Top-down Physics Case for LLPs @ the LHC

(inspired by the MATHIS La physics case theory white paper)
We proposed MATHUSLA as a general-purpose external LLP detector for the HL/HE-LHC

Theory community has been working on coherent formulation of the MATHUSLA physics case, white paper out in 1-2 weeks

→ Study of general theory motivations for LLP searches
Context

We proposed MATHUSLA as a general-purpose external LLP detector for the HL/HE-LHC

Theory community has been working on coherent formulation of the MATHUSLA physics case, white paper out in 1-2 weeks

→ Study of general theory motivations for LLP searches

LHC-LLP white paper focusing on guiding LLP searches at main detectors:

Together: comprehensive framework to generally discuss LLPs at the LHC!
Outline

1. Why look for LLPs at the LHC?
2. The MATHUSLA detector
3. Comparing MATHUSLA and the main detectors
4. MATHUSLA Physics Reach
5. Bonus: Cosmic Ray Physics
6. Timeline
7. Conclusion
I. Why look for LLPs at the LHC?
Motivation for (neutral) LLPs

1. Analogy to SM

Variety of mechanisms can suppress particle decay width: small coupling, approximate symmetries, heavy mediator, lack of phase space.

2. Bottom-up Theoretical Motivation

Same mechanisms can be active in BSM theories.

Additional motivation from symmetry structure of QFT: hidden sectors are generic possibility (Hidden Valleys, dark photons, singlet extensions, etc)

Higgs boson particularly enticing probe of relatively light new physics (Exotic Higgs Decays)
Motivation for (neutral) LLPs

3. Where is the new physics?

**Completely pragmatic.** So far, searches at LHC for (mostly prompt) BSM signals have only yielded null results.
Need to look under every lamp post!
**Luckily, LHC is great for the **Lifetime Frontier** (energy x intensity)**

4. Top-Down Theoretical Motivation

LLPs can arise in almost any BSM theory! Often play intrinsic role in the mechanism at the heart of the theory!

Could be involved in addressing big fundamental questions like Naturalness, Dark Matter, Baryogenesis, Neutrino Masses…

See several talks at this workshop!
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<th>Motivation</th>
<th>Top-down Theory</th>
<th>IR LLP Scenario</th>
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<td>Naturalness</td>
<td>RPV SUSY GMSB mini-split SUSY Stealth SUSY Axinos Sgoldstinos</td>
<td>BSM=/→LLP (direct production of BSM state at LHC that is or decays to LLP)</td>
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<td></td>
<td>UV theory</td>
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<td>Dark Matter</td>
<td>Asymmetric DM Freeze-In DM SIMP/ELDER Co-Decay Co-Annihilation</td>
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<td>Dynamical DM {</td>
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<td>Baryogenesis</td>
<td>WIMP Baryogenesis Leptogenesis</td>
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<td>Neutrino Masses</td>
<td>Minimal RH Neutrino with U(1)$<em>{B-L}$ Z' with SU(2)$</em>{R}$ $W_R$ long-lived</td>
<td>exotic Z decays</td>
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<td>scalars with Higgs portal from ERS Discrete Symmetries</td>
<td>exotic Higgs decays</td>
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<td>exotic Meson decays</td>
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<td>Naturalness</td>
<td>RPV SUSY GMSB mini-split SUSY</td>
<td>All signs point to LLPs!</td>
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<td>Dark Matter</td>
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<td>with SU(2)<em>{R} W</em>{R}</td>
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<td>long-lived scalars</td>
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<td>with Higgs portal</td>
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<td>from ERS</td>
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<td>Discrete Symmetries</td>
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MATHUSLA Physics Case, June 2018
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<th>BSM Scenario</th>
<th>Role of LLPs</th>
<th>Typical $\tau$</th>
<th>Role of MATHUSLA</th>
<th>Sec.</th>
<th>Fig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutral Naturalness</td>
<td>Discrete symmetry stabilizing Higgs mass $\rightarrow$ Hidden Valley with Higgs portal. Cosmology $\rightarrow$ HV particles are LLPs.</td>
<td>Any, but $Z_2$ arguments favor lower $\hat{\Lambda}_{QCD}$ and hence long lifetimes.</td>
<td>Mirror glueballs with long lifetimes can only be discovered at MATHUSLA.</td>
<td>4.2</td>
<td>22, 23</td>
</tr>
<tr>
<td>WIMP Baryogenesis</td>
<td>Out-of-equilibrium decay of WIMP-like LLP produces baryon asymmetry.</td>
<td>For weak-scale LLP masses, $\gtrsim 1$-$100$ m.</td>
<td>Decays to baryons $\rightarrow$ MATHUSLA likely much greater sensitivity than main detectors. MCFODO</td>
<td>6.1</td>
<td>32</td>
</tr>
<tr>
<td>FIMP DM</td>
<td>Freeze-in via decay requires LLPs with SM couplings.</td>
<td>Fixed by masses &amp; cosmology. Long lifetimes generic.</td>
<td>Model-dependent, but in long-lifetime regime MCFODO.</td>
<td>5.3</td>
<td>27, 28, 21</td>
</tr>
<tr>
<td>Co-decaying DM</td>
<td>Out-of-equilibrium decay of hidden sector LLP determines DM abundance. Also, small portal $\rightarrow$ visible sector LLPs.</td>
<td>For weak scale LLP masses, most of parameter space is long lifetimes.</td>
<td>Depending on model details (production &amp; decay mode), MCFODO.</td>
<td>5.4.3</td>
<td>31</td>
</tr>
<tr>
<td>Co-annihilating DM</td>
<td>DM relic abundance relies on small mass splitting with another state $\rightarrow$ other state is LLP.</td>
<td>Any, long lifetimes generic.</td>
<td>Depends on model details, but e.g. for Higgs Portal implementations, MCFODO.</td>
<td>5.5</td>
<td></td>
</tr>
<tr>
<td>SUSY: Axinos</td>
<td>High PQ-breaking scale $V_{PQ}$ suppresses axion/axino couplings, making LOSP an LLP.</td>
<td>Any, long lifetimes generic.</td>
<td>For high $V_{PQ}$, MCFODO.</td>
<td>4.1.5</td>
<td>21</td>
</tr>
<tr>
<td>SUSY: GMSB</td>
<td>Low SUSY breaking scale $F$ (motivated by flavor problem) leads to light gravitino and small couplings to LOSP, which can hence be LLP.</td>
<td>Any, long lifetimes generic.</td>
<td>MCFODO, depending on spectrum and lifetime.</td>
<td>4.1.2</td>
<td>15</td>
</tr>
<tr>
<td>SUSY: RPV</td>
<td>small RPV couplings (motivated by avoiding flavor violation, proton decay, baryon washout) $\rightarrow$ LOSP can be LLP</td>
<td>Any, long lifetimes generic.</td>
<td>MCFODO, especially for EW-charged LSPs or squeezed spectra.</td>
<td>4.1.1</td>
<td>14</td>
</tr>
<tr>
<td>SUSY: Sgoldstinos</td>
<td>SUSY breaking scale $F$ suppresses sgoldstino coupling to supercurrents $\rightarrow$ can be LLP.</td>
<td>Any. Long lifetimes $\rightarrow$ smallest production, hardest to probe.</td>
<td>Similar to SM+S. For masses $\lesssim 5$ GeV, MATHUSLA and/or SHiP may be only/first discovery opportunity.</td>
<td>4.1.6</td>
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<tr>
<td>minimal RH neutrino model</td>
<td>Type-1 see-saw $\rightarrow$ tiny mixing between $\nu_L$ and $\nu_R \rightarrow \nu_R$ LLPs</td>
<td>Any, long lifetimes favor lower $m_{\nu_R}$</td>
<td>In long-lifetime/low-mass regime, MATHUSLA and/or SHiP may be only/first discovery opportunity.</td>
<td>7.1 34, 35</td>
<td></td>
</tr>
<tr>
<td>$\leftrightarrow$ with $U(1)_{B-L} Z'$</td>
<td>Weakly gauged $B-L$ breaking generates $M_N$, additional $\nu_R$ production mode from $Z'$.</td>
<td>$m_{\nu_R} \sim 1-10$ GeV suggests long lifetime regime.</td>
<td>For sub-weak-scale $m_{\nu_R}$, MCFODO.</td>
<td>7.2.1 36</td>
<td></td>
</tr>
<tr>
<td>$\leftrightarrow$ with $SU(2)_L W_R$</td>
<td>$\nu_R$ part of gauged $SU(2)_R$, breaking generates $M_N$. Additional $\nu_R$ prod. from $W_R^\pm$.</td>
<td>Any, long lifetimes favor lower $m_{\nu_R}$.</td>
<td>For $m_{W_R} \sim 10$ TeV: main detector probes weak-scale $m_{\nu_R}$; MATHUSLA/SHiP only discovery opportunity for $m_{\nu_R} \lesssim 5$ GeV.</td>
<td>7.3.1 38</td>
<td></td>
</tr>
<tr>
<td>$\leftrightarrow$ with Higgs Portal</td>
<td>GUT motivates extra broken $U(1)$ gauge groups, extended scalar sectors mix with Higgs $\rightarrow$ produce $\nu_R$ in $H$ decays.</td>
<td>Any, long lifetimes favor lower $m_{\nu_R}$.</td>
<td>MCFODO, improves Br reach of main detectors by at least order of magnitude.</td>
<td>7.4 41</td>
<td></td>
</tr>
<tr>
<td>$m_{\nu}$ via discrete symmetries</td>
<td>Discrete sym. generates $m_{\nu}$ and stabilizes FIMP DM.</td>
<td>See FIMP DM.</td>
<td>LLPs with EW charge $\rightarrow$ MCFODO, especially for $m \lesssim 10$ GeV</td>
<td>7.5</td>
<td></td>
</tr>
</tbody>
</table>

Table 4: BSM scenarios discussed in this document where neutral LLP signals at MATHUSLA are a strongly motivated intrinsic part of the theory mechanism, and MATHUSLA Could be First or Only Discovery Opportunity (MCFODO). When discussing lifetimes, “any” means up to the BBN limit, “long” means the MATHUSLA regime. LOSP = lightest observable-sector supersymmetric particle.
<table>
<thead>
<tr>
<th>BSM Scenario</th>
<th>Role of LLPs</th>
<th>Typical $c\tau$</th>
<th>Role of MATHUSLA (long $c\tau$)</th>
<th>Sec.</th>
<th>Fig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hidden Valleys (HV)</td>
<td>Small portal to visible sector and possibly hidden sector confinement $\rightarrow$ meta-stable states.</td>
<td>Any.</td>
<td>MCFODO, especially if LLPs are significantly below the weak scale or decay hadronically.</td>
<td>8.1</td>
<td>44, 45</td>
</tr>
<tr>
<td>SM+S</td>
<td>Small mixing $\rightarrow$ scalar LLP for $m_S &lt; 2m_H$. Large mixing $\rightarrow$ $S$ could decay to HV LLPs.</td>
<td>Any.</td>
<td>MCFODO. Complementarity with SHiP.</td>
<td>8.4</td>
<td>52</td>
</tr>
<tr>
<td>SM+V</td>
<td>Dark photon/dark Higgs LLP could be produced in exotic Higgs/$Z$ decays. Dark photon with non-tiny kinetic mixing could be copiously produced at LHC and decay to HV LLPs.</td>
<td>Any.</td>
<td>MCFODO. Significantly extends main detector long-lifetime reach for dark photons and dark Higgs produced in exotic $H$ and $Z$ decays. For LLPs produced in dark photon decays, see HV.</td>
<td>8.5</td>
<td>56, 58, 60, ??</td>
</tr>
<tr>
<td>Exotic Higgs decays</td>
<td>Higgs coupling to new states, like HV or other LLPs, is highly generic and leads to large production rates at LHC.</td>
<td>Any.</td>
<td>MCFODO for $Br \lesssim 0.1 - 0.01$. Higgs portal motivates hadronic LLP decays, for which MATHUSLA has $10^3$ better $Br$ reach than main detectors. MATHUSLA also has significantly better sensitivity for LLP masses $\lesssim 10$ GeV even if they decay leptonically, or for LLPs with subdominant leptonic decays.</td>
<td>8.2</td>
<td>46, 47</td>
</tr>
<tr>
<td>Asymmetric DM</td>
<td>Relating DM to baryon abundance requires operator connecting DM number and Baryon/Lepton number $\rightarrow$ higher dimensional operator $\rightarrow$ LLPs</td>
<td>Any, depending on kind and scale of physics generating the operator.</td>
<td>MCFODO (highly dependent on production and decay mode).</td>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td>Dynamical DM</td>
<td>DM sector includes spectrum of states with varying life-time up to highly stable DM.</td>
<td>Any, long lifetimes generic in DM sector spectrum.</td>
<td>MCFODO (highly dependent on production and decay mode).</td>
<td>5.2</td>
<td>[DC\textsuperscript{5} TB]</td>
</tr>
<tr>
<td>SIMP/ELDER DM</td>
<td>Strong dynamics of HV generate DM abundance. HV $\rightarrow$ LLPs.</td>
<td>Any.</td>
<td>See HV.</td>
<td>5.4.1, 5.4.2</td>
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<tr>
<td>Relaxion</td>
<td>Relaxion or other new scalars in theory generically mix with Higgs $\rightarrow$ SM+S.</td>
<td>Any.</td>
<td>See SM+S.</td>
<td>4.4</td>
<td></td>
</tr>
<tr>
<td>Axion-like particles</td>
<td>ALP couplings to $h$ and $Z$ are generic in EFT framework. $1/f$ suppression makes ALP an LLP.</td>
<td>Any.</td>
<td>MCFODO for low-scale $f$.</td>
<td>8.6 63, 64, 65, 66, 67</td>
<td></td>
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<tr>
<td>Leptogenesis</td>
<td>Motivates minimal RH neutrino model and other neutrino extensions, which generically feature LLPs.</td>
<td>Any, long lifetimes favor lower $m_{\nu_R}$.</td>
<td>Generally very difficult to probe, especially at high leptogenesis scale. In long-lifetime/low-mass regime, MATHUSLA and/or SHiP may be only/first discovery opportunity.</td>
<td>6.2</td>
<td></td>
</tr>
<tr>
<td>Scalars in neutrino extensions</td>
<td>Gauge extensions in neutrino models give rise to new scalars that can mix with Higgs $\rightarrow$ SM+S. Also provides additional $S$ production modes via heavy gauge boson decay.</td>
<td>Any.</td>
<td>See SM+S, with some additional production modes (new heavy gauge bosons).</td>
<td>7.2.2, 7.3.2</td>
<td></td>
</tr>
</tbody>
</table>
... come back to this in more detail later.... but this demonstrates the general importance of LLPs in BSM theories!
2. The MATHUSLA Detector
An external LLP detector for the HL-LHC

Chou, DC, Lubatti
1606.06298

... searches for LLPs by reconstructing displaced vertices in air-filled decay volume.
Background Rejection

LLP DV signal has to satisfy many stringent geometrical and timing requirements ("4D DV" with cm/ns precision)

These signal requirements + a few extra geometry and timing cuts veto all backgrounds!

MATHUSLA can search for neutral LLP decays with near-zero backgrounds!
For the interested:
gory details on backgrounds and rejection strategies…
Background Rejection (gory details)

Most important part of background rejection is the *extremely* conspicuous, multi-faceted and tightly defined nature of LLP decay signal:

\[ \Delta t \approx 3.5 \text{ns per tracker layer,} \]
\[ 17 \text{ ns for all 5 layers} \]
\[ \text{tracker time resolution: } 1 \text{ ns} \]

Tracks are reconstructed in 3D
*and* with detailed timing information at each layer, so DV is really a “4D DV”

Shown is “leptonic” 2-body LLP decay. These requirements become exponentially more difficult to fake when decay is hadronic with \(~10\) charged final states!

\[ \Delta t \geq 3.5 \text{ ns per tracker layer,} \]
\[ 17 \text{ ns for all 5 layers} \]
\[ \text{tracker time resolution: } 1 \text{ ns} \]

most basic CR rejection: LLP decay products are upwards going tracks!

LLP trajectory known (from IP to DV)

Invisible LLP
Veto veto veto

Chou, DC, Lubatti 1606.06298
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tracks are reconstructed in 3D
*and* with detailed timing information at each layer,
so DV is really a "4D DV"

like so.

All ~10 tracks have to meet in both space and time at DV and pass vetos on floor/walls.

(Also, hadronic decay mode is perhaps a bit more of a MATHUSLA target due to main detector gap in coverage.)
Background Rejection (gory details)

Compare to Cosmic Rays: about $10^{15}$ charged particles over HL-LHC run

$\Delta t \approx 3.5\text{ns per tracker layer}$,
$17\text{ ns for all 5 layers}$
tracker time resolution: $1\text{ns}$

$\sim 1\text{m} \uparrow \downarrow$

For *single* downward-traveling charged particle from CR, assuming only *three* layers with $1\text{ns}$ timing resolution within $5\text{m}$, chance of downward *consistently* reconstructing as upward going is

$\epsilon_{\text{down} \rightarrow \text{up}} \approx 10^{-15}$

Chou, DC, Lubatti 1606.06298
In this naive estimate, simple up-vs-down rejection *easily* gets rid of *all* cosmic ray backgrounds by itself.

Of course, our estimate of $\epsilon_{\text{down}\rightarrow\text{up}}$ by itself is much too naive, based on purely gaussian time resolution, in reality tails are non-gaussian etc.

But this estimate only used 3 layers. We specified MATHUSLA to have 5.

Furthermore: single down→up fake does NOT fake the LLP signal. You need:
- *two* down→up fakes occurring `at same time' (so $\epsilon_{\text{down}\rightarrow\text{up}}^2$)
- they need to cross in space to form a DV: requires either spatial mismeasurements (most CRs don’t do this) OR very rare CR trajectory crossings
- the huge timing errors made by 5 tracking layers for each track have to be such that the tracks reconstruct to be coincident *in time* at the fake DV as well
- the scintillators have to fail to register the two CRs on their way out of the decay volume.
Most CR tracks are highly correlated, forming Extensive Air Showers:

Indeed, these showers are the best chance for all these unlikely things to occur and fake an LLP 4D-DV.

BUT YOU CAN JUST “BLIND” THE DETECTOR WHILE IT HAS HIGH OCCUPANCY THAT IS OBVIOUSLY FROM A CR SHOWER.

Blind time has negligible effect on uptime & LLP sensitivity.
Compare to Cosmic Rays: about $10^{15}$ charged particles over HL-LHC run

$\Delta t \gtrsim 3.5 \text{ns per tracker layer}, \quad 17 \text{ ns for all 5 layers}$

For *single* downward-traveling charged particle from CR, assuming only *three* layers with 1ns timing resolution within 5m, chance of downward *consistently* reconstructing as upward going is $\epsilon_{\text{down}} \rightarrow \epsilon_{\text{up}} \lesssim 10^{-15}$

There might be very weird things that give rise to DVs in CR events: neutron decays, air scatterings of CR particles etc…

These much rarer occurrences will be studied in detail, but again, most of them would occur in highly correlated CR showers that are vetoed just based on occupancy.

Finally, this CR background is inherently studyable: during ~50% of time when HL-LHC beam is off, you can very CR rejection strategies on data during ~50% of time when HL-LHC beam is off, you can very CR rejection strategies on data.
Muons from LHC: Have to have energy $\geq 50$ GeV to reach detector, incident with rate $\sim 10$Hz $\rightarrow \sim 10^9$ over HL-LHC run

They do travel upwards, but they do not reconstruct a displaced vertex.
Background Rejection (gory details)

Muons from LHC: Have to have energy $\geq 50$ GeV to reach detector, incident with rate $\sim 10$Hz $\rightarrow \sim 10^9$ over HL-LHC run

Ignoring orders-of-magnitude suppression from boost (!!)
$<< 10^7$ decay in volume, but again, *no DV*
(and detectable by intersection of final and initial state trajectory)
Muons from LHC: Have to have energy $\geq 50$ GeV to reach detector, incident with rate $\sim 10\text{Hz} \rightarrow \sim 10^9$ over HL-LHC run

$\sim 1000$ undergo rare decay into $\text{eee}\nu\nu$ ($\text{Br} \sim 3 \times 10^{-5}$) $\rightarrow$ genuine DV!

Two possible rejection strategies:

1) reject *narrow* decay cones (where all particles are caught by tracker) with *odd* numbers of tracks, indicating charged parent particle

2) reject with scintillator and main detector vetoes (assuming efficiencies 99% and 90% respectively)
Background Rejection (gory details)

Muons from LHC: Have to have energy \( \gtrsim 50 \text{ GeV} \) to reach detector, incident with rate \( \sim 10 \text{Hz} \rightarrow \sim 10^9 \) over HL-LHC run.

\( \sim 10 \) scatter off air and form genuine DV easily veto with scintillator alone.
Background Rejection (gory details)

Isotropic neutrino haze from CR interactions with atmosphere:

Most dangerous BG, naively it looks exactly like LLP signal

Can compute rate using Frejus measurements of atmospheric $\nu_\mu$ flux. ($\nu_e$ much lower, can be dealt with similarly)

$$
\frac{d\Phi}{dE_\nu} \sim 0.06 \left( \frac{\text{GeV}}{E_\nu} \right)^3 \text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}
$$
Background Rejection (gory details)

Only have to worry about neutrino scatters that give 2+ charged particles to give DV.

Exclusive scattering cross sections known at ~30% level \(^{\text{Formaggio, Zeller, 1305.7513}}\)

Can compute rate using Frejus measurements of atmospheric \(\nu\) flux. \((\nu_e\) much lower, can be dealt with similarly) Get about 60 events per year with proton in final state.

- Most of these protons are highly non-relativistic, can be tagged using MATHUSLA’s \(~0.05c\) speed resolution on charged particle tracks.
- Vetoing low-multiplicity DVs with single highly-NR track eliminates most of these BG events.
- Can also use geometric cuts: LLPs decaying to visible particles are either narrow cones pointing back to IP or broad cones. Neutrino final states (especially relatively high-energy ones with relativistic protons) are very narrow cones, mostly not pointing at IP.
  - applying both NR-proton-veto \((v < 0.6c)\) and geometric cut, get < 1 event/year (using very low cut on \(v\) and pessimistic estimates of final state kinematics)

Get about 10 events per year without protons in final state
  - This small number can be vetoed using above geometry cut alone
Background Rejection (gory details)

Also get neutrinos from LHC collisions, mostly low-energy, from hadron decays

Can estimate rate using generic GEANT simulation of main detector.

Cannot use naive geometric cut used on CR neutrinos, but after NR-proton-veto, only left with \(O(1)\) events per year.

There are other handles on their decay (detailed geometry, multiplicity, speed, …)
→ with further study should easily be able to reject.
Rarer BG processes: production of *isolated* Kaons in rocks from CR scattering that migrate to detector and decay, etc… estimates of rates << previous BGs

ALL OF THIS HAS TO BE STUDIED IN MORE DETAIL WITH MORE SIMULATIONS. Most importantly:

- CR simulations & MATHUSLA test stand data to sanity-test rejection strategies to the extent possible using MC statistics (+ some cleverness to go beyond simple statistical?)

- Full simulation of neutrino background and rejection strategies. Refine geometric veto, especially for neutrinos from LHC. Get more realistic estimate of NR-proton-veto efficiency (will be better than our estimates, due to pessimistic assumptions we made about final state kinematics, and by ignoring remnants of shattered nucleus)

None of these BG rejection strategies seriously affect signal efficiency.
… back to the main program
Practicalities

Design is completely flexible (precise position doesn’t matter) and scalable (probe $\sigma_{\text{LLP}} \propto 1/\text{area}$).

→ final design will be modular (e.g. 20x20x20m segments). Allows for incremental deployment and mass production.

Reliance on well-understood technology (RPC trackers, plastic scintillators) means this could be implemented in time for the HL-LHC.

… but parasitic nature of detector means it could function without modification for HE-LHC!

Unofficial cost estimates: 10 - 100 USD. More precise estimates will be part of LOI.

CERN owns some empty land of approximately right size near CMS.
Practicalities

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CERN owns some empty land of approximately right size near CMS
MATHUSLA experimental collaboration

Working on preparing Letter of Intent (this year), detector design studies, background studies, etc… (Join us!)

<table>
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<tr>
<th>Name</th>
<th>Email</th>
<th>Institution</th>
</tr>
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<tbody>
<tr>
<td>Cristiano Alpigiani</td>
<td><a href="mailto:cristiano.alpigiani@cern.ch">cristiano.alpigiani@cern.ch</a></td>
<td>University of Washington - Seattle</td>
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<td>Audrey Katherine Kvam</td>
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<td>University of Washington - Seattle</td>
</tr>
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<td>CERN</td>
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</tbody>
</table>

(member list probably outdated)

contact: mathusla.experiment@cern.ch
MATHUSLA Test Stand

2.5 x 2.5 x 5m MATHUSLA-type detector taking data in ATLAS SX1

Built using repurposed detectors (RPCs from ARGO, scintillators from D0 muon system) to take background measurements from cosmics and LHC collisions.

Will calibrate Monte Carlo simulations and allow background rejection strategies to be tested.
Sensitivity

\[ \text{MATHUSLA} \approx \text{ATLAS/CMS} \]

- short-lifetime sensitivity

\( \Rightarrow \) similar geometric acceptance for LLP decays in long-lifetime limit...

\( \Rightarrow \) ... you sacrifice sensitivity for short lifetimes...

\( \Rightarrow \) ... but you gain clean environment for LLP searches

Very easy to estimate sensitivity at MATHUSLA:

\[ N_{\text{MATHUSLA}} \approx \left( \# \text{ LLPs produced at LHC} \right) \times P_{\text{decay}}^{\text{MATHUSLA}} \]

\[ P_{\text{decay}}^{\text{MATHUSLA}}(c\tau) \approx \epsilon_{\text{geometric}} \times P_{\text{decay}}(\bar{b}c\tau, L_1, L_2) \]

\( \sim 0.05 \quad \sim \frac{30\text{m}}{\bar{b}c\tau} \) in long lifetime regime

only modest \( O(1) \) dependence on LLP production process.
Sensitivity

Any LLP production process with $\sigma > \text{fb}$ can give signal.

TeV+ mass reach!
Low-Mass Regime

Spatial resolution $\Delta x$ of trackers is most important bottleneck:

Corresponds to maximum LLP boost for which multi-pronged DV can be reconstructed, which is crucial for BG rejection!

$$b_{LLP}^{max} \sim 1000 \left( \frac{1cm}{\Delta x} \right)$$

$\rightarrow$ Minimum LLP mass that can be probed “without BG”

$$m_{LLP}^{min} \sim \frac{m_{parent}}{2b_{LLP}^{max}} \sim \left( \frac{m_{parent}}{2000} \right) \left( \frac{\Delta x}{1cm} \right)$$

$\sim 10$ MeV for LLPs from B decays

$\sim 0.1-1$ GeV for weak-TeV scale production

Interesting complementarity with SHiP?
LLP Diagnosis

Geometry of LLP final state trajectories reveals LLP *boost* event-by-event

Final state multiplicity can diagnose *decay mode*.

Optional: layer of material between tracking layers for $e/\mu$ discrimination and $\gamma$ detection

Correlate with main detector to diagnose *production mode*!

For known production mode, *boost $\sim$ LLP mass*!
3. LLPs at the LHC:
Comparing MATHUSLA and the main detectors
MATHUSLA vs ATLAS/CMS

Obviously main detectors are better at short lifetimes, so focus on long lifetimes $\tau \gtrapprox 100\text{m}$.

⇒ Main detector search should only require one LLP decay

One important benchmark:

$h \rightarrow XX$, $X =$ LLP decays via Higgs portal (mostly hadronically)

We have reasonable main detector comparison from study of inclusive single-LLP search in ATLAS Muon System (likely best-case projection for HL-LHC)

⟹ MATHUSLA wins by $10^3$!

How does MATHUSLA compare to ATLAS/CMS for other LLP signals?
Try and understand the space of LLP signals at the main detectors.

Important & related issues: **Background** and **Triggering**:

LLPs are spectacular geometric signals!

→ smaller BG than prompt, but often difficult to calculate. It helps if we can cut on non-geometric requirements (like leptons, jet energy) to cut BG to “zero”.

→ triggering on geometry of LLP decay at L1 is presently impossible (except ATLAS MS/CALO). *Would need tracker info (vertexing) at L1!*

⟹ use existing L1 triggers that are optimized for prompt objects.
Strategy

The spectacular nature of LLP (decay or visible propagation) means precise kinematics are less important than character (jets, leptons, …) and approx energy range (10 GeV, 100 GeV) of prompt objects produced with LLP and LLP decay products.

Do this with an eye for what we can trigger on, and cut on to reduce BG:

- **MET** (100s GeV), **hard jets** (100s GeV), **hard enough EM objects** (10s GeV)
- **DV** in ATLAS Muon System
- displaced jets in CMS tracker, as long as they pass L1 threshold
Simplified Models

Consider production and decay mode separately.

Geometrical nature of LLP decay signal means you imagine ‘pasting’ different LLP decays onto the same LLP event for different lifetimes.

Figure 2.1: Schematic illustrations of LLP production modes in our simplified model framework. From top to bottom and left to right: direct pair production (DP); heavy parent (HP); Higgs modes (HIG), including gluon fusion and VBF production (not shown here is VH production); heavy resonance (RES); charged current (CC).
## Simplified Models

### Neutral LLPs

<table>
<thead>
<tr>
<th>Production</th>
<th>Decay</th>
<th>$\gamma\gamma(+\text{inv.})$</th>
<th>$\gamma + \text{inv.}$</th>
<th>$jj(+\text{inv.})$</th>
<th>$jj\ell$</th>
<th>$\ell^+\ell^-(+\text{inv.})$</th>
<th>$\ell^+\ell^-_{\beta\neq\alpha}(+\text{inv.})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPP: sneutrino pair</td>
<td>$^+$</td>
<td>SUSY</td>
<td>SUSY</td>
<td>SUSY</td>
<td>SUSY</td>
<td>SUSY</td>
<td>SUSY</td>
</tr>
<tr>
<td>HP: squark pair, $\tilde{q} \rightarrow jX$ or gluino pair $\tilde{g} \rightarrow jjX$</td>
<td>$^+$</td>
<td>SUSY</td>
<td>SUSY</td>
<td>SUSY</td>
<td>SUSY</td>
<td>SUSY</td>
<td>SUSY</td>
</tr>
<tr>
<td>HP: slepton pair, $\tilde{\ell} \rightarrow \ell X$ or chargino pair, $\tilde{\chi} \rightarrow WX$</td>
<td>$^+$</td>
<td>SUSY</td>
<td>SUSY</td>
<td>SUSY</td>
<td>SUSY</td>
<td>SUSY</td>
<td>SUSY</td>
</tr>
<tr>
<td>HIG: $h \rightarrow XX$ or $\rightarrow XX + \text{inv.}$</td>
<td>Higgs, DM$^*$</td>
<td>$^+$</td>
<td>Higgs, DM$^*$</td>
<td>RH$\nu$</td>
<td>Higgs, DM$^*$</td>
<td>RH$\nu^*$</td>
<td>RH$\nu^*$</td>
</tr>
<tr>
<td>HIG: $h \rightarrow X + \text{inv.}$</td>
<td>DM$^*$, RH$\nu$</td>
<td>$^+$</td>
<td>DM$^*$</td>
<td>RH$\nu$</td>
<td>DM$^*$</td>
<td>$^+$</td>
<td>$^+$</td>
</tr>
<tr>
<td>RES: $Z(Z') \rightarrow XX$ or $\rightarrow XX + \text{inv.}$</td>
<td>$Z'$, DM$^*$</td>
<td>$^+$</td>
<td>$Z'$, DM$^*$</td>
<td>RH$\nu$</td>
<td>$Z'$, DM$^*$</td>
<td>$^+$</td>
<td>$^+$</td>
</tr>
<tr>
<td>RES: $Z(Z') \rightarrow X + \text{inv.}$</td>
<td>DM</td>
<td>$^+$</td>
<td>DM</td>
<td>RH$\nu$</td>
<td>DM</td>
<td>$^+$</td>
<td>$^+$</td>
</tr>
<tr>
<td>CC: $W(W') \rightarrow \ell X$</td>
<td>$^+$</td>
<td>$^+$</td>
<td>RH$\nu^*$</td>
<td>RH$\nu$</td>
<td>RH$\nu^*$</td>
<td>RH$\nu^*$</td>
<td>RH$\nu^*$</td>
</tr>
</tbody>
</table>

Filled entries are realized in simplest benchmark theories: SUSY-like, Higgs portal, gauge portal $Z'$, RH neutrinos, DM
Comparing MATHUSLA to ATLAS/CMS

Quantifying main detector LLP signal is relatively easy, similar to at MATHUSLA… At the O(1) level…*

*cue sobbing laughter from Nishita & rest of LLP recasting working group :) 

Big Problem: searches with single LLPs at main detectors often have some backgrounds. Difficult to quantify, not enough HL-LHC studies. (Yet! 😊)

This makes general and precisely quantitative comparison of sensitivities very involved.

Luckily, we can still extract very useful intuition from some simple estimates and some existing examples.
Model-Independent Approach

Define _long-lifetime sensitivity gain_ at MATHUSLA:

\[ R_s \equiv \frac{\sigma_{\text{sig}}^{\text{LHC limit}}}{\sigma_{\text{sig}}^{\text{MATHUSLA limit}}} \bigg|_{b c \tau \gg 200 \text{m}} \]

If \( R_s > 1 \), MATHUSLA has better sensitivity than main detectors.

Can we estimate this number for different LLP signals?
Model-Independent Approach

Compare MATHUSLA search for LLP X to main detector search for single X decay, with some geometrical requirements on where X decays (tracker, MS, ..) and some non-geometrical trigger/cut requirements.
Model-Independent Approach

Compare MATHUSLA search for LLP $X$ to main detector search for single $X$ decay, with some geometrical requirements on where $X$ decays (tracker, MS, ..) and some non-geometrical trigger/cut requirements.

\[
R_s \approx \begin{cases} 
\left( \frac{P_{\text{decay}}^{\text{MATH}}}{P_{\text{decay}}^{\text{LHC}}} \right) \left( \frac{\epsilon_{\text{LHC}}^{\text{LLP}}}{\epsilon_{\text{LLP}}} \right) \frac{1}{\epsilon_{\text{cuts}}} & \text{if the HL-LHC search is BG-free} \\
\sqrt{\frac{\sigma_{\text{BG \ after \ cuts}}}{\sigma_{R_s}}} & \text{if the HL-LHC search has BG} \gtrsim 10^{-3} \text{ fb}
\end{cases}
\]

\[
\sigma_{R_s} \approx (10^{-3} \text{ fb}) \left( \frac{P_{\text{decay}}^{\text{LHC}}}{P_{\text{decay}}^{\text{MATH}}} \right)^2 \left( \frac{\epsilon_{\text{LHC}}^{\text{LLP}}}{\epsilon_{\text{LLP}}} \right)^2 (\epsilon_{\text{cuts}})^2
\]
Model-Independent Approach

Compare MATHUSLA search for LLP X to main detector search for single X decay, with some geometrical requirements on where X decays (tracker, MS, ..) and some non-geometrical trigger/cut requirements.

efficiency of main detector trigger/kinematic/decay branching ratio requirements

\[ R_s \approx \left( \frac{P_{\text{LHC}}}{P_{\text{MATH}}} \right) \left( \frac{\epsilon_{\text{LHC}}}{\epsilon_{\text{LLP}}} \right) \left( \frac{1}{\epsilon_{\text{cuts}}} \right) \]

relative geometrical acceptance \( \sim 1 \)

if the HL-LHC search is BG-free

relative reconstruction efficiency \( \approx 1 \)

\[ \sigma_{R_s} \approx (10^{-3} \text{ fb}) \]

BG of main detector search

\[ \sigma_{R_s} \approx \left( \frac{P_{\text{LHC}}}{P_{\text{MATH}}} \right)^2 \left( \frac{\epsilon_{\text{LHC}}}{\epsilon_{\text{LLP}}} \right)^2 \left( \epsilon_{\text{cuts}} \right)^2 \]
Model-Independent Approach

Compare MATHUSLA search for LLP $X$ to main detector search for single $X$ decay, with some geometrical requirements on where $X$ decays (tracker, MS, ..) and some non-geometrical trigger/cut requirements.

**efficiency of main detector trigger/kinematic/decay branching ratio requirements**

$$R_s \approx \sqrt{\frac{\sigma_{BG \text{ after cuts}}}{\sigma_{Rs}}}$$

$\sigma_{Rs} \approx (10^{-3} \text{ fb}) \left( \frac{P_{LHC}}{P_{MATH}} \right)^2 \left( \frac{\epsilon_{LHC}}{\epsilon_{LLP}} \right)^2 (\epsilon_{cuts})^2$

if the HL-LHC search is BG-free

if the HL-LHC search has BG $\gtrsim 10^{-3} \text{ fb}$

<table>
<thead>
<tr>
<th>$\frac{P_{LHC}}{P_{MATH}}$</th>
<th>$\frac{\epsilon_{LHC}}{\epsilon_{LLP}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2</td>
<td>ATLAS Muon System</td>
</tr>
<tr>
<td>0.8</td>
<td>ATLAS HCAL</td>
</tr>
<tr>
<td>1.0</td>
<td>ATLAS or CMS tracker (full volume)</td>
</tr>
<tr>
<td>0.25</td>
<td>ATLAS tracker (DV reconstruction volume)</td>
</tr>
</tbody>
</table>
Upshot

This parameterization is useful because we can get order-of-magnitude understanding of MATHUSLA sensitivity gain for different classes of searches.

We can also plug in BG numbers for future searches, once they are available, and get more precise Rs number.

**MATHUSLA will have better sensitivity** than ATLAS/CMS in the long-lifetime regime whenever the corresponding main-detector LLP search suffers from *any* difficulties with

- backgrounds > ab
- trigger efficiency
- cut requirements
A few known examples…

LLPs decaying into well-separated leptons with \( m > O(10) \) GeV: negligible background, trigger easily, \( R_s \sim 1 \)

Probably similar if LLP decaying into anything is produced in association with (hard enough) leptons. Pay \( Br \) penalty? \( R_s \sim 1/Br! \)

but if LLP \( m < \sim 10 \) GeV and decays to leptons, have displaced lepton jets! \( \sigma_{BG} \) after cuts \( \sim 10 \) fb \( \rightarrow \) \( R_s \sim 10-100? \)

LLP decays hadronically with \( m < O(100s \) GeV) and nothing else in event: ATLAS MS, \( \sigma_{BG} \) after cuts \( \sim 100fb, \) \( R_s \sim 1000! \)

LLP decays hadronically with \( m > \) few 100 GeV, or produced in association with high-energy jets, will pass L1 triggers, can look with CMS displaced jet triggers. \( \sigma_{BG} \) after cuts \( < \sim ab \) \( \rightarrow \) \( R_s \sim 1 \)
What about MET searches?

Those are great if the LLP production xsec is sizable and MET is > few 100 GeV.

For LLP pair production (e.g. DM simplified models with unstable invisible particle) or SUSY-type models with slightly squeezed spectra, MATHUSLA can have much larger mass reach than main detector MET search!
Rules of thumb

ATLAS/CMS win at short lifetimes, and for LLPs with highly conspicuous prompt or decay final states (high-mass jet or leptonic decays, production in association with hard jets etc)

MATHUSLA wins at long lifetimes for anything else, e.g.

- LLPs with $m < \sim O(100 \text{ GeV})$ and hadronic decays
- LLPs decaying to lepton jets
- LLPs decaying to photons?? (if MATHUSLA can see?)
- LLPs with subdominant fraction of leptons in final state

with 10-1000x better LLP xsec sensitivity
NB: some thoughts on relationship between various LLP detector proposals to stimulate discussion :)

All need to be investigated more.

We really should just build them all, they’re (mostly) pretty cheap…

Some of these comparisons will be done “officially” as part of PBC BSM report*, keep eye out end of 2018!

(*for low-scale models that SHiP can access)
All need to be investigated more.

We really should just build them all, they’re (mostly) pretty cheap…

[We] “support every and all such upgrades”

Some of these comparisons will be done “officially” as part of PBC BSM report*, keep eye out end of 2018!

(*for low-scale models that SHiP can access)
CODEX-b

Dedicated DV detector underground, in existing cavity near LHCb

+ Definitely more affordable than something on MATHUSLA scale

+ Probably easier to instrument for < 10-100 MeV mass regime, and maybe even calorimetry/particle ID for detailed LLP investigations

- 1/200 MATHUSLA sensitivity, 1/50 if we burn out VELO with 1/ab
  \[ \rightarrow \text{scale down} \ R_s \ \text{by same factor} \]

Important detailed question for future: how does cost/capabilities compare to similar-reach surface detector?
FASER, MATHUSLA and SHiP (light LLPs)

**SHiP**: For shorter lifetimes and mass $< \sim 10$ MeV, SHiP is much better. MATHUSLA access higher scale physics and sees 10-100 more LLPs from exotic meson decays if lifetime $\gg 100\text{m}$.

**FASER**: “small” cylindrical ($R = 0.2\text{m}, L = 10\text{m}$) detector (far):

For SM+S model reach, **FASER + MATHUSLA > SHiP**!

Very intriguing! Does this interplay apply to other low-mass LLP scenarios?!

Will be explored in PBC report.
Main Detector Timing Upgrades??

Jia Liu, Zhen Liu, Lian-Tao Wang 1805.05957

Time delay of LLP decay products compared to prompt SM particles from PV:

$$\Delta t \sim \frac{\ell_{SM}}{c^2} \left( \frac{1}{3b^2} + \mathcal{O}(b^{-4}) \right)$$

$$\sim 1 \text{ ns} \left( \frac{\ell_{SM}}{1m} \right) \frac{1}{b^2}$$

Quite sizable even for reasonably high $\mathcal{O}(1)$ boosts, if you have e.g. 30ps timing!
Main Detector Timing Upgrades??

Consider $h \rightarrow XX$ (single LLP search).

Want to catch $h+j$ production events with single 30 GeV ISR jet.

30ps timing layer on inside of CMS ECAL:
- similar to proposed upgrades
- how to trigger at L1? Would need PV4d and DV4d (full timing vertices) at **Level 1**
- $\Delta t > 0.8$ns timing cut (26$\sigma$) to reduce hard jet fake DV background by $10^{-10}$ to $N < 1$

30ps timing layer on outside of ATLAS Muon Spectrometer
- L1 trigger OK using Muon ROI like existing DV search
- would be amazing, but $$$ for such a big 30ps timing layer? (10m radius)
- $\Delta t > 0.2$ns timing cut (7$\sigma$) to reduce hard jet fake DV background by $10^{-6}$ to $N < 1$
Main Detector Timing Upgrades??

If BG-free, each of these two searches has has $O(1/10)$ MATHUSLA sensitivity for long-lifetimes.

That seems extremely challenging since there are other backgrounds not considered in this analysis.

However, regardless of such details, timing will *definitely* improve main detector sensitivity significantly.

Furthermore, main detector LLP searches always have intrinsic advantages (full event reconstruction etc) so you want to improve those as much as you can.

Clearly, timing is incredibly exciting for LLP searches!
4. MATHUSLA Physics Reach
Divide discussion into two “great” classes, in all of which **MCFODO** (Mathusla Could be First or Only Discovery Opportunity)

1) BSM scenarios where neutral LLPs at MATHUSLA are strongly motivated & intrinsic part of theory mechanism

2) BSM scenarios where neutral LLPs at MATHUSLA are a strongly motivated generic possibility, often as part of a larger theory or parameter space.
<table>
<thead>
<tr>
<th>BSM Scenario</th>
<th>Role of LLPs</th>
<th>Typical $c\tau$</th>
<th>Role of MATHUSLA</th>
<th>Sec.</th>
<th>Fig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutral Naturalness</td>
<td>Discrete symmetry stabilizing Higgs mass $\rightarrow$ Hidden Valley with</td>
<td>Any, but $\mathbb{Z}_2$ arguments favor</td>
<td>Mirror glueballs with long lifetimes can only be discovered at MATHUSLA.</td>
<td>4.2</td>
<td>22, 23</td>
</tr>
<tr>
<td></td>
<td>Higgs portal. Cosmology $\rightarrow$ HV particles are LLPs.</td>
<td>lower $\Lambda_{QCD}$ and hence long</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WIMP Baryogenesis</td>
<td>Out-of-equilibrium decay of WIMP-like LLP produces baryon asymmetry.</td>
<td>For weak-scale LLP masses, $\gtrsim$ 1-100 m.</td>
<td>Decays to baryons $\rightarrow$ MATHUSLA likely much greater sensitivity than</td>
<td>6.1</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>main detectors. MCFODO.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FIMP DM</td>
<td>Freeze-in via decay requires LLPs with SM couplings.</td>
<td>Fixed by masses &amp; cosmology. Long</td>
<td>Model-dependent, but in long-lifetime regime MCFODO.</td>
<td>5.3</td>
<td>27, 28, 21</td>
</tr>
<tr>
<td></td>
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<td>Depending on model details (production &amp; decay mode), MCFODO.</td>
<td>5.4.3</td>
<td>31</td>
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<td>parameter space is long lifetimes.</td>
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<td>4.1.5</td>
<td>21</td>
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<tr>
<td></td>
<td>an LLP</td>
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<td>Low SUSY breaking scale $F$ (motivated by flavor problem) leads to light</td>
<td>Any, long lifetimes generic.</td>
<td>MCFODO, depending on spectrum and lifetime.</td>
<td>4.1.2</td>
<td>15</td>
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<td></td>
<td>baryon washout) $\rightarrow$ LOSP can be LLP</td>
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<td></td>
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1) intrinsic

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<td>4.2</td>
<td>22, 23</td>
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WIMP Baryogenesis

Out-of-equilibrium decay of WIMP-like LLP produces baryon asymmetry.

For weak-scale LLP masses, decays to baryons $\rightarrow$ MATHUSLA likely much greater sensitivity than main detectors. MCFODO

1) intrinsic

mirror glueballs from Higgs decays

mirror neutrinos from Higgs decays that cause asymmetric reheating
### 1) intrinsic

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<td>For weak-scale LLP masses, $\gtrsim 1$-100 m.</td>
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<td>6.1</td>
<td>32</td>
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<td>FIMP DM</td>
<td>Freeze-in via decay requires LLPs with SM couplings.</td>
<td>Fixed by masses &amp; cosmology. Long lifetimes generic.</td>
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<td></td>
<td></td>
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<td>14</td>
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![Graph](image-url)
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<td>Co-decaying DM</td>
<td>Out-of-equilibrium decay of hidden sector LLP determines DM abundance. Also, small portal $\rightarrow$ visible sector LLPs.</td>
<td>For weak scale LLP masses, most of parameter space is long lifetimes.</td>
<td>Depending on model details (production &amp; decay mode), MCFODO.</td>
<td>5.4.3</td>
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<td>Co-annihilating DM</td>
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<td>Low SUSY breaking scale $f$ (motivated by flavor problem) leads to light gravitino and small couplings to LOSP, which can hence be LLP.</td>
<td>Any, long lifetimes generic.</td>
<td>MCFODO, depending on spectrum and lifetime.</td>
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<td>Neutral Naturalness</td>
<td>Discrete symmetry stabilizing Higgs mass → Hidden Valley with Higgs portal. Cosmology → HV particles are LLPs.</td>
<td>Any, but more stringent for LLPs that stabilize Higgs mass.</td>
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<td>WIMP Baryogenesis</td>
<td>Out-of-equilibrium decay of WIMP-like LLP produces baryon asymmetry.</td>
<td>For small LLP mass decay widths &gt; 1-100 GeV.</td>
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<tr>
<td>FIMP DM</td>
<td>Freeze-in via decay requires LLPs with SM couplings.</td>
<td>Fixed by cosmological constraints on LLP lifetimes.</td>
</tr>
<tr>
<td>Co-decaying DM</td>
<td>Out-of-equilibrium decay of hidden sector LLP determines DM abundance. Also, small portal states visible.</td>
<td>For weak LLP mass decay widths.</td>
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<tr>
<td>Co-annihilating DM</td>
<td>DM relic abundance and mass splitting with an LL field state is necessary.</td>
<td>Model details, but e.g., implementations, MCFODO.</td>
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</table>

#### SUSY: Axinos

High PQ-breaking suppresses axion/axino LSP, making LOSP an LLP. 

#### SUSY: GMSB

Low SUSY breaking motivated by flavor protected light gravitino and small mixing to LOSP, which can have a standard deviation. 

#### SUSY: RPV

Small RPV couplings avoiding flavor violation. Baryon washout can make LLP. 

---

Matthew Reece, Eung Jin Chun, Sunghoon Jung
### 1) intrinsic

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**SUSY: RPV**

Small RPV couplings (motivated by avoiding flavor violation, proton decay, baryon washout) $\rightarrow$ LOSP can be LLP

| | | Any, long lifetimes generic. | MCFODO, especially for EW-charged LSPs or squeezed spectra. | 4.1.1 | 14 |

Csaba Csaki, Eric Kuflik, Salvator Lombardo, Jared Evans, Brock Tweedie, Tim Cohen, Zhen Liu, Patrick Meade

MATHUSLA Physics Case, June 2018
1) intrinsic

<table>
<thead>
<tr>
<th>minimal RH neutrino model</th>
<th>Type-1 see-saw $\rightarrow$ tiny mixing between $\nu_L$ and $\nu_R \rightarrow \nu_R$ LLPs</th>
<th>Any, long lifetimes favor lower $m_{\nu_R}$</th>
<th>In long-lifetime/low-mass regime, MATHUSLA and/or SHiP may be only/first discovery opportunity.</th>
</tr>
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<tr>
<td>SUSY: Sgoldstinos</td>
<td>SUSY breaking scale $F$ suppresses sgoldstino coupling to supercurrents $\rightarrow$ can be LLP.</td>
<td>Any. Long lifetimes $\rightarrow$ smallest production, hardest to probe.</td>
<td>Similar to SM+S. For masses $\lesssim 5$ GeV, MATHUSLA and/or SHiP may be only/first discovery opportunity.</td>
</tr>
</tbody>
</table>

### Diagram

![Graph showing $U_{eN}^2$ vs. $m_{\nu_R}$ with regions marked for MATHUSLA and SHiP with significance levels at $10^{-4}$, $10^{-5}$, and $10^{-6}$, and the text surrounding the graph indicating the suppression of sgoldstino coupling and the implications for LLPs, lifetimes, and discovery opportunities.]

- For sub-weak-scale $m_{\nu_R}$, $\lesssim 10$ TeV: main advantage for weak-scale $m_{\nu_R}$: SHiP only discovery for $m_{\nu_R} \lesssim 5$ GeV.
- Improves Br reach of LLPs by at least order of magnitude.

<table>
<thead>
<tr>
<th>BSM Scenario</th>
<th>Role of LLPs</th>
<th>Typical $c_T$</th>
<th>Role of MATHUSLA (long $c_T$)</th>
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<tr>
<td>Hidden Valleys (HV)</td>
<td>Small portal to visible sector and possibly hidden sector confinement $\rightarrow$ meta-stable states.</td>
<td>Any.</td>
<td>MCFODO, especially if LLPs are significantly below the weak scale or decay hadronically.</td>
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<td>SM+S</td>
<td>Small mixing $\rightarrow$ scalar LLP for $m_S &lt; 2m_H$. Large mixing $\rightarrow$ $S$ could decay to HV LLPs.</td>
<td>Any.</td>
<td>MCFODO. Complementarity with SHiP.</td>
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<td>SM+V</td>
<td>Dark photon/dark Higgs LLP could be produced in exotic Higgs/$Z$ decays. Dark photon with non-tiny kinetic mixing could be copiously produced at LHC and decay to HV LLPs.</td>
<td>Any.</td>
<td>MCFODO. Significantly extends main detector long-lifetime reach for dark photons and dark Higgs produced in exotic $H$ and $Z$ decays. For LLPs produced in dark photon decays, see HV.</td>
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<td>Exotic Higgs decays</td>
<td>Higgs coupling to new states, like HV or other LLPs, is highly generic and leads to large production rates at LHC.</td>
<td>Any.</td>
<td>MCFODO for $\text{Br} \lesssim 0.1 - 0.01$. Higgs portal motivates hadronic LLP decays, for which MATHUSLA has $10^3$ better $\text{Br}$ reach than main detectors. MATHUSLA also has significantly better sensitivity for LLP masses $\lesssim 10$ GeV even if they decay leptonically, or for LLPs with subdominant leptonic decays.</td>
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<tr>
<td>Asymmetric DM</td>
<td>Relating DM to baryon abundance requires operator connecting DM number and Baryon/Lepton number $\rightarrow$ higher dimensional operator $\rightarrow$ LLPs</td>
<td>Any, depending on kind and scale of physics generating the operator.</td>
<td>MCFODO (highly dependent on production and decay mode).</td>
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<tr>
<td>Dynamical DM</td>
<td>DM sector includes spectrum of states with varying life-time up to highly stable DM.</td>
<td>Any, long lifetimes generic in DM sector spectrum.</td>
<td>MCFODO (highly dependent on production and decay mode).</td>
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<td>BSM Scenario</td>
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<td>------------------------------------------------------------------------------</td>
<td>-----------------</td>
<td>---------------------------------------------------------------------------------------------</td>
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| Hidden Valleys (HV)  | Small portal to visible sector and possibly hidden sector confinement \ 
|                      | $\rightarrow$ meta-stable states                                           | Any.           | MCFODO, especially if LLPs are significantly below the weak scale or decay hadronically.     | 8.1  | 44, 45 |
| SM+S                 | Small mixing $\rightarrow$ scalar LLP for $m_s < 2m_H$. Large mixing $\rightarrow S$ \ 
|                      | could decay to HV LLPs.                                                     | Any.           | MCFODO. Complementarity with SHiP.                                                           | 8.4  | 52   |

---

**Diagram:**

- **Sin $\theta$** vs **$m_s$ (GeV)**
- **LEP**
- **K$\rightarrow$\pi$\nu\bar{\nu}$**
- **CHARM**
- **B$\rightarrow$K$^*$S$\rightarrow$$\mu^+\mu^-**
- **B$\rightarrow$K$^*$S$\rightarrow$$\mu^+\mu^-**
- **SHIP (mesons)**
- **MATHUSLA (mesons)**
- **MATHUSLA BR(h$\rightarrow$ss)**

Jared Evans
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<td>8.5</td>
<td>56, 58, 60, ??</td>
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<td>Any, depending on kind and scale of physics generating the operator.</td>
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<td>5.2</td>
<td>[DC]², TB</td>
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2) generic

### BSM Scenario | Role of LLPs
--- | ---
Hidden Valleys (HV) | Small portal to visible sector plus possibly hidden sector connected to meta-stable states.

SM+S | Small mixing → scalar bosons with mass $m_S < 2m_H$. Large mixing could decay to HV LLPs.

SM+V | Dark photon/dark Higgs LLP could be produced in exotic Higgs/ $Z$ decays. Dark photon with non-tiny kinetic mixing could be copiously produced at LHC and decay to HV LLPs.

---

**long-lived dark higgs production in exotic $Z$ decays**

---

**Dark photon through Higgs portal**

---

**Dark photon as Hidden Valley production mode**
## 2) Generic

<table>
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<tr>
<th>Category</th>
<th>Description</th>
<th>Requirements</th>
<th>Notes</th>
</tr>
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<tbody>
<tr>
<td>SIMP/ELDER DM</td>
<td>Strong dynamics of HV generate DM abundance. HV → LLPs.</td>
<td>Any.</td>
<td>See HV.</td>
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<tr>
<td>Relaxation</td>
<td>Relaxion or other new scalars in theory generically mix with Higgs → SM+S.</td>
<td>Any.</td>
<td>See SM+S.</td>
</tr>
<tr>
<td>Axion-like particles</td>
<td>ALP couplings to ( h ) and ( Z ) are generic in EFT framework. 1/f suppression makes ALP an LLP.</td>
<td>Any.</td>
<td>MCFODO for low-scale ( f ).</td>
</tr>
<tr>
<td>Leptogenesis</td>
<td>Motivates minimal RH neutrino model and other neutrino extensions, which generically feature LLPs.</td>
<td>Any, long lifetimes favor lower ( m_{\nu_R} ).</td>
<td>Generally very difficult to probe, especially at high leptogenesis scale. In long-lifetime/low-mass regime, MATHUSLA and/or SHiP may be only/first discovery opportunity.</td>
</tr>
<tr>
<td>Scalars in neutrino extensions</td>
<td>Gauge extensions in neutrino models give rise to new scalars that can mix with Higgs → SM+S. Also provides additional ( S ) production modes via heavy gauge boson decay.</td>
<td>Any.</td>
<td>See SM+S, with some additional production modes (new heavy gauge bosons).</td>
</tr>
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5. Bonus: Cosmic Ray Physics
Cosmic Ray Physics @ MATHUSLA

MATHUSLA is an excellent Cosmic Ray Telescope!

Has unique abilities in CR experimental ecosystem
(precise resolution, full coverage of its area)

\[ \sim 90\% \text{ e, } \sim 10\% \text{ } \mu, \text{ less hadrons} \]
Cosmic Ray Physics @ MATHUSLA

Primary Cosmic Ray spectra and composition

Cosmic Ray Anisotropies at PeV energies

Highly inclined Showers:
electron/photon-depleted, mostly muons.
Probe various shower parameters (attenuation length etc).
Probe neutrino production in atmosphere or Jura mountains (!)

Study of extended air showers, including precise spatial-temporal structure, to help develop hadron interaction models, important for all CR experiments

High-Multiplicity Muon Bundles, observed at LEP & ALICE, point to either Iron-rich CRs around knee (or BSM ????)

Guaranteed Physics Return!
6. Timeline
MATHUSLA Timeline

This year:
Theory LLP white paper released June 2018
Cosmic Ray white paper released mid-2018

currently working on Letter of Intent, finalize at dedicated collaboration meeting August 2018

Report of the PBC BSM Subgroup comparing MATHUSLA/CODEX-b/FASTER to ShiP: end of 2018

submit LOI to CERN/European Strategy end of 2018
7. Conclusion
Conclusion

The LHC is a unique opportunity to explore the Lifetime Frontier, providing both high energy and high intensity needed to explore weak-scale LLP physics.

It’s evident that LLP searches are fundamentally and strongly motivated, for many bottom-up and top-down reasons. Take your pick… (and see MATHUSLA white paper)

Future searches will benefit from systematic roadmap and coordination (LHC-LLP white paper etc). Fill out the search space!

Many exciting add-on detector proposals. MATHUSLA Could be First or Only Discovery Opportunity for lots of BSM scenarios.

Making LLPs is the expensive part! Let’s make sure we can actually see them!
— Thank you! —