Searches for long-lived particles around the globe

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Duke University

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Where are the new discoveries in collider physics?

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"If they don't find anything else [at the LHC], they're finished."

— *Prominent non-collider physicist & Nobel laureate*

Where are the new discoveries in collider physics?

Higher-energy machine?

$(g-2)_\mu$?

Scalar resonances at 95, 150, 680 GeV?

W mass?

Z decay asymmetries?

Multi-lepton anomalies?

Something else entirely?

Flavor anomalies?

> *"If they don't find anything else [at the LHC], they're finished."*
> *— Prominent non-collider physicist & Nobel laureate*

"Excuse me?" — Me

What is an experimental particle physicist?

Particle hunter

Cartographer

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The task of particle physics is

- ~~To find supersymmetry~~
- ~~To find dark matter~~
- ✓ To rule out all possible places where a discovery (i.e., deviation from background) could be hiding

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

Signature first, model second

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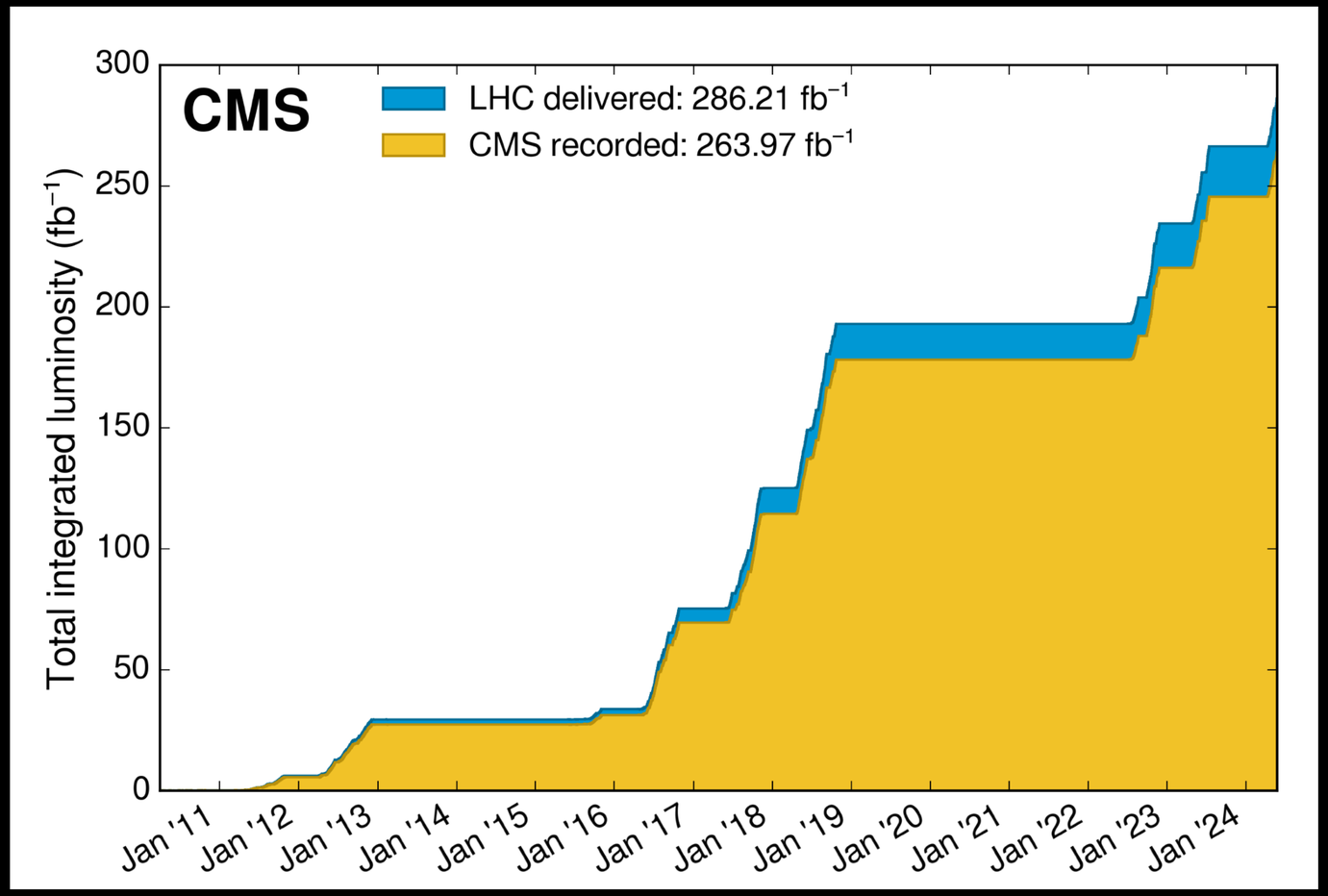
a.k.a.

Signature first, model second

a.k.a.

What are we missing?

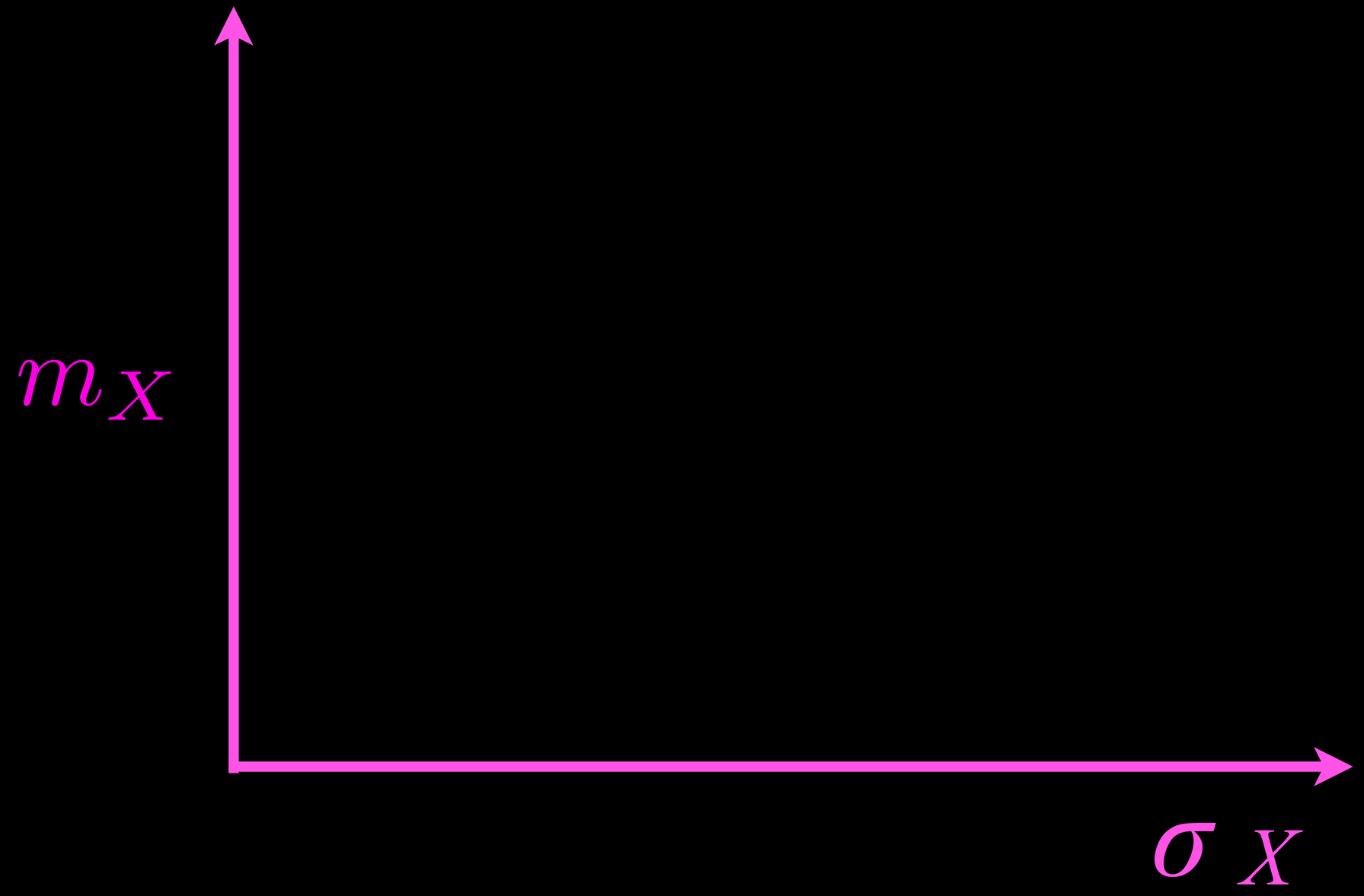
Start with the Large Hadron Collider: The LHC is a big-data exploration machine



Papers as of 26 May 2024	ATLAS	CMS
Exotic(s)(a)	320	241
Supersymmetry	205	140

Heroic amount of data, hundreds of published BSM searches

New physics "X" at colliders



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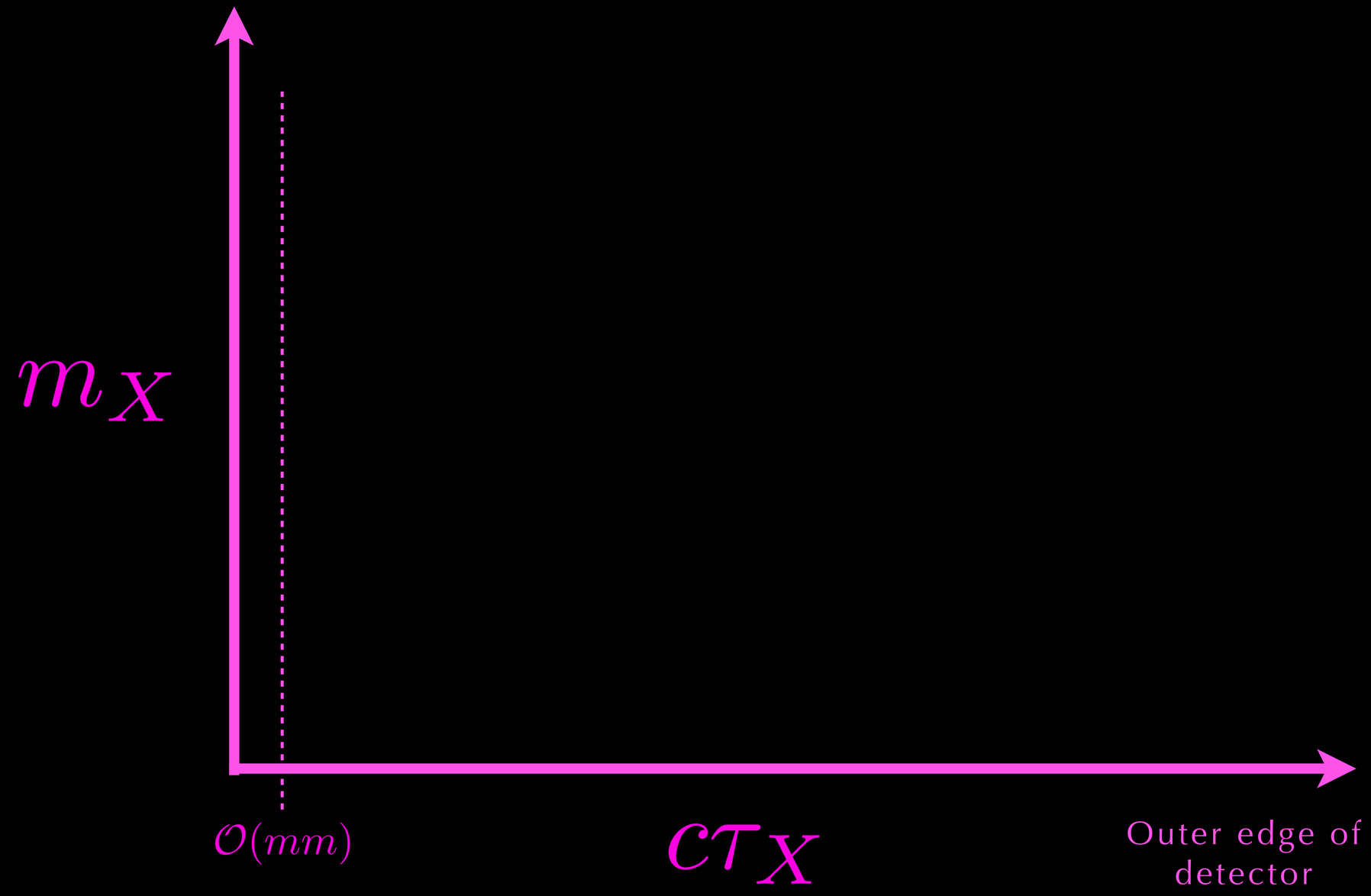

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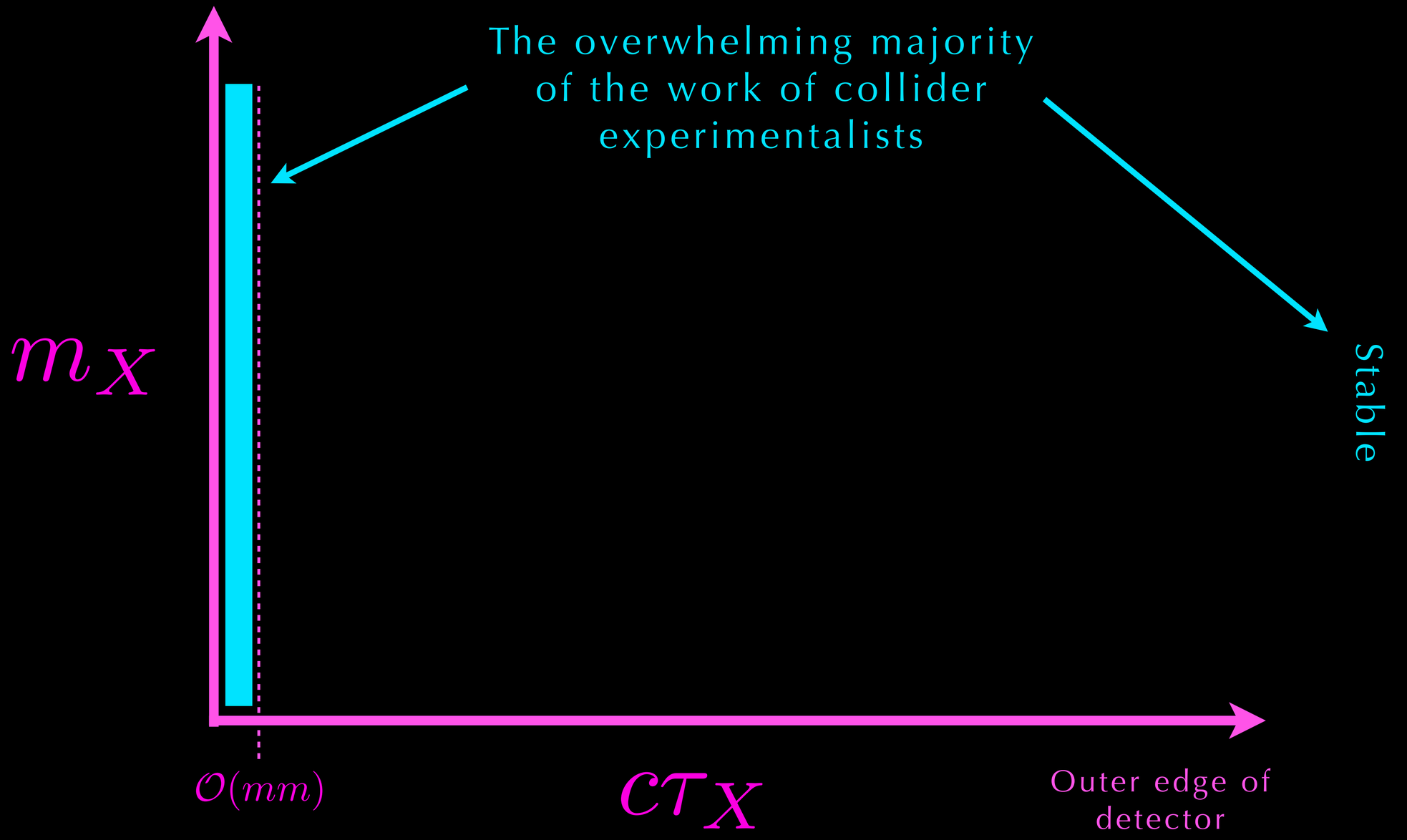

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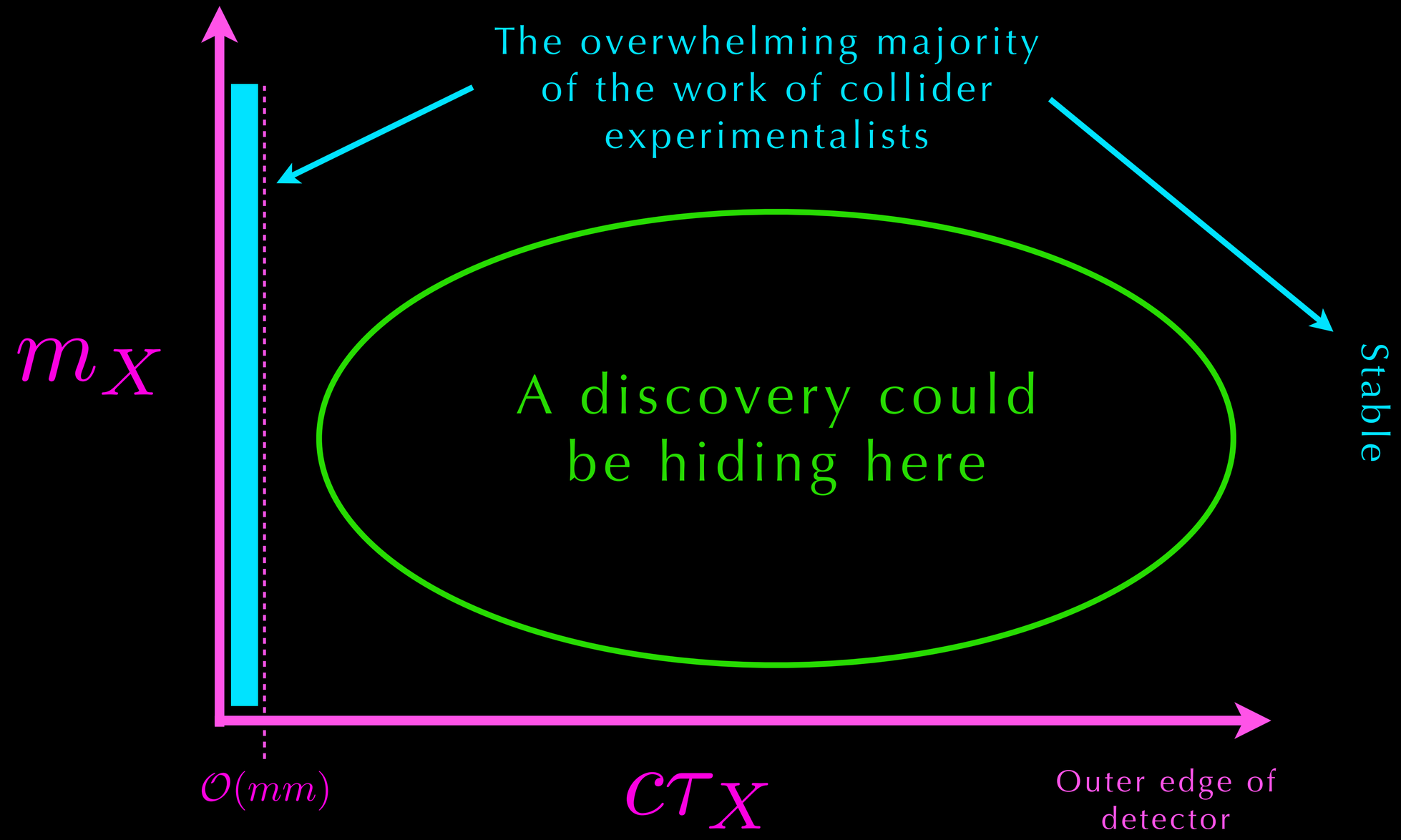
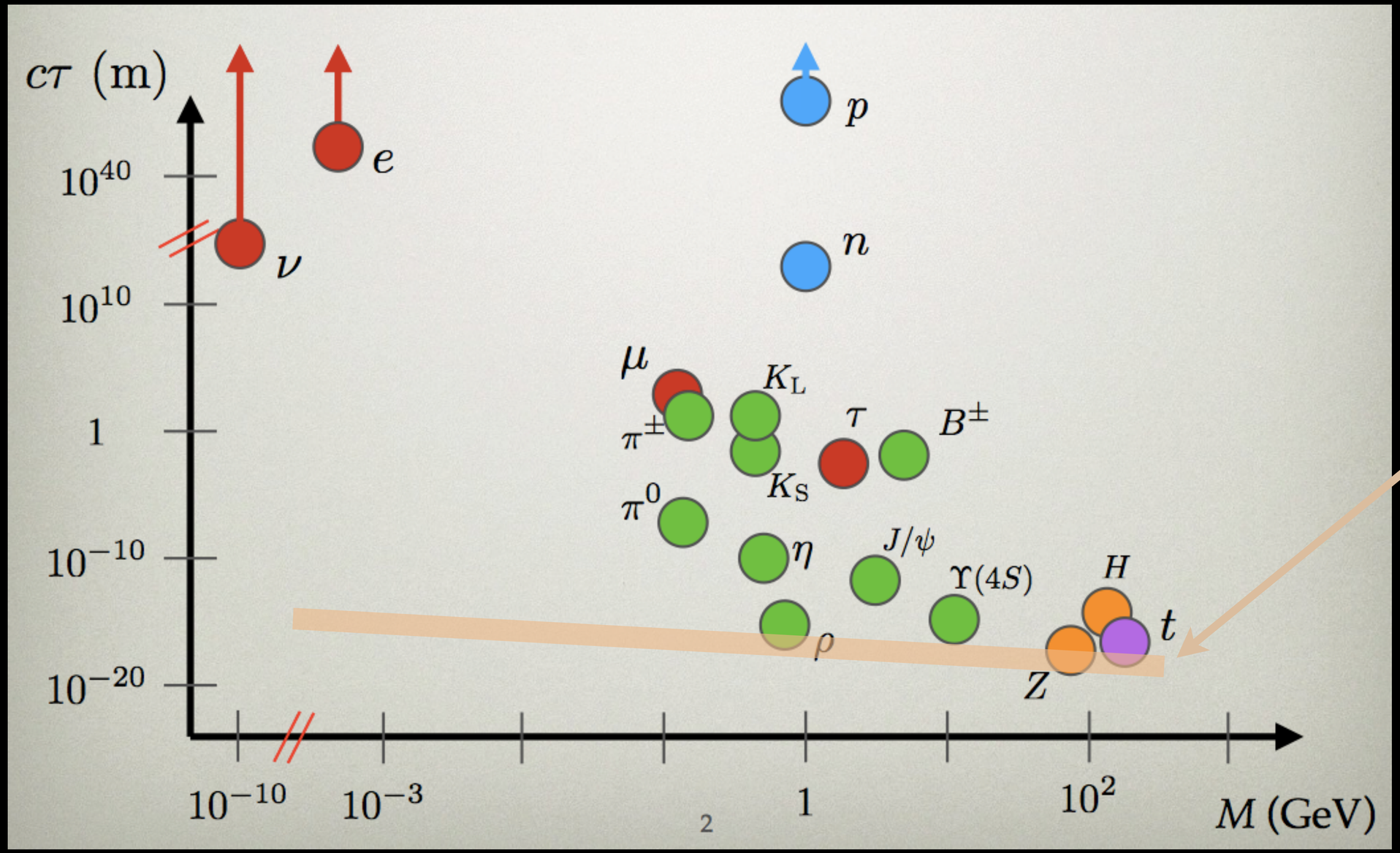


The Standard Model is filled with long-lived particles!

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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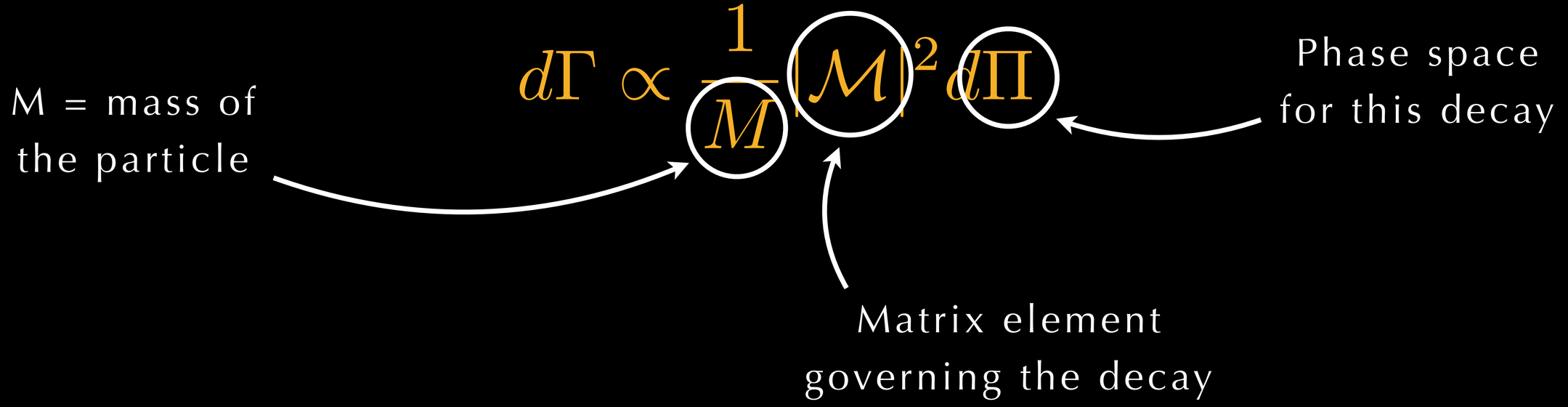

Small right side —> long-lived particle

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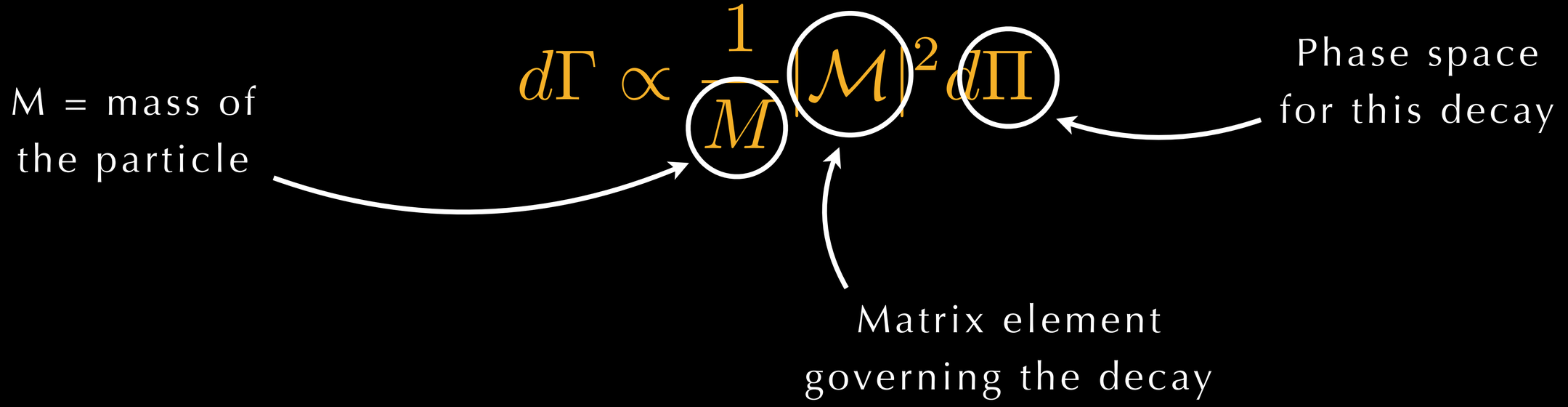


Small right side —> long-lived particle

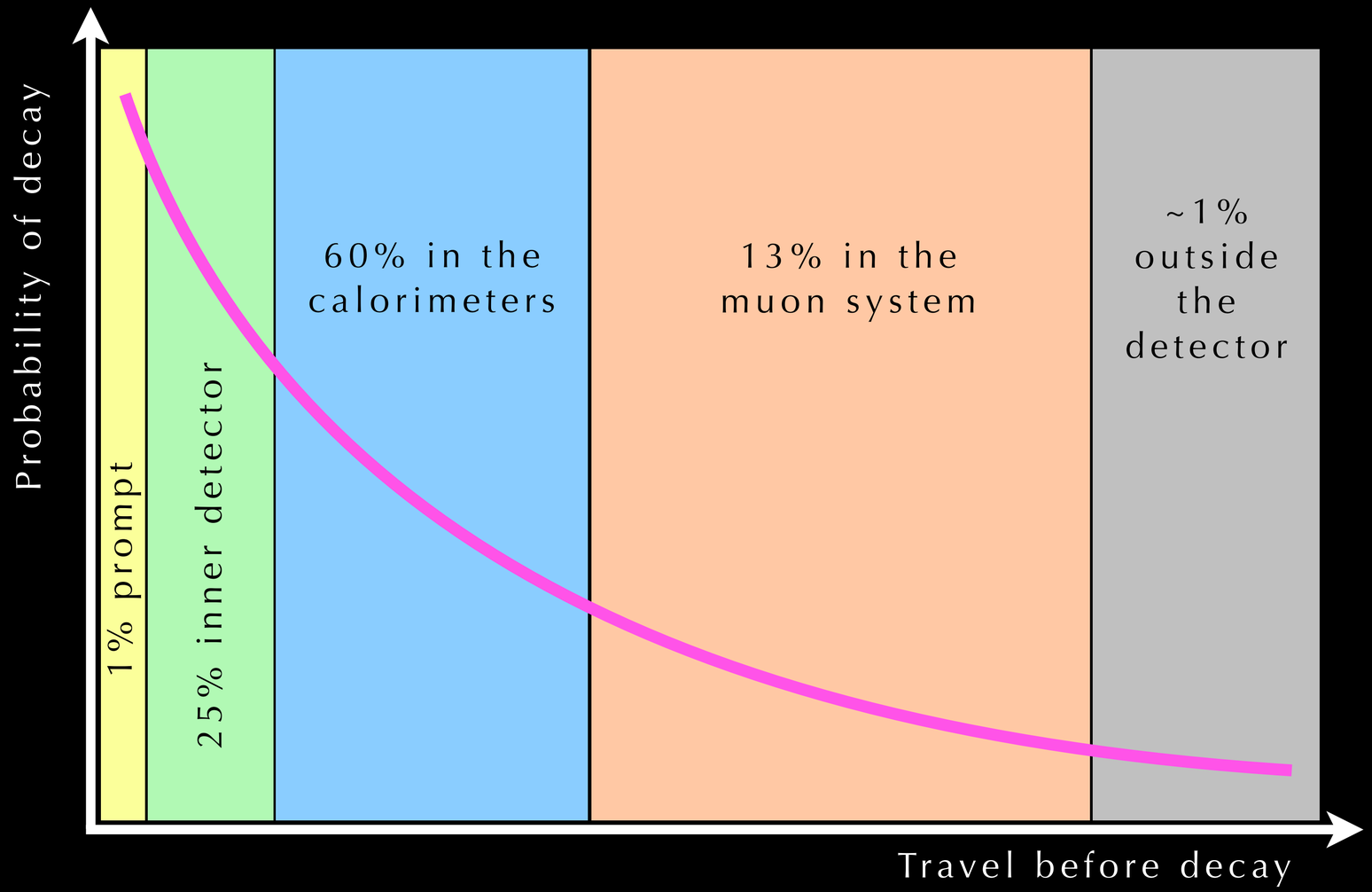
Long lifetimes typically arise in the SM when *approximate symmetries* make the particle stable — same principles generically apply in BSM theories

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, cτ)

$c\tau = 5$ cm

$\langle \beta\gamma \rangle \sim 30$



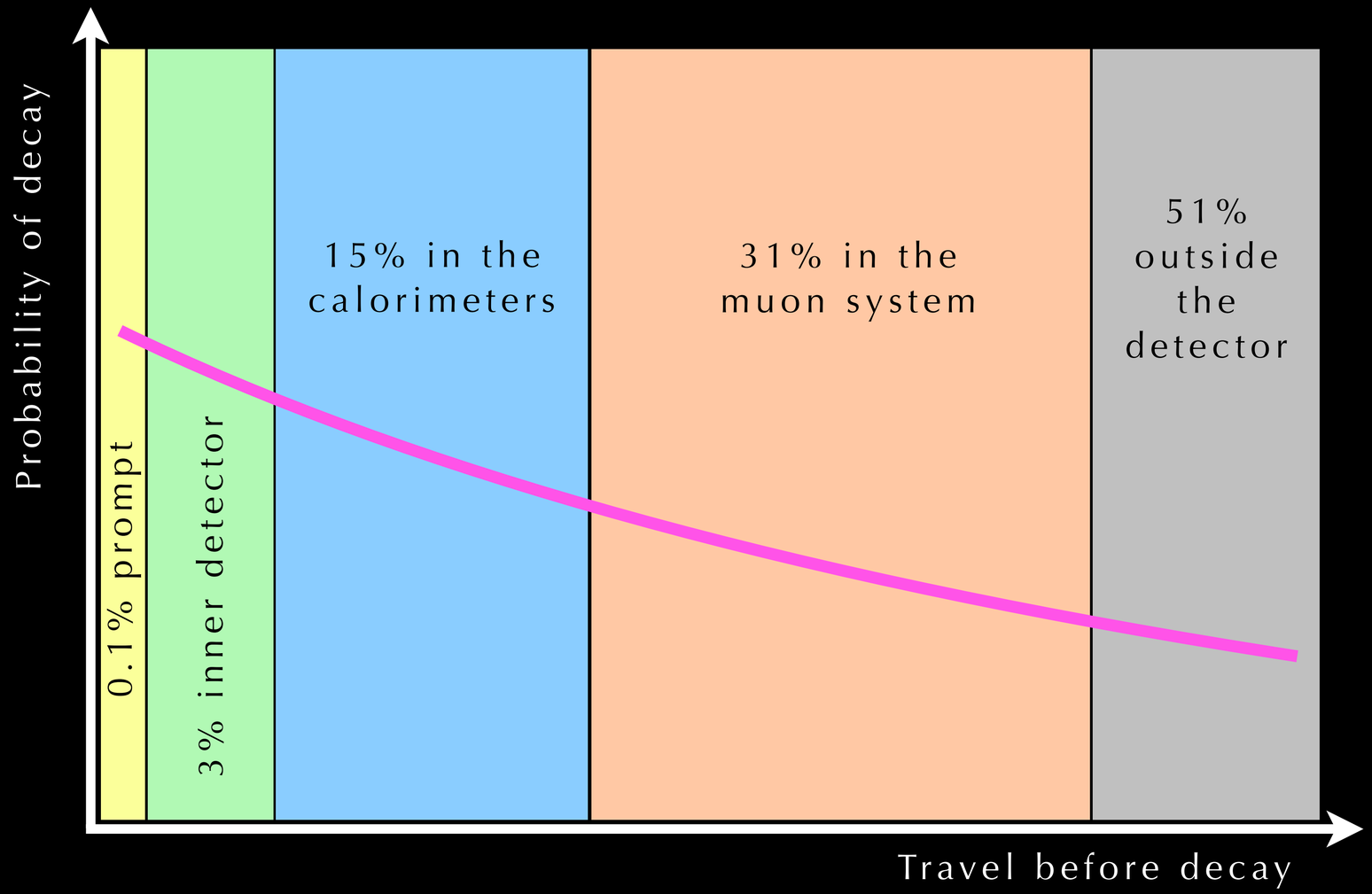
As a result, we use multiple search strategies targeting all subdetectors of ATLAS, CMS, and LHCb — and beyond the detectors

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, cτ)

$c\tau = 50$ cm

$\langle \beta\gamma \rangle \sim 30$



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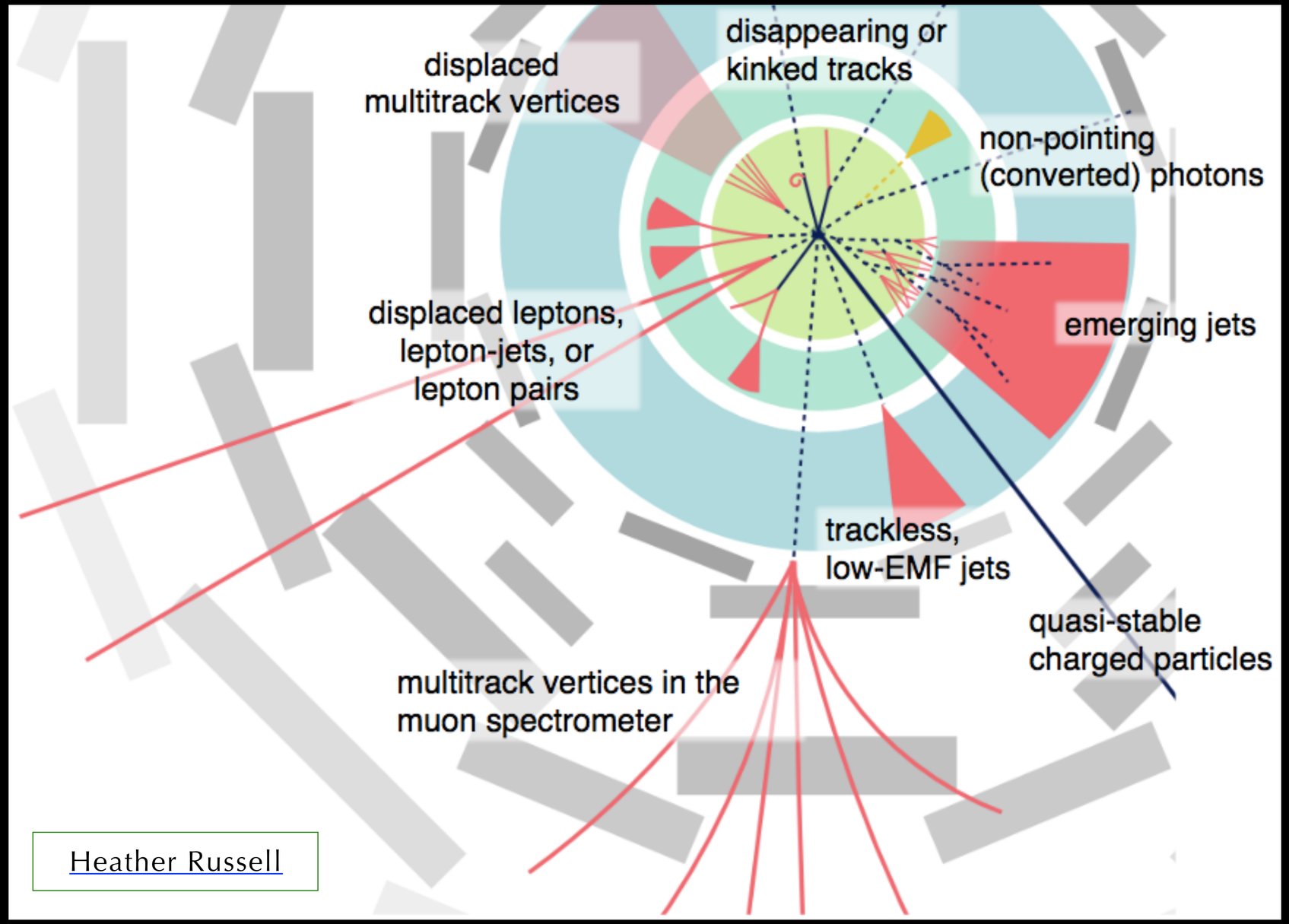
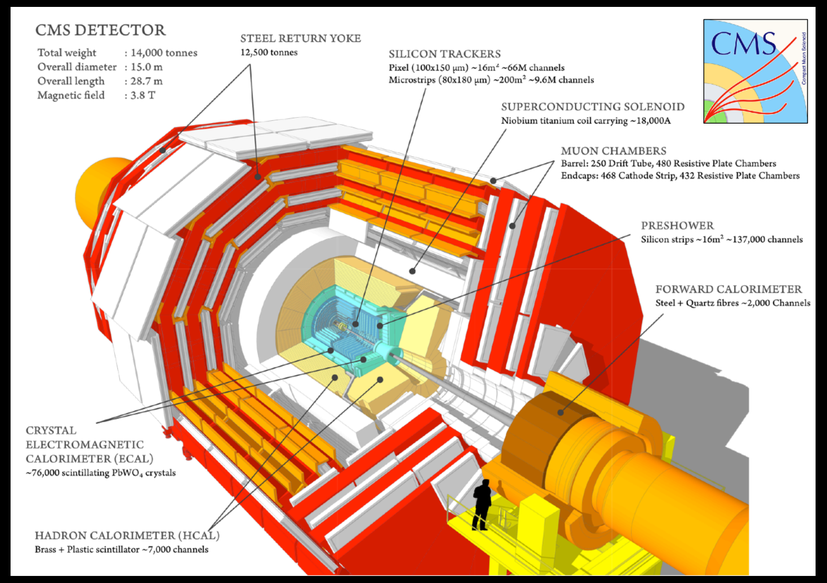
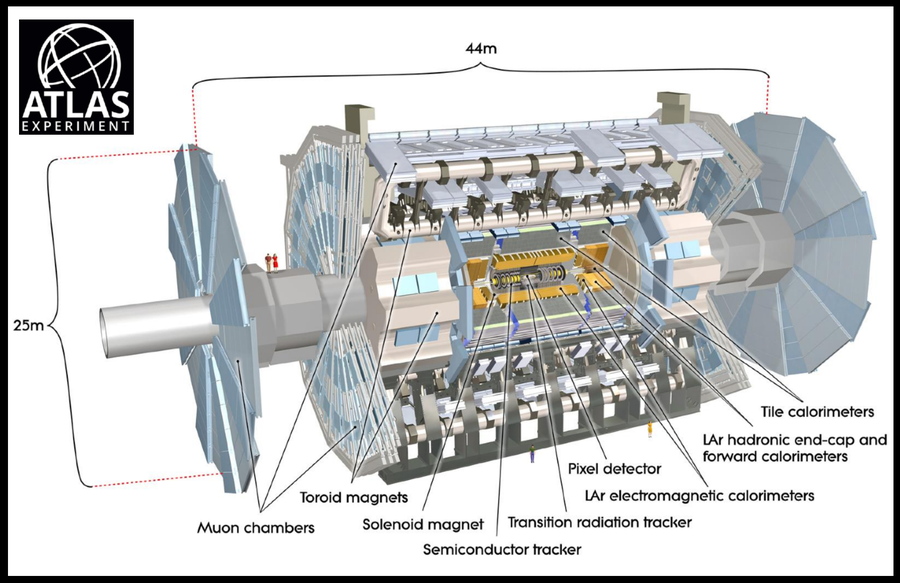
Long-lived particles mean many atypical detector objects

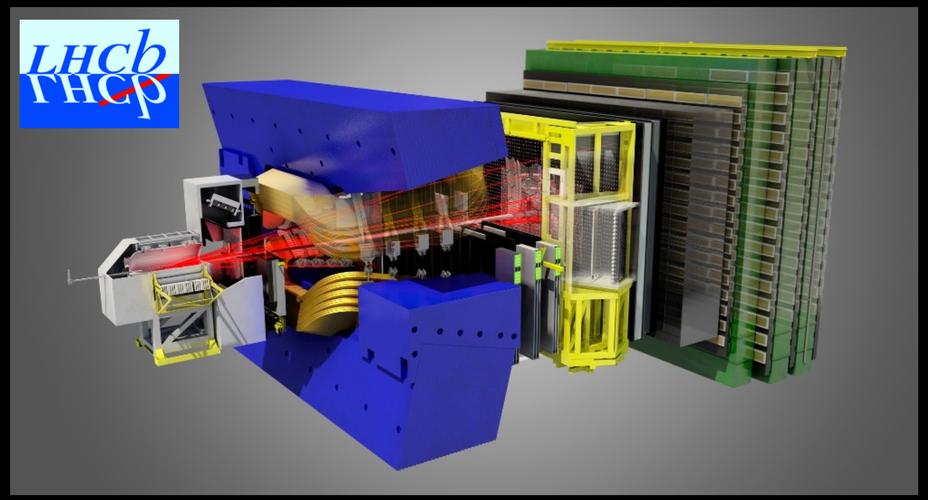


The central detectors of the LHC



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





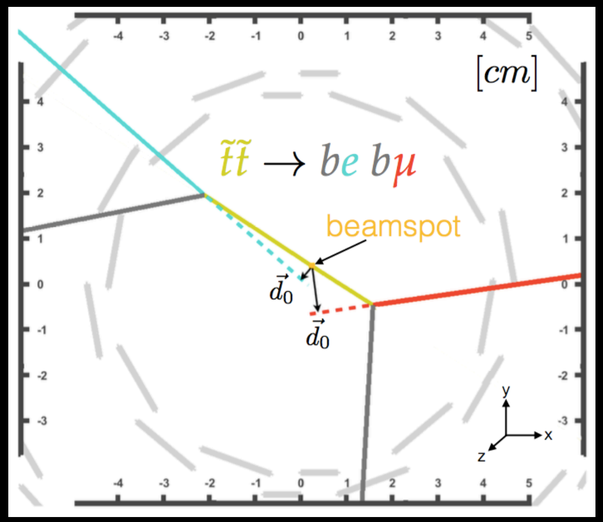
LHCb designed for precision measurements of b-hadrons

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

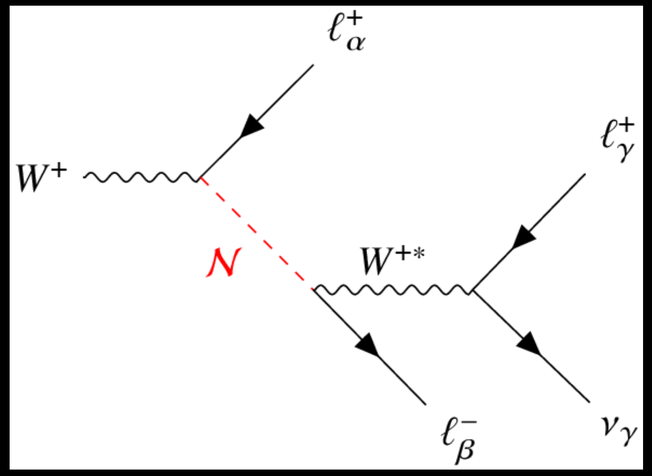
Neutral LLPs decaying to leptons

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-d0 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

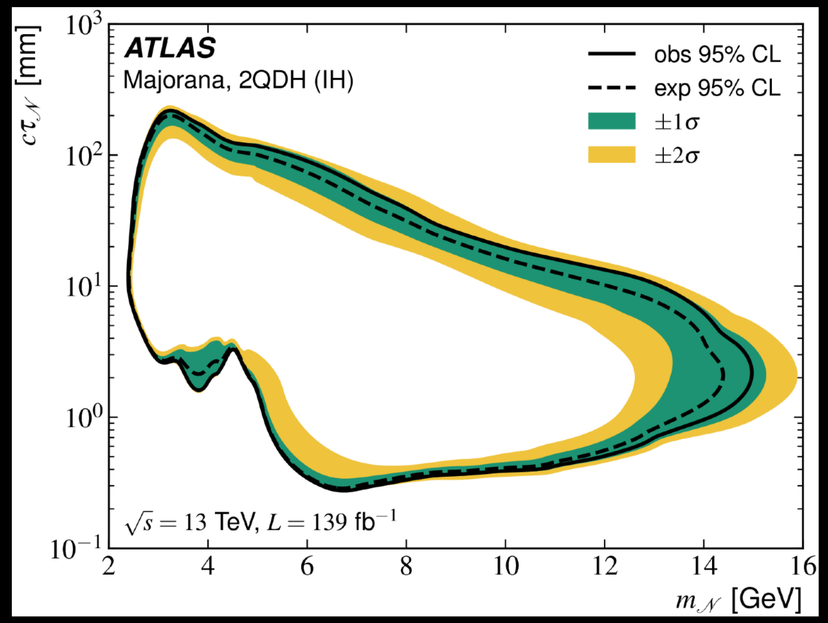


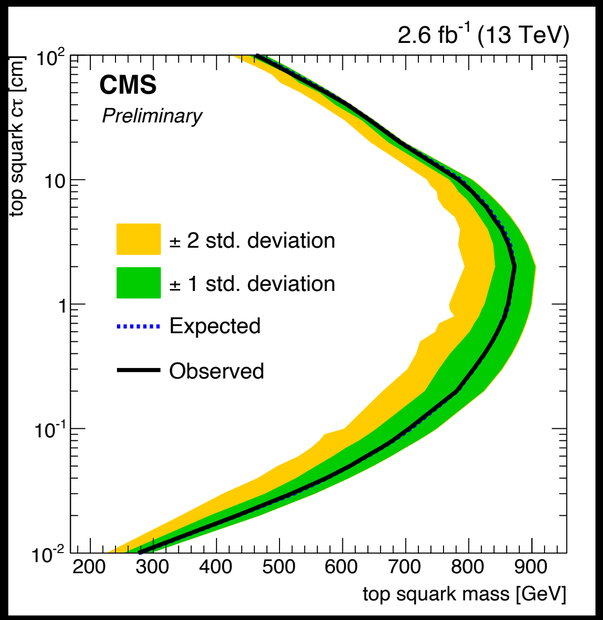
CMS-EXO-16-022



ATLAS (April 2022) PRL 131 (2023) 6, 061803

CMS (Jan. 2022) JHEP 07 (2022) 081

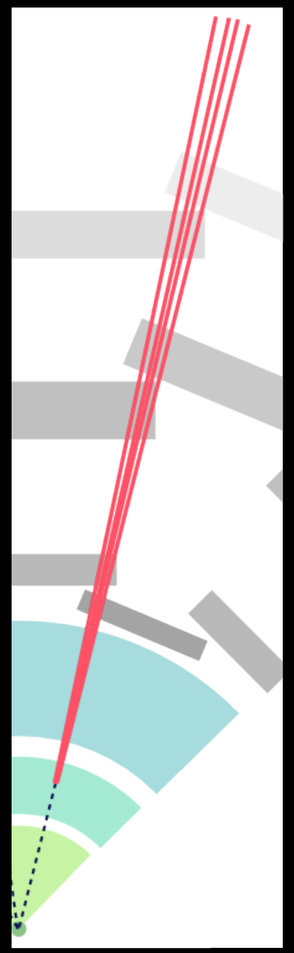




Neutral LLPs decaying to lepton-jets

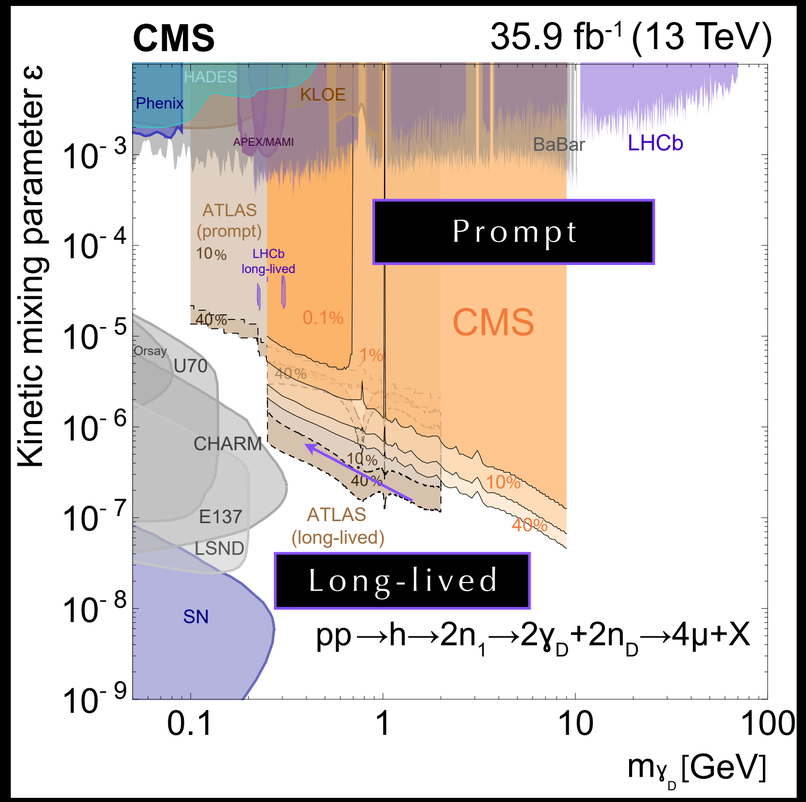
Lepton-jet = highly-collimated grouping of leptons from a low-mass (O(GeV)), boosted BSM particle like a dark photon / Z_{dark}

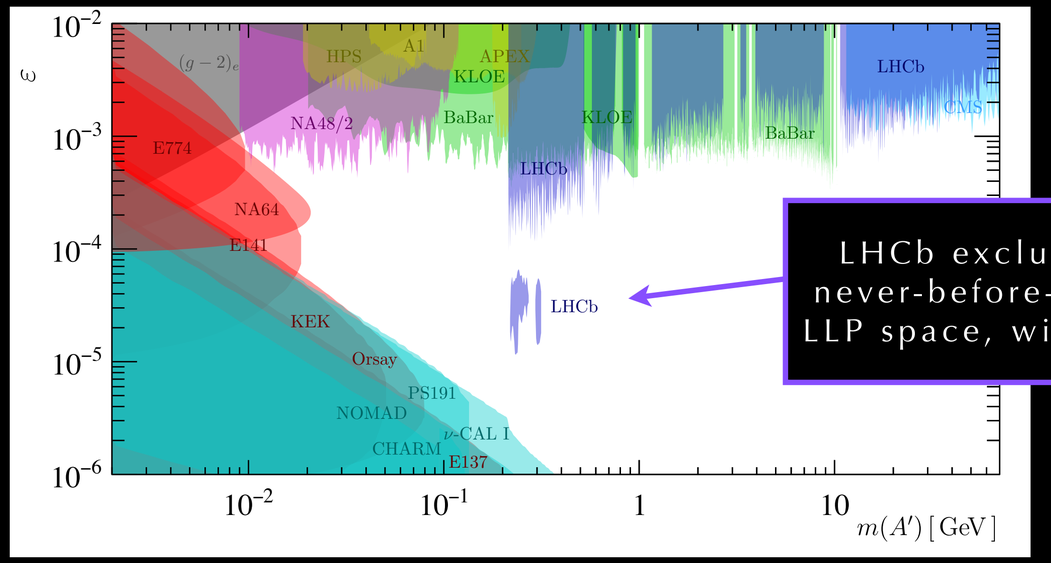
- Confounds standard lepton isolation criteria



PLB 796 (2019) 131

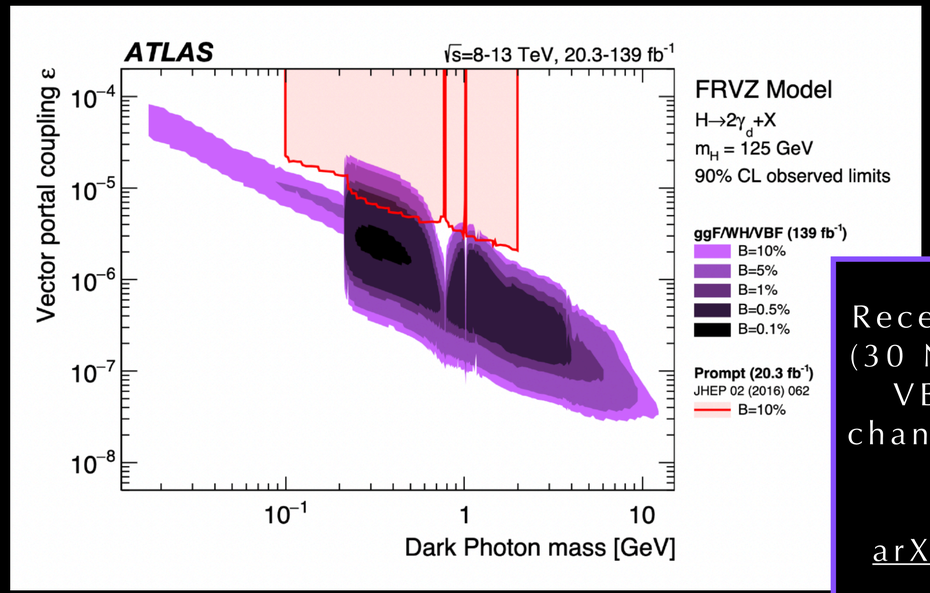
ATLAS-CONF-2016-042





LHCb exclusion in never-before-covered LLP space, with 5.5/fb

LHCb: PRL 124, 041801 (2020)

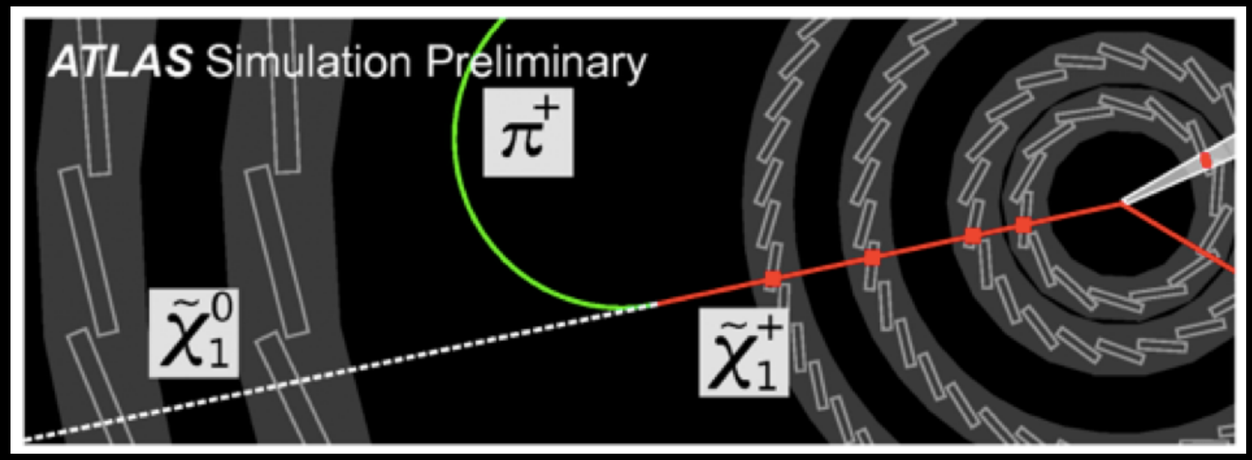


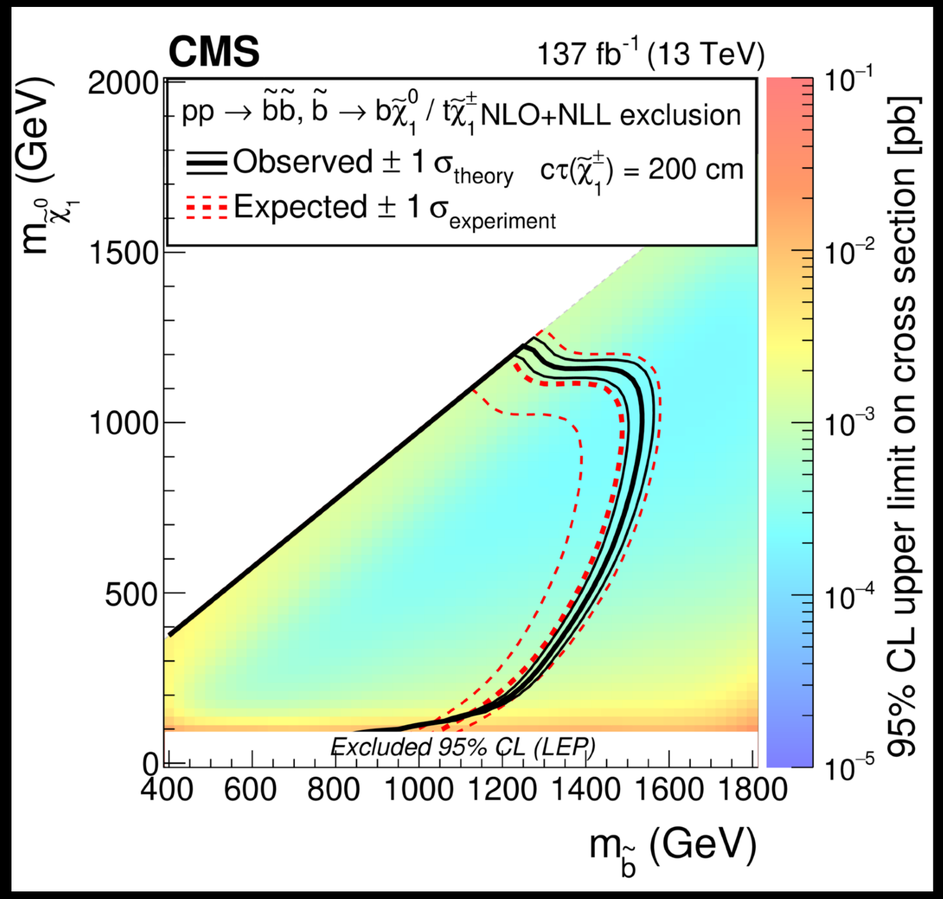
Recent ATLAS result (30 Nov. 2023) adds VBF production channel and extends mass range

arXiv:2311.18298

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 (public Sept. 2023) sets limits in the context of a particular SUSY model

PRD 109 (2024) 072007

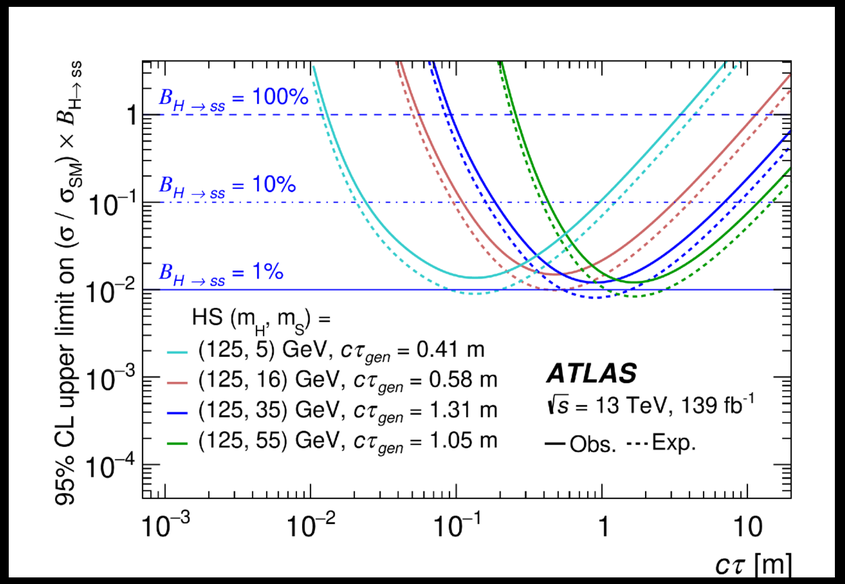
Neutral LLPs decaying to hadronic jets

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

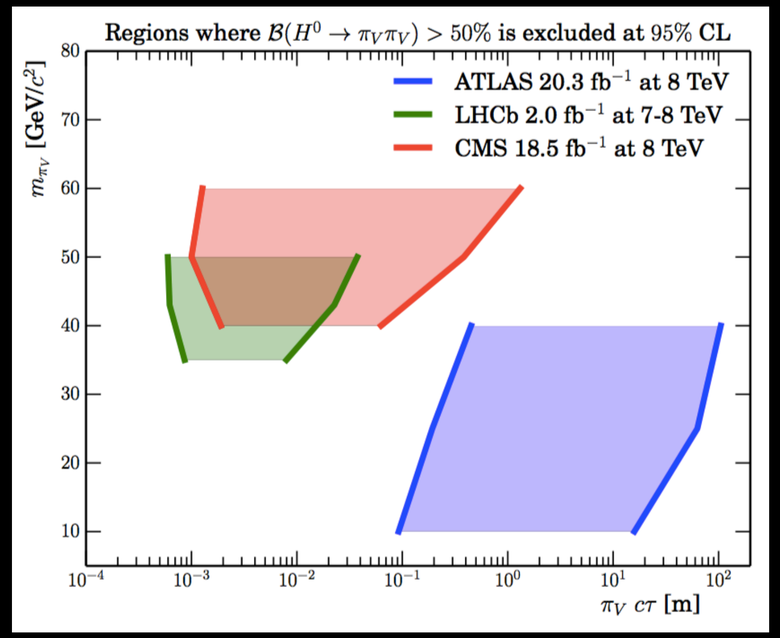
- Inner tracker —> Look for displaced multi-track vertices
- Calorimeters —> Look for large E_{Had} / E_{EM}
- Outer muon system —> Look for MS vertex

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

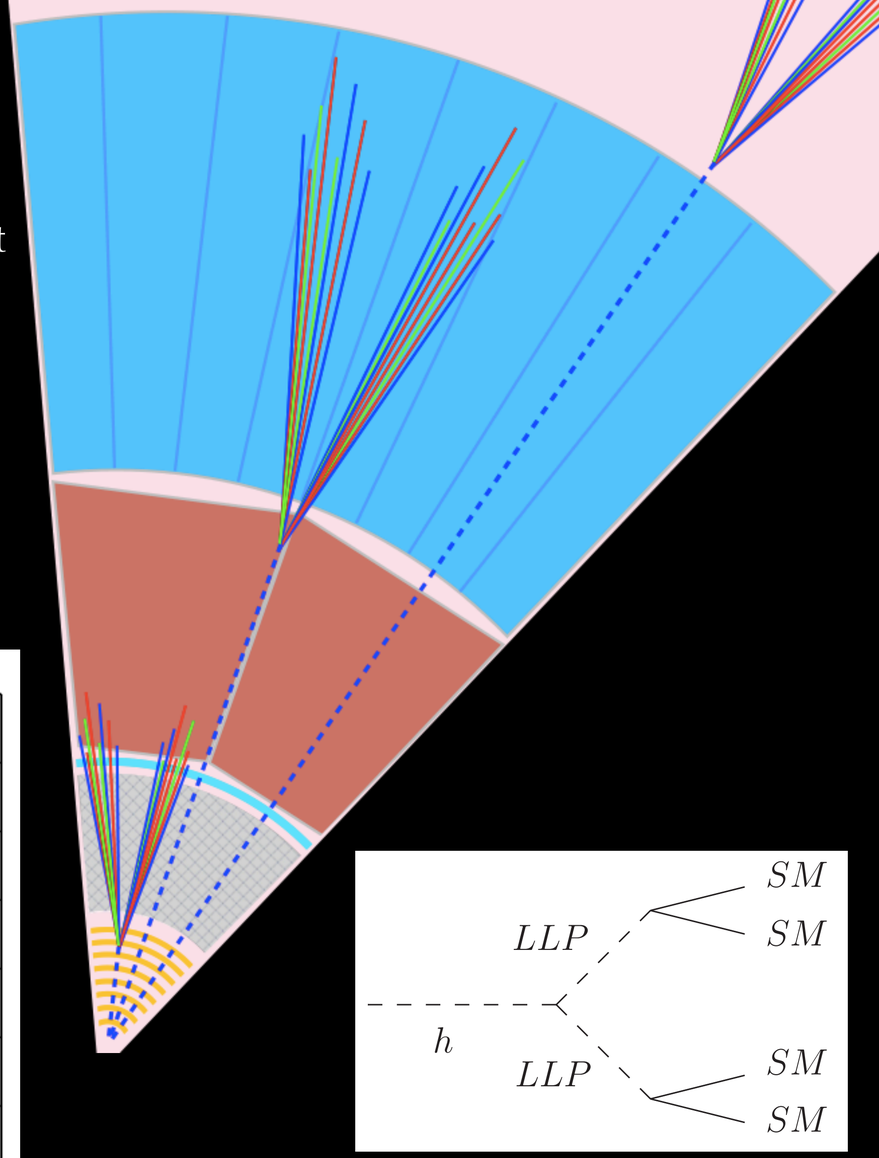
ATLAS, March 2022: JHEP 06 (2022) 005



See also:
CMS: PRD 104 (2021) 1, 012015

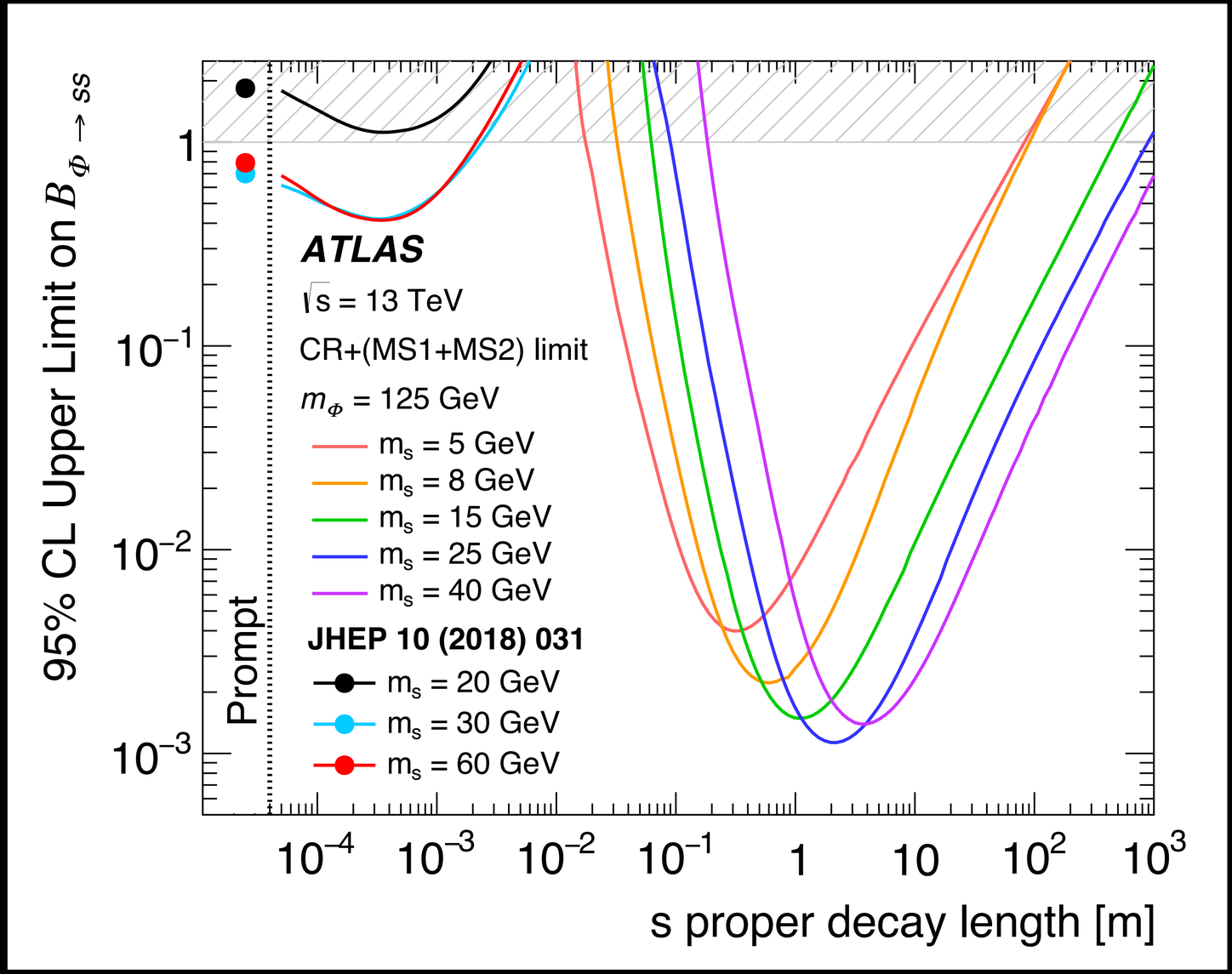


LHCb: EPJC 77 (2017) 812



One benchmark scenario:
h125 —> 2xLLP —> jets

Where do prompt and long-lived searches meet?



2018

JHEP 10 (2018) 031

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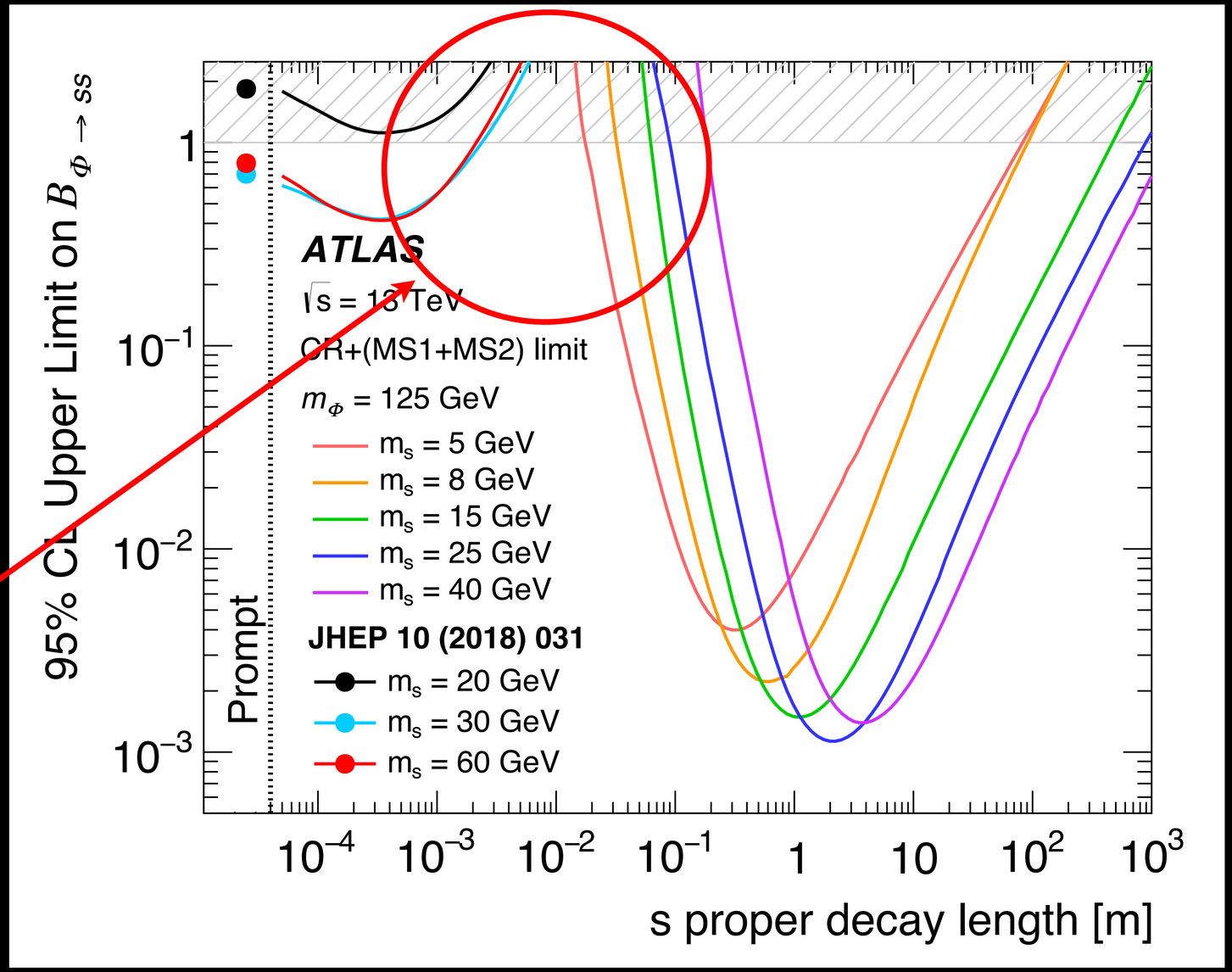

A discovery could be hiding here!

2018

JHEP 10 (2018) 031

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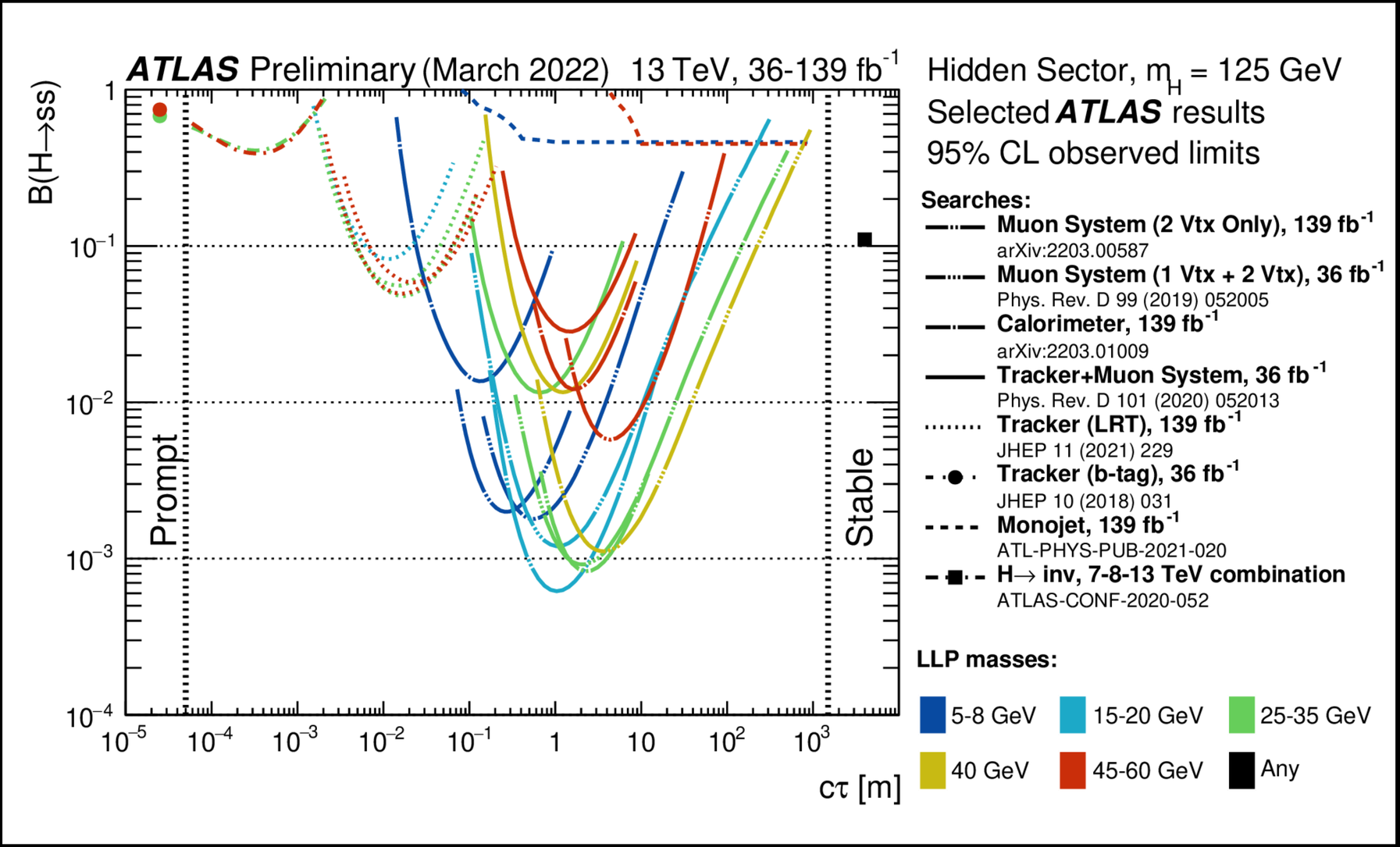

2022

ATLAS LLP summary plots

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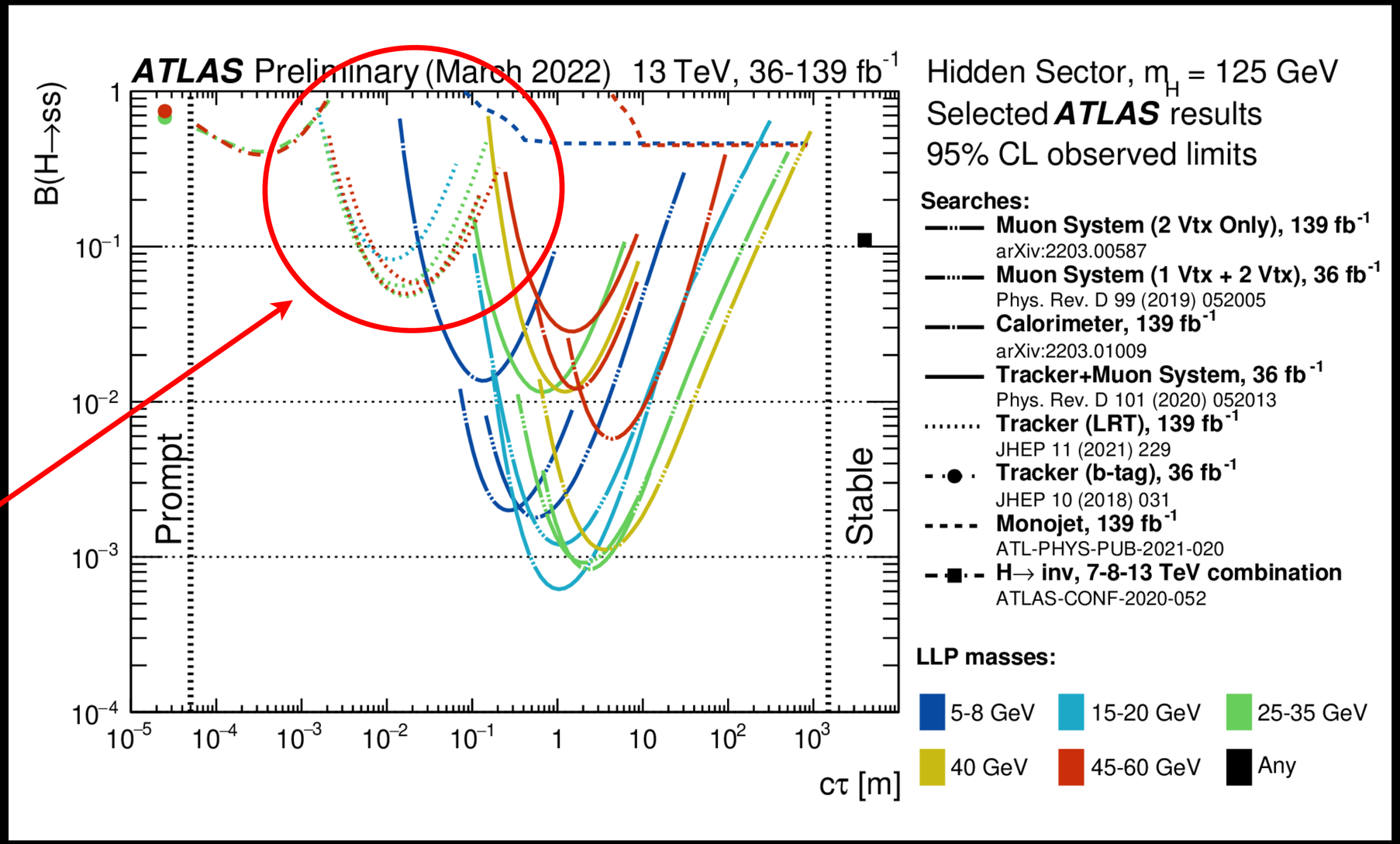

Starting to plug this hole!

2022

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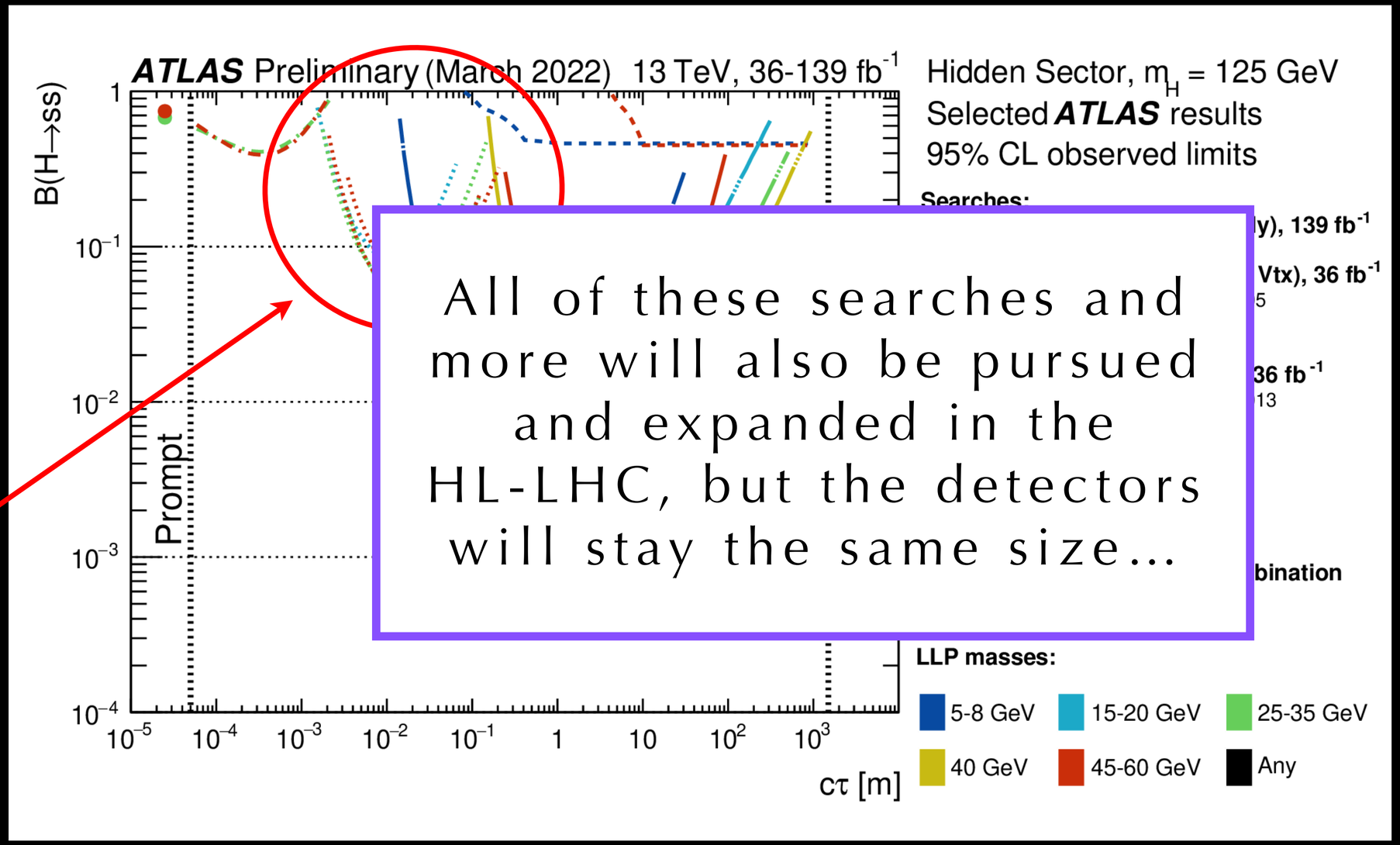


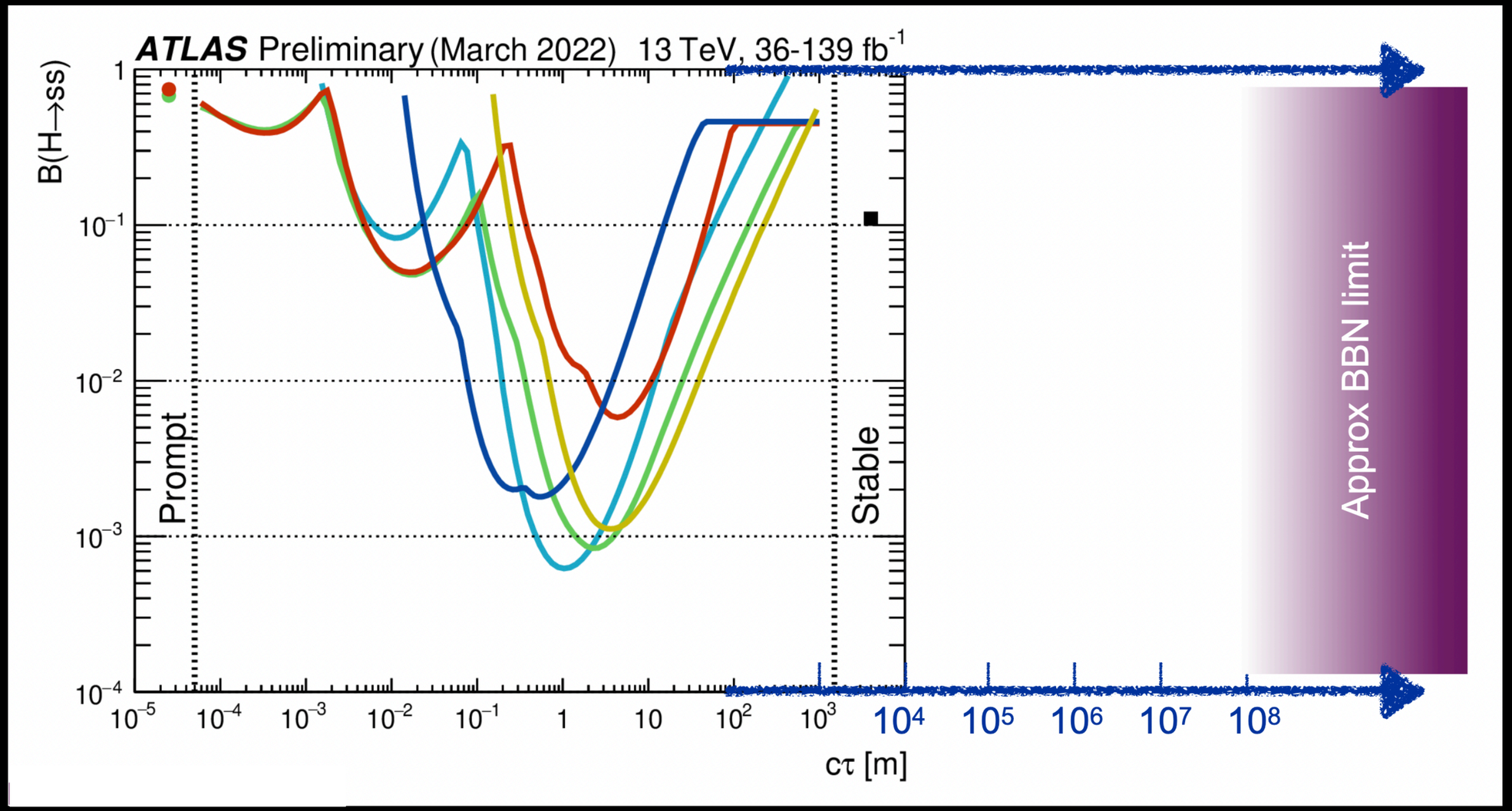
All of these searches and more will also be pursued and expanded in the HL-LHC, but the detectors will stay the same size...

Starting to plug this hole!

2022

ATLAS LLP summary plots

Very long-lived particles at the LHC



L. Corpe

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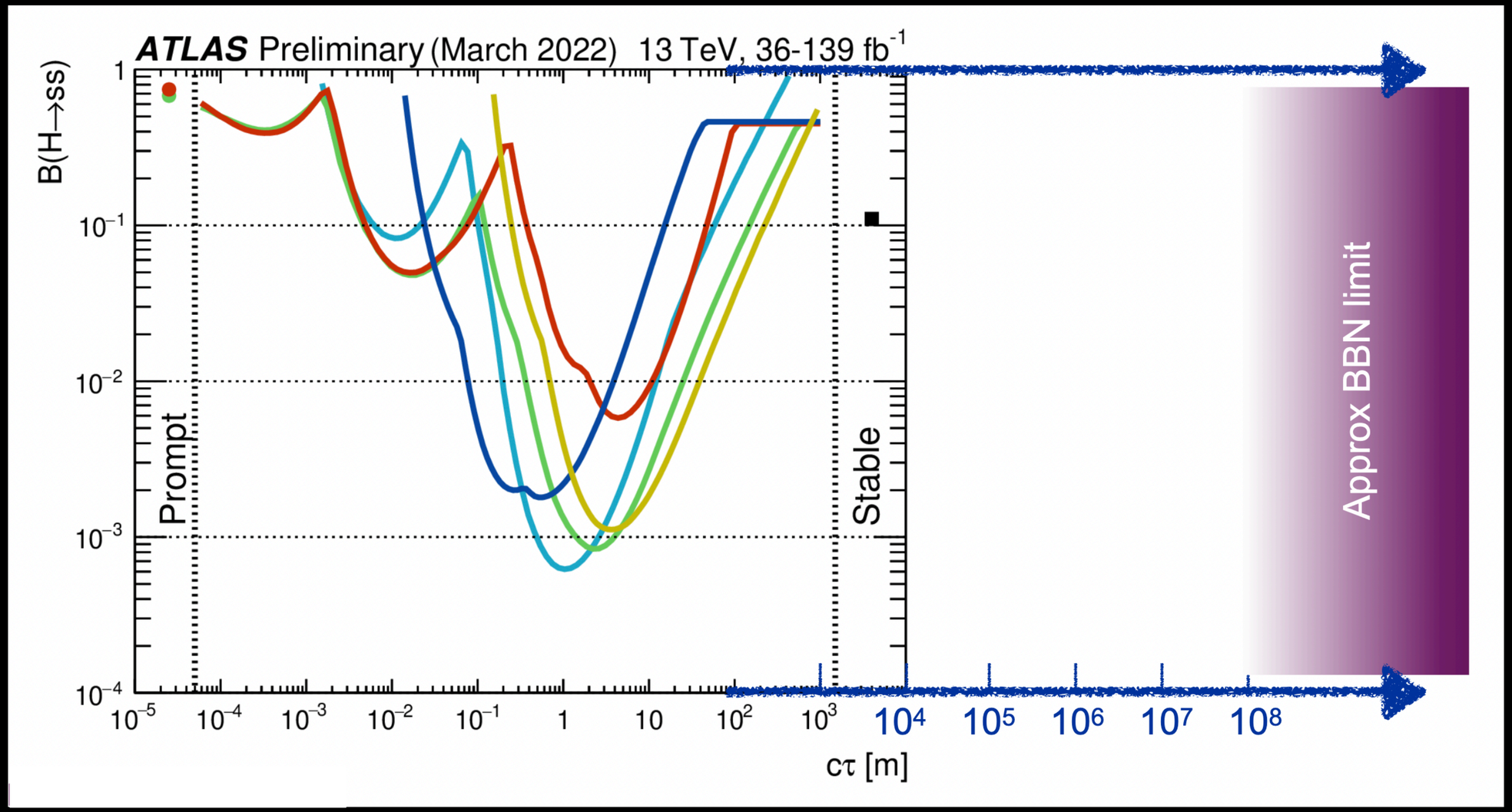
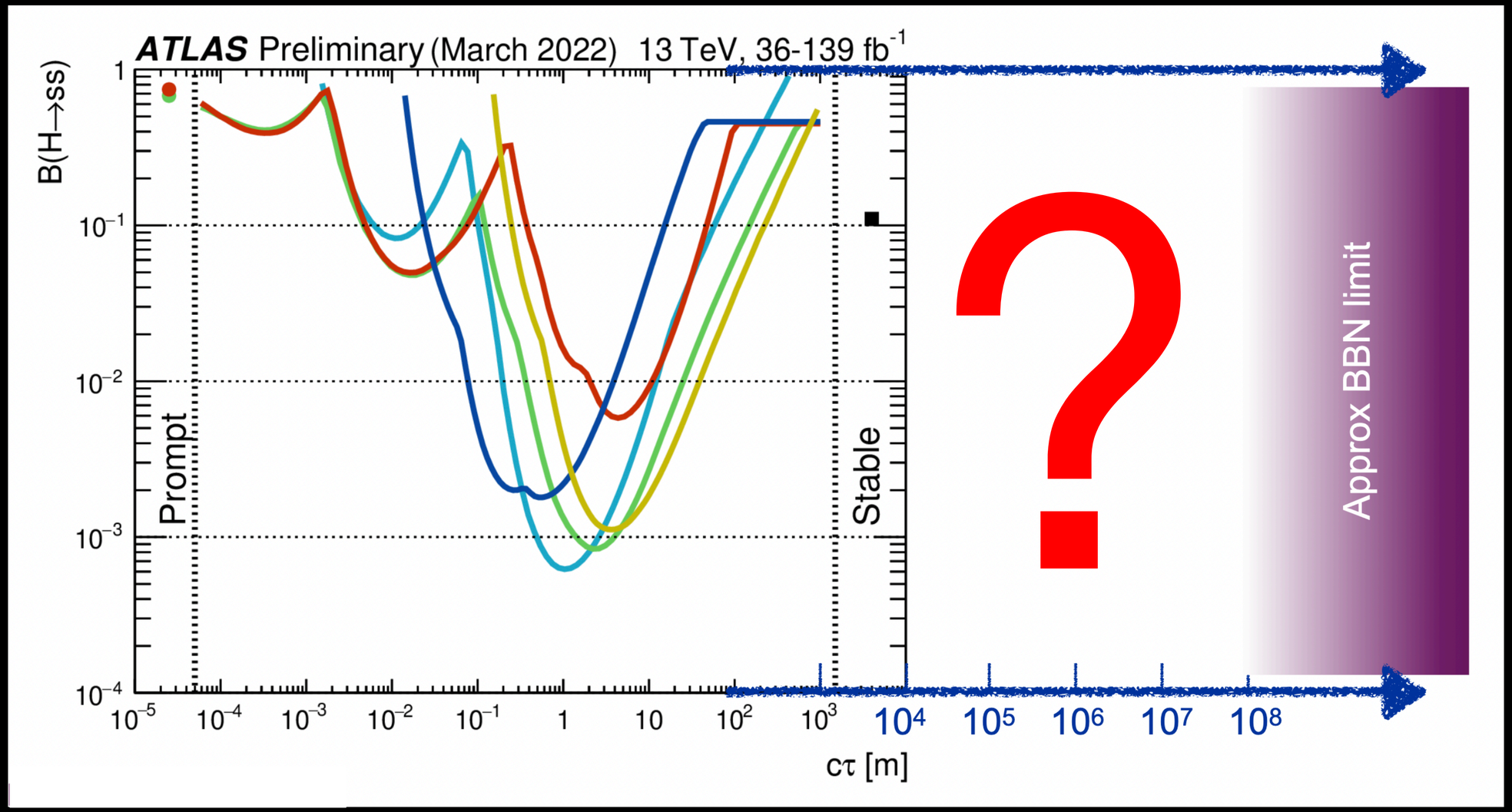


L. Corpe

Outer edge of ATLAS

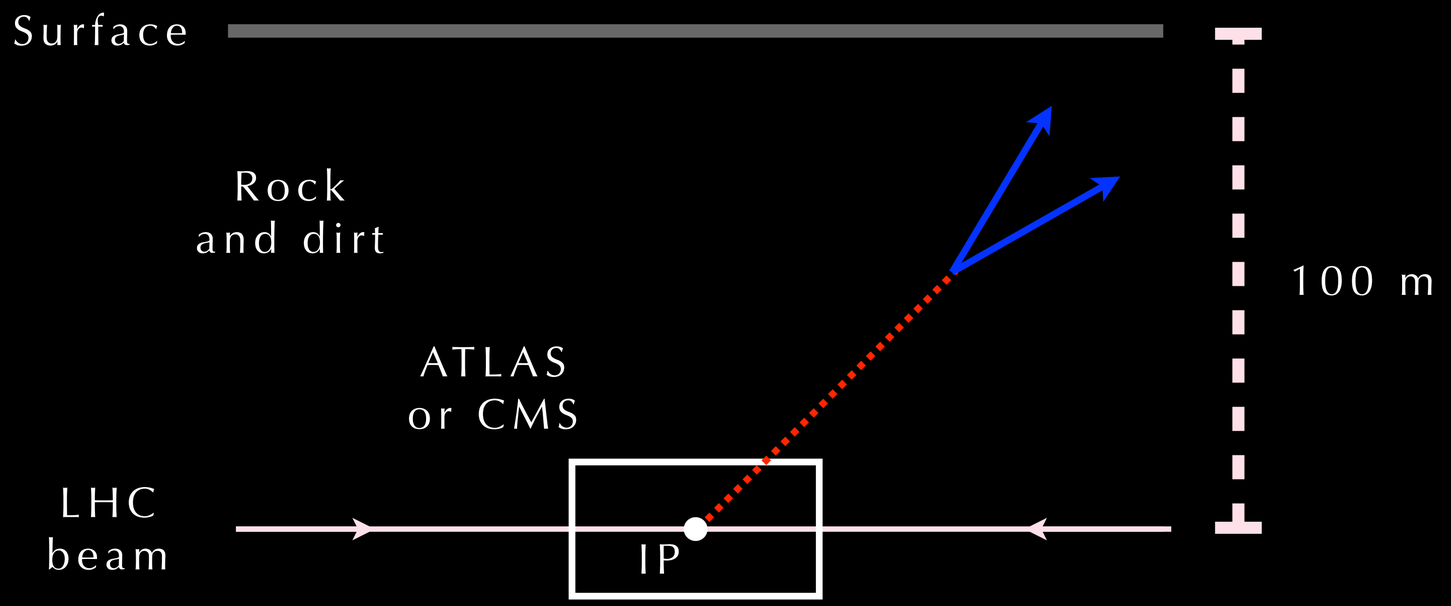
Very long-lived particles at the LHC



L. Corpe

Outer edge of ATLAS

Dedicated detectors for very long-lived particles at the LHC



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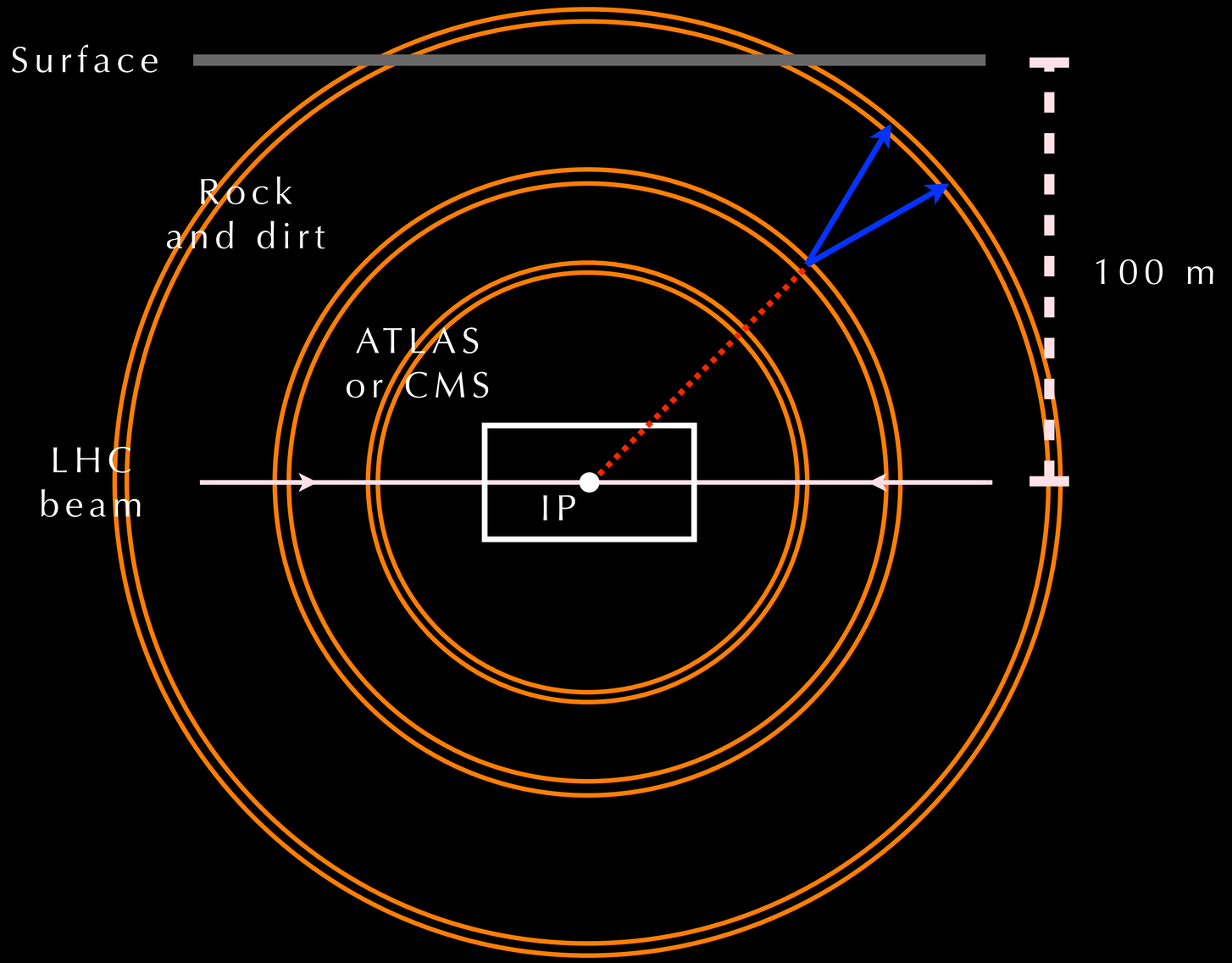

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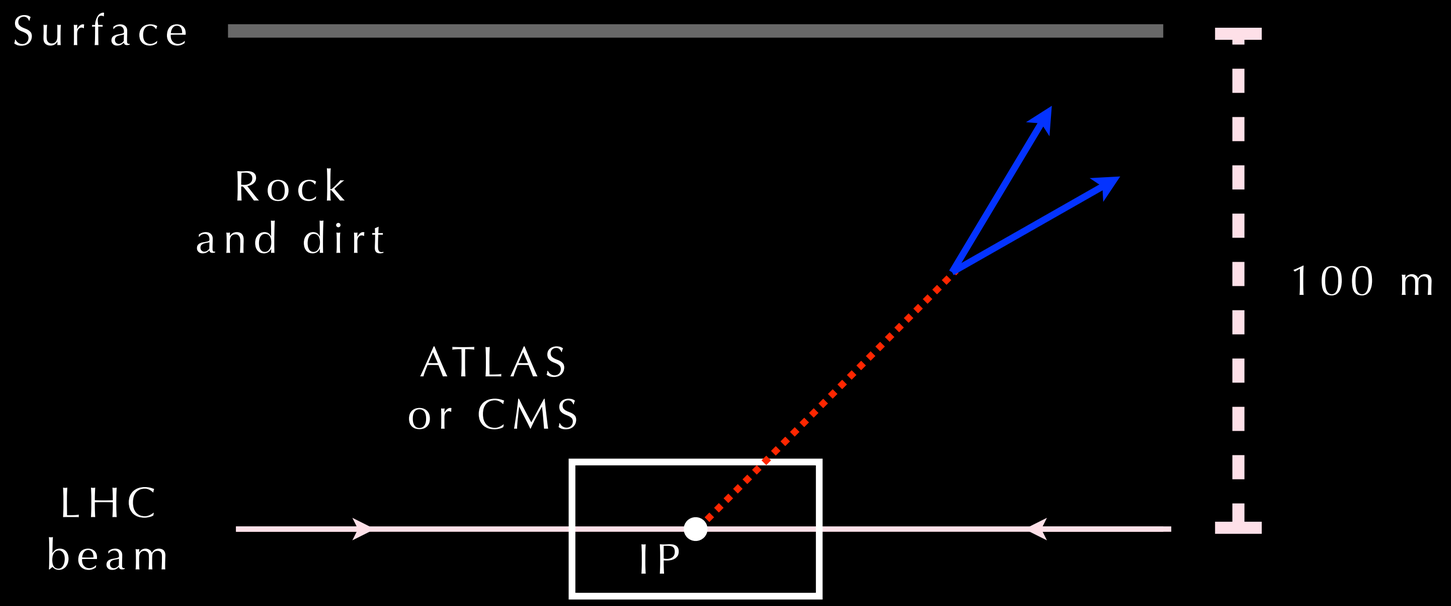

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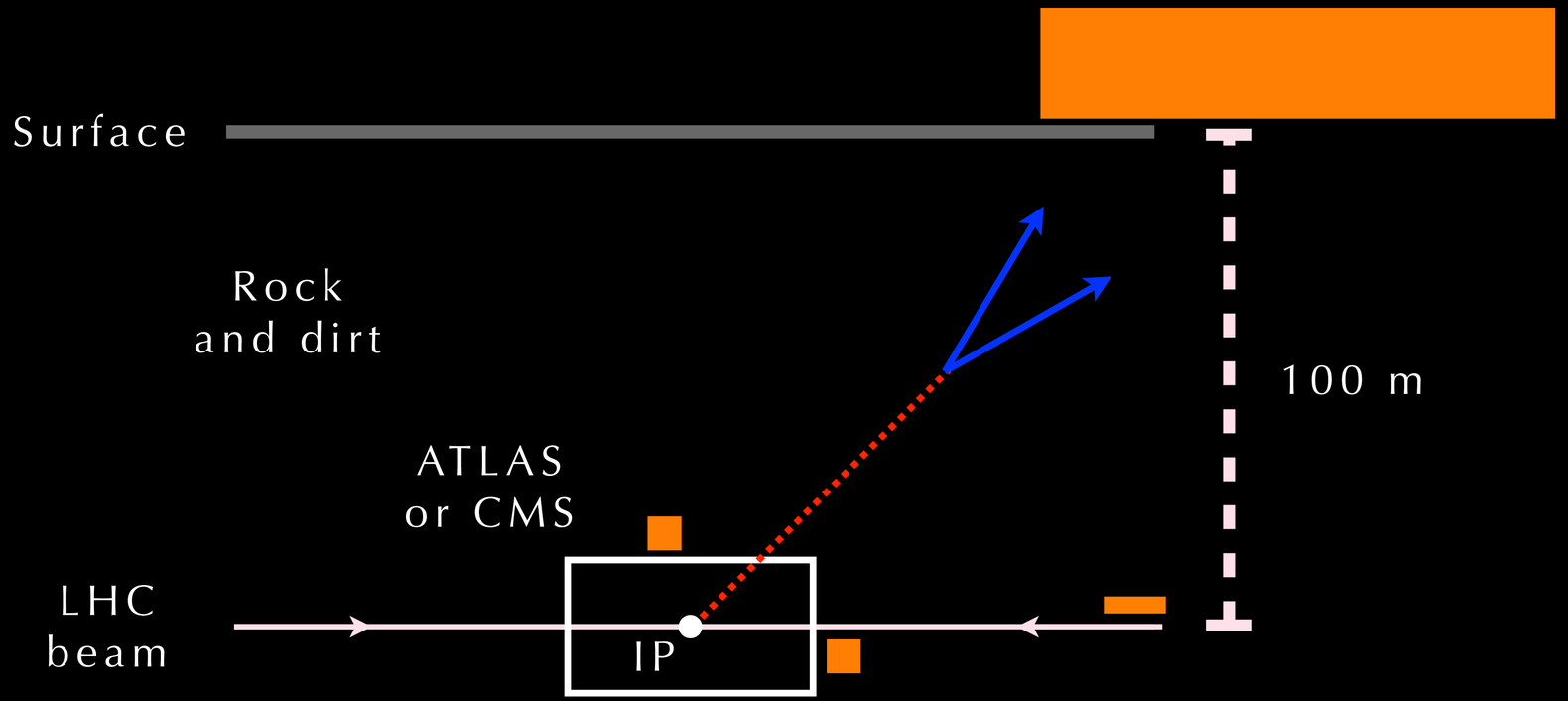

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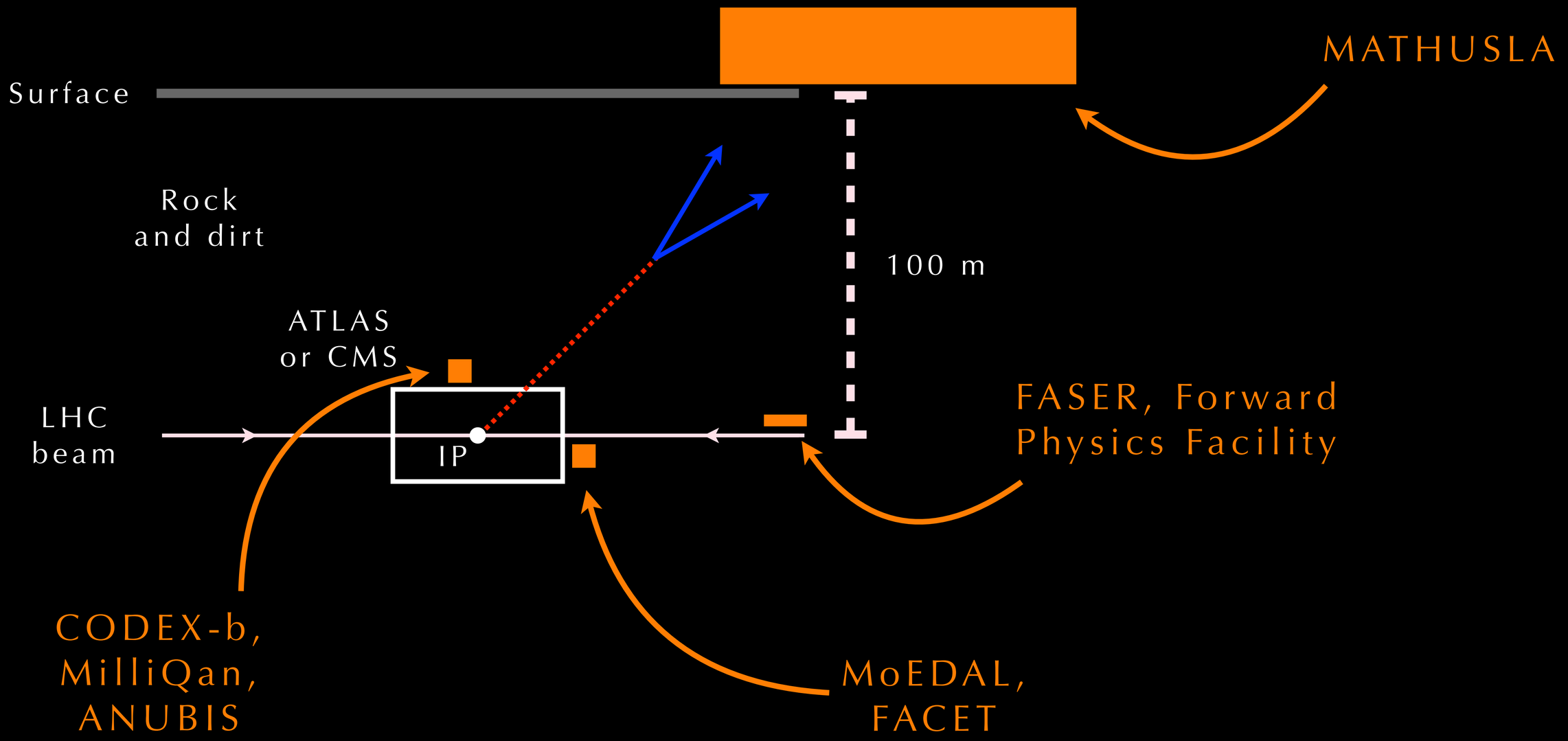

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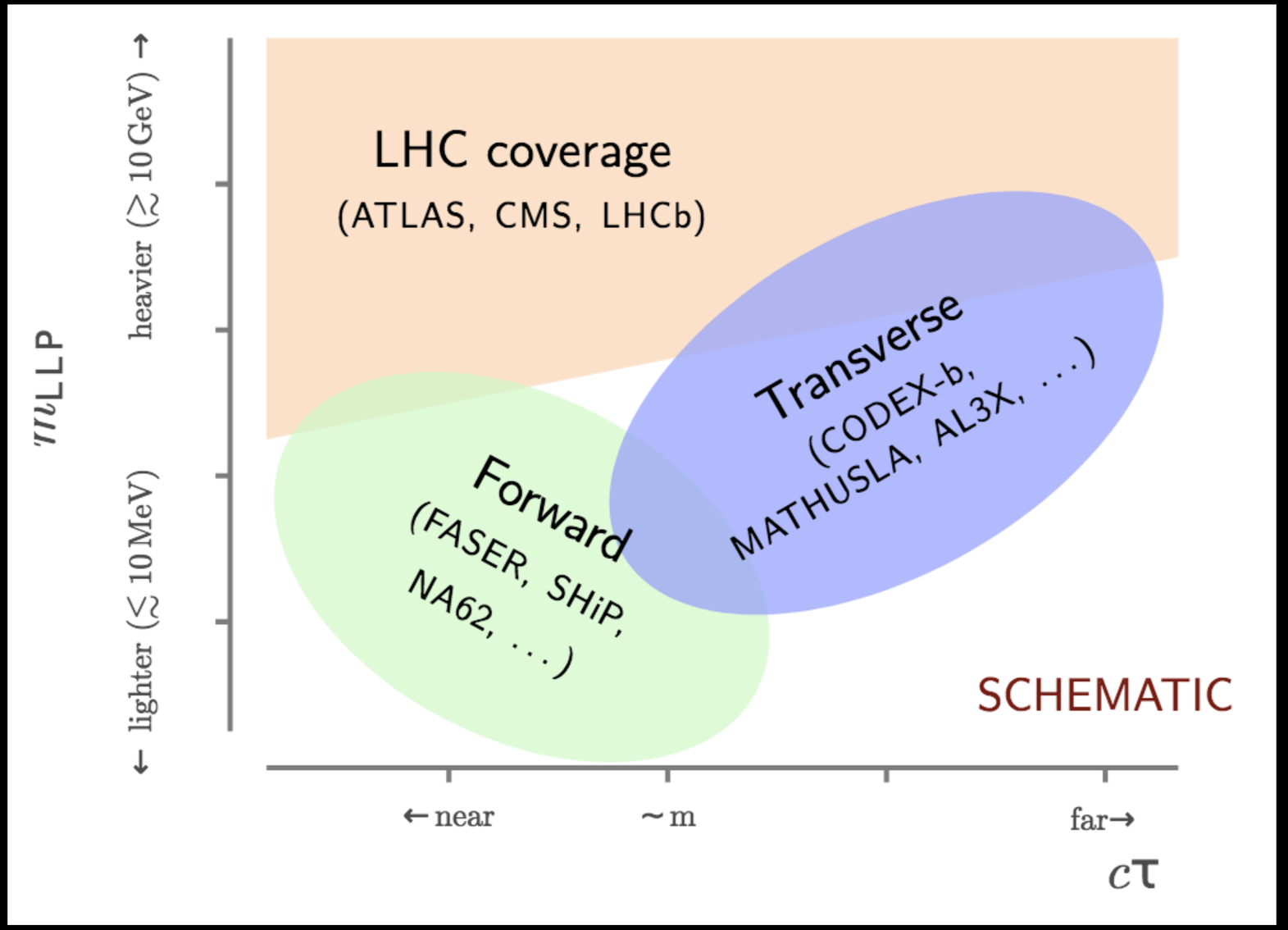
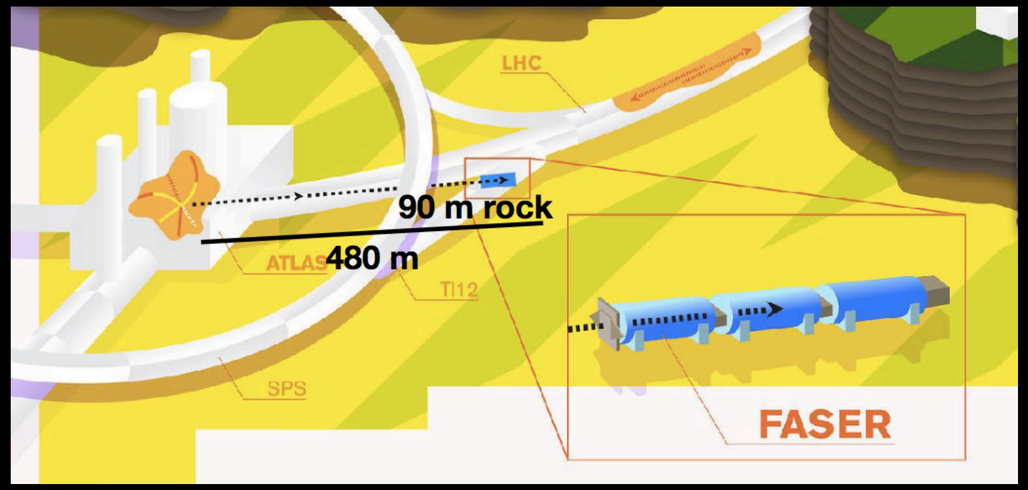


P. Ilten

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



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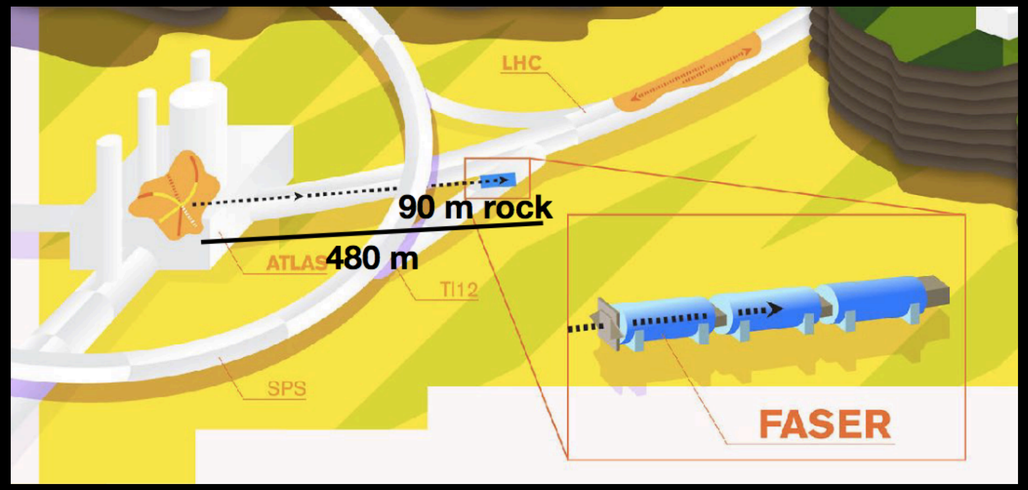
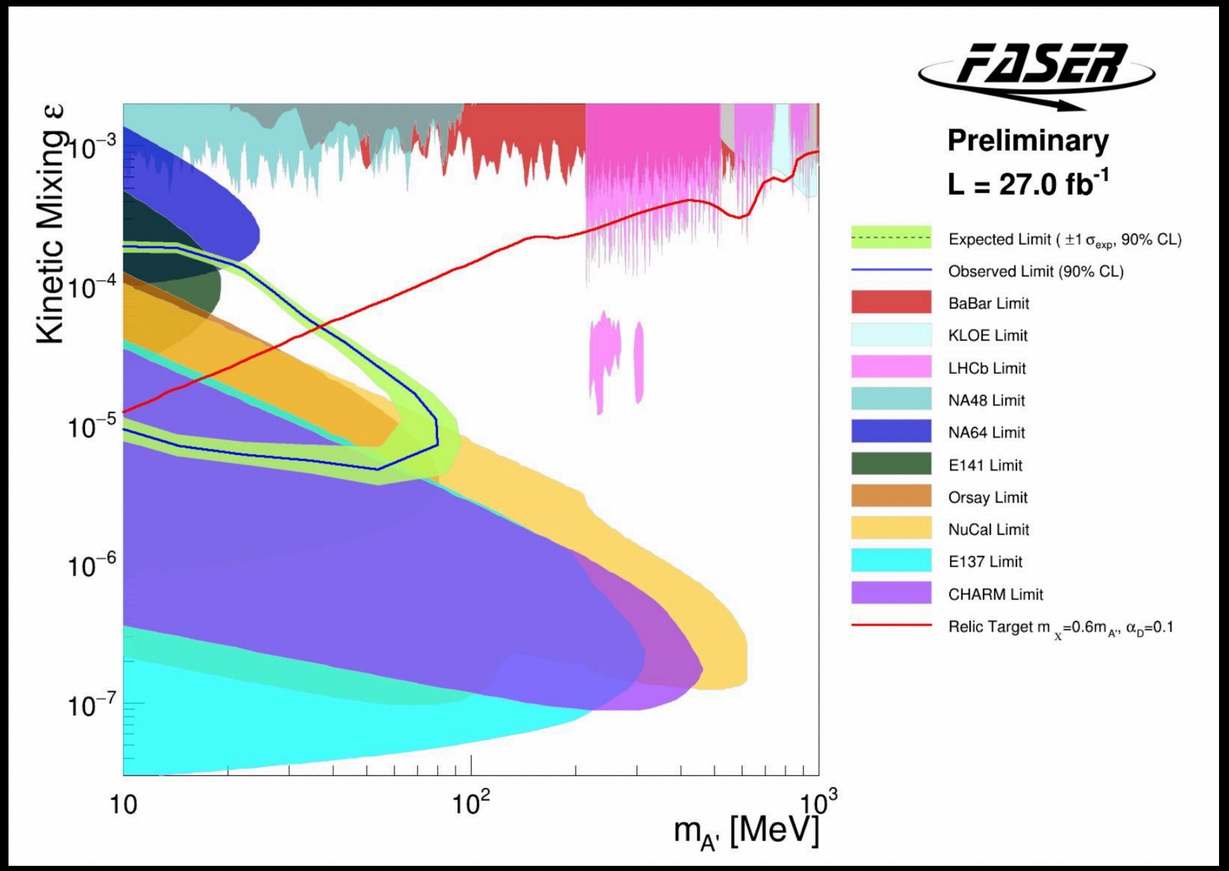


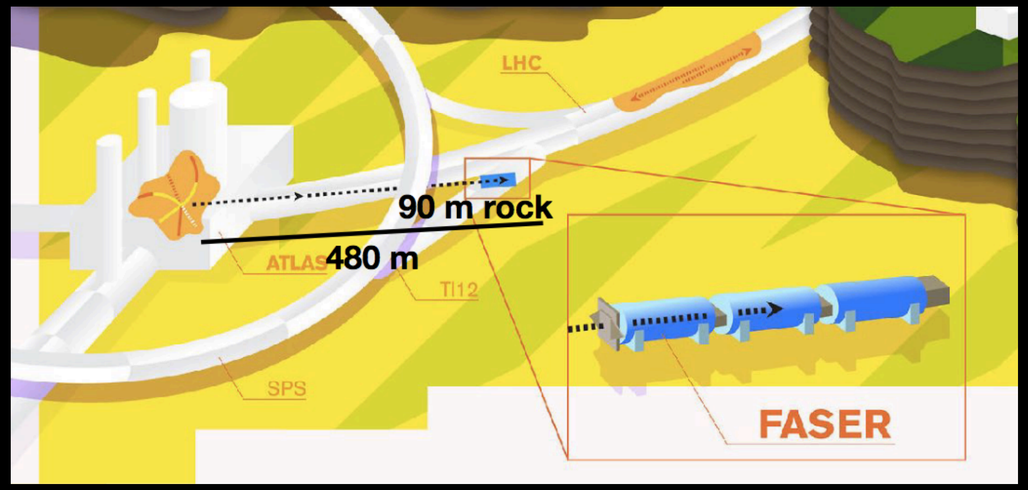
Was approved and installed in time for LHC Run 3 and has already produced results (here for dark photons)...



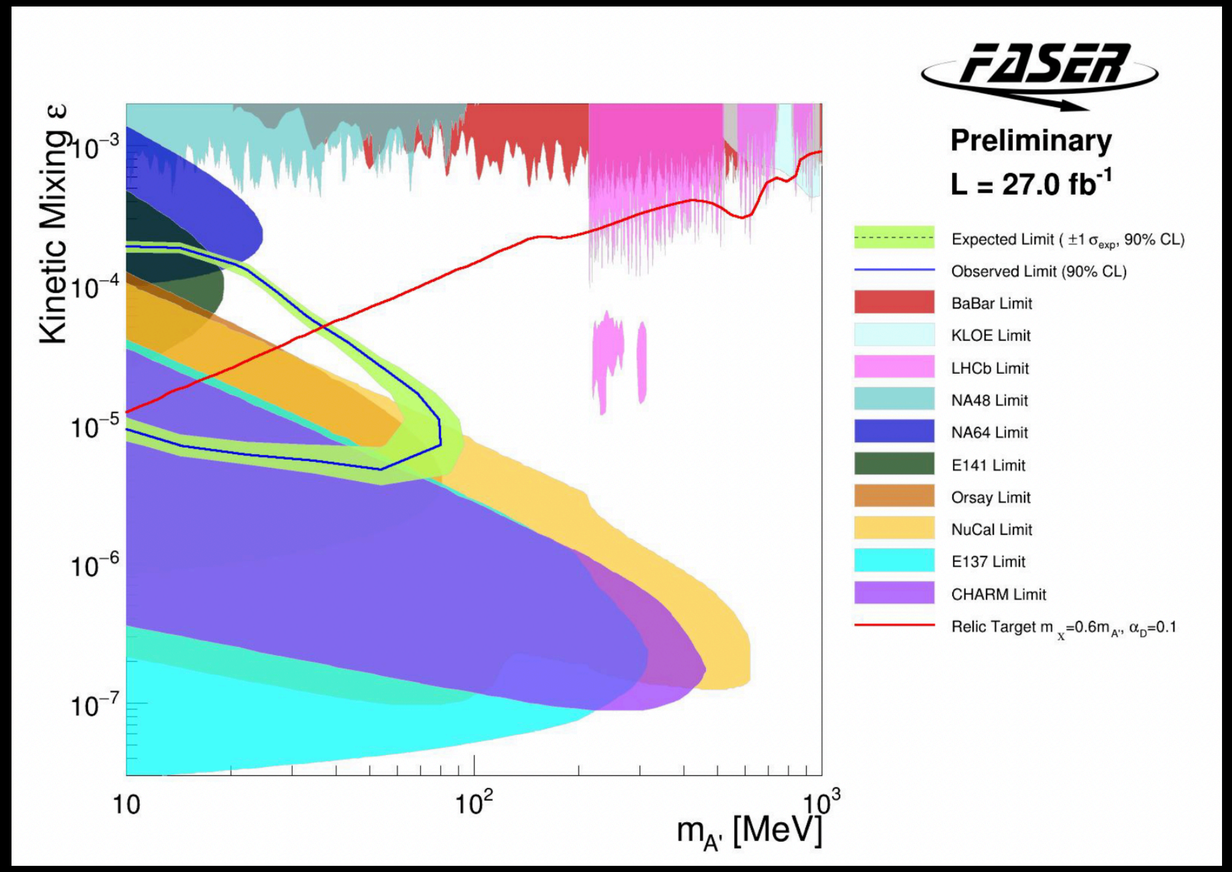
Public Aug. 2023: PLB 848 (2024) 138378

FASER / FASERnu

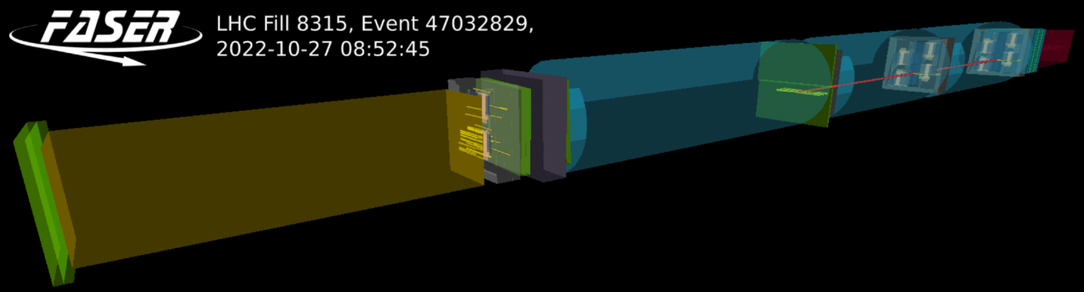
A small-ish (7m-long, 20cm-wide) detector about 0.5 km downstream from ATLAS to catch very far-forward LLPs that ATLAS can't catch



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



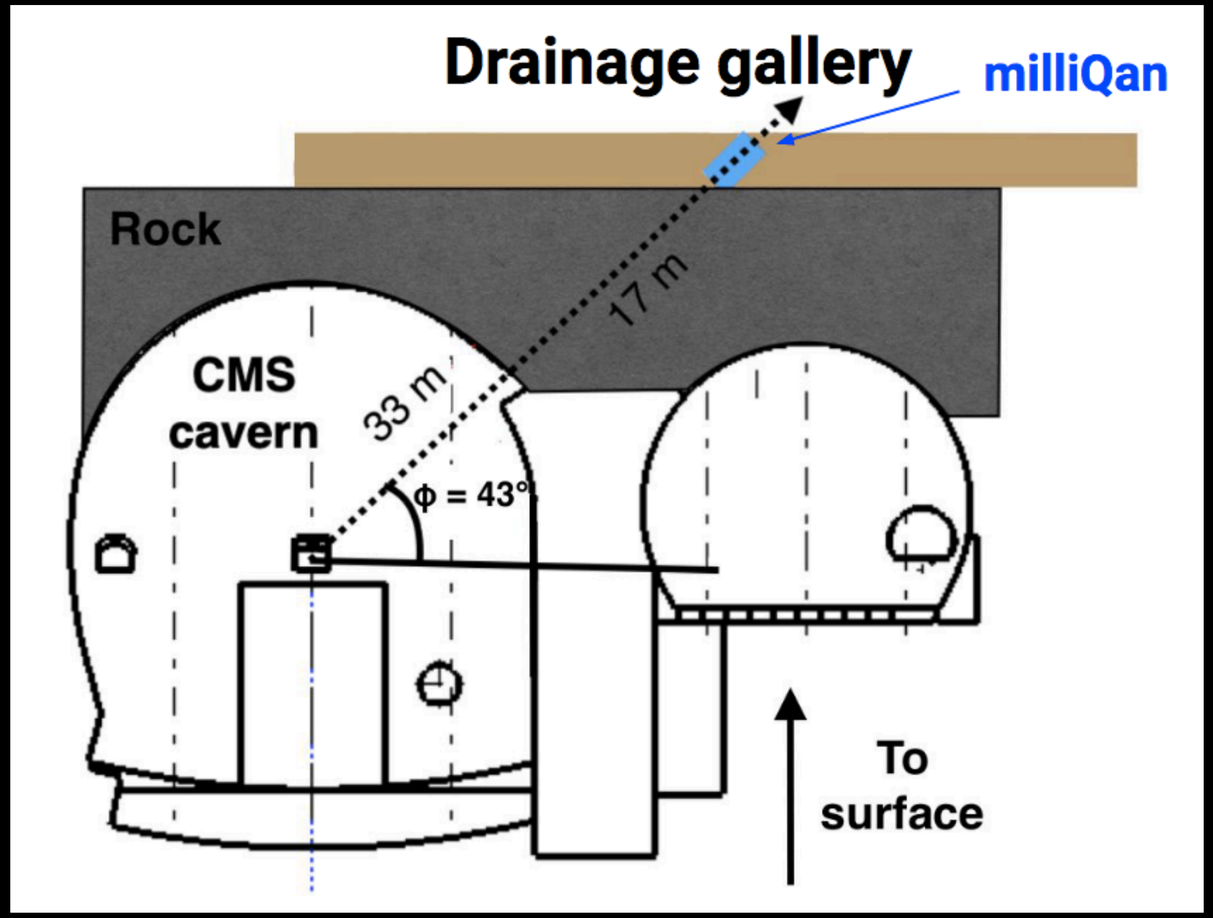
...including the first collider neutrinos ever directly detected

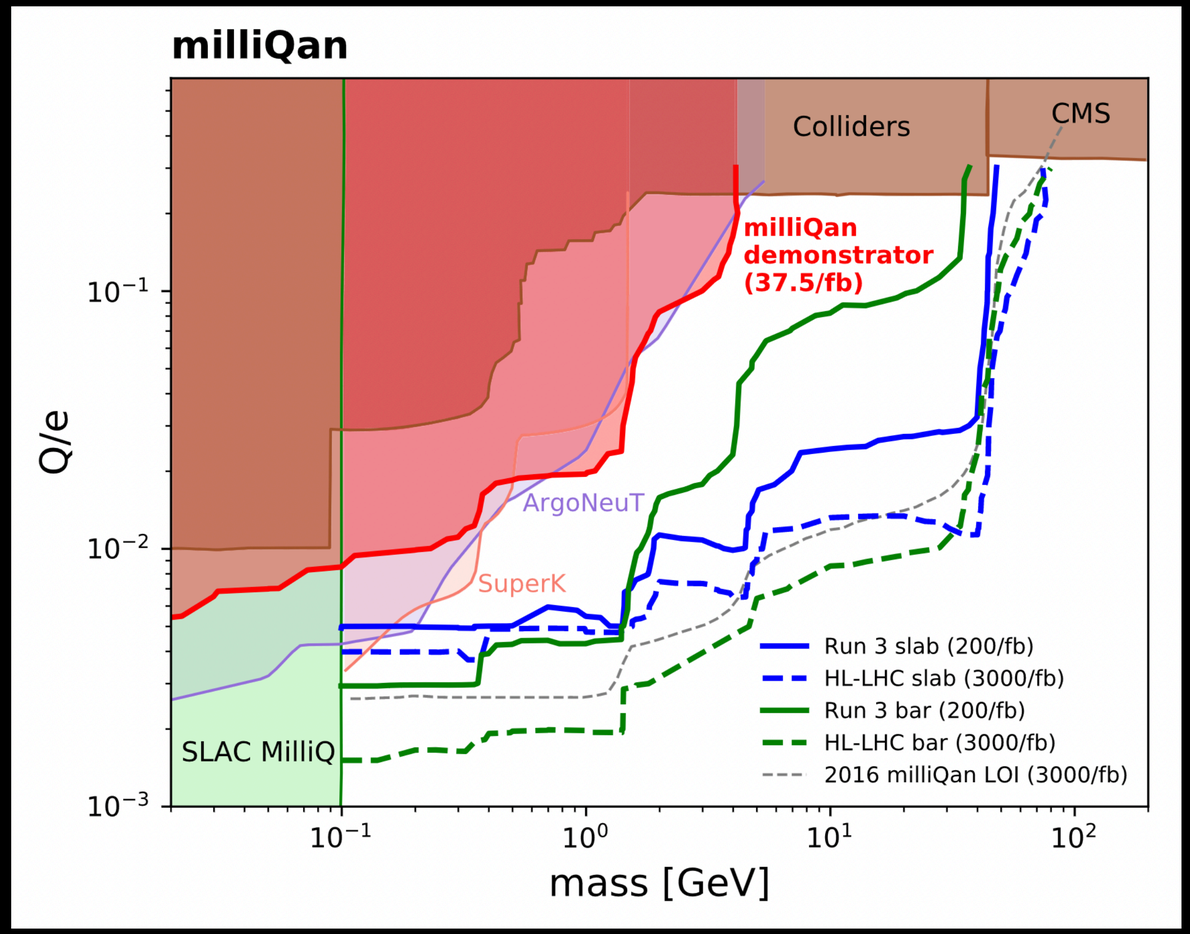


Public Aug. 2023: PLB 848 (2024) 138378

MilliQan

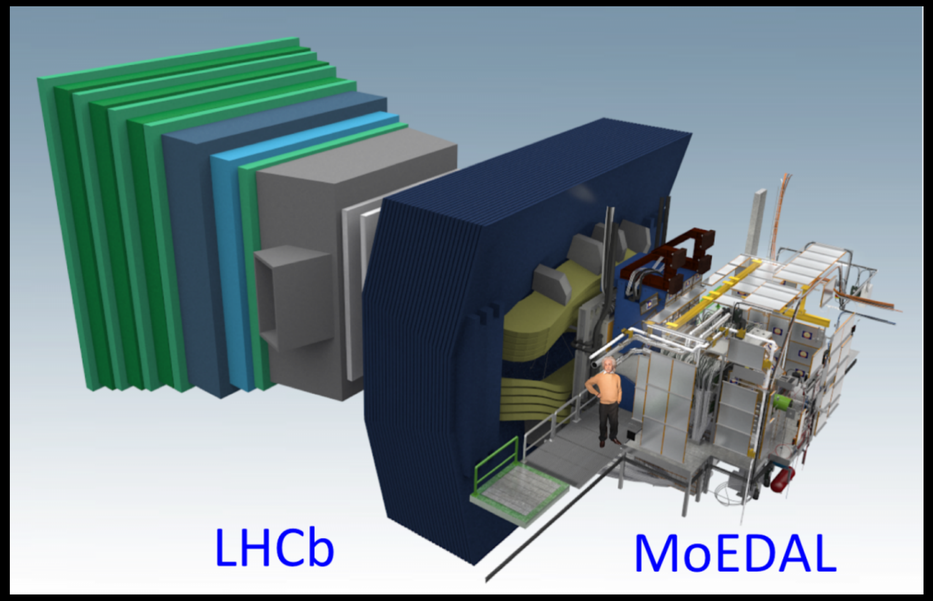
Small (3m x 1m^2) detector near CMS for new BSM dark fermions with very small amount of electric charge





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

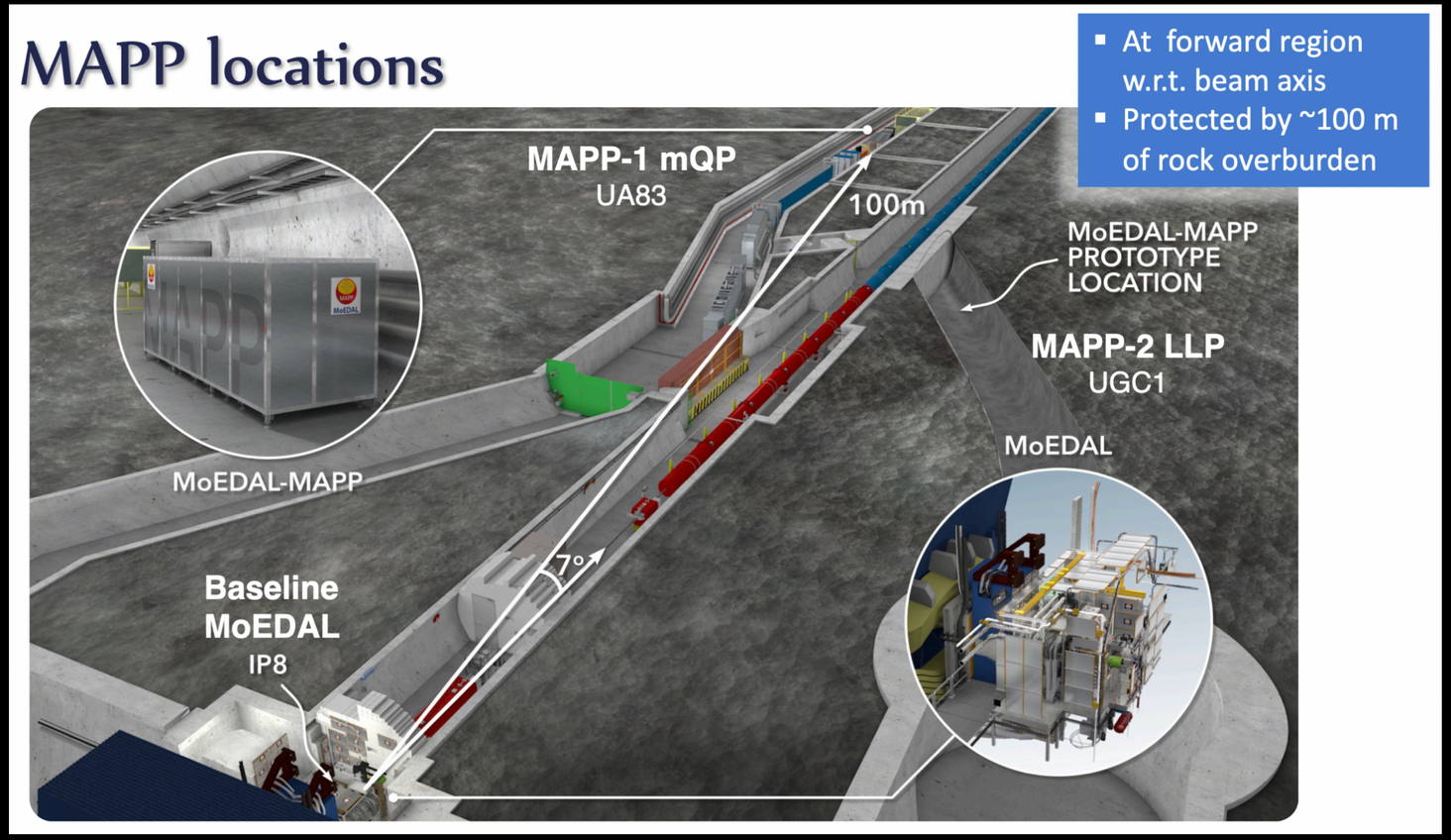
MoEDAL / MoEDAL-MAPP



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)

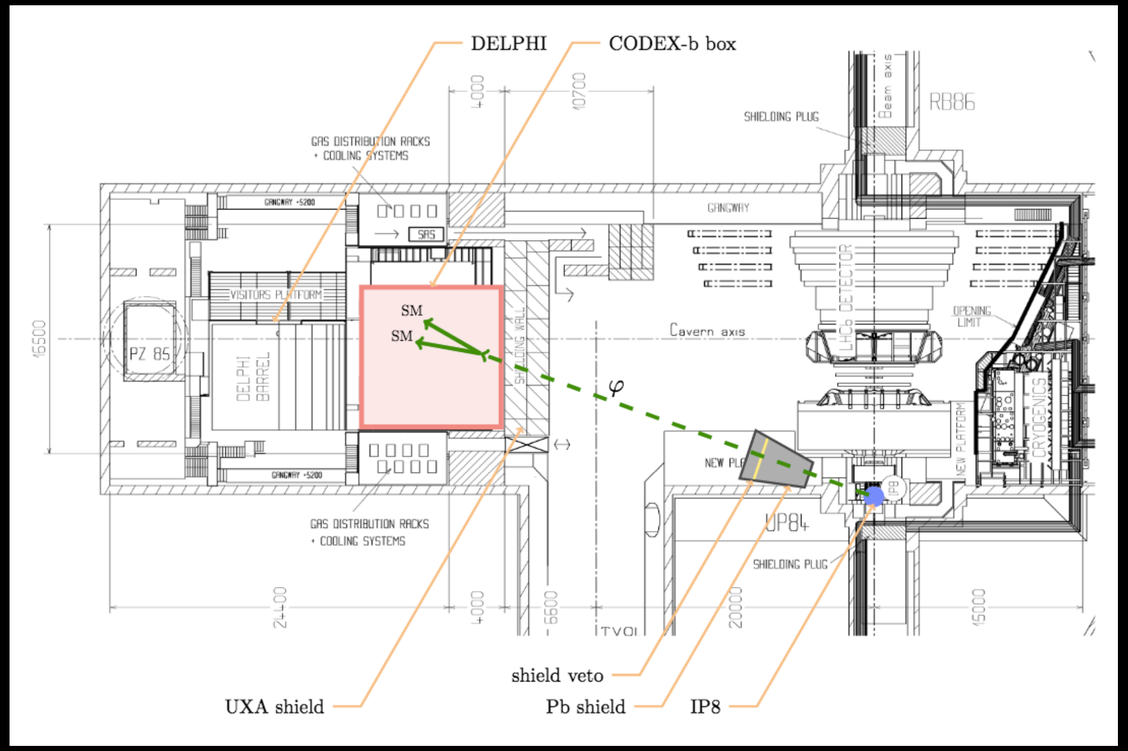


V. Mitsou

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

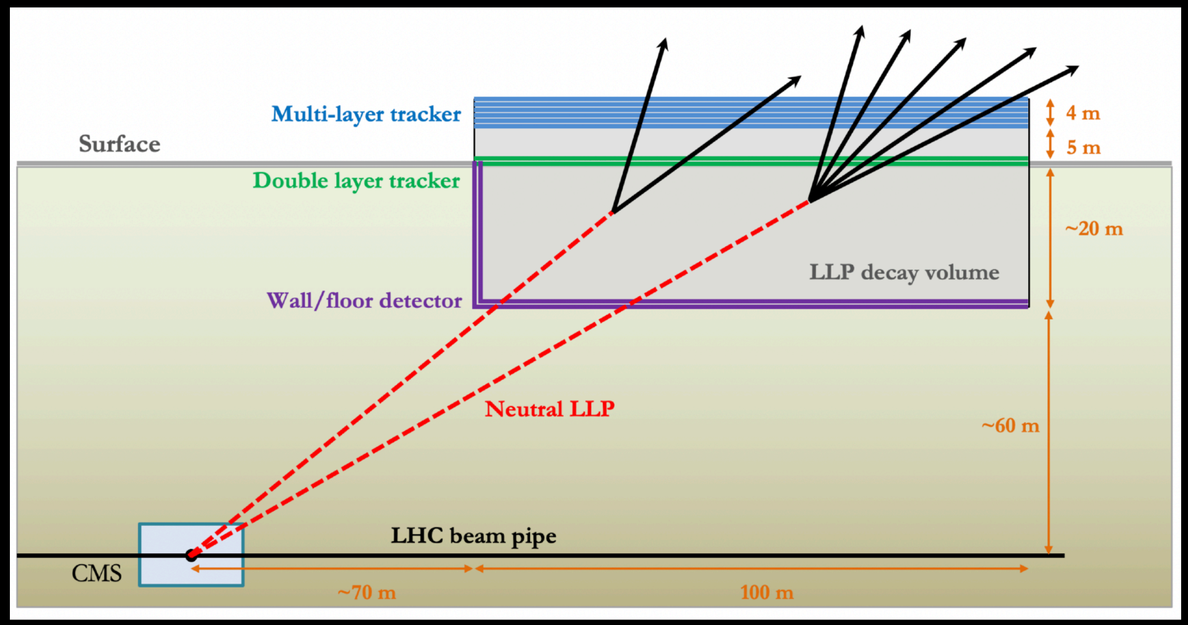


Building a demonstrator, CODEX-ß, right now, to hopefully take data in Run 3

MATHUSLA

A big (100m x 100m x 25m), mostly-empty box near the surface above CMS to catch displaced vertices

Physics case document
Letter of Intent

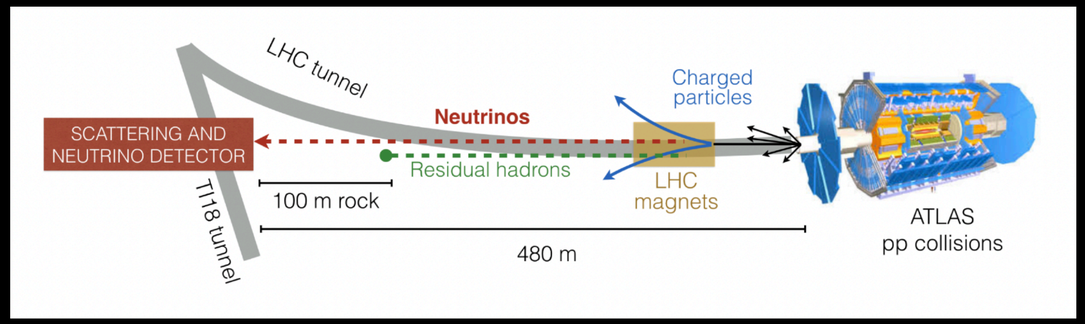


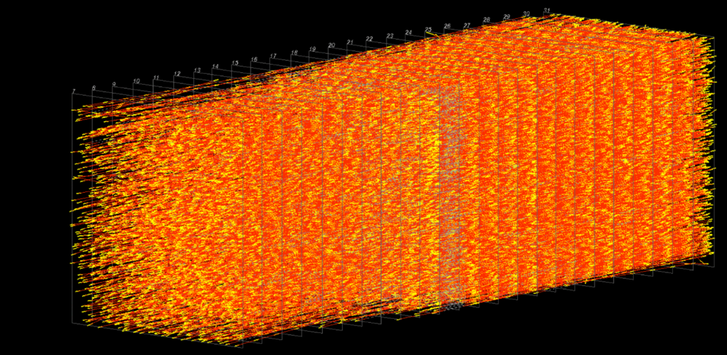
Proposed, with a demonstrator

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

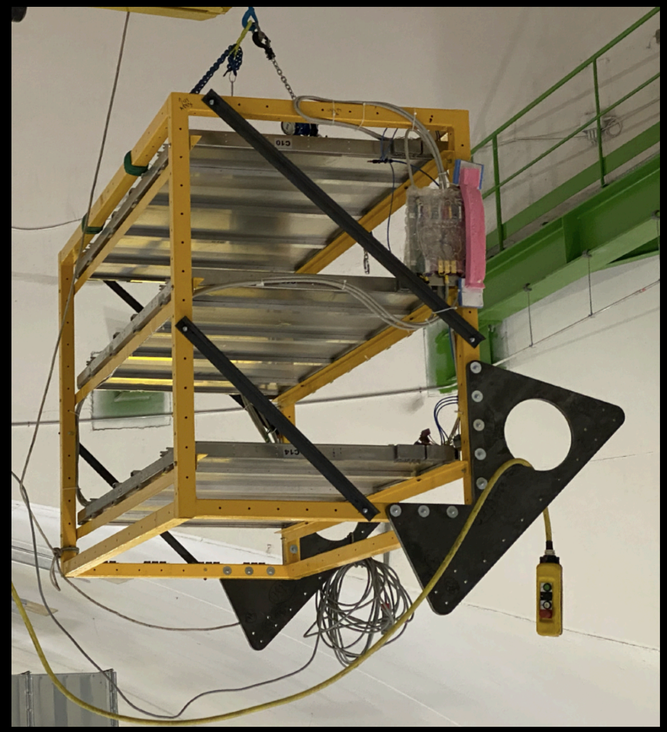




Already installed and has also already seen the first collider neutrinos:
PRL 131 (2023) 031802

ANUBIS

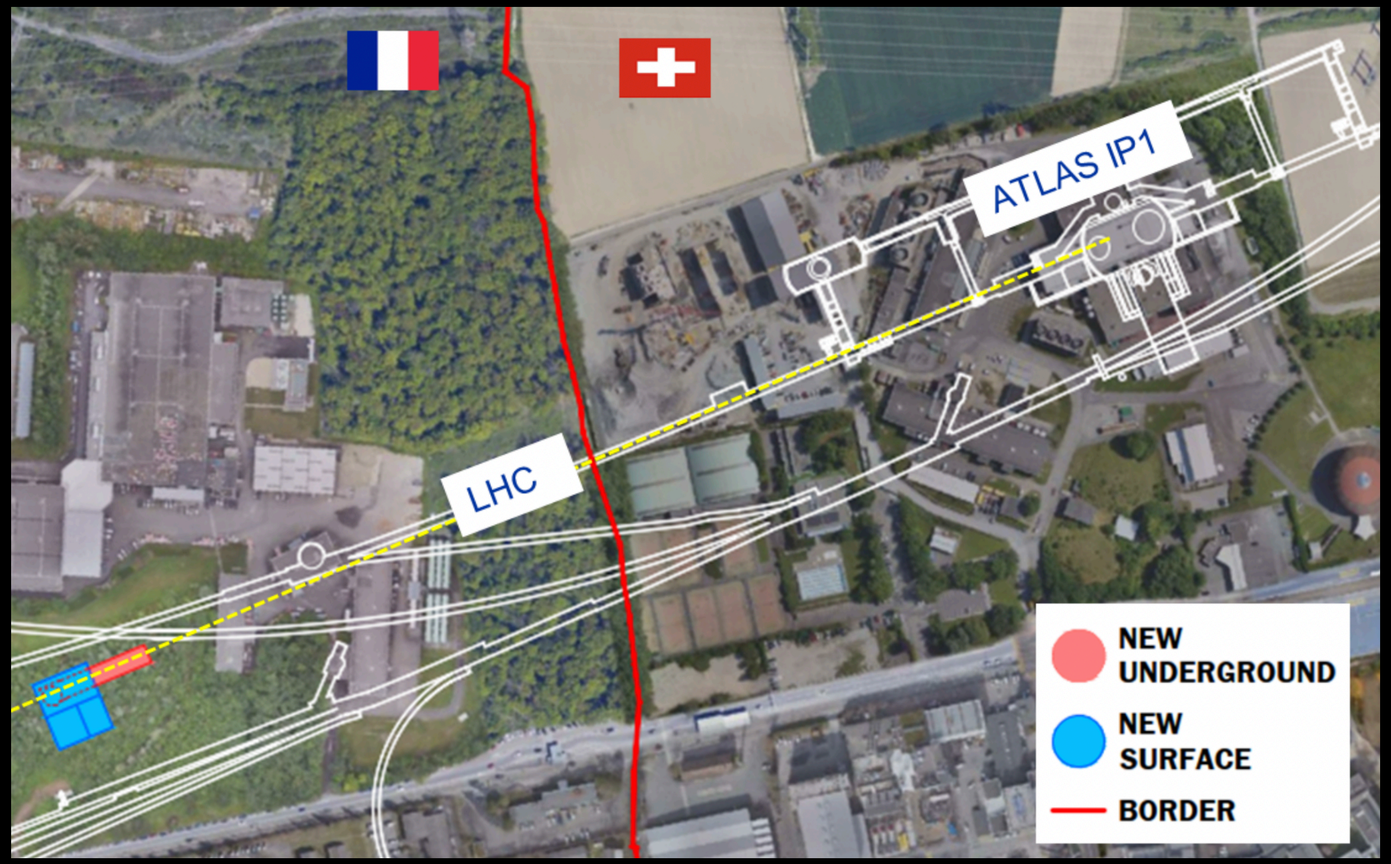
Proposal to instrument bottom of access shafts above ATLAS cavern, as well as cavern ceiling

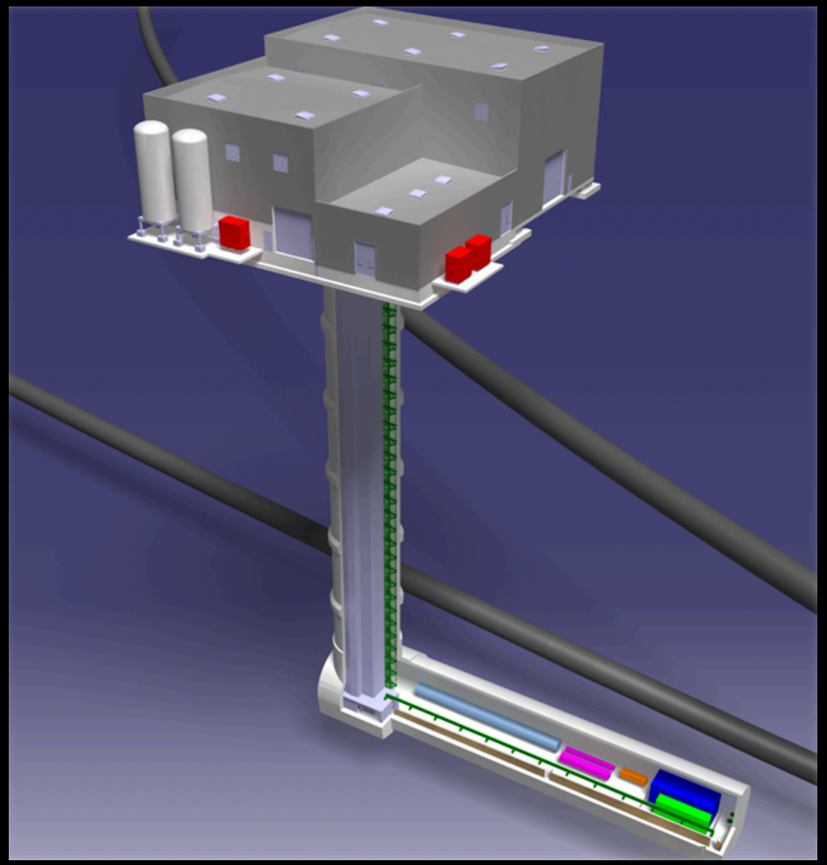


ProANUBIS installed in March 2023

Commissioning now

Forward Physics Facility



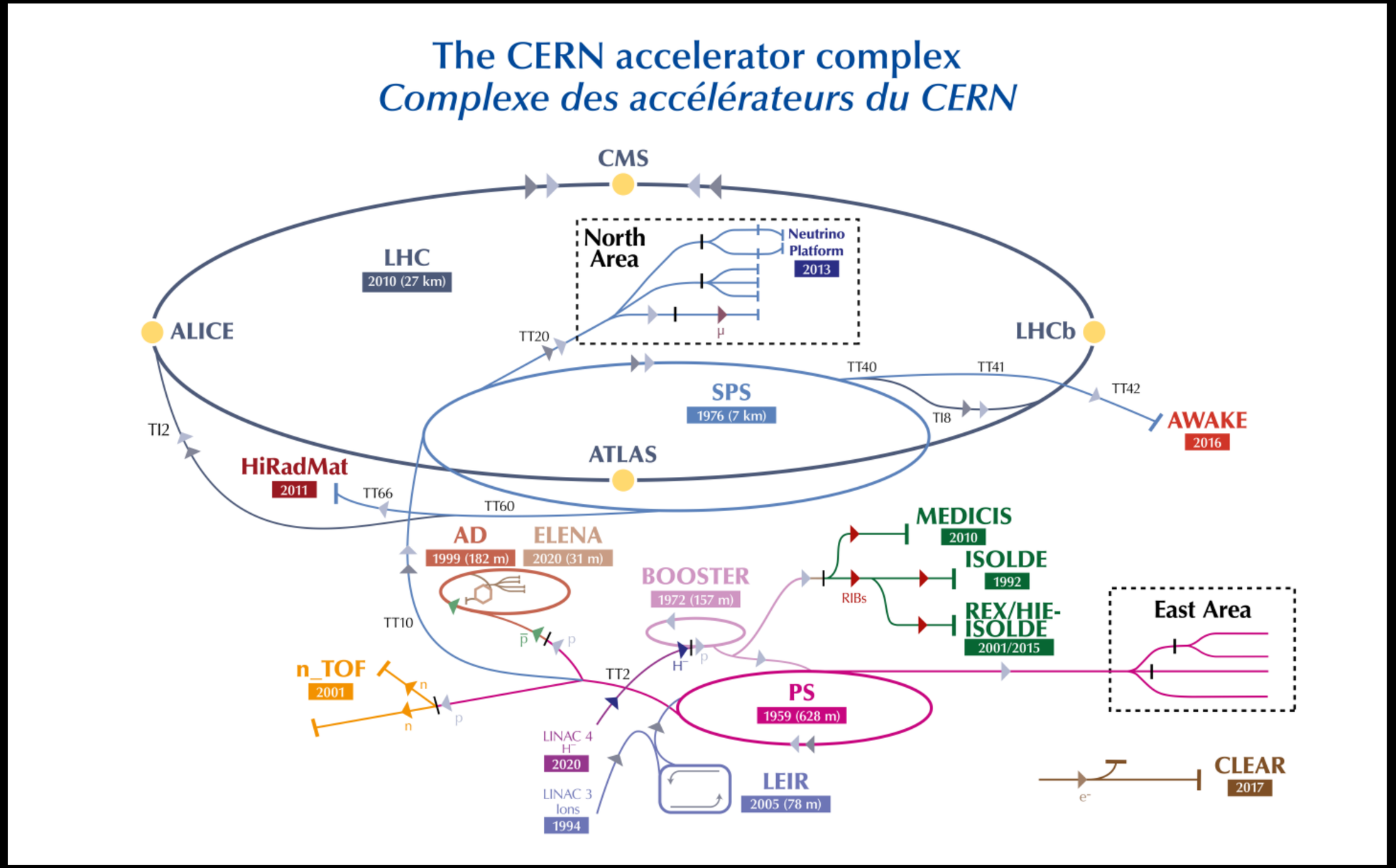


Proposal for a new facility, about 600 m from ATLAS, to house multiple experiments dedicated to LLP searches in the forward region

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

arXiv:2203.05090

LLPs from the SPS at CERN



LLPs from the SPS at CERN

NA64

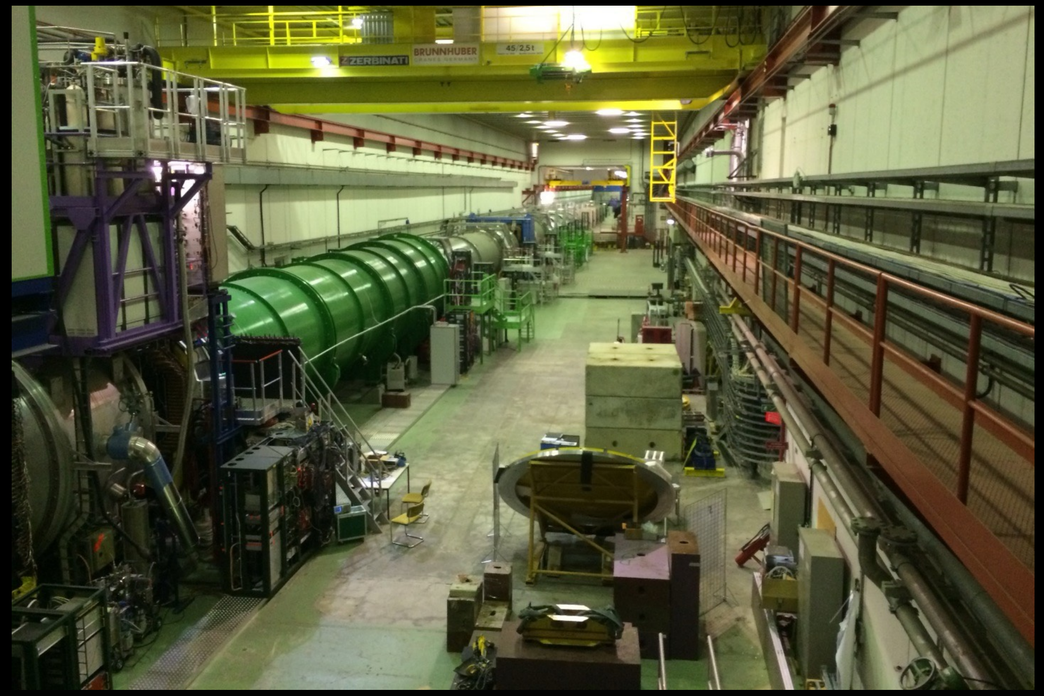
Uses 100 GeV electron beam to search for dark sector particles in the MeV-GeV range using active-beam-dump plus missing-energy approach

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 exotic decays results (Sept. 2023):
PoS FPCP2023 (2023) 073



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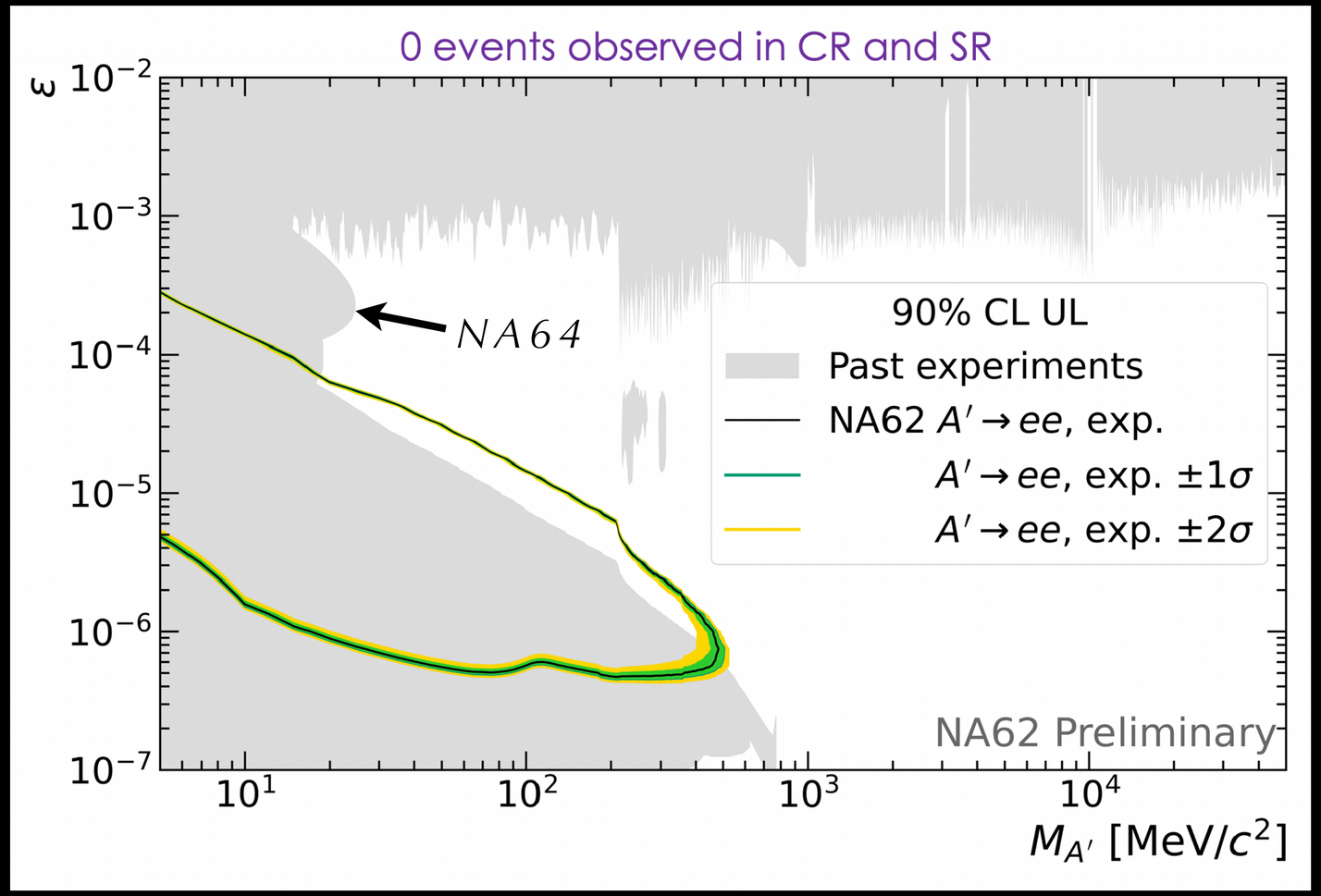
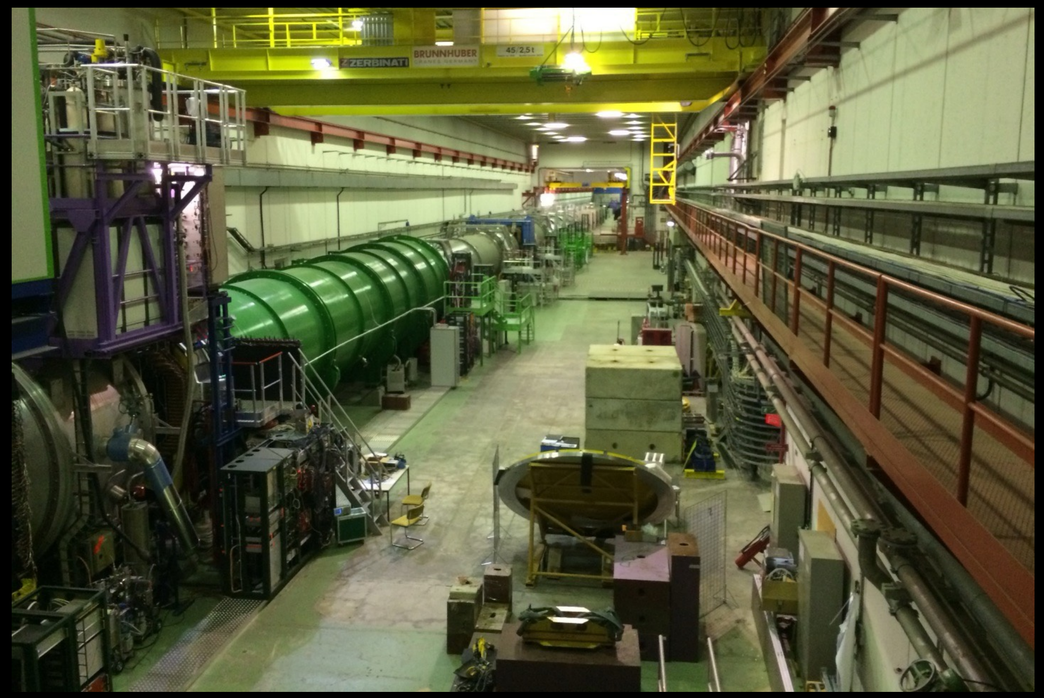


Nota bene:

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?

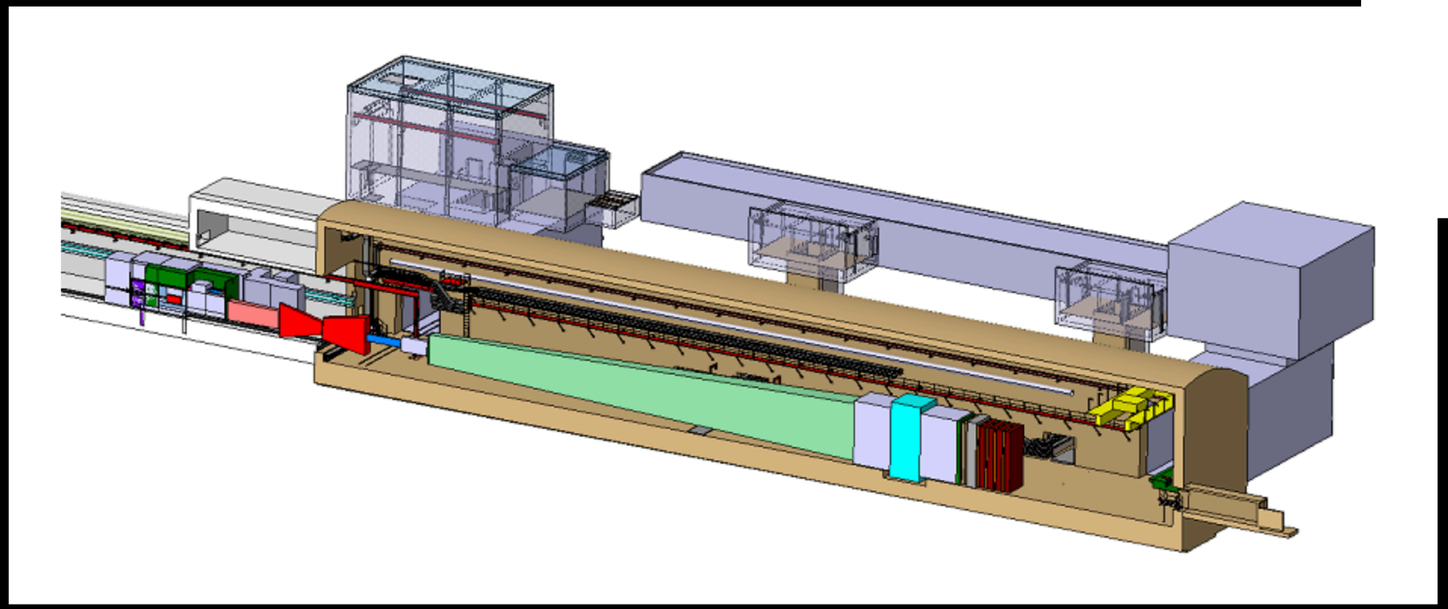


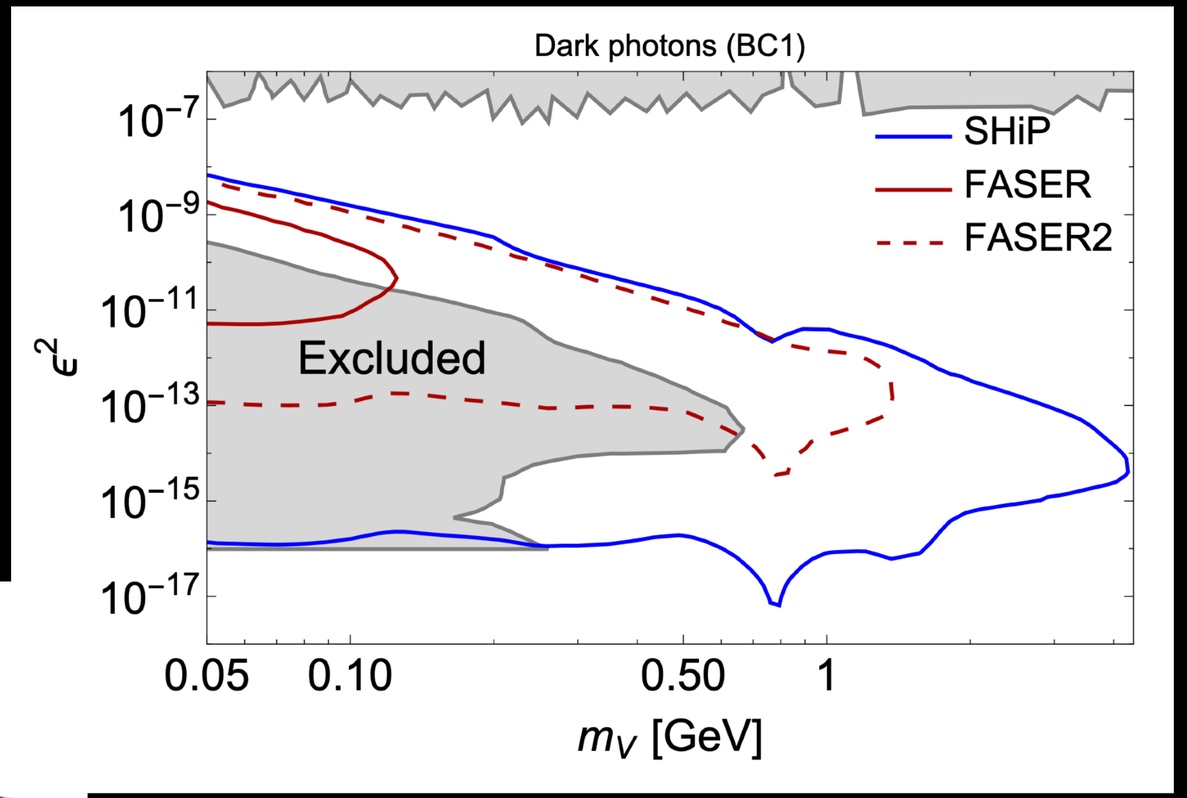
LLPs from the SPS at CERN: SHiP

SHiP: Search for Hidden Particles

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

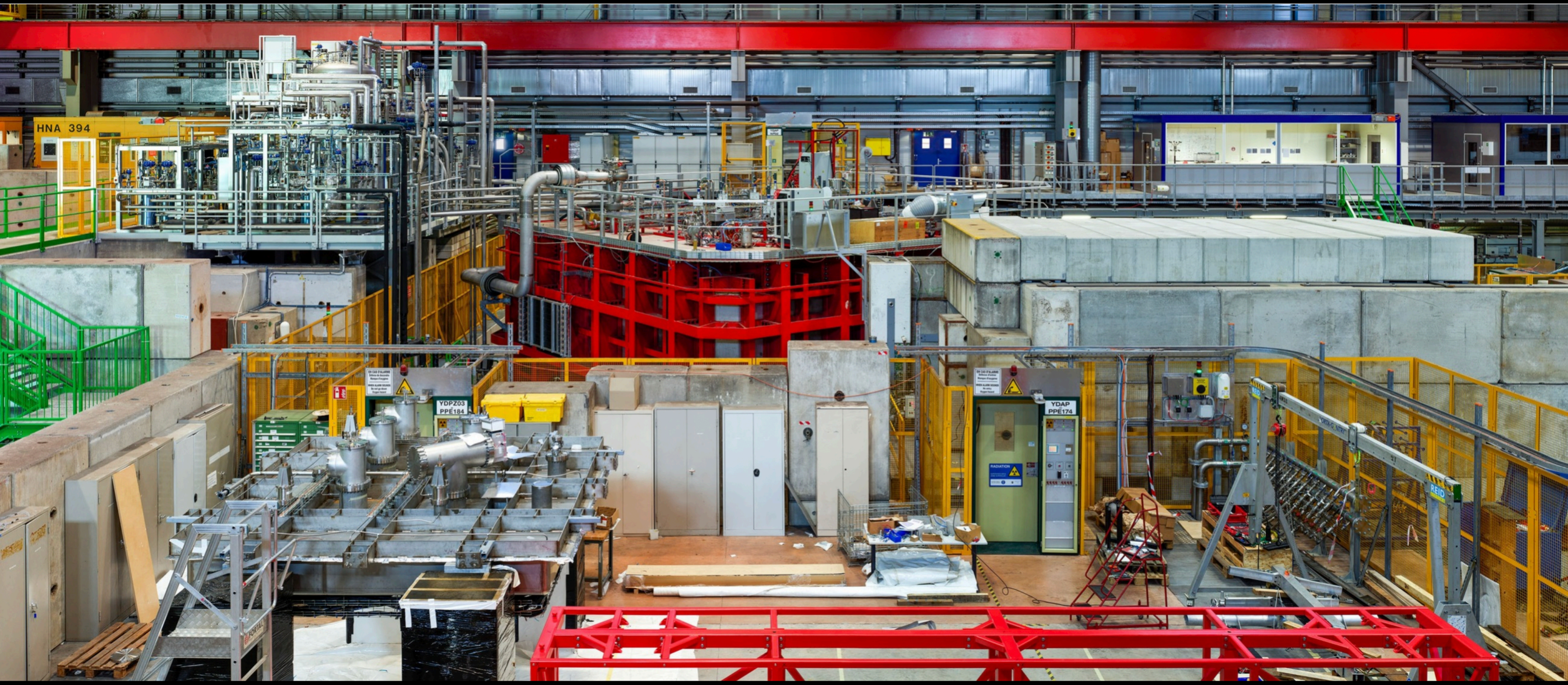
June 2023 talk





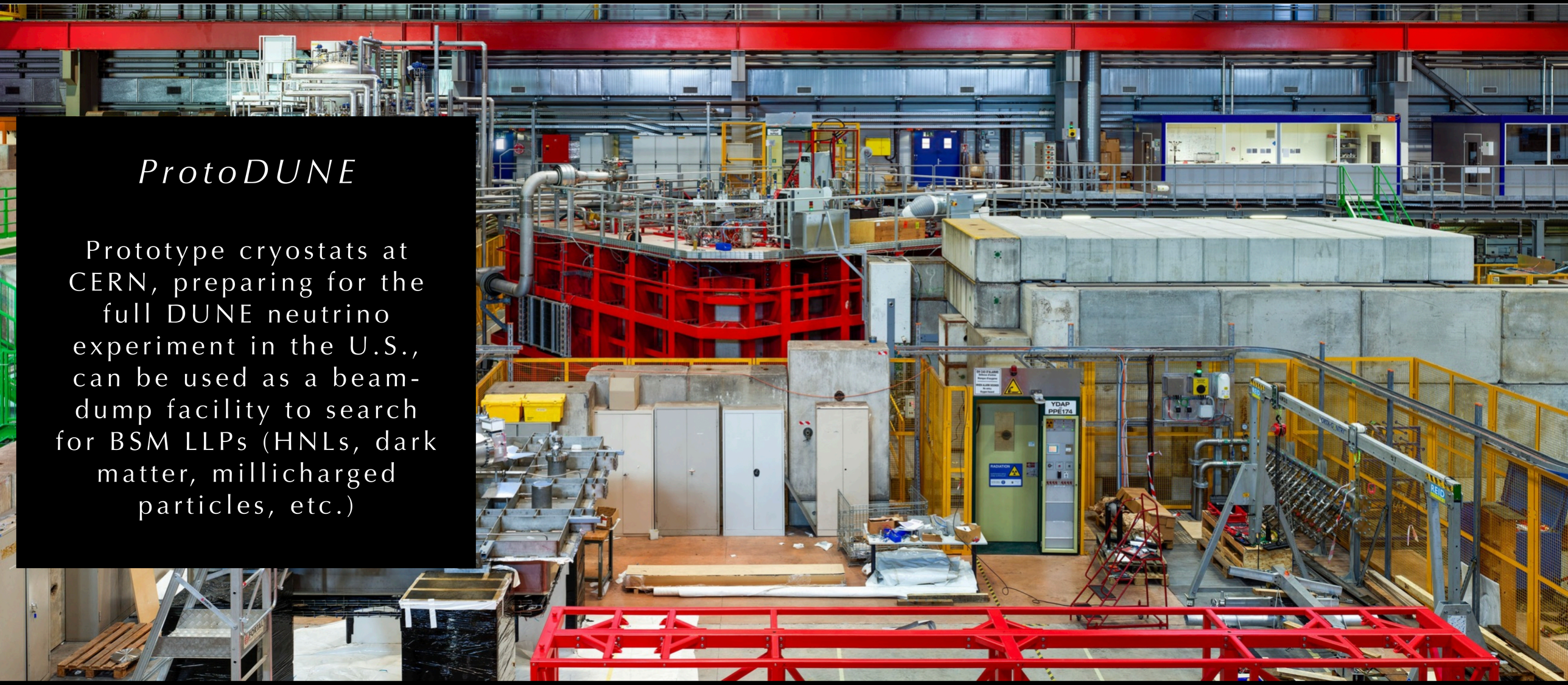
Projected exclusion for 15 years of running

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

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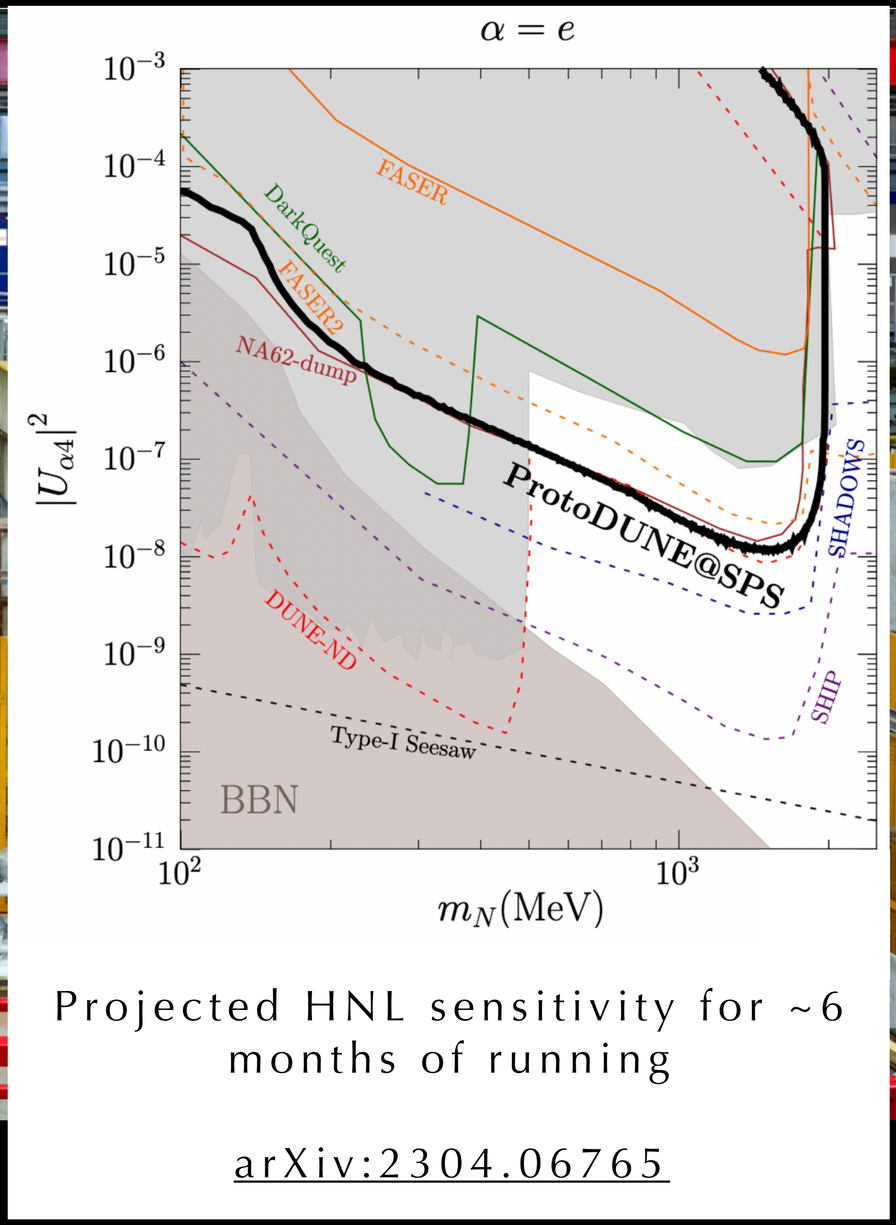
Thomas Struth, 2023



Projected HNL sensitivity for ~6 months of running

arXiv:2304.06765

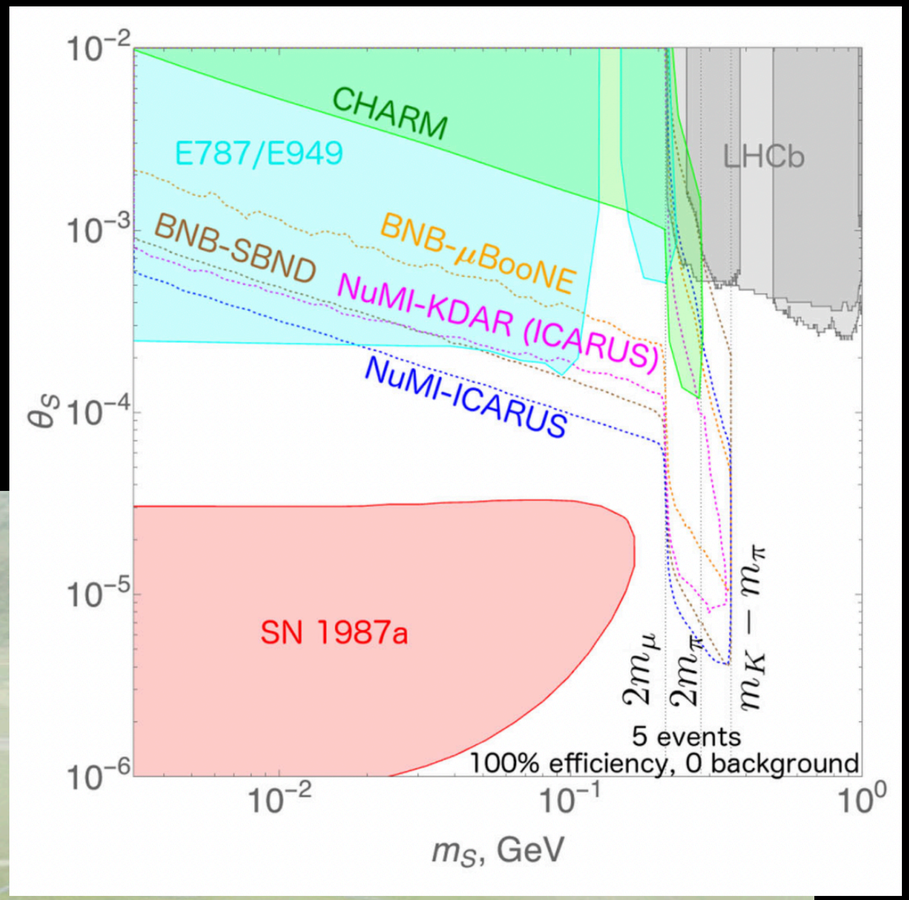
Short Baseline Neutrino Program at Fermilab

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



PRD 100 (2019) 115039

See also DarkQuest, DAMSA

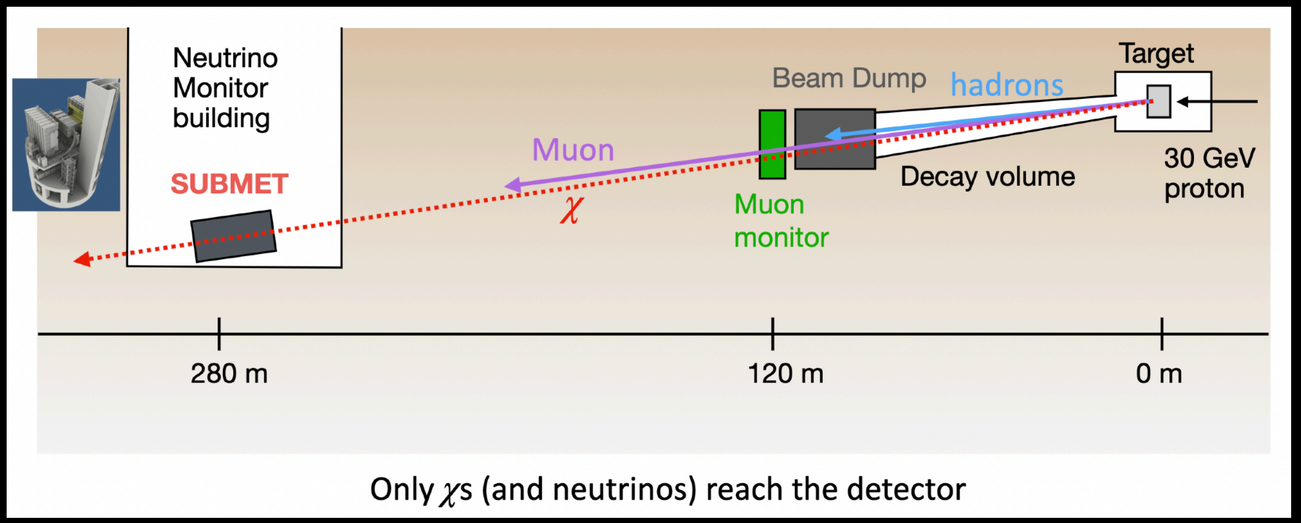
LLPs in Japan

SUBMET at J-PARC

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

Stage 2 approval already given

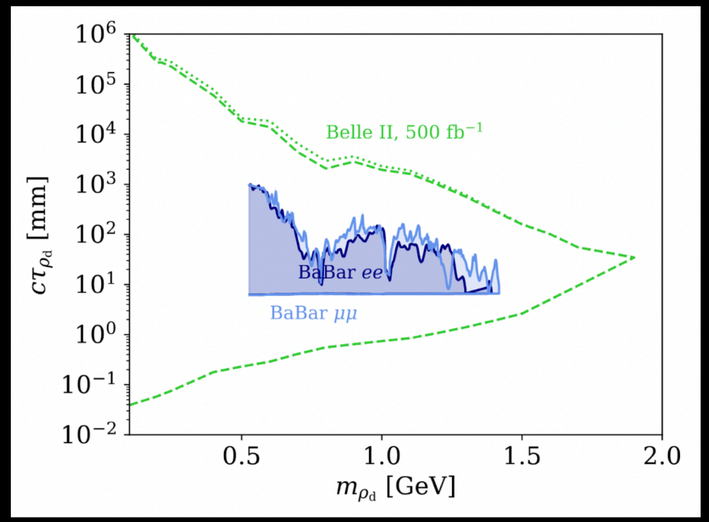
Recent talk



Only χs (and neutrinos) reach the detector

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

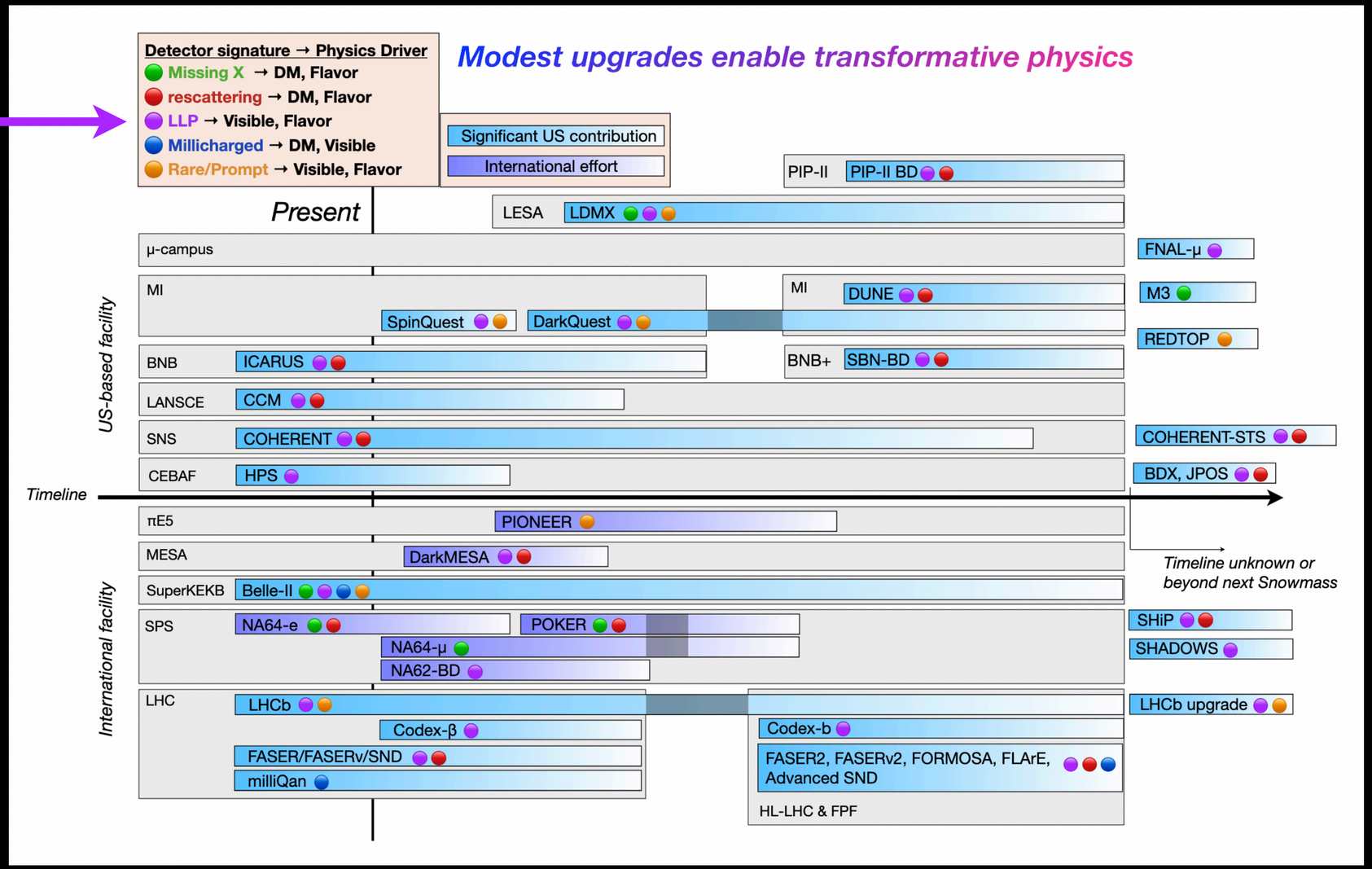
Super-Kamiokande

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

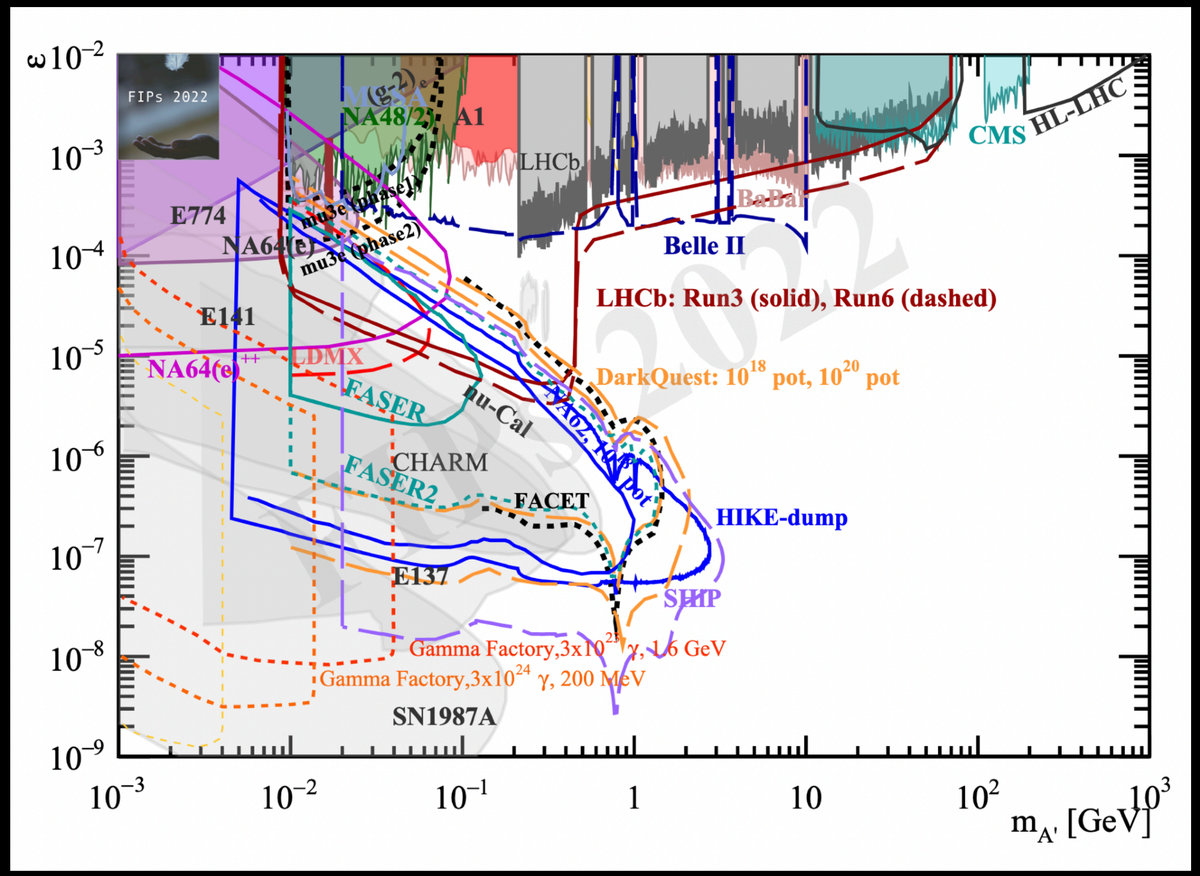
Broad international effort

LLPs →

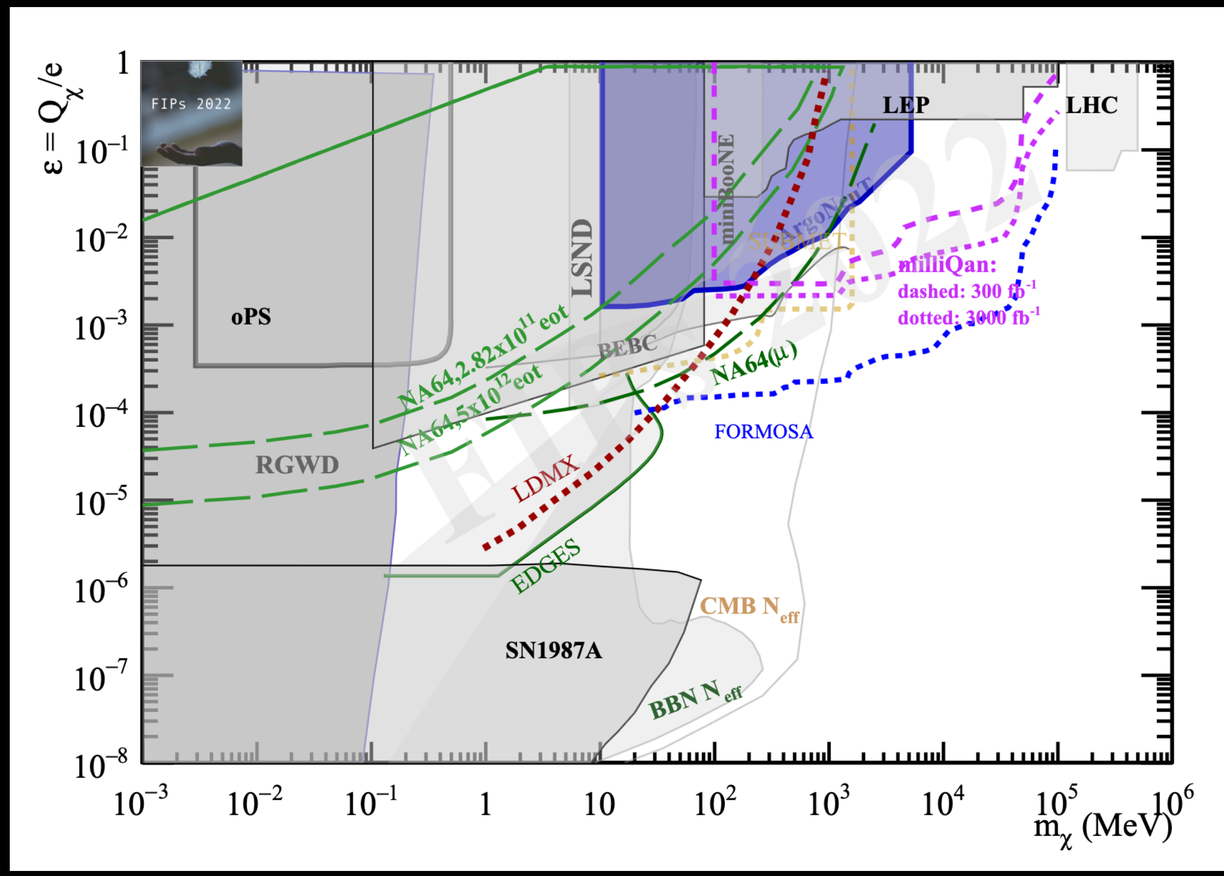


Snowmass "accelerator-based dark sector searches" report:
arXiv:2206.04220

This is what I mean by cartography



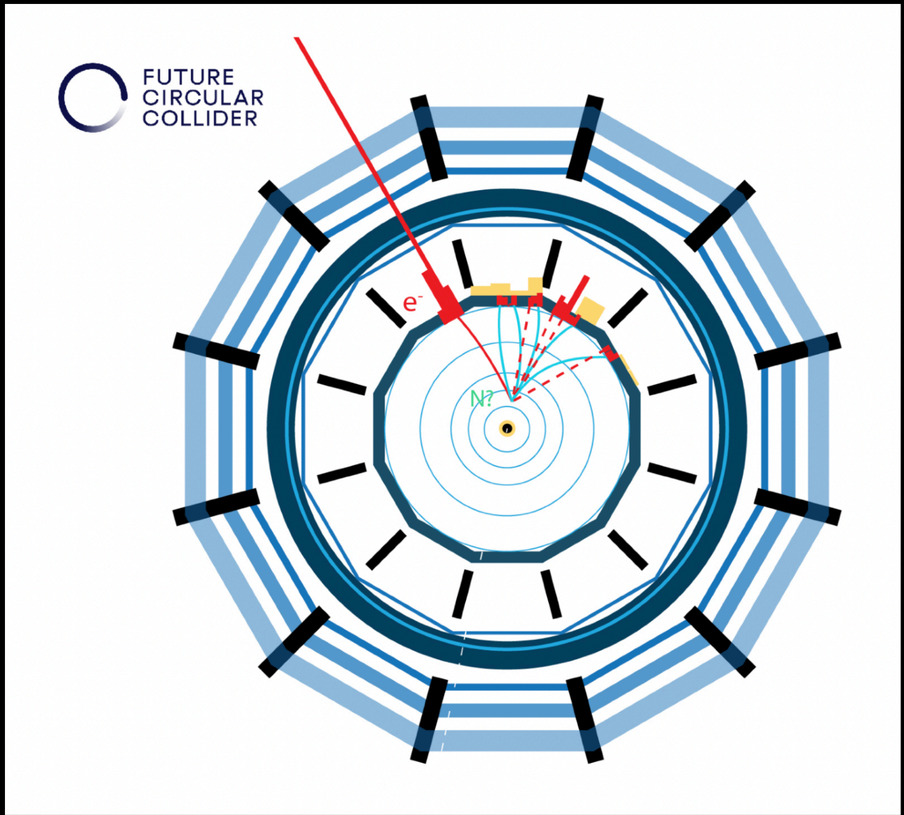
Dark photon (A′)



Millicharged particles

FIPs 2022 workshop report
arXiv:2305.01715

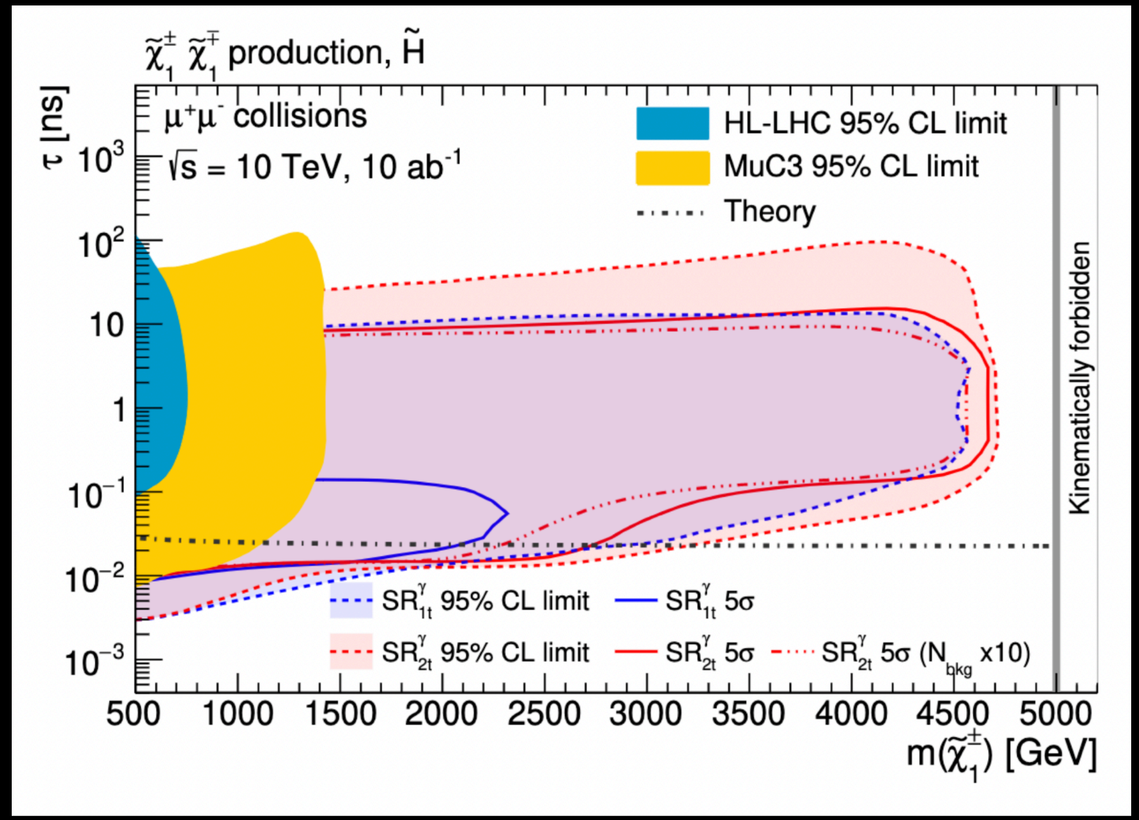
Looking forward to LLPs in the future



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*

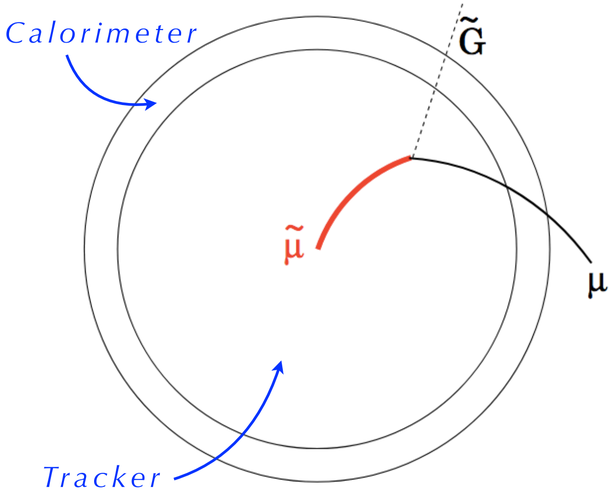
The next few years and decades will be exciting

END

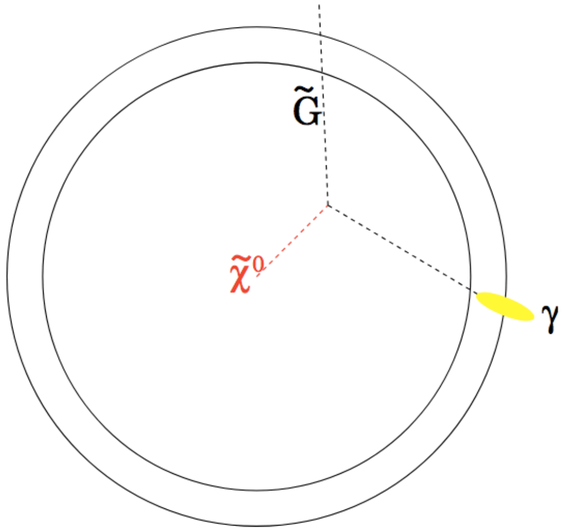
Long-lived particle searches at LEP and the Tevatron

LEP

$10^{-11}\ \mathrm{s} \lesssim \tau_\ell \lesssim 10^{-7}\ \mathrm{s}$

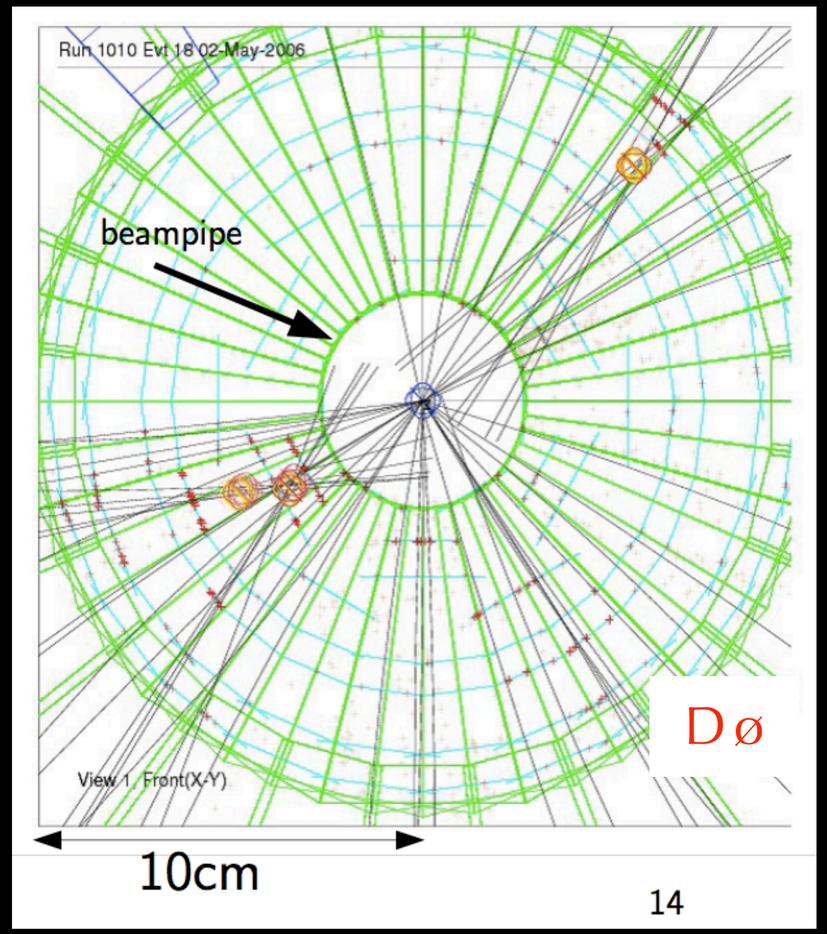


$\cdots \lesssim \tau_\chi \lesssim 10^{-8}\ \mathrm{s}$



M. Fanti talk about LLPs at LEP at first LHC LLP Mini-workshop, 2016

Tevatron

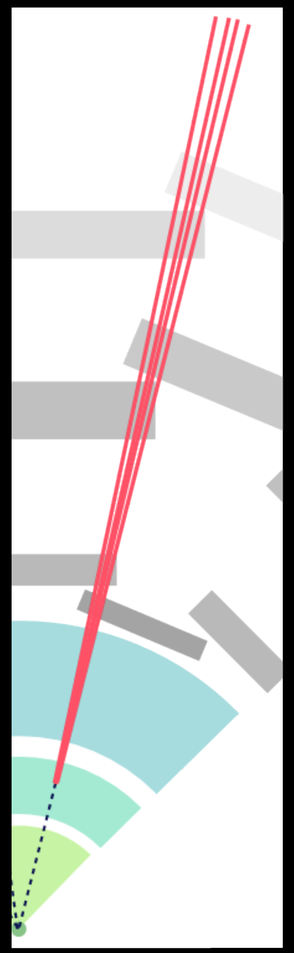


A. Haas talk about LLPs at Tevatron at the same

Neutral LLPs decaying to lepton-jets

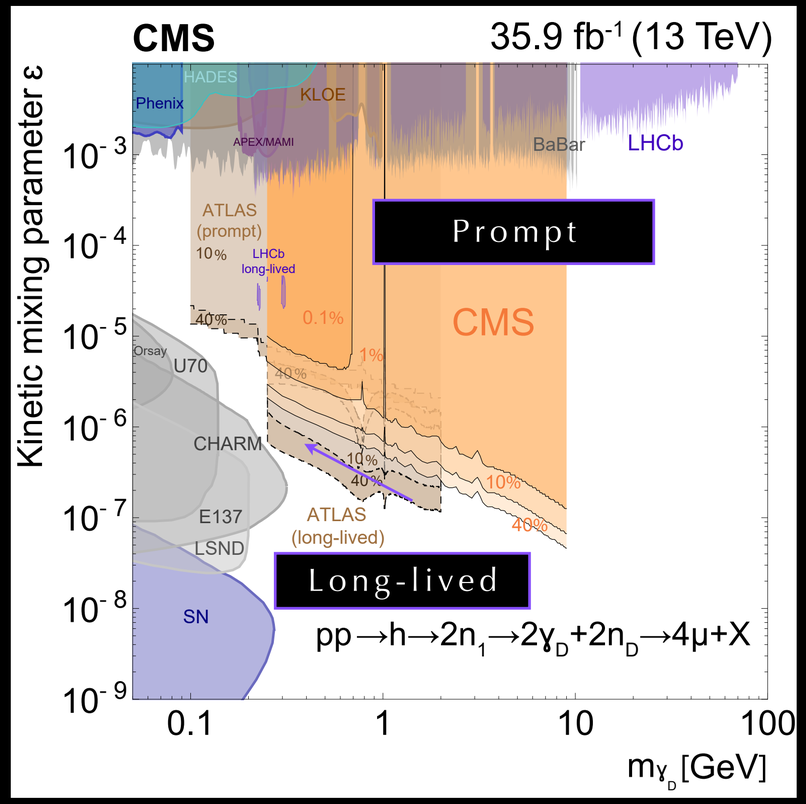
Lepton-jet = highly-collimated grouping of leptons from a low-mass (O(GeV)), boosted BSM particle like a dark photon / Z_{dark}

- Confounds standard lepton isolation criteria



PLB 796 (2019) 131

ATLAS-CONF-2016-042



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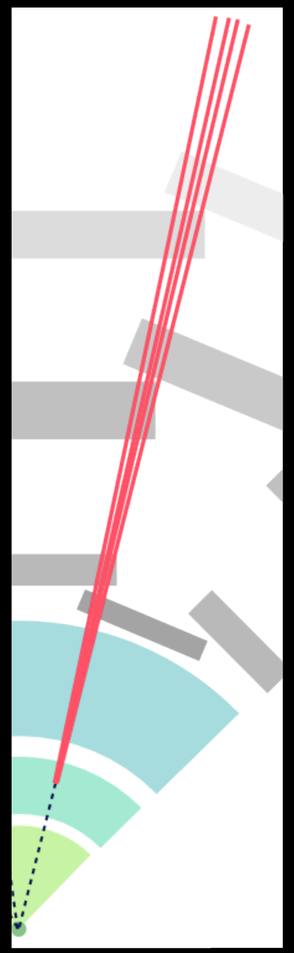
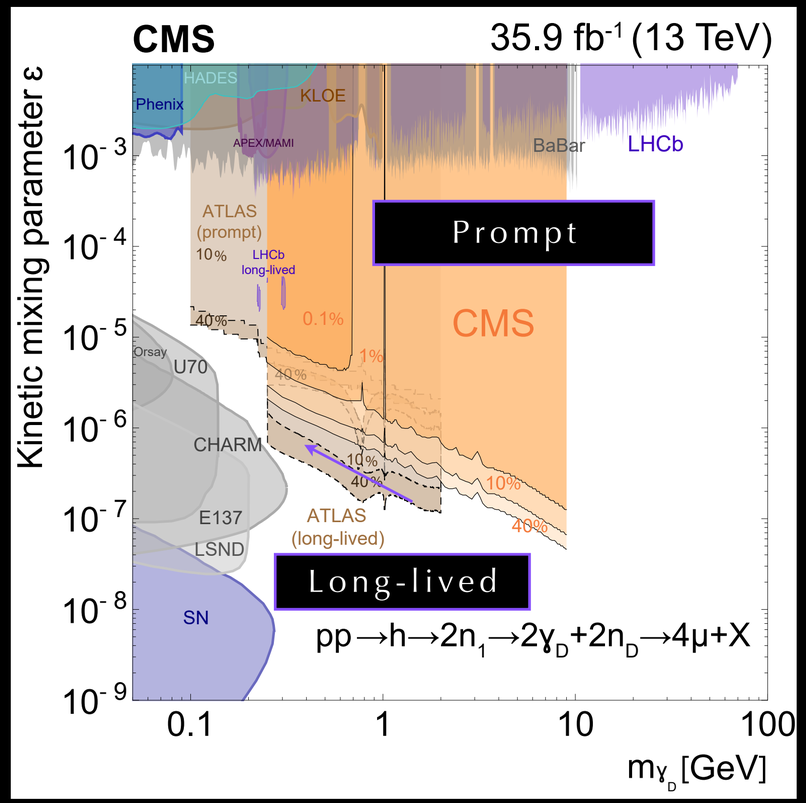
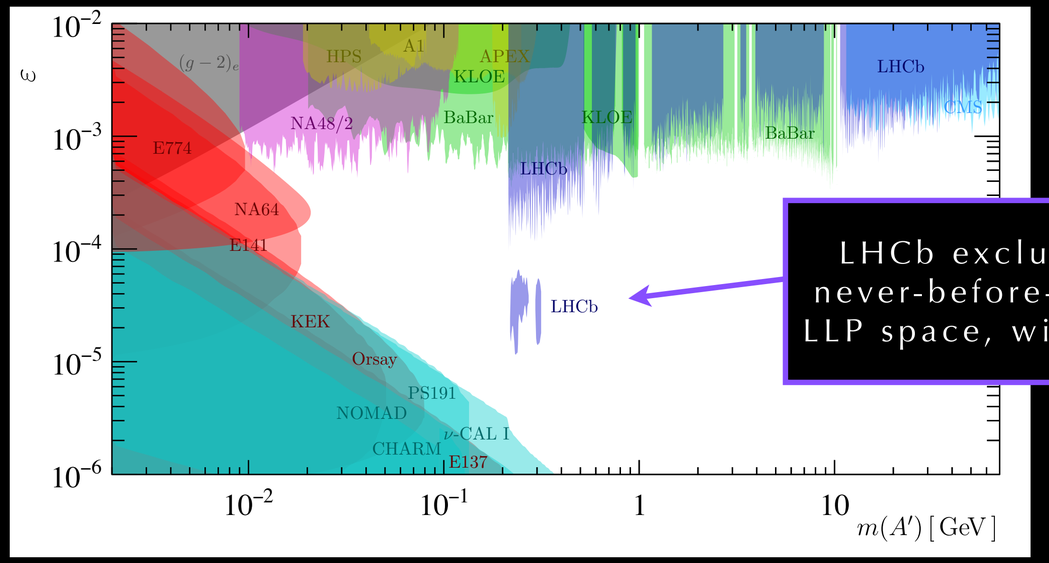


PLB 796 (2019) 131

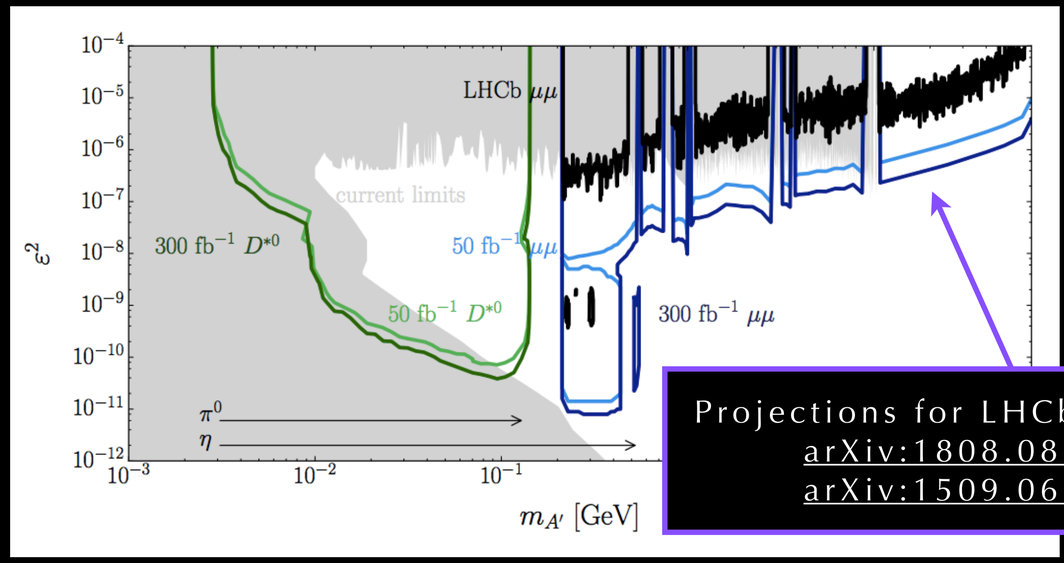
ATLAS-CONF-2016-042





LHCb exclusion in never-before-covered LLP space, with 5.5/fb

LHCb: PRL 124, 041801 (2020)

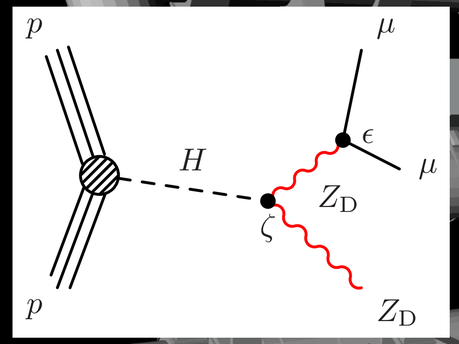


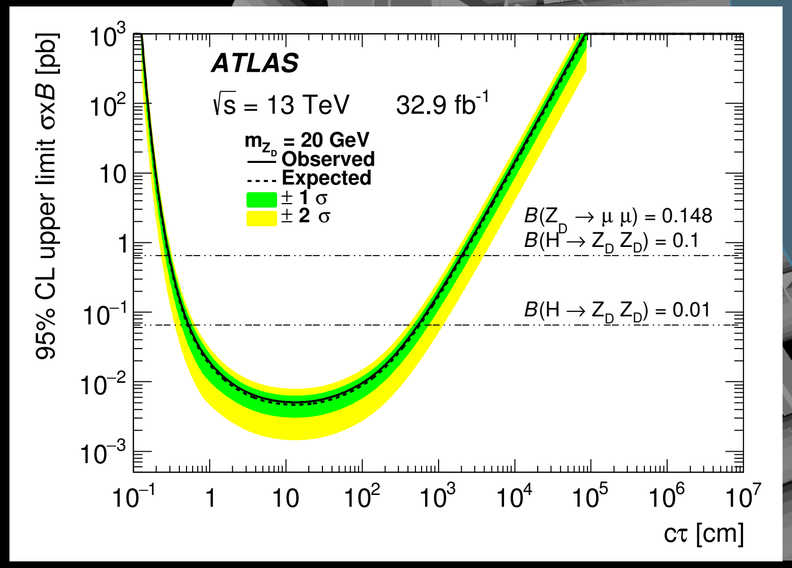
Projections for LHCb upgrade
arXiv:1808.08865
arXiv:1509.06765

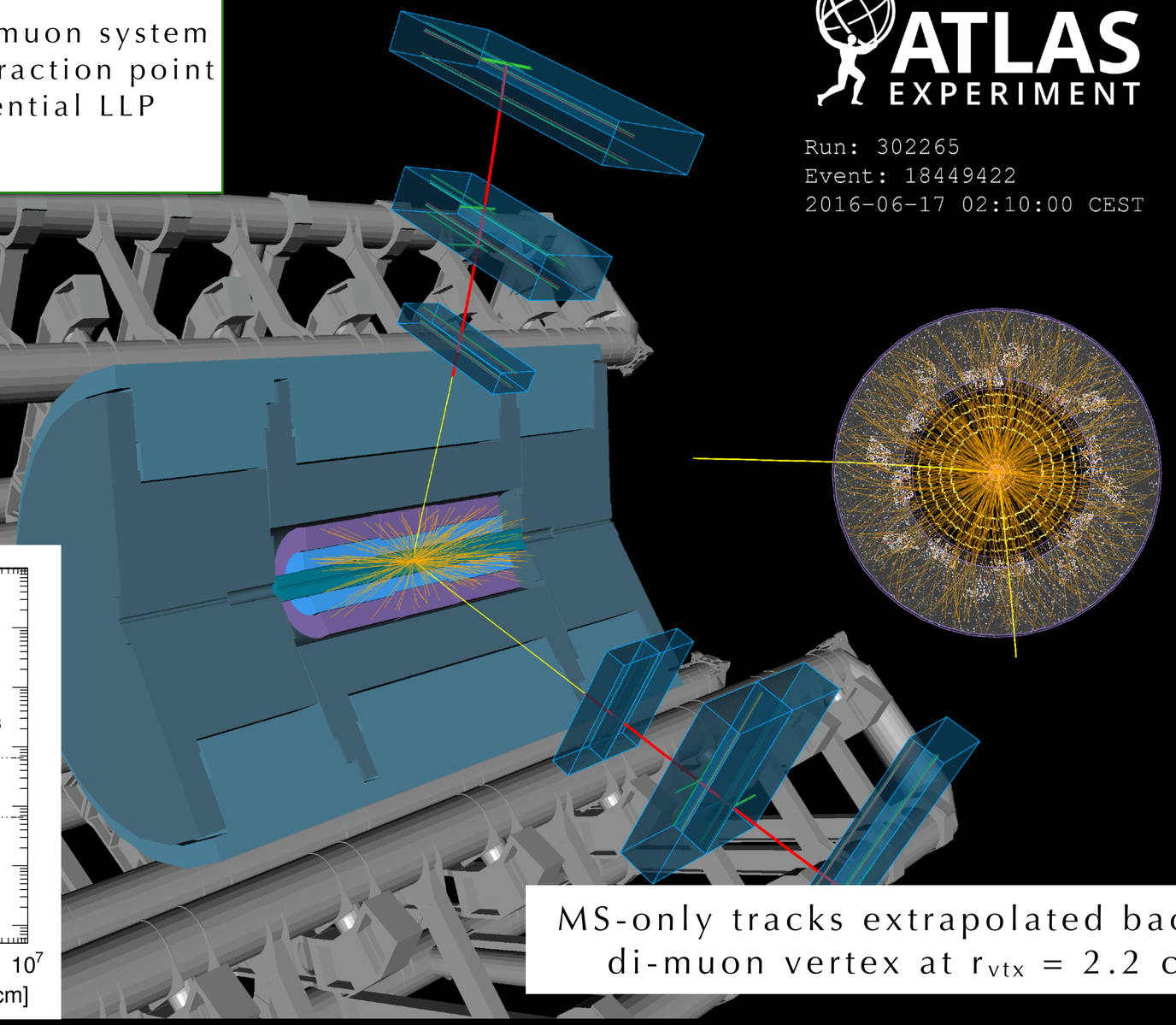
LHCb: PRL 120, 061801

Neutral LLPs decaying to leptons

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]





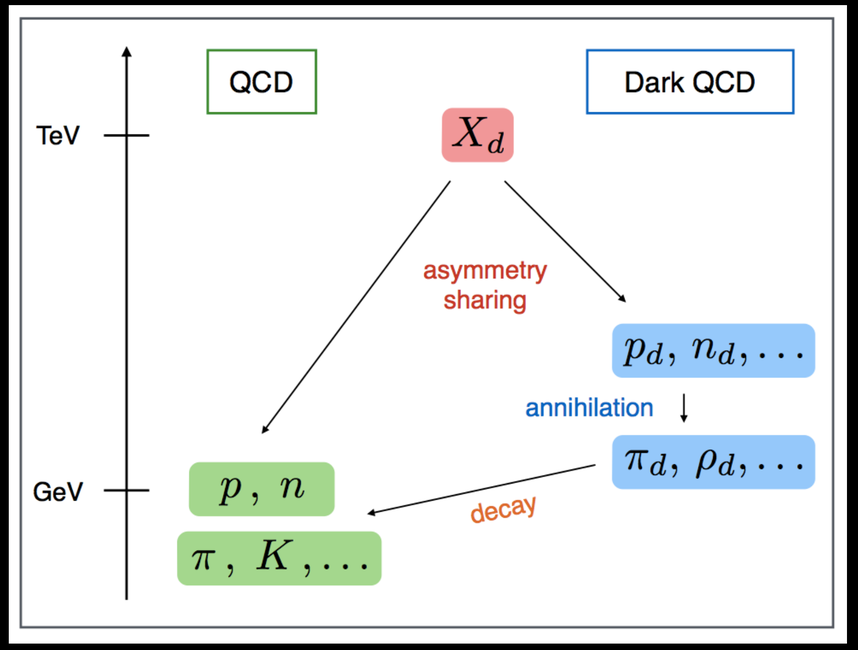


Run: 302265
Event: 18449422
2016-06-17 02:10:00 CEST

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

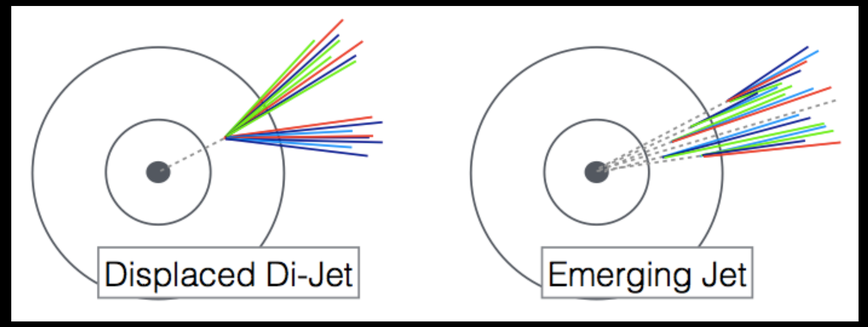
High-multiplicity neutral LLPs decaying hadronically: Emerging jets

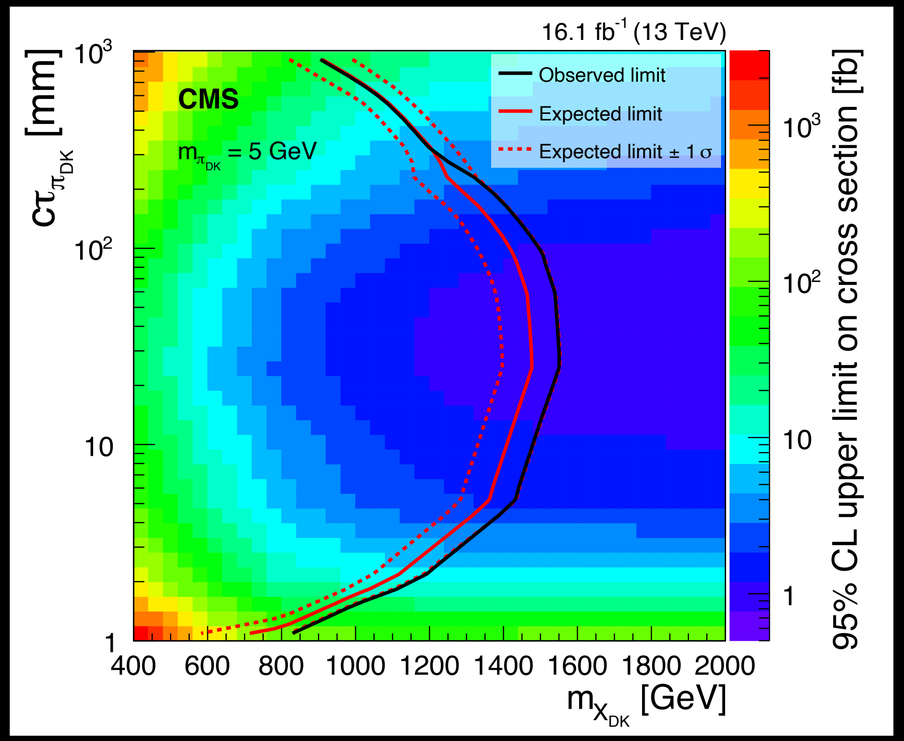
JHEP (2015) 2015: 59



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





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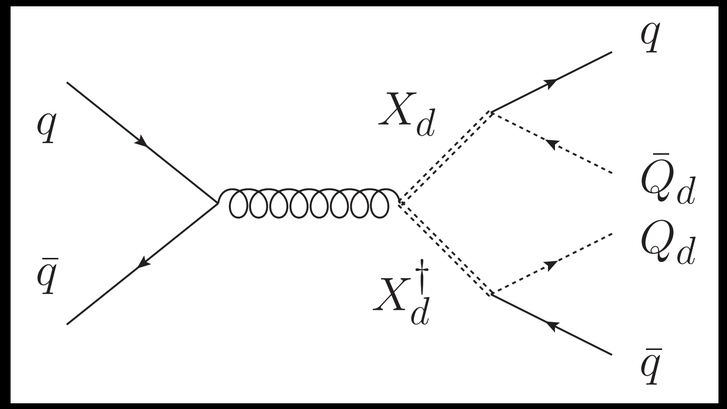
Thus, this is **neither prompt jets nor a pair of displaced jets** pointing to the same displaced vertex, but **emerging jets**

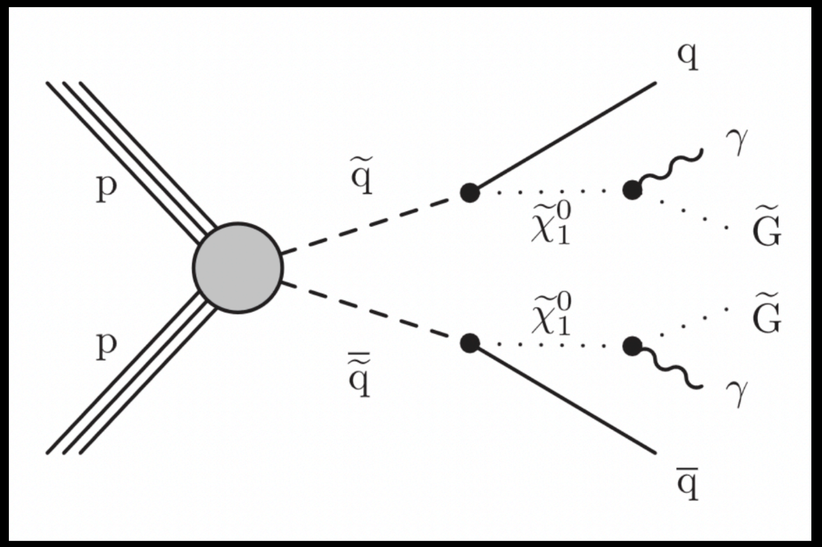


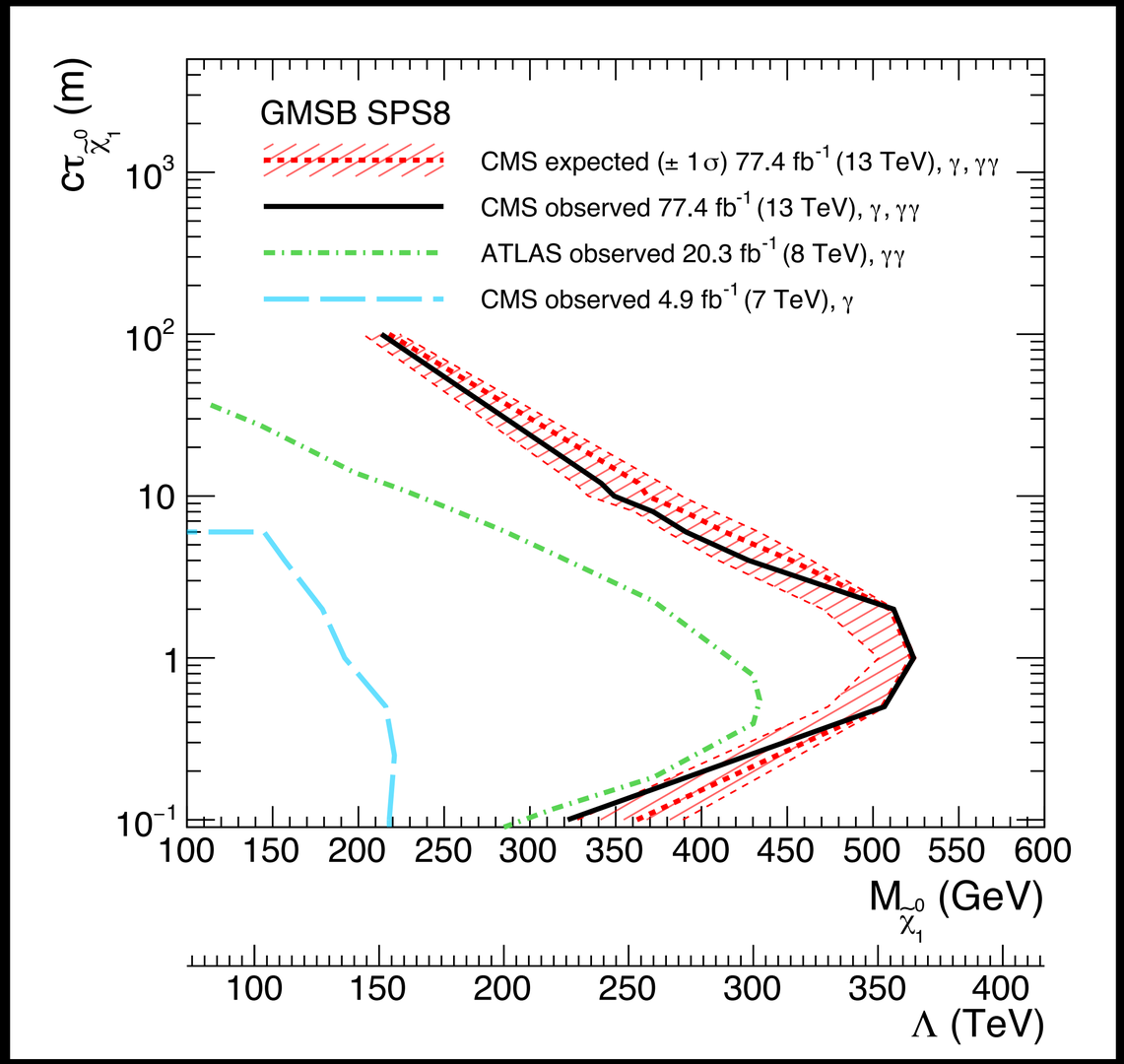
First results for this dark QCD model at the LHC from CMS — ATLAS search in progress

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

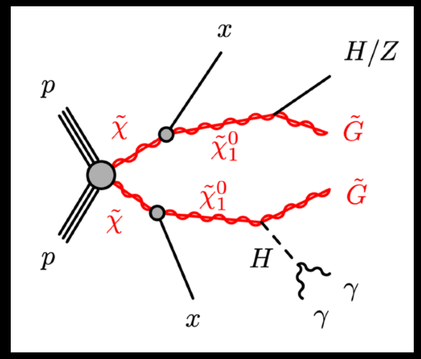


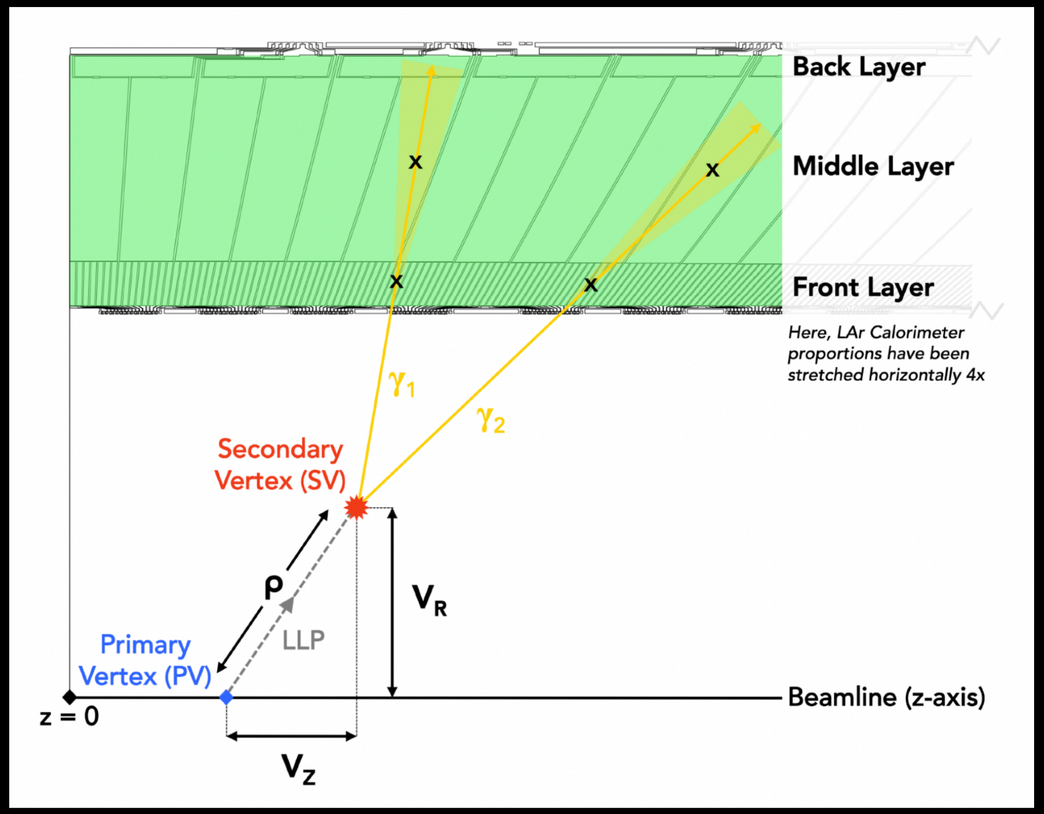


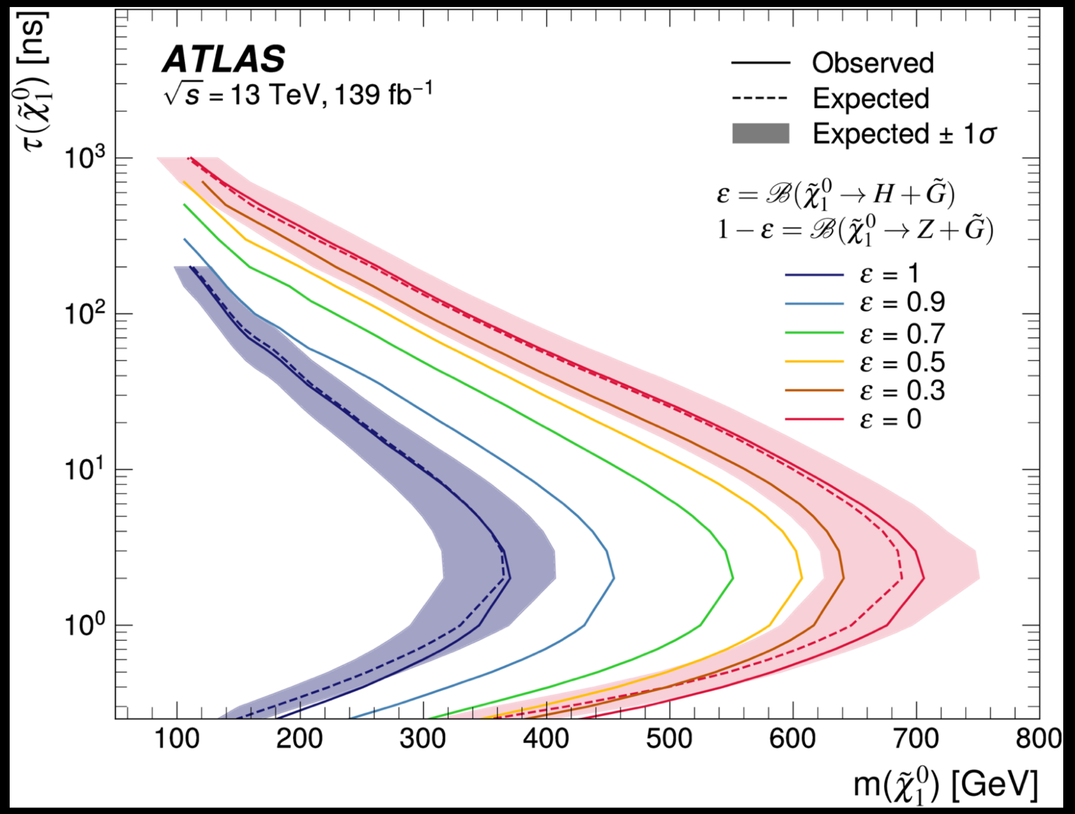
CMS, 13 TeV
PRD 100, 112003 (2019)

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





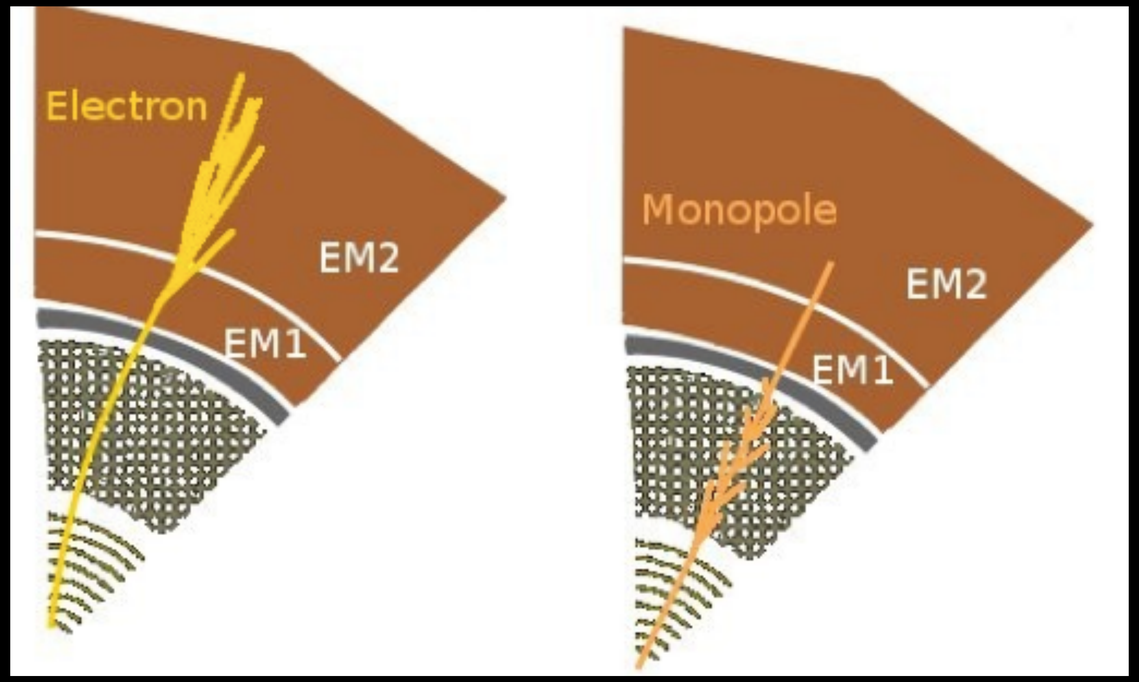


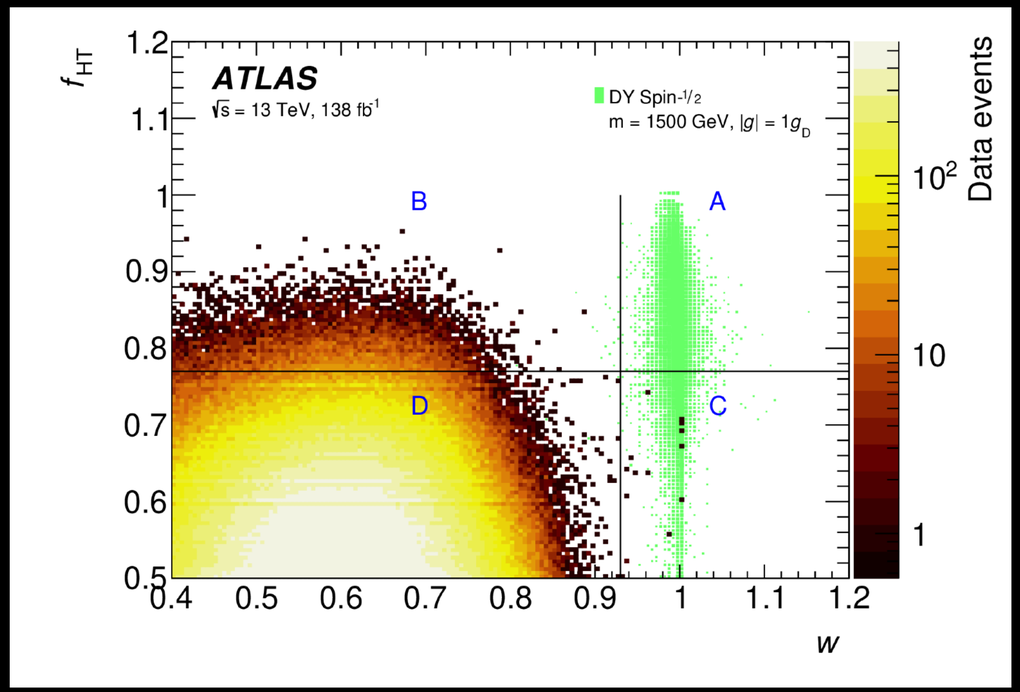
ATLAS: PRD 108 (2023) 1, 012012

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]

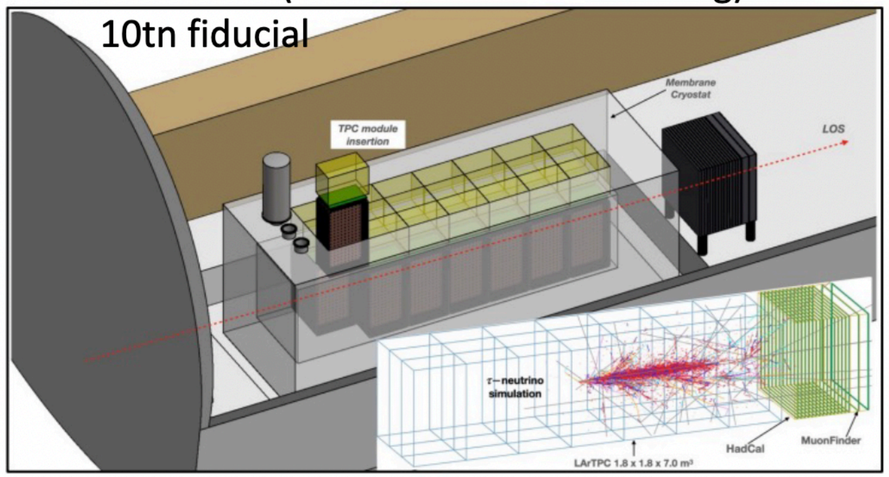
Other BSM charged particles can move much at speeds much slower than the speed of light or leave high ionization

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

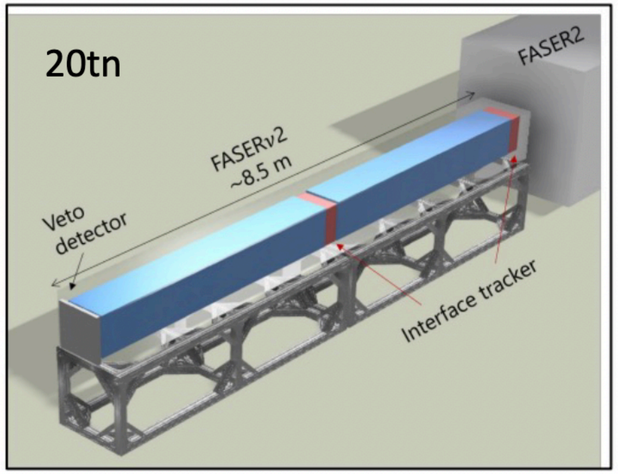
Forward Physics Facility

For FLArE, cf. LUXE at DESY

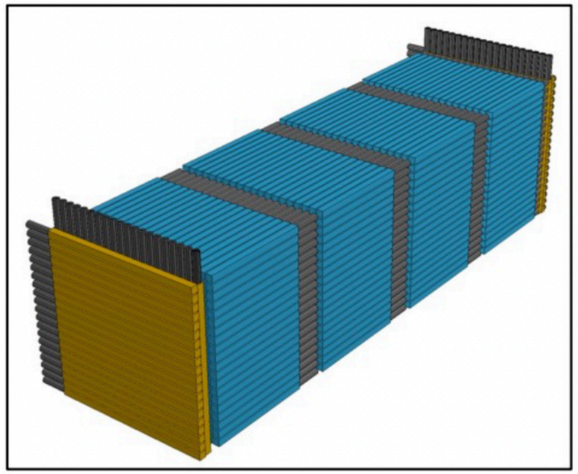
FLArE: LAr TPC (neutrinos + DM scattering)



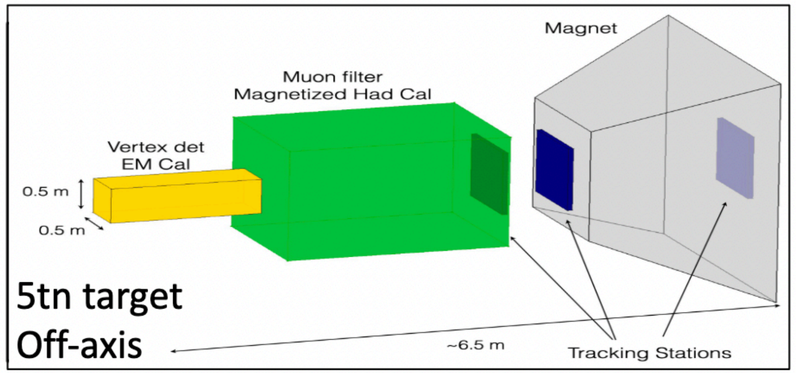
FASERv2: Emulsion (neutrinos)



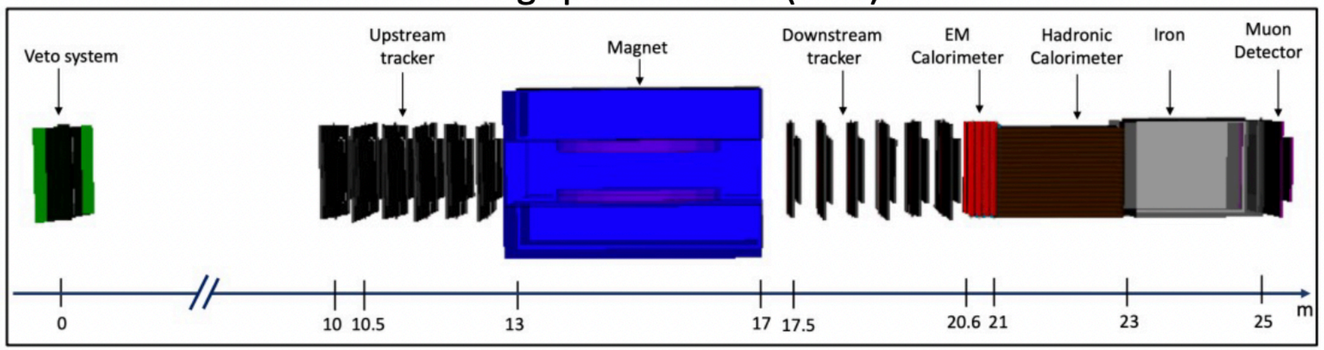
FORMOSA: Scintillators (milicharged



AdvSND: electronic (neutrinos)



FASER2: tracking spectrometer (LLPs)



J. Boyd

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

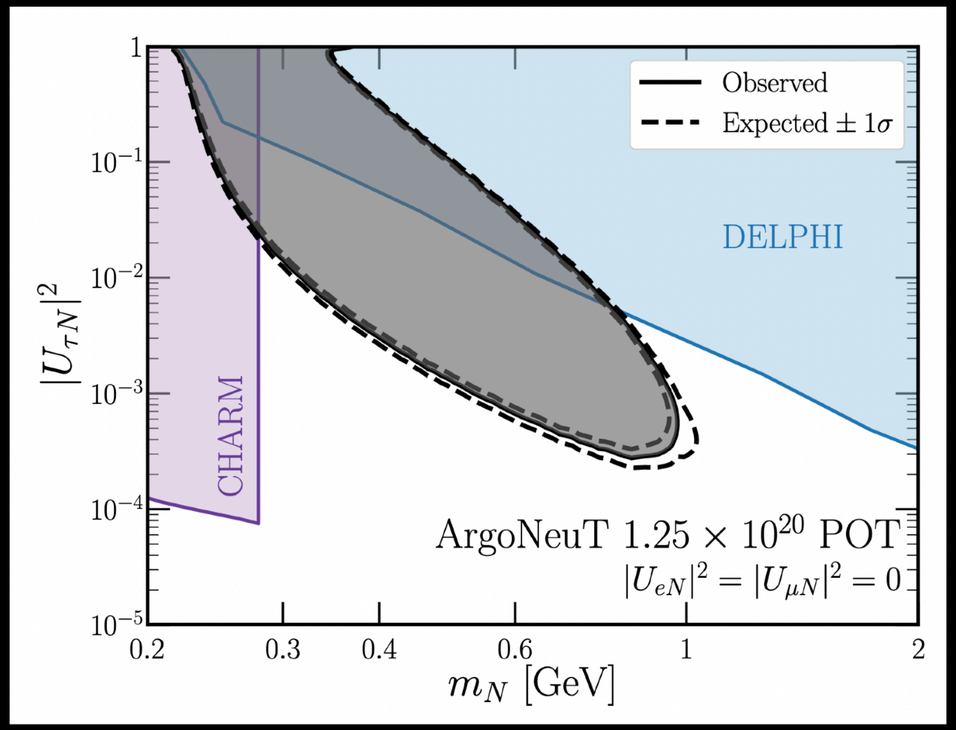
Site investigations ongoing (already drilled 100-meter-deep earth cores)

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

We're still learning about LLPs from past experiments

ARGONEUT

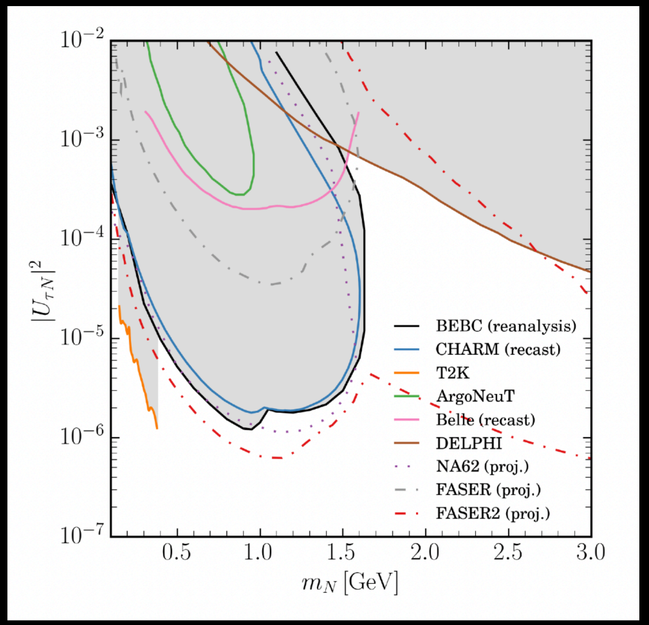
Was the first LArTPC in a neutrino beam in the U.S. (Fermilab), designed as a test experiment that took data in 2009-2010, recently re-analyzed for BSM LLP signatures



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



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