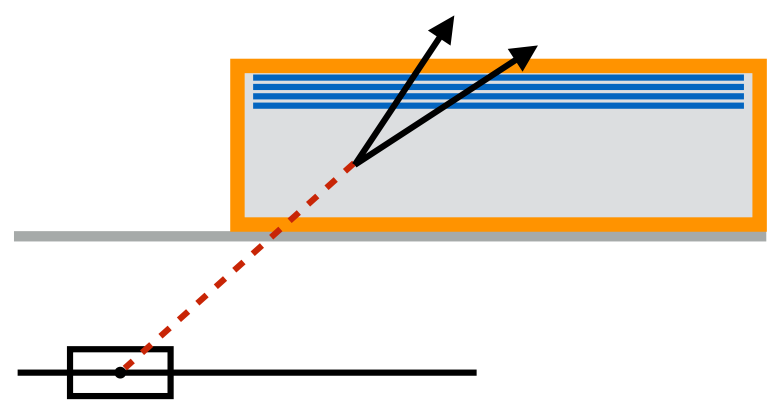
MATHUSLA Overview

MATHUSLA Workshop
Simons Center
Stony Brook University

27 August 2018

David Curtin

MATHUSLA



Context

MATHUSLA collaboration is working towards becoming "on-shell"

Long-Lived Particles at the Energy Frontier: The MATHUSLA Physics Case

1806.07396

Editors:
David Curtin[1], Marco Drewes[2], Matthew McCullough[3], Patrick Meade[4], Rabindra Mohapatra[5], Jessie Shelton[6], Brian Shuve[7,8].

Contributors:
Elena Accomando[9], Cristiano Alpigiani[10], Stefan Antusch[11], Juan Carlos Arteaga-Velázquez[12], Brian Batell[13], Martin Bauer[14], Nikita Blinov[8], Karen Salomé Caballero-Mora[15,16], Jae Hyeok Chang[4], Eung Jin Chun[17], Raymond T. Co[18], Timothy Cohen[19], Peter Cox[20], Nathaniel Craig[21], Csaba Csáki[22], Yanou Cui[23], Francesco D'Eramo[24], Luigi Delle Rose[25], P. S. Bhupal Dev[26], Keith R. Dienes[27,5], Jeff A. Dror[28,29], Rouven Essig[4], Jared A. Evans[30,6], Jason L. Evans[17], Arturo Fernández Tellez[31], Oliver Fischer[32], Thomas Flacke[33], Anthony Fradette[34], Claudia Frugiuele[35], Elina Fuchs[35], Tony Gherghetta[36], Gian F. Giudice[3], Dmitry Gorbunov[37,38], Rick S. Gupta[39], Claudia Hagedorn[40], Lawrence J. Hall[28,29], Philip Harris[41], Juan Carlos Helo[42,43], Martin Hirsch[44], Yonit Hochberg[45], Anson Hook[5], Alejandro Ibarra[46,17], Seyda Ipek[47], Sunghoon Jung[48], Simon Knapen[29,28], Eric Kuflik[45], Zhen Liu[49], Salvator Lombardo[22], Henry Lubatti[10], David McKeen[50], Emiliano Molinaro[51], Stefano Moretti[9,52], Natsumi Nagata[53], Matthias Neubert[54,22], Jose Miguel No[55,56], Emmanuel Olaiya[52], Gilad Perez[35], Michael E. Peskin[8], David Pinner[57,58], Maxim Pospelov[59,34], Matthew Reece[57], Dean J. Robinson[30], Mario Rodríguez Cahuantzi[31], Rinaldo Santonico[60], Matthias Schlaffer[35], Claire H. Shepherd-Themistocleous[52], Andrew Spray[33], Daniel Stolarski[61], Martin A. Subieta Vasquez[62,63], Raman Sundrum[5], Andrea Thamm[3], Brooks Thomas[64], Yuhsin Tsai[5], Brock Tweedie[13], Stephen M. West[65], Charles Young[8], Felix Yu[54], Bryan Zaldivar[55,66], Yongchao Zhang[26,67], Kathryn Zurek[29,28,3], José Zurita[32,68].

A Letter of Intent for MATHUSLA: a dedicated displaced vertex detector above ATLAS or CMS

Cristiano Alpigiani,[a] Austin Ball,[o] Liron Barak,[c] James Beacham,[ah] Yan Benhammo,[c] Tingting Cao,[c] Paolo Camarri,[f,g] Roberto Cardarelli,[f] Mario Rodríguez-Cahuantzi,[h] John Paul Chou,[d] David Curtin,[b] Miriam Diamond,[e] Giuseppe Di Sciascio,[f] Marco Drewes,[x] Sarah C. Eno,[u] Erez Etzion,[c] Rouven Essig,[q] Jared Evans,[v] Oliver Fischer,[w] Stefano Giagu,[k] Brandon Gomes,[d] Andy Haas,[l] Yuekun Heng,[z] Giuseppe Iaselli,[aa] Ken Johns,[m] Muge Karagoz,[u] Luke Kasper,[d] Audrey Kvam,[a] Dragoslav Lazic,[ae] Liang Li,[af] Barbara Liberti,[f] Zhen Liu,[y] Henry Lubatti,[a] Giovanni Marsella,[n] Matthew McCullough,[o] David McKeen,[p] Patrick Meade,[q] Gilad Mizrachi,[c] David Morrissey,[p] Meny Raviv Moshe,[c] Karen Salomé Caballero-Mora,[j] Piter A. Paye Mamani,[ab] Antonio Policicchio,[k] Mason Proffitt,[a] Marina Reggiani-Guzzo,[ad] Joe Rothberg,[a] Rinaldo Santonico,[f,g] Marco Schioppa,[ag] Jessie Shelton,[t] Brian Shuve,[s] Martin A. Subieta Vasquez,[ab] Daniel Stolarski,[r] Albert de Roeck,[o] Arturo Fernández Téllez,[h] Guillermo Tejeda Muñoz,[h] Mario Iván Martínez Hernández,[h] Yiftah Silver,[c] Steffie Ann Thayil,[d] Emma Torro,[a] Yuhsin Tsai,[u] Juan Carlos Arteaga-Velázquez,[i] Gordon Watts,[a] Charles Young,[e] Jose Zurita.[w,ac]

CERN-LHCC-2018-025

At this workshop, main goal is to make progress towards proposal for funding agencies & European Strategy, and incorporate feedback from our external review panel.

Thank you to Simons Center for hosting this workshop!

09:00	**welcome - opening**	*Luis Alvarez-Gaume*	*Simons center, Stony Brook, Simons Center for Geometry and Physics*	09:00 - 09:10
	Theory introductory talk (30+10)	*Michelangelo Mangano*	*Simons center, Stony Brook, Simons Center for Geometry and Physics*	09:10 - 09:50
10:00	**MATHUSLA overview in context of other experiments (30+10)**	*David Curtin*	*Simons center, Stony Brook, Simons Center for Geometry and Physics*	09:50 - 10:30
	coffee break		*Simons center, Stony Brook, Simons Center for Geometry and Physics*	10:30 - 10:50
11:00	**Cosmic Ray Physics at MATHUSLA (30+10)**	*Juan Carlos Arteaga*	*Simons center, Stony Brook, Simons Center for Geometry and Physics*	10:50 - 11:30
	MATHUSLA Test Stand Experimental Update	*Cristiano Alpigiani*	*Simons center, Stony Brook, Simons Center for Geometry and Physics*	11:30 - 11:50
12:00	**Update on Background Studies (30+10)**	*Gordon Watts*	*Simons center, Stony Brook, Simons Center for Geometry and Physics*	11:50 - 12:30
13:00	**LUNCH**		*Simons center, Stony Brook, Simons Center for Geometry and Physics*	12:30 - 13:40
14:00	**MATHUSLA Design Overview (30+10)**	*Erez Etzion et al.*	*Simons center, Stony Brook, Simons Center for Geometry and Physics*	13:40 - 14:20
15:00	**RPC Detectors for MATHUSLA (30+20)**	*Rinaldo Santonico et al.*	*Simons center, Stony Brook, Simons Center for Geometry and Physics*	14:20 - 15:10
16:00	**RPC or other options for MATHUSLA (30+20)**	*Yuekun Heng*	*Simons center, Stony Brook, Simons Center for Geometry and Physics*	15:10 - 16:00
	coffee break		*Simons center, Stony Brook, Simons Center for Geometry and Physics*	16:00 - 16:30
17:00	**Discussion session with Reviewers: Detector layout (technology independent, physics driven). Erez, Cristiano**			

Outline

1. Why look for LLPs at the LHC?
2. MATHUSLA Overview & outstanding issues
3. MATHUSLA in the context of other LLP detector proposals

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.

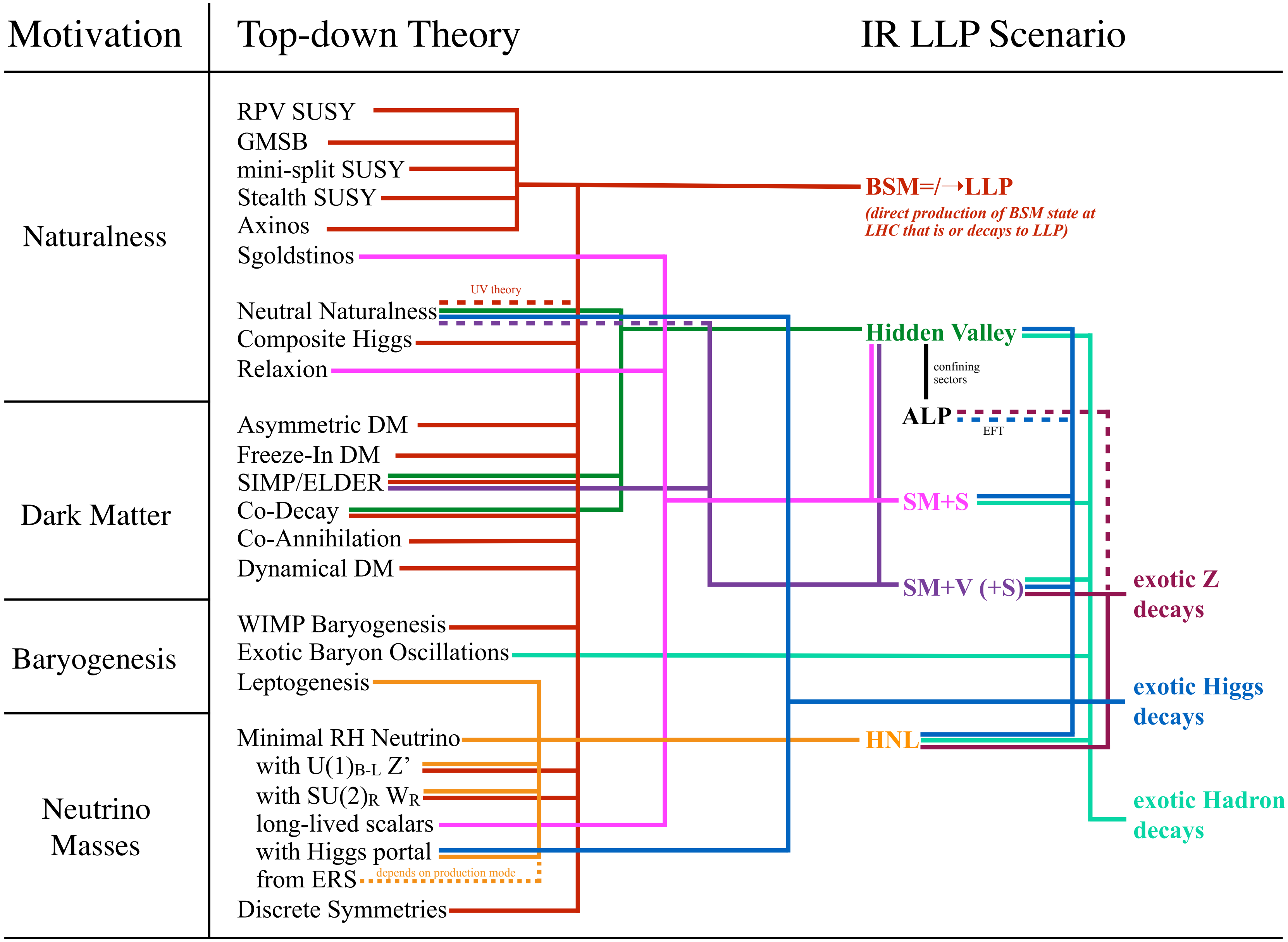
LHC is great for the *Lifetime Frontier* (energy x intensity)!
Very long-lived particles are inherently *rare* signals but you also want *high energy* to produce them via high-scale processes

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…

Long-Lived Particles at the Energy Frontier:
The MATHUSLA Physics Case 1806.07396



Long-Lived Particles at the Energy Frontier: The MATHUSLA Physics Case 1806.07396

BSM Scenario	Role of LLPs	Typical $c\tau$	Role of MATHUSLA	Sec.	Fig.
Neutral Naturalness	Discrete symmetry stabilizing Higgs mass $\rightarrow$ hidden valley with Higgs portal. Cosmology $\rightarrow$ hidden valley particles are LLPs.	Any, but $\mathbb{Z}_2$ arguments favor lower $\tilde{\Lambda}_{QCD}$ and hence long lifetimes.	Smoking gun signal are mirror glueball LLPs. For long lifetimes, they can only be discovered at MATHUSLA.	4.2	22, 23
WIMP Baryogenesis	Out-of-equilibrium decay of WIMP-like LLP produces baryon asymmetry.	$\gtrsim$ cm for weak-scale LLP masses.	Decays to baryons $\rightarrow$ MATHUSLA likely much greater sensitivity than main detectors. MCFODO	6.1	34
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 $\rightarrow$ 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 $\rightarrow$ other state is LLP.	Any, long lifetimes generic.	Depends on model details, but e.g. for Higgs Portal implementations, MCFODO.	5.1	
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) $\rightarrow$ LOSP can be LLP	Any, long lifetimes generic.	MCFODO, especially for EW-charged LLPs or squeezed spectra.	4.1.1	14
SUSY: Sgoldstinos	SUSY breaking scale F suppresses sgoldstino coupling to supercurrents $\rightarrow$ can be LLP.	Any. Long lifetimes $\rightarrow$ 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	
Exotic Baryon Oscillations	Exotic Baryon is LLP and induces oscillations that generate baryon number.	$\gtrsim$ 100m	Heavy baryon decays produce LLP. MATHUSLA and/or SHiP may be only/first discovery opportunity.	6.2	
minimal RH neutrino model	Type-1 see-saw $\rightarrow$ tiny mixing between ν_L and $\nu_R \rightarrow$ ν_R LLPs	Any, long lifetimes favor lower m_N	In long-lifetime/low-mass regime, MATHUSLA and/or SHiP may be only/first discovery opportunity.	7.1	36, 37
$\hookrightarrow$ with $U(1)_{B-L}$ Z'	Weakly gauged $B-L$ breaking generates M_N, additional ν_R production mode from Z'.	$m_N \sim$ 1-10 GeV suggests long lifetime regime.	For sub-weak-scale m_N, MCFODO.	7.2.1	38
$\hookrightarrow$ with $SU(2)_L$ W_R	ν_R part of gauged $SU(2)_R$, breaking generates M_N. Additional ν_R production mode from $W_R^{\pm}$.	Any, long lifetimes favor lower m_N.	For $m_{W_R} \sim$ 10 TeV: main detector probes weak-scale m_N. MATHUSLA/SHiP only discovery opportunity for $m_N \lesssim$ 5 GeV.	7.3.1	40
$\hookrightarrow$ with Higgs Portal	GUT motivates extra broken $U(1)$ gauge groups, extended scalar sectors mix with Higgs $\rightarrow$ produce ν_R in Higgs and other scalar decays.	Any, long lifetimes favor lower m_N.	MCFODO, improves Br reach of main detectors by at least order of magnitude.	7.4	43
m_ν via discrete symmetries	Discrete sym. generates m_ν and stabilizes FIMP DM.	See FIMP DM.	LLPs with EW charge $\rightarrow$ MCFODO, especially for $m \lesssim$ 10 GeV	7.5	

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 $\rightarrow$ meta-stable states.	Any.	MCFODO, especially if LLPs are significantly below the weak scale or decay hadronically.	8.1	46, 47
SM+S	Small mixing $\rightarrow$ scalar LLP, produce in exotic Higgs decays for $m_S < m_H/2$. Large mixing $\rightarrow$ S could decay to HV LLPs.	Any.	MCFODO. Complementarity with SHiP.	8.4	55
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	59, 61, 63, 64
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	48, 49
Asymmetric DM	Relating DM to baryon abundance requires operator connecting DM number and Baryon/Lepton number $\rightarrow$ higher dimensional operator $\rightarrow$ LLPs	Any, depending on kind and scale of physics generating the operator.	MCFODO (highly dependent on production and decay mode).	5.2	
Dynamical DM	Dark sector includes spectrum of states with varying life-time up to hyperstable DM states.	Any, DDM ensemble contains short to hyperstable $c\tau$.	MCFODO (highly dependent on production and decay mode).	5.5	32, 33
SIMP/ELDER DM	Strong dynamics of HV generate DM abundance. HV $\rightarrow$ LLPs.	Any.	See HV.	5.4.1, 5.4.2	
Relaxion	Relaxion or other new scalars in theory generically mix with Higgs $\rightarrow$ 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	66, 67, 68, 69, 70
Leptogenesis	Motivates minimal RH neutrino model and other neutrino extensions, which generically feature LLPs.	Freeze-out LG favors weak-scale m_N but not so for other scenarios. Lower m_N favor long lifetimes.	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.	6.3	
Scalars in neutrino extensions	Gauge extensions in neutrino models give rise to new scalars that can mix with Higgs $\rightarrow$ SM+S. 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	

“intrinsically” and “generically” motivated LLP scenarios for MATHUSLA & main detectors

Lifetime frontier should be a focus of the upcoming decade at the LHC

The MATHUSLA Detector

MATHUSLA

MAssive Timing Hodoscope
for Ultra-Stable NeutraL PArticles

Chou, DC, Lubatti 1606.06298
DC, Peskin 1705.06327
Physics Case White Paper 1806.07396
Letter of Intent: CERN-LHCC-2018-025

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/

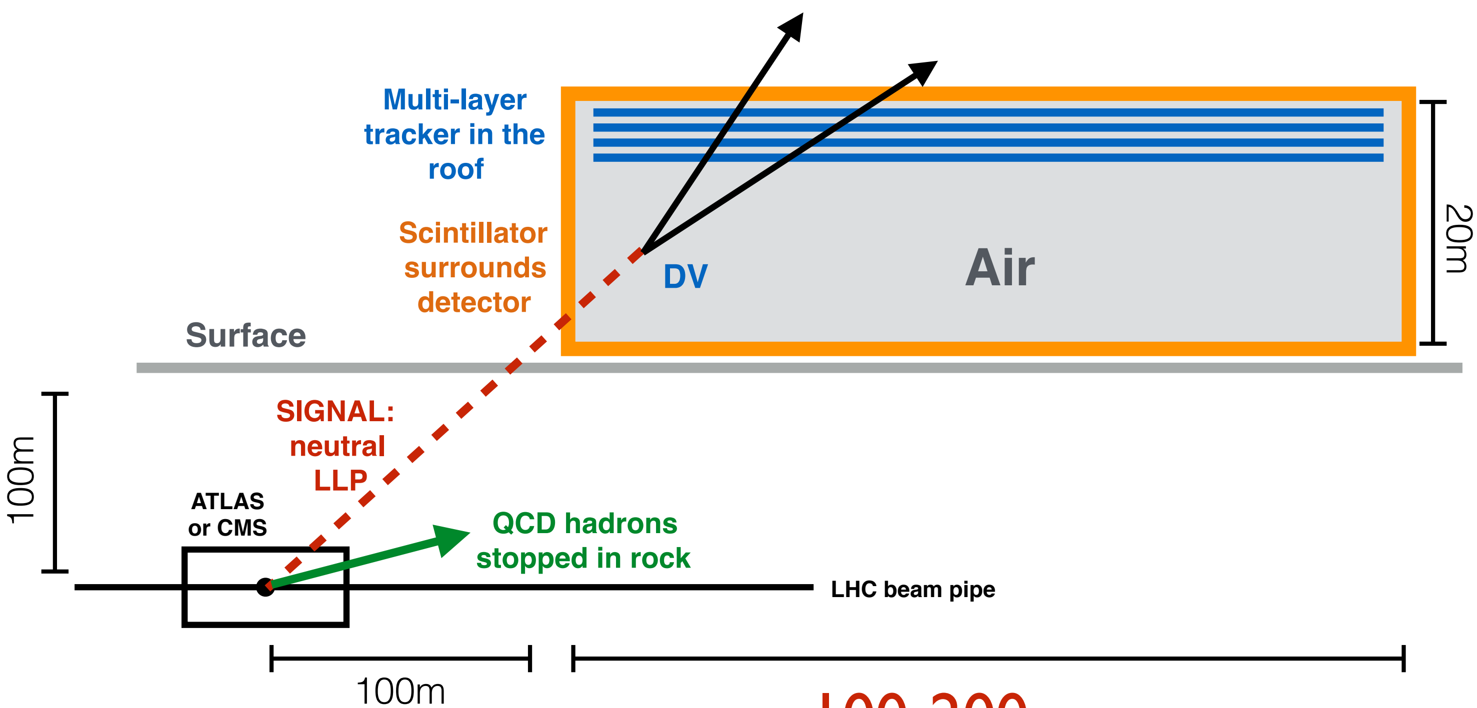
"Nuclear Detectives Hunt Invisible Particles That Escaped the World's Largest Atom Smasher", Live Science, May 2018 https://www.livescience.com/62633-lhc-stray-particles-mathusla-detection.html

PHYSICS TODAY
Quanta
WIRED
LIVESCIENCE

An external LLP detector for the HL-LHC

Chou, DC, Lubatti
1606.06298

Plan to take data mid-2020s



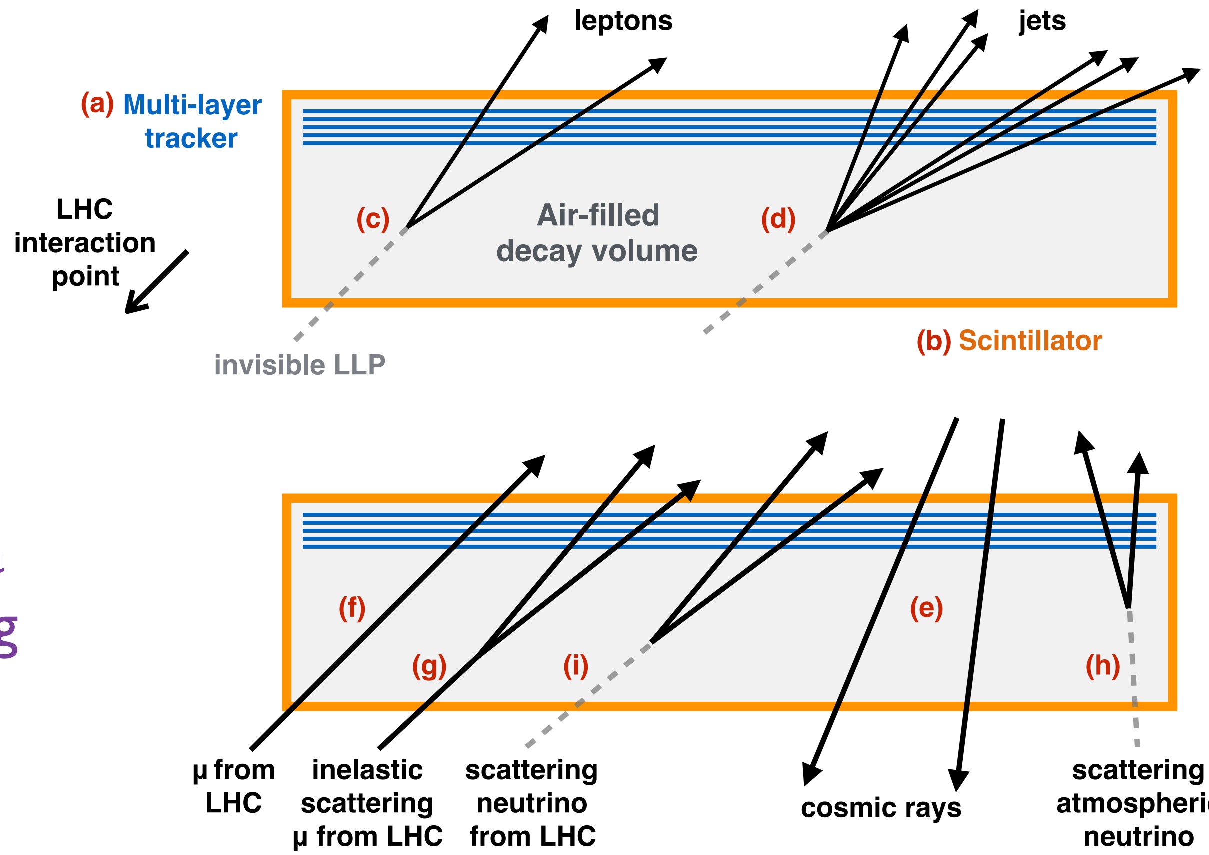
100-200m square

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

Same geometric acceptance as main detector for long lifetimes!

LLP Detection & 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!

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:

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

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

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

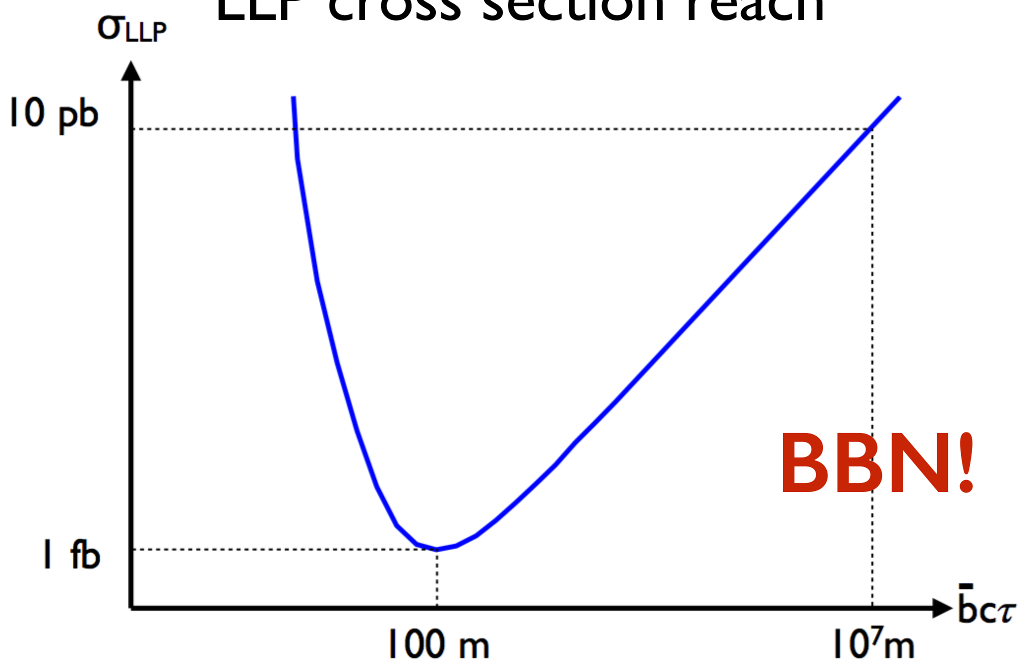
~ 0.05

$\sim \dfrac{(30\text{m})}{\bar{b}c\tau}$

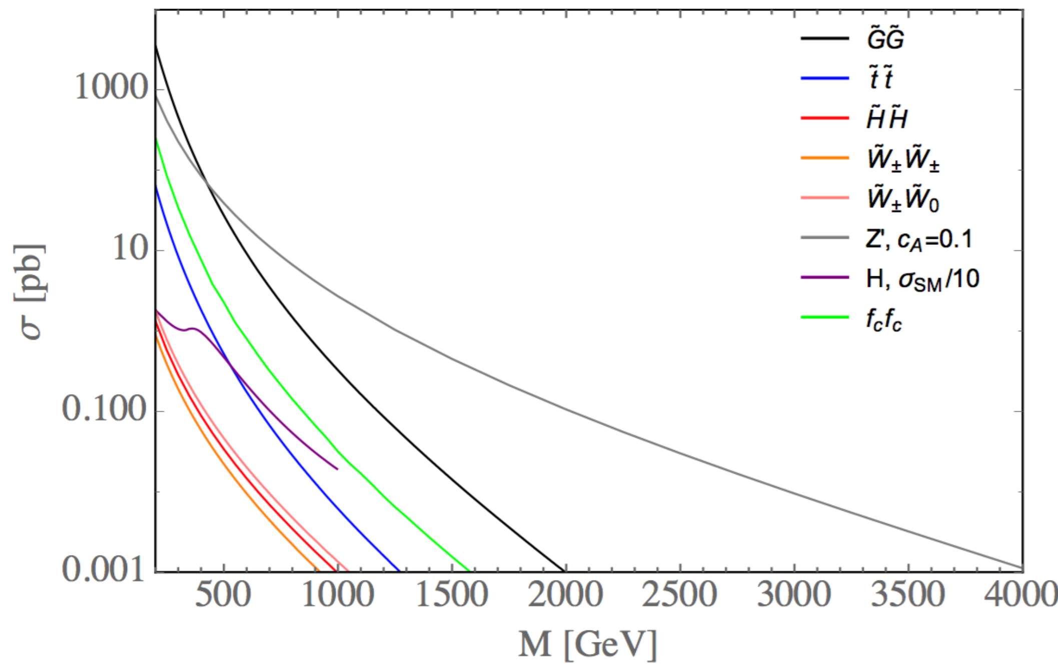
in long lifetime regime

Sensitivity

LLP cross section reach



Some example production xsecs



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

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

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

Probe TeV+ scales!

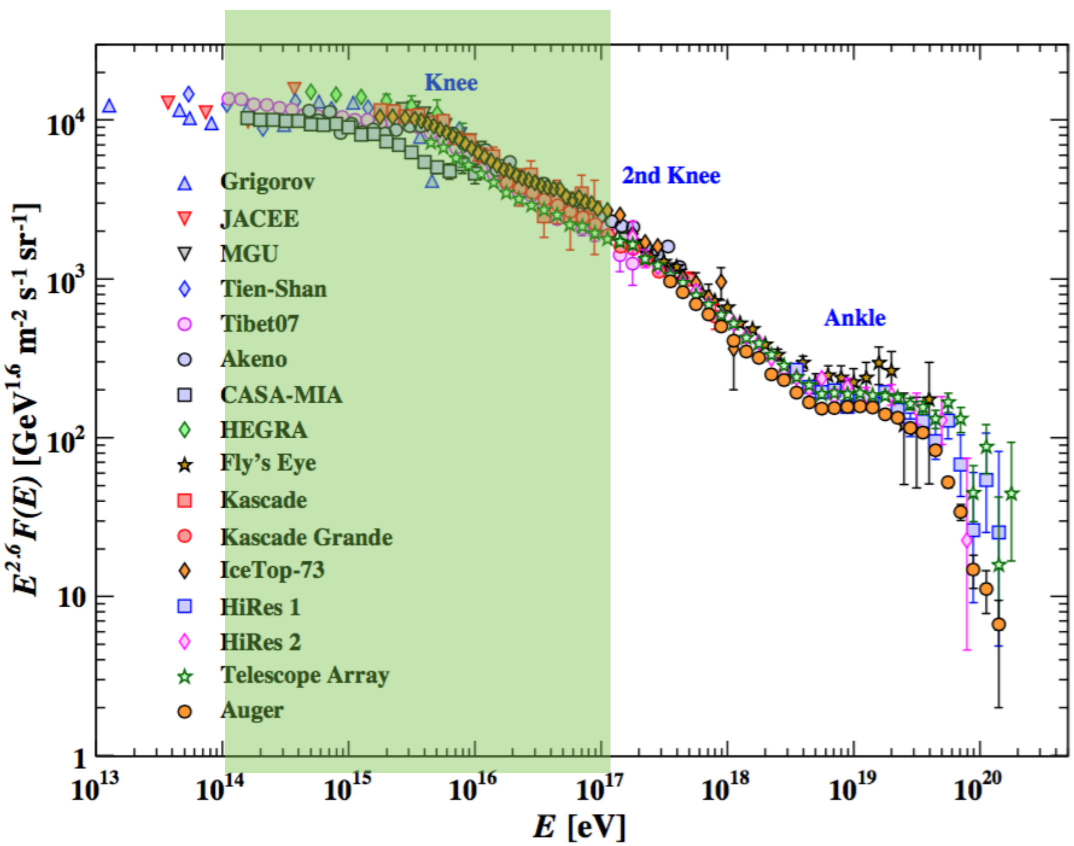
10^{-5} Exotic Higgs decays!

MATHUSLA Physics Case, 1806.07396

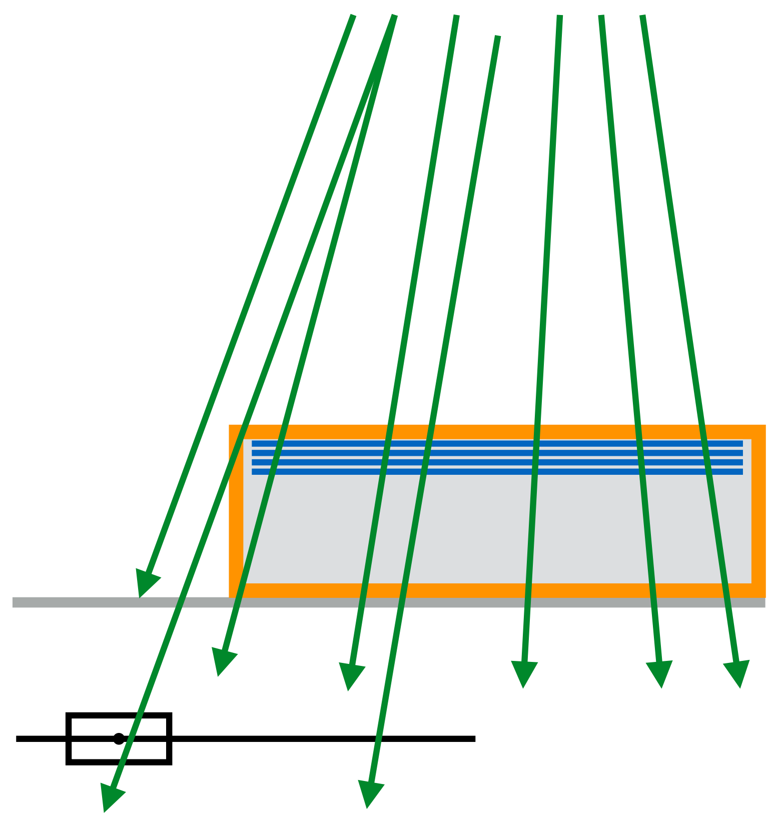
Cosmic Ray Physics @ MATHUSLA

MATHUSLA is an excellent Cosmic Ray Telescope!

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



~90% e, ~10% μ, less hadrons



See Juan Carlos' talk

Backgrounds @ MATHUSLA

Cosmics: LLP signal of 4-dimensional DV with 2 or more tracks is very hard to fake by downward (or even sideways) going cosmics, and high-multiplicity showers where coincidences have higher chance are easily vetoed.
Detailed simulation studies in progress!

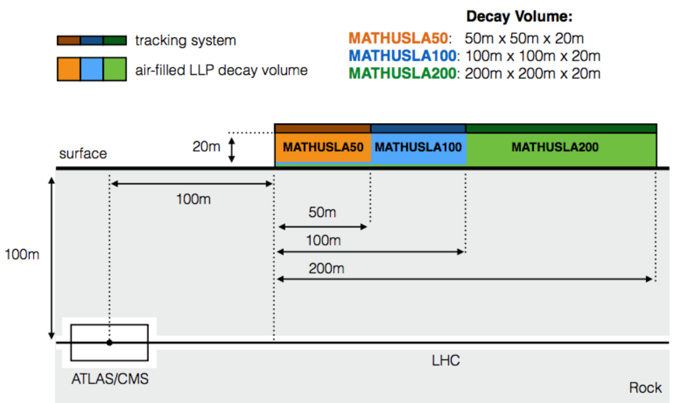
Muons from LHC: either do not satisfy signal requirement or can be vetoed with material veto (hard scattering) and opening angle cuts (delta rays).
Studied muon penetration through rock in GEANT, then analytical calculation of behavior in MATHUSLA (scattering rates etc)

Neutrinos: can be vetoed with cuts on final state *speed (slow protons)*, opening angle & orientation. (Over-)estimated rates using measured cross sections and analytical calculations of kinematics. Detailed simulation studies in progress.

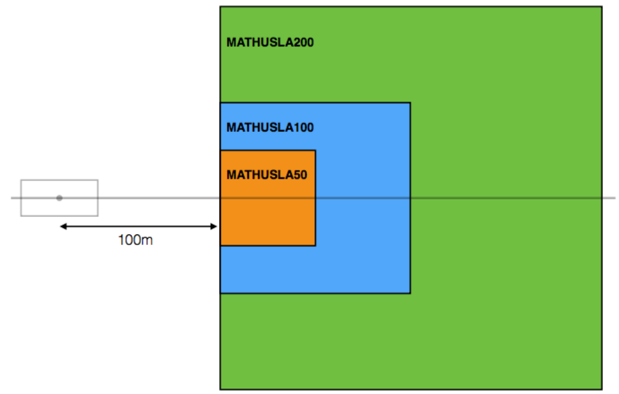
Other things: rare scatterings in the floor, cosmic albedo, etc etc… Reason to believe they are small, but detailed studies required.

See Gordon's talk

Geometry & Site Selection



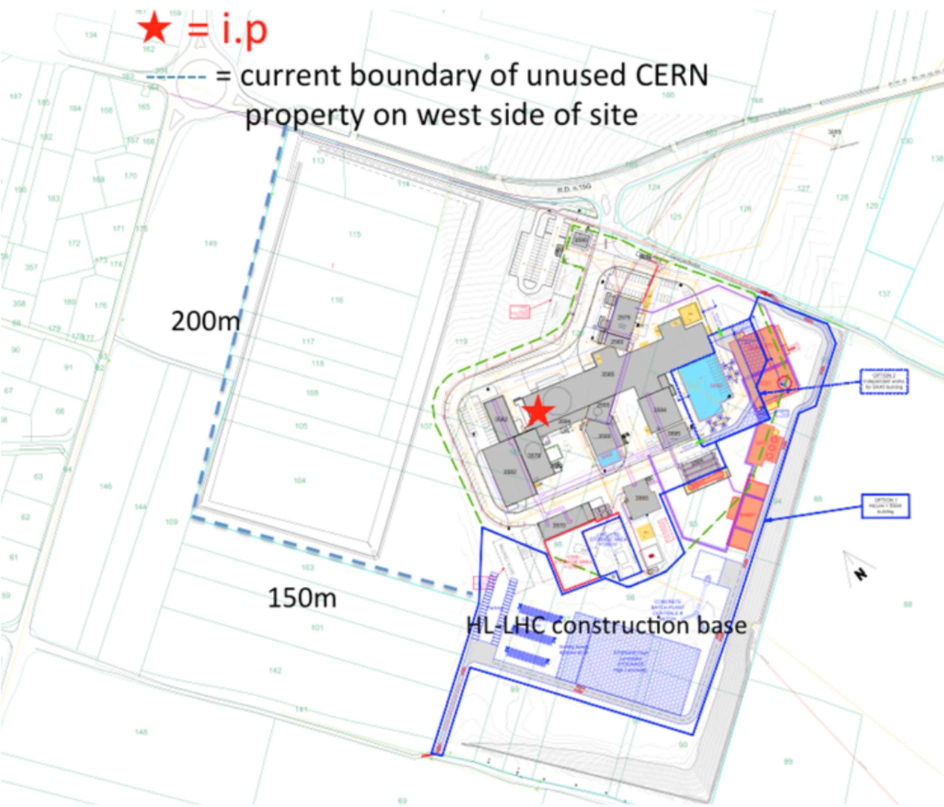
side view



aerial view

Simple benchmark geometries from LOI

MATHUSLA100 is current benchmark



Something like MATHUSLA100 would have very similar sensitivity to early benchmark (“MATHUSLA200”), especially if it was a bit closer to IP.

There is room near CMS!!

Detector Technology & Layout

Need a tracking technology that is cost-effective, reliable, and can deliver ~ns timing resolutions for directionality & CR rejection.

(Slightly open question for studies in progress: what spatial resolution is required? Default right now is 1cm.)

Detector + Electronics will likely dominate cost of MATHUSLA.

Current benchmark choice:
Resistive Plate Chambers (RPCs).

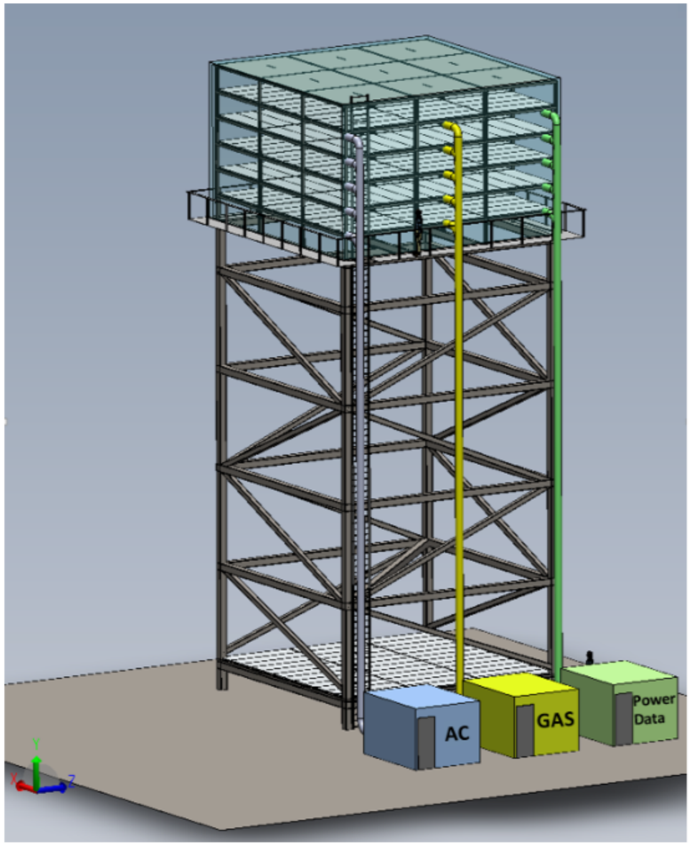
Would allow for MATHULSA100 with sensor cost in the 10s of M.
Significant R&D opportunity to scale production & bring cost down!

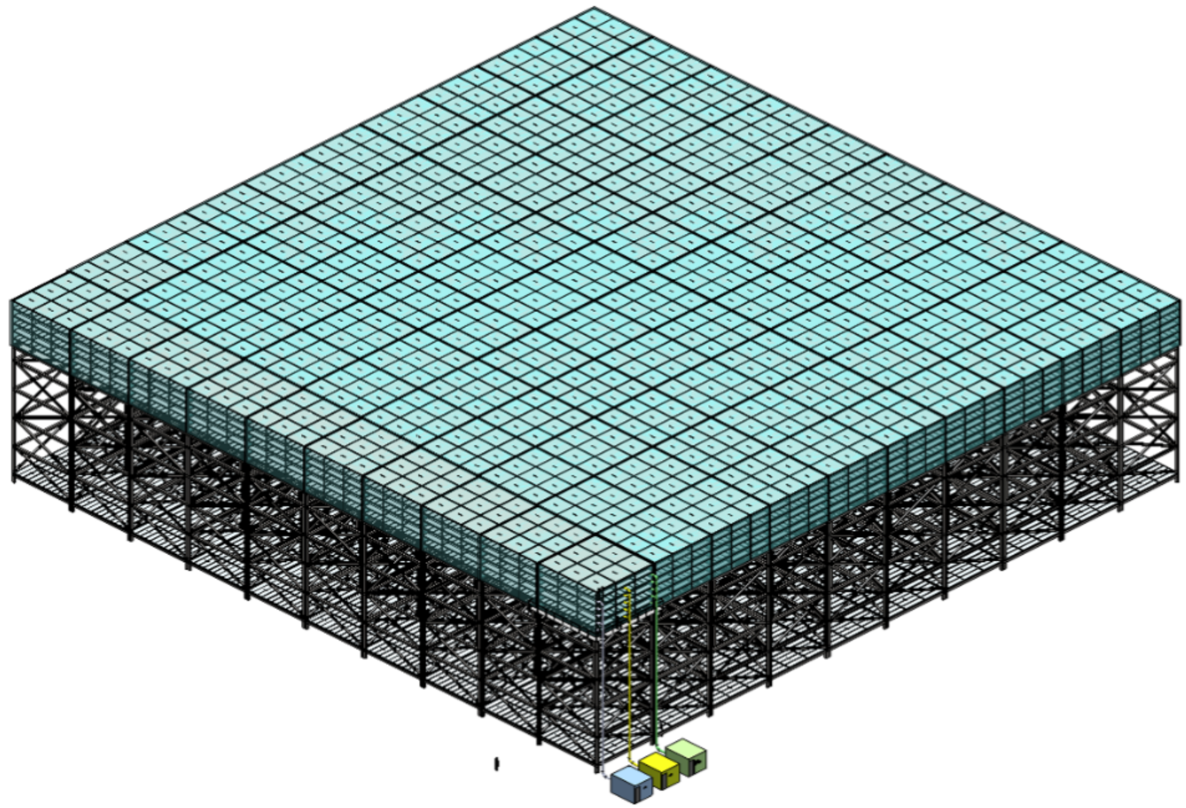
Other technologies (plastic or liquid scintillator) must also be explored.

See Rinaldo's, Erez's talks

Modular detector design

See Erez's talk





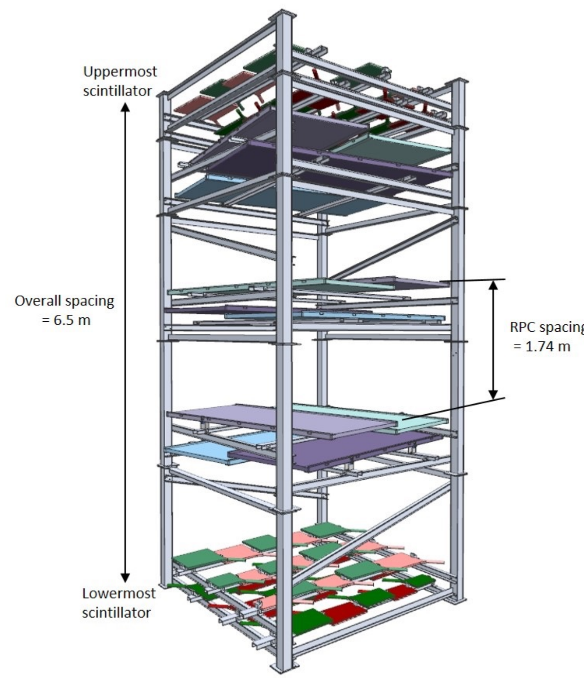
Modular construction is flexible and scalable.
We're hoping we don't need "side wall" vetoes, but this depends on outcome of detailed neutrino & cosmic BG studies.

MATHUSLA Test Stand

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

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, allow background rejection strategies to be tested, and allows us to build up analysis capability in anticipation of full detector.



See Cristiano's talk

MATHUSLA

in the context of

other LLP detectors

HL-LHC
main detectors

MATHUSLA vs HL-LHC Main Detectors

Define *long-lifetime sensitivity gain* at MATHUSLA:

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

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

MATHUSLA Physics Case, 1806.07396

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

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)

The above may be physics targets we can sacrifice for MATHUSLA if it makes life a lot easier? *(e.g. high-mass LLP decays to two leptons, which have low reconstruction efficiency in minimal geometry)*

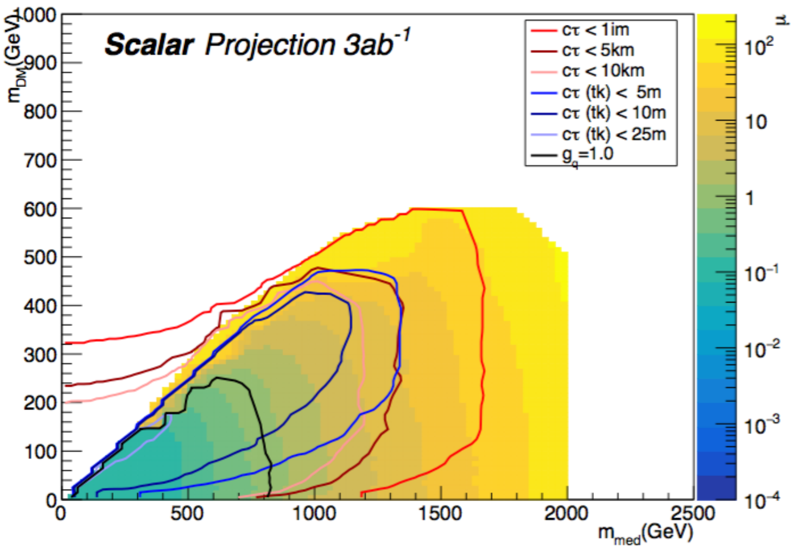
MATHUSLA wins at long lifetimes for anything else, e.g.
- LLPs with m < ~ O(100 GeV) and hadronic decays
- LLPs decaying to lepton jets
- LLPs with subdominant fraction of leptons in final state

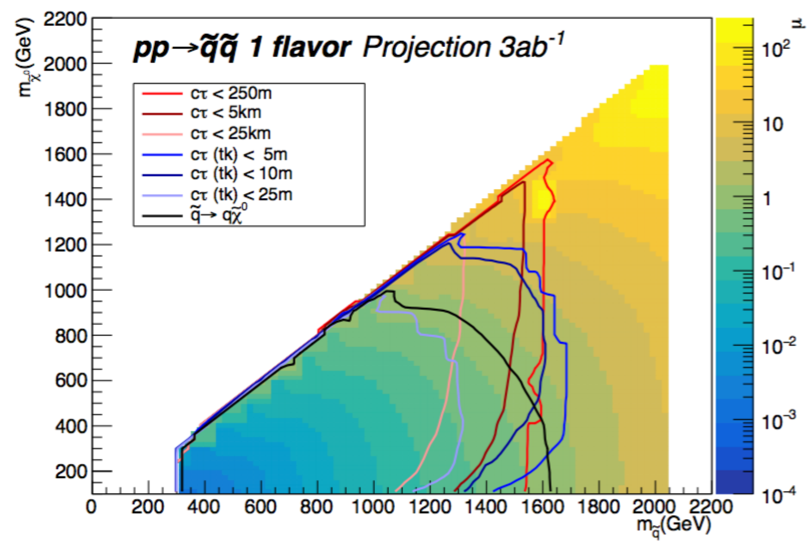
with ~10-1000x better LLP xsec sensitivity

THESE ARE PRIMARY MATHUSLA TARGETS: *LLP searches that will be difficult at main detectors even after LLP search program has matured!*

What about MET searches?

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

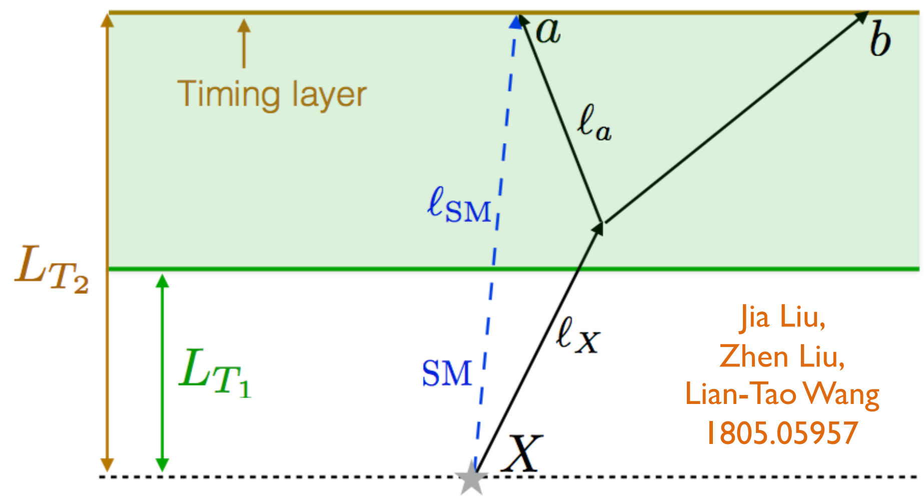




For LLP pair production (e.g. DM simplified models with unstable invisible particle) or SUSY-type models with slightly squeezed spectra, MATHUSLA can have much larger mass reach than main detector MET search!

What about possible timing upgrades?

Timing at the HL-LHC main detectors



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

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

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

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

b = boost

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

What could you do with timing upgrades?

Jia Liu, Zhen Liu, Lian-Tao Wang 1805.05957

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

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

Scenarios considered:

30ps timing layer on inside of CMS ECAL:

see next few slides

+ 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 (13 STDEV of PU time distribution) 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 (4 STDEV of PU time distribution) to reduce hard jet fake DV background by 10^{-6} to N < 1

Example of time-flat backgrounds: CRs in ATLAS MS

Cosmic ray muons > ~ 60 GeV can reach ATLAS cavern, scatter off material in MS, and give a DV. **Material veto difficult due to low resolution!**

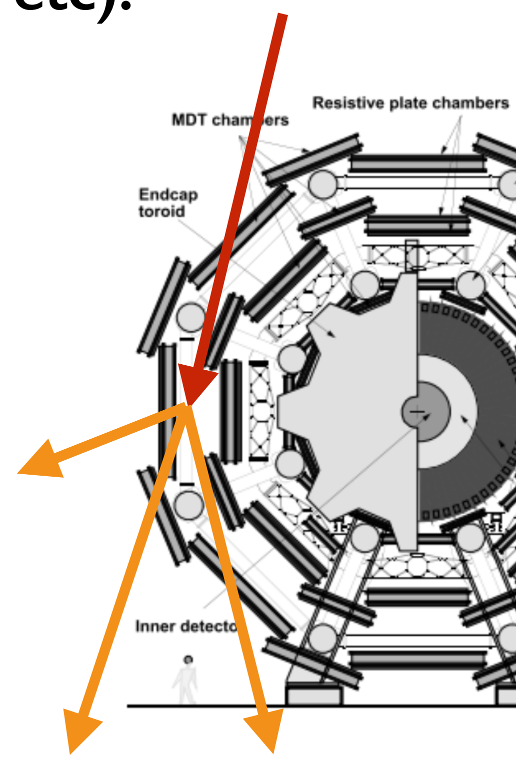
Directionality won't help a huge amount in rejecting them, since hadronic LLP decays in MS can look the same.

VERY ROUGH RATE ESTIMATE (without DV efficiencies etc):

cosmic muon flux > 20 GeV in ATLAS cavern: ~ 1.34 /s/m^2
CERN-THESIS-2011-118

Muon-Iron inelastic scattering xsec at
Emu ~ 20 GeV: 7 microbarn
hep-ph/0611008

Assuming each muon goes through
10cm of iron in MS, you get ~ 10^5 events @ HL-LHC



"~30fb". Could be significant 0.01 - O(1) fraction of BG!

Potential Sensitivity Gain?

If BG-free, timing-enhanced searches could have O(1/10) MATHUSLA sensitivity for long-lifetimes.

The background-free results in 1805.05957 relies on assuming BG has GAUSSIAN time-structure of pile-up and you can cut by many STDEV.

However, material interactions, punchthrough, cosmic rays, beam halo, etc are all either **FLAT** in time or come with built-in **time-delay. They constitute a non-negligible BG constituent (e.g. CR in ATLAS MS).**
Also PU is not exactly Gaussian…
⇒ projected 10^{-6} - 10^{-10} rejection factors not realistic.

This paper ignored these backgrounds, and its quantitative conclusions are incorrect.

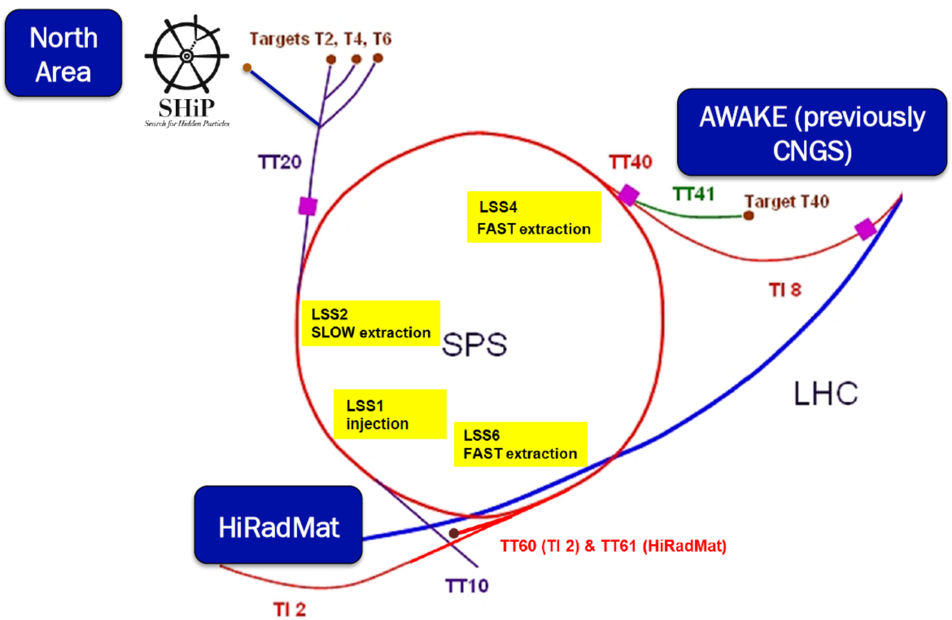
Regardless of such details, timing is definitely very exciting and will improve main detector sensitivity (but not to MATHUSLA levels…)

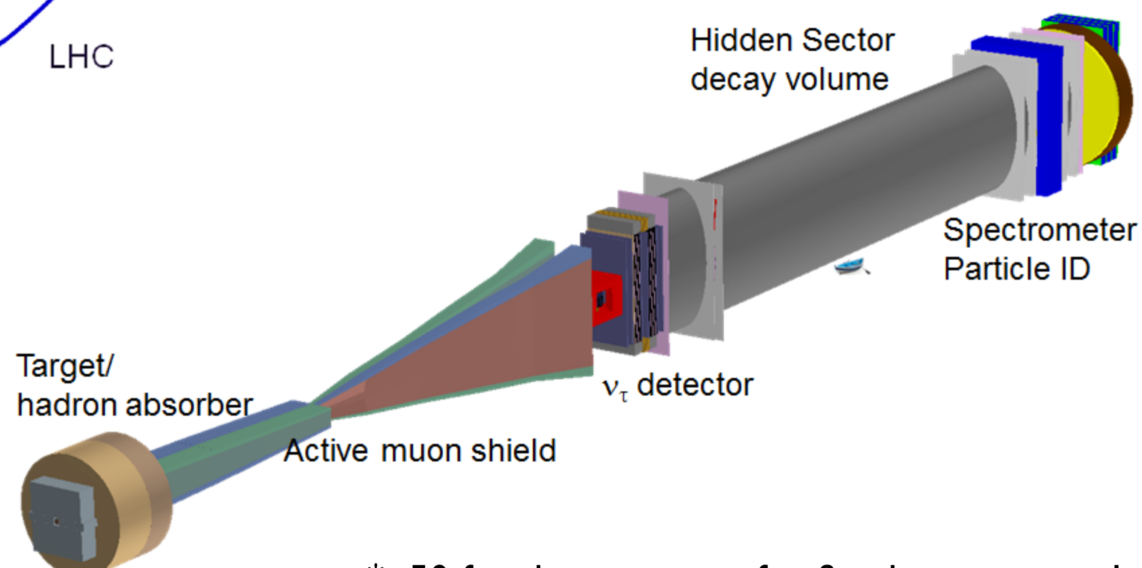
SHiP

SHiP

$\sqrt{s}$ = 38 GeV fixed target facility proposed for SPS, specifically for low-mass hidden sectors via LLP searches.

Flagship "Intensity Frontier" proposal. Total cost ~ 200-300M*





*~50 for detector, rest for fixed target complex

SHiP

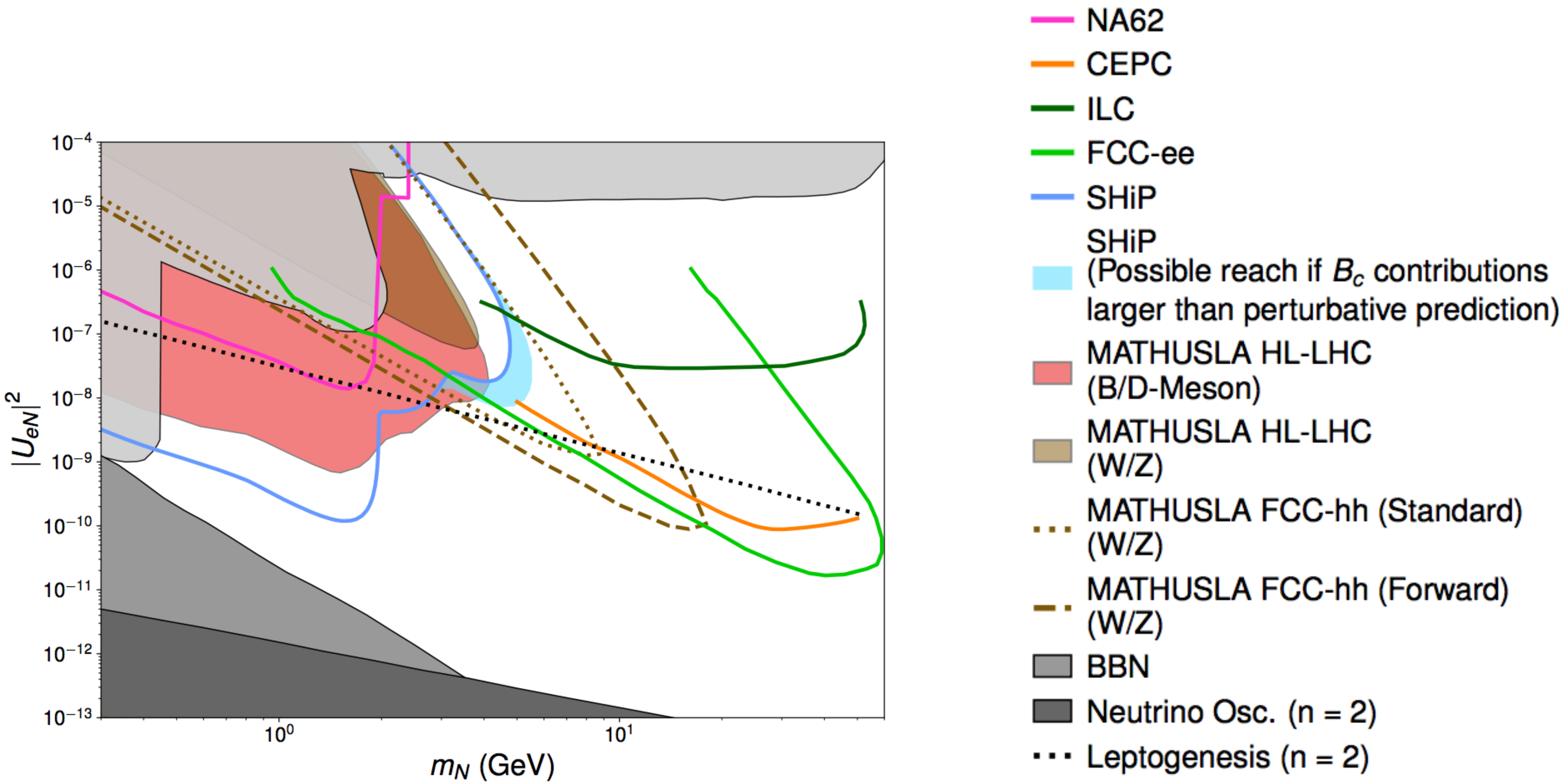
For shorter lifetimes and mass < ~ 10 MeV, SHiP is much better.

MATHUSLA access higher scale physics above the GeV scale!

MATHUSLA sees 10-100 more LLPs from exotic meson decays if lifetime >> 100m, so can have better sensitivity even at low masses.

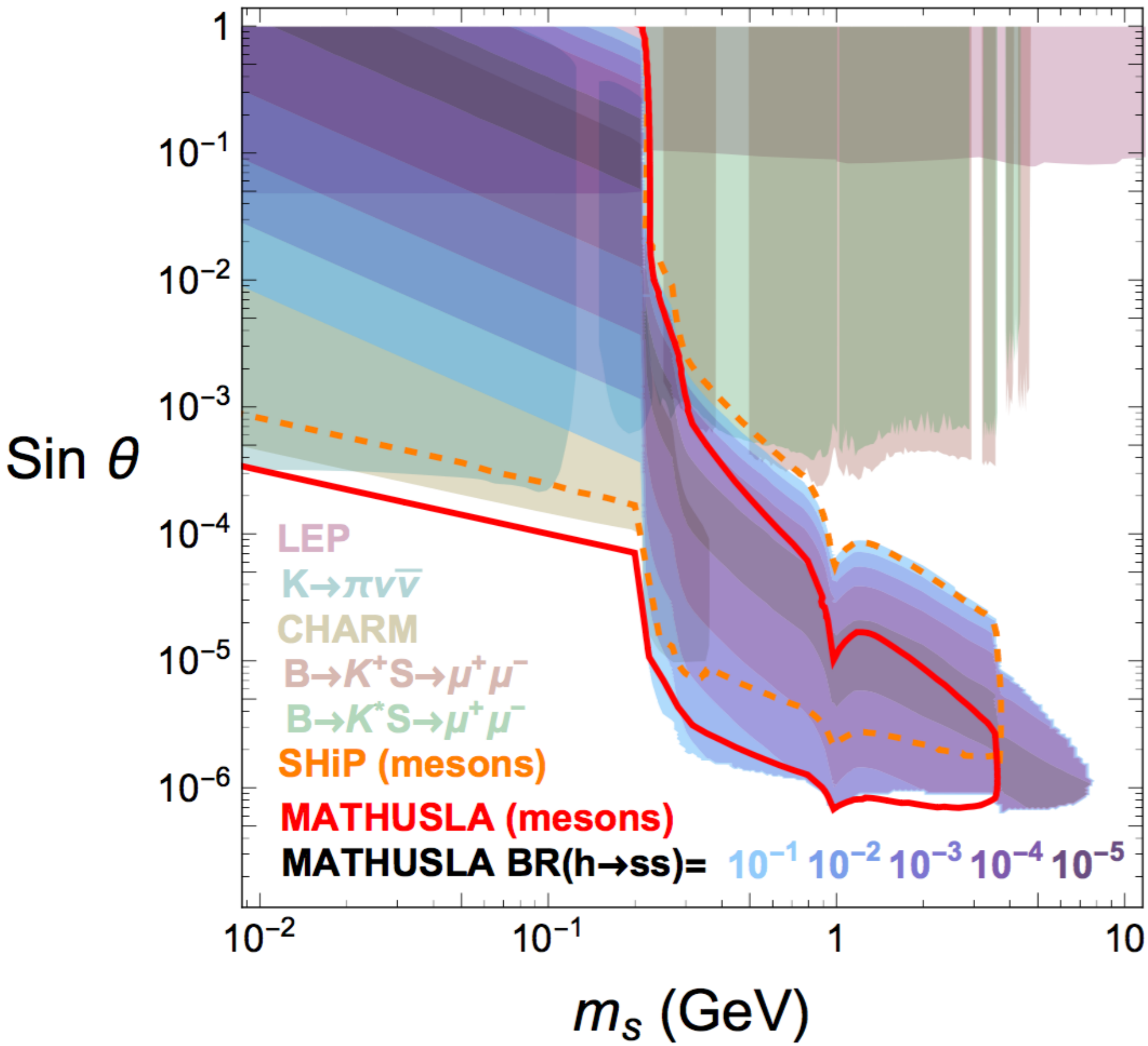
We have computed MATHUSLA reach estimates for *their benchmark models* so they can be included in the document of the Physics Beyond Colliders working group & its submission to European Strategy.

MATHUSLA & SHiP for Heavy Neutral Leptons



MATHUSLA200 is comparable/complementary to SHiP!

MATHUSLA & SHiP for Minimal Scalar Extension



MATHUSLA beats SHiP for long lifetimes.
Can also access exotic Higgs decay LLP production mode.

Dark Photons & Axions

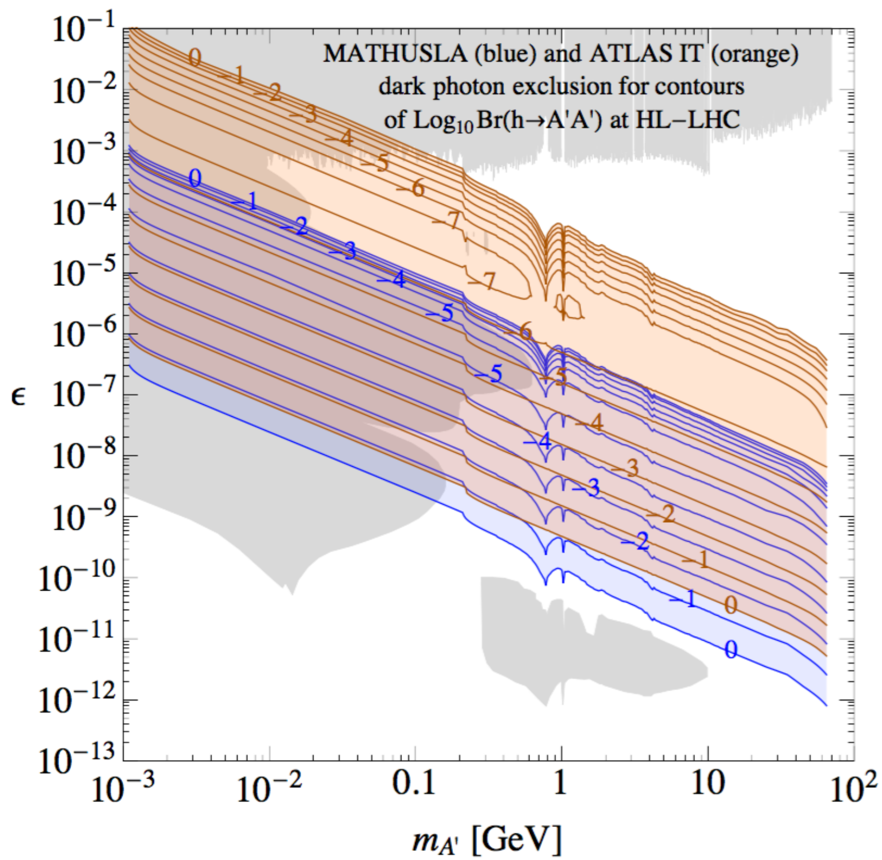
For HNL and scalars, MATHUSLA does well in this **intensity frontier regime** because it wins by LHC B-meson production rate.

SHiP beats MATHUSLA for minimal dark photon & minimal axion models, since
- you don't win much with LHC energy (direct production of very low mass states)
- production & decay are via same coupling and MATHUSLA's long distance means the long lifetime required for signal kills xsec.

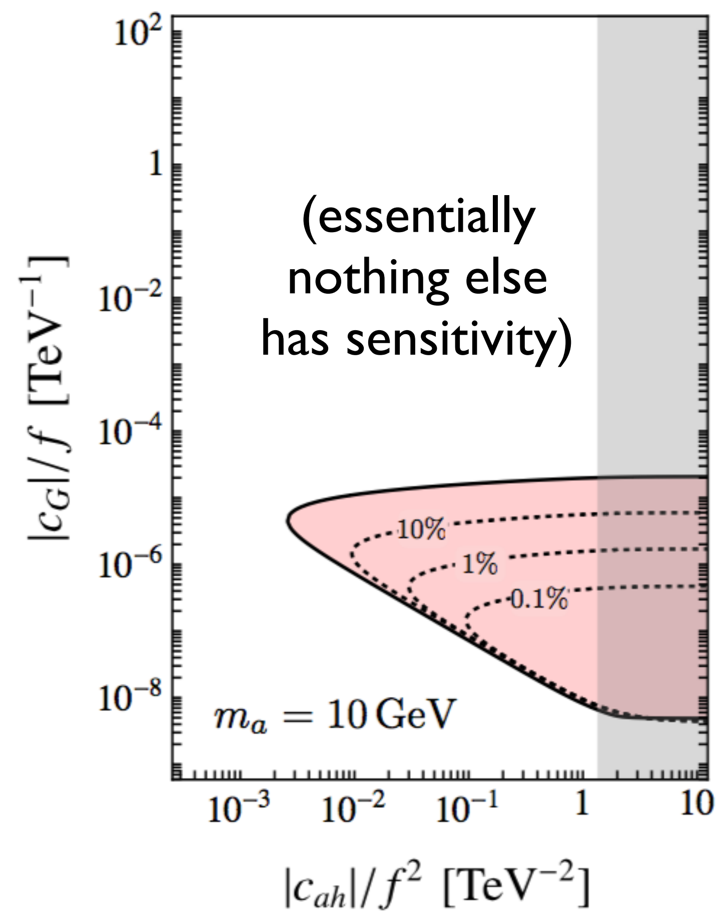
However, as soon as the theory departs from these extremely minimal benchmark models, MATHUSLA can win by a lot because high-mass production modes open up

Dark Photons & Axions-like particles

Dark photons from exotic Higgs decays



ALPs from exotic higgs decays



MATHUSLA inspired an ecosystem of external LLP detector proposals

CODEX-b

Gligorov, Knapen, Papucci, Robinson, 1708.09395

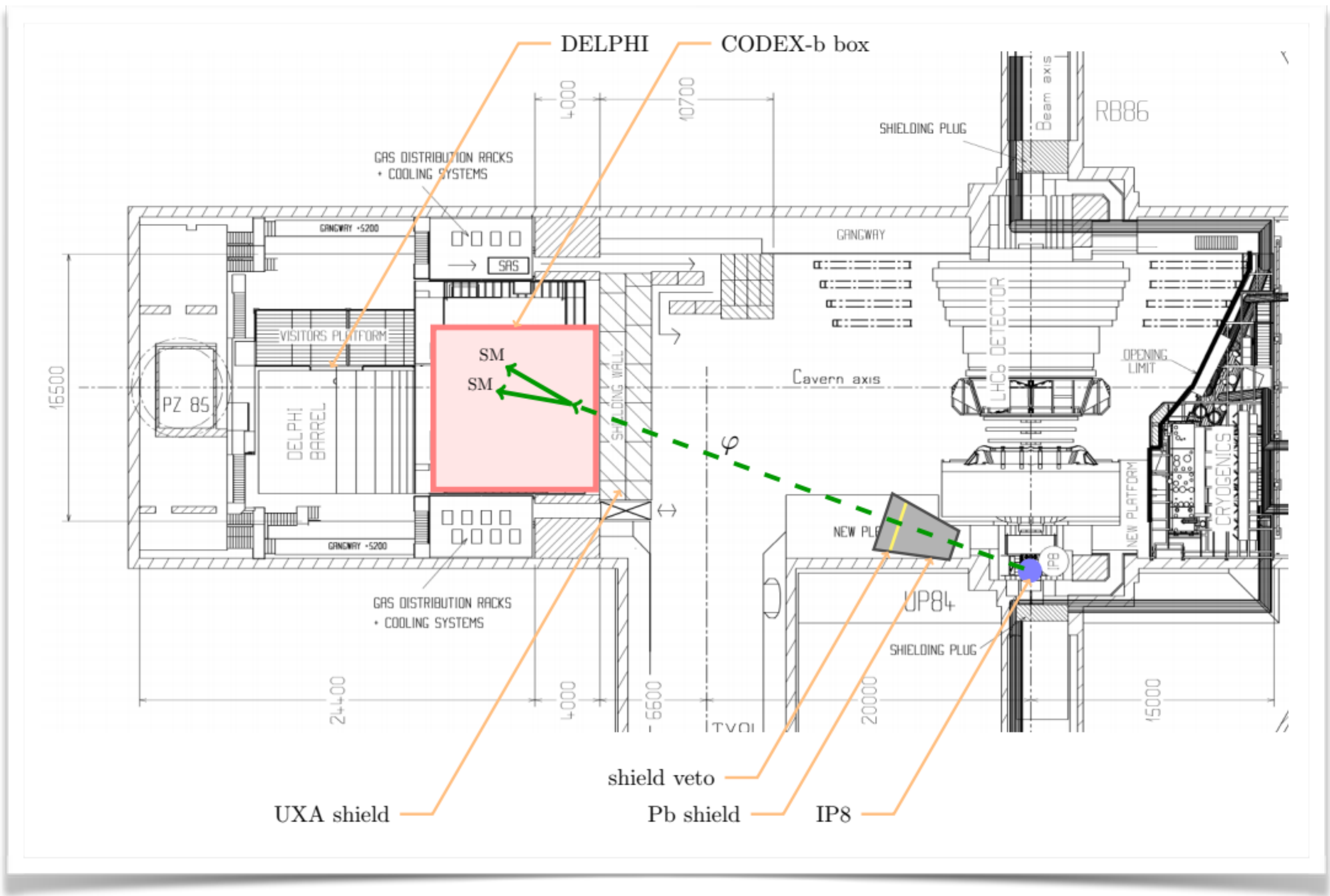
"mini-MATHUSLA" in existing cavity near LHCb

+ Definitely more affordable than something on MATHUSLA scale

+ smaller volume can have more sophisticated instrumentation to explore the low-mass LLP regime < 10-100 MeV.

+ Easy interface with LHCb!

- ~1/100 MATHUSLA sensitivity



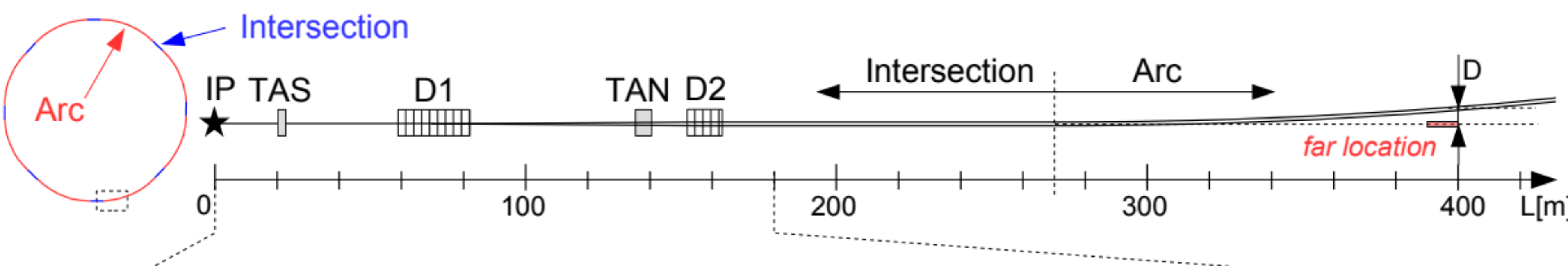
FASER

Feng, Galon, Kling, Trojanowski 1710.09387

Relatively small and cheap detector.

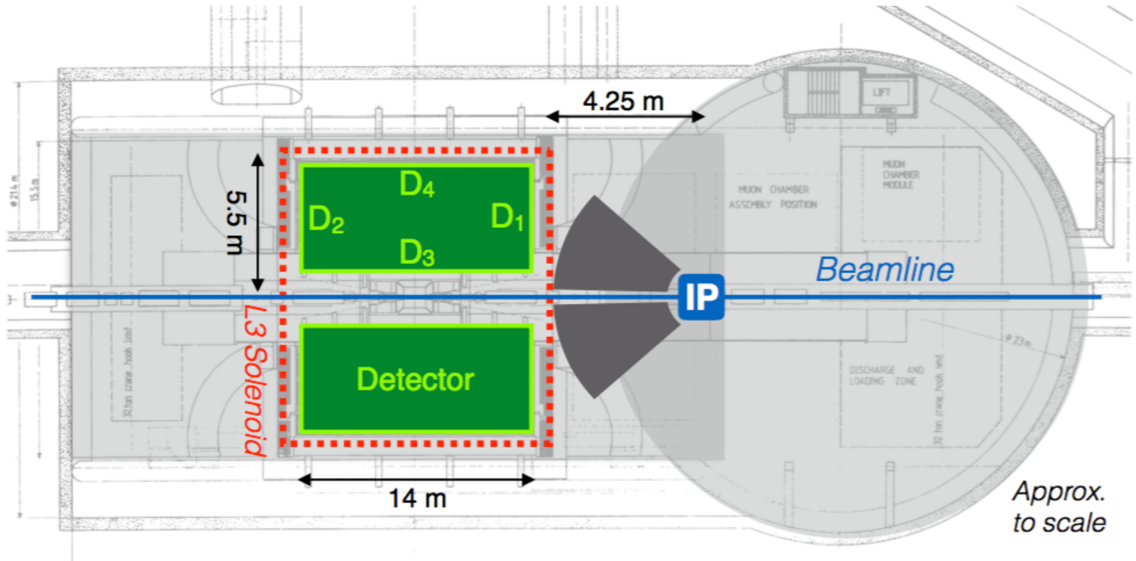
cylindrical (R = 0.2m, L = 10m), can be placed in ‘condemned’ access tunnel with minimal excavation

curvature of LHC tunnel provides >100m of shielding



Exploits large forward (small angle) cross section enhancement for low-scale LLP production processes to probe sub-GeV regime. Highly complementary to MATHUSLA!

AL3X *(Zombie-ALICE)*



Gligorov, Knapen, Nachman, Papucci, Robinson, to appear

Radically reconfigure ALICE detector and its collision point at HL-LHC for dedicated LLP search.

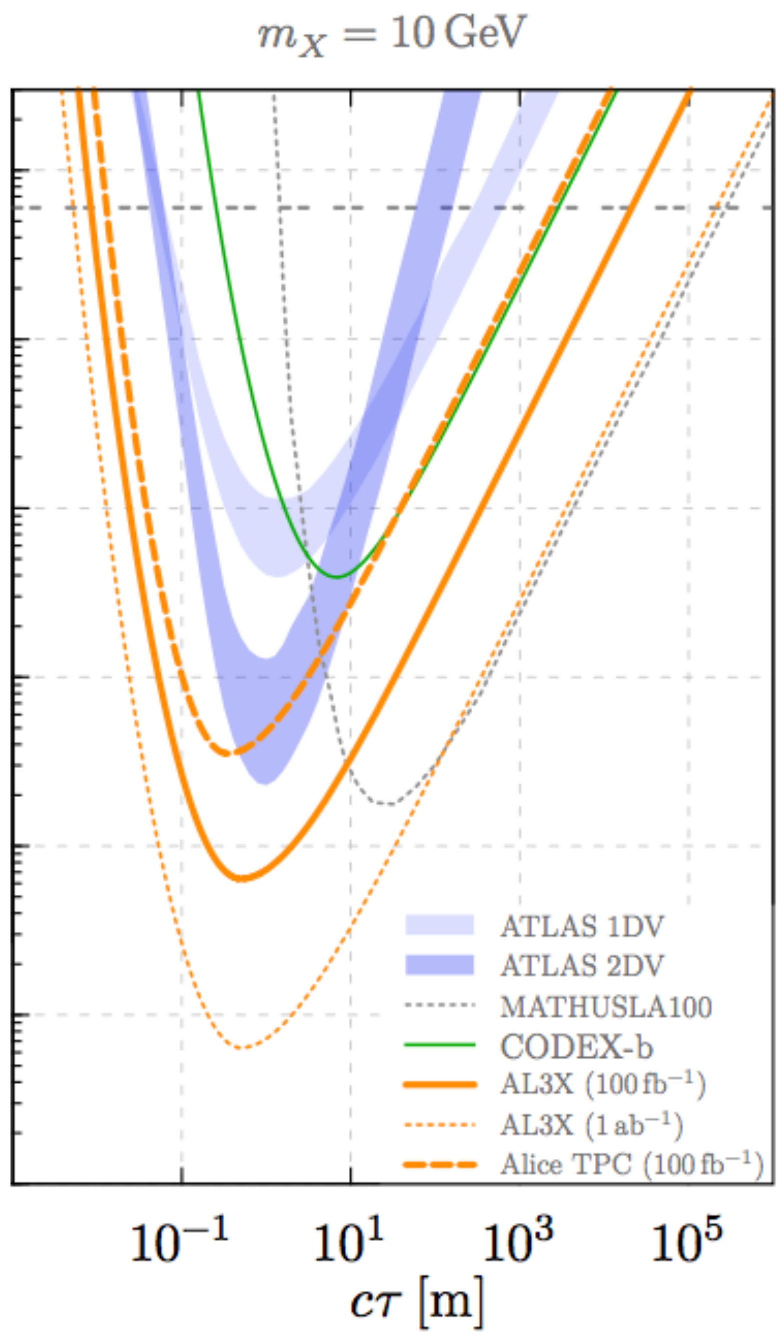
1/10 - 1 x MATHUSLA sensitivity at long lifetimes, MUCH BETTER at short lifetimes.

Requires ≲ (Eiffel Tower) worth of shielding, significant upgrades to beam optics.

Very audacious, not sure how likely. Would be amazing!!

comparative reach

exotic Higgs decay to LLPs



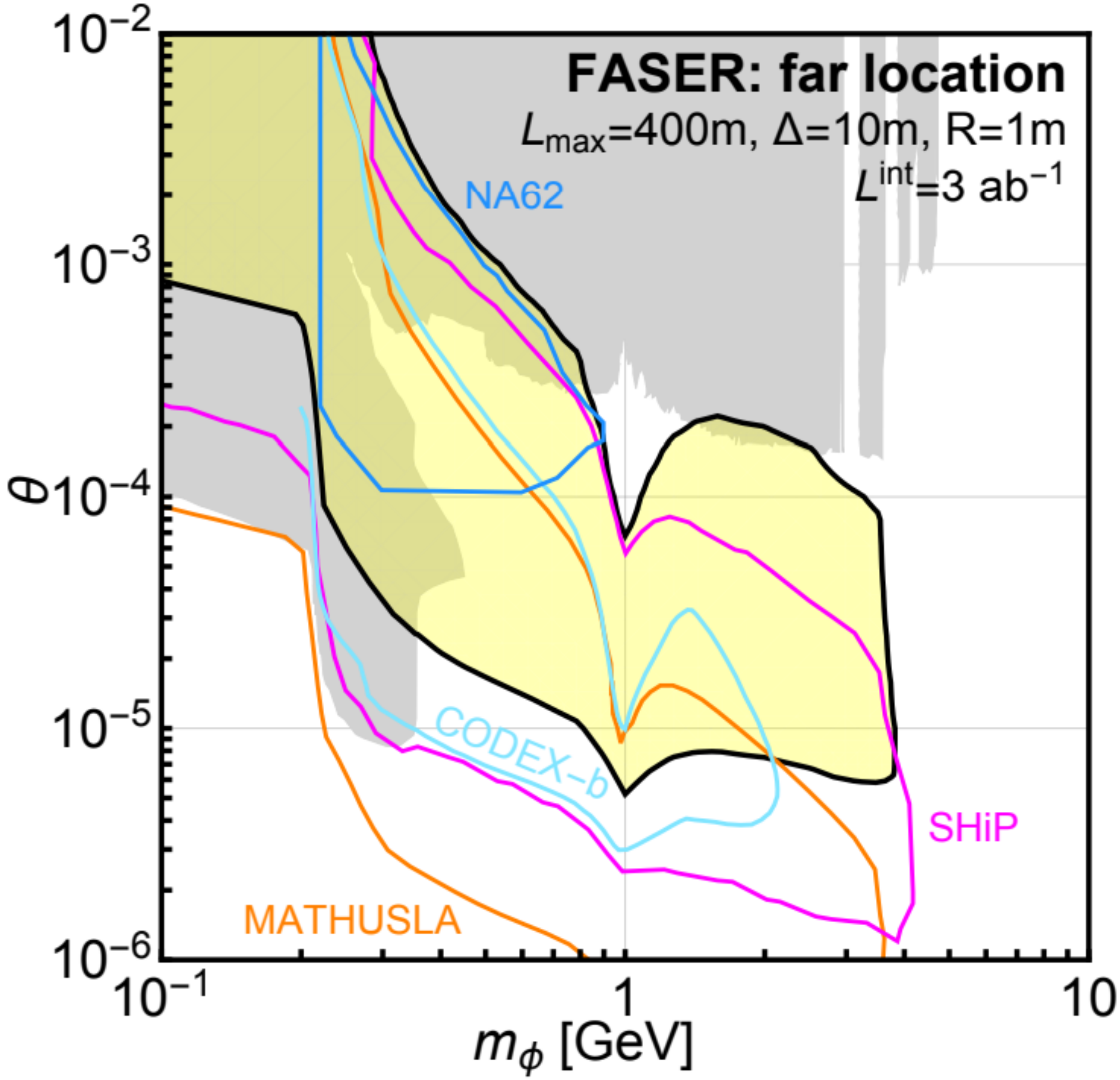
nothing beats
MATHUSLA
except
the most ambitious
AL3X

Gligorov, Knapen, Nachman, Papucci, Robinson, to appear

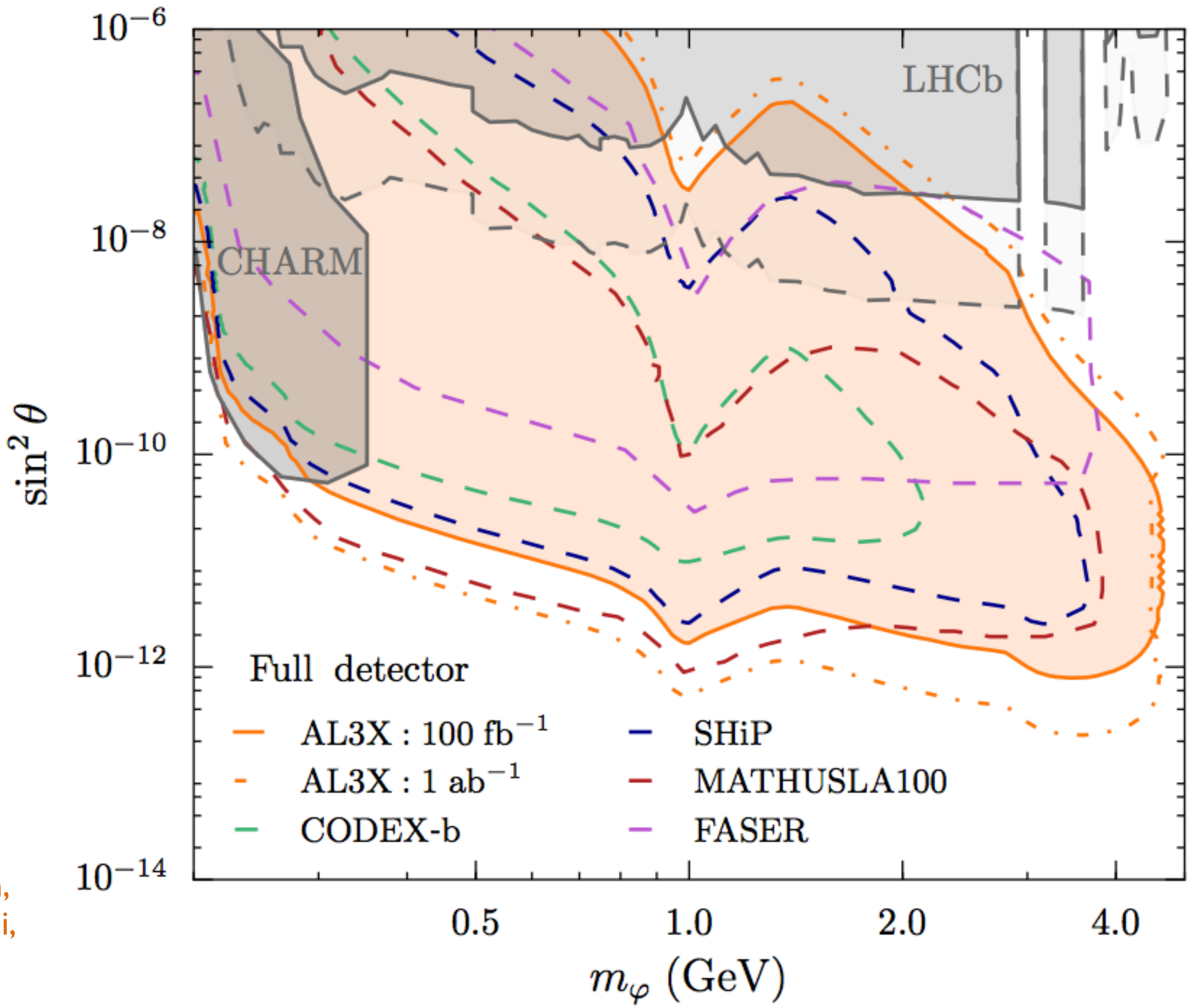
SM+S

scalar extension w/o exotic Higgs decays

FASER + MATHUSLA ≳ SHiP

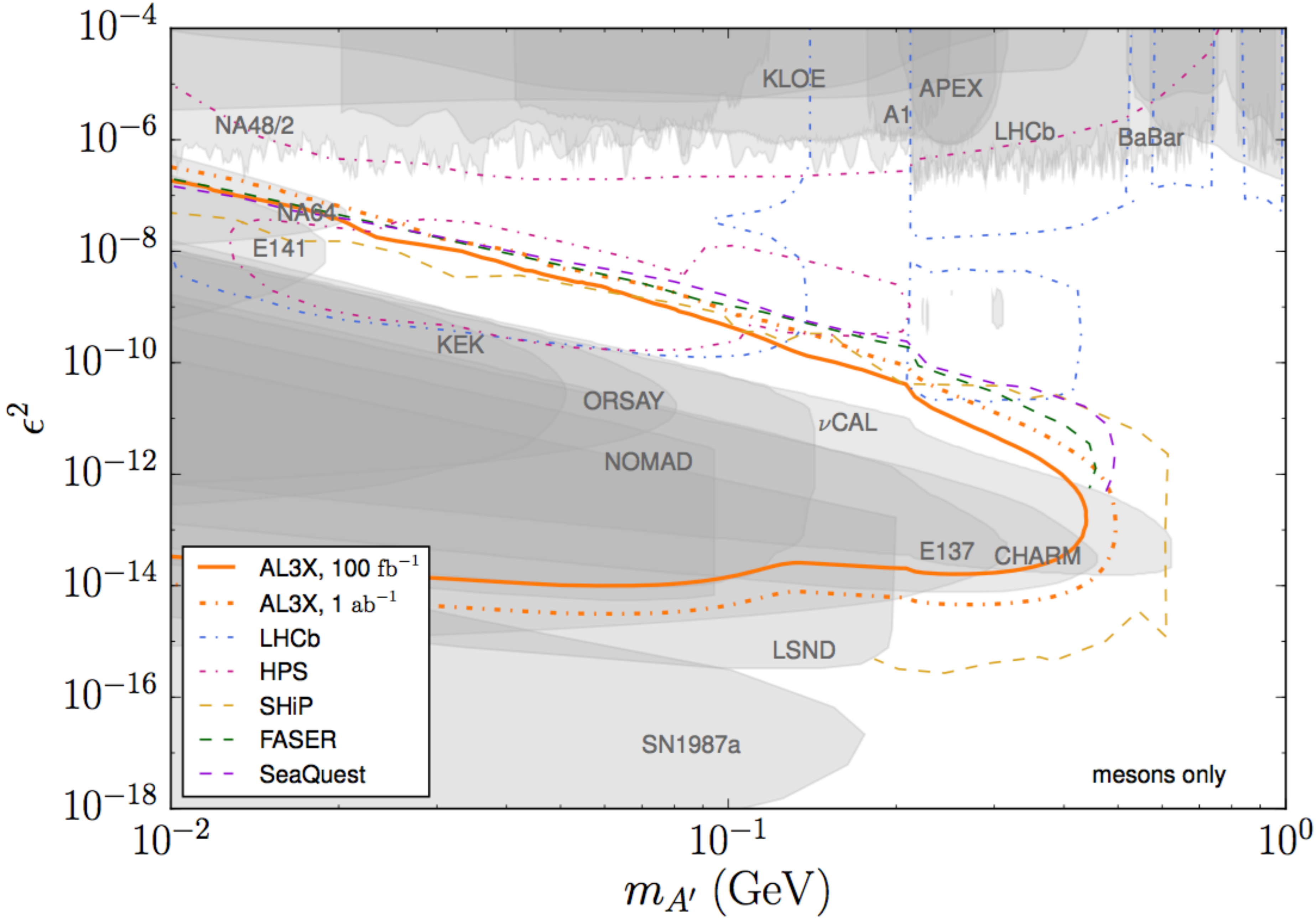


“all proposals”
minimal higgs portal scalar LLP production via B decay



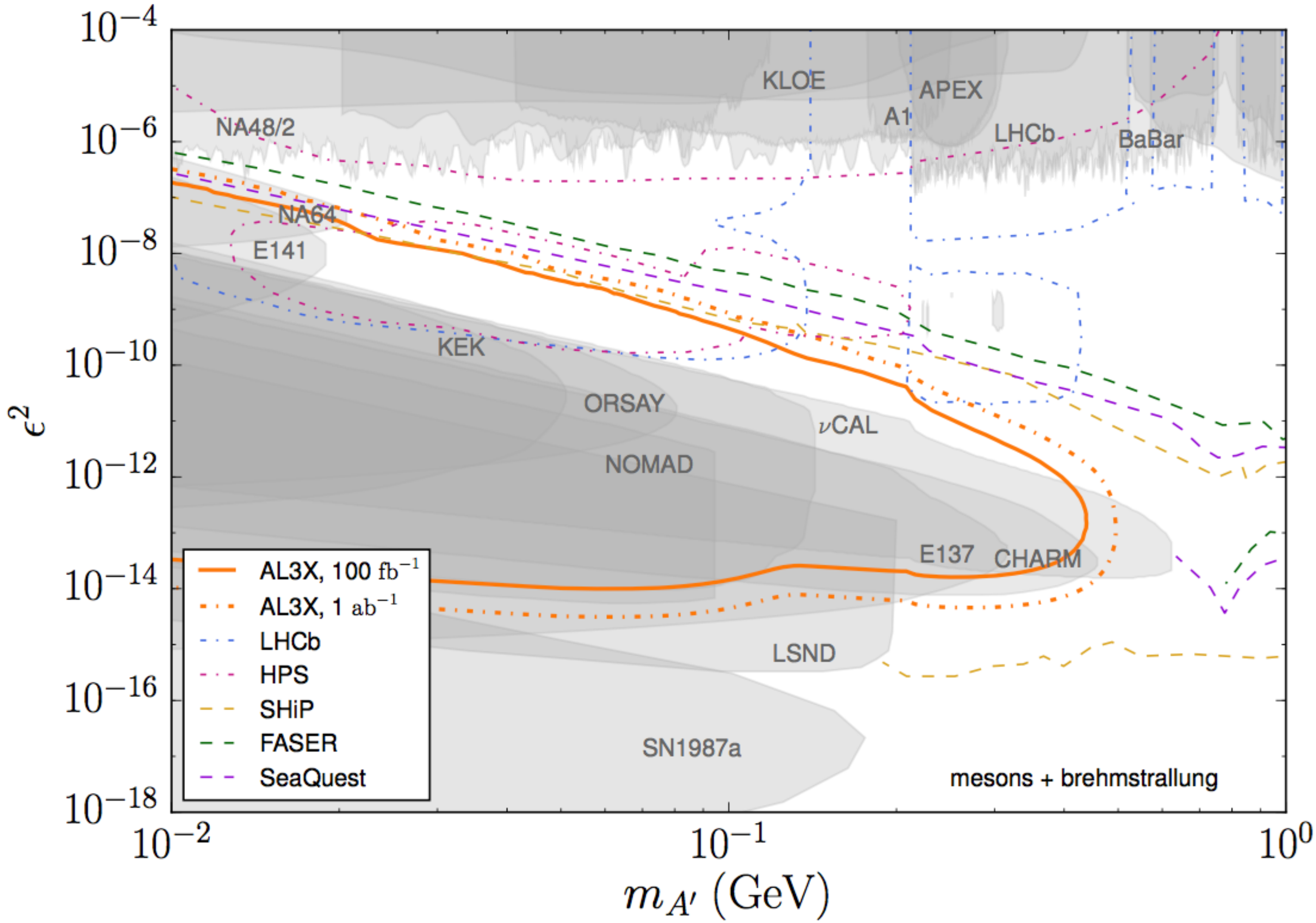
Gligorov, Knapen, Nachman, Papucci, Robinson, to appear

“all proposals”, minimal dark photon, with bremsstrahlung



Gligorov, Knapen, Nachman, Papucci, Robinson, to appear

“all proposals”, minimal dark photon, with bremsstrahlung



Gligorov, Knapen, Nachman, Papucci, Robinson, to appear

Conclusion

Conclusion

MATHUSLA takes advantage of high HL-LHC energy and BG-free environment to probe general sub-GeV to TeV scale new physics.

Compared to HL-LHC detectors, orders of magnitude sensitivity gain.

Bonus: also competitive with Intensity Frontier experiments for several important low-scale models.

Guaranteed Physics Return: Cosmic Ray Physics Program.

Proposal is realistic in terms of cost and minimal disruption to HL-LHC operations/upgrades.