Exploring the Lifetime and Cosmic Frontier with the MATHUSLA Detector

Cristiano Alpigiani

on behalf of the MATHUSLA Collaboration

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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

Not surprising that LLP might exist also beyond the SM

[Diagram showing the mass spectrum with regions of interest labeled as STABLE and Region largely unexplored, along with the coupling constant and mass values.]

**AGS @ BNL (1964)**

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

**arXiv:1903.04497**

Long-lived particles (LLP) in the SM $10^{-24} < c\tau < 10^{41}$ s

**Region largely unexplored**

**STABLE**

**Coupling**

**Covered by current searches**

NP too heavy for LHC direct production

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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

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

muons (E>20 GeV) entering ATLAS at z=22.6 m [arXiv:1810.04450]
A LHC background free detector with no trigger limitations...
Dedicated detector **sensitive to neutral long-lived particles that have lifetime up to the Big Bang Nucleosynthesis (BBN) limit** \((10^7 - 10^8 \text{ m})\) 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)

\[ \sigma_{\text{LLP}} \propto \frac{1}{\text{area}} \]
Cosmic muon rate of about $\sim 2$ 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), $\sim$1 events from low-E neutrinos ($\pi/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
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Test Stand Data Analysis

- 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 $< \sim 4^\circ$ consistent with upward going tracks from IP when collisions occur

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

Modular concept

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

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

Jura Side
Beam line

Three 20T Cranes - yellow

9mx9m detector modules

24.5m

Assembly Area

Cone Support Column

Detector modules
RED
Guaranteed return on the investment!
CR up to the knee ($3 \times 10^{15}$ eV) originate in Supernova Remnants (SNRs) and are accelerated by 1\textsuperscript{st} order Fermi mechanism in shock waves.

The evolution of light nuclei spectra ($p+\text{He}$) 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.
Several structures in the current CR measurements

- Good measurements in the energy range $10^{15} - 10^{17} \text{ eV}$ 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 $p+\text{He}$, intermediate mass nuclei and Fe up to $10^{16} \text{ eV}$

- MATHUSLA full coverage will allow a lower energy threshold ($\sim 100 \text{ GeV}$) than KASCADE ($\sim 1 \text{ PeV}$)
  - 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 measure shower energies above a PeV ($\sim 10^{17} \text{ eV}$)
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)

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

See backup for results on position and angle measurements, muon content, etc
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
    - 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
    - Energy scale estimated from the amplitude of the lateral distribution
    - Primary composition studied by using the steepness of the LDF (++lighter and +++energetic air shower $\rightarrow$ 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 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 \( \sim (9 \text{ m})^2 \) 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!
BACKUP
**LLP in BSM - Top-down Theoretical Motivations**


<table>
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<th>Motivation</th>
<th>Top-down Theory</th>
<th>IR LLP Scenario</th>
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<td><strong>Naturalness</strong></td>
<td>RPV SUSY, GMSB, mini-split SUSY, Stealth SUSY, Axinos, SGoldstinos</td>
<td>BSM=$\rightarrow$LLP (direct production of BSM state at LHC that is or decays to LLP)</td>
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<td>UV theory, Neutral Naturalness, Composite Higgs, Relaxion</td>
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<td><strong>Dark Matter</strong></td>
<td>Asymmetric DM, Freeze-In DM, SIMP/ELDER, Co-Decay, Co-Annihilation, Dynamical DM</td>
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<tr>
<td><strong>Baryogenesis</strong></td>
<td>WIMP Baryogenesis, Exotic Baryon Oscillations, Leptogenesis</td>
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<td><strong>Neutrino Masses</strong></td>
<td>Minimal RH Neutrino with $U(1)<em>{B-L}$, $Z'$, with $SU(2)</em>{R}$ $W_{R}$, long-lived scalars with Higgs portal from ERS, Discrete Symmetries</td>
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Big variety of LLPs that are neutral, weakly coupled and can decay to different final states (hadrons, leptons, photons, etc)
But How Much Long?

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 $\sim 10 \text{ s} - 15 \text{ minutes}$ 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 $h \rightarrow ss$, 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 $\tau$ can go up to $1 \text{ s}$
  - For $2m_\mu < m_s < m_h/2$ the lifetime $\tau < 0.1 \text{ s}$

- Conclusion does not depend strongly on BR($h \rightarrow ss$)
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 $\Rightarrow$ 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 $\Rightarrow$ theories of asymmetric DM
  - Small coupling $\Rightarrow$ 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

MATHUSLA – Physics Reach

Can probe LLPs at GeV to TeV

Good sensitivity for mass scale above ~ 5 GeV, and for lifetime >> 100 m even at low masses

ATLAS/CMS Run1 lifetime sensitivity

Good sensitivity for small masses

Heavy Neutral Leptons

Higher sensitivity for long lifetimes


h → inv HL-LH limit
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 on 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 $\Phi$ that decays to a pair of long-lived scalars, ss, that each in turn decay to quark pairs – Hidden Valley, Neutral Naturalness, ...
    - Vector ($\gamma_{\text{dark}}, Z'$) mixing with SM gauge bosons – kinetic mixing
  - **Production of a single object P with an AO** – Many SUSY models
    - AO jets if results from decay of a colored object
    - AO leptons if LLP produced via EW interactions with SM

- Common detector signatures $\Rightarrow$ generic searches
Neutral Long-lived Particles

- Neutral LLPs lead to displaced decays with no track connecting to the IP, a distinguishing signature
  - SM particles predominantly yield prompt decays (good news)
  - SM cross sections very large (eg. QCD jets) (bad news)
- To reduce SM backgrounds many Run 1 ATLAS searches required two identified displaced vertices or one displaced vertex with an associated object
  - Resulted in good rejection of rare SM backgrounds
  - BUT limited the kinematic region and/or lifetime reach
- None the less, these Run 1 searches were able to probe a broad range of the LLP parameter space (LLP-mass, LLP-cτ)
- ATLAS search strategy for displaced decays - based on signature driven triggers that are detector dependent
MATHUSLA detector → MAssive Timing Hodoscope for Ultra Stable neutrAL pAricles

- Dedicated detector sensitive to neutral long-lived particles that have lifetime up to the Big Bang Nucleosynthesis (BBN) limit (10^7 – 10^8 m) for the HL-LHC
- Large-volume, air filled detector located on the surface above and somewhat displaced from ATLAS or CMS interaction points
- HL-LHC → order of \( N_h = 1.5 \times 10^8 \) Higgs boson produced
- Observed decays:

\[
N_{\text{obs}} \sim N_h \cdot \text{Br}(h \rightarrow \text{ULLP} \rightarrow \text{SM}) \cdot \epsilon_{\text{geometric}} \cdot \frac{L}{b c \tau}
\]

\( \epsilon = \) 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 \( n = 2, m_X \geq 20 \text{ GeV} \)

- To collect a few ULLP decays with \( c \tau \sim 10^7 \text{ m} \) requires a 20 m detector along direction of travel of ULLP and about 10% geometrical acceptance
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)

Active area ~ 2.5 x 2.5 x 6.0 m³

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

$$\text{Upward tracks (} \theta < 4^\circ, |\phi| < 90^\circ\text{)}$$

$$= (4.48 \pm 0.16) \times \left( \frac{\text{Integrated luminosity}}{10^{34} \text{ cm}^{-2} \text{ s}^{-1} \text{ h}} \right) + (-0.02 \pm 0.03)$$
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/(cm²·minute) which gives ~ 2MHz rate. With 9 x 9 m² 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 $\beta = 0.7$, optical fiber transmission to CMS with $v_{\text{fiber}} = 5 \, \mu \text{s}/100\text{m}$

  - 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 MATHUSLA 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 of hits increases with E

- Used only events with $N_{hits} > 100$
- Bias decreases with primary energy
EAS Studies with Scintillators (Preliminary)

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Fraction of signals induced by muons

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

Very high efficiency

60 < \theta < 70

70 < \theta < 85
EAS Core Position Estimation - Details

$\text{Hits} = a_x e^{-b_x|x - xc|}$

- $a_x$ = Amplitude of distribution
- $b_x$ = Inclination of profile
- $xc = x$ coordinate of core position

Peak reveals the core position

From J.C. Arteaga-Velázquez

MATHUSLA Preliminary

Estimate arrival direction from shower core positions
Use top and bottom planes at the moment
EAS Core Position Estimation - Details

From J.C. Arteaga-Velázquez

\[ \text{e}^\pm, \text{hadrons, } \mu^\pm \]

Event: Proton
\[
\log_{10}(E/\text{GeV}) = 8.39 \\
\theta(\text{deg}) = 65.76
\]

Obtain arrival direction from a fit with a plane to the shower front

e's are concentrated in the core

MATHUSLA Preliminary
Result of the 3D fit with a plane to a set of points \((x, y, t)\):
From the fit, we get the arrival direction \((\theta, \phi)\) 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

- 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

MATHUSLA @ ICPPA 2020

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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**
  - 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
  - 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
  - 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