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 coupled to SiPMs are considered (good time/space resolution)

- Cosmic muon rate of about $\sim 2$ MHz (100m$^2$) and 0.1 Hz LHC muon rejected with timing

- 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
Updates outline

• Test stand data analysis
• Detector layout and technology
• Extensive Air Shower (EAS) Studies
Test Stand @ P1

- Cosmic background (~) well understood
- 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
Test Stand Data Analysis

- Took data in different LHC conditions (w/wo beam)
- MC simulation for cosmic muons and for particles generated at the ATLAS IP
- Preliminary results – MC not corrected for efficiency or multiple scattering
  - Angular distribution for down tracks (cosmic muons) match very well expected from MC
  - Arbitrary normalization

- Accumulation for zenith angle < ∼ 4° consistent with upward going tracks from IP when collisions occur
- Up tracks no beam consistent with downwards tracks faking upwards tracks
Example of downward track followed by an upward tracks separated by $\frac{1}{4}$ of the muon lifetime

- Are upward tracks with no beam created by cosmic muon decays creating upward electrons?

- Analysis still on-going...but the hypothesis seems to be confirmed by simulation...

Results will be published soon
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

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

- 68 m to IP on surface and IP ~80m below surface
- ~7.5m offset to the beam line
- ~95% sensitivity of MATHUSLA200
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

Beam line

Jura Side
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
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
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 depend on the amplitude of the distribution, the inclination of the profile, and x coordinate of the core position
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 1\(^{st}\) particle that reaches the bar (in a 1 ns window)

**Energy estimation**

The number of hits increases with **E**

→ can be used to estimate **E of EAS**

**Core position**

Used only events with **N\(_{\text{hits}}\) > 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)

Arrival direction

Fraction of signals induced by muons

⇒ Bias decreases with primary energy
⇒ Fraction of muons > 90% for E > 10^{6.5} GeV
Summary & Conclusions & Plans

- MATHUSLA is a **complementary detector**
  - Might made the LHC LLP search program more comprehensive
  - Might have the potential to significantly **enhance and extend the new physics reach** and capabilities of the current LHC detectors

- Test stand analysis almost finalized

- Simulations showed good performance for inclined EAS (**quite good angular resolution**)

- 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**. It will provide reliable input to the cost and schedule for MATHUSLA

- Goal to complete the Technical Design Report (TDR) by end 2020
BACKUP
Unconventional Challenges

- 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
  - Constraints in triggering

- At HL-LHC ➔ best possible sensitivity from ATLAS displaced vertex search in the muon spectrometer (**shielded and able to trigger on LLP at L1**), but searches (**arXiv:1605.02742**) suggest that various backgrounds (punch through, cosmics, etc) of the order 100 fb
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 ($\gamma$, $Z$) portal couplings

  - **Wide range of possible lifetimes from $\mathcal{O}(mm)$ up to $\mathcal{O}(m/km)$**

  ![Diagram of Higgs mixing with hidden sector](image)

  The mixing of Higgs with HS results in a Higgs like particle decaying into LLPs: **small coupling $\rightarrow$ long lifetimes** [Phys. Lett. B6512 374-379, 2007]

  ~ $10^8$ Higgs boson @ HL-LHC
Unconventional Searches @ LHC

- Current searches at 13 TeV show an **impressive agreement** with the SM expectations

- New physics should be present at
  - High mass → no hints so far
  - **Small coupling** → not fully explored

- Many extensions of the SM include particles that
  - Are **neutral, weakly coupled**, and **long-lived** that can decay to different final states (hadrons, leptons, photons, etc)
    - Several mechanism behind long-lived particles (LLPs): approximate symmetry, heavy mediators, etc...
  - Are **charged** meta-stable/stable
    - Multi-charged particles predicted by Technibaryons, almost-commutative leptons, doubly charged Higgs

Need to **exploit the full LHC potential and reduce to negligible the possibility of losing new physics at the LHC!**
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

Heavy Neutral Leptons

Higher sensitivity for long lifetimes
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 a 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 - 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/ATLAS

  - 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/ATLAS bunch crossing (at HL-LHC trigger has ~12 microsecond latency)

Guaranteed return on the investment!
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 to establish the components of source and distribution of incident particles)
- 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)
MATHUSLA detector \(\rightarrow\) 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 \((10^7 - 10^8 \text{ m})\) 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 \(\rightarrow\) 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
Simulated muons coming from LHC and passing 100 m of rocks made of 45.3m of sandstone, 18.25m of marl (calcium and clay), 36.45m mix (marl and quartz)

Minimum energy ~ 70 GeV

What a muon can do inside the detector?

- **Pass through** → detected as a single upwards track
- **Decay** → entirely to $e\nu\nu$ (single $e$ deflected wrt muon direction), but also to $e e e + \nu\nu$ with BR $\sim 3 \times 10^{-5}$ (looks like a genuine DV decay, but rejected through floor layer veto or main trigger muon trigger)
- **Inelastic scattering** → off the air or the support structure (rejected using floor layer veto)

Over the entire HL-LHC run expected $\sim 10^6$ muons pass through MATHUSLA, corresponding to $\sim 0.1$ Hz

- **3000** muons decaying to $e\nu\nu$ (electron deflected from original muon trajectory by angle $\sim 1$/$\text{muon boost}$ ($\sim 5$-10 degrees)
- **0.1** muons decaying to $e e e + \nu\nu$
- $<1$ muon scattering off air
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

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

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

Active area \( \sim 2.5 \times 2.5 \times 6.0 \, \text{m}^3 \)
A recent paper [A. Fradette and M. Pospelov, arXiv:1706.01920v1] examines the BBN lifetime bound on lifetimes of long-lived particles in the context of constraints on a scalar model coupled through the Higgs portal, where the production occurs via $h \rightarrow ss$, where the decay is induced by the small mixing angle of the Higgs field $h$ and scalar $s$.

For $m_s > m_\pi$ the lifetime $\tau < 0.1 \text{ s}$.

Conclusion does not depend strongly on BR($h \rightarrow ss$)
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 $v_{\text{fiber}} = 5 \mu s/100m$
  - 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 MATHUSLA in “combined” mode will be crucial for both cosmic ray studies and LLP searches
EAS Core Position Estimation - Details

\[ \text{Hits} = a_x e^{-b_x|x - x_c|} \]

- \( a_x \) = Amplitude of distribution
- \( b_x \) = inclination of profile
- \( x_c \) = \( x \) coordinate of core position

Peak reveals the core position

From J.C. Arteaga-Velázquez

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

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

From J.C. Arteaga-Velázquez

**e^+, hadrons, μ^+**

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
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.
For long $c*\tau$ detector sensitivity $\propto$ angular coverage and detector size

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\eta$ coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>MATHUSLA</td>
<td>0.9 – 1.4</td>
</tr>
<tr>
<td>AL3X</td>
<td>0.9 – 3.7</td>
</tr>
<tr>
<td>Codex-b</td>
<td>0.2 – 0.6</td>
</tr>
</tbody>
</table>

These experiments can exploit the full LHC potential and reduce to negligible the possibility of losing new physics at the LHC!