

Experimental searches for long-lived particles



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Where are the new discoveries in collider physics?



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$(g-2)_\mu$?

*Scalar resonances at
95, 150, 680 GeV?*

W mass?

*Multi-lepton
anomalies?*

*Z decay
asymmetries?*

*Something else
entirely?*

Flavor anomalies?

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“Excuse me?” — Me

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What is an experimental particle physicist?

Particle
hunter

Cartographer

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~~Particle
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Cartographer

The task of particle physics is

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~~Particle
historian~~



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The task is to look everywhere
with all experiments
both existing and future
without theory bias or favor

Signature first, model second

Signature first, model second

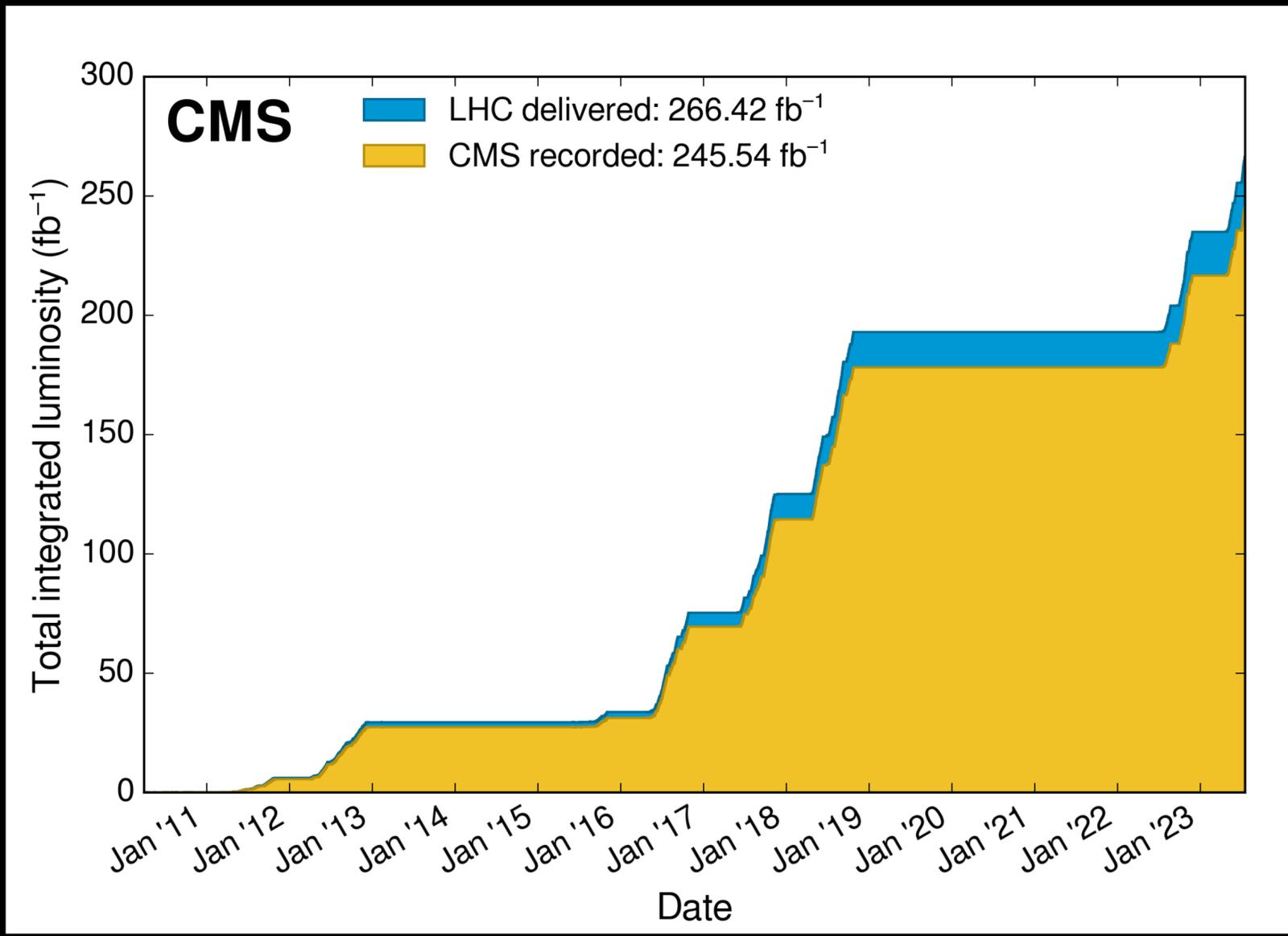
a.k.a.

Signature first, model second

a.k.a.

What are we missing?

The Large Hadron Collider is a big-data exploration machine



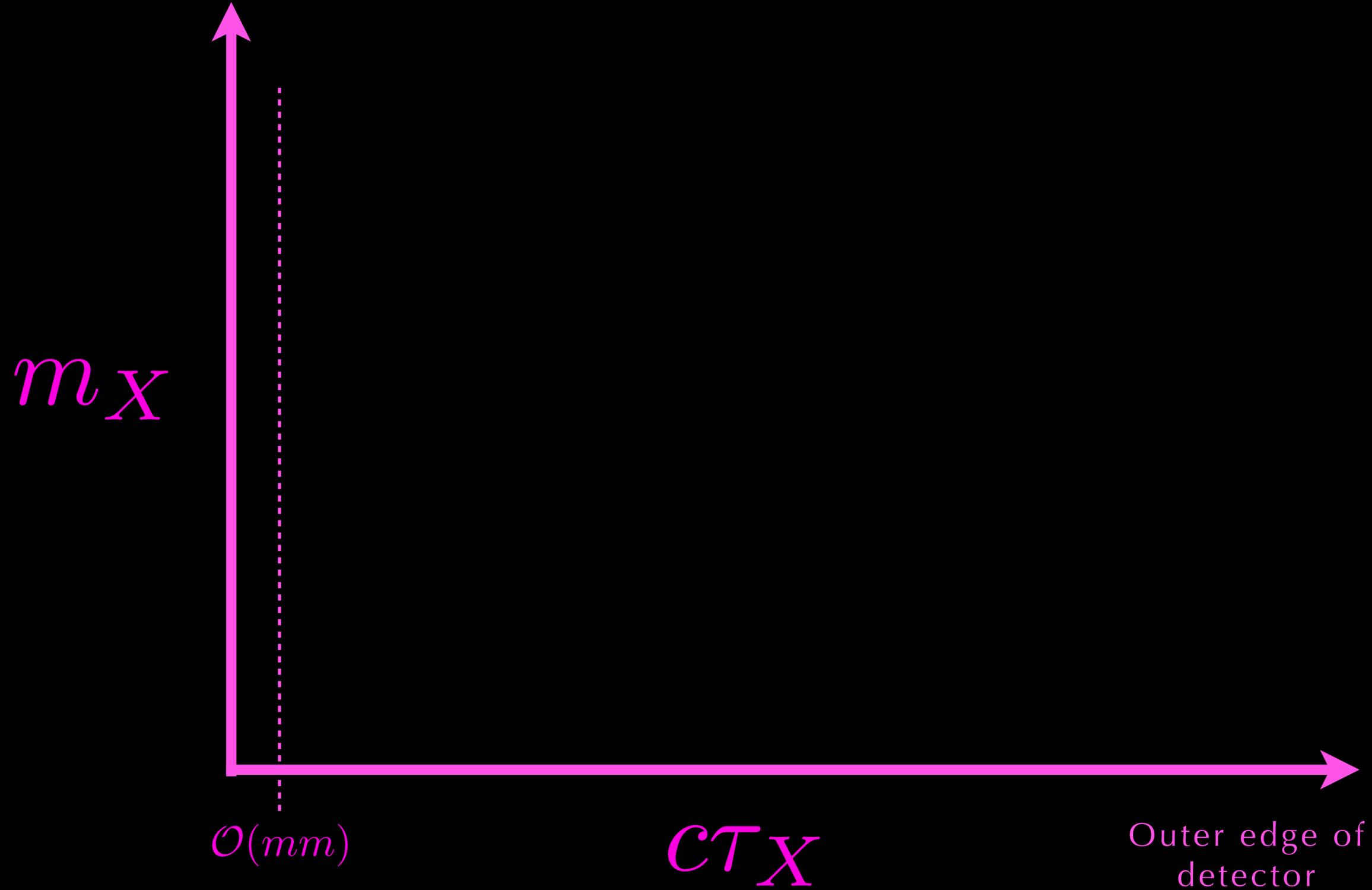
Papers as of 11 Dec. 2023	ATLAS	CMS
Exotic(s) (a)	305	224
Supersymmetry	194	139

Heroic amount of data, hundreds of published BSM searches

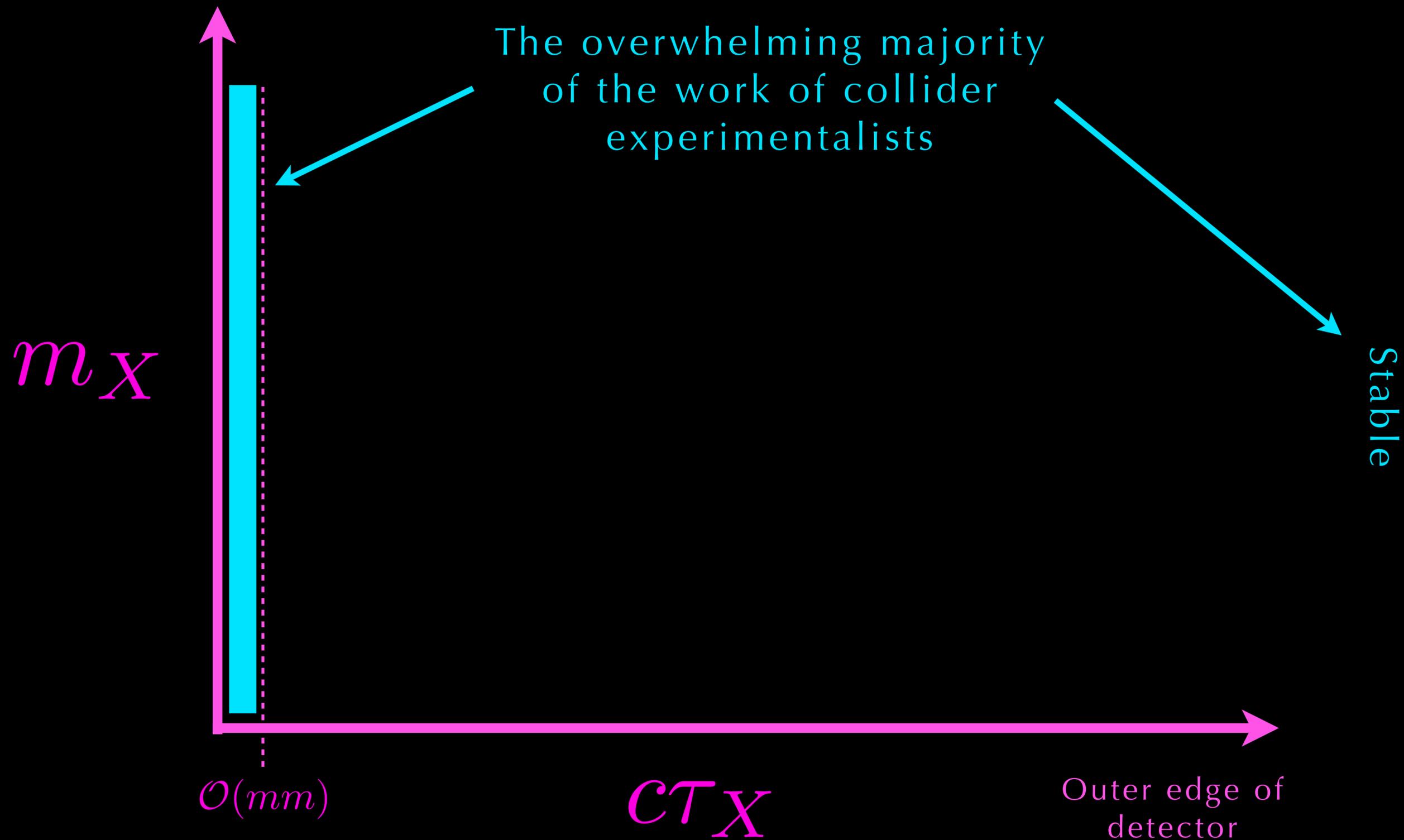
New physics "X" at colliders



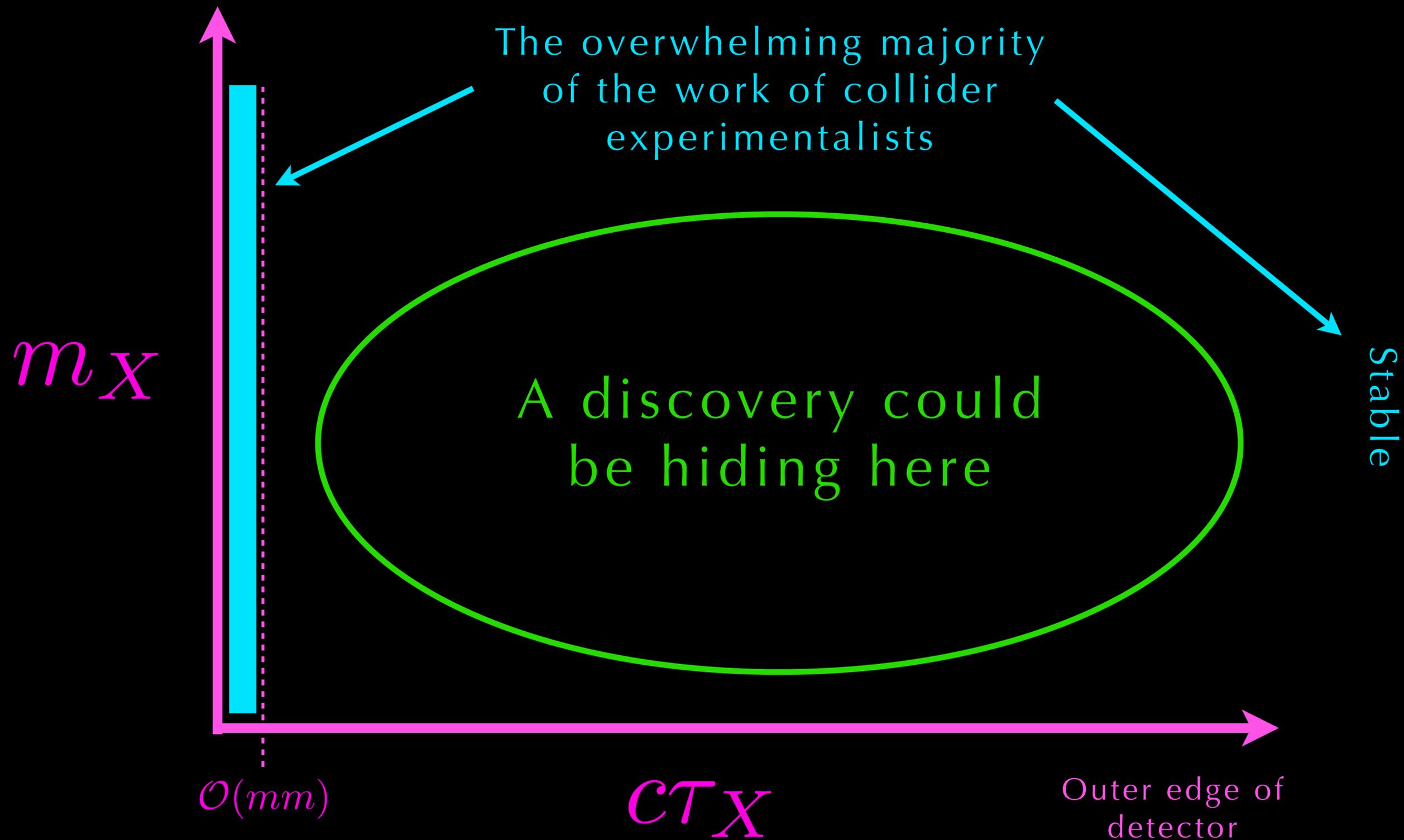
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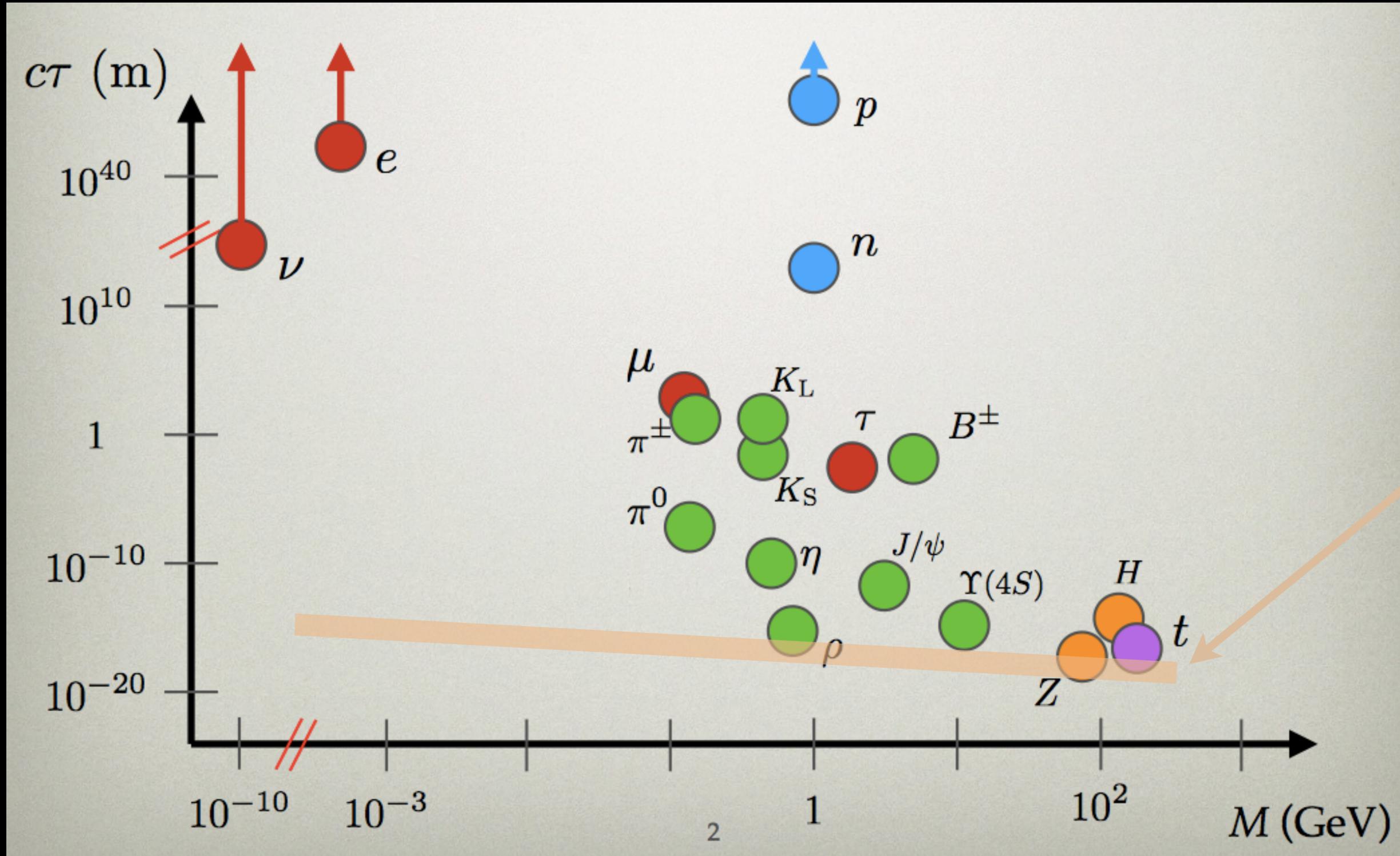


New physics "X" at colliders



The Standard Model is filled with long-lived particles!

Via [Knapen](#), [Shuve](#); see also [Craig](#)



Naive dimensional analysis

$$\tau = \frac{\hbar}{M}$$

Modified from [J.Phys.G 47 \(2020\) 9, 090501](#)

Particle lifetime

The proper lifetime τ of any particle is given by the inverse of its decay width (or decay rate) Γ , the probability per unit time that it will decay

$$d\Gamma \propto \frac{1}{M} |\mathcal{M}|^2 d\Pi$$

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$M = \text{mass of the particle}$ → M

→ $|\mathcal{M}|^2$ Matrix element governing the decay

→ $d\Pi$ Phase space for this decay

Small right side → long-lived particle

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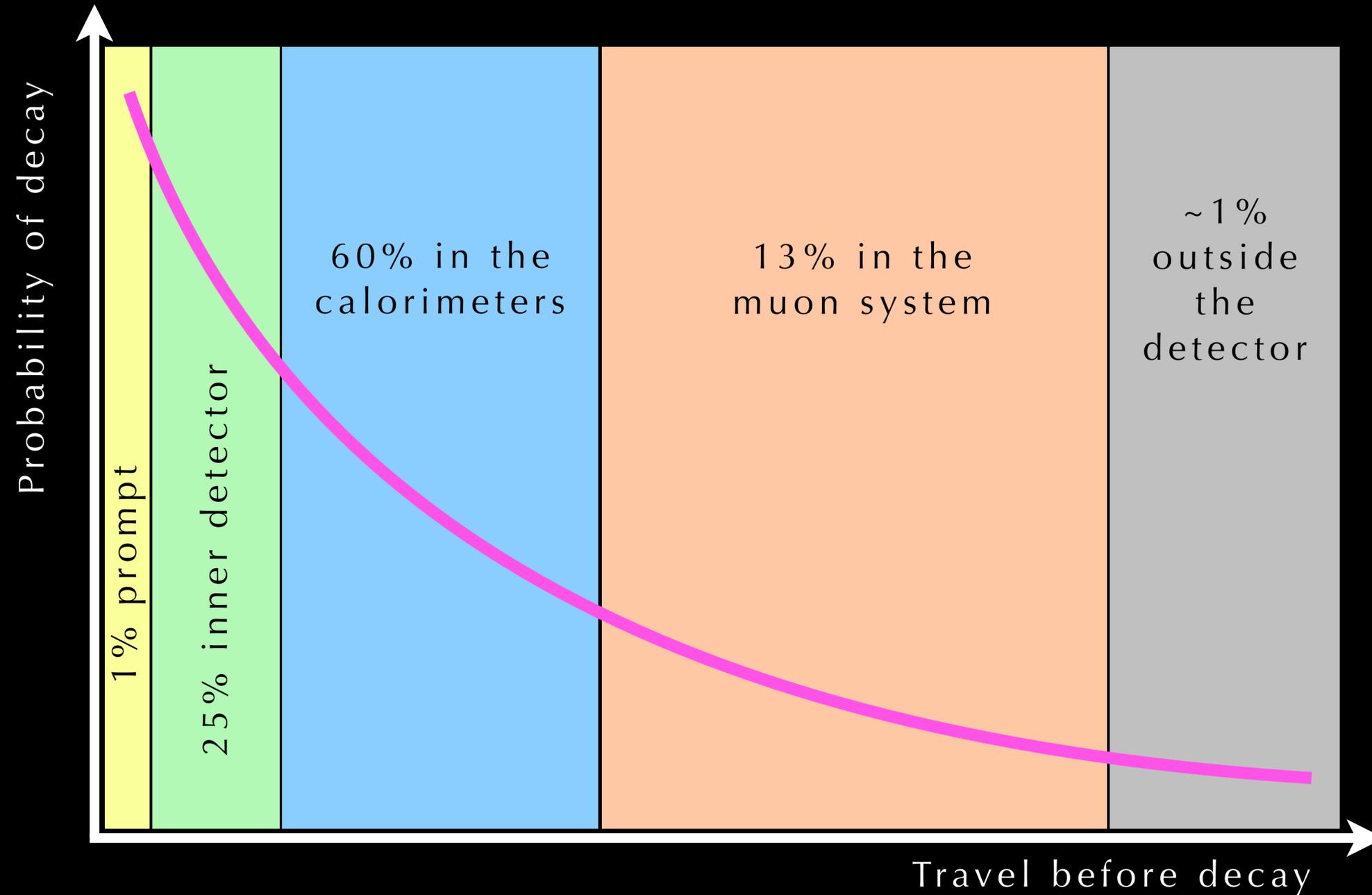
Small right side \rightarrow long-lived particle

Long lifetimes typically arise in the SM when *approximate symmetries* make the particle stable — same principles generically apply in BSM theories

Long-lived particles at the LHC

The observed lifetime of a particle is sampled from an exponential with a shape set by its proper lifetime τ (often expressed as proper decay length, $c\tau$)

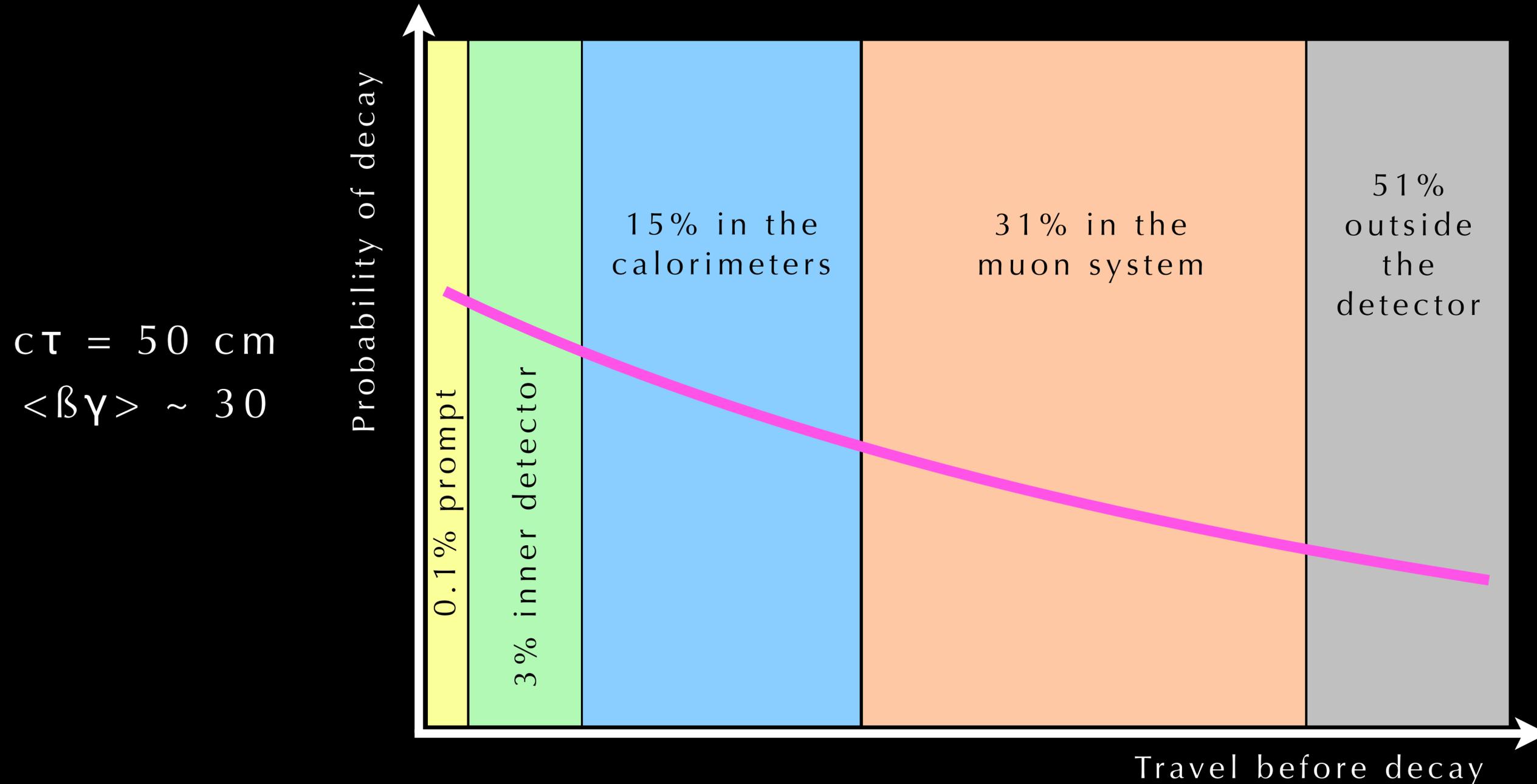
$c\tau = 5 \text{ cm}$
 $\langle\beta\gamma\rangle \sim 30$



As a result, we use multiple search strategies targeting all subdetectors of ATLAS, CMS, and LHCb — and beyond the detectors

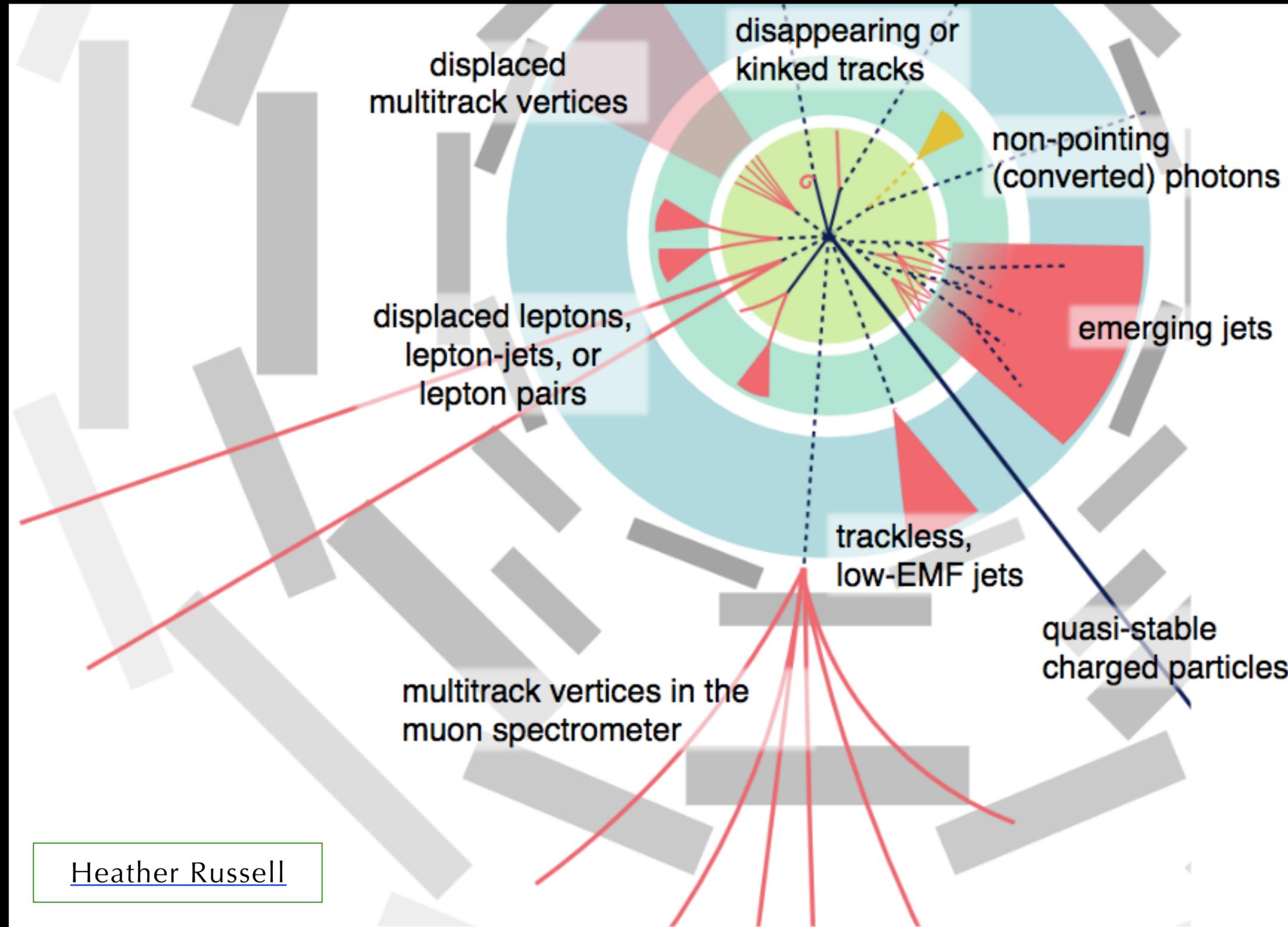
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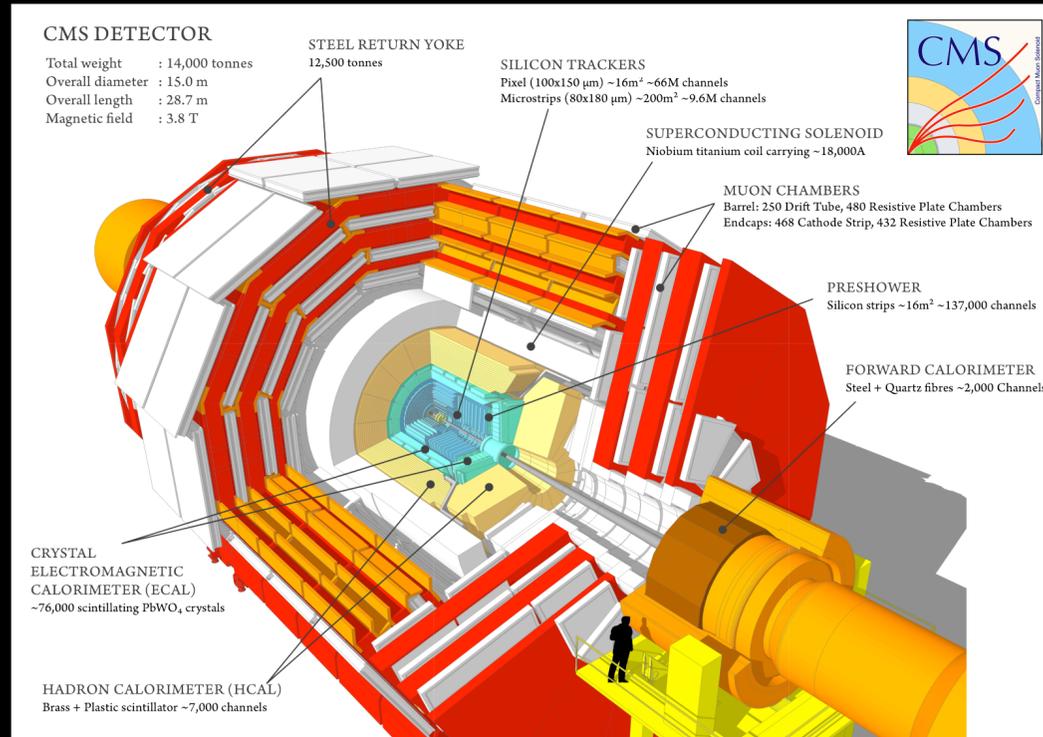


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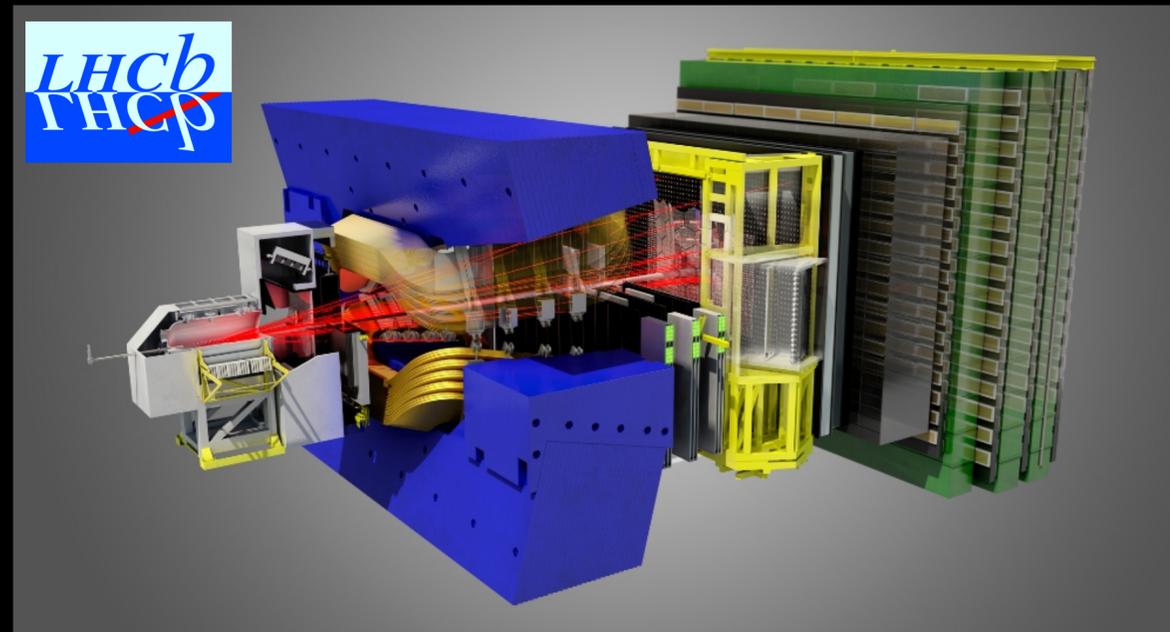
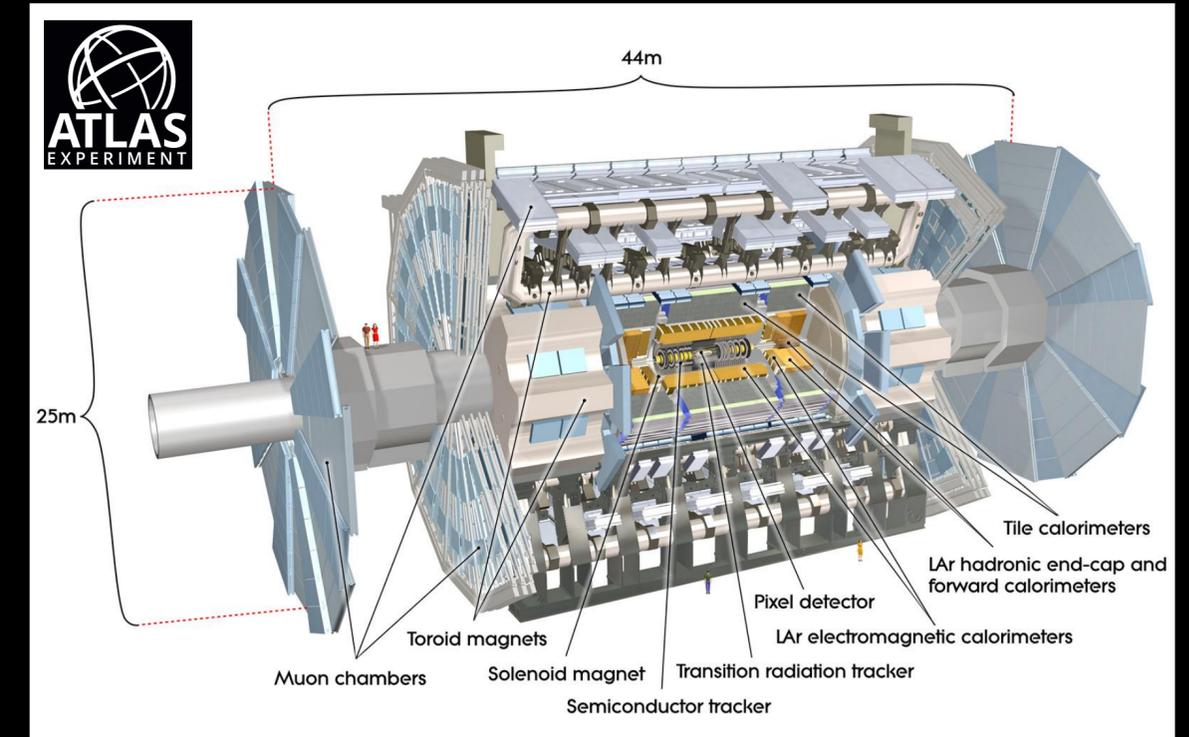
Long-lived particles mean many new detector objects



The central detectors of the LHC



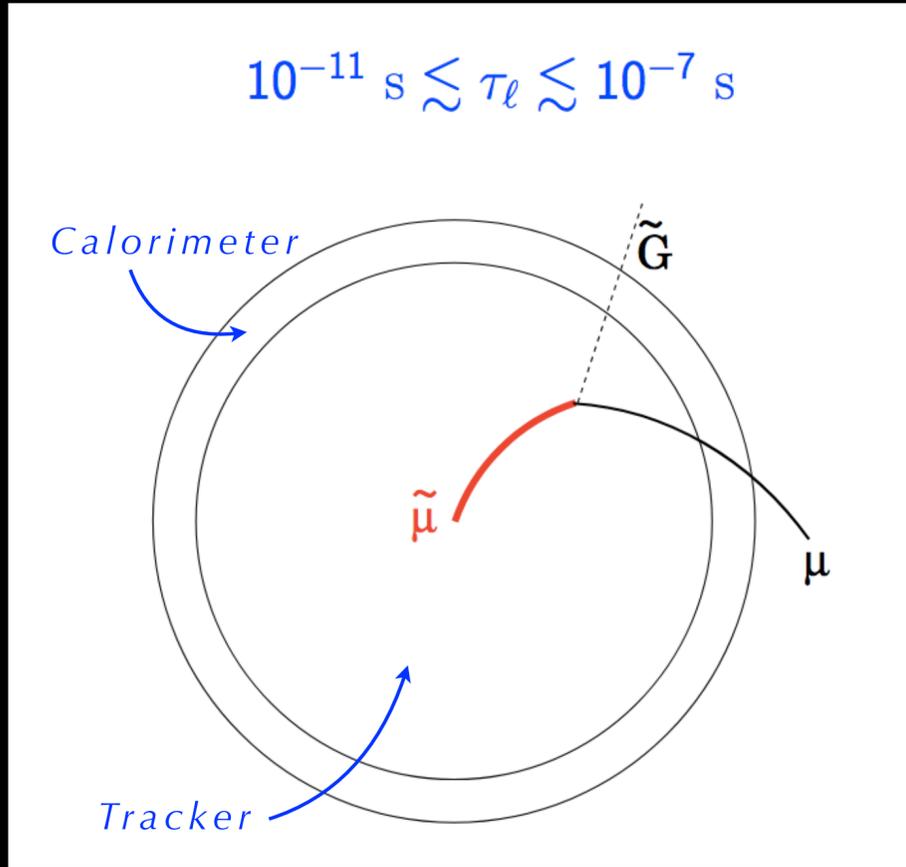
CMS and ATLAS have similar but slightly different designs but intended to be general-purpose, i.e., to be able to search for a wide range of phenomena



LHCb designed for precision measurements of b-hadrons

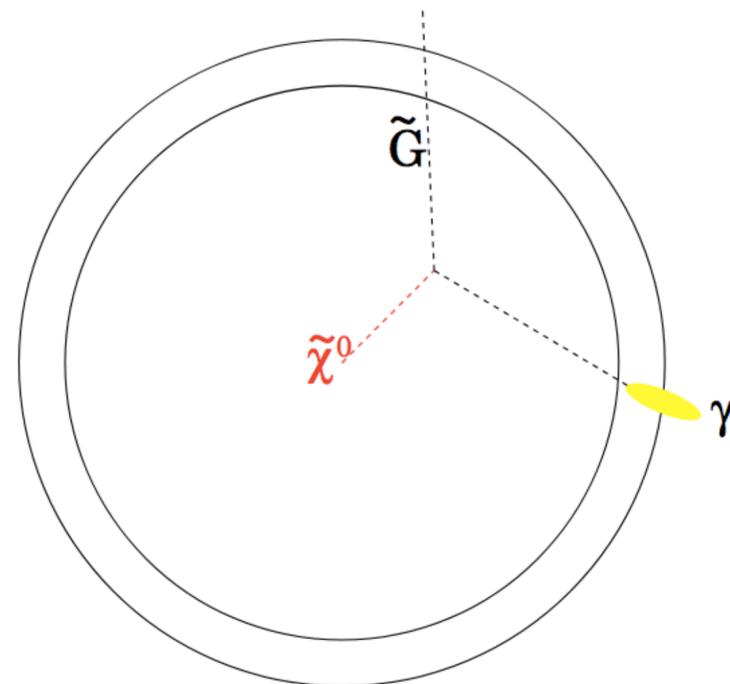
Long-lived particle searches at LEP and the Tevatron

Tevatron

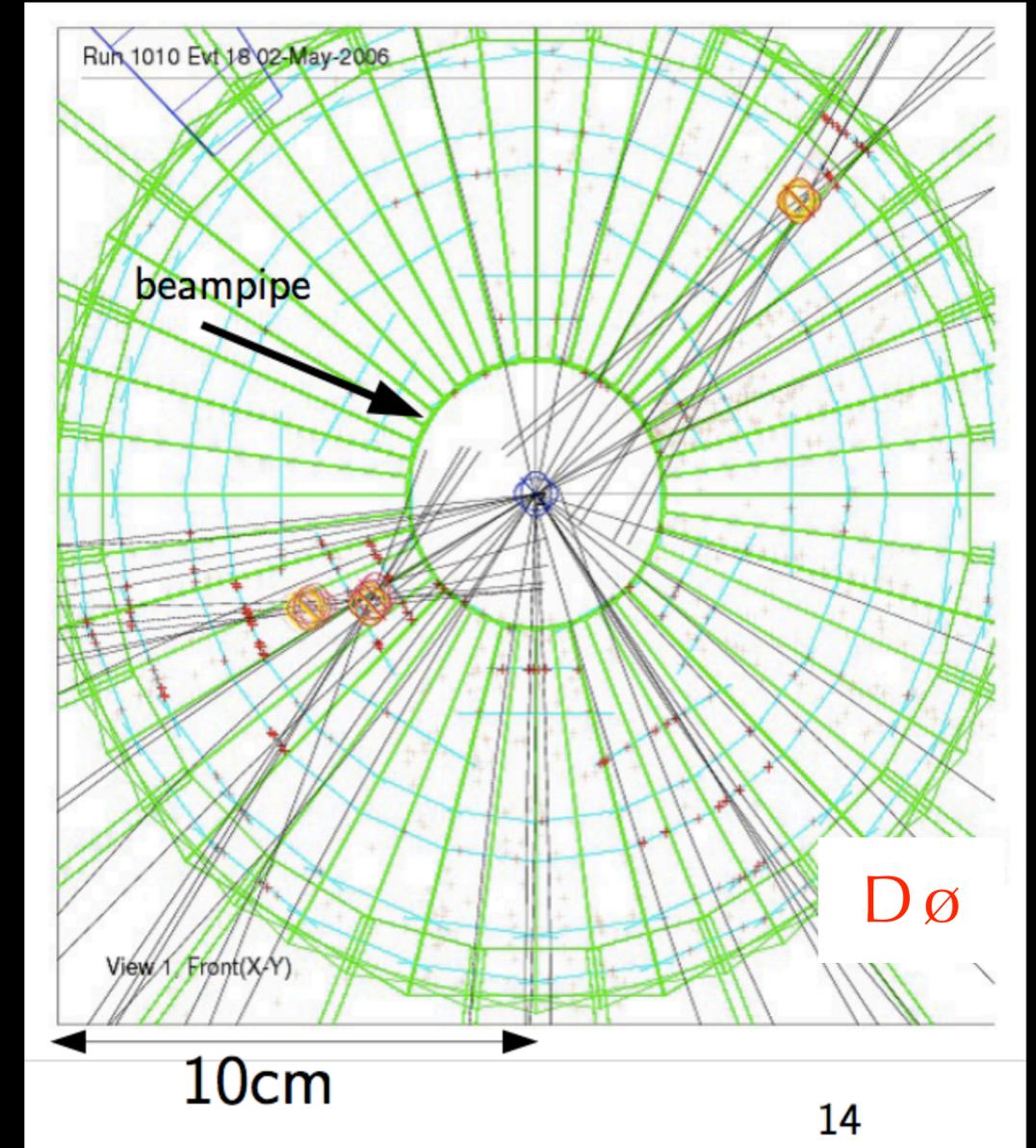


LEP

$\dots \lesssim \tau_\chi \lesssim 10^{-8} \text{ s}$



M. Fanti [talk](#) about LLPs at LEP at first LHC LLP Mini-workshop, 2016



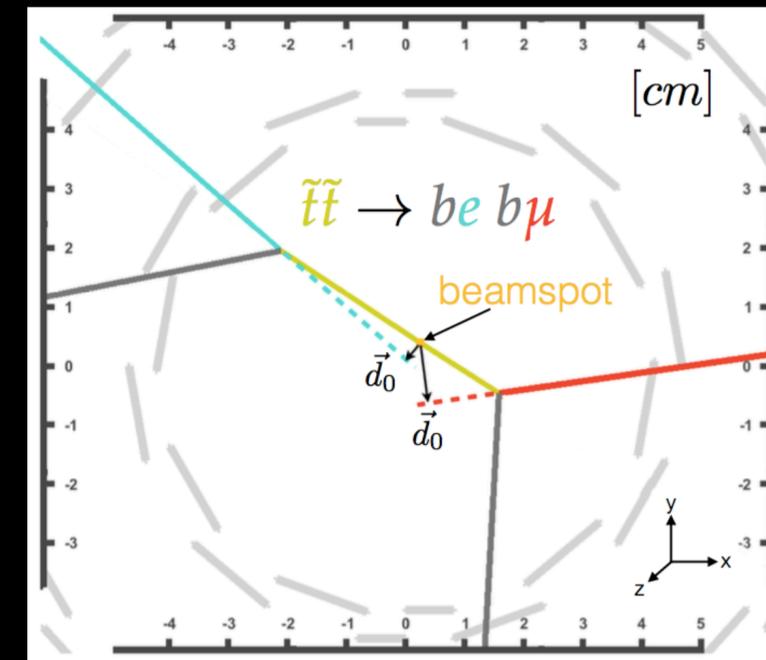
A. Haas [talk](#) about LLPs at Tevatron at the same

A sampling of LLP searches with
ATLAS, CMS, and LHCb at the LHC

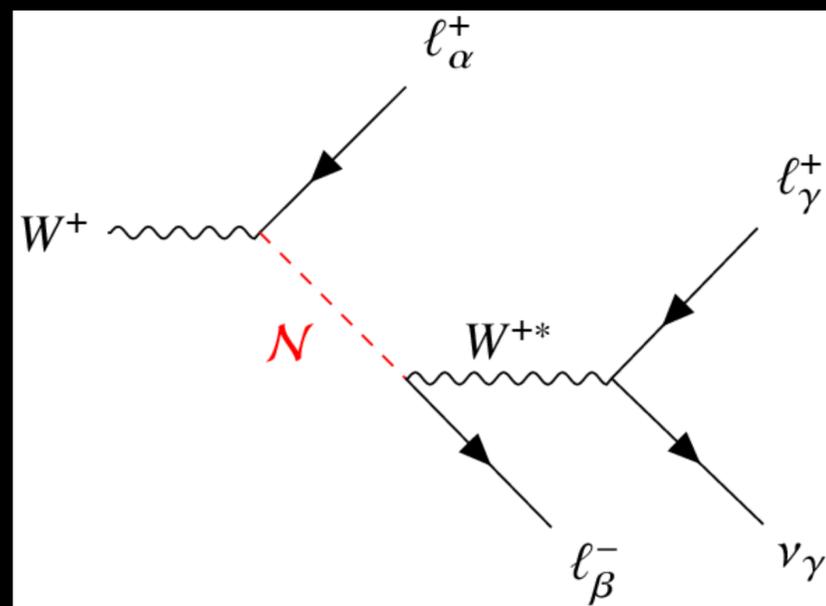
Neutral $LLPs$ decaying to leptons

Identifying displaced charged particles requires the capacity to find tracks with large impact parameters

- If LLP decay occurs in the inner tracker, can use large- d_0 tracking
- CMS has good tracking for such cases by default
- ATLAS previously needed to run special re-tracking [[ATLAS large radius tracking note](#)] and re-vertexing on a subset of events
- Both approaches require customized triggering strategies
- Can lead to various signatures involving one displaced lepton, a pair of separately displaced leptons, or a combination of prompt and displaced

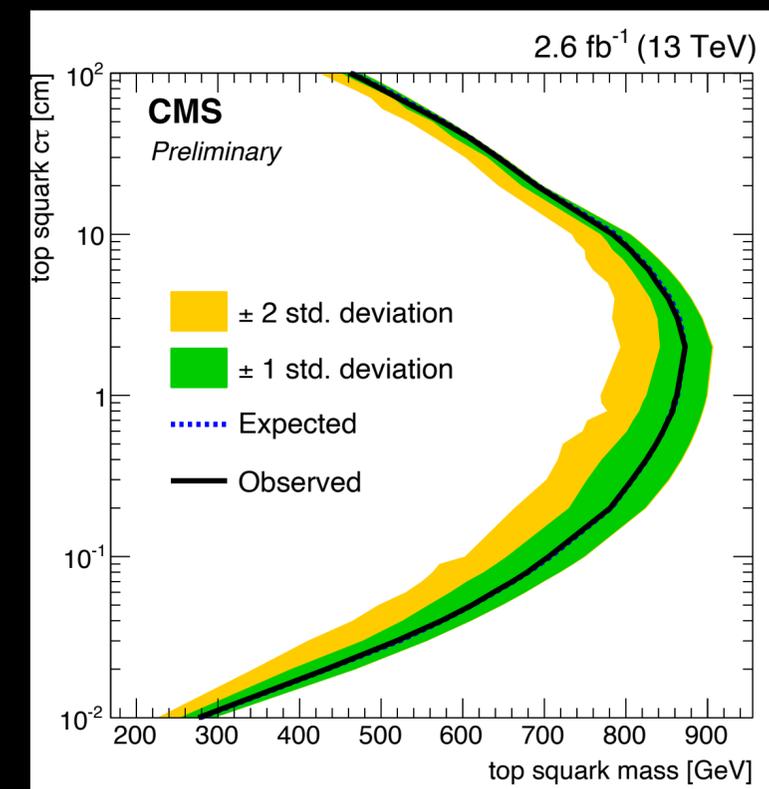
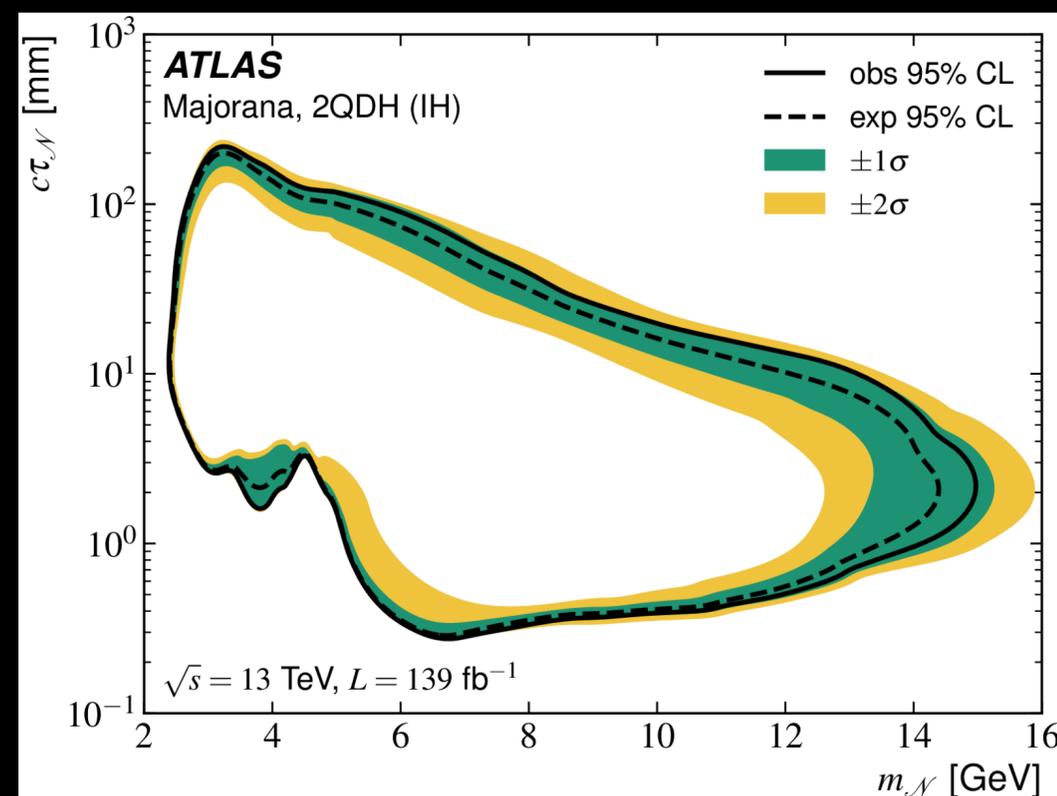


CMS-EXO-16-022



ATLAS (April 2022) [PRL 131 \(2023\) 6, 061803](#)

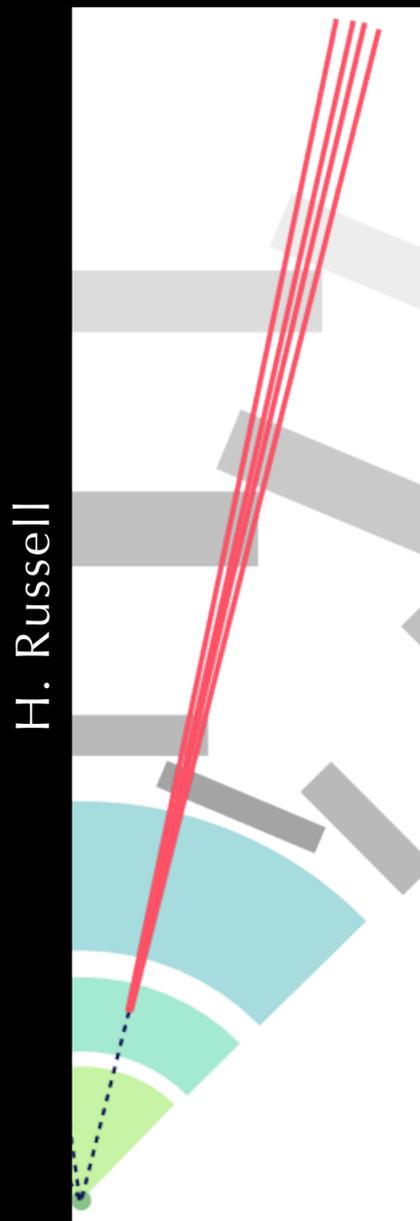
CMS (Jan. 2022) [JHEP 07 \(2022\) 081](#)



Neutral $LLPs$ decaying to lepton-jets

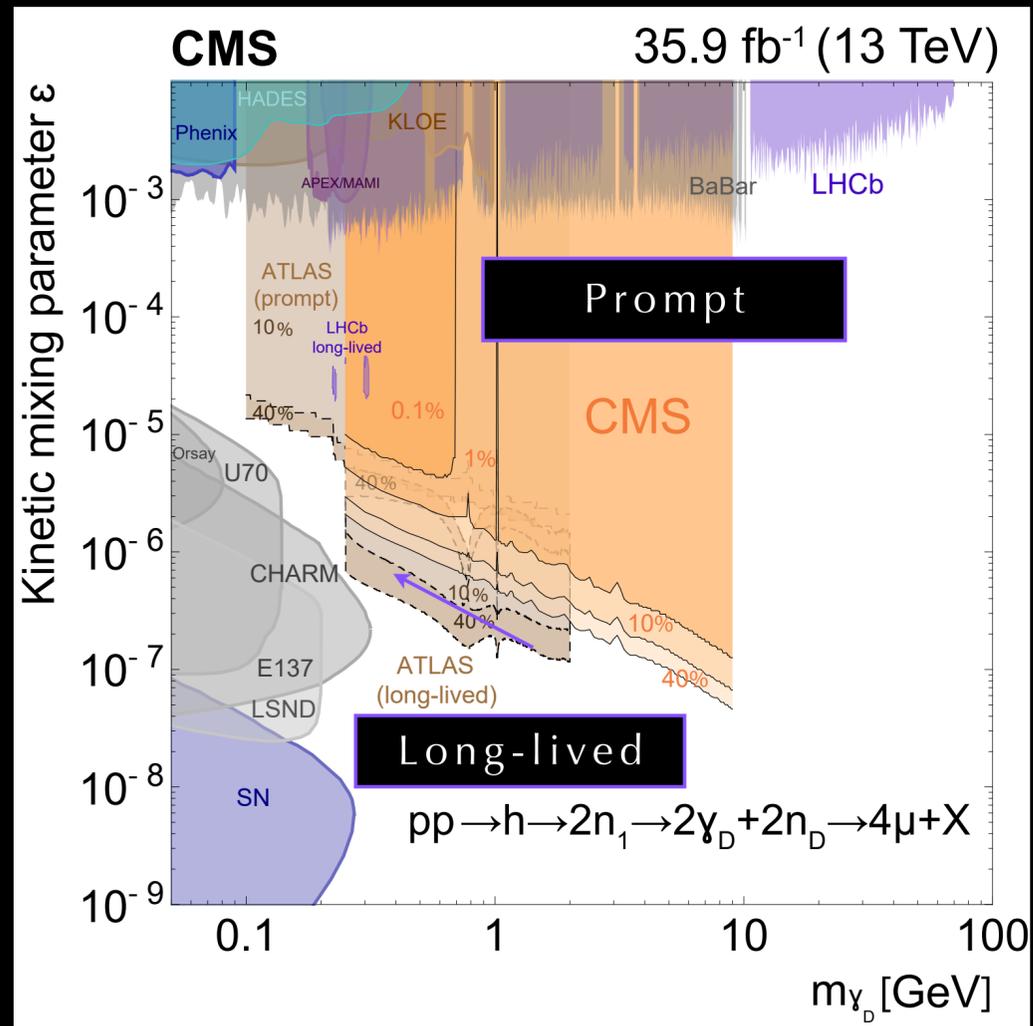
Lepton-jet = highly-collimated grouping of leptons from a low-mass ($O(\text{GeV})$), boosted BSM particle like a dark photon / Z_{dark}

- Confounds standard lepton isolation criteria



H. Russell

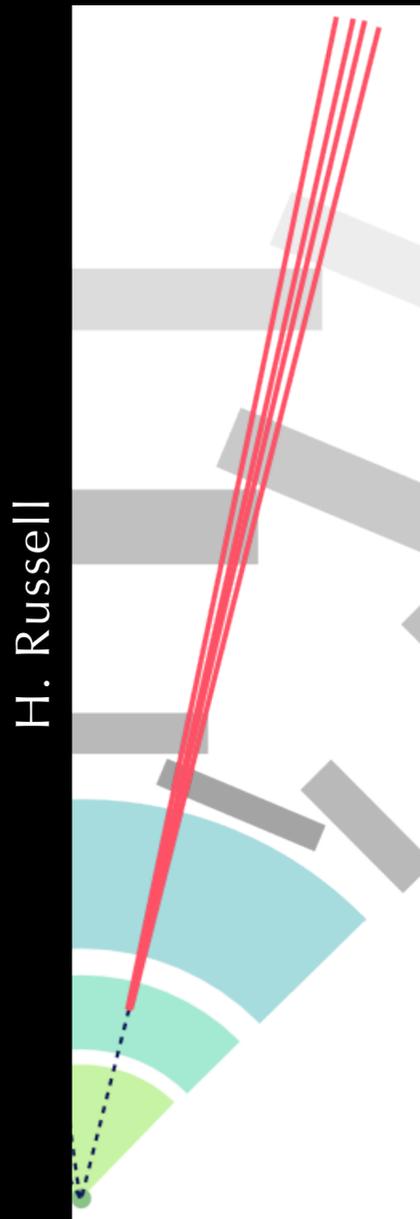
PLB 796 (2019) 131
ATLAS-CONF-2016-042



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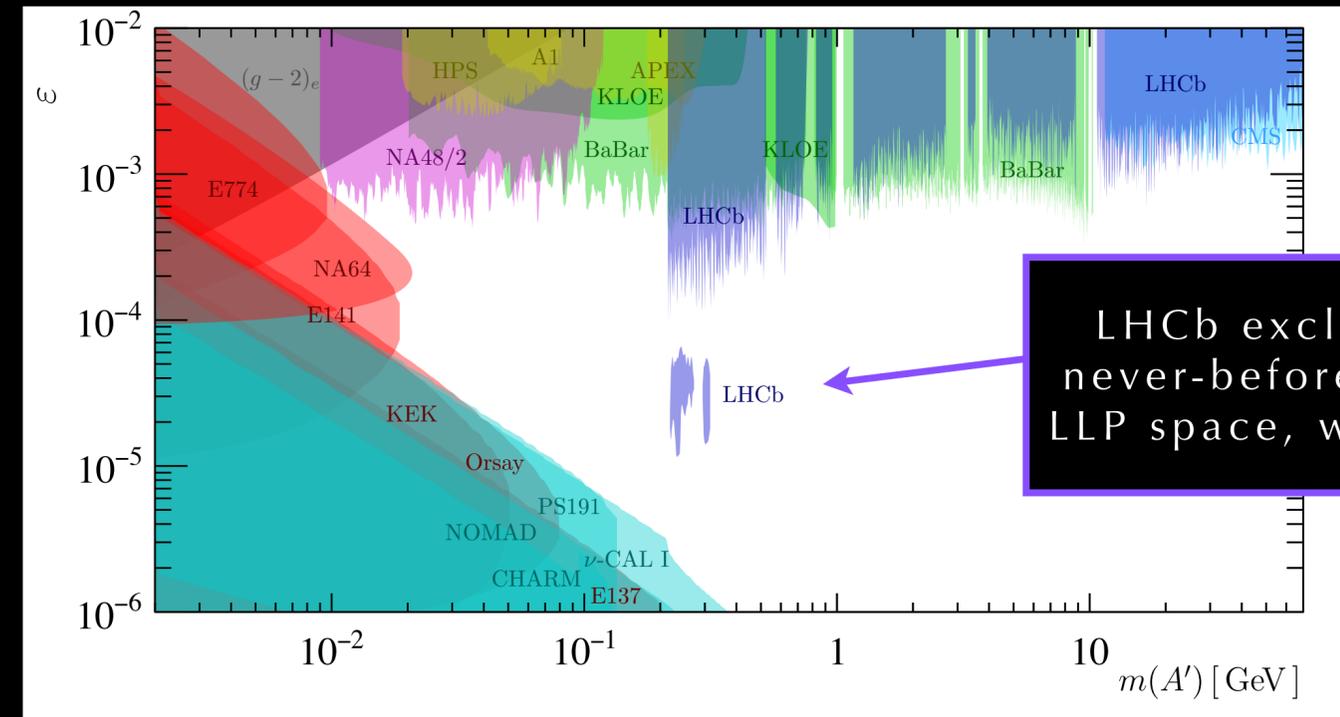
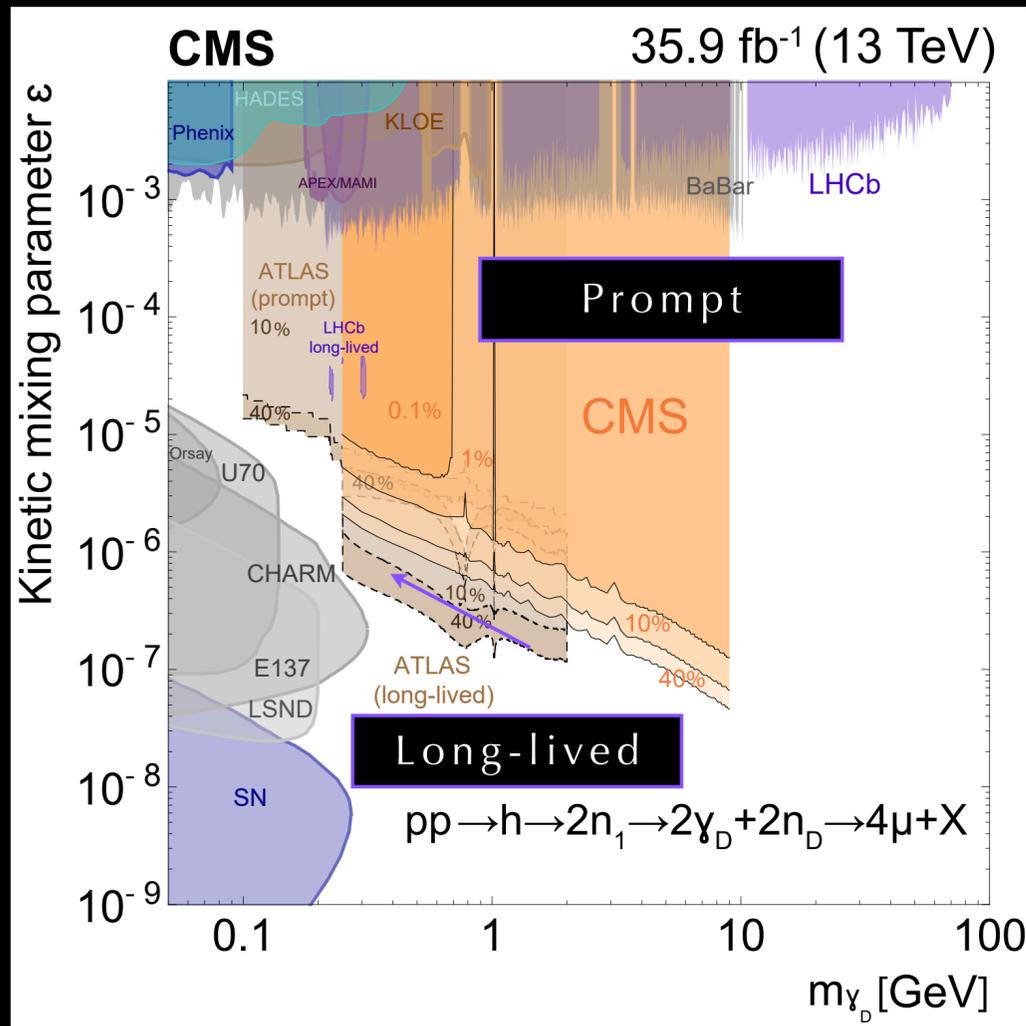
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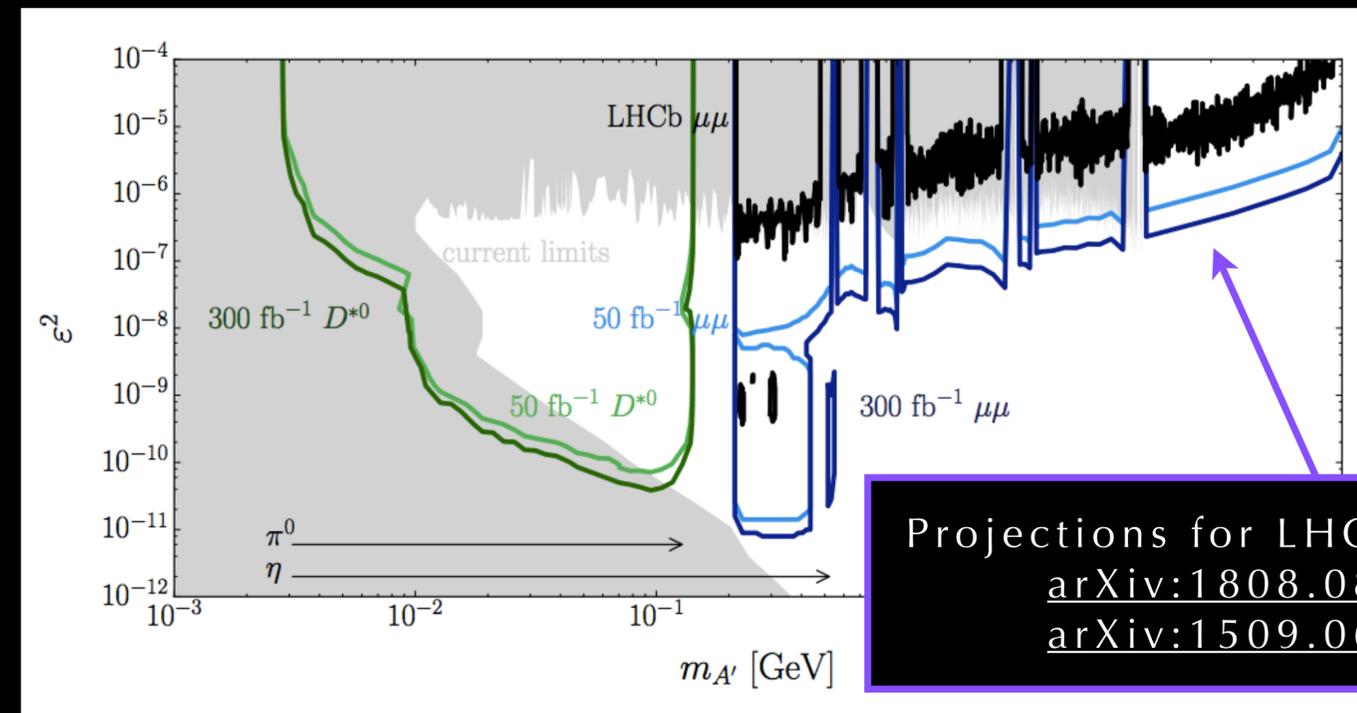


H. Russell

PLB 796 (2019) 131
ATLAS-CONF-2016-042



LHCb: PRL 124, 041801 (2020)



Projections for LHCb upgrade
[arXiv:1808.08865](https://arxiv.org/abs/1808.08865)
[arXiv:1509.06765](https://arxiv.org/abs/1509.06765)

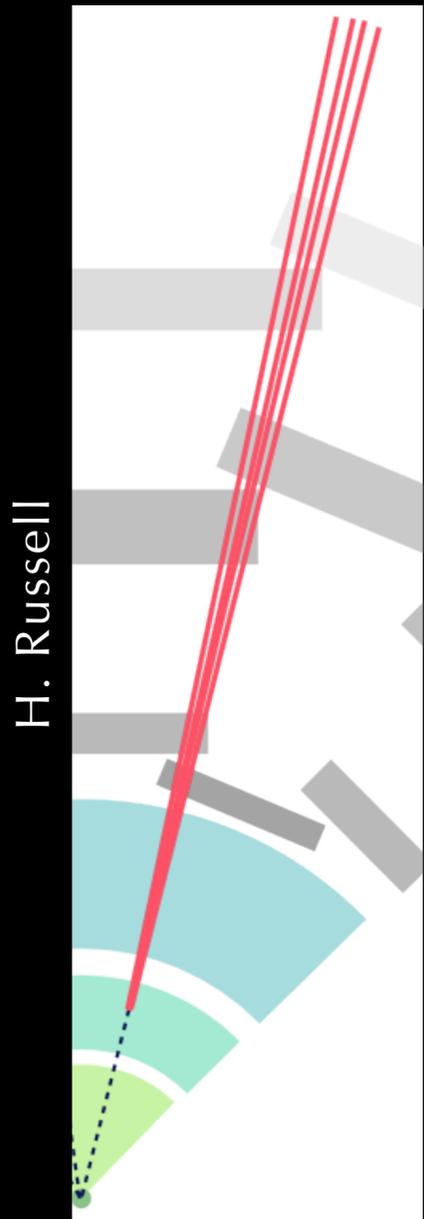
LHCb: PRL 120, 061801

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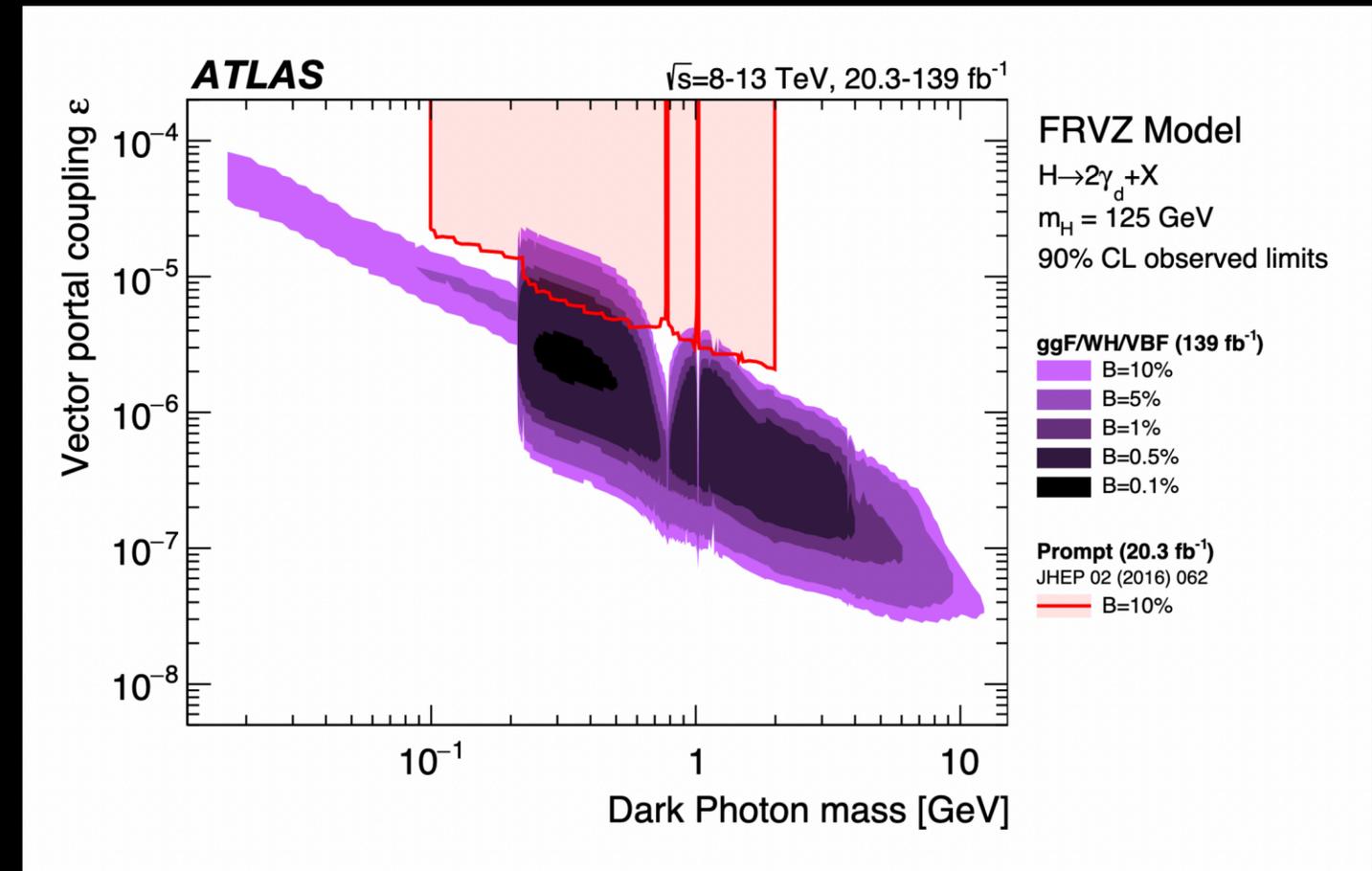
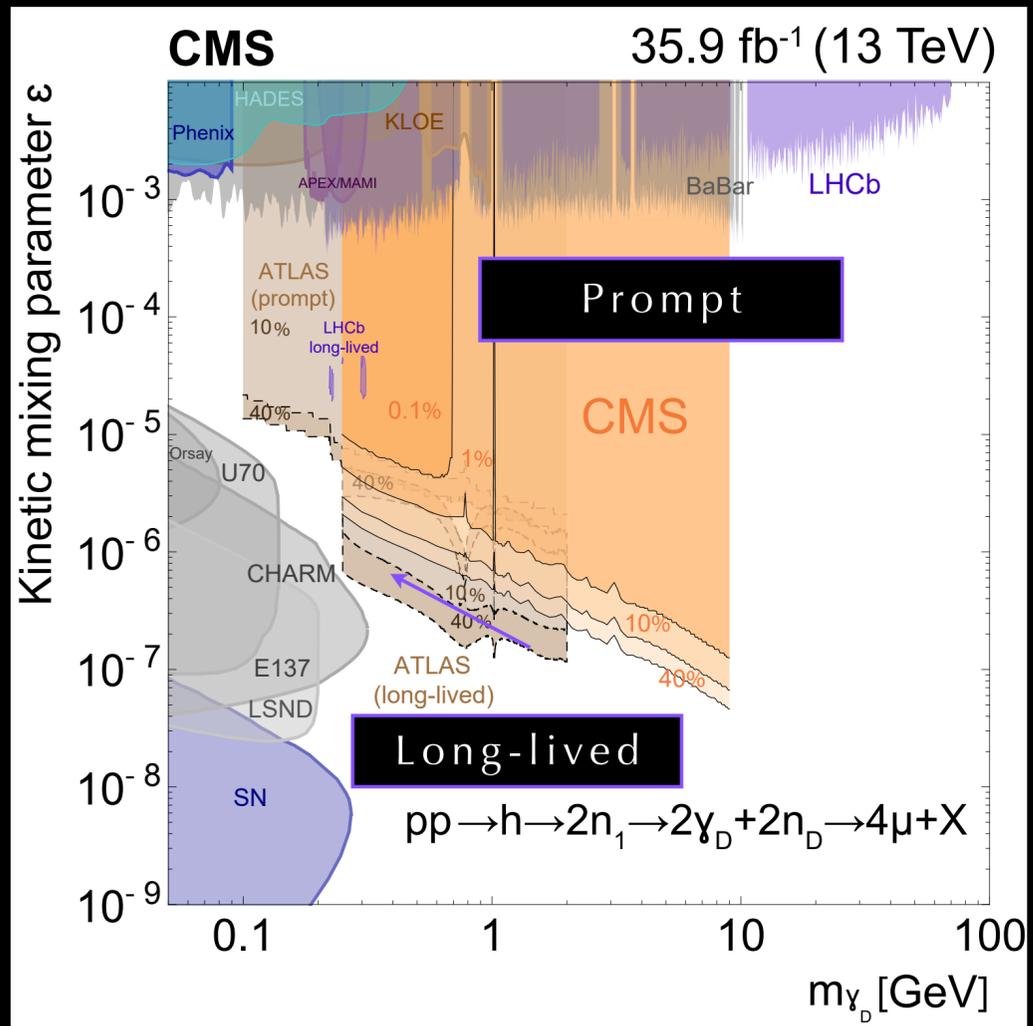
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New ATLAS result (30 Nov. 2023) adds VBF production channel and extends mass range
[arXiv:2311.18298](https://arxiv.org/abs/2311.18298)



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[PLB 796 \(2019\) 131](#)
[ATLAS-CONF-2016-042](#)

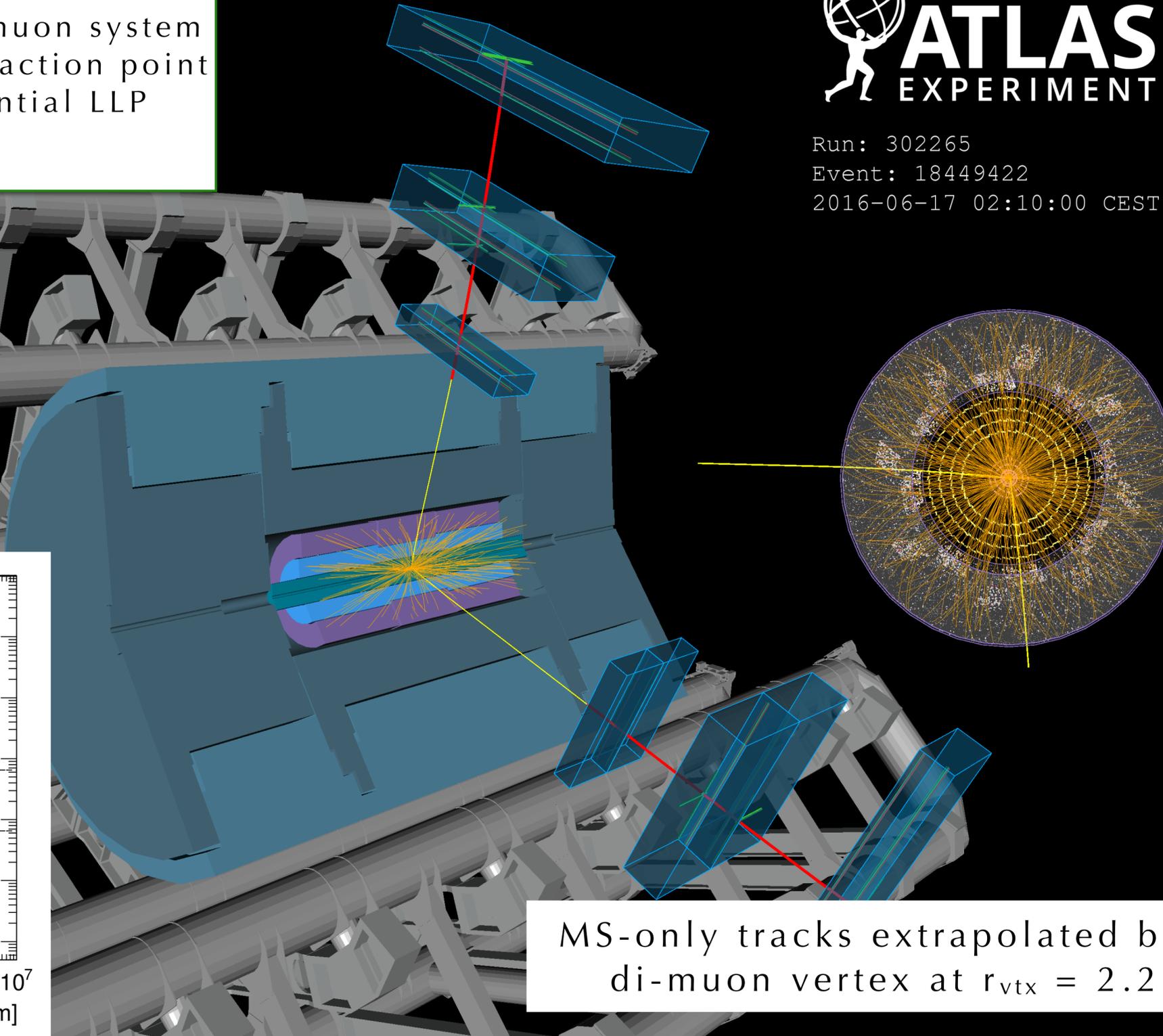
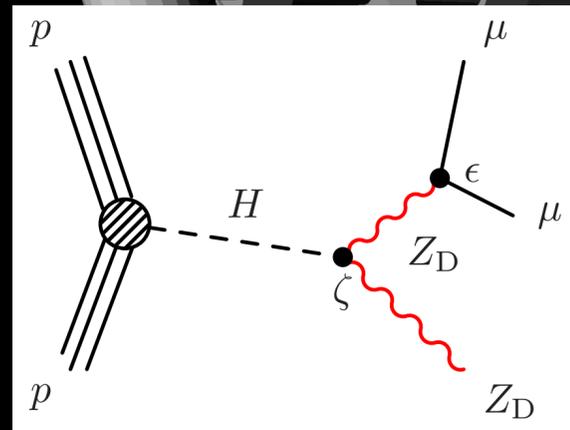


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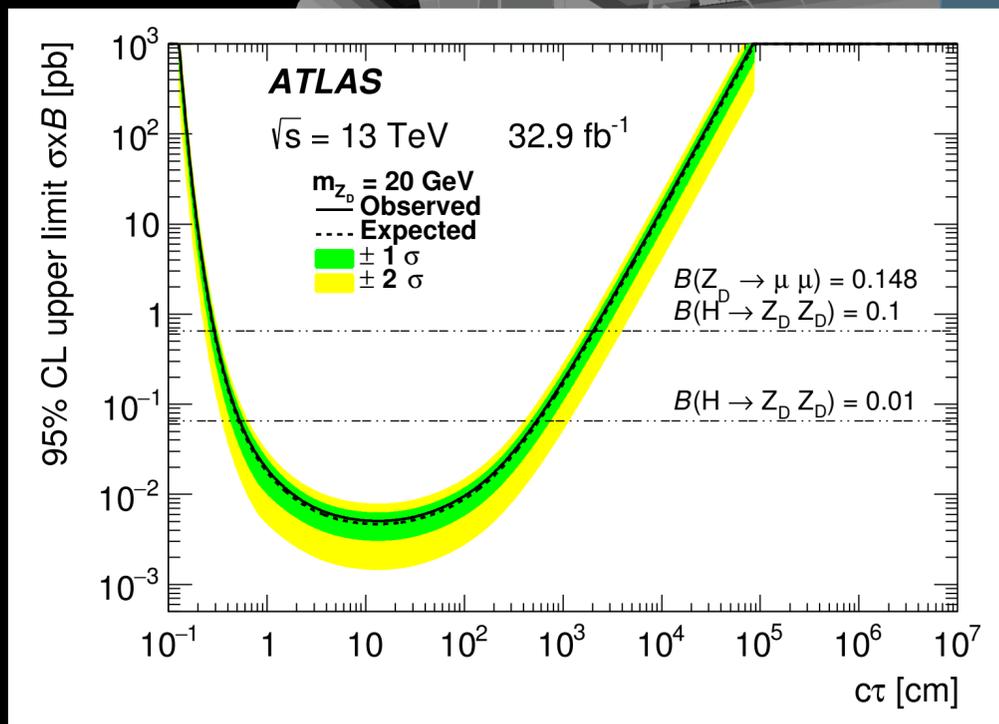
ATLAS result using tracks only in the muon system
 — can still point back toward the interaction point
 for small displacements of the potential LLP
PRD 99, 012001 [2019]



Run: 302265
 Event: 18449422
 2016-06-17 02:10:00 CEST

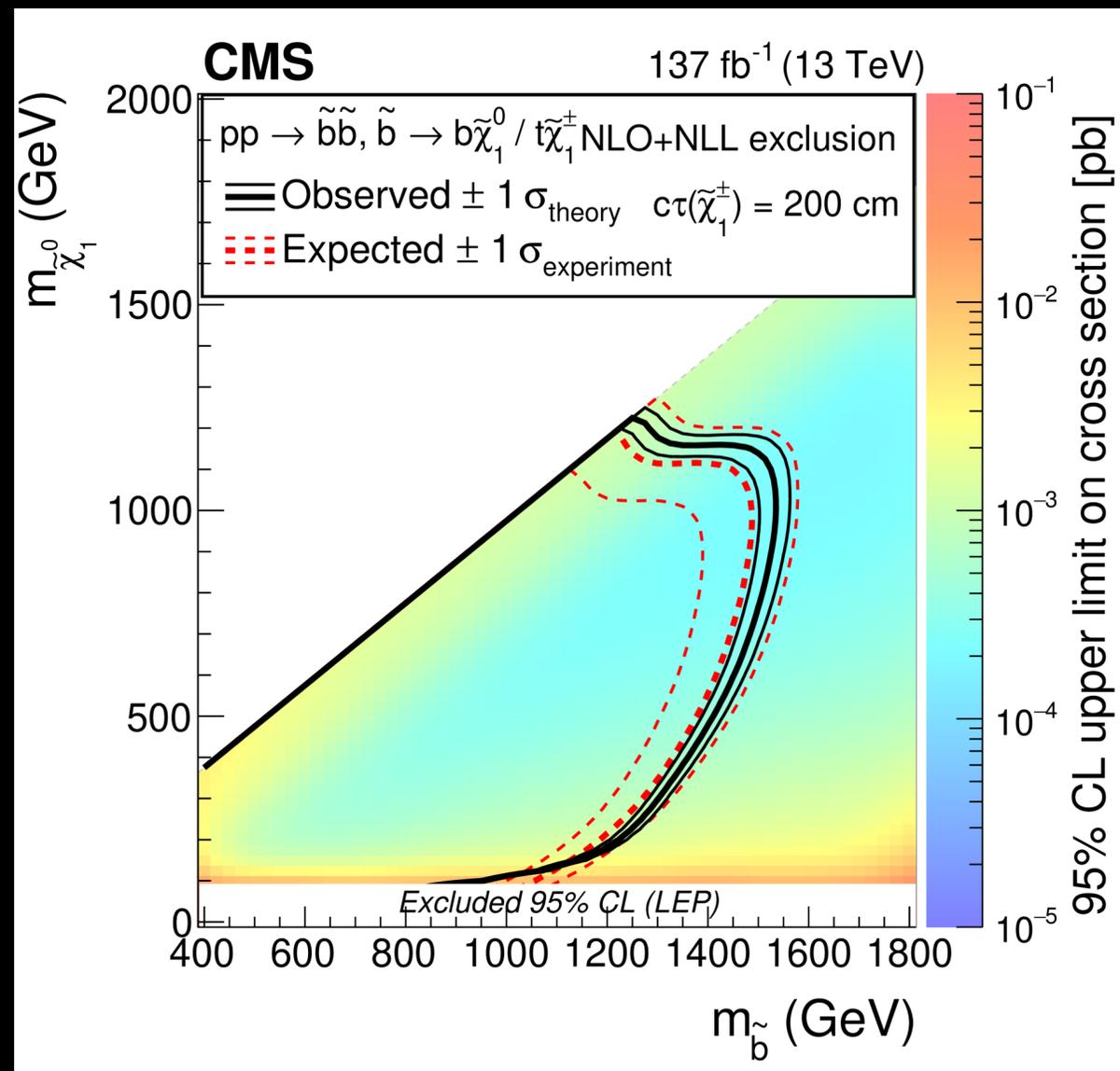
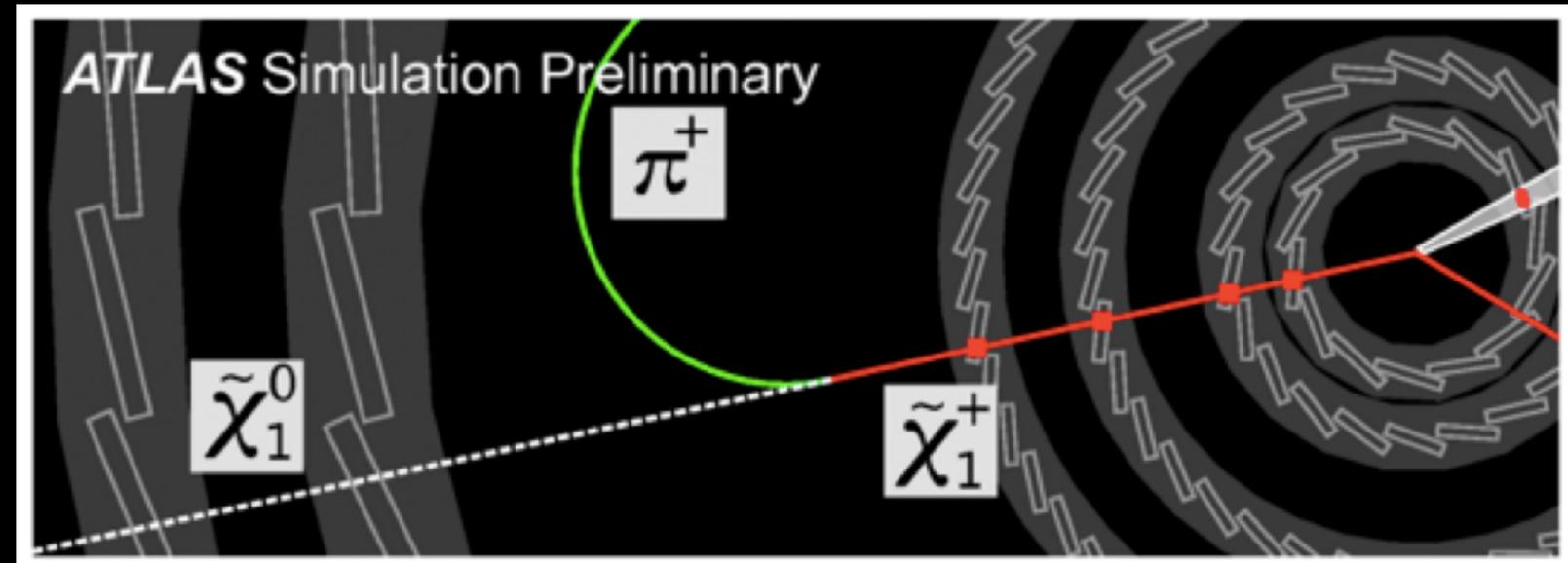


MS-only tracks extrapolated back to
 di-muon vertex at $r_{vtx} = 2.2$ cm



Disappearing tracks

Charged BSM LLP decays to neutral BSM particle with nearly degenerate mass and a very low-momentum charged SM particle that curves around in the magnetic field
—> a disappearing track



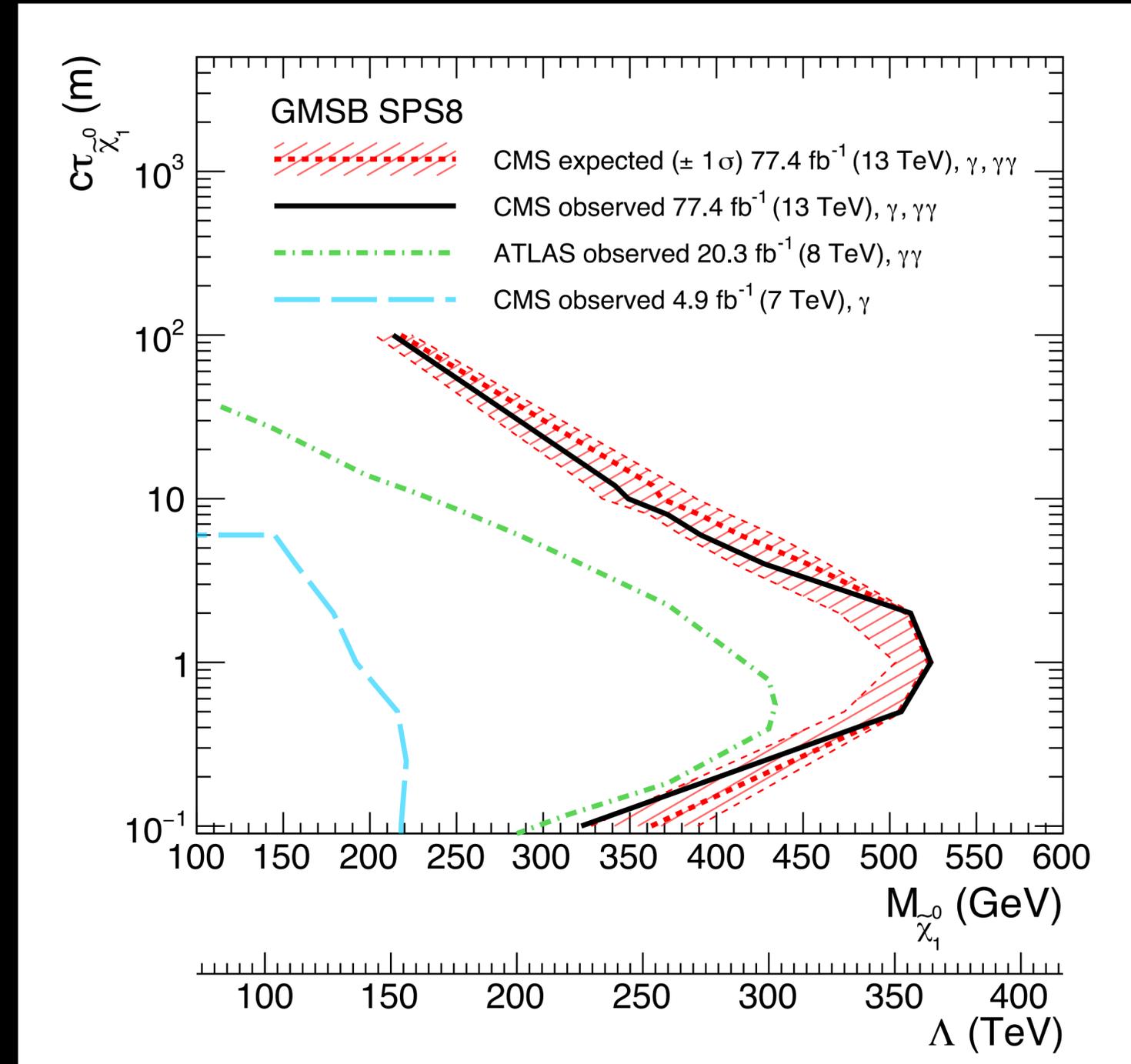
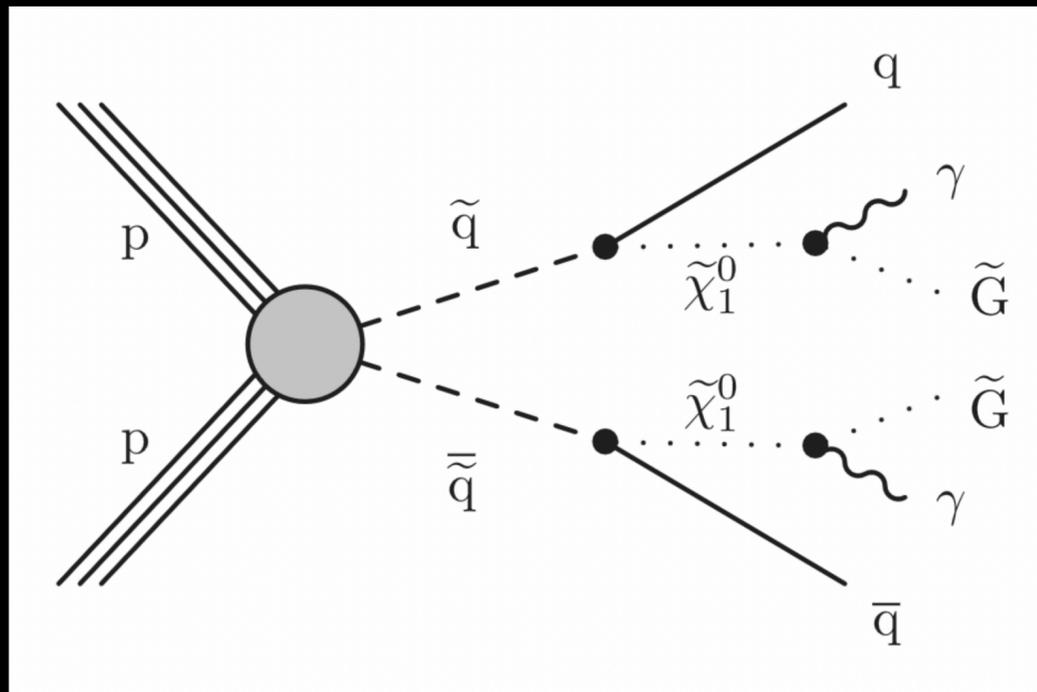
Recent CMS result (Sept. 2023) sets limits in the context of a particular SUSY model

[arXiv:2309.16823](https://arxiv.org/abs/2309.16823)

Delayed or non-pointing photons

Single photons or pairs of photons that enter the electromagnetic calorimeter (Ecal) at unusual angles

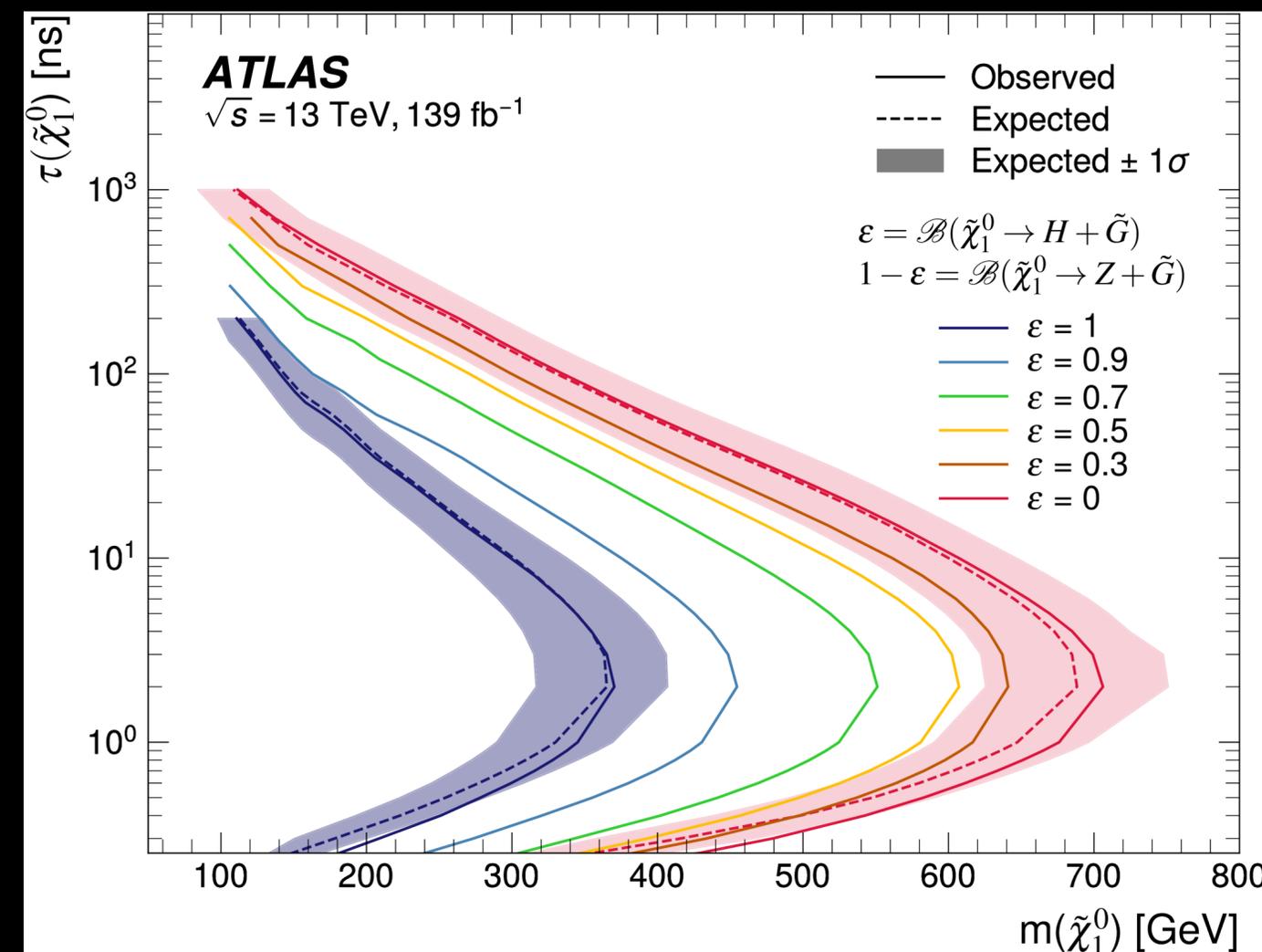
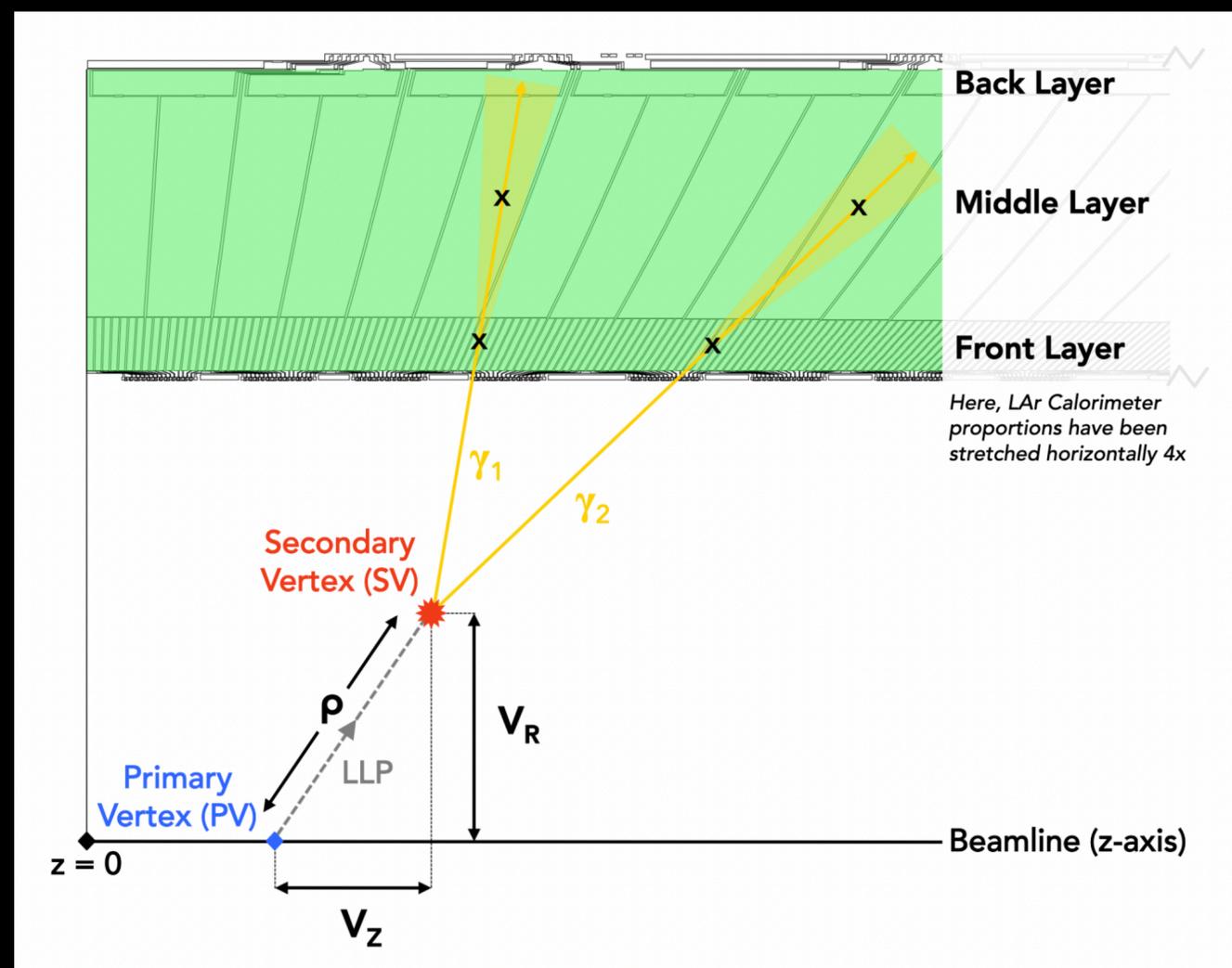
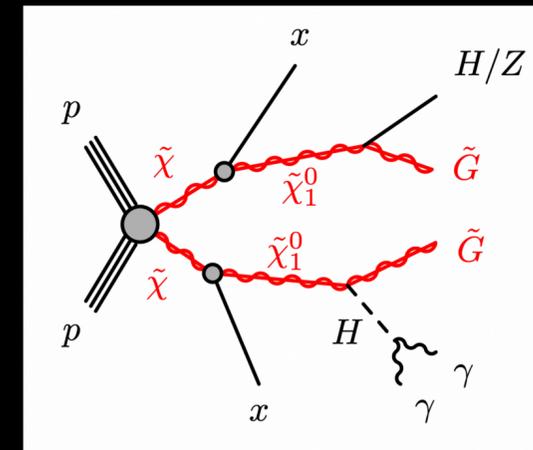
- Benchmark gauge-mediated SUSY-breaking scenario with long-lived neutralino
- Combination of standard photon and dedicated triggers looking for Ecal deposits with an elliptical shape
- 2019 result from CMS with 77.4/fb at 13 TeV



CMS, 13 TeV
PRD 100, 112003 (2019)

Delayed or non-pointing photons

Recent ATLAS search for displaced / delayed photons or electrons from Higgs or Z decays, where the H or Z is itself the decay product of an LLP (in the context of a gauge-mediated SUSY-breaking model)

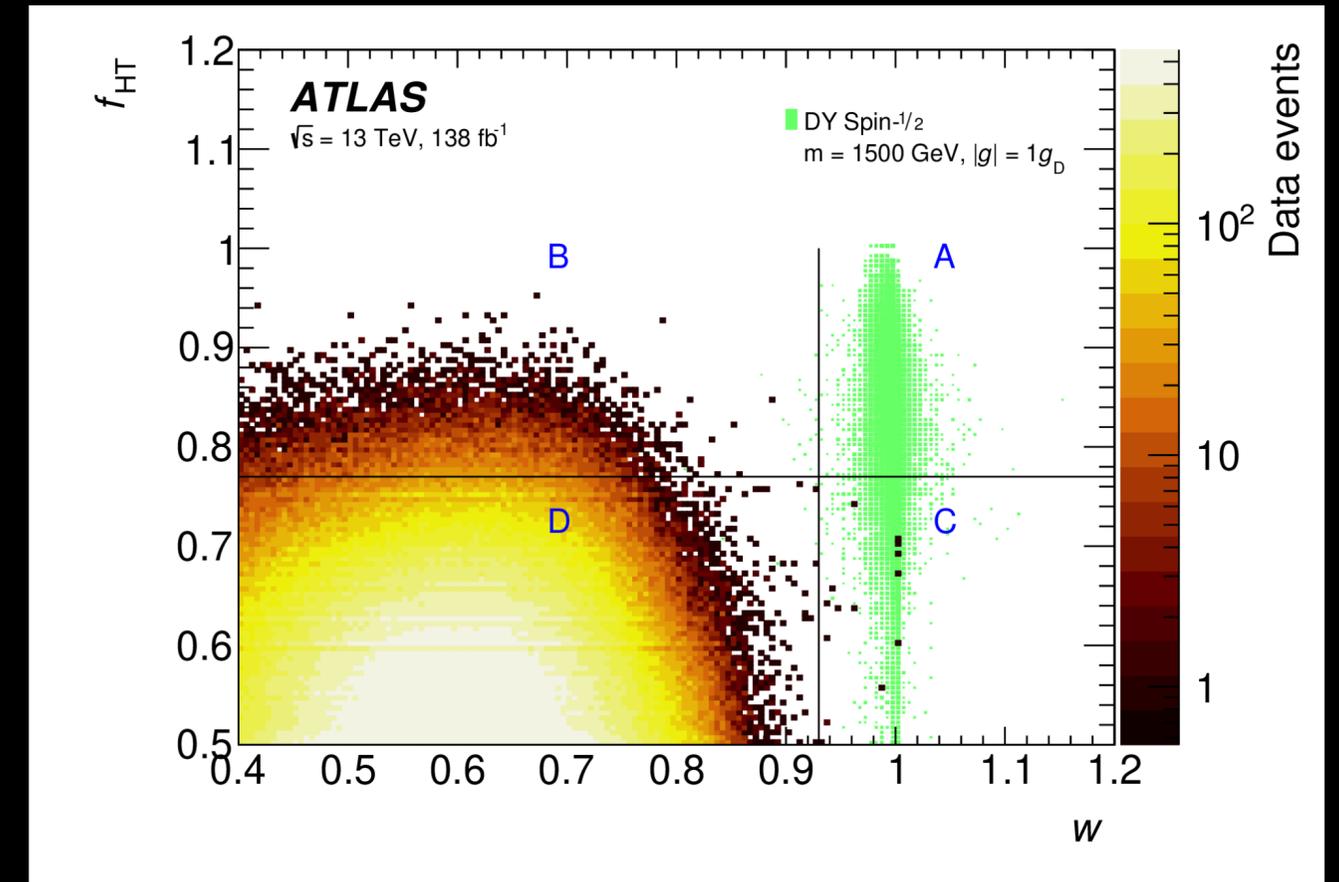
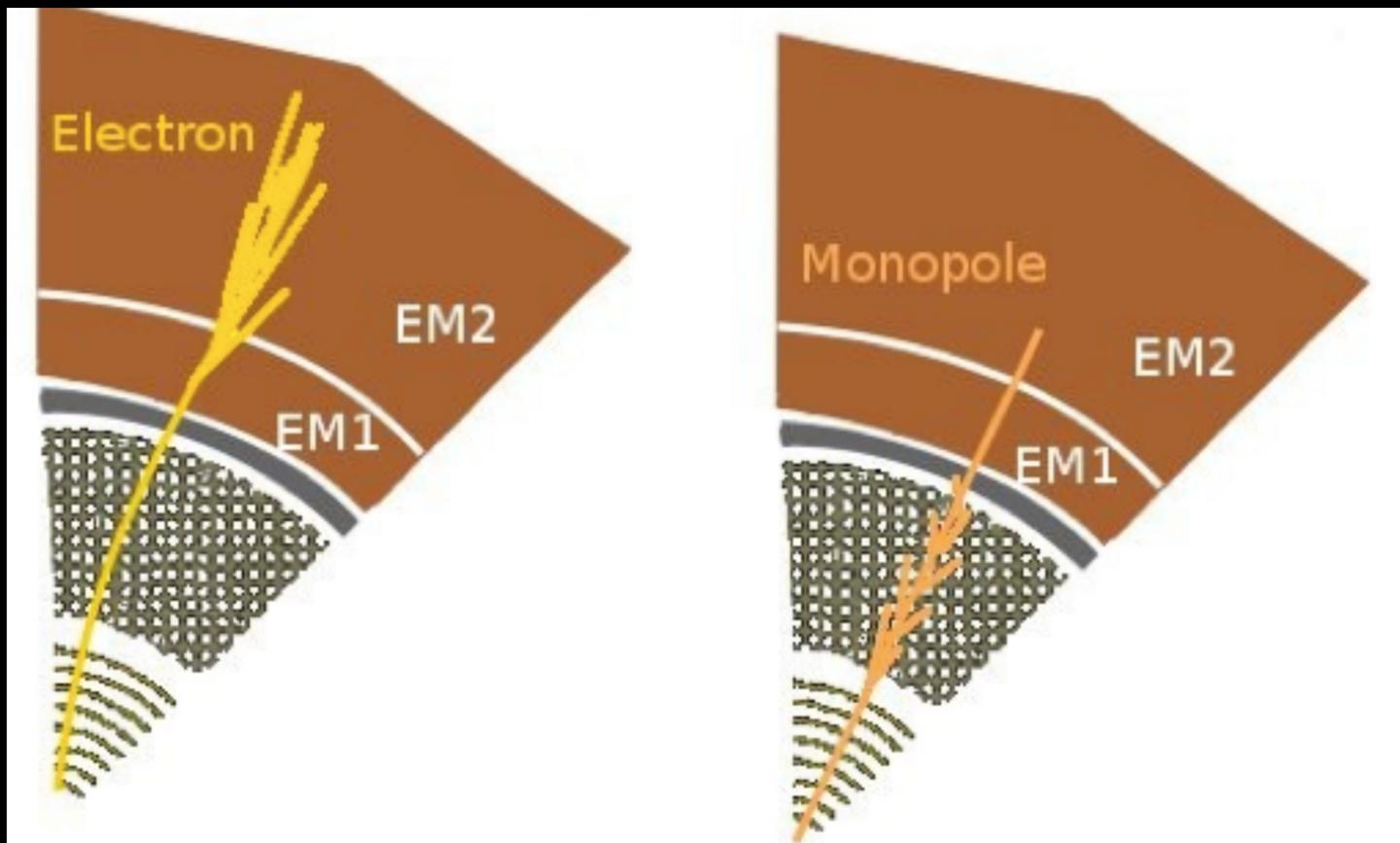


ATLAS: [PRD 108 \(2023\) 1, 012012](https://arxiv.org/abs/2208.04610)

Quasi-stable charged particles

A new high-electric-charge object would sort of behave the opposite of an electron in ATLAS — would leave a road of high-threshold hits in the transition radiation tracker and very little shower in the electromagnetic calorimeter and wouldn't curve in the same way in the magnetic field

Example: A magnetic monopole with charge 68.5 times the electron charge (Dirac monopole argument)



ATLAS [[JHEP 11 \(2023\) 112](#)] search, Aug. 2023, for high-electric-charge objects

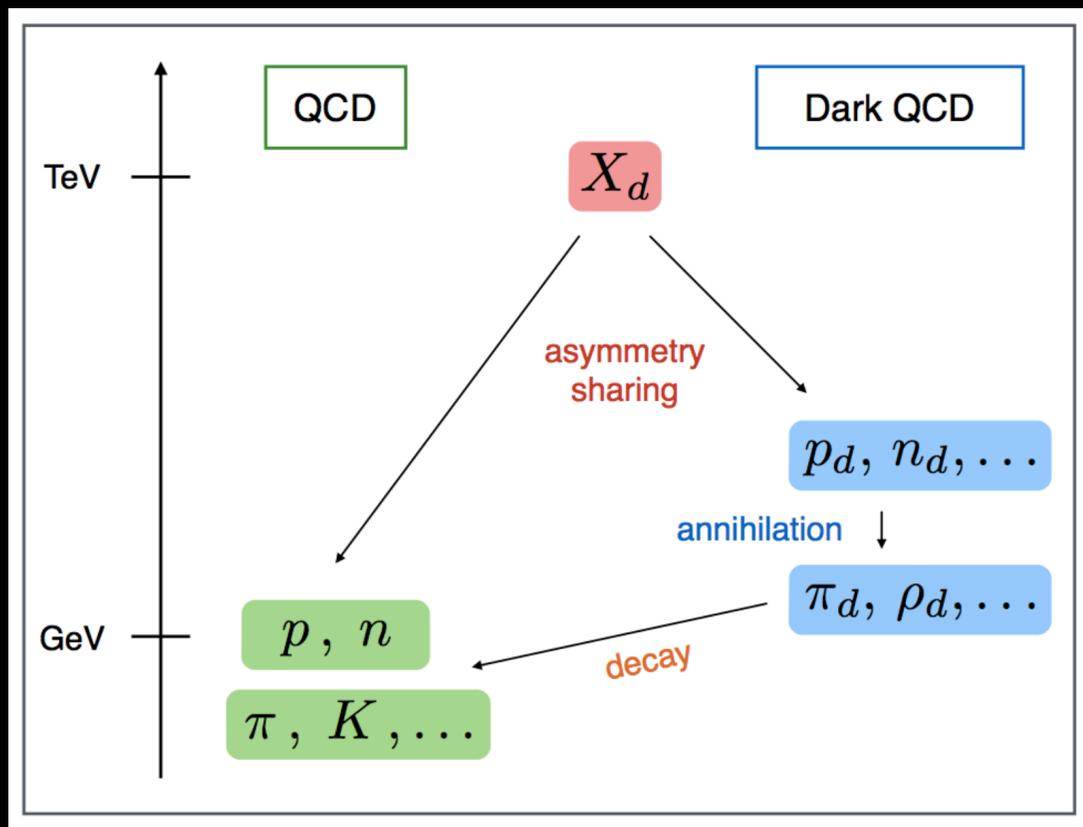
See also CMS [[EXO-16-036](#)] and LHCb [[EPJC \(2015\) 75: 595](#)]

Other BSM charged particles can move much at speeds much slower than the speed of light or leave high ionization

ID them via atypical ways that the charged particle interacts with the detector material

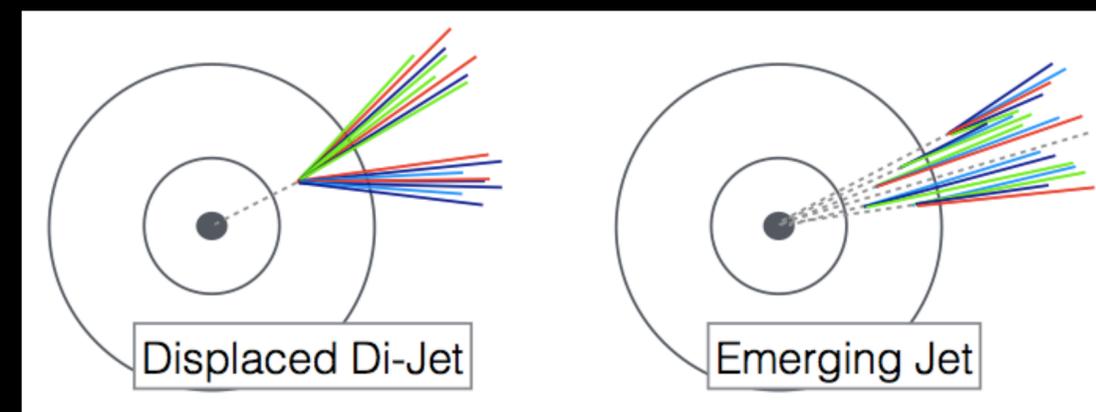
High-multiplicity neutral LLPs decaying hadronically: Emerging jets

JHEP (2015) 2015: 59

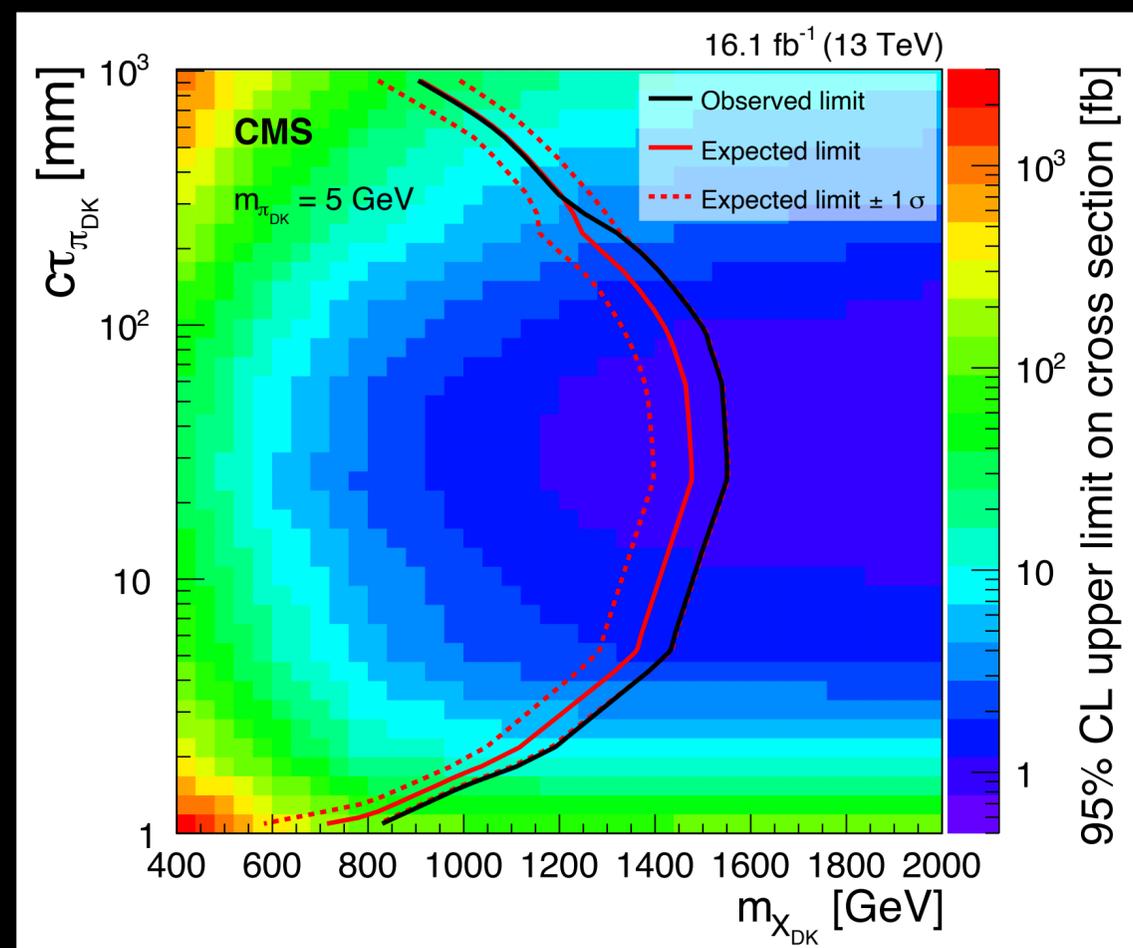
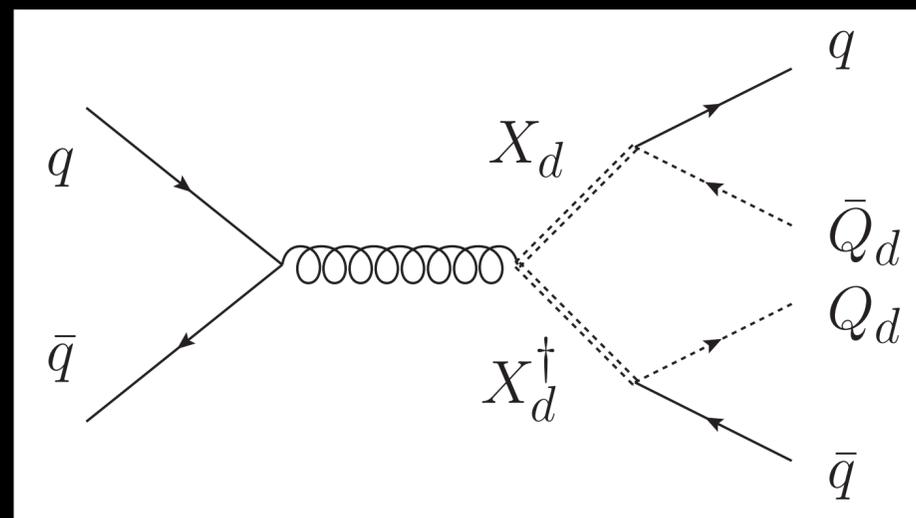


Hidden-valley-style dark sector with complex dynamics:

Dark quarks hadronize first in the hidden sector and, e.g., long-lived dark pions then decay to the visible sector via multiple displaced vertices of varying displacements within the same jet object



Thus, this is **neither prompt jets nor a pair of displaced jets** pointing to the same displaced vertex, but **emerging jets**



First results for this dark QCD model at the LHC from CMS — ATLAS search in progress

JHEP 02 (2019) 179

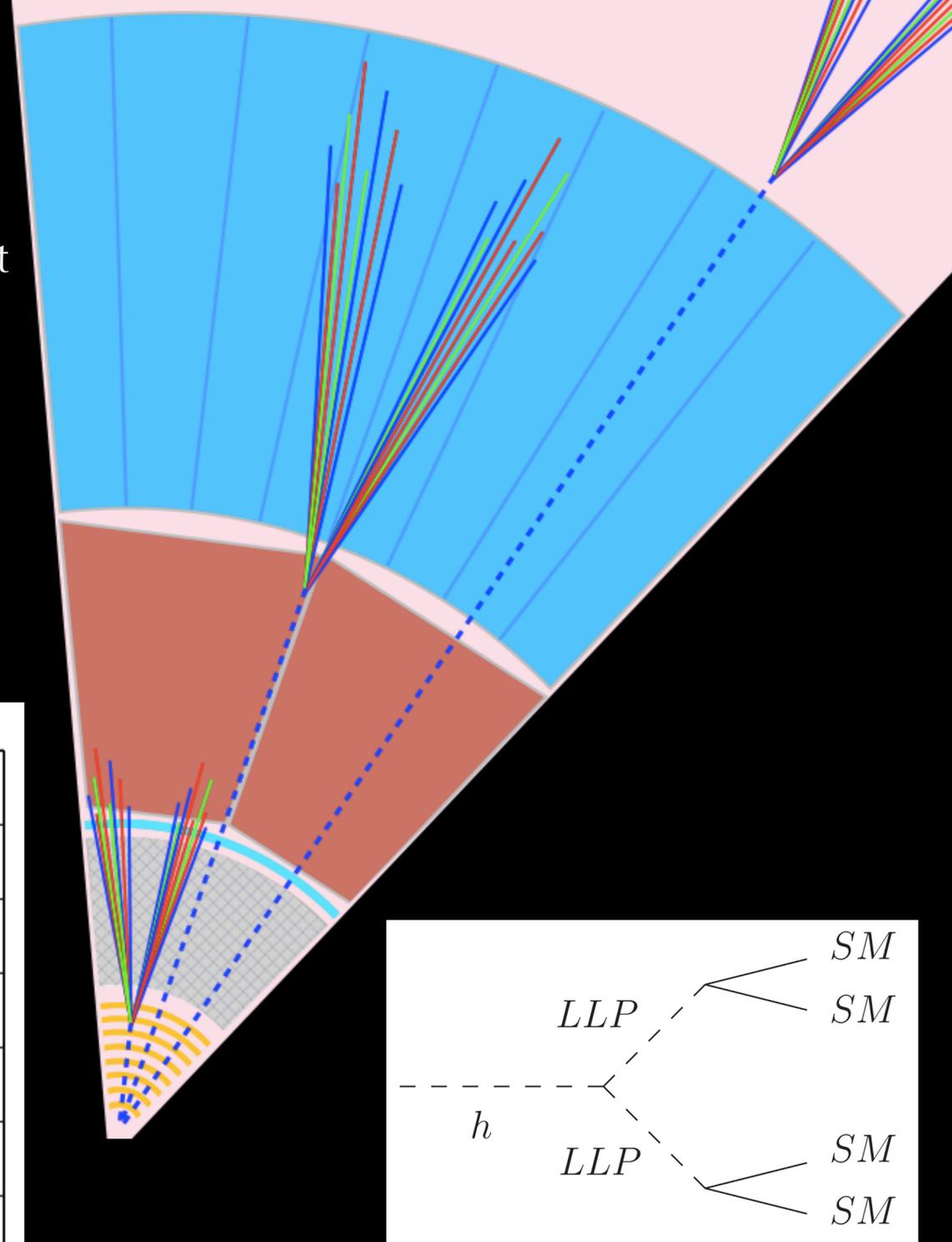
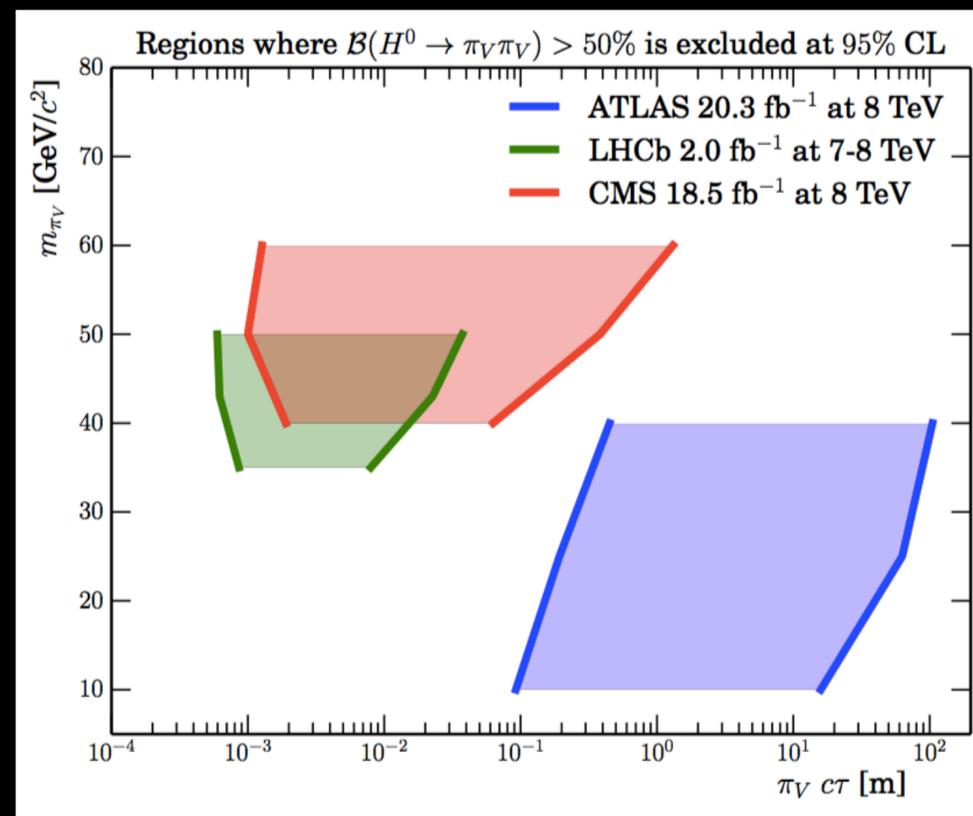
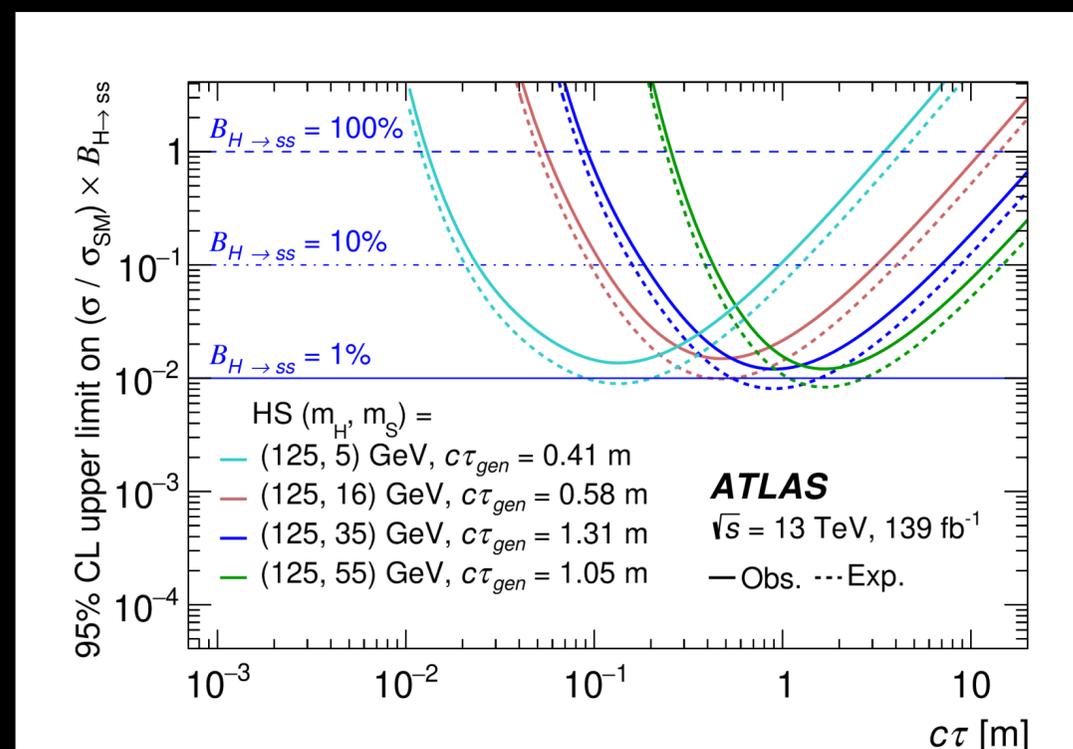
Neutral **LLPs** decaying to hadronic jets

Hadronic LLP decays in different parts of the detectors require different search strategies

- Inner tracker \rightarrow Look for displaced multi-track vertices
- Calorimeters \rightarrow Look for large $E_{\text{Had}} / E_{\text{EM}}$
- Outer muon system \rightarrow Look for MS vertex

ATLAS, CMS, and LHCb use slightly different and complementary methods to isolate such potential signals

ATLAS, March 2022: [JHEP 06 \(2022\) 005](#)



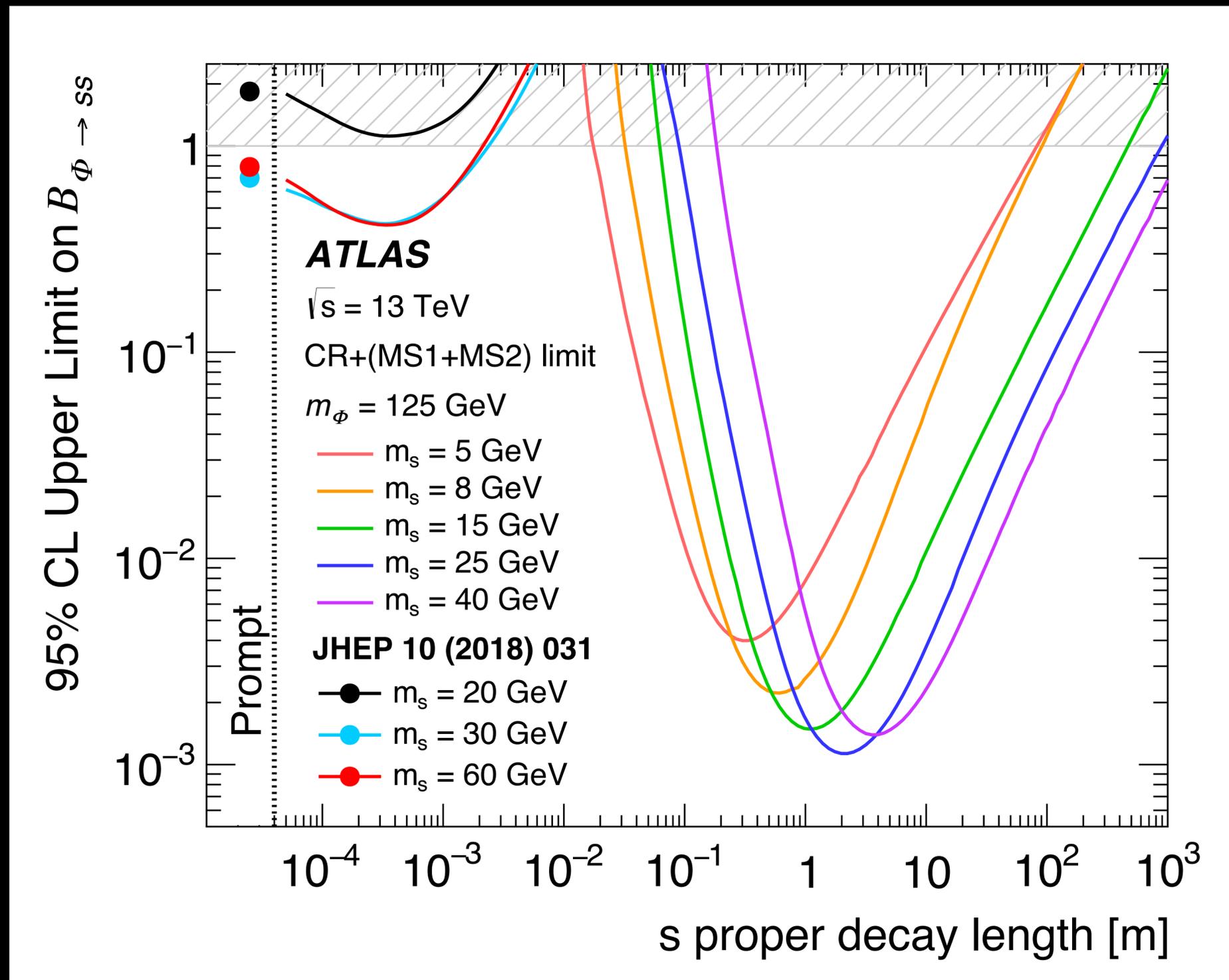
One benchmark scenario:
 $h_{125} \rightarrow 2 \times \text{LLP} \rightarrow \text{jets}$

See also:

CMS: [PRD 104 \(2021\) 1, 012015](#)

LHCb: [EPJC 77 \(2017\) 812](#)

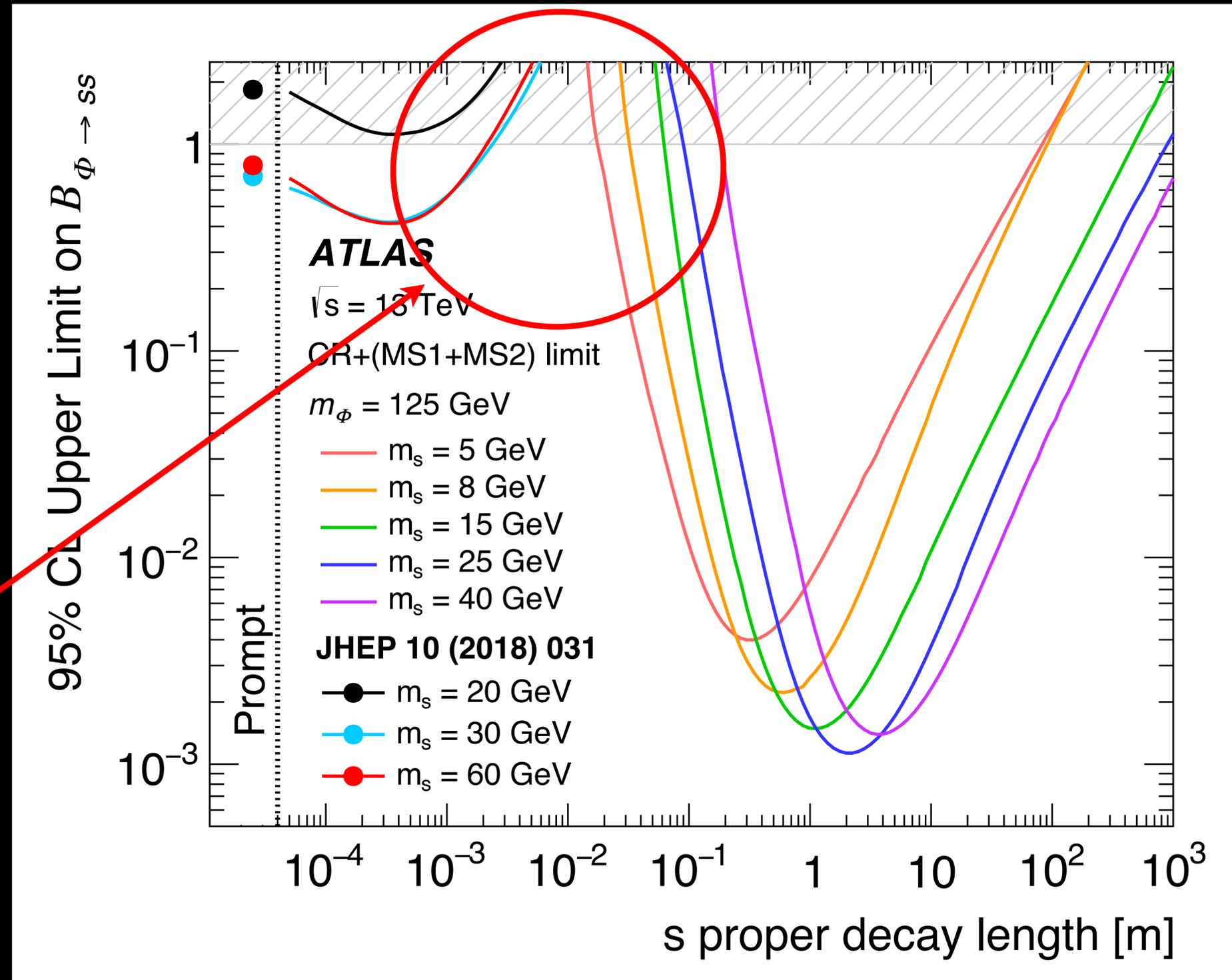
Where do prompt and long-lived searches meet?



2018

JHEP 10 (2018) 031

Where do prompt and long-lived searches meet?

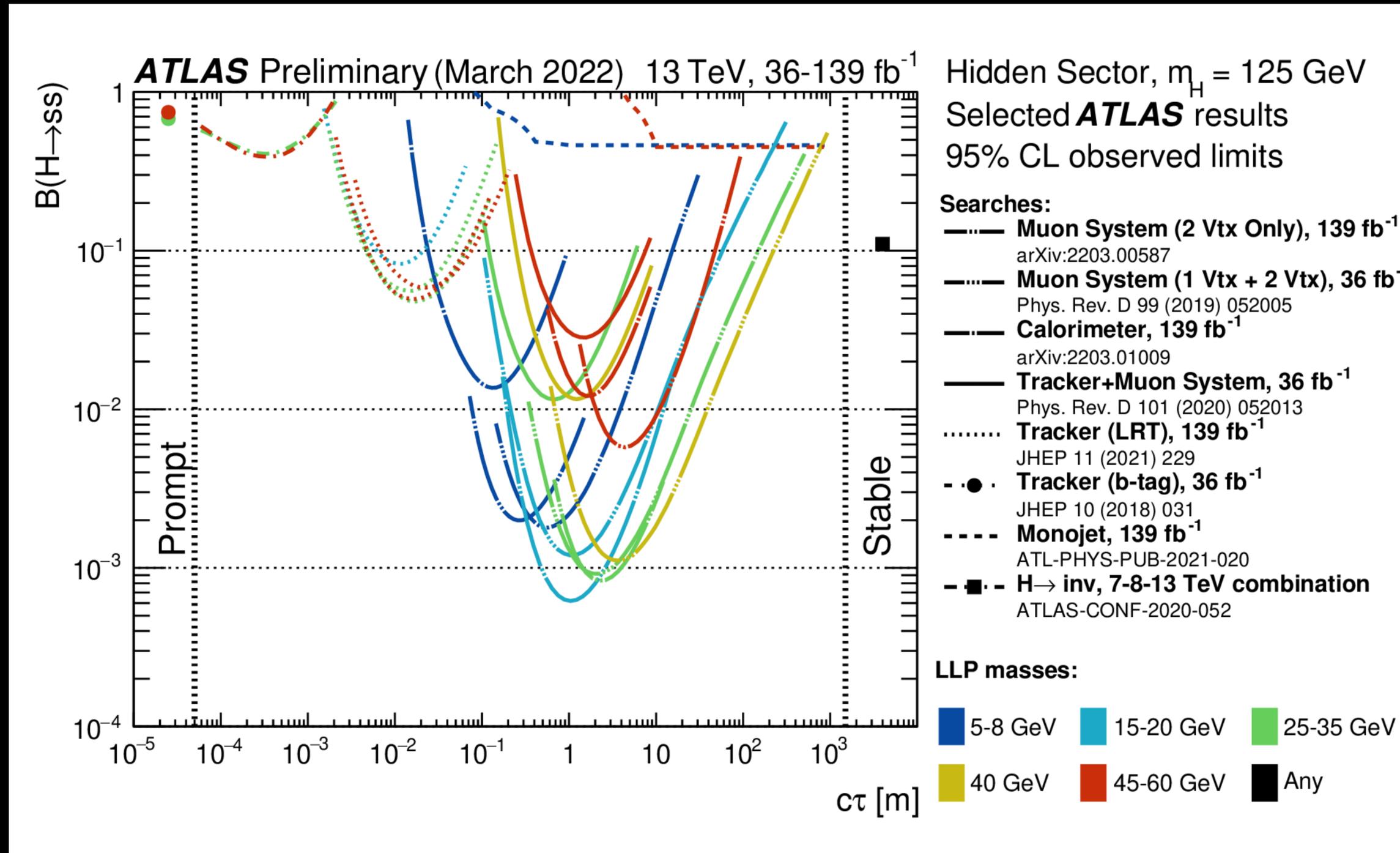


A discovery could be hiding here!

2018

JHEP 10 (2018) 031

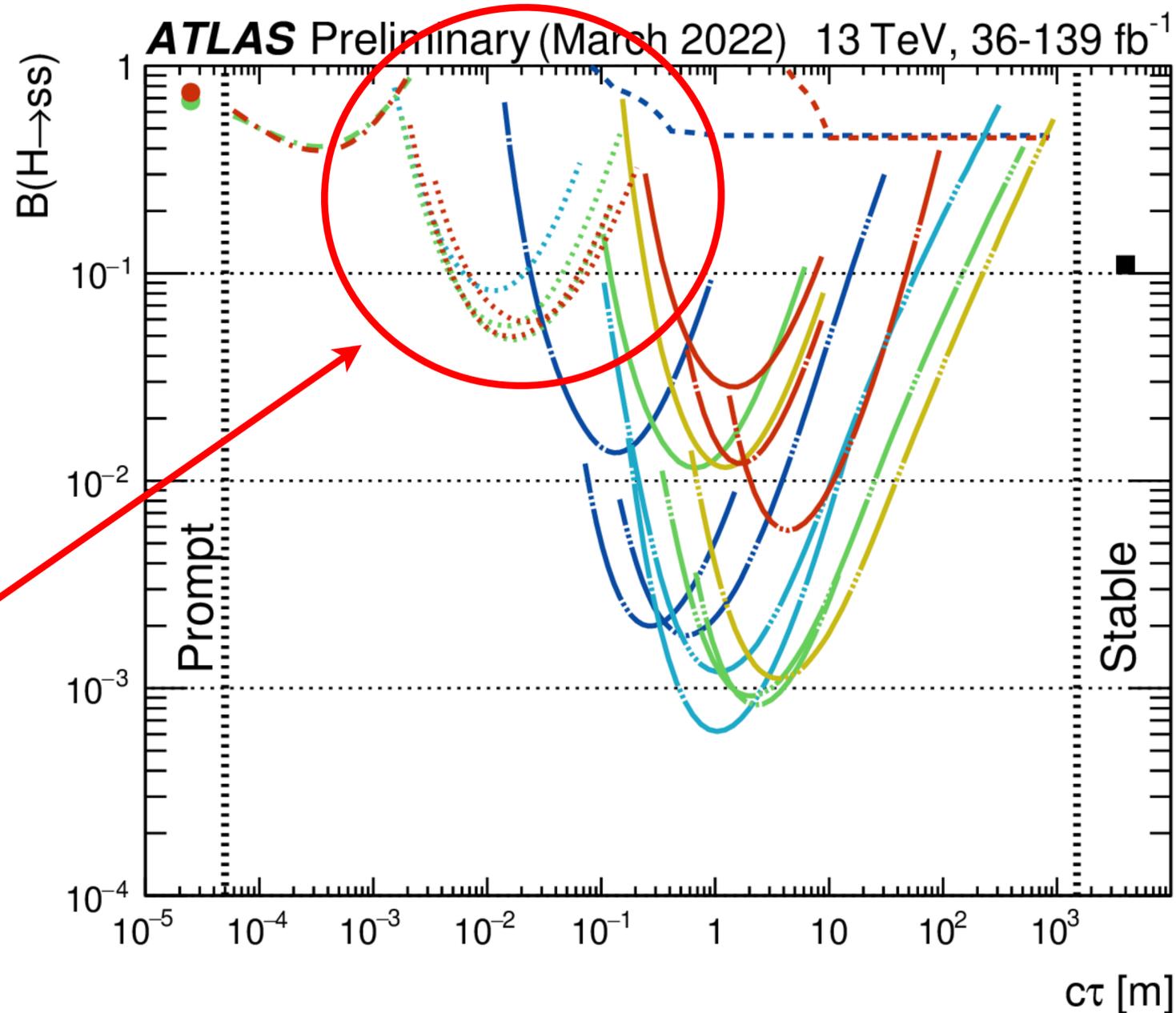
Where do prompt and long-lived searches meet?



2022

ATLAS LLP summary plots

Where do prompt and long-lived searches meet?

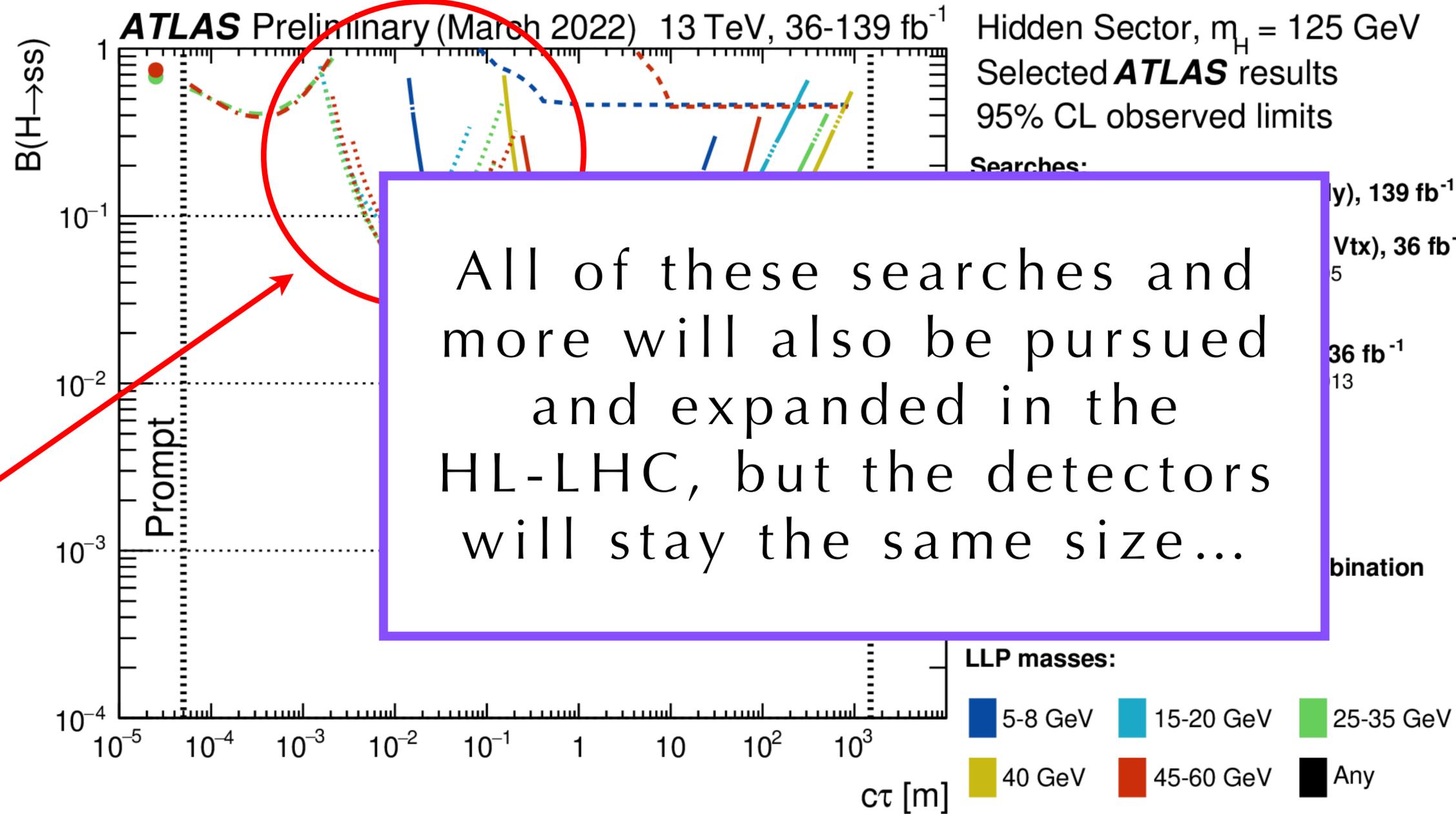


2022

Starting to plug this hole!

ATLAS LLP summary plots

Where do prompt and long-lived searches meet?

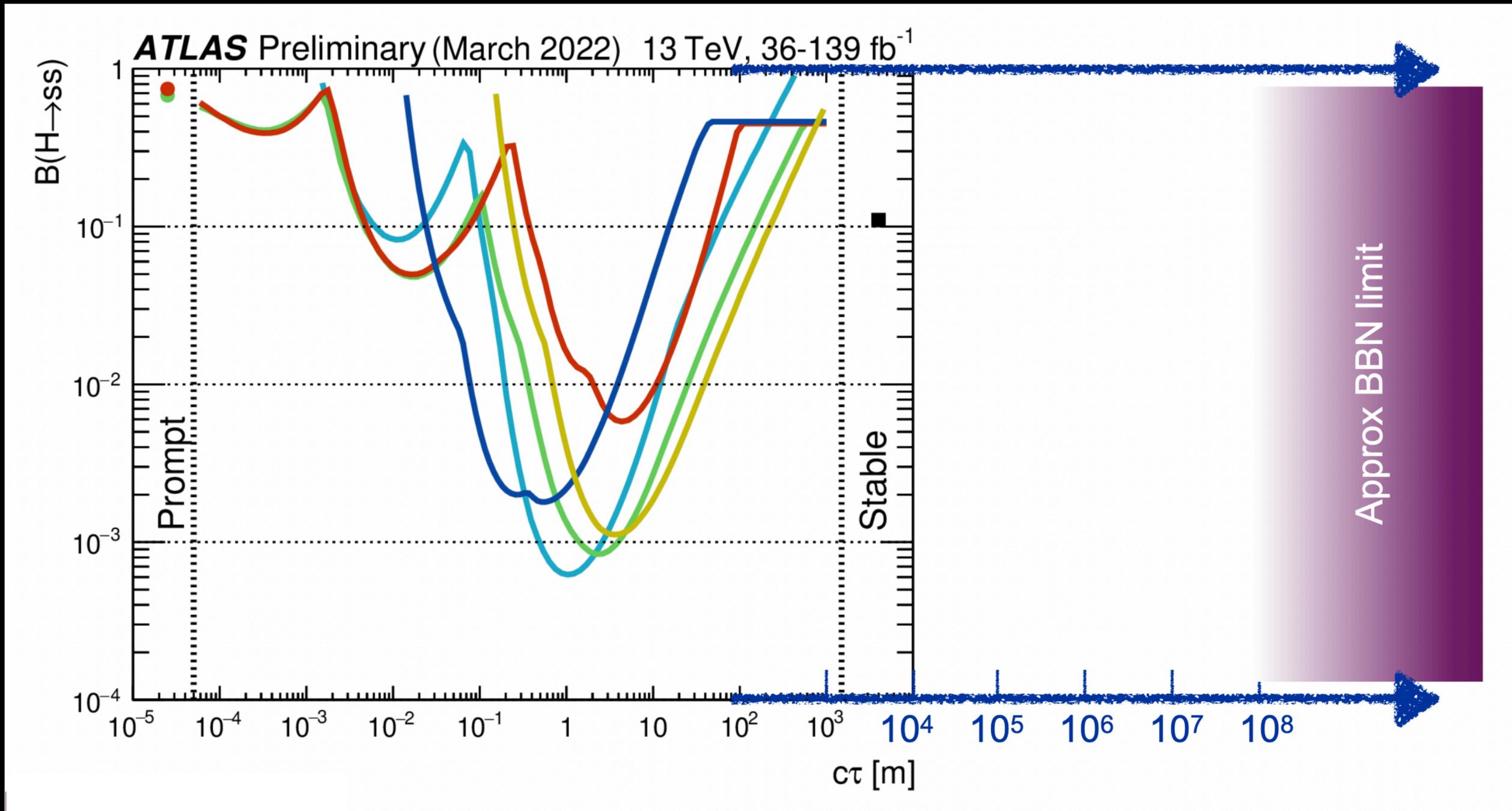


All of these searches and more will also be pursued and expanded in the HL-LHC, but the detectors will stay the same size...

2022

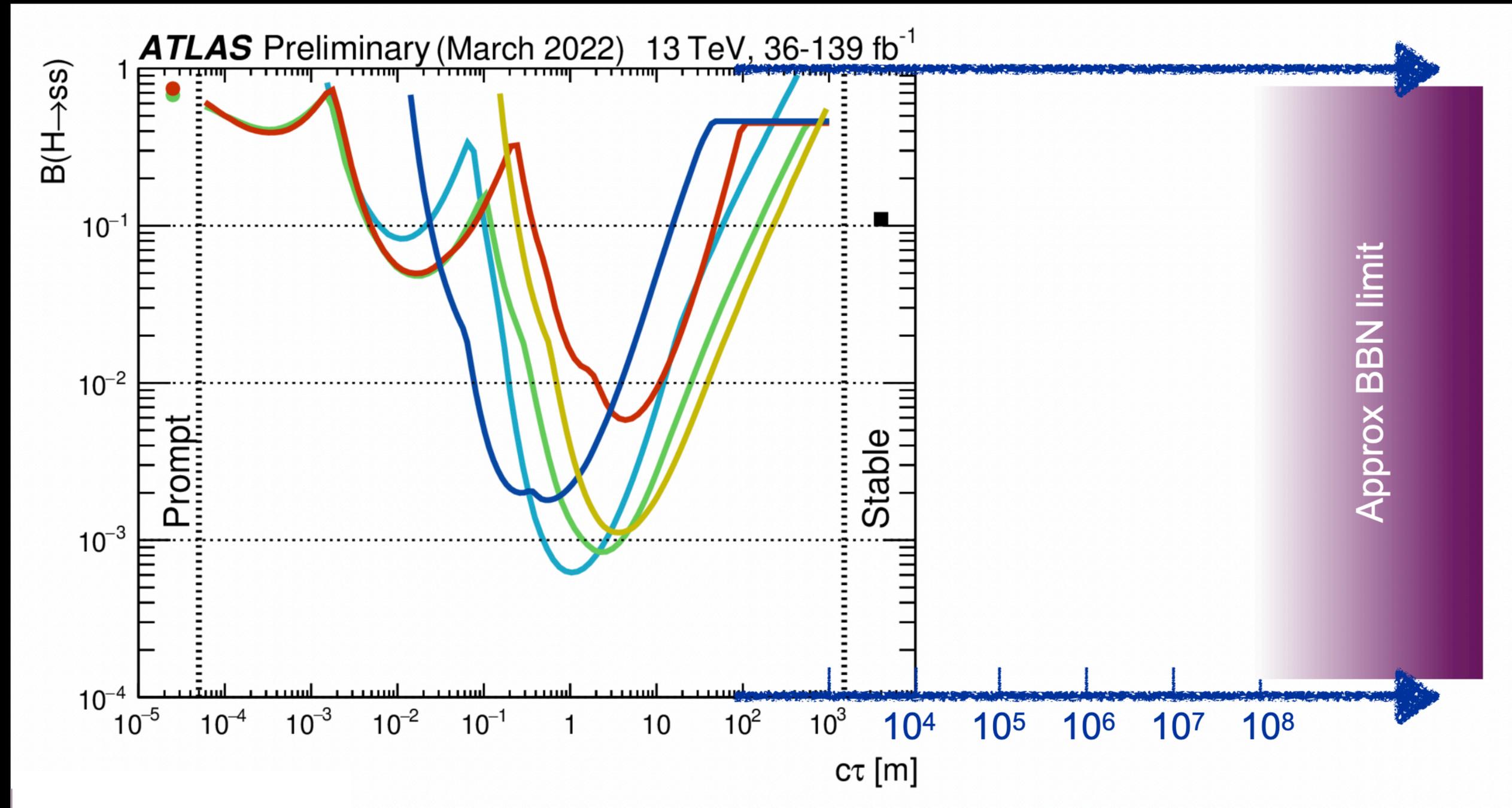
ATLAS LLP summary plots

Very long-lived particles at the LHC



L. Corpe

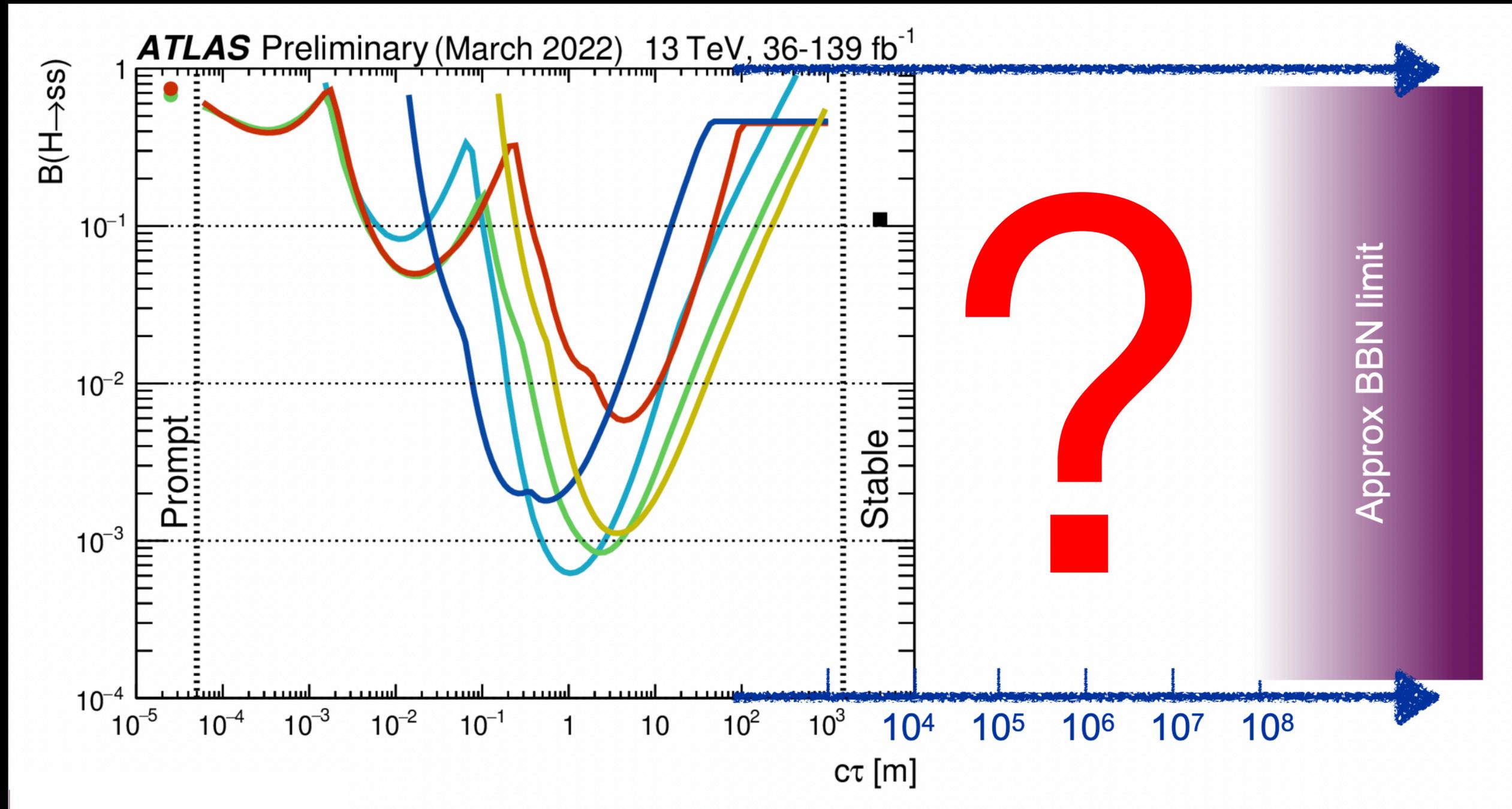
Very long-lived particles at the LHC



L. Corpe

Outer edge of ATLAS

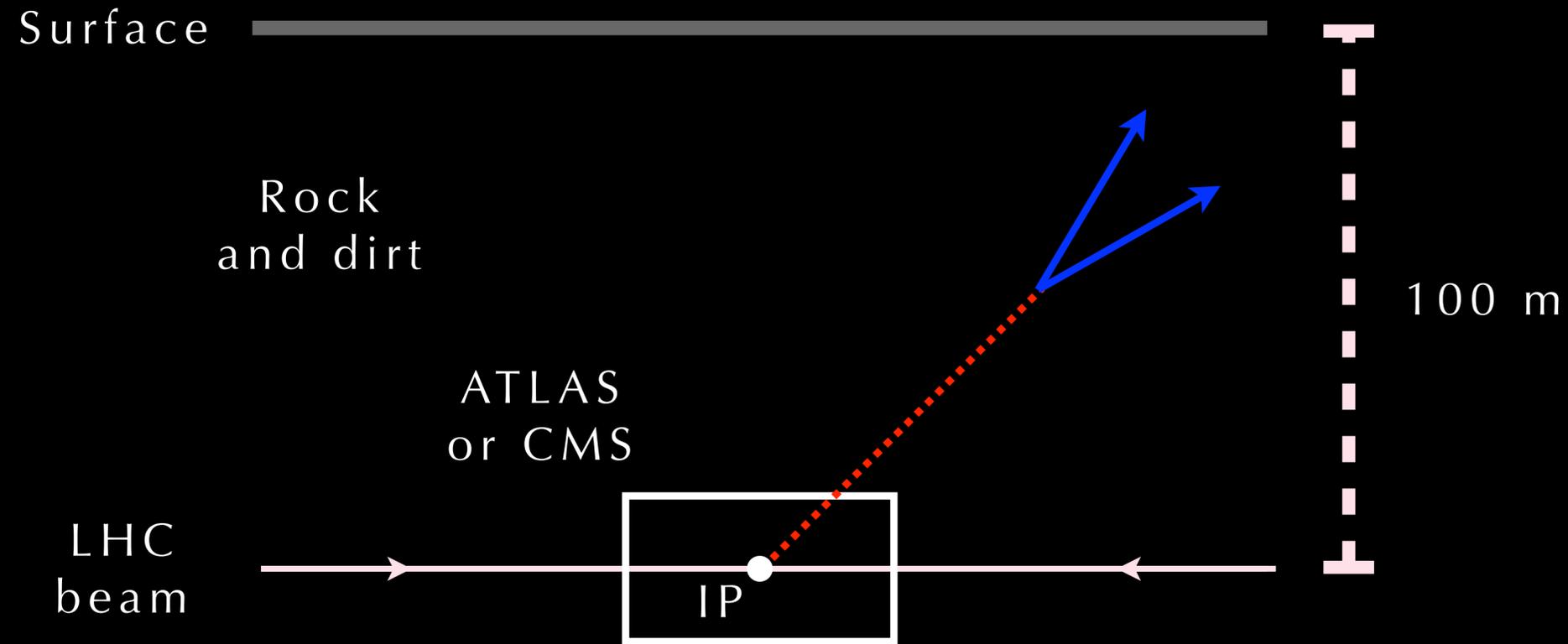
Very long-lived particles at the LHC



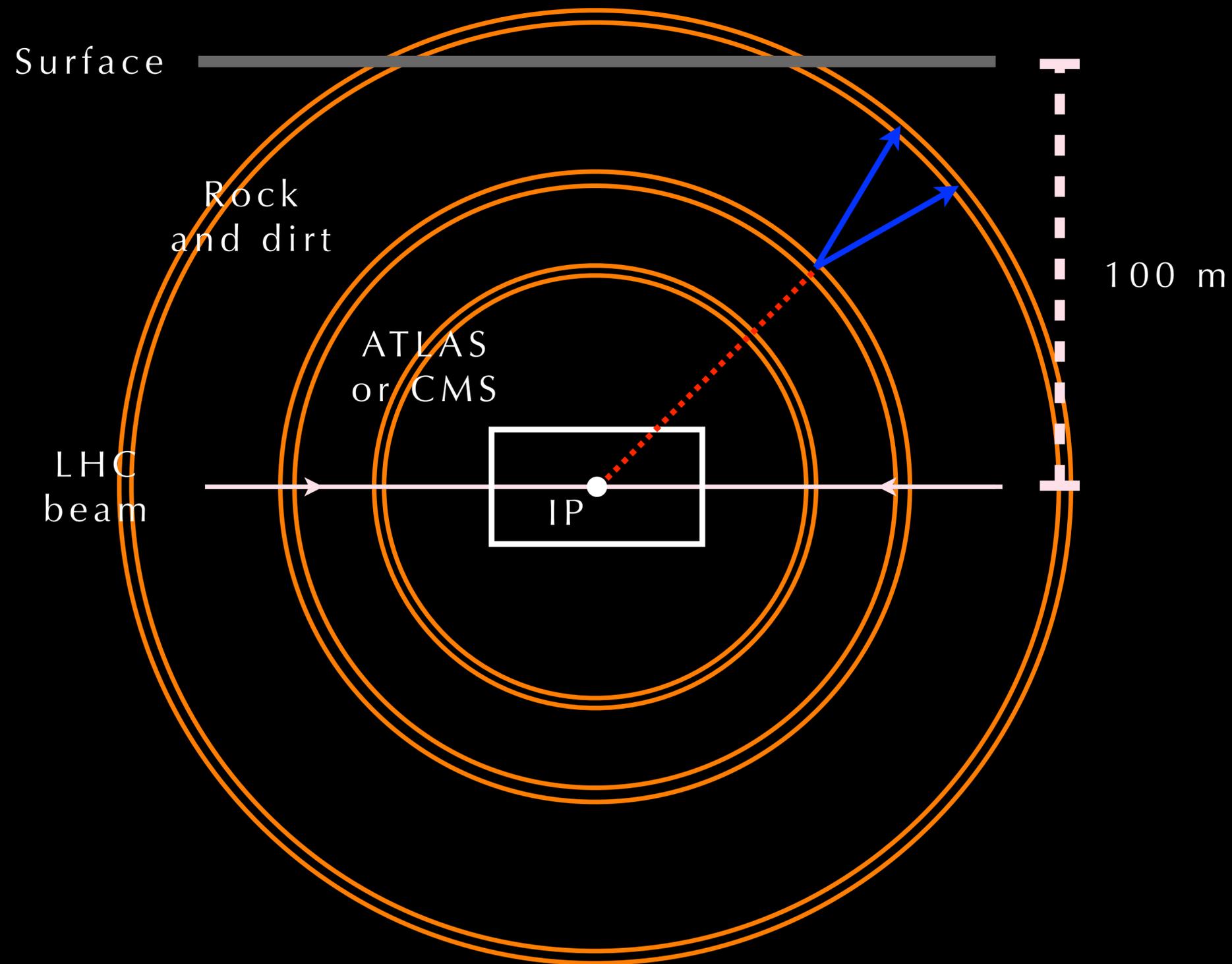
Outer edge of ATLAS

L. Corpe

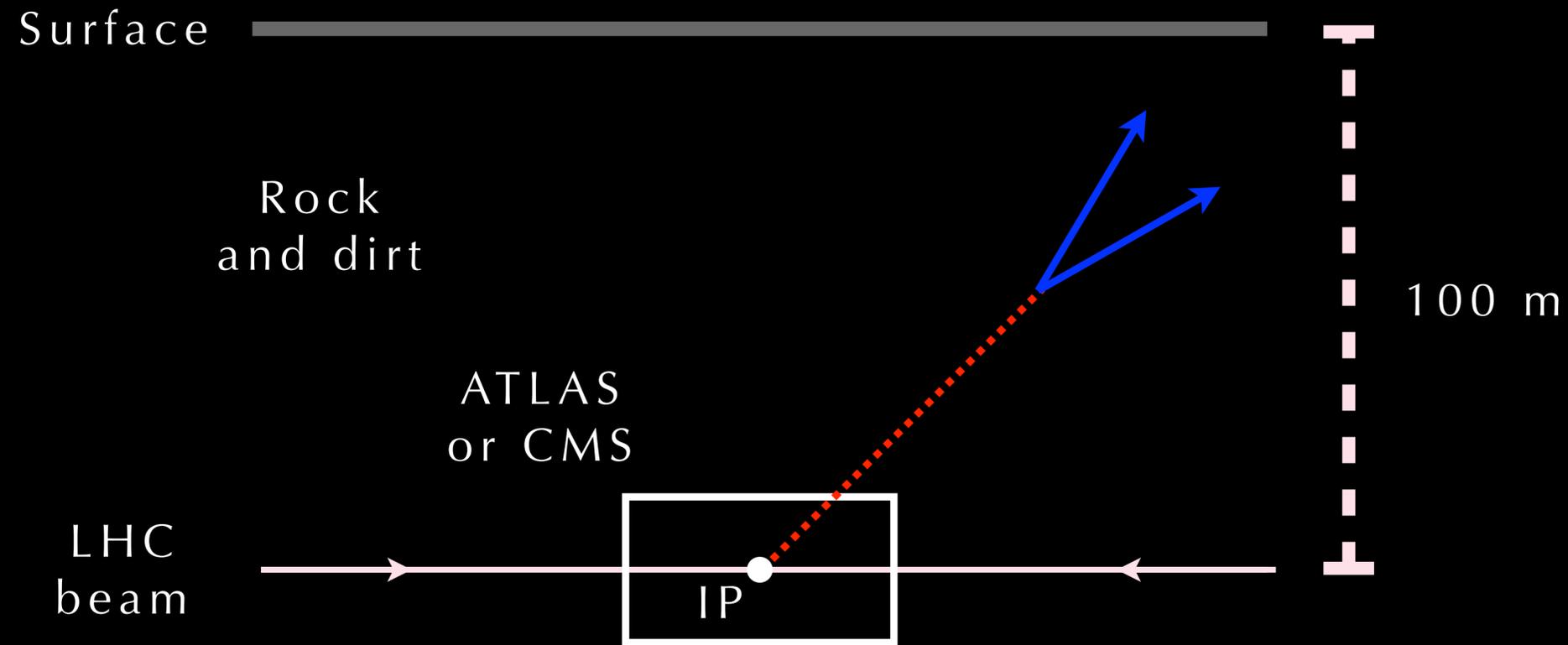
Dedicated detectors for very long-lived particles at the LHC



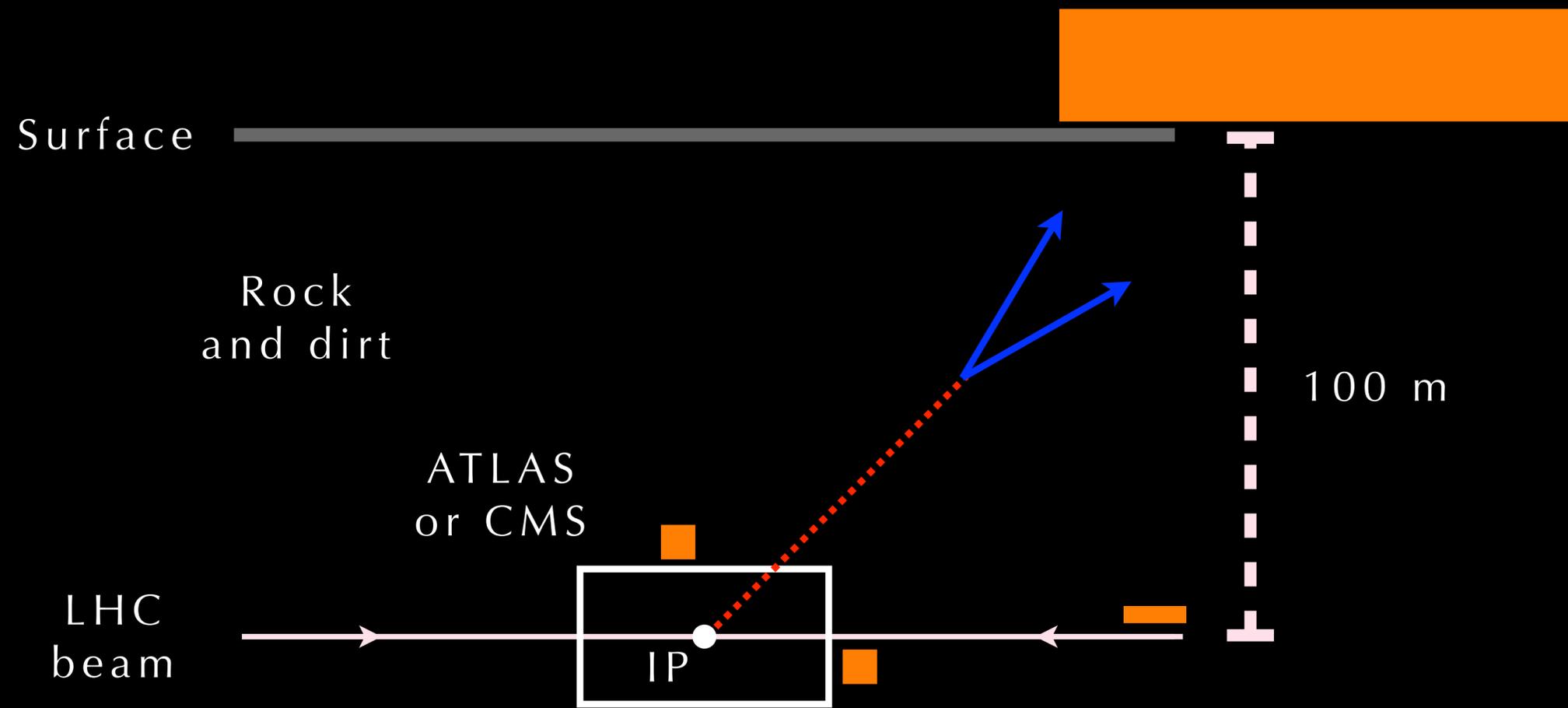
Dedicated detectors for very long-lived particles at the LHC



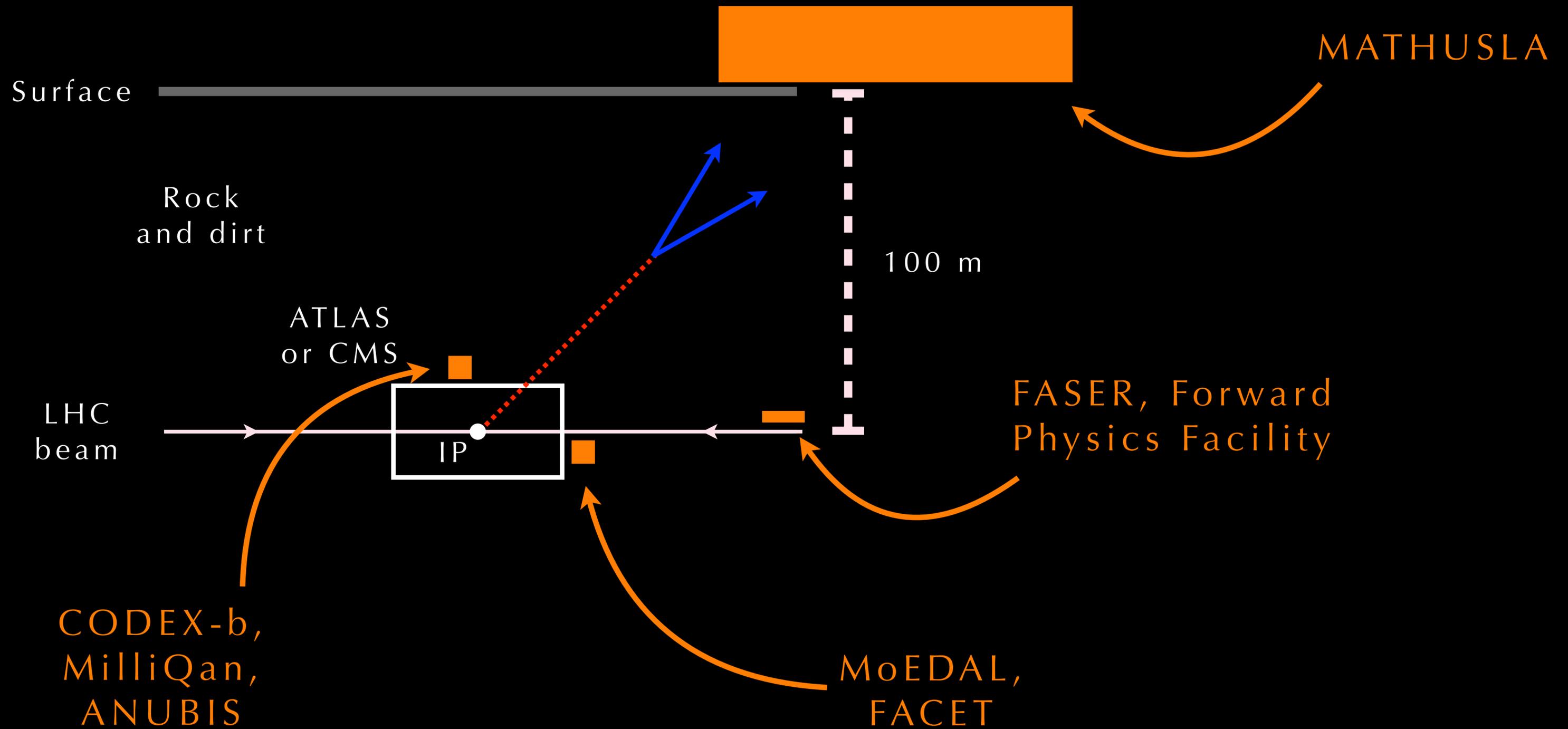
Dedicated detectors for very long-lived particles at the LHC



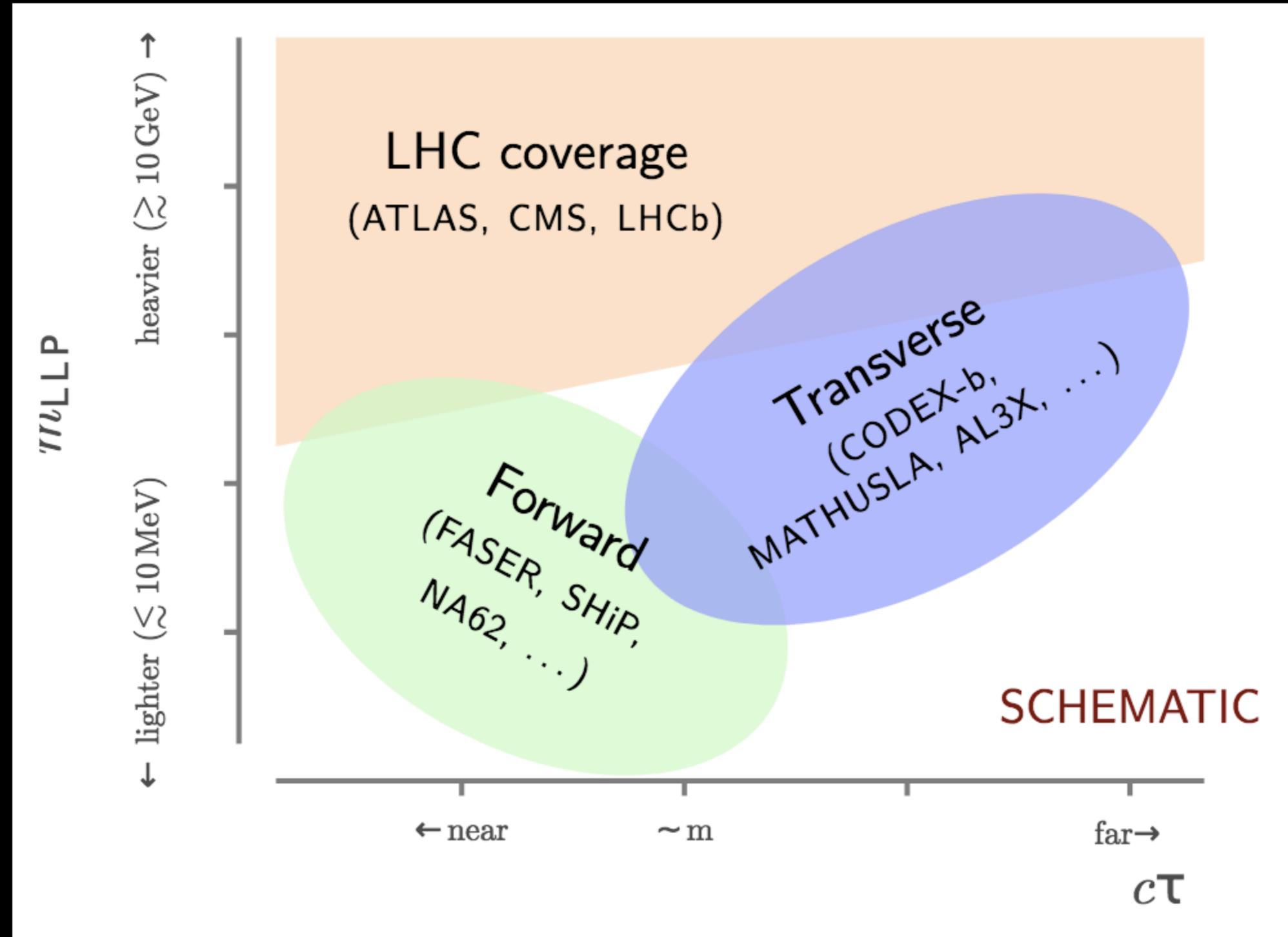
Dedicated detectors for very long-lived particles at the LHC



Dedicated detectors for very long-lived particles at the LHC



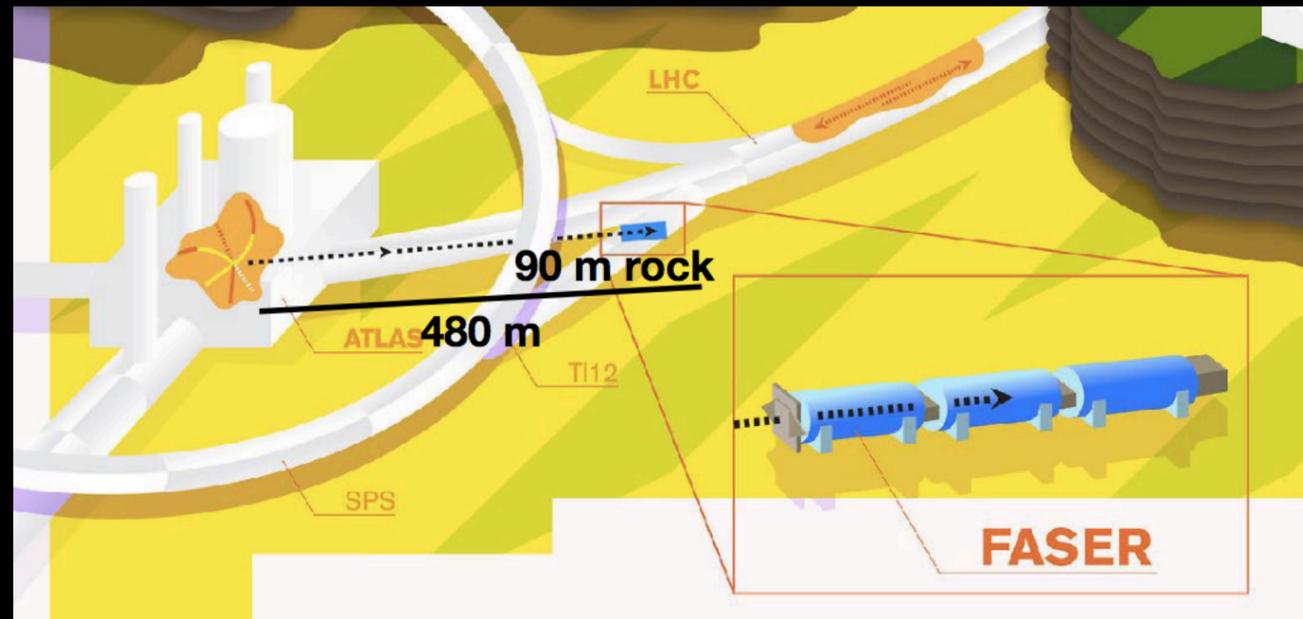
Dedicated detectors for very long-lived particles at the LHC



P. Ilten

FASER / FASERnu

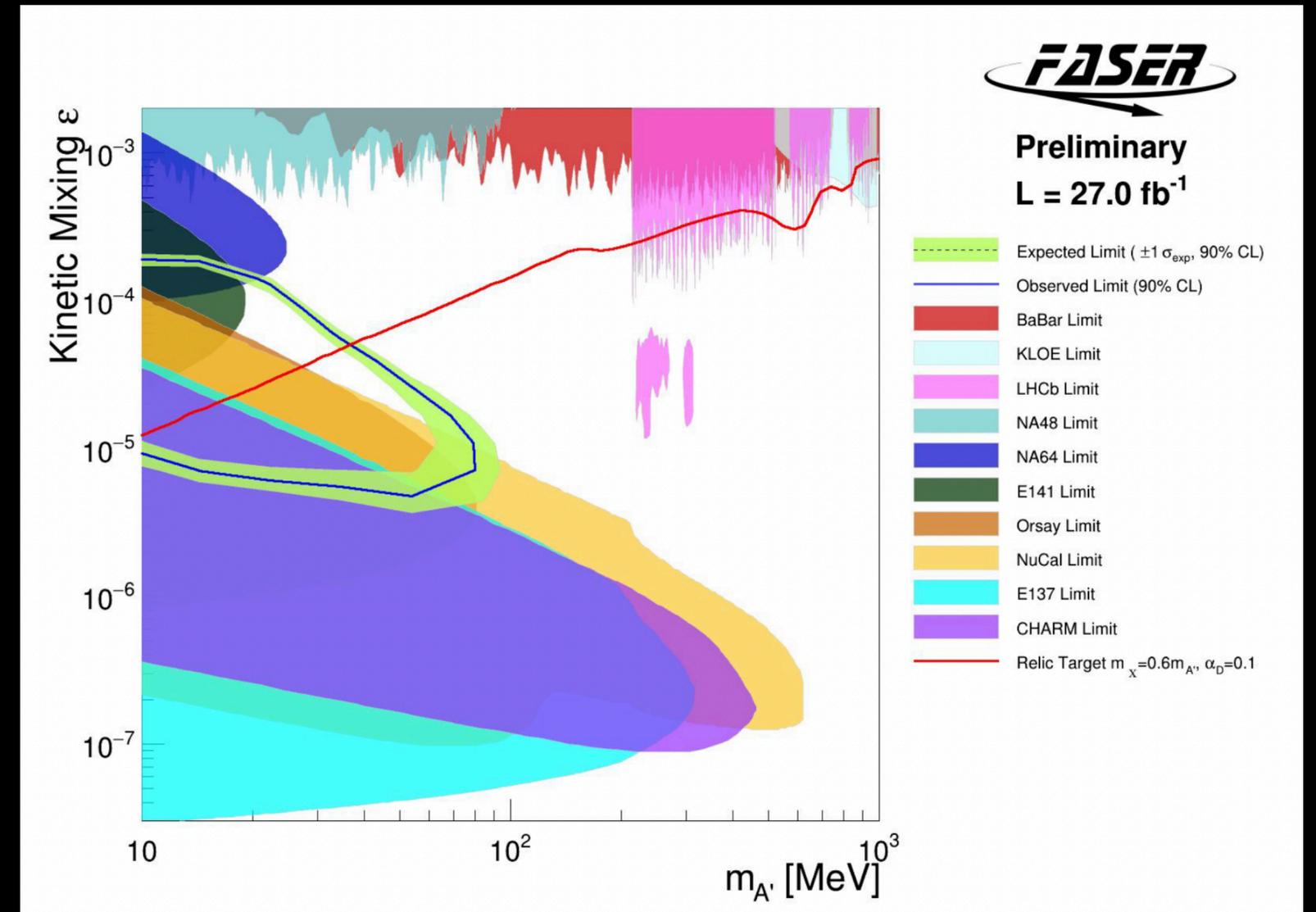
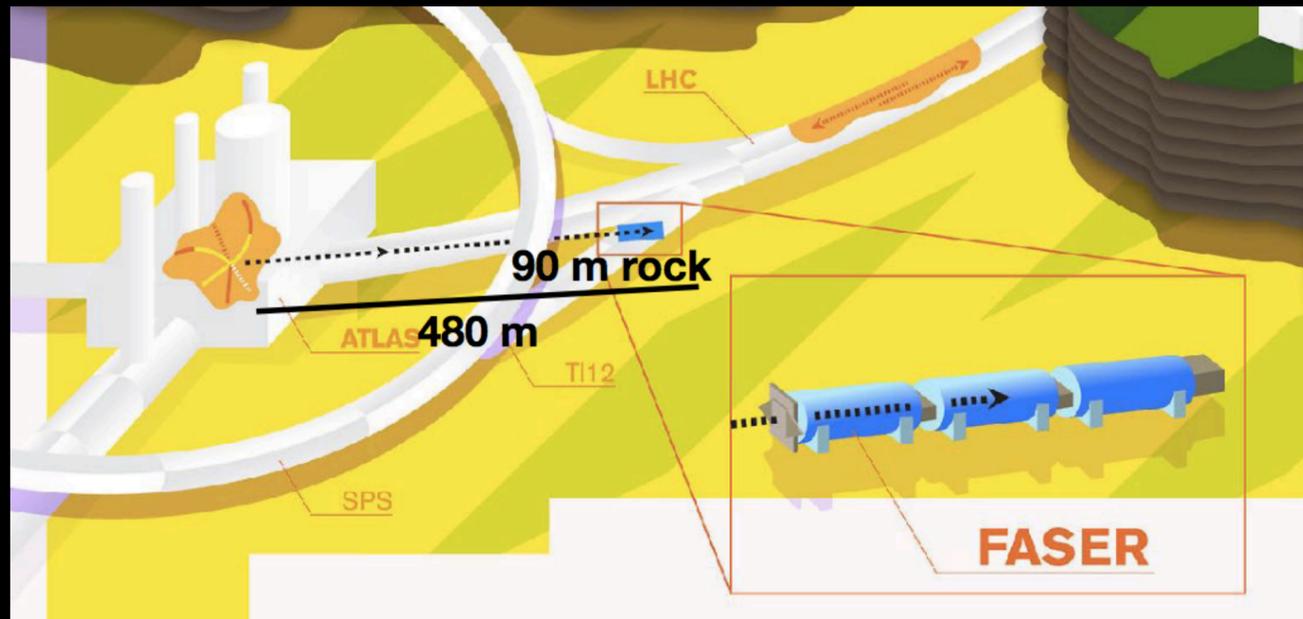
A small-ish (7m-long, 20cm-wide) detector about 0.5 km downstream from ATLAS to catch very far-forward LLPs that ATLAS can't catch



FASER / FASERnu

A small-ish (7m-long, 20cm-wide) detector about 0.5 km downstream from ATLAS to catch very far-forward LLPs that ATLAS can't catch

Was approved and installed in time for LHC Run 3 and has already produced results (here for dark photons)...

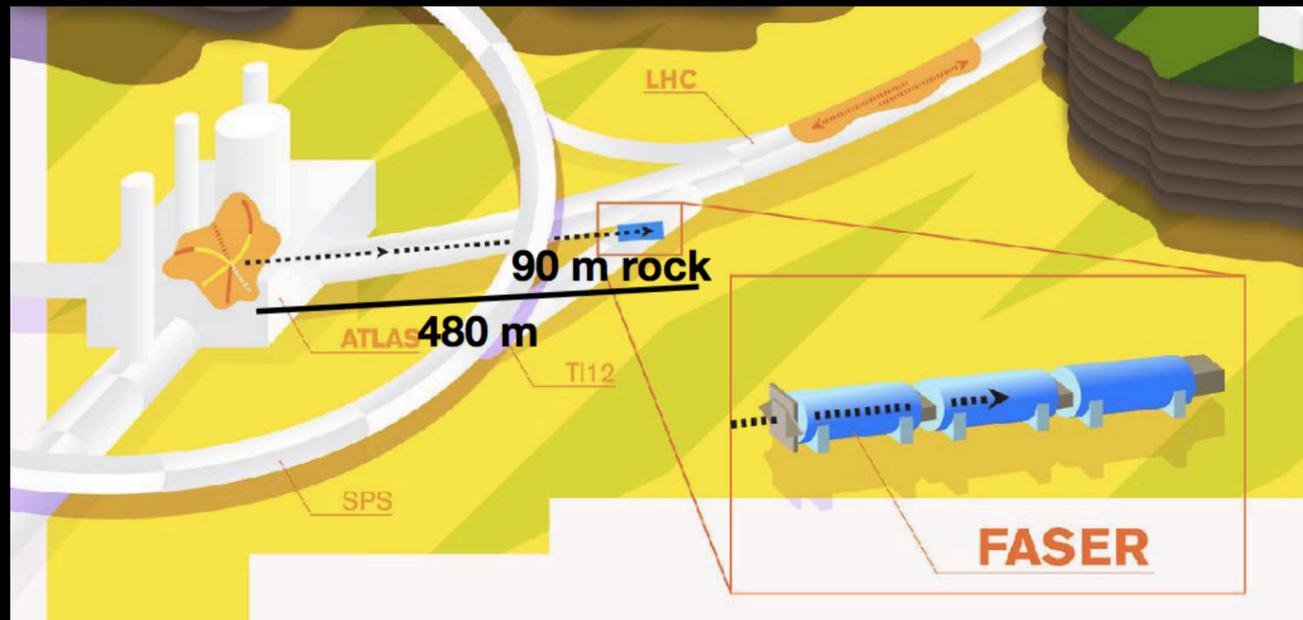


Aug. 2023: [arXiv:2308.05587](https://arxiv.org/abs/2308.05587)

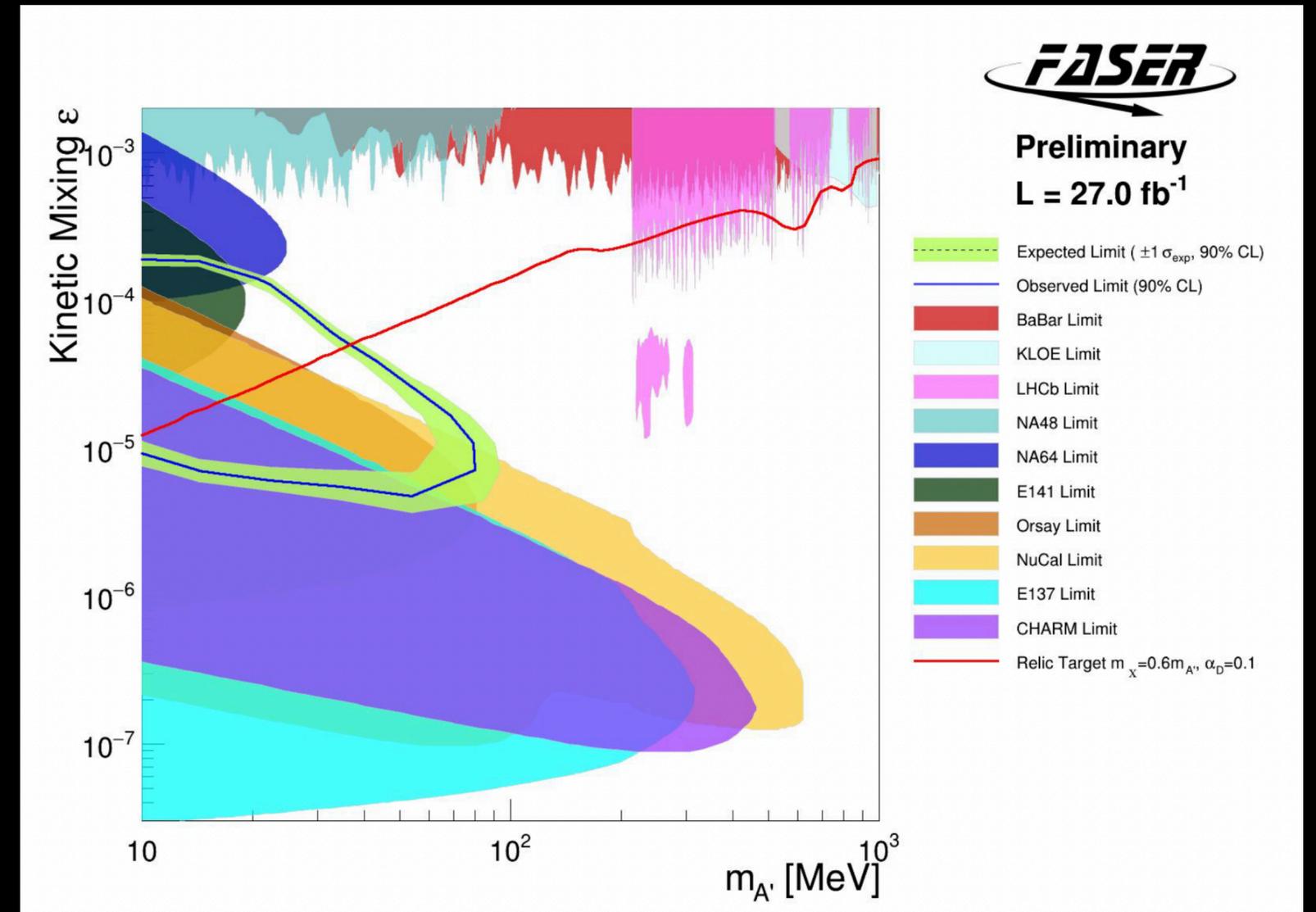
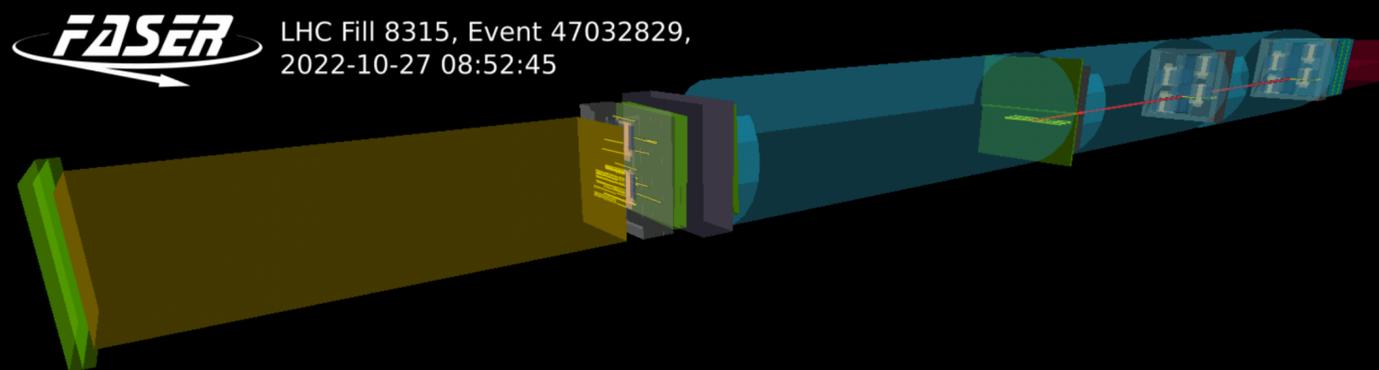
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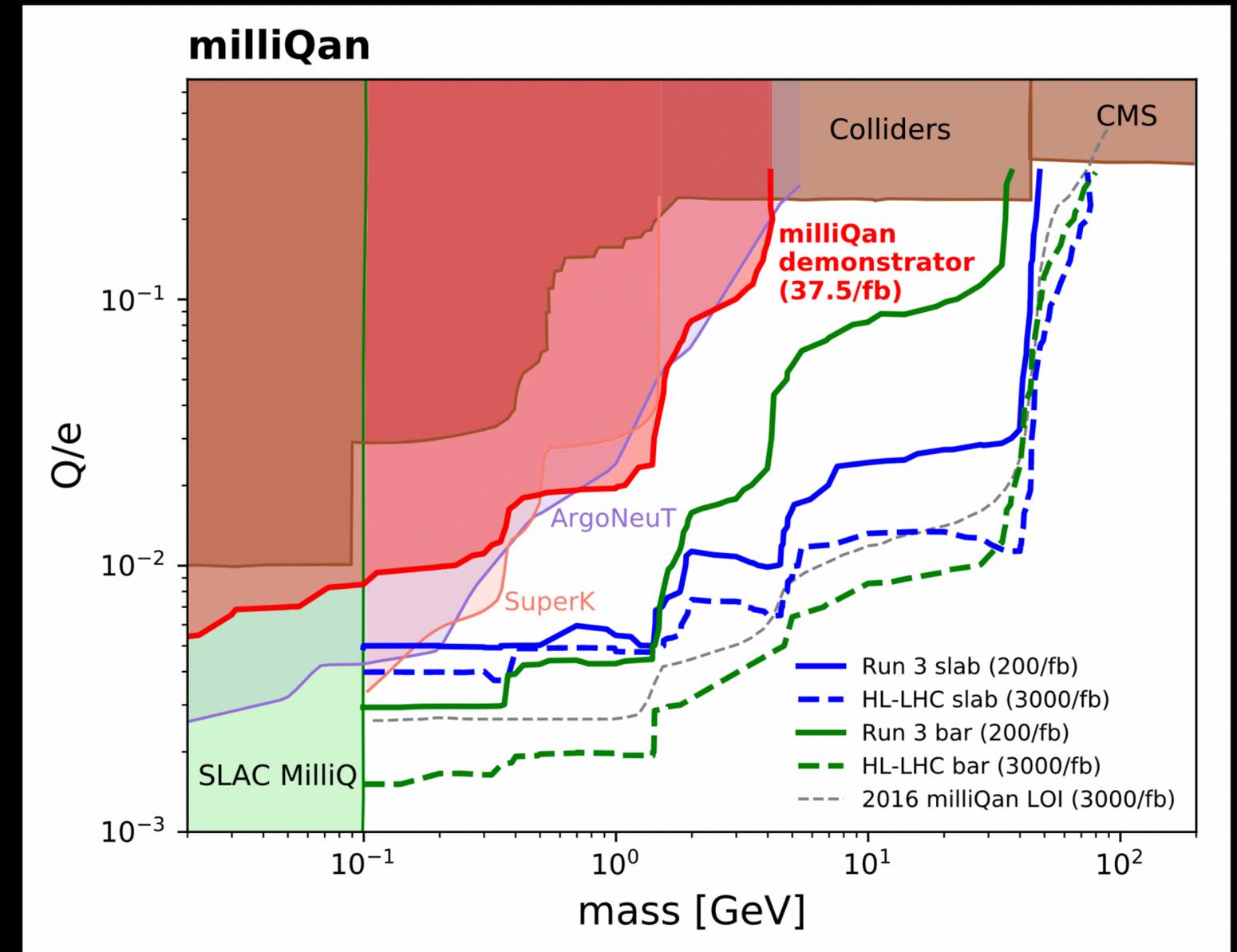
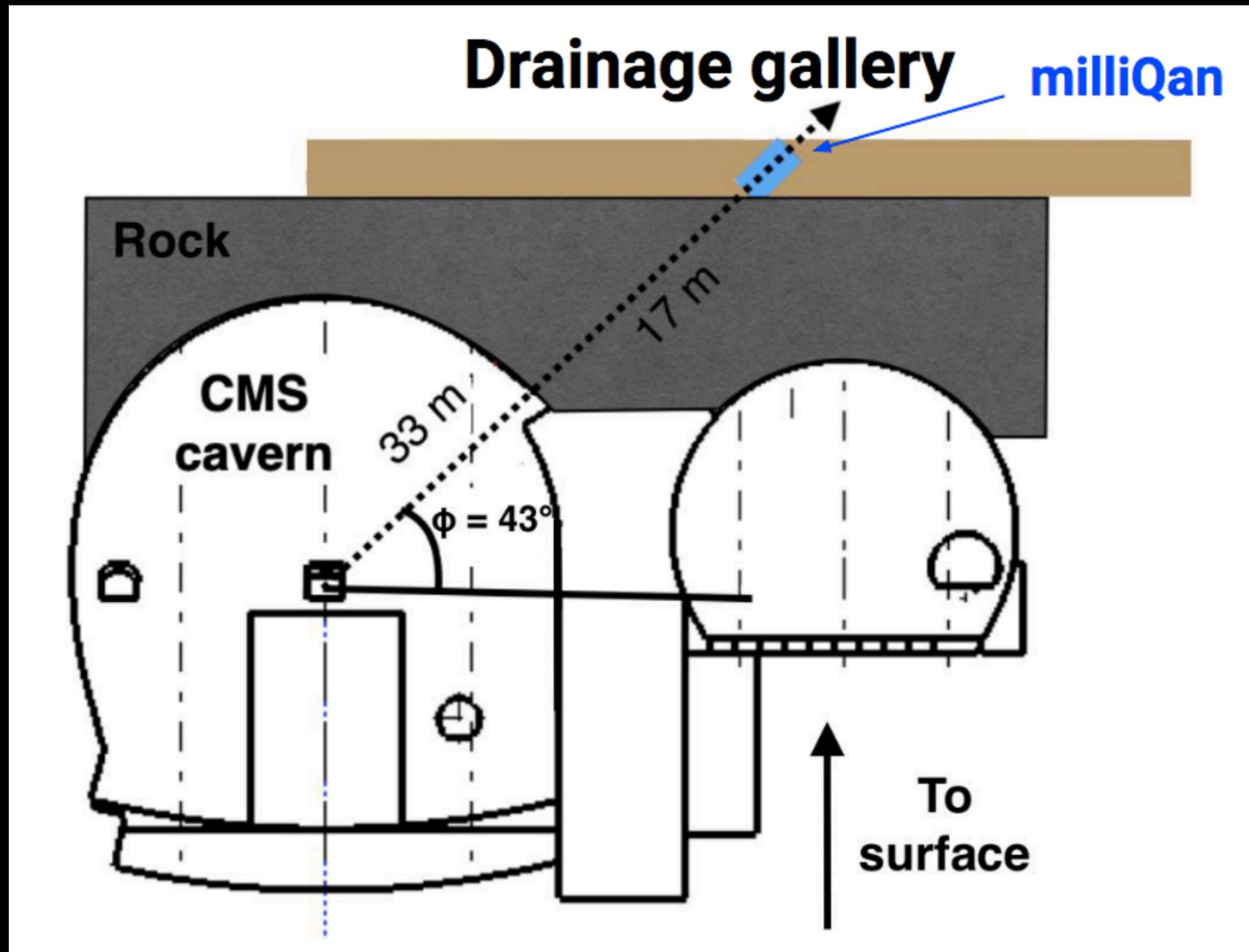
...including the first collider neutrinos ever directly detected



Aug. 2023: [arXiv:2308.05587](https://arxiv.org/abs/2308.05587)

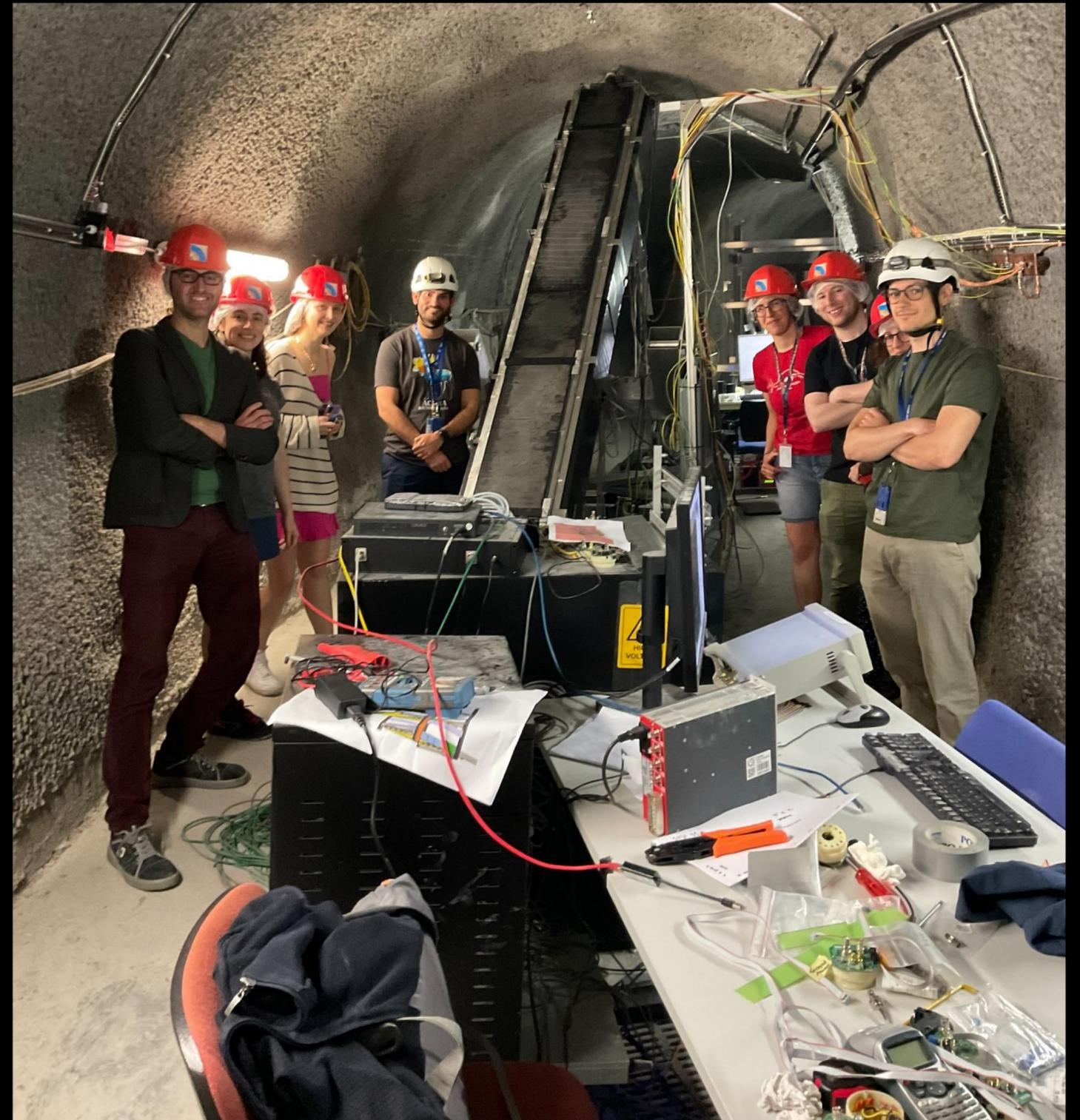
MilliQan

Small ($3\text{ m} \times 1\text{ m}^2$) detector near CMS for new BSM dark fermions with very small amount of electric charge

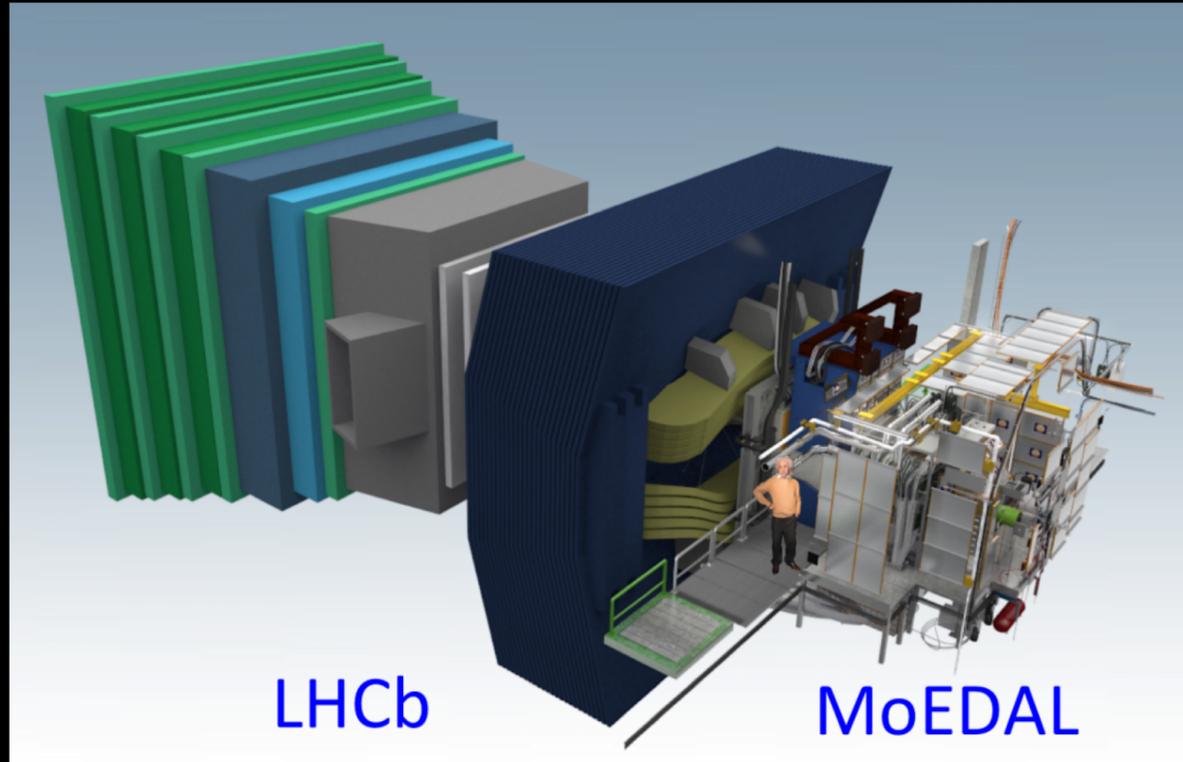


Demonstrator ran in Run 2 with physics results [[PRD 102 \(2020\) 3, 032002](#)] and this year, in Run 3, with detector improvements — results soon

MilliQan visit at LLP13
workshop at CERN in
June 2023



MoEDAL / MoEDAL-MAPP

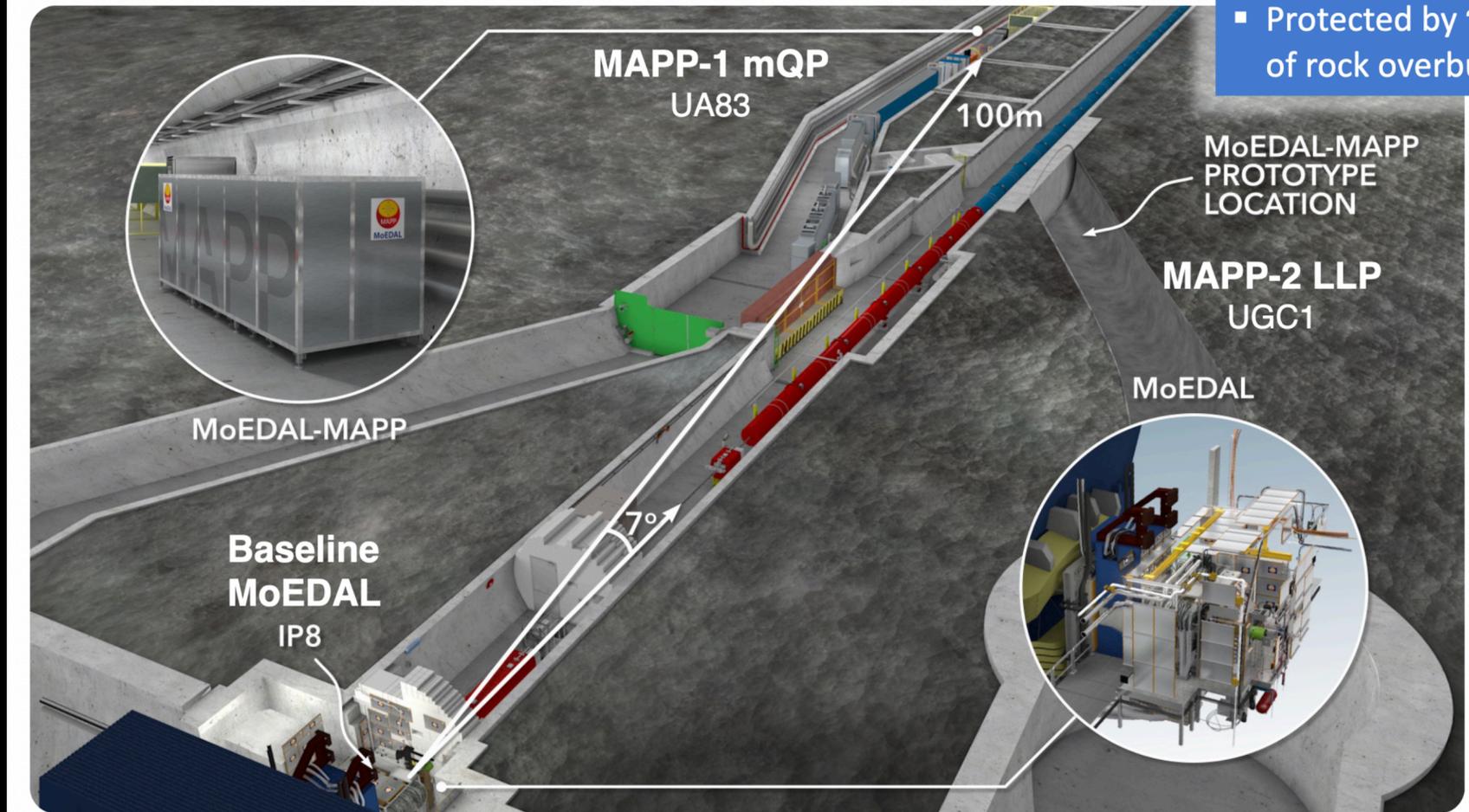


MoEDAL is the LHC's first dedicated LLP experiment, approved in 2010 and taking data since 2015

Shares the cavern with LHCb and searches for magnetic monopoles and highly-ionizing particles

Proposed extensions to search for neutral LLPs and millicharged particles, a.k.a. MoEDAL-MAPP (2022 Snowmass contribution)

MAPP locations

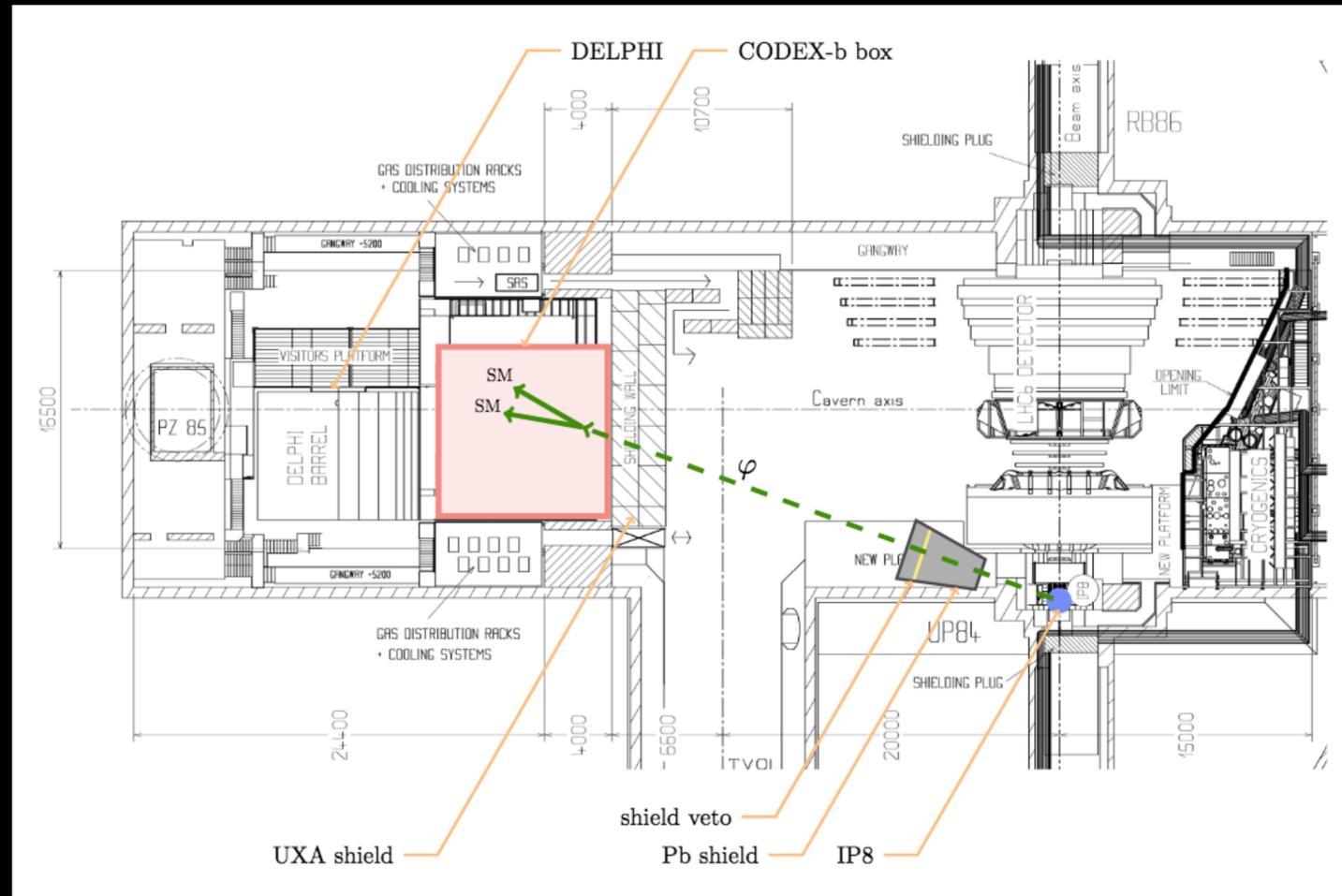


- At forward region w.r.t. beam axis
- Protected by ~100 m of rock overburden

Dedicated detectors for long-lived particles at the LHC

CODEX-b

A medium-sized (10m^3) detector for neutral LLP decays a few meters from LHCb

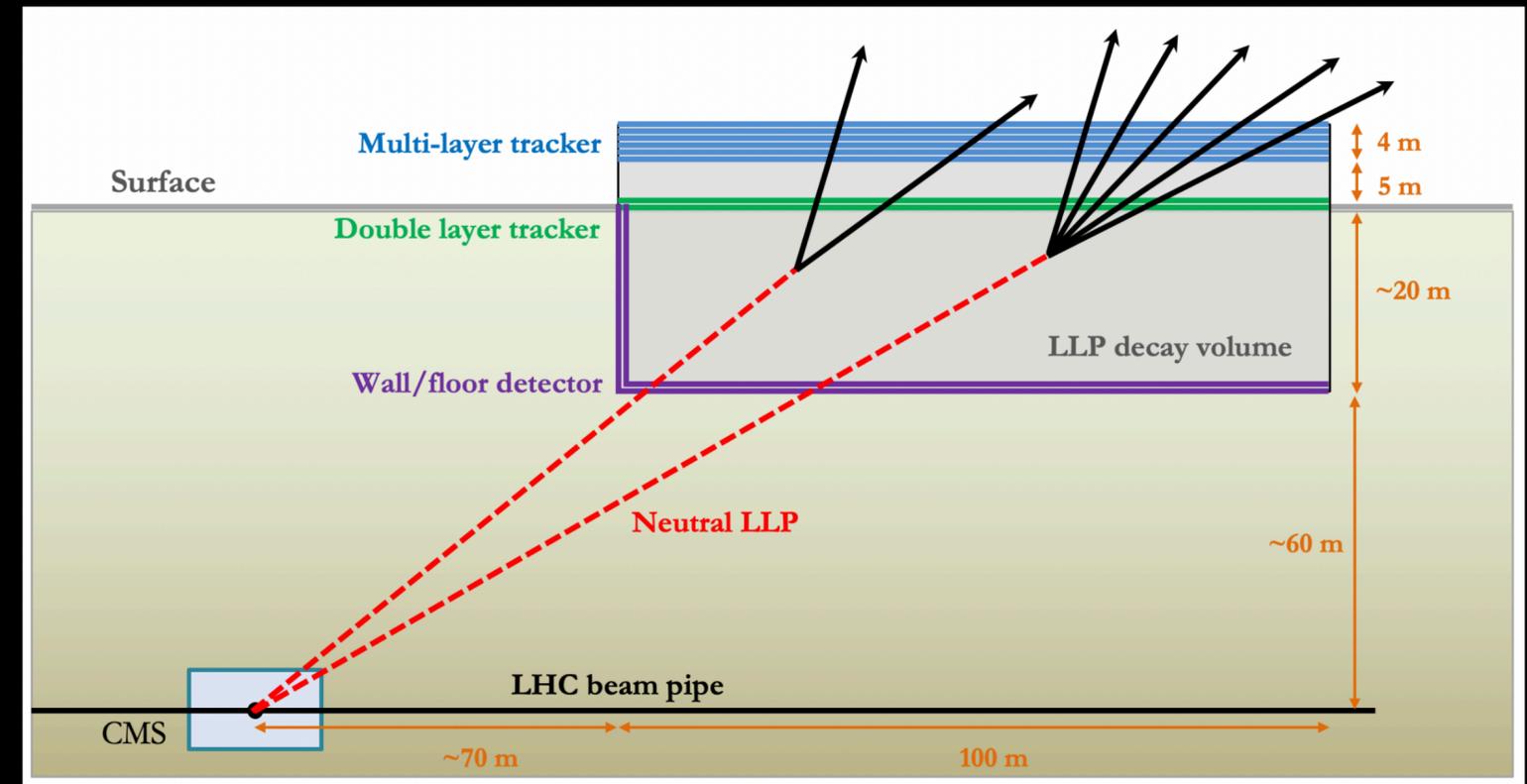


Building a demonstrator, CODEX- β , right now, to hopefully take data in Run 3

MATHUSLA

A big ($100\text{m} \times 100\text{m} \times 25\text{m}$), mostly-empty box near the surface above CMS to catch displaced vertices

Physics case document
Letter of Intent

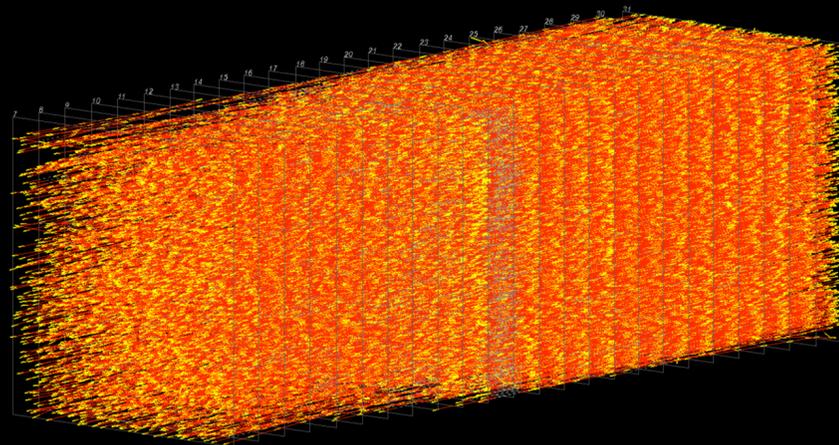
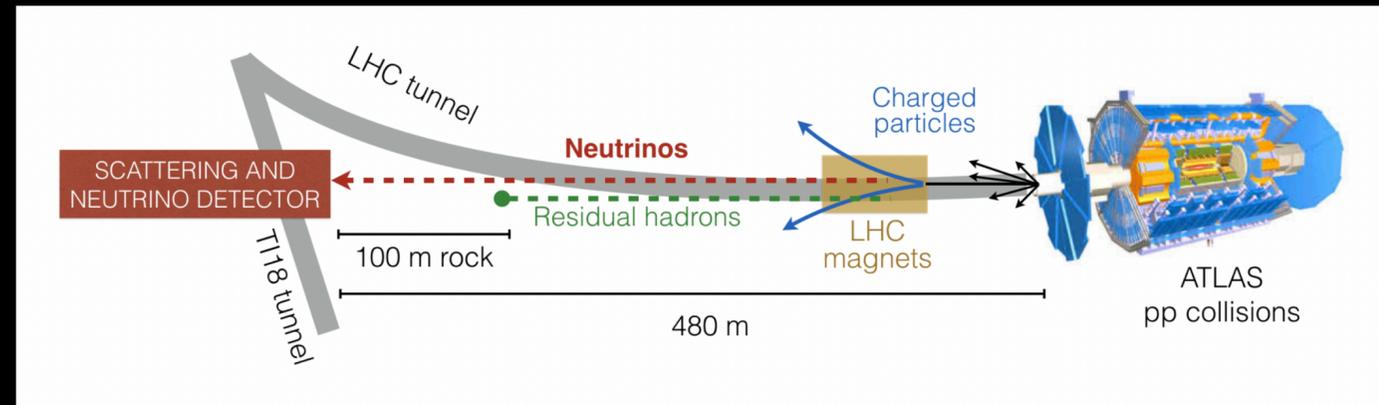


Proposed, with a demonstrator

Dedicated detectors for long-lived particles at the LHC

SND@LHC

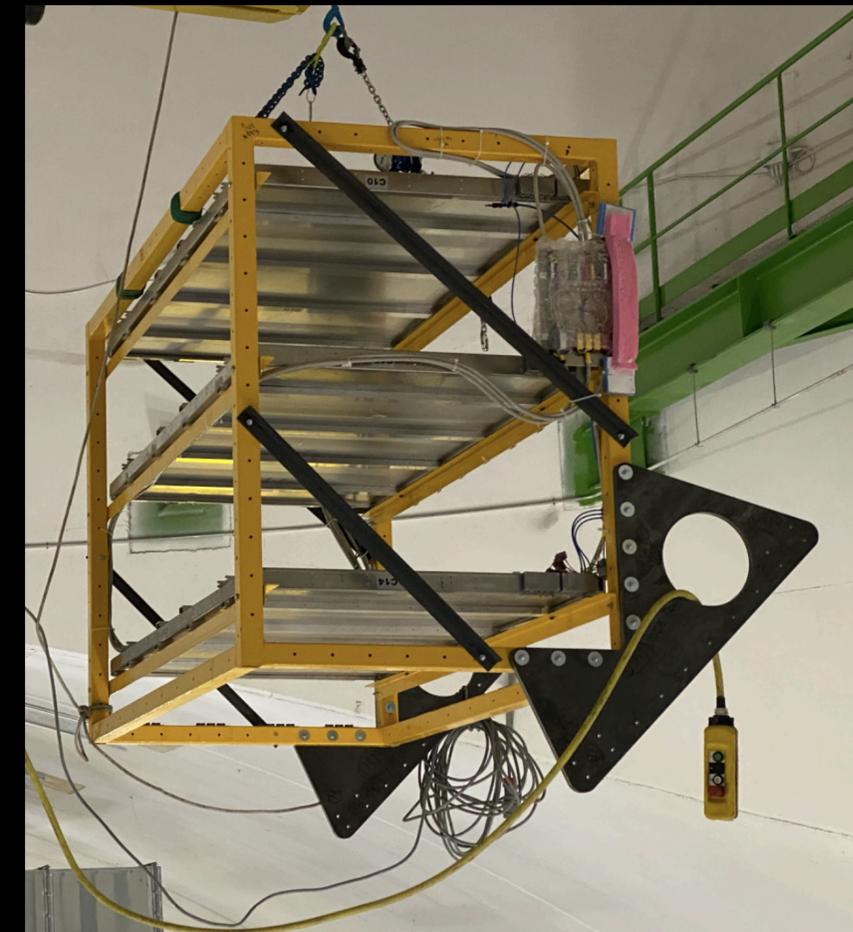
About 0.5 km away from ATLAS on the side opposite FASER, sensitive to similar things



Already installed and has also already seen the first collider neutrinos:
[arXiv:2305.09383](https://arxiv.org/abs/2305.09383)

ANUBIS

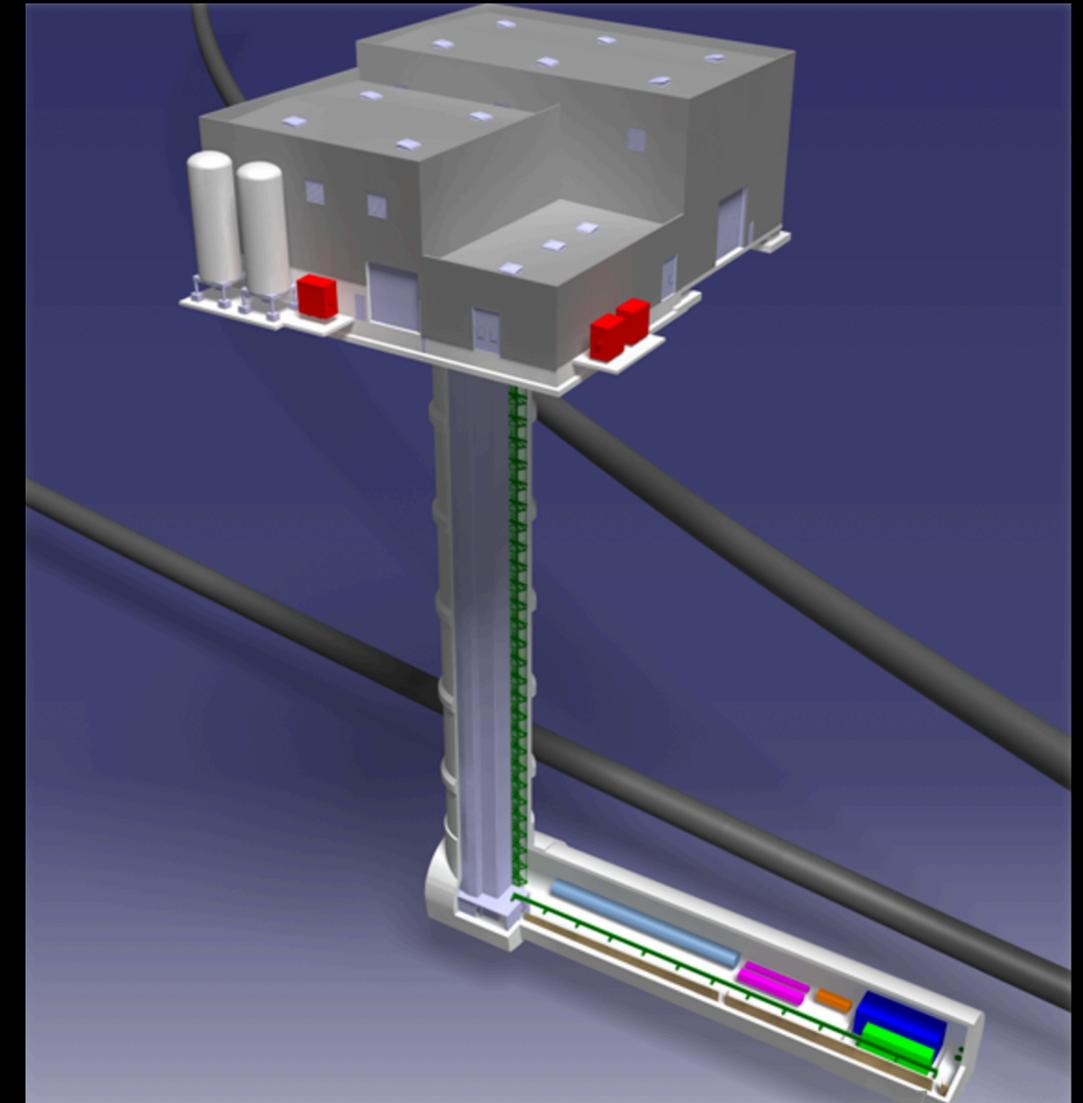
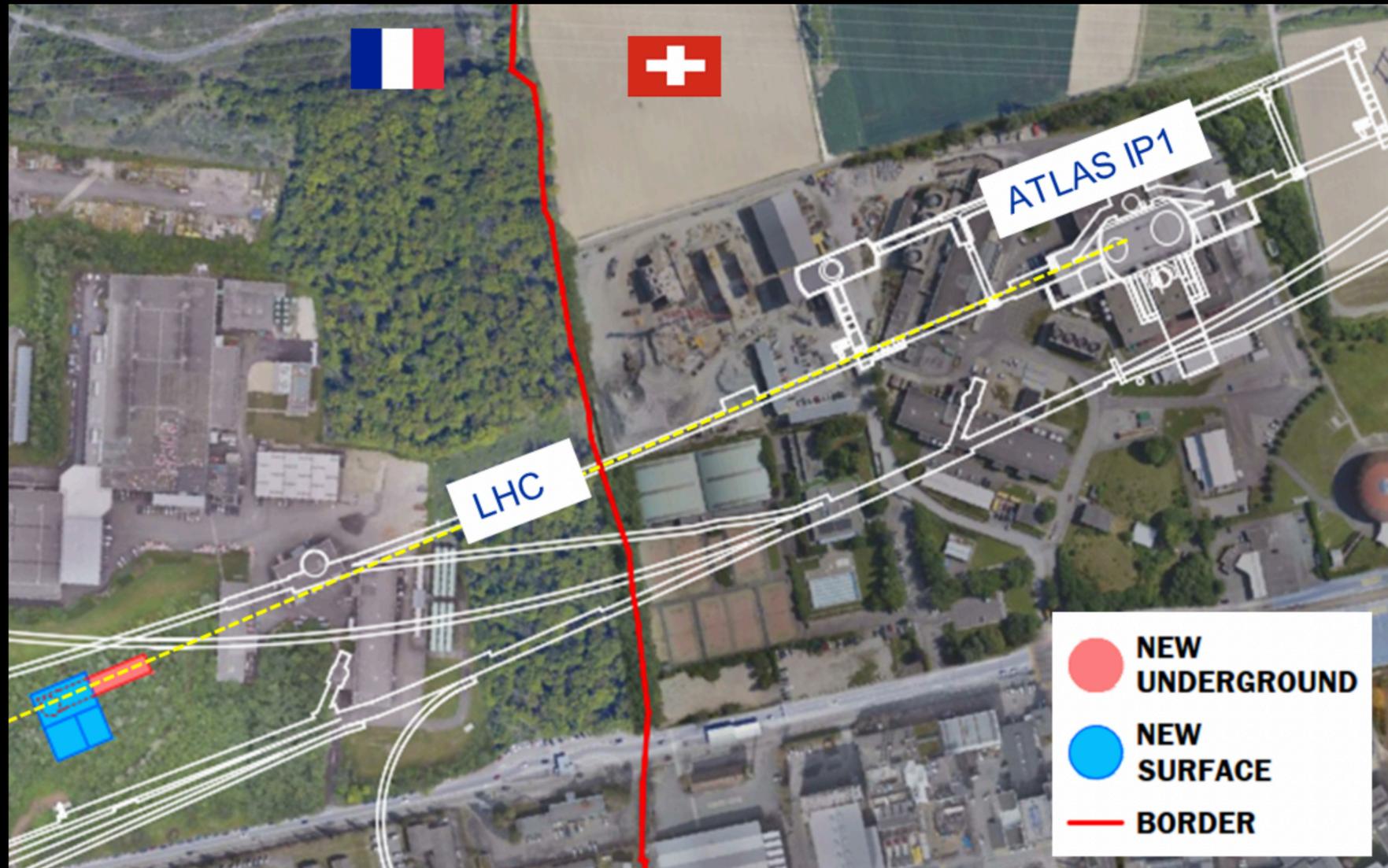
Proposal to instrument bottom of access shafts above ATLAS cavern, as well as cavern ceiling



ProANUBIS installed in March 2023

Commissioning now

Forward Physics Facility



Proposal for a new facility, about 600 m from ATLAS, to house multiple experiments dedicated to LLP searches in the forward region

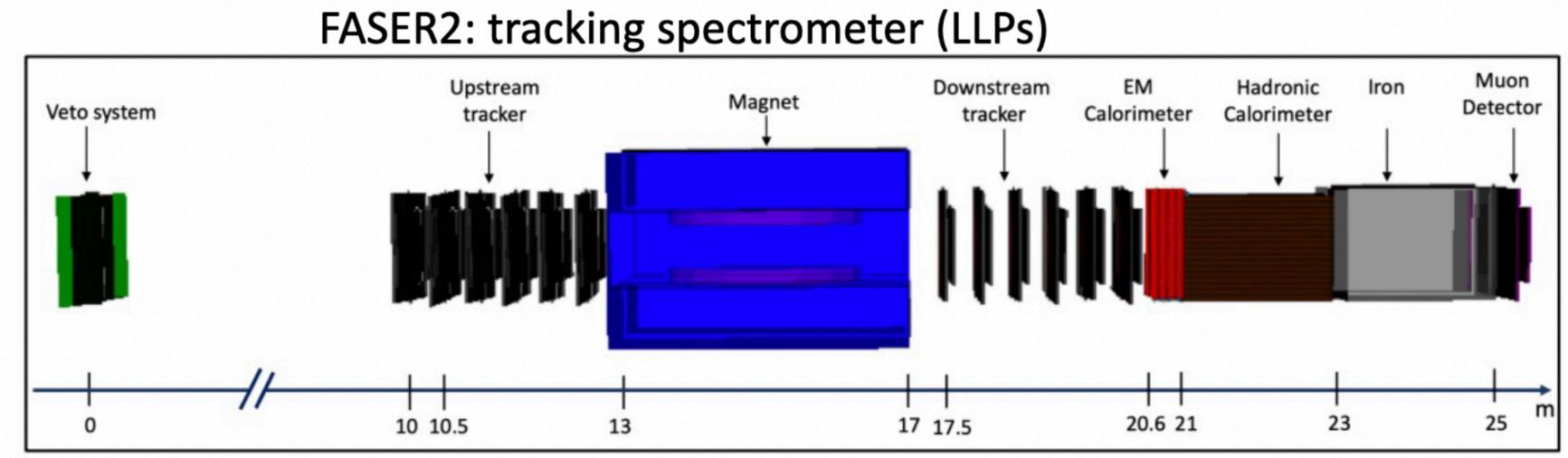
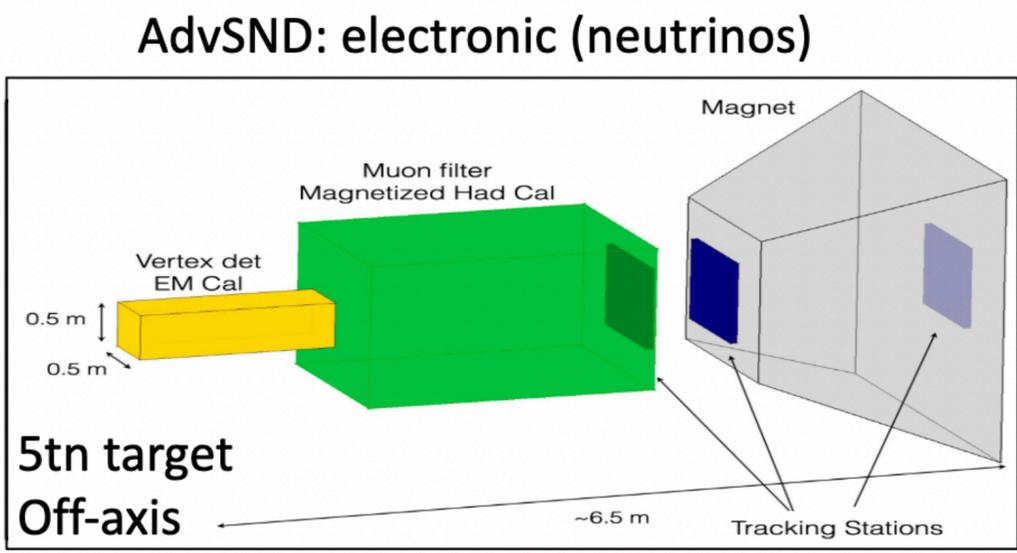
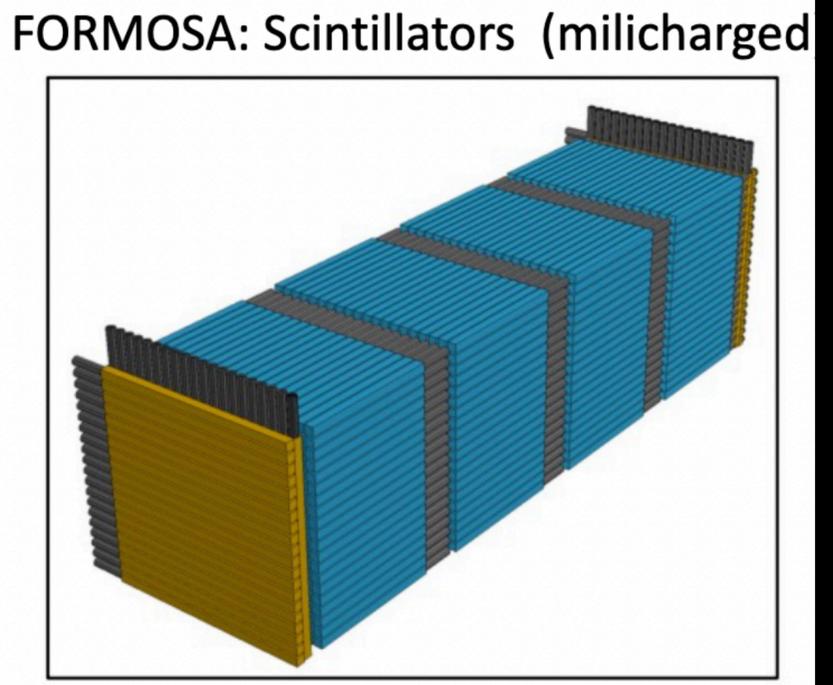
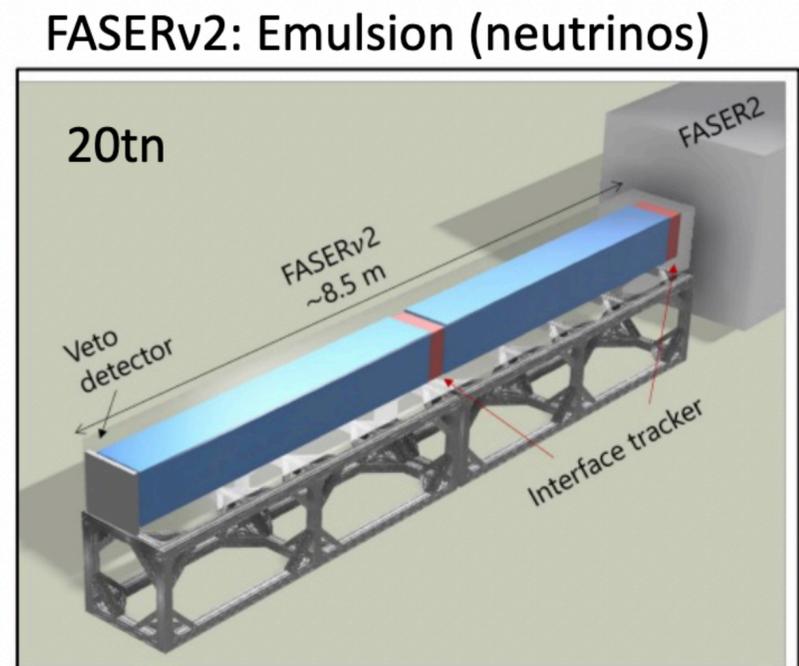
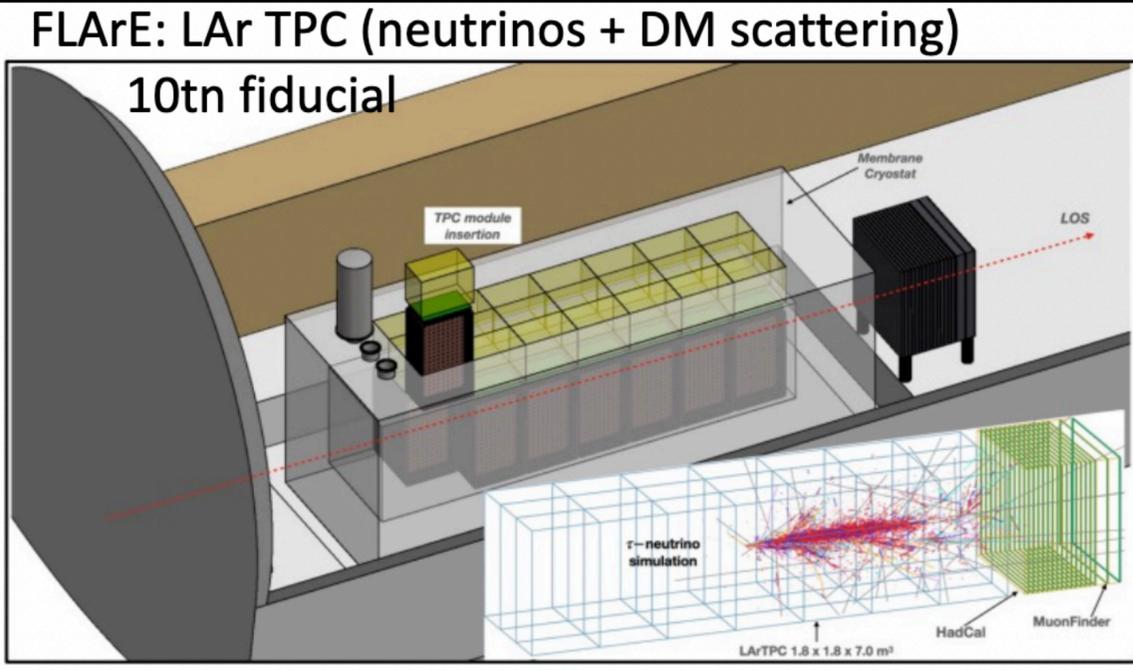
Proposed for the High-Luminosity LHC (HL-LHC), 2027 or later

[arXiv:2203.05090](https://arxiv.org/abs/2203.05090)

Forward Physics Facility

For FLArE, cf.
LUXE at DESY

L. Boyd



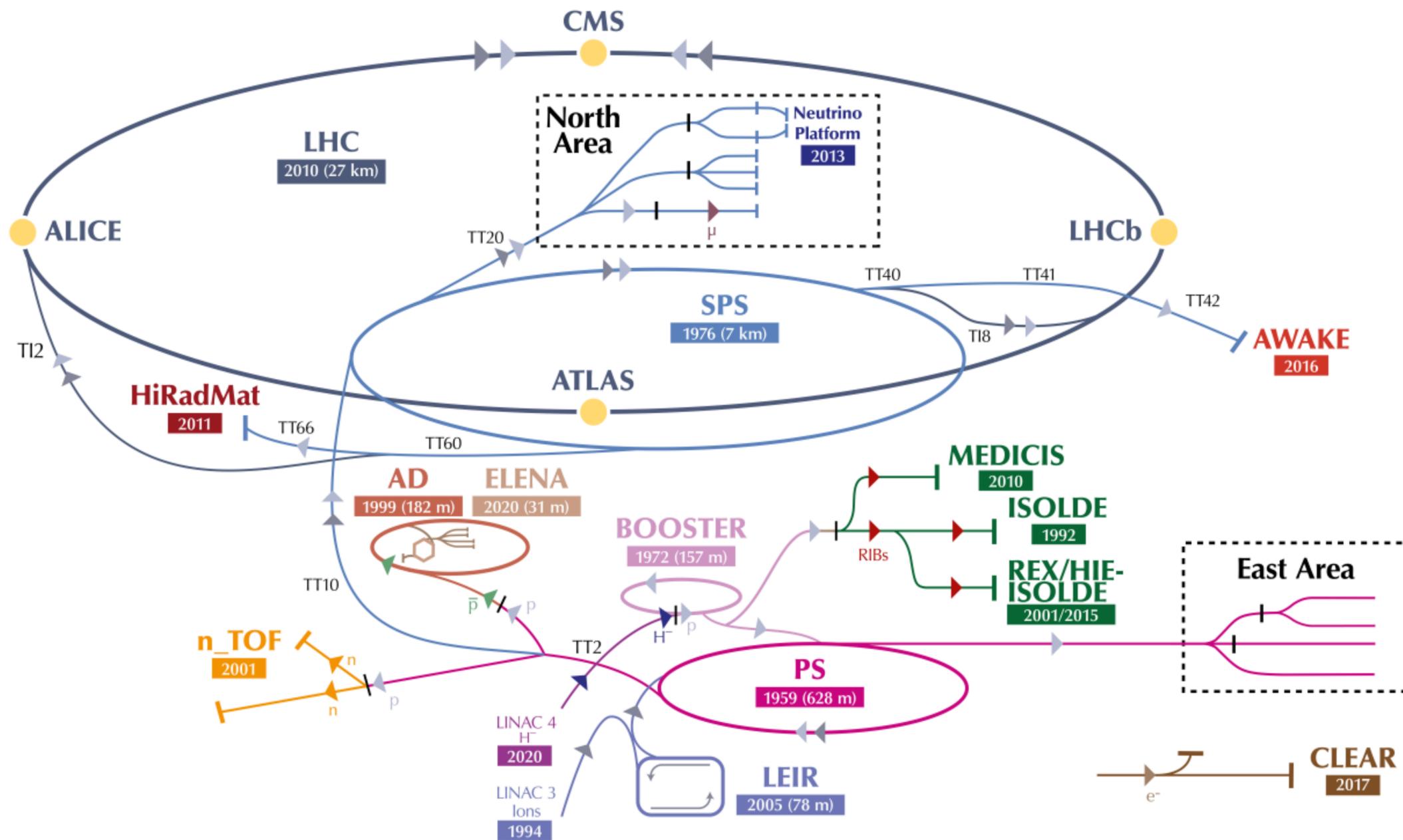
Physics case is strong; as we've seen, most of these have predecessors that already have results

Site investigations ongoing (already drilled 100-meter-deep earth cores)

Goal is to submit Letter of Intent to LHCC in early 2025

LLPs from the SPS at CERN

The CERN accelerator complex *Complexe des accélérateurs du CERN*



LLPs from the SPS at CERN

NA64

Uses 100 GeV electron beam to search for dark sector particles in the MeV-GeV range using active-beam-dump plus missing-energy approach

Recent light dark matter result:
[PRL 131 \(2023\) 16, 161801](#)



NA62

250-meter-long experiment that uses 450 GeV protons from SPS to do precision measurements of kaon decays and also search for BSM LLPs

New exotics decays results (Sept. 2023):
[PoS FPCP2023 \(2023\) 073](#)



LLPs from the SPS at CERN

NA64

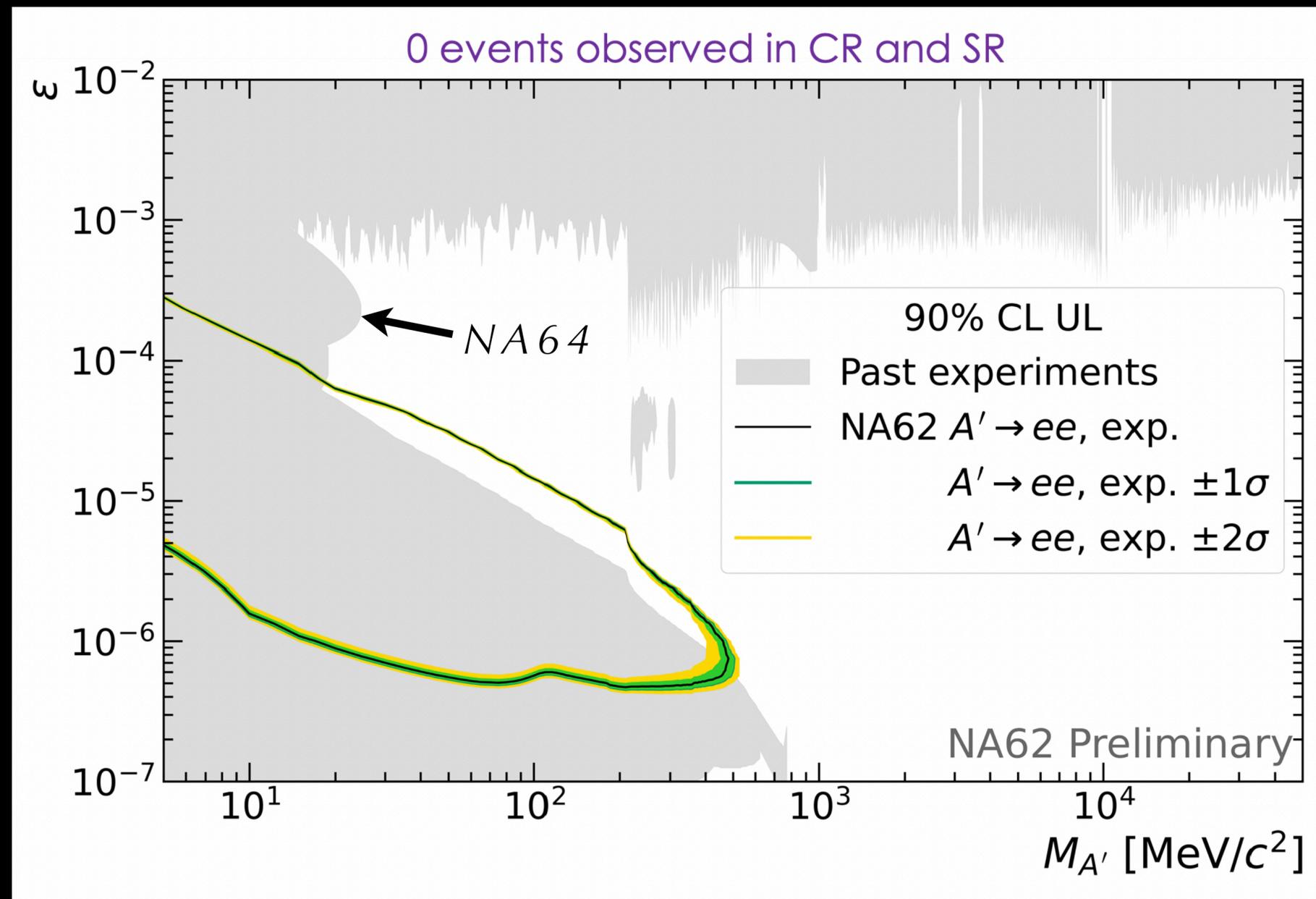
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[PoS FPCP2023 \(2023\) 073](#)



Nota bene:

NA62

Currently in a hall called ECN3 in the North Area at CERN, but approved to operate until LHC Long Shutdown 3, from 2026-2028

What to do with ECN3 — which has an excellent beam — afterward?



LLPs from the SPS at CERN

SHADOWS

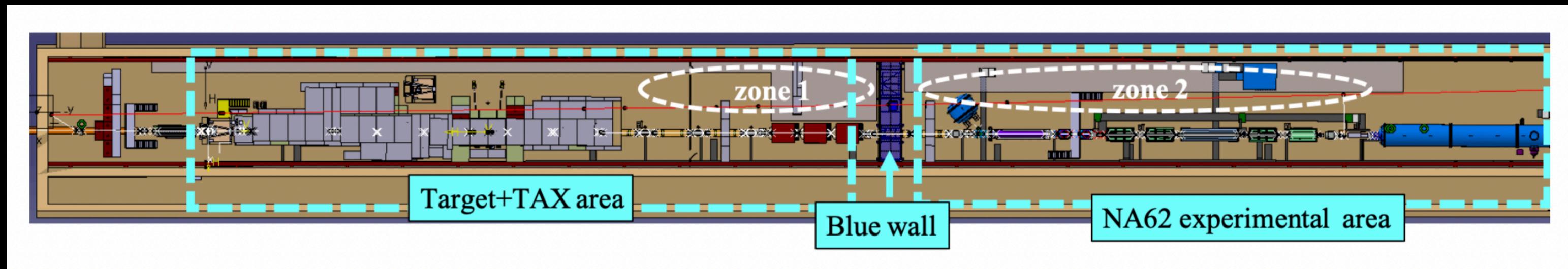
Proposed beam-dump experiment to be installed in ECN3, to search for BSM LLPs such as ALPs, HNLs, dark scalars

[arXiv:2110.08025](https://arxiv.org/abs/2110.08025)

SHiP

Originally proposed as a new standalone facility (new beamline and hall) at CERN; now a proposal for a beam-dump experiment in ECN3

[Recent \(June 2023\) talk](#)

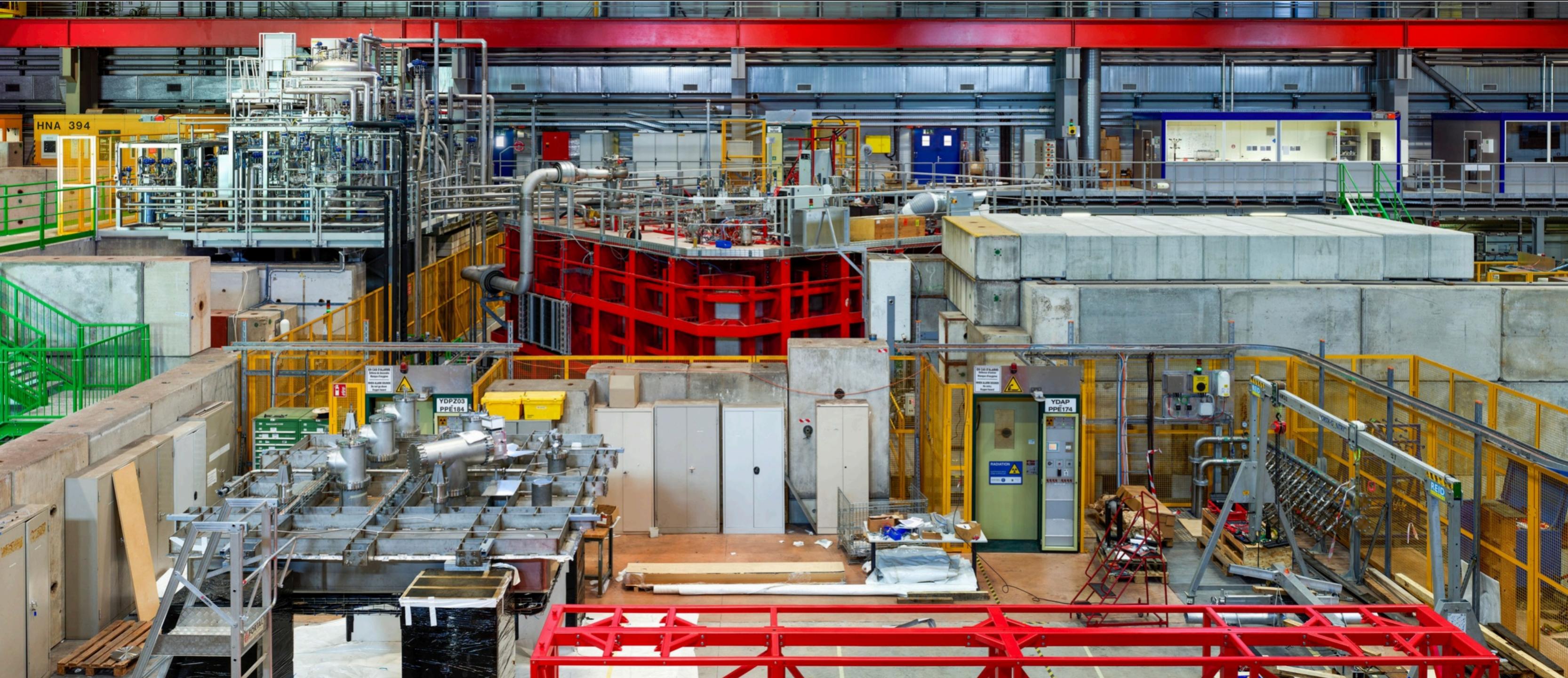


ECN3, CERN North Area

Decision about what to do with ECN3 will be made in March 2024

Oct. 2023 paper discussing this: [arXiv:2310.17726](https://arxiv.org/abs/2310.17726)

LLPs from the SPS at CERN — ProtoDUNE



Thomas Struth, 2023

LLPs from the SPS at CERN — ProtoDUNE

ProtoDUNE

Prototype cryostats at CERN, preparing for the full DUNE neutrino experiment in the U.S., can be used as a beam-dump facility to search for BSM LLPs (HNLs, dark matter, millicharged particles, etc.)

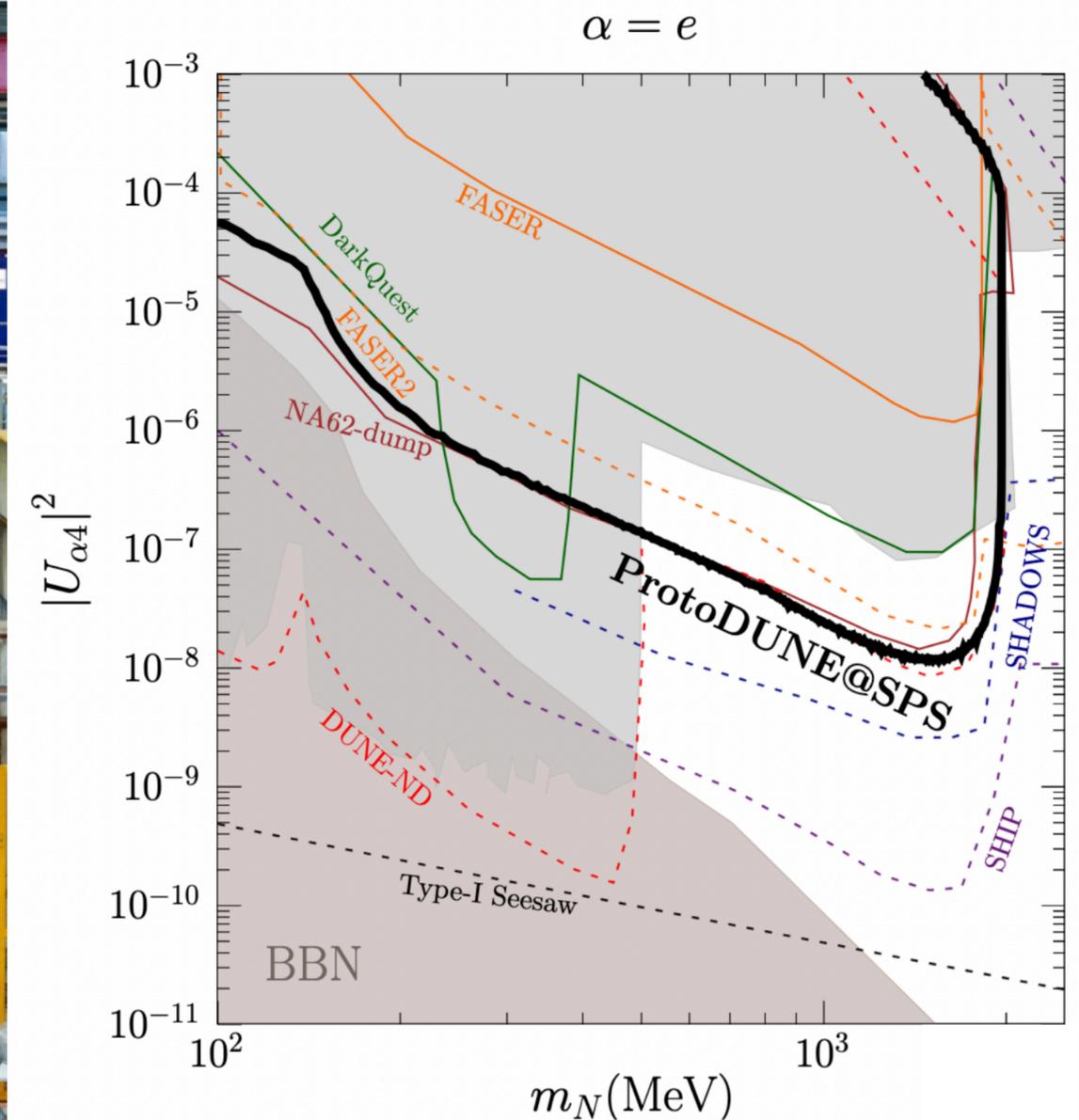


Thomas Struth, 2023

LLPs from the SPS at CERN — ProtoDUNE

ProtoDUNE

Prototype cryostats at CERN, preparing for the full DUNE neutrino experiment in the U.S., can be used as a beam-dump facility to search for BSM LLPs (HNLs, dark matter, millicharged particles, etc.)



Projected HNL sensitivity for ~6 months of running

[arXiv:2304.06765](https://arxiv.org/abs/2304.06765)

[Thomas Struth, 2023](#)

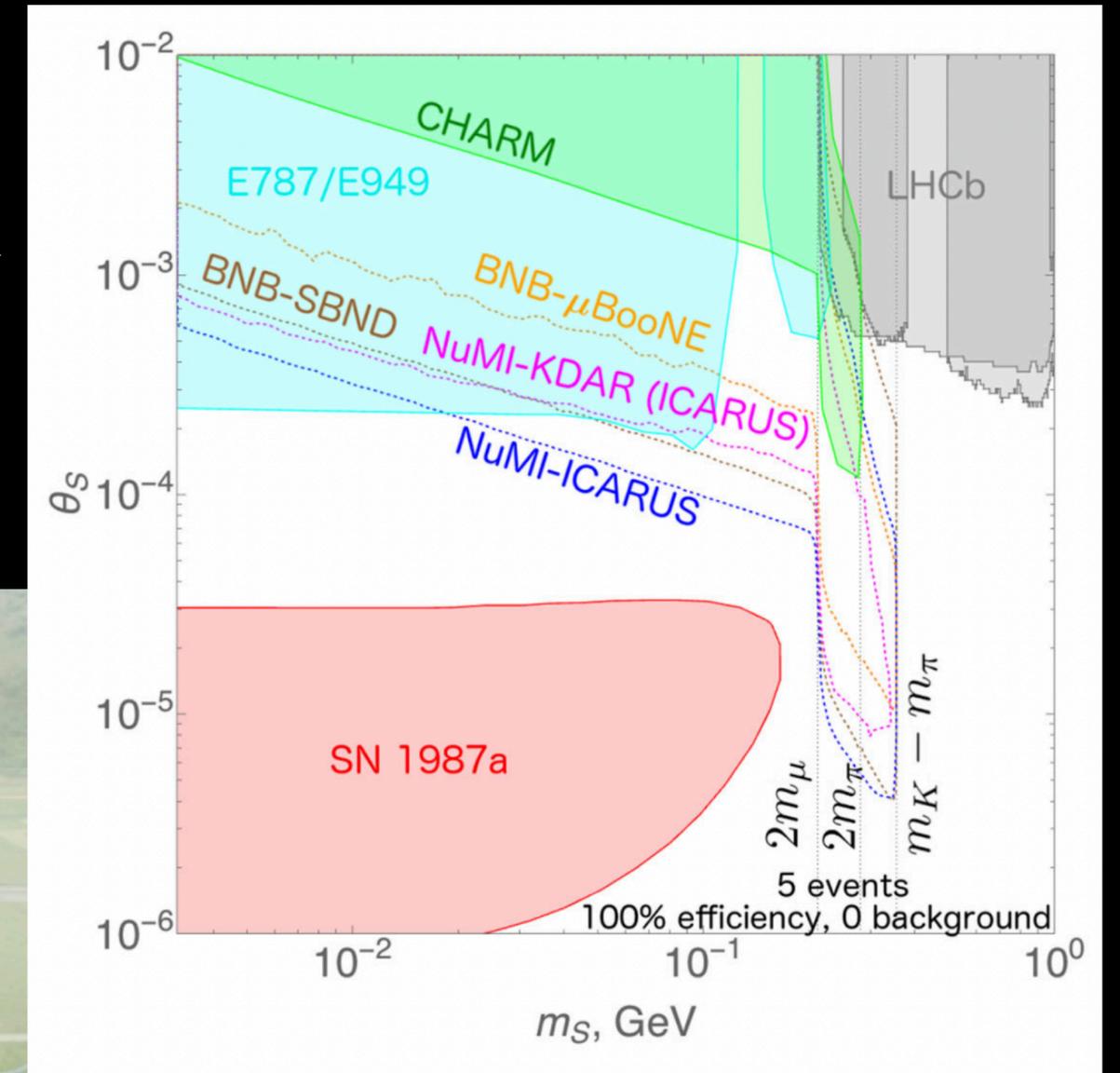
Short Baseline Neutrino Program at Fermilab

Three liquid argon neutrino detectors along the Booster Neutrino Beam (BNB)

Designed to prepare for DUNE, but can also be used for BSM LLPs

Results expected soon(?)

Projections for Higgs portal scalar, for example, but other scenarios, as well



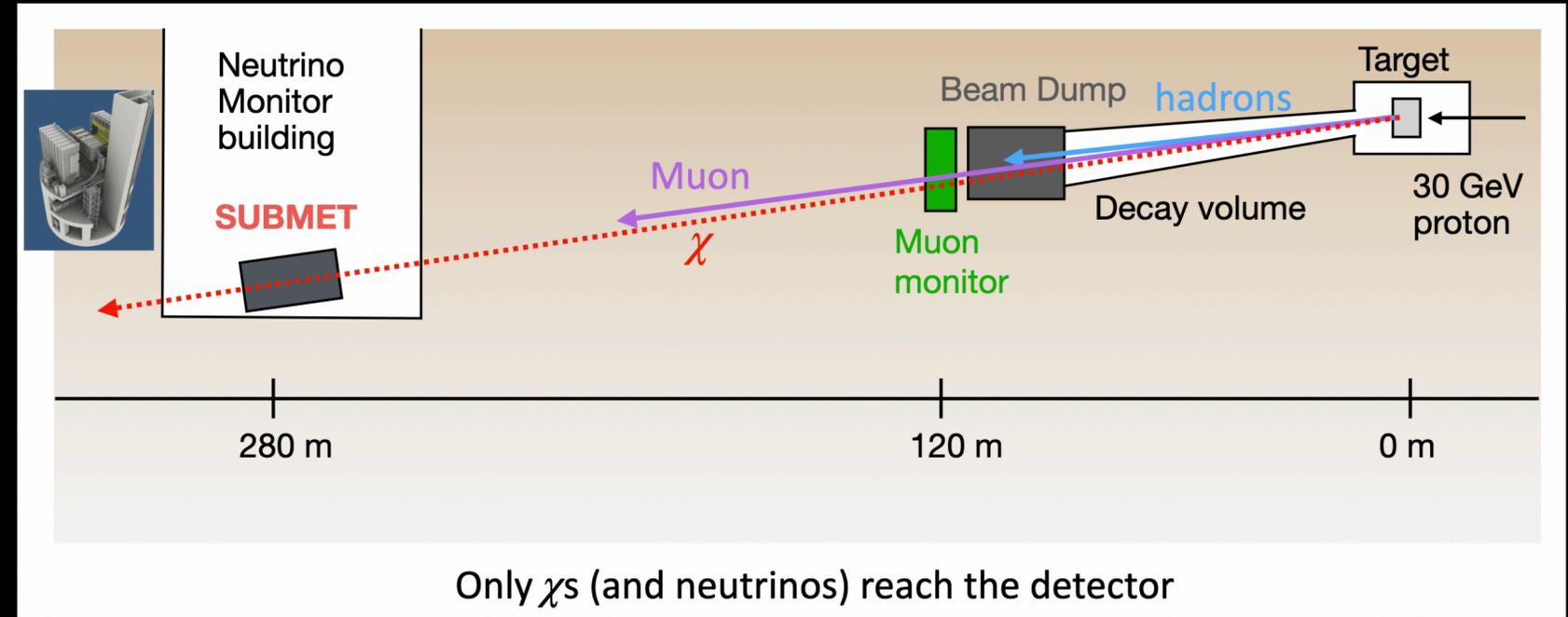
LLPs in Japan

SUBMET at J-PARC

Search for millicharged particles inspired by MilliQan (with some of the same people)

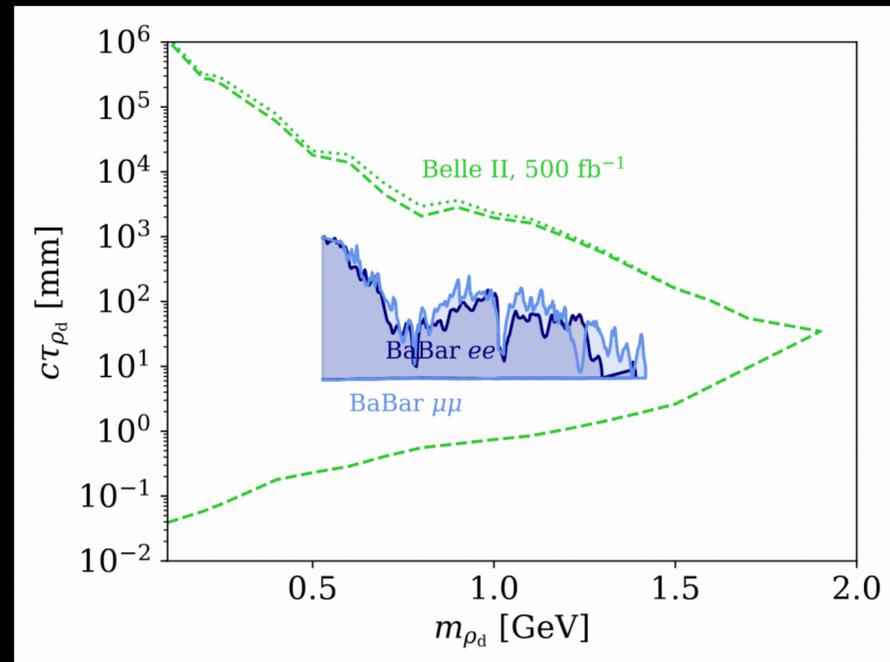
Stage 2 approval already given

Recent talk



Belle-II at SuperKEKB

Clean e^+e^- environment at SuperKEKB allows for substantial probing of many dark sector signatures...



...including dark QCD
[arXiv:2203.08824](https://arxiv.org/abs/2203.08824)

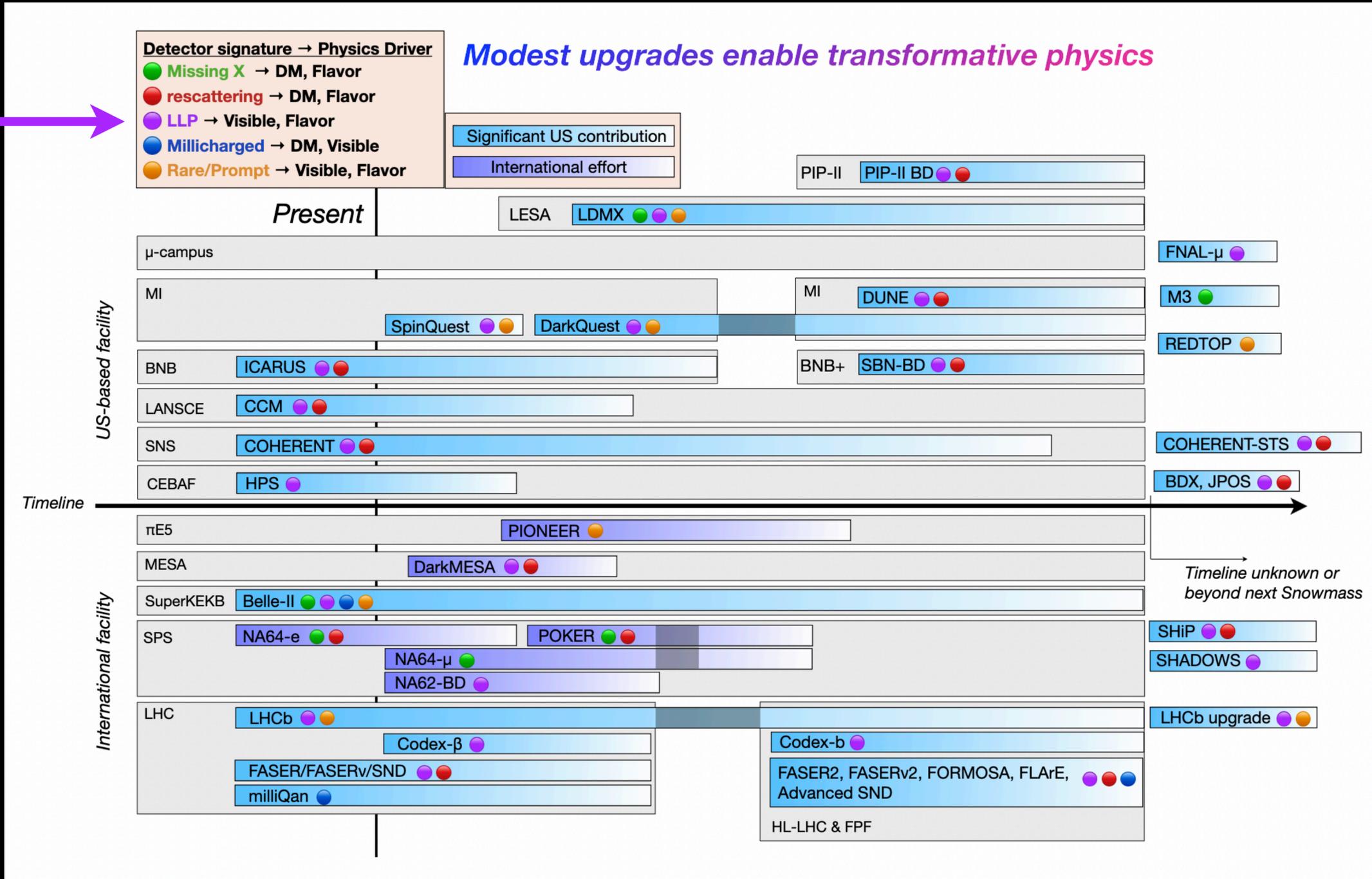
Super-Kamiokande

Long-lived light ALPs produced from air showers, travel towards the Earth's surface, and decay into two photons inside Super-Kamiokande

[arXiv:2208.05111](https://arxiv.org/abs/2208.05111)

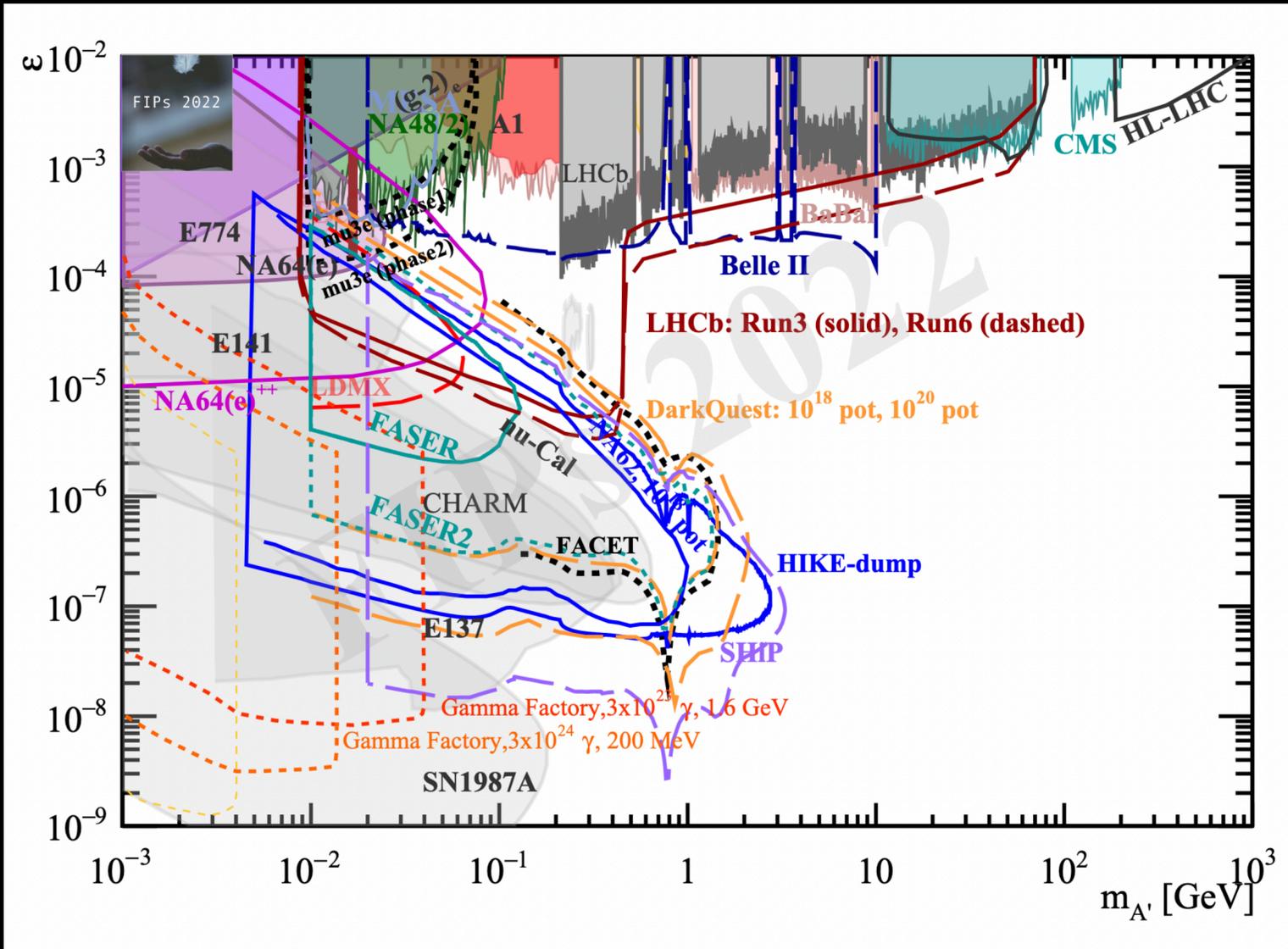
Broad international effort

LLPs

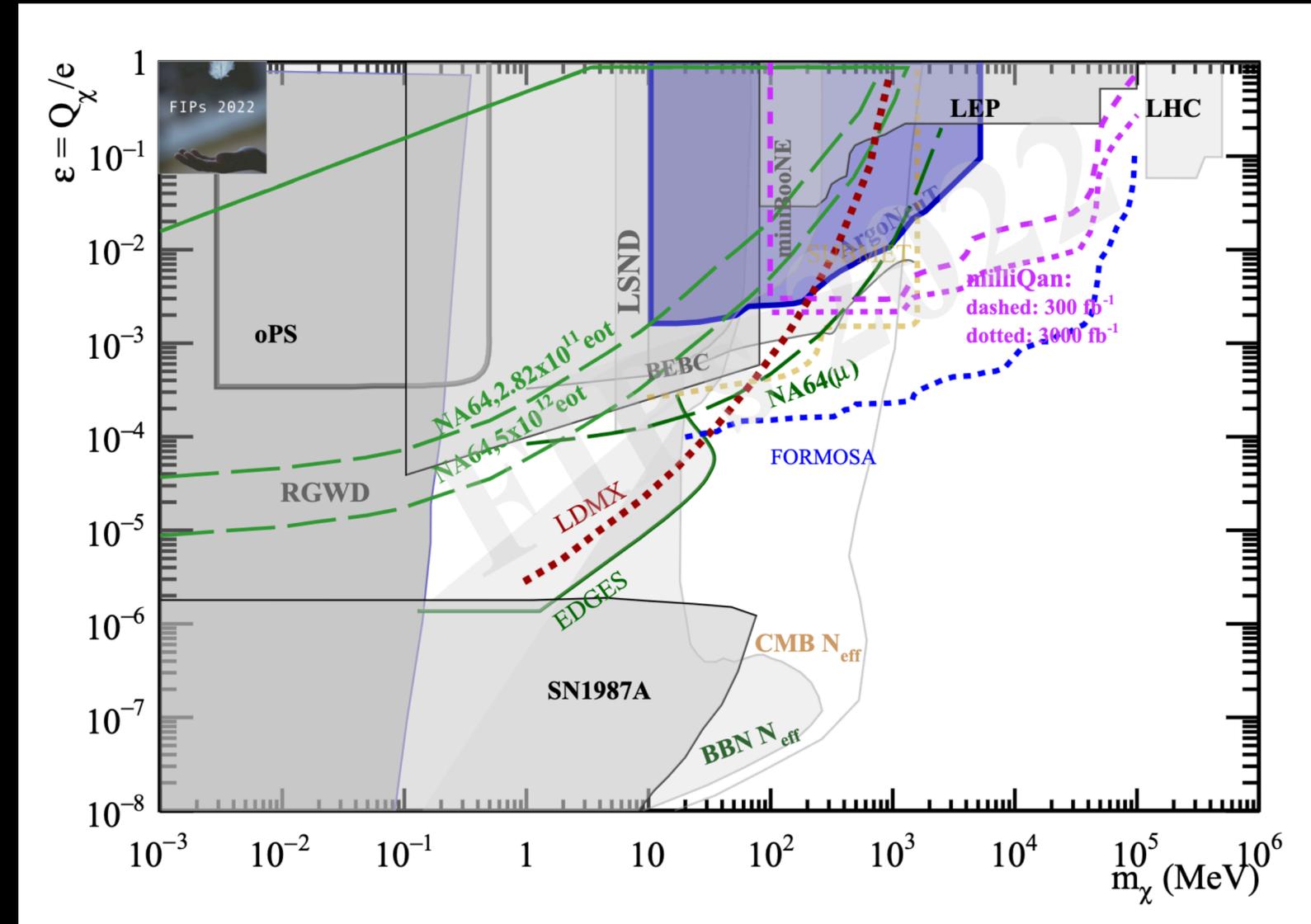


Snowmass “accelerator-based dark sector searches” report:
[arXiv:2206.04220](https://arxiv.org/abs/2206.04220)

This is what I mean by cartography



Dark photon (A')



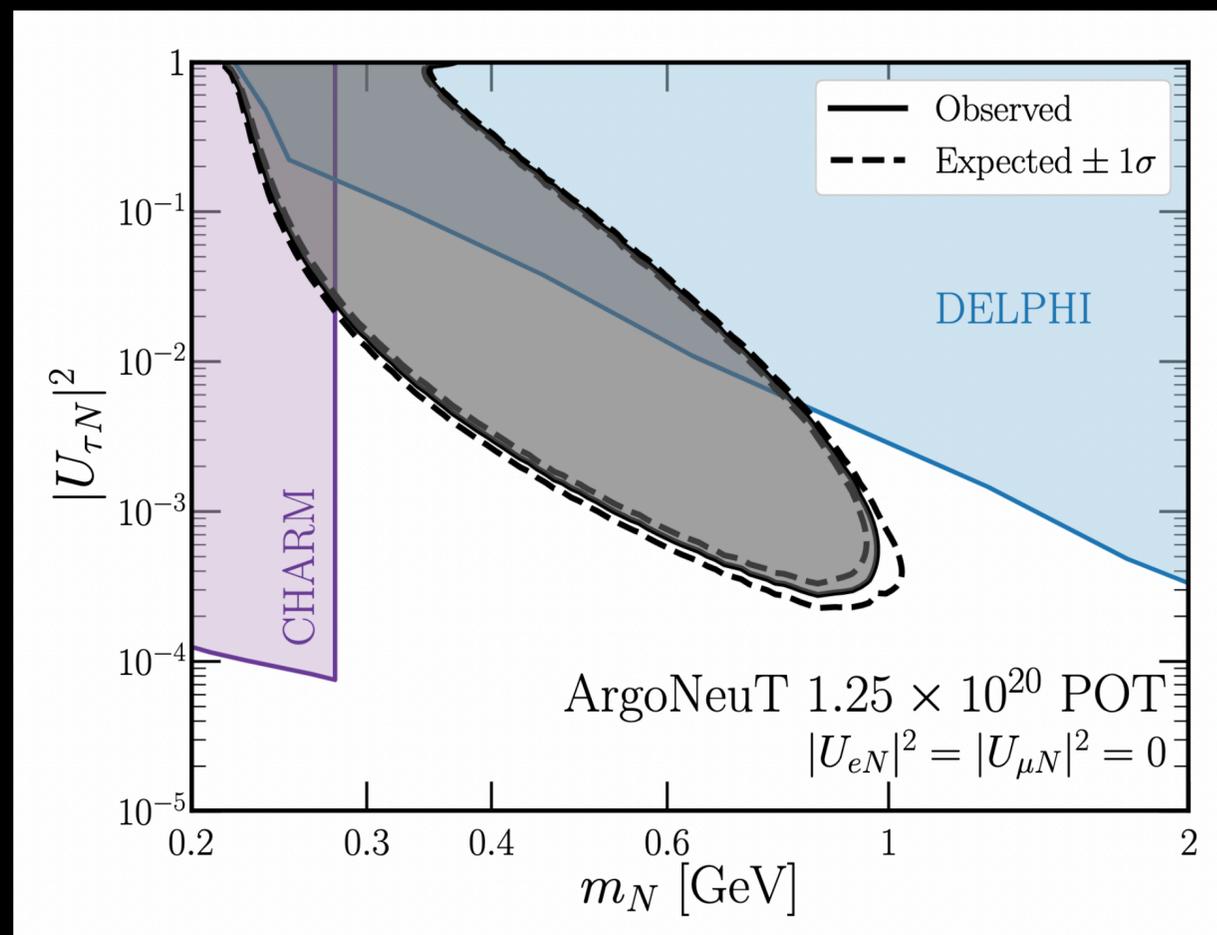
Millicharged particles

FIPs 2022 workshop report
[arXiv:2305.01715](https://arxiv.org/abs/2305.01715)

We're still learning about LLPs from past experiments

ARGONEUT

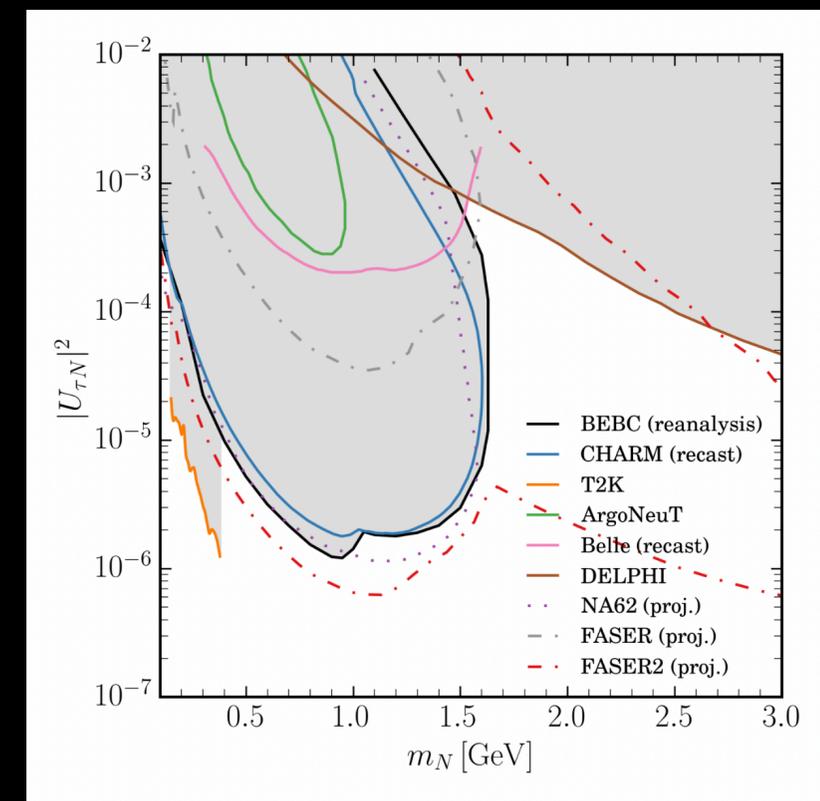
Was the first LArTPC in a neutrino beam in the U.S. (Fermilab), designed as a test experiment that took data in 2009-2010, recently re-analyzed for BSM LLP signatures



[PRL 124, 131801](#), [PRL 127, 121801](#), [PRL 130, 221802](#)

BEBC

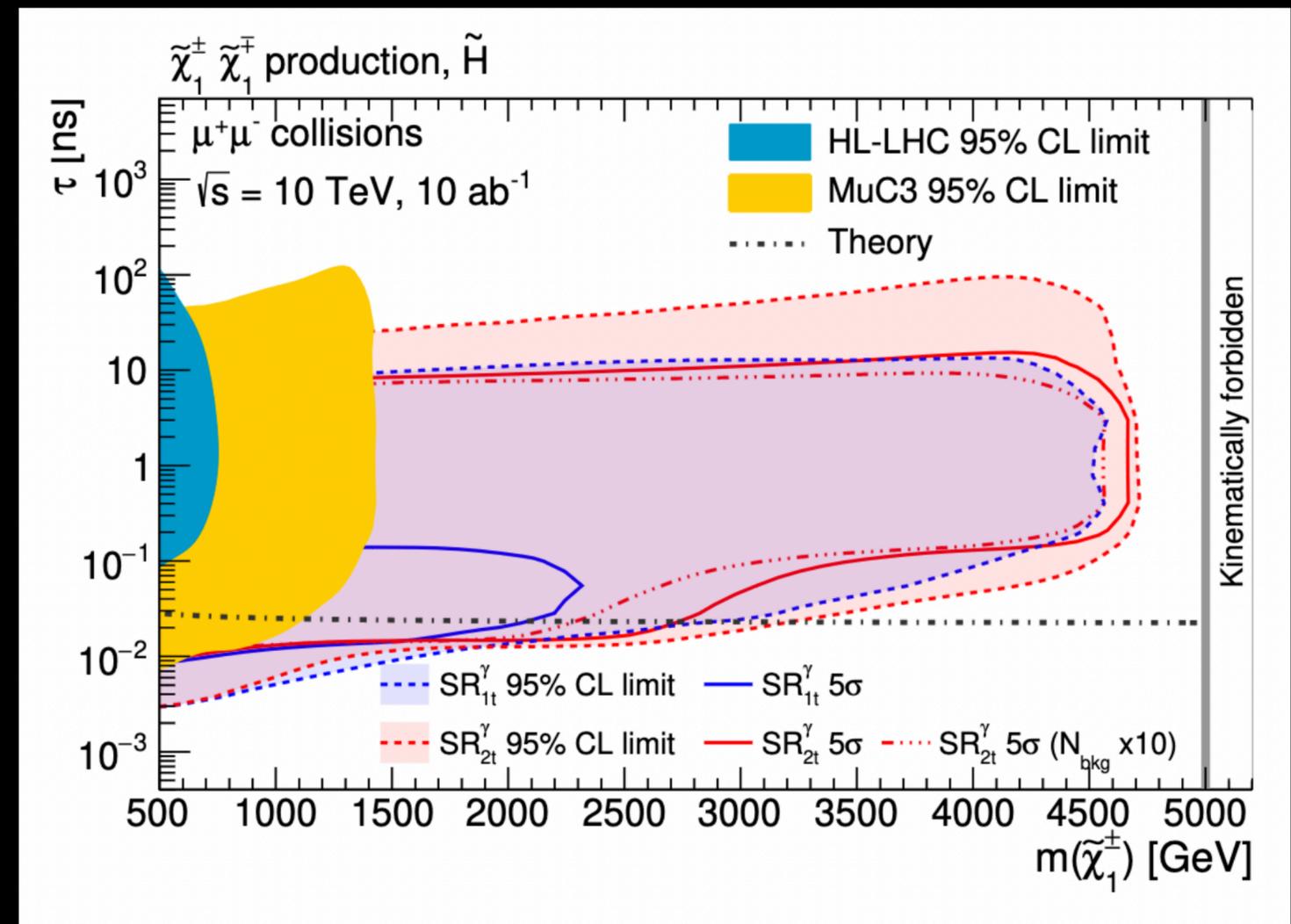
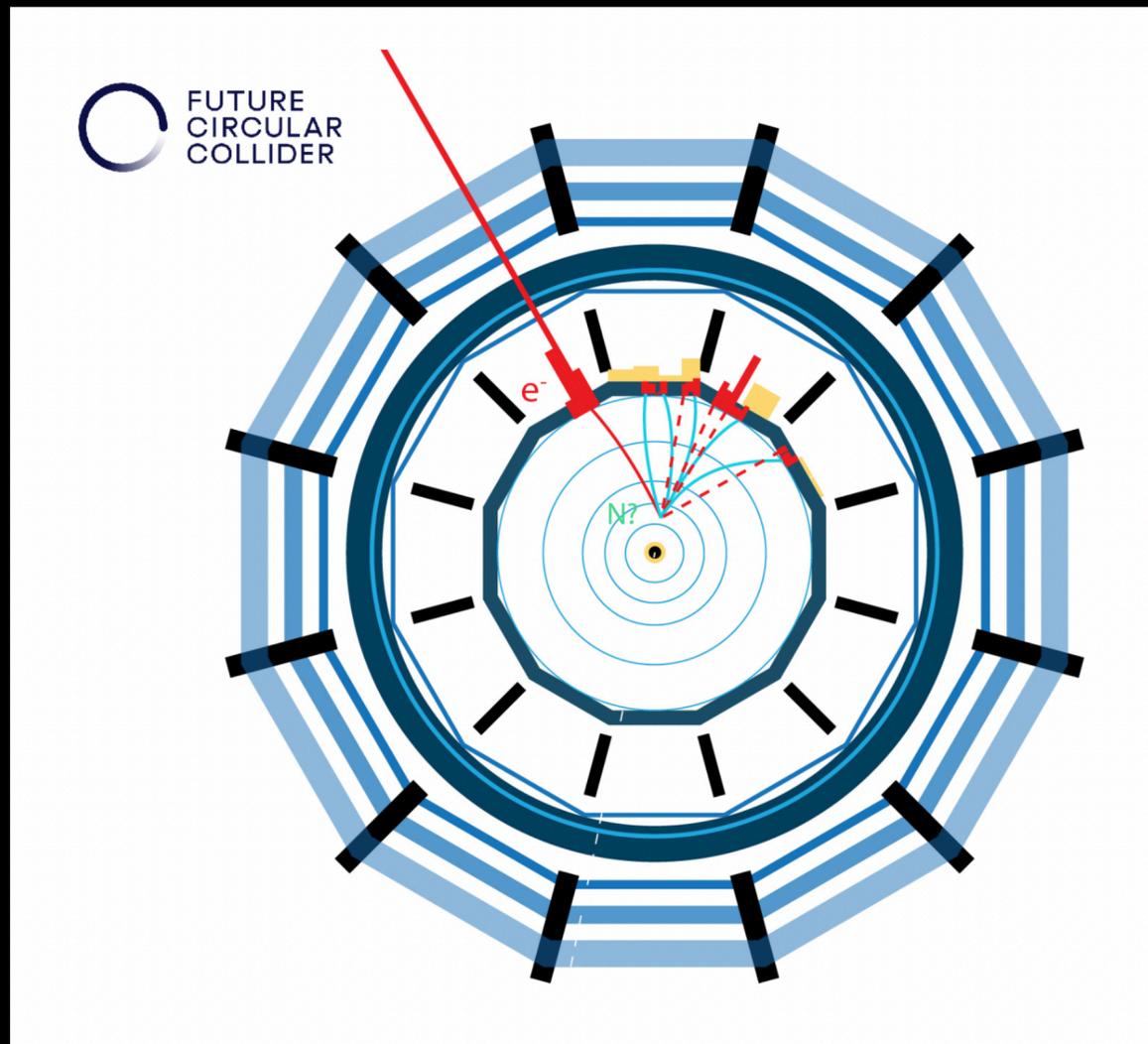
Beam dump experiment on the SPS from 1982, recently with results re-analyzed for BSM signatures



[SciPost Phys. 10 \(2021\) 2, 043](#)

[SciPost Phys. 13 \(2022\) 118](#)

Looking forward to LLPs in the future



Discussions already well underway to ensure LLP signatures are covered at future machines, including digging caverns for very LLPs at FCC, both ee and hh
[Snowmass study for FCC-ee](#); [CLIC](#)

See also: DELIGHT, FOREHUNT for FCChh

Disappearing tracks at a future Muon Collider at 10 TeV
[JHEP 06 \(2021\) 133](#)

We're in a new era of particle physics

Big open questions but no big, obvious hints

Embrace and celebrate the fact that
experimental collider physics is cartography

We need to look everywhere (like astronomy)

What ~~are~~ were we missing? *The lifetime frontier*

The next few years and decades will be exciting

END

