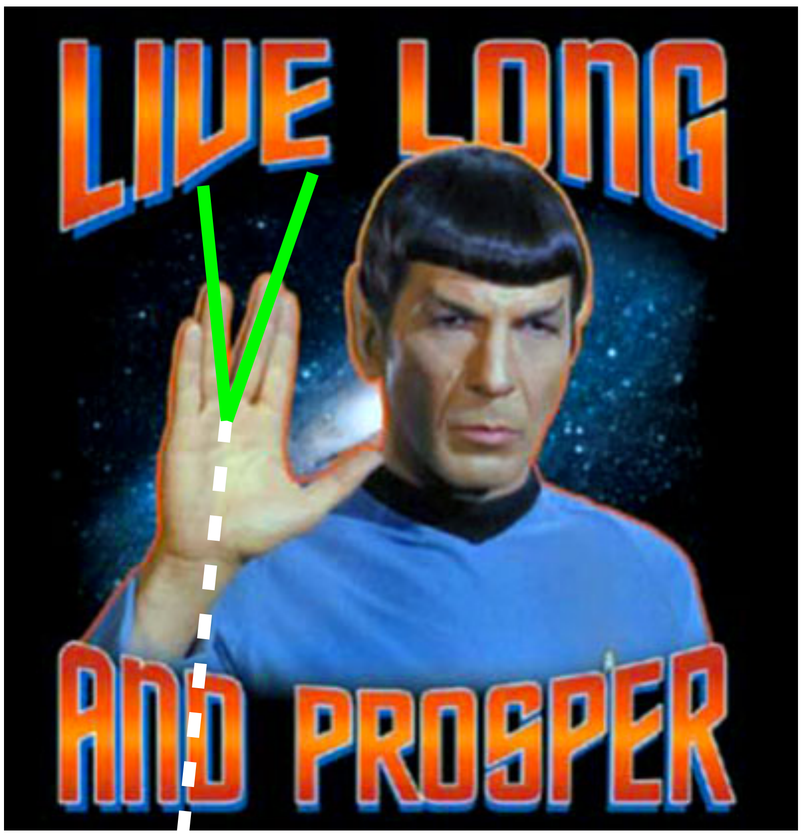
Hidden Sectors and Long-Lived Particle Signatures



SUSY 2019
Corpus Christi, Texas

22 May 2019

David Curtin

UNIVERSITY OF TORONTO

Outline

1. Theory and Motivation
   for the Lifetime Frontier

2. LLPs at the LHC

3. Going beyond the LHC

4. Complementarity with
   Cosmology and Astrophysics

5. Conclusion

1. Theory and Motivation for the Lifetime Frontier

Motivation

The usual fundamental mysteries (Hierarchy Problem, DM, Baryogenesis, Neutrinos, …) aren't going anywhere!

Maybe our prompt searches for high-pT objects have been looking in the wrong place?

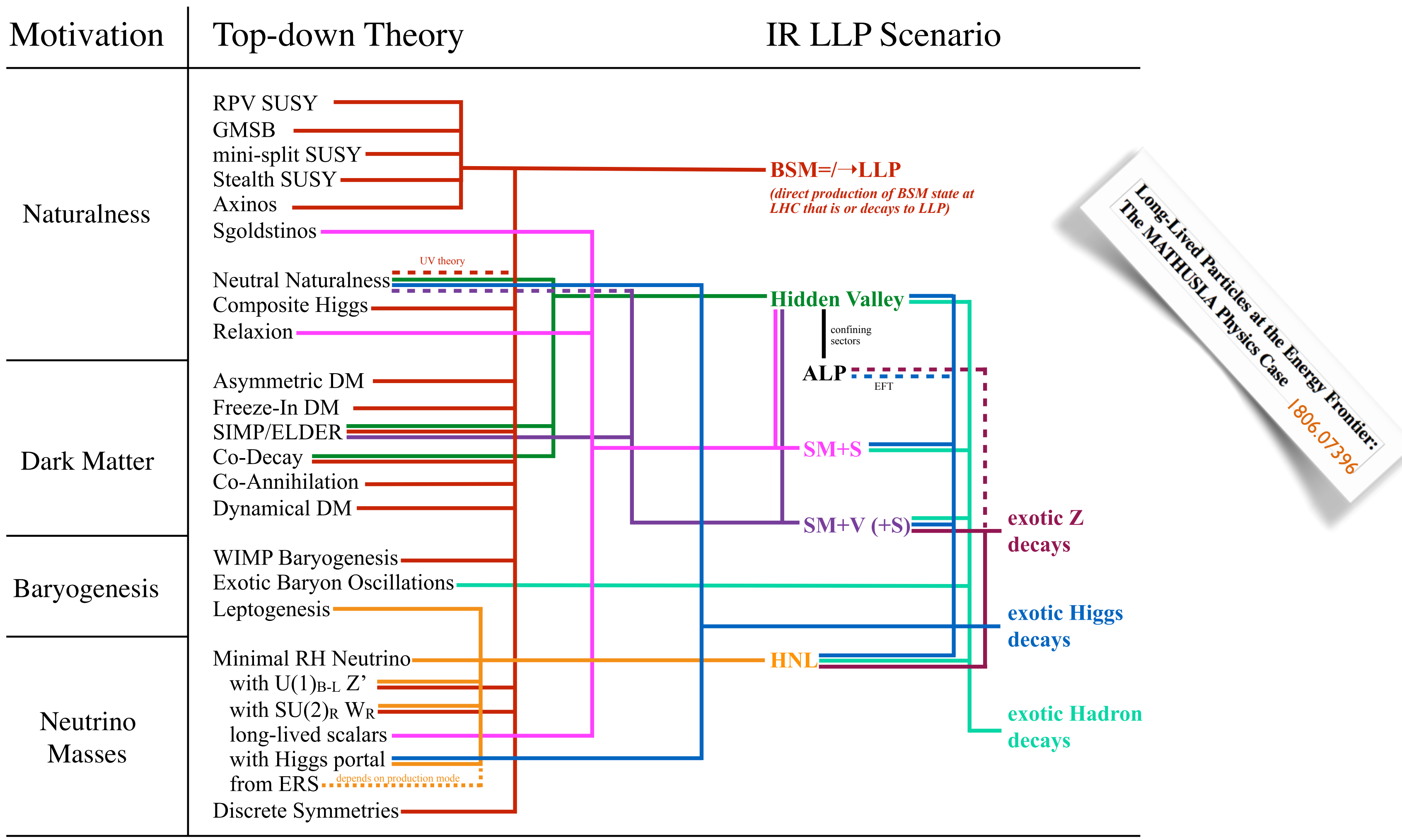
Long-Lived Particles (LLPs) occur in the SM. Tiny decay width for many reasons (approx symmetry, heavy mediator, etc…).

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

Bottom-up point of view:
same mechanisms → LLPs in BSM theories.

Top-down point of view:
LLPs can solve these fundamental mysteries!

Top-Down LLP Motivation

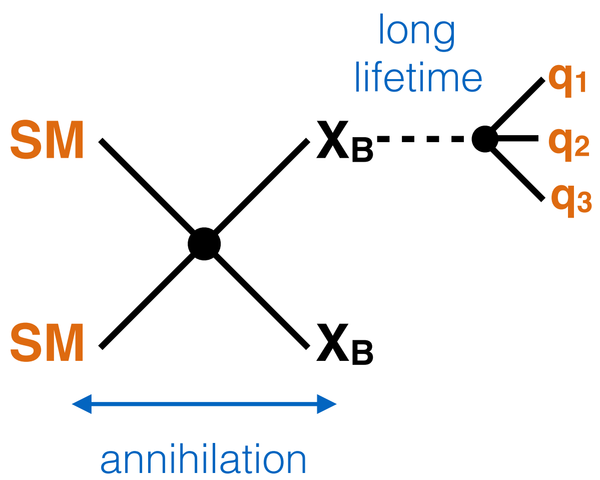


Most of these scenarios are still very poorly constrained at the LHC!

Two Examples

WIMP Baryogenesis:

Cui, Sundrum 1212.2973



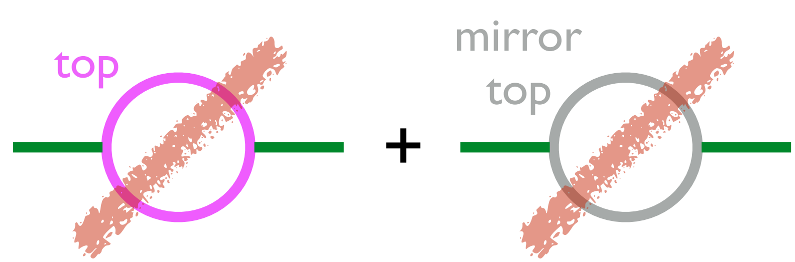
decays produce baryon asymmetry

Meta-stable WIMP-like parent can be made at colliders with observable decay length.

Neutral Naturalness:

hep-ph/0506256 Chacko, Goh, Harnik
hep-ph/0609152 Burdman, Chacko, Goh, Harnik

Discrete Symmetry relates SM to mirror copy with its own set of gauge forces



Hidden valley LLP signatures!

Neutral top partners stabilize Higgs mass

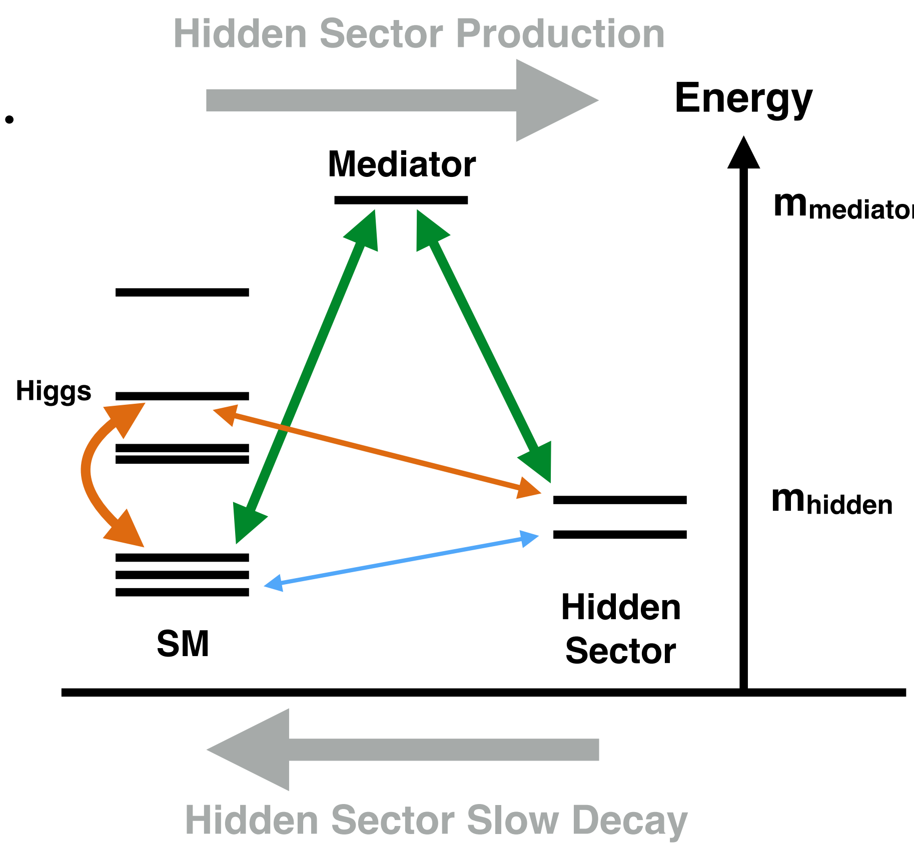
Bottom-up: Hidden Sectors

Particles & forces hidden from us due to small coupling, not high mass.

Generically arise due to the grammar of QFT.

Confirmed examples: ν's, DM

Give non-minimal IR spectra from minimal theory input
(e.g. QCD cousins like Hidden Valleys)



Can couple to SM via small portal couplings, e.g.
Heavy Mediators **Higgs Portal** **Photon Portal**

Lessons

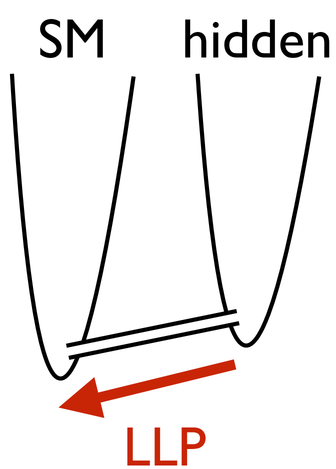
1. Exotic Higgs Decays as probes

LHC can probe tiny exotic branching ratios if decays spectacular.
Sizable Higgs Portal couplings to new physics are generic.

2. Long Lived Particles (LLPs) are generic

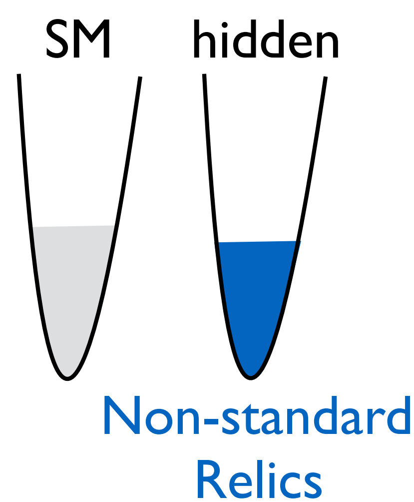
Once produced, Hidden Sector states can only decay back to SM via small portal couplings, generically leading to long lifetimes.
The LLP lifetime is (almost…) a free parameter!

3. Complementarity between Cosmology and Colliders



Models which avoid signatures in one will often show up in the other

(e.g. dark radiation,
DM with structure, etc.)



2. LLPs at the LHC

Looking for LLPs: Rules of the game

LLPs are spectacular signatures:

- if they are charged/colored, very conspicuous
- invisible if neutral, but their decay is spectacular, usually reconstructed as a "displaced vertex" (DV)

harder, focus here

Neutral LLPs: geometrical nature can be **difficult to trigger** on at L1. **Backgrounds low but hard to predict**, so often try to eliminate BG completely.
(MET searches are usually insensitive due to small xsecs.)

Most searches today & near future try to solve these problems via **"LLP + X"** strategy. Require:
- *geometric nature* of LLP decay ("LLP")
- something else ("X") to *eliminate background* (X could be a second LLP) and *help triggering* (high HT, lepton, …)

Recent Analyses

These analyses are difficult and take a long time.

Significant experimental progress in recent years!

For Neutral LLPs, *most* current cutting edge searches could be classified as:

- standard prompt trigger + offline DV search
  (e.g. prompt lepton + DVs from VH, H->LLPs)

- ATLAS Muon System: L1 trigger, look for any DV inside MS, muon DVs anywhere

- CMS displaced jet HLT triggers: lower L1 HT cut than prompt, displaced search at HLT

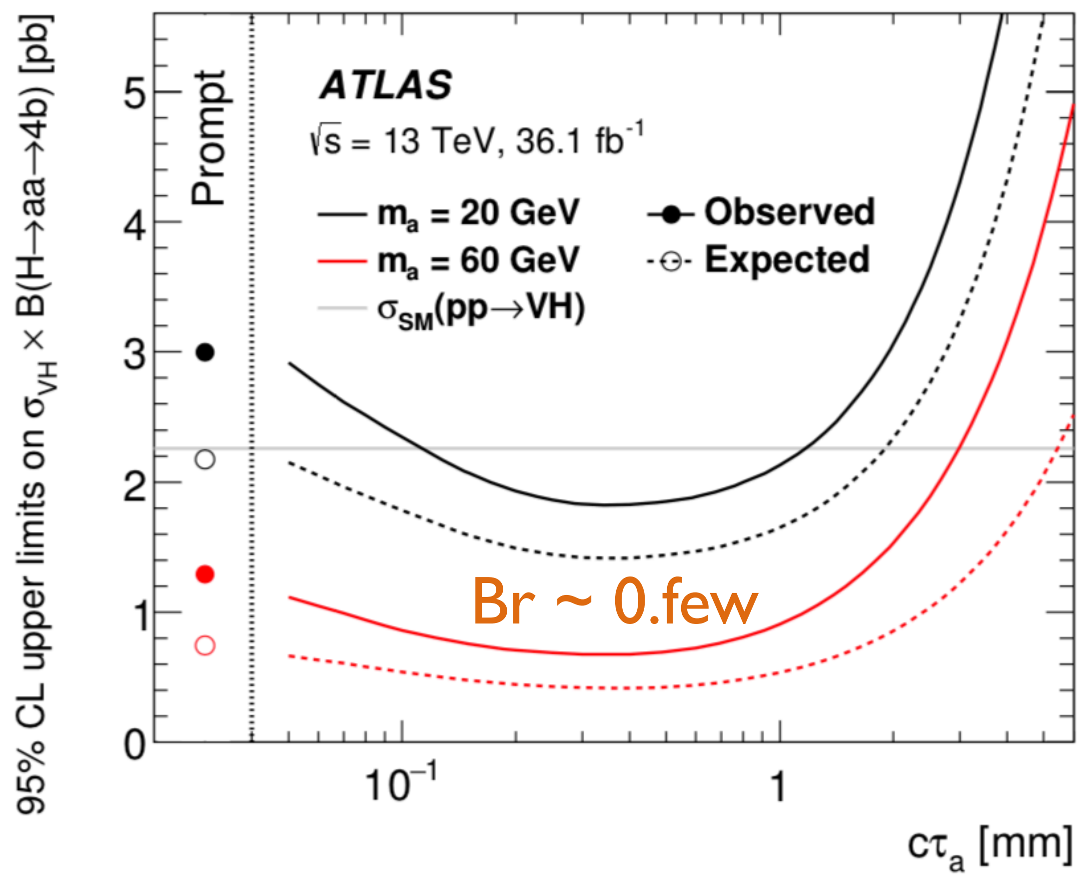
(there are also searches in Calorimeter, e.g. ATLAS 1902.03094, disappearing track searches, etc…)

H → 2a → 4b (ATLAS)

Searches for VH production, H → 2a → 4b. 1806.07355

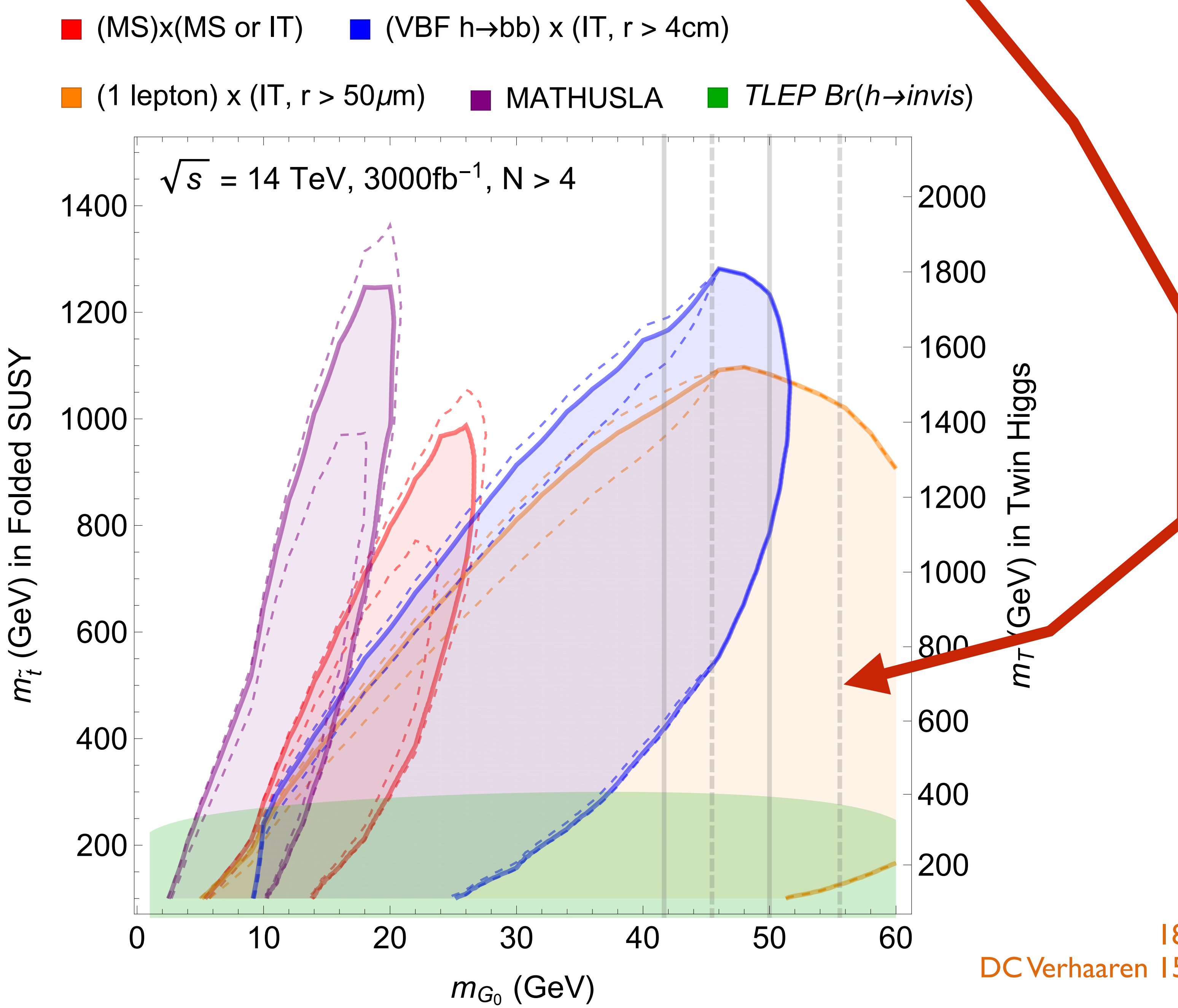
TRIGGER: relies on lepton from V. **Exactly what we want** for inclusive LLP searches from exotic Higgs decays, since LLP in this mass range is difficult to trigger on.

HOWEVER, this is a **PROMPT** search where they compute sensitivities to macroscopic lifetimes as well.
(Important new way of presenting prompt results!)



Hopefully dedicated LLP analyses with this trigger coming in the near future.

We need this channel for Neutral Naturalness!!



1806.07396
DC Verhaaren 1506.06141

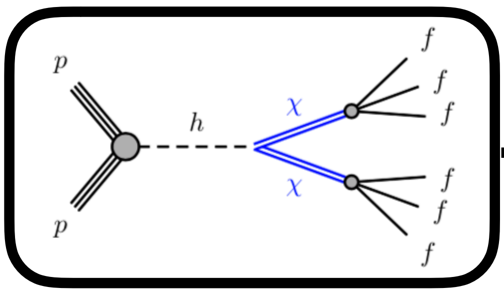
1 or 2 jj DVs *inside* ATLAS Muon System

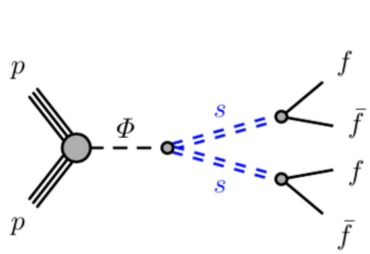
ATLAS MS can trigger on hadronic LLP decay at L1!

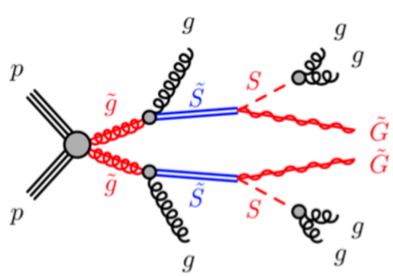
based on 1605.02742 Coccaro, DC, Lubatti, Russell, Shelton

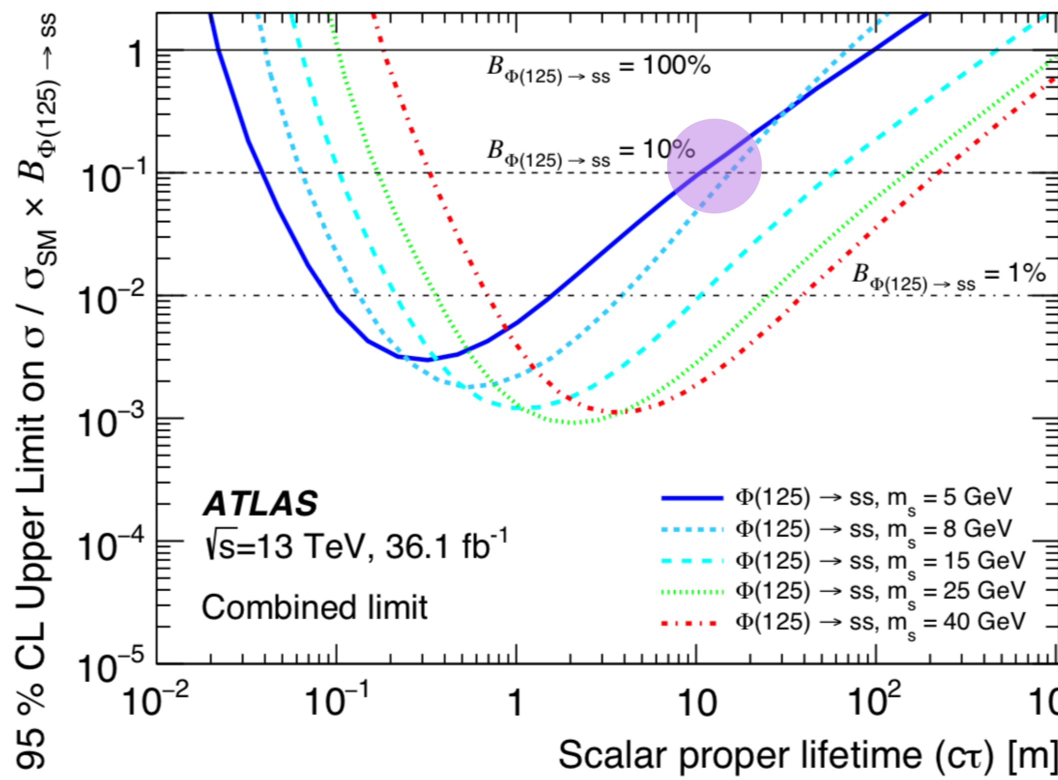
Require either 2DVs, or
1DV + (MET > 30 GeV), or 1DV + (pTJJ > 150 GeV)

1DV search has significant background, but extends long-lifetime reach!









1811.07370

1 μμ DV anywhere with ATLAS MS

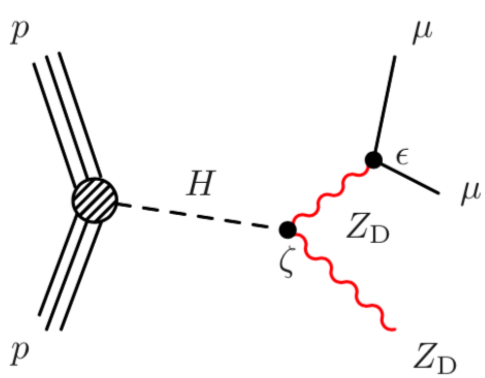
ATLAS MS can trigger on L1. Very inclusive search for single LLP → μμ anywhere within 4m of beam

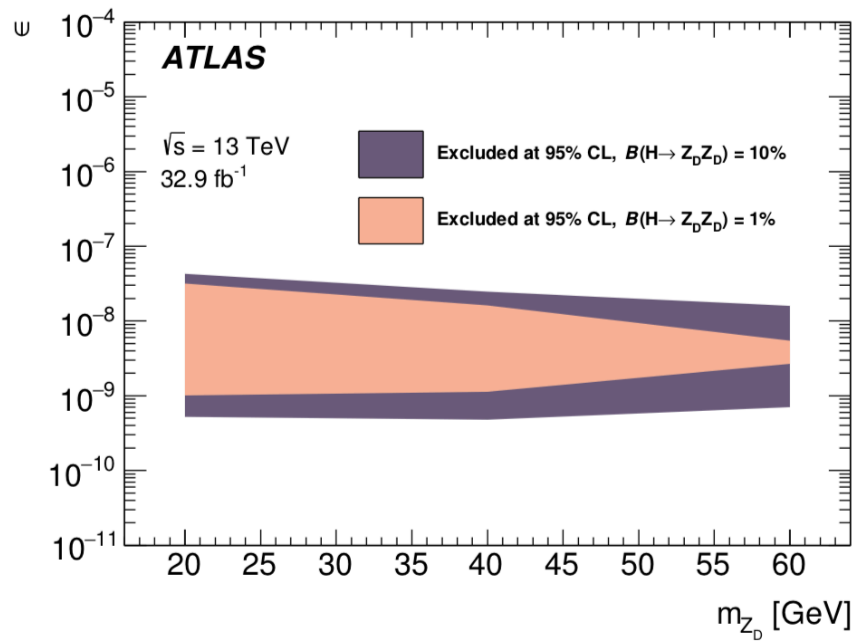
Low-mass SR: fully inclusive.

N_{BG} ~ 10 , equiv to σ_{BG} ~ 0.3fb. **Not zero BG! (surprise?)**

High-mass SR: MET > 110 GeV.

N_{BG} ~ 0



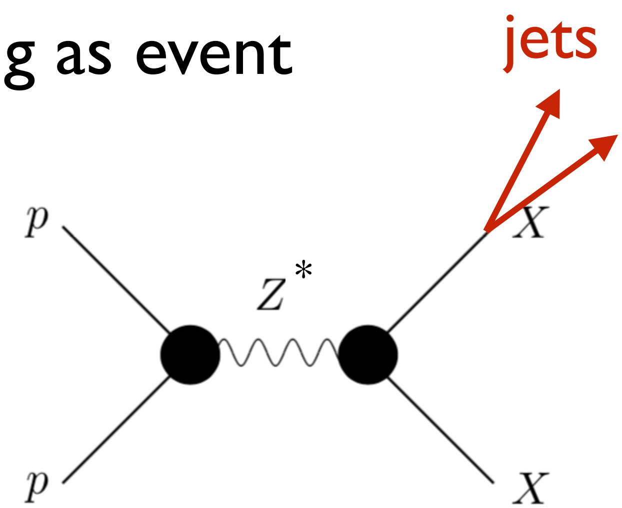


1808.03057

CMS Displaced Jets

1811.07991

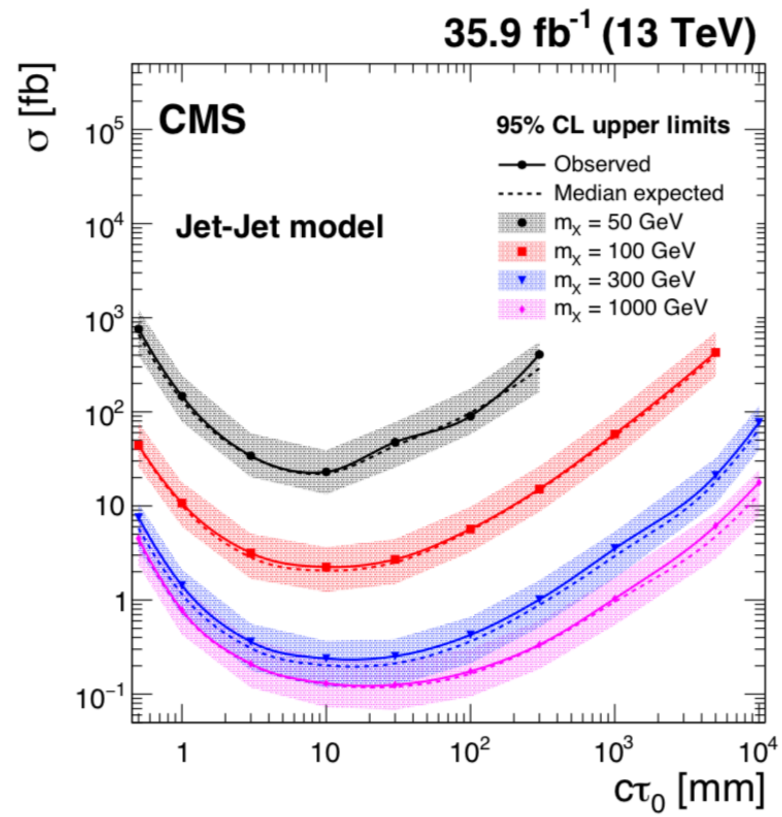
CMS can trigger on displaced jets at HLT as long as event passes L1 HT seed → **HT > 400 GeV**



Benchmark model of LLP X pair production via Z* mediator. X -> jets.

Very efficient for heavy LLPs.
Stringent HT cut eliminates BG.

Surprising: also get significant limits for mX = 50 GeV!



Why not use this to get limits on exotic Higgs decays? (Naively expect <~ 1% efficiency from boosted fraction p_{TH} > 200 GeV → Br limit 0.few?)

What's next?

A Coordinated LLP Search Program

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

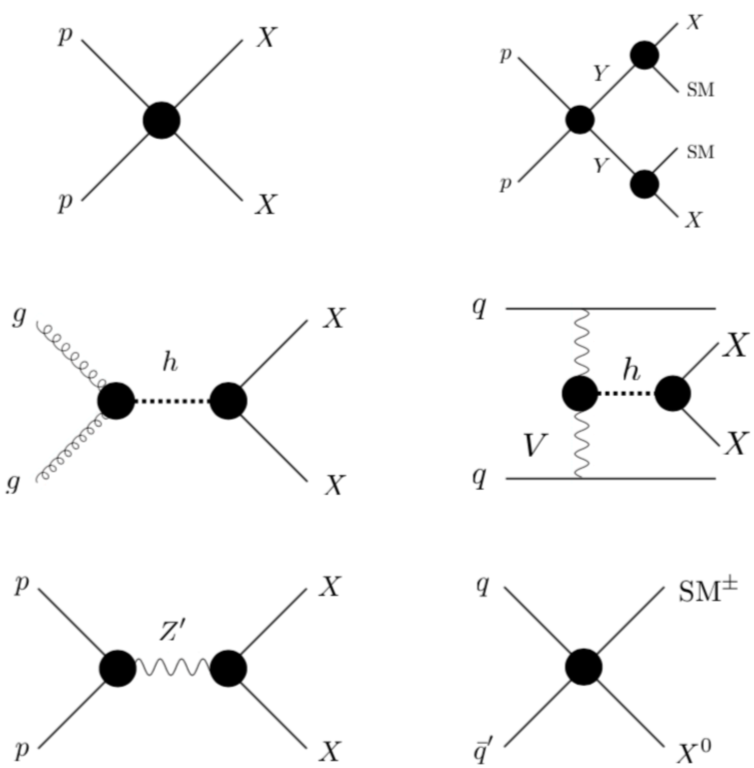
March 6, 2019

1903.04497

Particles beyond the Standard Model (SM) can generically have lifetimes that are long compared to SM particles at the weak scale. When produced at experiments such as the Large Hadron Collider (LHC) at CERN, these long-lived particles (LLPs) can decay far from the interaction vertex of the primary proton-proton collision. Such LLP signatures are distinct from those of promptly

LHC LLP Community

Simplified Model Roadmap of LLP Signature Space:

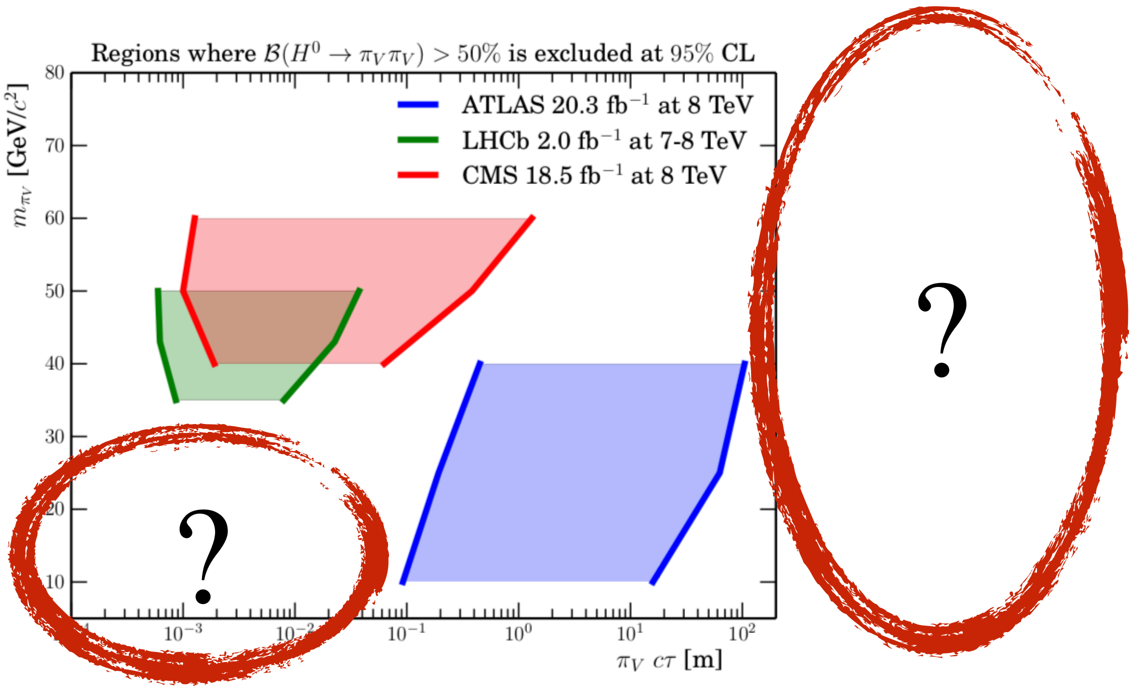


Production \ Decay	$\gamma\gamma(+\text{inv.})$	$\gamma+\text{inv.}$	$jj(+\text{inv.})$	$jj\ell$	$\ell^+\ell^-(+\text{inv.})$	$\ell^+_\alpha\ell^-_{\beta\neq\alpha}(+\text{inv.})$
DPP: sneutrino pair or neutralino pair	$\dagger$	SUSY	SUSY	SUSY	SUSY	SUSY
HP: squark pair, $\tilde{q}\to jX$ or gluino pair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

A Coordinated LLP Search Program

Identify and Target Gaps in Coverage:

e.g. for exotic Higgs decays with relatively high rate (Br = 0.5)



e.g. **Dark Showers**

hidden valley can give rise to high-multiplicity soft final states (soft unclustered energy patterns SUEPs). Soft Multi-Muon Searches?

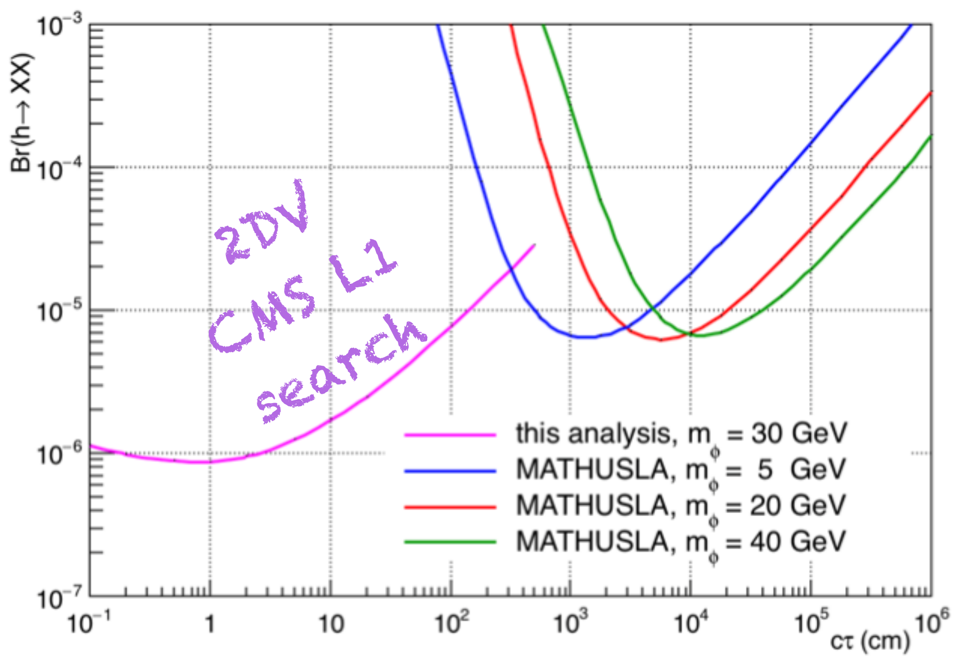
... and more

Upgrades: L1 DV triggers

L1 tracking upgrade considered at ATLAS and CMS to reduce Pile-Up.

CMS in particular could use track stubs at L1 to reconstruct DV

Example: H → XX, both X decay to hadrons in tracker



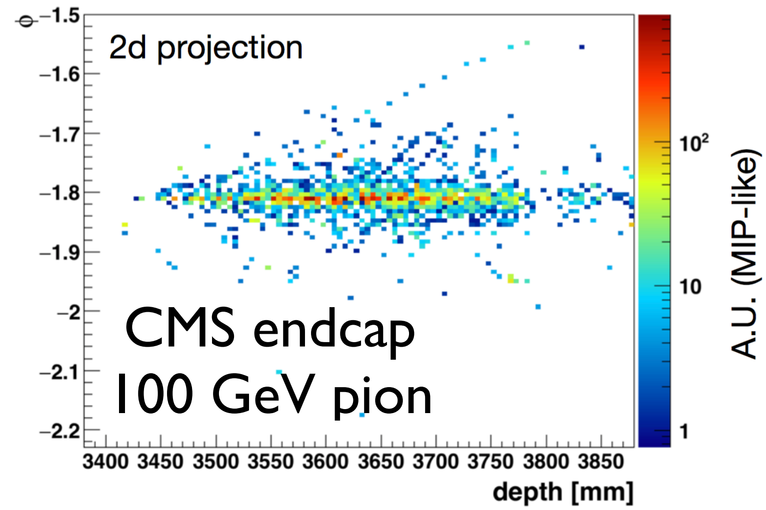
For shorter lifetimes, gain ~ order of magnitude in reach compared to e.g. VH search??

Gershtein1705.04321

Upgrades: fancy calorimeters

ATLAS and CMS forward calo upgrades have ~30ps timing, great spatial resolution.

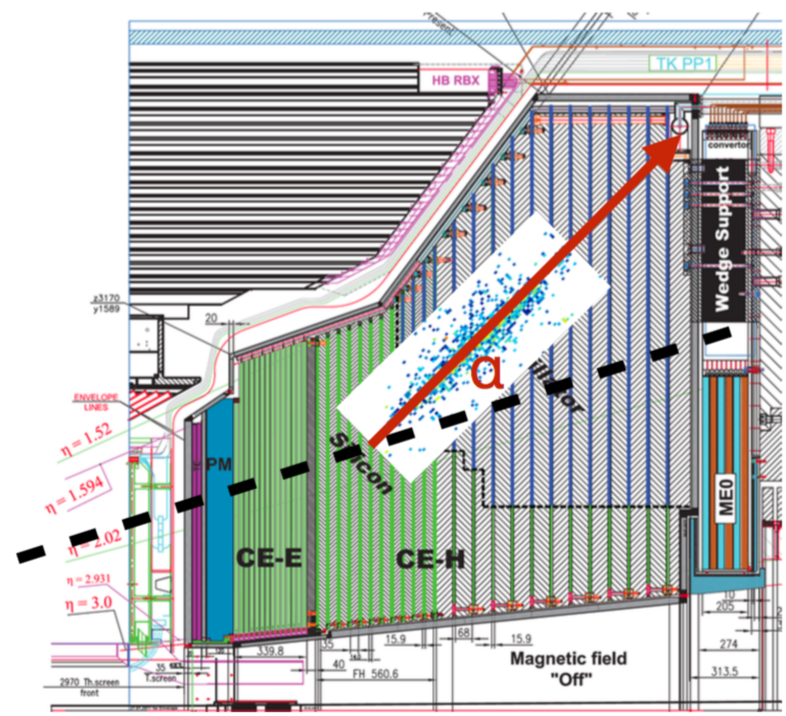
In CMS case, get 4D shower reconstruction.



LLP Opportunities:

1. Search for LLPs decaying to photon via timing information

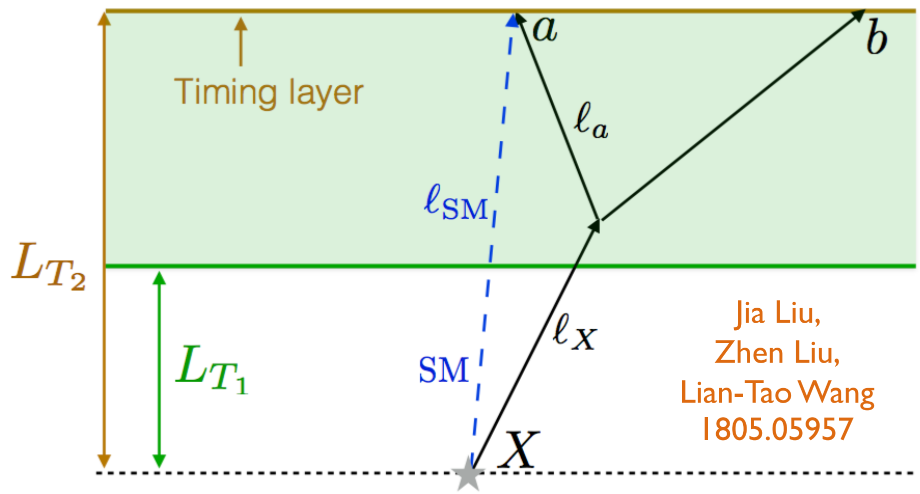
2. Reconstruct LLP decays in great detail, get a "Calo DV"!
Could L1 trigger on this!
Rival the ATLAS MS for DV searches???



Upgrades: Timing

E.g. CMS MIP timing detector in the barrel for PU reduction

Will obviously be
extremely useful
for LLP searches as well!



See Jia Liu's talk

Interesting challenge:
can timing information be used for triggering?

Timing in tracker will definitely not eliminate LLP background to zero (plenty of BG is out-of-time), but incorporating timing information into LLP searches has the potential to significantly increase LLP sensitivity.

3. Going beyond the LHC

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
European Strategy submission: 1901.04040 & 1901.09966
…

mathusla.web.cern.ch

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

The Problem of Long Lifetimes

LLP lifetime is free parameter up to
BBN bound of ~ 10^7m

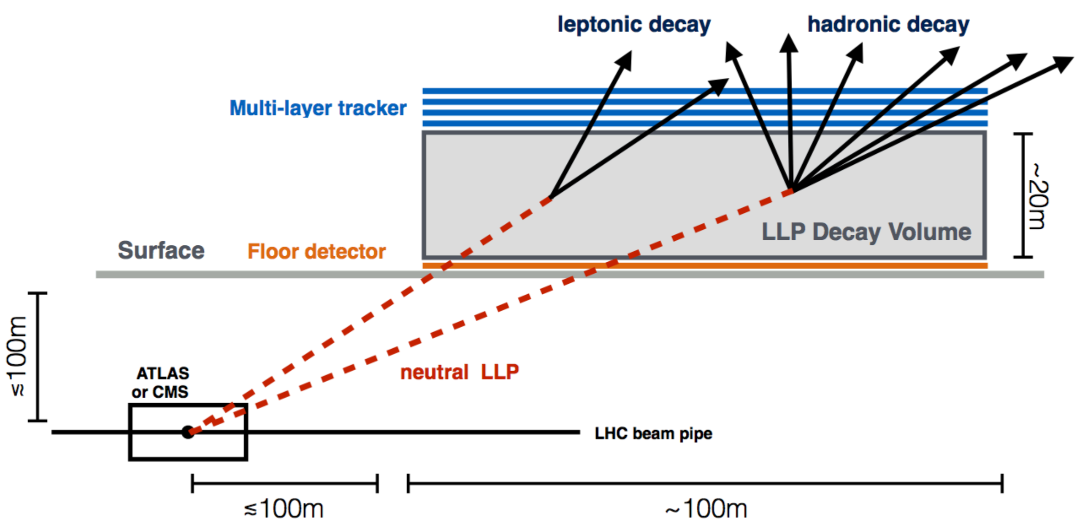
If LLP lifetime is >> detector size, then acceptance is

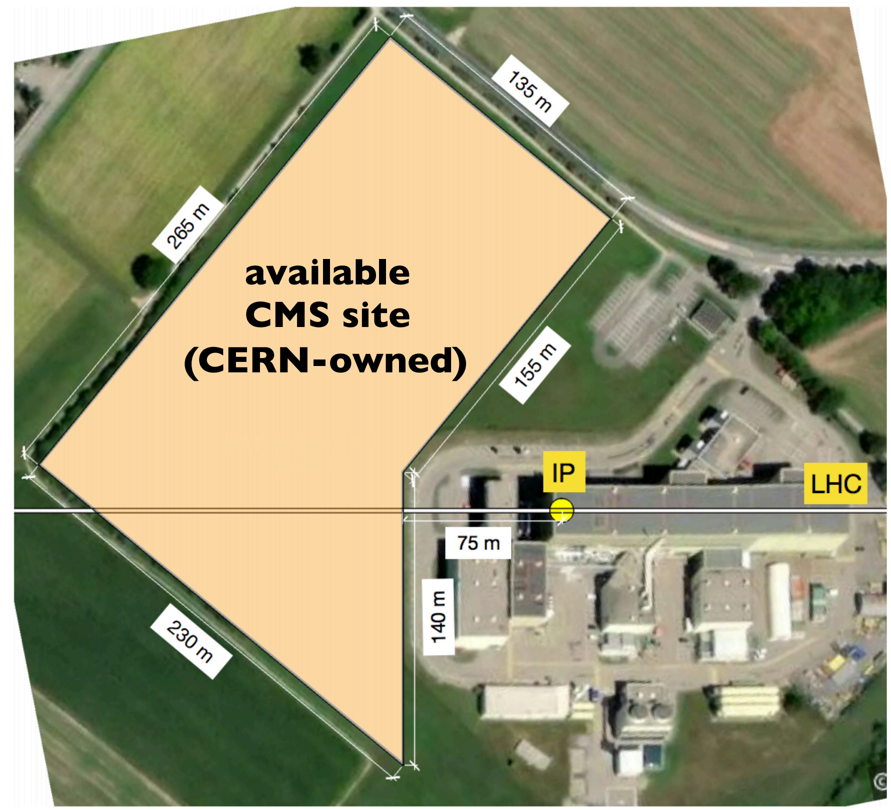
(angular coverage) * (detector size) / (decay length)

so Ultra-Long-Lived particle decays
are always inherently **rare** events.

→ zero-background environment is critical!

An external LLP detector for the HL-LHC

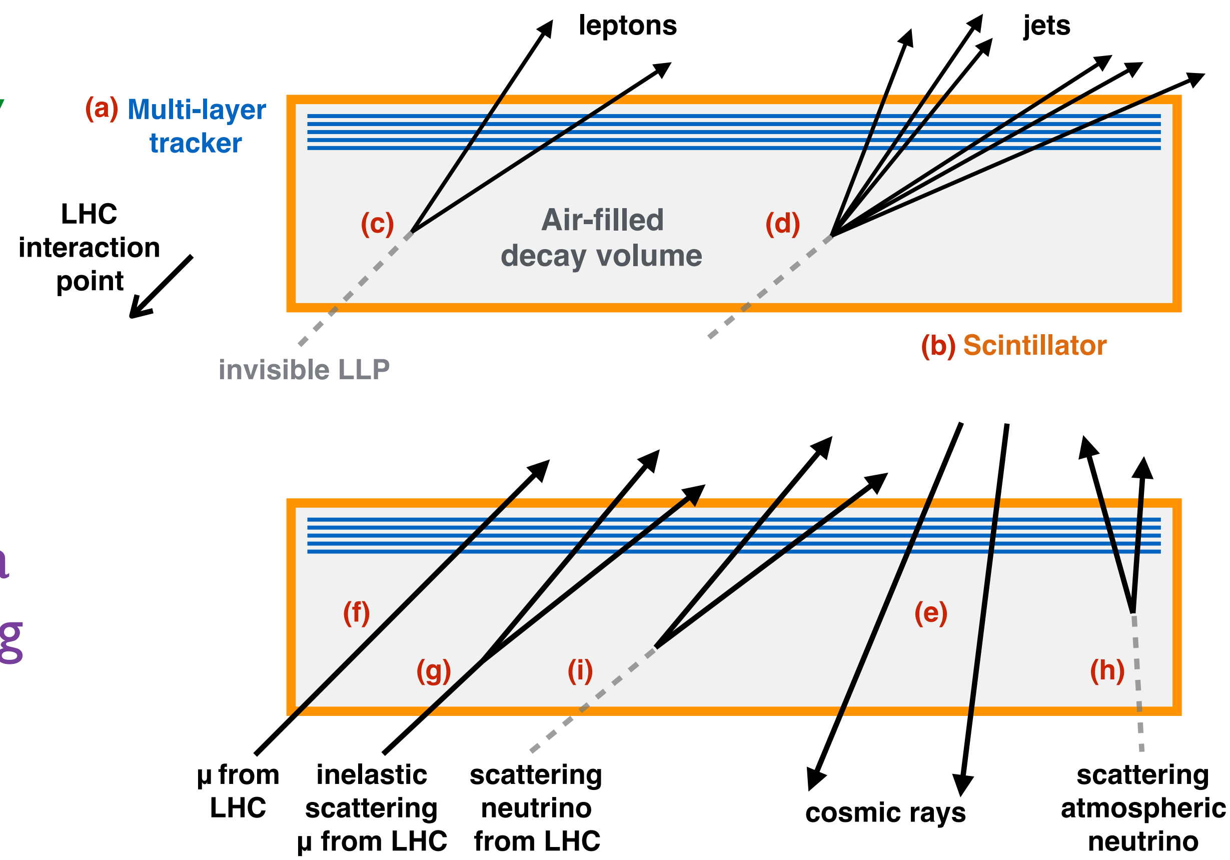




… searches for LLPs by reconstructing displaced vertices in air-filled decay volume, removed from LHC collision backgrounds.

Signal vs Background

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



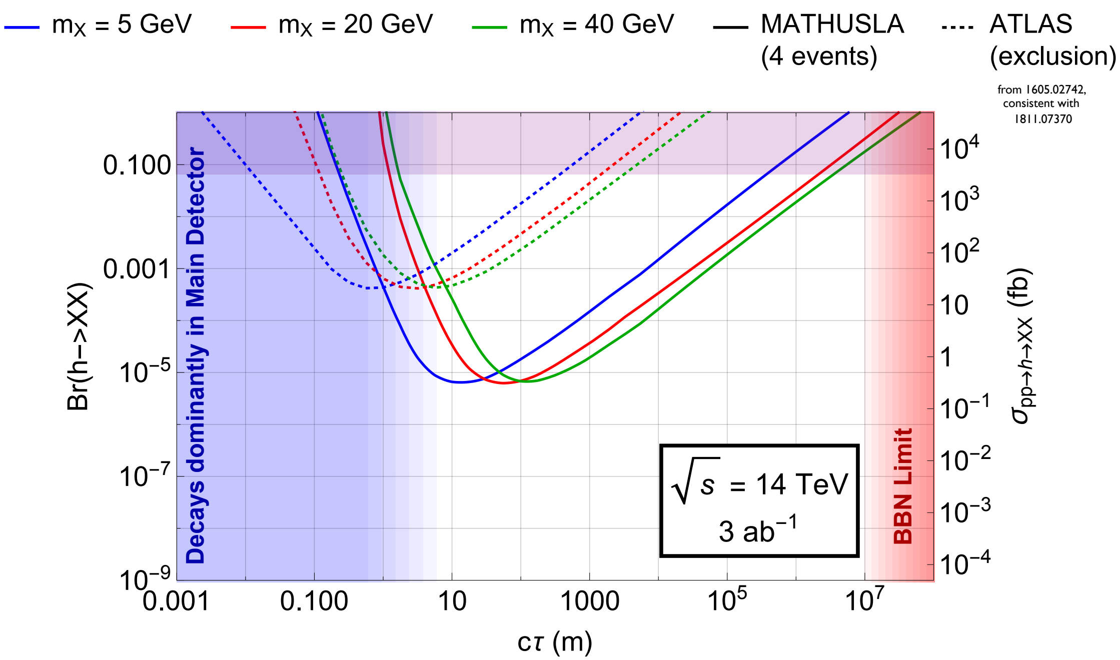
These signal requirements + a few extra geometry and timing cuts veto all backgrounds!

MATHUSLA can search for neutral LLP decays with near-zero backgrounds!

Sensitivity

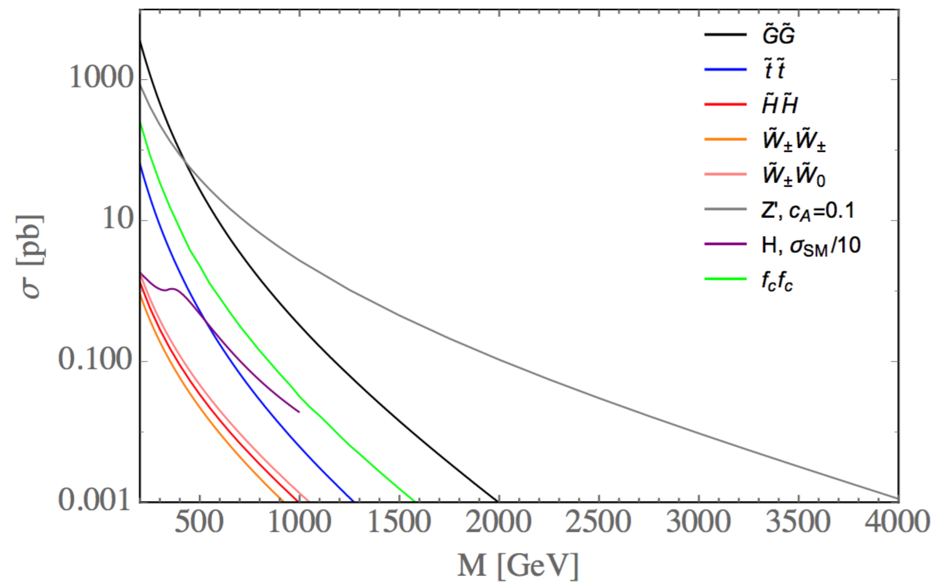
Physics Case White Paper 1806.07396

LLP cross section reach (exotic Higgs decay example)



Up to 1000x better sensitivity than main detectors

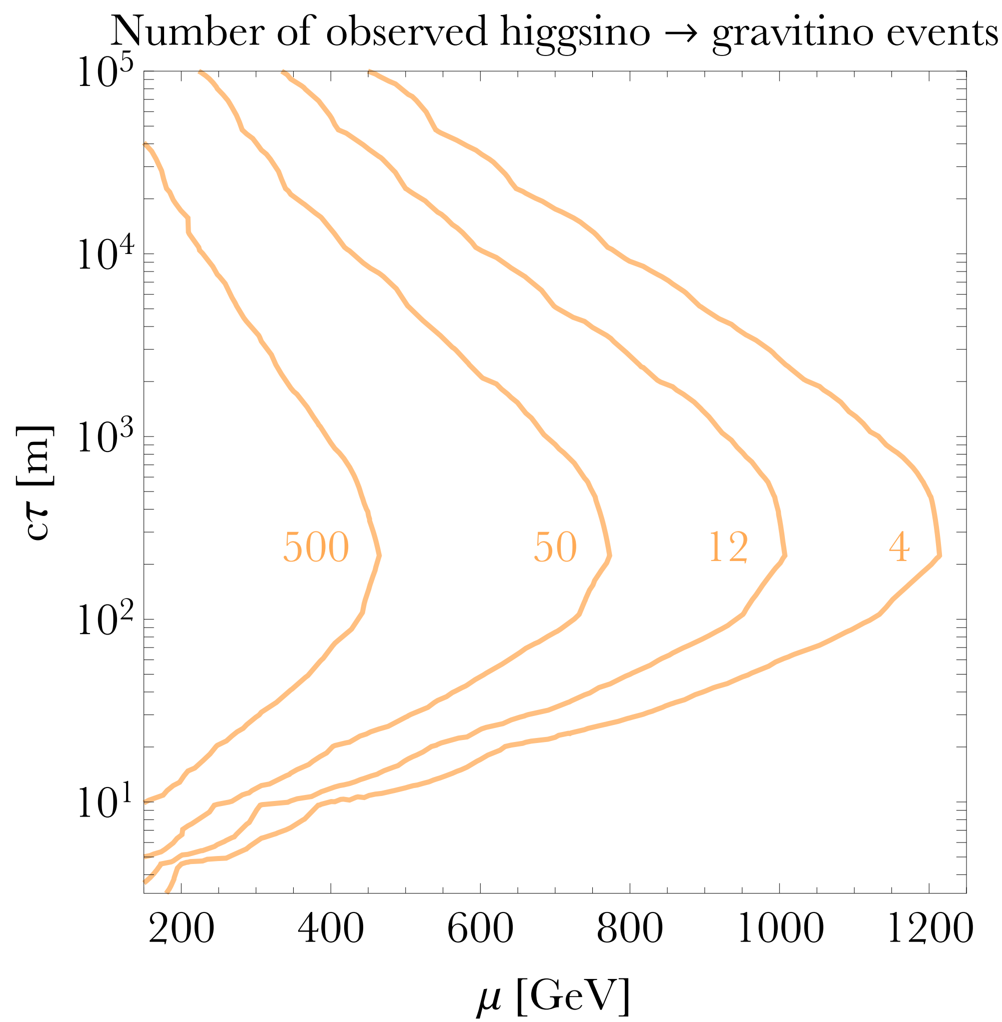
Any LLP production process with σ > fb can give signal.



Probe TeV+ scales!

200m x 200m x 20m detector volume is **physics benchmark** sensitivity that can be reached by realistic detector shape near CMS.

A high-mass LLP example: Higgsinos

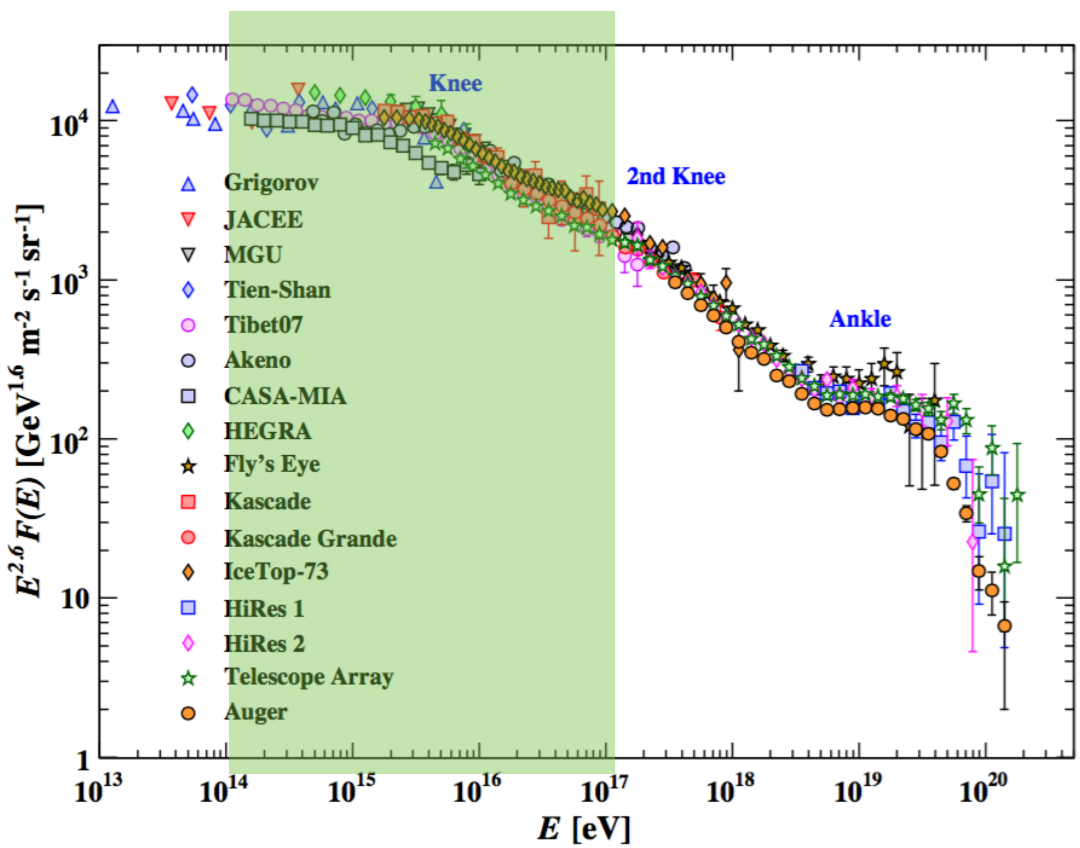


1806.07396

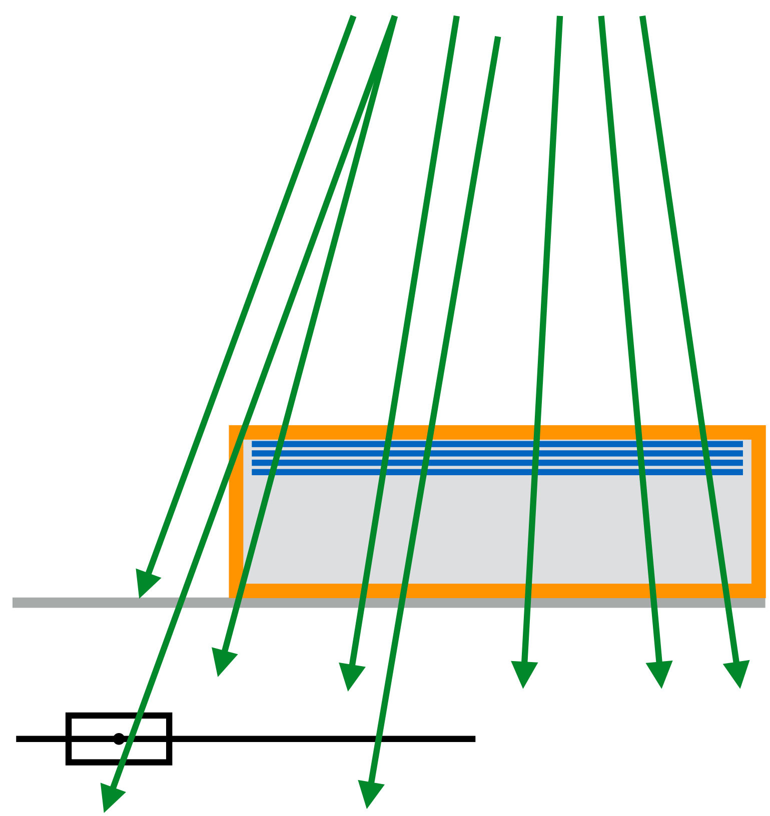
Guaranteed Physics Return

MATHUSLA is an excellent Cosmic Ray Telescope!

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



mostly muons at sea level



MATHUSLA collaboration

1811.00927

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 Beach
Tingting Cao,[c] Paolo Camarri,[f,g] Roberto Cardarelli,[f] Mario R
John Pa
Drewes, ,[q] Jared E
Stefano kun Heng,
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Li,[a f] Bar ovanni Ma
McCullo Mizrachi,
Meny Ra Piter A.
Policicc o,[ad] Joe R
Santoni ian Shuve
Vasquez ro Fernán
Tejeda M ftah Silver
Emma T lázquez,[i]
Young,[e]

2018 Test Stand above ATLAS

1901.04040

MATHUSLA

MATHUSLA: A Detector Proposal to Explore the Lifetime Frontier at the HL-LHC

Input to the update process of the European Strategy for Particle Physics
18. December 2018

Henry Lubatti (Corresponding Author),[1,*] Cristiano Alpigiani,[1] Juan Carlos Arteaga-Velázquez,[2] Austin Ball,[3] Liron Barak,[4] James Beacham,[5] Yan Benhammo,[4] Karen Salomé Caballero-Mora,[6] Paolo Camarri,[7] Tingting Cao,[4] Roberto Cardarelli,[7] John Paul Chou,[8] David Curtin,[9] Albert de Roeck,[3] Giuseppe Di Sciascio,[7] Miriam Diamond,[9] Marco Drewes,[10] Sarah C. Eno,[11] Rouven Essig,[12] Jared Evans,[13] Erez Etzion,[4] Arturo Fernández Téllez,[14] Oliver Fischer,[15] Jim Freeman,[16] Stefano Giagu,[17] Brandon Gomes,[8] Andy Haas,[18] Yuekun Heng,[19] Giuseppe Iaselli,[20] Ken Johns,[21] Muge Karagoz,[11] Audrey Kvam,[1] Dragoslav Lazic,[22] Liang Li,[23] Barbara Liberti,[7] Zhen Liu,[11] Giovanni Marsella,[24] Piter A. Paye Mamani,[25] Mario Iván Martínez Hernández,[14] Matthew McCullough,[3] David McKeen,[26] Patrick Meade,[12] Gilad Mizrachi,[4] David Morrissey,[26] Meny Raviv Moshe,[4] Antonio Policicchio,[17] Mason Proffitt,[1] Marina Reggiani-Guzzo,[27] Mario Rodríguez-Cahuantzi,[14] Joe Rothberg,[1] Rinaldo Santonico,[7] Marco Schioppa,[28] Jessie Shelton,[29] Brian Shuve,[30] Yiftah Silver,[4] Daniel Stolarski,[31] Martin A. Subieta Vasquez,[25] Guillermo Tejeda Muñoz,[14] Steffie Ann Thayil,[8] Yuhsin Tsai,[11] Emma Torro,[1] Gordon Watts,[1] Charles Young,[32] and Jose Zurita[33]

MATHUSLA collaboration

Now trying to secure
O(million USD) funding for
detector R&D,
larger-scale prototype,
preparing TDR
in next few years

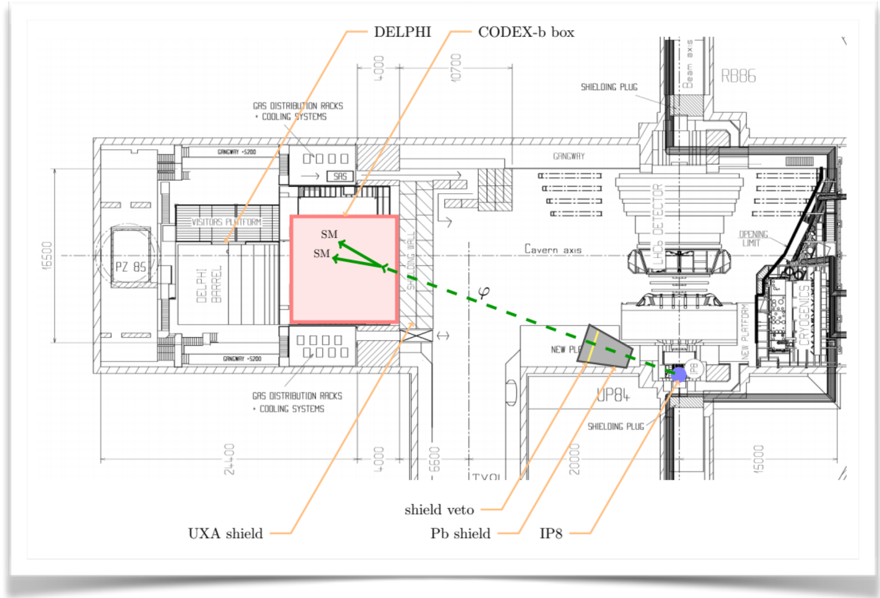
Full-scale detector cost @ HL-LHC
< 100 million USD

LLP Detector Ecosystem

Other Proposed External LLP Detectors for the LHC (for light LLPs)

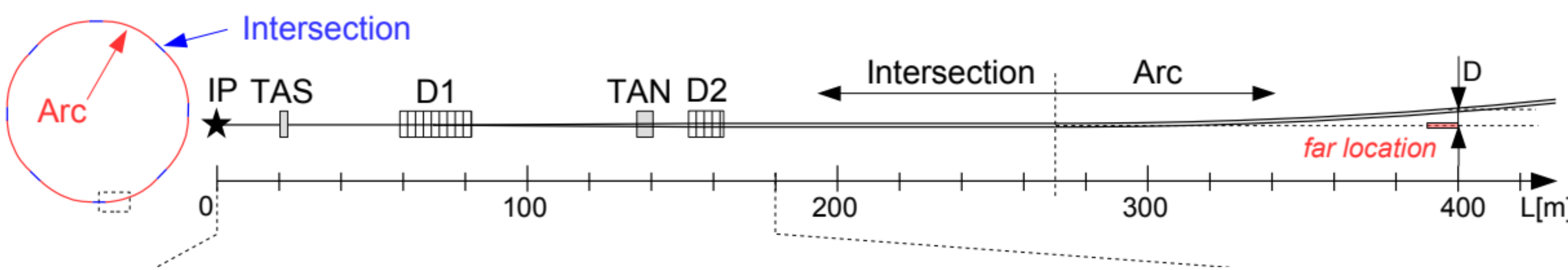
CODEX-b:
"mini-MATHUSLA" near LHCb

Gligorov, Knapen, Papucci, Robinson, 1708.09395



See Jonathan Feng's talk

FASER: tracker telescope staring along beam axis into ATLAS collision



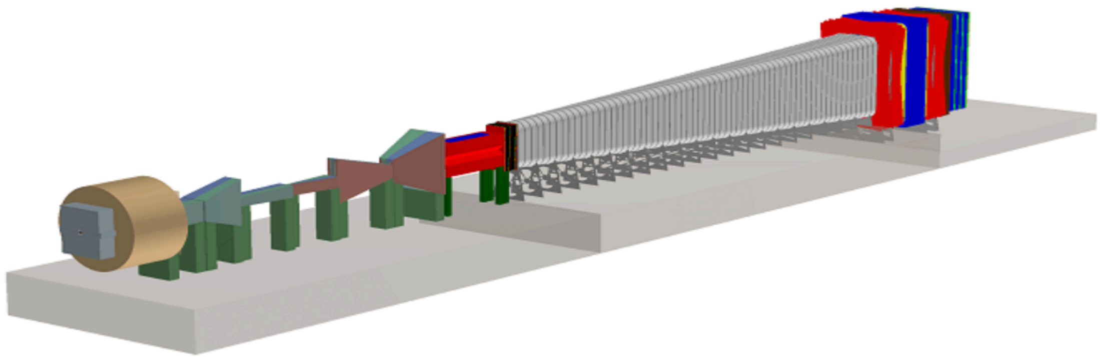
Relatively Cheap & <u>FUNDED</u>!!!

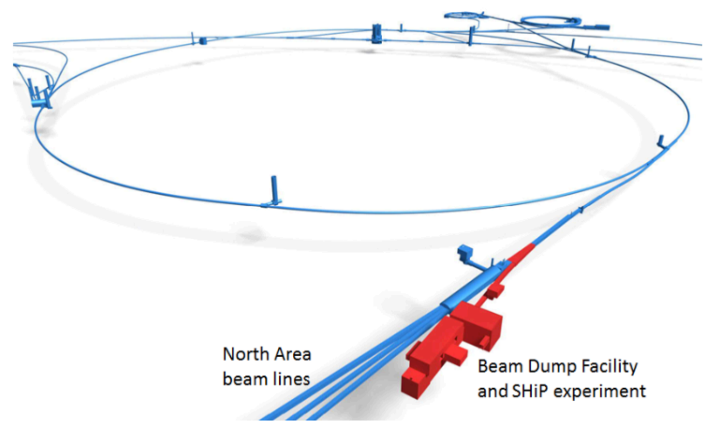
Feng, Galon, Kling, Trojanowski 1710.09387

SHiP

ship.web.cern.ch

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





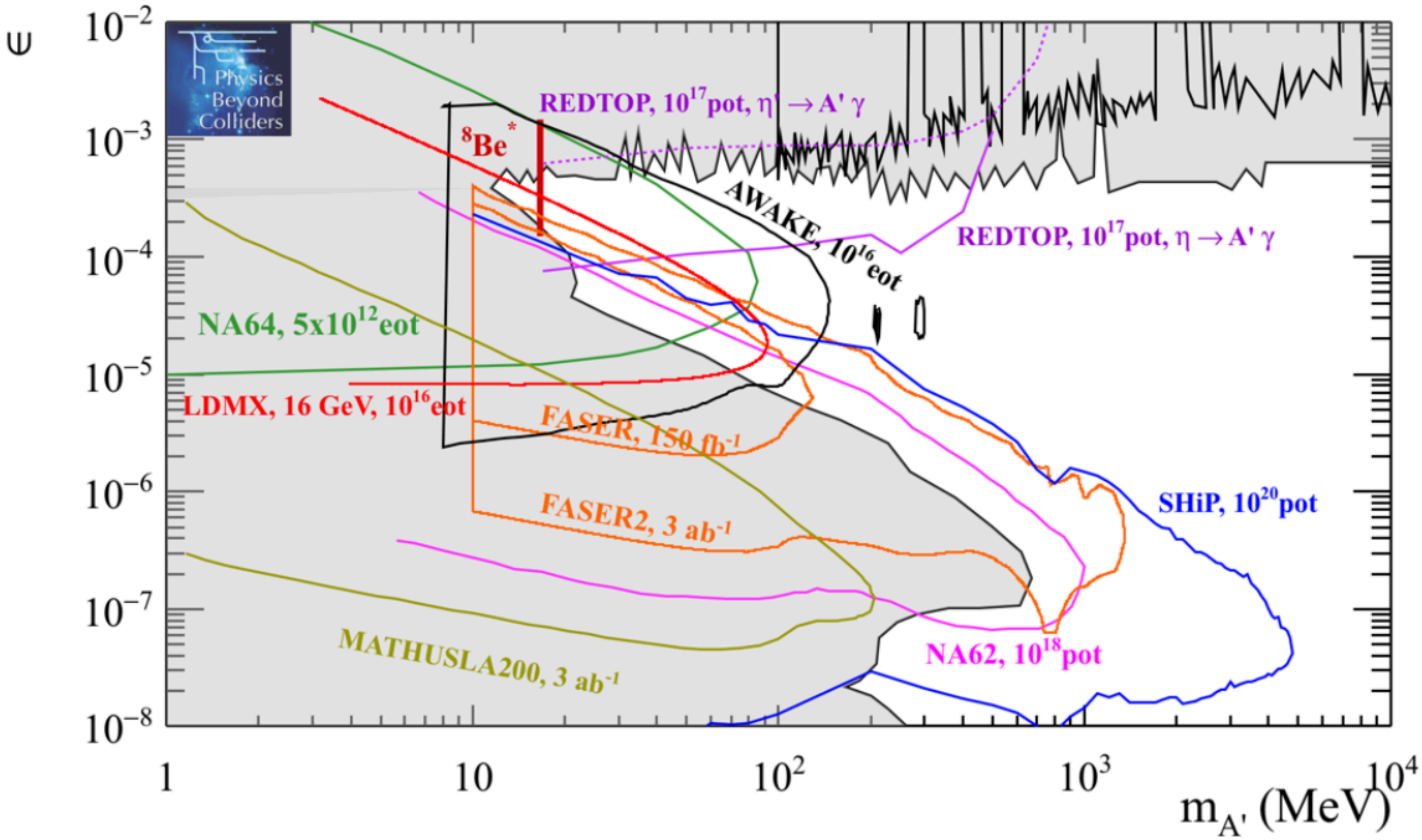
Physics case for SHiP examined by Physics Beyond Colliders (PBC) working group at CERN.

PBC compared SHiP reach for low-mass LLP simplified models to MATHUSLA, CODEX, Faser. (This does not examine full physics case for MATHUSLA & CODEX, which can probe higher masses.)

Compare reach for

low-mass LLP scenarios

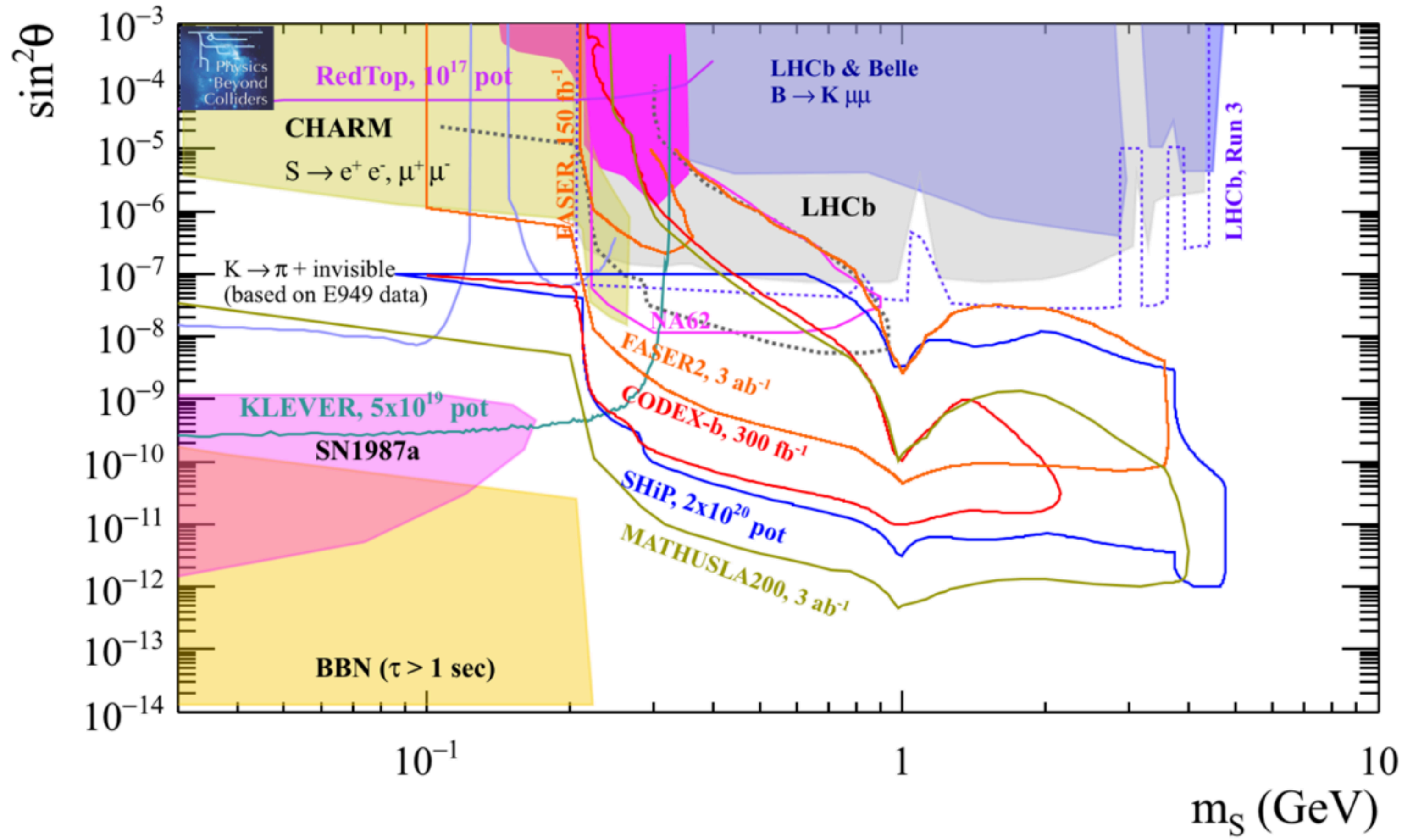
Dark Photon only



For < ~GeV dark photon + invisible or milli-charged states, need LDMX, milliQan

PBC BSM working group report 1901.09966

Dark Scalar only



very complementary coverage… MATHUSLA, SHiP and FASER cover longer, intermediate and shorter lifetimes.

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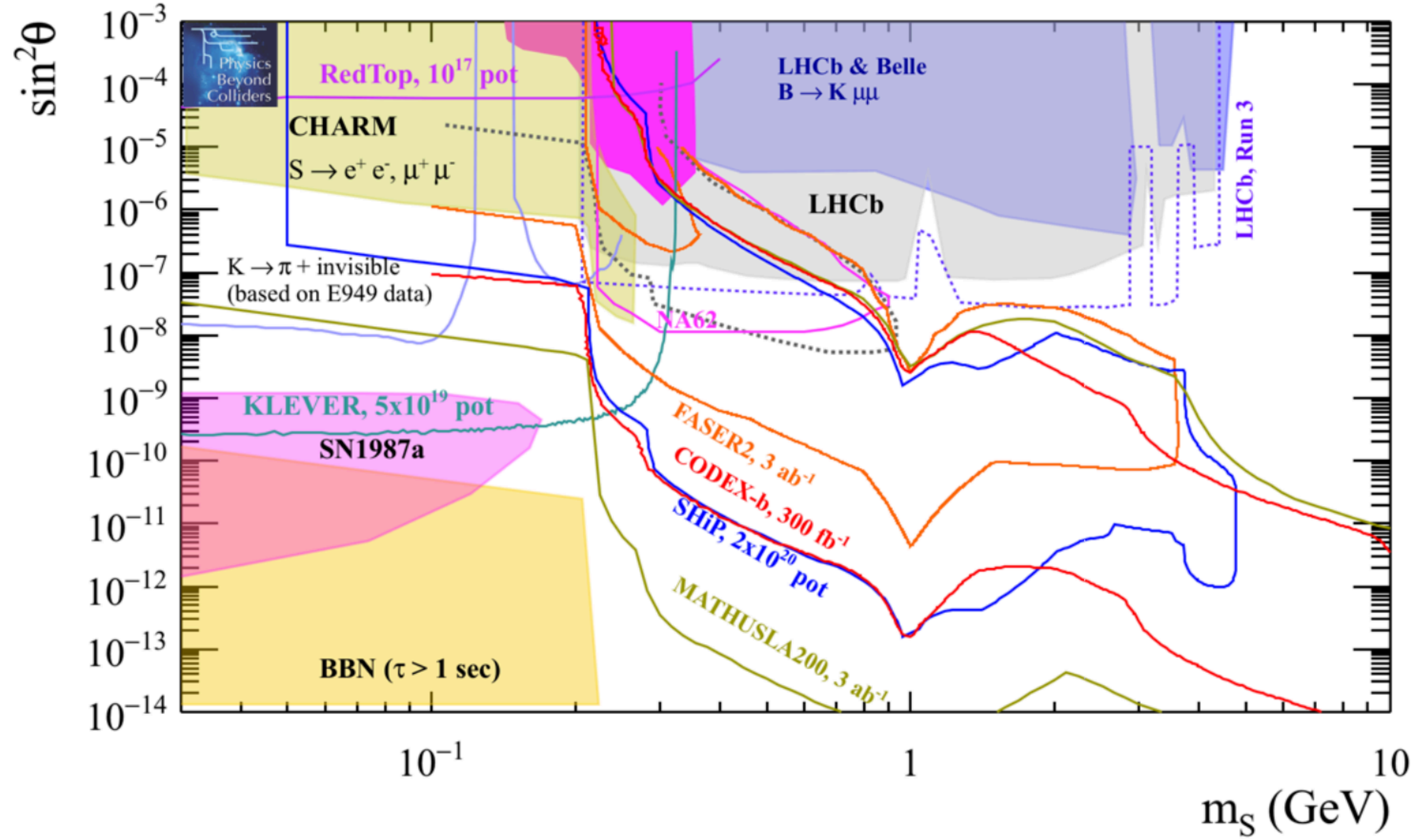
Dark Scalar with exotic higgs decays



LHC external detectors probe higher masses

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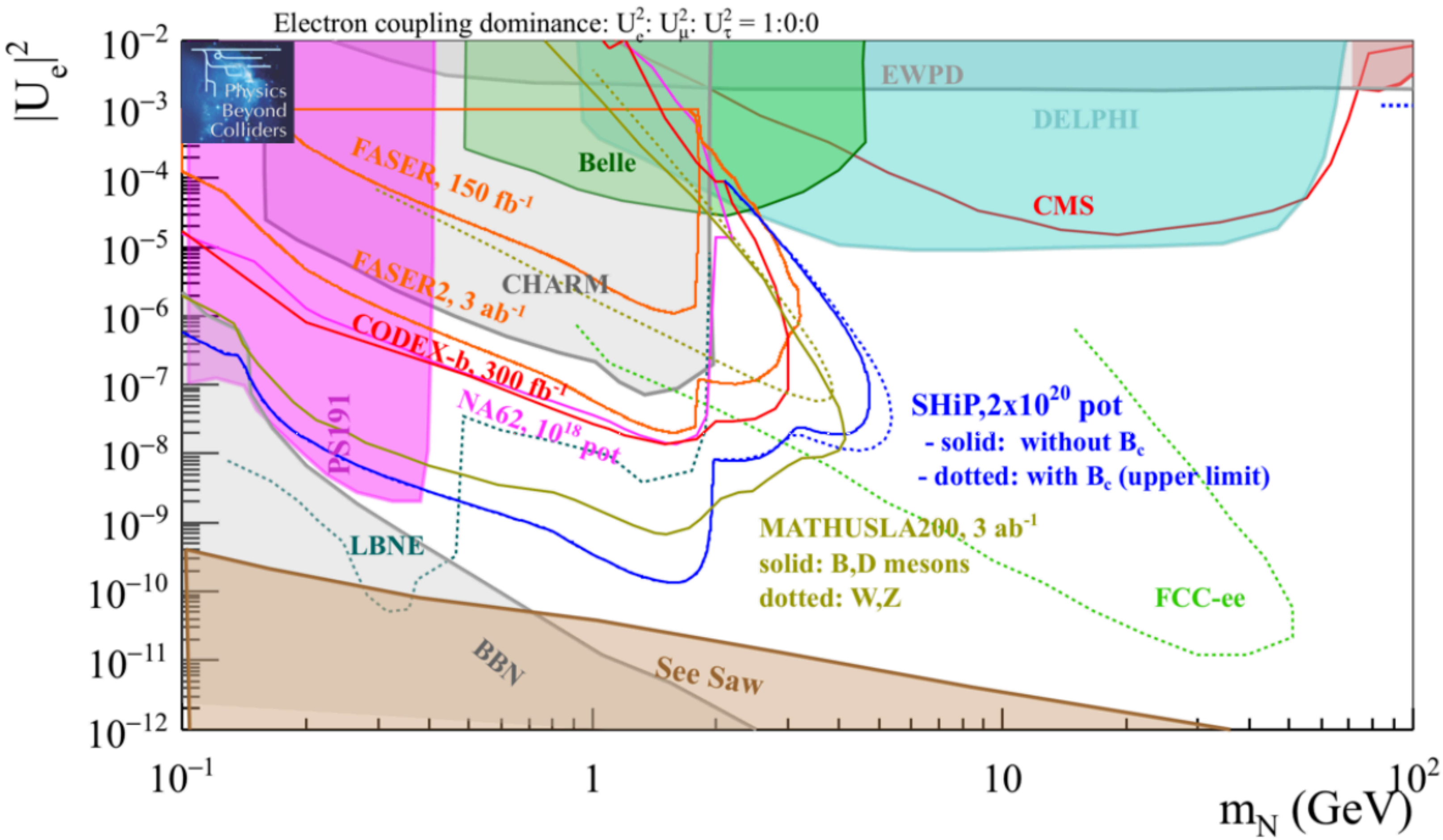
Sterile RH Neutrinos



very complementary coverage…

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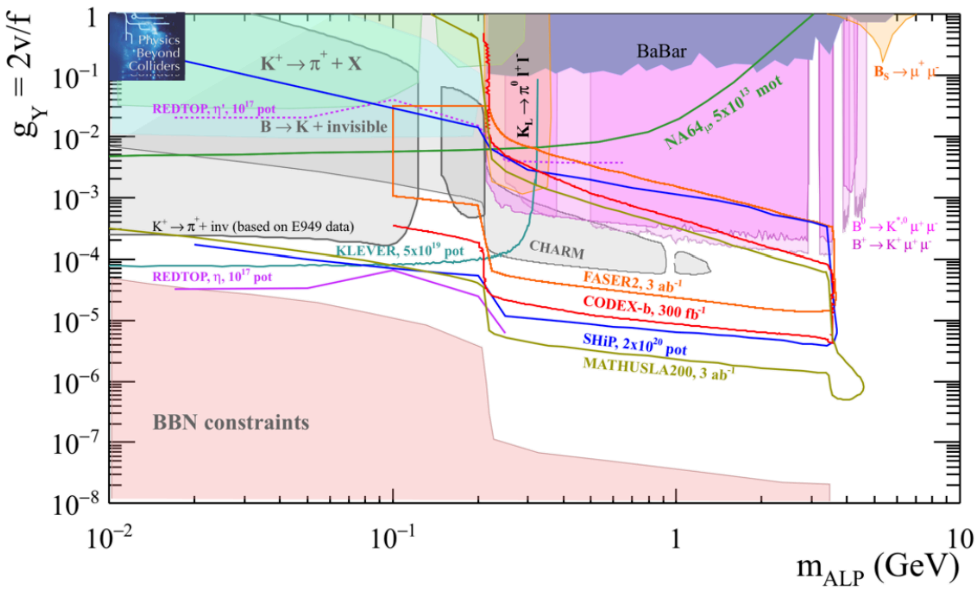
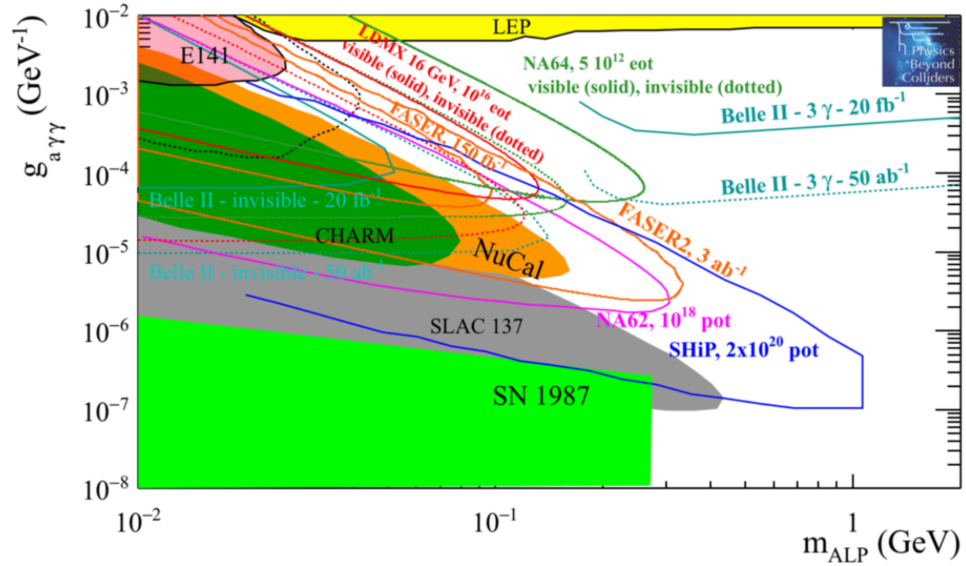
Axion-like Particles

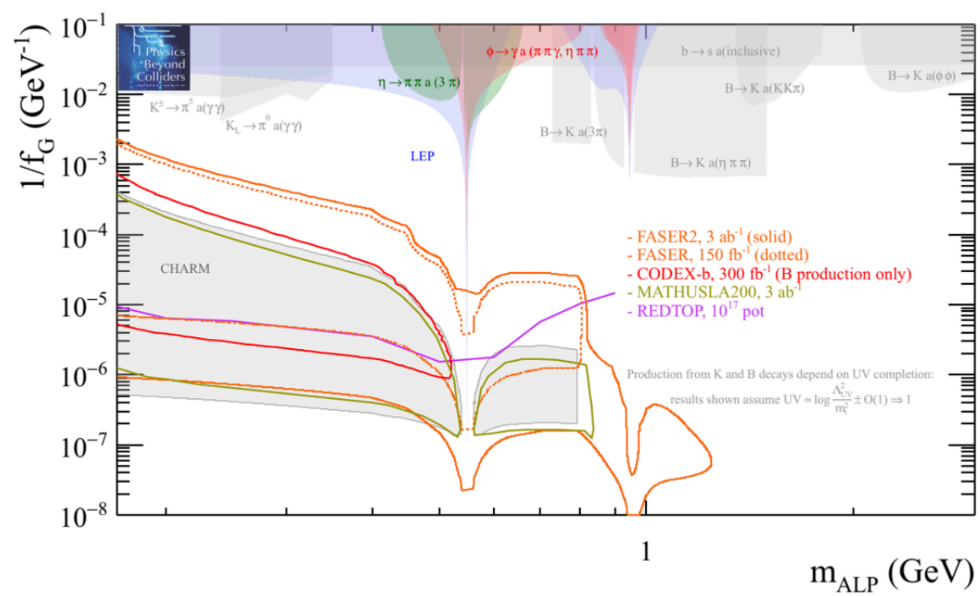
pure fermion coupling



pure photon coupling



pure gluon coupling



Theory predictions still very uncertain for pure gluon coupling scenario

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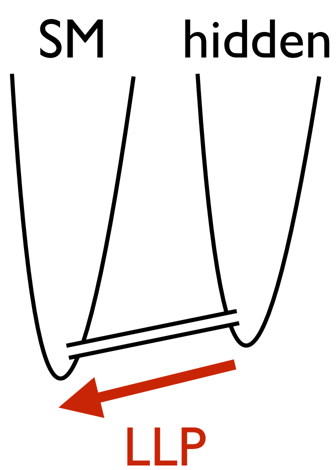
4. Collider $\longleftrightarrow$ Cosmo/Astro

Complementarity

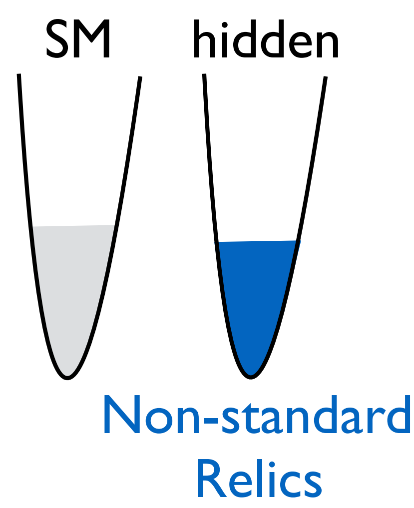
If a hidden sector cannot decay to the SM, it is produced in the early universe and still around!

3. Complementarity between Cosmology and Colliders



Models which avoid signatures in one will often show up in the other

(e.g. dark radiation, DM with structure, etc.)



Collider $\longleftrightarrow$ Cosmo/Astro

Bottom-up investigations of cosmology (CMB, LSS) and astro signals (stellar cooling, …) of minimal hidden sectors is very important.

But hidden sector can be arbitrarily complicated! Start with examples motivated by fundamental questions (e.g. Neutral Naturalness) to **explore richer signature space!**

For example: BBN, LSS, CMB, direct detection .. in the Asymmetrically Reheated Minimal Twin Higgs

1803.03263, 1905.xxxxx Chacko, DC, Geller, Tsai

Even funner: Dark Matter Mirror Stars!

Motivated by Hierarchy Problem.

Observable with optical & Xray observations, and extremely weird.

See parallel talk by Jack Setford!

1906.xxxxx DC, Jack Setford

5. Conclusion

LLPs at colliders: Conclusion

LLPs and Hidden Sectors are highly top-down and bottom-up motivated. Huge signature space still very unconstrained.

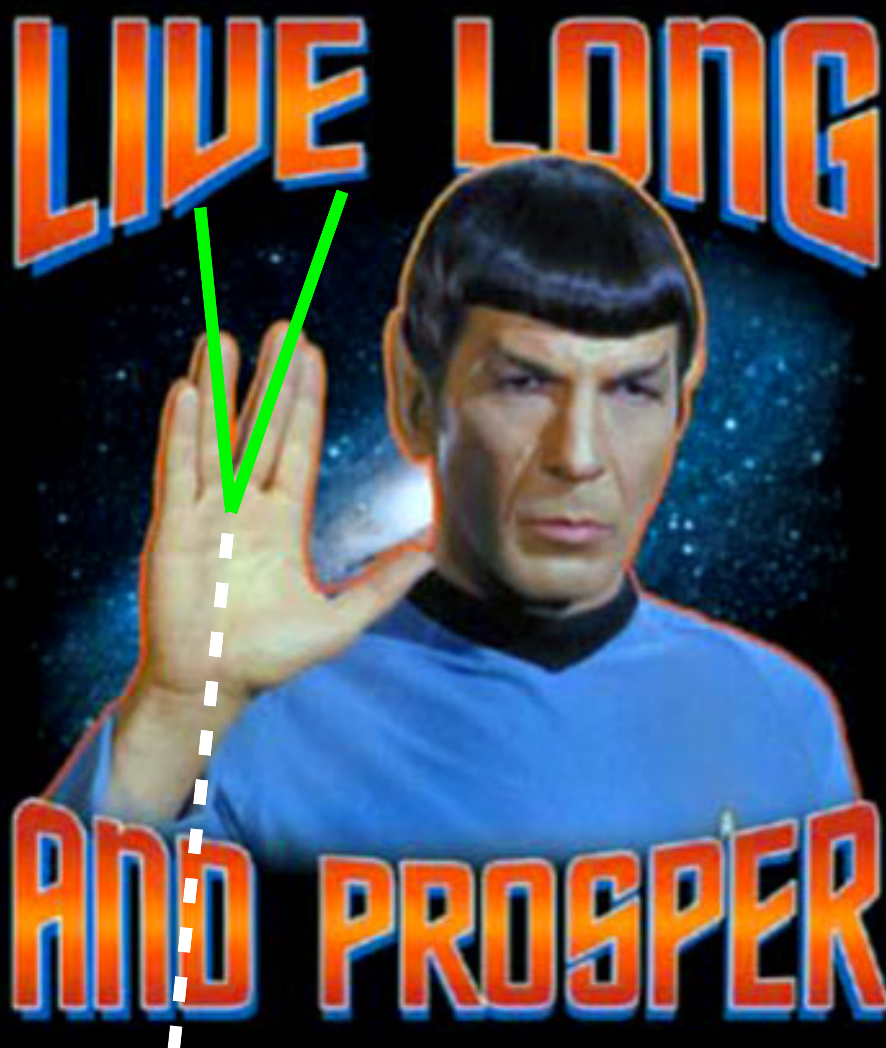
Recent LHC analyses make significant progress to extend searches. Enhance our understanding of what main detectors can/cannot do.

Embarking on systematic search program: simplified models, address gaps in coverage, etc.

ATLAS/CMS upgrades will bring exciting new capabilities (L1 tracking, 4D high-res calorimetry, 4D tracking)

External detectors like MATHUSLA, CODEX, FASER give huge bang-for-buck and extend LHC LLP reach for MeV to TeV masses

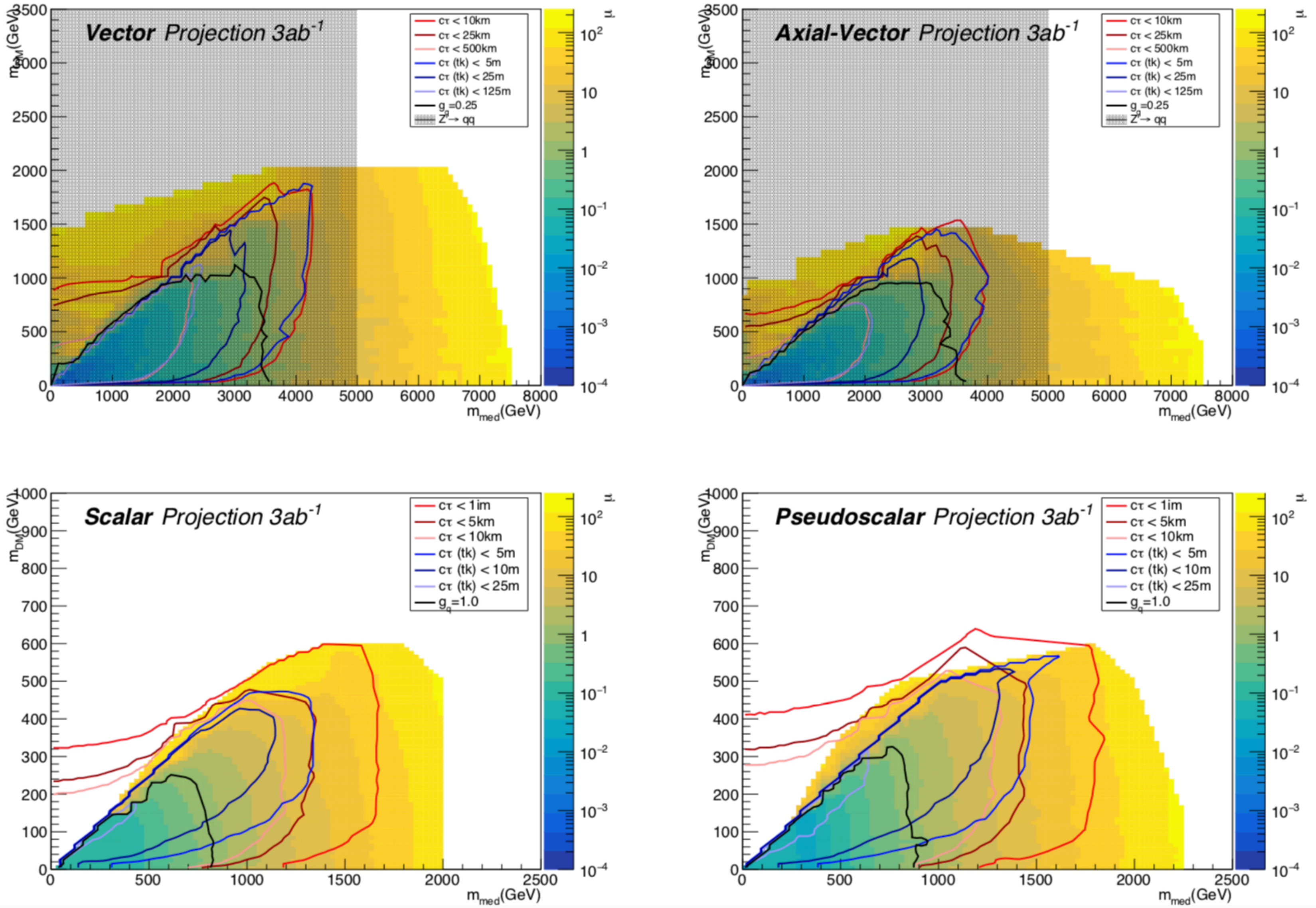
For low-mass models, this is highly complementary to SHiP reach.



—Thank you —

Backup

LLP searches: MET vs DV



1806.07396