Transverse dedicated LLP detectors

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11th LHC LLP Workshop
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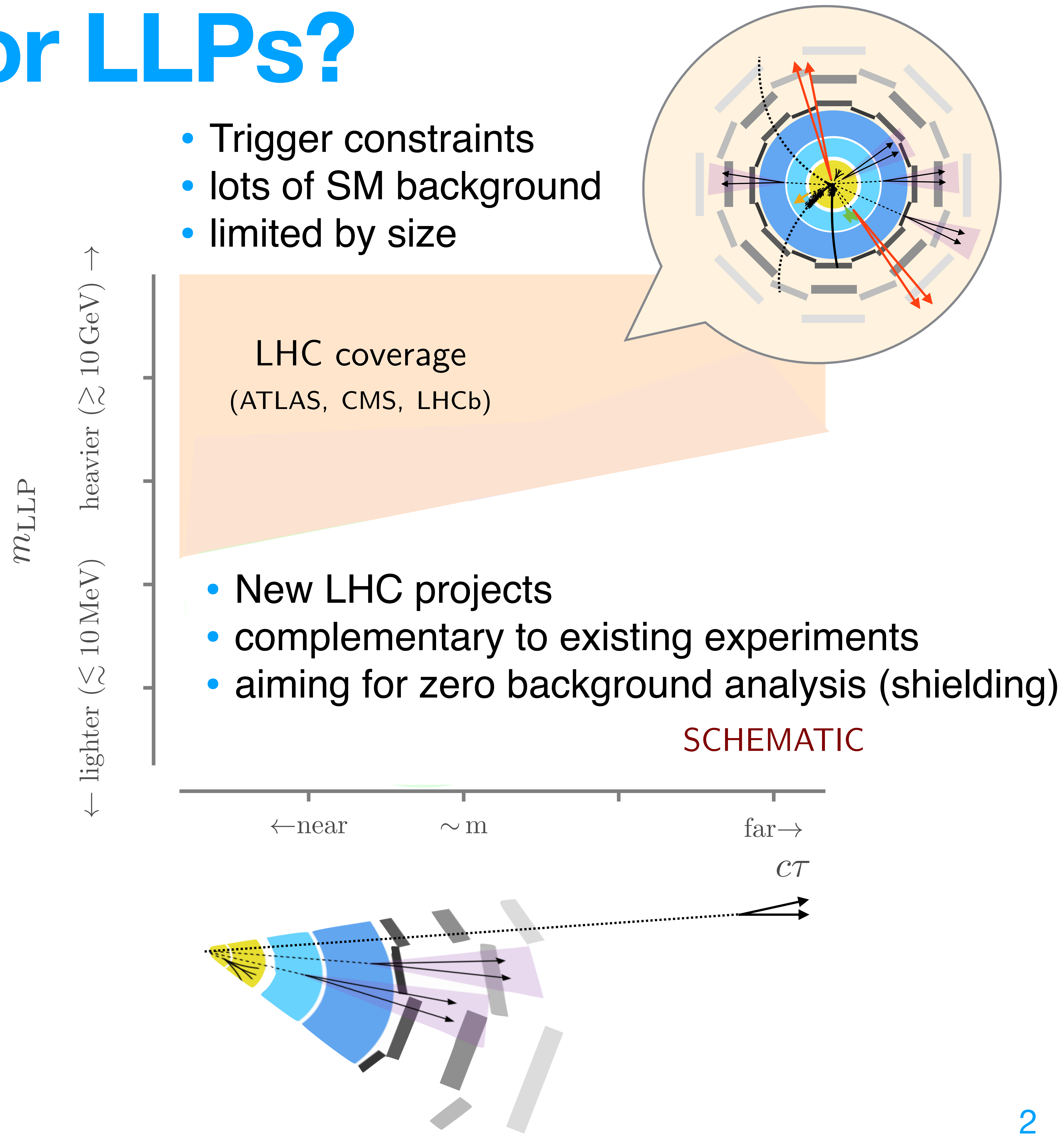
Where should we look for LLPs?

- Many of the theories involving Long-lived particles give no specifications on lifetimes

- LLPs with very long lifetimes could decay after traversing the main LHC detectors (O(10m))

- Need of dedicated experiments far away from the IP!



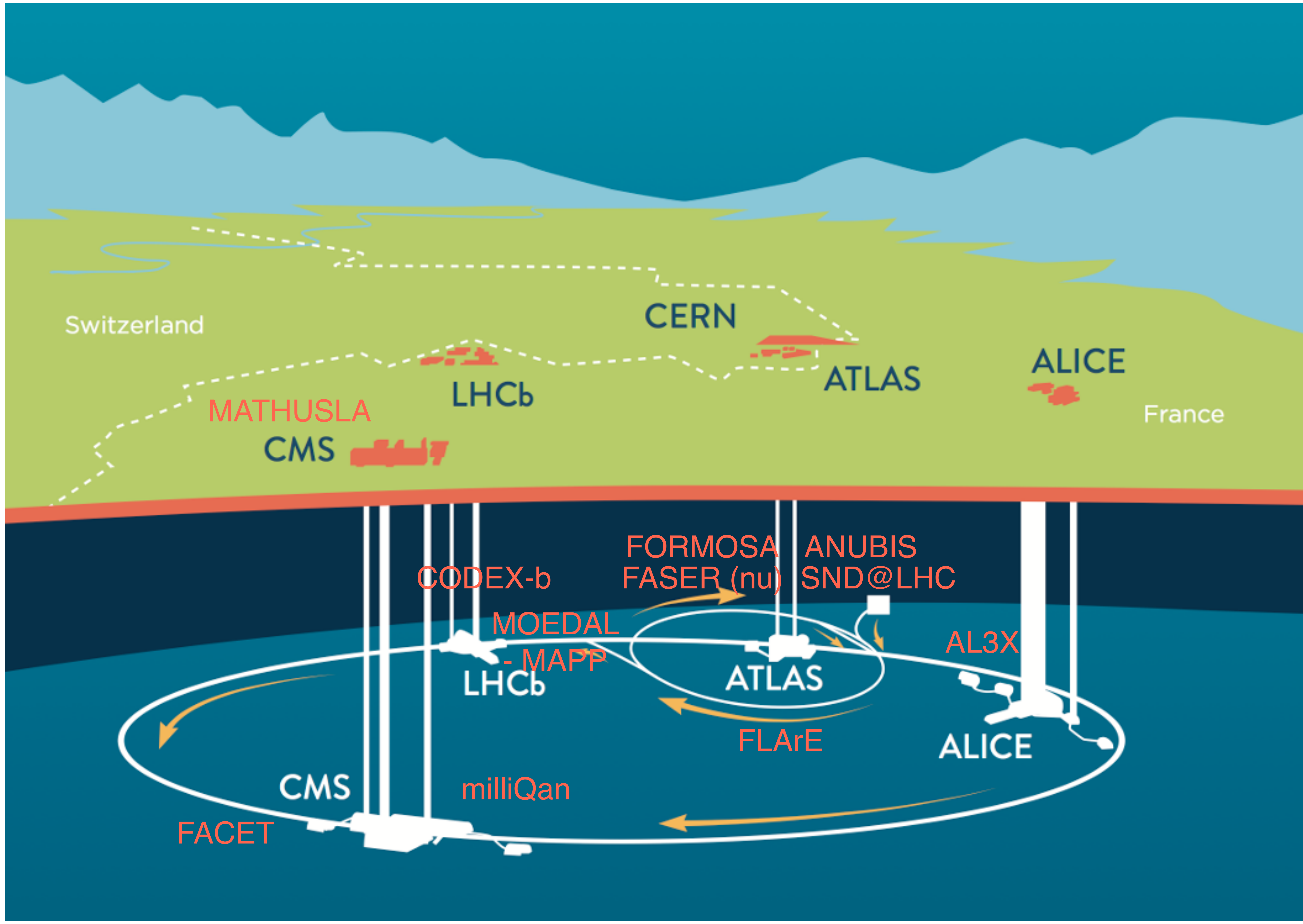
Overview of proposed LLP detectors at the LHC

- Huge range of lifetimes from ~10m to 10^8 m covered by different detector volume and distance form IP

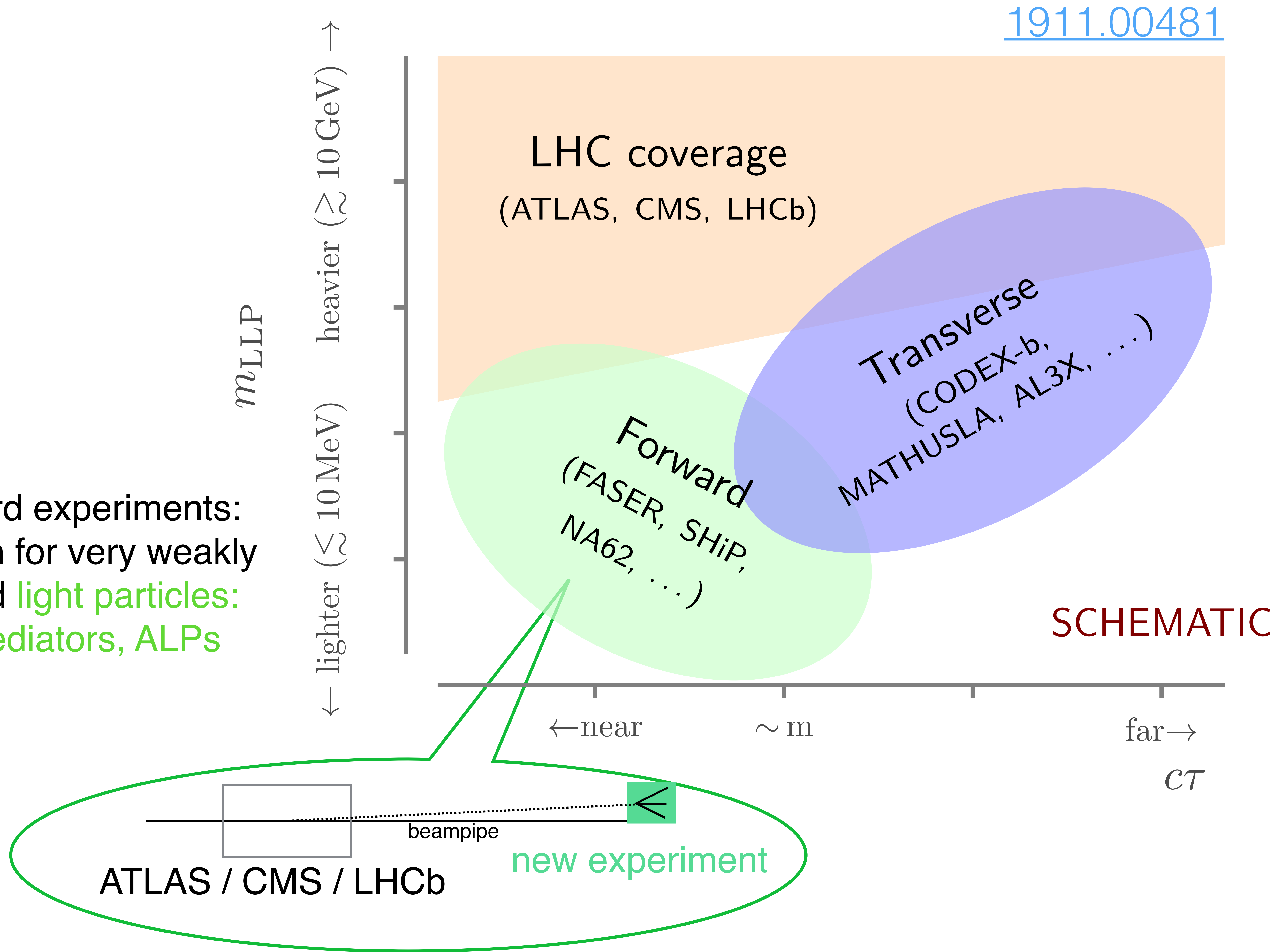
- Range of models, couplings and masses covered by different angle wrt beam axis

- Small couplings, small production cross sections
  - Zero background searches
  - Huge integrated luminosities
- Many possible decay modes!

- Need variety of detectors = complementary

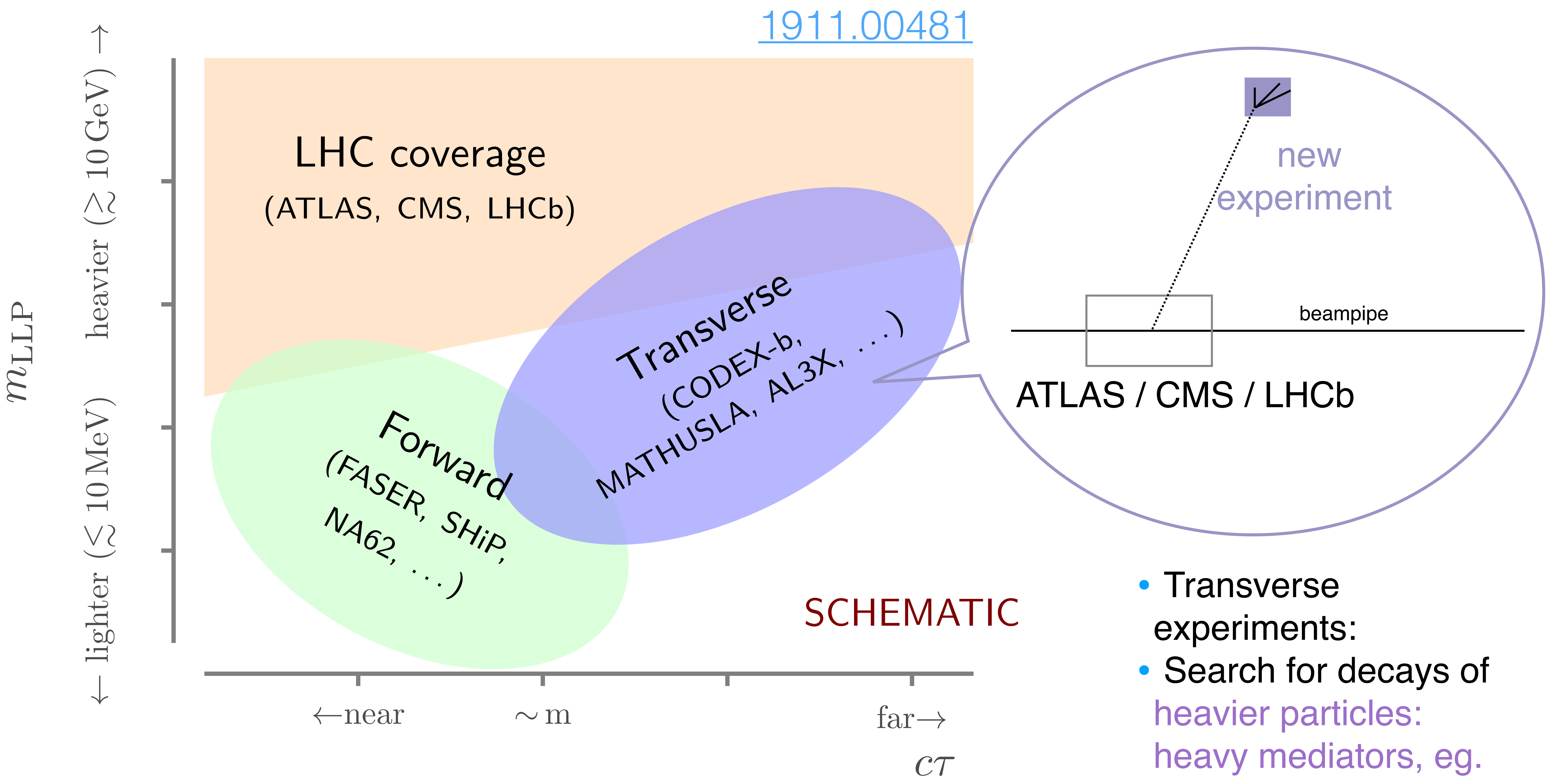


Overview of proposed LLP detectors at the LHC



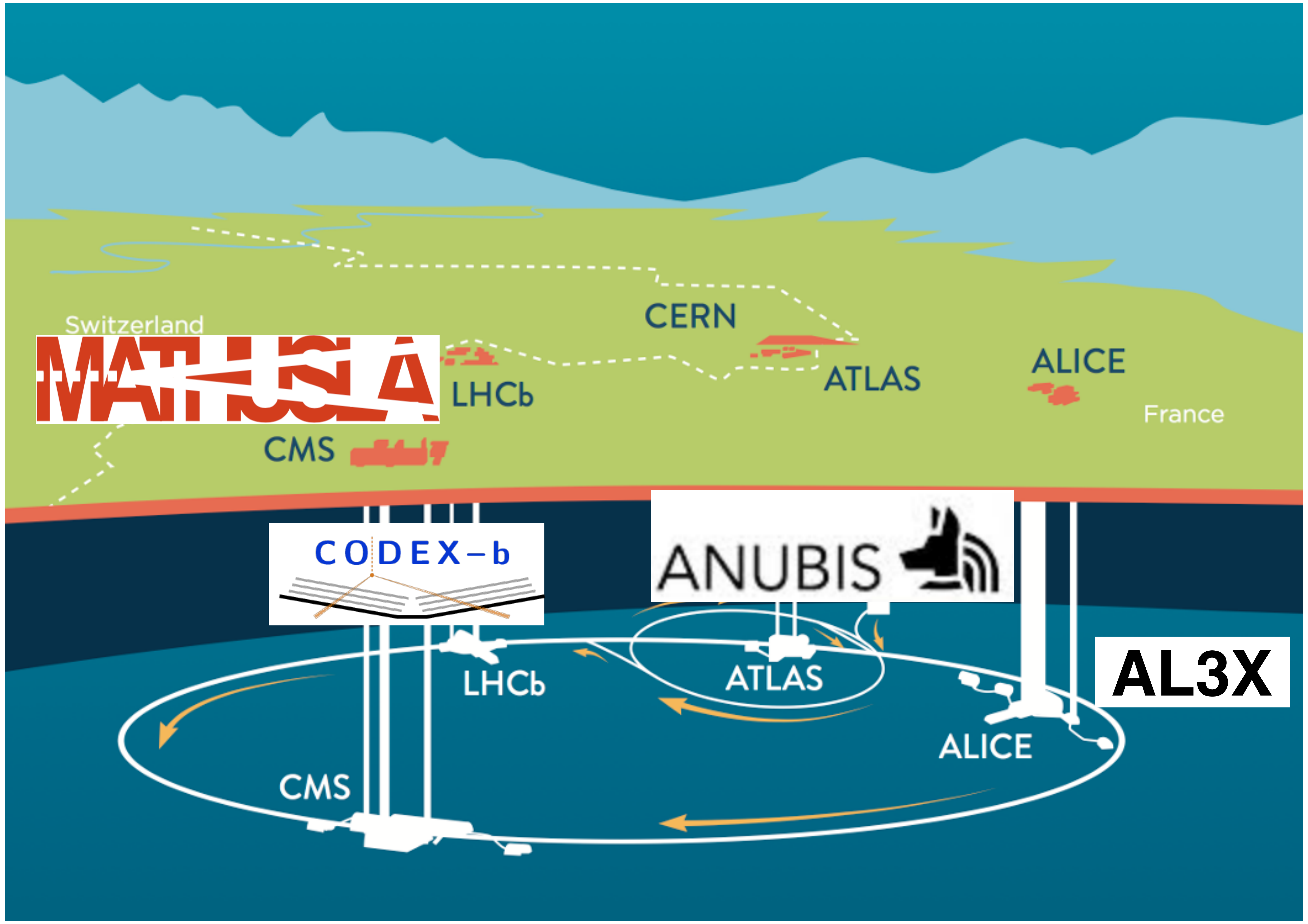
- Forward experiments:
- Search for very weakly coupled light particles: light mediators, ALPs

Overview of proposed LLP detectors at the LHC



- Transverse experiments:
- Search for decays of heavier particles: heavy mediators, eg. Higgs

Neutral LLPs @ transverse LHC experiments

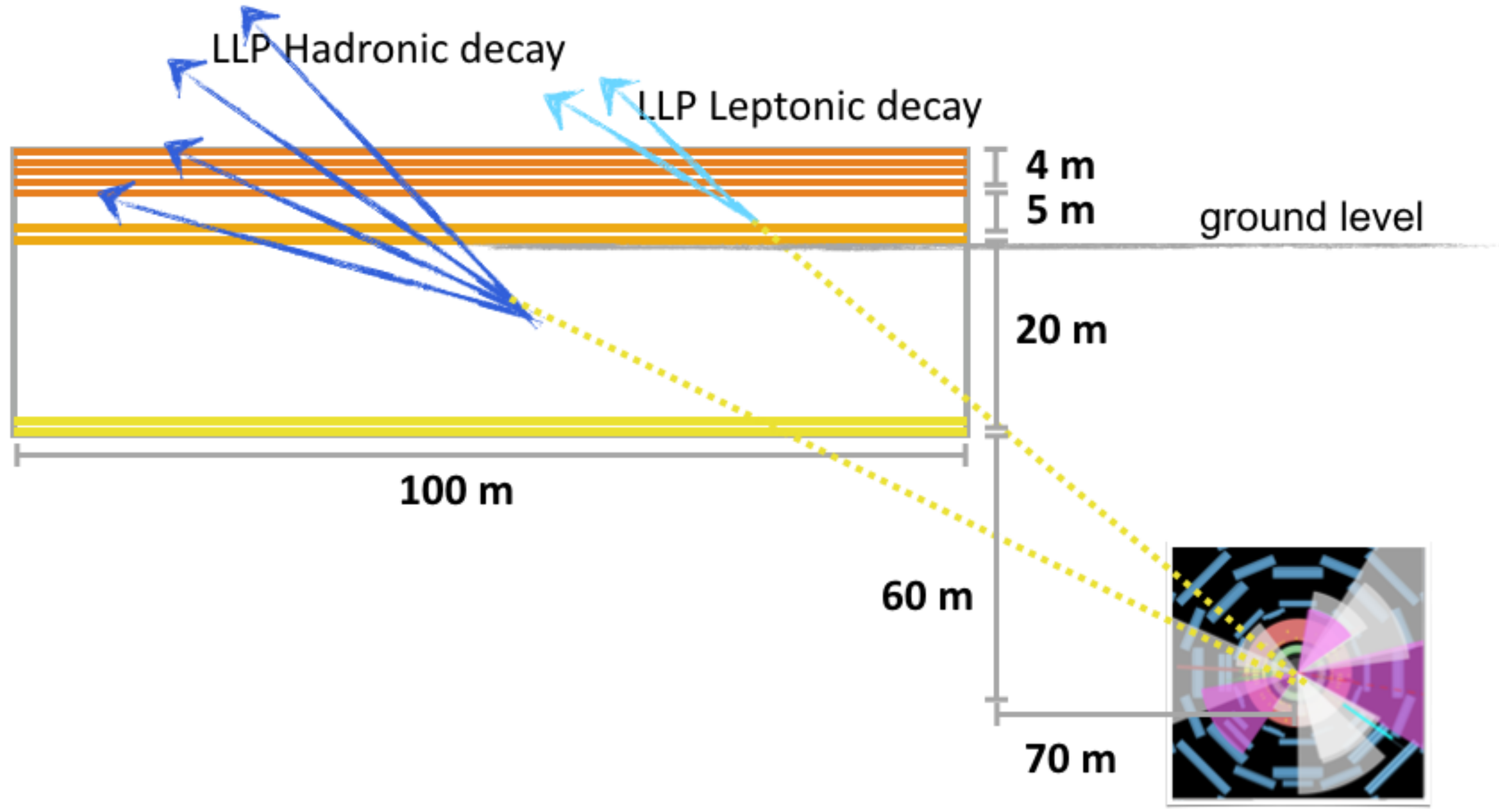


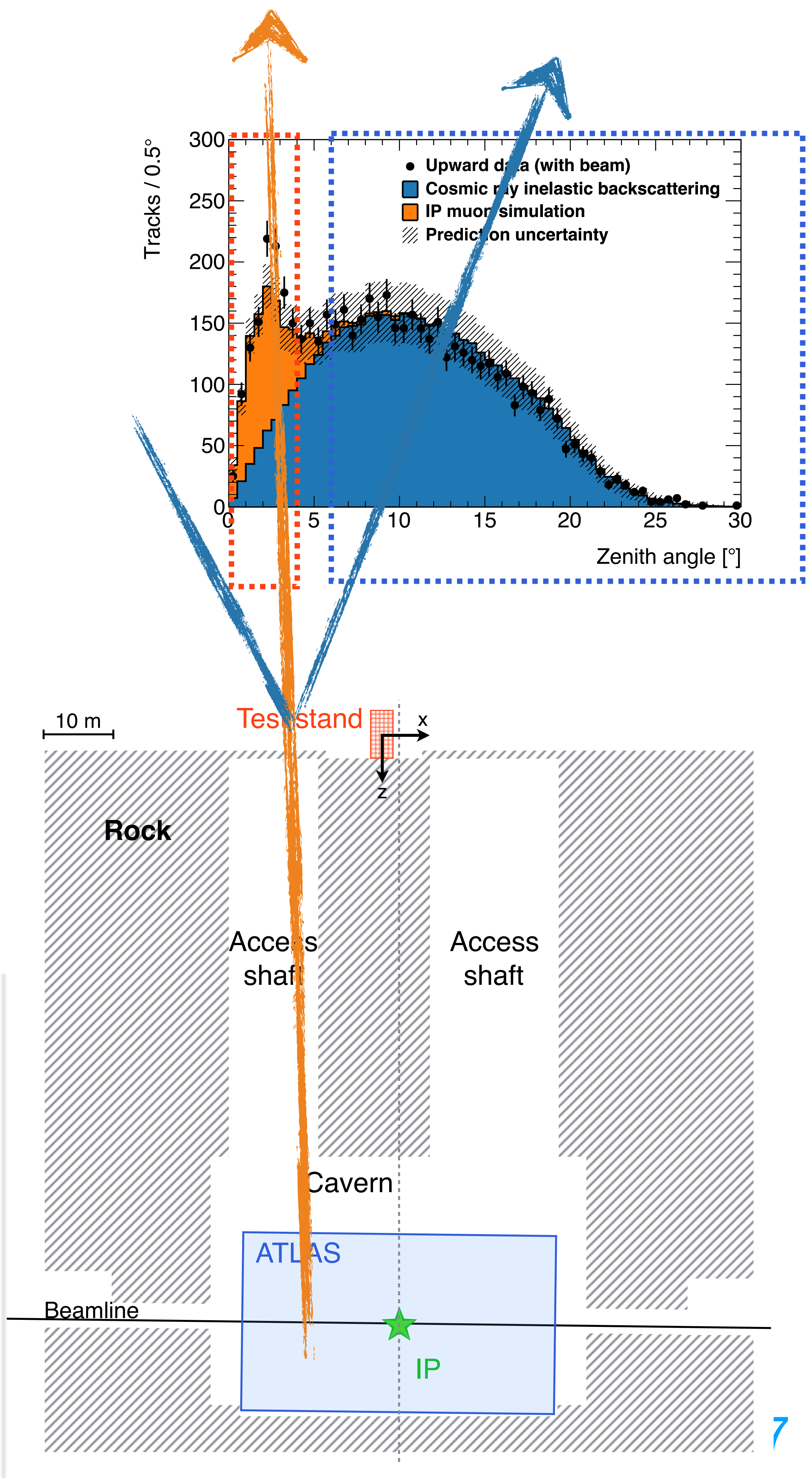
MATHUSLA

MAsive Timing Hodoscope for Ultra Stable neutraL pArticles

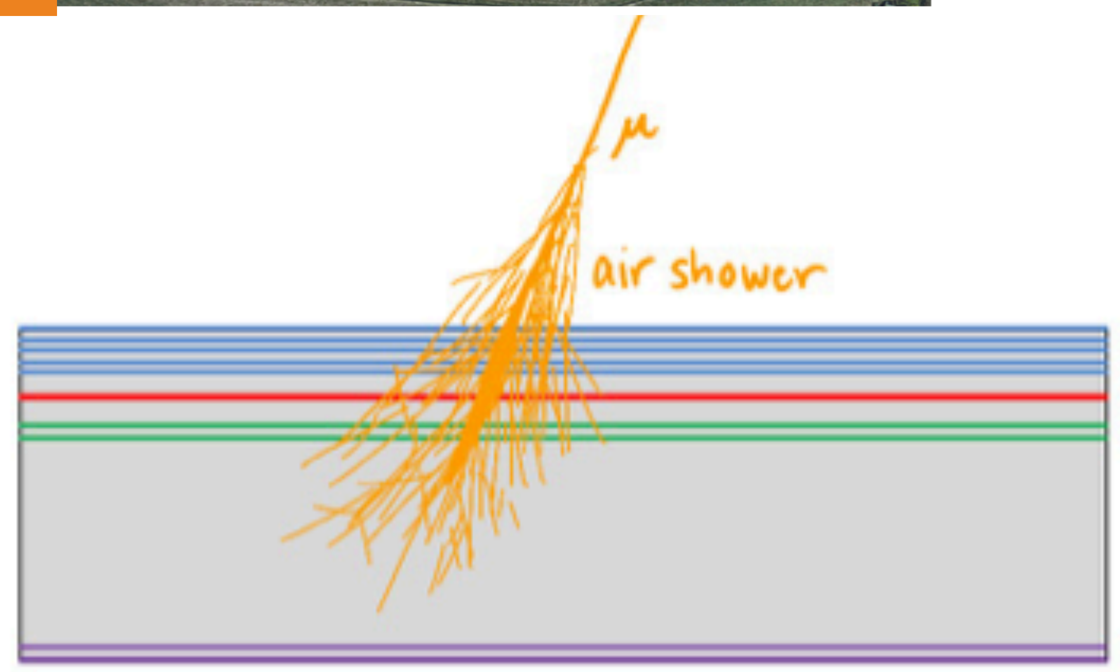
LoI: 1811.00927
Test stand: 2005.02018
Updated LoI: 2009.01693
Snowmass: 2203.08126

- Sensitive to LLPs with lifetime up to 10^8 m (BBN limit)
- Placed on the surface above CMS during HL-LHC: rock shielding
  - Aiming for zero background analysis
- Large air decay volume with several scintillator layers for tracking
- Test stand with 2018 confirmed background hypothesis and gives confidence in projected physics reach





- Extra: cosmics physics return: studies of the air showers core structure around the “knee”
- Studying the addition of an RPC chamber (less saturation) to measure vertical air showers

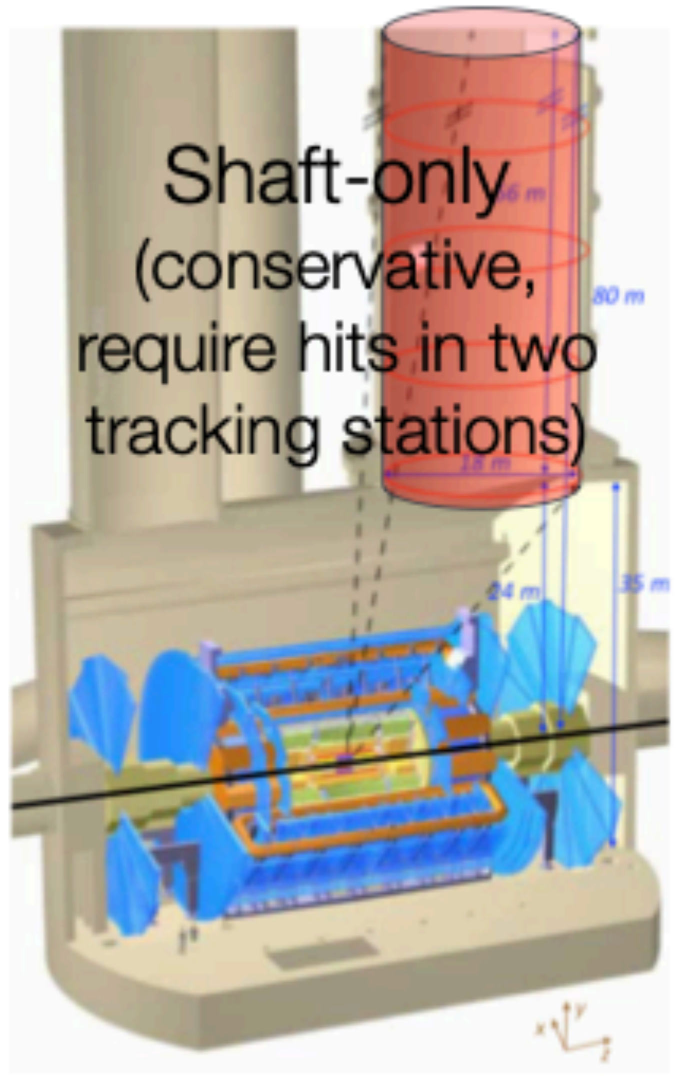


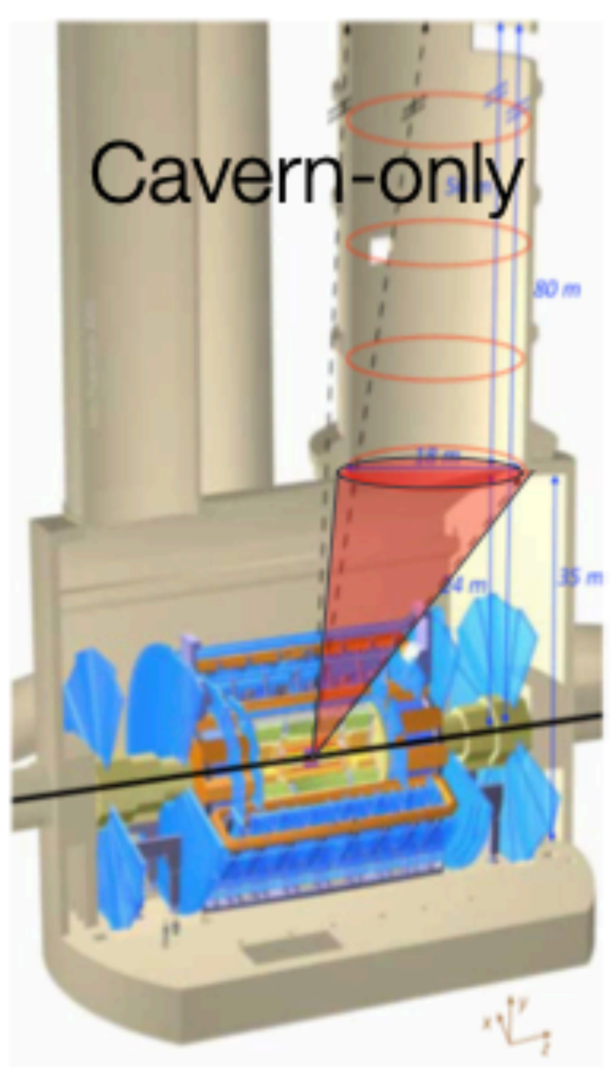
ANUBIS

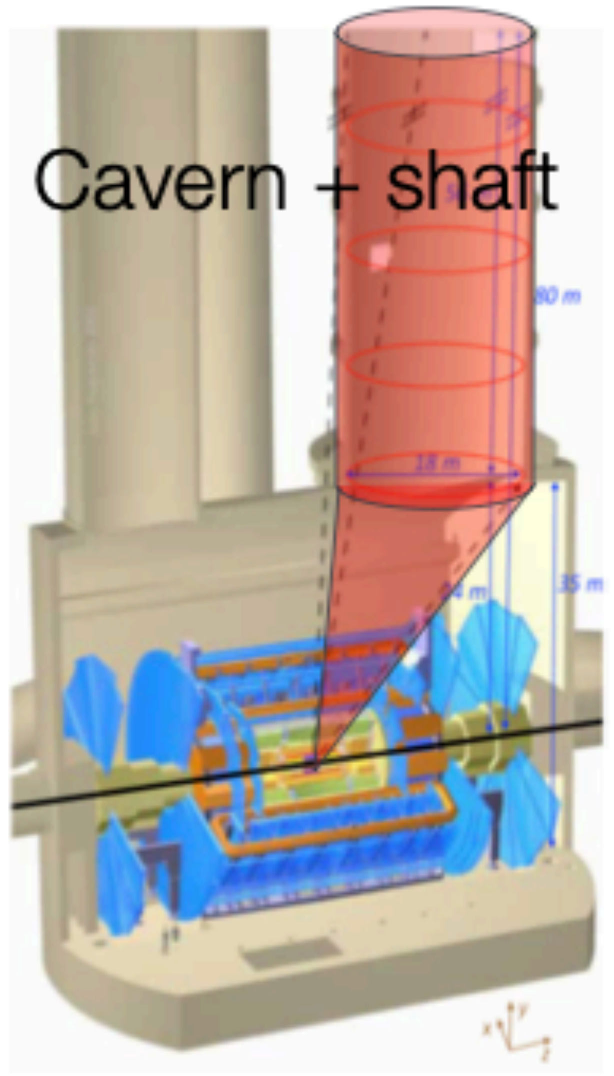
An Underground Belayed In-Shaft

Proposal: [1909.13022]

- Instrumenting ATLAS access shaft (56m) for HL-LHC
  - 3 possible configurations using the shaft and/or part of the cavern

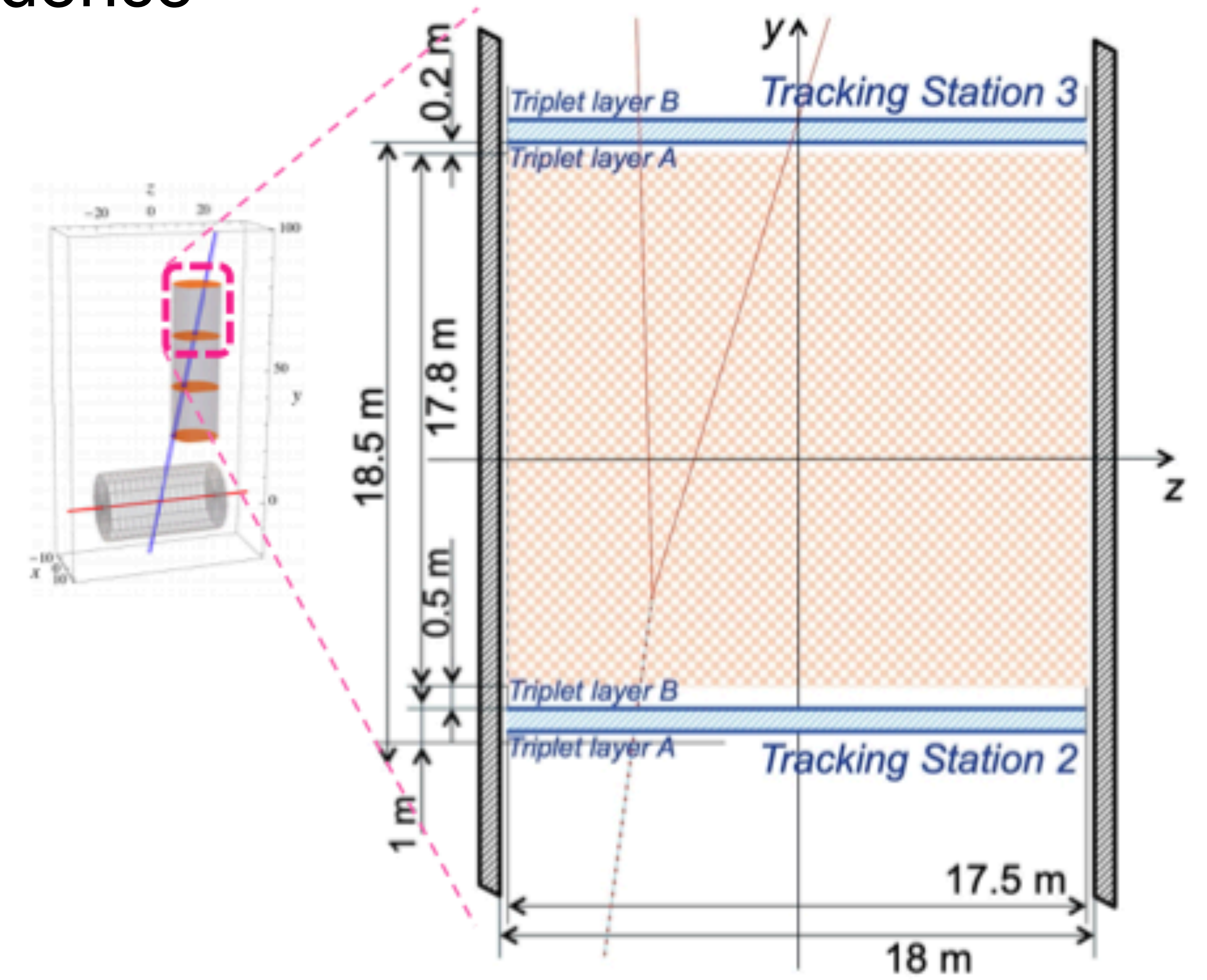






- Plan: installing a demonstrator for Run 3

- 4 RPC layers for tracking (2 triplet layers each)
- Use timing to reject cosmic rays
- Can be combined with ATLAS information as veto and background estimator
  - For a background similar to the LLP searches in ATLAS muon system, ANUBIS will need 4-50 events for evidence

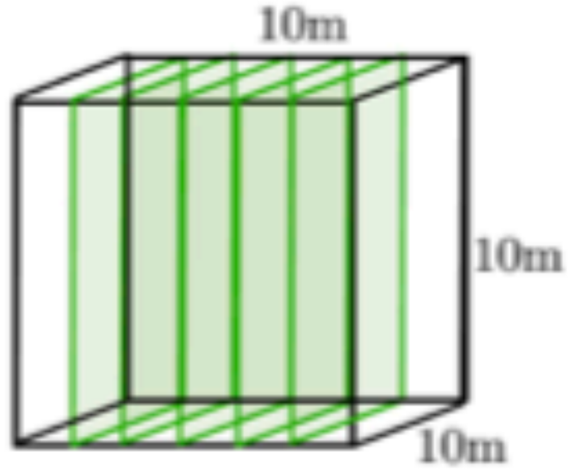


CODEX-b / β

Compact Detector for Exotics at LHC-b

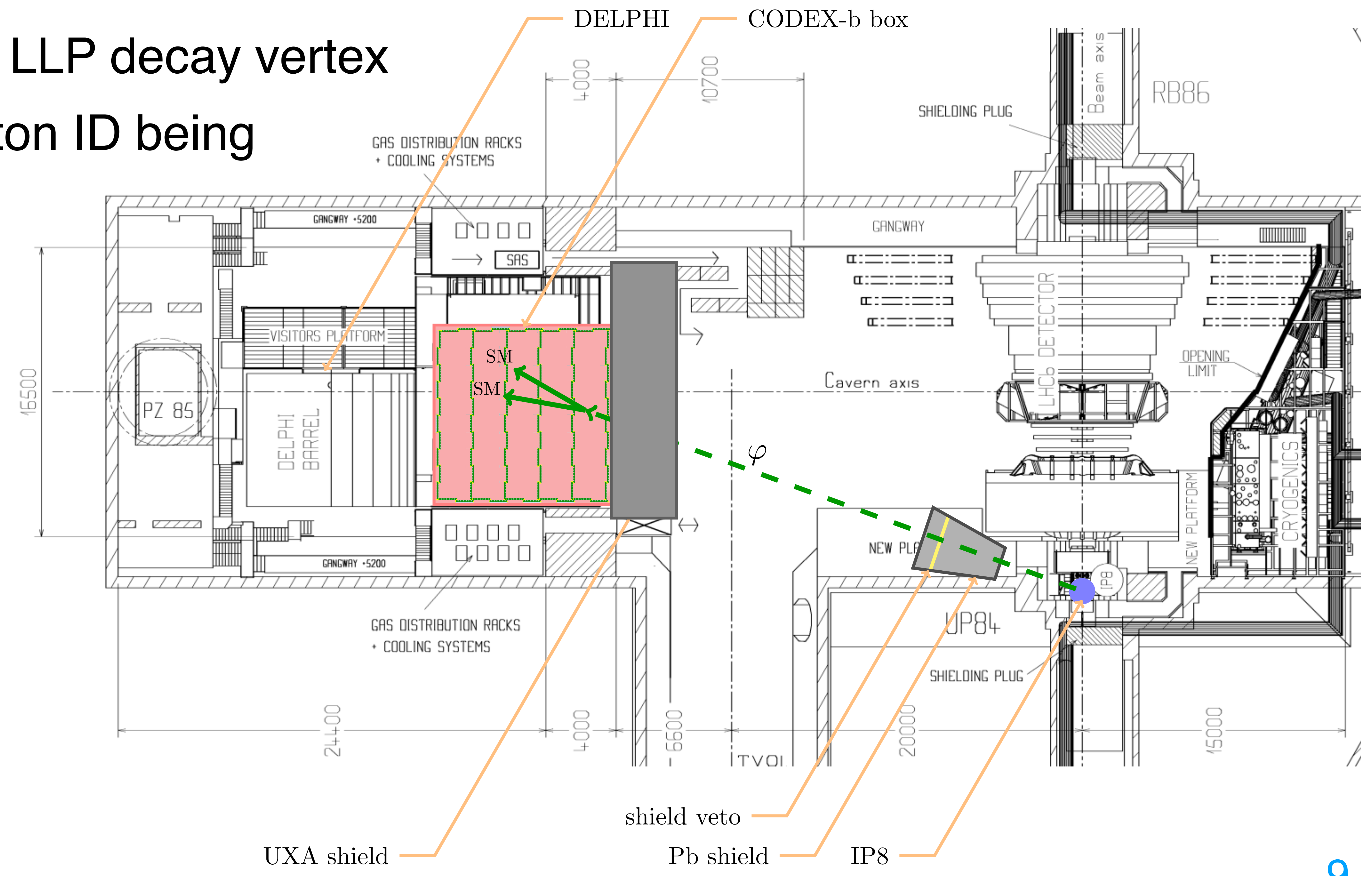
Proposal: 1911.00481
Snowmass: 2203.07316

- Target: light, 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 on each wall to reconstruct LLP decay vertex
  - Addition of calorimetry or other material layers for photon ID being considered
- Shield veto agains collision backgrounds

- Codex-beta:
  - demonstrator, 2x2x2 m^3
  - data-taking in Run 3
  - Integrated with LHCb
  - will check backgrounds and technology
  - Full detector for Run 5

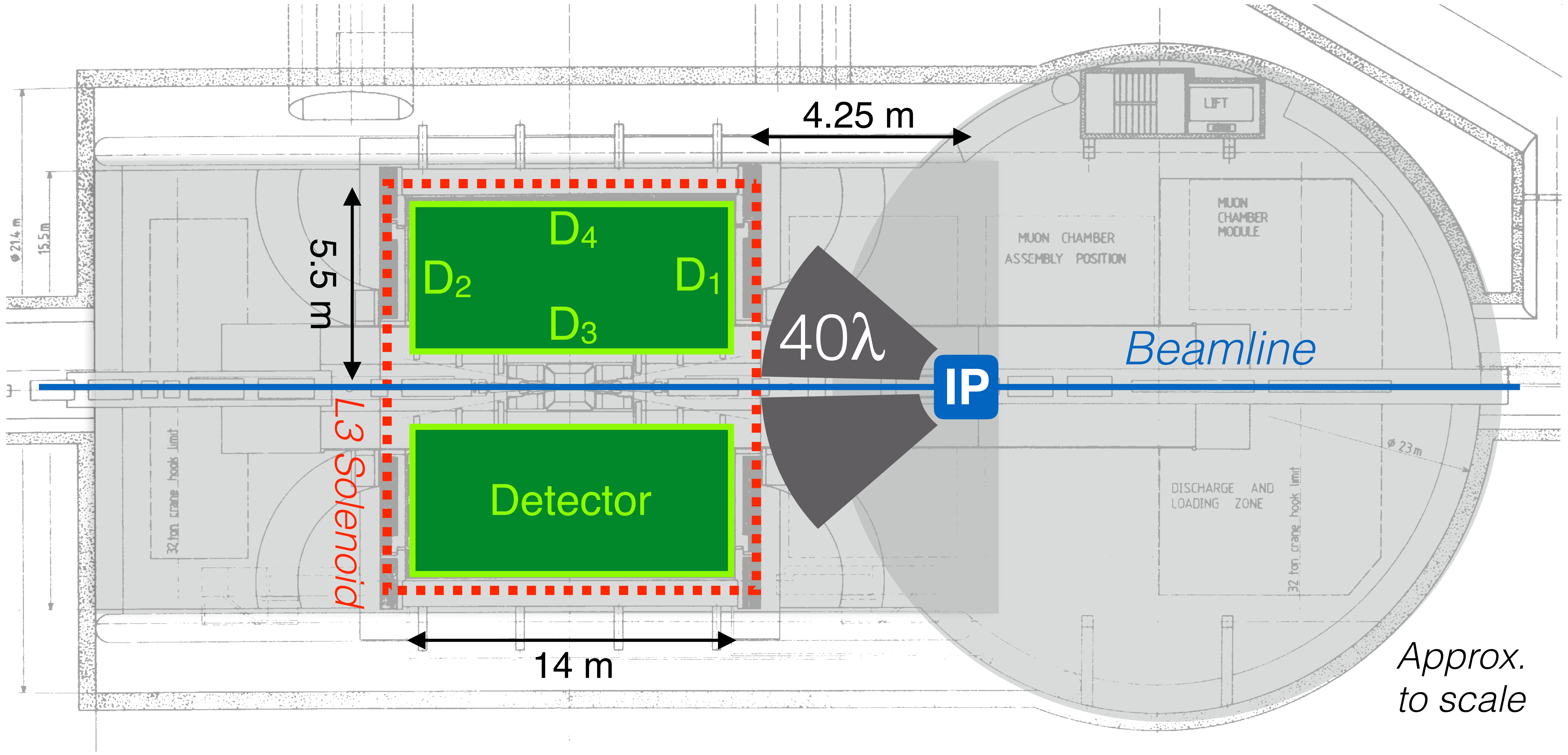


AL3X

A Laboratory for Long-Lived eXotics

Proposal: [PRD.99.015023]

- Use ALICE's cavern and magnet for LLP searches
- Implies that ALICE is removed!
- Requires upgrading IP2 to run at the nominal LHC luminosity
- The IP has to be moved so that the LLP has enough space to decay (would require adjusting magnets)
- Use existing magnets for momentum measurements
- Add absorber, aiming at zero background
- Quite unlikely to be built, but a good example on how to use existing caverns for LLP detectors



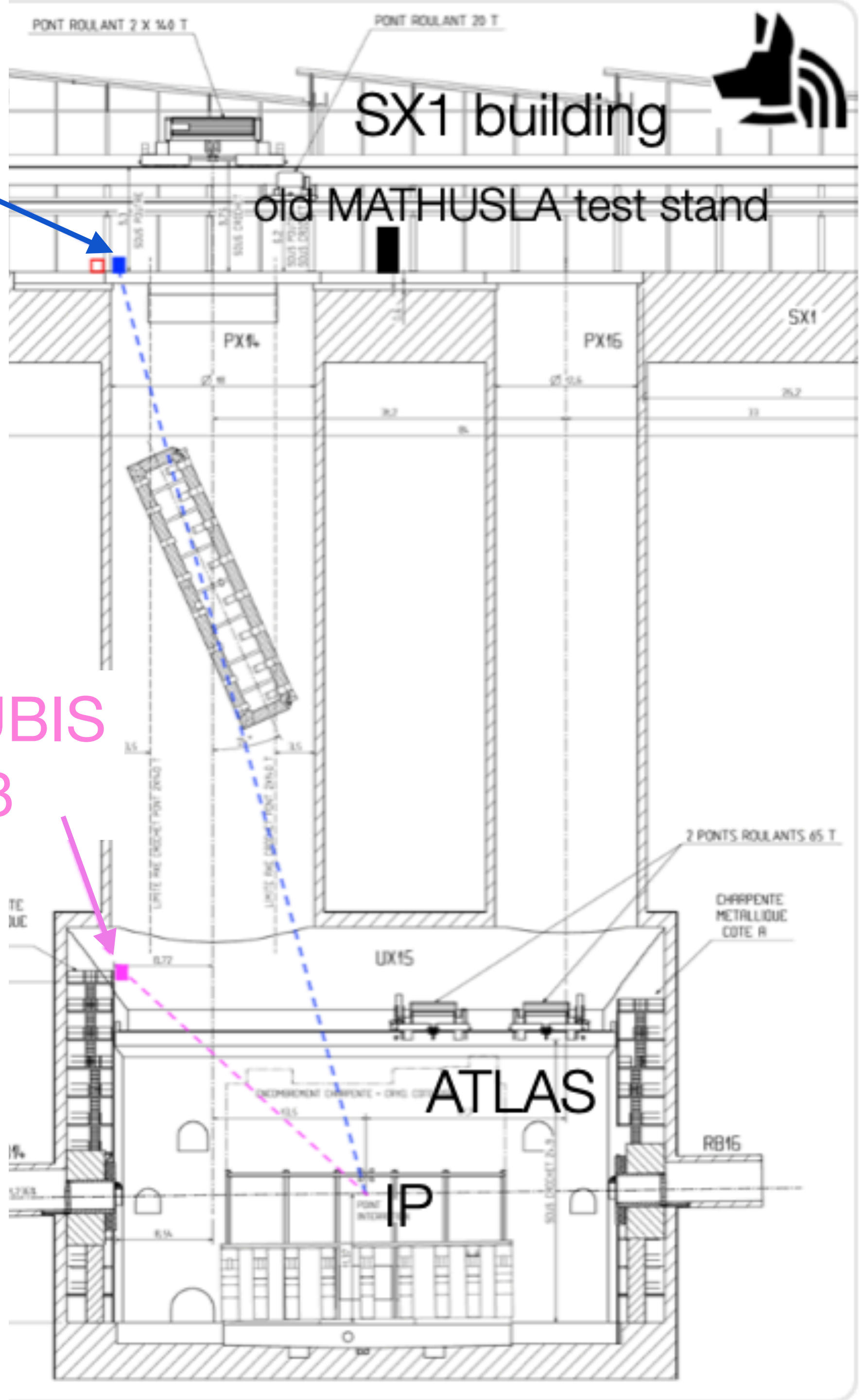
Comparison of detector design — Neutral LLPs @ LHC

	Collision point	Distance from IP	Fiducial volume	Use main experiment?	Shielding cosmics	Shielding collision	Technology
MATHUSLA	CMS	~90 m	25m x 100m x 100m	Under study	NO	YES	Scintillators (+ 1 RPC)
ANUBIS	ATLAS	~25 m	~56m x $(9\text{m})^2$	YES	Partial	NO	RPC (scintillators to be explored)
CODEX-b	LHCb	~35 m	10m x 10m x 10m	Under study	YES	YES	RPC
AL3X	ALICE	~4.25 m	~12m x $(2.5\text{m})^2$	NO	YES	YES	Gas TPC

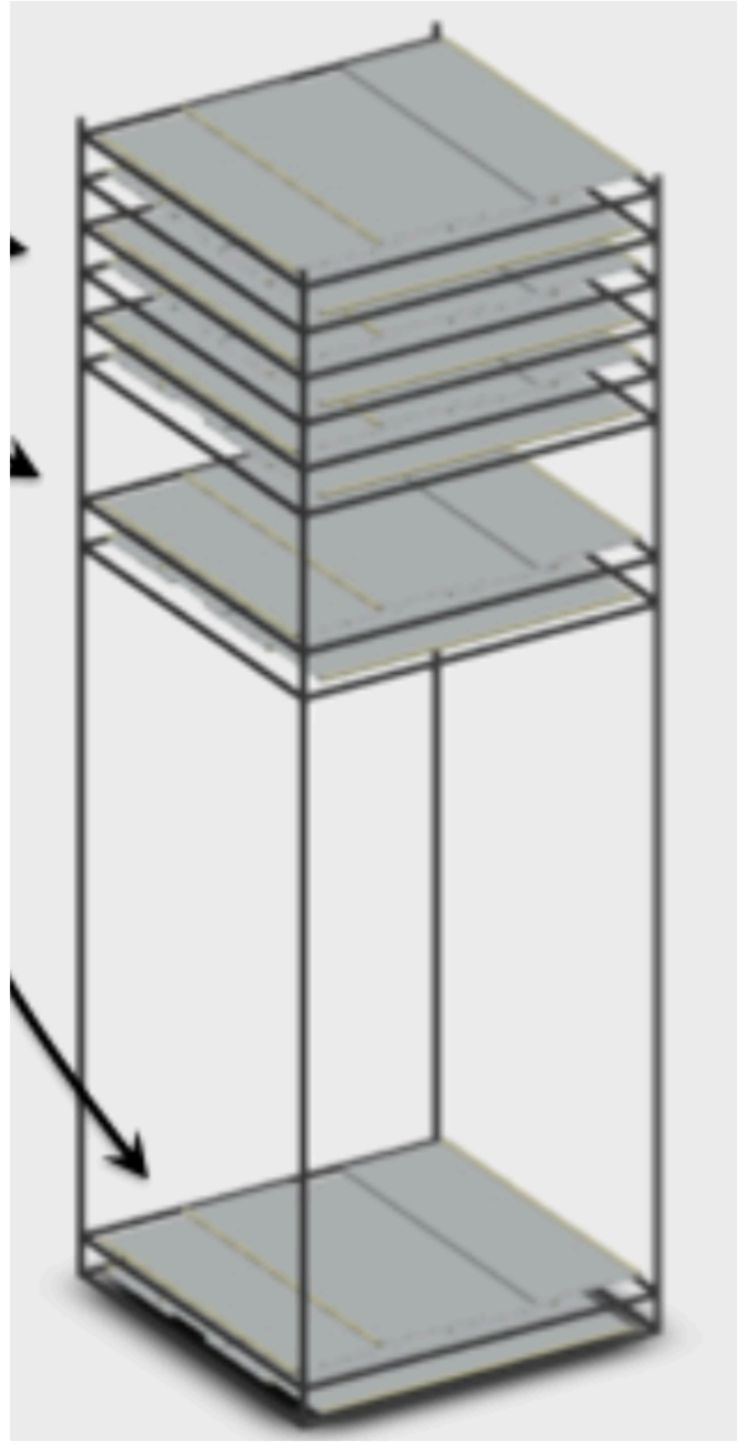
- For a given decay volume,
  - More solid angle if closer to the IP
  - Number of decays higher if closer to the IP
  - LHC collision backgrounds more important if closer to the IP (depending on shielding)

Short time plans — neutral LLPs @ LHC

- proANUBIS
  - Small section for commissioning
  - Test backgrounds like punch-through jets or K_L
  - Test synchronisation with ATLAS
  - Production in progress

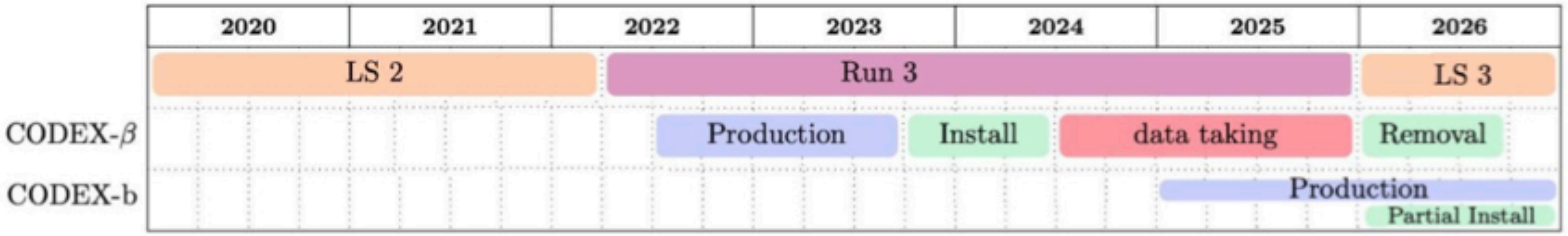


- MATHUSLA module planned to be build before the whole detector
  - Modular design permits a staged assembly
  - Test backgrounds and technology
- TDR coming soon

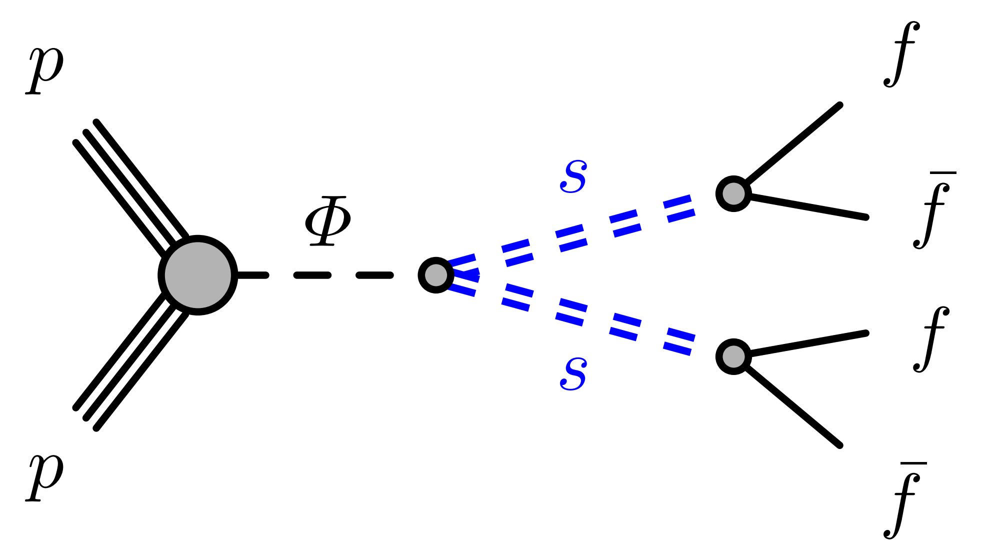


- CODEX-β
  - Reduced surface
  - No active shielding
  - To validate reconstruction and background estimates
  - Production in progress

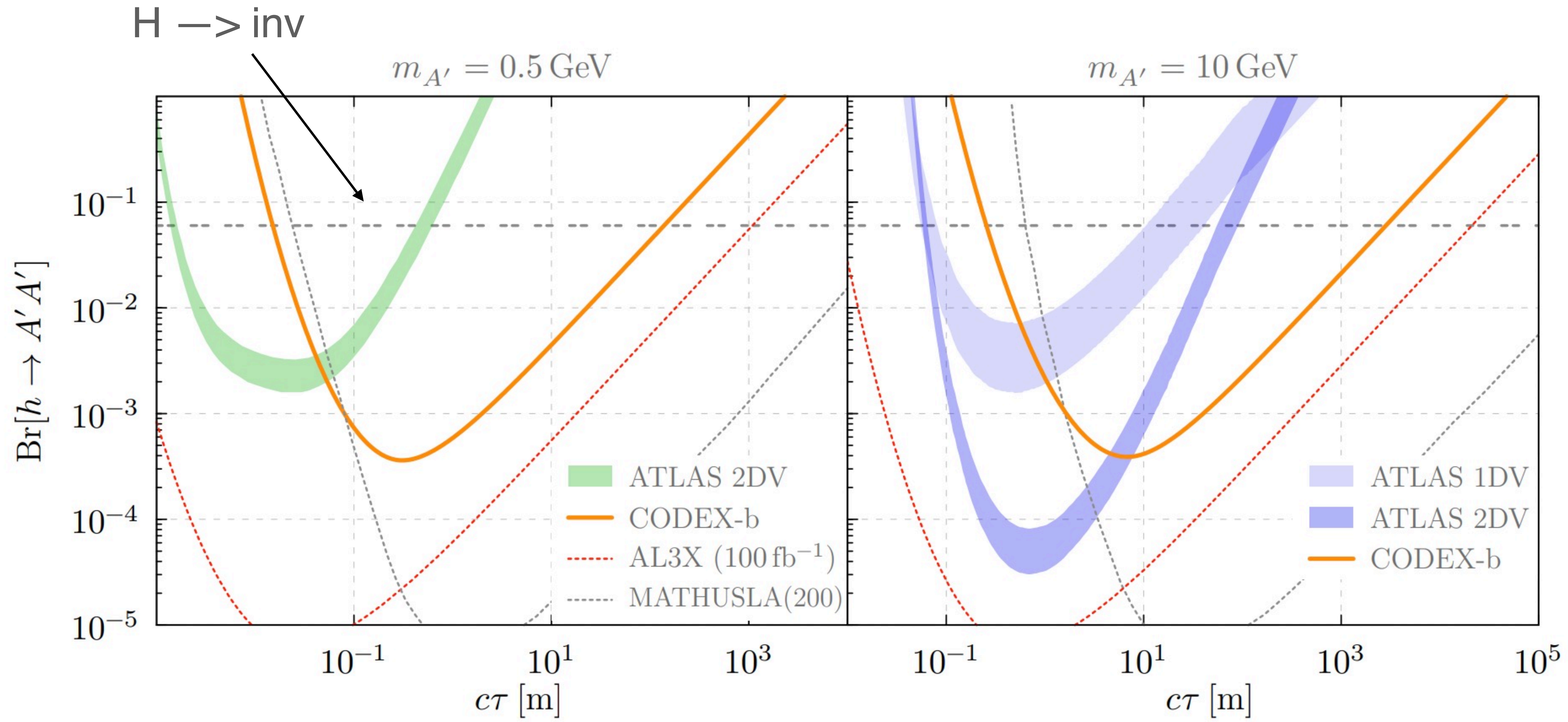
! Temptative schedule !



Sensitivity — neutral LLPs @ LHC Scalar mediators

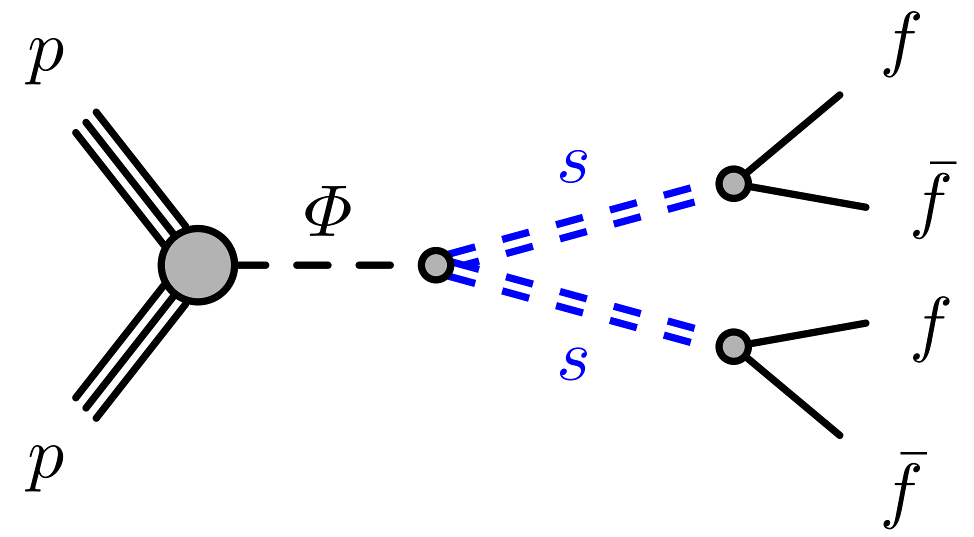


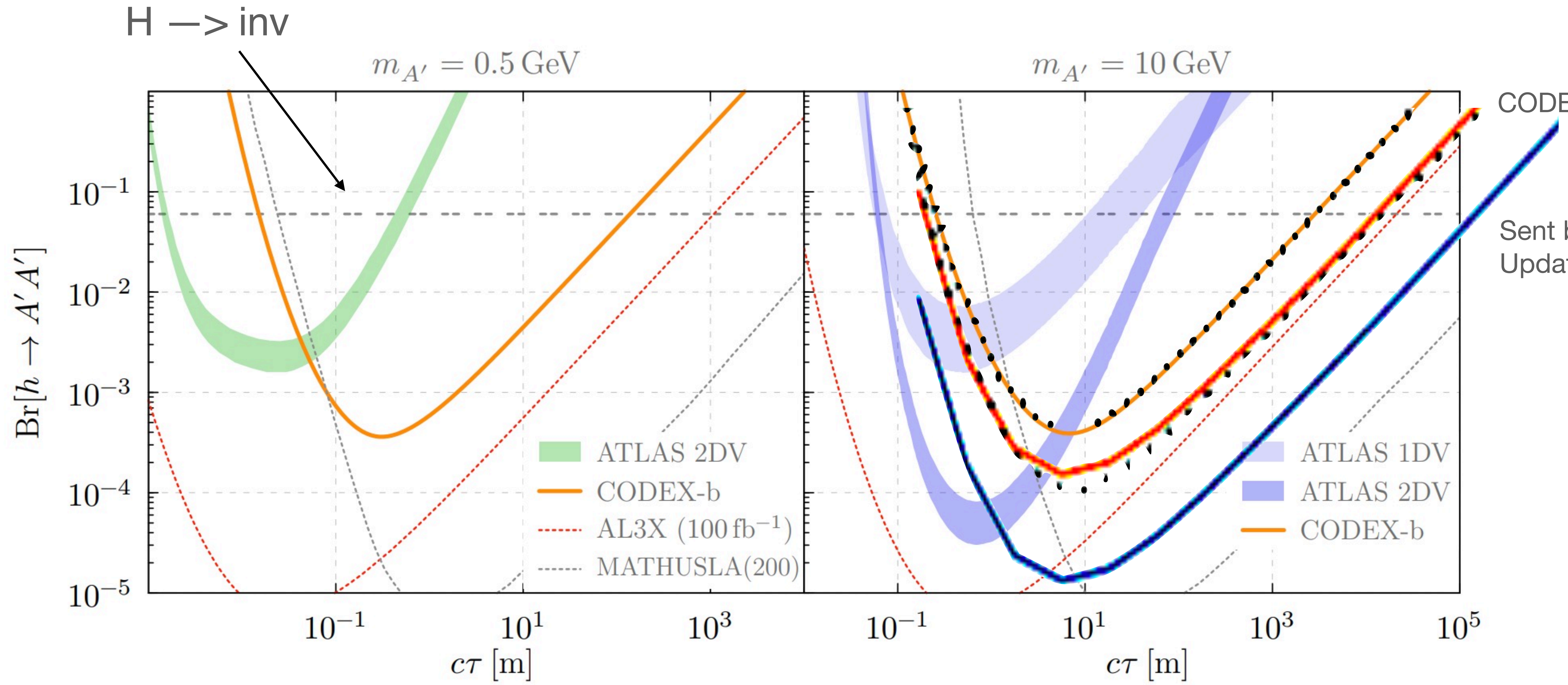
CODEX-b EoI: 1911.00481



- Mathusla: Good sensitivity for mass > 5 GeV and lifetime >> 100 m, even at low masses
- Al3x complementary in the shorter lifetimes
- Codex-b 300/fb, complementary to MATHUSLA at shorter lifetimes

Sensitivity — neutral LLPs @ LHC
Scalar mediators





CODEX-b EoI: 1911.00481

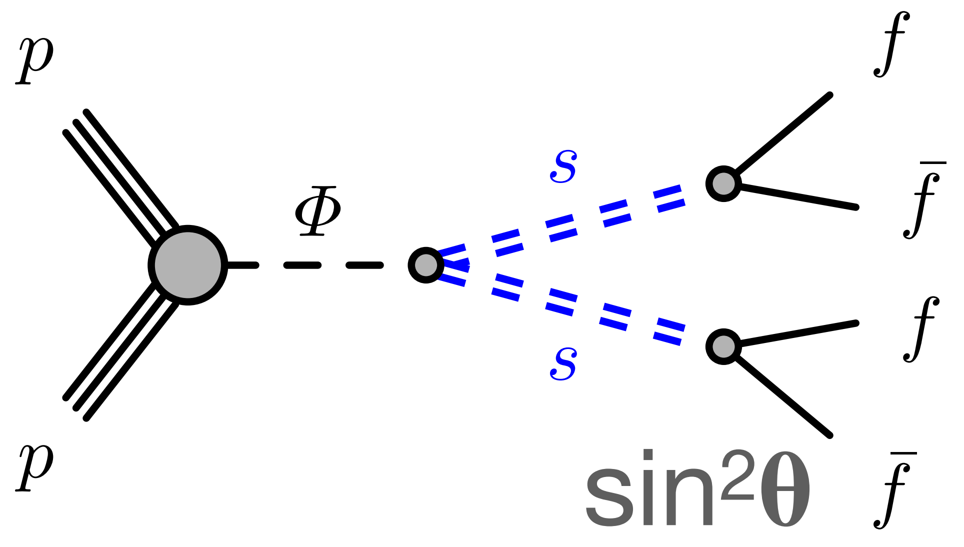
Sent by Oleg Brandt
Updated from 1909.13022

Background as in ATLAS MS vertex search
Similar reach as Codex 1/at

- Mathusla: Good sensitivity for mass > 5 GeV and lifetime >> 100 m, even at low masses
- Al3x complementary in the shorter lifetimes
- Codex-b 300/fb, complementary to MATHUSLA at shorter lifetimes

Anubis Cavern + shaft, 3/ab, 50 events
Anubis Cavern + shaft, 3/ab, 4 events
Codex-b 10m x 10m x 10m, 300/fb
Codex-b 20m x 10m x 10m, 1/ab

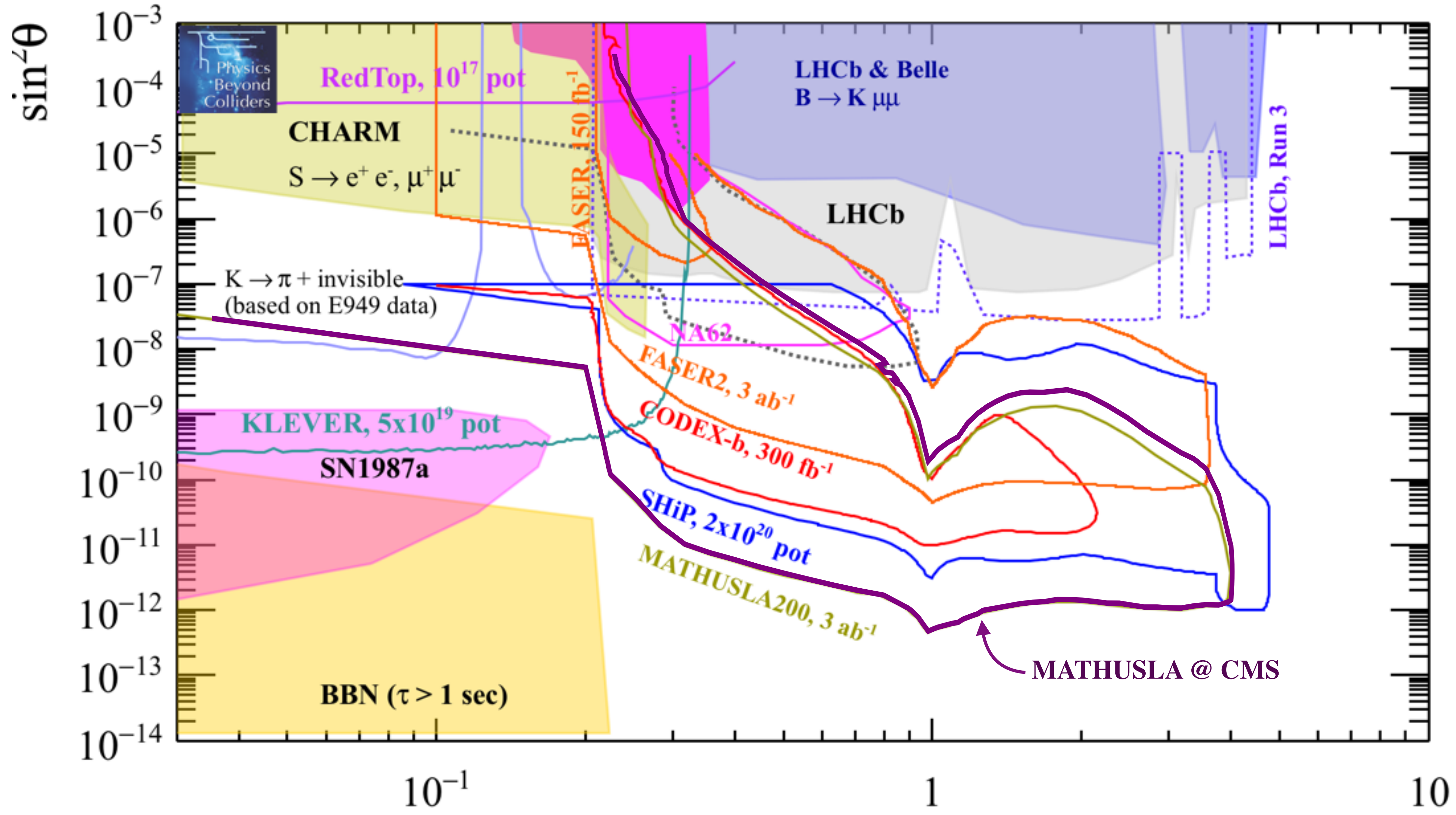
Sensitivity — neutral LLPs @ LHC
SM + S



- Singlet scalar LLP s mixing with Higgs mixing angle θ

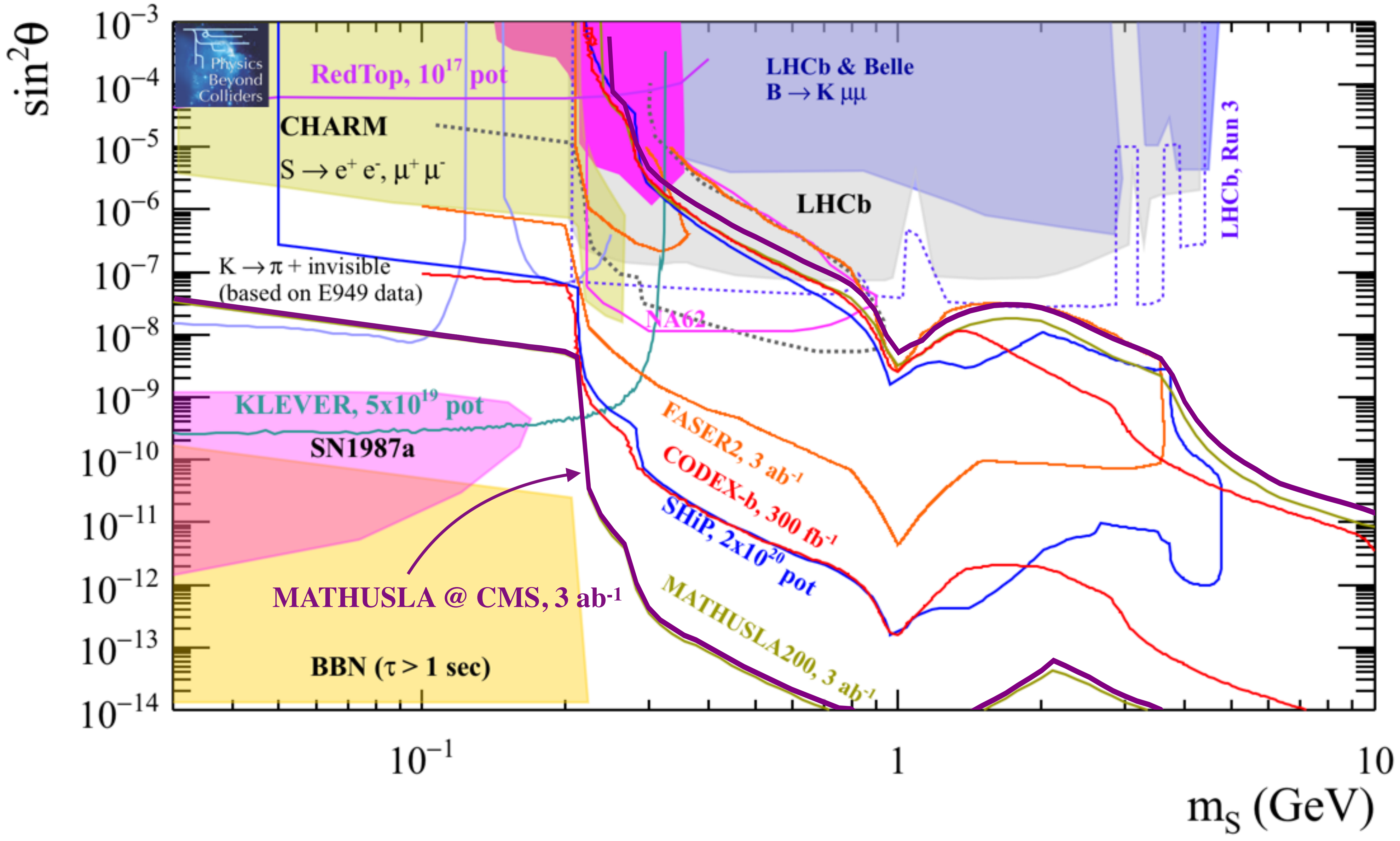
$\sin^2\theta \downarrow$ $c\tau \uparrow$

- Assuming production in exotic B, D, K meson decays only



(a)

- Assuming additional production in exotic Higgs decays with Br(h → ss) = 0.01



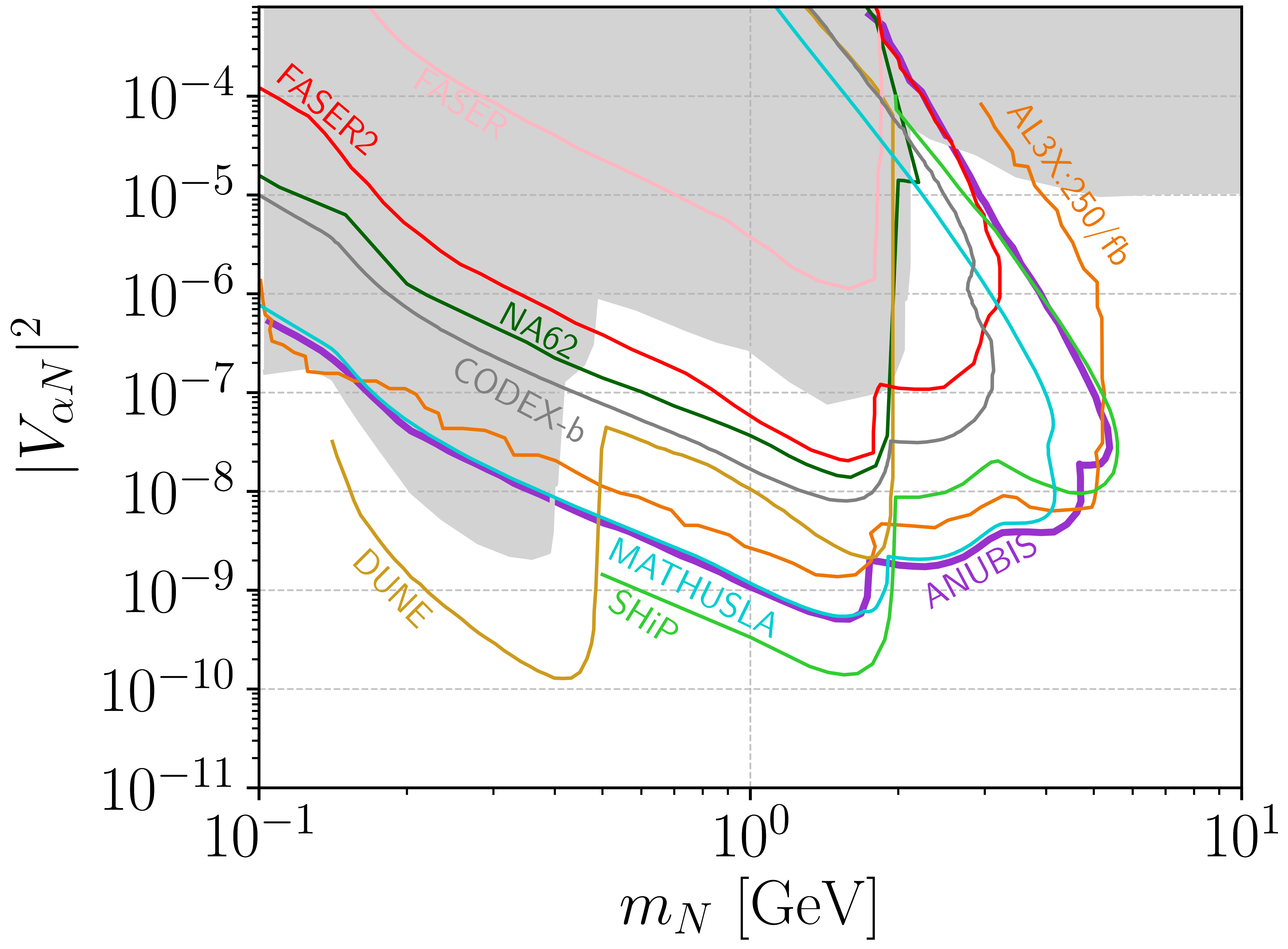
- Mathusla: higher sensitivity for long lifetimes

Mathusla Updated LoI: 2009.01693

Sensitivity — neutral LLPs @ LHC HNLs

$\alpha = e, \mu$

$V_{\alpha N_j} \propto \sqrt{m_\nu / m_N}$

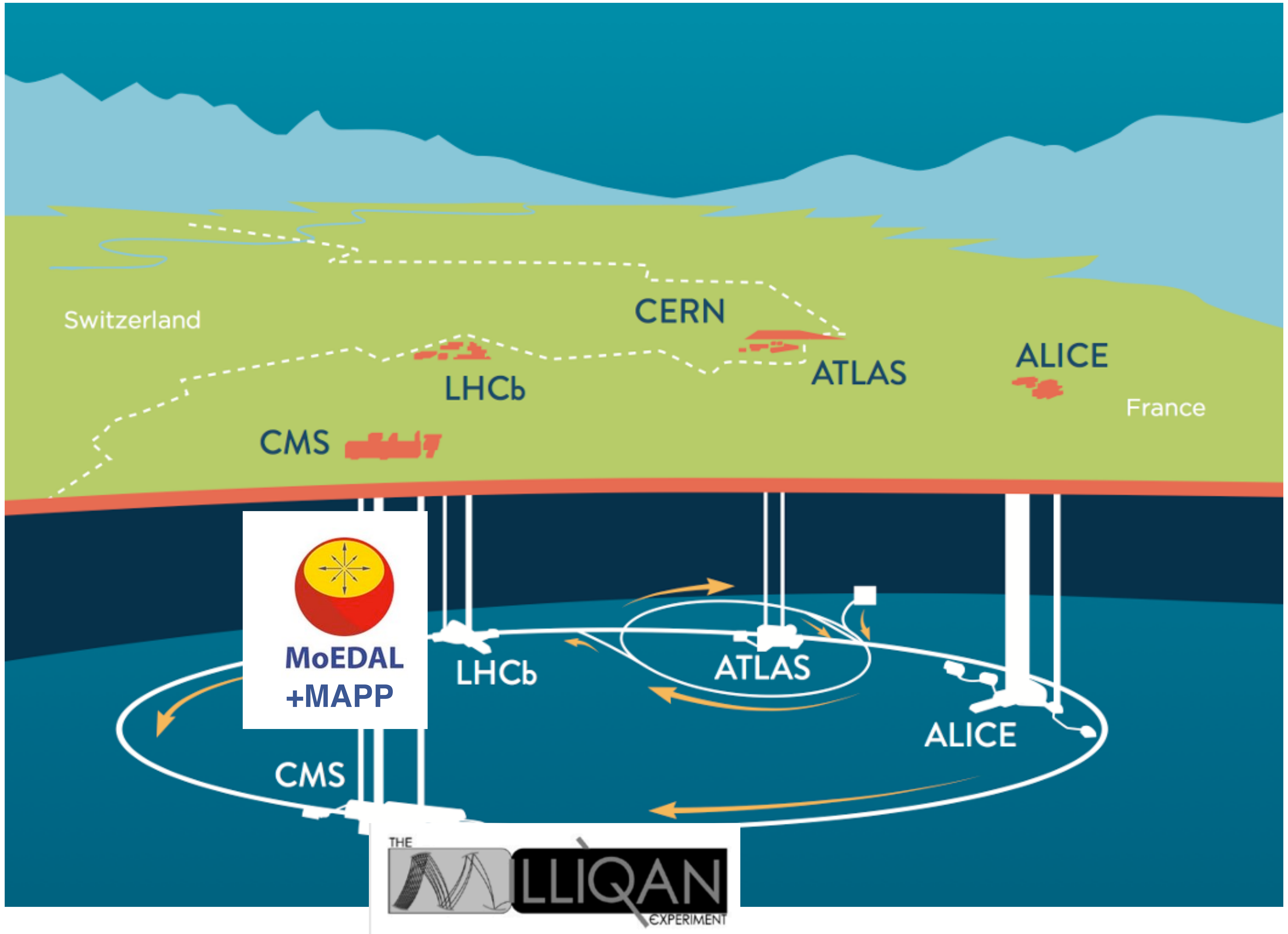


2001.04750

CODEX-b 300/fb
MATHUSLA 3/ab
ANUBIS shaft only 3/ab
FASER 3/ab
SHiP 2×10^{20} protons on target

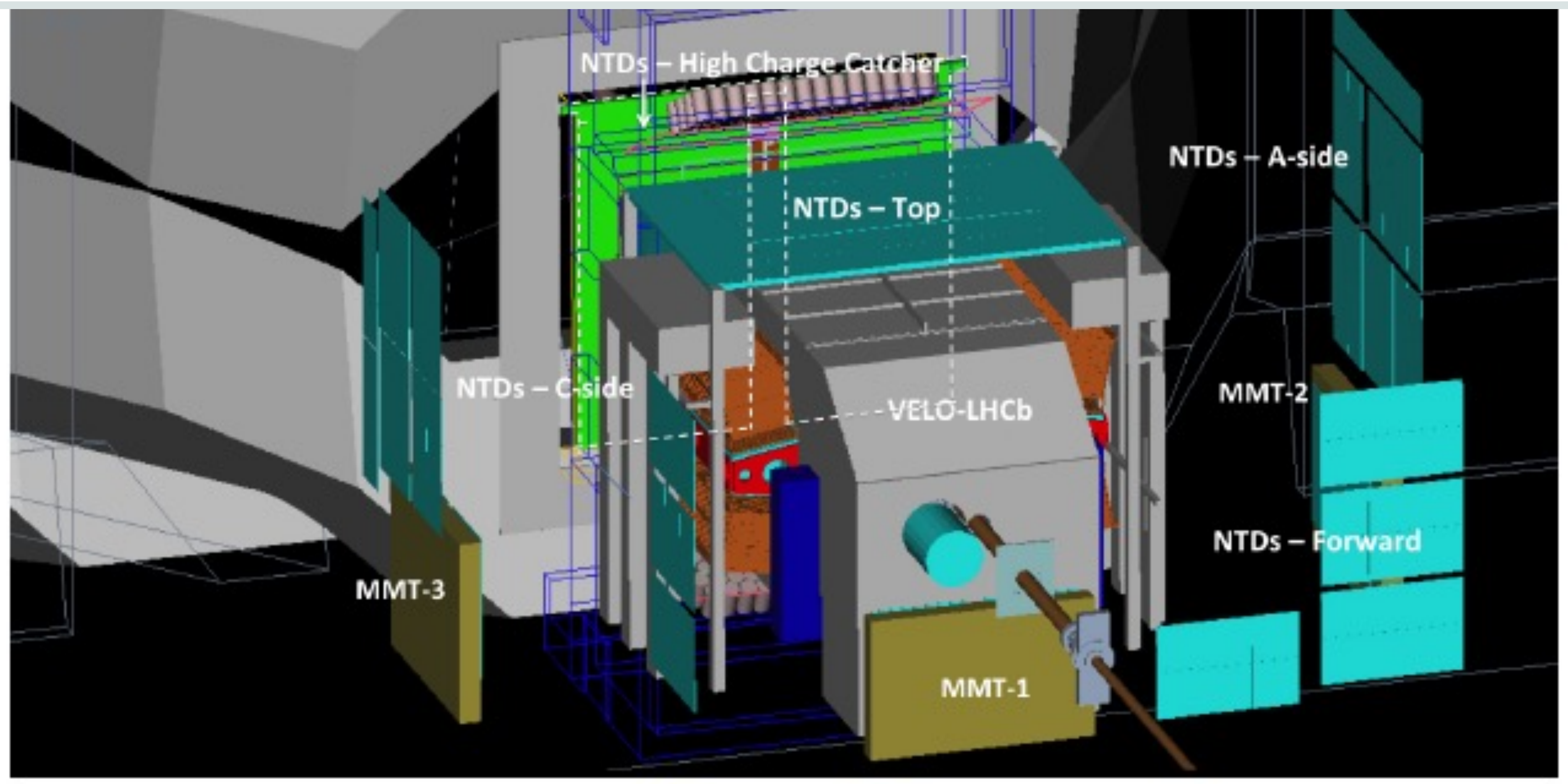
- SHiP covers most of the space
- MATHUSLA, ANUBIS, AL3X better at masses > 1 GeV
- Complementarity between forward and transverse detectors!

Charged LLPs @ transverse LHC experiments

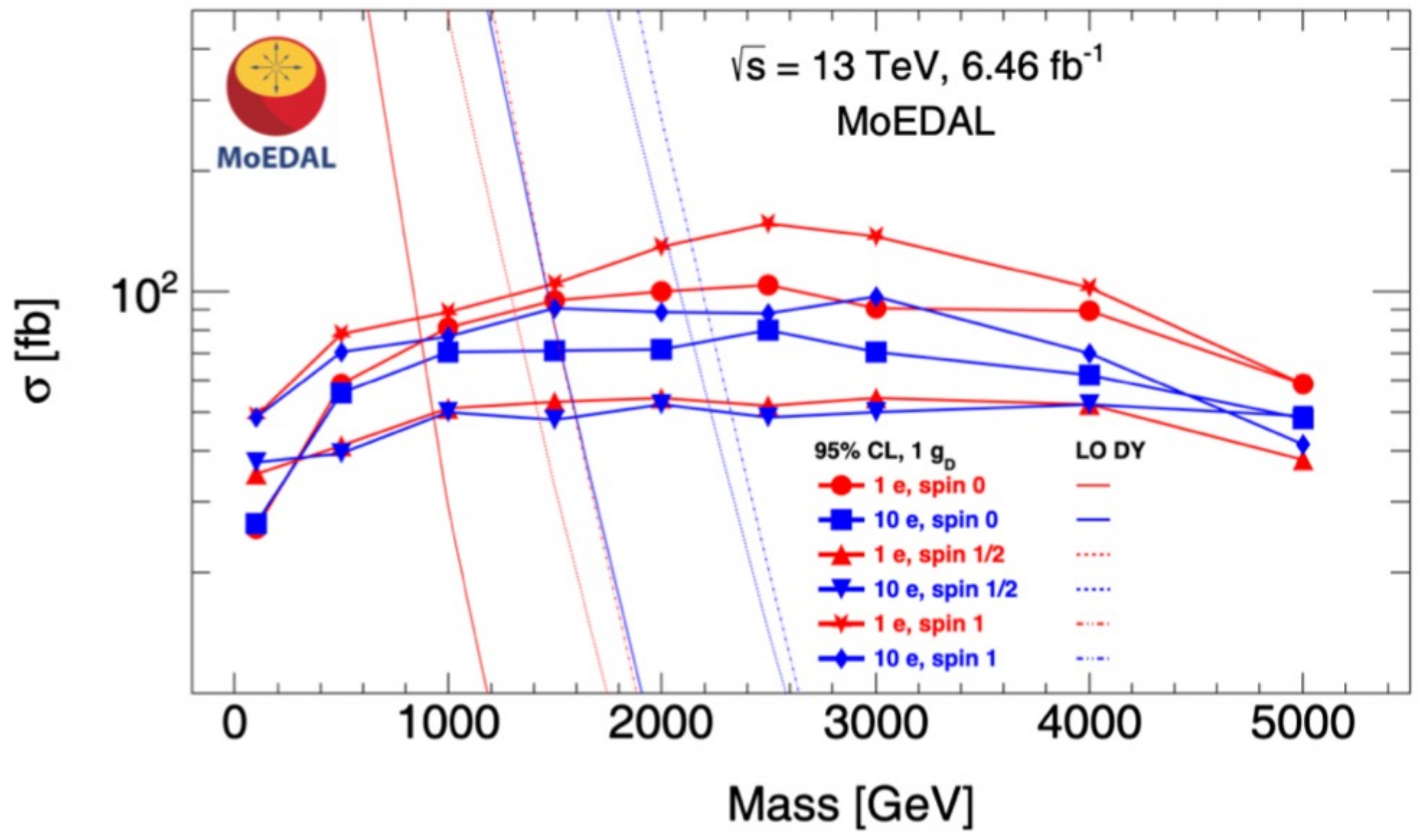


Moedal

- Located at LHCb cavern, approved in 2010
- Target: highly ionizing particles, magnetic monopoles, massive pseudo-stable charged particles (sleptons, R-hadrons) , …
  - Magnetic Monopole traps
    - bind a magnetically charged particles with an energy of 0.5 - 2.5 MeV and capture it inside the atomic lattice
  - Nuclear Track Detectors: when a HIP passes through the NTD, it creates an invisible damage along its track

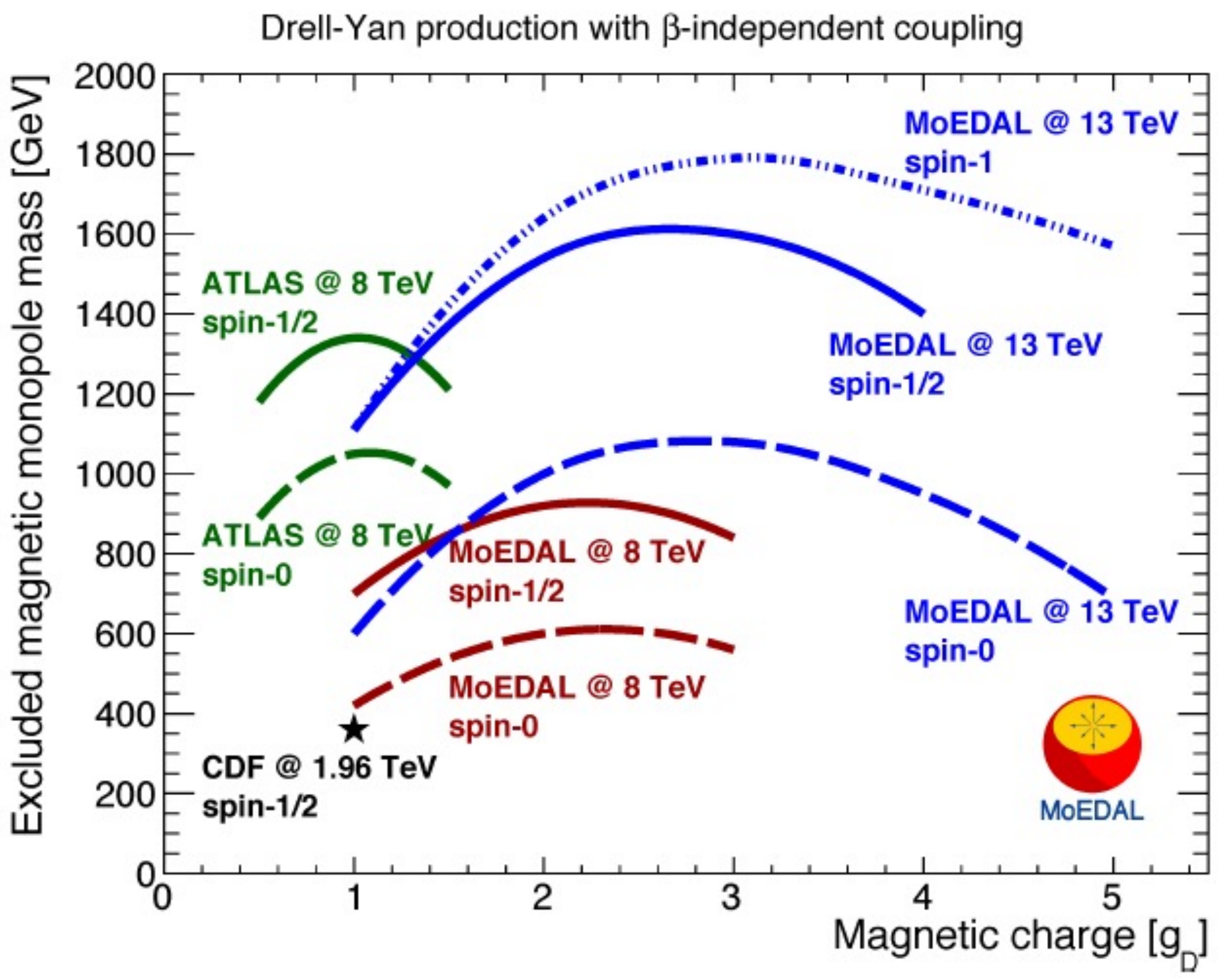


- Plans for future (~forward):
- MAPP (Run3): for detecting milli charged particles (0.001e)
- MALL: for detecting charged, very long-lived particles



PhysRevLett.126.071801

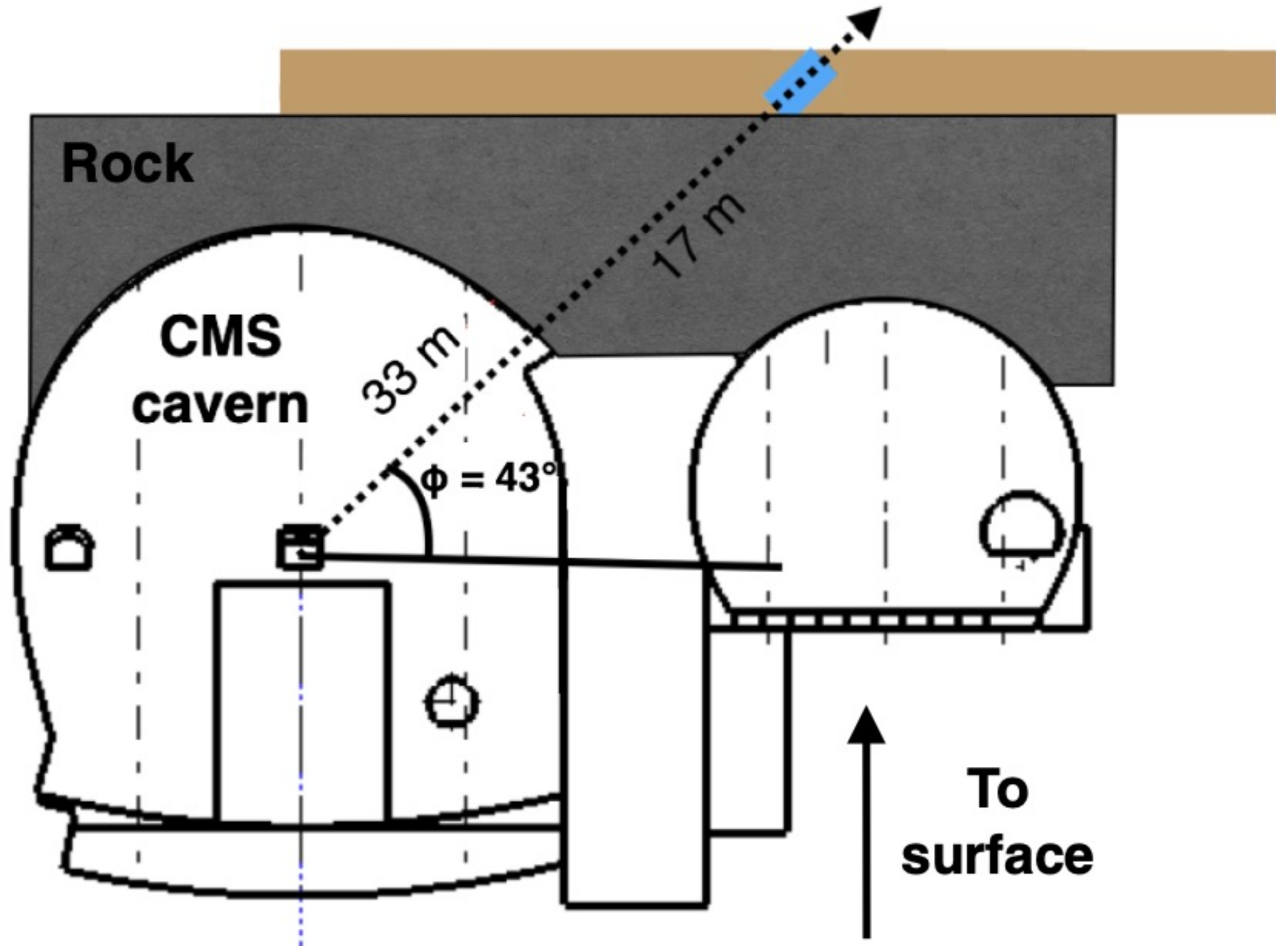
- First search for Dyons in Moedal



PhysRevLett.123.021802

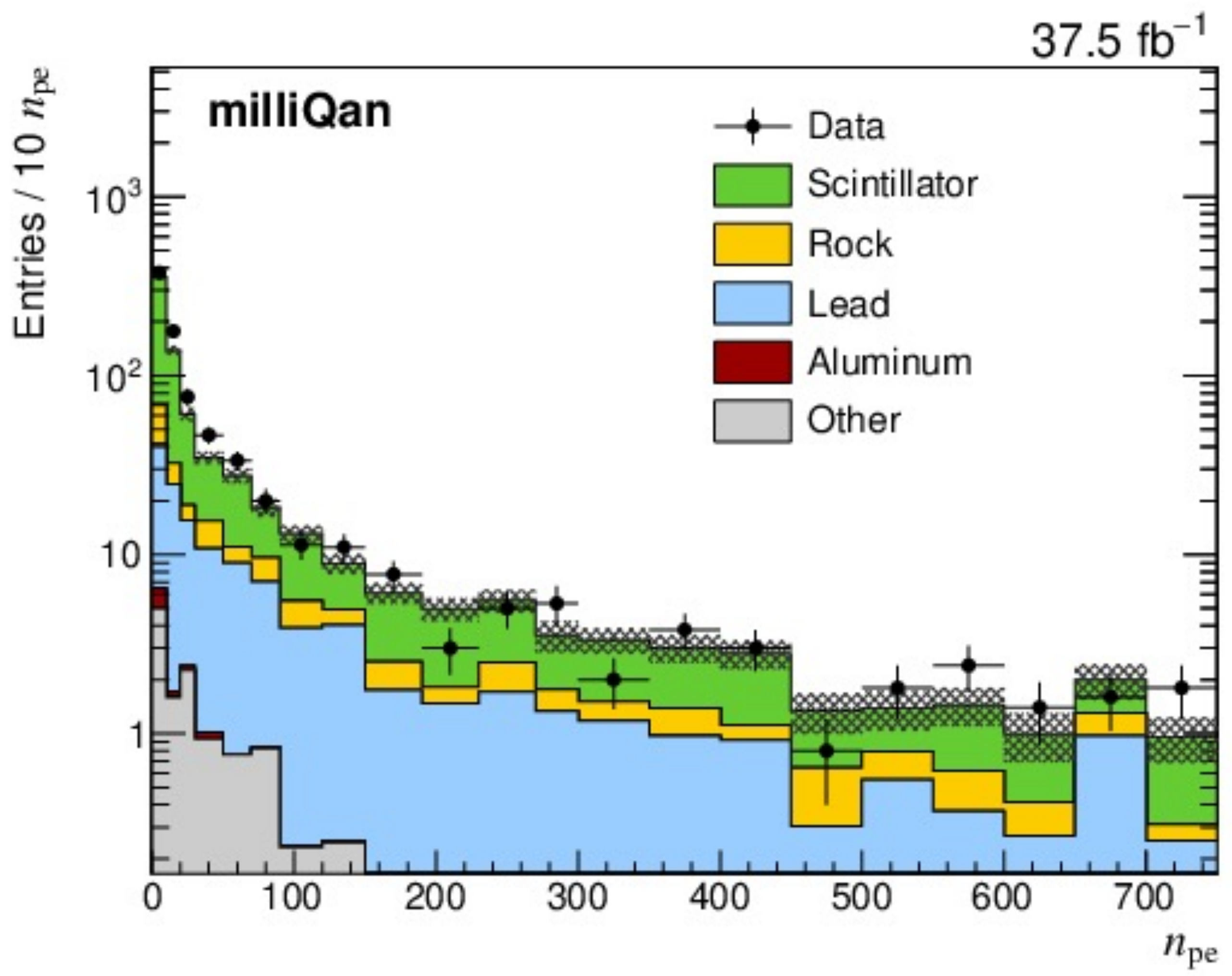
- Moedal's results for monopoles: leading mass limits

[2104.07151v1](2104.07151v1)
[1607.04669](1607.04669)

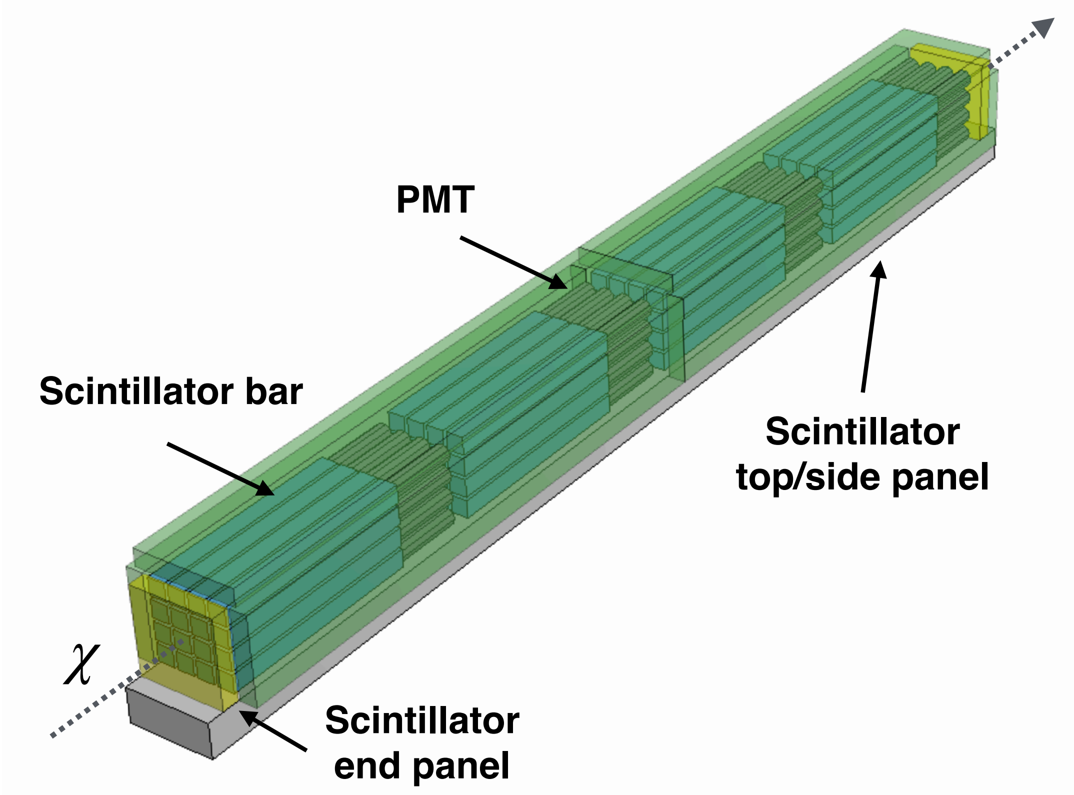


- Target Millicharged particles in dark QED with mass O(GeV)
- 70m underground (shielded from cosmics) and 33m from CMS IP (17m of rock, shiel from LHC)
- Scintillator bars + PMTs allow small ionisation signal from mCPs to be detected

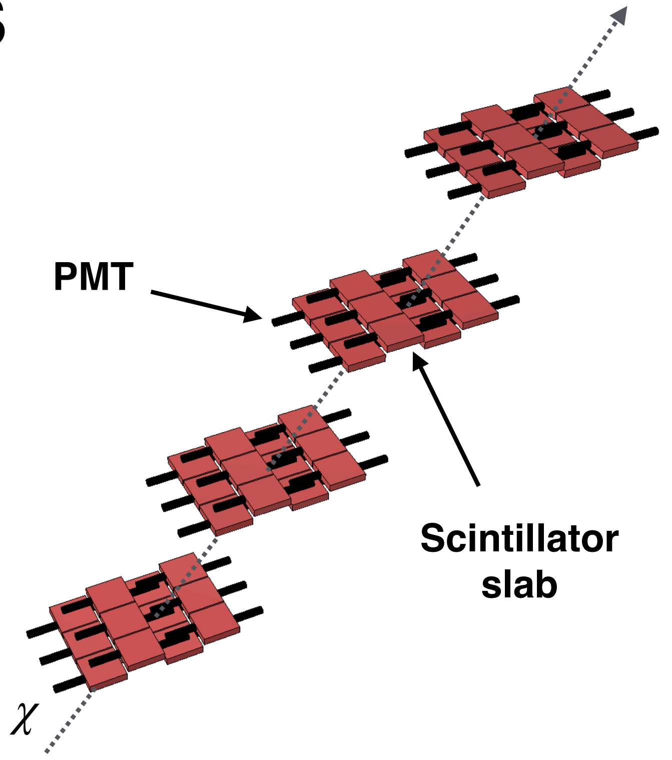
- Prototype took data in 2018 (~1% of full detector), confirmed background expectatior



- Two detectors for Run 3
  - Bar detector (upgrade from milliQan demonstrator)
    - 0.2 m x 0.2 m x 3 m plastic scintillators bars
    - Background estimation validated with demonstrator

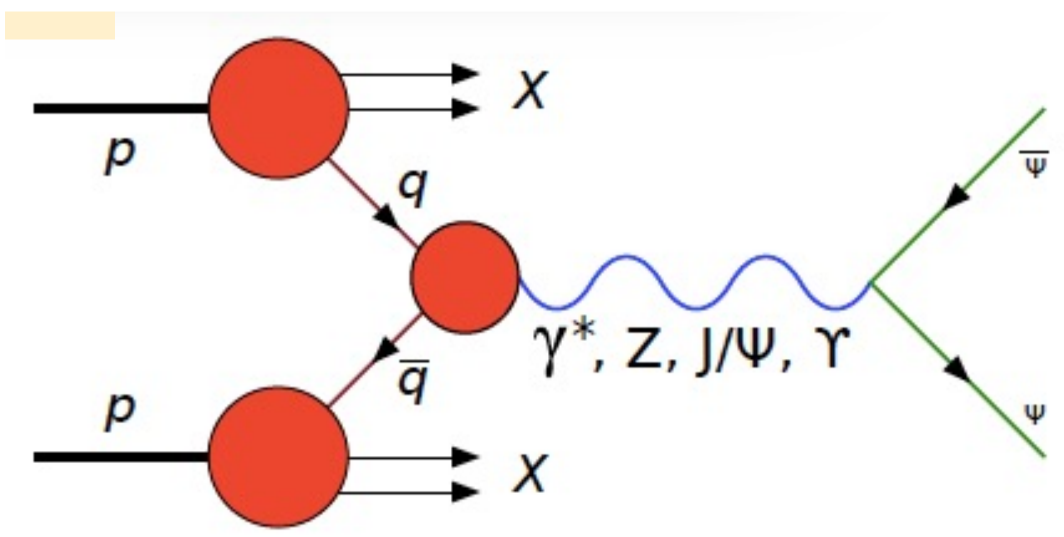


- Slab detector
  - 40 cm x 60 cm x 5 cm scintillator slabs
  - Helps with background rejection
  - Increased reach for heavier mCPs



Comparison of sensitivity — charged LLPs @ LHC

- Milli-charged particles, mCPs:
  - New massless U(1) gauge field of a dark photon A' and massive fermion ψ (mCP)
  - mCP is charged under hyper charge with a fractional charge, proportional to the kinetic mixing, ε
- MilliQan (and Moedal-MAPP) will significantly improve current limits
- mCPs generated over broad spectrum of production modes
- Slab detector drives sensitivity in acceptance limited regions
- Combination Bar+slab detectors increases reach!



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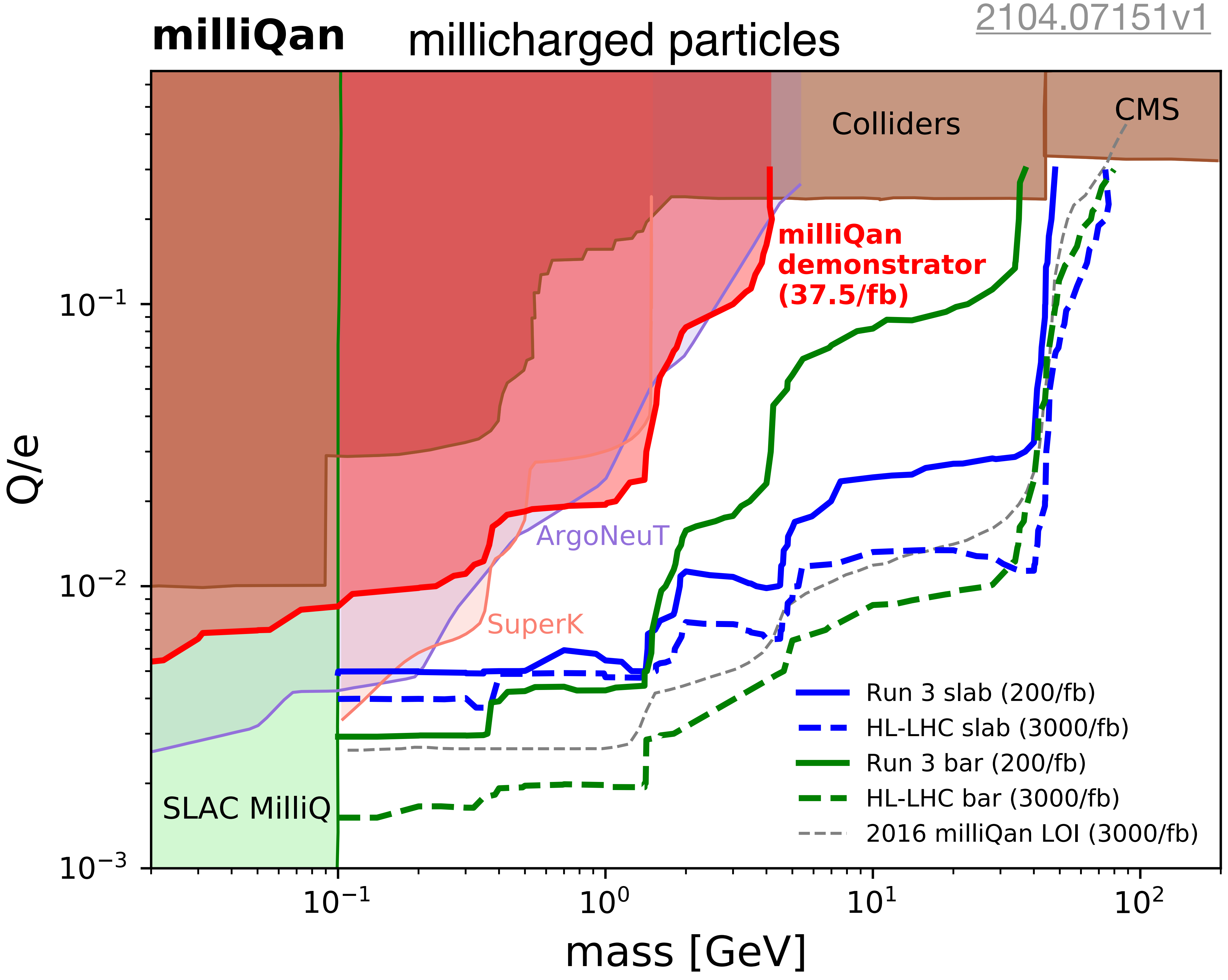

Comparison of sensitivity — charged LLPs @ LHC

M. Staelens, PhD thesis, U.Alberta

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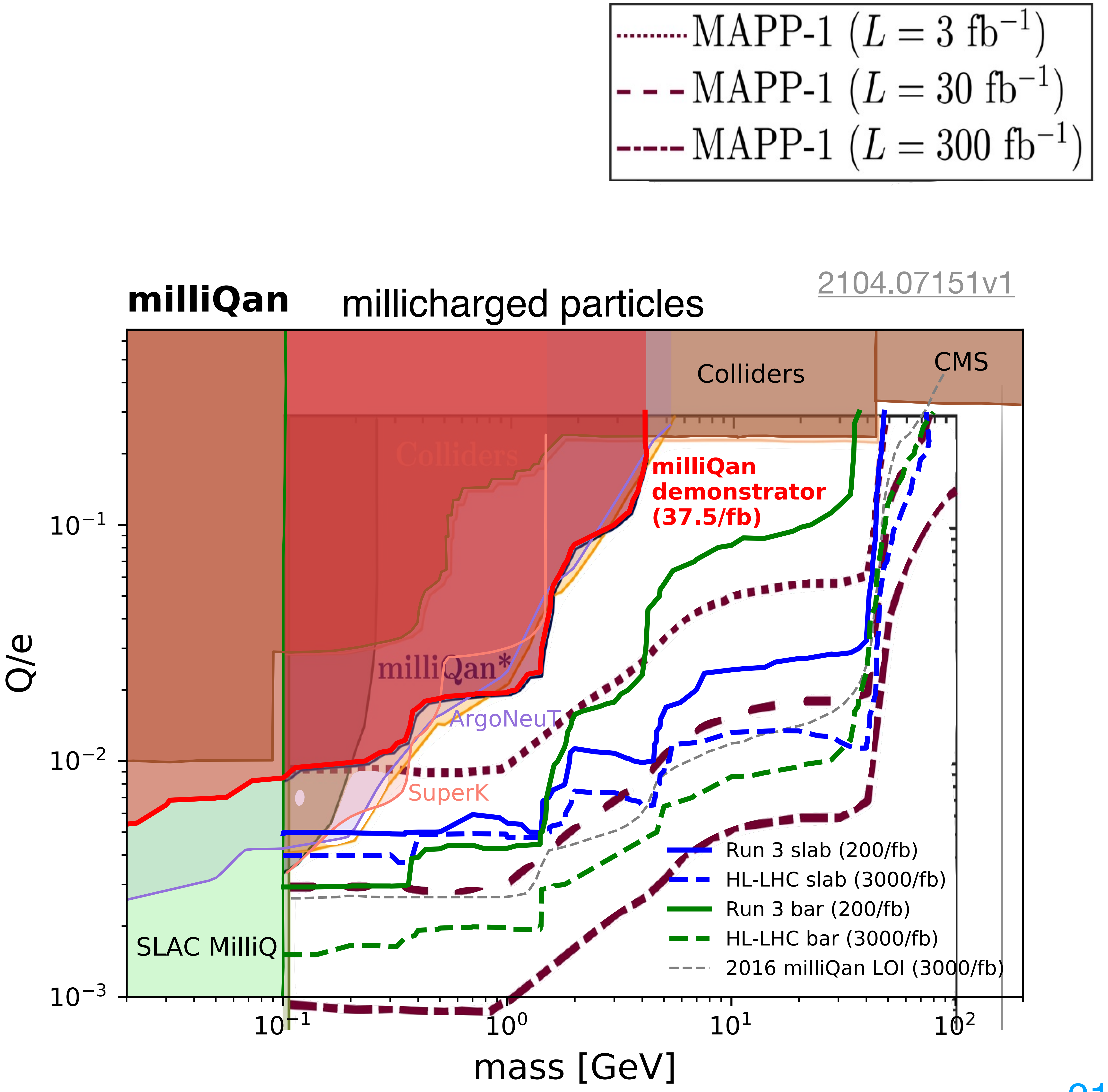
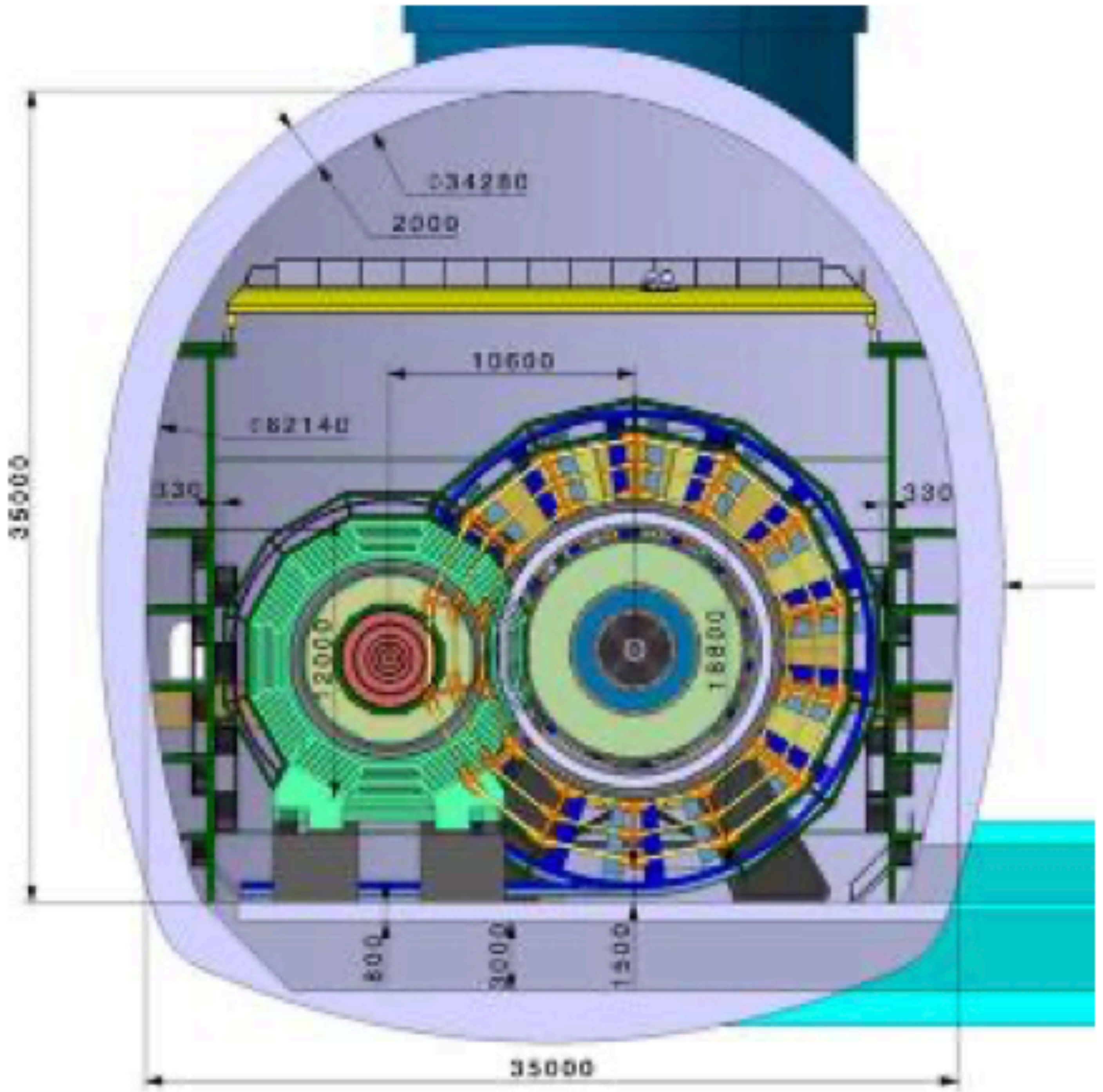


LLPs @ FCC-hh, FCC-ee

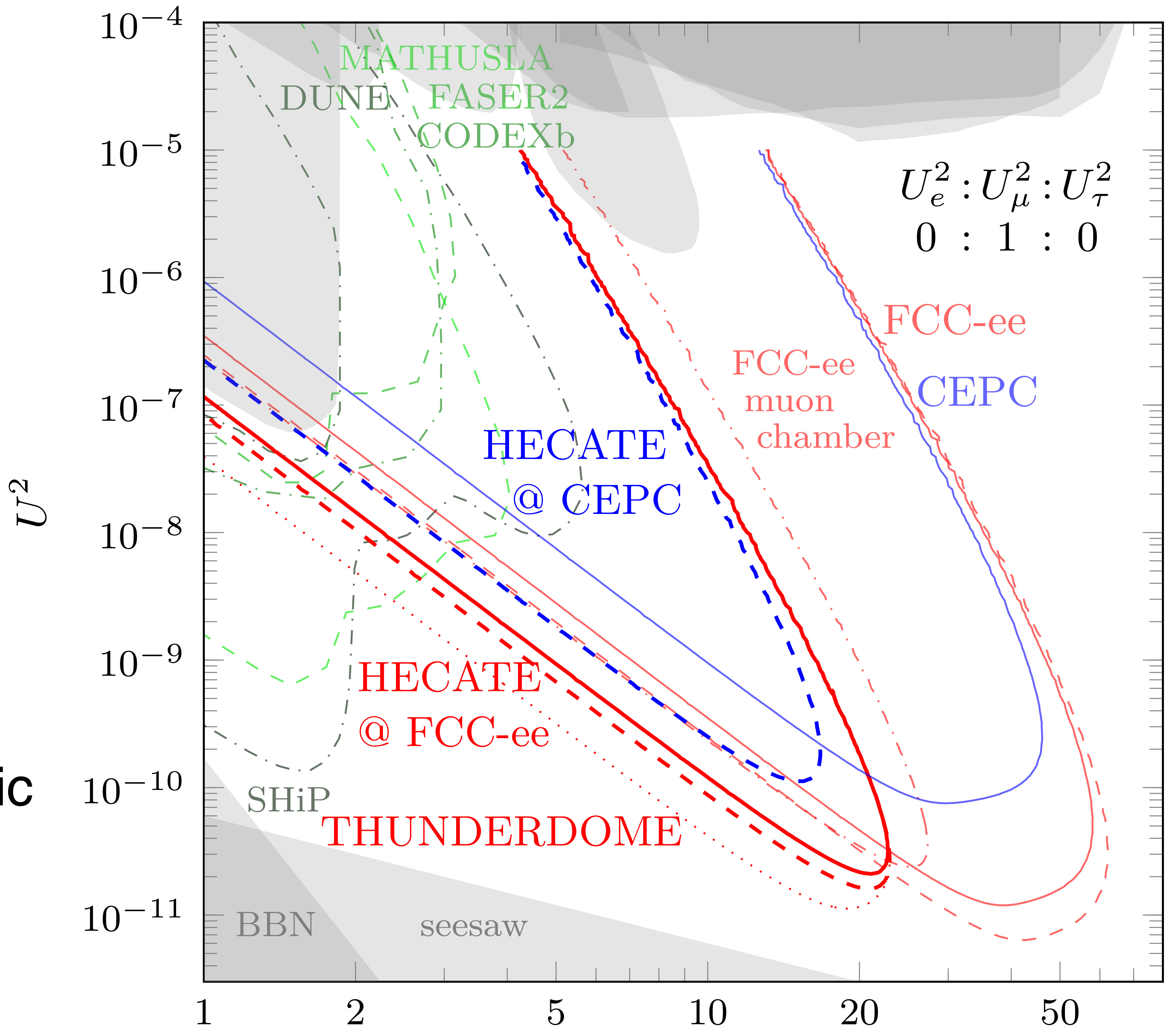
Proposal: 2011.01005

HECATE: HErmetic CAvern TrackER. A long-lived particle detector concept for FCC-ee or CEPC

- 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 m² separated by a sizeable distance — timing
  - >= 4 layers for good tracking
  - 4**π** coverage LLP detector
- FCC main detector as active veto
- Sensitive to a unique area of phase space



- Cavern size: r~15 m and z~50 m
- Main detector size =(10m)



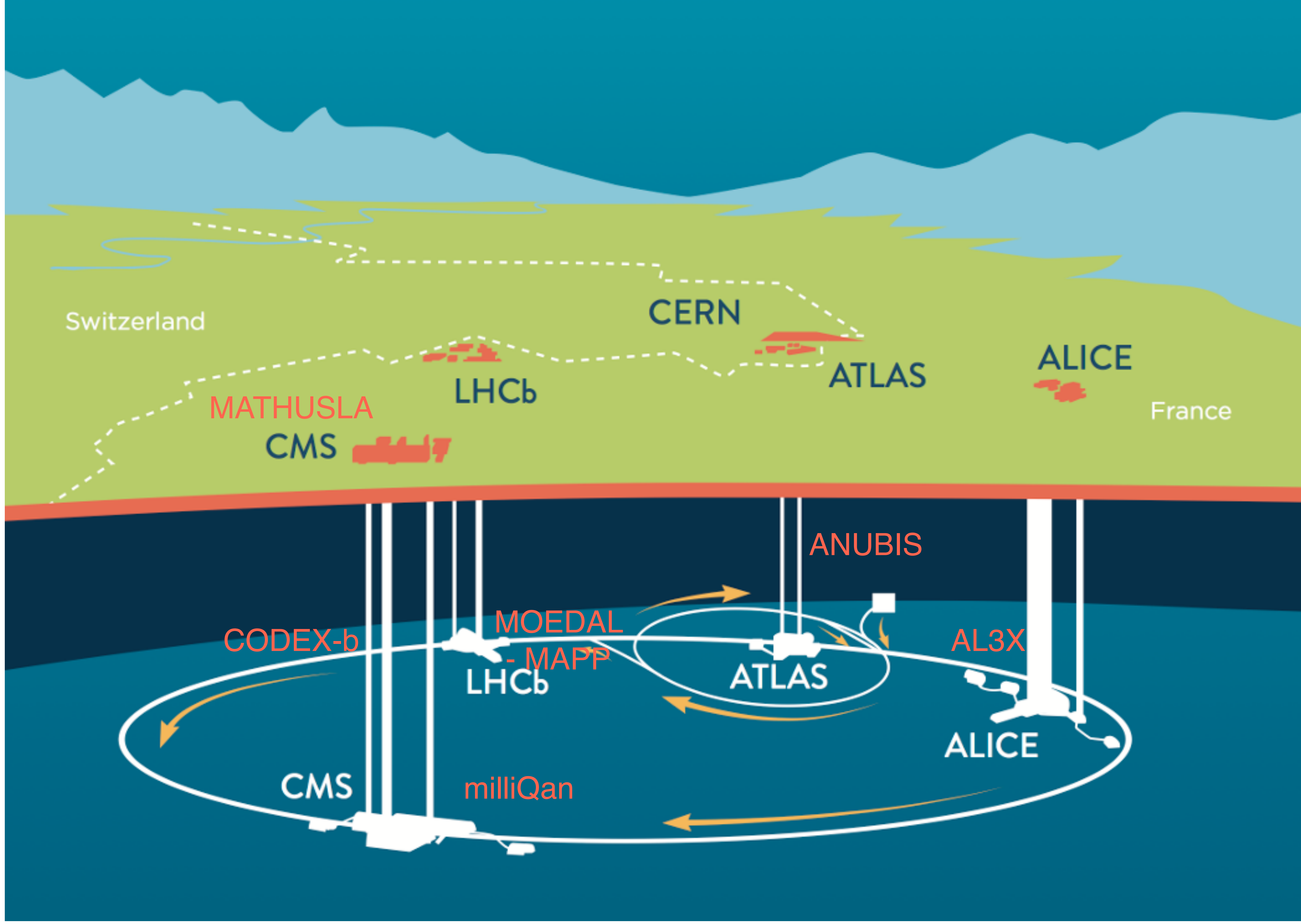
- Example: HNLs
  - THUNDERDOME: Totally Hyper-UNrealistic DEtectoR in a huge DOME (maximum distance from IP=100m for comparison)

Conclusion

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

- Many ideas for dedicated LLP detectors!
- Dedicated transverse LLP are a relatively cheap way to explore a large region of the parameter space
- Complementarity among different detectors (also forward)

- Most of the current proposed experiments are aiming for data collection in HL-LHC



  - For the future FCC….
    - FCC could probe a large part of the LLP parameter space
    - Would be good to include LLPs in the main physics program when the main detectors are designed