Dark Higgs searches in dedicated LLP detectors. MATHUSLA, CODEX-b, ANUBIS, FASER, and SHiP

Emma Torró Pastor

Big thanks to CODEX-b, ANUBIS, FASER and SHiP for input

Higgs 2023
Beijing
Dec 1st 2023

MATHUSLA | IFIC INSTITUT DE FÍSICA CORPUSCULAR | CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS | VNIVERSITAT DE VALÈNCIA | ATLASVLC Instituto de Física Corpuscular - Valencia | GENERALITAT VALENCIANA Conselleria d'Educació, Cultura i Esport | Gen—T

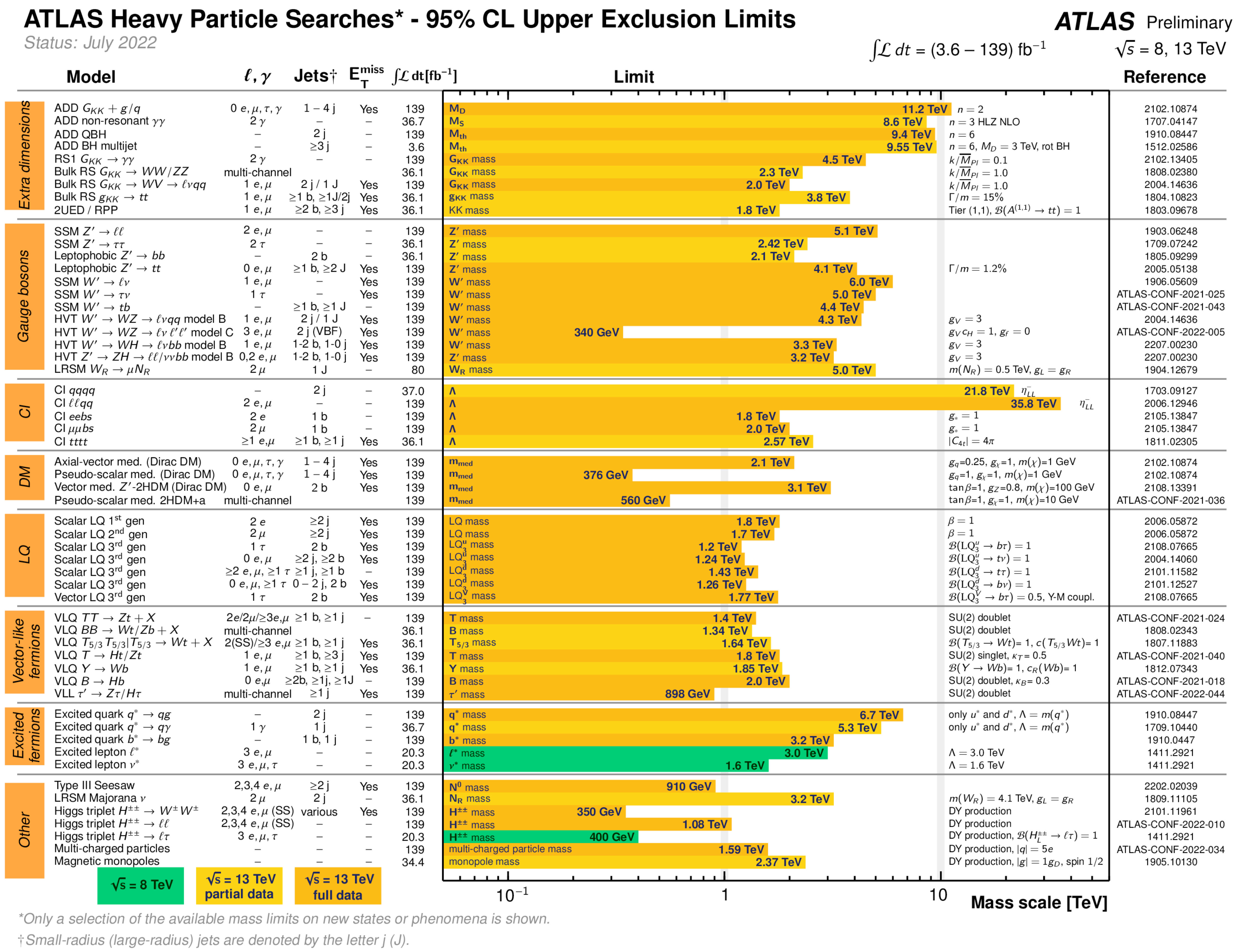
Why search for Long-lived particles?

The search for new Physics is one of the main goals in HEP

- What is Dark Matter made of?
- Neutrinos have a mass ≠ 0
- Matter and antimatter are not symmetric
- …

- Precision measurements
- Explicit searches:
  - 90% searching for promptly decaying new particles
  - But!! Most robust problems (DM, neutrino masses) naturally point to very weakly interacting particles
  - New particles could have long lifetimes!!

- We need to make sure that every possibility has been explored
  - Diversity in searches
  - New ideas

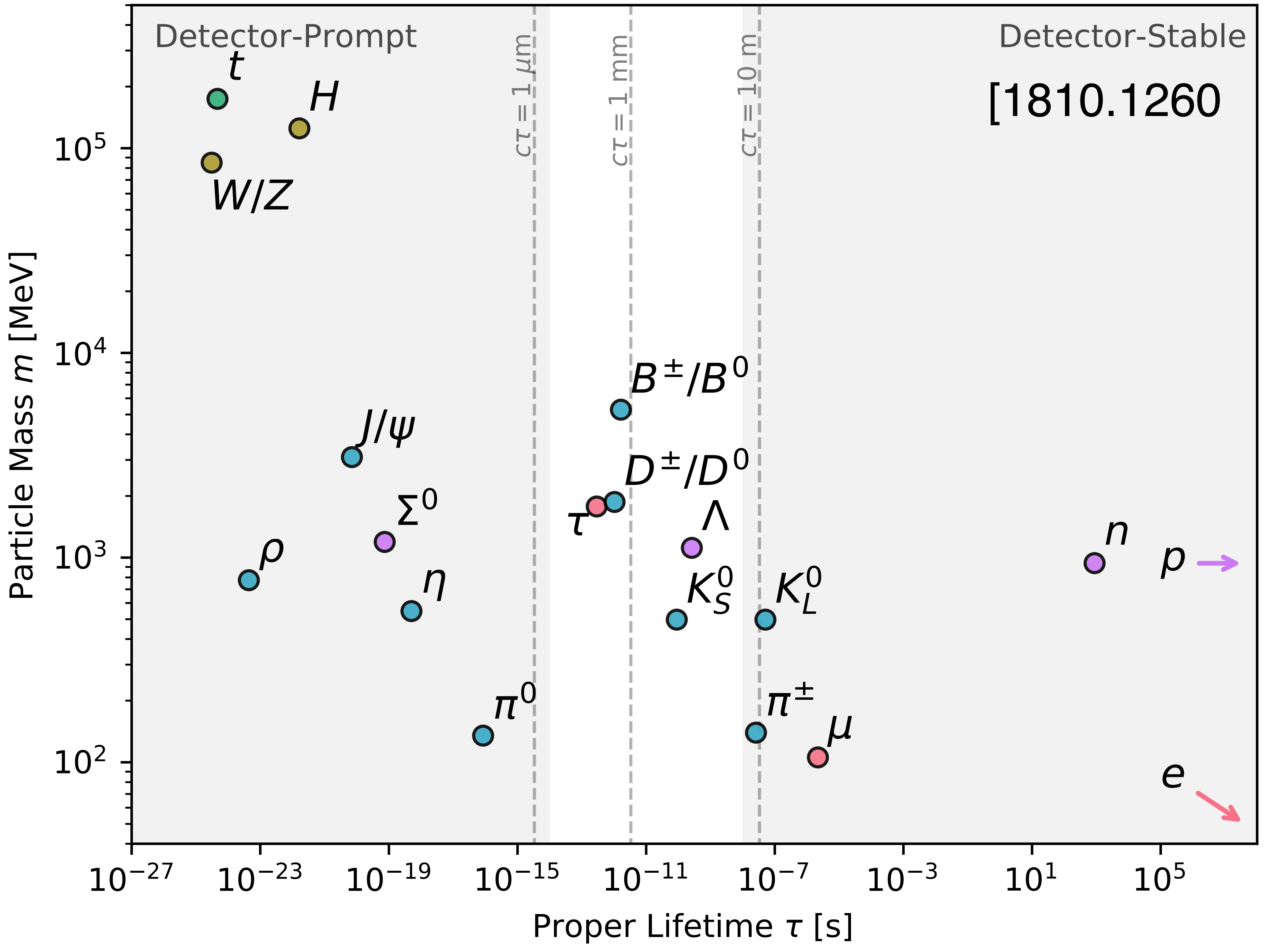


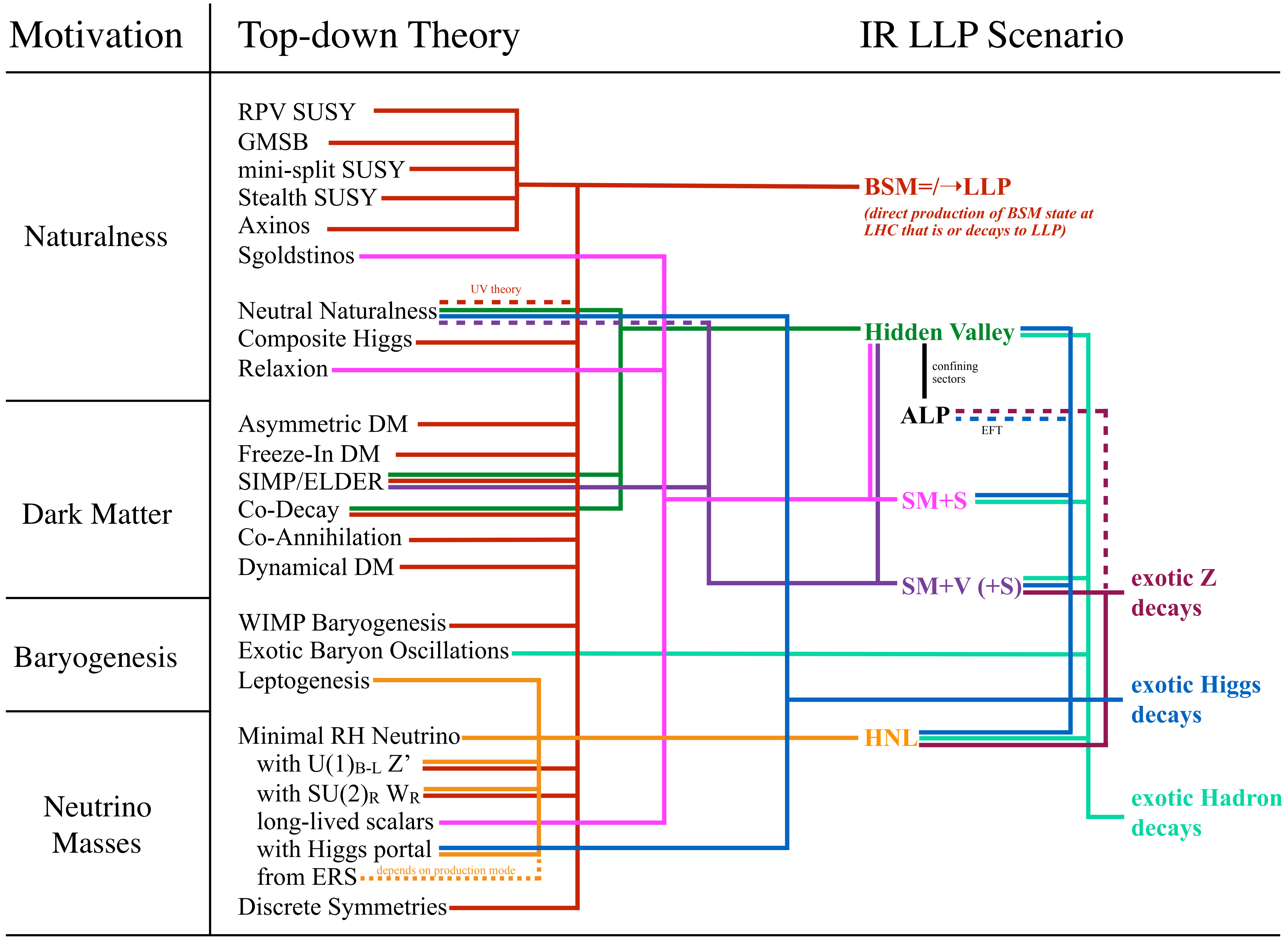
To date, **O(100) ATLAS, CMS, LHCb papers** on BSM searches with full Run 2 dataset!

Still, no evidence of new physics…

Why search for Long-lived particles?

- Semi-stable particles are very abundant in the SM
- It would not be surprising that new physics contains them too
- Very easily identified as background
  - Specific searches needed!



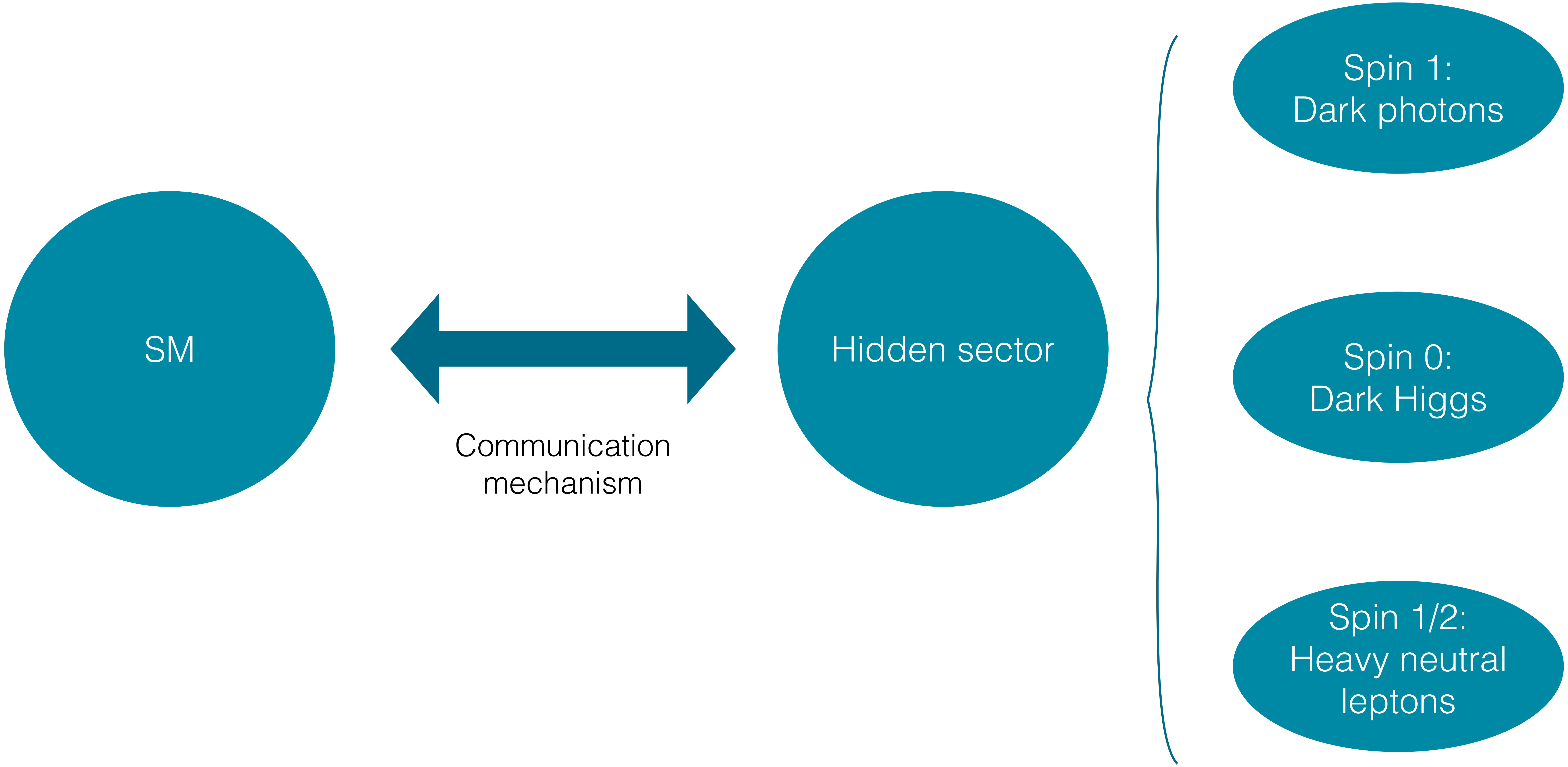


New physics could have long lifetimes

Signatures in ATLAS and CMS not visible in standard searches!!

Dark Higgs and exotics Higgs decays with LLPs

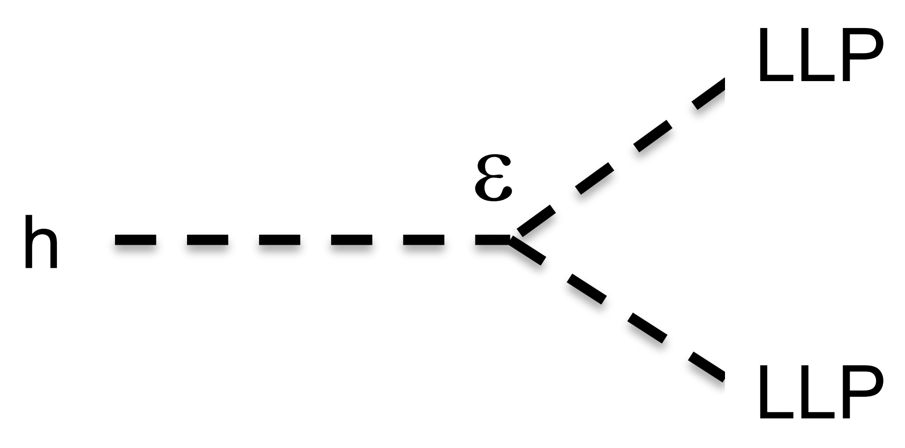
- Dark/Hidden sectors: new sector very weakly coupled to the SM
- In its minimal version, need only one state that acts as mediator between the two sectors
- Lots of examples during this conference (ex. Wei Liu's talk, Hengne Li's talk)

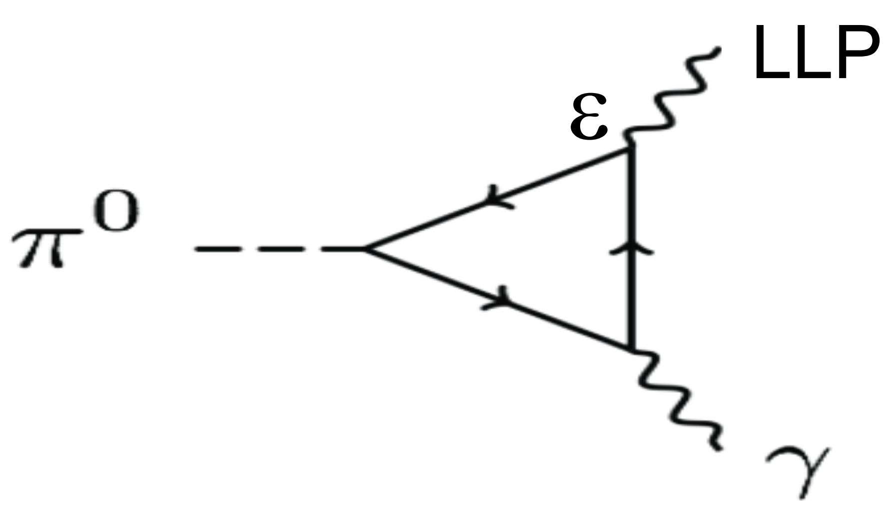


- Coupling to SM with couplings proportional to charge
- Coupling to SM with couplings proportional to mass
- Mixes with SM neutrinos with mixing

Dark Higgs and exotics Higgs decays with LLPs

- Dark/Hidden sectors: new sector very weakly coupled to the SM
- In its minimal version, need only one state that acts as mediator between the two sectors
- Lots of examples during this conference (ex. Wei Liu's talk, Hengne Li's talk)
    - Can include new neutral particles with extremely weak interactions
        - New long-lived particles lead to new phenomenology!!
    - They can be produced in the decay of both heavy and light SM particles or in other ways

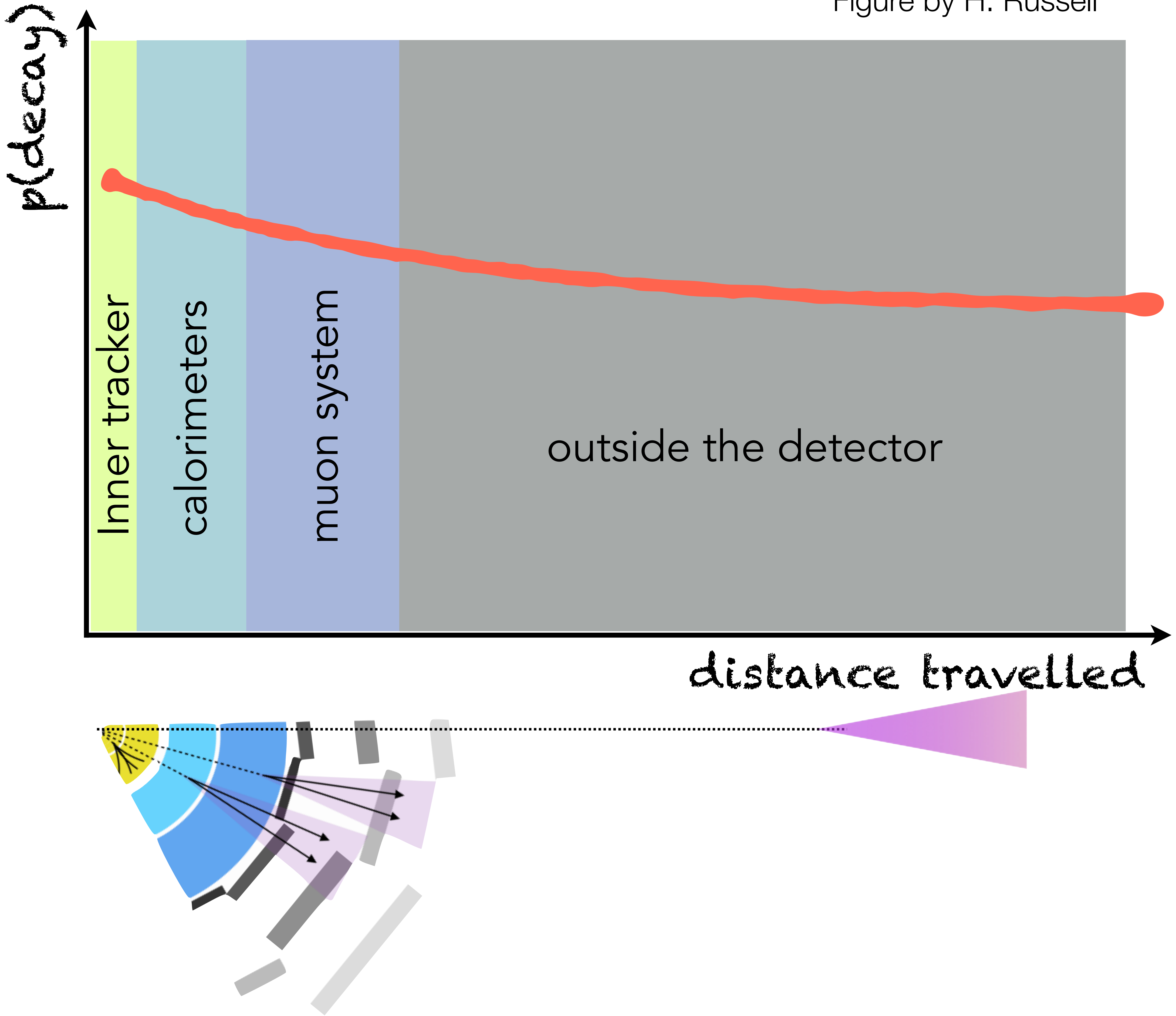




- If they are weakly interacting and long lived, they pass through matter leaving no signature and decay to visible particles after a long distance

Where should we look for LLPs in collider experiments?

Figure by H. Russell



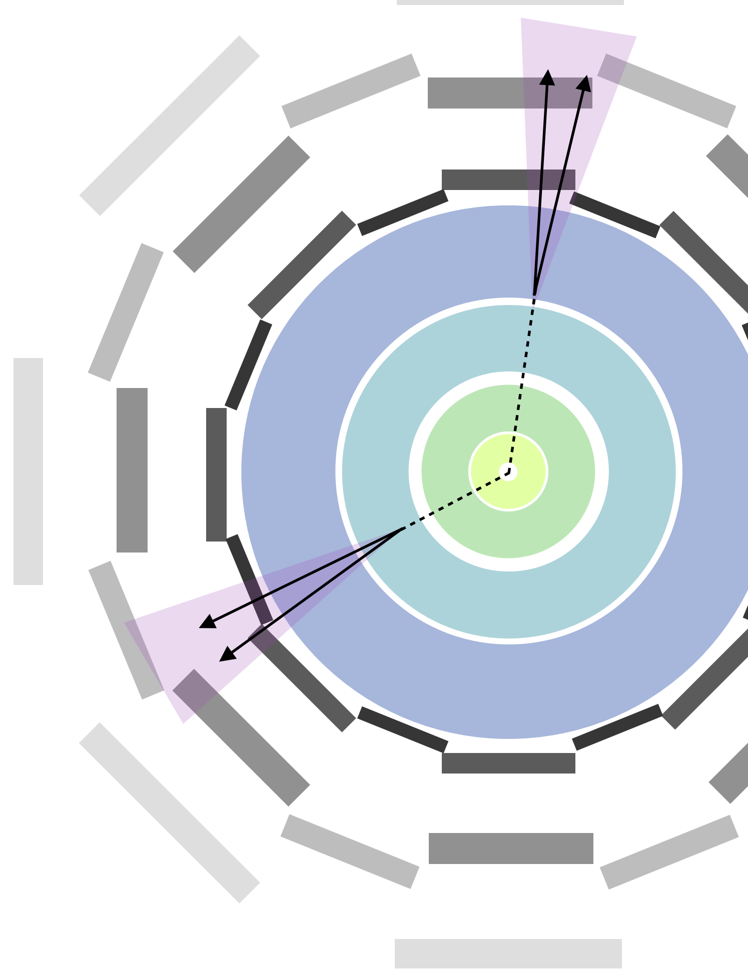
That depends on the lifetime: where is it more probable to find a LLP decay?

- In the main LHC detectors we can use information from different sub detectors for different targets.
  - Large SM backgrounds
  - Tight triggers

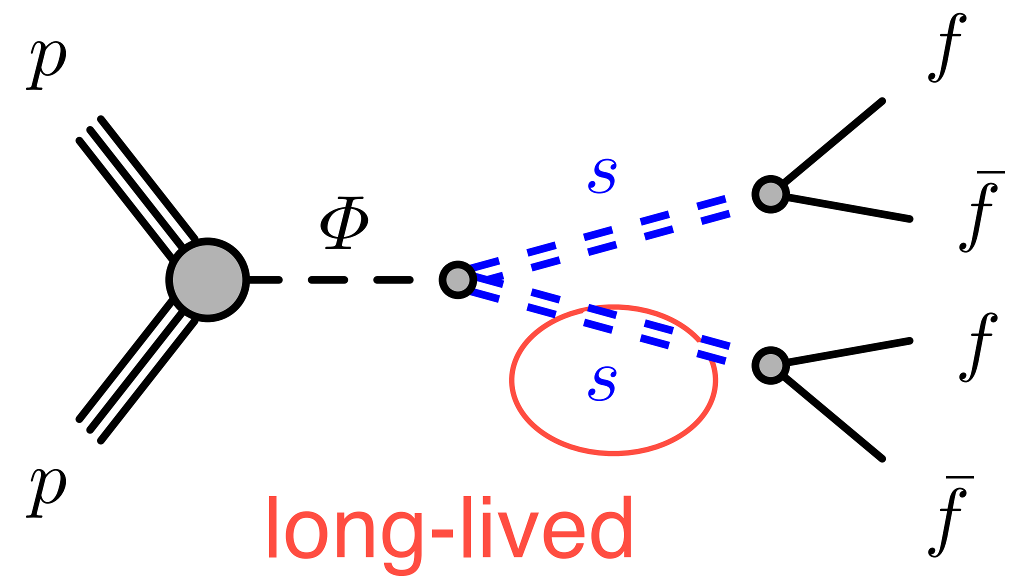
- Particles with long lifetimes decay mainly outside the LHC main detectors.

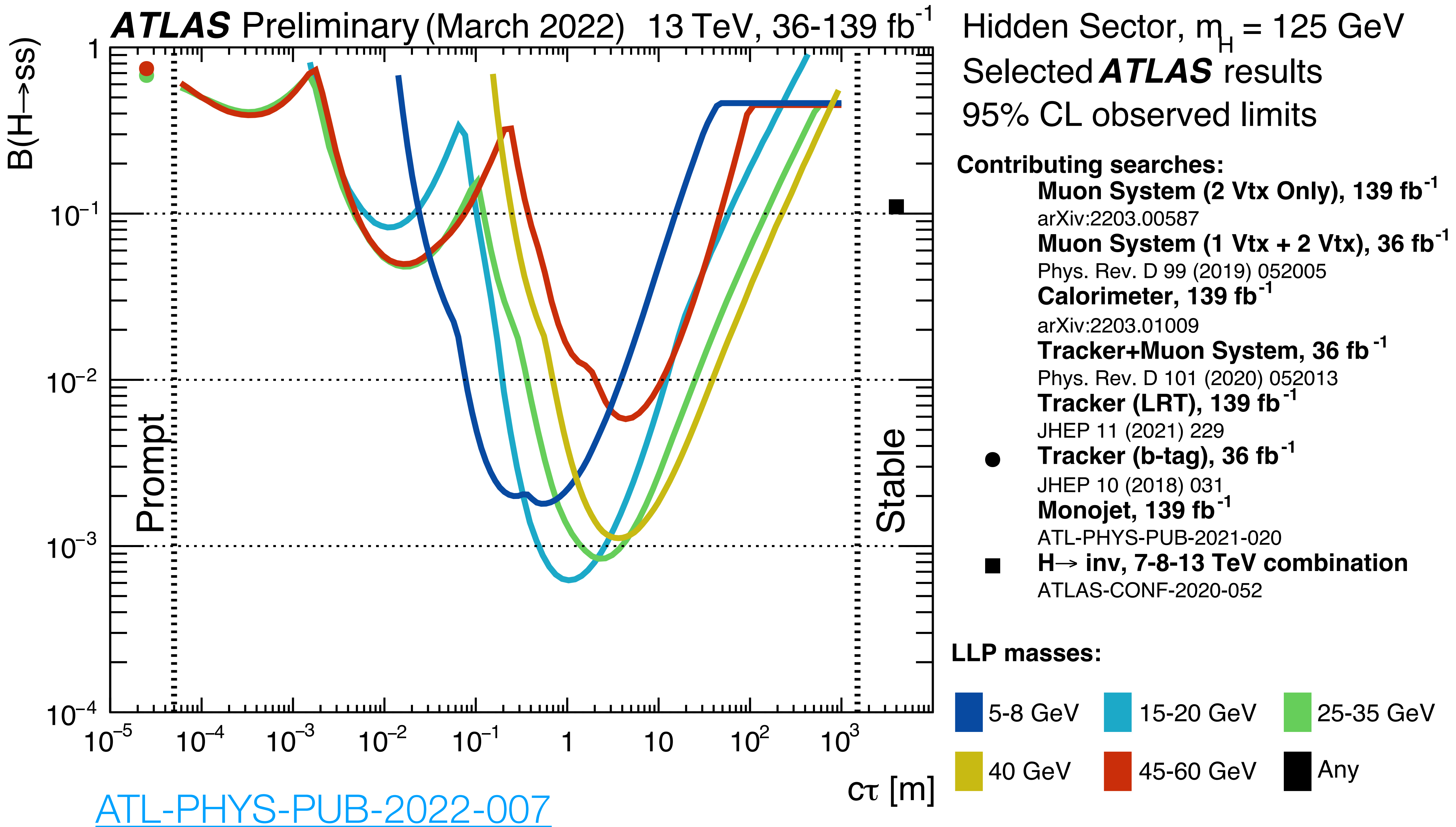
For long lifetimes we need different detectors!

Current limits at the LHC experiments



- The main LHC experiments count with a large program for the search of LLPs
- Example benchmark: **Hidden sector** with a heavy neutral boson, ϕ, decaying to two new long-lived neutral scalars, s, that decay to pairs of SM fermions.
  - New boson can be
    - Higgs-like (125 GeV); m(s) = 5 - 55 GeV
    - or heavier (200, 1000 GeV); m(s) = 8 - 400 GeV





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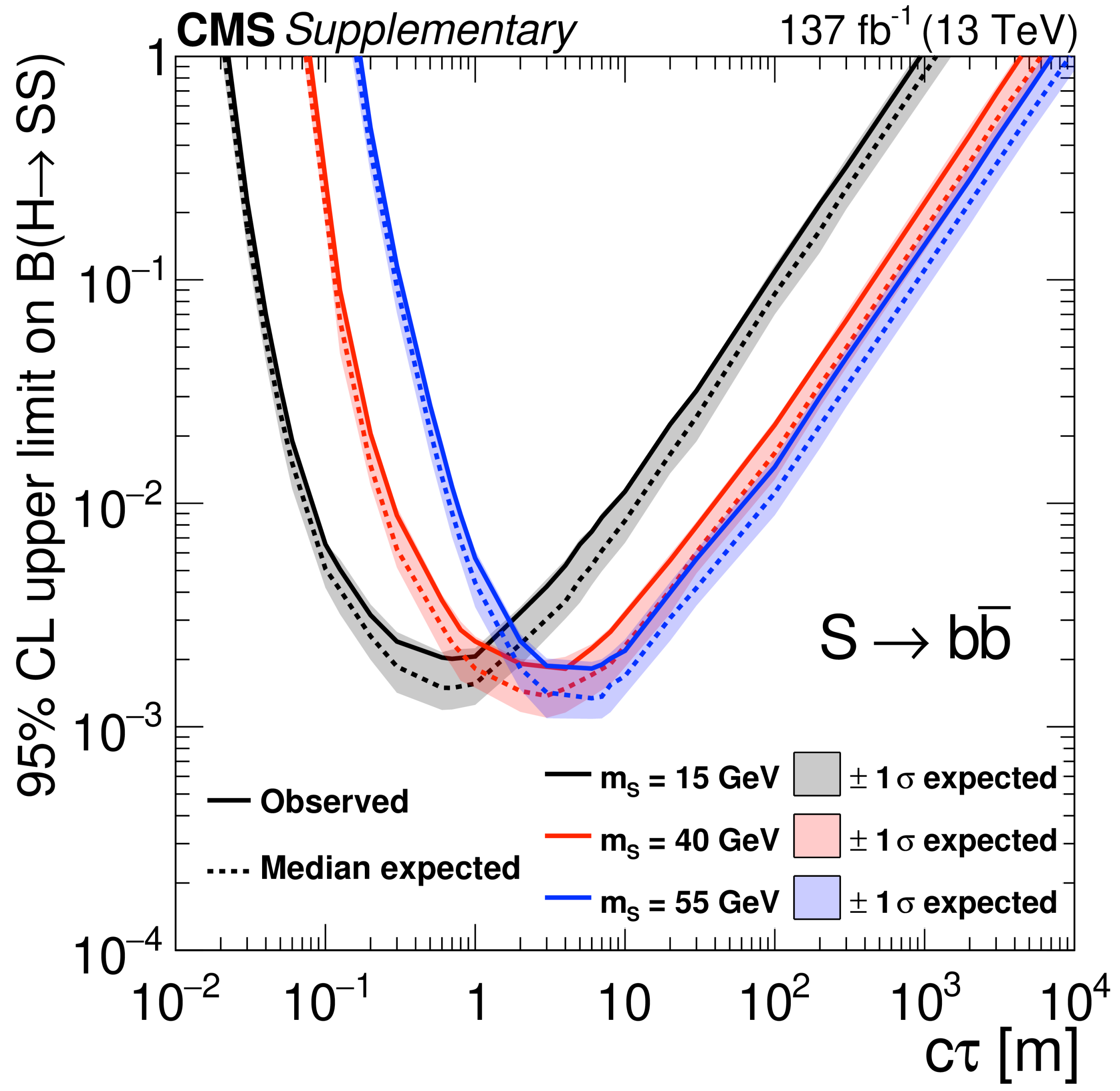
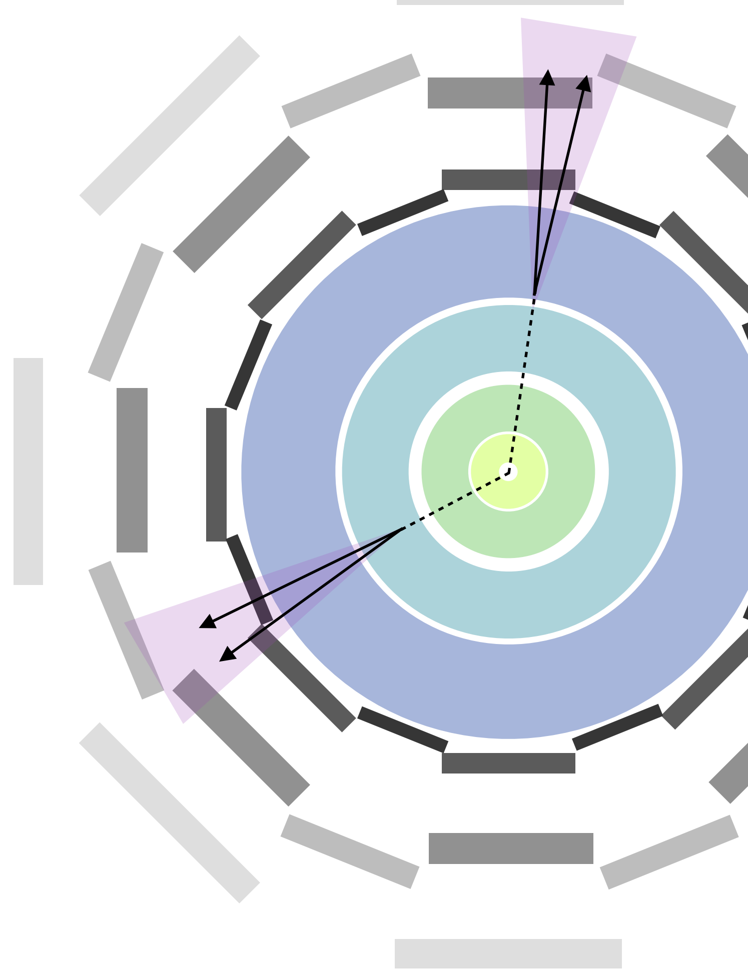


Phy. Rev. Lett. 127 (2021) 261804

Current limits at the LHC experiments



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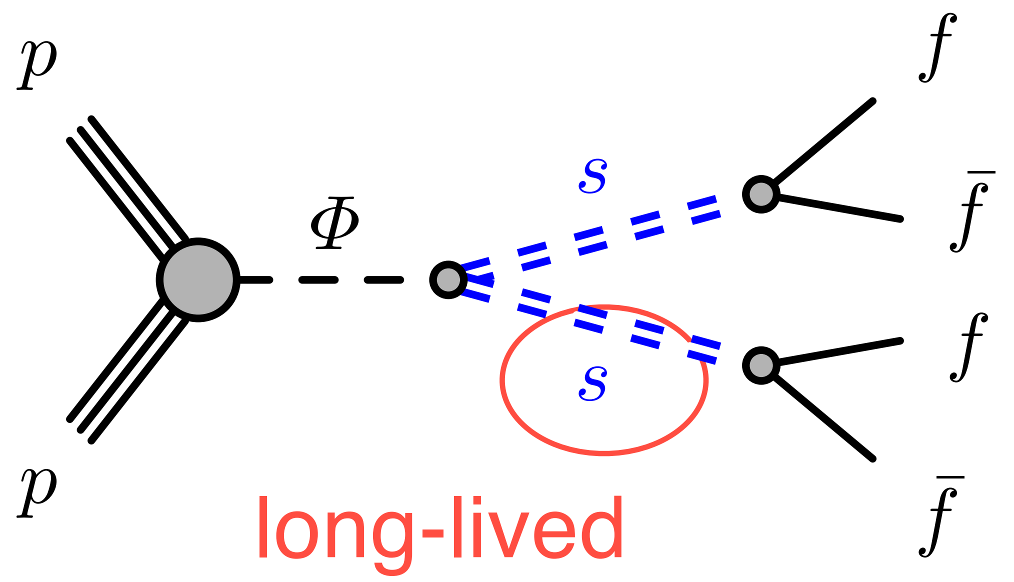
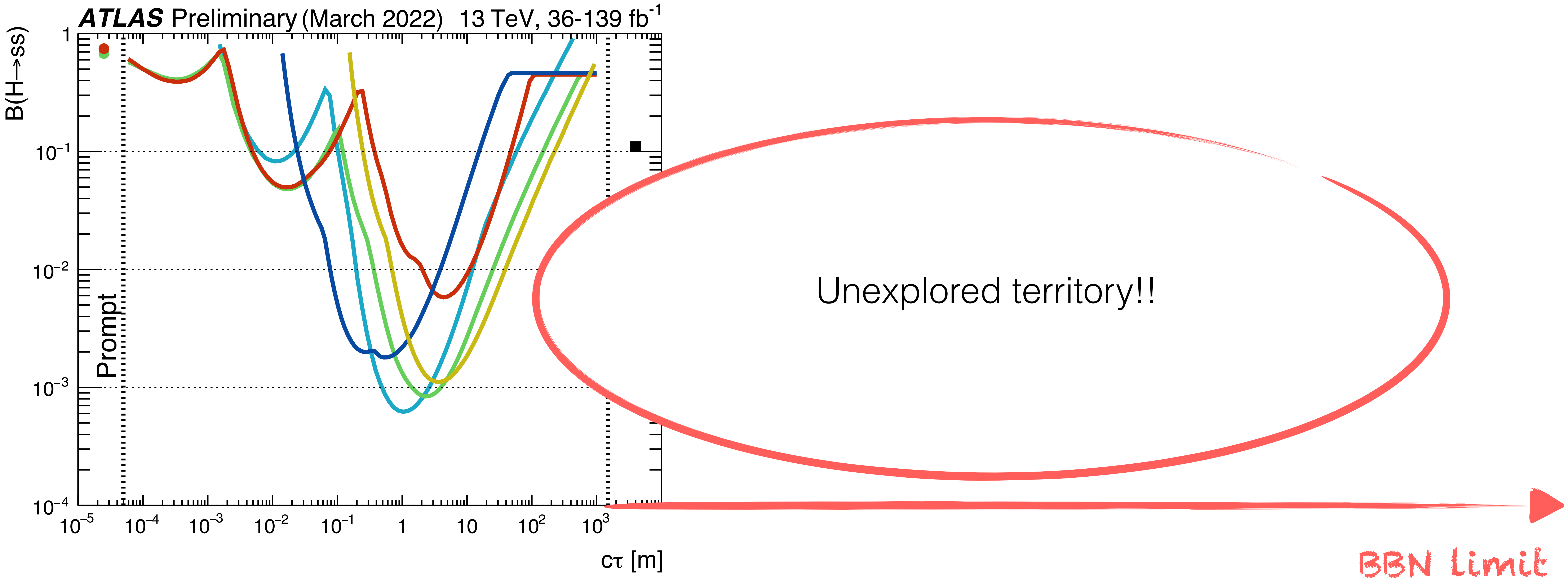
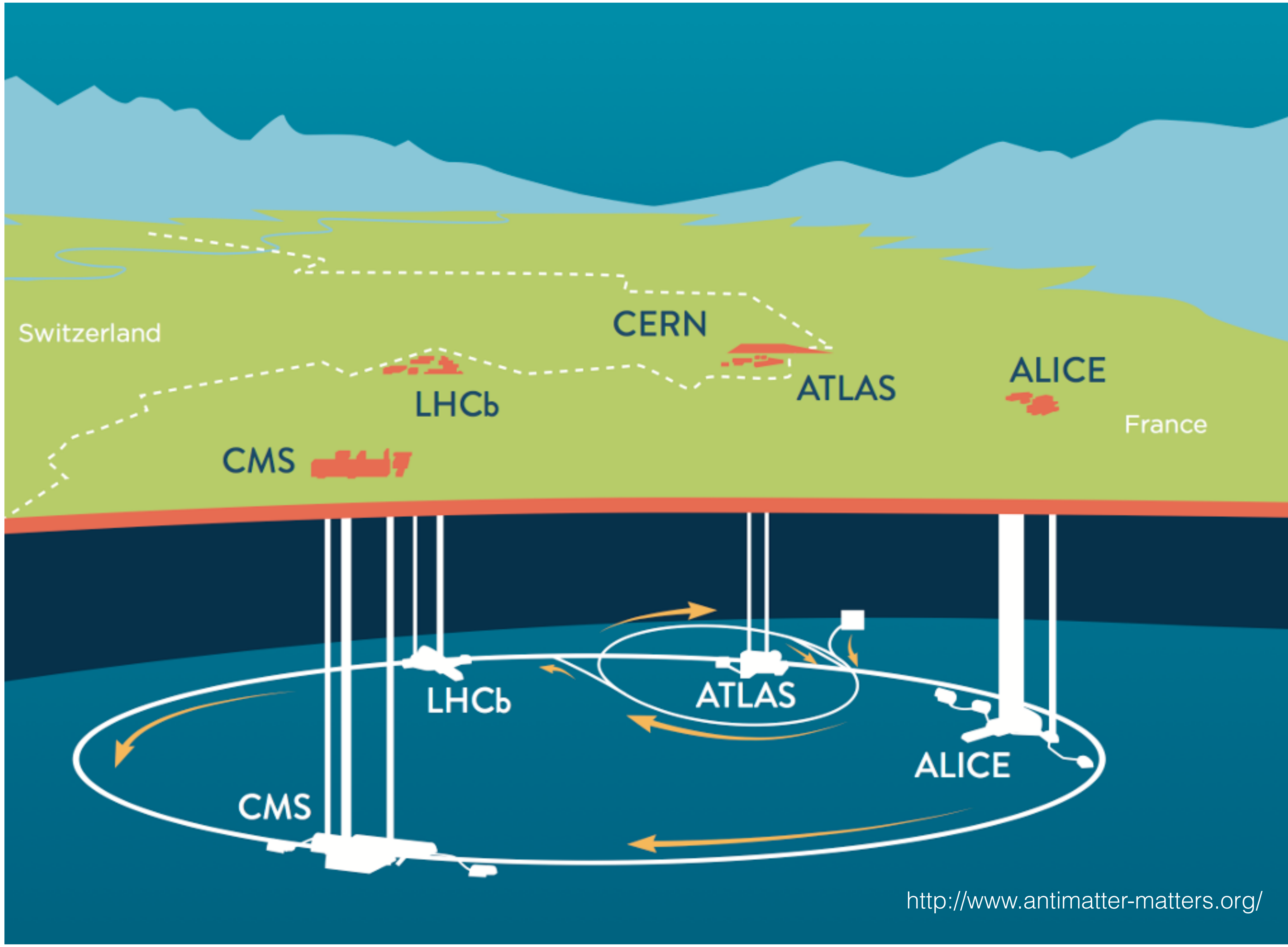




Overview of proposed LLP detectors at the LHC

- Huge range of lifetimes from ~50m to 10^8 m (BBN limit): covered by different detector volume and distance form IP
- Range of models, couplings and masses covered by different angles wrt beam axis
- Many possible decay modes!
- Need variety of detectors = complementary



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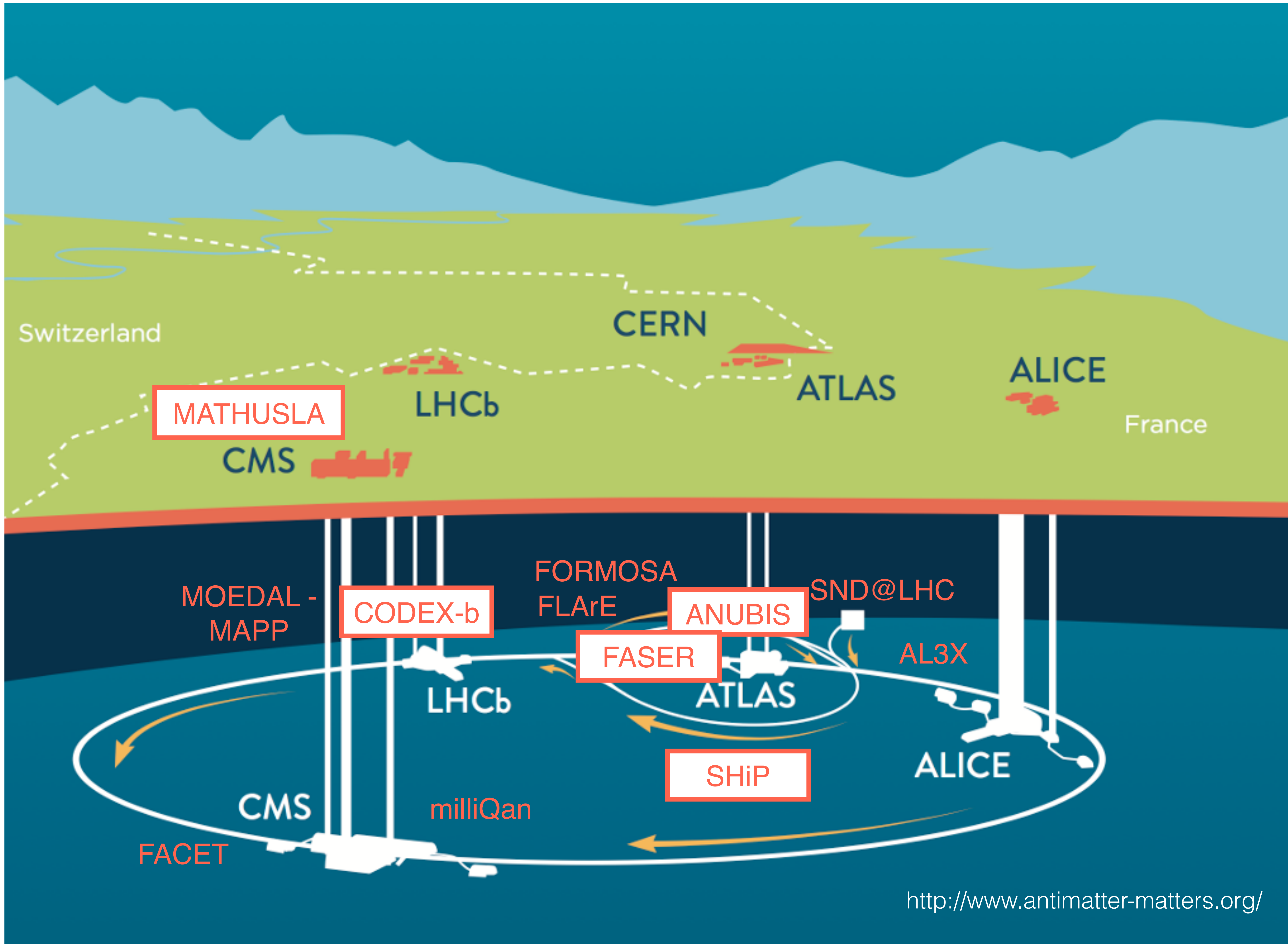

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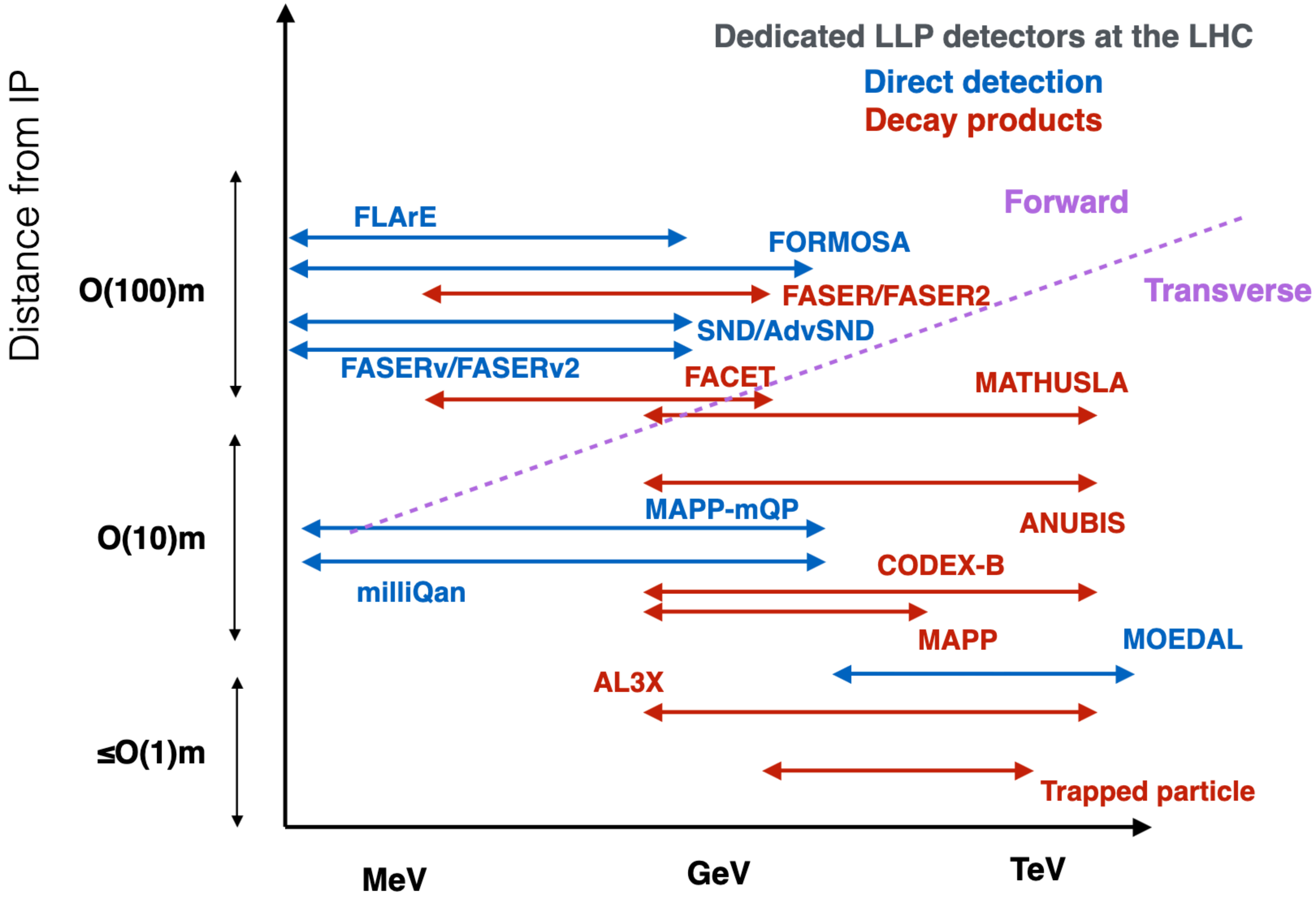


Matthew Citron

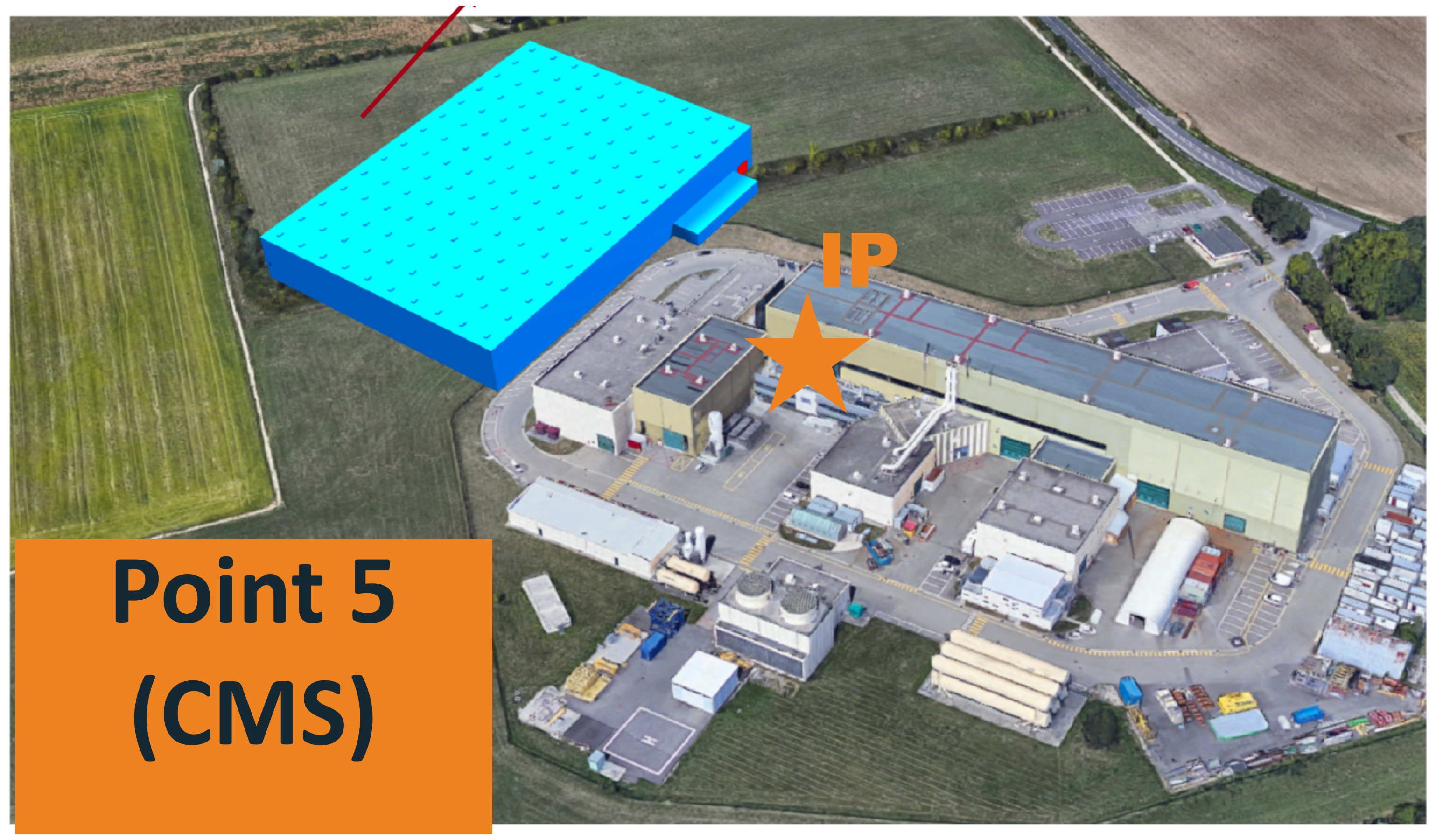
MATHUSLA

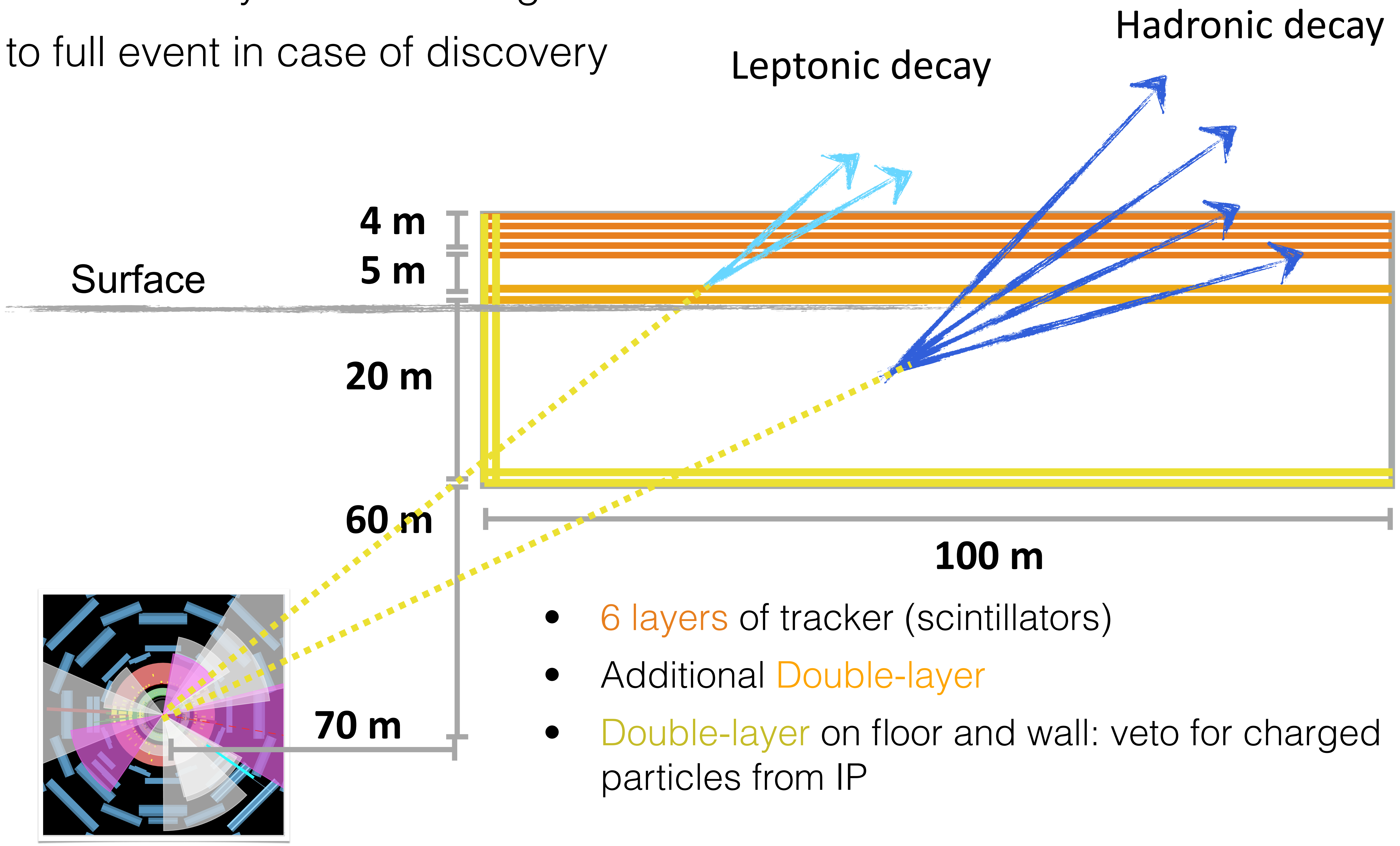
MAsive Timing Hodoscope for Ultra Stable neutraL pArticles

https://mathusla-experiment.web.cern.ch

Updated LHCC Letter of Intent: arXiv 2009.01693

- Objective: **ultra long-lived particles**
  - Most decays happen far from the IP: placed on the surface above CMS during HL-LHC
  - Aim at ~**zero background** analysis (~100m rock shielding) for sensitive to LLPs with lifetime up to 10^8 m (BBN limit)
- Large air decay volume with several scintillator layers for tracking
- Integrated with CMS trigger. Access to full event in case of discovery





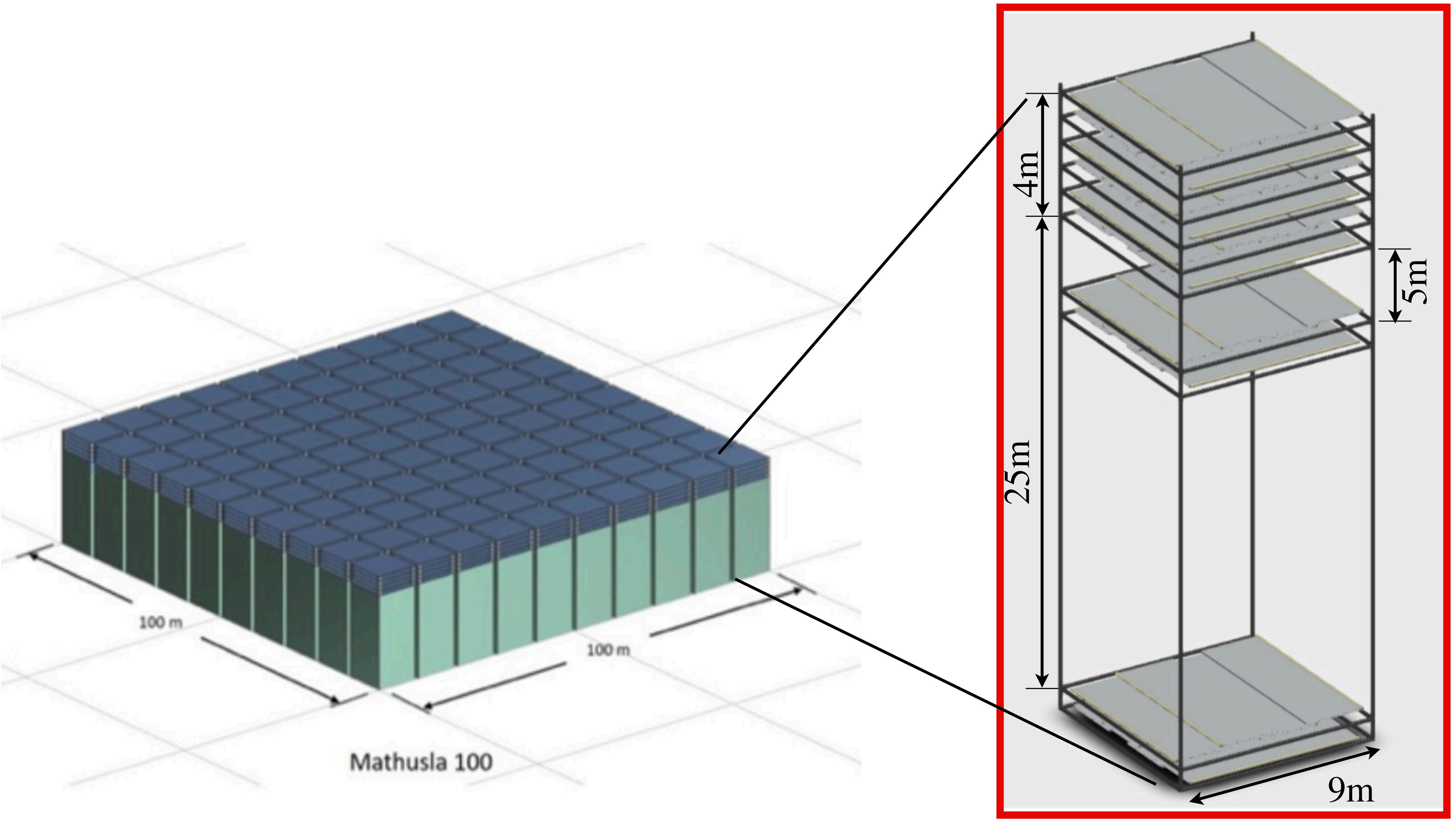
- 6 layers of tracker (scintillators)
- Additional Double-layer
- Double-layer on floor and wall: veto for charged particles from IP

MATHUSLA detector layout

https://mathusla-experiment.web.cern.ch

Updated LHCC Letter of Intent: arXiv 2009.01693

- Decay volume ~100 x 100 x 25 m^3
- Modular design (100 modules of 9 x 9 x 30 m^3)
    - Assembly time line not governed rigidly by HL-LHC beam schedule
- Data taking can **start after installation of the first module**



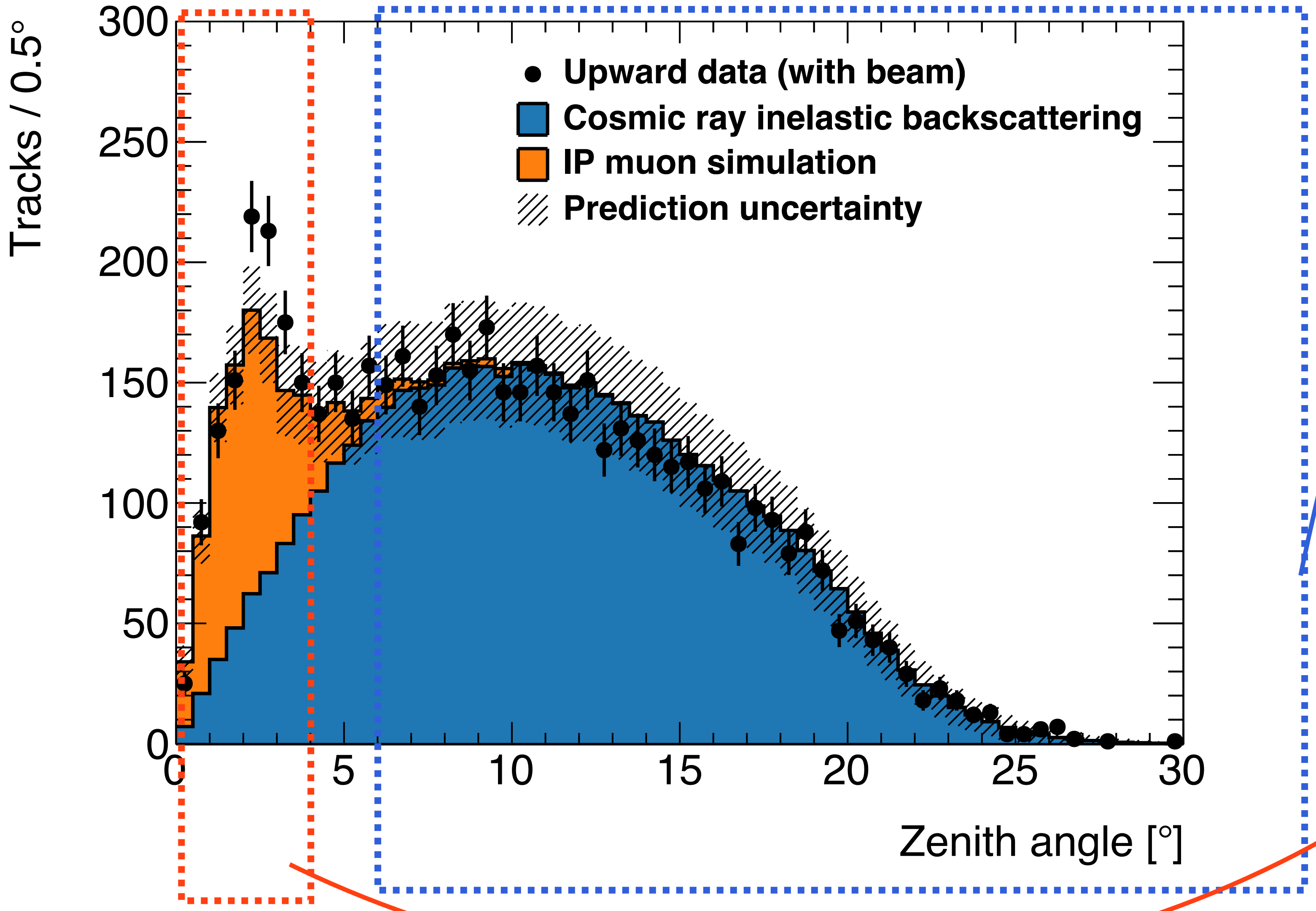
- Current status:
    - Detector technology has been studied extensively
    - Small lab-scale prototype units are under construction
    - Conceptual design report (CDR) in preparation
- Goal is to be ready for the start of HL-LHC running

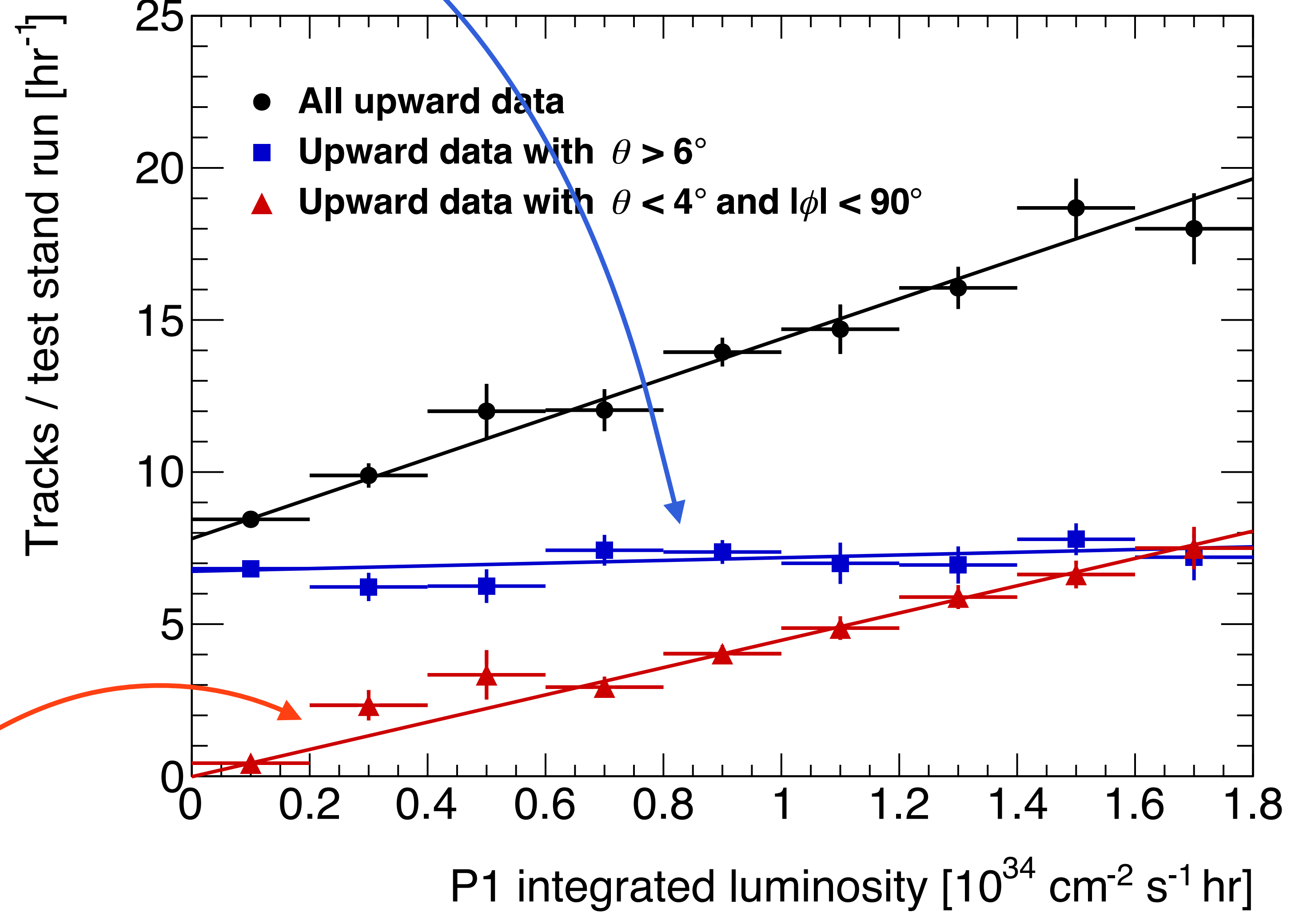
MATHUSLA Test Stand

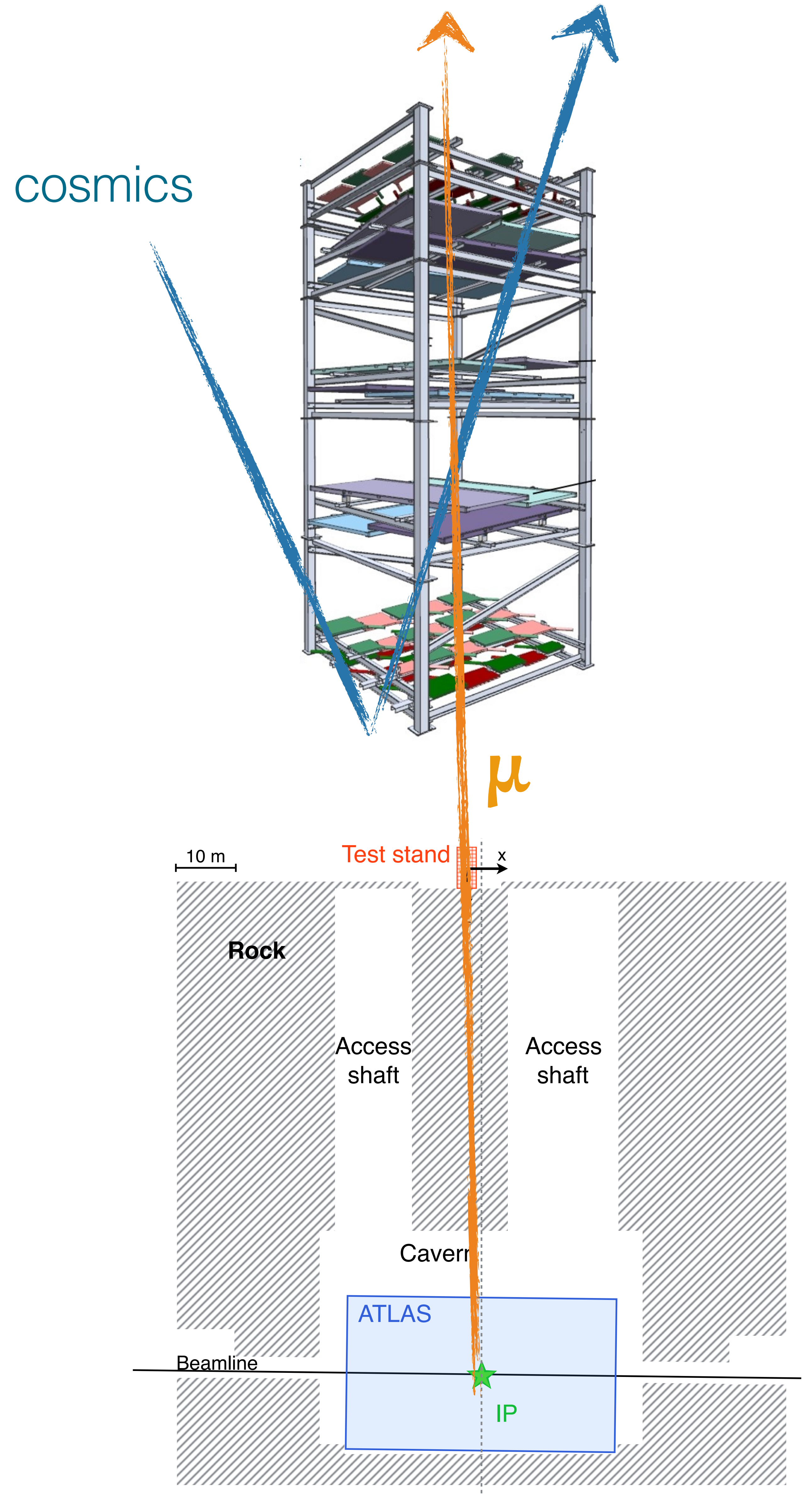
NIMA 985 (2021) 164661

MATHUSLA Test Stand

- Prototype built on the surface above ATLAS
- Data taking during 2018 both with and without beam running
- During collisions, two types of processes creating upward going tracks:
  - inelastic backscattering cosmic rays: constant rate with LHC luminosity
  - Charged particles from LHC collisions: rate increases linearly with luminosity







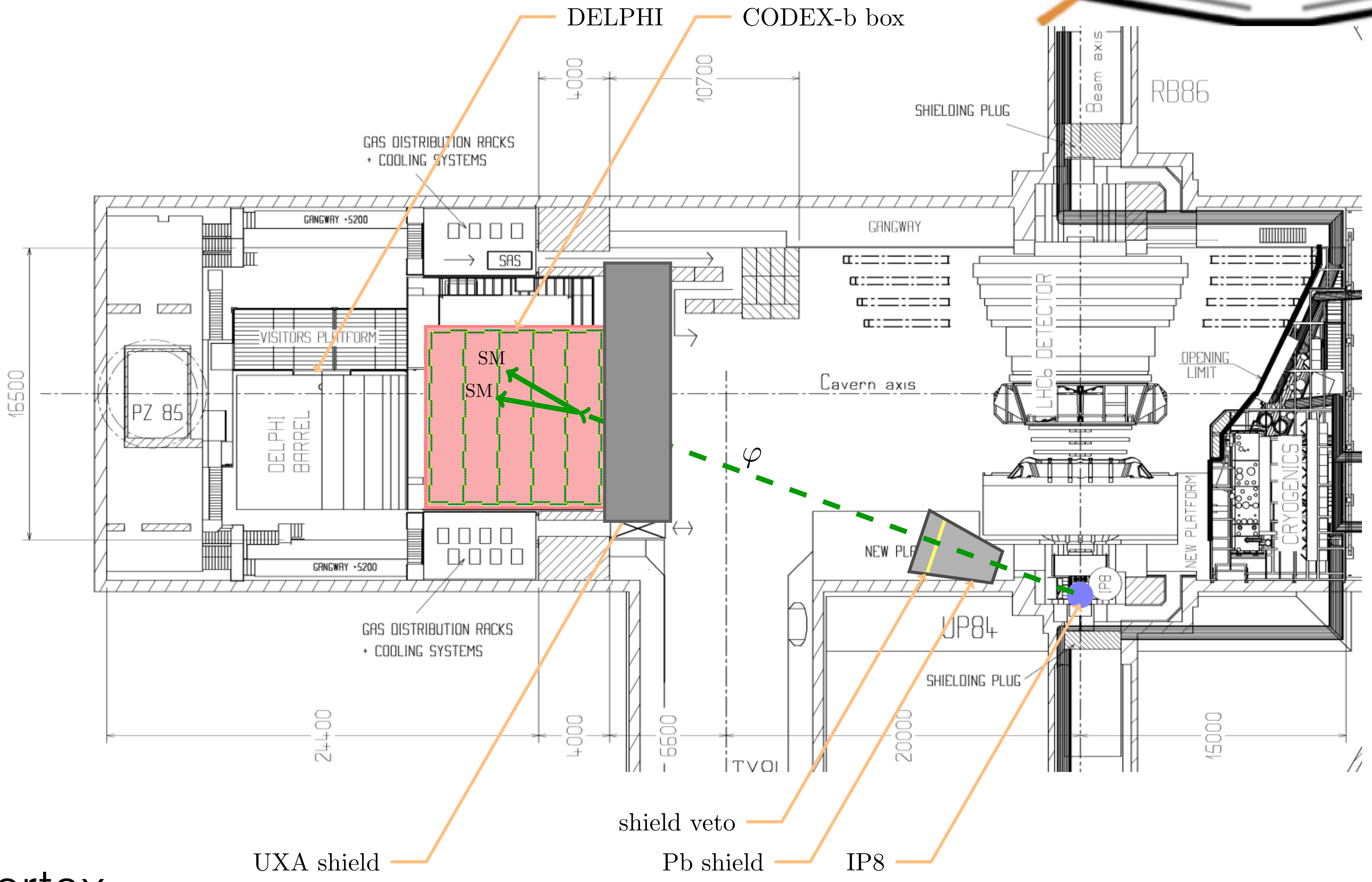
Results validate the background hypothesis in the sensitivity calculations for MATHUSLA

Codex-b

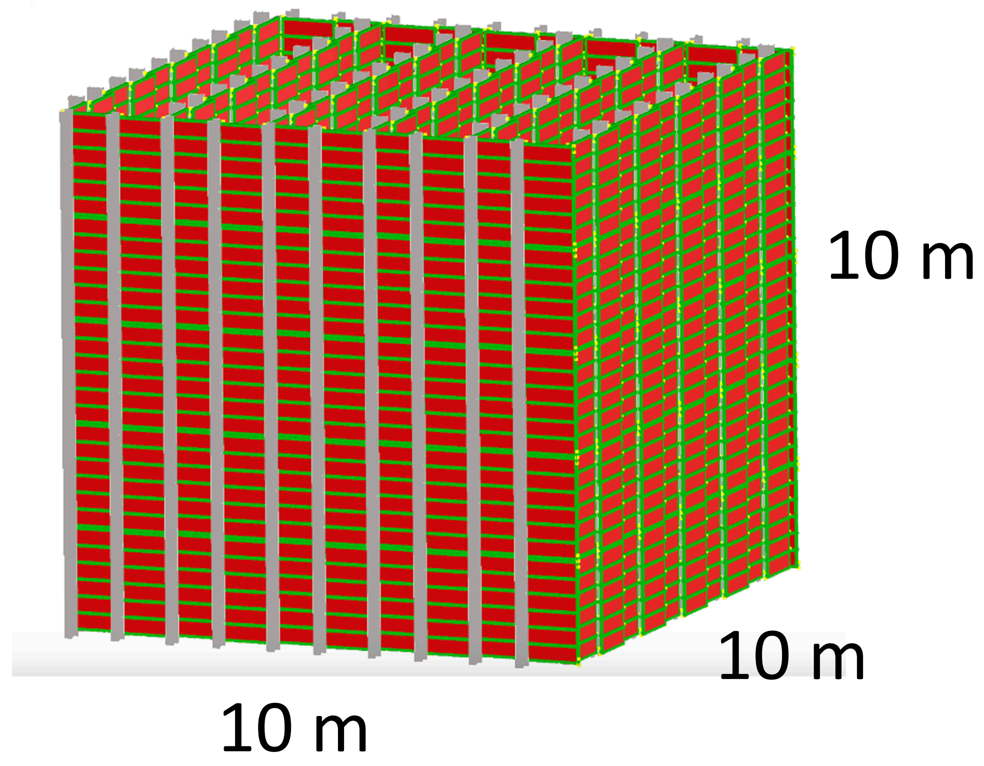
Proposal: [1911.00481]
Snowmass: [2203.07316]

Compact Detector for Exotics at LHC-b

- To be placed near the LHCb cavern
- Target: weakly interacting LLPs at HL-LHC
- Use LHCb trigger CPUs space in LHCb cavern / DELPHI location



- 10x10x10 m^3 box
- 6 layers of RPCs for tracking to reconstruct LLP decay vertex
  - same RPC as the ATLAS muon system upgrade. No dedicated R&D
  - Addition of calorimetry or other material layers for photon ID being considered
- Active and passive shield veto agains collision backgrounds
- Integrated with LHCb triggerless DAQ: assuming a production mechanism, able to measure LLP velocity, boost and mass

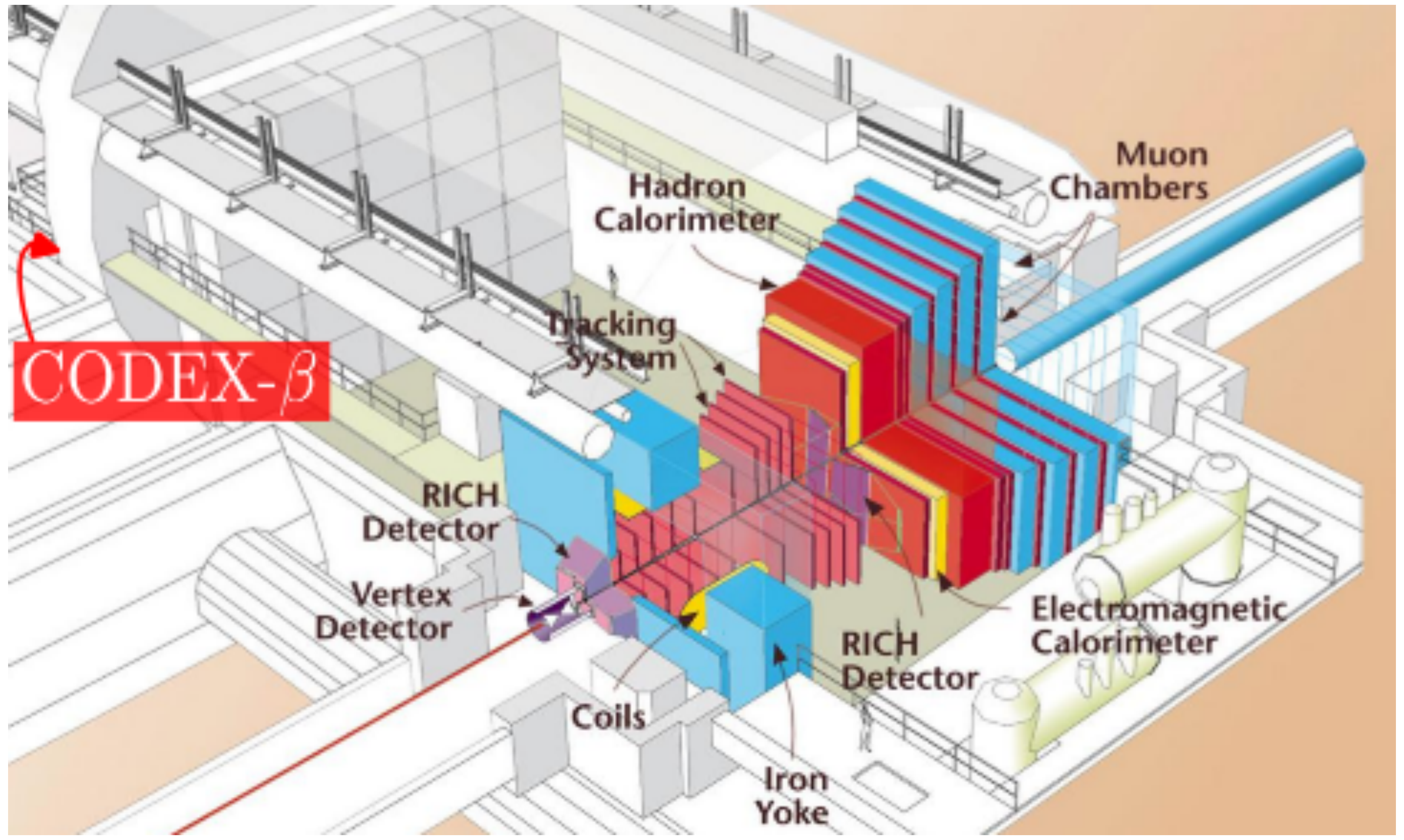


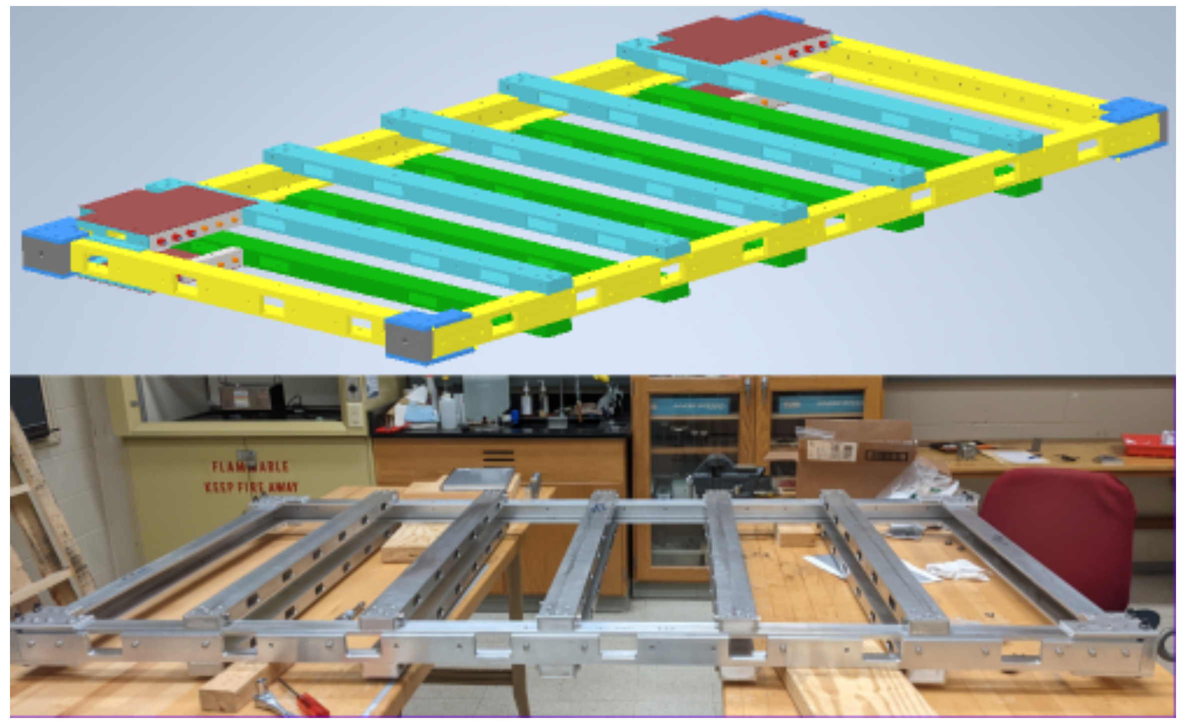
Codex-β

- Demonstrator, 2x2x2 m^3 tracking volume in approx. future location for CODEX-b
- Same RPCs planned for CODEX-b
  - RPC triplets being built NOW. The first RPCs have been built and tested
- Mechanical support structure is well developed
- Target installation during 2024, data-taking in 2025

- Main objectives:
  - Confirm control of backgrounds:
    - Target zero-background CODEX-b
  - Calibrate detector simulation
  - Integrated with LHCb: pave the way for integration with LHCb DAQ/trigger

- Full detector for Run 5



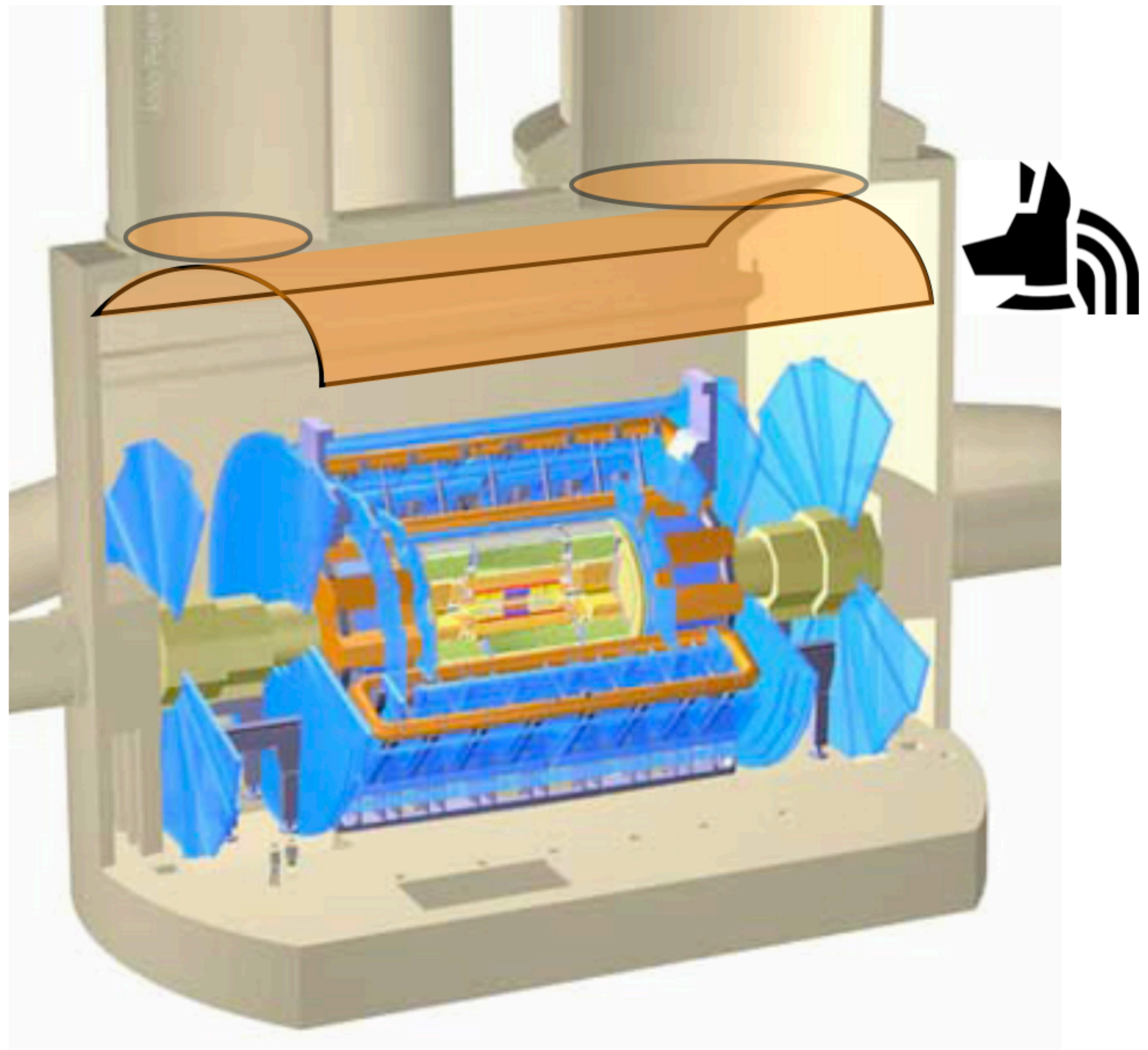


ANUBIS

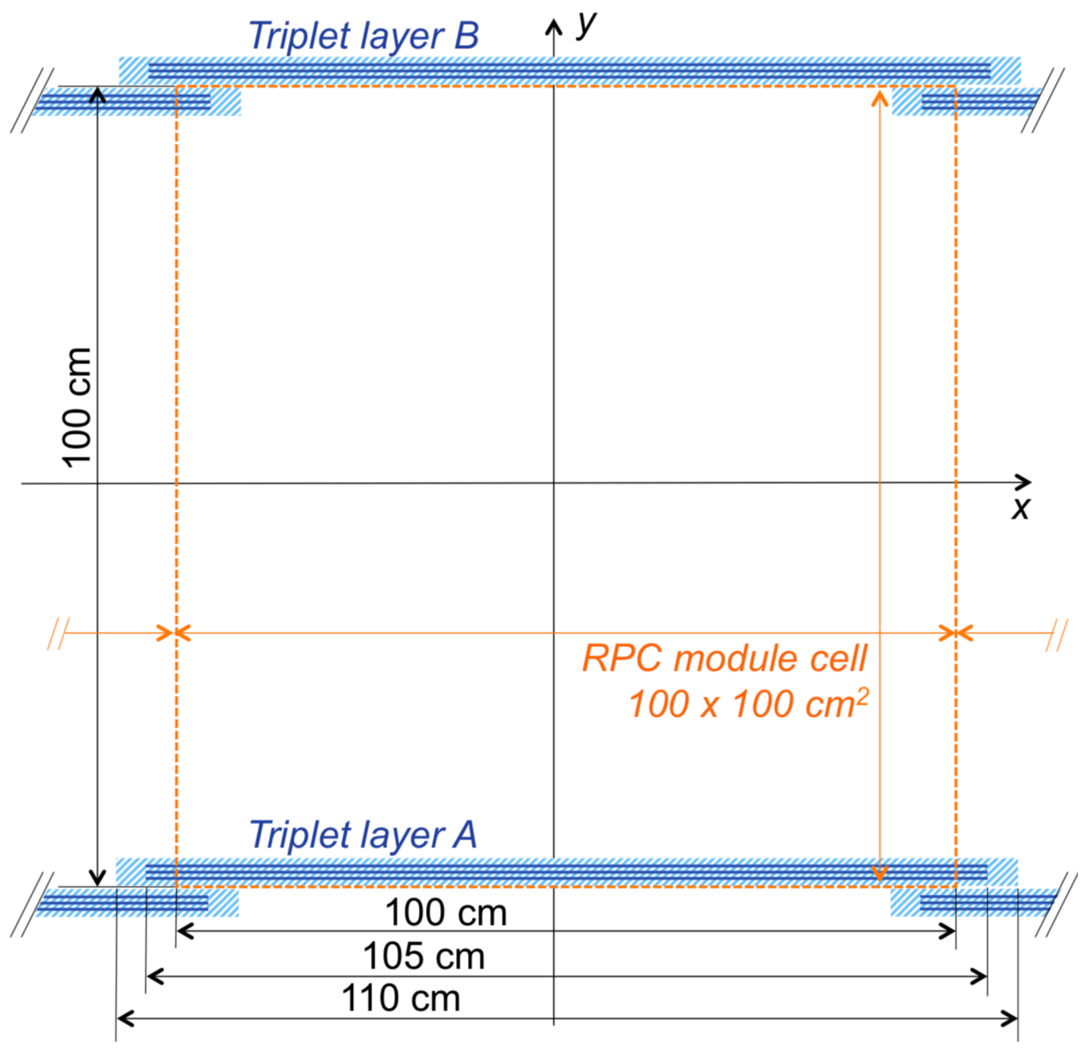
An Underground Belayed In-Shaft

Proposal: 1909.13022

- Instrumenting ATLAS access shaft bottom and cavern ceiling for HL-LHC
- Detector ~25m from IP. ATLAS Cavern acts as decay volume
- Integrated with ATLAS trigger
  - No shielding against collisions besides the ATLAS detector
  - For a background similar to the LLP searches in ATLAS muon system, ANUBIS will need 50-90 events for evidence
- Incorporated as an official sub-project of ATLAS



- Same RPC as the ATLAS muon system upgrade.
  - No dedicated R&D
  - Large production lowers costs
- Layers of RPC triplets separated by air gap



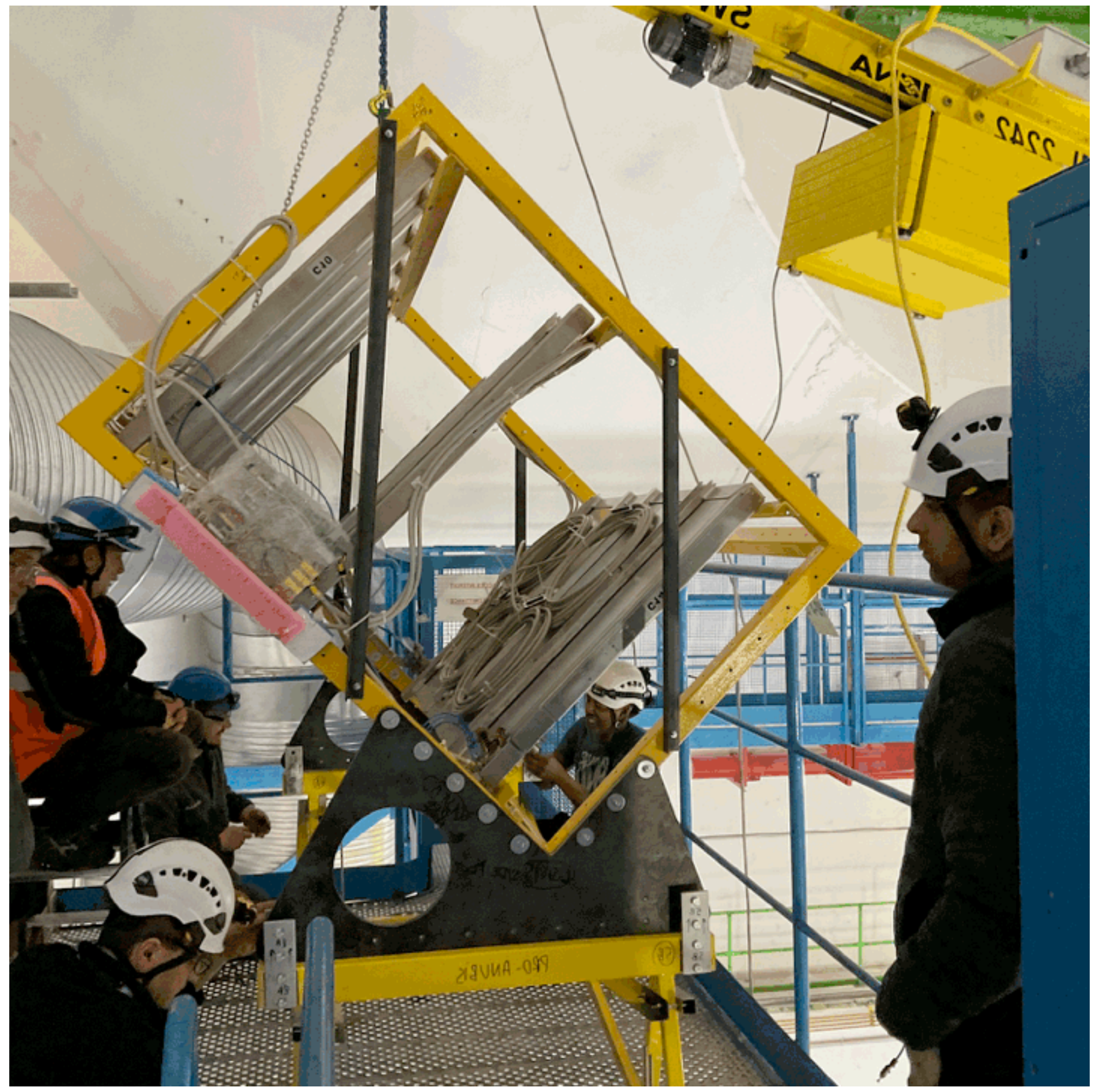
Parameter	Specification
Time resolution	$\delta t \lesssim 0.5$ ns
Angular resolution	$\delta\alpha \lesssim 0.01$ rad
Spatial resolution	$\delta x, \delta z \lesssim 0.5$ cm
Per-layer hit efficiency	$\varepsilon \gtrsim 98\%$

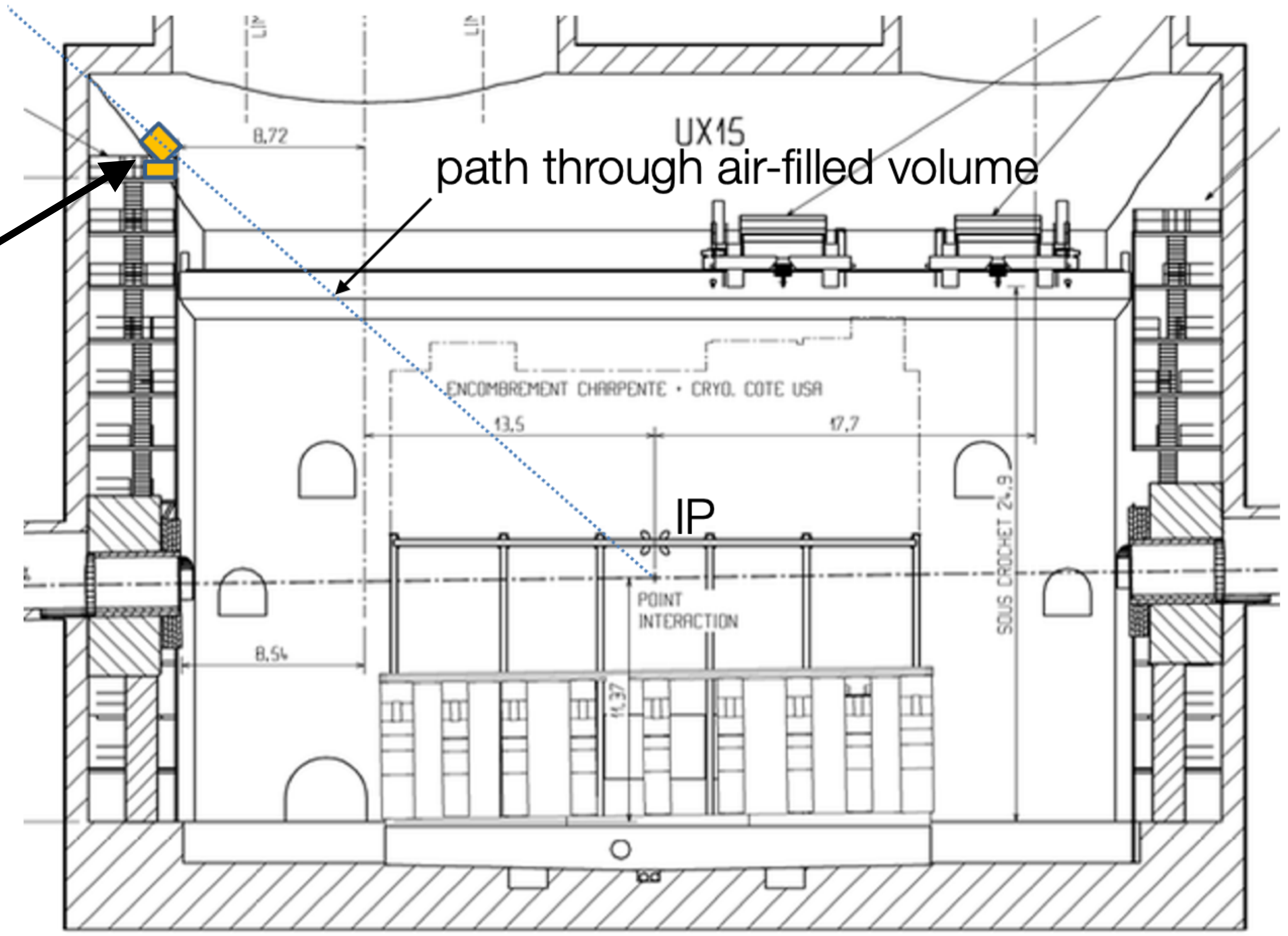
proAnubis

ANUBIS

Proposal: [1909.13022](1909.13022)

- proANUBIS: demonstrator built during 2022, installed in ATLAS cavern in March 2023
  - Three-layer tracking station using ATLAS HL-LHC upgrade RPCs
- Main mission: validate background estimations:
  - Measure hit/track efficiency
  - Identify muons from ATLAS triggers
  - Measure punch-through rates
  - Measure comics
  - Gauge cavern background radiation's impact on occupancy rate
- Currently commissioning!!





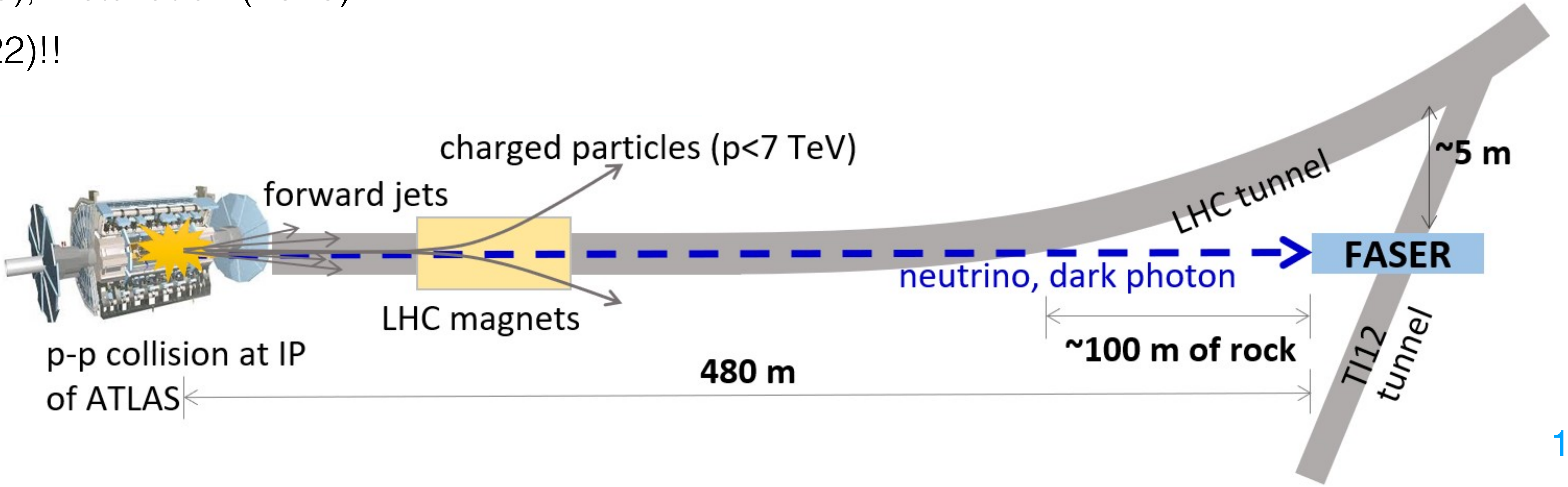
FASER

ForwArd Search ExpeRiment at the LHC

Proposal: 1708.09389
Tech. Proposal: https://cds.cern.ch/record/2651328

- Forward region close to ATLAS: 480m downstream of the ATLAS IP
- Utilises the large LHC light particle production rate in the forward region to target: light, very weakly interacting LLPs (HNL, dark vector, dark scalar, axions, light SUSY particles)
    - very rarely produced
    - along the beamline at low pT ~2% of pions produced within FASER angular acceptance
- Also measurements on collider-produced neutrinos

- Fast! LoI (2018), approved (2019), Installation (2020)
- Data-taking started in Run3 (2022)!!



FASER details

- Small detector composed of:
  - Emulsion based neutrino detector (FASERnu)
    - For neutrino physics, acts as shielding for LLP searches
  - Decay volume of 1.5m
  - Multiple scintillator systems (triggering, timing, vetoing)
    - 4 tracking stations (IFT and 3 stations 3x3 of ATLAS SCT strip modules. 0.5 B-field applied
  - Calorimeter system

Proposal: 1708.09389
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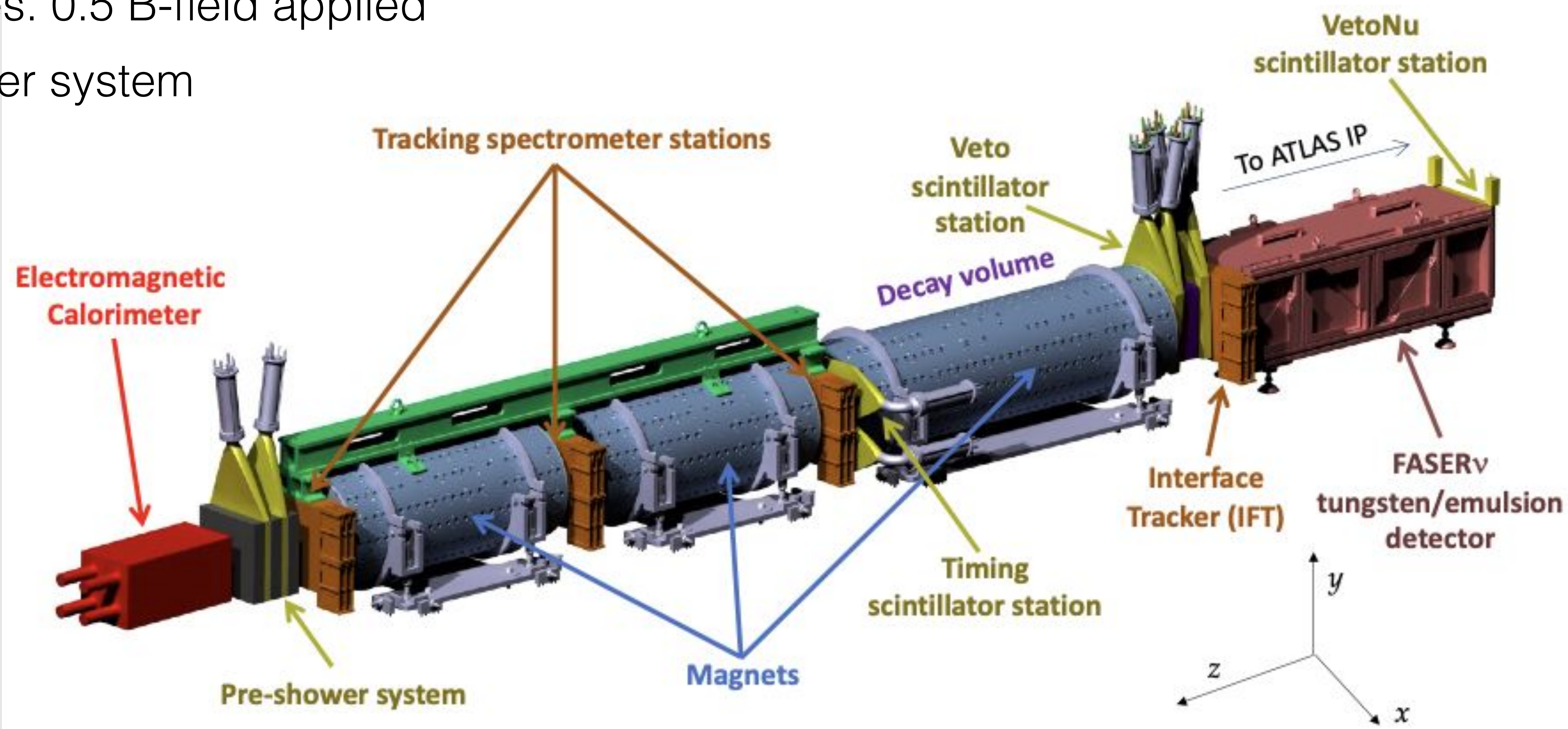
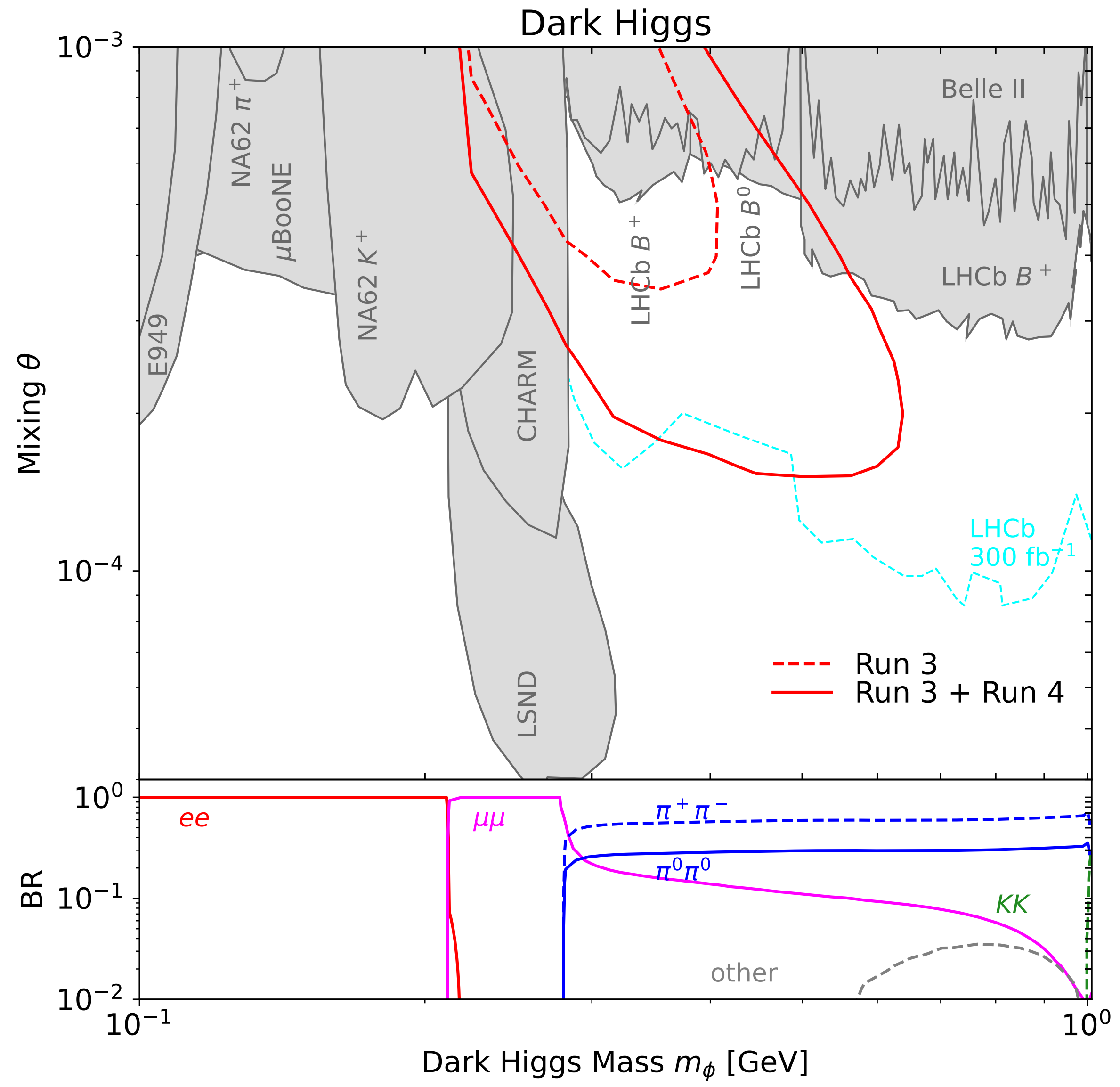
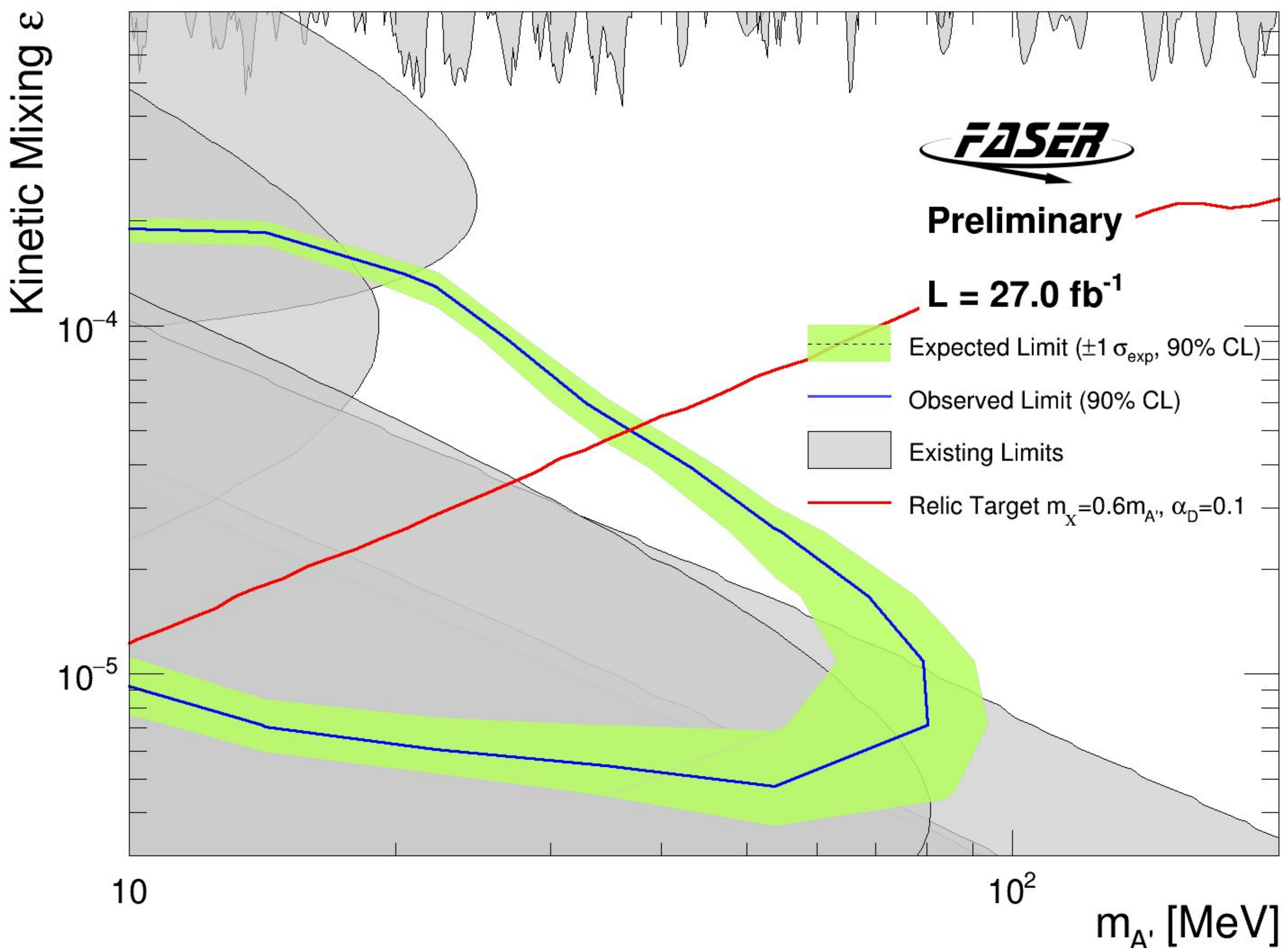


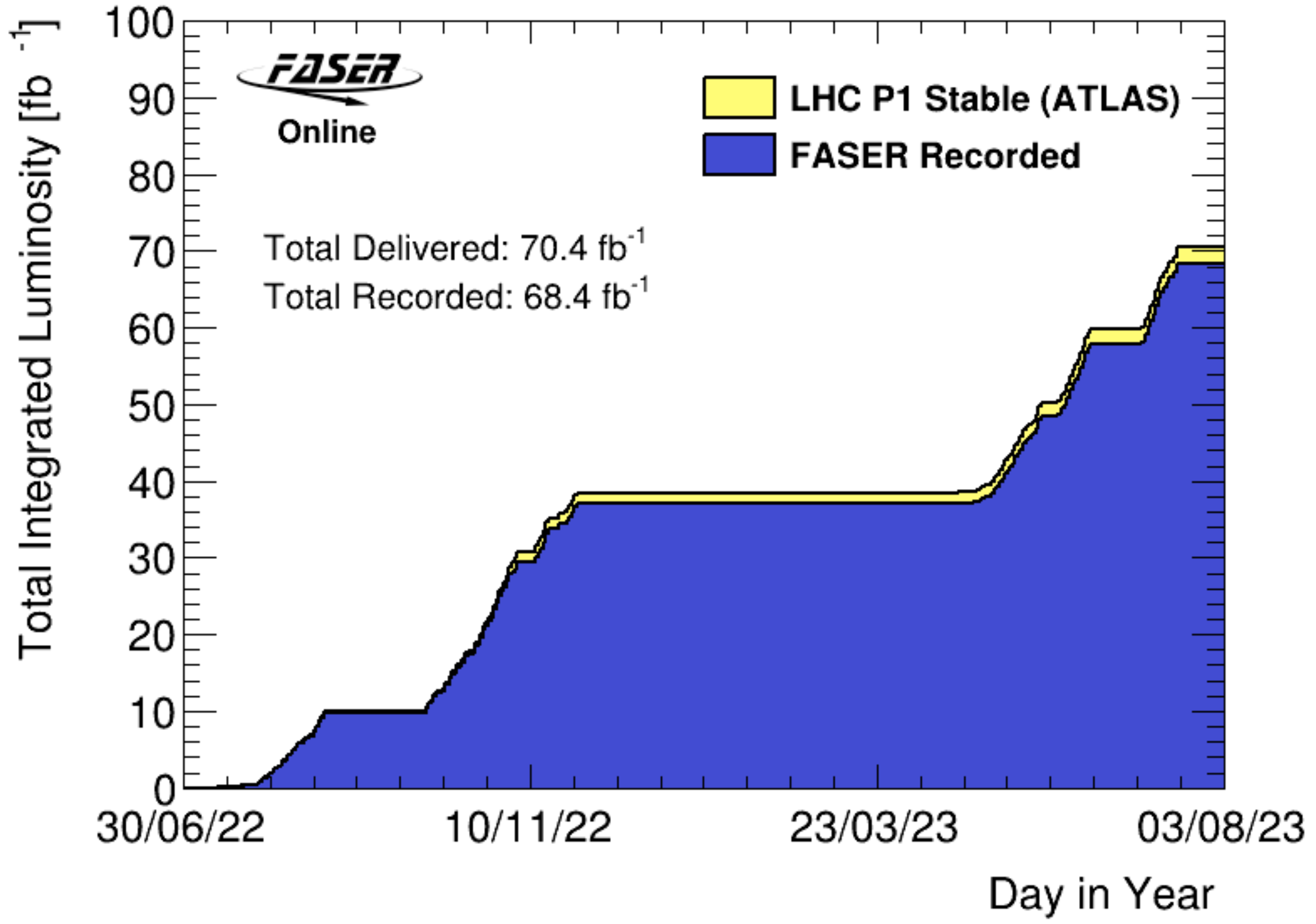


FASER prospects in LHC Run 4
CERN-LHCC-2023-009

FASER operations and first results!

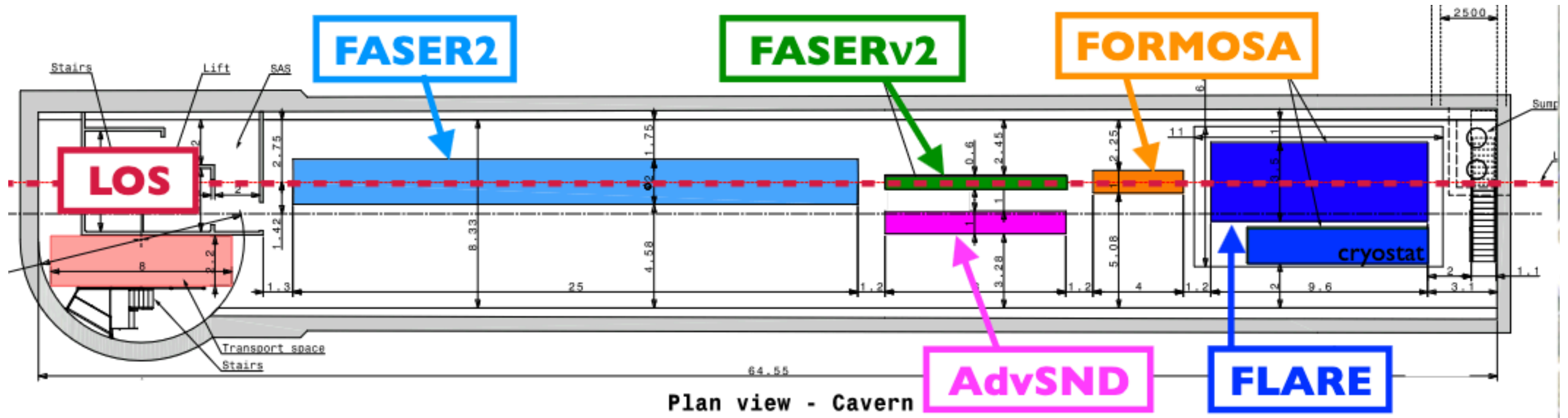
- Installed and commissioned during 2021/2022
- Recorded 37/fb of data in 2022!!
- First Dark photon analysis with 27/fb!!
  - 90%CL limits in previously unproved phase space





Dark photons results: 2207.11427

- Successful 2023 data taking: > 30/fb collected
  - x10 more data expected!
  - Proposed large upgrade to FASER being discussed: Forward Physics Facility (https://arxiv.org/pdf/2203.05090.pdf)
    - much better sensitivity for dark Higgs for **FASER2** (5m decay volume) at the **FPF** (see slide27)



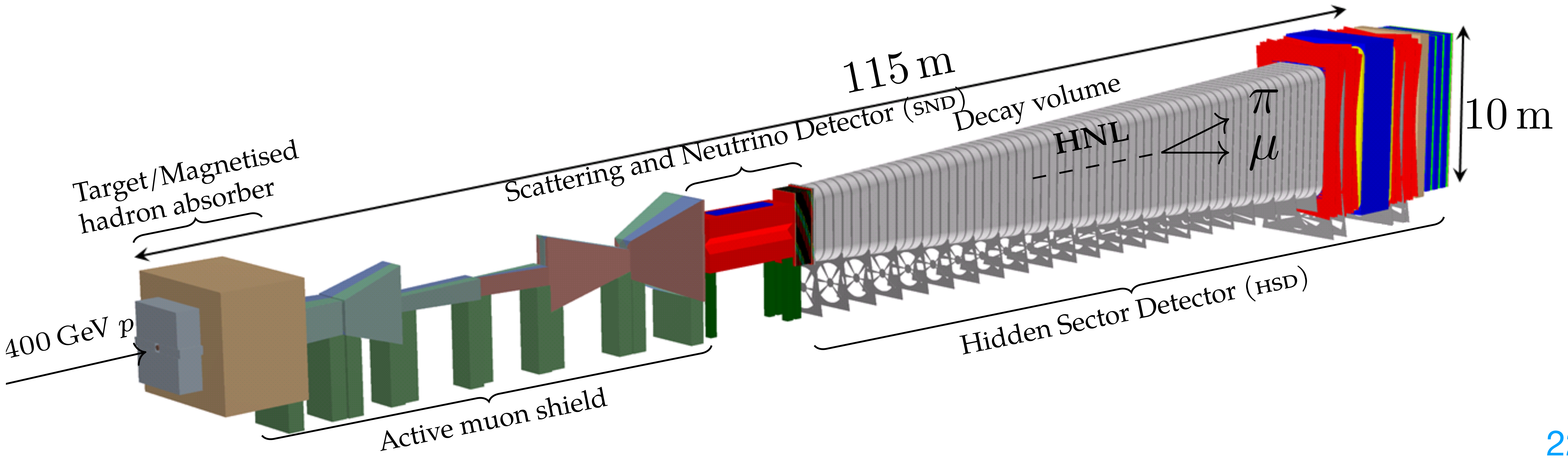
SHiP

Search for Hidden Particles

Proposal for ECN3 (Oct 2023): SPSC-P-369.pdf

- General purpose beam dump experiment at the SPS North Area
- Target: light, very weakly interacting long lived particles (HNL, dark vector, dark scalar, axions, light SUSY particles)

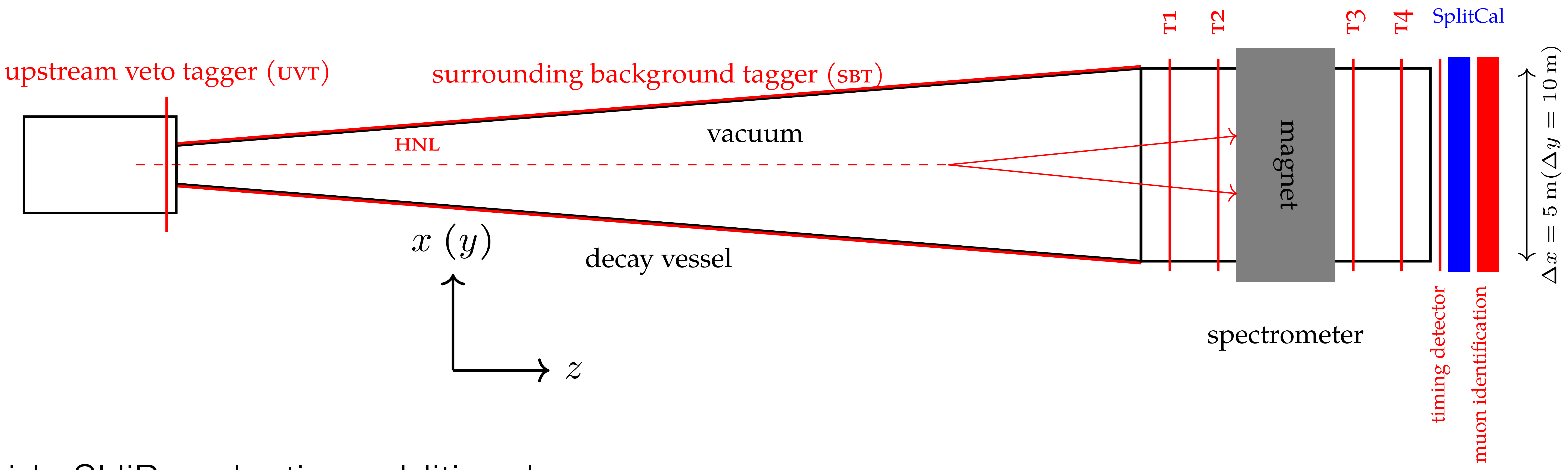
- Originally designed for dedicated new beam line with a new experimental cavern (ECN4)… now fully re-optimised for existing beam line and ECN3 cavern
  - New location at existing beam line with improved muon shield: similar physics reach at much lower cost!
  - Proposal to be part of ECN3 submitted to SPSC in Oct 23for a decision expected before the end of the year
  - Aiming for commission with beam in 2030, to begin taking data in 2031, running for 15 years of running



SHiP details

Proposal for ECN3 (Oct 2023): [SPSC-P-369.pdf]

- Full spectrometer allows measurements of
  - Invariant masses, impact parameter, decay vertex
  - Distinguish between signal models
- If LLPs are discovered, detector can perform precision measurements of LLPs
- Background taggers and timing detector allow powerful background rejection



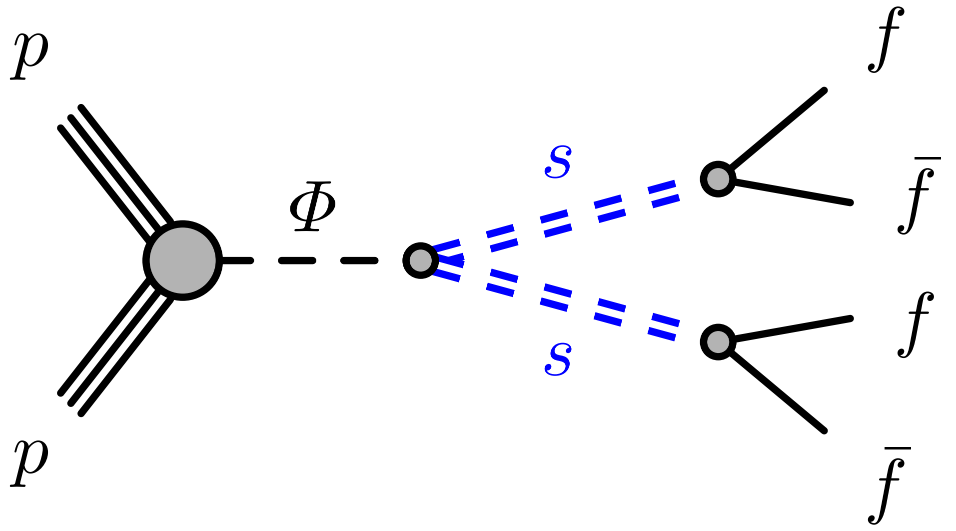
- Several groups outside SHiP evaluating additional uses:
  - Development of radiation hard electronics
  - Nuclear physics

Sensitivity in Exotics Higgs decays

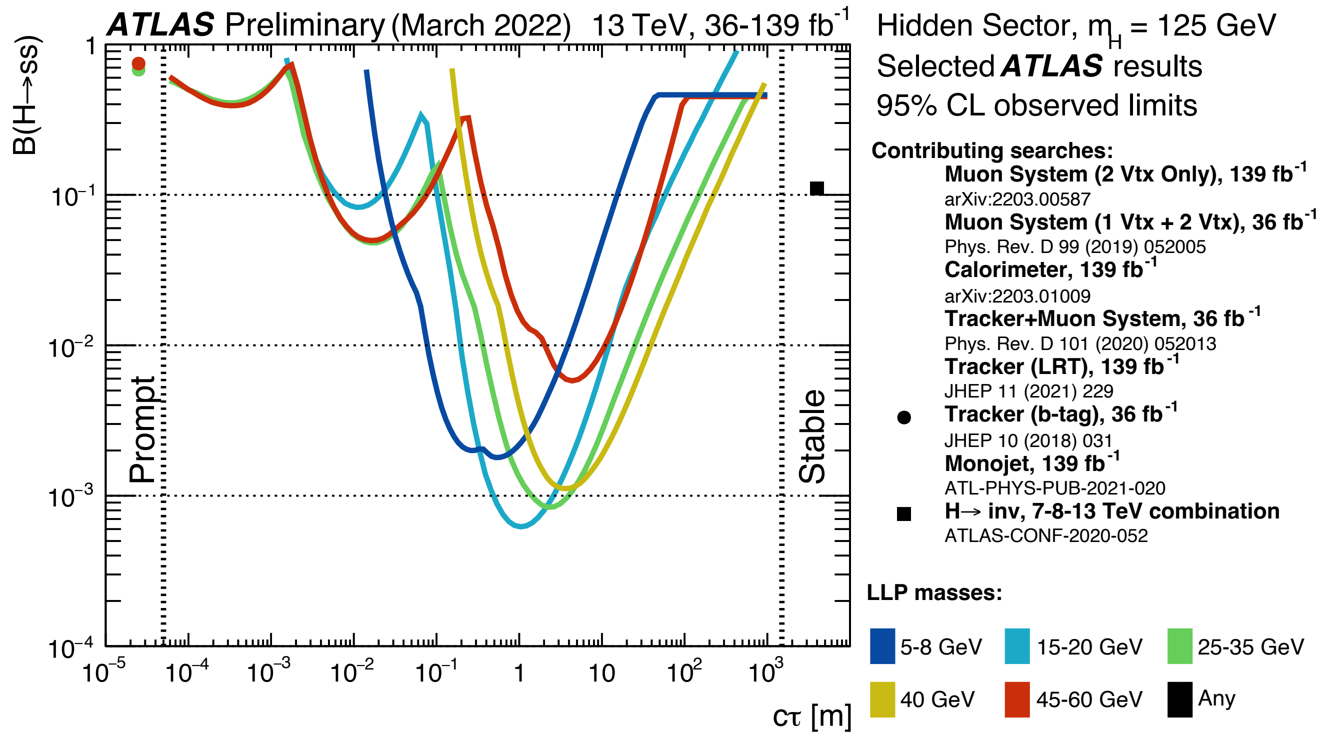
Main benchmark in transverse detectors:

O(100GeV) physics

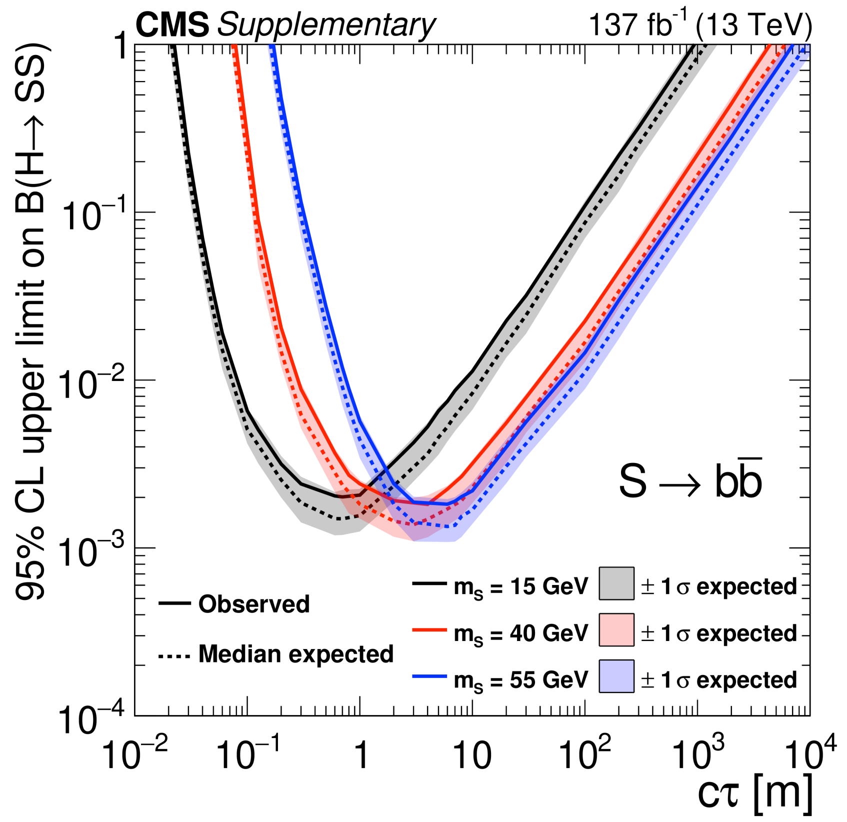
- Exotics Higgs decays
- Dark sector new scalars



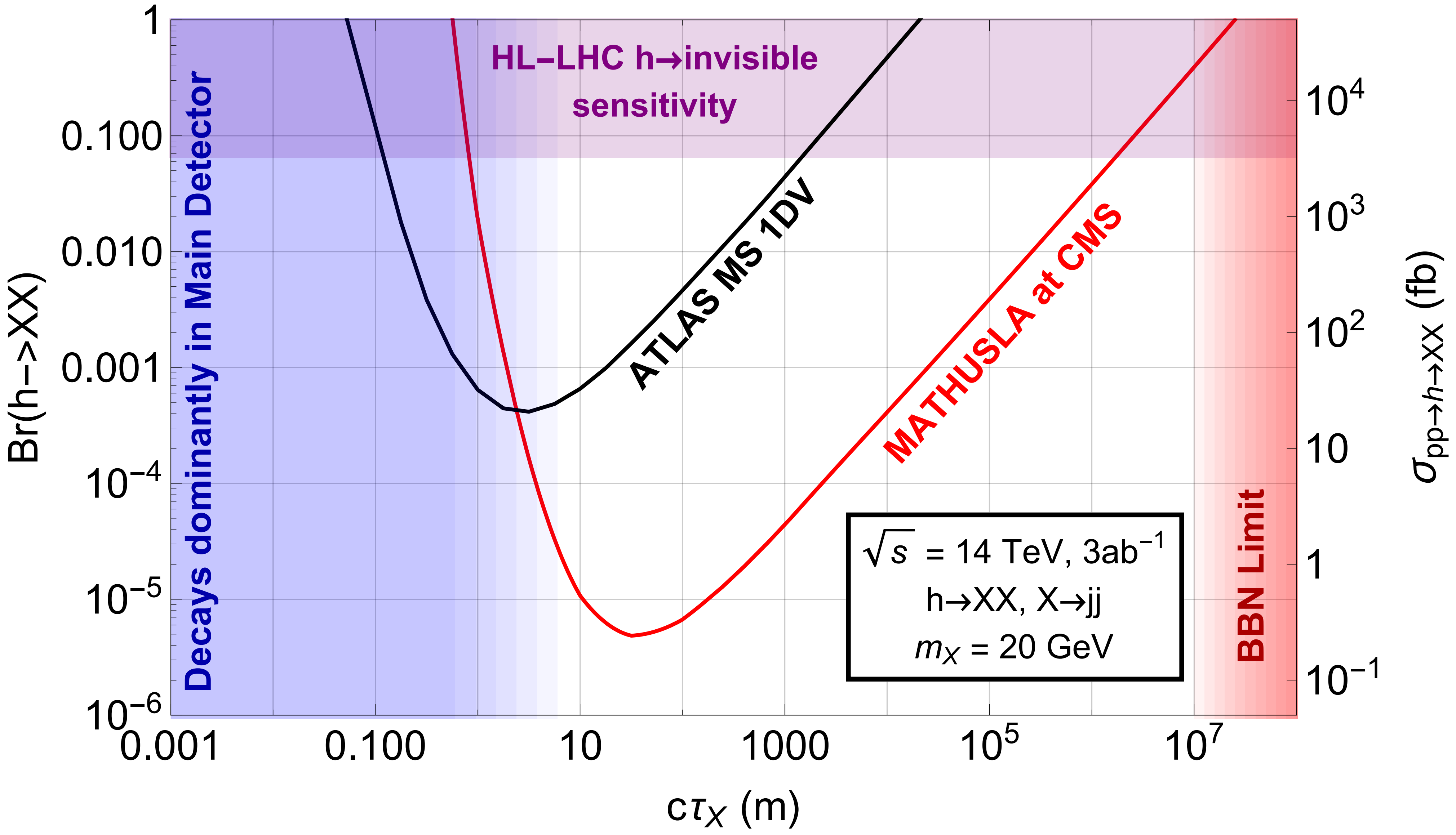
ATLAS



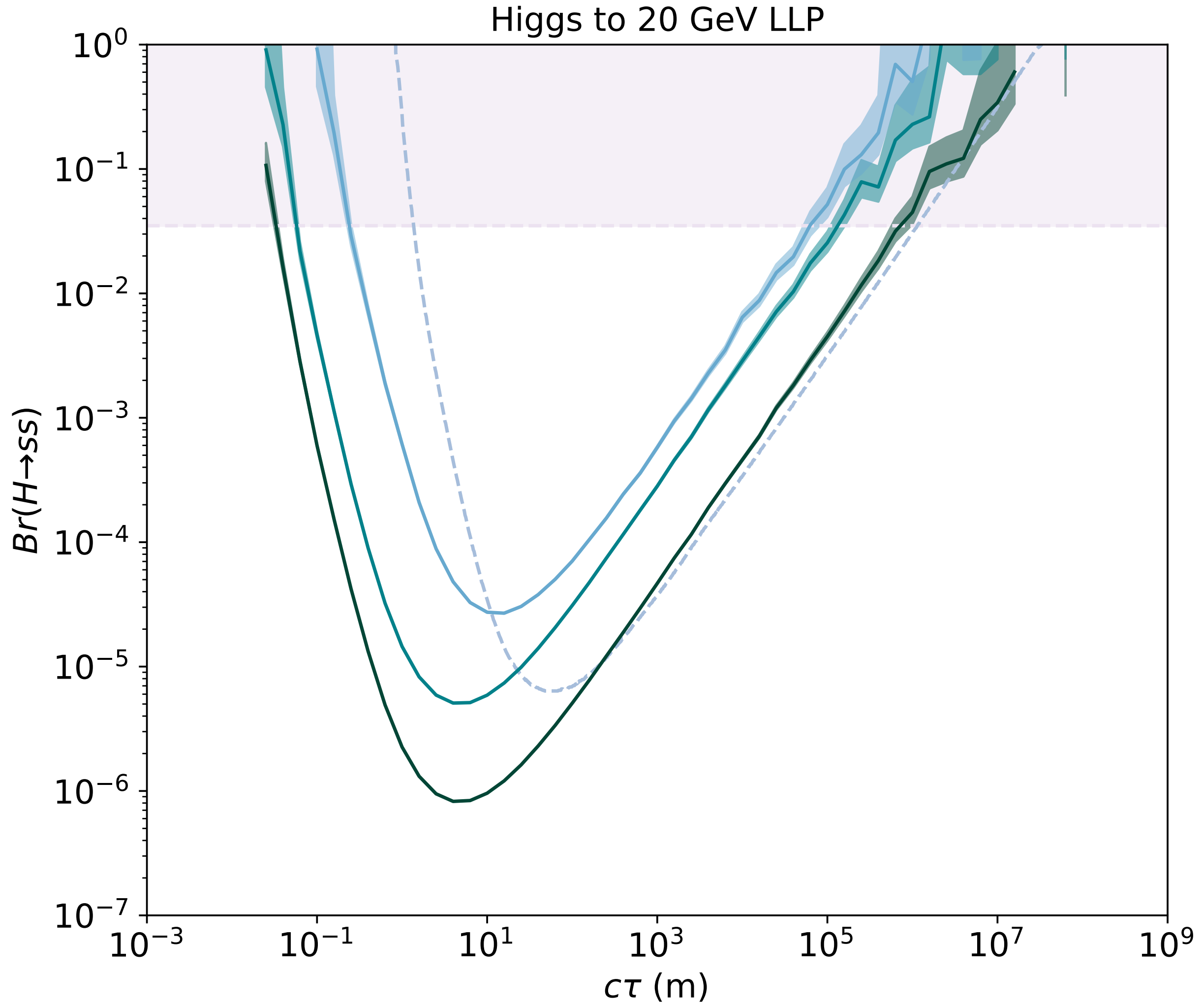
CMS
m(LLP) = 15 GeV
(careful!! Not exactly the same benchmark!)



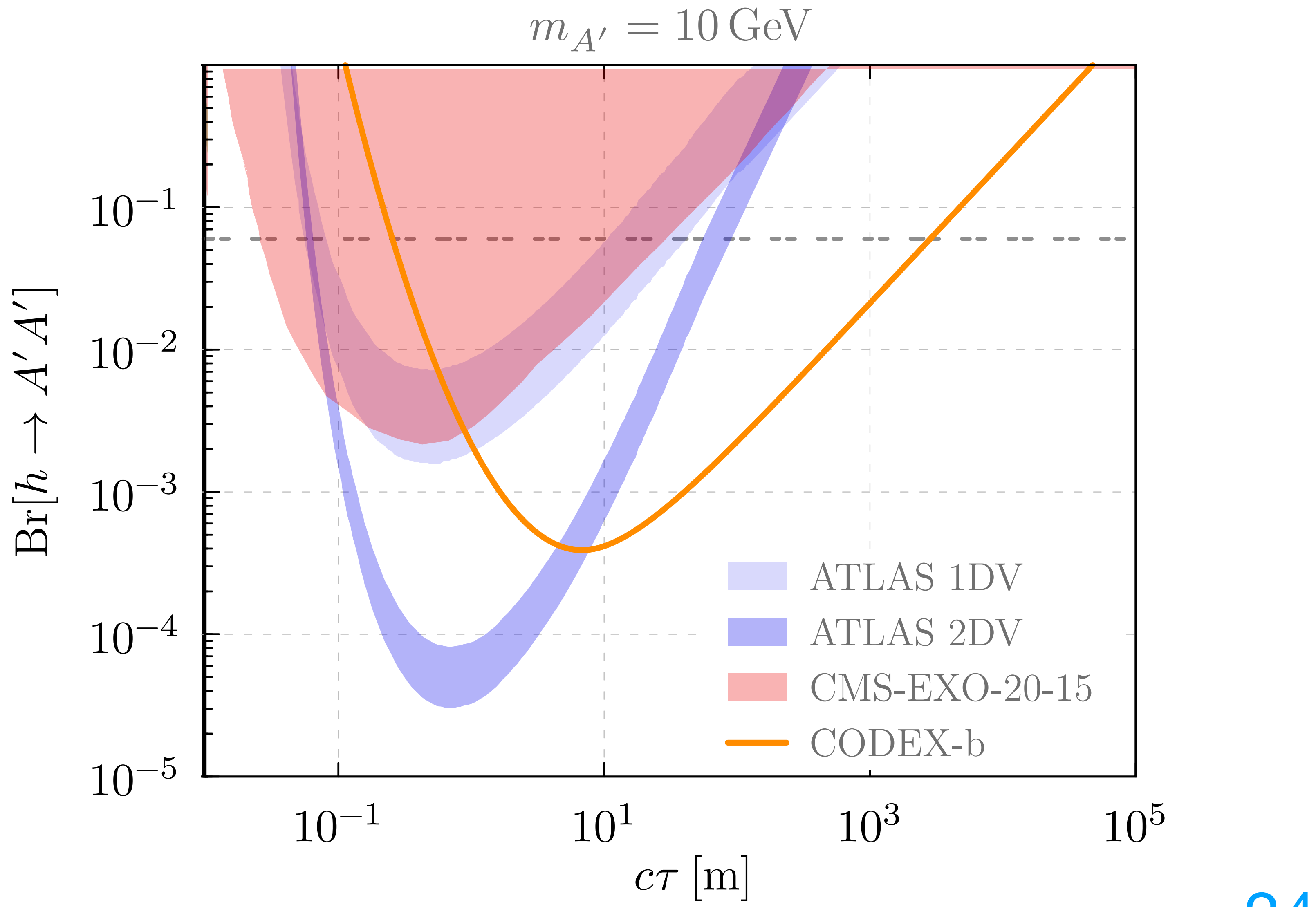
Mathusla Updated LoI: [2009.01693]()
m(LLP) = 20 GeV



ANUBIS (FIP2 2022): [2009.01693]()
m(LLP) = 20 GeV



Codex-b (FIP2 2022):
m(LLP) = 10 GeV
(careful!! Not exactly the same benchmark!)



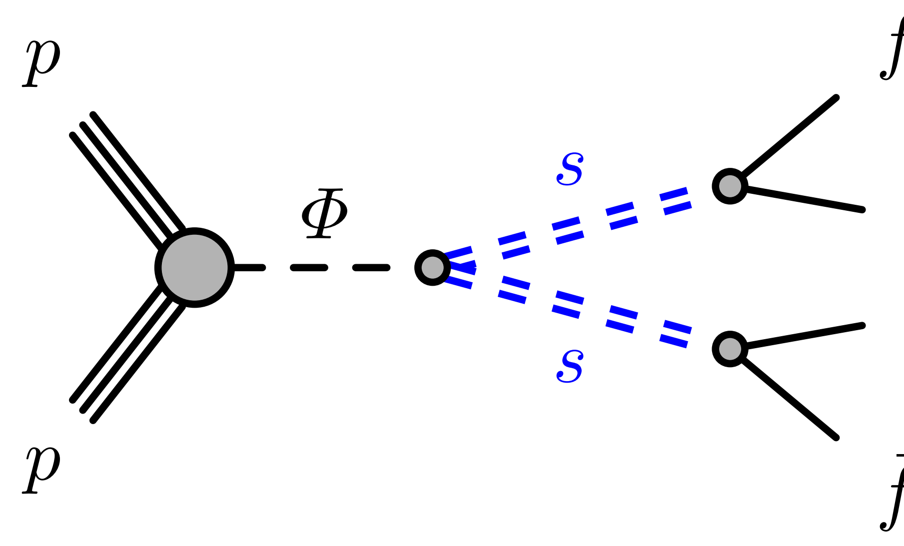
Sensitivity in Exotics Higgs decays

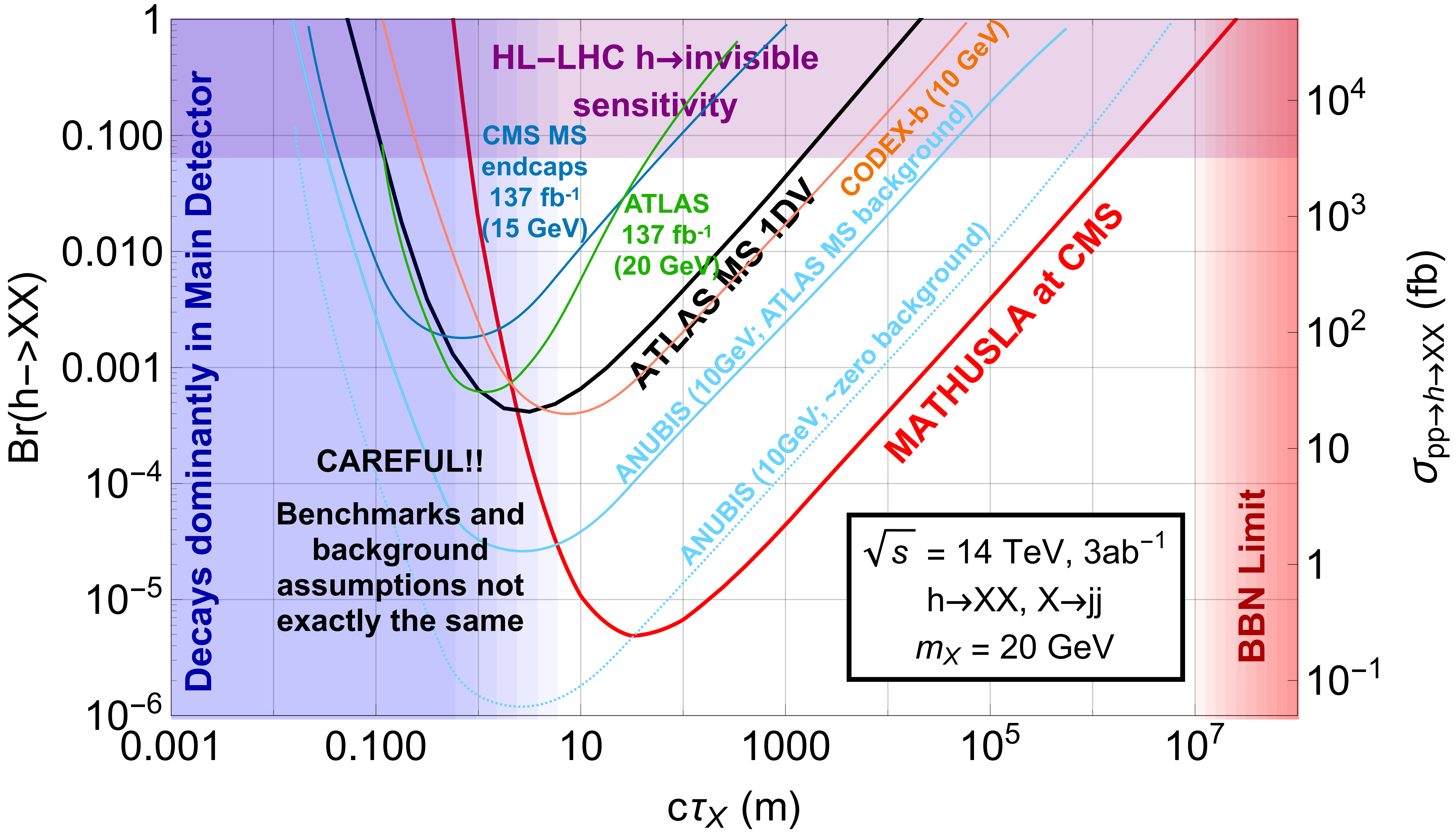
Main benchmark in transverse detectors:

O(100GeV) physics

- Exotics Higgs decays
- Dark sector new scalars

Adding everything in one plot for comparison…





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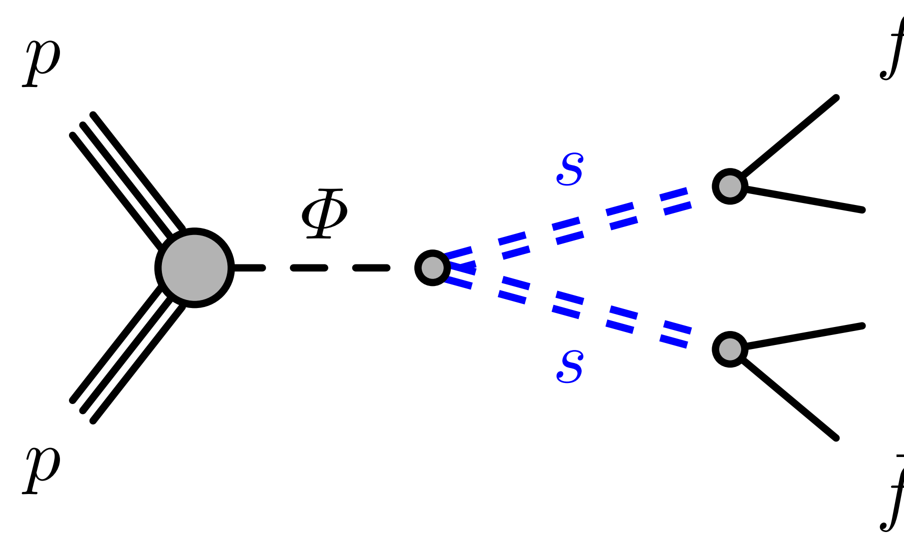
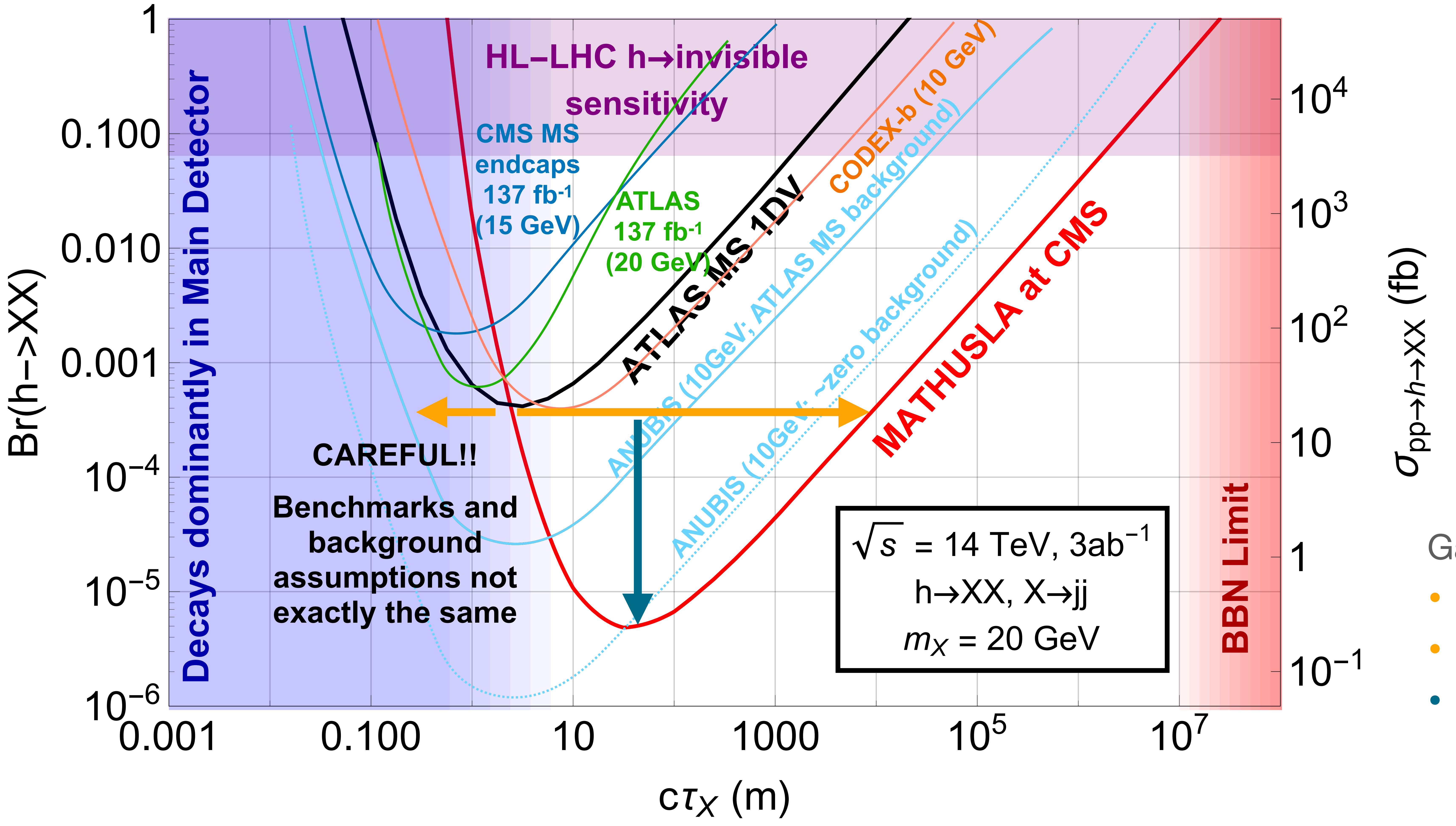




Gain in sensitivity wrt ATLAS/CMS HL-LHC:

- 3 orders of magnitude towards high ctau
- ~1 order of magnitude towards lower ctau
- ~2 orders of magnitude in sensitivity

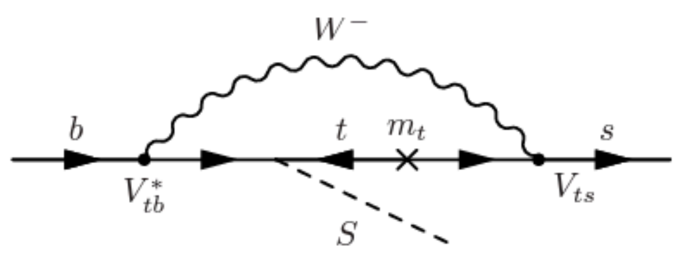
Sensitivity to dark scalars

FIPs 2022 workshop report: 2305.01715
More details on FASER2 prospects: 2203.05090

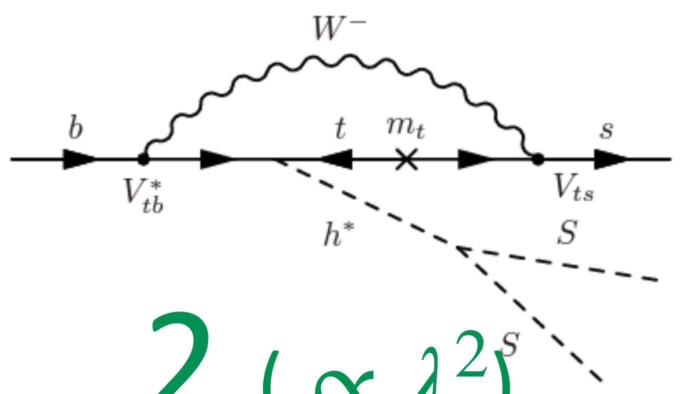
Secondary benchmark in transverse, one of the main in forward detectors: O(1GeV) physics

- Singlet scalar LLP s mixing with Higgs mixing angle θ

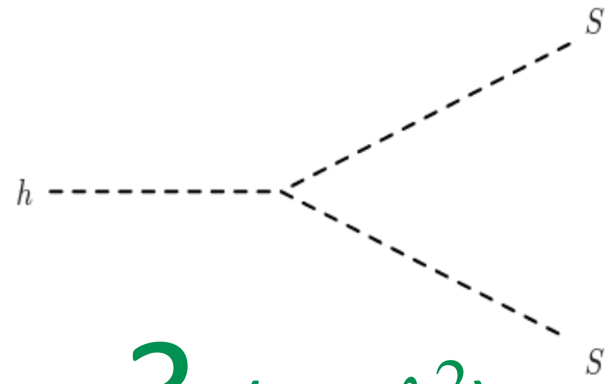
$\sin^2\theta \downarrow$ $c\tau \uparrow$



1 ($\propto \sin^2\theta$)



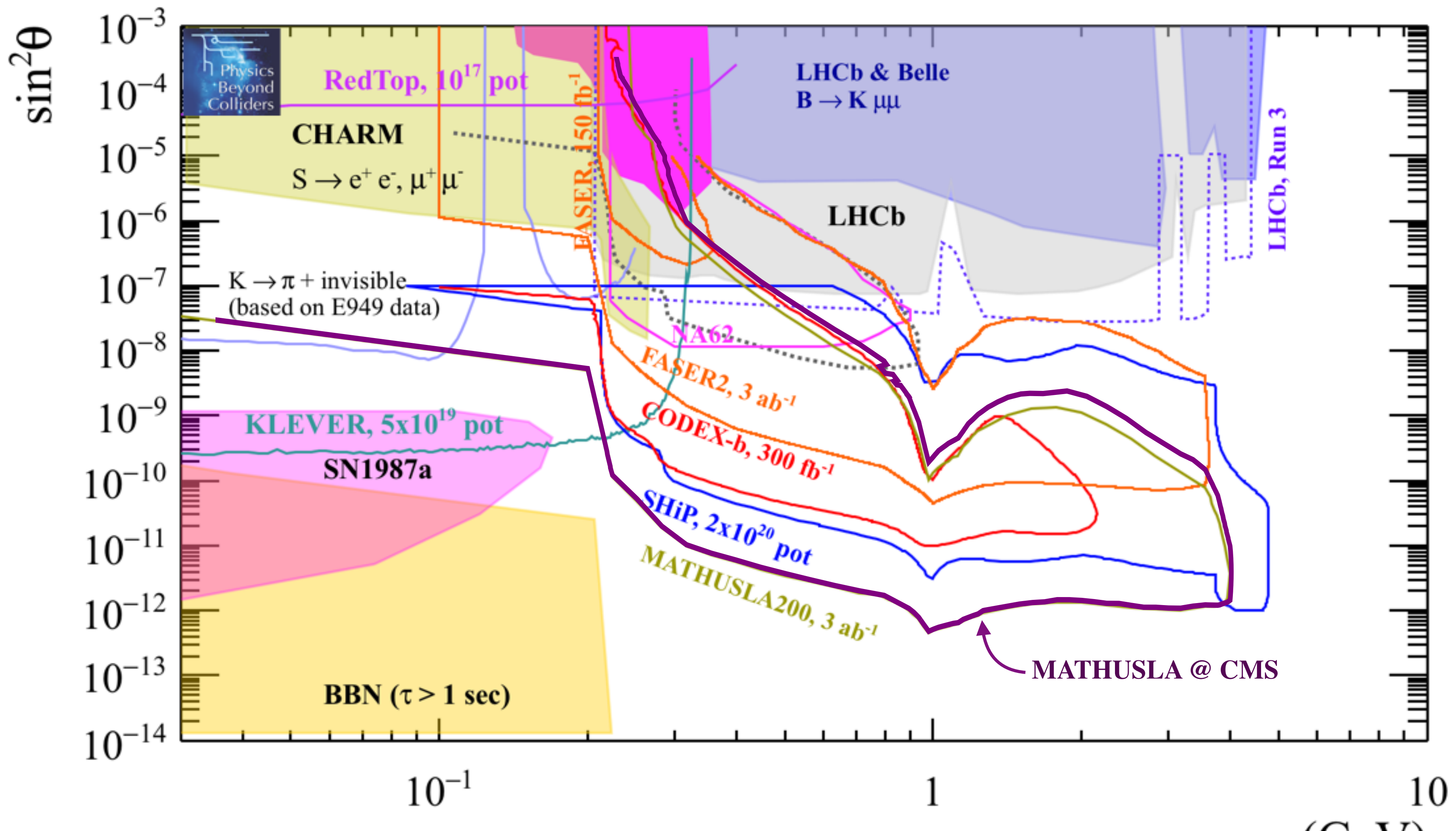
2 ($\propto \lambda^2$)



3 ($\propto \lambda^2$)

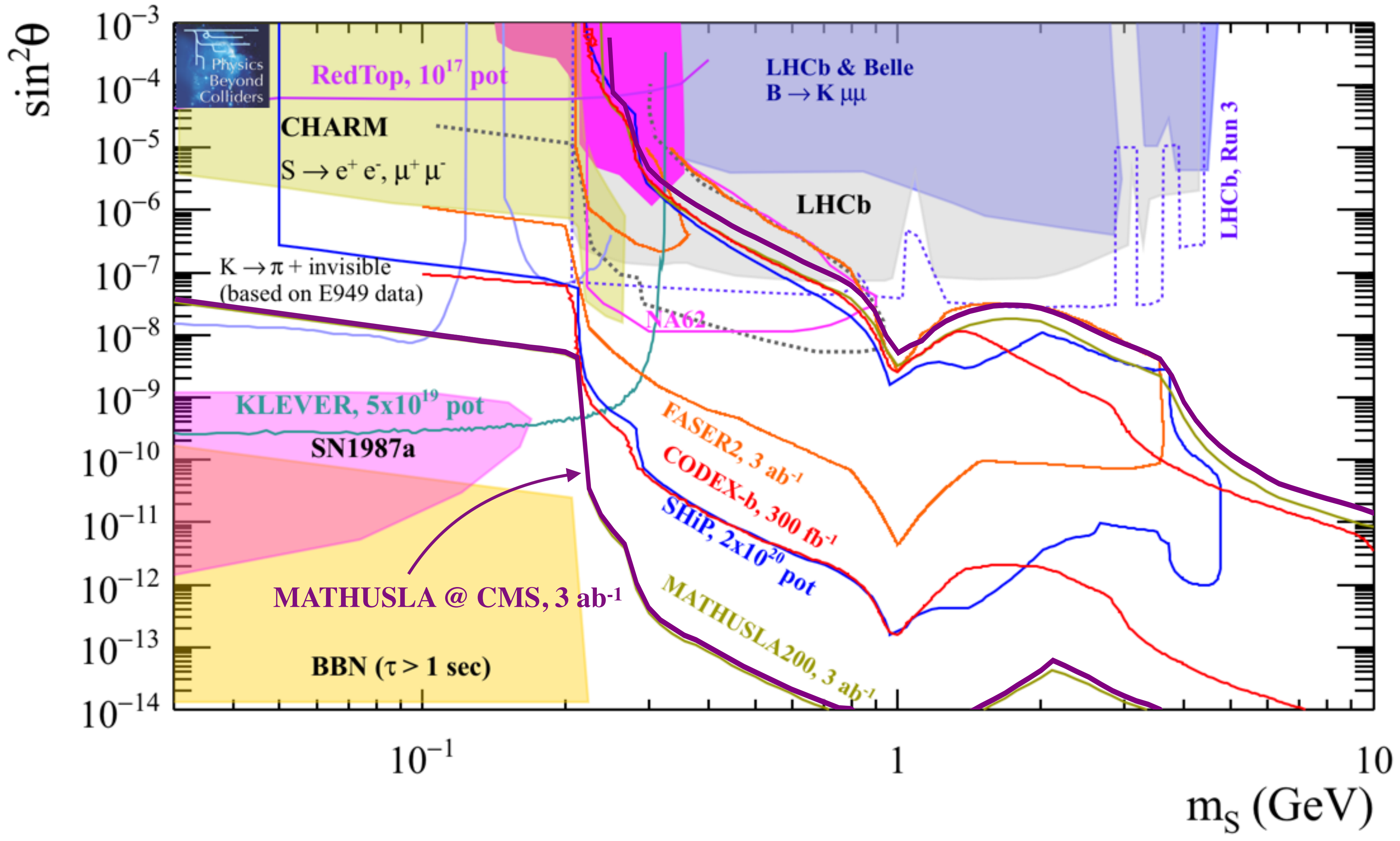
Diagrams by J. Alimena

1 : Production in exotic B, D, K meson decays only



(a)

1, 2, 3 : Additional production in exotic Higgs decays with Br(h → ss) = 0.01



- Nice complementarity:
  - SHIP better at short lifetimes and mass < 10 MeV
  - For O(GeV) FASER, SHIP better sensitivity for shorter lifetimes
  - Mathusla: higher sensitivity for long lifetimes

Sensitivity to dark scalars

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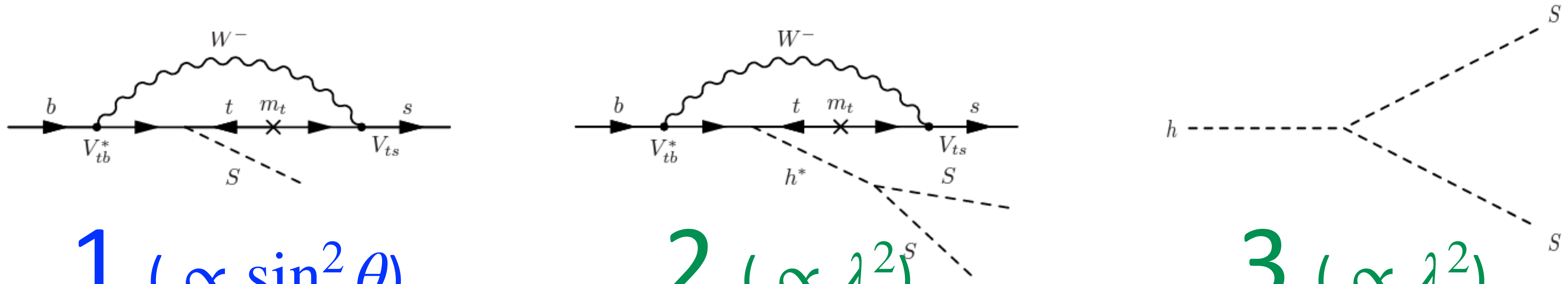
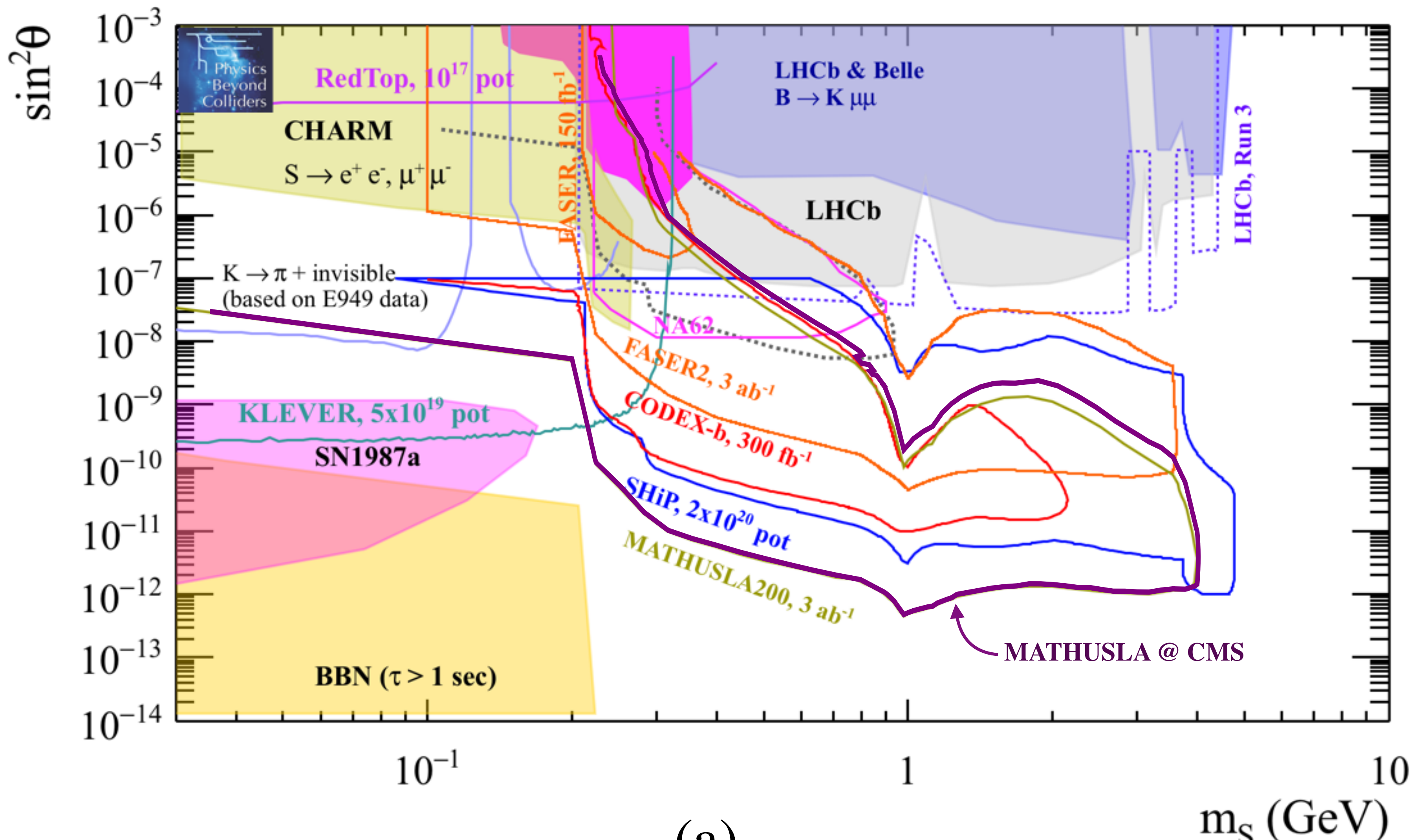


1 ($\propto \sin^2\theta$) 2 ($\propto \lambda^2$) 3 ($\propto \lambda^2$)

Diagrams by J. Alimena

1 : Production in exotic B, D, K meson decays only



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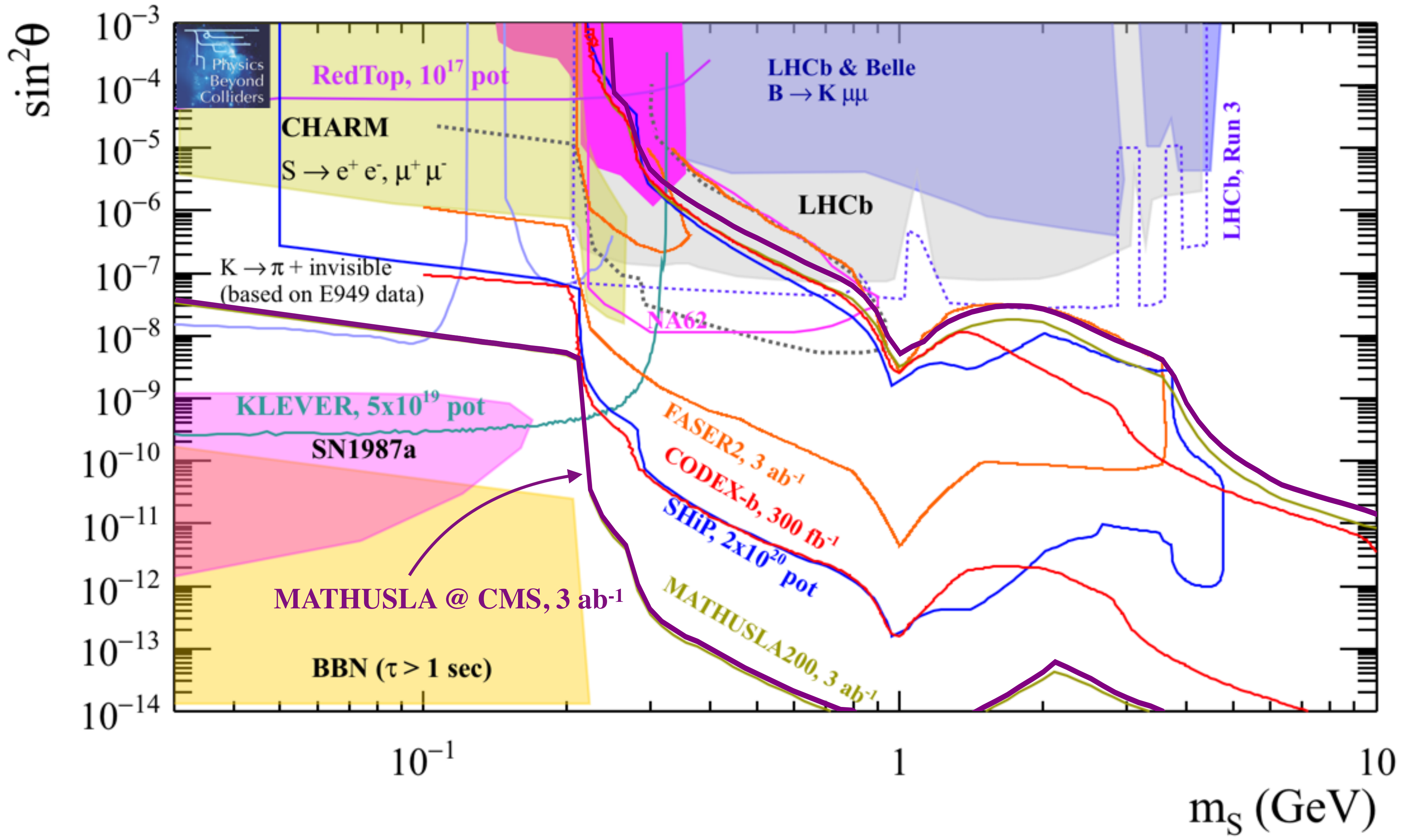


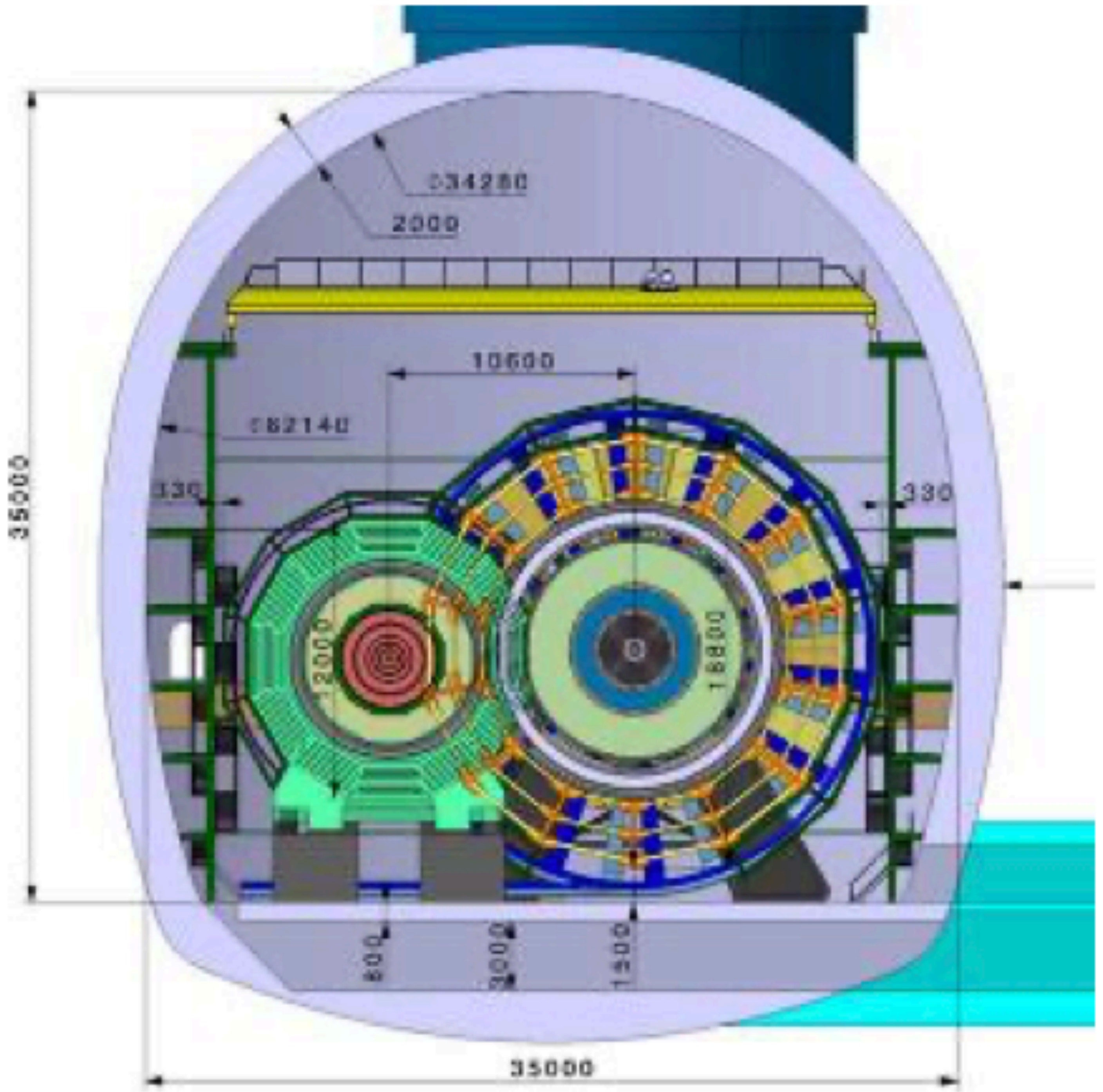
- New detectors explore orders of magnitude of new parameter space.
- All combined, they extend the reach of various intensity-frontier proposals like FASER

Proposal: 2011.01005

Bonus: LLPs @ FCC-hh, FCC-ee

HECATE: HErmetic CAvern TrackER.

A long-lived particle detector concept for FCC-ee or CEPC



Cavern size: r~15 m and z~50 m

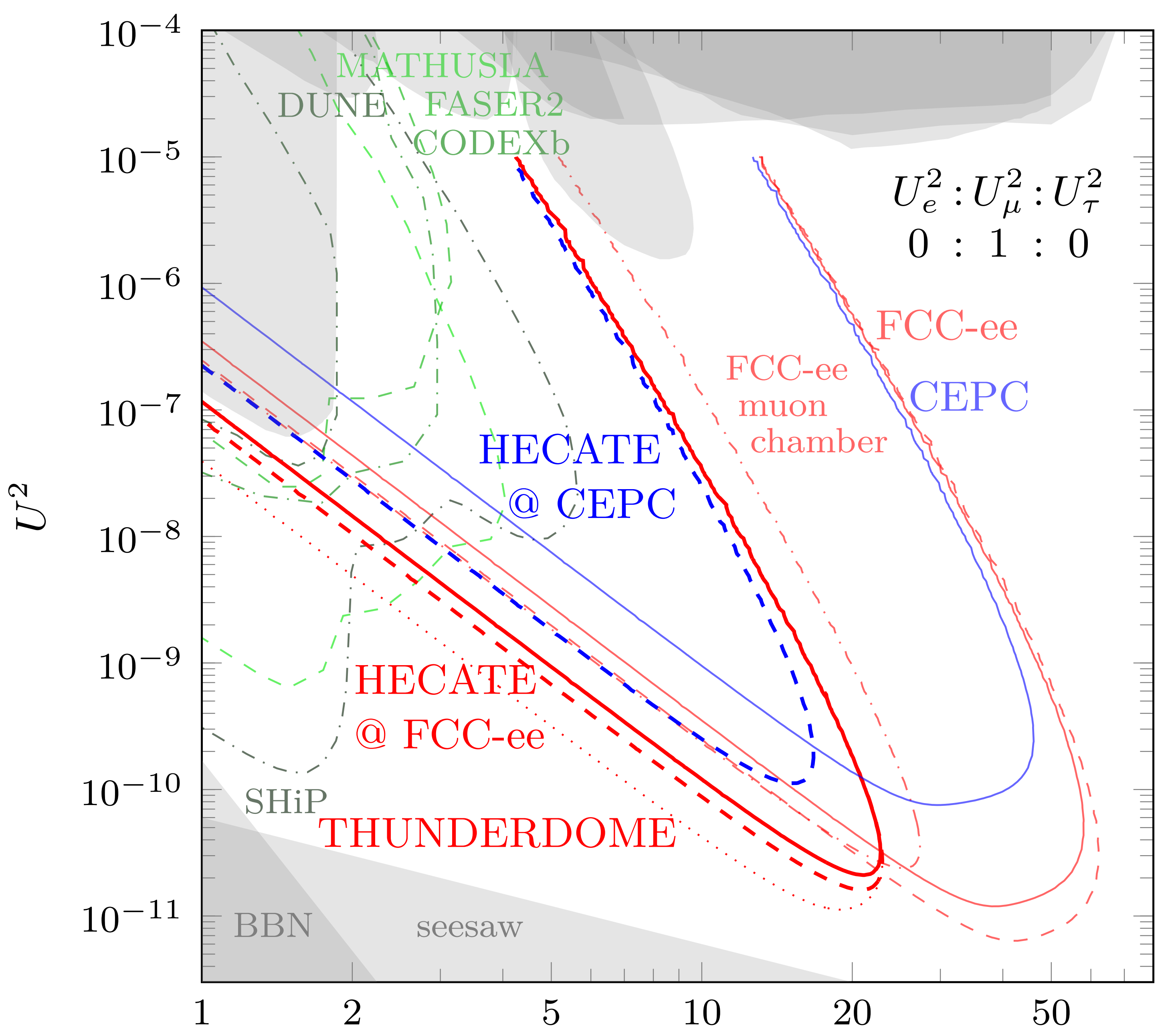
Main detector size =(10m)

For FCC-hh / FCC-ee, main detector will be relatively smaller than the cavern

- Cover detector cavern walls with scintillator plates or RPCs
- >= 2 layers of 1 m^2 separated by a sizeable distance — timing
- >= 4 layers for good tracking
- 4π coverage LLP detector
- FCC main detector as active veto

- Sensitive to a unique area of phase space

Example: HNLs

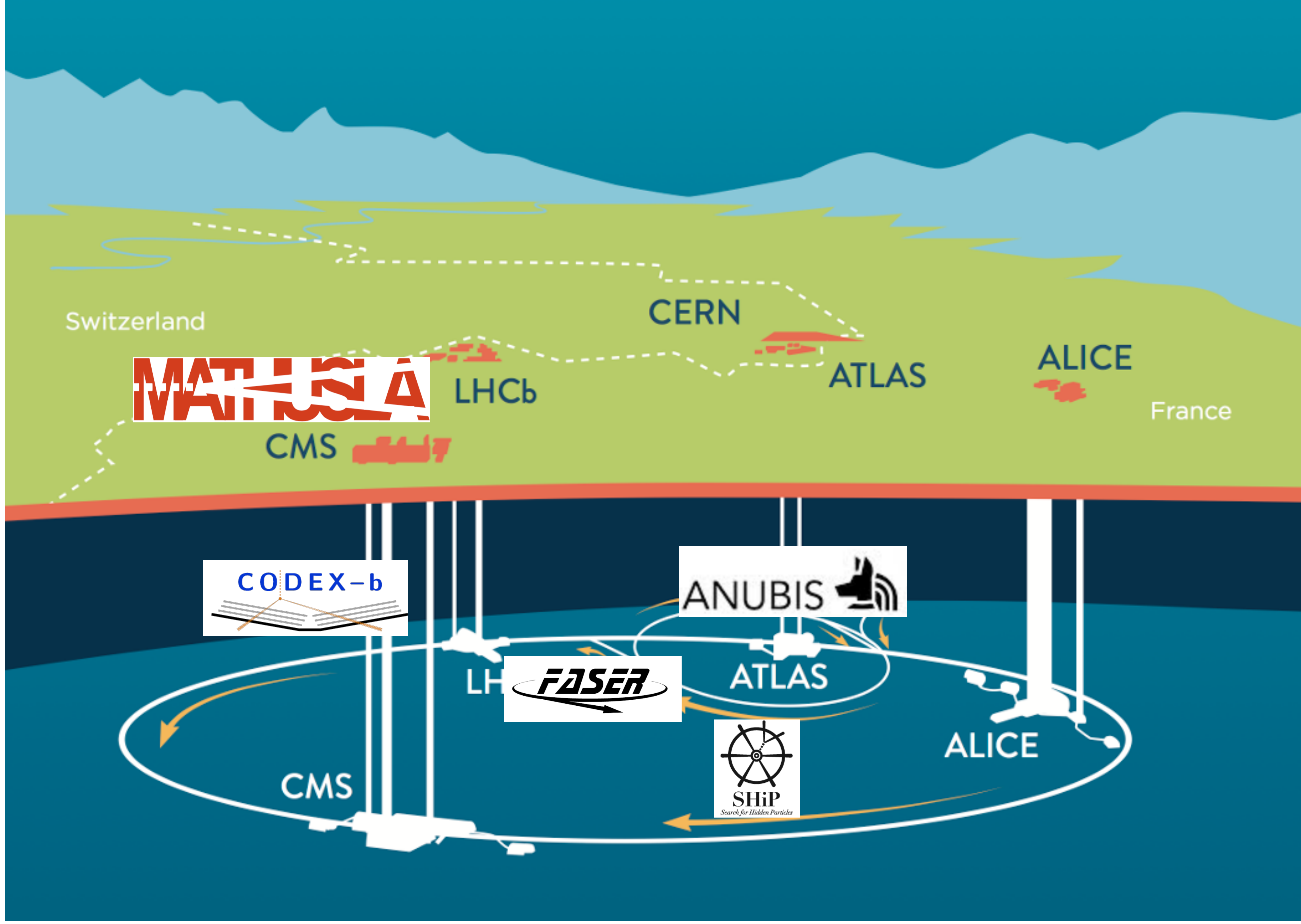


Conclusion

- Future experiments will be sensitive to large regions of phase space

- Many ideas for dedicated LLP detectors!
  - A relatively cheap way to explore a large region of the parameter space
  - Complementarity among different detectors

- Most of the current proposed experiments are aiming for data collection in HL-LHC.
  - Some already running!



- For the future….
  - Future colliders could probe a large part of the LLP parameter space
  - Good to include LLPs in the main physics program when the main detectors are being designed