MATHUSLA and the Lifetime Frontier

KITP Sensitivity Frontier Workshop
UC Santa Barbara

23 May 2018

David Curtin
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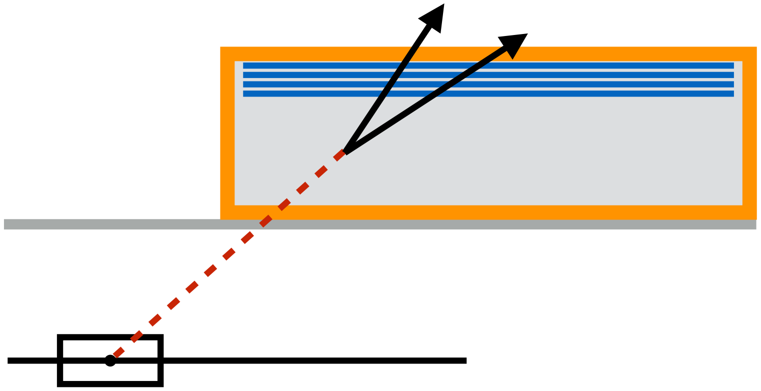


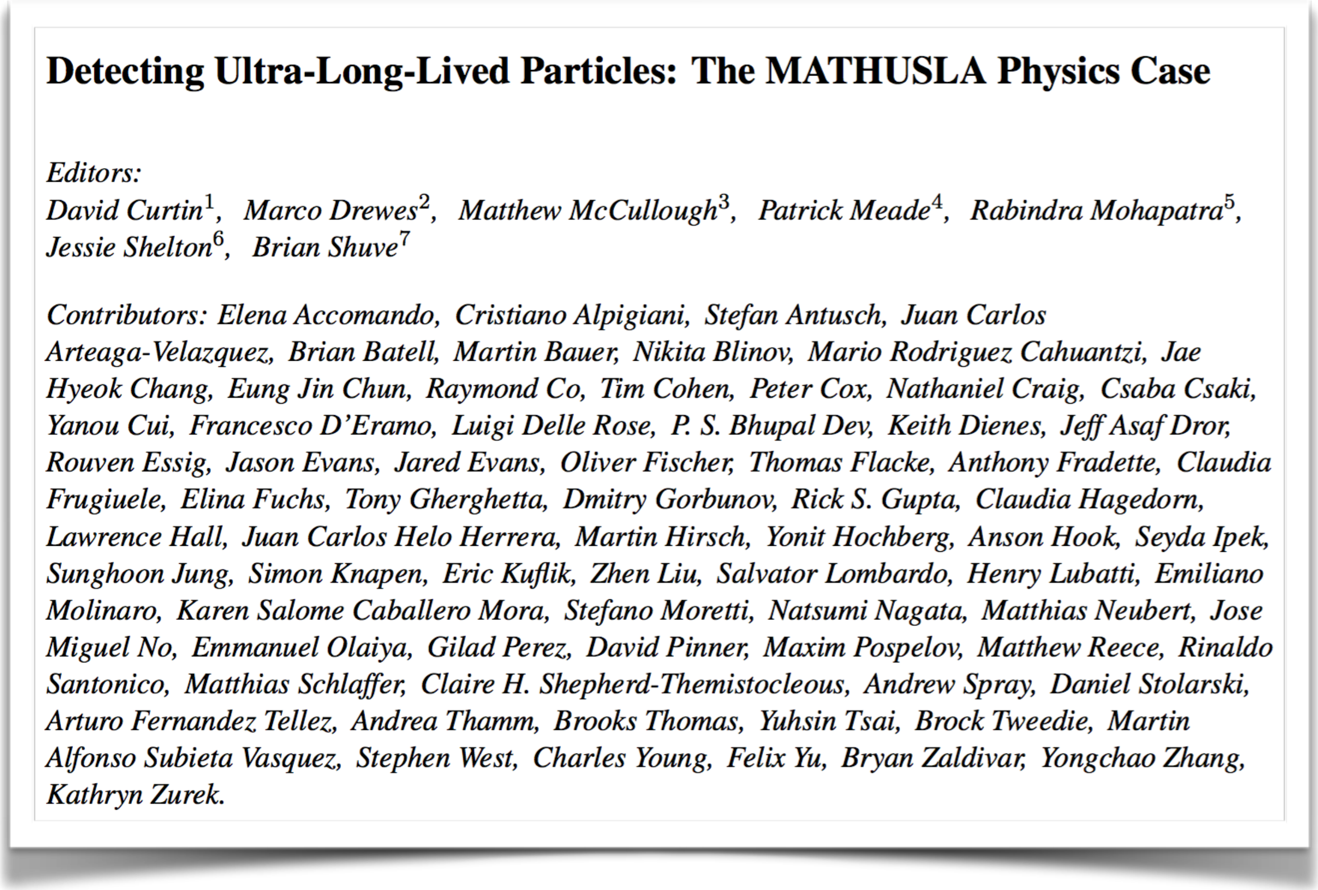
Context

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

Chou, DC, Lubatti 1606.06298

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



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

Editors:
David Curtin[1], *Marco Drewes*[2], *Matthew McCullough*[3], *Patrick Meade*[4], *Rabindra Mohapatra*[5], *Jessie Shelton*[6], *Brian Shuve*[7]

Contributors: Elena Accomando, Cristiano Alpigiani, Stefan Antusch, Juan Carlos Arteaga-Velazquez, Brian Batell, Martin Bauer, Nikita Blinov, Mario Rodriguez Cahuantzi, Jae Hyeok Chang, Eung Jin Chun, Raymond Co, Tim Cohen, Peter Cox, Nathaniel Craig, Csaba Csaki, Yanou Cui, Francesco D'Eramo, Luigi Delle Rose, P. S. Bhupal Dev, Keith Dienes, Jeff Asaf Dror, Rouven Essig, Jason Evans, Jared Evans, Oliver Fischer, Thomas Flacke, Anthony Fradette, Claudia Frugiuele, Elina Fuchs, Tony Gherghetta, Dmitry Gorbunov, Rick S. Gupta, Claudia Hagedorn, Lawrence Hall, Juan Carlos Helo Herrera, Martin Hirsch, Yonit Hochberg, Anson Hook, Seyda Ipek, Sunghoon Jung, Simon Knapen, Eric Kuflik, Zhen Liu, Salvator Lombardo, Henry Lubatti, Emiliano Molinaro, Karen Salome Caballero Mora, Stefano Moretti, Natsumi Nagata, Matthias Neubert, Jose Miguel No, Emmanuel Olaiya, Gilad Perez, David Pinner, Maxim Pospelov, Matthew Reece, Rinaldo Santonico, Matthias Schlaffer, Claire H. Shepherd-Themistocleous, Andrew Spray, Daniel Stolarski, Arturo Fernandez Tellez, Andrea Thamm, Brooks Thomas, Yuhsin Tsai, Brock Tweedie, Martin Alfonso Subieta Vasquez, Stephen West, Charles Young, Felix Yu, Bryan Zaldivar, Yongchao Zhang, Kathryn Zurek.

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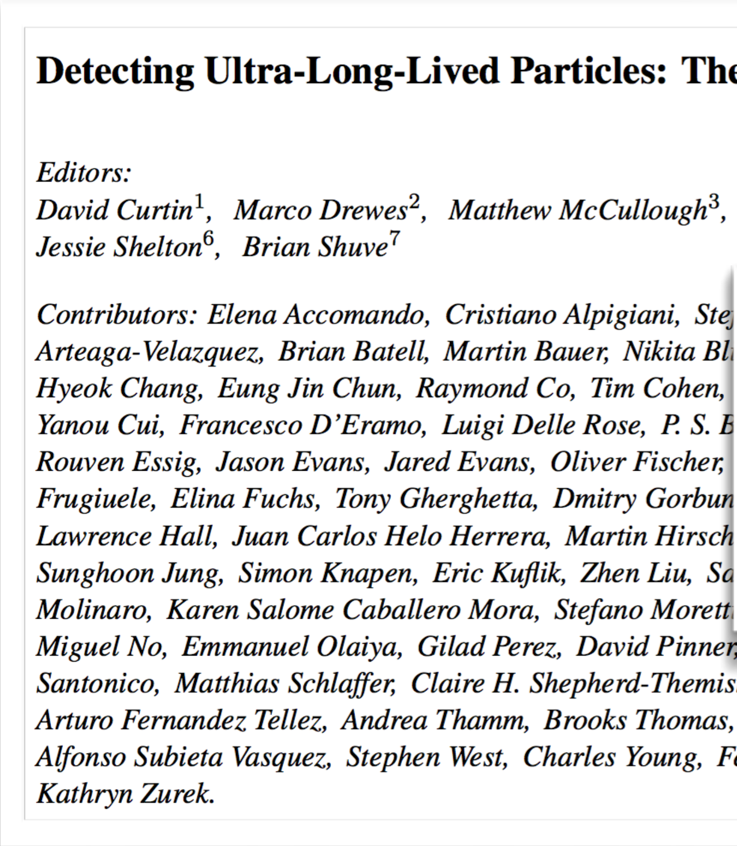

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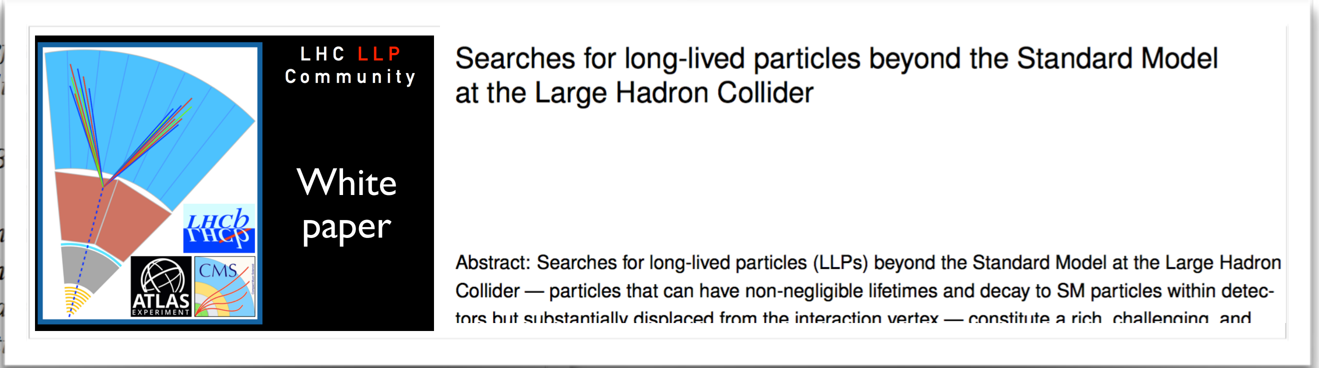
LHC-LLP white paper focusing on guiding LLP searches at main detectors:



LHC LLP Community

White paper

Searches for long-lived particles beyond the Standard Model at the Large Hadron Collider

Abstract: Searches for long-lived particles (LLPs) beyond the Standard Model at the Large Hadron Collider — particles that can have non-negligible lifetimes and decay to SM particles within detectors but substantially displaced from the interaction vertex — constitute a rich, challenging, and

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

1. 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.

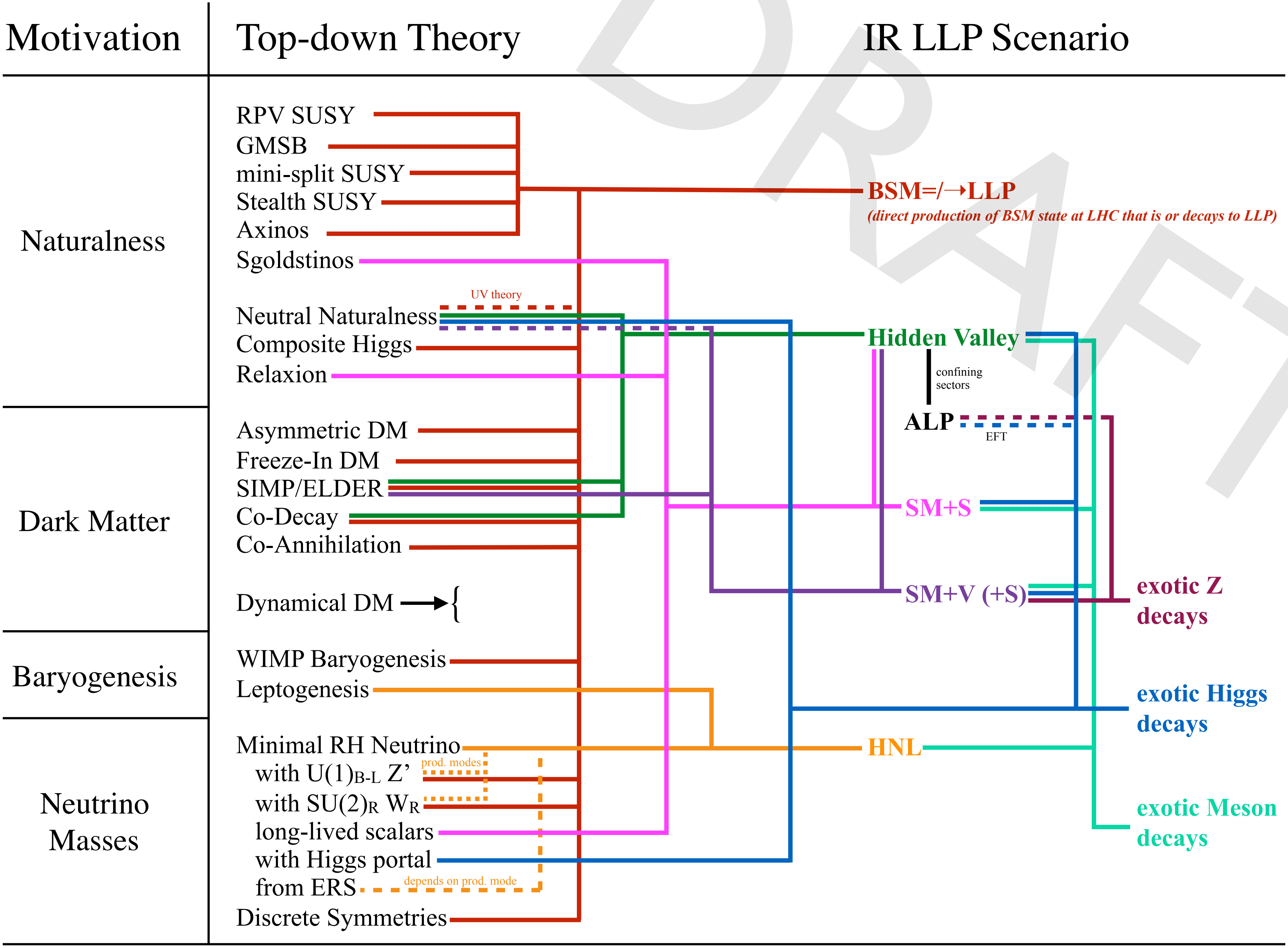
Need to look under every lamp post!

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…



Motivation

Top-down Theory

IR LLP Scenario

Naturalness

RPV SUSY
GMSB
mini-split SUSY
Stealth SUSY
Axinos
Sgoldstinos

UV theory

Neutral Naturalness
Composite Higgs
Relaxion

Dark Matter

Asymmetric DM
Freeze-In DM
SIMP/ELDER
Co-Decay
Co-Annihilation

Dynamical DM ⟶ {

Baryogenesis

WIMP Baryogenesis
Leptogenesis

Neutrino Masses

Minimal RH Neutrino
with U(1)$_{B-L}$ Z’
with SU(2)$_R$ W$_R$
long-lived scalars
with Higgs portal
from ERS
Discrete Symmetries

prod. modes

depends on prod. mode

BSM=/→LLP

(direct production of BSM state at LHC that is or decays to LLP)

Hidden Valley

confining sectors

ALP

EFT

SM+S

SM+V (+S)

HNL

exotic Z decays

exotic Higgs decays

exotic Meson decays

MATHUSLA Physics Case, June 2018

Motivation

Top-down Theory

IR LLP Scenario

RPV SUSY
GMSB
mini-split SUSY

Naturalne

is or decays to LLP)

Dark Mat

xotic Z
lecays

Baryogene

xotic Higgs
lecays

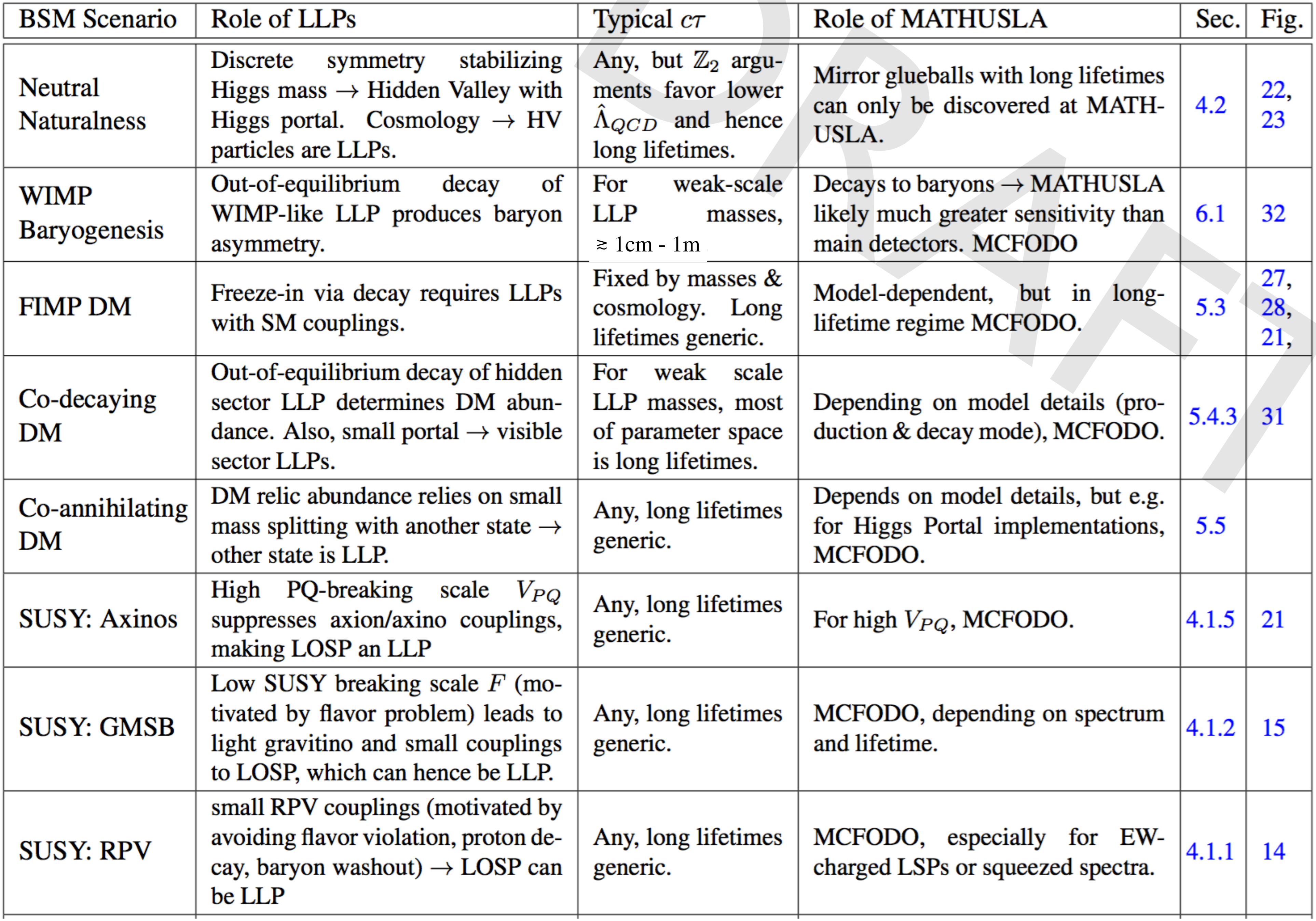
All signs point to LLPs!

Neutrino Masses

Minimal RH Neutrino
with U(1)$_{B\text{-}L}$ Z’
prod. modes
with SU(2)$_R$ W$_R$
long-lived scalars
with Higgs portal
from ERS
depends on prod. mode
Discrete Symmetries

HNL

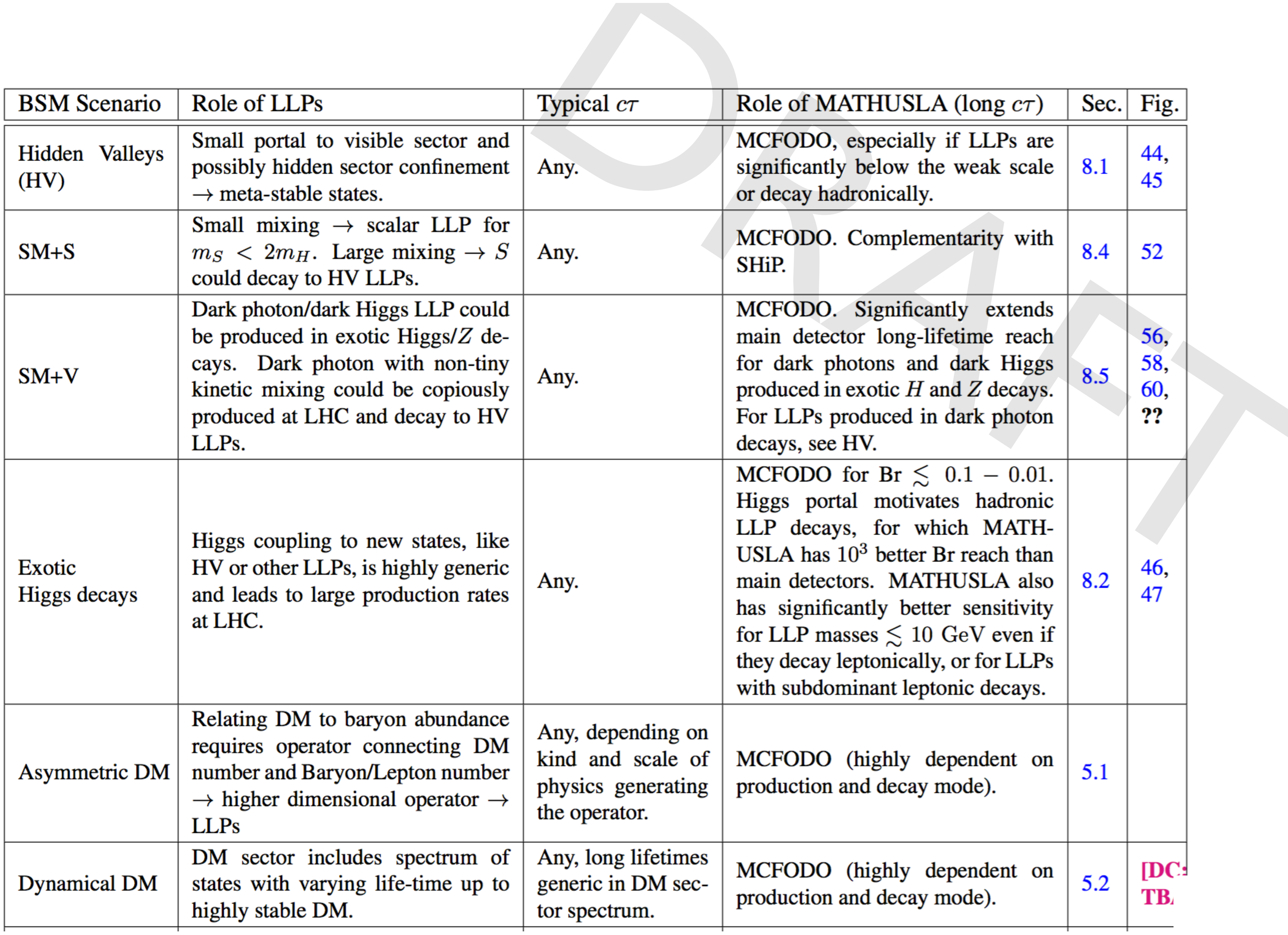
exotic Meson
decays



BSM Scenario	Role of LLPs	Typical $c\tau$	Role of MATHUSLA	Sec.	Fig.
Neutral Naturalness	Discrete symmetry stabilizing Higgs mass → Hidden Valley with Higgs portal. Cosmology → HV particles are LLPs.	Any, but $\mathbb{Z}_2$ arguments favor lower $\hat{\Lambda}_{QCD}$ and hence long lifetimes.	Mirror glueballs with long lifetimes can only be discovered at MATHUSLA.	4.2	22, 23
WIMP Baryogenesis	Out-of-equilibrium decay of WIMP-like LLP produces baryon asymmetry.	For weak-scale LLP masses, $\gtrsim$ 1cm - 1m	Decays to baryons → MATHUSLA likely much greater sensitivity than main detectors. MCFODO	6.1	32
FIMP DM	Freeze-in via decay requires LLPs with SM couplings.	Fixed by masses & cosmology. Long lifetimes generic.	Model-dependent, but in long-lifetime regime MCFODO.	5.3	27, 28, 21,
Co-decaying DM	Out-of-equilibrium decay of hidden sector LLP determines DM abundance. Also, small portal → visible sector LLPs.	For weak scale LLP masses, most of parameter space is long lifetimes.	Depending on model details (production & decay mode), MCFODO.	5.4.3	31
Co-annihilating DM	DM relic abundance relies on small mass splitting with another state → other state is LLP.	Any, long lifetimes generic.	Depends on model details, but e.g. for Higgs Portal implementations, MCFODO.	5.5	
SUSY: Axinos	High PQ-breaking scale V_{PQ} suppresses axion/axino couplings, making LOSP an LLP	Any, long lifetimes generic.	For high V_{PQ}, MCFODO.	4.1.5	21
SUSY: GMSB	Low SUSY breaking scale F (motivated by flavor problem) leads to light gravitino and small couplings to LOSP, which can hence be LLP.	Any, long lifetimes generic.	MCFODO, depending on spectrum and lifetime.	4.1.2	15
SUSY: RPV	small RPV couplings (motivated by avoiding flavor violation, proton decay, baryon washout) → LOSP can be LLP	Any, long lifetimes generic.	MCFODO, especially for EW-charged LSPs or squeezed spectra.	4.1.1	14

SUSY: Sgoldstinos	SUSY breaking scale F suppresses sgoldstino coupling to supercurrents → can be LLP.	Any. Long lifetimes → smallest production, hardest to probe.	Similar to SM+S. For masses $\lesssim$ 5 GeV, MATHUSLA and/or SHiP may be only/first discovery opportunity.	4.1.6	
minimal RH neutrino model	Type-1 see-saw → tiny mixing between ν_L and ν_R → ν_R LLPs	Any, long lifetimes favor lower m_{ν_R}	In long-lifetime/low-mass regime, MATHUSLA and/or SHiP may be only/first discovery opportunity.	7.1	34, 35
↪ with $U(1)_{B-L}$ Z'	Weakly gauged $B-L$ breaking generates M_N, additional ν_R production mode from Z'.	$m_{\nu_R} \sim$ 1-10 GeV suggests long lifetime regime.	For sub-weak-scale m_{ν_R}, MCFODO.	7.2.1	36
↪ with $SU(2)_L$ W_R	ν_R part of gauged $SU(2)_R$, breaking generates M_N. Additional ν_R prod. from $W_R^{\pm}$.	Any, long lifetimes favor lower m_{ν_R}.	For $m_{W_R} \sim$ 10 TeV: main detector probes weak-scale m_{ν_R}; MATHUSLA/SHiP only discovery opportunity for $m_{\nu_R} \lesssim 5$ GeV.	7.3.1	38
↪ with Higgs Portal	GUT motivates extra broken $U(1)$ gauge groups, extended scalar sectors mix with Higgs → produce ν_R in H decays.	Any, long lifetimes favor lower m_{ν_R}.	MCFODO, improves Br reach of main detectors by at least order of magnitude.	7.4	41
m_ν via discrete symmetries	Discrete sym. generates m_ν and stabilizes FIMP DM.	See FIMP DM.	LLPs with EW charge → MCFODO, especially for $m \lesssim 10$ GeV	7.5	

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.



BSM Scenario	Role of LLPs	Typical $c\tau$	Role of MATHUSLA (long $c\tau$)	Sec.	Fig.
Hidden Valleys (HV)	Small portal to visible sector and possibly hidden sector confinement → 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 → scalar LLP for $m_S < 2m_H$. Large mixing → S could decay to HV LLPs.	Any.	MCFODO. Complementarity with SHiP.	8.4	52
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.	Any.	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.	8.5	56, 58, 60, **??**
Exotic Higgs decays	Higgs coupling to new states, like HV or other LLPs, is highly generic and leads to large production rates at LHC.	Any.	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.	8.2	46, 47
Asymmetric DM	Relating DM to baryon abundance requires operator connecting DM number and Baryon/Lepton number → higher dimensional operator → LLPs	Any, depending on kind and scale of physics generating the operator.	MCFODO (highly dependent on production and decay mode).	5.1	
Dynamical DM	DM sector includes spectrum of states with varying life-time up to highly stable DM.	Any, long lifetimes generic in DM sector spectrum.	MCFODO (highly dependent on production and decay mode).	5.2	**[DC: TB**

SIMP/ELDER DM	Strong dynamics of HV generate DM abundance. HV → LLPs.	Any.	See HV.	5.4.1, 5.4.2	
Relaxion	Relaxion or other new scalars in theory generically mix with Higgs → SM+S.	Any.	See SM+S.	4.4	
Axion-like particles	ALP couplings to h and Z are generic in EFT framework. $1/f$ suppression makes ALP an LLP.	Any.	MCFODO for low-scale f.	8.6	63, 64, 65, 66, 67
Leptogenesis	Motivates minimal RH neutrino model and other neutrino extensions, which generically feature LLPs.	Any, long lifetimes favor lower m_{ν_R}.	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.	6.2	
Scalars in neutrino extensions	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.	Any.	See SM+S, with some additional production modes (new heavy gauge bosons).	7.2.2, 7.3.2	

… come back to this in more detail later….
but this demonstrates the general
importance of LLPs in BSM theories, and
urgency of exploring the Lifetime Frontier!

2. The MATHUSLA Detector

MAssive Timing Hodoscope
for Ultra-Stable NeutraL PArticles

Chou, DC, Lubatti 1606.06298
DC, Peskin 1705.06327
Physics Case White Paper 1806.xxxxx
Letter of Intent 18xx.xxxxx

Easy reading:

Physics Today article about LLPs and hidden sectors (DC, Raman Sundrum, June 2017)
http://physicstoday.scitation.org/doi/10.1063/PT.3.3594

In-depth feature article in Quanta and Wired magazine, September 2018
https://www.quantamagazine.org/how-the-hidden-higgs-could-reveal-our-universes-dark-sector-20170926/ https://www.wired.com/story/hidden-higgs-dark-sector/

“Nuclear Detectives Hunt Invisible Particles That Escaped the World's Largest Atom Smasher”, Live Science, May 2018 https://www.livescience.com/62633-lhc-stray-particles-mathusla-detection.html

An external LLP detector for the HL-LHC

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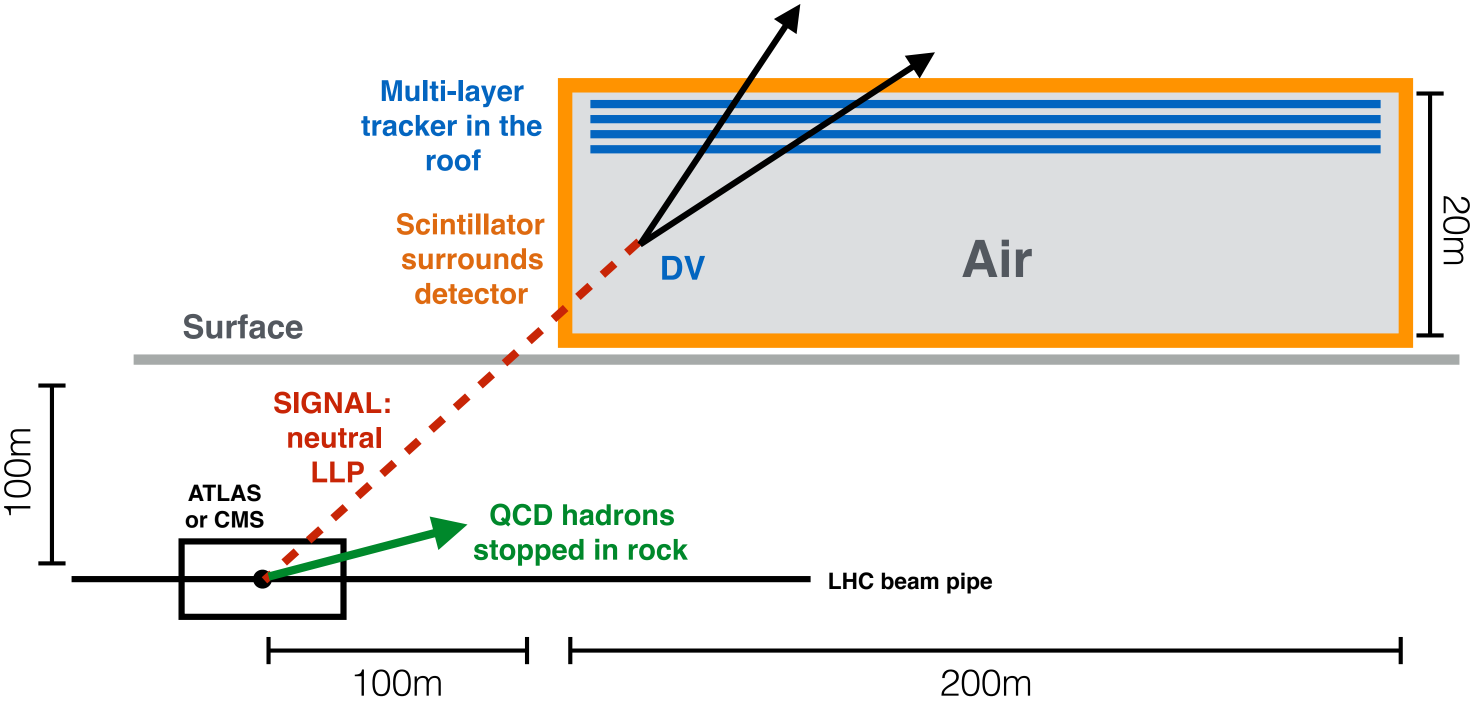
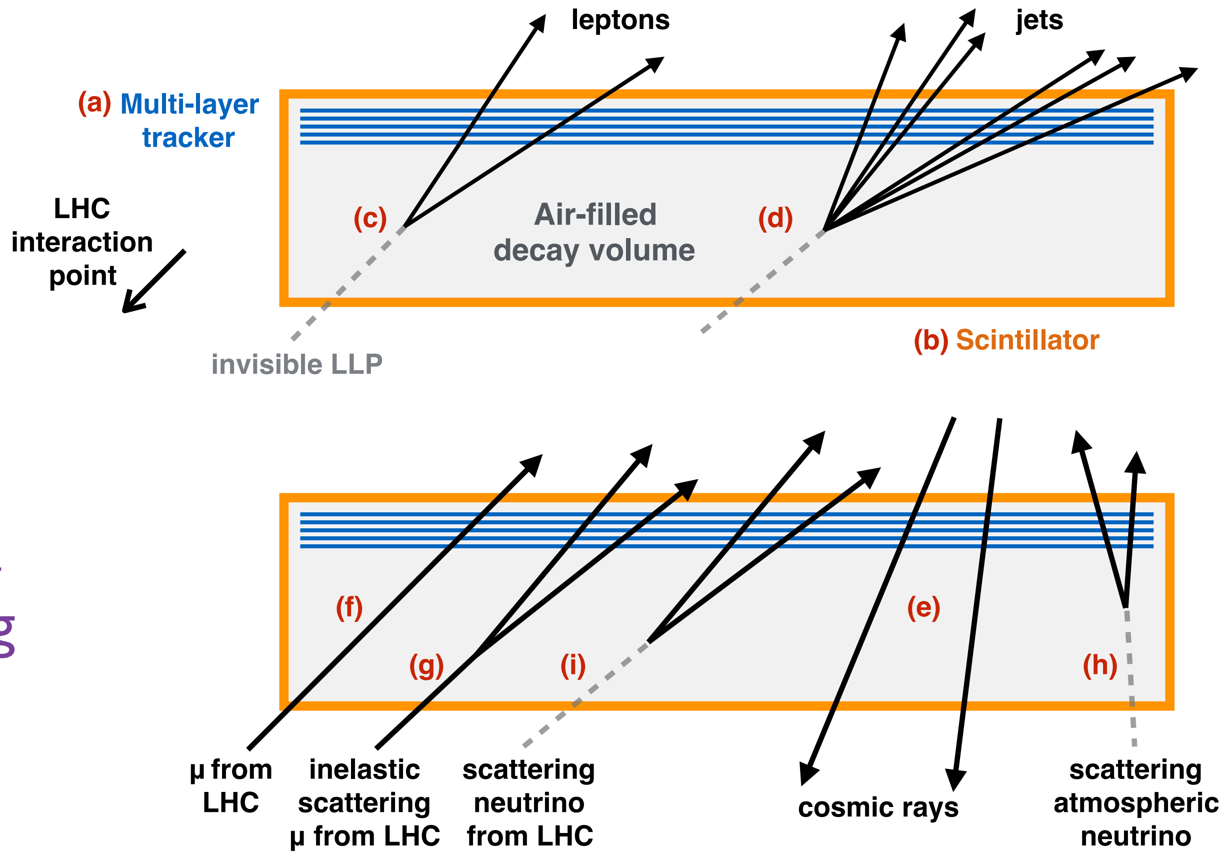
1606.06298



… 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)

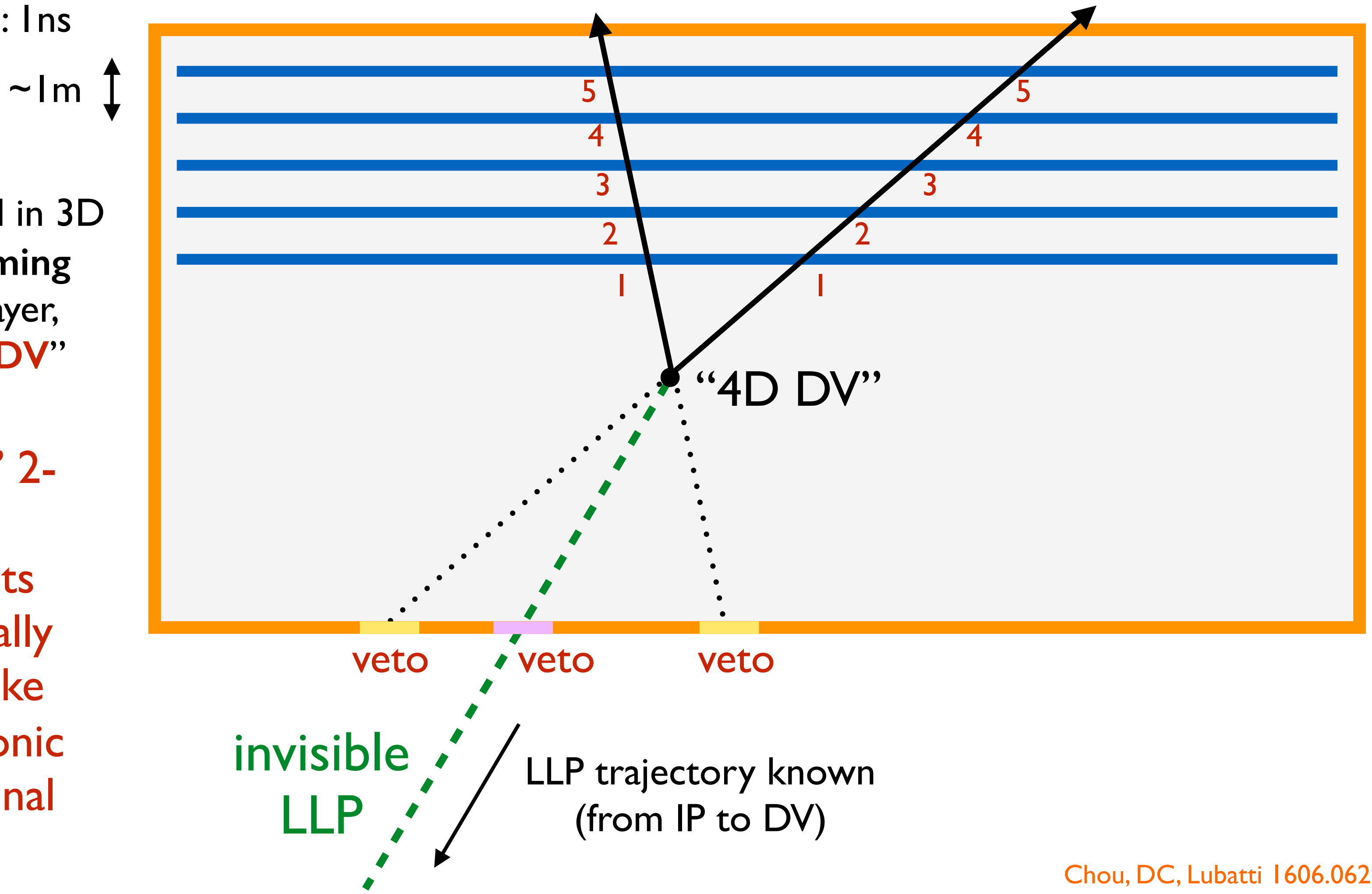
Most important part of background rejection is the *extremely* conspicuous, multi-faceted and tightly defined nature of LLP decay signal:

Δt ≳ 3.5ns per tracker layer,
17 ns for all 5 layers
tracker time resolution: 1ns

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!

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



LLP trajectory known (from IP to DV)

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Δt ≳ 3.5ns per tracker layer,
17 ns for all 5 layers
tracker time resolution: 1ns

~1m

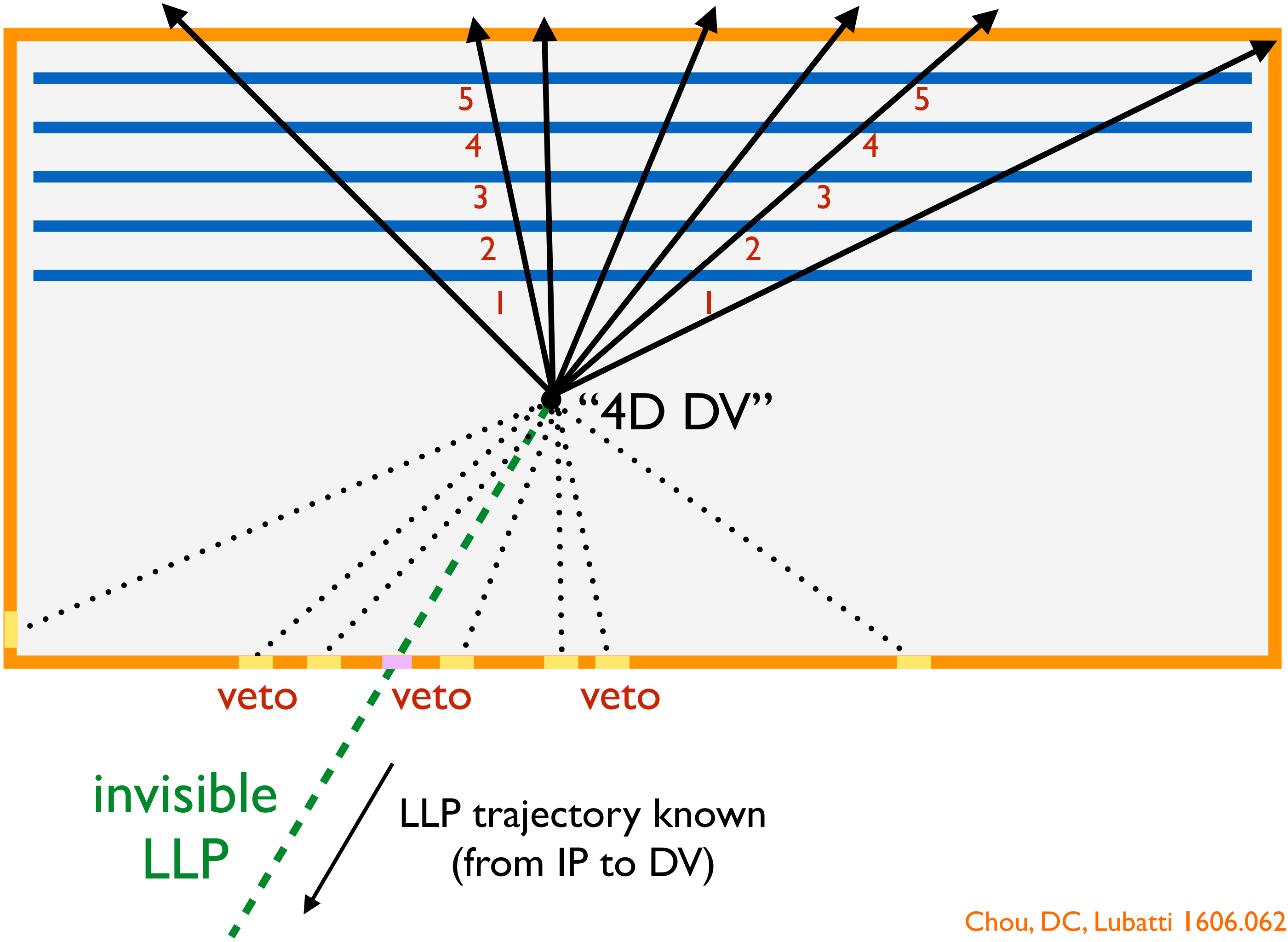
tracks are reconstructed in 3D *and* with detailed **timing** information at each layer, so DV is really a "**4D DV**"

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.)

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



LLP trajectory known (from IP to DV)

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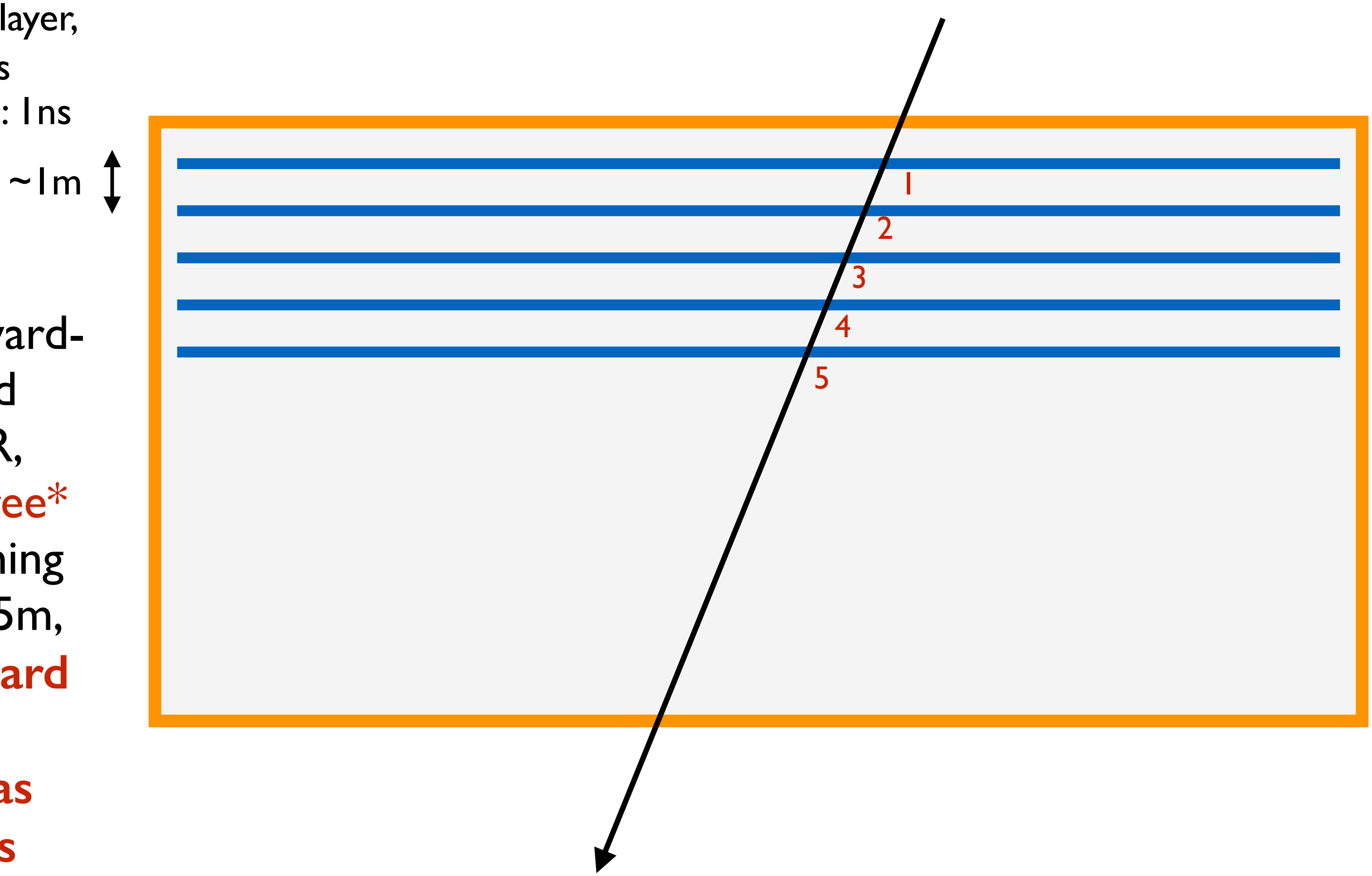
Background Rejection (gory details)

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

$\Delta t \gtrsim 3.5$ns per tracker layer,
17 ns for all 5 layers
tracker time resolution: 1ns



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 $\epsilon_{down\to up} \lesssim 10^{-15}$**

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Background Rejection (gory details)

Com

run

Δt ≳ 3

17

tracker

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

Of course, our estimate of $\epsilon_{down\to up}$ 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 $\epsilon_{down\to up}^2$)
- 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.

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Background Rejection (gory details)

Com

run

Δt ≳ 3

17

tracker

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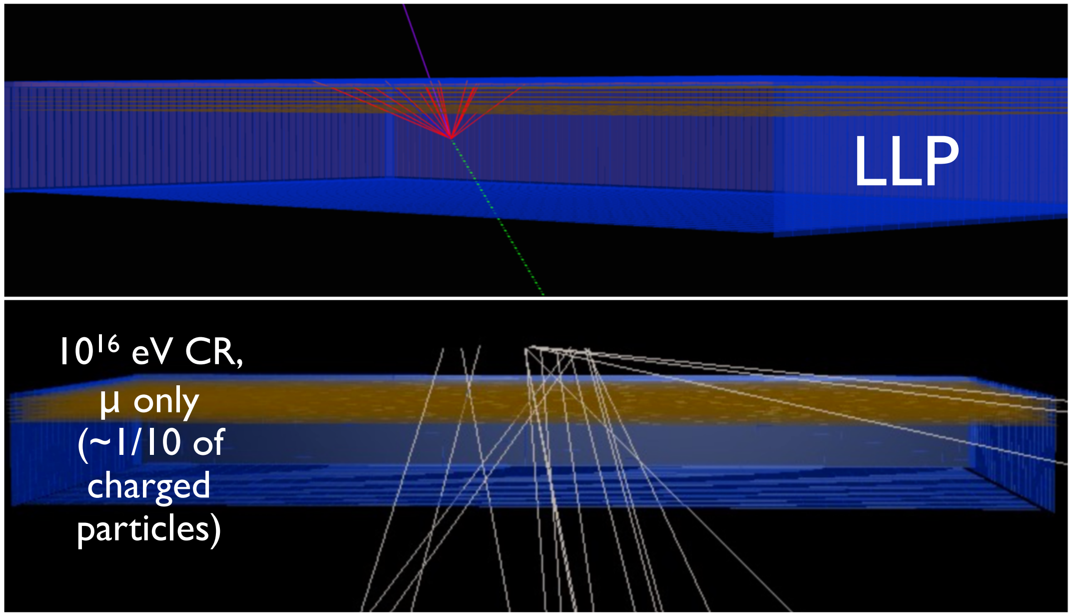
Most CR tracks are highly correlated, forming Extensive Air Showers:



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.

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Background Rejection (gory details)

Com run

$\Delta t \gtrsim 3$

17

tracker

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 verify CR rejection strategies on data that is guaranteed to be only background.

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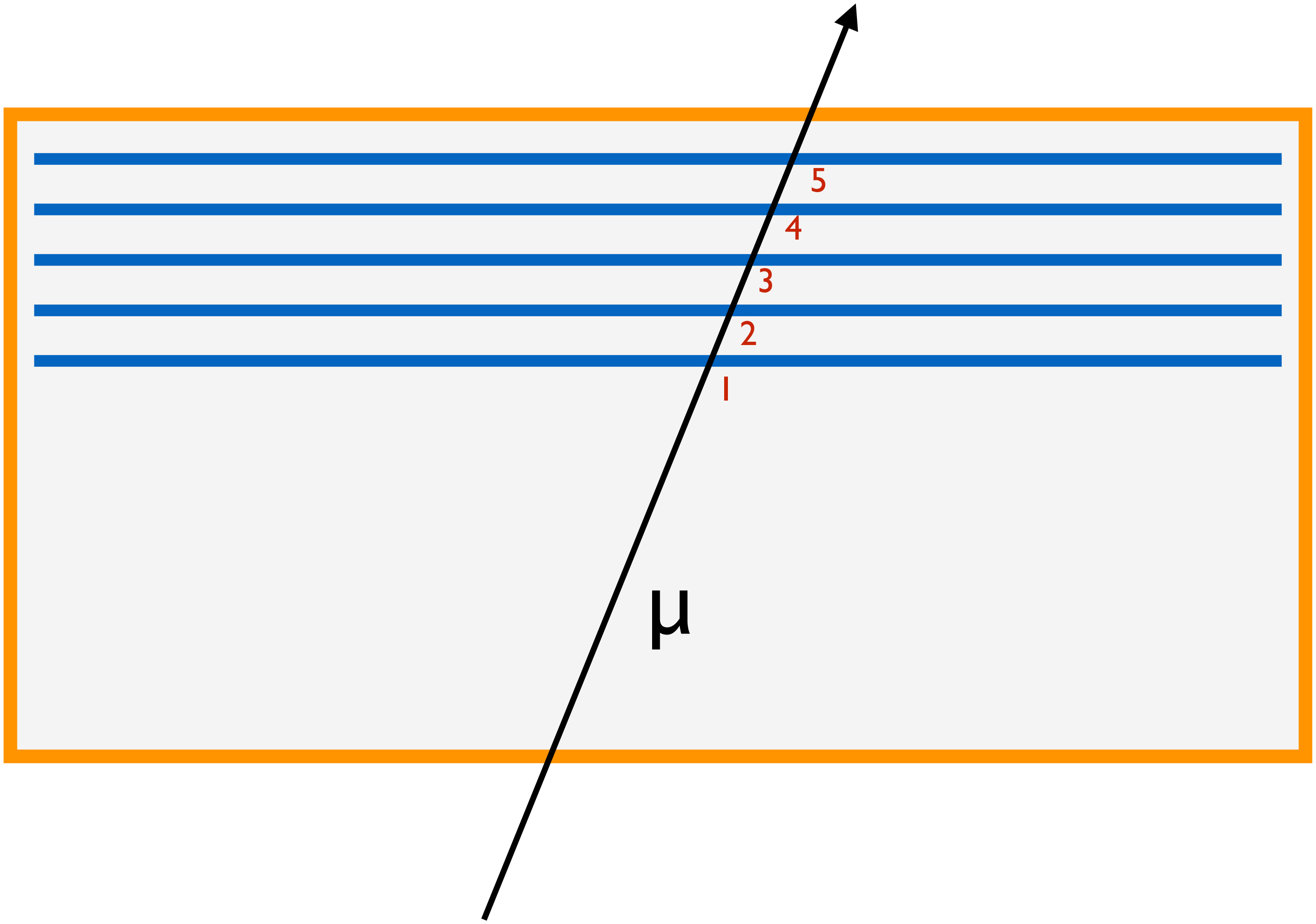
Background Rejection (gory details)

Muons from LHC: Have to have energy ≳ 50 GeV to reach detector, incident with rate ~10Hz → ~10^9 over HL-LHC run

They do travel upwards, but they do not reconstruct a displaced vertex.



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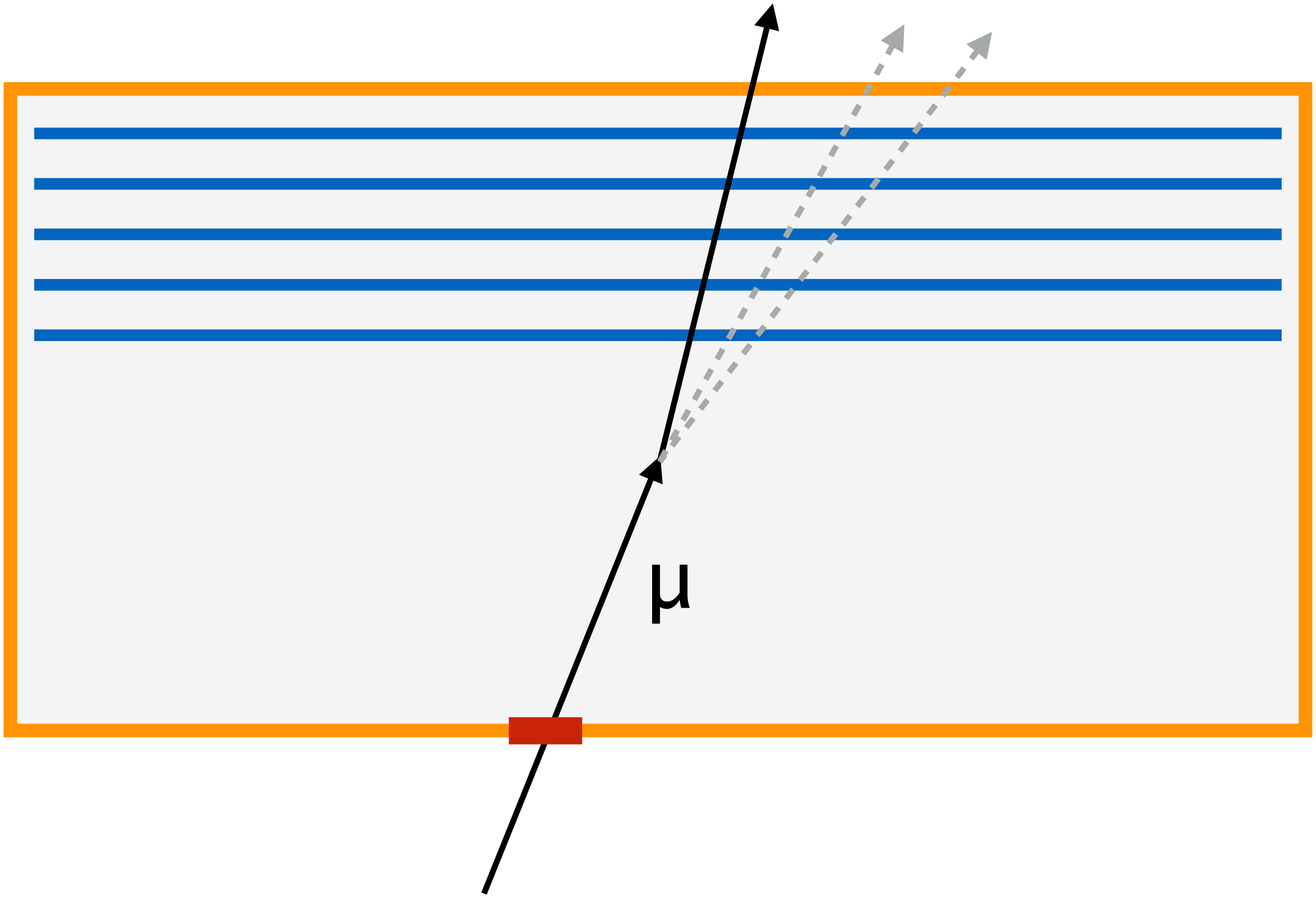
Background Rejection (gory details)

Muons from LHC: Have to have energy $\gtrsim$ 50 GeV to reach detector, incident with rate ~10Hz → ~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)



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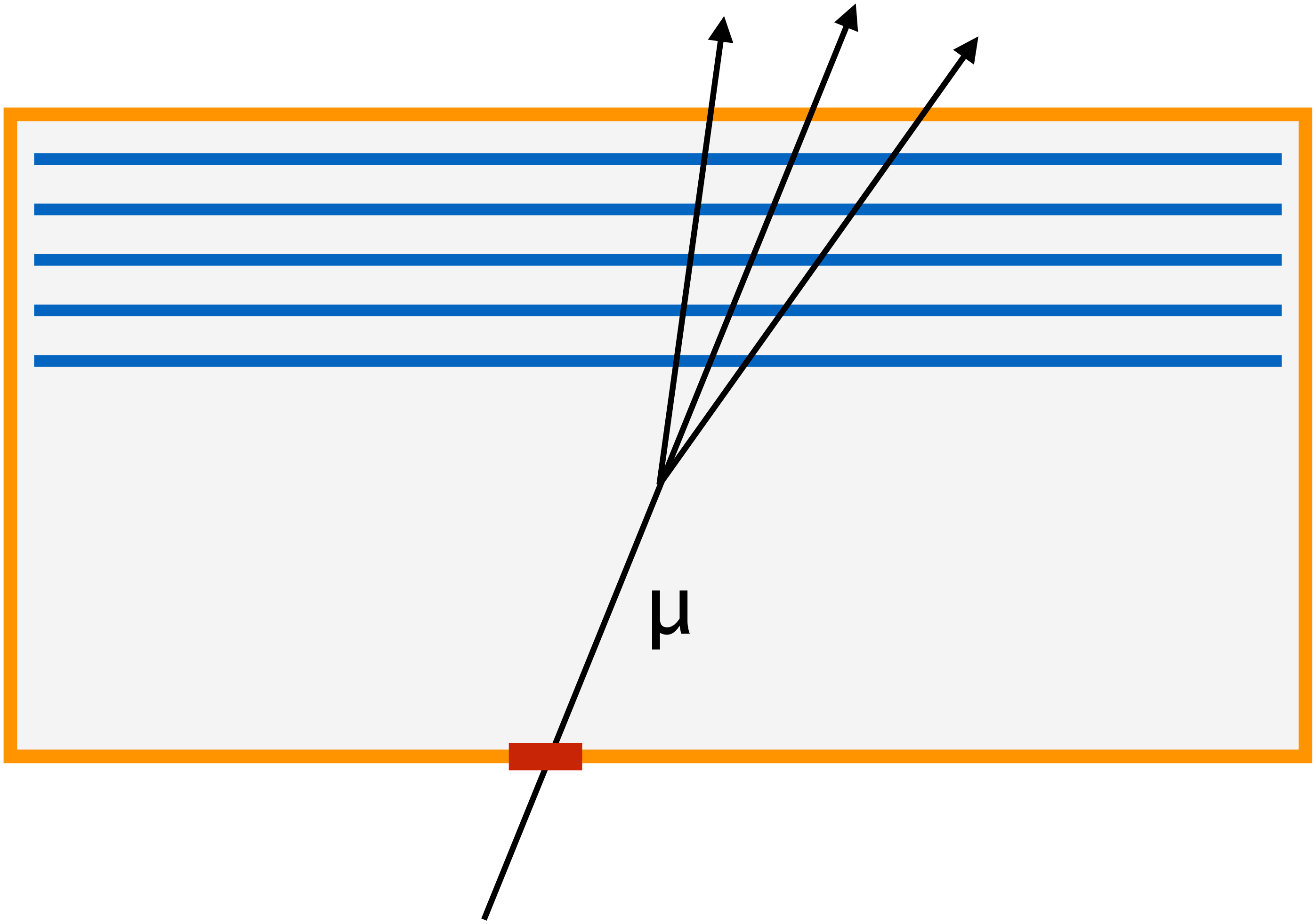
Background Rejection (gory details)

Muons from LHC: Have to have energy ≳ 50 GeV to reach detector, incident with rate ~10Hz → ~10^9 over HL-LHC run

~ 1000 undergo rare decay into eeνν (Br ~ 3 × 10^{-5}) → 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)



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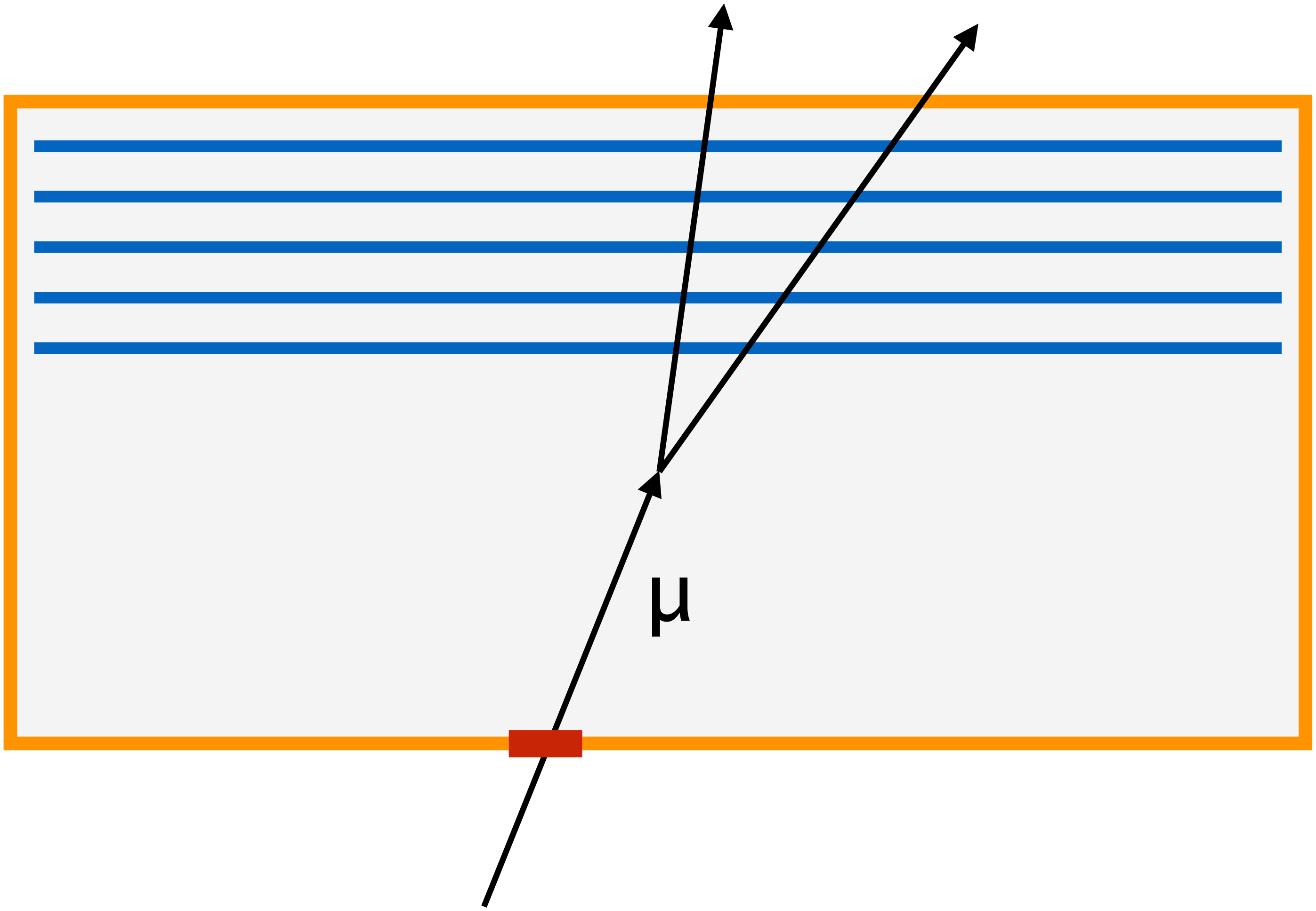
Background Rejection (gory details)

Muons from LHC: Have to have energy ≳ 50 GeV to reach detector, incident with rate ~10Hz → ~10^9 over HL-LHC run

~ 10 scatter off air and form genuine DV

easily veto with scintillator alone.



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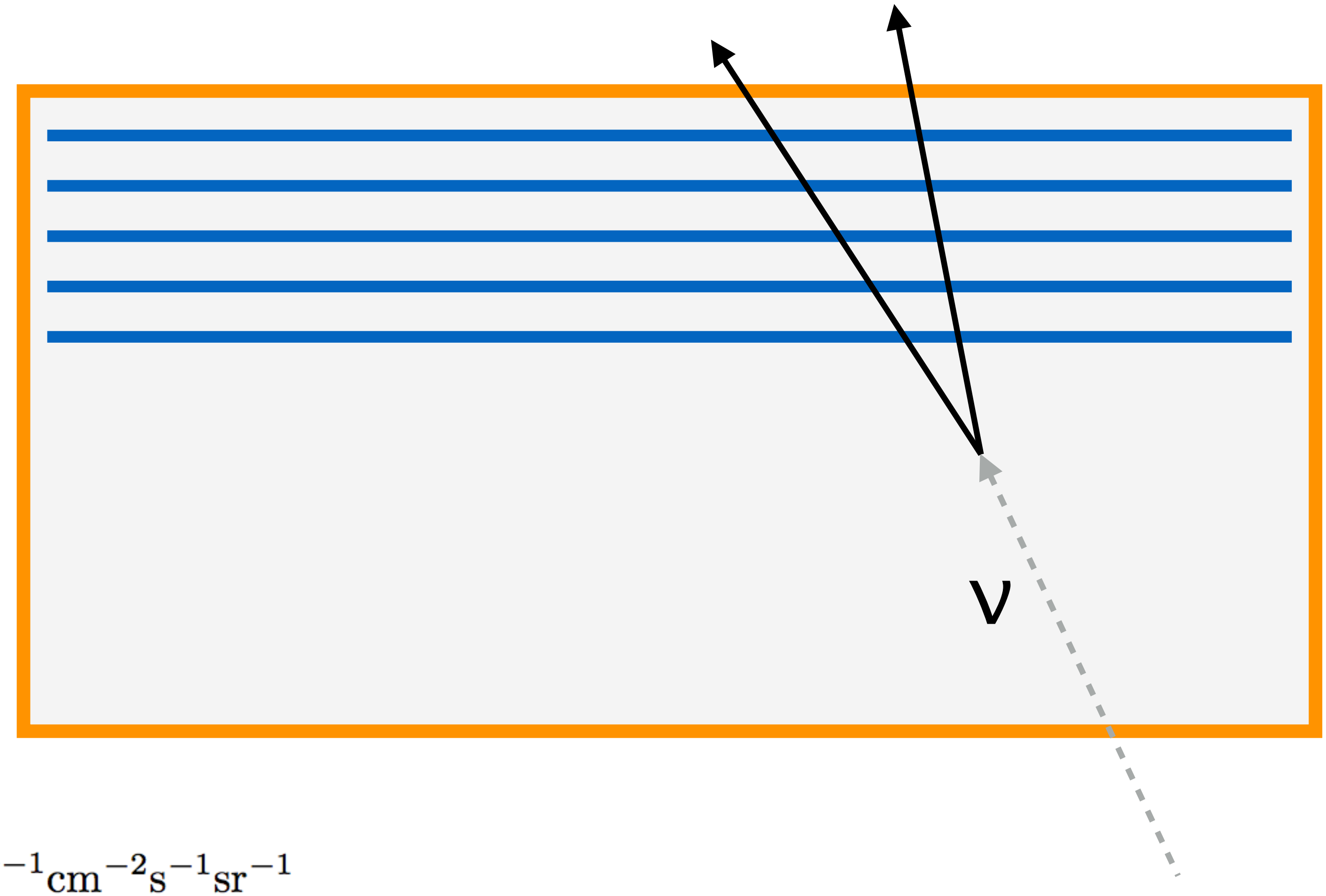
Background Rejection (gory details)

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 ν_μ flux. (ν_e much lower, can be dealt with similarly)



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

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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 Formaggio, Zeller, 1305.7513

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

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$\frac{d\Phi}{dE_\nu} \sim$

1606.06298

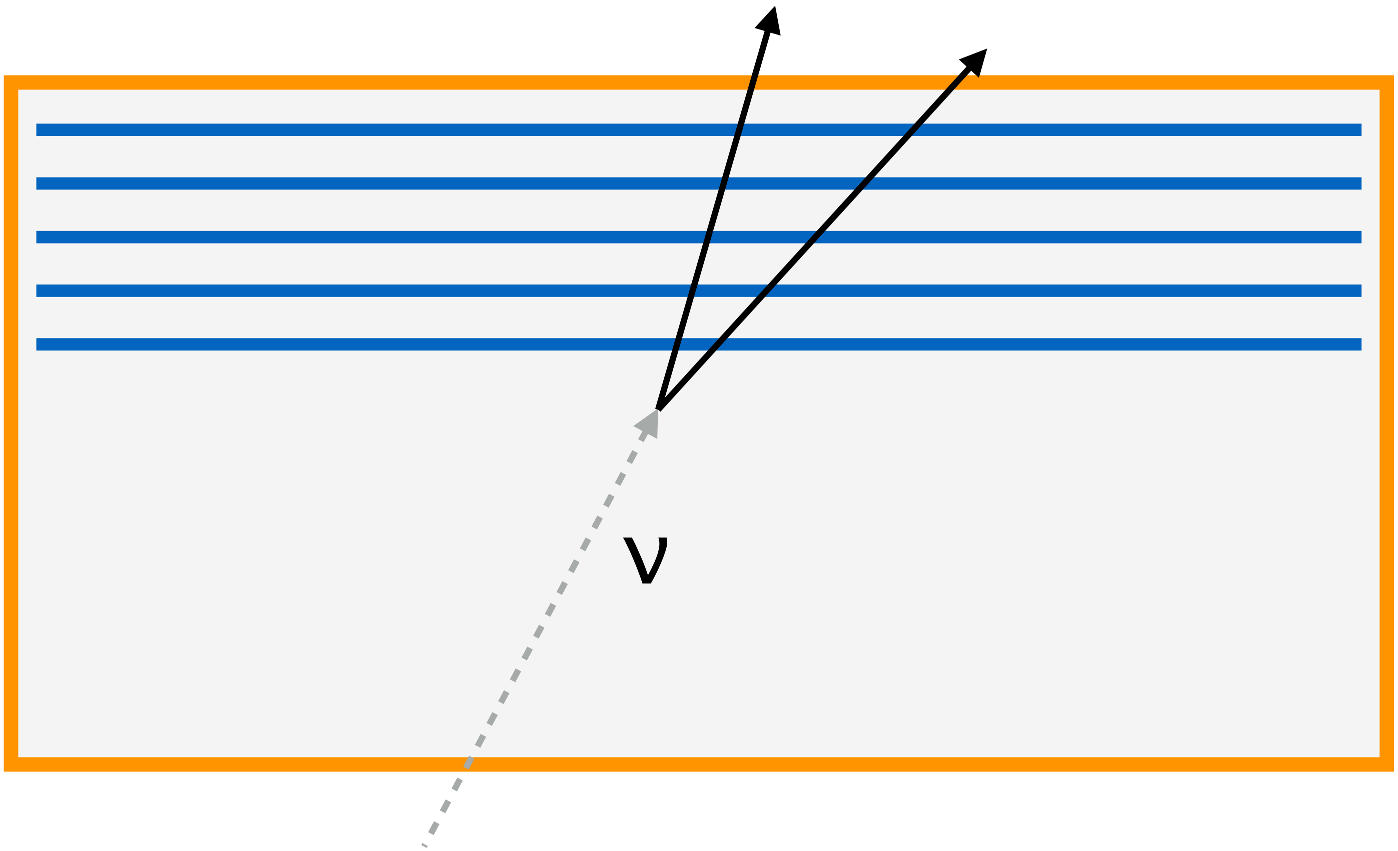
Background Rejection (gory details)

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.



Chou, DC, Lubatti 1606.06298

Background Rejection (gory details)

None of these BG rejection strategies seriously affect signal efficiency.

*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)

… back to the main story

Practicalities

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

→ 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: ~ 50 million USD.
More precise estimates will be part of LOI.

CERN owns some empty land of *approximately* right size near CMS

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MATHUSLA experimental collaboration

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

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(member list probably outdated)

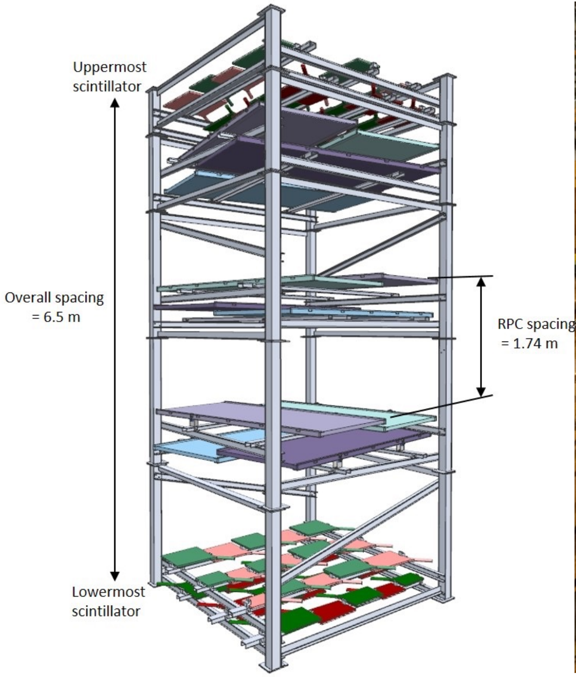
contact: mathusla.experiment@cern.ch

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

MATHUSLA ≈ ATLAS/ CMS - short-lifetime sensitivity + zero BG, no trigger issues

similar geometric acceptance for LLP decays in long-lifetime limit…

… you sacrifice sensitivity for short lifetimes…

… but you gain clean environment for LLP searches

Very easy to estimate sensitivity at MATHUSLA:

$$N_{\text{MATHUSLA}} \approx (\#\ \text{LLPs produced at LHC}) \times P^{\text{MATHUSLA}}_{\text{decay}}$$

$$P^{\text{MATHUSLA}}_{\text{decay}}(c\tau) \;\approx\; \epsilon_{\text{geometric}} \quad P_{\text{decay}}(\bar{b}c\tau, L_1, L_2)$$

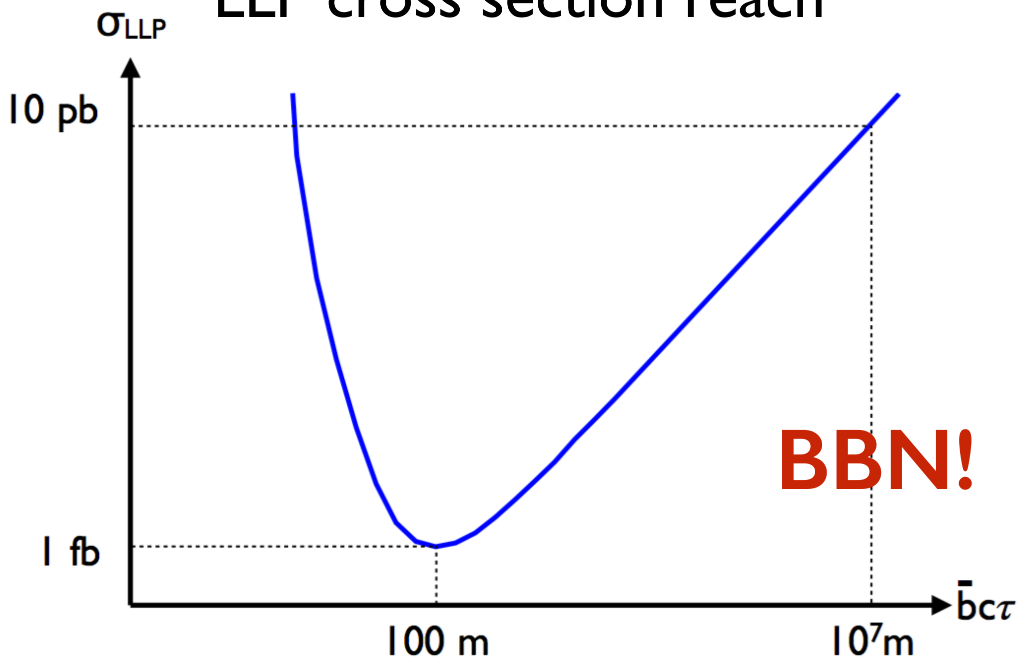
only modest O(1) dependence on LLP production process.

$$\sim 0.05 \qquad \sim \frac{(30\text{m})}{\bar{b}c\tau}$$

in long lifetime regime

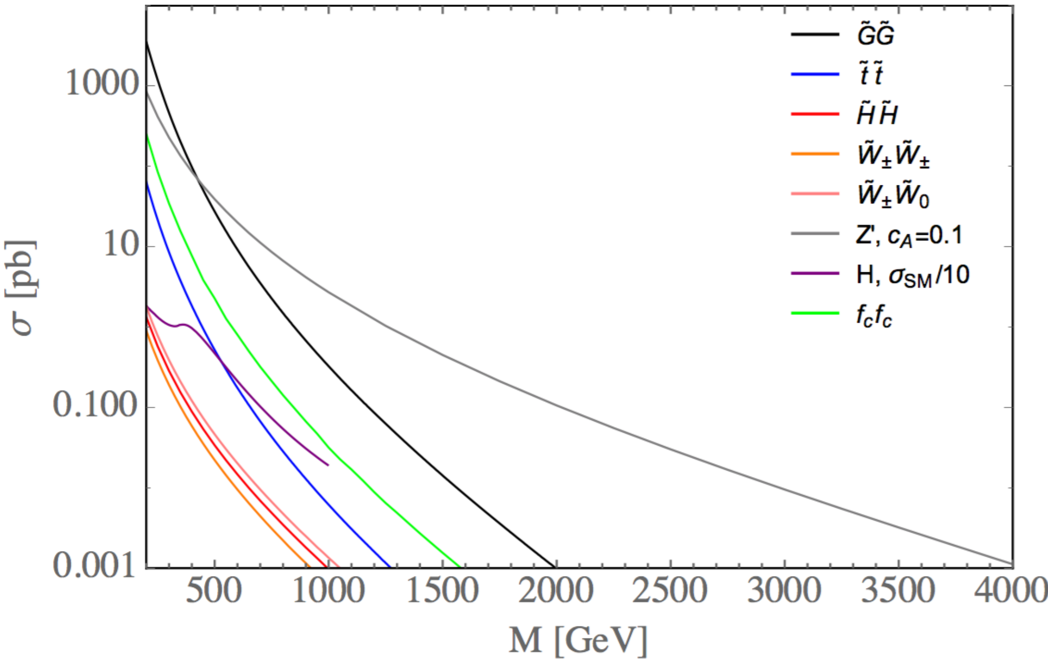
Sensitivity

LLP cross section reach



BBN!

Some example production xsecs



$$\bar{b} = \frac{m_{\text{eff}}}{2m_{\text{LLP}}}$$

$$\bar{b}c\tau_{\text{max}} \sim (10^3 \text{ m}) \left(\frac{\sigma_{\text{sig}}^{\text{LHC}}}{\text{fb}} \right)$$

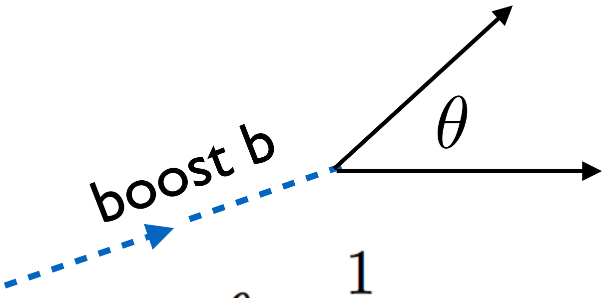
Any LLP production process with σ > fb can give signal.

TeV+ mass reach!

Low-Mass Regime

Spatial resolution Δx 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!



$$\theta \sim \frac{1}{b}$$

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

→ Minimum LLP mass that can be probed "without BG"

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

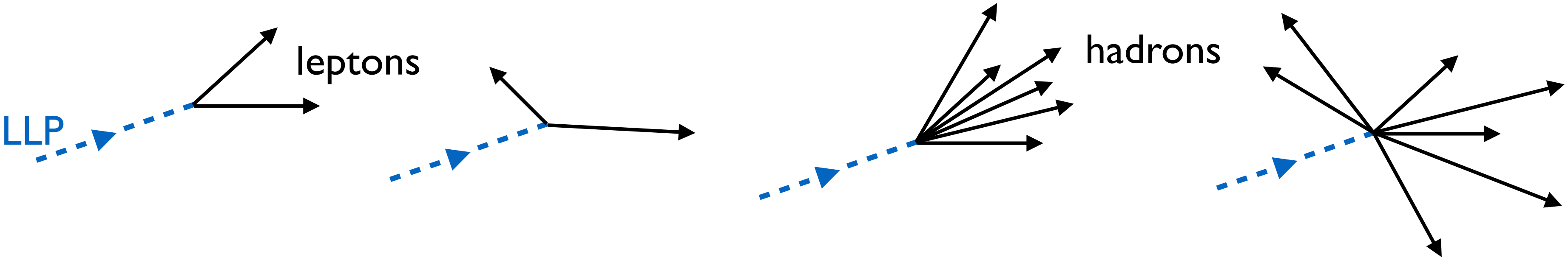
~ 10 MeV for LLPs from B decays

~ 0.1-1 GeV for weak-TeV scale production

Interesting
complementarity
with SHiP?

LLP Diagnosis

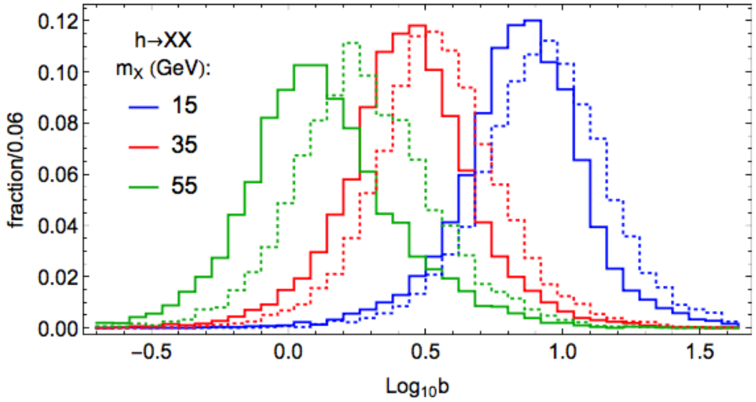
DC, Peskin
1705.06327



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/μ discrimination and γ detection



Correlate with main detector to diagnose **production mode!**

For known production mode, **boost ~ LLP mass**!

3. LLPs at the LHC: Comparing MATHUSLA and the main detectors

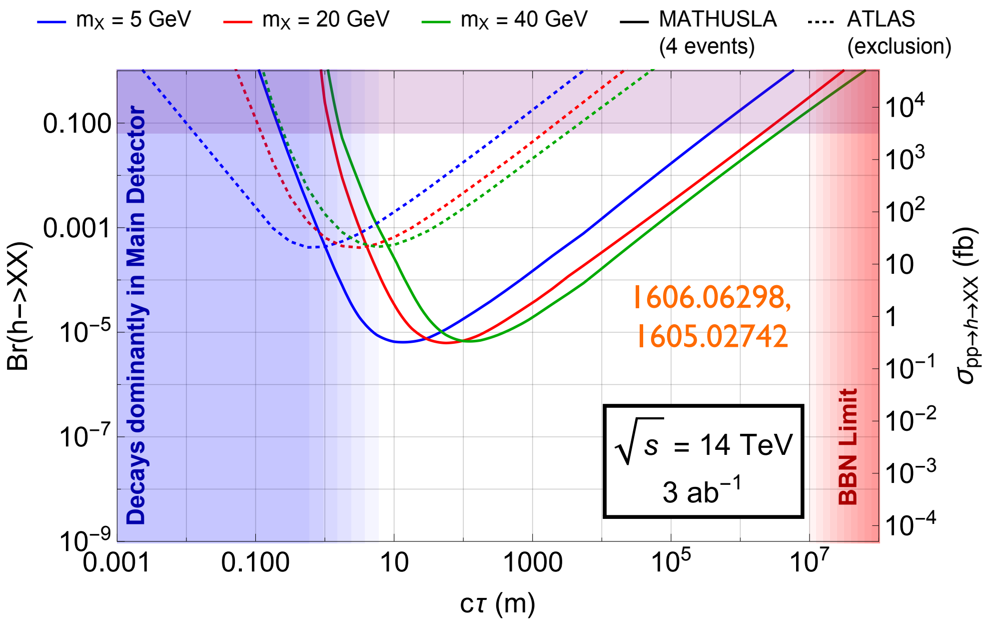
MATHUSLA vs ATLAS/CMS

Obviously main detectors are better at short lifetimes, so focus on **long lifetimes** b$c\tau \gtrsim$ 100m.

⇒ Main detector search should only require **one** LLP decay

One important benchmark:

h→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)

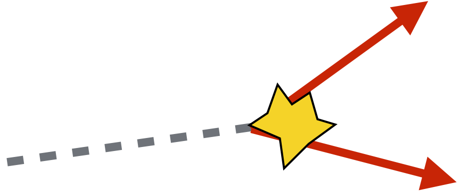
⟹ MATHUSLA wins by 10^3!

How does MATHUSLA compare to ATLAS/CMS for other LLP signals?

LLPs @ LHC main detectors

Try and understand the space of LLP signals at the main detectors.

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

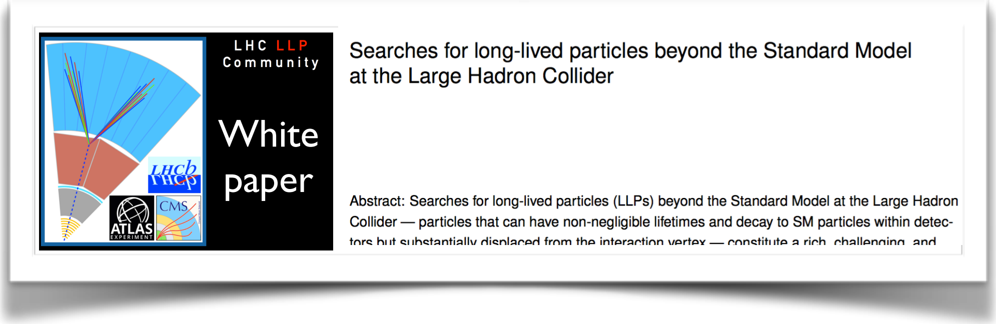


LLPs are spectacular *geometric* signals!

→ 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".
→ **DV + X search**

→ 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



Searches for long-lived particles beyond the Standard Model at the Large Hadron Collider

Abstract: Searches for long-lived particles (LLPs) beyond the Standard Model at the Large Hadron Collider — particles that can have non-negligible lifetimes and decay to SM particles within detectors but substantially displaced from the interaction vertex — constitute a rich, challenging, and

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

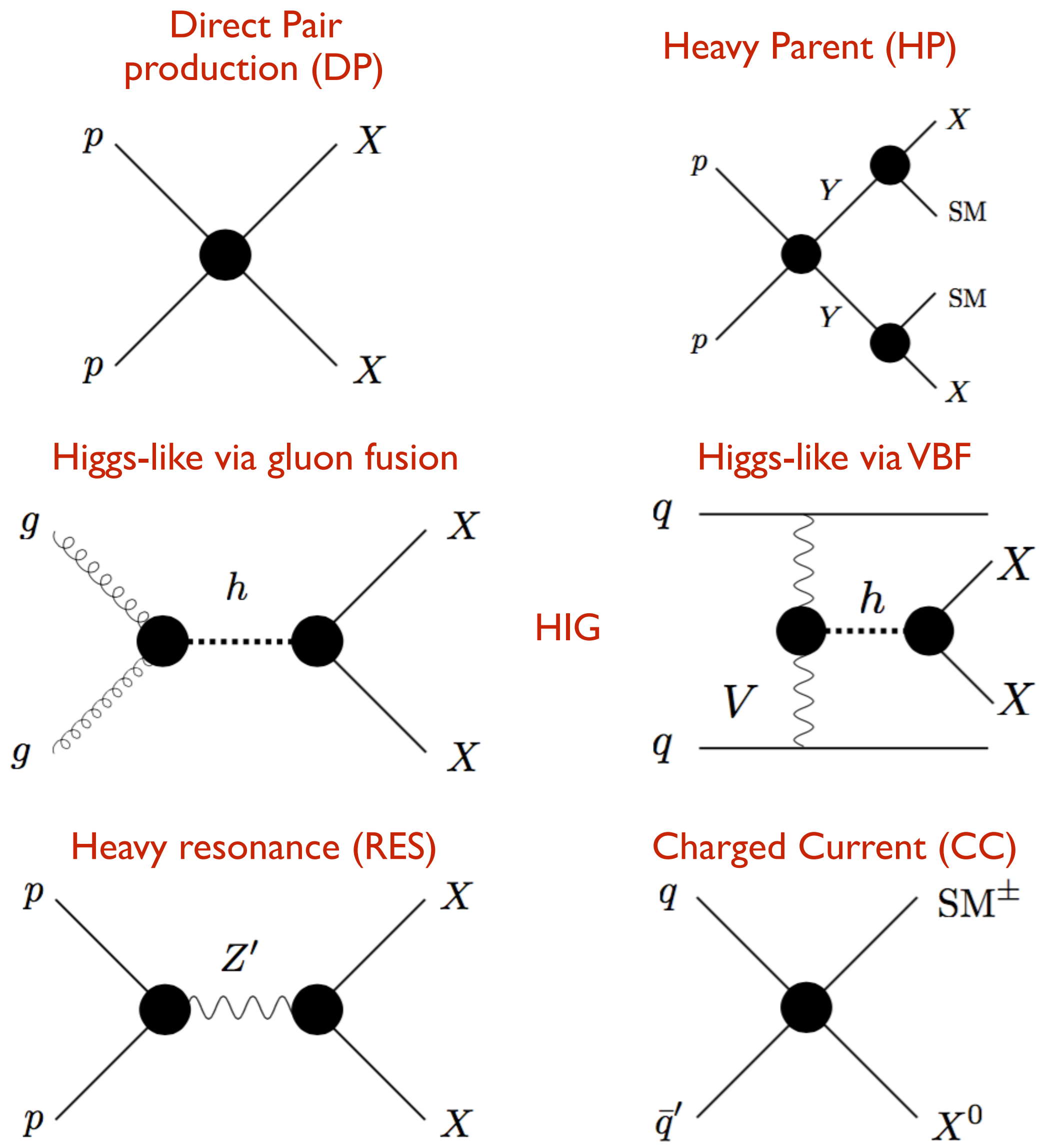
Do this with an eye for what we can trigger on, and cut on to reduce BG:

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.



Direct Pair production (DP)

Heavy Parent (HP)

Higgs-like via gluon fusion

Higgs-like via VBF

HIG

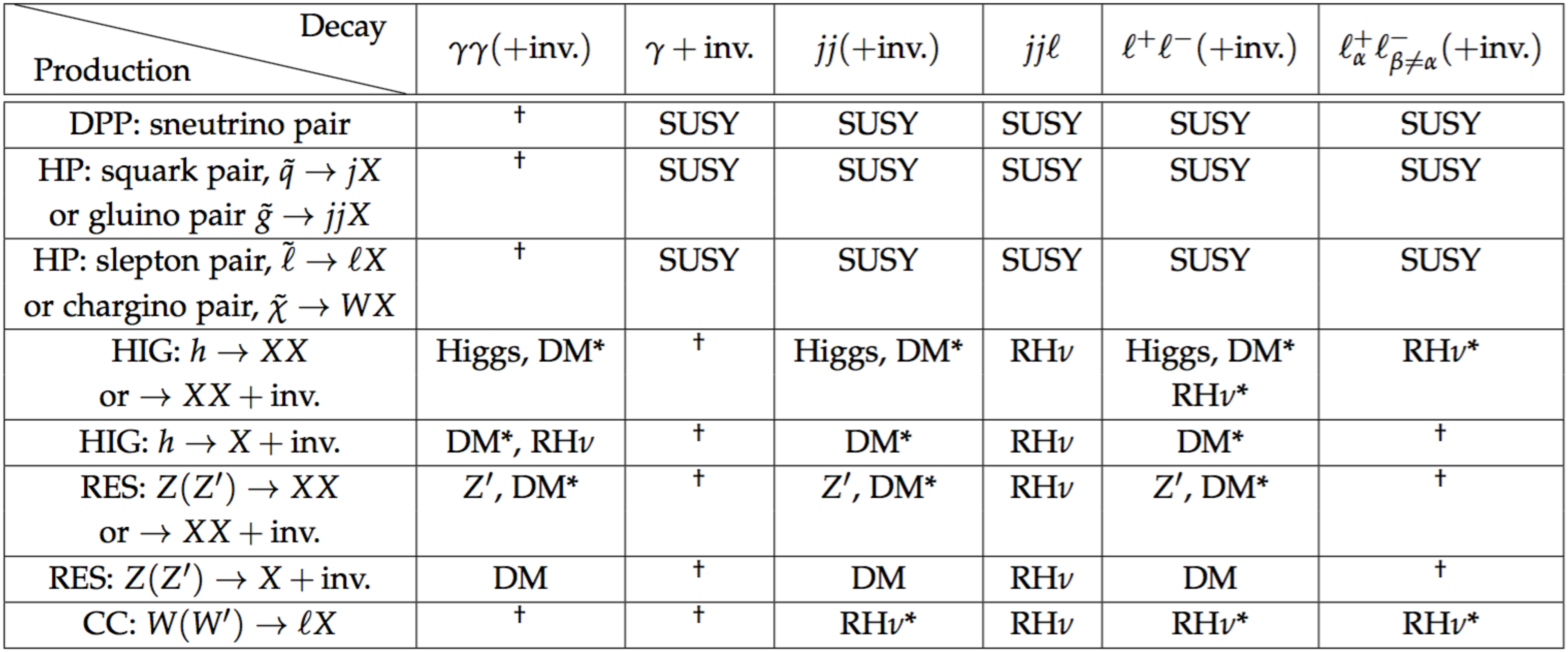
Heavy resonance (RES)

Charged Current (CC)

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 (DPP); 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



Decay / Production	$\gamma\gamma(+\text{inv.})$	$\gamma+\text{inv.}$	$jj(+\text{inv.})$	$jj\ell$	$\ell^+\ell^-(+\text{inv.})$	$\ell^+_\alpha \ell^-_{\beta\neq\alpha}(+\text{inv.})$
DPP: sneutrino pair	†	SUSY	SUSY	SUSY	SUSY	SUSY
HP: squark pair, $\tilde{q} \to jX$ or gluino pair $\tilde{g} \to jjX$	†	SUSY	SUSY	SUSY	SUSY	SUSY
HP: slepton pair, $\tilde{\ell} \to \ell X$ or chargino pair, $\tilde{\chi} \to WX$	†	SUSY	SUSY	SUSY	SUSY	SUSY
HIG: $h \to XX$ or $\to XX+\text{inv.}$	Higgs, DM*	†	Higgs, DM*	RHν	Higgs, DM* RHν*	RHν*
HIG: $h \to X+\text{inv.}$	DM*, RHν	†	DM*	RHν	DM*	†
RES: $Z(Z') \to XX$ or $\to XX+\text{inv.}$	Z', DM*	†	Z', DM*	RHν	Z', DM*	†
RES: $Z(Z') \to X+\text{inv.}$	DM	†	DM	RHν	DM	†
CC: $W(W') \to \ell X$	†	†	RHν*	RHν	RHν*	RHν*

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
at O(1) level, similar to at MATHUSLA

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:

$$R_s \equiv \left.\frac{\sigma_{\text{sig}}^{\text{LHC limit}}}{\sigma_{\text{sig}}^{\text{MATHUSLA limit}}}\right|_{\text{b}c\tau \gg 200\text{m}}$$

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.

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

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

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$$\frac{P_{\rm decay}^{\rm LHC}}{P_{\rm decay}^{\rm MATH}} \approx \begin{cases} 2.2 & \text{ATLAS Muon System} \\ 0.8 & \text{ATLAS HCAL} \\ 1.0 & \text{ATLAS or CMS tracker (full volume)} \\ 0.25 & \text{ATLAS tracker (DV reconstruction volume)} \end{cases}$$

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

relative geometrical acceptance ~ 1

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

relative reconstruction efficiency ≳ 1

BG of main detector search

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

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BG of main detector search

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

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, Rs ~ 1

1411.6977

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

but if LLP m < ~ 10 GeV and decays to leptons, have displaced lepton jets! $\sigma_{\text{BG after cuts}}$ ~ 10 fb → Rs ~10-100?

ATLAS-CONF-2016-042

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

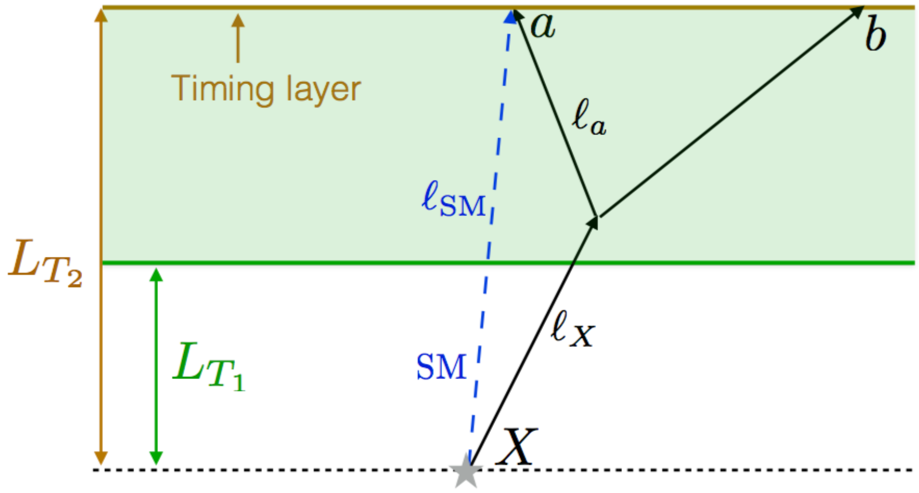
1606.06298,
1605.02742

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. $\sigma_{\text{BG after cuts}}$ < ~ ab → Rs ~ 1

1411.6530

Main Detector Timing Upgrades??

Jia Liu, Zhen Liu, Lian-Tao Wang 1805.05957



Opening angle of
LLP decay products
~ (boost)$^{-1}$

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

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

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

b = boost

Quite sizable even for reasonably high O(1) boosts, if you have e.g. 30ps timing!

Main Detector Timing Upgrades??

Jia Liu, Zhen Liu,
Lian-Tao Wang 1805.05957

Consider h→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 (26σ)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 (7σ)to reduce hard jet fake DV background by 10^{-6} to $N < 1$

Main Detector Timing Upgrades??

Jia Liu, Zhen Liu,
Lian-Tao Wang 1805.05957

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

That quantitative reach is not realistic, given the backgrounds not considered in the analysis and assumptions made about triggering.

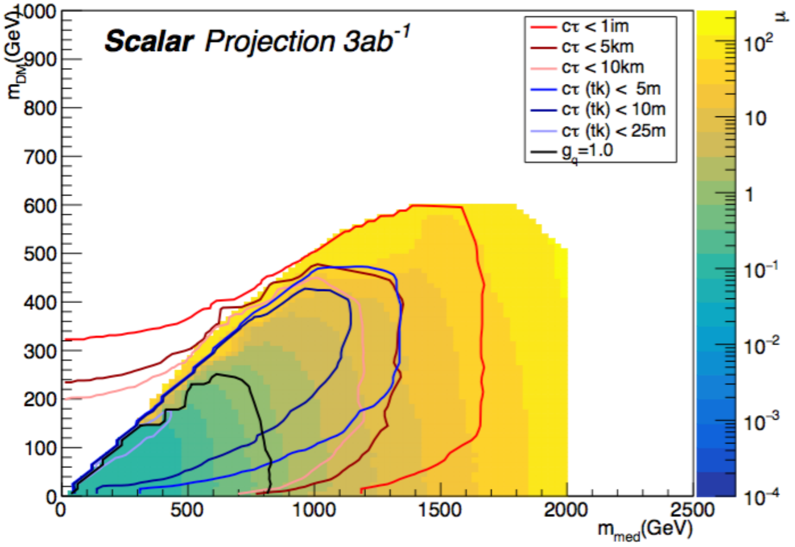
However, regardless of such details, timing will *definitely* improve main detector sensitivity significantly.

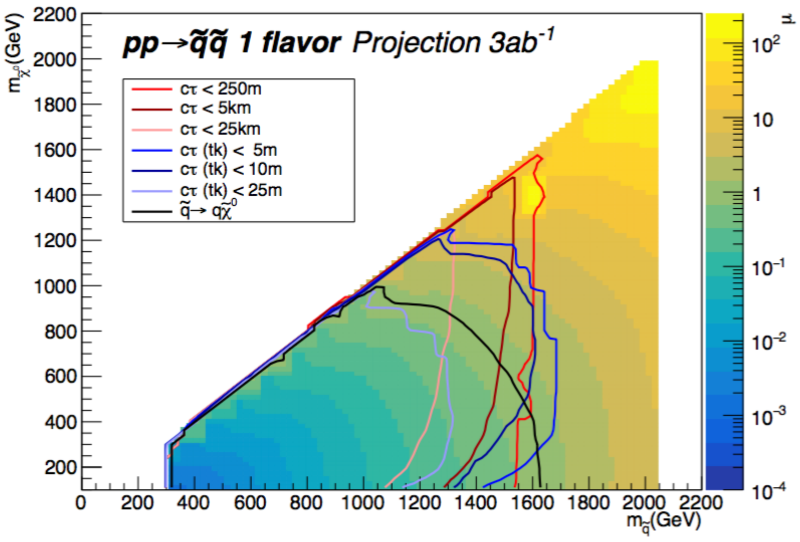
Furthermore, main detector LLP searches always have intrinsic advantages (full event reconstruction etc) so you want to improve those as much as you can.

Clearly, timing is incredibly exciting for LLP searches!

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 < ~ O(100 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

These are LLP searches that will likely remain difficult at main detectors even after LLP search program has matured!

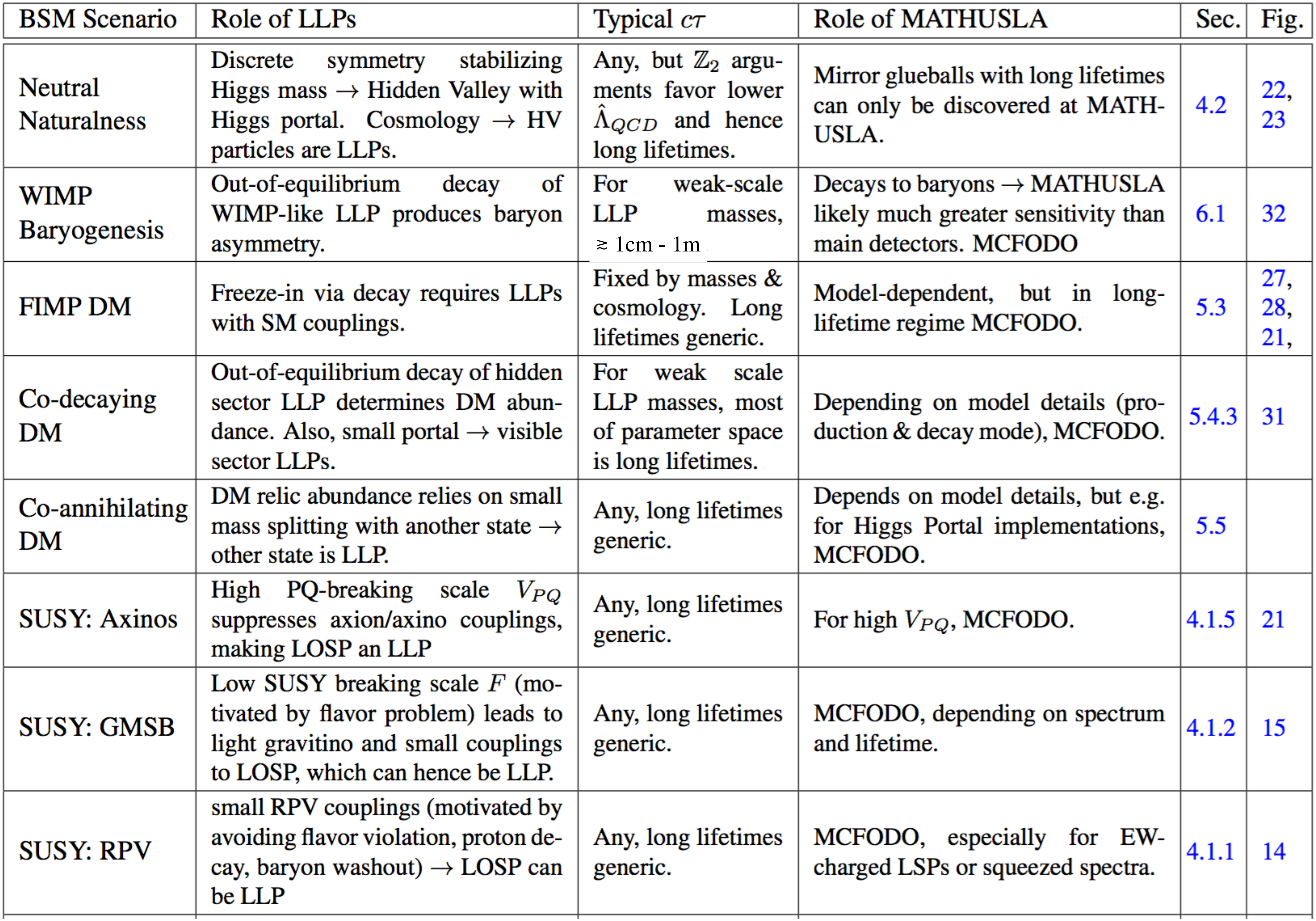
4. MATHUSLA Physics Reach

Divide discussion into two “great” classes,
in all of which **MCFODO**
(**M**athusla **C**ould be **F**irst or **O**nly **D**iscovery **O**pportunity)

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.

1) intrinsic



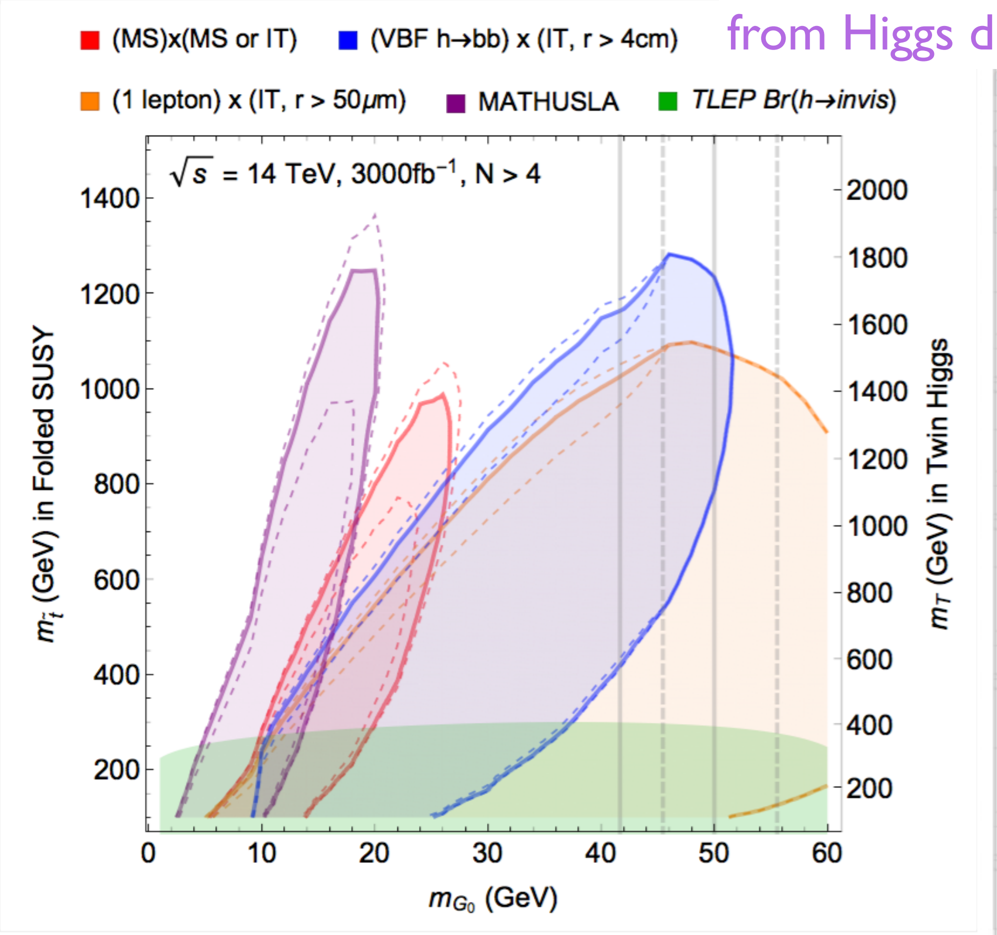
BSM Scenario	Role of LLPs	Typical $c\tau$	Role of MATHUSLA	Sec.	Fig.
Neutral Naturalness	Discrete symmetry stabilizing Higgs mass → Hidden Valley with Higgs portal. Cosmology → HV particles are LLPs.	Any, but $\mathbb{Z}_2$ arguments favor lower $\hat{\Lambda}_{QCD}$ and hence long lifetimes.	Mirror glueballs with long lifetimes can only be discovered at MATHUSLA.	4.2	22, 23
WIMP Baryogenesis	Out-of-equilibrium decay of WIMP-like LLP produces baryon asymmetry.	For weak-scale LLP masses, $\gtrsim$ 1cm - 1m	Decays to baryons → MATHUSLA likely much greater sensitivity than main detectors. MCFODO	6.1	32
FIMP DM	Freeze-in via decay requires LLPs with SM couplings.	Fixed by masses & cosmology. Long lifetimes generic.	Model-dependent, but in long-lifetime regime MCFODO.	5.3	27, 28, 21,
Co-decaying DM	Out-of-equilibrium decay of hidden sector LLP determines DM abundance. Also, small portal → visible sector LLPs.	For weak scale LLP masses, most of parameter space is long lifetimes.	Depending on model details (production & decay mode), MCFODO.	5.4.3	31
Co-annihilating DM	DM relic abundance relies on small mass splitting with another state → other state is LLP.	Any, long lifetimes generic.	Depends on model details, but e.g. for Higgs Portal implementations, MCFODO.	5.5	
SUSY: Axinos	High PQ-breaking scale V_{PQ} suppresses axion/axino couplings, making LOSP an LLP	Any, long lifetimes generic.	For high V_{PQ}, MCFODO.	4.1.5	21
SUSY: GMSB	Low SUSY breaking scale F (motivated by flavor problem) leads to light gravitino and small couplings to LOSP, which can hence be LLP.	Any, long lifetimes generic.	MCFODO, depending on spectrum and lifetime.	4.1.2	15
SUSY: RPV	small RPV couplings (motivated by avoiding flavor violation, proton decay, baryon washout) → LOSP can be LLP	Any, long lifetimes generic.	MCFODO, especially for EW-charged LSPs or squeezed spectra.	4.1.1	14

MATHUSLA Physics Case, June 2018

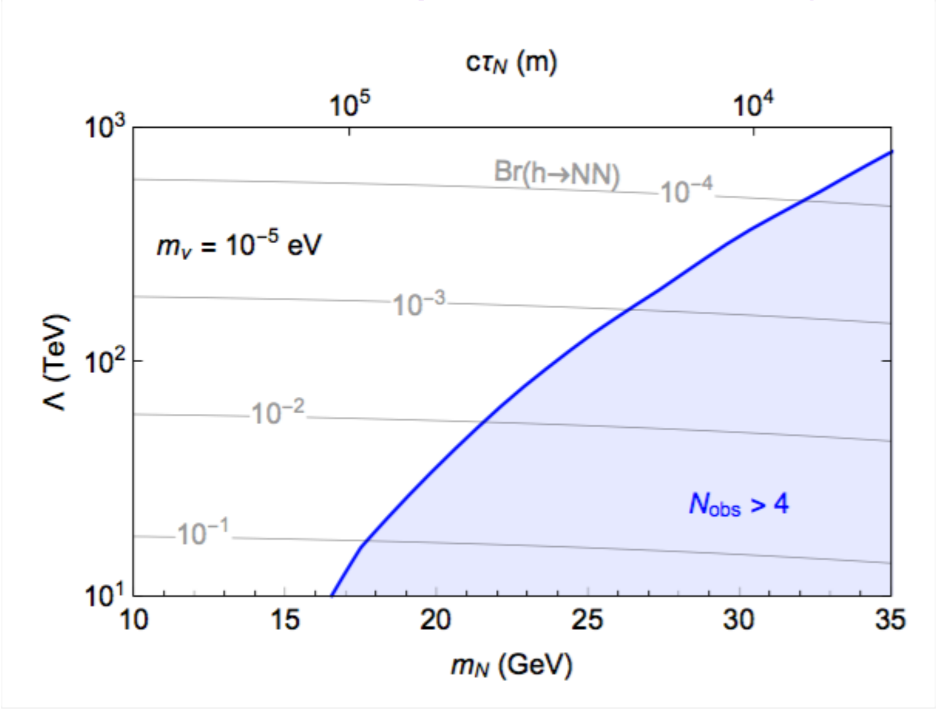
1) intrinsic

BSM Scenario	Role of LLPs	Typical $c\tau$	Role of MATHUSLA	Sec.	Fig.
Neutral Naturalness	Discrete symmetry stabilizing Higgs mass → Hidden Valley with Higgs portal. Cosmology → HV particles are LLPs.	Any, but $\mathbb{Z}_2$ arguments favor lower $\hat{\Lambda}_{QCD}$ and hence long lifetimes.	Mirror glueballs with long lifetimes can only be discovered at MATHUSLA.	4.2	22, 23
WIMP Baryogenesis	Out-of-equilibrium decay of WIMP-like LLP produces baryon asymmetry.	For weak-scale LLP masses, n.	Decays to baryons → MATHUSLA likely much greater sensitivity than main detectors. MCFODO	6.1	32

mirror glueballs from Higgs decays



mirror neutrinos from Higgs decays that cause asymmetric reheating



Nathaniel Craig, David Curtin, Yuhsin Tsai MATHUSLA Physics Case, June 2018

1) intrinsic

BSM Scenario	Role of LLPs	Typical $c\tau$	Role of MATHUSLA	Sec.	Fig.
Neutral Naturalness	Discrete symmetry stabilizing Higgs mass → Hidden Valley with Higgs portal. Cosmology → HV particles are LLPs.	Any, but $\mathbb{Z}_2$ arguments favor lower $\hat{\Lambda}_{QCD}$ and hence long lifetimes.	Mirror glueballs with long lifetimes can only be discovered at MATHUSLA.	4.2	22, 23
WIMP Baryogenesis	**Out-of-equilibrium decay of WIMP-like LLP produces baryon asymmetry.**	**For weak-scale LLP masses, ≳ 1cm - 1m**	**Decays to baryons → MATHUSLA likely much greater sensitivity than main detectors. MCFODO**	6.1	32
FIMP DM	Freeze-in via decay requires LLPs with SM couplings.	Fixed by masses & cosmology. Long lifetimes generic.	Model-dependent, but in long-lifetime regime MCFODO.	5.3	27, 28, 21,
Co-decaying DM				5.4.3	31
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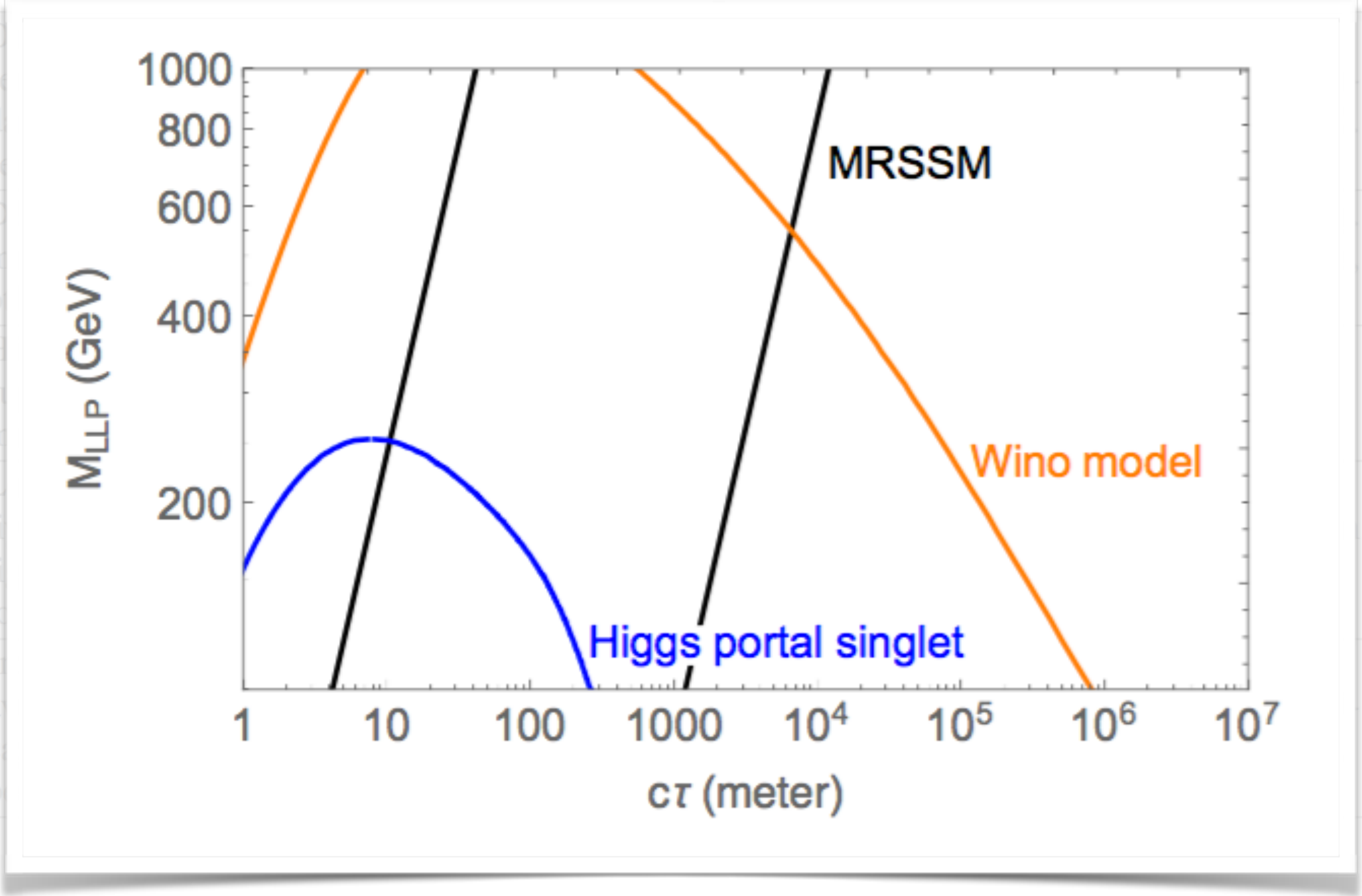
SUSY: Axinos				4.1.5	21
SUSY: GMSB				4.1.2	15
SUSY: RPV				4.1.1	14



Yanou Cui, Seyda Ipek

1) intrinsic

BSM Scenario	Role of LLPs	Typical $c\tau$	Role of MATHUSLA	Sec.	Fig.
Neutral Naturalness	Discrete symmetry stabilizing Higgs mass → Hidden Valley with Higgs portal. Cosmology → HV particles are LLPs.	Any, but $\mathbb{Z}_2$ arguments favor lower $\hat{\Lambda}_{QCD}$ and hence long lifetimes.	Mirror glueballs with long lifetimes can only be discovered at MATHUSLA.	4.2	22, 23
WIMP Baryogenesis	Out-of-equilibrium decay of WIMP-like LLP produces baryon asymmetry.	For weak-scale LLP masses, $\gtrsim$ 1-100 m.	Decays to baryons → MATHUSLA likely much greater sensitivity than main detectors. MCFODO	6.1	32
FIMP DM	Freeze-in via decay requires LLPs with SM couplings.	Fixed by masses & cosmology. Long lifetimes generic.	Model-dependent, but in long-lifetime regime MCFODO.	5.3	27, 28, 21,
Co-decaying DM	Out-of-equilibrium decay of hidden sector LLP determines DM abundance. Also, small portal → visible sector LLPs.	For weak scale LLP masses, most of parameter space is long lifetimes.	Depending on model details (production & decay mode), MCFODO.	5.4.3	31
Co-annihilating DM	DM relic abundance relies on small mass splitting with another state → other state is LLP.	Any, long lifetimes generic.	Depends on model details, but e.g. for Higgs Portal implementations, MCFODO.	5.5	
SUSY: Axinos	High PQ-breaking scale V_{PQ} suppresses axion/axino couplings, making LOSP an LLP	Any, long lifetimes generic.	For high V_{PQ}, MCFODO.	4.1.5	21
SUSY: GMSB	Low SUSY breaking scale F (motivated by flavor problem) leads to light gravitino and small couplings to LOSP, which can hence be LLP.	Any, long lifetimes generic.	MCFODO, depending on spectrum and lifetime.	4.1.2	15
SUSY: RPV	small RPV couplings (motivated by avoiding flavor violation, proton decay, baryon washout) → LOSP can be LLP	Any, long lifetimes generic.	MCFODO, especially for EW-charged LSPs or squeezed spectra.	4.1.1	14

1) intrinsic

BSM Scenario	Role of LLPs	Typical		ig.
Neutral Naturalness	Discrete symmetry stabilizing Higgs mass → Hidden Valley with Higgs portal. Cosmology → HV particles are LLPs.	Any, but ments fa $\hat{\Lambda}_{QCD}$ a long lifet		2, 3
WIMP Baryogenesis	Out-of-equilibrium decay of WIMP-like LLP produces baryon asymmetry.	For w LLP $\gtrsim$ 1-100		2
FIMP DM	Freeze-in via decay requires LLPs with SM couplings.	Fixed by cosmolog lifetimes		
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Co-annihilating DM	DM relic abundance r mass splitting with an other state is LLP.	del details, but e.g. l implementations,	5.5	
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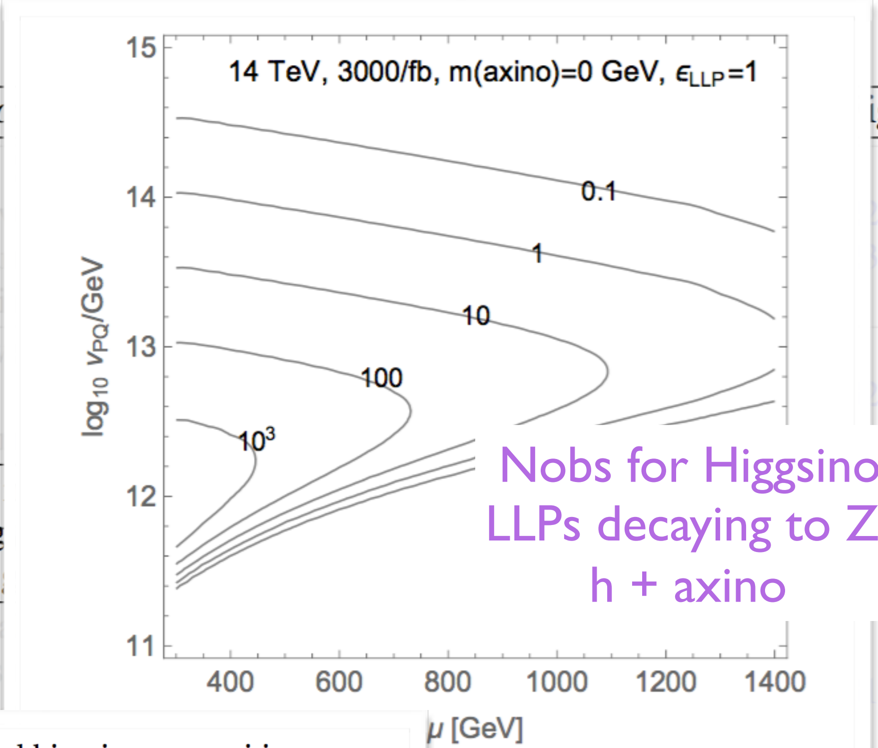
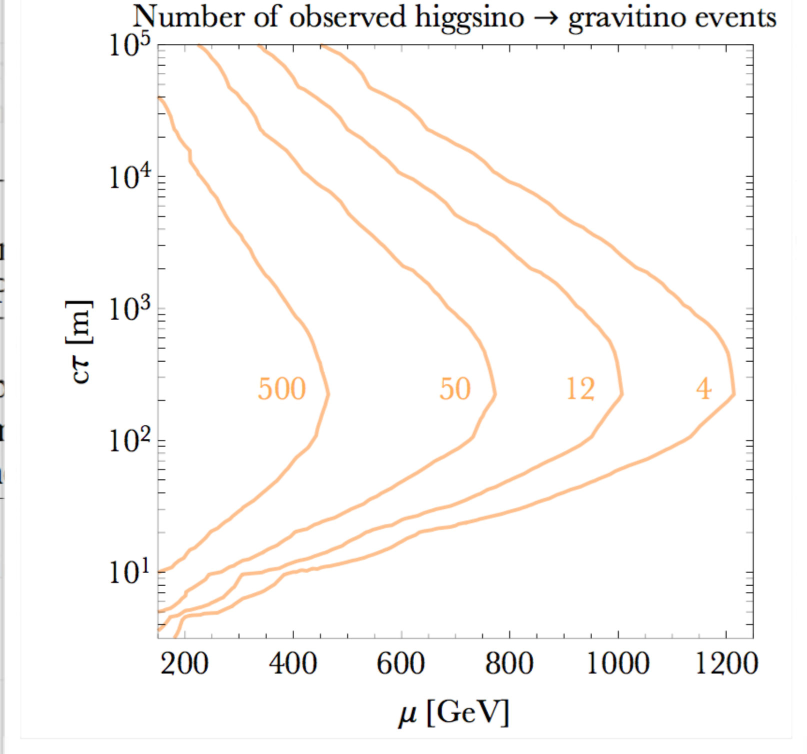


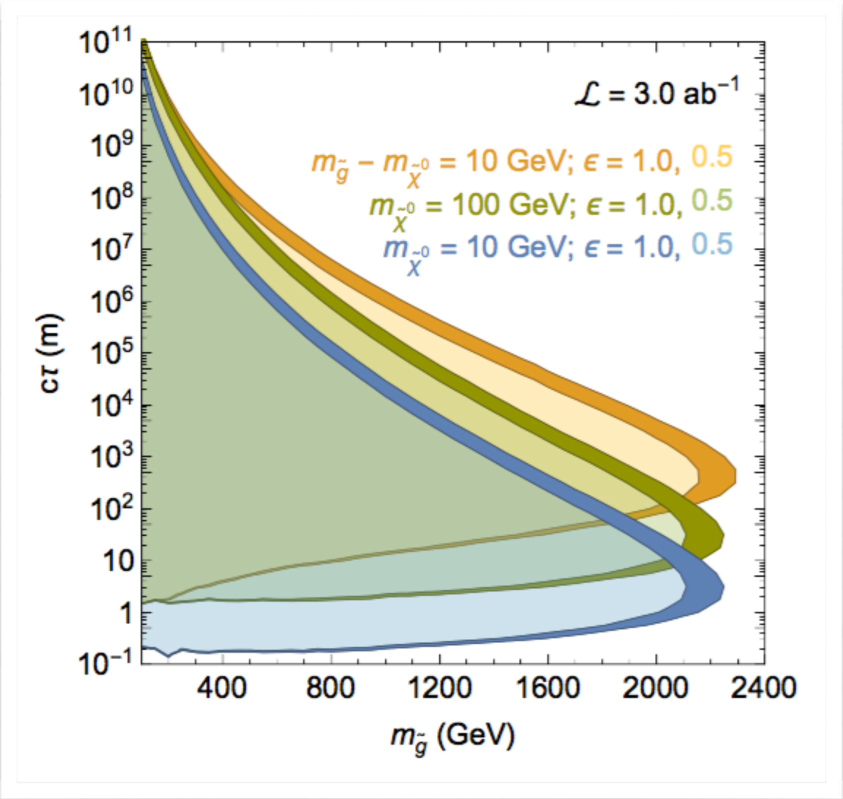
Nobs for Higgsino LLPs decaying to Z/h + axino

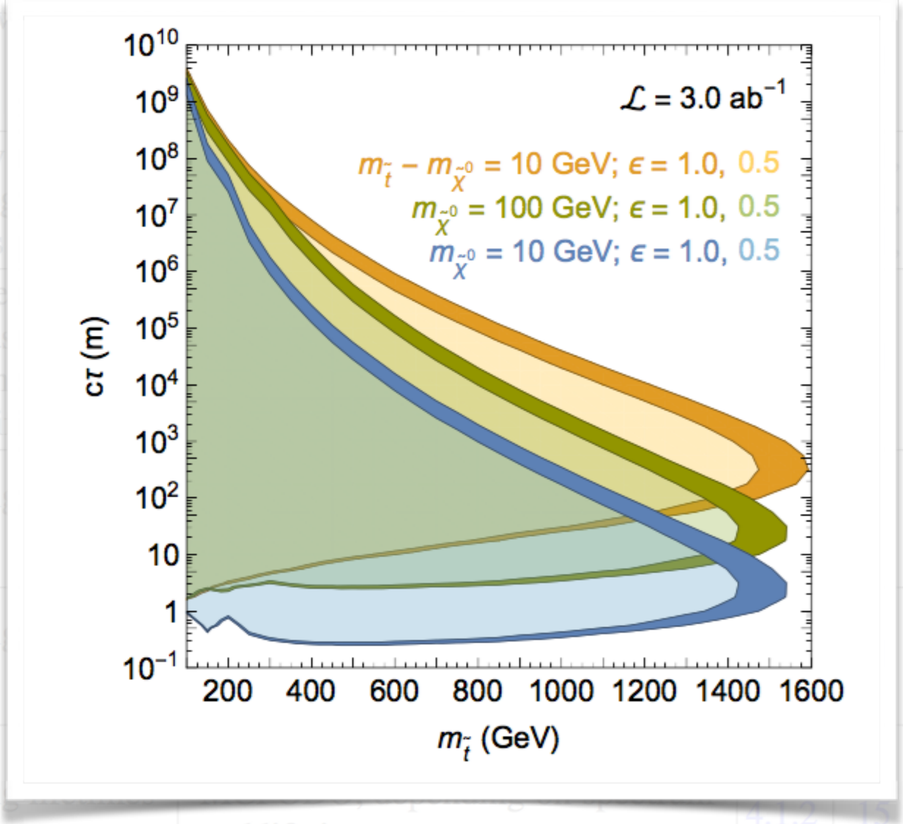

Number of observed higgsino → gravitino events

Matthew Reece, Eung Jin Chun, Sunghoon Jung

1) intrinsic

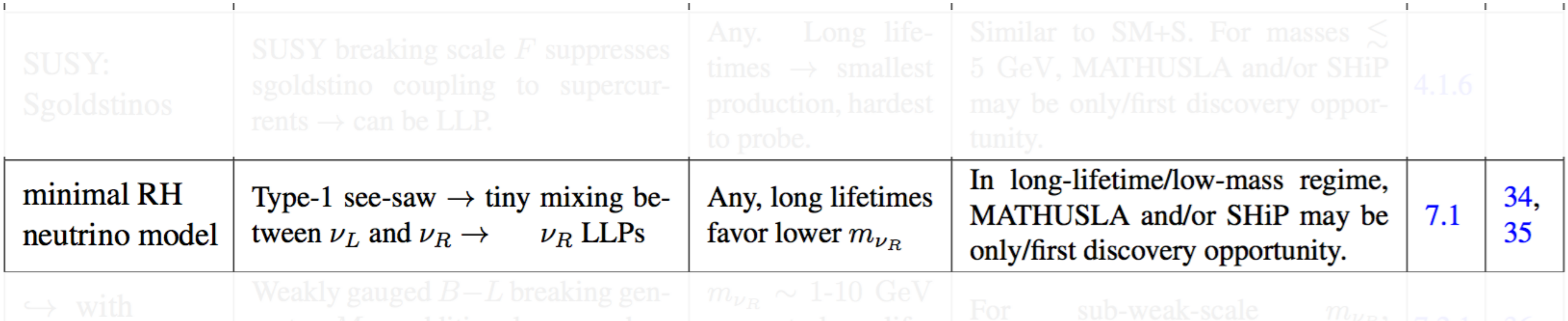
BSM Scenario	Role of LLPs	Typical $c\tau$	Role of MATHUSLA	Sec.	Fig.
Neutral Naturalness	Discrete symmetry stabilizing Higgs mass → Hidden Valley with Higgs portal. Cosmology → HV particles are LLPs.	Any, but $\mathbb{Z}_2$ arguments favor lower $\hat{\Lambda}_{QCD}$ and hence long lifetimes.	Mirror glueballs with long lifetimes can only be discovered at MATHUSLA.	4.2	22, 23
V F		or LP 1-100			
F		ixed by osmolog fetimes			
C I		or we LP ma f param long li			
C I		ny, lon eneric.			
S		ny, lon eneric.			
SUSY: GMSB	light gravitino and small couplings to LOSP, which can hence be LLP.	ny, lon generic.	and lifetime.	4.1.2	15
SUSY: RPV	small RPV couplings (motivated by avoiding flavor violation, proton decay, baryon washout) → LOSP can be LLP	Any, long lifetimes generic.	MCFODO, especially for EW-charged LSPs or squeezed spectra.	4.1.1	14





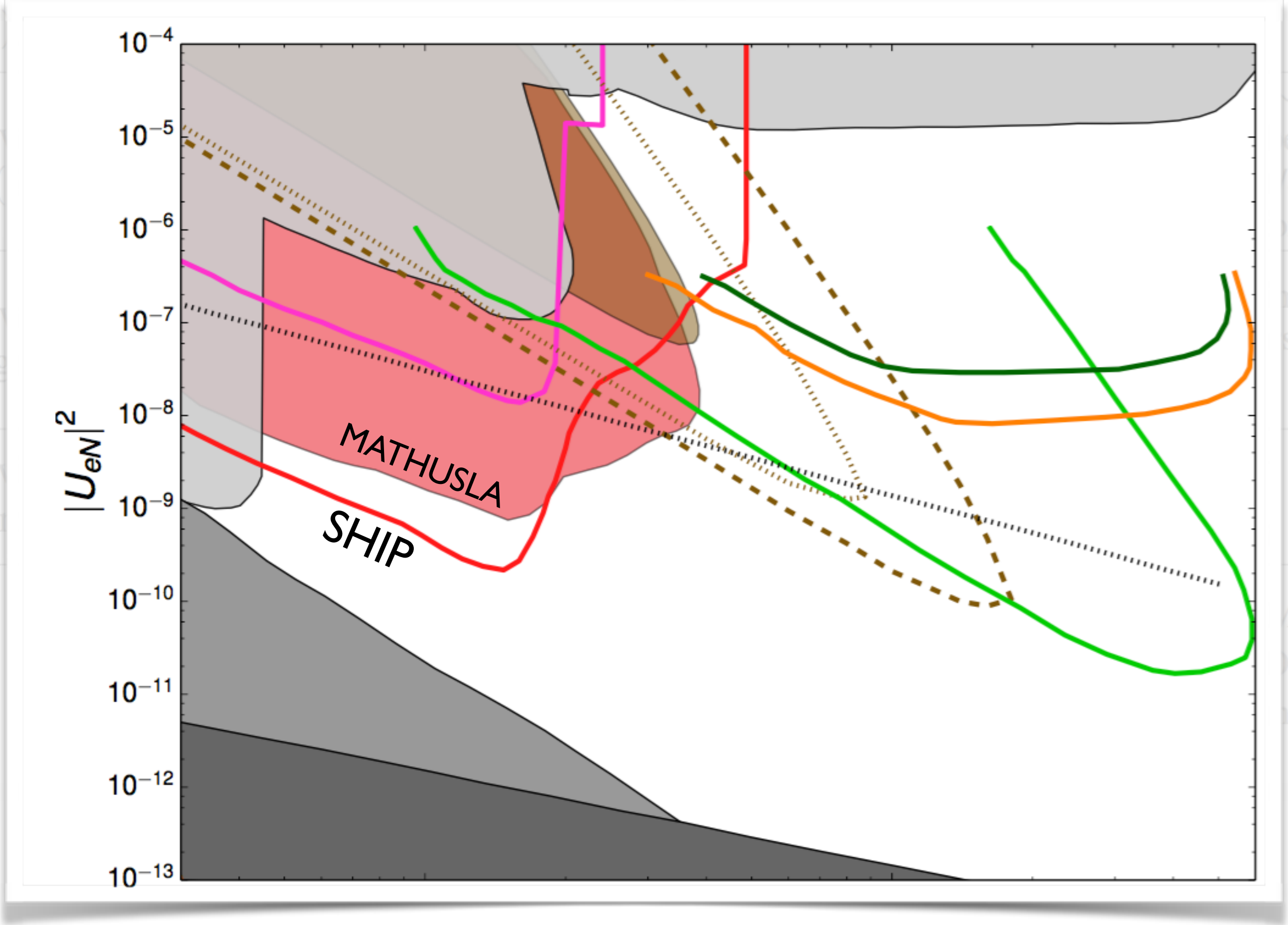
Csaba Csaki, Eric Kuflik, Salvator Lombardo, Jared Evans, Brock Tweedie, Tim Cohen, Zhen Liu, Patrick Meade

1) intrinsic



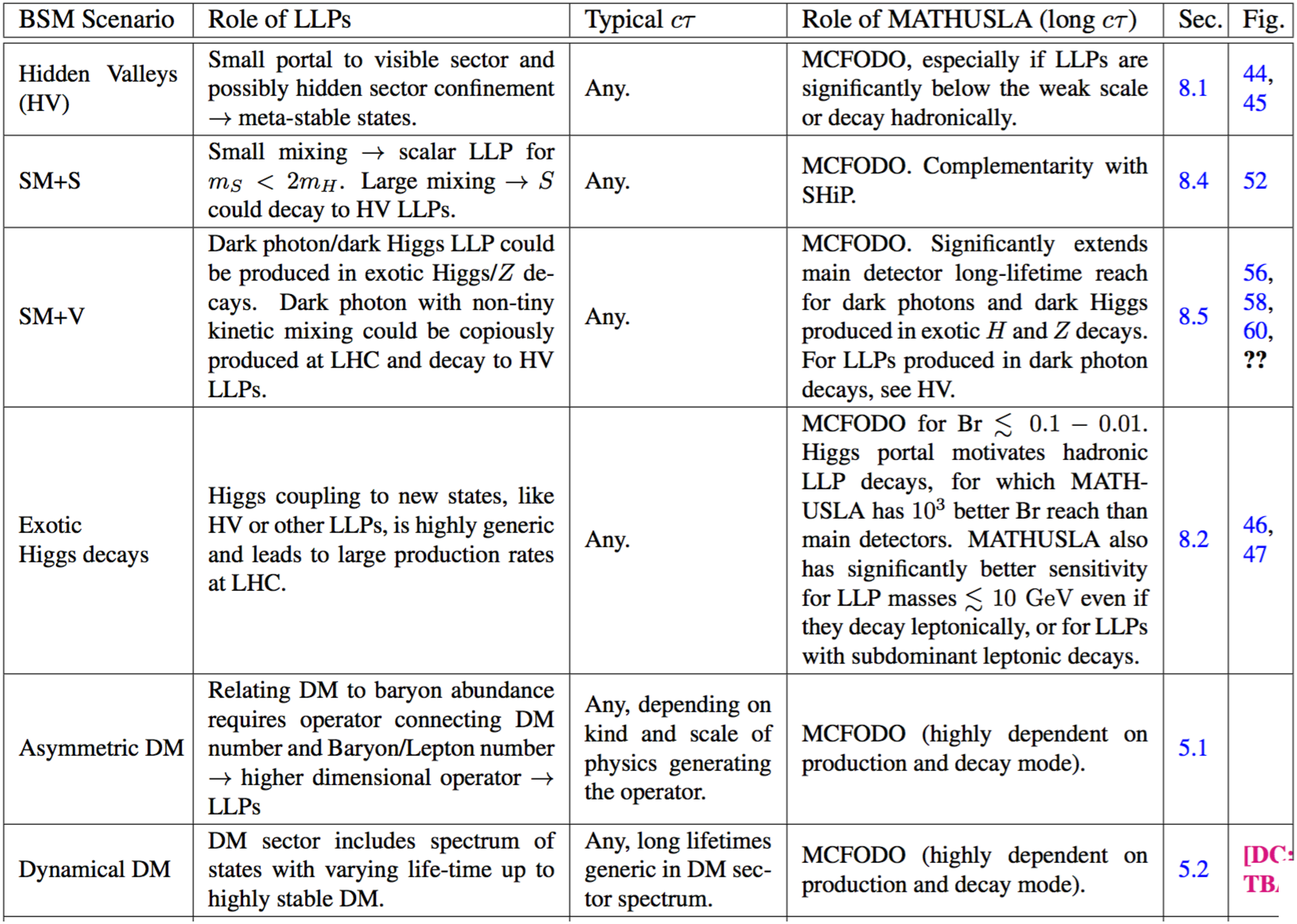
SUSY: Sgoldstinos	SUSY breaking scale F suppresses sgoldstino coupling to supercurrents → can be LLP.	Any. Long lifetimes → smallest production, hardest to probe.	Similar to SM+S. For masses $\lesssim$ 5 GeV, MATHUSLA and/or SHiP may be only/first discovery opportunity.	4.1.6	
minimal RH neutrino model	Type-1 see-saw → tiny mixing between ν_L and ν_R → ν_R LLPs	Any, long lifetimes favor lower m_{ν_R}	In long-lifetime/low-mass regime, MATHUSLA and/or SHiP may be only/first discovery opportunity.	7.1	34, 35
↪ with $U(1$	Weakly gauged $B-L$ breaking gen-	$m_{\nu_R} \sim$ 1-10 GeV	For sub-weak-scale m_{ν_R},	7.2.1	36
↪ w $SU($			∼ 10 TeV: main es weak-scale m_{ν_R}; SHiP only discovery r $m_{\nu_R} \lesssim$ 5 GeV.	7.3.1	38
↪ w Higg			mproves Br reach of s by at least order of	7.4	41
m_ν sym			EW charge → especially for	7.5	

ATHUSLA are a strongly nly Discovery Opportunity s the MATHUSLA regime.



S. Antusch, B. Batell, M. Drewes, O. Fischer, J. C. Helo, M. Hirsch, D. Gorbunov, J. M. No

2) generic

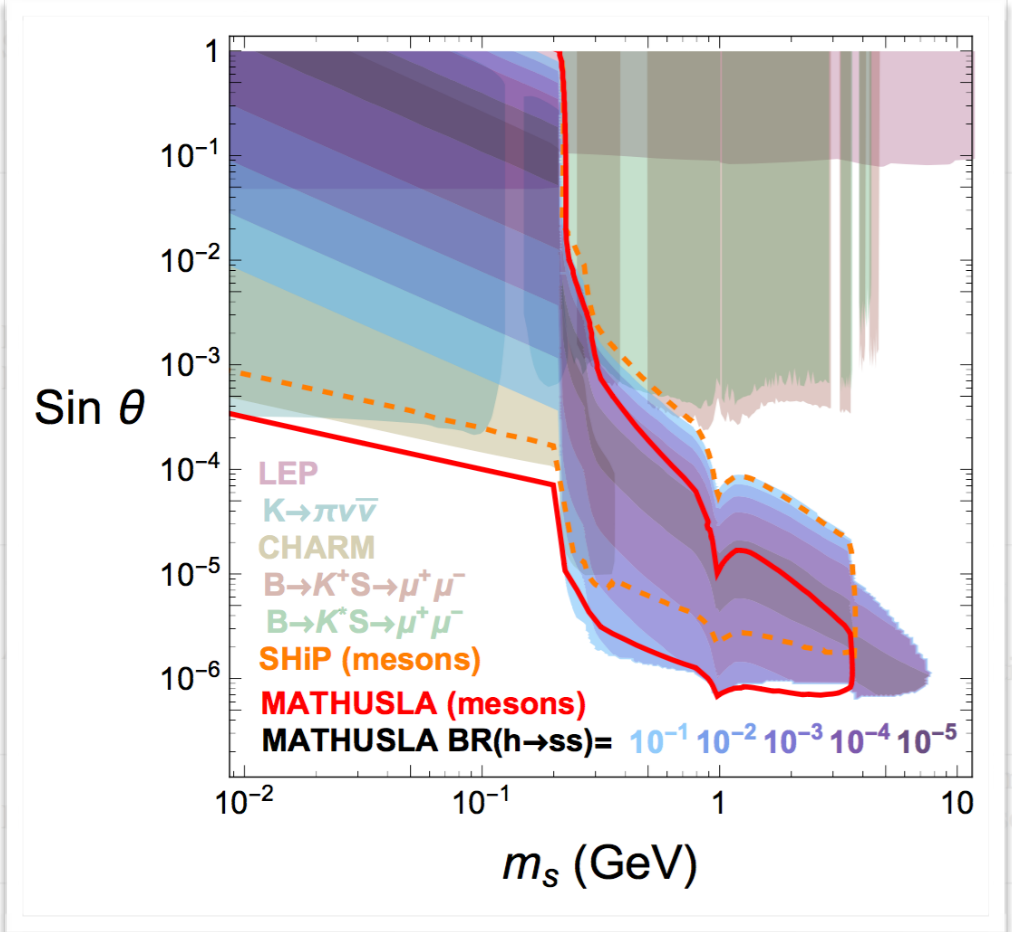


BSM Scenario	Role of LLPs	Typical $c\tau$	Role of MATHUSLA (long $c\tau$)	Sec.	Fig.
Hidden Valleys (HV)	Small portal to visible sector and possibly hidden sector confinement → meta-stable states.	Any.	MCFODO, especially if LLPs are significantly below the weak scale or decay hadronically.	8.1	44, 45
SM+S	Small mixing → scalar LLP for $m_S < 2m_H$. Large mixing → S could decay to HV LLPs.	Any.	MCFODO. Complementarity with SHiP.	8.4	52
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.	Any.	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.	8.5	56, 58, 60, **??**
Exotic Higgs decays	Higgs coupling to new states, like HV or other LLPs, is highly generic and leads to large production rates at LHC.	Any.	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.	8.2	46, 47
Asymmetric DM	Relating DM to baryon abundance requires operator connecting DM number and Baryon/Lepton number → higher dimensional operator → LLPs	Any, depending on kind and scale of physics generating the operator.	MCFODO (highly dependent on production and decay mode).	5.1	
Dynamical DM	DM sector includes spectrum of states with varying life-time up to highly stable DM.	Any, long lifetimes generic in DM sector spectrum.	MCFODO (highly dependent on production and decay mode).	5.2	**[DC:** **TB**

MATHUSLA Physics Case, June 2018

2) generic

BSM Scenario	Role of LLPs	Typical $c\tau$	Role of MATHUSLA (long $c\tau$)	Sec.	Fig.
Hidden Valleys (HV)	Small portal to visible sector and possibly hidden sector confinement → 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 → scalar LLP for $m_S < 2m_H$. Large mixing → S could decay to HV LLPs.	Any.	MCFODO. Complementarity with SHiP.	8.4	52
	Dark photon/dark Higgs LLP could be produced in exotic Higgs/Z de-		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.	8.5	56, 58, 60, ??
			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.	8.2	46, 47
	on of ing		MCFODO (highly dependent on production and decay mode).	5.1	
	nes ec-		MCFODO (highly dependent on production and decay mode).	5.2	[DC: TB.



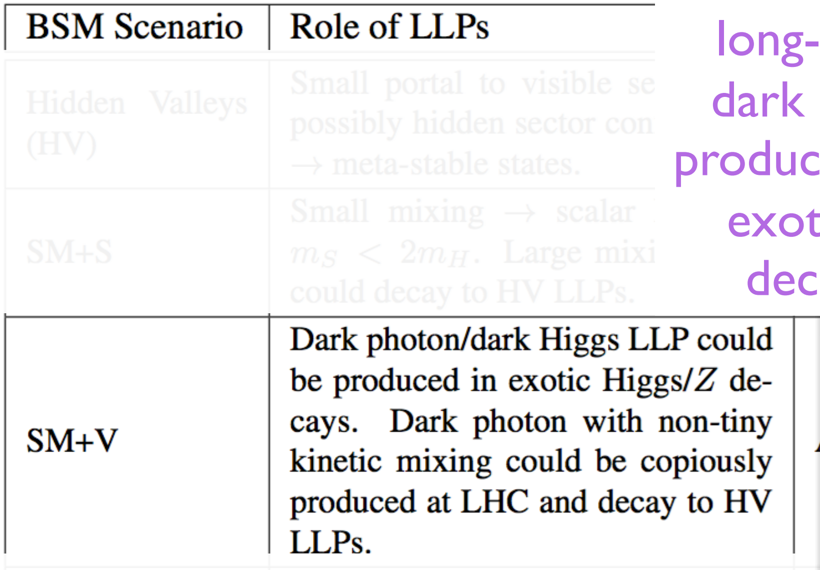
2) generic

Nikita Blinov, Jae Hyeok Chang, David Curtin, Rouven Essig, Brian Shuve

BSM Scenario	Role of LLPs	Typical $c\tau$	Role of MATHUSLA (long $c\tau$)	Sec.	Fig.
Hidden Valleys (HV)	Small portal to visible sector and possibly hidden sector confinement → 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 → scalar LLP for $m_S < 2m_H$. Large mixing → S could decay to HV LLPs.	Any.	MCFODO. Complementarity with SHiP.	8.4	52
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.	Any.	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.	8.5	56, 58, 60, ??
Exotic Higgs decays	Higgs coupling to new states, like HV or other LLPs, is highly generic and leads to large production rates at LHC.	Any.	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.	8.2	46, 47
Asymmetric DM	Relating DM to baryon abundance requires operator connecting DM number and Baryon/Lepton number → higher dimensional operator → LLPs	Any, depending on kind and scale of physics generating the operator.	MCFODO (highly dependent on production and decay mode).	5.1	
Dynamical DM	DM sector includes spectrum of states with varying life-time up to highly stable DM.	Any, long lifetimes generic in DM sector spectrum.	MCFODO (highly dependent on production and decay mode).	5.2	[DC: TB

2) generic

Nikita Blinov, Jae Hyeok Chang, David Curtin, Rouven Essig, Brian Shuve



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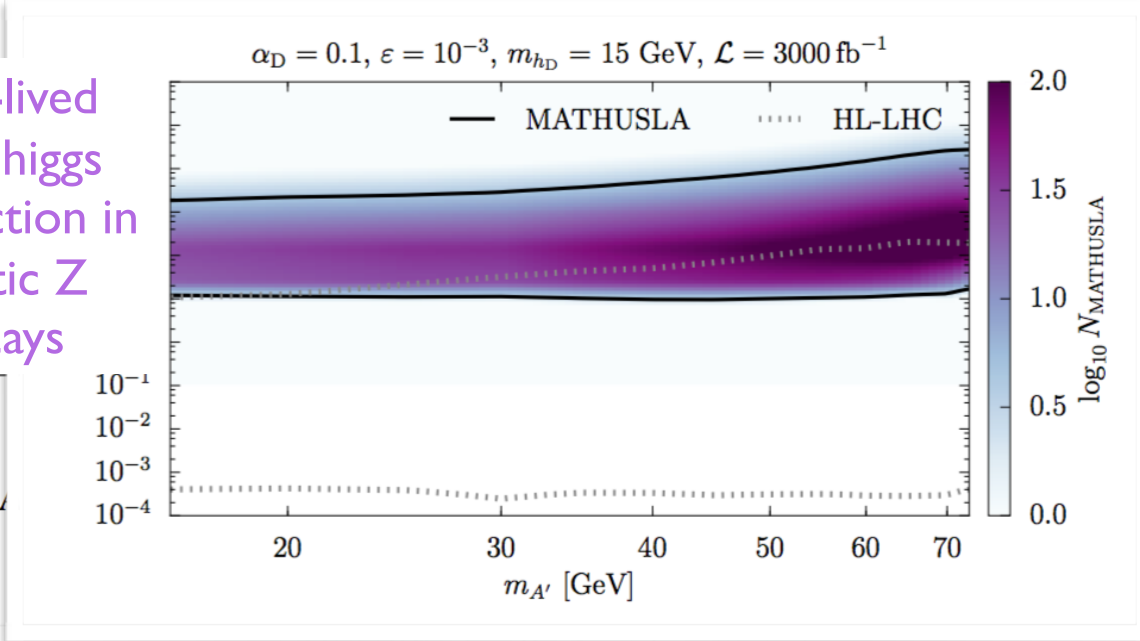
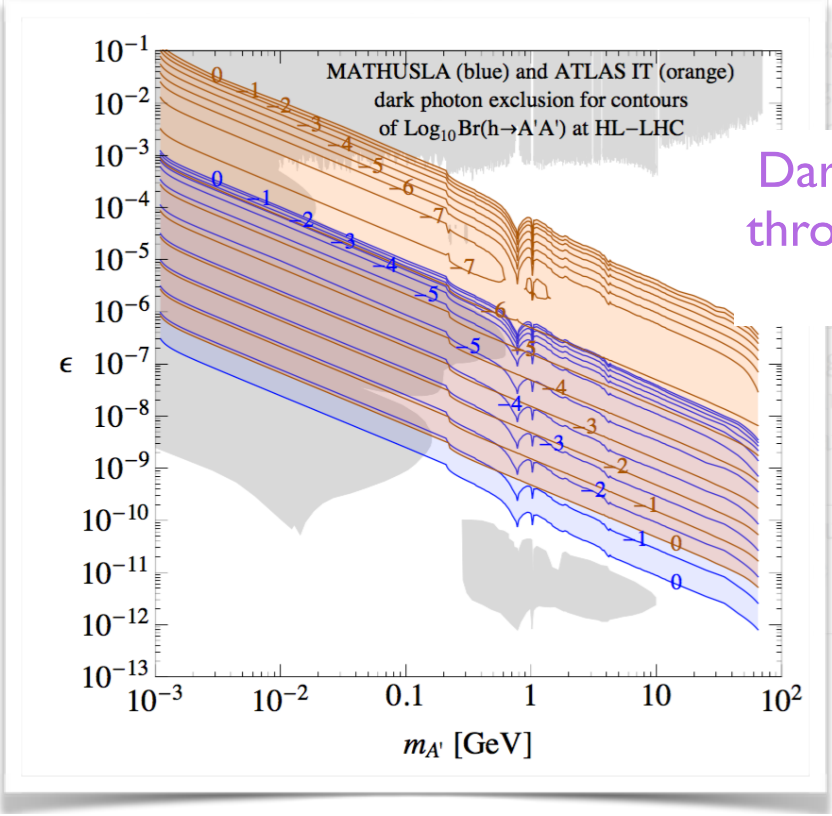
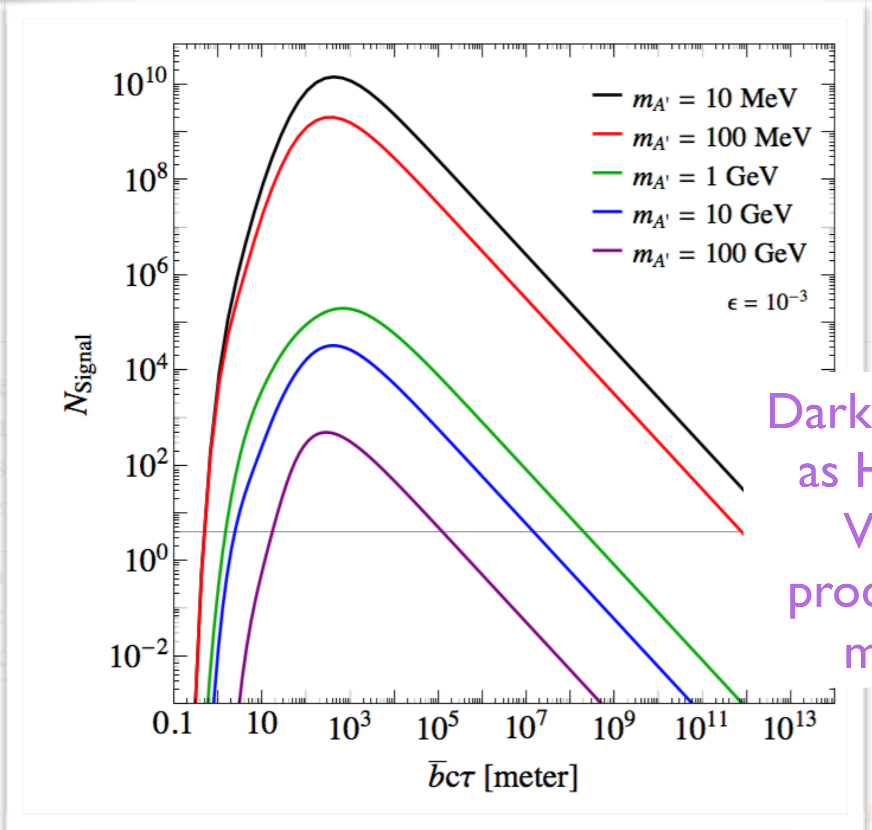
SM+V	Dark photon/dark Higgs LLP could be produced in exotic Higgs/Z decays. Dark photon with non-tiny kinetic mixing could be copiously produced at LHC and decay to HV LLPs.

long-lived dark higgs production in exotic Z decays



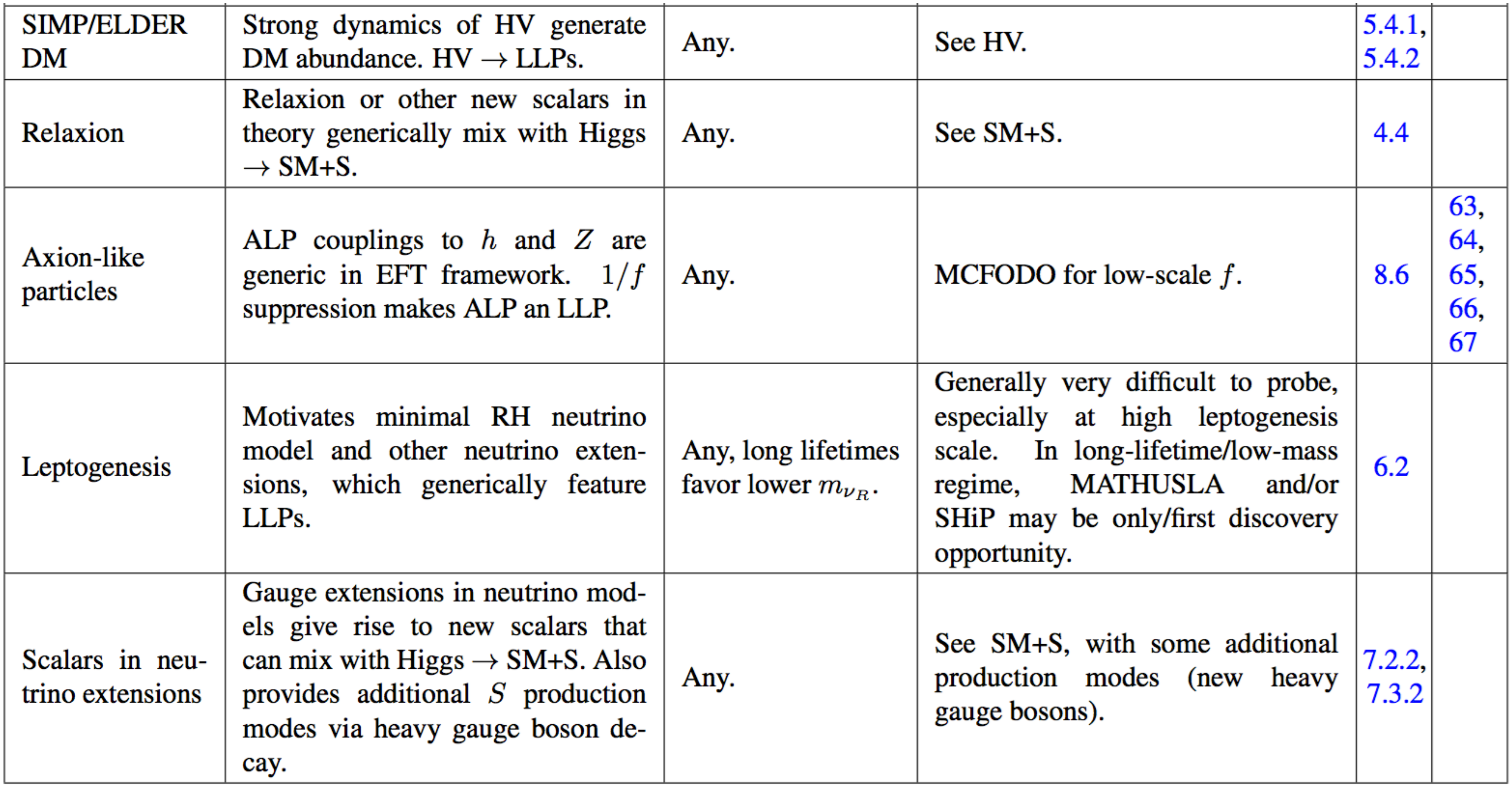


Dark photon through Higgs portal

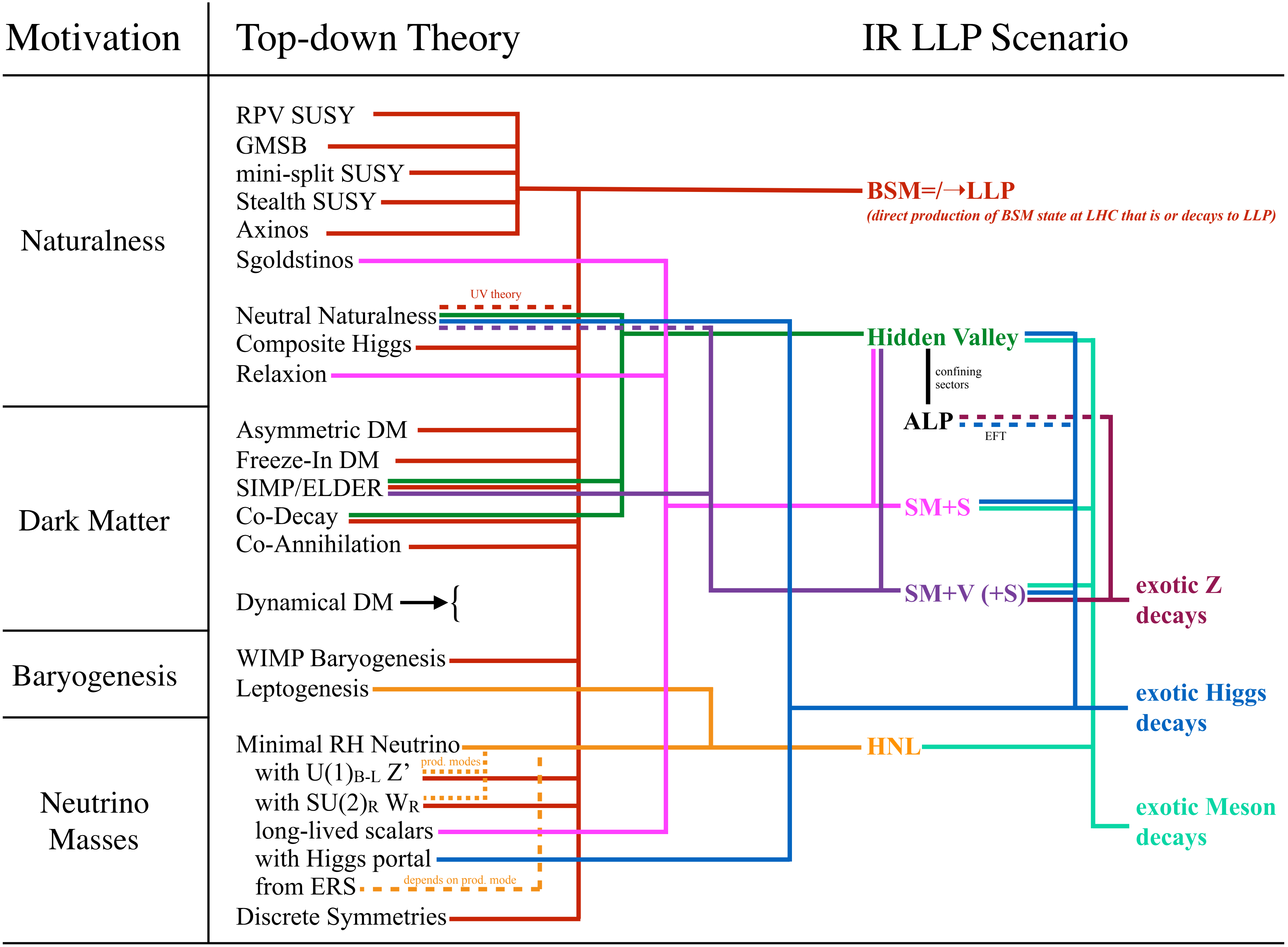


Dark photon as Hidden Valley production mode

2) generic



SIMP/ELDER DM	Strong dynamics of HV generate DM abundance. HV → LLPs.	Any.	See HV.	5.4.1, 5.4.2	
Relaxion	Relaxion or other new scalars in theory generically mix with Higgs → SM+S.	Any.	See SM+S.	4.4	
Axion-like particles	ALP couplings to h and Z are generic in EFT framework. $1/f$ suppression makes ALP an LLP.	Any.	MCFODO for low-scale f.	8.6	63, 64, 65, 66, 67
Leptogenesis	Motivates minimal RH neutrino model and other neutrino extensions, which generically feature LLPs.	Any, long lifetimes favor lower m_{ν_R}.	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.	6.2	
Scalars in neutrino extensions	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.	Any.	See SM+S, with some additional production modes (new heavy gauge bosons).	7.2.2, 7.3.2	



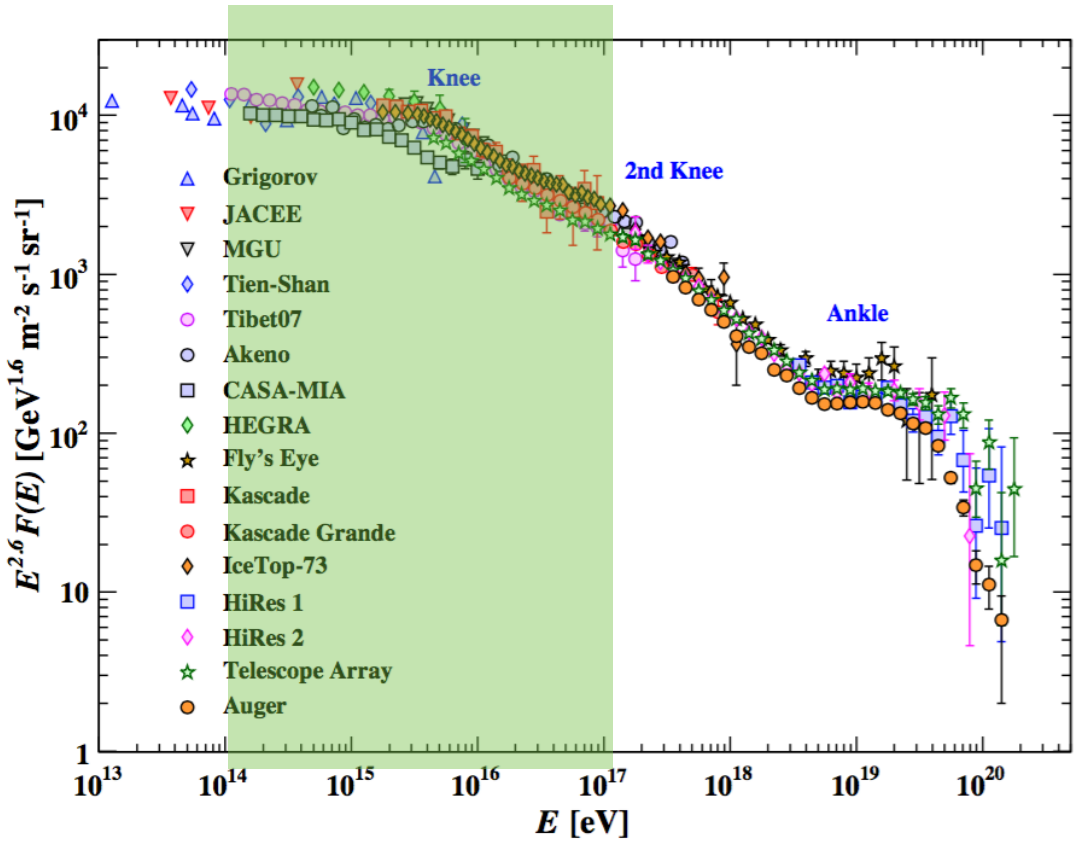
MATHUSLA Physics Case, June 2018

5. Bonus: Cosmic Ray Physics

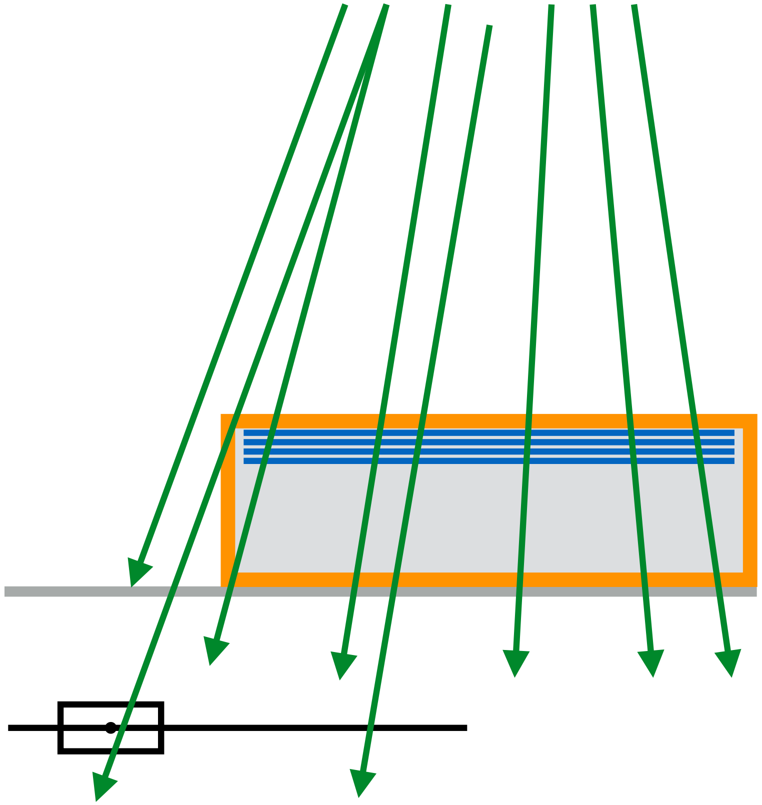
Cosmic Ray Physics @ MATHUSLA

MATHUSLA is an excellent Cosmic Ray Telescope!

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



~90% e, ~10% μ, 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/FASER 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! —

NB: some thoughts on relationship between various LLP detector proposals

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)

CODEX-b

Gligorov, Knapen, Papucci, Robinson, 1708.09395

Dedicated DV detector underground, in existing caviity near LHCb

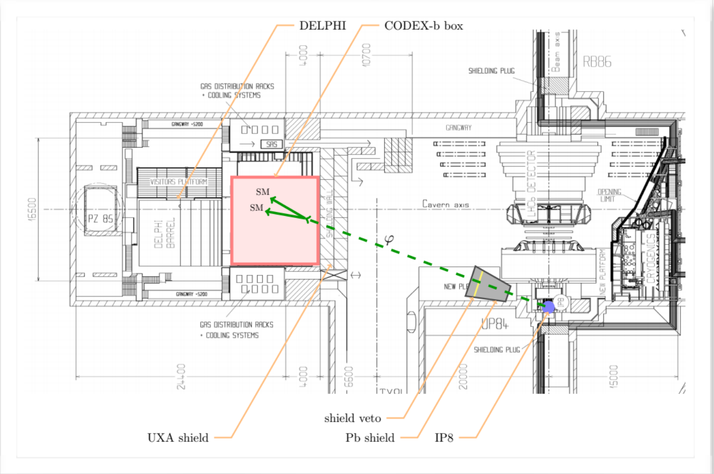
\+ Definitely more affordable than something on MATHUSLA scale

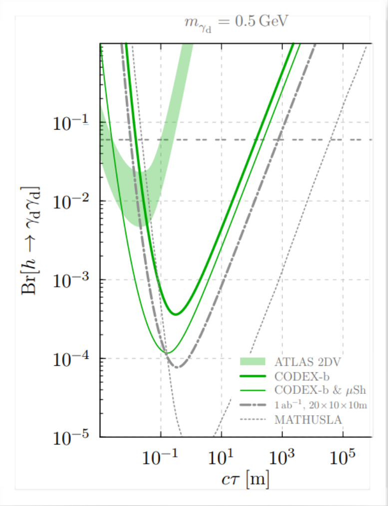
\+ Probably easier to instrument for < 10-100 MeV mass regime, and maybe even calorimetry/particle ID for detailed LLP investigations

\- 1/200 MATHUSLA sensitivity, 1/50 if we burn out VELO with 1/ab

→ *scale down R_s by same factor*

Important detailed question for future: how does cost/capabilities compare to similar-reach surface detector?

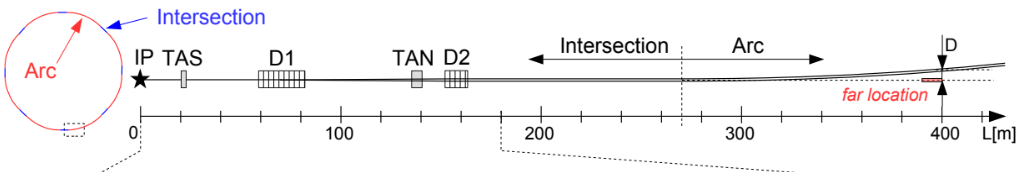




FASER, MATHUSLA and SHiP *(light LLPs)*

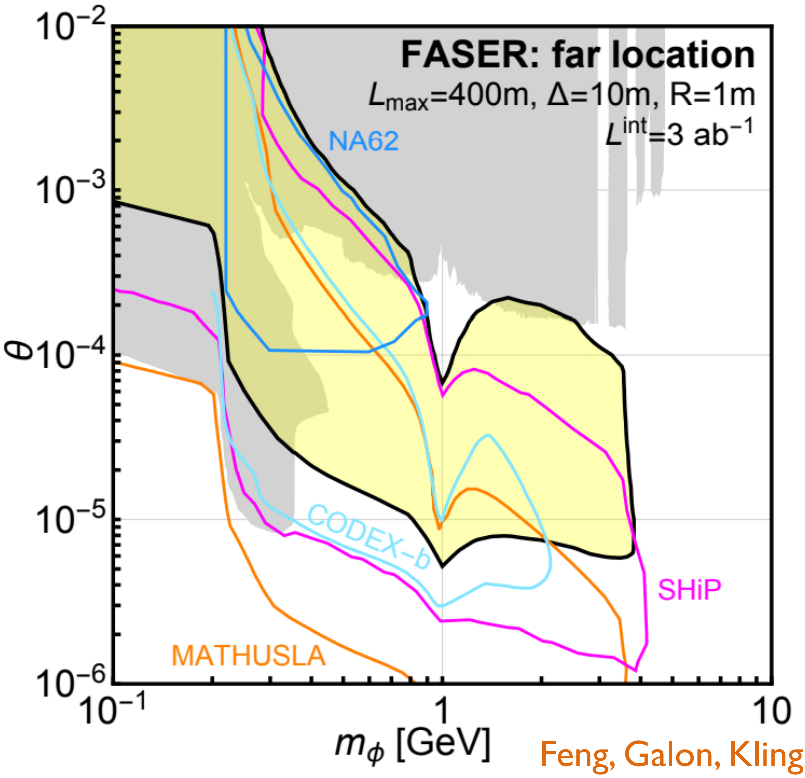
SHiP: For shorter lifetimes and mass < ~ 10 MeV, SHiP is much better.
MATHUSLA access higher scale physics and sees 10-100 more LLPs from exotic meson decays if lifetime >> 100m.

FASER: "small" cylindrical (R = 0.2m, L = 10m) 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.



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