Exploring the Lifetime and Cosmic Frontier with the MATHUSLA *Detector*

Cristiano Alpigiani

on behalf of the MATHUSLA Collaboration

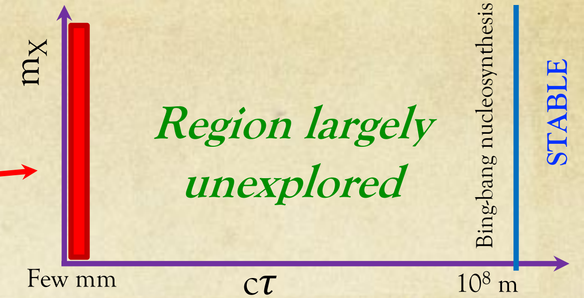
UNIVERSITY *of* WASHINGTON

6th October 2020

ICPPA 2020

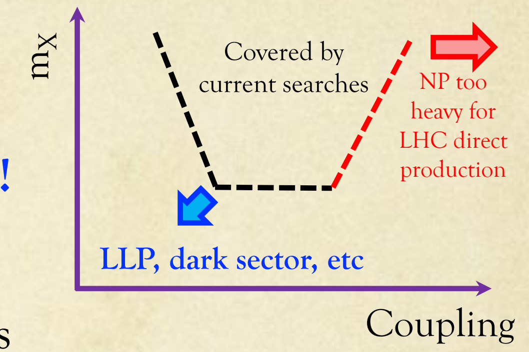
Why Long-Lived Particles?

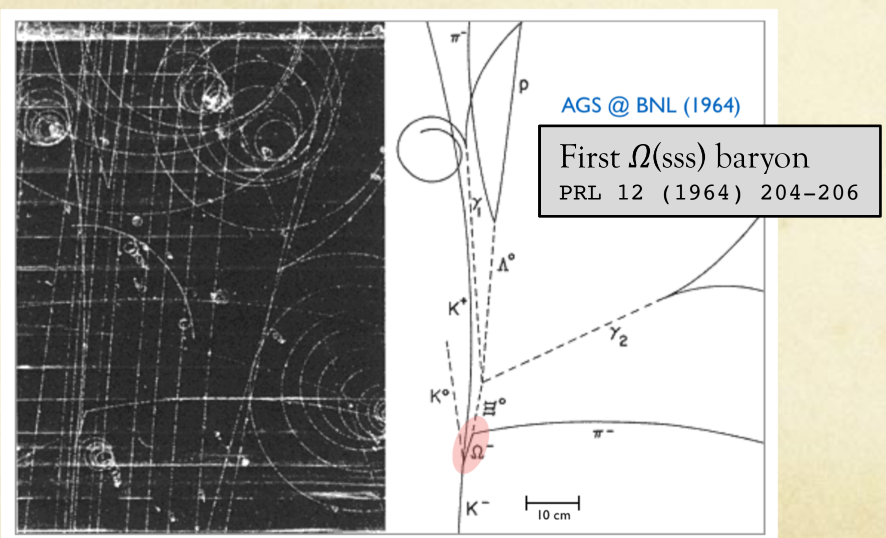
Most new physics searches focus on production and prompt decay at the p-p interaction point…

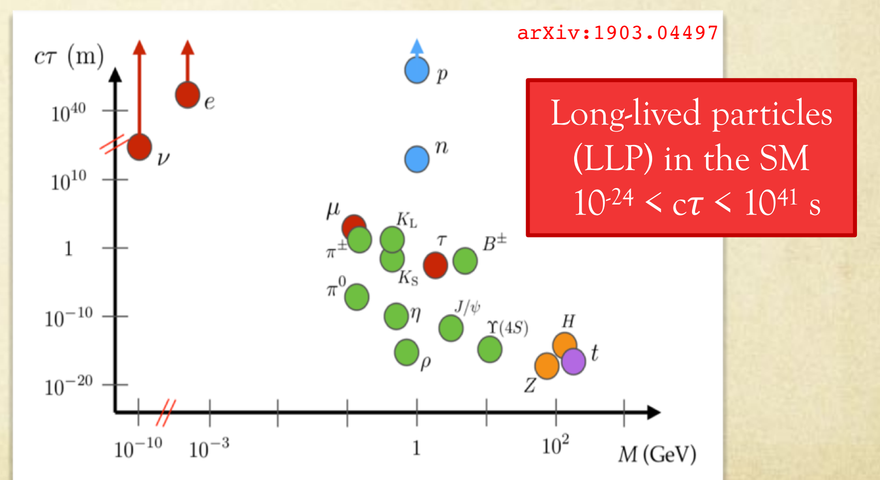


- Current measurements in **impressive agreement with SM expectations**
- Why this lack of any evidence of new phenomena?
  - New **particles** might be more likely **labelled as background**
- Need to **reduce to negligible the possibility of losing NP at the LHC!**
- **Naturalness does not seem to be a guiding principle of Nature**
- Nature is plenty of particles with macroscopic detectable decay lengths

OR

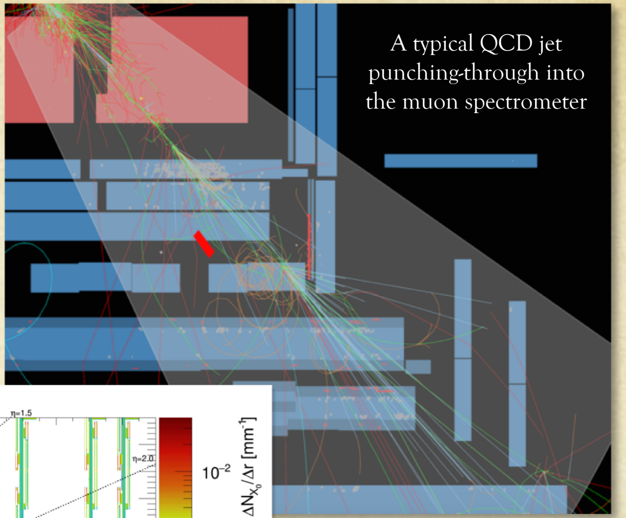






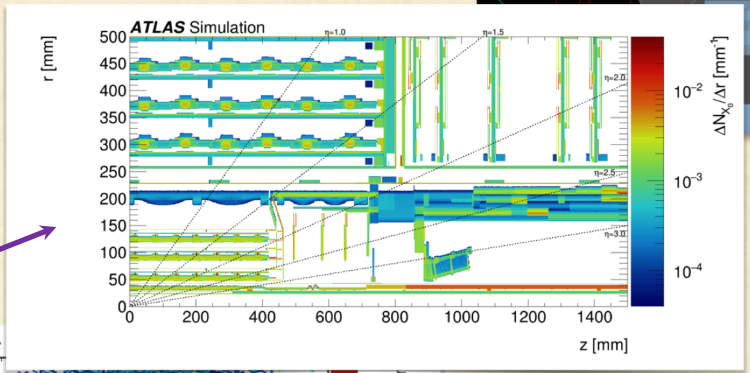
Not surprising that LLP might exist also beyond the SM

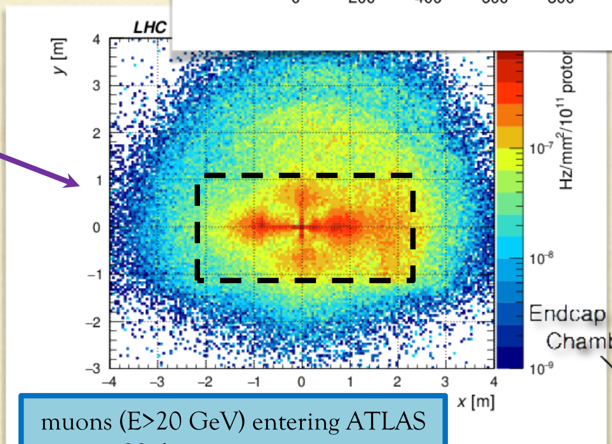
Unconventional Challenges



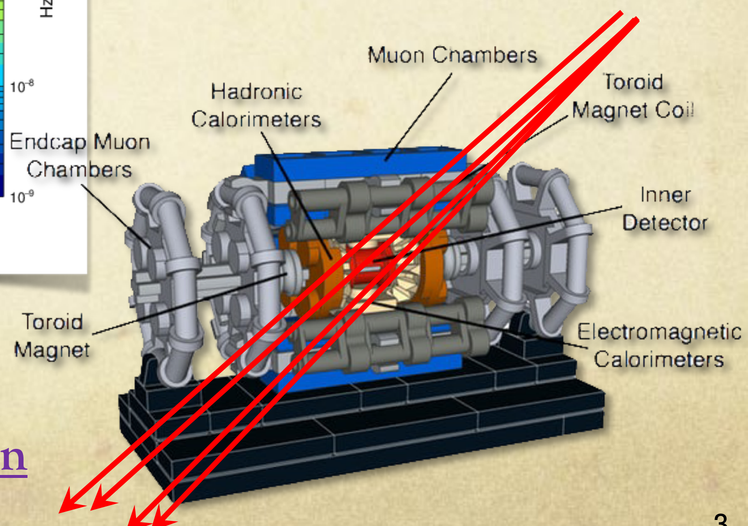
LHC detectors are optimised to detect prompt SM particles

- 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)
  - ✓ Cosmic background





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



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

MATHUSLA

A LHC background free detector with no trigger limitations…

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

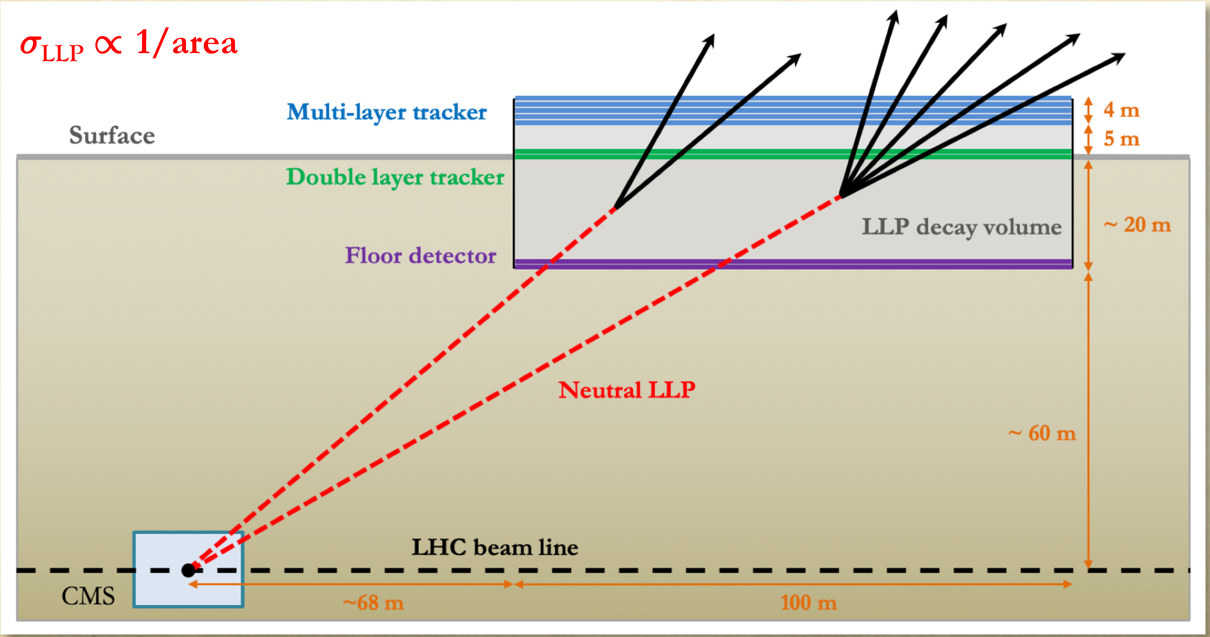
➢ Proposed a **large area surface detector located above CMS**

✓ Need **robust tracking**

✓ Need **excellent background rejection**

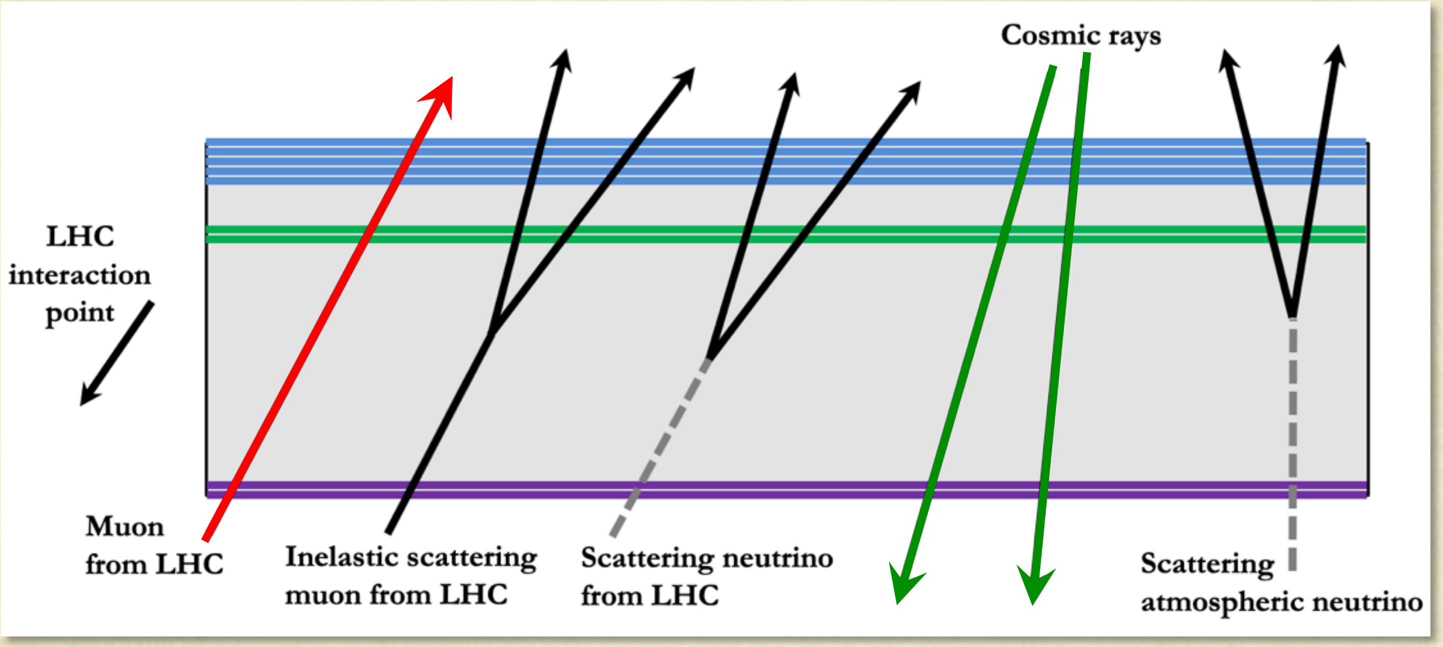
✓ Need a floor detectors to reject interactions occurring near the surface

✓ Both **RPCs** and **extruded scintillators + SiPMs** are considered (good time/space resolution)



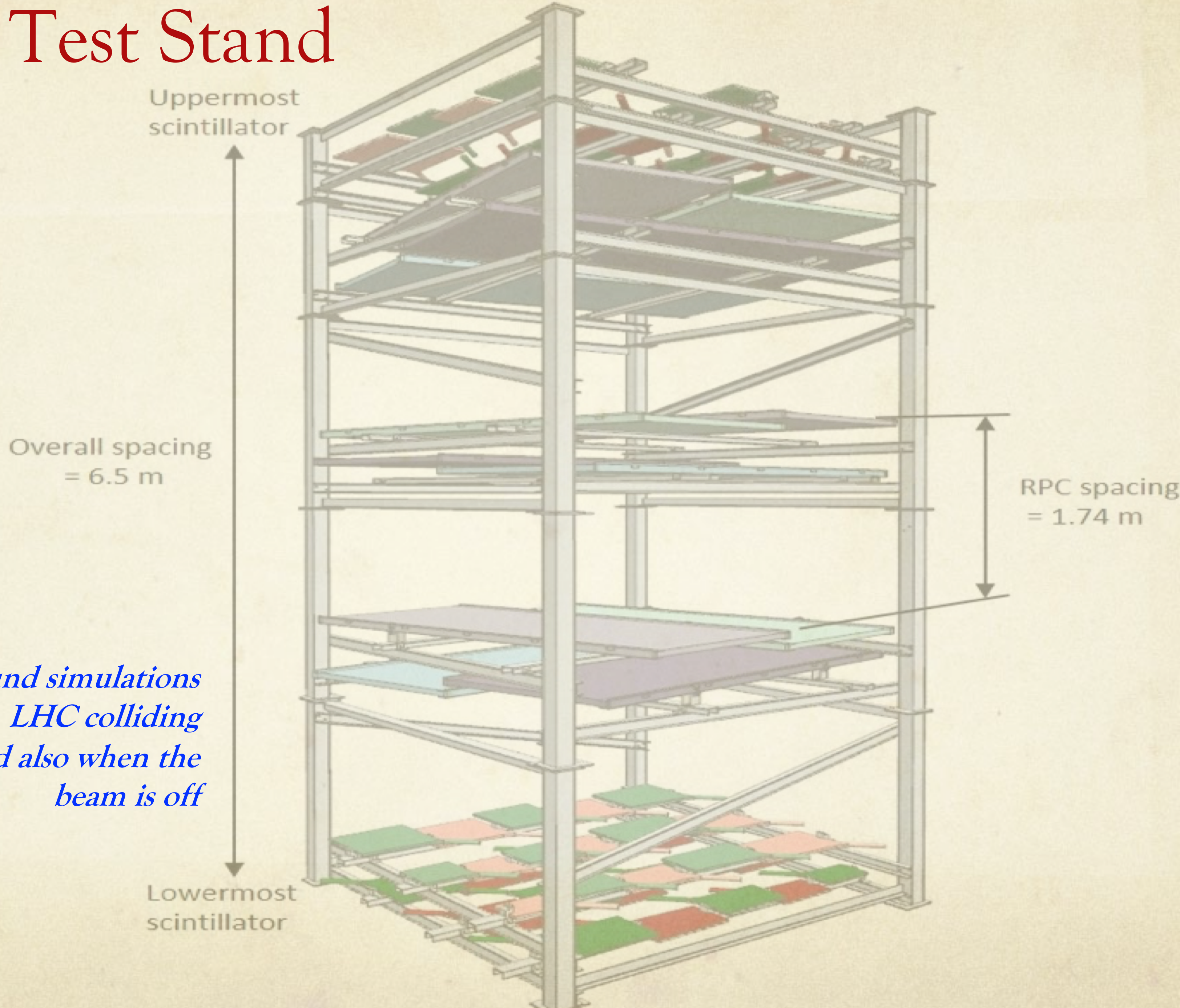
MATHUSLA - Backgrounds

Main backgrounds…



- Cosmic muon rate of about **~2 MHz** (100 m^2)
- LHC muon rate of about **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)

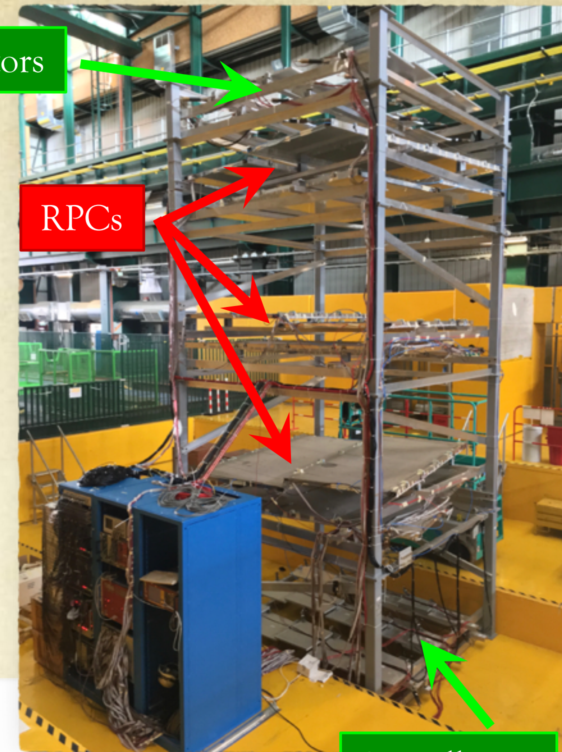
The Test Stand

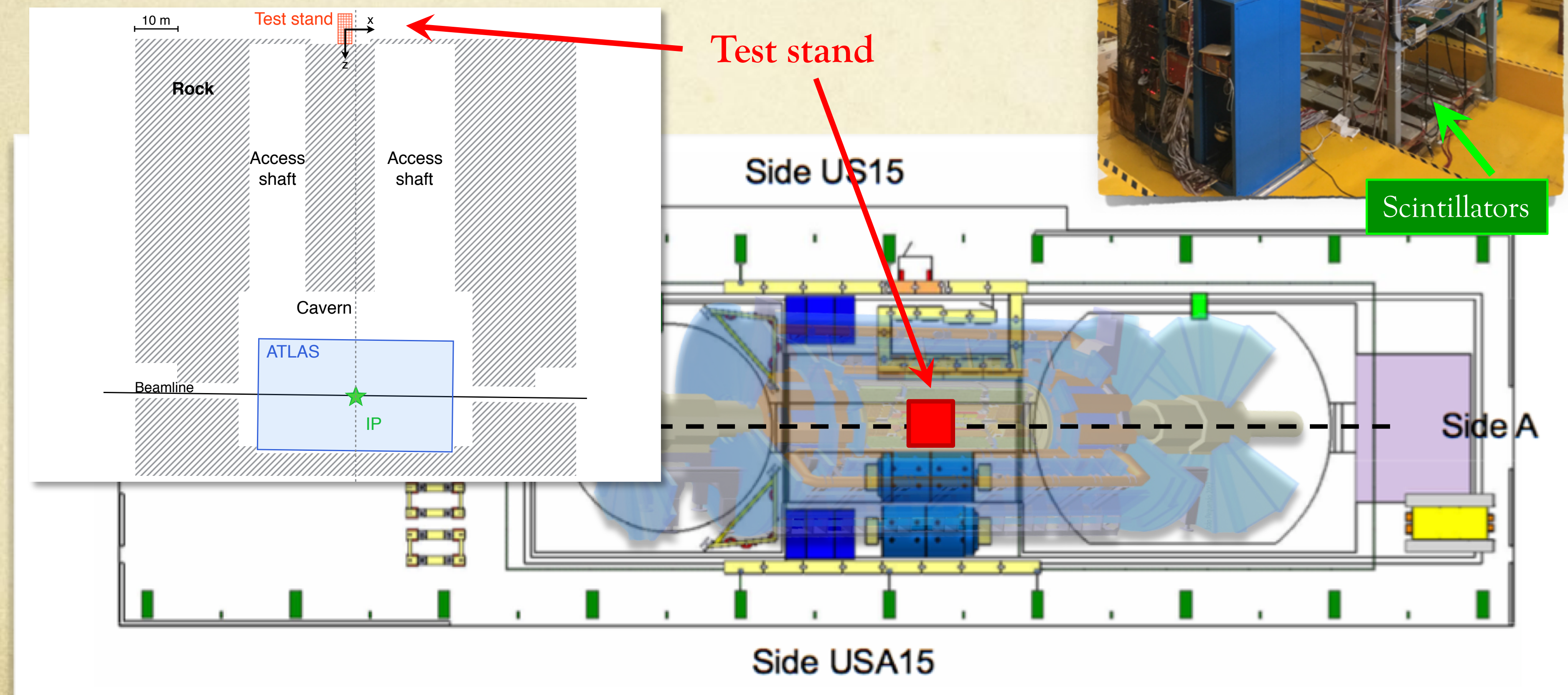


MC background simulations need data with LHC colliding protons and also when the beam is off

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)
  - ✓ Perform measurements with beam on and off during 2018





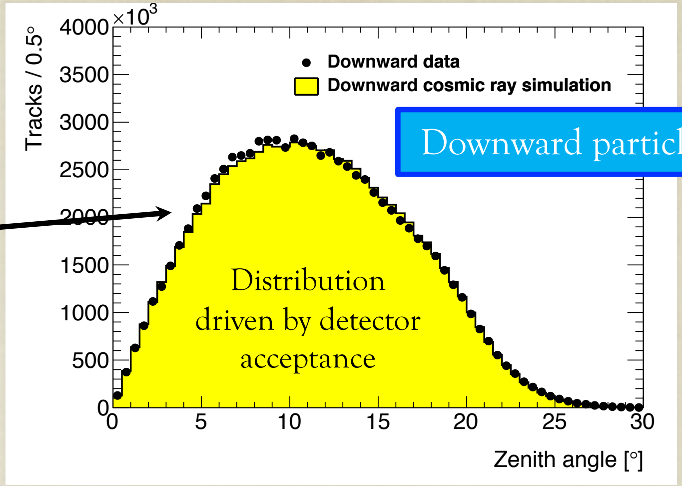
tand Data Analysis

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

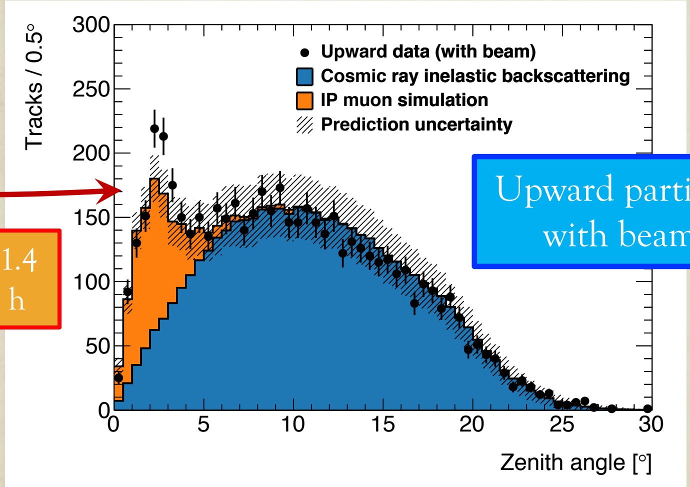
- MC simulation for cosmic muons and for particles generated at the ATLAS IP
  - Angular distribution for down tracks (cosmic muons) match very well expected from MC

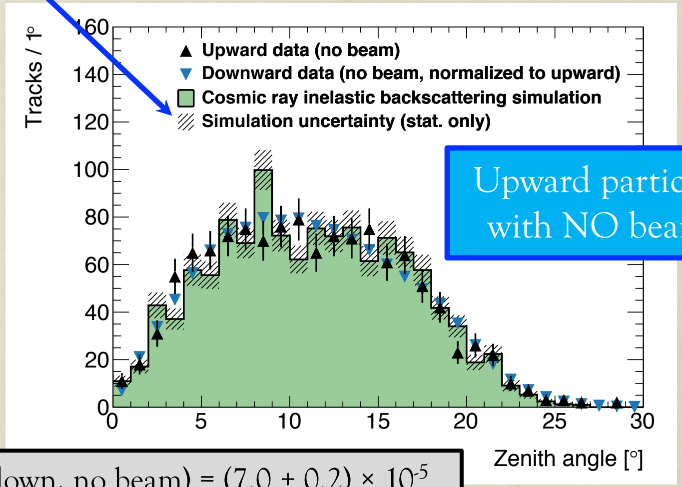
❖ **Up tracks no beam** consistent with **downwards tracks faking upwards** tracks (muon backscattering)

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



Expected 12.3 ± 1.4 upward tracks / h





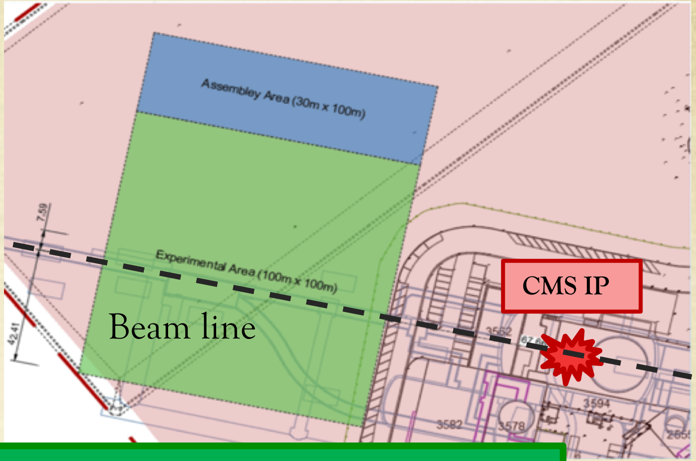
R(up/down, no beam) = $(7.0 \pm 0.2) \times 10^{-5}$

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

Detector layout

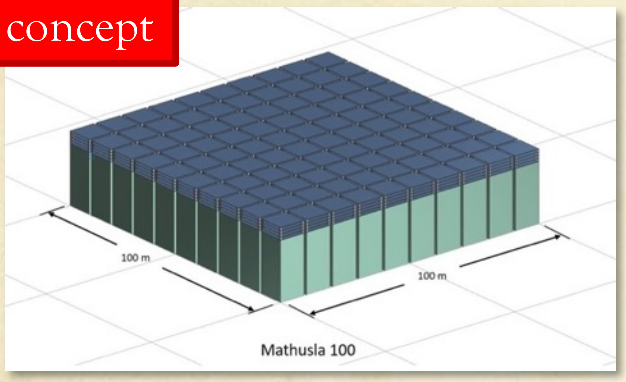
MATHUSLA @ P5

- 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

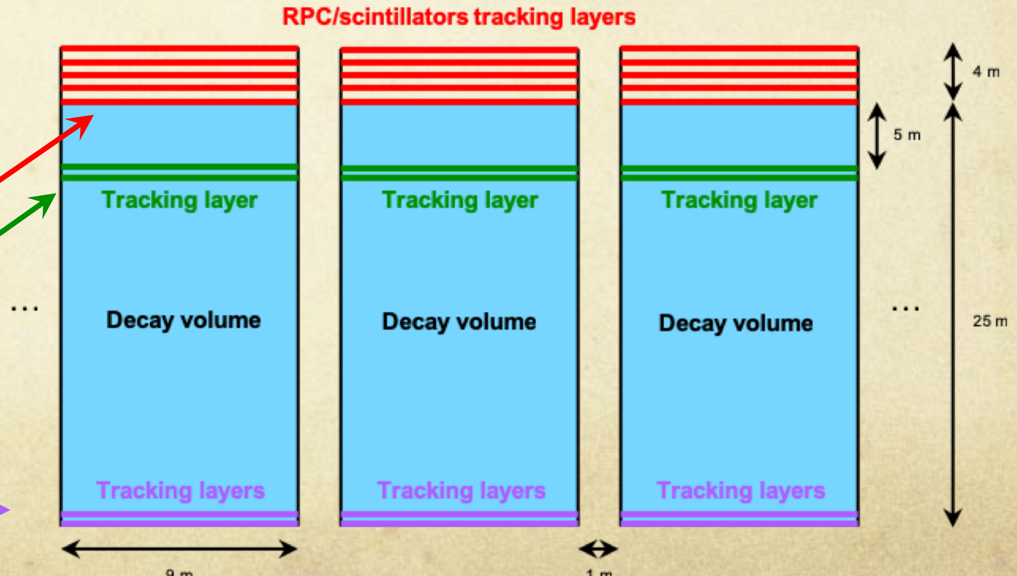


- ~70 m to IP on surface and IP ~80m below surface
- ~7.5m offset to the beam line

Modular concept

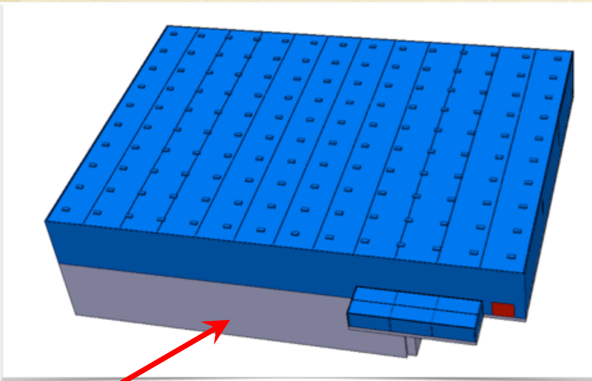


- Assume ~ **25 meter decay volume**
- Individual detector units **9 x 9 x 30 m^3**
- **5 layers of tracking/timing detectors** separated by 1m
- Additional **tracking/timing layer 5m**
- **Double layer floor detector (tracking/timing)**

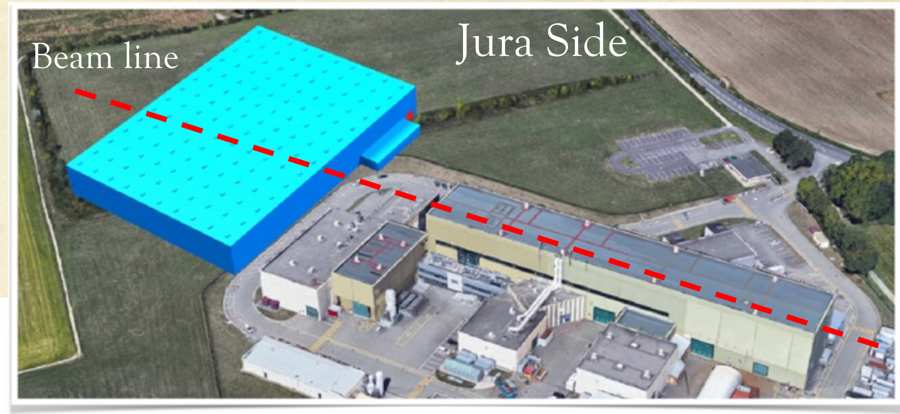


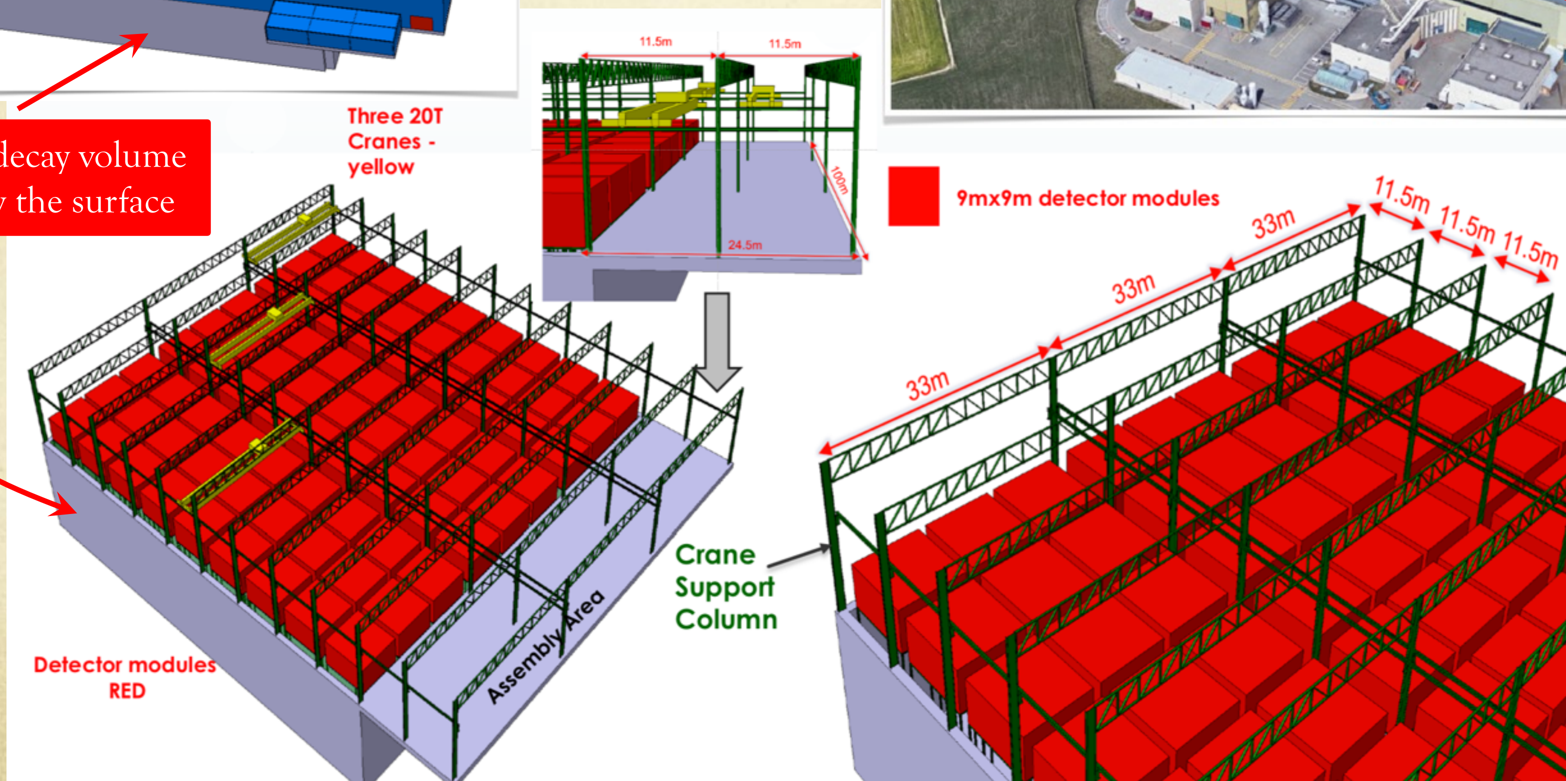
MATHUSLA @ P5

- 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

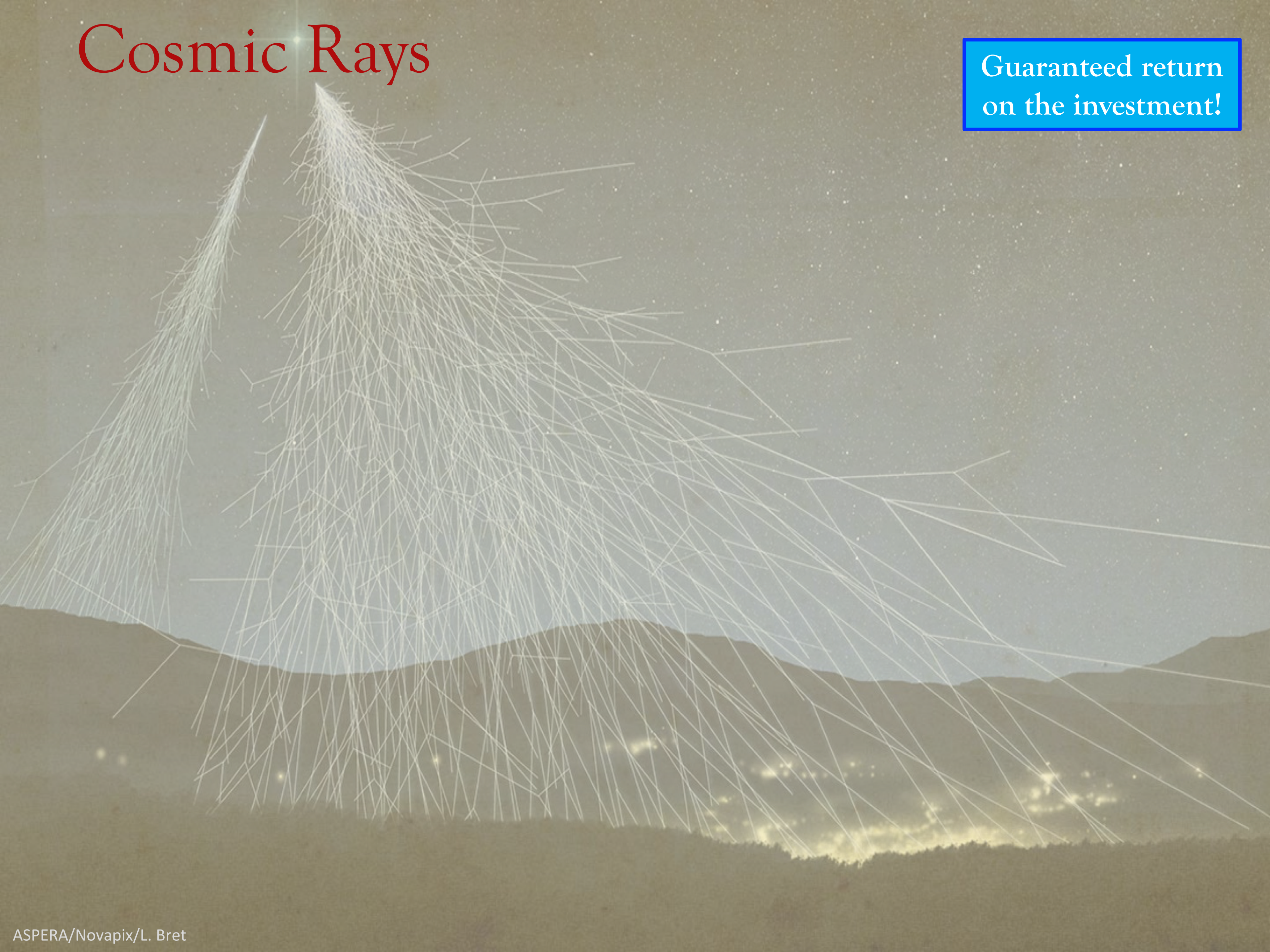


20 m decay volume
Below the surface





Cosmic Rays



Guaranteed return on the investment!

ASPERA/Novapix/L. Bret

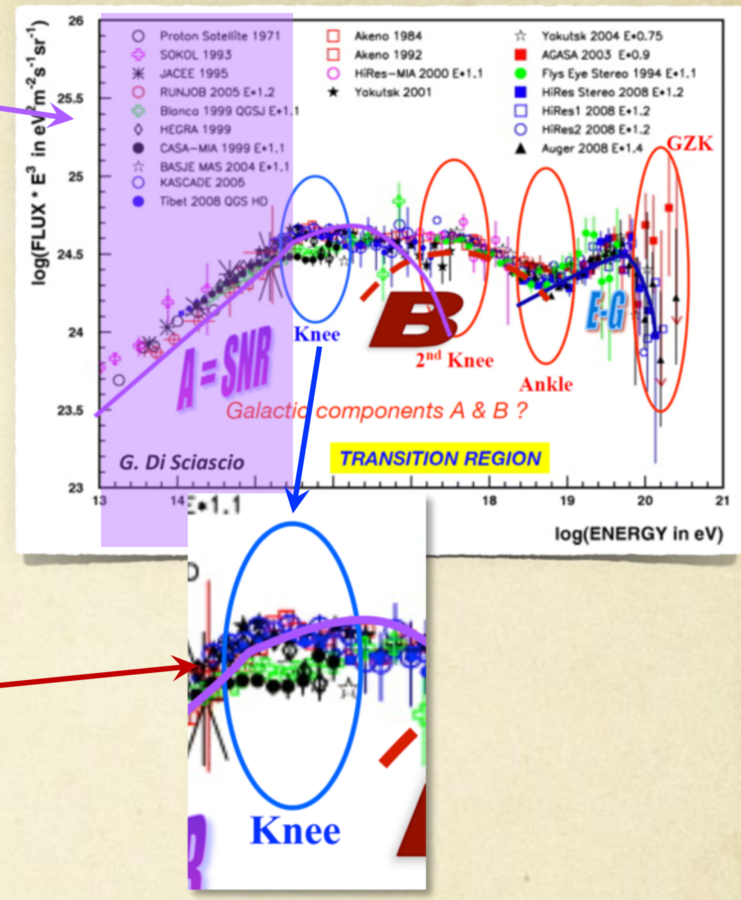
Setting the Stage (1)...

- CR up to the knee (3-4 10^{15} eV) originate in Supernova Remnants (SNRs) and are accelerated by 1st order Fermi mechanism in shock waves

- The **evolution of light nuclei spectra** (p+He) could be an indication of the **contribution of different populations** of CR (coming from different chemical compositions)

- Around the knee, CR measurements are performed through **EAS arrays**

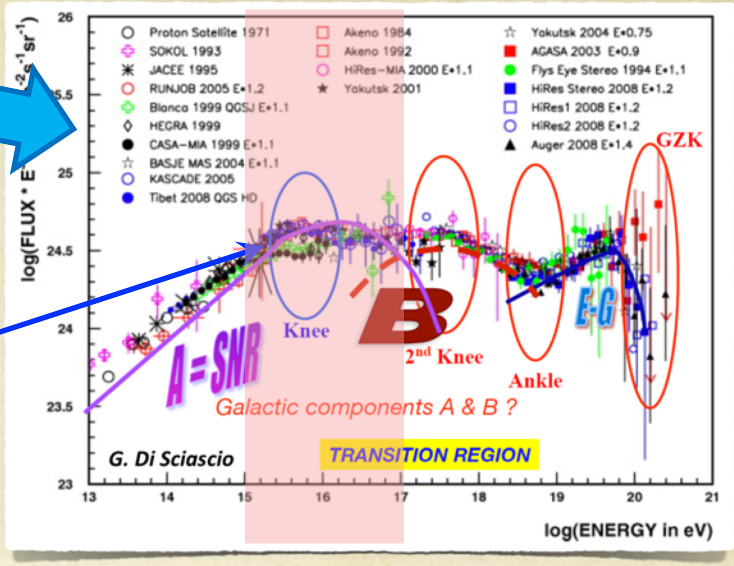
- **Some "tension" in the current results**
  - Mass of the knee due to p and He spectra?
  - Mass of the knee due to higher nuclei?



- Analyse **primary proton spectrum** is crucial to understand **CR acceleration** and **propagation** in the Galaxy
  - ✓ A precise flux could allow to calculate the **rate of secondary CR** and of **atmospheric neutrinos**

Setting the Stage (2)...

Several structures in the current CR 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 CR physics** (**requires high statistic and good measurements** to establish the components of source and distribution of incident particles)
- 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 full coverage will allow a **lower energy threshold** (~ 100 GeV) than KASCADE (~ 1 PeV)

  ✓ Lower threshold allows **comparison with satellite/balloon measurements** (CREAM, Calet, HERD)

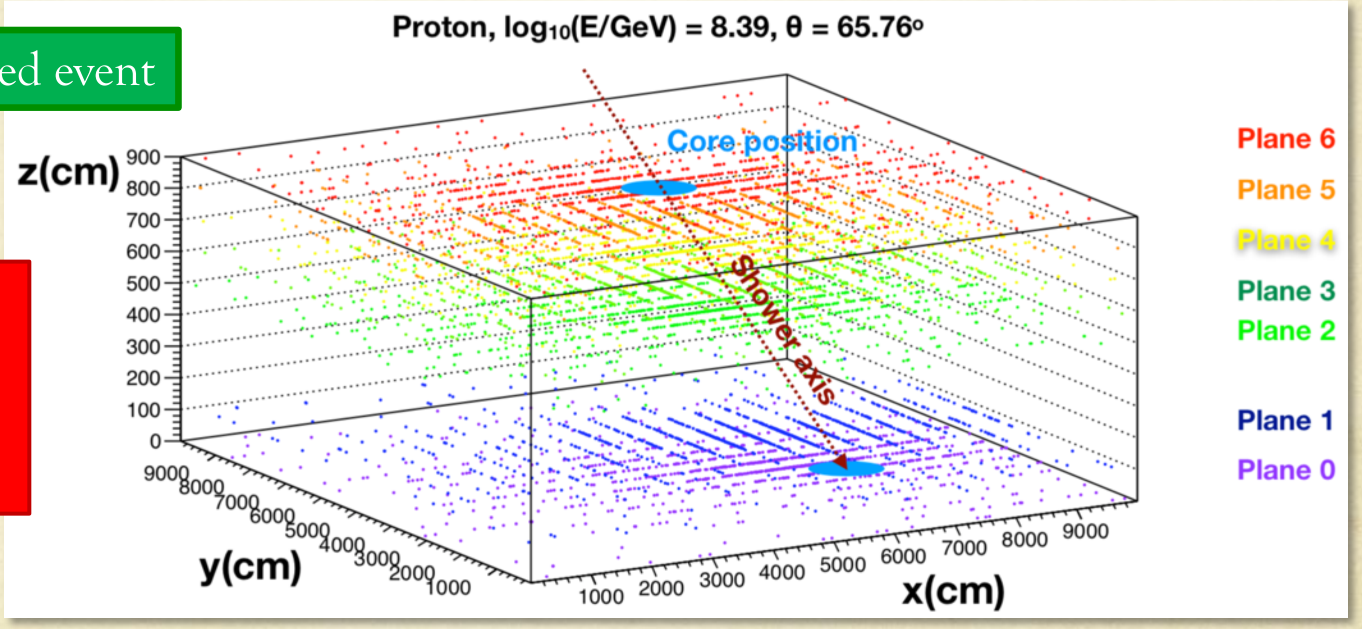
❖ MATHUSLA **multiple tracking layers** may help to **understand better the energy spectrum**

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

EAS Studies with Scintillators (Preliminary)

- 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**)

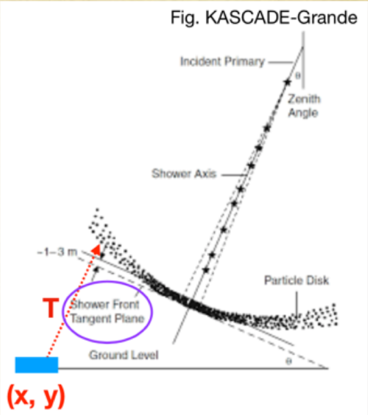
Reconstruction of inclined event



See backup for results on position and angle measurements, muon content, etc

- The **number of hits depends on** the amplitude of the distribution, the inclination of the profile, and x coordinate of the core position

CR Studies with RPCs



A layer of RPCs with digital and analog readout (like ARGO-YBJ) would greatly improve the performance of MATHUSLA

- Digital readout
  - ✓ Spatial and temporal structure of the EAS, low density measurements
  - ❖ Good time-spatial determination of the shower front would help to **improve the determination of the core and the arrival direction of the shower**
    - o Important for **vertical EAS** where the saturation effects in the scintillation planes can lower the core and arrival direction precision
- Analog readout
  - ✓ Measure **high density of particles** up to $10^4/m^2$ **expanding measurements of CR beyond the knee**
  - ✓ **Charge measurements of the shower front**
  - ❖ The **lateral density distribution** (LDF) of charged particles can be **obtained event-by-event**, which can help to determine the **energy scale of the primary CR** and the **composition of the CR nuclei**
    - o Energy scale estimated from the amplitude of the lateral distribution
    - o Primary composition studied by using the steepness of the LDF (++lighter and ++energetic air shower → bigger LDF steepness)
- RPCs can **improve the measurements** of energy and the deposited charge **for vertical and inclined events**

See backup for more details

Conclusions & Plans

mathusla.experiment@cern.ch

https://mathusla-experiment.web.cern.ch/

- MATHUSLA is a **complementary detector**
  - ✓ Will make the LHC LLP search program more comprehensive and significantly **enhance and extend the new physics reach** and capabilities of the current LHC detectors
- MATHUSLA can also work as a **cosmic ray telescope**
  - ✓ Preliminary simulation studies indicate good performance for inclined EAS (quite good angular resolution)
    - It can do nice and **competitive measurements for very inclined showers**
  - ✓ **A layer of RPCs would improve the performance of CR measurements, extending the sensitivity at higher energies and allowing to perform many more interesting studies**
- Planning to build a **demonstrator** ~$(9\ \text{m})^2$ made up of a **few construction units**
  - ✓ Will **validate the design and construction procedure of individual units**
  - ✓ Will provide **reliable input to the cost and schedule for MATHUSLA**
- Cosmic ray studies with MATHUSLA will be published soon
- Goal to complete and submit the Technical Design Report (TDR) by end 2021

The MATHUSLA collaboration welcomes participation of more cosmic ray institutes. Please contact Henry Lubatti (lubatti@uw.edu) and CA (Cristiano.Alpigiani@cern.ch) if interested!

The MATHUSLA Collaboration

Universitas Major Pacensis Divi Andreae

Shanghai Jiao Tong University

Stanford

KIT Karlsruher Institut für Technologie

UHH Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

University of Toronto

NISER

Universidad Tecnica Federico Santa Maria

Fermilab

Virginia Tech

Boston University

Tel Aviv University

UNACH Universidad Autónoma de Chiapas

University of Oxford

SLAC National Accelerator Laboratory

Benemérita Universidad Autónoma de Puebla 1578

Cal State East Bay

INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Università di Roma Tor Vergata

Universidad Michoacana de San Nicolás de Hidalgo

INFN Istituto Nazionale di Fisica Nucleare
Sezione di Bari

cnrs IN2P3

Universidad Nacional de La Plata

OU

Università del Salento

CERN

Rutgers The State University of New Jersey 1766

Tsinghua University 1911

Institute of High Energy Physics
Chinese Academy of Sciences

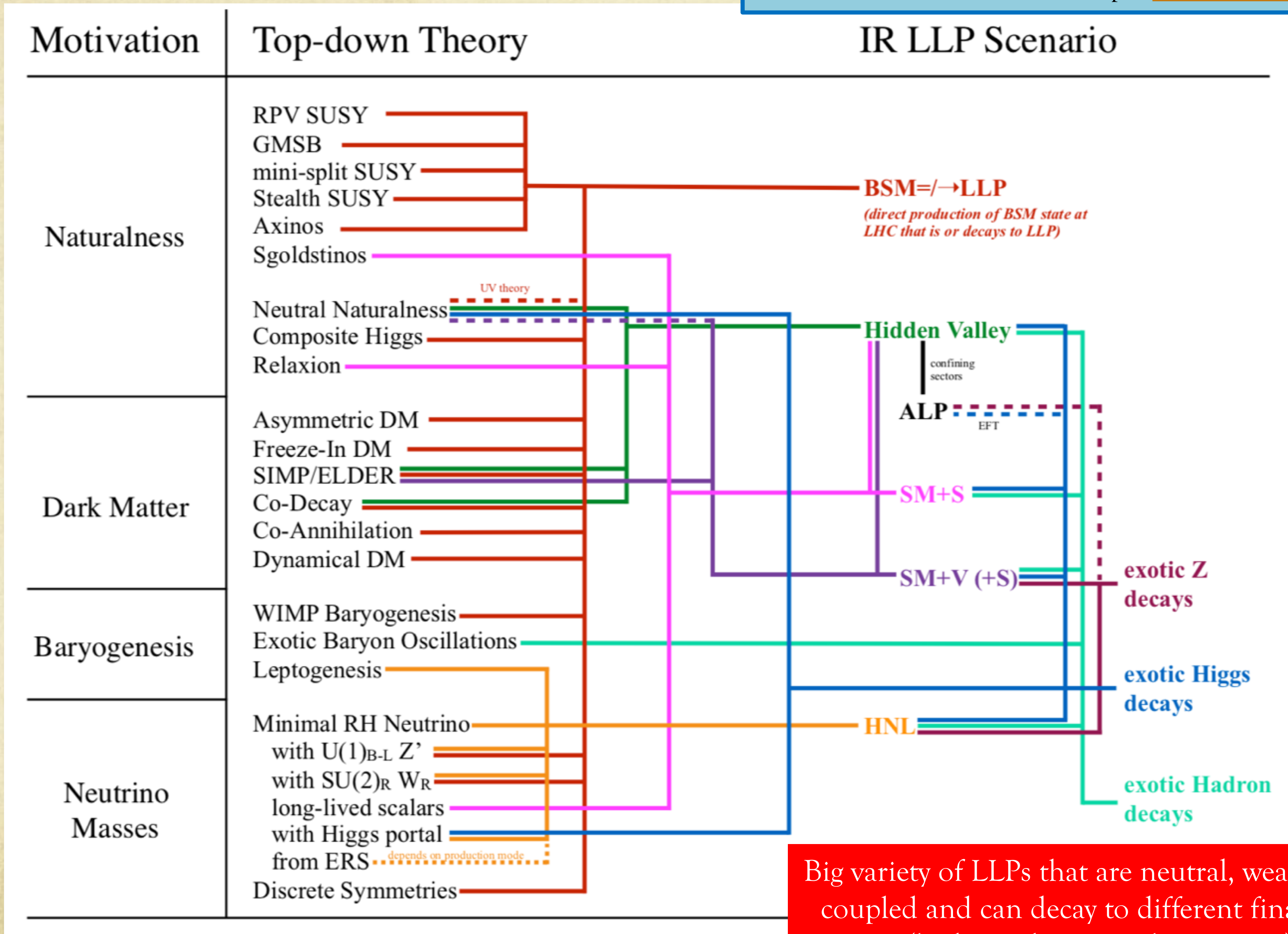
The University of Arizona

University of Washington 1861

BACKUP

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)

But How Much Long?

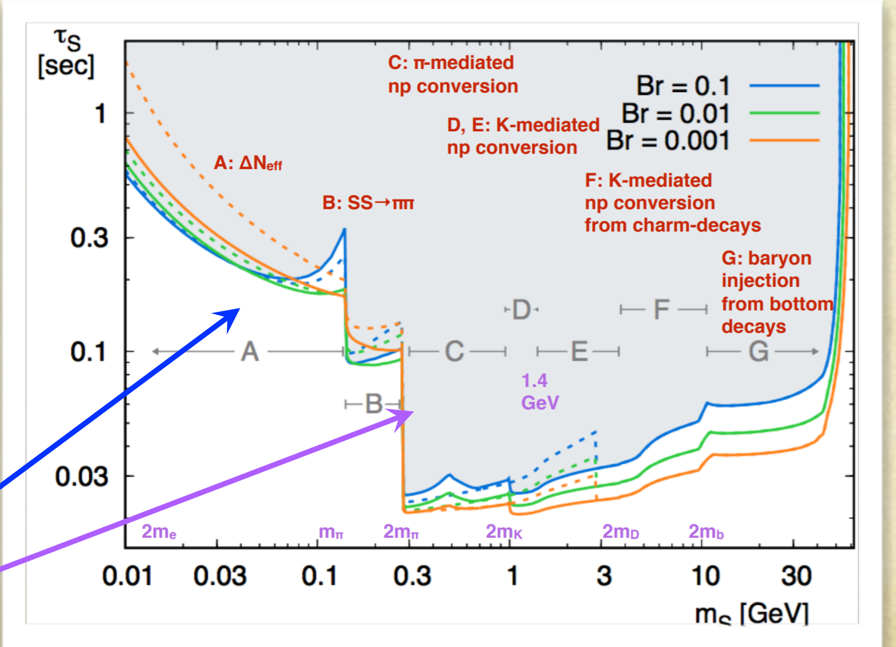
arXiv:1706.01920v1

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

- BBN very well understood within SM physics and well constrained
  - ✓ Happened in an interval between ~10 s – 15 minutes 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, where the production occurs via $h \to ss$, where the decay is 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

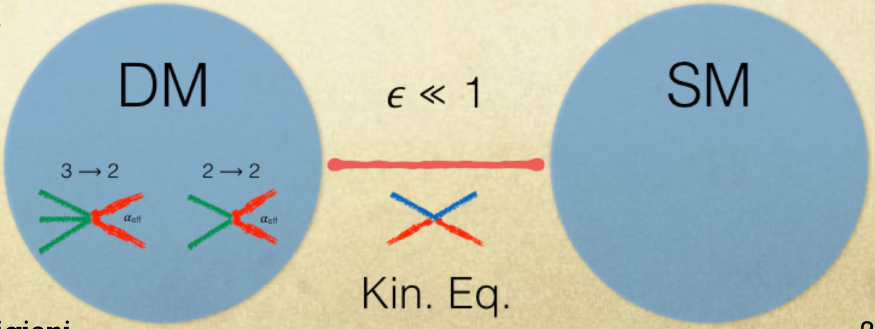


❑ Conclusion does not depend strongly on BR($h \to ss$)

Dark Matter and LLP

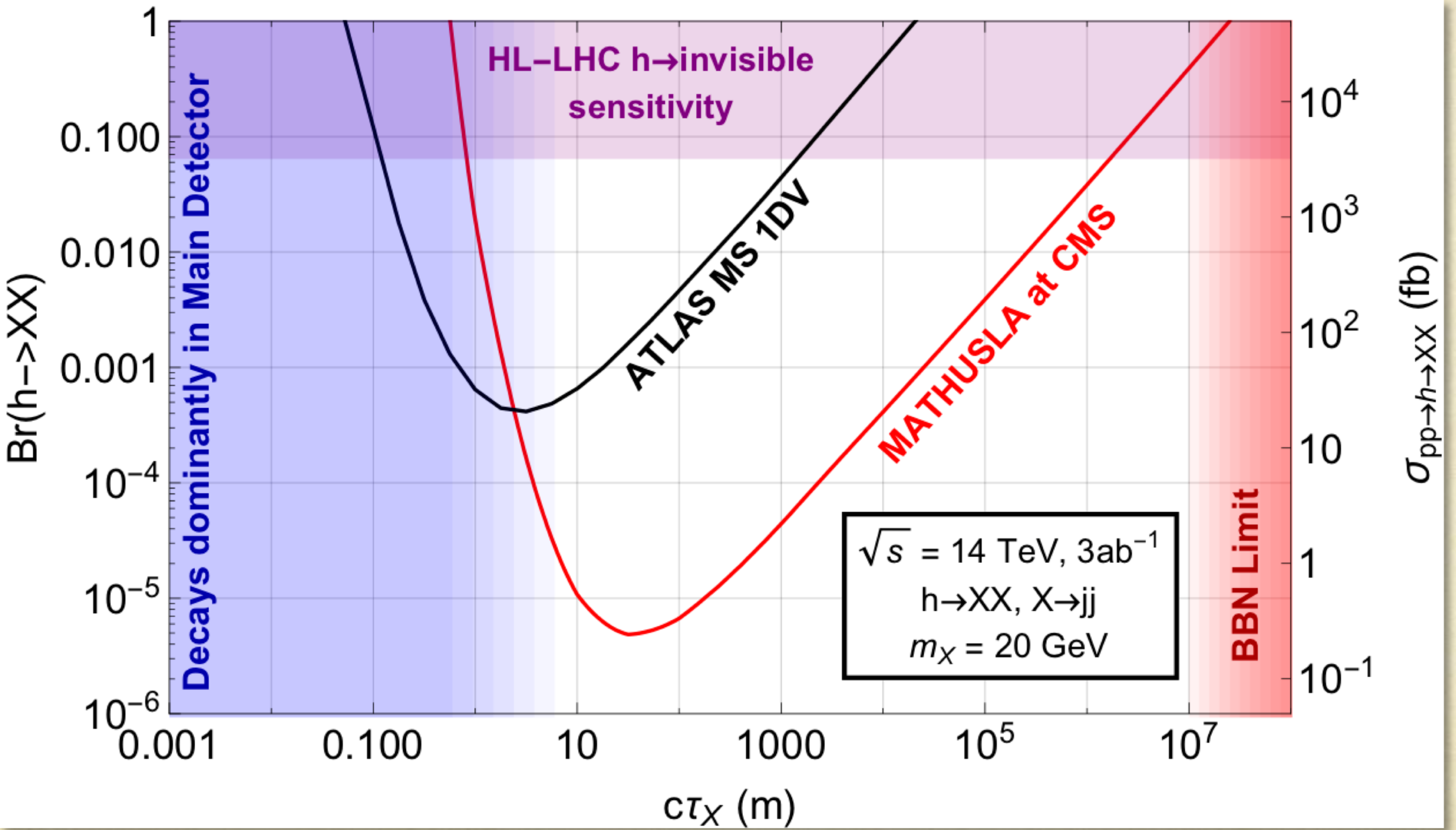
Variety of possible DM candidates whose experimental signals are intimately connected to the mechanism responsible for generating DM in the early universe

- These **DM models often require new BSM states in addition to DM itself**
  - In many cases, the **mechanism yielding the correct relic density** for DM naturally and generically **results in one or more of these BSM states having a long proper decay length**
  - In other cases, **long lifetimes are not a direct consequence of the mechanism determining the DM relic abundance**, but a generic feature of models that implement it
- Mechanisms giving a particle a long lifetime are naturally realised in well-motivated DM models
  - Small phase space → generic prediction of models where **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 $3 \rightarrow 2$ process. Small couplings to the visible sector allow for thermalisation of the two sectors, thereby allowing heat to flow from the dark sector to the visible one



MATHUSLA @ P5

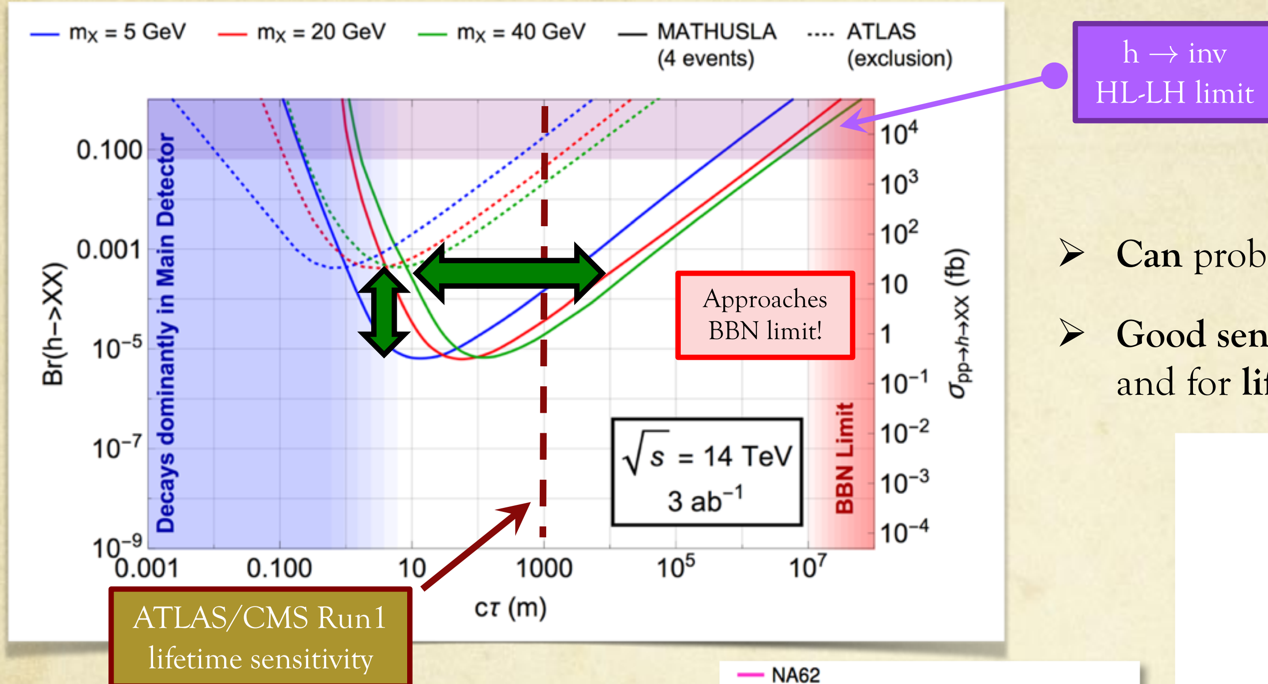
- Worked with Civil Engineers to define the **building and the layout of MATHUSLA at P5**
- **Layout restricted by existing structures** based on current concept and engineering requirements

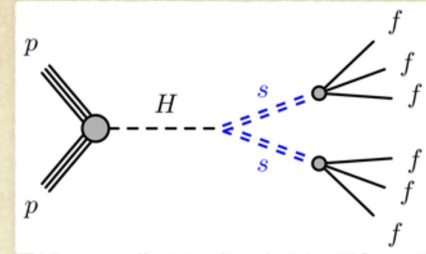


More details on the comparison MATHUSLA200/Engineering benchmark in
Imran Alkhatib thesis, *"Geometric Optimization of the MATHUSLA Detector"* - arXiv:1909.05896

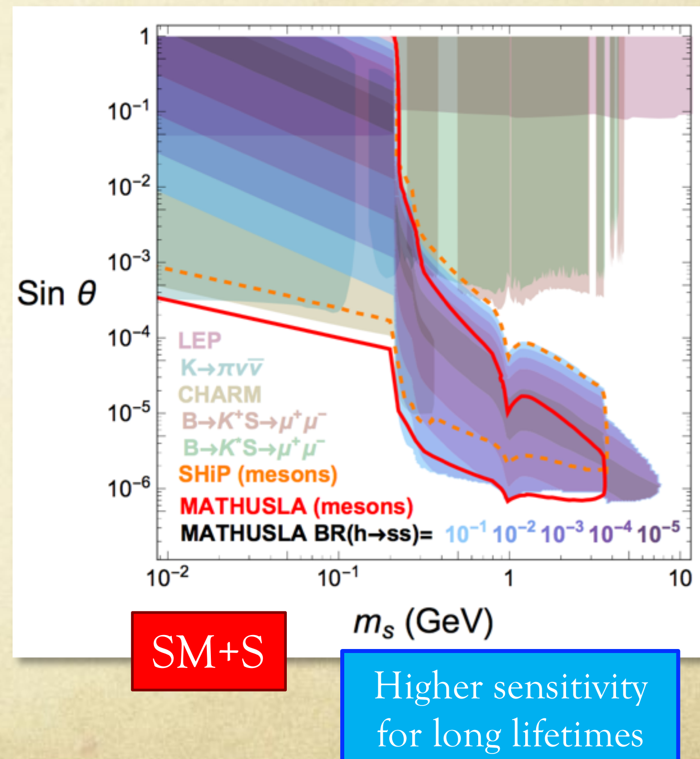
MATHUSLA – Physics Reach

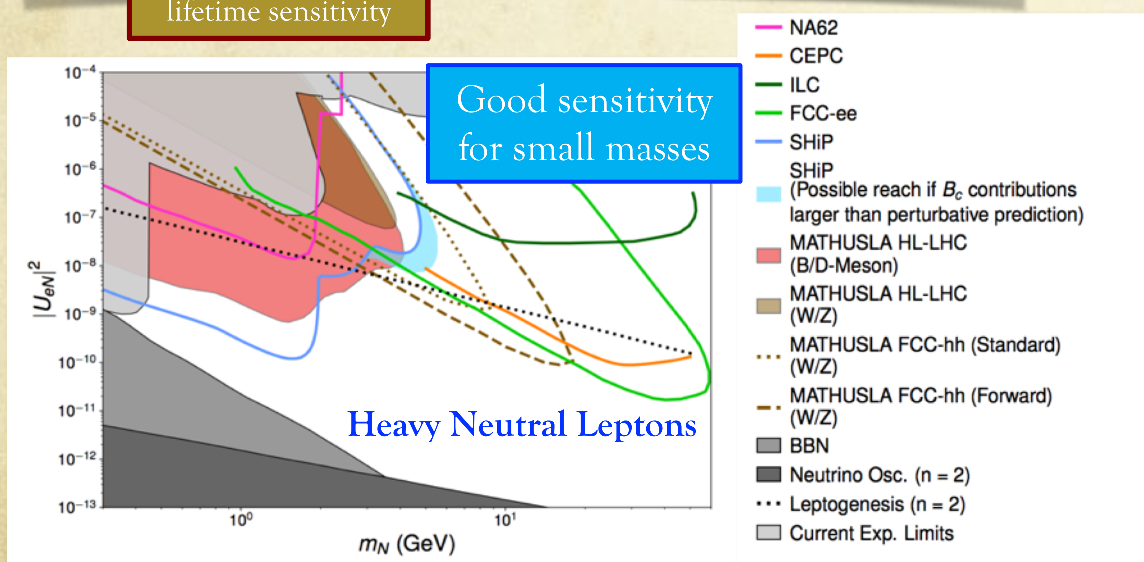
arXiv:1806.07396 [hep-ph]





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



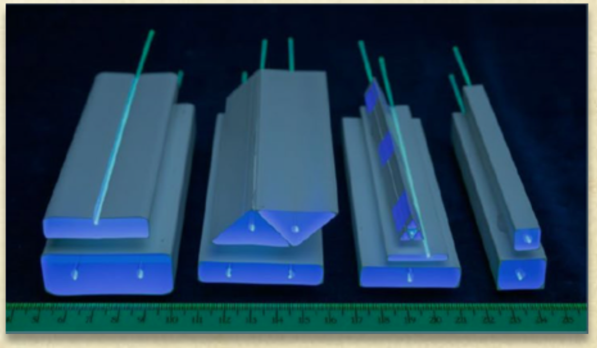


What's the best tracking technology?

RPCs used in many LHC detectors

- ✓ Pros ☺
  - Proven technology with good timing and spatial resolution
  - Costs per area covered are low
- ✓ Cons ☹
  - Require HV ~10 KV
  - Gas mixture used for ATLAS and CMS has high Global Warming Potential (GWP) and will not be allowed for HL-LHC (attempting to find a replacement gas)
  - Very sensitive to temperature and atmospheric pressure

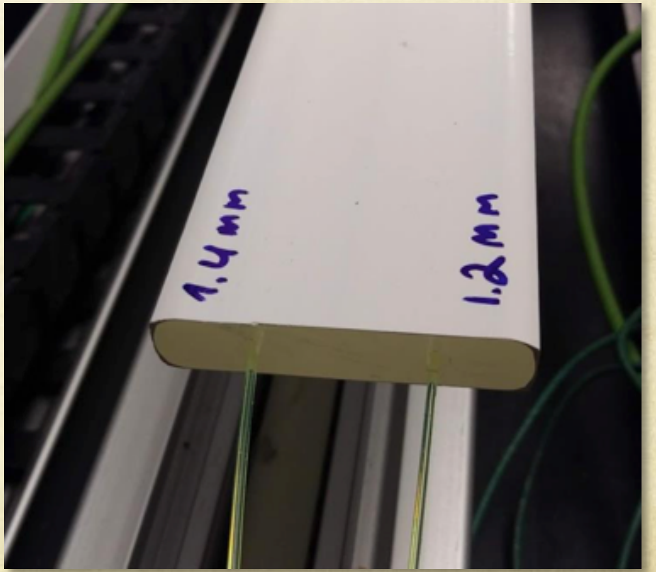
Extruded scintillator bars with wavelength shifting fibers coupled to SiPMs makes this technology cost wise competitive with RPCs



- ✓ Pros ☺
  - 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 scintillators @ Fermilab

- 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 (1/2 labor, 1/2 chemicals)
  - Target of **$10/kg in large quantity**
- Tested at Fermilab
  - 3.2 m Mu2e extrusion (**co-extruded with white polyethylene reflector**)
  - Scintillator extrusion has lots of light (>70 pe/MIP worst case in middle)
  - Spatial resolution 15 cm with simple algorithm, can likely do better



- Tests done with **Other solutions are possible**
  - **0.5 cm** thick bars? 1 cm thick bars.
  - **Two fibers** present in extrusion

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

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

MATHUSLA detector → MAssive Timing Hodoscope for Ultra Stable neutraL pArticles

- 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**

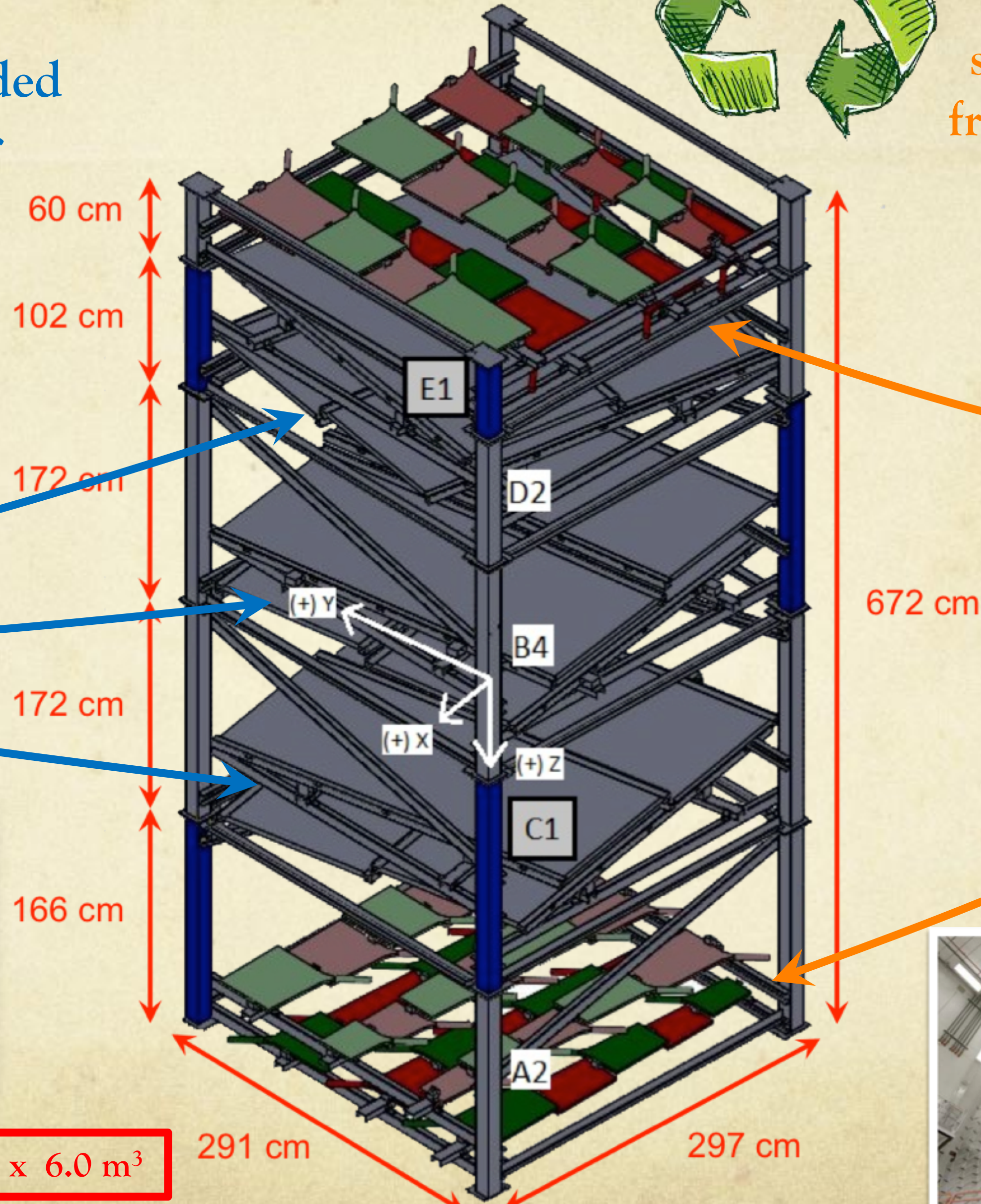
$$L \sim (20\text{ m}) \left(\frac{b}{3}\right) \left(\frac{0.1}{\epsilon_{\text{geometric}}}\right) \frac{0.3}{\text{Br}(h \to \text{ULLP})}$$

The past…

- **2016**
  - MATHUSLA idea proposed for the first time
- **2017**
  - Started working on the test stand design and construction
  - First (short data taking period in P1) then cosmic ray tests in 887
- **2018**
  - P1 data taking
  - Main detector design
  - MATHUSLA White Paper
  - MATHUSLA LoI submitted to LHCC (July 2018, arXiv:1811.00927)
- **2019**
  - Cost estimate

The MATHUSLA Test Stand

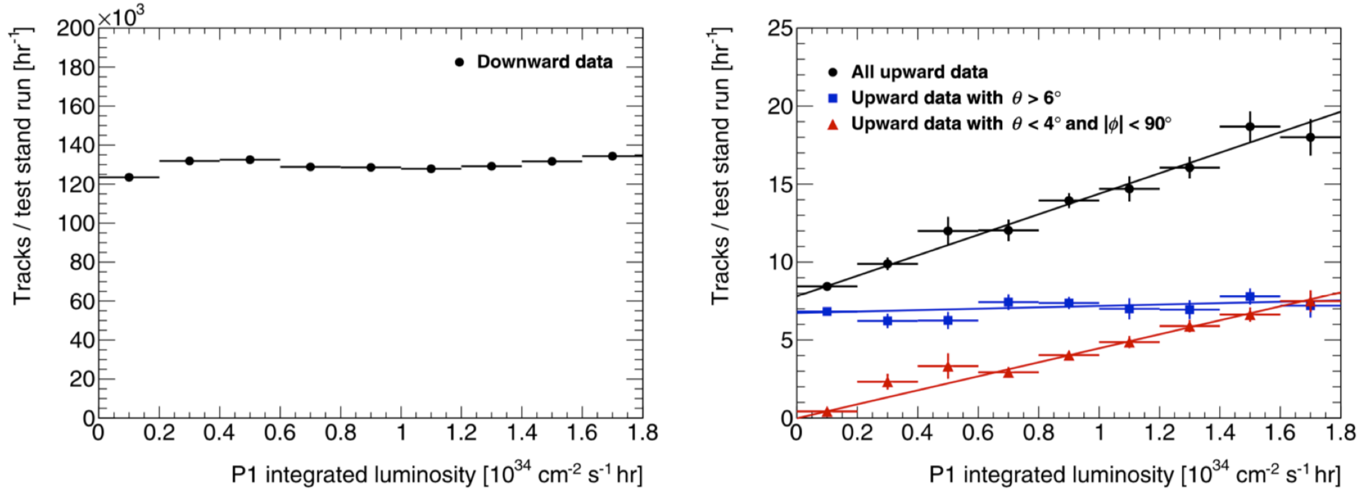
3 layers of RPCs provided by University of Tor Vergata (Rome) by Rinaldo Santonico (from Argo-YBJ Experiment)



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

Active area ~ 2.5 x 2.5 x 6.0 m^3

The MATHUSLA Test Stand



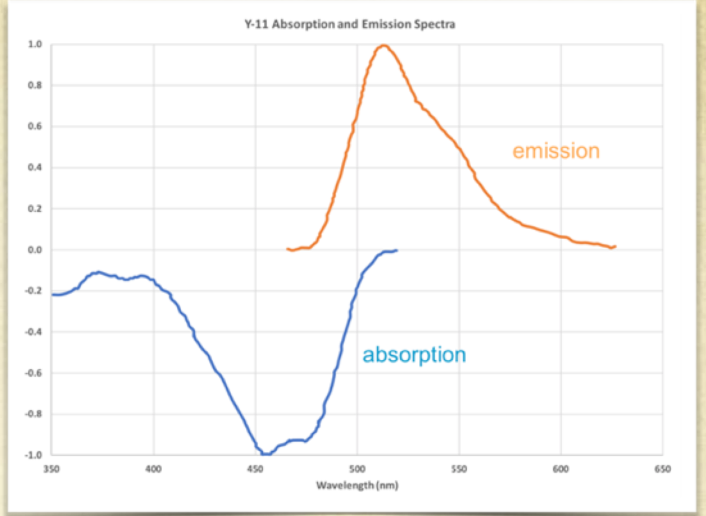
(a) (b)

Fig. 11. Distribution of the number of reconstructed tracks as a function of the ATLAS integrated luminosity during each one-hour test stand run. Left: Downward tracks. Right: Upward tracks (black circles), including tracks with a zenith angle (θ) > 6° (blue squares) and tracks with a zenith angle < 4° and absolute value of azimuthal angle (ϕ) < 90° (red triangles).

- Rate of downward tracks is independent of the luminosity, as expected from cosmic rays
- Rates for upward tracks with a zenith angle less than 4° and an absolute value of azimuthal
- angle (ϕ) less than 90° correspond mainly to particles coming from LHC *pp* collisions.
  - ✓ The rate increasing linearly with the luminosity

$$\text{Upward tracks } (\theta < 4°,\ |\phi| < 90°) = (4.48 \pm 0.16) \times \left(\frac{\text{Integrated luminosity}}{10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{h}} \right) + (-0.02 \pm 0.03)$$

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
  - Best(?) that can be done with off-the-shelf items
- 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)
  - Engineering R&D effort guesstimated to be 3 person-months

Possible options:

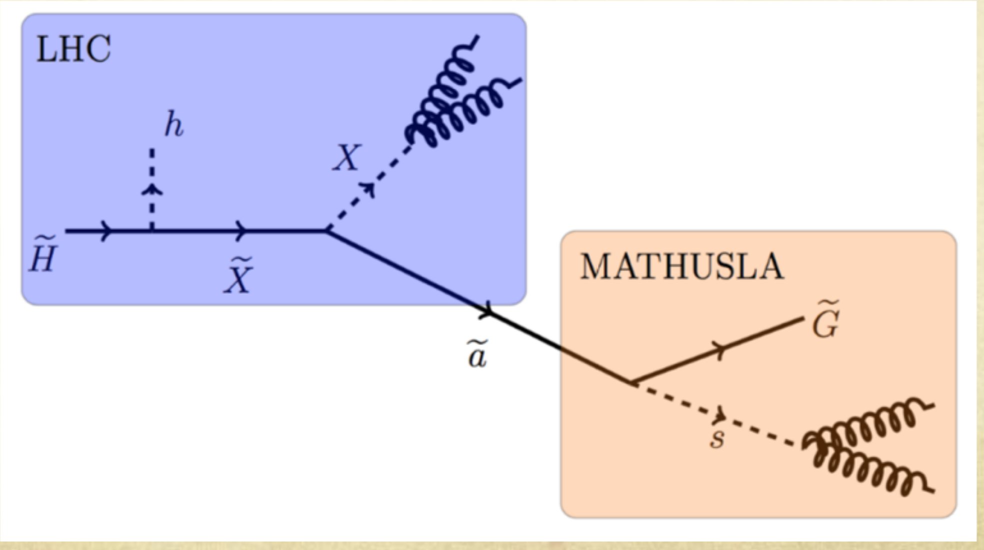
- S14160-3050HS: 3x3mm
- S14160-6050HS: 6x6mm

Readout & Data Taking

- **Readout**
  - **8 tracking layers** (5 tracking layers + 5m below + 2 on the floor)
  - 4 cm scintillators with readout in both ends results in 800K 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)

Trigger

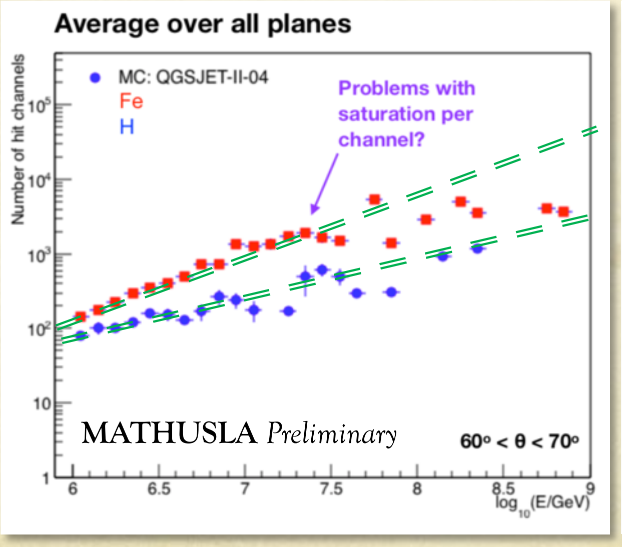
- **CMS Level-1 trigger** latency is 12.5 μs for HL-LHC
  - ✓ Conservatively assuming a 200m detector with height = 25m located 100m from IP, LLP with β = 0.7, optical fiber transmission to CMS with v_{fiber} = 5 μs/100m
  - ✓ MATHUSLA has 9 μs or more to form trigger and get information to CMS Level-1 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



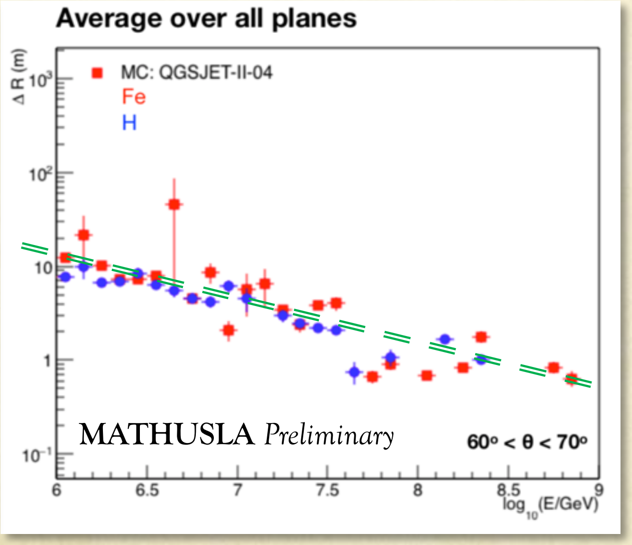
EAS Studies with Scintillators (Preliminary)

- 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**)

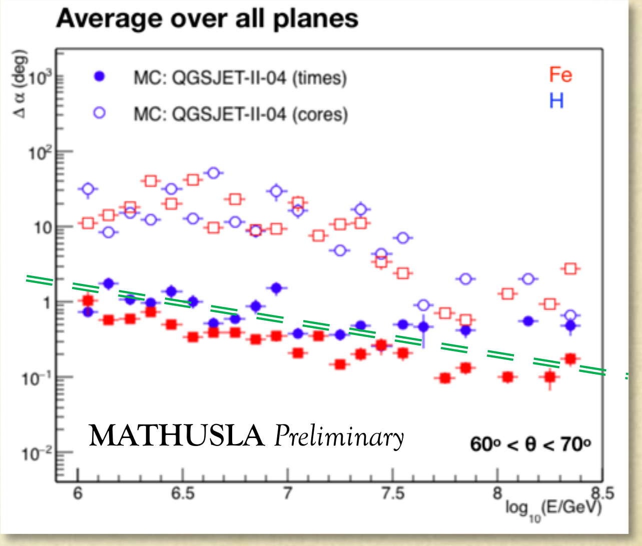
Energy estimation



Core position meas. bias



Core direction meas. bias



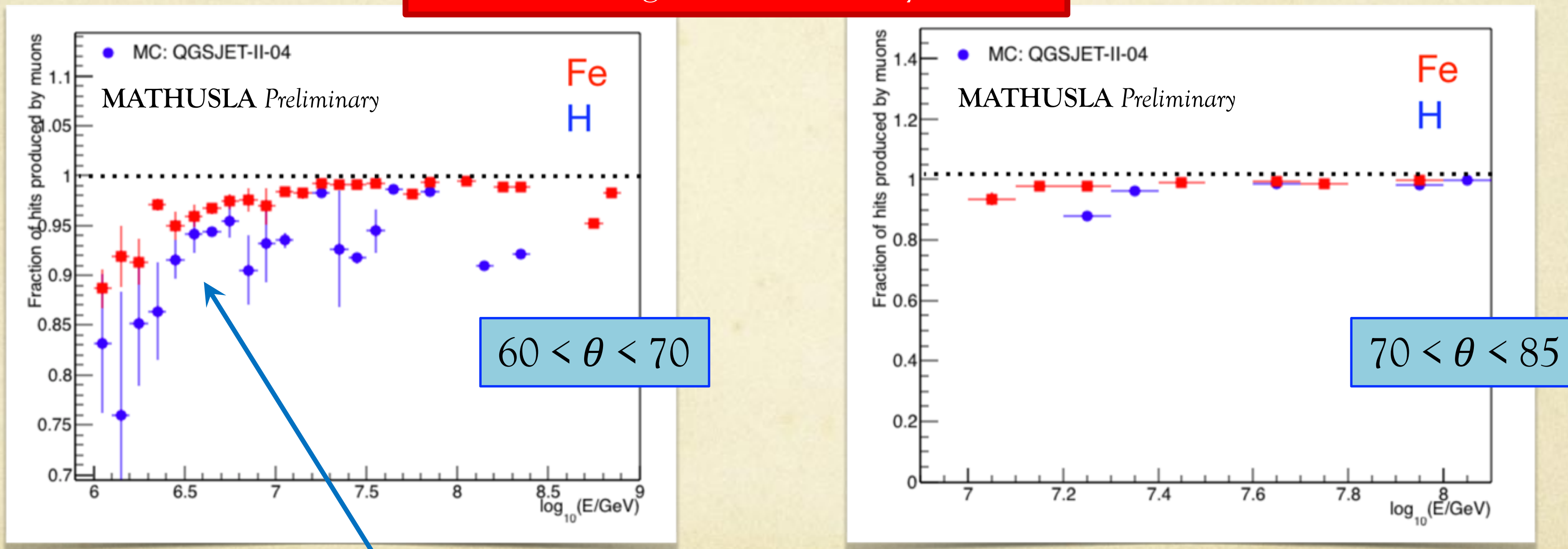
The number oh hits increases with E

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

EAS Studies with Scintillators (Preliminary)

- 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**)

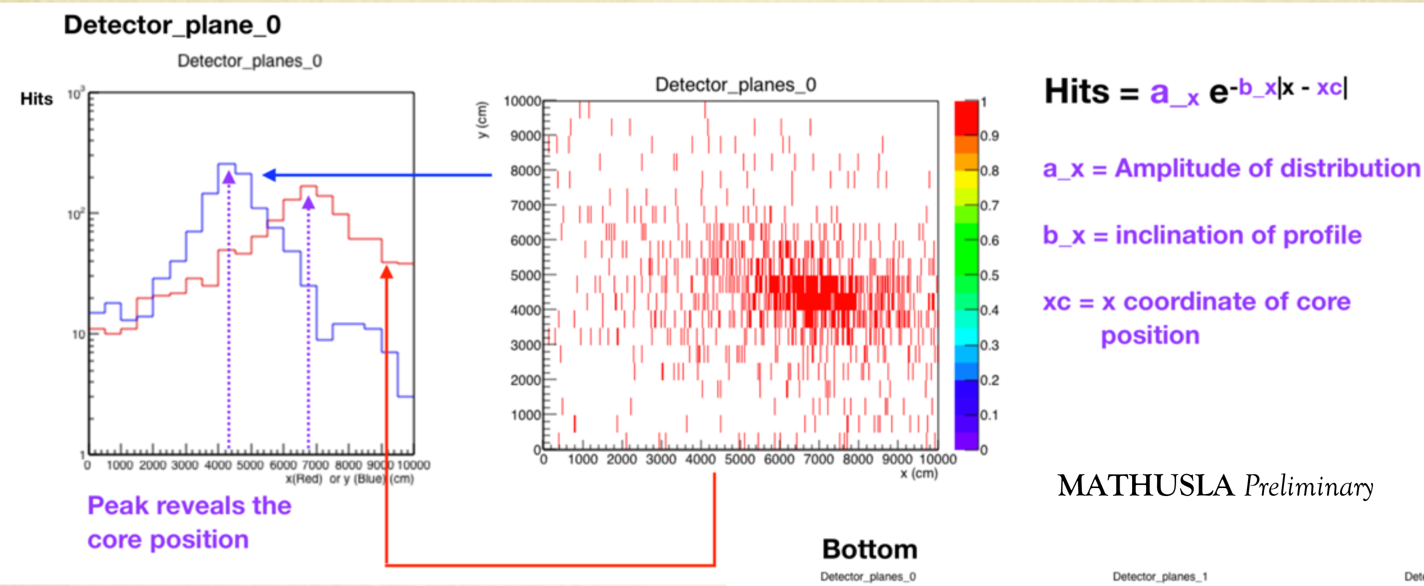
Fraction of signals induced by muons

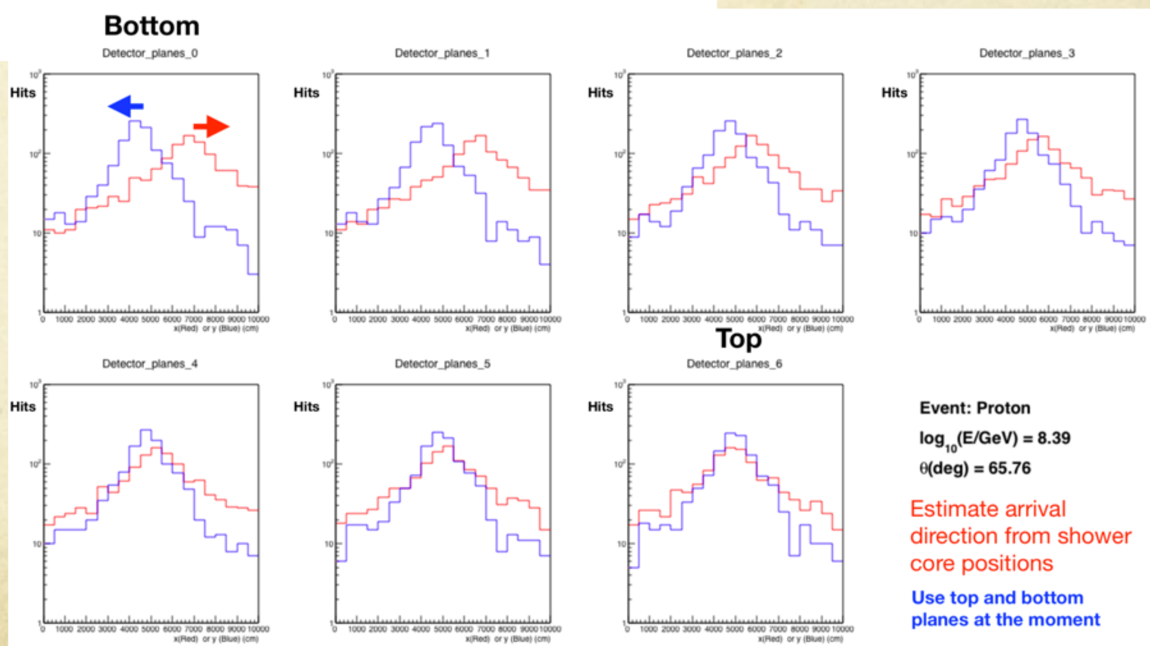


Fraction of muons > 90% for E > $10^{6.5}$ GeV

Very high efficiency

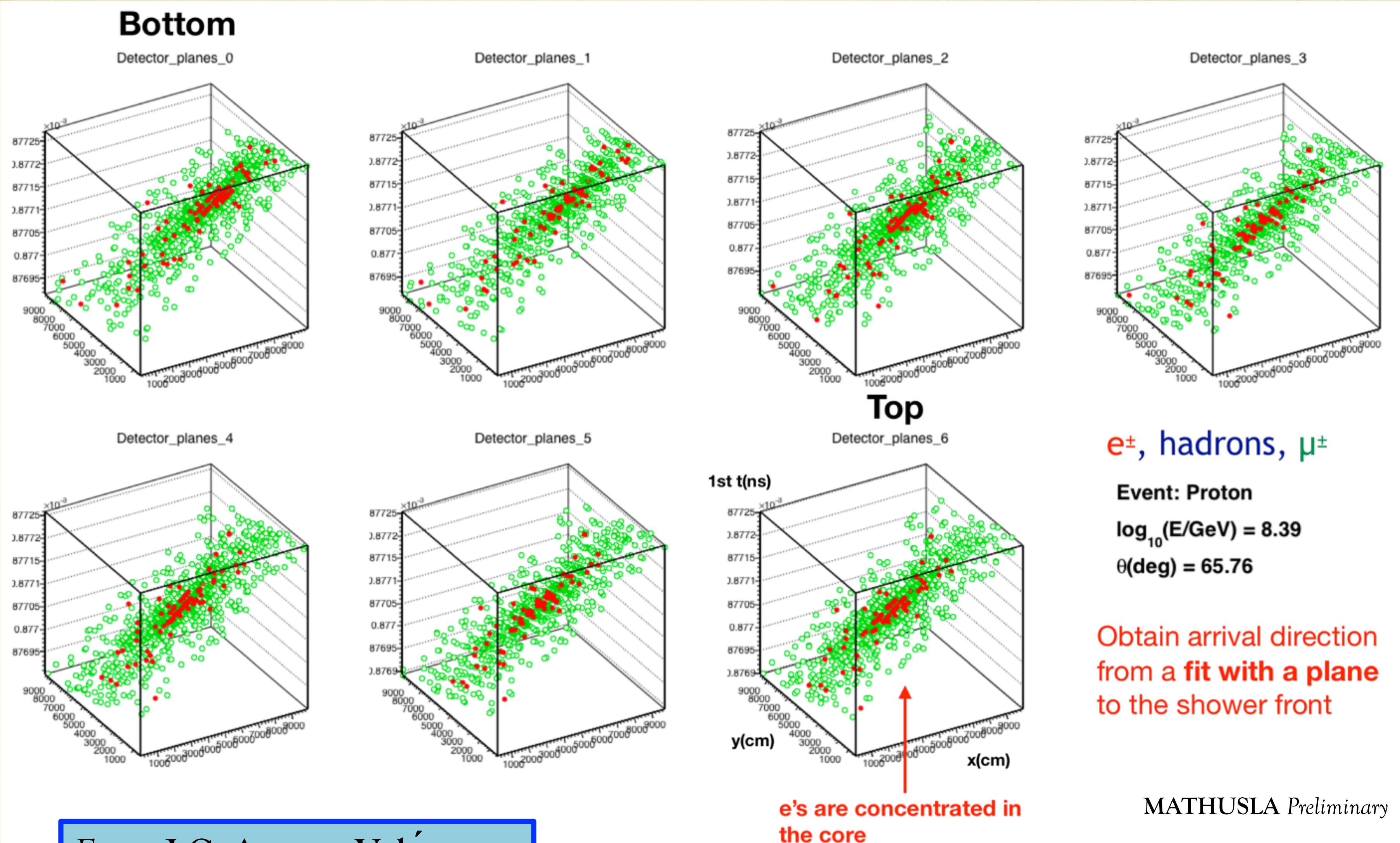
EAS Core Position Estimation - Details





From **J.C. Arteaga-Velázquez**

EAS Core Position Estimation - Details



From **J.C. Arteaga-Velázquez**

EAS Core Position Estimation - Details

Fig. KASCADE-Grande

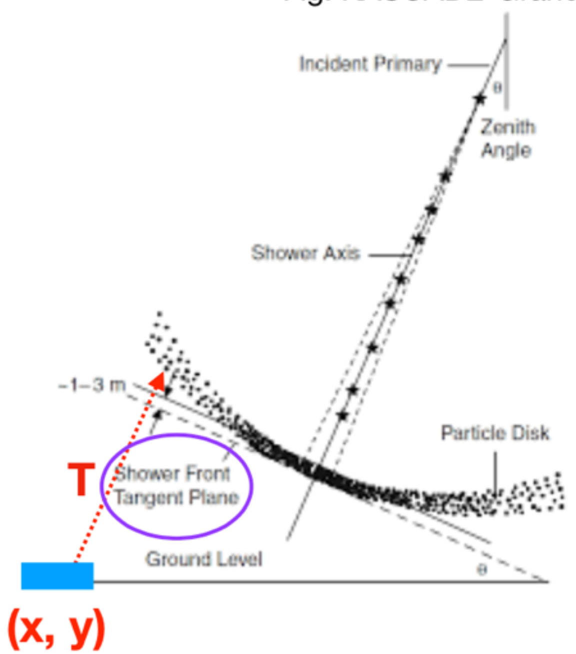
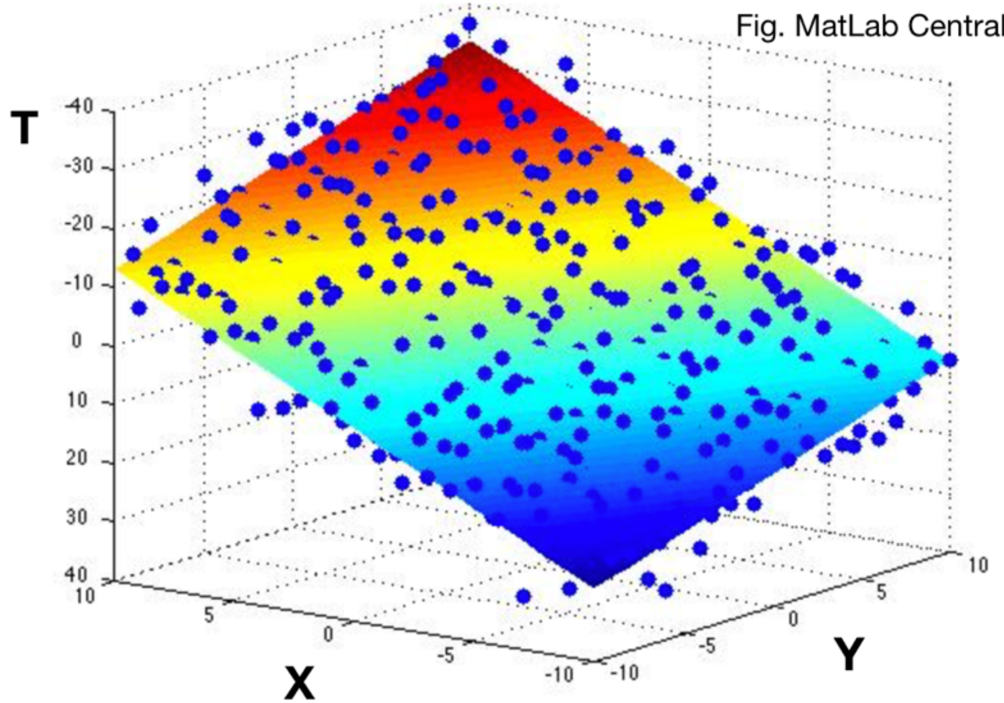


Fig. MatLab Central



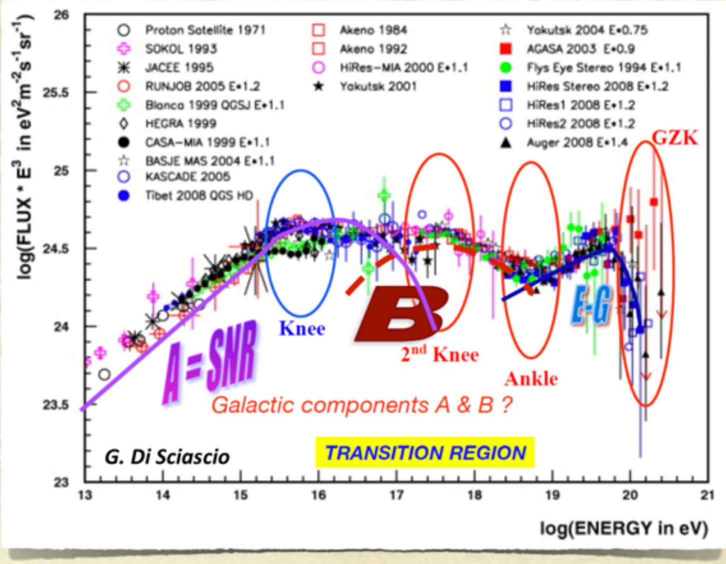
Result of the **3D fit** with a plane to a set of points (x, y, t):

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

From **J.C. Arteaga-Velázquez**

CR – EAS (Exploring the Knee)

- **KASCADE** is currently a leading experiment in this energy range
  - ✓ Has larger area than MATHUSLA (**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 **9 detector planes**



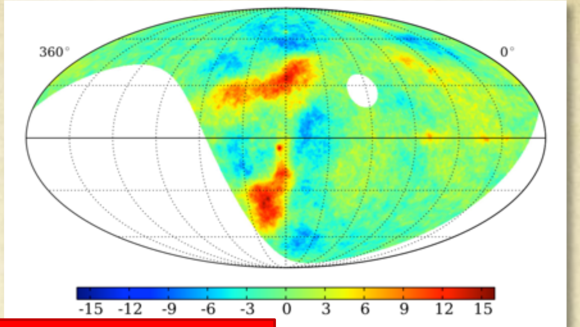
❑ MATHUSLA standalone

- ✓ 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, CMS trigger has ~12 microsecond latency)

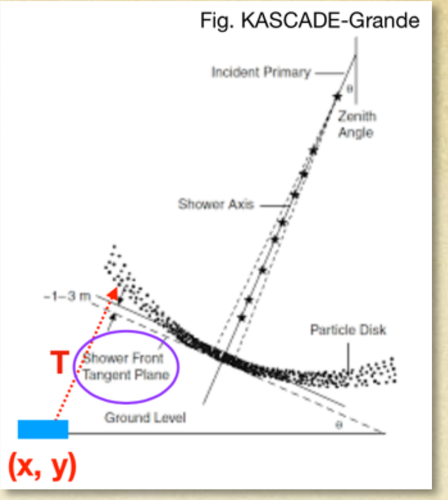
EAS Studies with Scintillators - Physics Outcome



ARGO-YBJ measurement

- High precision spatial distribution of the CR **arrival direction**
  - ✓ Detailed study of **CR anisotropies**
  - ✓ Important to constrain the **propagation of CR in the interstellar space**
  - ✓ Constrain models of the **interstellar magnetic field**
- **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?
  - ✓ **Set limits to BSM physics**
  - ✓ **Test hadronic interaction models at high energies.** Sensitivity to **relative abundances mass groups of CR**
- **Muon content** of very inclined EAS
  - ✓ **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**
    - **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, tuned with results of particle accelerators at energies lower than what found in CR
    - **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

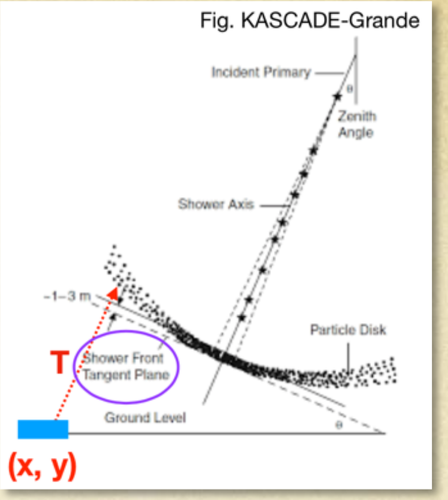
CR Studies with RPC - Physics



A layer of RPCs with digital and analog readout (like ARGO-YBJ) would greatly improve the performance of MATHUSLA

- **CR physics**
  - ✓ Reconstruction of the all-particle energy spectrum from vertical and inclined events at PeV energies, 1 PeV - 100 PeV (energy calibration will depend on the hadronic interaction model used to interpret the data)
  - ✓ Study the composition of CR
    - o Estimate the CR composition using the **total number of charged particles** and the **steepness of the lateral distributions** of charged particles
  - ✓ Obtain large scale anisotropy maps in arrival directions of CR
    - o Possible to obtain maps with very good angular resolution using the capabilities of the RPC layer
  - ✓ Measure small scale anisotropies in arrival directions and search for point sources
    - o It could be possible to look for clusters in arrival directions of CR thanks to the time resolution of the RPC layer

CR Studies with RPC - Physics



A layer of RPCs with digital and analog readout (like ARGO-YBJ) would greatly improve the performance of MATHUSLA

- **Test hadronic interaction models**
  - ✓ Study the **zenith angle evolution** of the charged particle content of air showers to look for possible deviations from MC predictions
  - ✓ Analyse the **evolution of the LDF** of charged particles with the energy and the arrival zenith angle
  - ✓ Improve (wrt scintillator only measurement) the studies of the **muon content of very inclined EAS** for r = [0,100] m, the **muon density distributions**, **arrival time** of muons and **muon production height** of muons
    - By comparing the muon measurements with the predictions of the hadronic interaction models we can test the same models
    - The **muon sector** is **very sensitive to the hadronic interaction model employed** in the simulations as it is produced in the decay of charged pions which are produced copiously in the hadron collisions