Mathusla

Henry Lubatti
Higgs boson measured decay modes or why worry about SM

Combined ATLAS-CMS Run 1 results wrt standard model expectations

Good agreement with SM

BUT
Higgs boson measured decay modes

Combined ATLAS-CMS Run 1 results wrt standard model expectations

Good agreement with SM

BUT > 30% BSM allowed
The SM today and...

- SUSY models are constrained no evidence for SUSY particles
- Higgs couplings studies allow for 30-40% invisible decays
- $m_h = 125$ GeV is very low
- No evidence for other light scalars
- Dark matter not in SM

Hidden sectors?

higgs portal to the hidden sector

Let there be light
Much of the recent theoretical work and experimental work in particle physics is focused on three open dark matter, particle asymmetry (Baryogenesis) and the hierarchy problem. All of these have been connected to hidden sectors containing new particles and new forces that lead to long-lived particles.
Why Long-lived Particles - summary

- Standard Model (SM) completed by discovery of Higgs boson in 2012
- Focused attention on what SM does not address
  - Dark Matter
  - Matter-antimatter asymmetry of our universe
  - Naturalness of electro-weak scale, absent obvious TeV-scale signals of physics Beyond the SM (BSM)
- Virtually every theory/model that extends the SM to address these open issues either allows for or requires long-lived particles (LLPs)
  - Life-times ($c\tau$) can range from a few $100 \mu m$ to the Big Bang Nucleosynthesis (BBN) limit of $10^7 - 10^8$ meters
  - Covering such a large $c\tau$ range poses a major experimental challenge
- Higgs boson a particularly good place to search for LLPs
  - Very narrow width $\Gamma/m$ almost two orders of magnitude smaller than most SM particles
  - Studies of Higgs couplings allow for 30-40% invisible decays
  - Higgs couples well to hidden sector scalar portals
Theories with Long-lived Particles

- BSM Theories that extend SM require or allow for LLPs*
  - Mini split supersymmetry (arXiv:1212.6971)
  - RPV (R-parity violating) SUSY (arXiv:1309.5957)
  - Models of Baryogenesis (arXiv:1409.6729)
  - Dark Photons (arXiv:1604:00044)
  - Theories of Neutral Naturalness (arXiv:1512.05782)
  - Models generating neutrino masses (arXiv:1604.06099)

* Reference are to a relatively recent paper that contains earlier work.
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-ττ)

ATLAS search strategy for displaced decays - based on signature driven triggers that are detector dependent
ATLAS Detector

- Muon chambers
- Toroid magnets
- Solenoid magnet
- Transition radiation tracker
- Pixel detector
- Semiconductor tracker
- LAr electromagnetic calorimeters
- LAr hadronic end-cap and forward calorimeters
- Tile calorimeters
CMS Detector

One of four detectors at the LHC
Total weight: 12,500 T
Overall diameter: 15 m (50 ft.)
Overall length: 21.5 m (70 ft.)

SUPERCONDUCTING MAGNET COIL

CALORIMETERS
ECAL Scintillating PbWO4 Crystals

HCAL Plastic scintillator/brass

IRON YOKE

TRACKER
Silicon Microstrips Pixels

MUON BARREL
Drift Tube Chambers (DT) Resistive Plate Chambers (RPC)

MUON ENDCAPS
Cathode Strip Chambers (CSC) Resistive Plate Chambers
CMS

CMS inner tracking entirely silicon based (pixels + strips)

$E_{\text{CAL}}$ uses PbWO$_4$ crystals – very good energy resolution

Muon system tracking chambers buried in Fe return yoke of magnet
Pixel Detector (Three + IBL layers - double sided)
  • $|\eta| < 2.5$ with $\sigma_{r\phi} \sim 10 \, \mu m$, $\sigma_z \sim 115 \, \mu m$ (80M channels)

Semiconductor Tracker (SCT): single sided Si strips
  • stereo pairs
  • Four barrel layers and 2x9 end-cap disks stereo
  • $|\eta| < 2.5$ with $\sigma_{r\phi} \sim 17 \, \mu m$, $\sigma_z \sim 580 \, \mu m$ (6.3M channels)

Pixel and strips provide good resolution tracking measurements

Transition Radiation Tracker (tracking and e-p separation)
  • 73 barrel straw layers and 2x160 end-cap radial layers
  • $|\eta| < 2.0$ with $\sigma_{r\phi} \sim 130 \, \mu m$ (350k channels)
  • Average of 32 hits/track

The ID embedded in a 2 Tesla solenoidal magnetic field
- Allows for Photon ID based on longitudinal and lateral segmentation of the ECAL (shower shapes)
- High granularity in S1 gives in good $\gamma$ direction and separation power for $\pi^0$ decays to $\gamma \gamma$
- Photon direction from shower centroids in layers 1 and 2 gives longitudinal (z) position
- For two $\gamma$ (eg. $H \rightarrow \gamma \gamma$) combine to improve z-resolution of interaction point (IP)
- For displaced decays get $\gamma$ direction in layers 1 and 2 to determine z of closest approach
ATLAS Calorimeters

- Electromagnetic Calorimeter (ECAL)
  - Lead accordion with liquid argon
  - Three longitudinal segments
- Hadronic Calorimeter (HCAL)
  - Barrel Fe Scintillator plates with polystyrene
  - Forward Cu Liquid Ar
- Barrel Dimensions
  - ECAL $1.1m < r < 2.25m$
  - HCAL $2.25m < r < 4.25m$
- Calorimeters cover $|\eta| \leq 3.9$
ATLAS Muon Spectrometer (MS)

- **Air core toroid -** magnetic field allows for stand-alone momentum measurements and vertex reconstruction

**Trigger Chambers**
- RPC’s in barrel region covering $|\eta|<1.05$ and TGC’s in Forward region $1.05<|\eta|<2.4$
- Trigger chambers provide second coordinate ($\phi$) for track reconstruction

**Precision Chambers**
- Monitored Drift Tube (MDT) chambers in barrel and most of forward spectrometer
  - Barrel MDTs ~ 4.5, 7 and 10 m
  - Forward MDTs ~ 7.5 and 14 m
- MDT chamber has two multilayers (ML) with 3 or 4 layers of MDT tubes
- Multilayers separated: up to 32 cm
- Cathode Strip Chambers (CSC’s) for $2.0<|\eta|<2.7$
- Resolution $\sigma_{p_T}/p_T \sim 4\%$ at 50 GeV and $\sim 11\%$ at 1 TeV
ATLAS simulation of two displaced decays – Note unique signatures of decays in MS and HCal

- Decay in MS
  - Cluster of His in RPCs

- Decay at beginning of HCal
  - Low EM energy deposition
**ATLAS Run-1 results**

- **Searches requiring two displaced decays**
  - Two low EM fraction (EMF) jets (decays in the HCal)
  - Two reconstructed displaced vertices
    - 2MS vertices or MS vertex plus ID vertex
  - Sensitive to Higgs decaying to long-lived scalar pairs

- **No evidence for two vertex events in the Run-1 data**

  Set limits for Higgs decay to long-lived scalar pairs, Stealth SUSY and heavy \( Z' \) decay (long-lived particles indicated by double lines)

<table>
<thead>
<tr>
<th>Scalar boson mass [GeV]</th>
<th>( \pi_v ) mass [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>10, 25</td>
</tr>
<tr>
<td>125</td>
<td>10, 25, 40</td>
</tr>
<tr>
<td>140</td>
<td>10, 20, 40</td>
</tr>
<tr>
<td>300</td>
<td>50</td>
</tr>
<tr>
<td>600</td>
<td>50, 150</td>
</tr>
<tr>
<td>900</td>
<td>50, 150</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( Z' ) mass [TeV]</th>
<th>( \pi_v ) mass [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>120</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( \tilde{g} ) mass [GeV]</th>
<th>( \tilde{S}, S ) mass [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>100, 90</td>
</tr>
<tr>
<td>250</td>
<td>100, 90</td>
</tr>
<tr>
<td>500</td>
<td>100, 90</td>
</tr>
<tr>
<td>800</td>
<td>100, 90</td>
</tr>
<tr>
<td>1200</td>
<td>100, 90</td>
</tr>
</tbody>
</table>

**Table:**

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Applicable topologies</th>
<th>Benchmarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon RoI Cluster</td>
<td>IDVx+MSVx, 2MSVx</td>
<td>Scalar boson, Stealth SUSY</td>
</tr>
<tr>
<td>Jet+( E_T^{\text{miss}} )</td>
<td>2IDVx, IDVx+MSVx, 2MSVx</td>
<td>( Z' )</td>
</tr>
</tbody>
</table>

**Diagram:**

- **ATLAS**
  - Run = 8 TeV, 19.5 fb\(^{-1}\), 20.3 fb\(^{-1}\)
  - \( m_H = 125 \) GeV

**Graph:**

- 95% CL Upper Limit on \( \sigma_{SM} \) vs. \( \pi_v \) proper lifetime (ct) [m]
ATLAS Run-1 Results


- $\pi^0$ proper decay lengths excluded at 95% CL assuming 30%, 15%, 5%, or 1% BR for $m_{H^0} = 125$ GeV.

- $\sigma \times \text{BR}$ 95% CL limits for scalar boson samples: $m_\phi = 300$ GeV, 600 GeV, and 900 GeV

<table>
<thead>
<tr>
<th>$m_{\pi^0}$ [GeV]</th>
<th>1% BR</th>
<th>5% BR</th>
<th>15% BR</th>
<th>30% BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>no limit</td>
<td>0.24–4.2</td>
<td>0.16–8.1</td>
<td>0.12–11.8</td>
</tr>
<tr>
<td>25</td>
<td>1.10–5.35</td>
<td>0.43–18.1</td>
<td>0.28–32.8</td>
<td>0.22–46.7</td>
</tr>
<tr>
<td>40</td>
<td>2.82–7.45</td>
<td>1.04–30.4</td>
<td>0.68–55.5</td>
<td>0.52–79.2</td>
</tr>
</tbody>
</table>
ATLAS Run-2 Results (13 TeV)

- Limits for hidden-sector, heavy Higgs-like scalars decaying to hadronic jets in the ATLAS hadronic calorimeter in 3.2 fb\(^{-1}\) (2015 13 TeV data set)

<table>
<thead>
<tr>
<th>(m_\phi) [GeV]</th>
<th>(m_s) [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>50, 100</td>
</tr>
<tr>
<td>600</td>
<td>50, 150</td>
</tr>
<tr>
<td>1000</td>
<td>50, 150, 400</td>
</tr>
</tbody>
</table>

- Trigger selects narrow jets in Hcal [60 GeV in 0.2x0.2 (\(\Delta\eta, \Delta\phi\)) region] and \(\log_{10}(E_H/E_{EM}) > 1.2\) and no track pointing to jet

- Uses Boosted Decision Tree (BDT) to discriminate between QCD-like and signal-like jets (jet \(p_T\), jet width, track variables, …)

Yukawa coupling heavy quarks dominant
Multijet backgrounds estimated using ABCD method using uncorrelated variables $\Sigma \text{BDT}$ [sum of two jets having highest BDT values] and $\Sigma \Delta R_{\text{min}}(\text{jet,tracks})$ [sum angle between jet axis and closest track with $p_T>2$ GeV].

### A-signal region

![A-signal region diagram]

### Limits for $m_\Phi = 1000$ GeV

![Limits for $m_\Phi = 1000$ GeV]

<table>
<thead>
<tr>
<th>$m_\Phi$</th>
<th>$m_\Phi = 50$ GeV</th>
<th>$m_\Phi = 100$ GeV</th>
<th>$m_\Phi = 150$ GeV</th>
<th>$m_\Phi = 400$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_\Phi = 400$ GeV</td>
<td>(0.20, 2.4) m</td>
<td>(0.52, 4.6) m</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$m_\Phi = 600$ GeV</td>
<td>(0.09, 2.7) m</td>
<td>–</td>
<td>(0.38, 8.2) m</td>
<td>–</td>
</tr>
<tr>
<td>$m_\Phi = 1$ TeV</td>
<td>(0.05, 2.0) m</td>
<td>–</td>
<td>(0.14, 7.2) m</td>
<td>(0.78, 16) m</td>
</tr>
</tbody>
</table>
ATLAS Run-1 Results

ATLAS Run 1 RPV SUSY LLP Searches

- Extensive Analysis with no observed events
- Require DV with high-$p_T\mu$ or $e$ that comes from DV, missing $E_T$, and one DV per event

- Limits for various scenarios
ATLAS Displaced lepton-jets Run-1 Results

- Displaced Lepton-Jets
  - kinetic mixing of light $\gamma_d$ with SM $\gamma$ through vector portal

- Searched for $2\gamma_d$ and $4\gamma_d$ decaying to lepton jets
- Used a lepton-jet gun to simulate individual displaced LJs from one $\gamma_d$ decay and hidden scalar $s_d \rightarrow \gamma_d \gamma_d$
- Generate efficiency maps uniform in $p_T$, $\eta$, and decay position with LJ gun samples that are independent of a specific model

Type 0: all $\gamma_d \rightarrow \mu$'s
Type 1: $1\gamma_d \rightarrow ee$ or $\pi \pi$, $1\gamma_d \rightarrow 2\mu$
Type 2: all $\gamma_d \rightarrow ee$ or $\pi \pi$
Main Backgrounds are cosmic and QCD jets

- Used empty bunches to determine cosmic background

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Events in B</th>
<th>Events in C</th>
<th>Events in D</th>
<th>Expected Events in A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmic-ray data</td>
<td>0</td>
<td>0</td>
<td>60 ± 13</td>
<td>40 ± 10</td>
</tr>
<tr>
<td>Data (cosmic rays subtracted)</td>
<td>362 ± 19</td>
<td>99 ± 10</td>
<td>19 ± 16</td>
<td>70 ± 58</td>
</tr>
</tbody>
</table>

- QCD jets is irreducible background - evaluated using ABCD method where $\Delta \phi$ is azimuthal angle between the two lepton jet

- Data is consistent with expected backgrounds

- Type2-Type2 have largest background – most sensitive limit by excluding these events

No Type2-Type2

<table>
<thead>
<tr>
<th>FRVZ model</th>
<th>Excluded $c\tau$ [mm]</th>
<th>BR(10%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow 2\gamma_d + X$</td>
<td>$14 \leq c\tau \leq 140$</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow 4\gamma_d + X$</td>
<td>$15 \leq c\tau \leq 260$</td>
<td></td>
</tr>
</tbody>
</table>
ATLAS Run 1 displaced lepton jet results

- Results obtained from the lepton-gun MC efficiencies

ATLAS limits in the global $\epsilon$ vs $m_{Y_d}$ plot
NB: ATLAS result depend on BRs and are for specific final states.

- Benchmark models:
  - SUSY production of dark $\chi$
  - FRVZ Higgs-portal

- Two scenarios $\gamma_d \rightarrow \text{ee, } \mu\mu \text{ or } \pi\pi$ and $s_d \rightarrow \gamma_d \gamma_d$

- Event selection: requires 2 LJs from combinations of e-jet (eLJ), $\mu$-jet ($\mu$LJ), mixed (e$\mu$LJ) where jet $\geq 2$ tracks

6 categories of events:
- $eLJ-eLJ$, $\muLJ-\muLJ$, $eLJ-\muLJ$
- $e\muLJ$, $\muLJ-eLJ$, $e\muLJ-e\muLJ$

- $\gamma_d$ high boost – small opening angles
- $\muLJ$ requires at least two muons with $p_T > 10$ GeV within $\Delta R = 0.5$ of LJ

Use EM-Cal segmentation to separate electrons from $\pi^0$
Run-1 ATLAS combined lepton-jet results

NB the $\epsilon$ vs $m_{\gamma_d}$ results from both prompt and displaced LJs is model dependent (FRVZ)
Search for 4 muons in $\eta < 2.4$
In topology with two pairs of closely spaced muons
Run-2 displaced analysis – can we do better

- Run 1 displaced decay searches either

(I) Required two displaced object per event
   - Works only for LLPs that are produced in pairs
     - reduced lifetime sensitivity - scales like $1/(c\tau)^2$

(II) Required one displaced vertex plus an associated high energy object ($m$, MET..)
   - OK for SUSY models but not for many other BSM models

   e.g. RPV with long-lived neutralino
Single vertex analyses – New approach

- No SM displaced objects, but plenty of jet production
  - Main source of background for neutral LLP displaced JETS searches from jets that fake a displaced object in HCal or punch through to MS and reconstruct as a displaced vertex that looks exactly like expected signal
    - Requiring 2 reconstructed displaced vertices in MS (Run-1) kills this background

- MS displaced decay in MS - trigger selection

- NB life-time reach of 2 vertex analysis scales like $1/(c \tau)^2$ while for single vertex scales like $1/c \tau$
ABCD Method

- Can use ABCD method to estimate background in signal region
- If axis are independent and no correlations, then $AD = BC$

- Rescaling function $r_{\text{noiso} \rightarrow \text{iso}} = N_C / N_D$

Choice of $Y$ depends on search goals – tailored to a specific model or class of models.
What about ultra-long lived particles

ULLPs

Near the Big Bang Nucleosyntheses
limit ≲ 10^7 m – 10^8 m
What about ultra-long lived particles

ULLPs

Near the Big Bang Nucleosyntheses
limit \( \lesssim 10^7 \text{ m} - 10^8 \text{ m} \)

Existing detectors limited by size and very large SM QCD backgrounds
What about ultra-long life times

Higgs boson a particularly good place to search for exotic, neutral long-lived particles (scalar portal)
Higgs production at HL-LHC

- HL-LHC will produce order of $N_h = 1.5 \times 10^8$ Higgs Bosons
- Observed decays: $N_{\text{obs}} \sim N_h \cdot Br(h \rightarrow ULLP \rightarrow SM) \cdot \varepsilon_{\text{geom}} \cdot L/bc\tau$
  - L-size of detector along ULLP direction of travel
  - $\varepsilon_{\text{geom}}$ geometrical acceptance
  - $b(\text{Lorentz boost}) \sim m_h/nmX \leq 3$ for Higgs boson decaying to $n=2 \ mX \geq 20 \text{ GeV}$

Assuming $b \leq 3$ particles 100% to SM

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

- Assuming $b \leq 3$ and $n=2 \ mX \geq 20 \text{ GeV}$ conclude that a detector with linear size of 20 m in direction of ULLP travel and about 10 m decay length can detect ULLPs near BBN limit
MASSIVE TIMING Hodoscope for Ultra-Stable Neutral Particles

Large area surface detector above an LHC pp IP dedicated to detection of ultra long-lived particles

J-P Chou, D. Curtin, HL arXiv 1606.06298
Could be located above either ATLAS or CMS

Surface space available near both IPs
Equivalent to two soccer pitches
MAssive Timing Hodoscope for Ultra-Stable Neutral Particles

Dedicated detector sensitive to long-lived neutral long-lived particles that have lifetimes up to the Big Bang Nucleosynthesis (BBN) limit ($10^7$ – $10^8$ m) for the HL-LHC

Air filled detector located on the surface above and somewhat displaced from ATLAS or CMS interaction points

Goal to search for long-lived particles that have no SM interactions and decay with a finite life to SM particles
Placing MATHUSLA on the surface above ATLAS or CMS provides shielding from pp interaction particles but requires a very large detector.

To establish a displaced decays requires robust tracking and good cosmic background rejection:

- RPCs planes can be an attractive choice for tracking and vertex reconstruction.
- Scintillator planes for redundant background rejection - timing.

Approximately 5% geometrical coverage.
MATHUSLA

  - Dedicated detector sensitive to long-lived neutral long-lived particles that have lifetimes up to the Big Bang Nucleosynthesis (BBN) limit ($10^7 – 10^8$ m) for the HL-LHC
  - A large-volume, air filled detector located on the surface above and somewhat displaced from ATLAS or CMS interaction points

- HL-LHC will produce order of $N_h = 1.5 \times 10^8$ Higgs Bosons
  - Observed decays: $N_{\text{obs}} \sim N_{\text{h}} \cdot \text{Br}(h \to \text{ULLP} \rightarrow \text{SM}) \cdot \varepsilon_{\text{geom}} \cdot L/\text{bct}$
    - $L$-size of detector along ULLP direction of travel
    - $\varepsilon_{\text{geom}}$ geometrical acceptance
    - $b(\text{Lorentz boost}) \sim m_h/nmX \leq 3$ for Higgs boson decaying to $n=2$ $mX \geq 20$ GeV
    - Requires
      $$L \sim (20 \text{ m}) \left( \frac{b}{3} \right) \left( \frac{0.1}{\varepsilon_{\text{geom}}} \right) \frac{0.3}{\text{Br}(h \rightarrow \text{ULLP})}$$
  - To collect a few ULLP decays with $c\tau \sim 10^7$ m requires a 20 meter detector along direction of travel of ULLP and about 10% geometrical acceptance
MATHUSLA - backgrounds

- Cosmic muon rate or order 10 MHz (200 m$^2$)

Scintillators 1.5 ns timing resolution

If these muons have inelastic interaction in air decay volume they will not result in a reconstructed vertex - scintillator timing can also be used to reject
MATHUSLA - backgrounds

- Upward going muons from LHC with inelastic interaction

![Diagram showing rejection with scintillator timing and entrance hit position](image)

- Reject with scintillator timing and entrance hit position

- ~ 10 Hz!
MATHUSLA - backgrounds

Cosmic neutrinos traveling upwards that have inelastic interactions in the decay volume

- Estimate Low rate ~ 10-100 per year above 300 MeV.

Most have a low momentum proton - reject with time-of-flight measurement in RPCs.

RPCs

Estimated total number of cosmic ray $\nu$-$\bar{\nu}$ scatterings off air in MATHUSLA (all solid angles, entire detector volume, $E_{\nu} = E_{\nu}^\text{max}$)
MATHUSLA - backgrounds

- Cosmic neutrinos traveling upwards that have inelastic interactions in the decay volume

**None LHC collisions backgrounds can be measured when no LHC collisions**

Most have a low momentum proton - reject time-of-flight measurement in RPCs

Estimate **Low rate**

~ 10-100 per year above 300 MeV.
MATHUSLA - backgrounds

- Neutrinos from LHC interactions (subdominant background)

Preliminary estimate is that MATHUSLA should observe a few events during HL-LHC data taking period – needs more work, but appears to be subdominant.
Effort underway to develop GEANT simulations of the backgrounds discussed above

- Current plan to deal with muons and neutrinos traveling upwards is to create a “gun” that shoots particles into MATHUSLA
- For cosmic muons from above plan to use standard cosmic muon simulation code - will seek input from Arturo & colleagues
- Simulation needs data anchor with LHC colliding protons and also when there are no pp collisions in LHC – beam OFF
- To anchor our MC simulations need data
Three layers of RPCs provided by University of Rome, Tor Vergata
Rinaldo Santonico

Scintillator layers top and bottom from Tevatron D0 experiment provided by Dmitri Denisov
Excellent for students - participation at all stages of an experiment: design, test components, install, take data and analysis.

Three layers of RPCs provided by University of Rome, Tor Vergata Rinaldo Santonico.

Goal is to install in late spring 2017 and be ready when pp data taking begins.

Scintillator layers top and bottom from Tevatron D0 experiment provided by Dmitri Denisov.
Detected Ultra-Long-Lived Particles: The MATHUSLA Physics Case

Editors:
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Goal is to have comprehensive document finished by early 2017

Contributions from broad spectrum of theory community
Current Test Module Participants

Henry Lubatti
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Audrey Kvam

John Paul Chou
Amit Lath
Steffie Thayil

Charles Young
Robert Mina

Sunanda Banerjee

Rinaldo Santonico
Roberto Cardarelli

David Curtin
Theory input
Future – Life-time Frontier

Go where no one has gone before HL-LHC

13-14 TeV, > 100s fb$^{-1}$