The Lifetime Frontier

Henry Lubatti
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LHCP 2017
Shanghai, China 15 – 20 May 2017
Hidden Sectors

- The Standard Model (SM) is a great success, but many open questions...
  - Dark matter, particle asymmetry (Baryogenesis), hierarchy problem (naturalness)
  - Many of the BSM models proposed to address these phenomena contain long-lived particles (LLPs) with macroscopic decay lengths that are limited only by Big Bang Nucleosynthesis - $\mathcal{O}(10^7)$ meters.
  - LLPs occur naturally in coupling to a hidden sector via small portal couplings
  - For example, scalar (Higgs) and vector ($\gamma$, $Z$) portals.

The notion of a hidden sector with a gauge group $G_{HS}$ and a phenomenology similar to our standard model sector $G_{SM}$ described by Strassler and Zurek (Phys. Lett. B6512 374-379, 2007)

Mixing of Higgs with hidden sector (hs) scalar results in hs “Higgs” that decays to pair of hs long-lived scalars that decay to SM fermion pairs – small couplings result in long lifetimes
Coupling to hidden sector

Higgs decay to hidden sector scalars $\phi_{hs}$

HL-LHC will produce $\sim 10^8$ Higgs boson

$L_{\text{INT}} \sim h^2 \phi^2$

LHC detector searches
Limited by large QCD Backgrounds – need LHC Background-free detector
MATHUSLA


- Dedicated detector sensitive to 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

- Order of $N_h = 1.5 \times 10^8$ Higgs Bosons produced in full HL-LHC run

- Observed decays: $N_{obs} \sim N_h \cdot Br(h \to ULLP \to SM) \cdot \varepsilon_{geom} \cdot \frac{L}{b_{ct}}$
  
  - $L$-size of detector along ULLP direction of travel
  
  - $\varepsilon_{geom}$ geometrical acceptance
  
  - $b(\text{Lorentz boost}) \sim \frac{m_h}{m_X} \leq 3$ for Higgs boson decaying to $n = 2 \ m_X \geq 20 \text{ GeV}$

  - Requires $L \sim (20 \text{ m}) \left( \frac{b}{3} \right) \left( \frac{0.1}{\varepsilon_{\text{geom}}} \right) \frac{0.3}{Br(h \to ULLP)}$

- 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
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. Air decay volume with tracking chambers surrounded by scintillators.

- Need robust tracking
- Excellent background rejection
- RPCs planes are an attractive choice
- Good space and time resolution for vertex reconstruction and cosmic ray rejection
- Scintillator planes for redundant background rejection - timing

No LHC Background, BUT…
MATHUSLA - backgrounds

- Cosmic muon rate of about $10^6$ Hz
- LHC collision backgrounds
  - LHC muons about 10 Hz  
    Reject with scintillator timing and entrance hit position
- Upward atmospheric neutrinos that interact in air decay volume
  - Estimate Low rate $\sim 10$-100 per year above 300 MeV
  - Most have low momentum proton - reject with time of flight - non-collision backgrounds can be measured when no LHC collisions

Scintillators 1.5 ns timing resolution in 20 m have $\Delta t \approx 70$ ns top to bottom
MATHUSLA - backgrounds

- Neutrinos from LHC interactions (subdominant background)

Preliminary estimate is that MATHUSLA should observe a few events during entire HL-LHC data taking period – needs more work, but appears to be subdominant.
Sensitivity estimate

- Decay of Higgs boson to pair of scalars, $x$, for several $m_x$
- No QCD backgrounds $\rightarrow$ sensitivity gain
- Can approach BBN limit

Comparison: $h \rightarrow \text{invis}$
HL-LHC limit

Cross section limit
$\sim$ applies to other LLP production processes (up to boost factors)
MATHUSLA – background studies

- 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 colleagues.
  - Simulation needs data with LHC colliding protons and also when there are no pp collisions in LHC – beam OFF
Three layers of RPCs provided by University of Rome, Tor Vergata, Rinaldo Santonico and friends

Scintillator layers top and bottom from Tevatron D0 experiment provided by Dmitri Denisov
MATHUSLA Test Module

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

Goal is to install at Point 1 in late summer 2017
# MATHUSLA test team

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**LHCP 2017**

**H. Lu batti**

**19 May 2017**
MATHUSLA theory white paper

- Collaboration of 70+ theorists
- Aiming for publication in 2017

Detecting Ultra-Long-Lived Particles: The MATHUSLA Physics Case

Editors:
David Curtin\textsuperscript{1}, Marco Drewes\textsuperscript{2}, Matthew McCullough\textsuperscript{3}, Patrick Meade\textsuperscript{4}, Rabindra Mohapatra\textsuperscript{1}, Michele Papucci\textsuperscript{5}, Jessie Shelton\textsuperscript{6}, Brian Shuve\textsuperscript{7}

Detection of cosmic showers with a full coverage surface detector allows a detailed study of the core structure, giving crucial information to determine the atomic number $Z$ of the primary cosmic particle.

The combination of a large area detector of atmospheric showers that observes both the muon and $e$, electron component of the shower with a LHC detector where only muon component is observed provides a more complete picture of Air Showers (EAS).

Muon bundles in a LHC detector
Milli-charged particles search

- Quantization of charge – WHY
- Many searches for mcps (milli-charged particles) with $\varepsilon = Q_{mcp}/e$
- Current limits on mass and charge of fractionally charged particles cover large region of mass and charge of mcps.
  - Indirect constraints from CMB, Big-Bang nucleosynthesis, and Universe over-closure bounds (could avoid with extra degrees of freedom)
  - Constraints from direct searches at accelerators, but significant region of $(M_{mcp}, \varepsilon)$ space not explored $[10^{-3} < \varepsilon < 10^{-1} \text{ for } 0.1 < M_{mcp} < 100\text{GeV}]$
  - The challenge: $dE/dx$ proportional to $Q_{mcp}^2 \Rightarrow 10^{-6}$ of mip
  - If produced in LHC detector, not enough energy loss to see a track
- A new dedicated detector proposed to cover $10^{-3} < \varepsilon < 10^{-1}$ and $0.1 < M_{mcp} < 100\text{GeV}$

arXiv:1607.04669v1

A Letter of Intent to Install a Milli-charged Particle Detector at LHC P5

LHCP 2017
H. Lubatti
19 May 2017
milliQan experiment

- Phys. Lett. adds new U(1)’ that mixes with SM U(1)
  - charge carriers of U(1)’ have charge proportional to mixing (small) $O(10^{-2} – 10^{-3})$
  - Not detectable in current LHC detectors $[10^{-6} – 10^{-4} \, \text{mip}]$
- Propose dedicated scintillator detector pointed towards IP and isolated by sufficient material to absorb standard SM particles from pp collisions.
  - Small charge requires sensitivity to 1 photo-electron.
  - Sensitivity scales like $1/(\text{distance to IP})^2$
  - Team found an almost ideal space at CMS, the PX56 drainage gallery, where they plan to install an approximately 1 m X 1m x 3 m scintillator array that points toward IP
  - PX56 is 33 m from IP (17 m rock absorber) and ~43° inclination
  - Backgrounds from PM dark current pulses and muons believed to be manageable
    - Three fold coincidence in 15 ns window suppresses PMT dark current pulses
      - For 1 kHz dark current rate, 3-fold coincidence in 15 ns window gives $O(50)$ events in 3000 fb^{-1}.
    - Muons result in very large number of photons in scintillator – no problem
    - Can measure backgrounds when no collisions in LHC
milliQan detector

- Detector consists of a 20 by 20 by 3 array 5 cm² by 80 cm long BC408 plastic scintillator bars – covers 0.01 of solid angle

- Dimensions driven by space available
  - Each bar has a HPK R7725 PMT

- Estimate sensitivity by simulating production of mcps using modified Drell-Yan and propagate particles through CMS and rock

- Model reflectivity, light attenuation length and scintillator shape

- Simulation inputs include input the PMT quantum efficiency, spectrum of scintillator light time constants, and digitized waveforms.
The 95% (dashed) and $3\sigma$ (solid) exclusion limits for 300 fb$^{-2}$ (black) and 3000 fb$^{-2}$ (blue) from A. Hass, C. Hill, E. Izzaguirre, I. Yavin arXiv:1410:6816, Phys.Lett.B746 117 2015 modified for current detector dimensions.

Going forward

- Install 1/100 detector during TS2 (end of 2017) before end of Run 2 (2018)
- Determine beam-on backgrounds
- Install full scale detector to be ready for Run 3 data taking

From Cristopher Hill, Long-lived particle workshop CERN 26-4-17 https://indico.cern.ch/event/607314/timetable/
Going forward

- Cooling of PMT to -20°C reduces dark current to 80 Hz
- Sensitivity estimate on previous slide assumed 550 Hz
- Investigating impact on infrastructure and safety issues

- Plan to test a small prototype during 2018 LHC data taking period
- milliQAN is an independent experiment - CMS asked only to provide power, Ethernet, delivered luminosity and LHC clock.

- **GOAL** is to have full detector ready for data taking at beginning of Run 2
Could be located above either ATLAS or CMS

Surface space available near both IPs
Equivalent to two soccer pitches
The Standard Model

- 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 SM like sectors?
SUSY models are constrained no evidence for SUSY particles

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Hidden SM like sectors?
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