Long Lived Particles

Discussion Session

CERN Theory Workshop
"Physics at the LHC and Beyond"

2 August 2018

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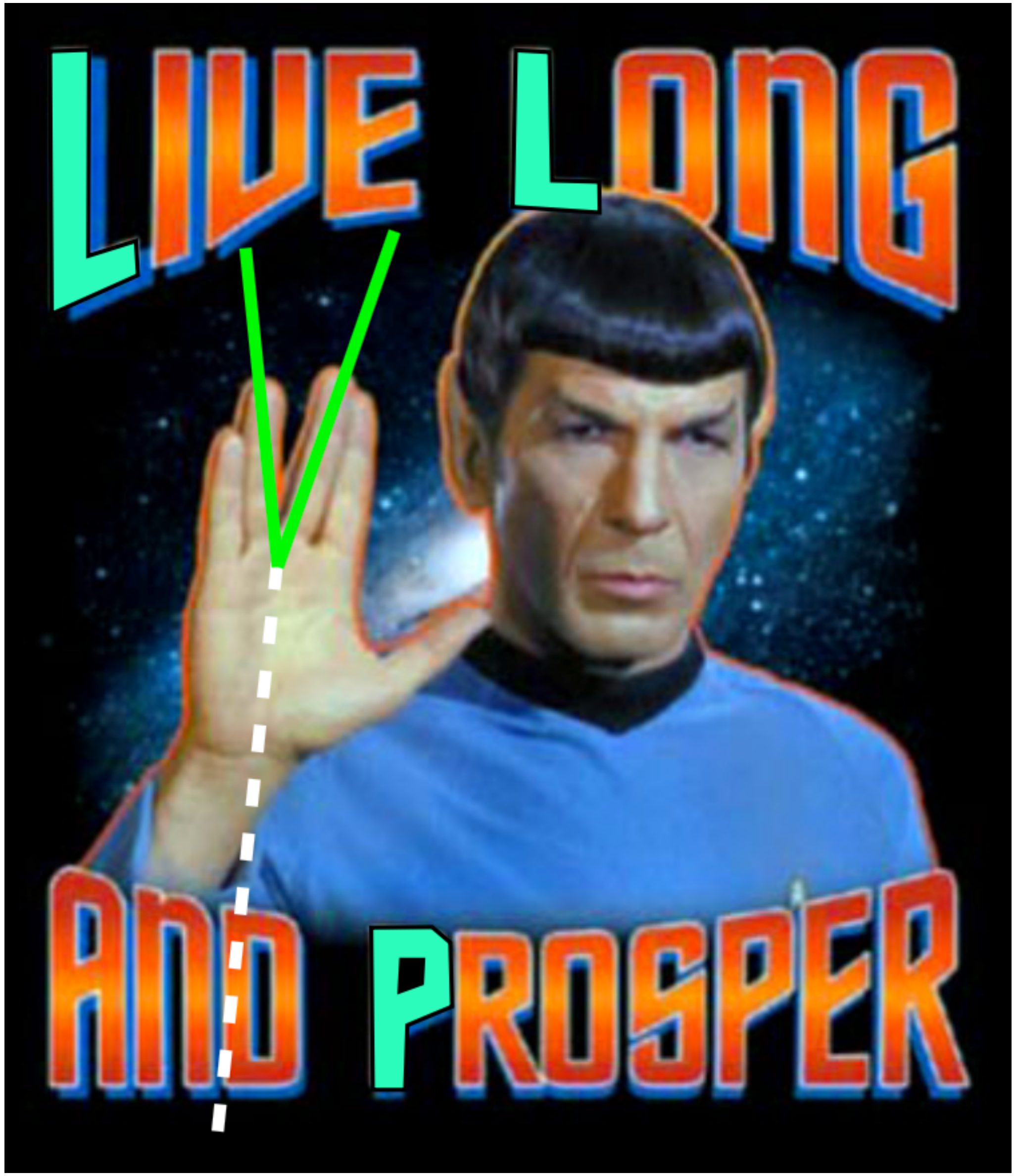
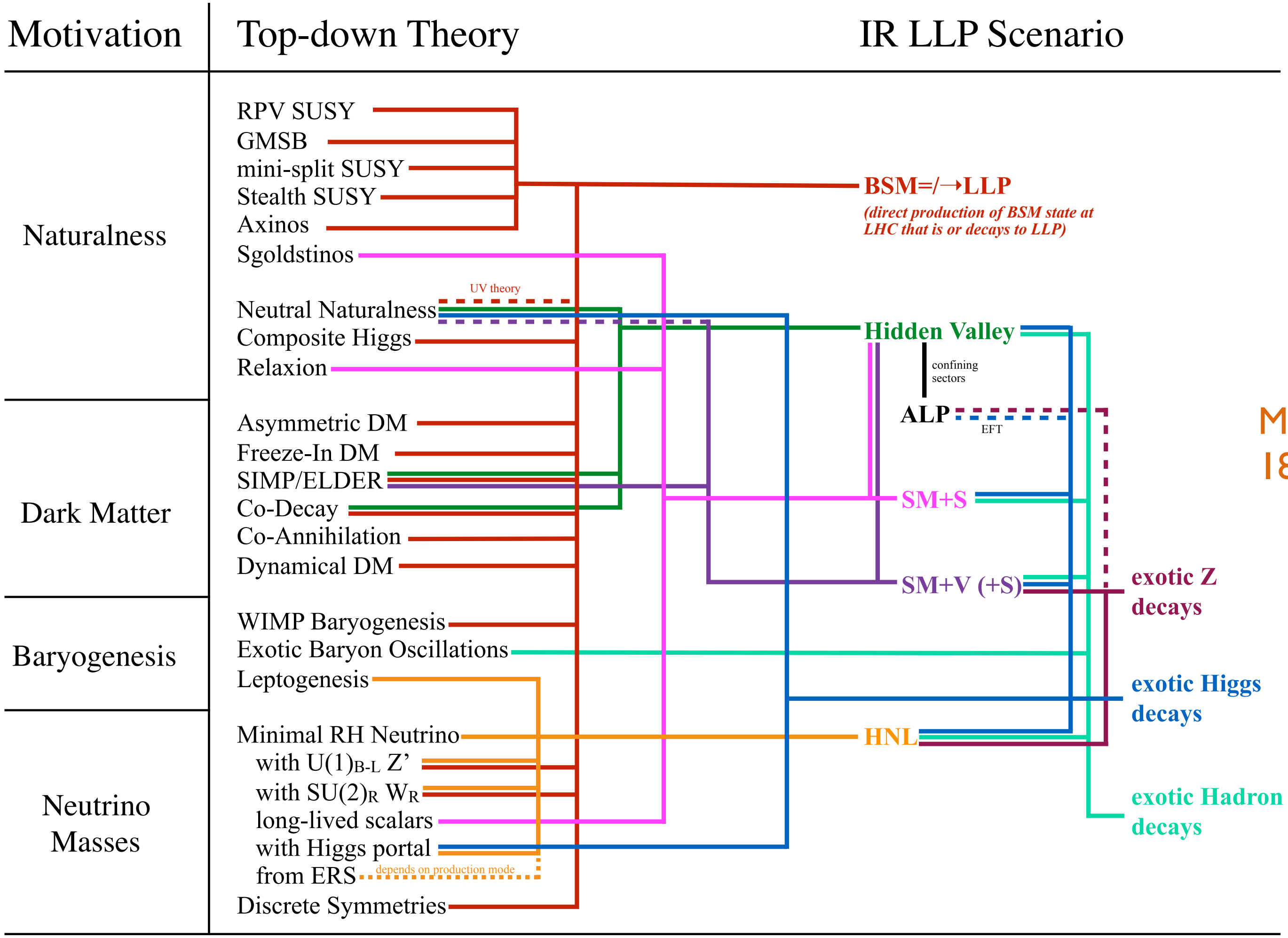
University of Toronto



Motivation

1. LLPs ≠ "exotics". SM is full of them, so is BSM.
2. top-down: LLPs solve big problems.



MATHUSLA physics case
1806.07396

3. Bonus: poorly constrained by current searches!

Looking for LLPs: Rules of the game

LLPs are spectacular signatures:

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

harder, focus here

Neutral LLP searches have lower background than most prompt searches, BUT main detectors are not optimized for them: serious TRIGGER limitations especially at L1.

Most searches today & near future:

"LLP + X"

i.e. search ends up requiring "geometric nature" of single displaced LLP decay + something else (leptons or high-E jets in final state, 2nd LLP, …)

Topics:

1. Conservative outlook for main detector LLP searches

2. Qualitatively new possibilities for searches @ main detectors:
   L1 tracking, pixilated forward calorimeters, and timing

3. The difficulty of probing long lifetimes
   ("it sure is noisy in the main detectors…")

4. Brief review, update, comparison of external LLP detector proposals (MATHUSLA, CODEX-b, FASER) + SHiP

5. On timing in LLP searches
   (and why it's super-duper-awesome but also not magic)

1. Conservative outlook for main detector LLP searches

Main detector LLP searches

Most LLP searches have to use "prompt" L1 triggers, so you have to pass jet/lepton/MET thresholds.

(Exception: ATLAS Muon System can trigger on hadronic LLP decay only.)

This means most existing searches without leptons cover masses above few 100 GeV

Currently poor coverage for e.g. $H \to XX$, X LLP decays to hadrons (generic higgs portal).
Smoking gun signal of Neutral Naturalness etc.
→ This is clearly low-hanging fruit. Implementing e.g. single lepton + inclusive higgs -> LLP searches (VH) is in progress.

Outlook I

Big on-going effort by LHC LLP community to help guide LLP search program.

Whitepaper out in O(1) months.

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

Version: 0.1.2

March 31, 2018

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 increasingly fascinating avenue via which new physics may be discovered at the LHC. Members of the ATLAS, CMS, and LHCb experiments in conjunction with theorists, phenomenologists, and those working on dedicated experiments such as Moedal, MilliQan, MATHUSLA, CODEX-b, and FASER, here report upon the sta
els for LLP searches; survey the
and enumerate gaps in this cove
mental collaborations to ensure t
for the upcoming high-luminosity
strategies for LLPs in ATLAS, CM
of recommendations for the pres
recasting for LLP searches; disc
sector QCD-like theoretical ideas
inherent in LLP searches, includi

The LHC LLP Community CERN

Contact editors: lhc-llp-admin@c

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	†	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*	†
ZP: $Z(Z') \to XX$ or $\to XX + \text{inv.}$	Z', DM*	†	Z', DM*	RHν	Z', DM*	†
ZP: $Z(Z') \to X + \text{inv.}$	DM	†	DM	RHν	DM	†
CC: $W(W') \to \ell X$	†	†	RHν*	RHν	RHν*	RHν*

Outlook 2

Modulo people-power shortage, what's going to be difficult at the main detectors?

1. Very SHORT lifetimes ($< \sim$ mm)

   - higher background but also high efficiency?
     (Certainly 100% geometric efficiency)

   - some coverage with prompt searches:
     recasts being done!

   - (a sub-mm LLP bump-hunting search using b-tagging techniques should be someone's PhD thesis!)

Outlook 2

2. Anything that is tough to look for with "LLP + X"

- i.e. LLP decays which are by themselves not spectacular enough to pass triggers & reduce background. (m < ~ few-10 GeV if decays to leptons, < ~ 100-200 GeV if decays to hadrons)

- in some cases can look for two LLP decays but others (e.g. exotic higgs decays to LLPs that decay via higgs portal) you have to rely on e.g. ISR, VBF or associated leptons. THIS WORKS but with 1/10 - 1/100 signal penalty…

Outlook 2

3. Very LONG lifetimes (> ~ 100m)

- geometric acceptance of detector is
  ~ (detector size)/(decay length)
  so these are intrinsically RARE signals

- has to be a single-LLP search even if you produce multiple LLPs per event.
  → In many cases can't rely on LLP+X

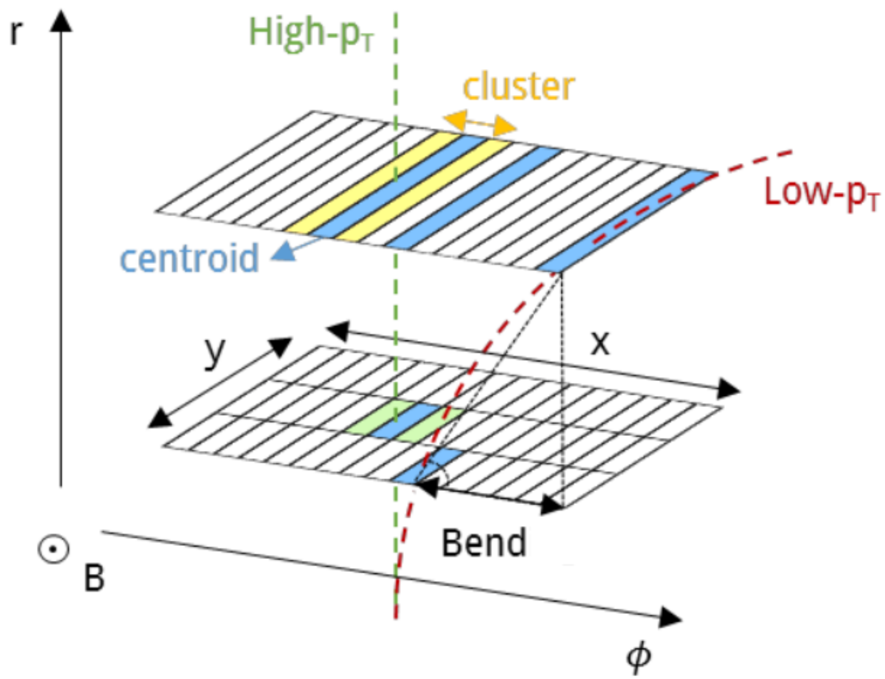
- background reduction & efficient triggering becomes crucial. Best detector right now:
  ATLAS Muon System due to
  L1 triggering + HCAL shielding (see later slides)

2. Qualitatively new possibilities for LLP searches at LHC main detectors

L1 tracking

Both ATLAS (FTK) and CMS are considering adding this capability, primarily to deal with pile-up @ HL-LHC.

CMS in particular plans to upgrade its tracker to supply track STUBS at L1 (consistent with >2-3 GeV prompt tracks)



See Yuri Gershtein's paper 1705.04321, and his slides at last month's LBNL LLP workshop
https://indico.physics.lbl.gov/indico/event/633/

Observation: some LLP decays in tracker could be reconstructed using these stubs @ L1. Can we use this to trigger on LLPs?

L1 tracking

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

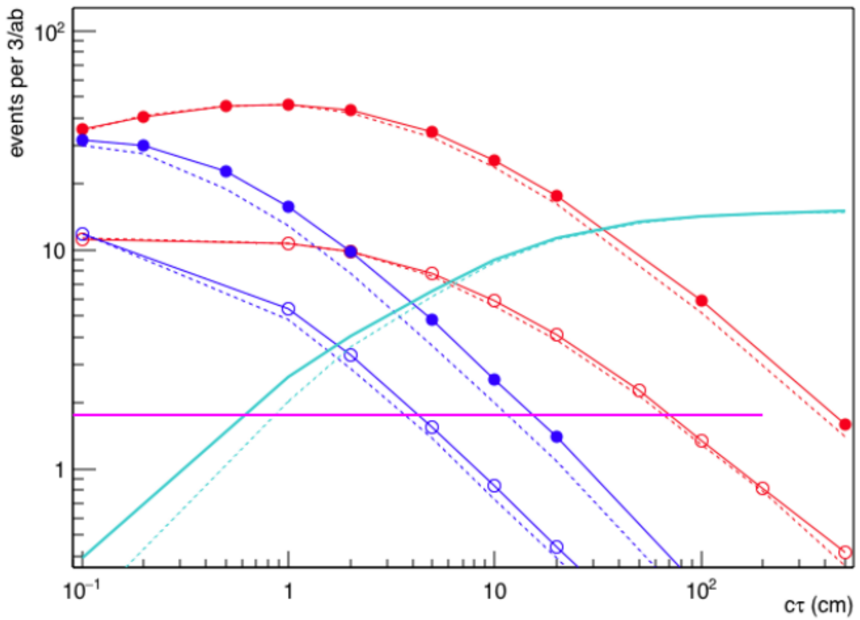
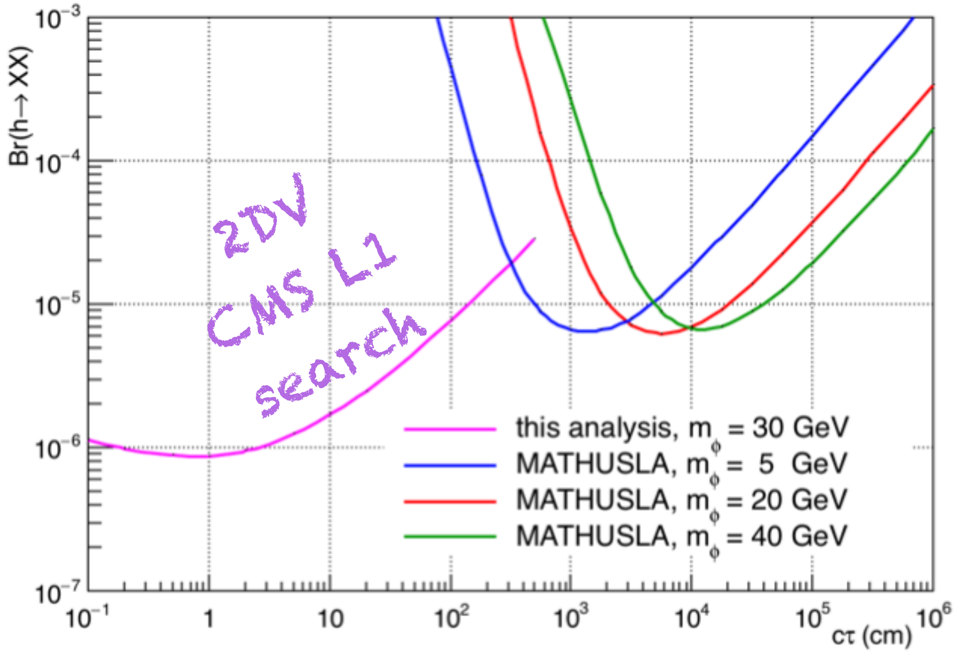
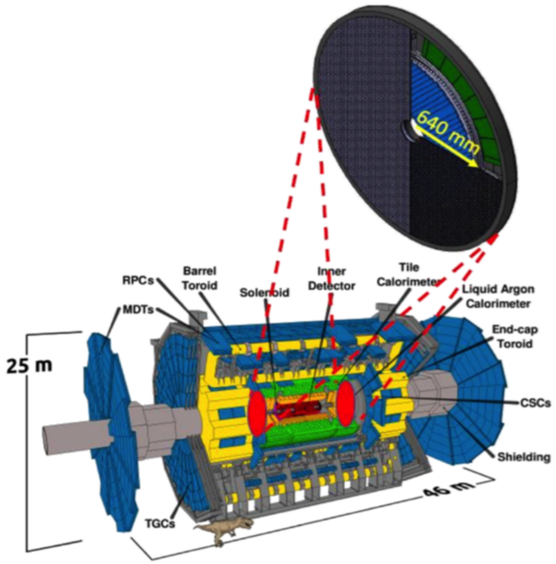


FIG. 10. Event yields for $Br[h \to \phi\phi \to 4q] = 10^{-5}$ as a function of ϕ proper lifetime. Red curves correspond to quad loose track jet trigger, blue - to quad tight track jet trigger. Open circles indicate track jets with p_T above 20 GeV, filled circles - displaced track jets above 10 GeV. Teal curve corresponds to the no-track 70 GeV di-jet trigger. Purple line shows the expected yield from Wh production triggered by a lepton from W. See text for details.



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

Forward Calorimeters



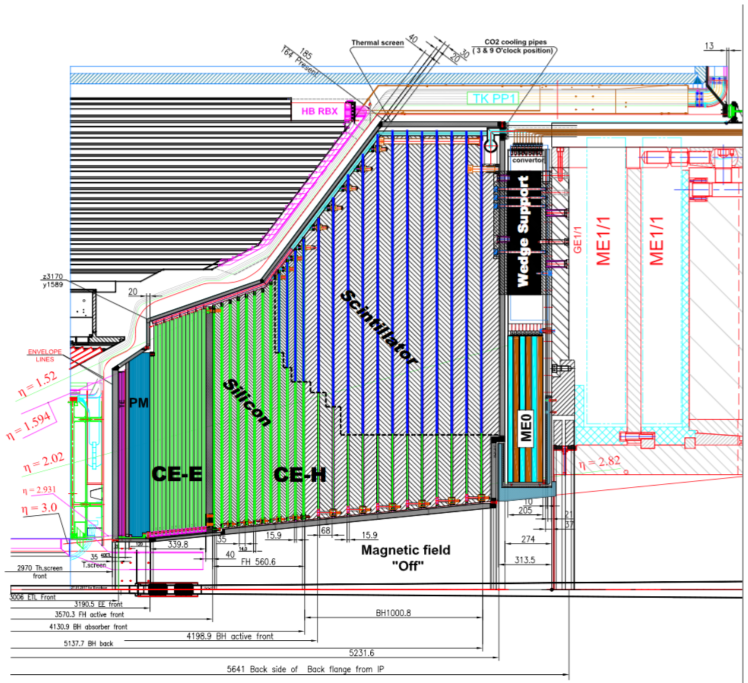
z [cm]

Pseudorapidity coverage	$2.4 < \|\eta\| < 4.0$
Thickness in z	75 mm (+50 mm moderator)
Position of active layers in z	3435 mm $< z <$ 3485 mm
Radial extension:	
Total	110 mm $< R <$ 1000 mm
Active area	120 mm $< R <$ 640 mm
Time resolution per track	30 ps
Number of hits per track:	
$2.4 < \|\eta\| < 3.1$	2
$3.1 < \|\eta\| < 4.0$	3
Pixel size	1.3×1.3 mm^2
Number of channels	3.54M
Active area	6.3 m^2

ATLAS Forward High Granularity Timing Detector

Main motivations again related to pile-up.

- $1.5 < |\eta| < 3$
- $\sim$ 25 ps resolution
- 52 sampling layers
- 4D shower reconstruction
- $\sim$ 1.18 cm^2 cells
- $\sim$ 4 mrad pointing ($\sim$few cm displaced)



CMS Endcap Calorimeter

See slides/work by Jared Evans, Ted Kolberg + others at last month's LBNL LLP workshop
https://indico.physics.lbl.gov/indico/event/633/

Forward Calorimeters

Both have ~30ps timing, great spatial resolution.

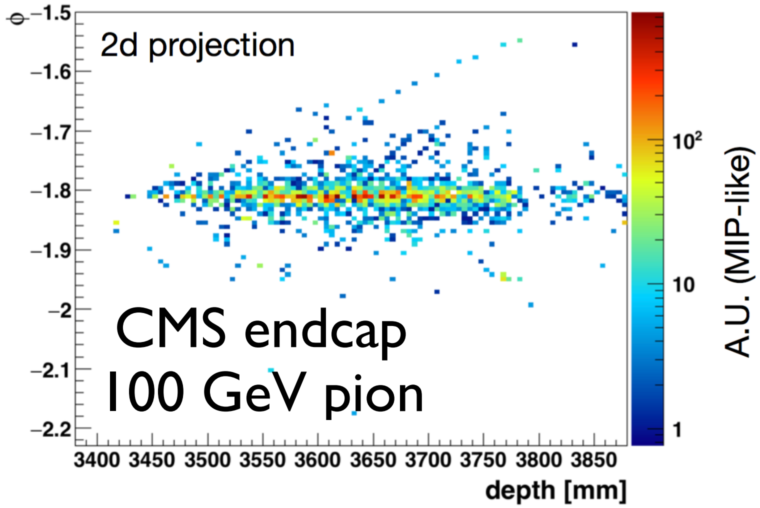
In CMS case, get 4D shower reconstruction.

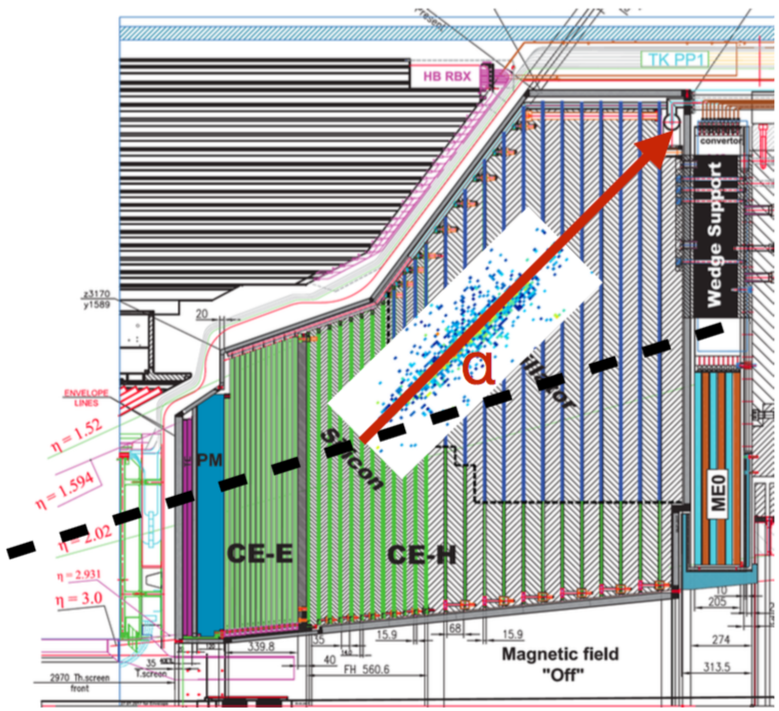
For LLP searches: ignore forward-ness in ‘targeting physics models’, that’s just the geometric cost you pay for timing/granularity.

What can you do??

- LLP -> photon searches with timing information (see next slides)

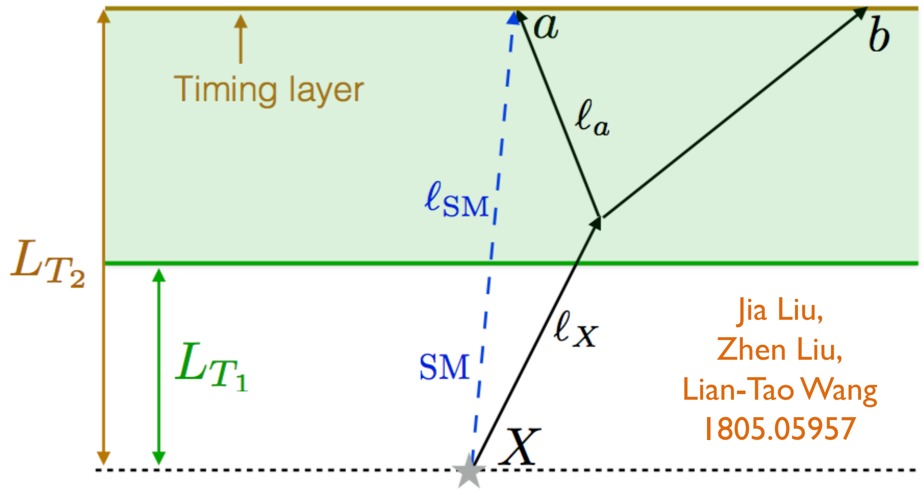
- CMS 4D shower can reconstruct LLP decays. This is compatible with trigger primitives, could do at L1! Rival the ATLAS MS for DV searches???





Timing

Timing will be extremely useful for LLP searches, since signal has time delay compared to *prompt* backgrounds (boost & path length)



Proposed HL-LHC upgrades:

- CMS MIP Timing Detector (barrel), ~ 30-50ps
- ATLAS forward detector, ~30ps
- CMS ECAL/endcap: cluster time stamp for E > 20 GeV: ~ 30ps

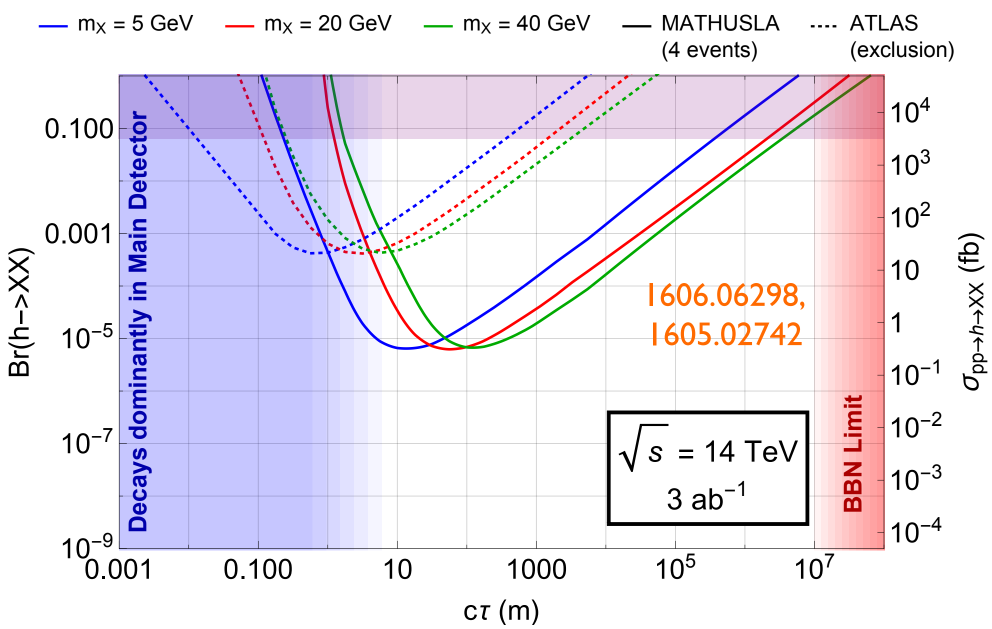
This has lots of physics/background overlap with long lifetimes, so let me discuss long lifetimes first and come back to this!

3. The difficulty of long lifetimes

Single-DV search in ATLAS Muon System

The ATLAS Muon System is the best subdetector to find LLPs with very long lifetimes.

Muon ROI trigger @ L1 + active HCAL shield/veto
→ least trigger/background problems for single LLP search at modest mass scales, e.g. H → XX, X → hadrons



Real search in progress, but public data & studies suggests **~ few 100fb of background** ("fake DVs") for fully inclusive single hadronically decaying LLP search.

Sci-fi story time: can you improve ATLAS MS?

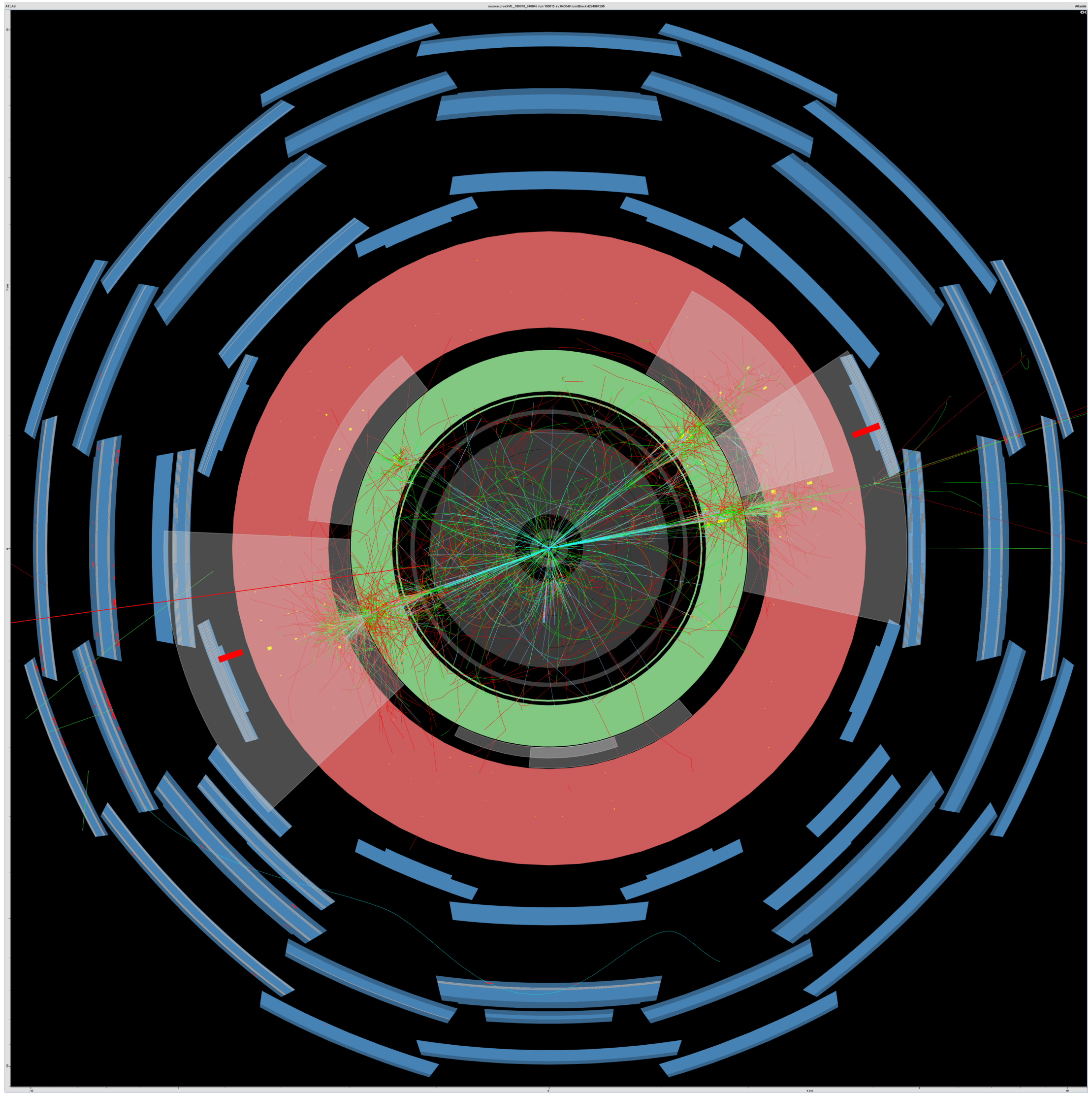
Those few 100fb of background greatly limit sensitivity. If we could improve background rejection by **~10^6**, search would enter BG-free regime with ~1000x better sensitivity

An instructive exercise: could you "realistically" upgrade the ATLAS MS to reduce this background?
(modulo ps timing, likely very expensive, see later slides)

See slides/work by James Beacham, DC, Andy Haas at last month's LBNL LLP workshop
https://indico.physics.lbl.gov/indico/event/633/

Redesigning ATLAS MS

Start with **hypothesis** that ATLAS MS BG is mostly **punch-through** related. That's still a bit mysterious (there are **vetoes** on calorimeter and track activity below DV) but OK…



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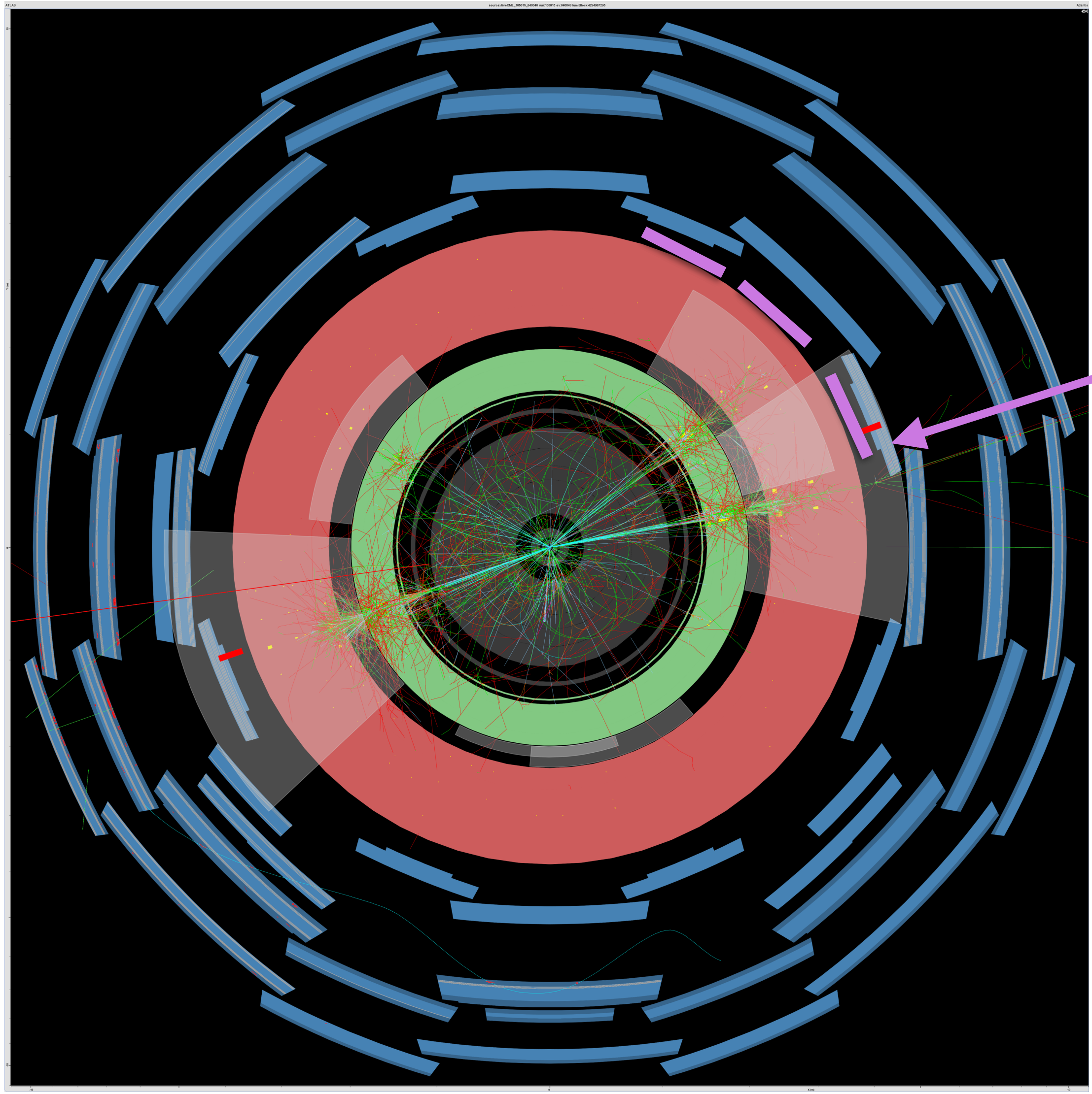


Could you add additional "cheap" puchthrough veto layers?

Adding a puchthrough veto to the ATLAS MS

Could imagine 'cheap' scintillator panels to veto punchthrough below first MS multi-layer.

Problem: scintillator unfeasible due to huge 10MeV photon cavern background (near-constant activation without 10+cm lead shield).

You could use a detector that is insensitive to photons… RPCs?

==> Upshot: no need to add another layer. Just use the first Muon System multi-layer as a punch-through veto.

==> The ATLAS MS already has all the ingredients you need to start improving the 1DV search strategy.

What are other possible background sources?

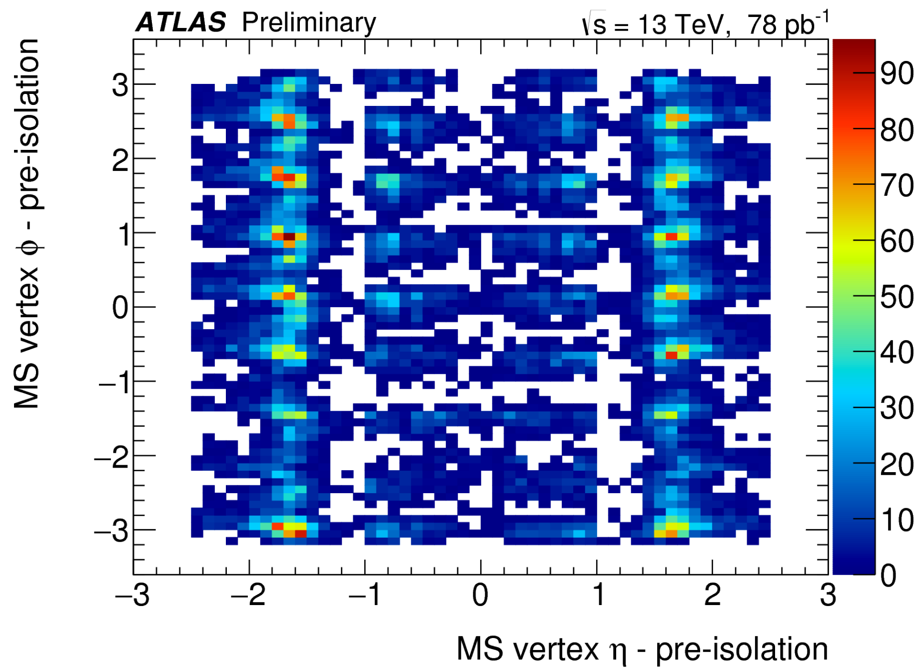
Maybe all just noise?

there are lots of charged particle flying around everywhere, ALTAS MS is not an amazing tracker and hadrons suffer significant deflection ($\Delta\theta \sim 100$ MeV/E_{π} per interaction length) passing through each layer…

Material interactions?

Likely a significant factor.
Why not just implement a material veto on DV location in MS?

Maybe… DV spatial resolution in MS is ~ 30cm. Also signal efficiency follows material. Huge signal eff cost?



The Muon System was not designed for LLP searches!

Cosmic Rays in ATLAS MS

Cosmic ray muons > ~ 60 GeV can reach ATLAS cavern, scatter off material in MS, and give a DV.

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

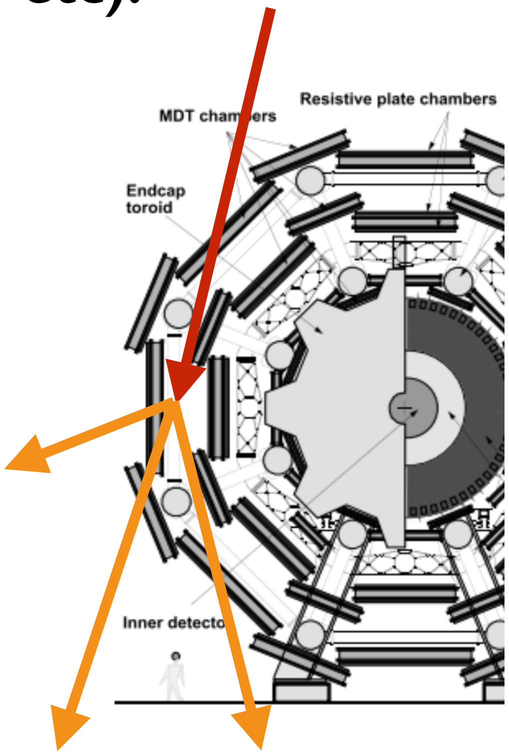
VERY ROUGH RATE ESTIMATE (without DV efficiencies etc):

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!



Can you improve an ATLAS MS 1DV search?

It's unclear how much you gain, but the following will be explored:

1. Optimize track/calo vetos of activity below the Muon ROI.
Make sure reconstruction quality cuts on the objects-to-be-vetoed do not reduce veto efficiency. (Tracks?)

2. Use the 1st multi-layer of the MS as a punch-through veto.
O(50%) reduction in signal acceptance, and have to handle backsplash from hadronic LLP decay, but could reduce punch-through-related BG.

3. Explore vetoes of cosmic ray-material interactions
May be difficult if you want to keep some signal efficiency (downward direction doesn't help a huge amount for hadronic LLP decays in MS).

Can you improve an ATLAS MS 1DV search?

4. Material veto on DV location in MS between 1st and 2nd layer.
Reject DVs originating in structure/magnet. May be very difficult due to low O(30cm) MS DV spatial resolution, and the fact that signal efficiency also follows material (!). Would likely greatly reduce signal efficiency.

5. Study noise bursts in MS in low/no lumi data runs.
Existing analyses account for these, but maybe there are other forms of noise.

Important to keep in mind the reach in LLP production rate would change by a factor

$$\frac{\epsilon_{LLP}}{\sqrt{\epsilon_{BG}}}$$

so some of the above may do more harm than good.

However, ~ order of magnitude reach improvement MAYBE possible?

4. External LLP Detector Proposals for the (HL-) LHC

The MATHUSLA Detector

MAssive Timing Hodoscope
for Ultra-Stable NeutraL PArticles

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

Easy reading:

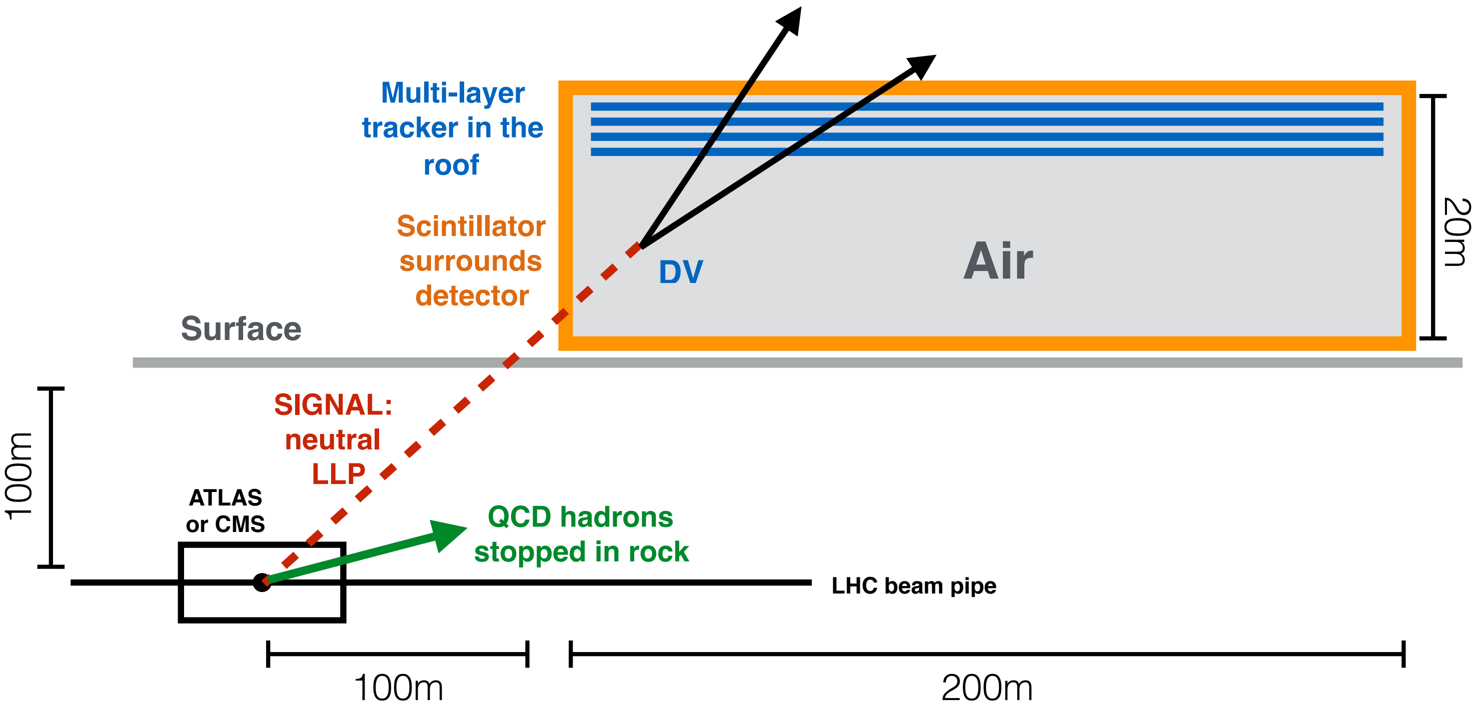
Physics Today article about LLPs and hidden sectors (DC, Raman Sundrum, June 2017)
http://physicstoday.scitation.org/doi/10.1063/PT.3.3594

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

An external LLP detector for the HL-LHC

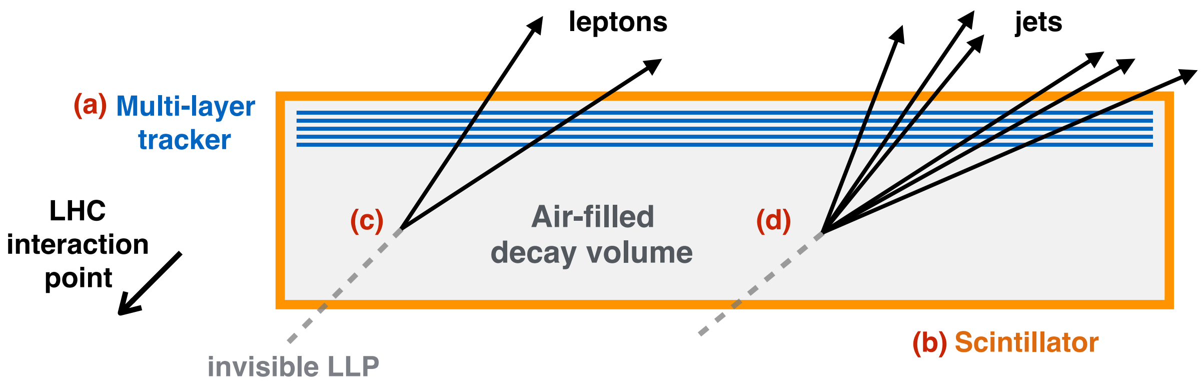
Chou, DC, Lubatti
1606.06298



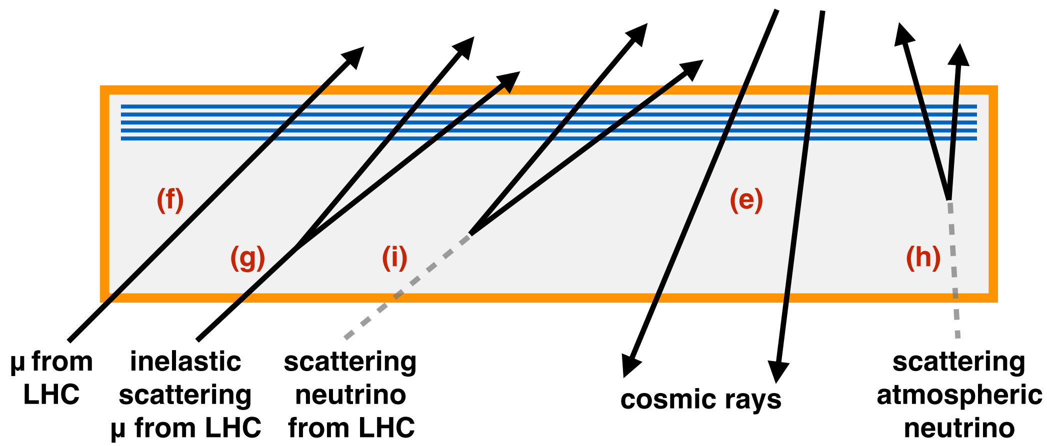
… searches for LLPs by reconstructing displaced vertices in air-filled decay volume.

Background Rejection

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



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

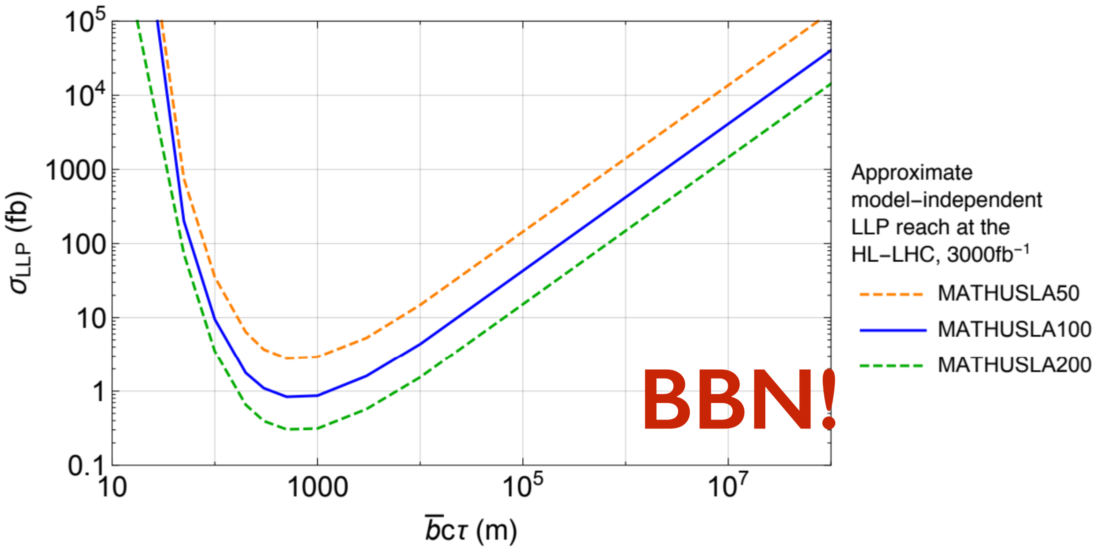


MATHUSLA can search for neutral LLP decays with near-zero backgrounds!

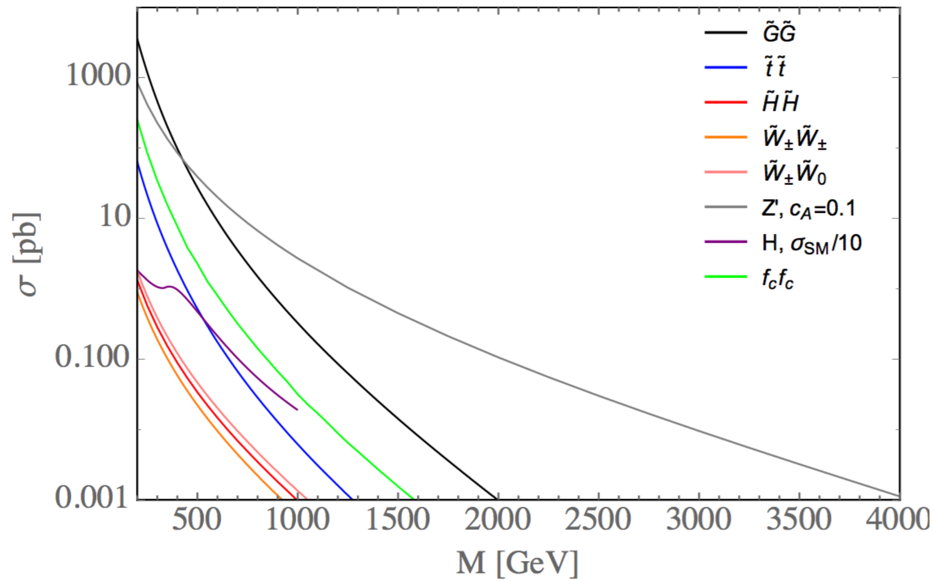
(see backup slides for more details)

Sensitivity

LLP cross section reach



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.

Probe TeV+ scales!

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

1806.07396

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Goes into great detail to explain motivation and how much you gain compared to HL-LHC main detectors.

Sensitivity gain can be 3 orders of magnitude, e.g. H->XX etc

Letter of Intent

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

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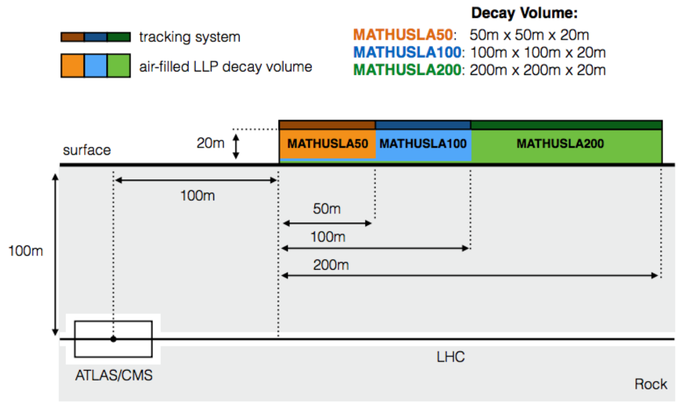
CERN-LHCC-2018-025

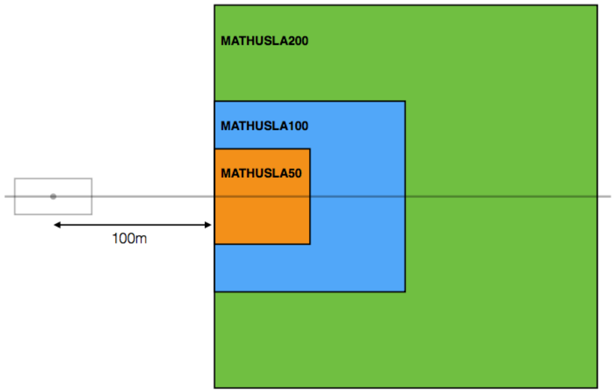
Submitted to LHCC on Jul 16.
Significant further details on detector design, reconstruction efficiency, location, backgrounds…

more work needed (especially cosmic ray simulation), another document after workshop & external review in late August

Geometry & Site Selection



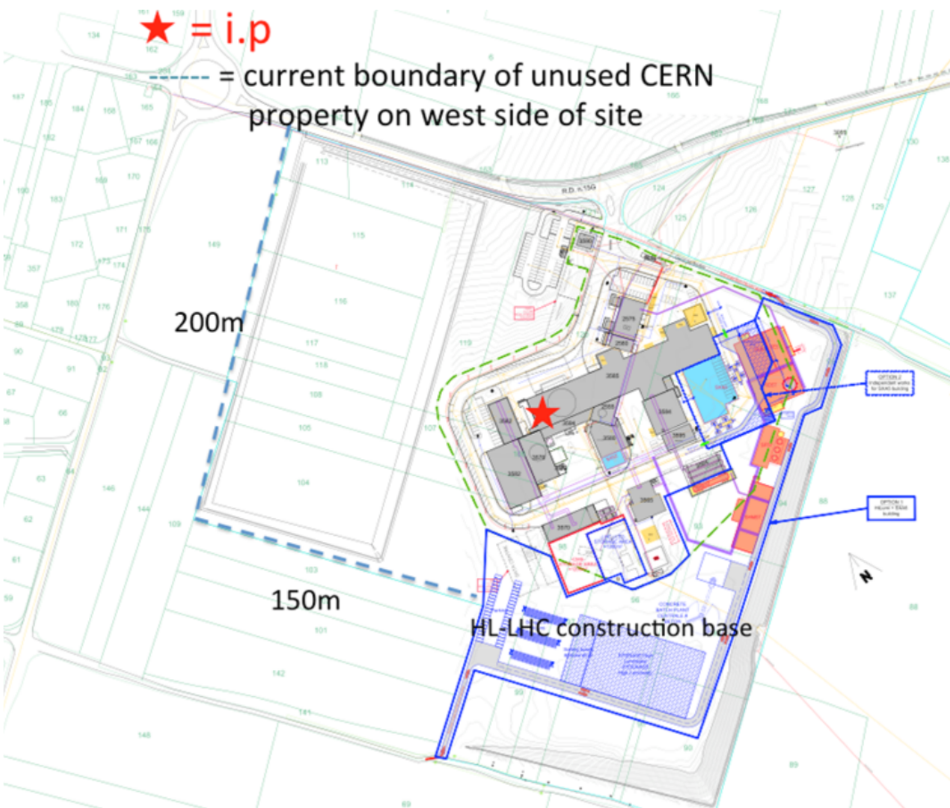
side view



aerial view

Simple benchmark geometries from LOI

There is room near CMS!



Something like MATHUSLA100 would have very similar sensitivity to early benchmark ("MATHUSLA200")

Cost estimates are technology dependent. RPCs are in neighborhood of 30M + engineering + services. Other technologies (plastic or liquid scintillator) are still being explored and may be cheaper.

Modular detector design

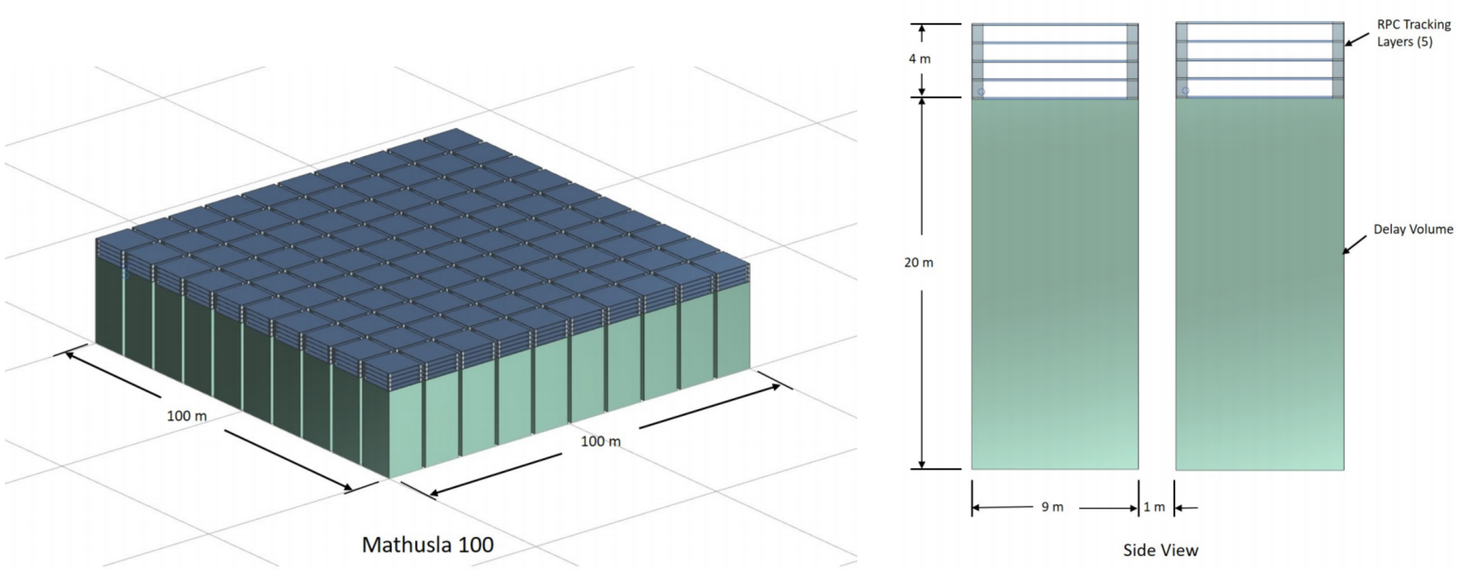
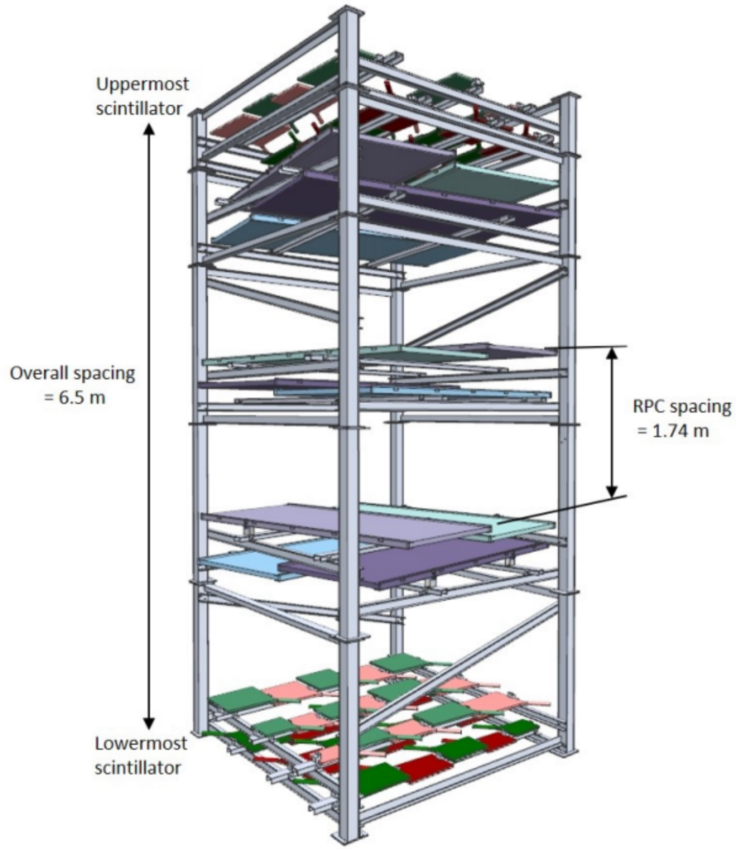


Figure 17. Layout of a modular implementation of the MATHUSLA100 geometry considered in this letter, with $10 \times 10 = 100$ modules, each with area 9×9 m, situated 1 m apart. The decay volume has a height of 20 m, topped by five layers of RPCs that are 1 m apart.

Simple Benchmark from LOI.

Test stand taking data at ATLAS now



(a)

(b)

Ecosystem of LLP detector proposals

CODEX-b

Gligorov, Knapen, Papucci, Robinson, 1708.09395

Dedicated DV detector underground, in existing caviity near LHCb

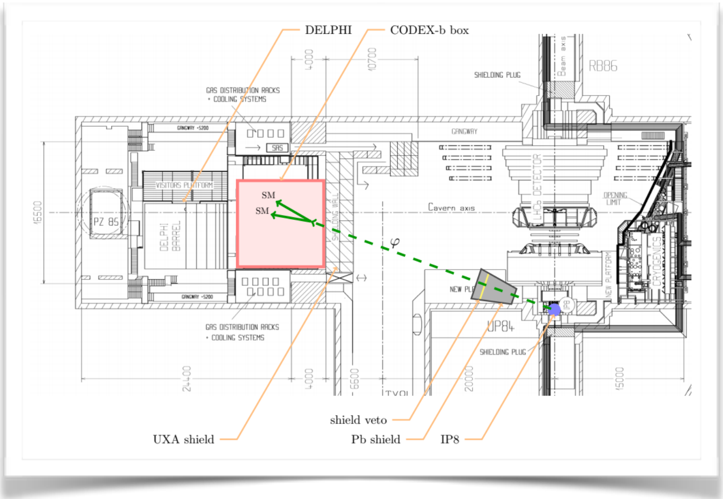
+ Definitely more affordable than something on MATHUSLA scale

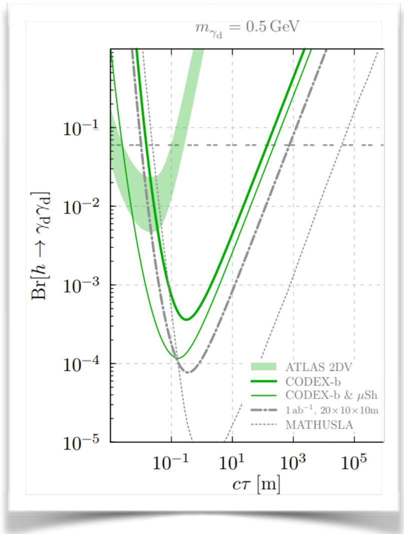
+ easier to instrument for < 10-100 MeV mass regime, and maybe even calorimetry/particle ID for detailed LLP investigations.

+ Easy interface with LHCb!

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

$\rightarrow$ *scale down R_s by same factor*

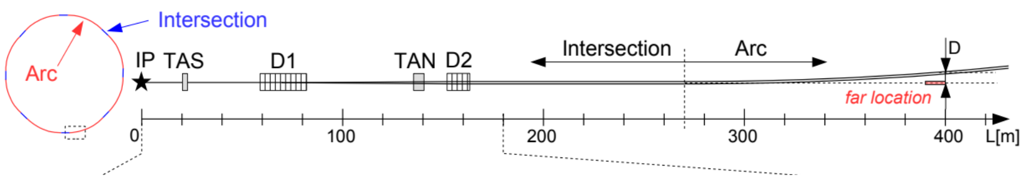




FASER, MATHUSLA and SHiP *(light LLPs)*

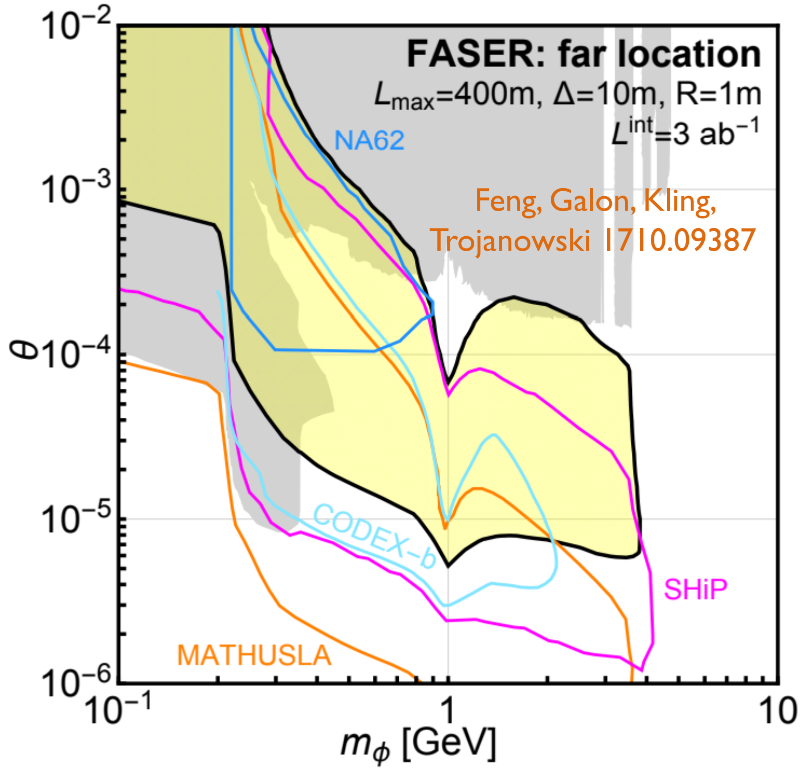
SHiP: $\sqrt{s}$ = 38 GeV fixed target facility proposed for SPS, specifically for low-mass hidden sectors via LLP searches.
For shorter lifetimes and mass < ~ 10 MeV, SHiP is much better.
MATHUSLA access higher scale physics and sees 10-100 more LLPs from exotic meson decays if lifetime >> 100m.

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

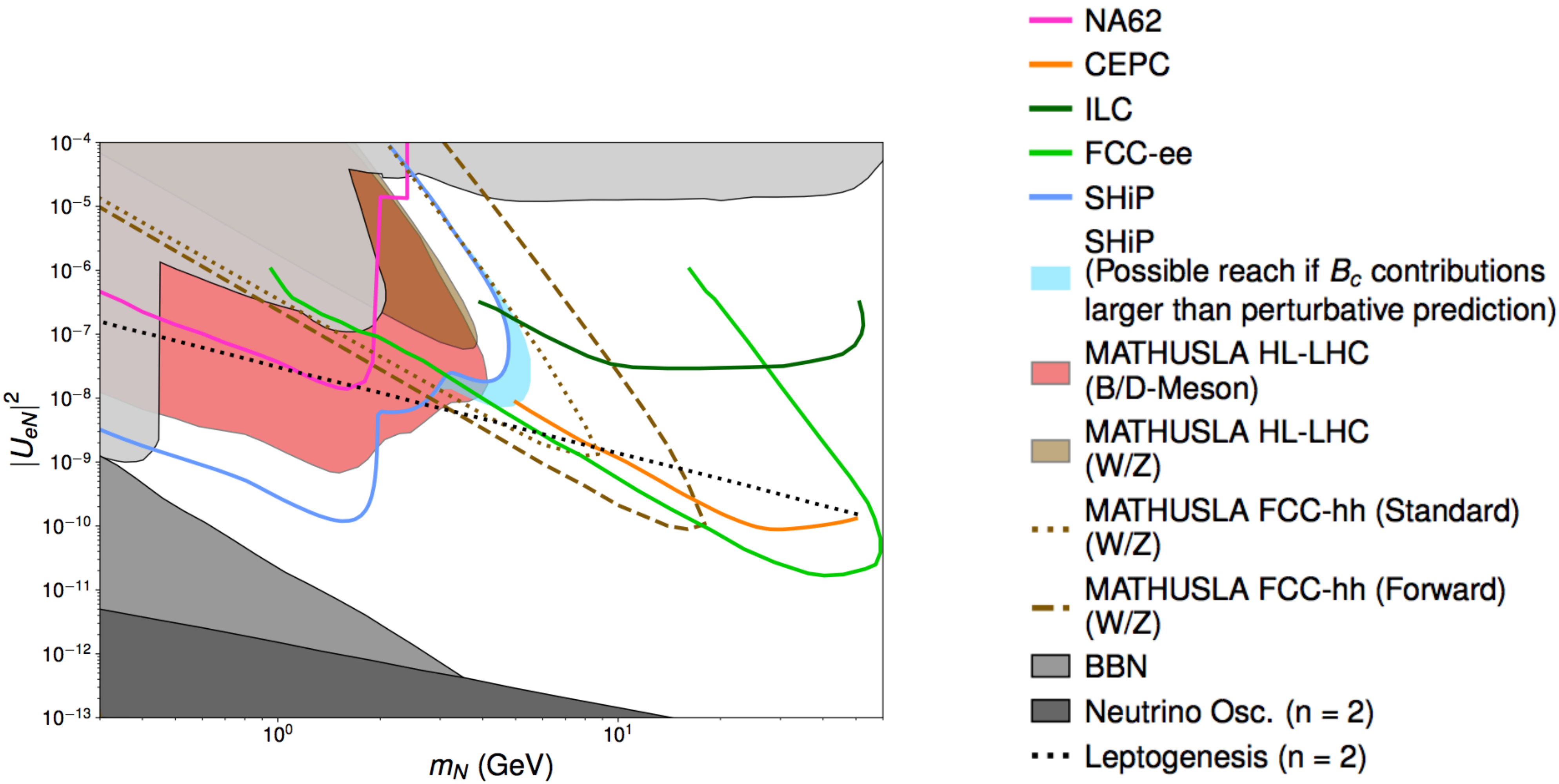


For SM+S model reach,
FASER + MATHUSLA > SHiP !

Very intriguing!



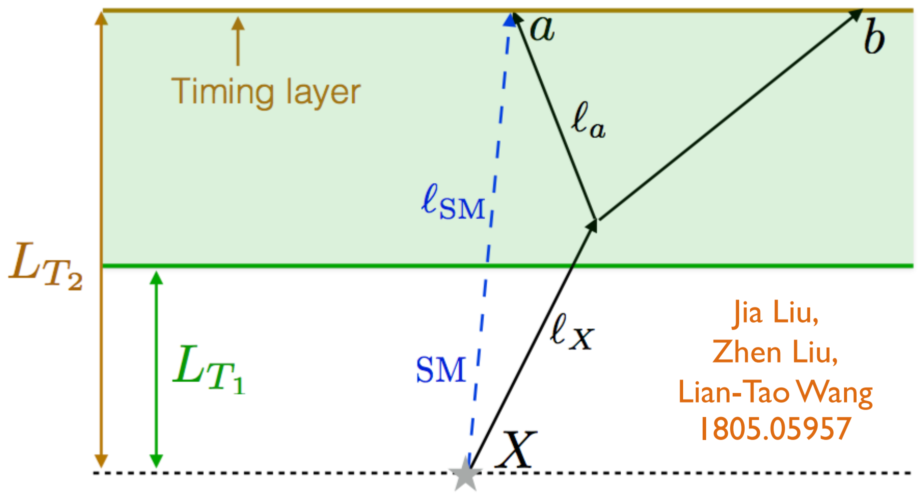
MATHUSLA & SHiP on HNLs



MATHUSLA200 is comparable/complementary to SHiP

5. Timing at the HL-LHC Main Detectors

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)$^{-1}$

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

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

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→XX (single LLP search).

You can do even better with slower LLPs like Higgsinos! (see paper)

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

Potential Sensitivity Gain?

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

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

Unfortunately, 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 (see ATLAS MS DV discussion).** ⇒ projected 10^{-6} - 10^{-10} rejection factors not realistic.

However, regardless of such details, timing will *definitely* greatly improve main detector sensitivity.
Order-of-magnitude LLP xsec sensitivity gains could be realistic.

Clearly, timing is incredibly exciting for LLP searches!

L1 triggering with CMS timing layer?

Important question:
could you use timing layer for triggering on LLPs at L1?

See slides/work by
Hsin-Chia Cheng, Yangyang Cheng, Matthew Citron, Jia Liu, Zhen Liu, Matthew Low, Christian Ohm, Xiaoping Wang, Si Xie
at last month's LBNL LLP workshop
https://indico.physics.lbl.gov/indico/event/633/

Compared to full 40MHz rate, need to reduce rate by ~100 for read-out (not yet L1, just L1 decision-making).
This can be achieved by requiring hits in clusters of mtd cells and linking adjacent mtd-readout-chips.

Then you need to get the trigger rate to L1-feasible levels. Jet requirements (70ish GeV) + timing requirement may be feasible?
All super preliminary but very promising work in progress!

Backup Slides

How does MATHUSLA reach the zero-background regime?

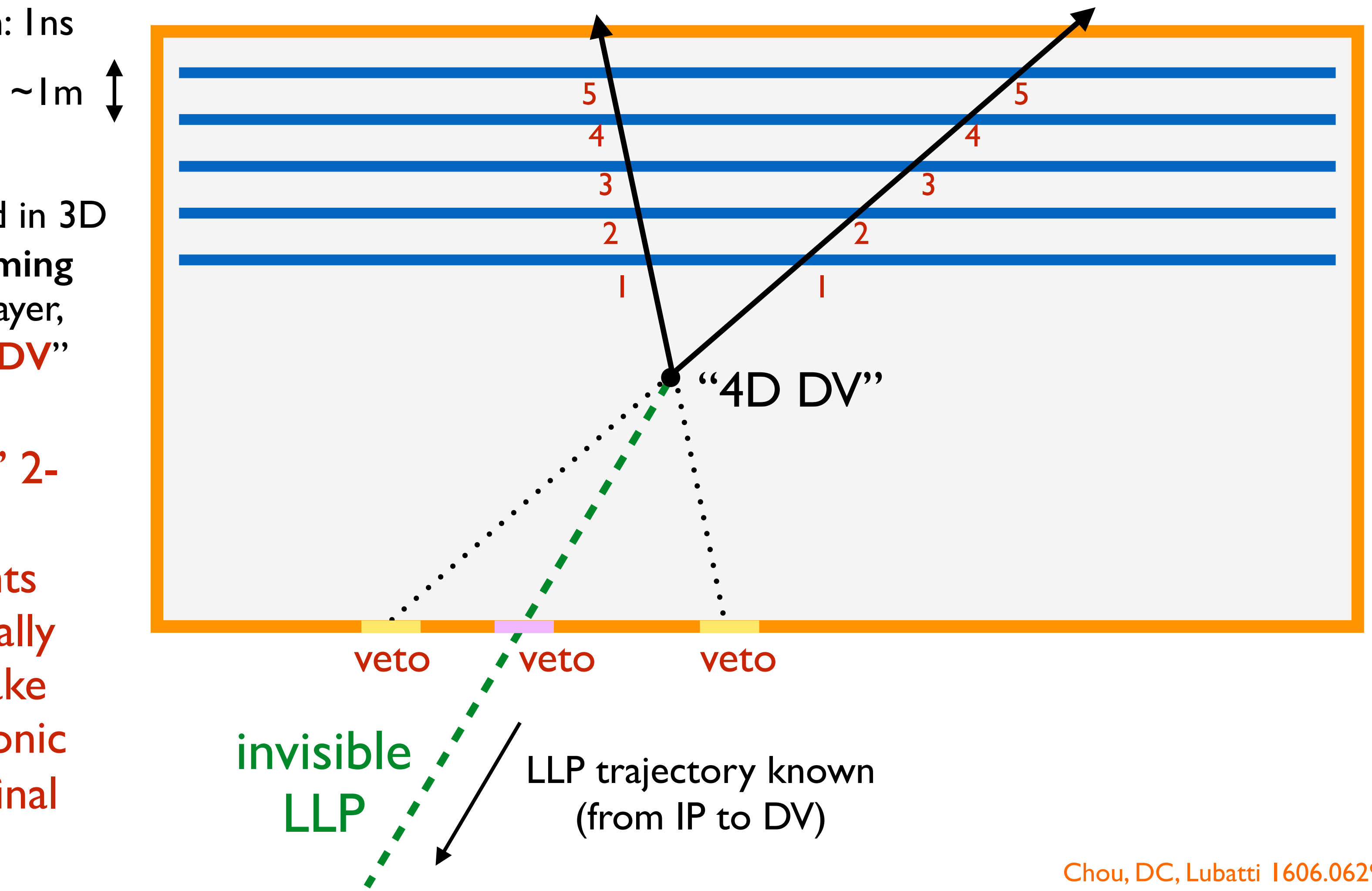
Background Rejection (gory details)

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

$\Delta t \gtrsim 3.5$ns 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!



Chou, DC, Lubatti 1606.06298

Background Rejection (gory details)

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

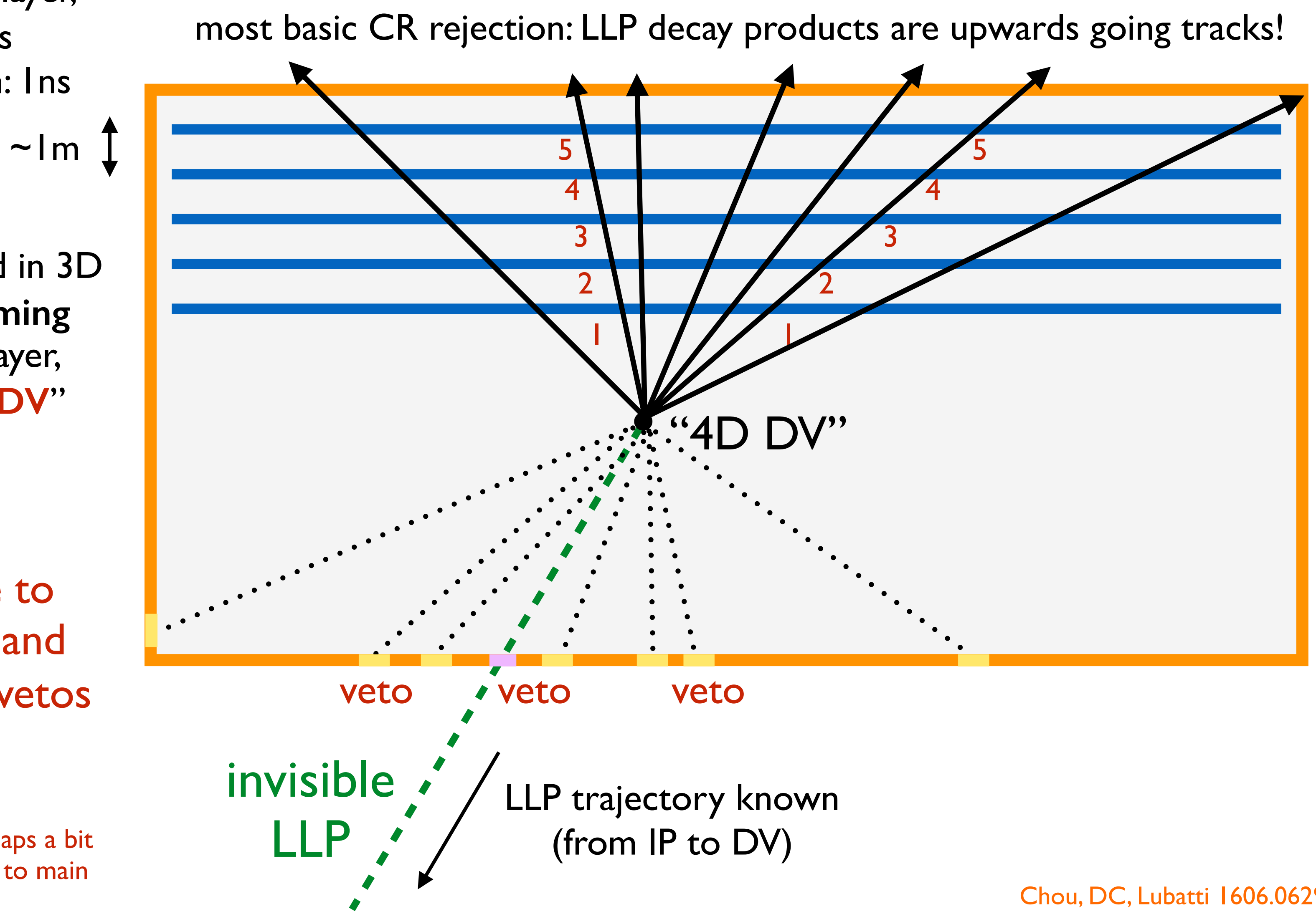
Δt ≳ 3.5ns per tracker layer,
17 ns for all 5 layers
tracker time resolution: 1ns

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

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.)

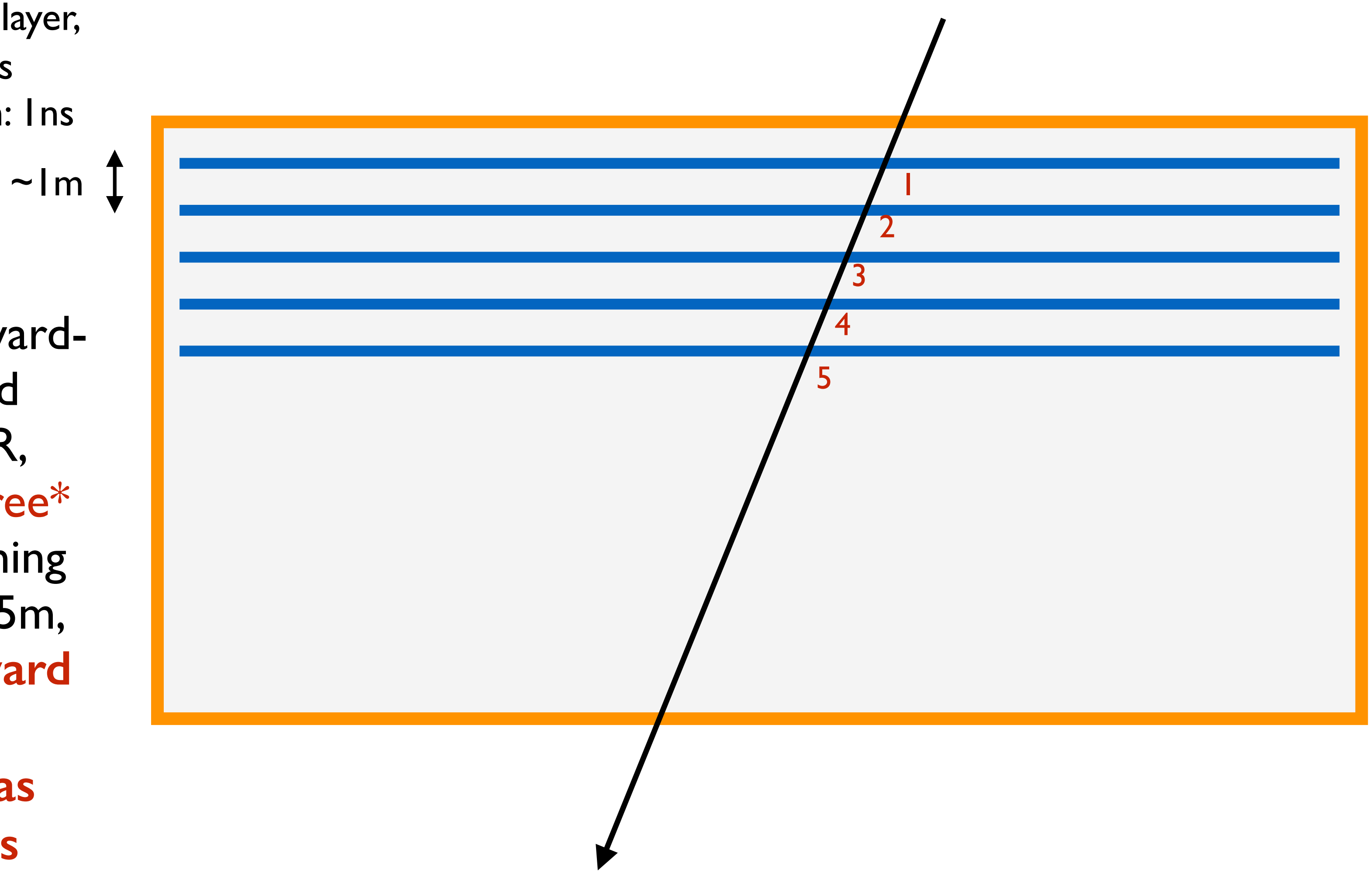


Chou, DC, Lubatti 1606.06298

Background Rejection (gory details)

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

$\Delta t \gtrsim$ 3.5ns 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 $\epsilon_{down \to up} \lesssim 10^{-15}$**

Chou, DC, Lubatti 1606.06298

Background Rejection (gory details)

Com… …run

$\Delta t \gtrsim 3$…

17

tracker…

For *s…

tra…

par…

assun…

layers…

resol…

chanc…

*c…

rec…

up…

ϵ_{do}…

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.

…Lubatti 1606.06298

Background Rejection (gory details)

Com … run

Δt ≳ 3
17
tracker

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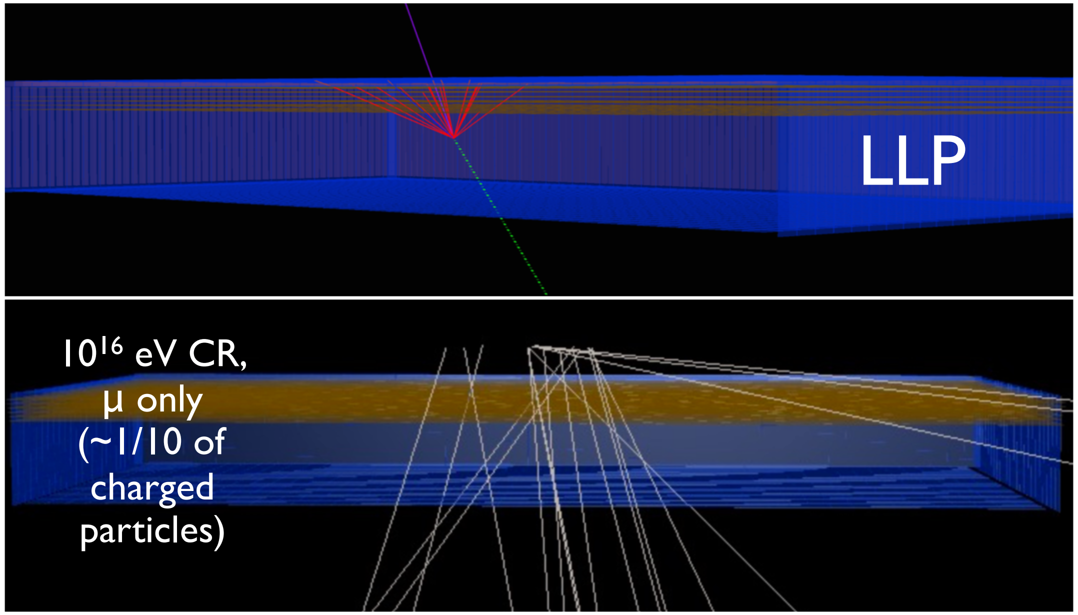
Most CR tracks are highly correlated, forming Extensive Air Showers:



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.

Chou, DC, Lubatti 1606.06298

Background Rejection (gory details)

Com ... run

$\Delta t \gtrsim 3$.
17
tracker

For *s
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par
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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.

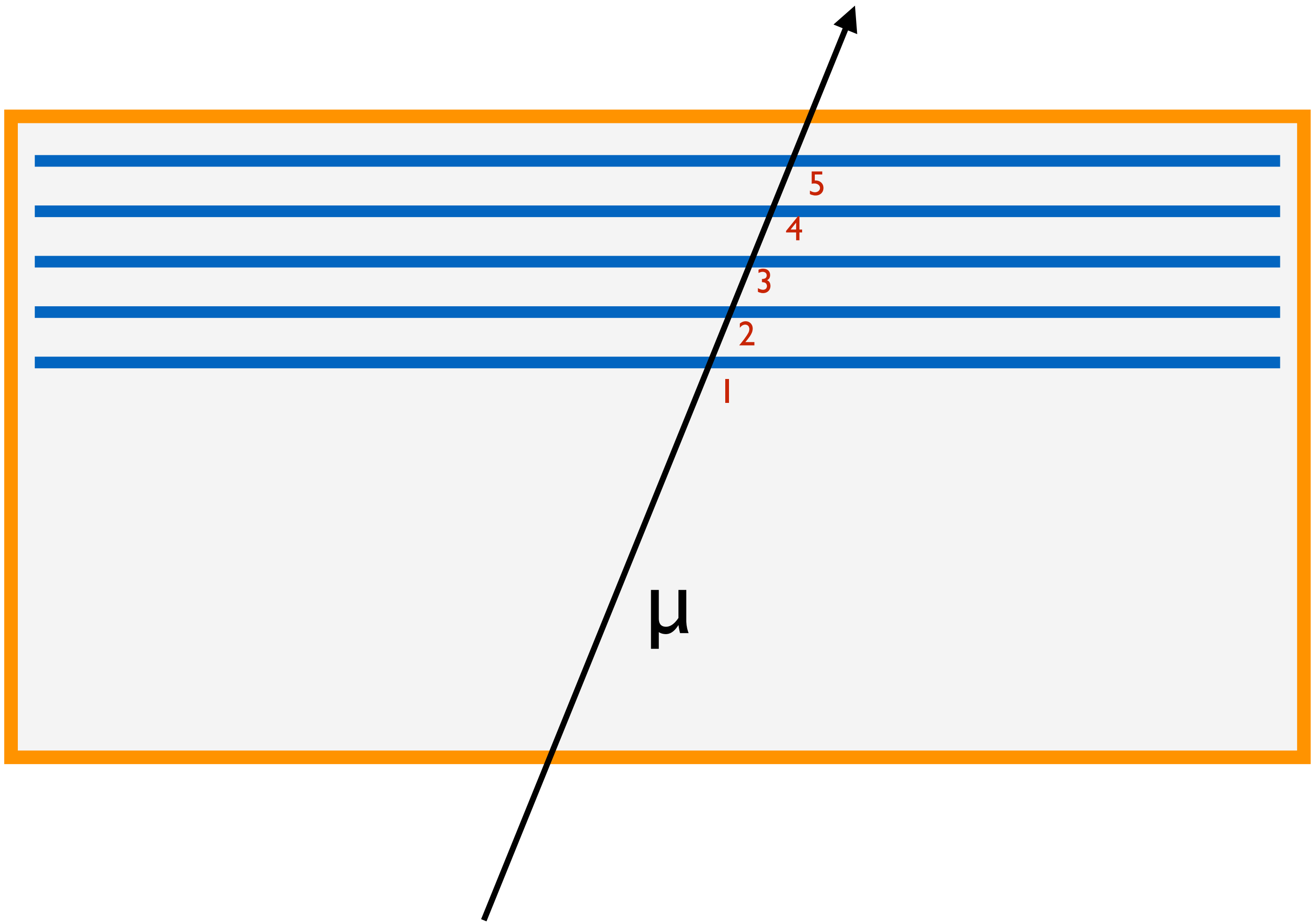
Finally, this CR background is inherently *studyable*: during ~50% of time when HL-LHC beam is off, you can verify CR rejection strategies on data that is guaranteed to be only background.

...Lubatti 1606.06298

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 without something extra happening.



Background Rejection (gory details)

Process	MATHUSLA100	MATHUSLA200	Comments
Upwards-traversing μ in decay volume	$(2.0-2.5)\times 10^6$	$(3.1-4.0)\times 10^6$	Does not satisfy DV signal requirements. Corresponds to rate of $\mathcal{O}(1)$ per minute.
$\mu \to e\nu\nu$	$(3.0-3.2)\times 10^3$	$(5.5-6.8)\times 10^3$	Does not satisfy DV signal requirements. Boost of decaying μ is 1-100 in decay volume, so e may be detectably deflected off muon trajector.
$\mu \to ee e\nu\nu$	0.10 - 0.11	0.19 - 0.23	Genuine background to LLP DV search, but low expected rate can be vetoed, see caption.
Inelastic Scattering (air in decay volume)	$0.3-0.6$	0.8 - 1.1	Ditto.
Inelastic Scattering (support structure)	$(200-350)\times\left[\frac{\xi_{\rm iron}}{10\%}\right]$	$(490-680)\times\left[\frac{\xi_{\rm iron}}{10\%}\right]$	Can be partially vetoed, see caption. Can also be effectively rejected by applying material veto from position of reconstructed DV within support structure.
Delta Rays (μ liberating atomic e with $E_e > 1$ GeV in decay volume)	120 - 160	210 - 310	Can be partially vetoed, see caption. Can be vetoed by requiring two-pronged DVs to have opening angle $\theta > 2°$.

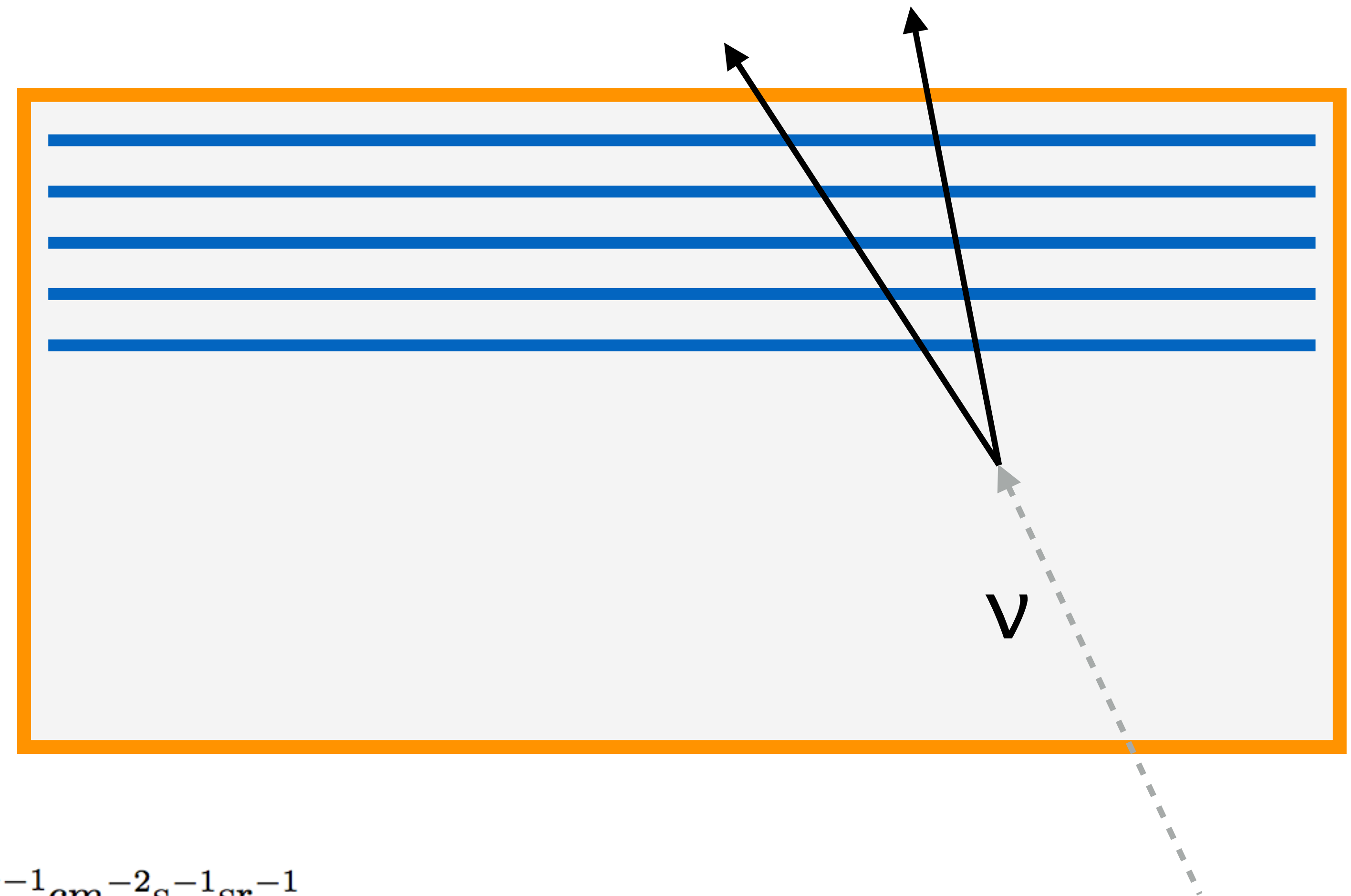
Muons are ok!

https://cds.cern.ch/record/2631491/files/LHCC-I-031.pdf

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)

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

Chou, DC, Lubatti 1606.06298

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

Most naively lik

Can co Frejus r atmosp much lo wi

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

1606.06298

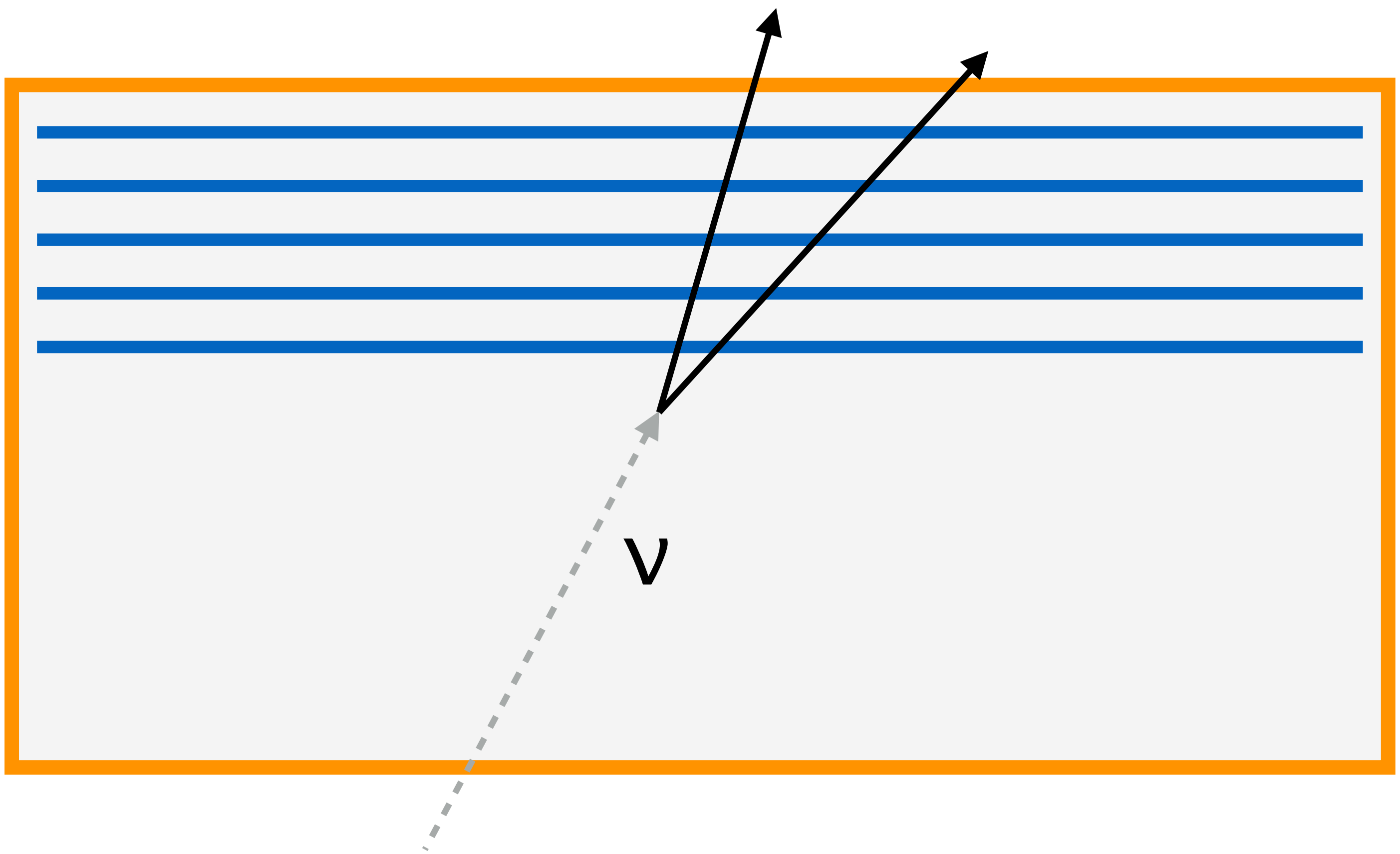
Background Rejection (gory details)

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?)

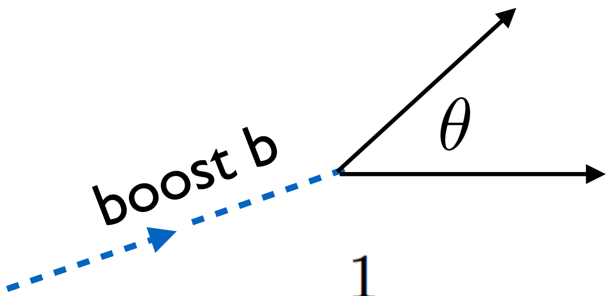
- Full simulation of neutrino background and rejection strategies. Refine geometric veto, especially for neutrinos from LHC.
  Get more realistic estimate of NR-proton-veto efficiency (will be better than our estimates, due to pessimistic assumptions we made about final state kinematics, and by ignoring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

Further details on MATHUSLA LLP sensitivity

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"

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

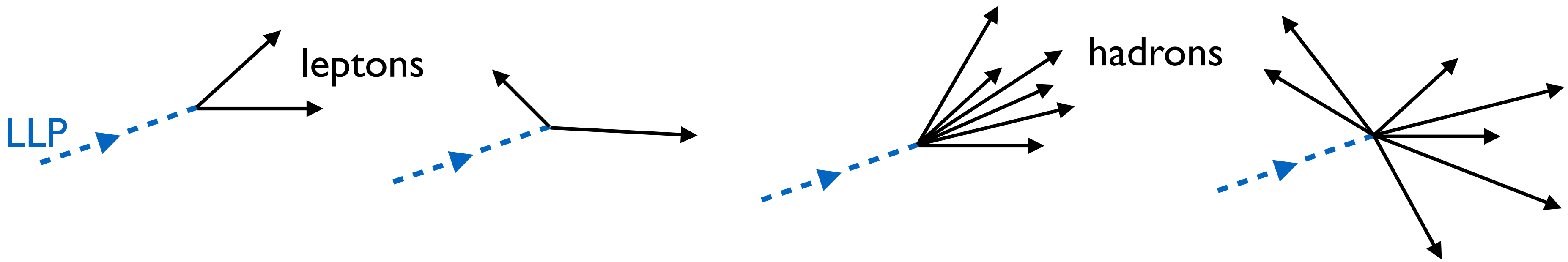
~ 10 MeV for LLPs from B decays

~ 0.1-1 GeV for weak-TeV scale production

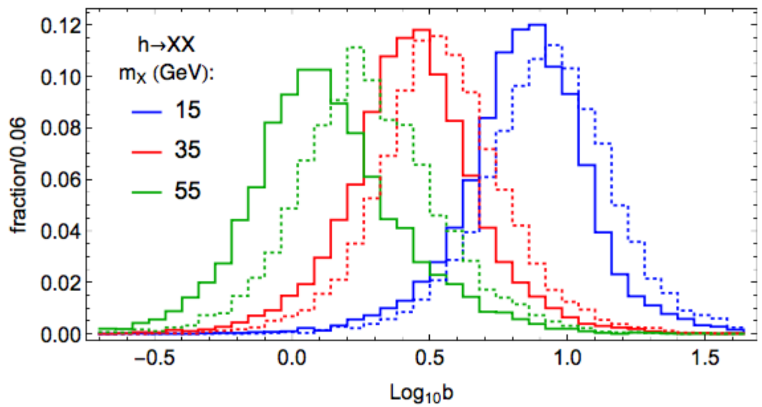
Interesting complementarity with SHiP?

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**.

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

Optional: layer of material between tracking layers for e/μ discrimination and γ detection

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