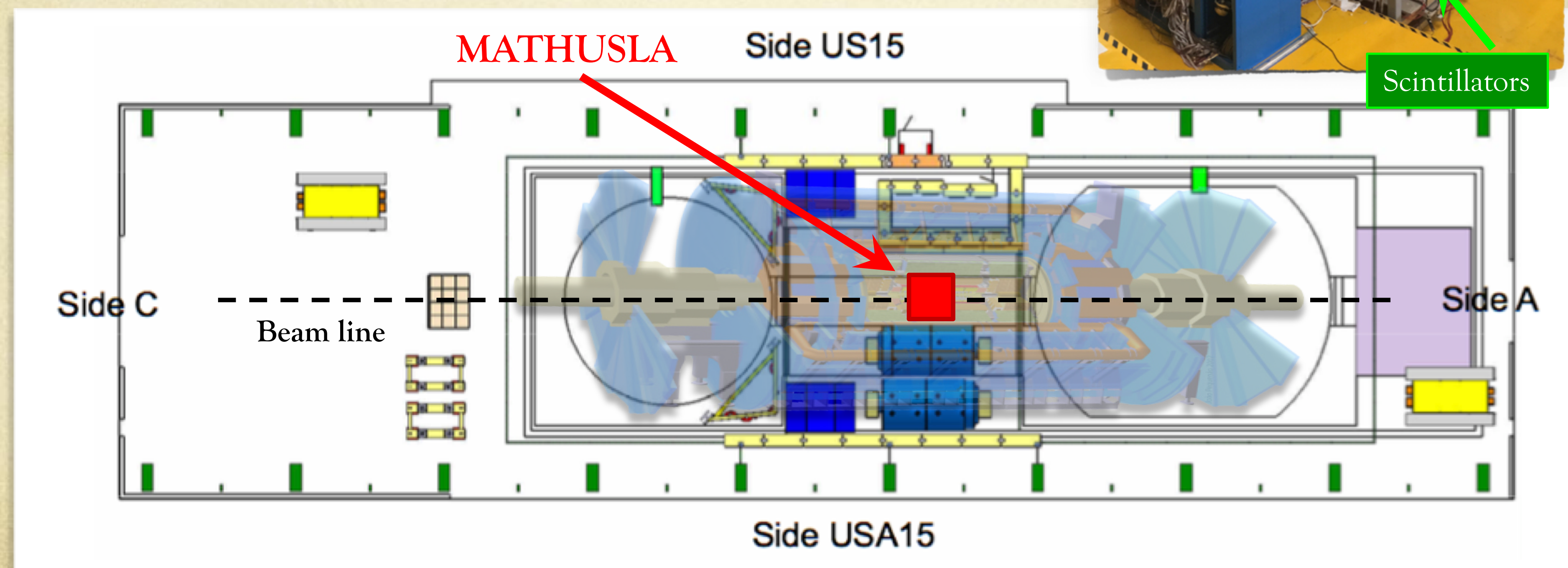
Final numbers still under discussion

Test Stand @ P1

Need to quantify the **background from ATLAS**

- Test stand installed on the surface area above ATLAS (~exactly above IP) in November 2017 (during ATLAS operations this space is empty)
  - ✓ **Performed measurements with beam on and off during 2018**

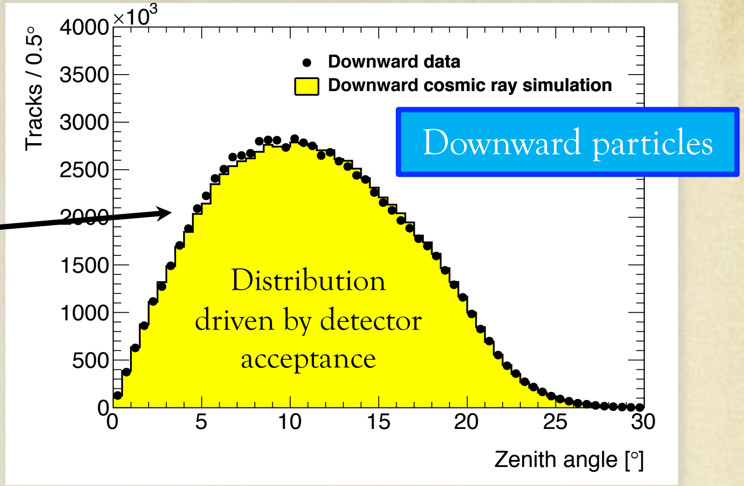




Test Stand Data Analysis

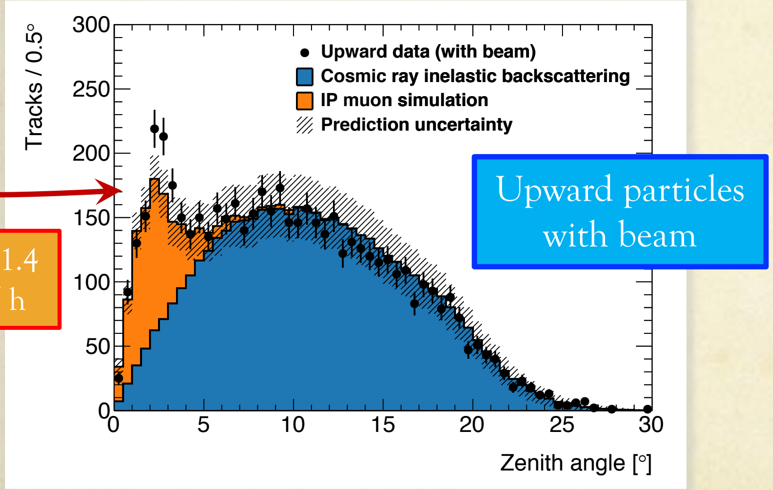
Nuclear Inst. and Methods in Physics Research, A 985 (2021) 164661

- MC simulation for cosmic muons and for particles generated at the ATLAS IP
  - Angular distribution for down tracks (**cosmic muons**) match very well expected from MC

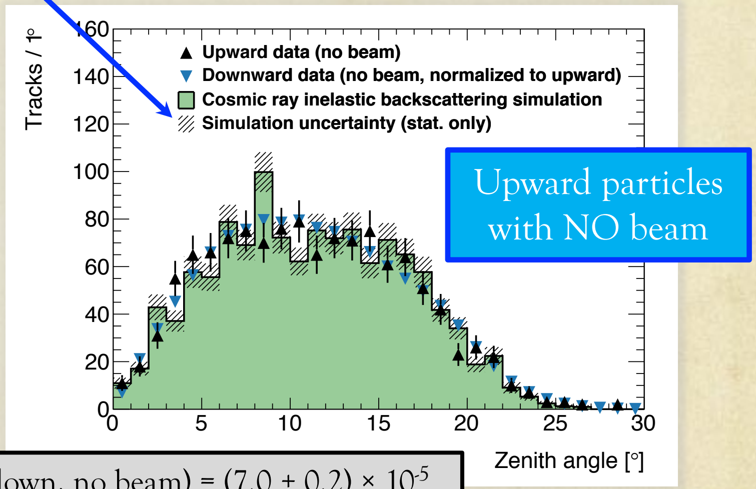


❖ **Up tracks no beam** consistent with **downward tracks faking upwards** tracks (muon backscattering)

❖ Accumulation for zenith angle < ~ 4° consistent with **upward going tracks from IP when collisions occur**



Expected 12.3 ± 1.4 upward tracks / h



R(up/down, no beam) = $(7.0 \pm 0.2) \times 10^{-5}$

Test stand results confirm the background assumptions in the MATHUSLA proposal and demonstrate that there are no unexpected sources of background

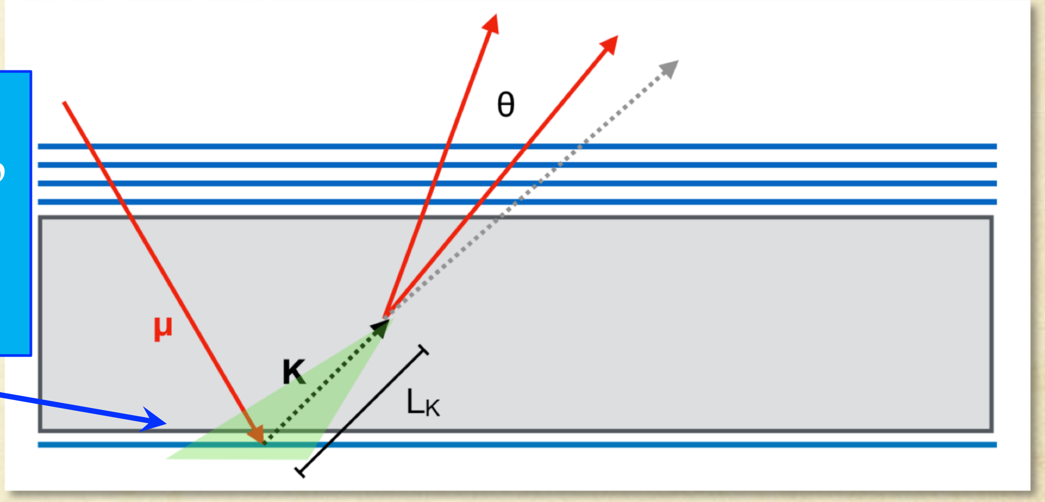
What we have learned from TS data? (Part 2)

We have learned a lot from the test stand data…

- From preliminary simulations: the albedo that creates SM LLP is made of **muons** (~91%), **e^+-e^-** (~8%), and **protons** (~1%)
- **Expect ~10^8 up-tracks at MATHUSLA** (during entire HL-LHC, assuming LHC always running)
  - ✓ If these particles are fast, they can fake a low-mass boosted BSM LLP
- **K^0_L most dangerous background**

Consider a relativistic K^0_L with b >> 1
→ angle between the charged tracks **~ 1/b**

K^0_L originated from a region of the floor of area ~ $(1/b\ L_K)^2$



- Chance that a real boosted two-pronged LLP decay fails this veto is < ~ 0.01 * $1/b^2$
- Point-back-veto will reduce background from fast SM LLPs

Search for light BSM LLPs should be unaffected by fast SM LLP background!

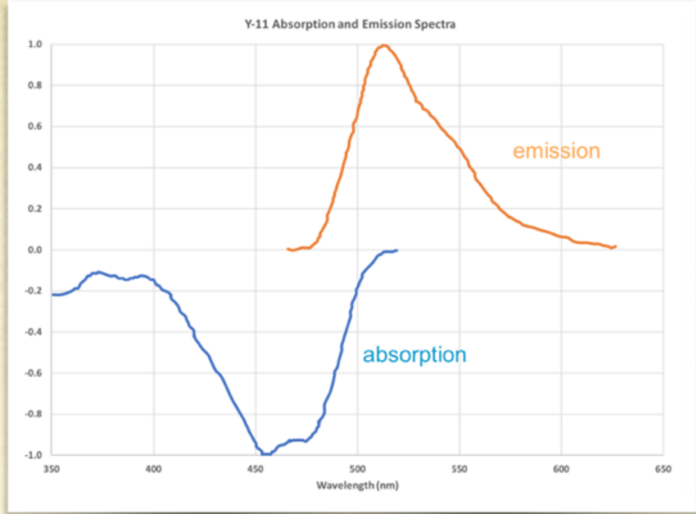
What we have learned from TS data? (Part 2)

We have learned a lot from the test stand data…

- CRs hitting the floor/walls of MATHUSLA might produce, over its full run,
  - O(1) **pion decaying** to *e e e*
  - O(10-100) probably **fast muons decaying** to *e e e*
  - **Neutrons** are only observable if they are very fast (precise estimations are on-going)
  - O(10^5) K^0_L , mostly non-relativistic

- **Possible requirements (for DVs from LLPs) to eliminate this background**
  1) If the DV has **large opening angle** ($\theta > \theta_{max}$), have at least 3 charged tracks,
     - ✓ LLPs with mass > several GeV decaying to hadrons will pass with efficiency ~ 1
  2) OR if DV has **small opening angle** ($\theta < \theta_{max}$), require no CRs hitting the possible floor/wall areas where a kaon could have come from, AND to point back to IP
     - ✓ A light LLP produced in meson decays will almost always pass
  3) OR if DV **has two charged tracks** with large opening angle, require no CRs in detector within ~500ns of DV
     - ✓ Heavy LLPs decaying to two leptons will always fail 1), 2), and 3) (with some O(1) chance) → some reduction in sensitivity (BUT least motivated physics target)

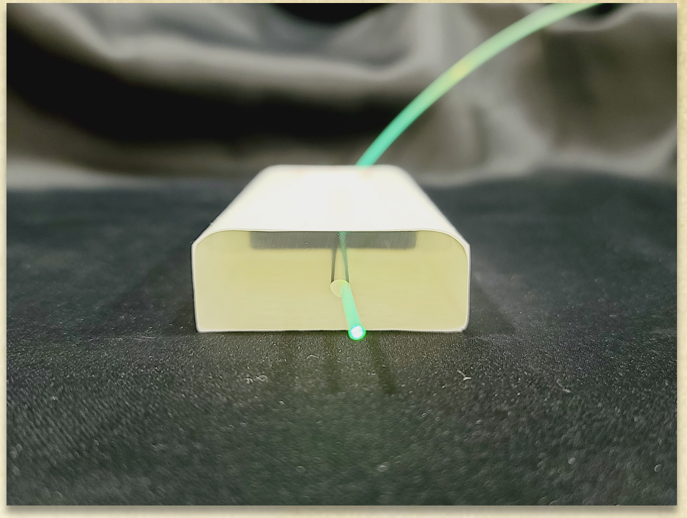
WLS fibre & SiPM



- For **WLS** considering **Kuraray Y-11** (< $5/m)
  - Cutoff below ~500 nm by self-absorption
  - Peak at ~520nm **(green)**
- SiPM used in HEP
  - Detection efficiency typically peaks around **450 nm**
  - Drops off for longer wavelengths
  - Reasonably matched to scintillation light (blue) but not as well for WLS
- Possible **improvements in SiPM spectral response**?
  - Green light penetrates deeper in silicon than blue light
  - Sometimes electrons liberated beyond collection layer
  - Manufacturing process can be tweaked to increase thickness of the collection layer
  - Improvement over standard processing by a factor of 1.5 seems possible (for wavelengths away from peak efficiency)

Possible options:
- S14160-3050HS: 3x3mm
- S14160-6050HS: 6x6mm

Tracking Technology

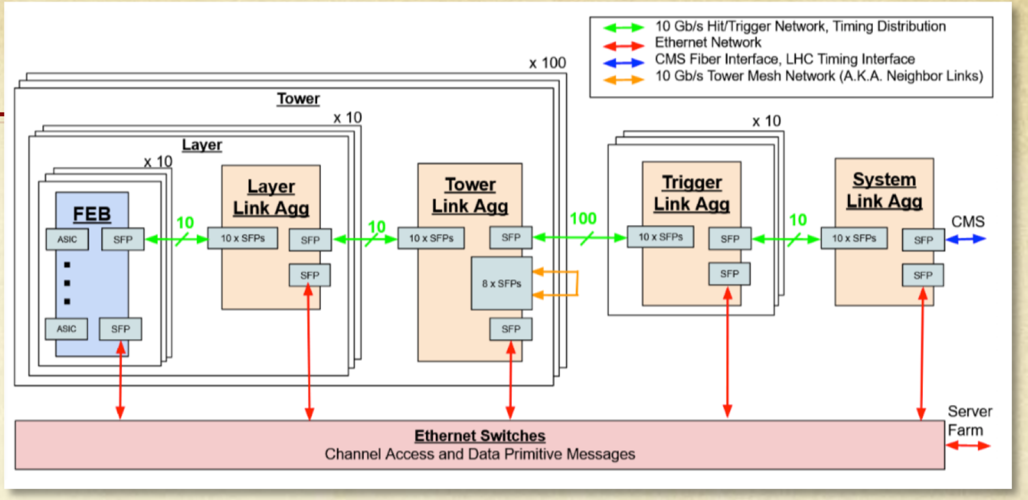


- **Extruded scintillator bars with wavelength shifting fibers coupled to SiPMs** are very competitive
  - SiPMs operate at low-voltage (25 to 30 V)
  - **No gas** involved
  - **Timing resolution can be competitive with RPCs**
  - Tested extrusion facilities - **FNAL** and Russia. Used in several experiments: Bell muon system trigger upgrade (scintillators from FNAL and Russia), Mu2E, and KIT (FNAL scintillators)
- **Extruded scintillator facility at Fermilab**
  - 100 ton per year using 6 hour shifts 4 days per week (2 shifts → 200 t/y)
  - Typical production 50t/y, demand driven
  - Used for many experiments, most recently **Mu2e, KIT**
  - Cost \$20/kg in ~ small quantity
  - Target of **\$10/kg in large quantity**

Readout & Data Taking

- **Readout**
  - **9 tracking layers** (6 tracking layers + 5m below + 2 on the floor)
  - 4 cm scintillators with readout at one end results in 400K channels
  - Rates dominated by cosmic ray rate (~2 MHz)
    - ✓ Does not require sophisticated ASIC
    - ✓ **Aiming for 1 CHF per channel for frontend**
- **Data taking**
  - Baseline is to **collect all detector hits** with no trigger selection and **separately record trigger information**
  - Data rate dominated by cosmic rays 1/(cm^2-minute) which gives ~ 2MHz rate. With 9 x 9 m^2 modules, two hits/module with 4 bites per readout and readout 7 layers to readout gives **~ 30 TB /y per module**
  - Move information to central trigger processor
  - Trigger separately recorded (and used for connecting to CMS detector bunch crossing in the future main detector)

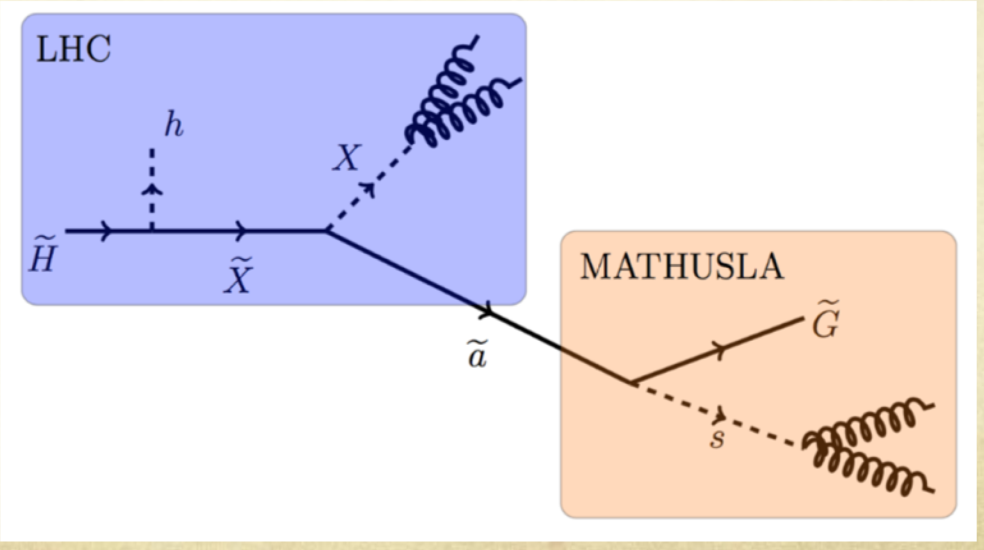
DAQ Design



- **DAQ**
  - ✓ Modular design of the Front End Boards and link aggregation boards
  - ✓ All hits stored in buffer storage
  - ✓ Data rate is well within COTS server
- **Trigger**
  - ✓ Tower aggregation module triggers on upward going tracks within 3 x 3 tower volumes
  - ✓ Selects data from buffer for permanent storage
- **Trigger to CMS**
  - ✓ Upward-going vertex forms trigger to CMS
  - ✓ MATHUSLA trigger latency estimates appear compatible with CMS L1 latency budget

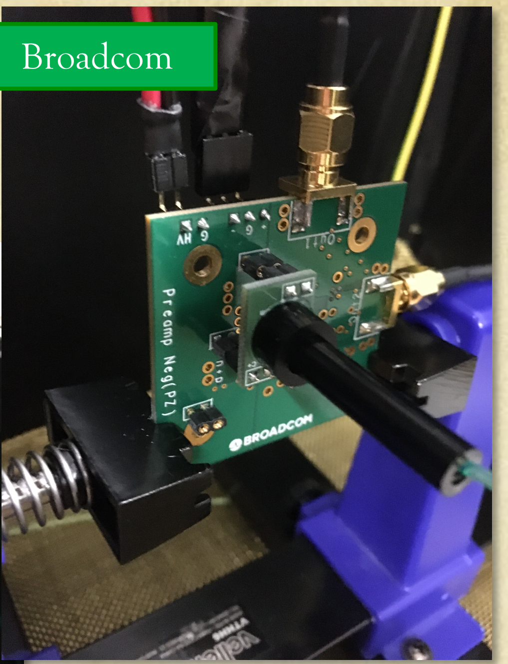
Trigger

- **CMS Level-1 trigger** latency is 12.5 μs for HL-LHC
  - ✓ Conservatively assuming a 200m detector with height = 25m located 100m from IP, LLP with β = 0.7, optical fiber transmission to CMS with v_{fiber} = 5 μs/100m
  - ✓ MATHUSLA has 9 μs or more to form trigger and get information to CMS Level-1 trigger
  - ✓ If problem to associate MATHUSLA trigger to unique bunch crossing (b.c.) the approved CMS HL-LHC Level-1 allows for recording multiple b.c's
- Running **CMS and MAHUSLA in "combined" mode** will be crucial for both cosmic ray studies and LLP searches

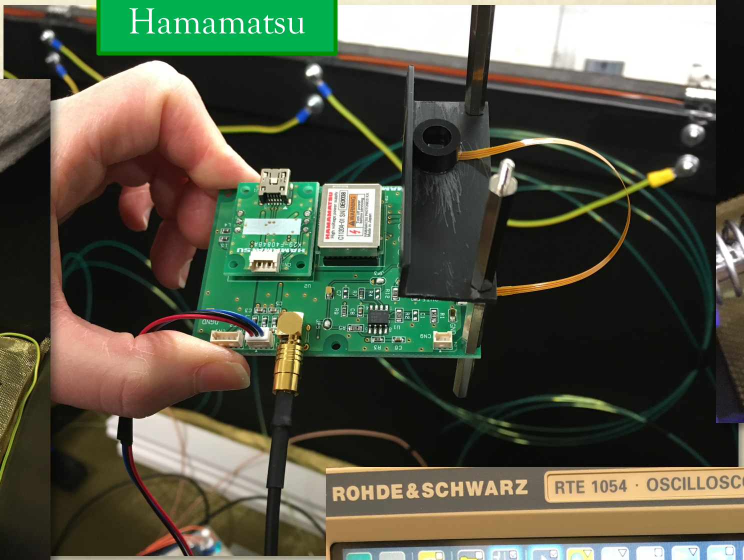


SiPM Tests @ CERN

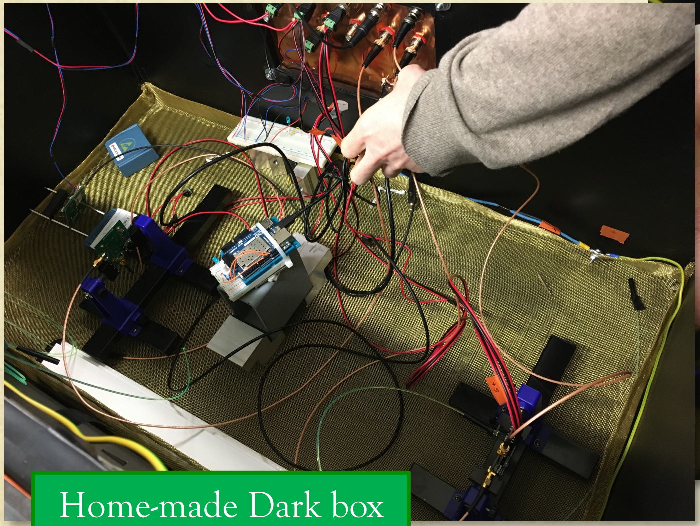
- Performed some **dark count measurements** (i.e. do we need to cool the SiPM?)



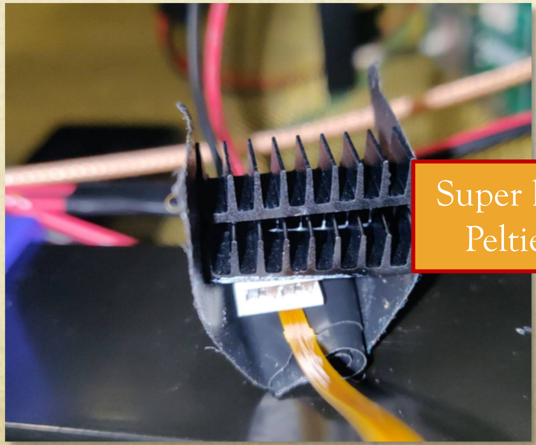
Broadcom



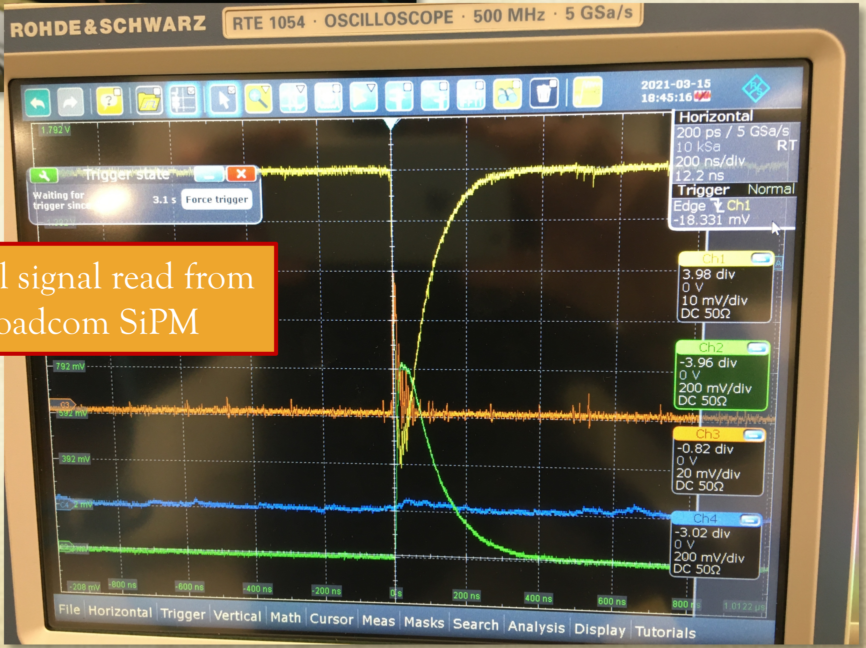
Hamamatsu



Home-made Dark box

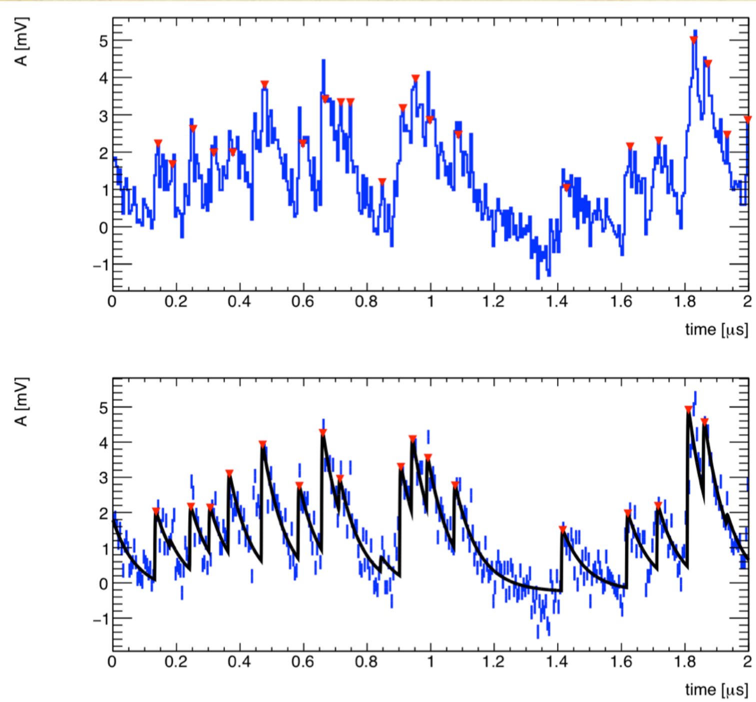


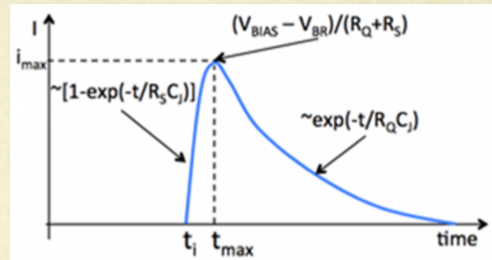
Super home-made Peltier cooling

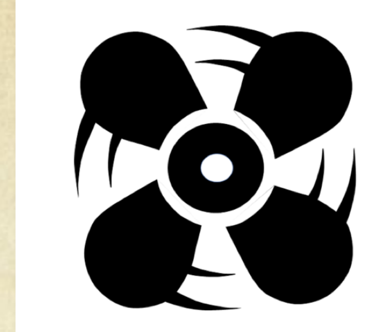


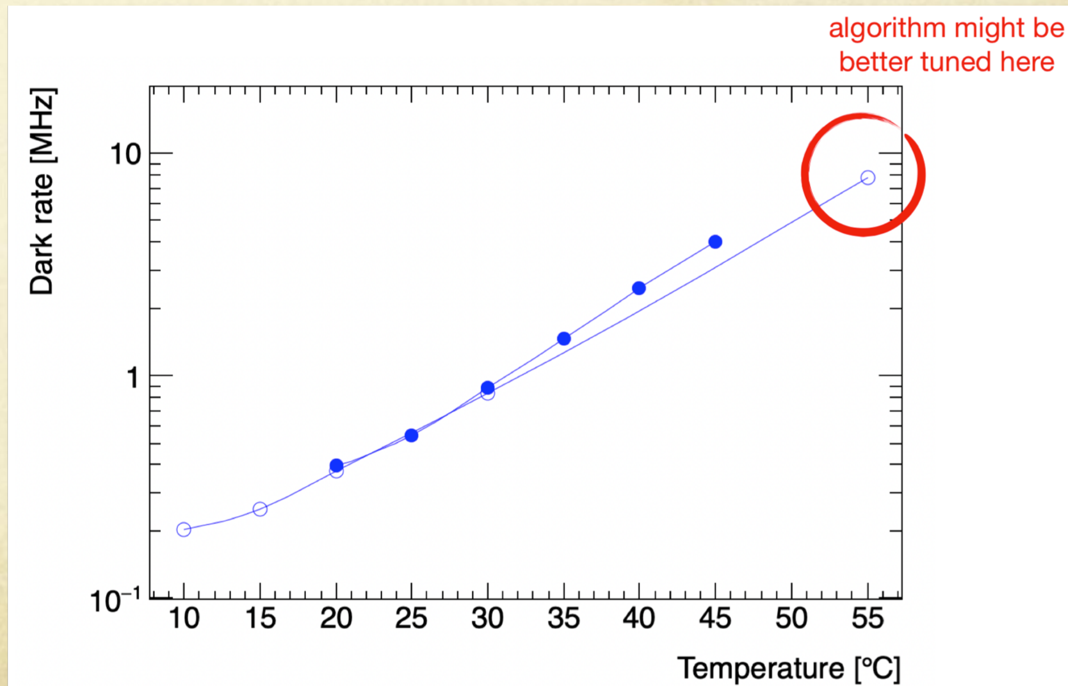
Typical signal read from Broadcom SiPM

SiPM Tests @ CERN – Dark Current





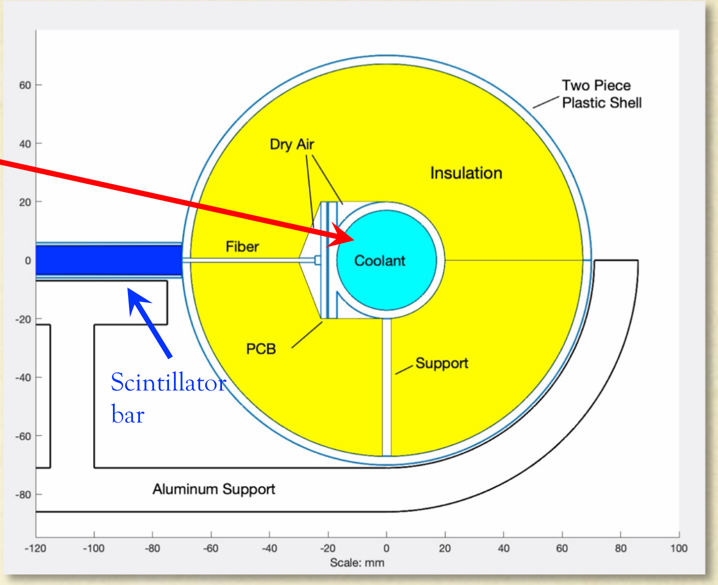




- Probably need some temperature control system to keep the dark count rate stable
- Difficult (if not impossible) to keep MATHUSLA building at a stable temperature (big excursion between winter and summer)

SiPM Cooling Studies

- Considering the possibility of **cooling down SiPM PCB to ~ 0 C** via circulating liquid coolant (Peltiers not practical)
  - ✓ Coolant will circulate in aluminum extrusions 4 cm in diameter with PCB mounting plate

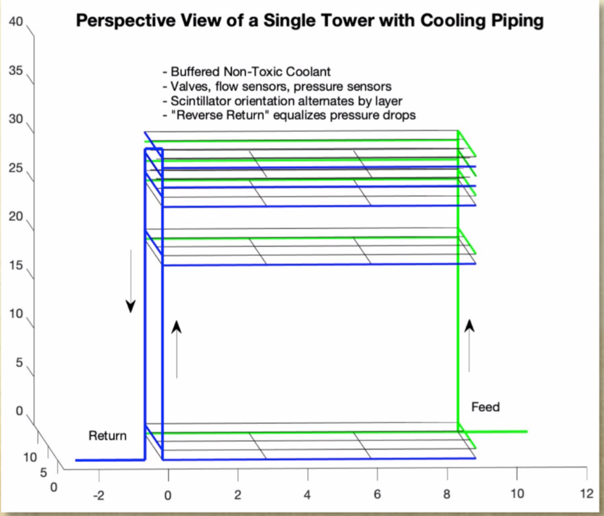


- With 50% **glycerol-water,** flow of order 0.1 liter per second is adequate to keep temperature rise to 0.1 C @ 0 C along the 9 m at a MATHUSLA Hall temperature of 30 C. Total Flow: order 325 liter/s

- Heat load dominated by Polyisocyanurate insulation leakage (5 cm thick), not electronics

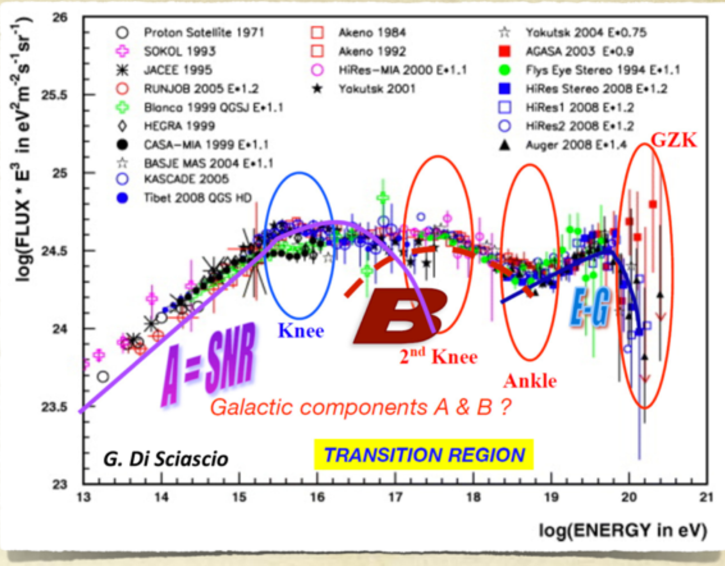
- Heat load is order 2.5 W/m @ 20 C ambient

- Raw load (w/o pumps, transport pipes, etc.) ≃ 100 kW → 250 kW chiller (?)



Ongoing work with CERN cooling group to design a possible chiller system

MATHUSLA - Cosmic Rays - EAS



- **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
- MATHUSLA has **better time**, **spatial** and **angular resolution**, and five detector planes

❑ MATHUSLA standalone

- ✓ 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), **slope of the radii distribution of particle densities**, total **number of charged particles** (**core shape is not well studied → MATHUSLA could provide new information**)

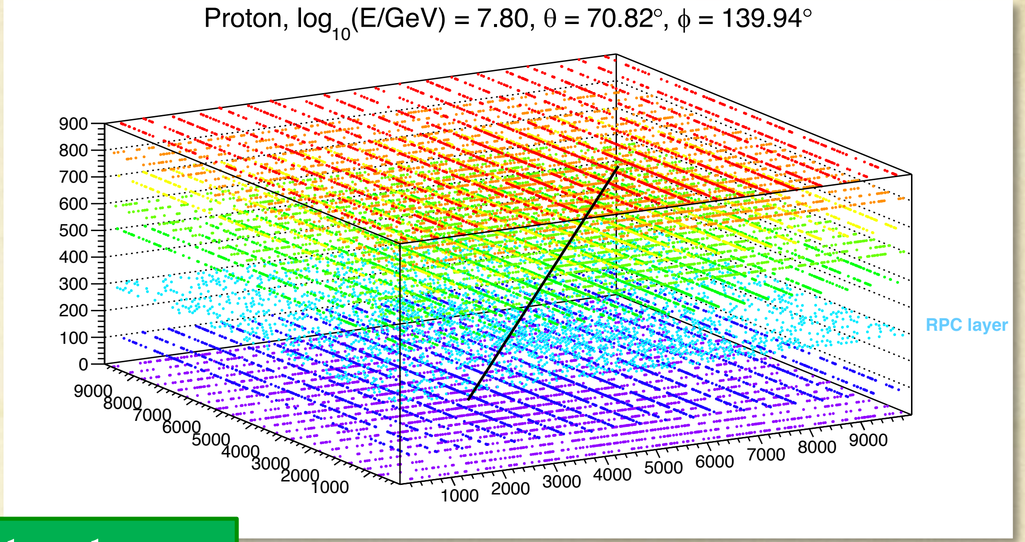
❑ MATHUSLA+CMS

- ✓ Uniquely able to analyse muon bundles going through both detectors. This is a **powerful probe of heavy primary cosmic ray spectra and astrophysical acceleration**
- ✓ Lot of time to connect MATHUSLA with CMS bunch crossing (at HL-LHC trigger has ~12 microsecond latency)

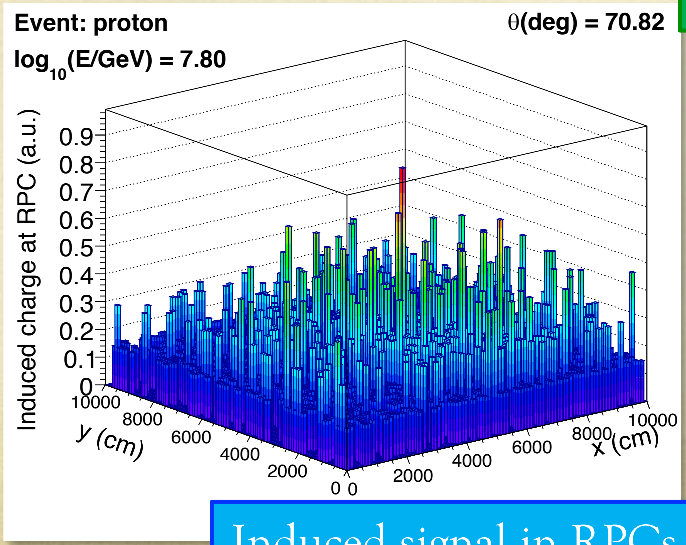
EAS Studies with Scintillators and RPC

These studies are considering 5 tracking layers on top

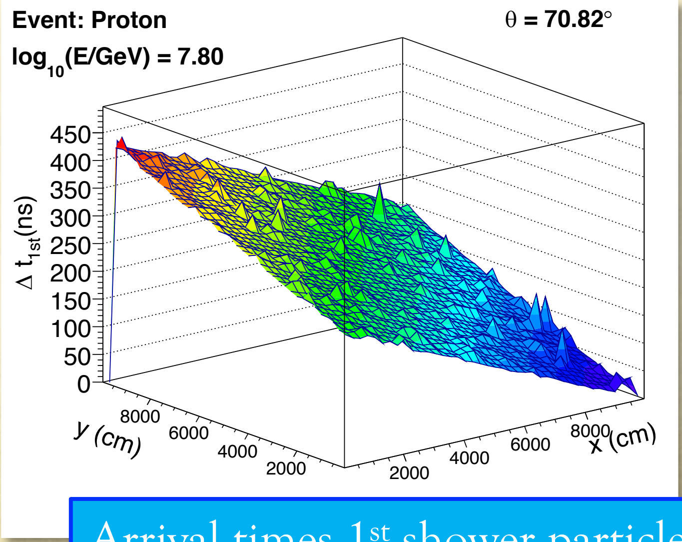
- MATHUSLA has good performance for inclined (>60°) air showers induced by **Fe/H nuclei**
- Studying the possibility of adding a layer of RPC to improve the performance for vertical EAS
- For these tests considered **4 cm x 5 m** scintillator bars. **Coordinate of the hit = center of the bar**



Inclined event



Induced signal in RPCs

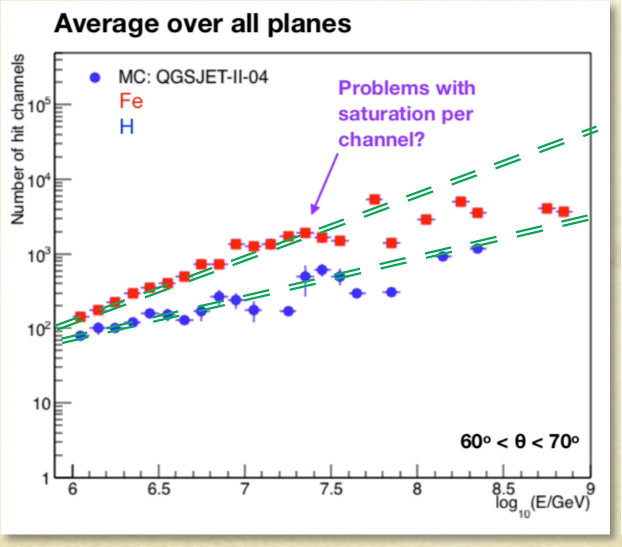


Arrival times 1st shower particles

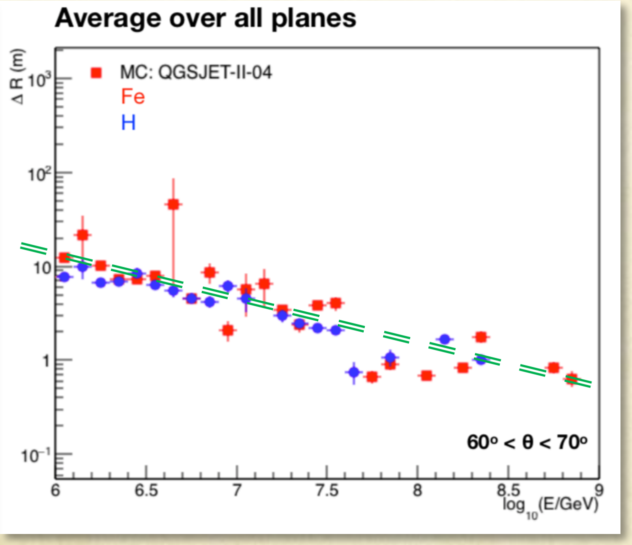
Extensive Air Showers Studies

- Studied MATHUSLA performance for **inclined** (> 60 degrees) **EAS** induced by **Fe/H nuclei**
- CR simulated using **CORSIKA**. Core of the EAS put at the center of MATHUSLA
- For these tests considered **4 cm x 5 m** scintillator bars. **Coordinate of the hit = center of the bar**
- Only register the arrival time of the 1st particle that reaches the bar (in a 1 ns window)

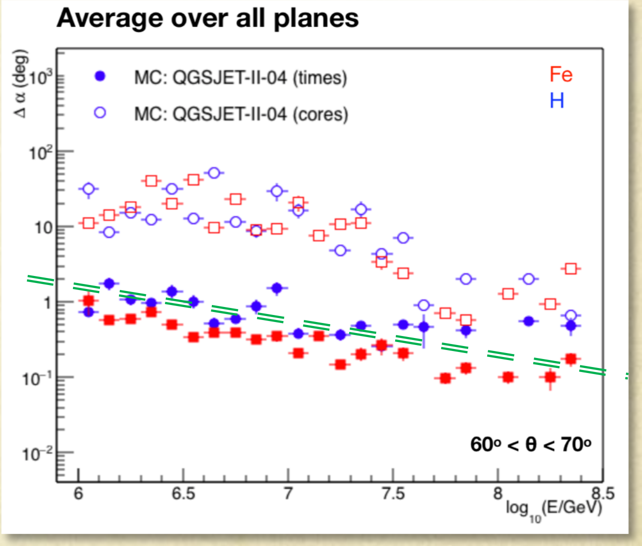
Energy estimation



Core position meas. bias



Core direction meas. bias



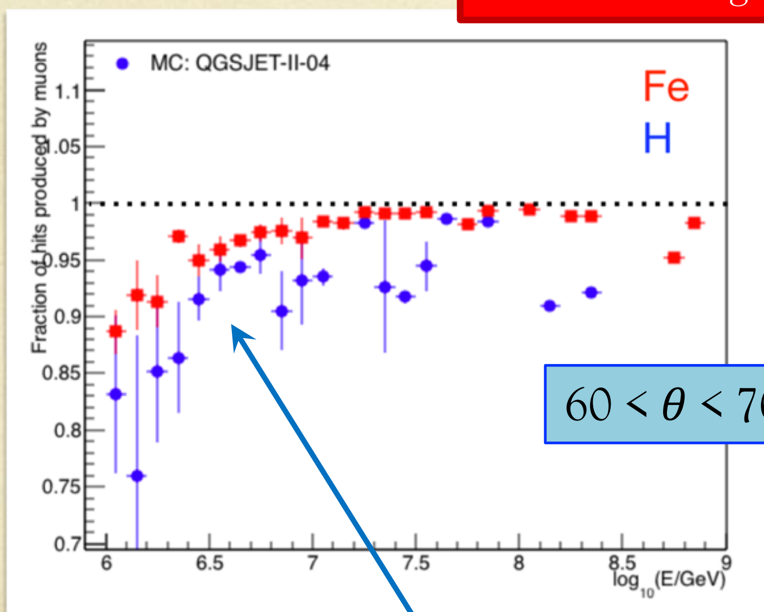
The number oh hits increases with E

- Used only events with $N_{hits} > 100$
- Bias decreases with primary energy

Extensive Air Showers Studies

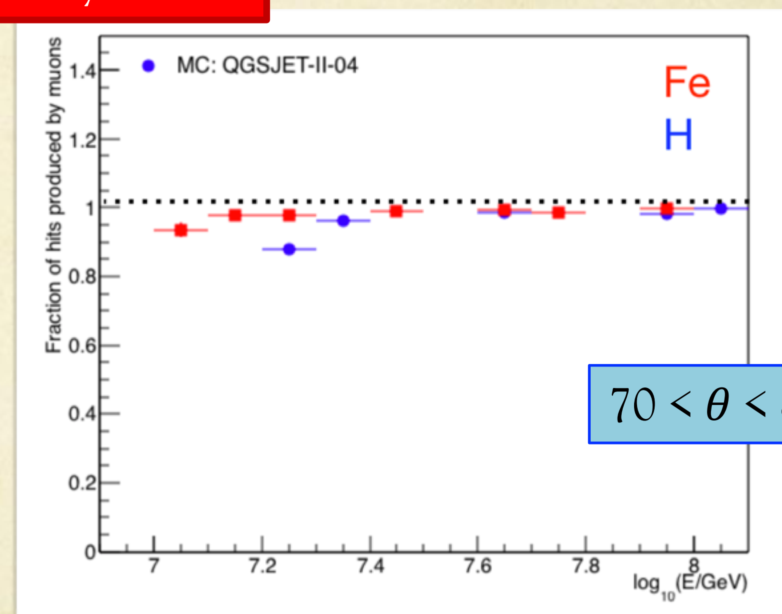
- Studied MATHUSLA performance for **inclined** (> 60 degrees) **EAS** induced by **Fe/H nuclei**
- CR simulated using **CORSIKA**. Core of the EAS put at the center of MATHUSLA
- For these tests considered **4 cm x 5 m** scintillator bars. **Coordinate of the hit = center of the bar**
- Only register the arrival time of the 1st particle that reaches the bar (in a 1 ns window)

Fraction of signals induced by muons



$60 < \theta < 70$

Fraction of muons > 90% for E > $10^{6.5}$ GeV



$70 < \theta < 85$

Very high efficiency

EAS Core Position Estimation - Details

Fig. KASCADE-Grande

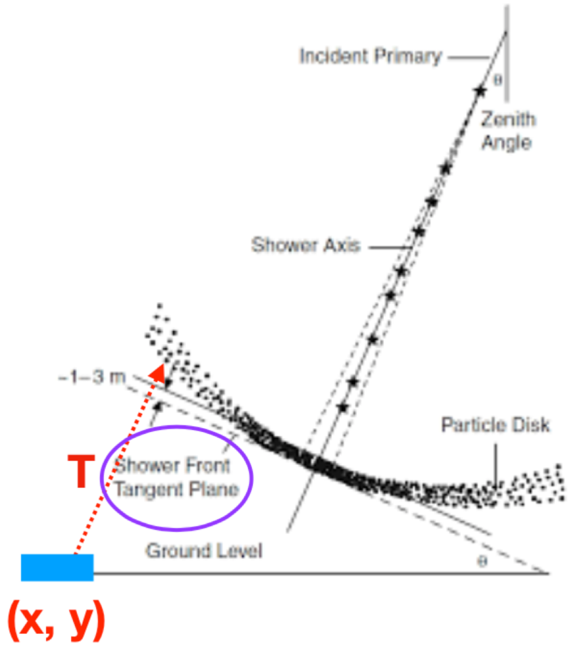
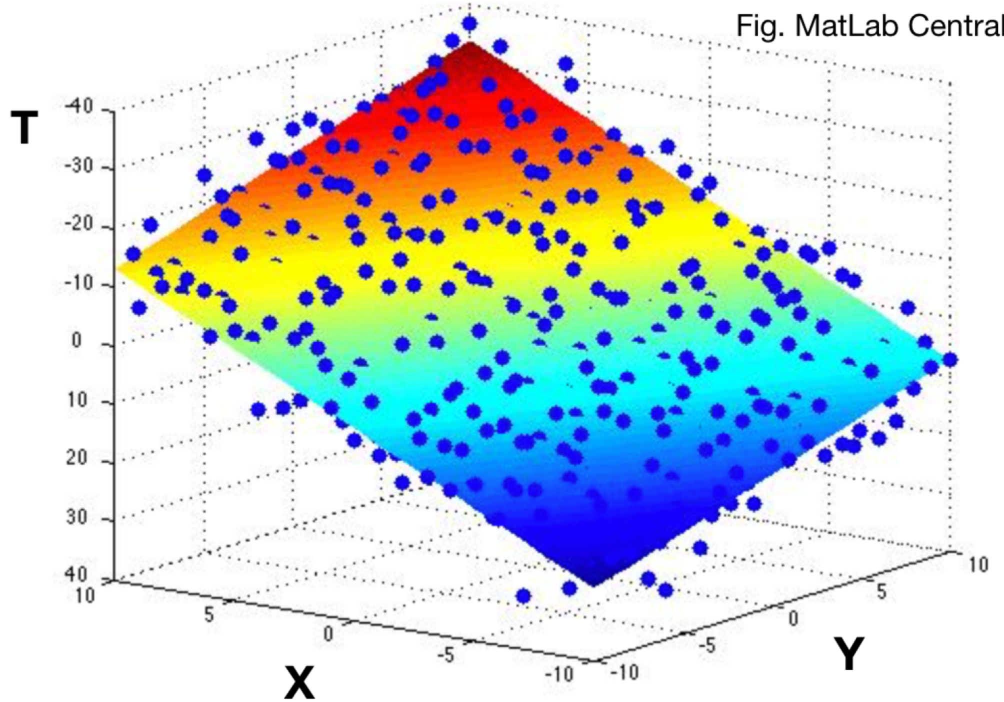


Fig. MatLab Central



Result of the **3D fit** with a plane to a set of points (x, y, t):

From the fit, we get the arrival direction **(θ, ϕ)** of the shower plane that best describes the data

From **J.C. Arteaga-Velázquez**

What Can We Learn From CM? (1)

- MATHUSLA's excellent tracker will allow to study the **spatial distribution of the arrival direction of cosmic rays with high precision**
  - ✓ **PHYSICS OUTCOMES**
    - Study **cosmic ray anisotropies** in more detail
    - Important to constrain the **propagation of cosmic rays in the interstellar space**
    - Constrain models of **the interstellar magnetic field**

- MATHUSLA's detector planes will allow to study **muon bundles for inclined air showers**
  - ✓ **Origin of muon bundles is unknown!** New physics? Problem with hadronic interaction models? Differences due to the heavy component of CRs?
  - ✓ **PHYSICS OUTCOMES**
    - Set limits to BSM physics
    - **Test hadronic interaction models at high energies**
    - Sensitive to the relative abundances mass groups of cosmic rays

What Can We Learn From CM? (2)

- MATHUSLA's design will allow to measure the **muon content of inclined air showers**
  - ✓ Time structure of EAS, truncated muon number, radial densities, production height
  - ✓ General distribution of directional tracks and spatial structure
  - ✓ **Measurements at the shower cores are possible for very inclined events**
  - ✓ PHYSICS OUTCOMES
    - **Constrain QCD at the highly forward**, high $\sqrt{s}$ region: this region is mostly non perturbative in QCD and it is treated with phenomenological models, which are tuned with results of particle accelerators at energies lower than what found in cosmic rays
    - **May help to make ALL OTHER CR measurements (spectra, composition,…) more reliable, including other experiments that probe higher energy ranges and CR from extra galactic origin**

More Considerations About Backgrounds

- Four SM particles with lifetimes above a mm: K^0_L, μ, π+, neutrons
- Qualitative consideration that are under validation using MC simulation
  - K^0_L → most dangerous particle: decays to 2 charged particles + neutrals almost all the time, its decays are not phase space squeezed (next slide)
  - **Neutron→** to make a 50 MeV electron, the neutron has to have a boost of about 40, i.e. ~40 GeV momentum! Cosmic ray showers where individual particles have enough energy to liberate such neutrons are far **too rare for this to be a serious background**
  - μ → of course could be a problem if they fly backwards (LHC rate dominant)
  - π+ → should **not be dangerous**. It has a $e^+e^-e^+$nu decay mode with Br ~ 10^{-9}, but ~10^{14} charged particles from cosmic ray hitting the floor
    - ✓ From test stand analysis
      - Several particles from μ hitting the floor are genuine albedo, i.e. π, not just slow decaying μ
      - N_{up}/N_{down} is 10^{-4}
      - In MATHUSLA100 N_{up}/N_{down} 10^{-6} (better acceptance for downward tracks)

        → 10^8 upward going particles at MATHUSLA from cosmic ray albedo. If they are all pions with Br(pi+ → $e^+e^-e^+$nu) ~ 10^{-9} the contribution is small
      - π can be very easily studied in simulation, since the pion production rate in muons hitting the floor is large enough (unlike kaons) to be seen in simulations

More Considerations About Backgrounds

- How likely is it that a Kaon produced from a downwards traveling muon hitting the floor flies upwards with a chance for its decay products to hit the MATHUSLA ceiling?
  - Even without knowing the cross section or the matrix elements for kaon production, we can OVERESTIMATE this dangerous kaon fraction by assuming **kaons are made in 2→3 processes involving a n/p initial or final state**. In reality, the final state often has higher multiplicity, which will lower the chance the kaon makes it into the decay volume
  - Assuming isotropic muon distribution hitting the floor, the result for 0.7 - 10 GeV muons is always about the same: the chance for produced kaon to be dangerous is 2-4% (gross overestimate, the real answer is 1-2 orders of magnitude lower)
- What is the Kaon production rate from muons hitting the floor?
  - Estimate number of produced kaons by treating muons hitting floor as a fixed target experiment, with target width of order ~ hadron interaction length (if the kaon is produced too deep, it won't escape the floor)
  - For 10^{14} muons, this gives $N_{kaon} \sim 10^3$ * (Kaon production xsec in pb) given the 10^{-2} (calculated) phase space suppression, we can therefore write
    - **$N_{kaon\_LLP\_background} \sim 10$ * (Kaon production xsec in pb)** → **O(0.1 pb) kaon production xsec to be dangerous** (much larger than typical kaon production xsecs from 1 - 10 GeV leptons hitting a fixed target)