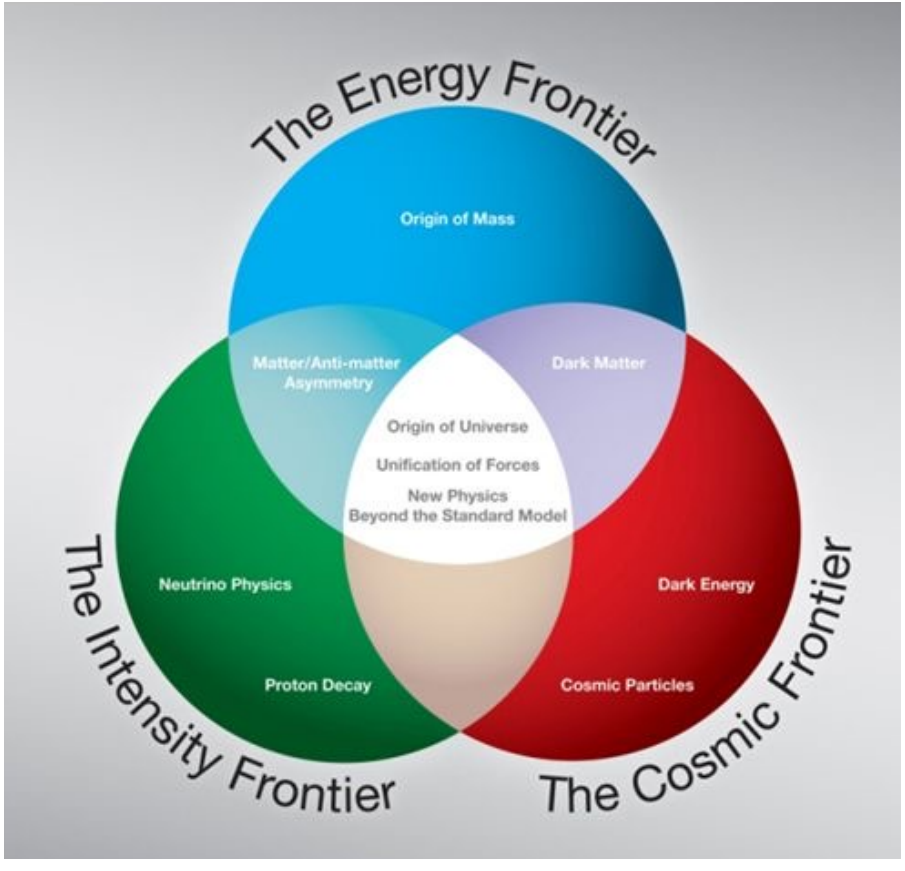
Dedicated experiments for feebly interacting particles

(@ LHC mostly…)

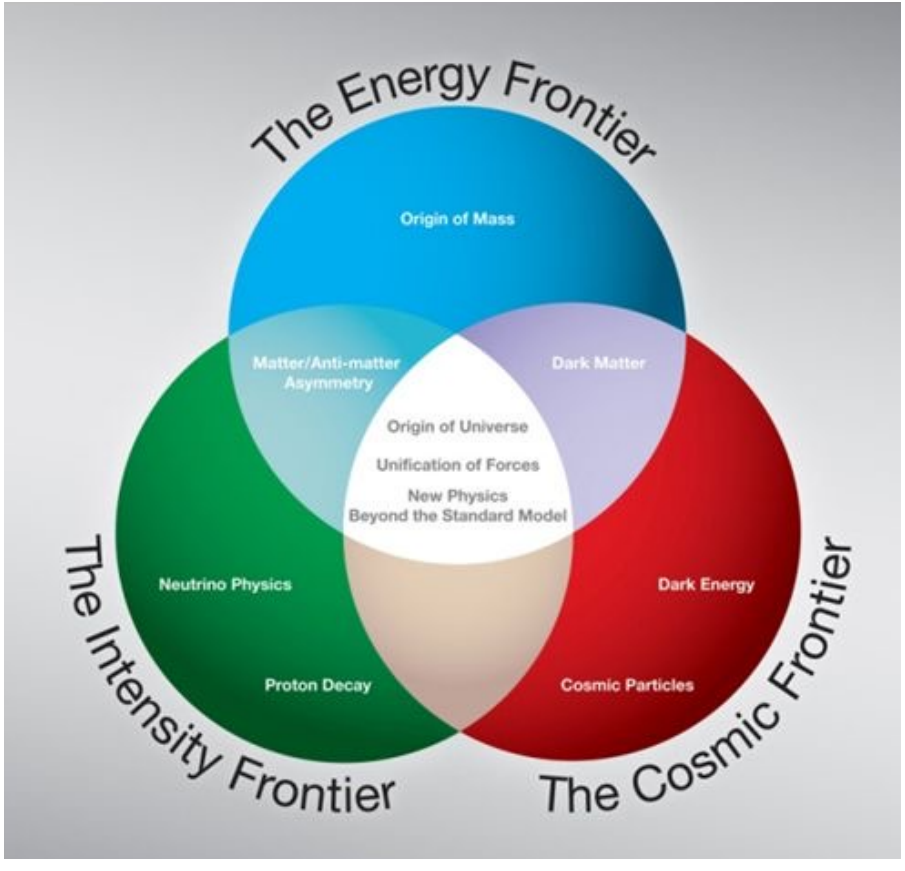
Vasiliki A. Mitsou

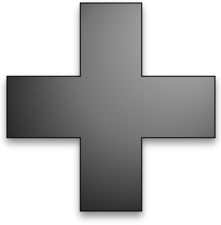
HEP2023 – 40th Conference on Recent Developments in High Energy Physics and Cosmology
5–8 April 2023, Ioannina, Greece

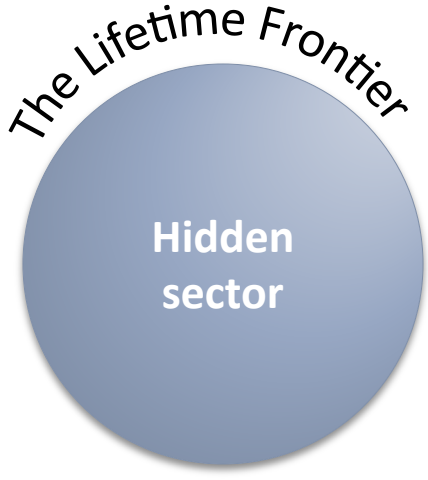
The three frontiers



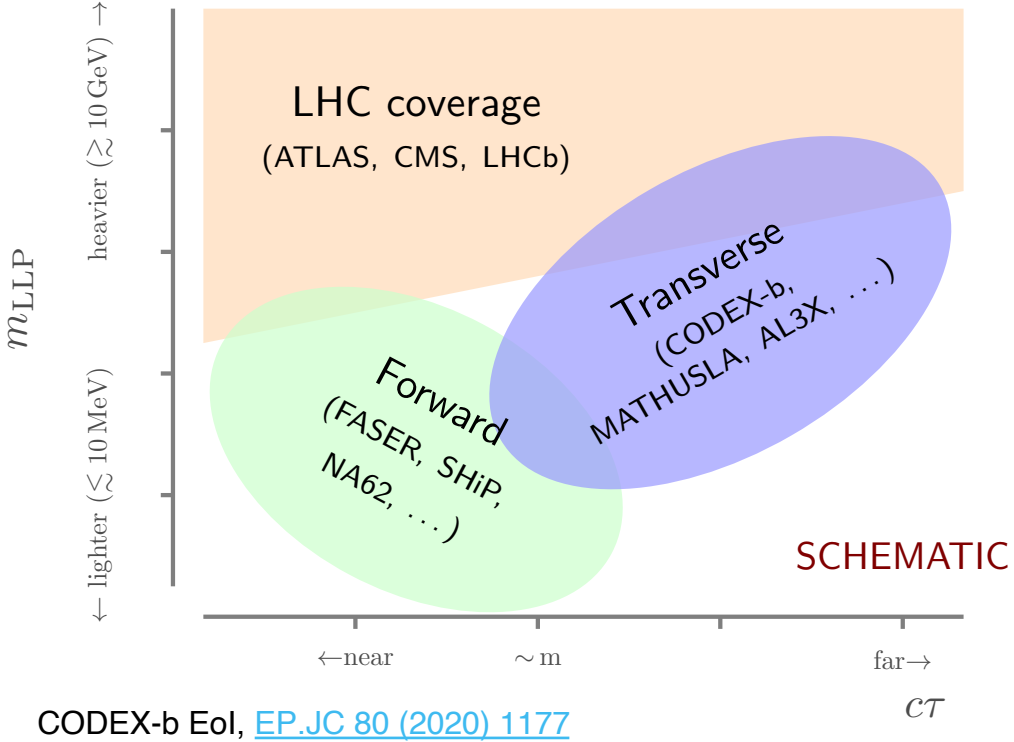
The ~~three~~ *four* frontiers







The lifetime frontier

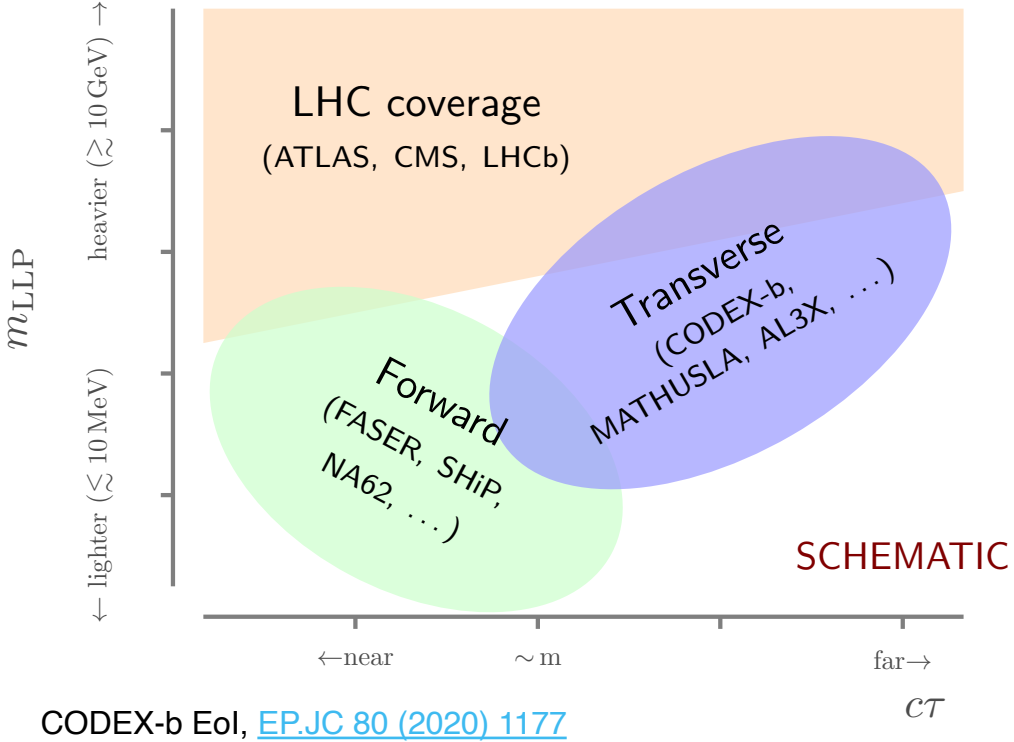


CODEX-b EoI, EP.JC 80 (2020) 1177

- ATLAS, CMS and LHCb mainly optimised for new particles that decay *promptly* ⇒ *strongly coupled*
- Development of new trigger/reconstruction/analysis strategies allow also probing new *long-lived* particles
- Variety in signatures and lifetime range require designing and building dedicated experiments for long-lived BSM particles

☞ John Strologas's & Stelios Angelidakis's talks on CMS & ATLAS results

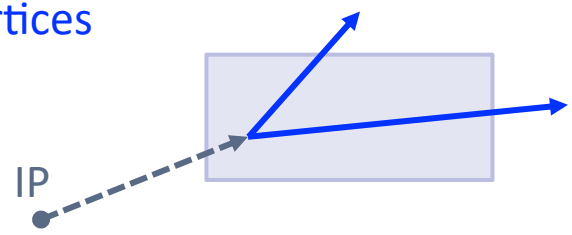
The lifetime frontier



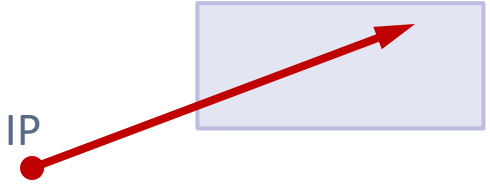
CODEX-b EoI, EP.JC 80 (2020) 1177

* Strong interest in **highly ionising states**, too.
Not the focus of this talk.

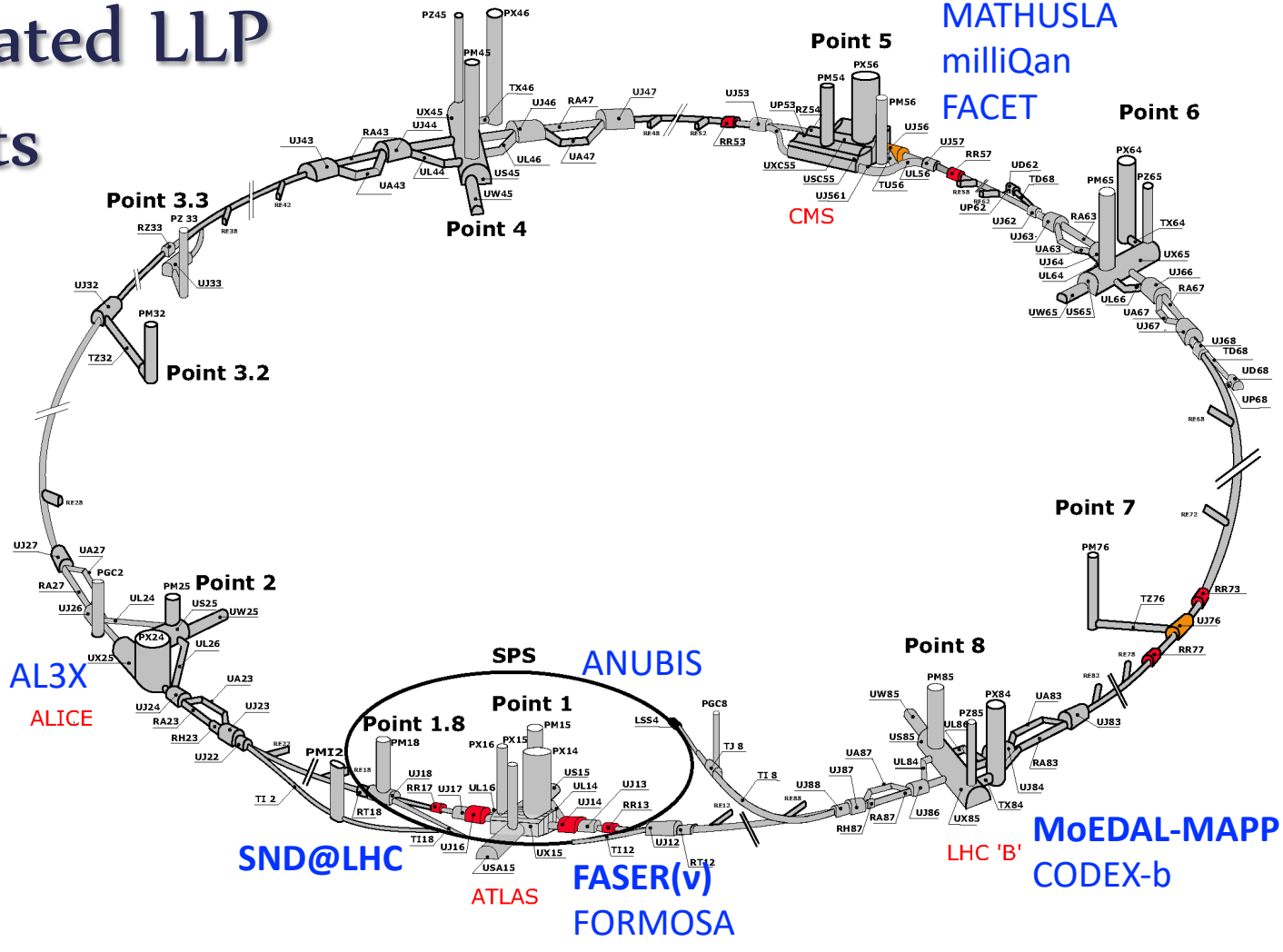
LLPs may be neutral and decay to visible particles ➜ displaced vertices



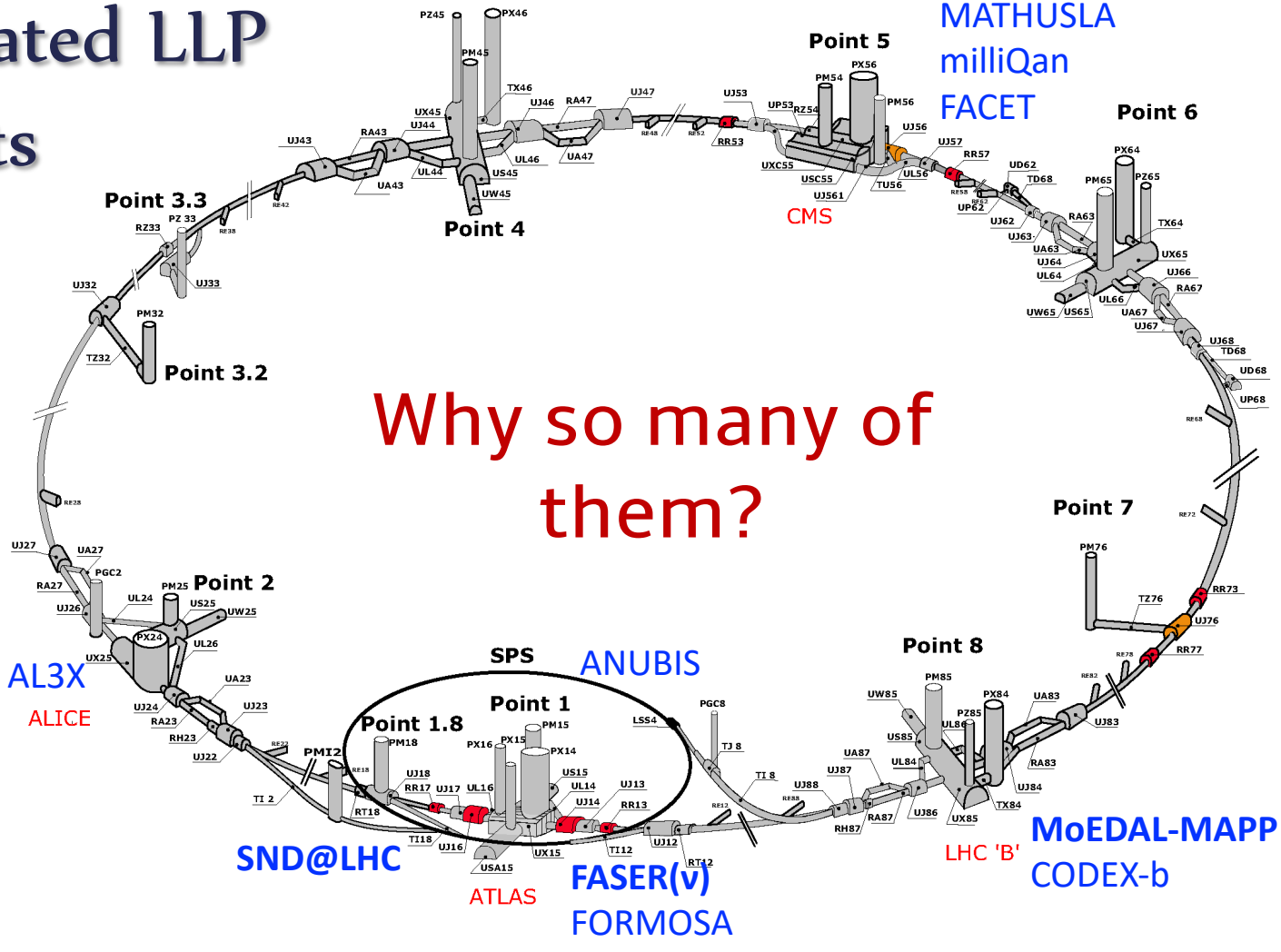
LLPs may induce anomalous ionisation*, e.g. millicharged particles ($Q \sim 10^{-3}e$)



LHC dedicated LLP experiments

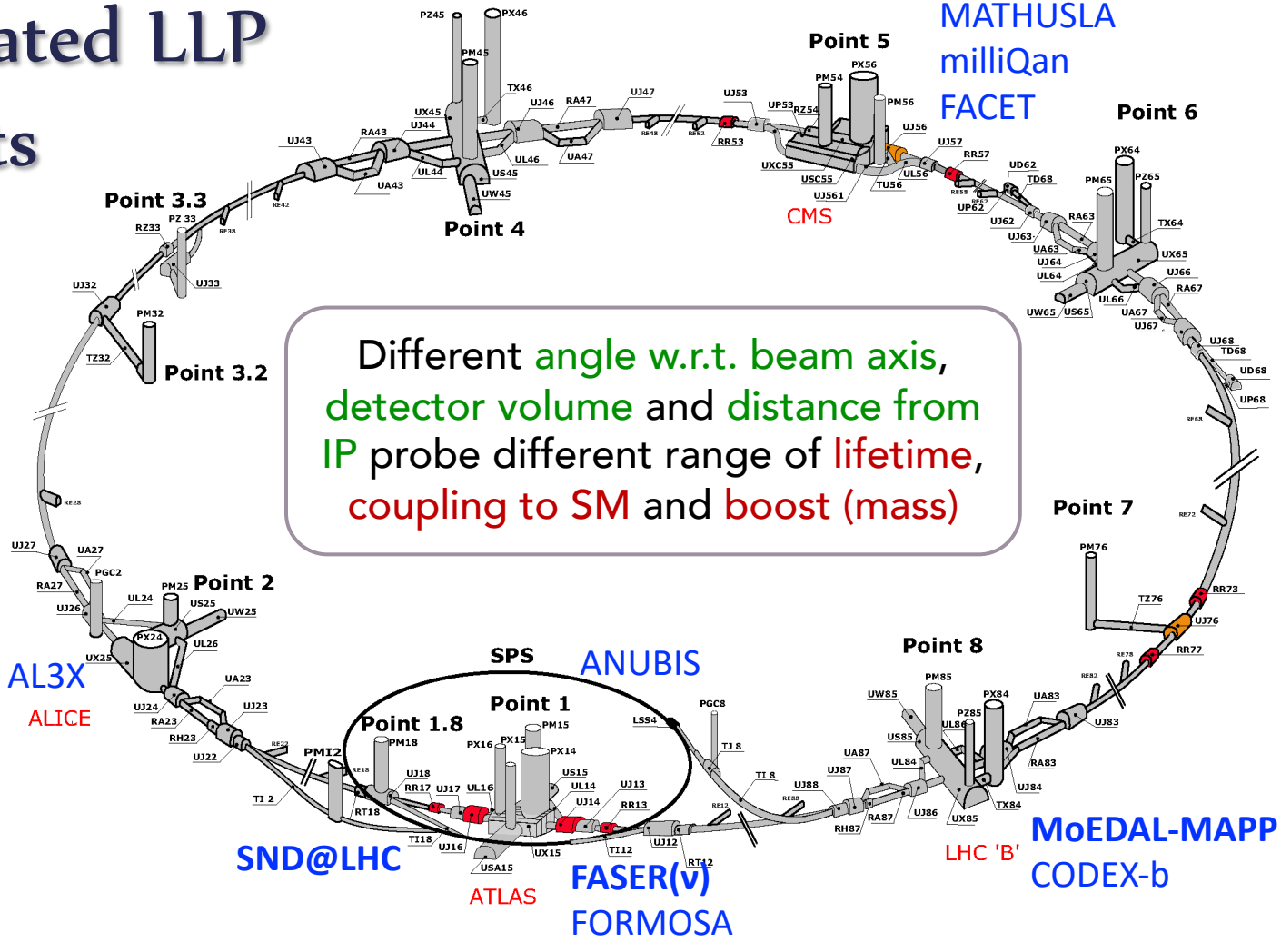


LHC dedicated LLP experiments



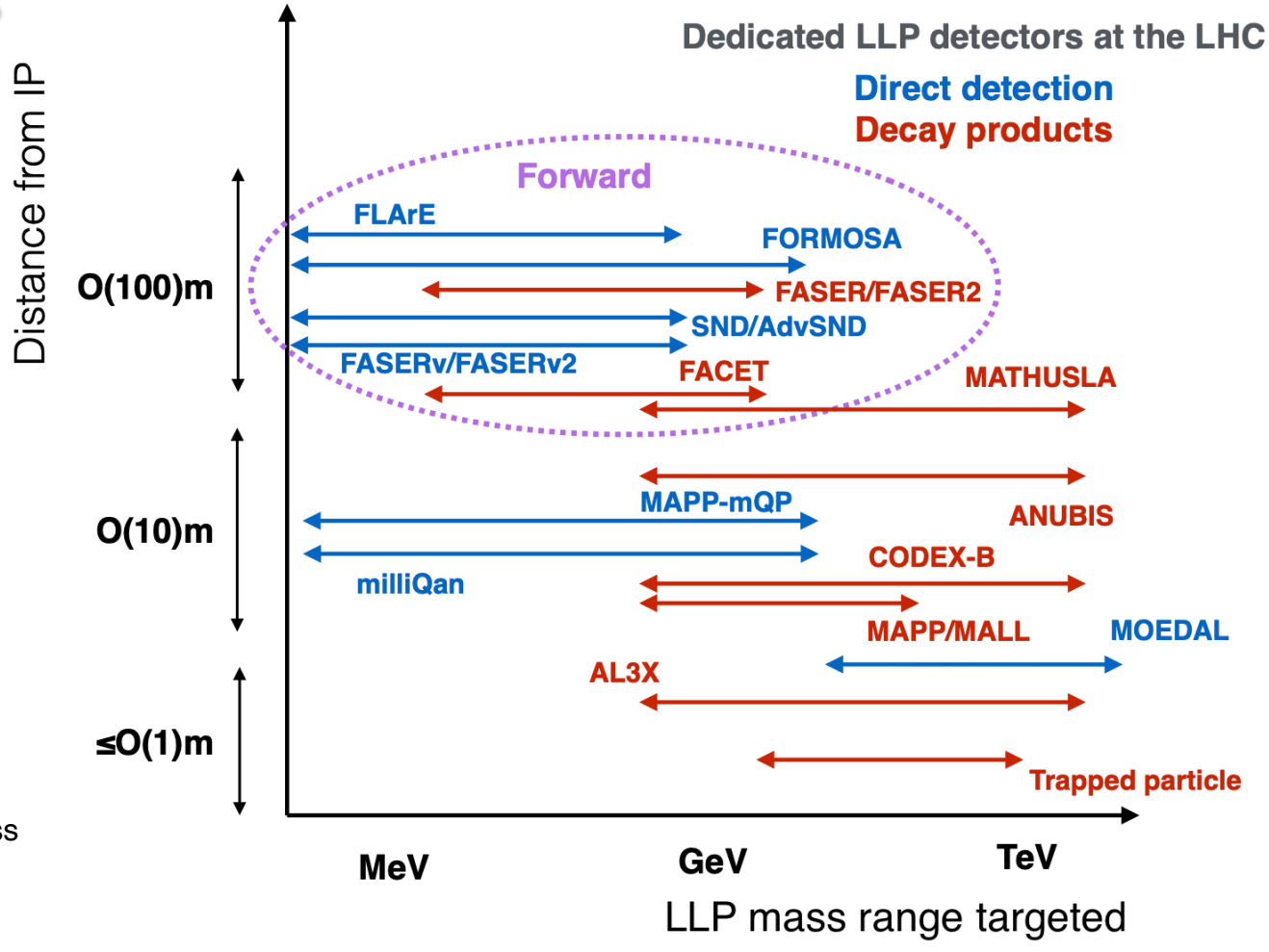
Why so many of them?

LHC dedicated LLP experiments



Different angle w.r.t. beam axis, detector volume and distance from IP probe different range of lifetime, coupling to SM and boost (mass)

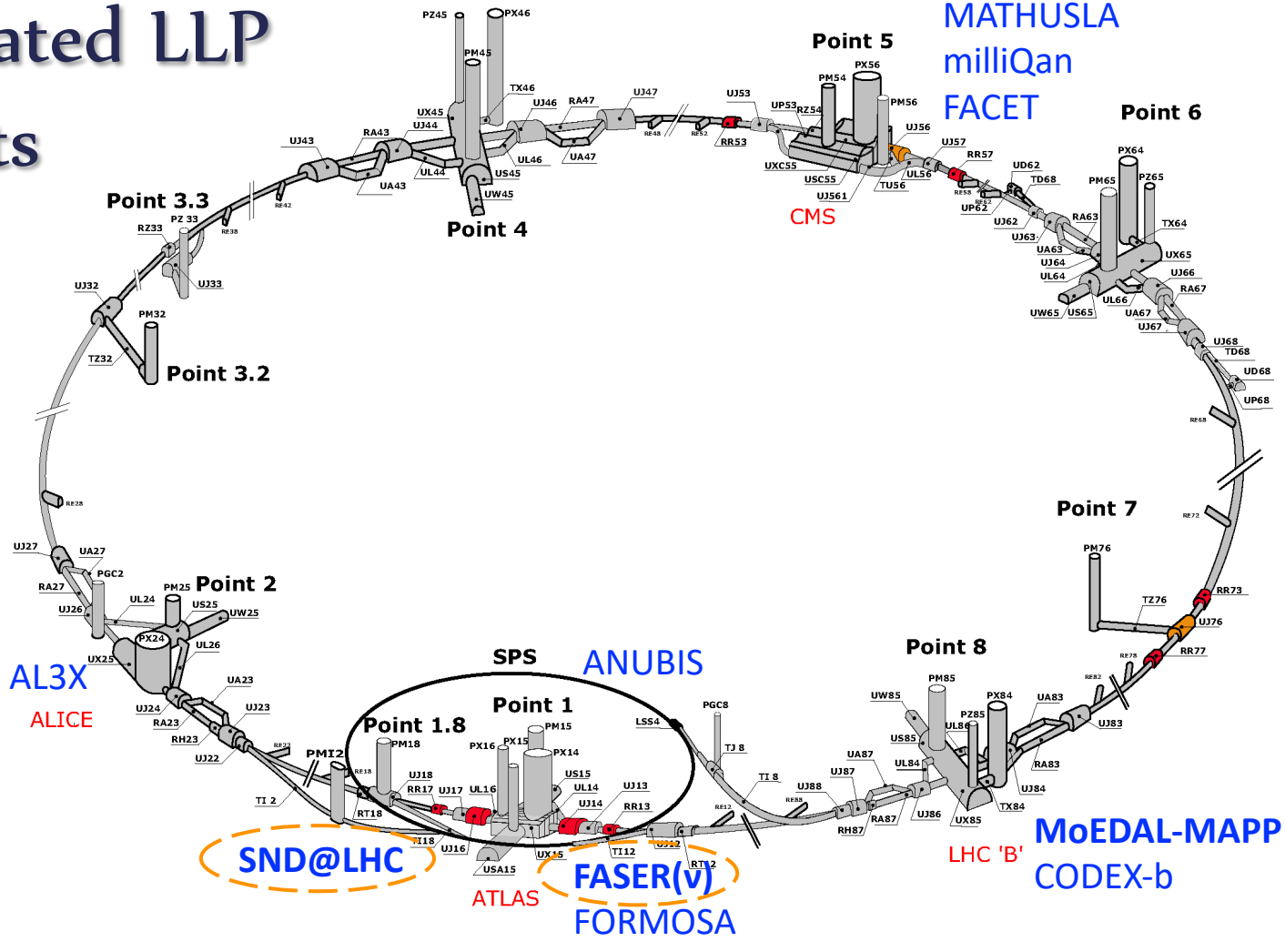
Lifetime–mass summary



Plot by Matthew Citron.
BSM Energy Frontier Snowmass Report, arXiv:2209.13128

LHC dedicated LLP experiments

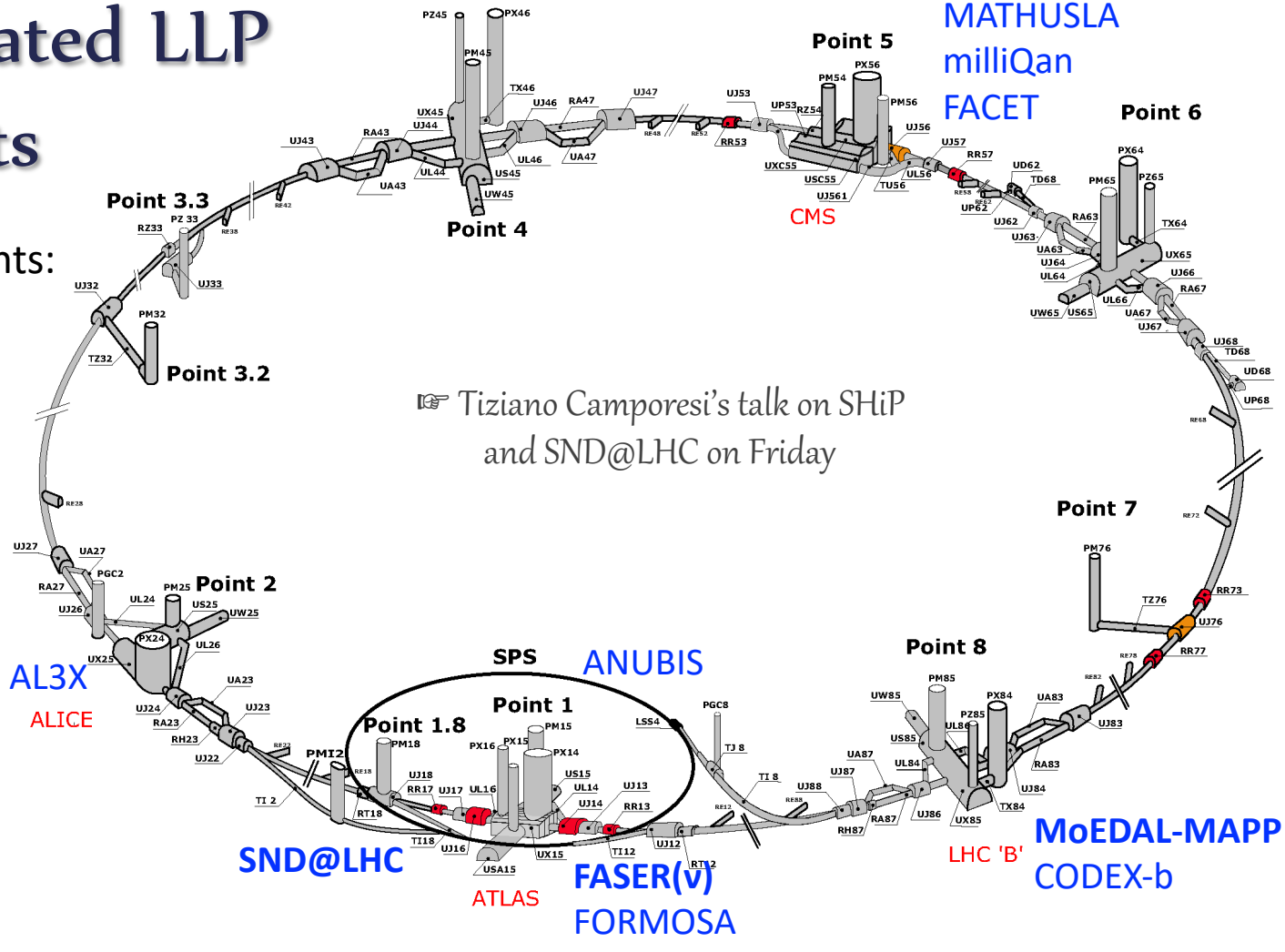
Some of these experiments also measure **neutrinos** produced in colliders



LHC dedicated LLP experiments

Non-LHC experiments:

- SHiP
- NA48/2
- NA62
- NA64
- SHADOWS
- SeaQuest
- LUXE
- Solid
- GAZELLE
- HECATE
- SUBMET
- …

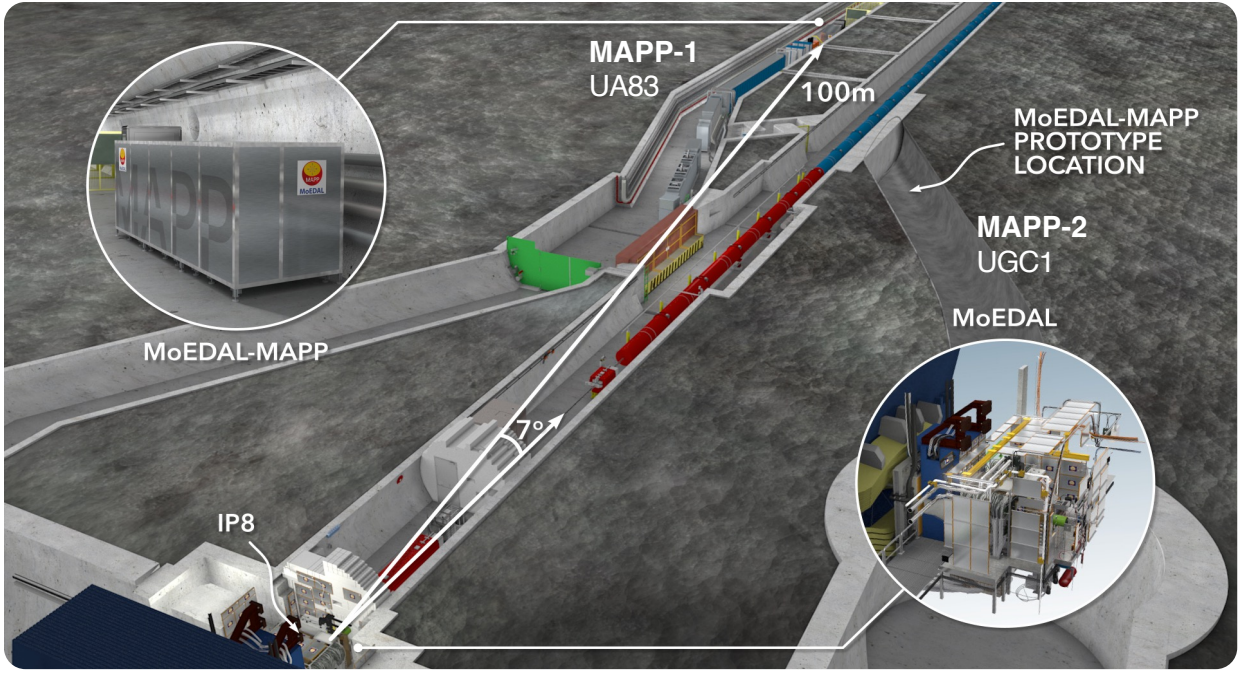


MAPP: MoEDAL Apparatus for Penetrating Particles

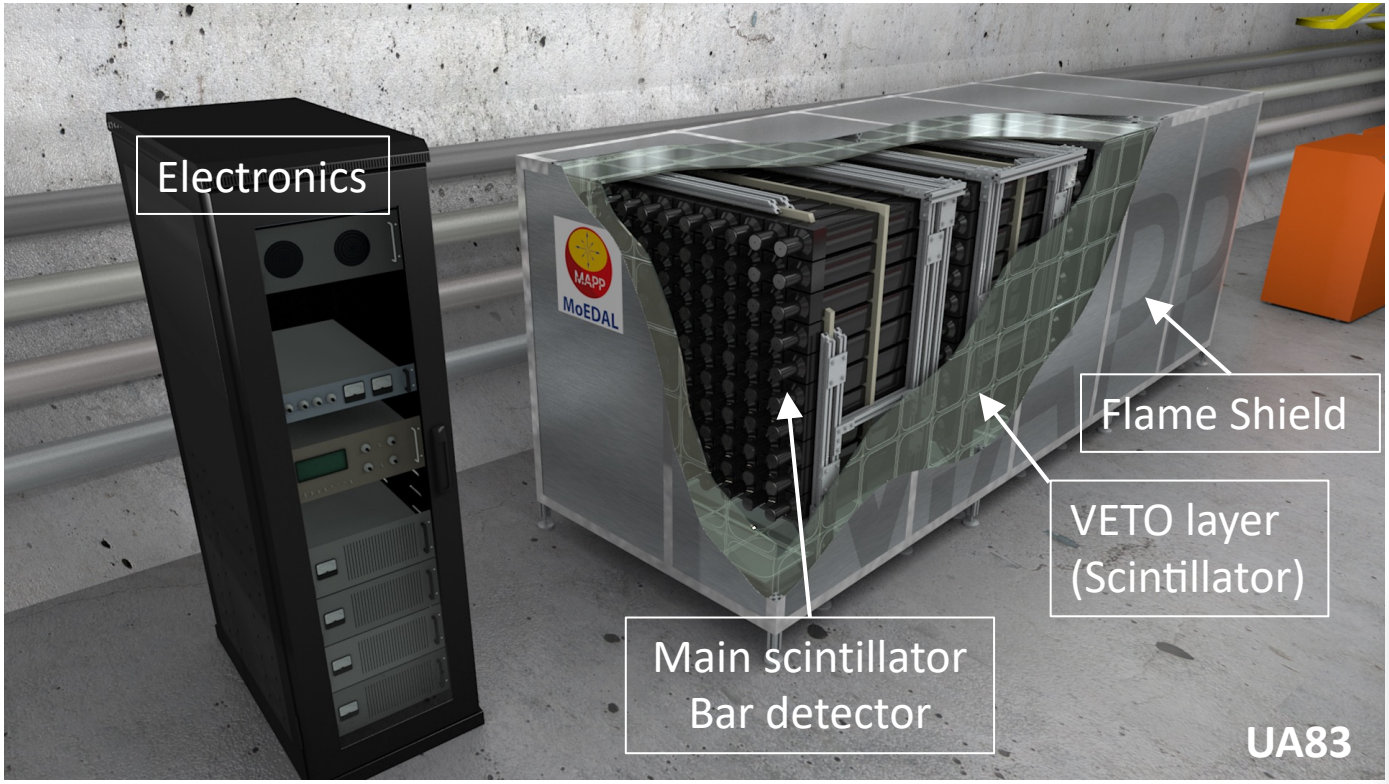
- **MAPP-mQP:** sensitive to low ionisation induced by millicharged particles
- **MAPP-LLP:** sensitive to long-lived neutral particles through visible decay
- Phase-1 ***approved*** *by CERN Research Board* in Dec 2021
- **Phase-1** for **Run-3**: **MAPP-mQP** installation in UA83 is underway
- **Phase-2** for **HL-LHC**: Reinstall Phase-1 in UA83 and add **MAPP-LLP** in UGC1

MoEDAL contribution to Snowmass Study, arXiv:2209.03988 [hep-ph]

MoEDAL-MAPP flythrough



MAPP-mQP Phase-1 detector concept



- 400 scintillator bars (10×10×75 cm^3) in 4 sections readout by PMTs
- Protected by a hermetic VETO counter system

Prototype mQP in 2018 in UGC1 gallery

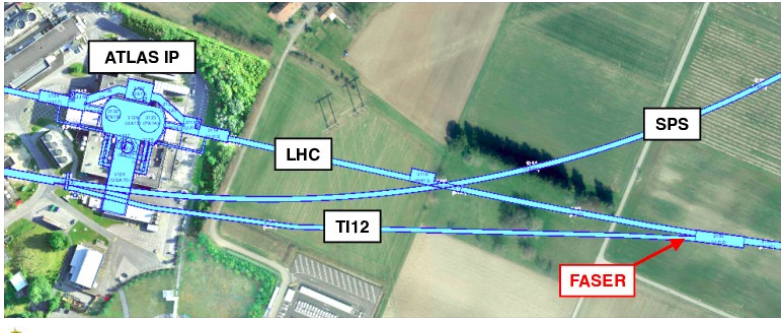
FASER

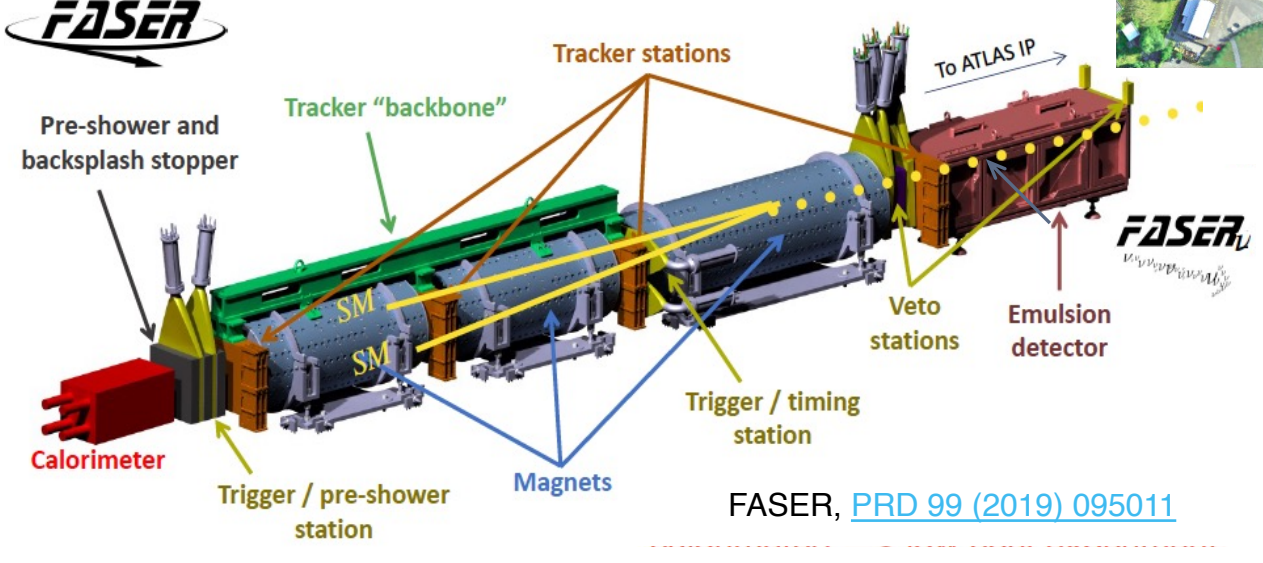
***F**orw**A**rd **S**earch **E**xpe**R**iment at the LHC*

Search for new particles produced in decays of light mesons copiously present at zero angle

Situated along beam collision axis line of sight

- small (20 cm diameter, ~ 7 m long) detector covering mrad regime ($\eta > 9.1$)
- ~480 m from IP1 (ATLAS)





FASER, PRD 99 (2019) 095011

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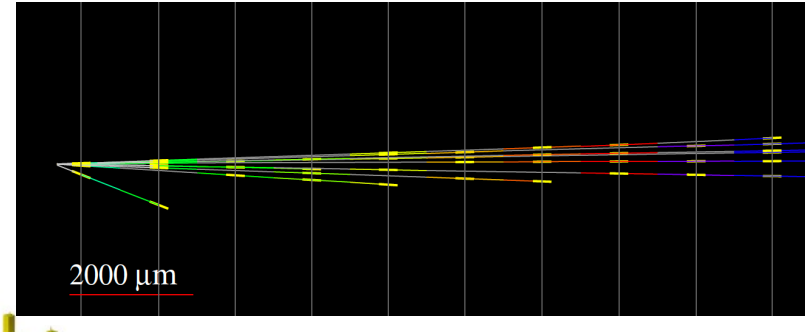

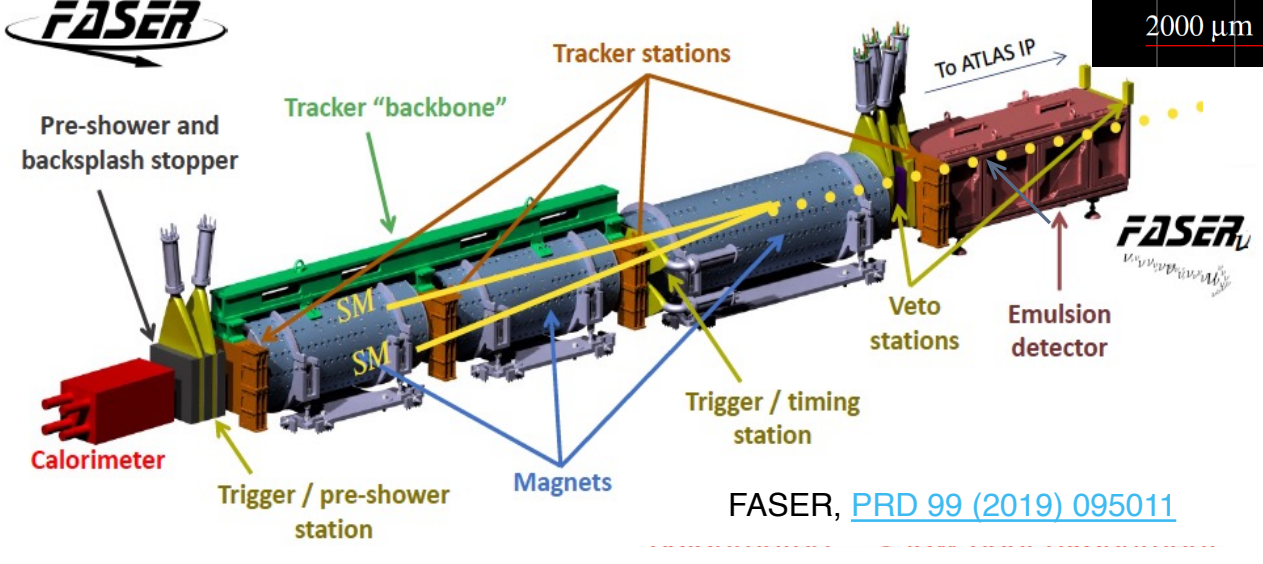

FASER, PRD 99 (2019) 095011

FASERν detects and measures collider neutrinos

PRD 104 (2021) L091101

FASER

*F*orw*A*rd *S*earch *E*xpe*R*iment at the LHC

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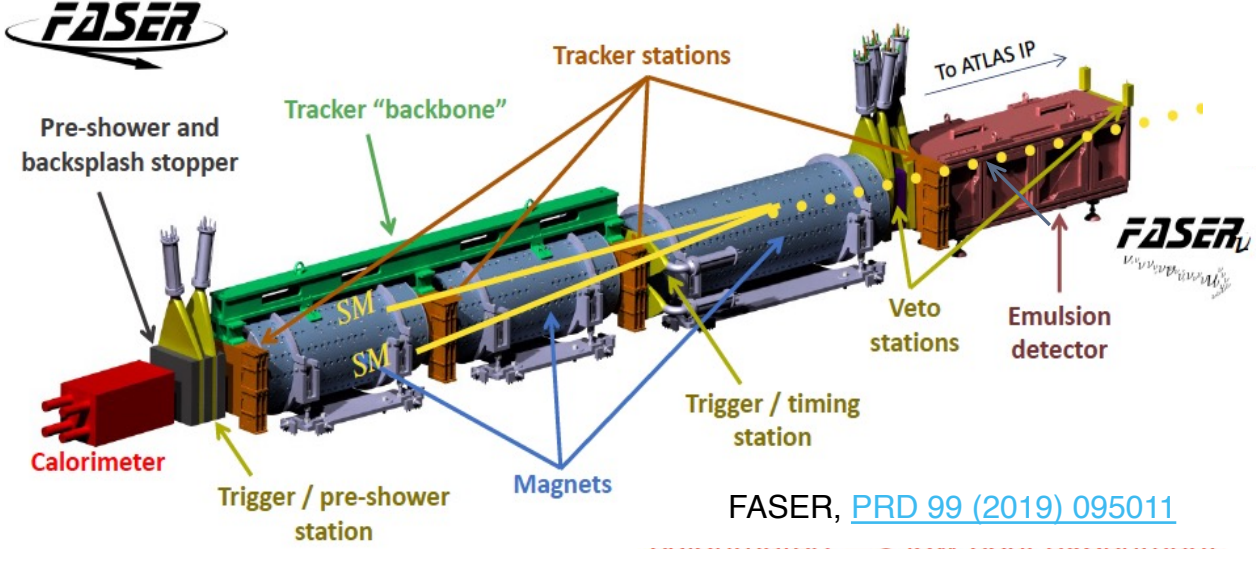
- ~480 m from IP1 (ATLAS)

Search for new particles produced in decays of light mesons copiously present at zero angle

Upgrade

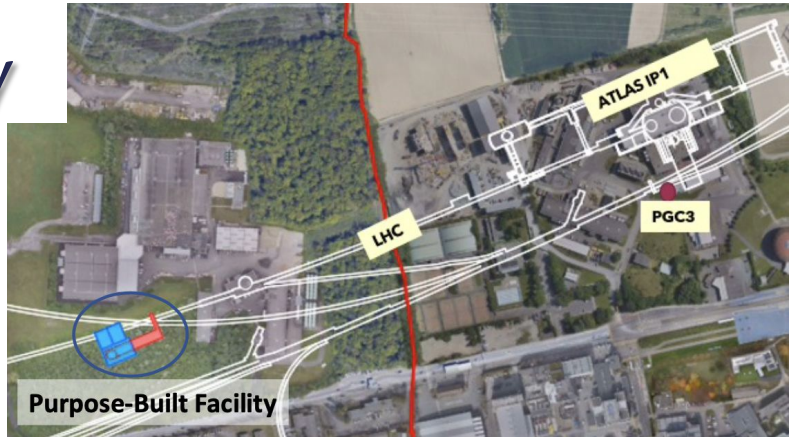
FASER2 for HL-LHC with a larger radius of ~1 m at FPF



FASER, PRD 99 (2019) 095011

FPF – Forwards Physics Facility

- FPF planned to enhance LHC physics potential in BSM physics searches, neutrino physics and QCD
- Operational in HL-LHC

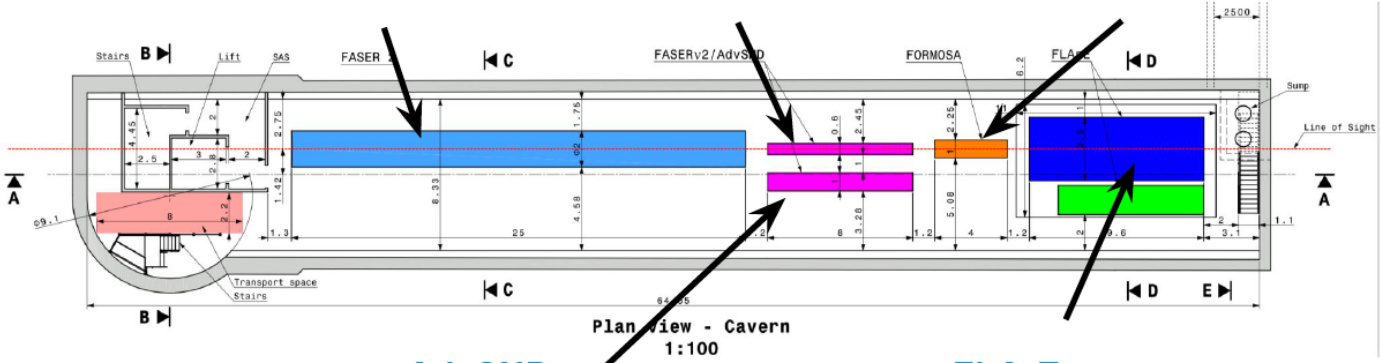


620-685 m west of the ATLAS IP

FASER2
magnetized spectrometer for BSM searches

FASERv2
emulsion-based neutrino detector

FORMOSA
plastic scintillator array for BSM searches



AdvSND
electronic neutrino detector

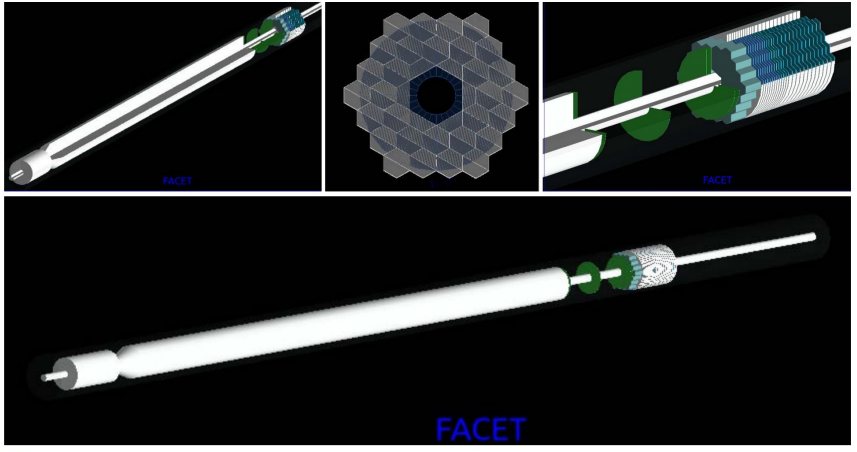
FLArE
LAr based neutrino detector

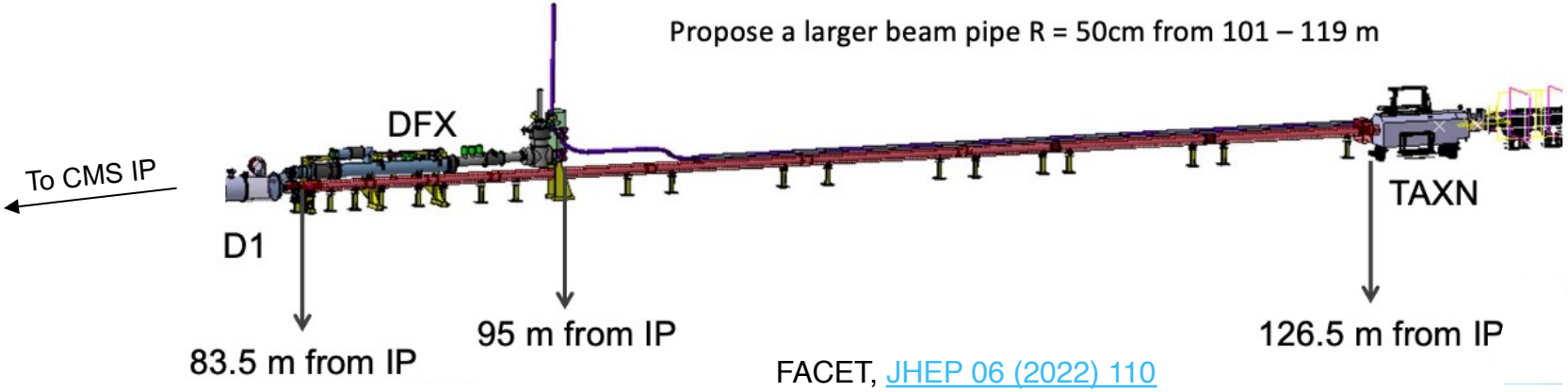
FPF Paper Phys.Rept. 968 (2022) 1

FPF Snowmass Whitepaper J.Phys.G 50 (2023) 030501

FACET – Forward-Aperture CMS ExTension

- Multi-particle spectrometer at z ~ +100 m from the IP5 (CMS)
- Detector will have a radius of ~50 cm and coverage 6 < η < 8
- Much closer to the IP and much larger decay volume than FASER
- Aiming for operation in HL-LHC

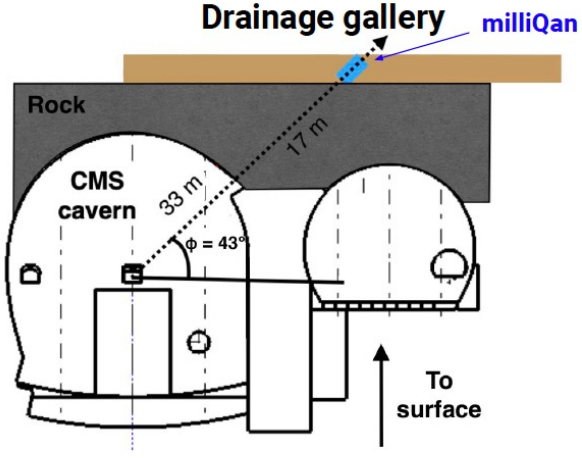




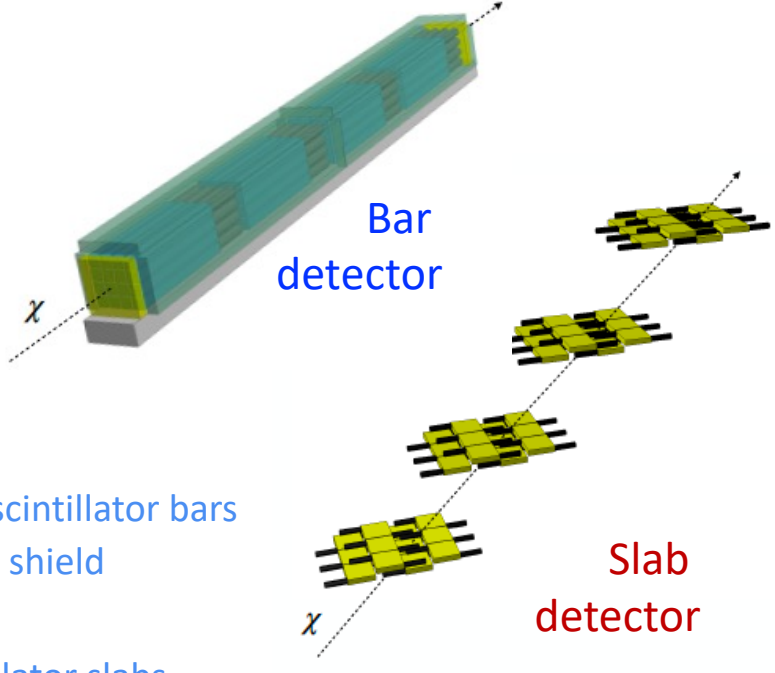
FACET, JHEP 06 (2022) 110

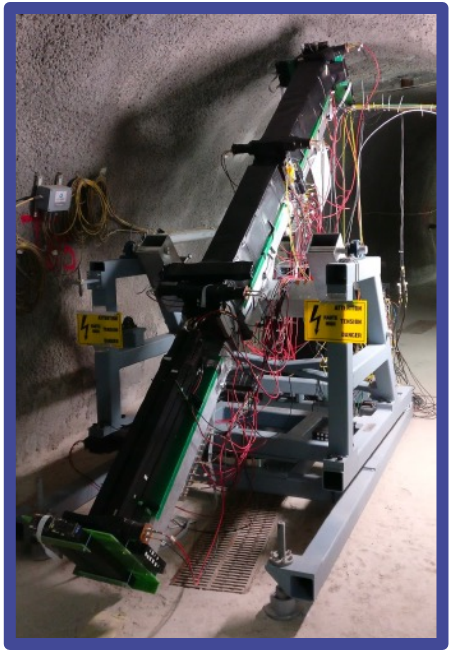
THE MILLIQAN EXPERIMENT

Detector & demonstrator



Proof of concept: ~1% prototype of the full detector: **the milliQan demonstrator**





Two detectors for Run 3:

- Bar detector
  - 0.2 m × 0.2 m × 3 m plastic scintillator bars
  - surrounded by active μ veto shield
- Slab detector
  - 40 cm × 60 cm × 5 cm scintillator slabs
  - increased reach for heavier mCPs

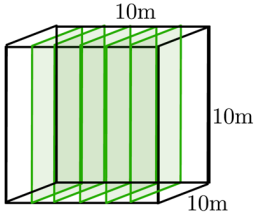
milliQan, PRD 104 (2021) 032002

milliQan, PRD 102 (2020) 032002

CODEX-b

A COmpact Detector for EXotics at LHCb

- Transverse detector at the LHC
- **RPCs**: fast, precise, cheap for large area
- Behind 3.2 m thick concrete shielding
  - very low SM background
  - effectively zero background with passive Pb shield
- CODEX-β demonstrator ($2\times2\times2$ m^3) planned for Run-3



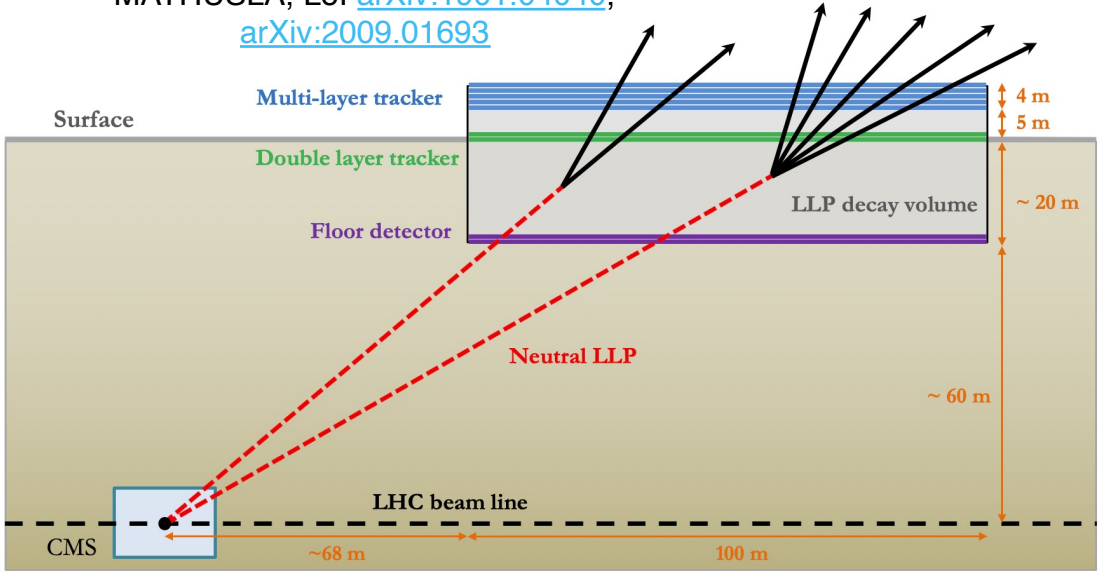
CODEX-b EoI Eur.Phys.J.C 80 (2020) 1177

MATHUSLA

MAsive Timing Hodoscope for Ultra Stable neutraL pArticles

- Large footprint (area 100×100 m^2) & large decay volume (height 25 m)
- Decay volume filled with air with several detector layers for tracking

MATHUSLA, LoI arXiv:1901.04040, arXiv:2009.01693



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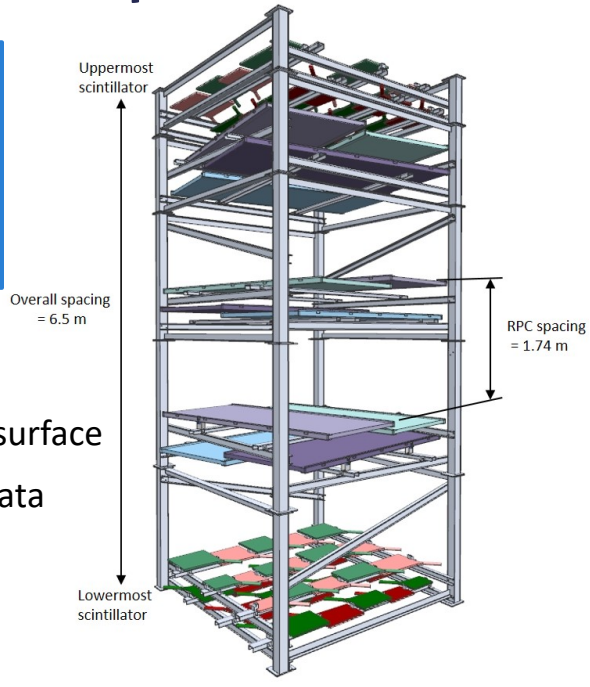
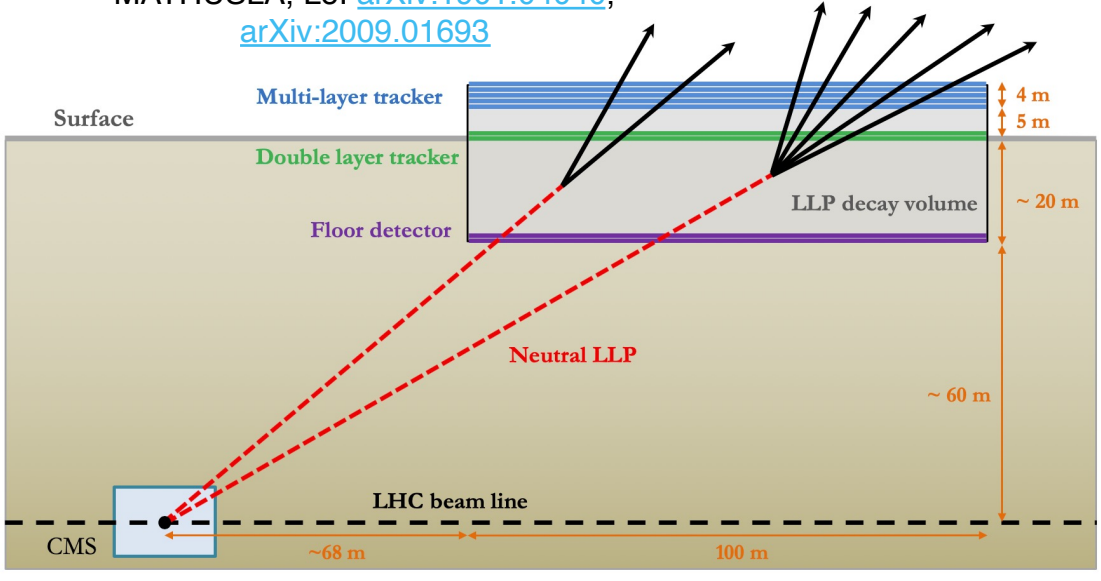
2.5×2.5×6.5 m^3 test stand with eight layers of trackers confirms background assumptions and gives confidence in projected physics reach



ATLAS surface 2018 data

MATHUSLA, Nucl.Instrum.Meth.A 985 (2021) 164661

MATHUSLA, LoI arXiv:1901.04040, arXiv:2009.01693



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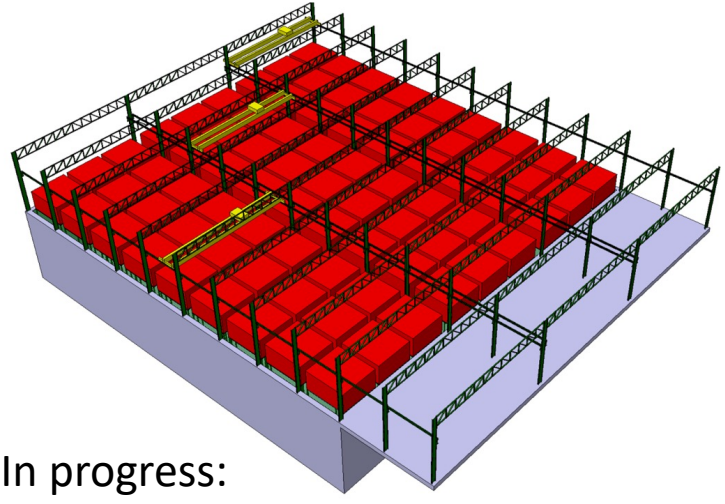
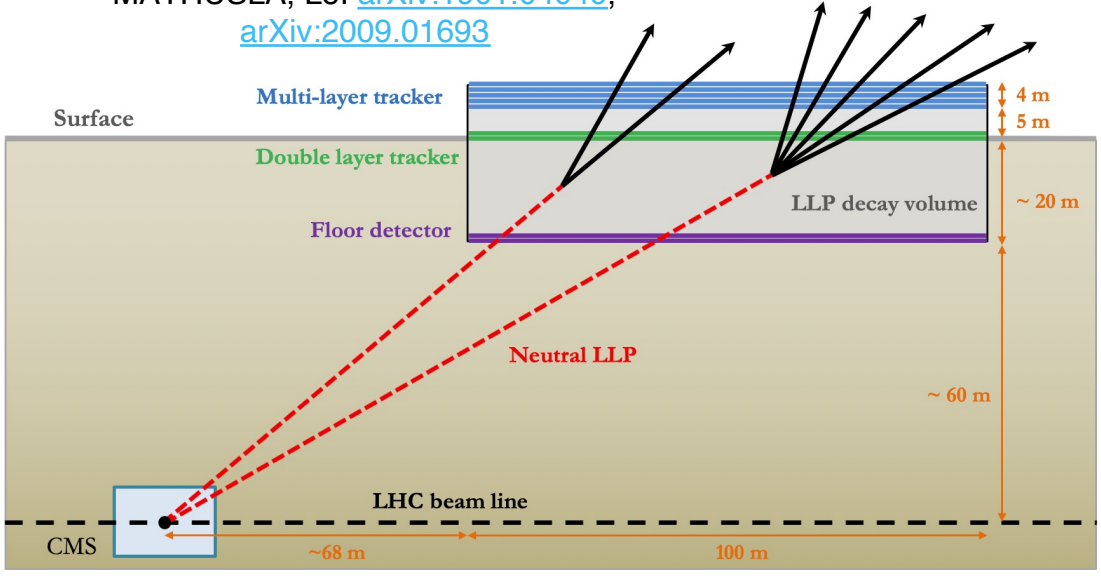
- Decay volume filled with air with several detector layers for tracking

9×9 units, each with a 9m×9m footprint, 30m tall



MATHUSLA, LoI arXiv:1901.04040, arXiv:2009.01693

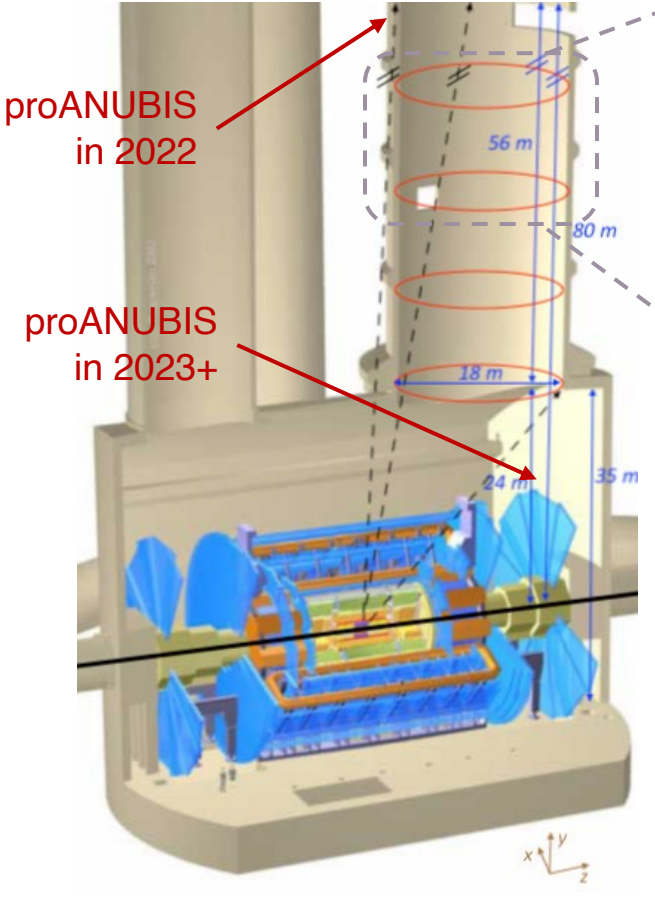


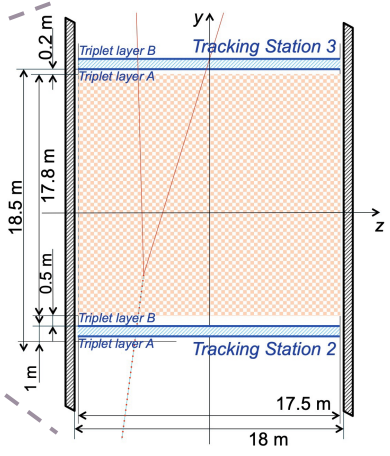
In progress:

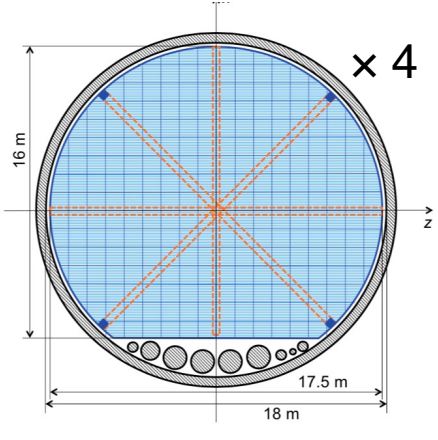
- Construction of prototype detector
- Detailed tracking and vertex reconstruction studies
- Development of trigger and data acquisition

MATHUSLA Snowmass contribution, arXiv:2203.08126

ANUBIS AN Underground Belayed In-Shaft search experiment







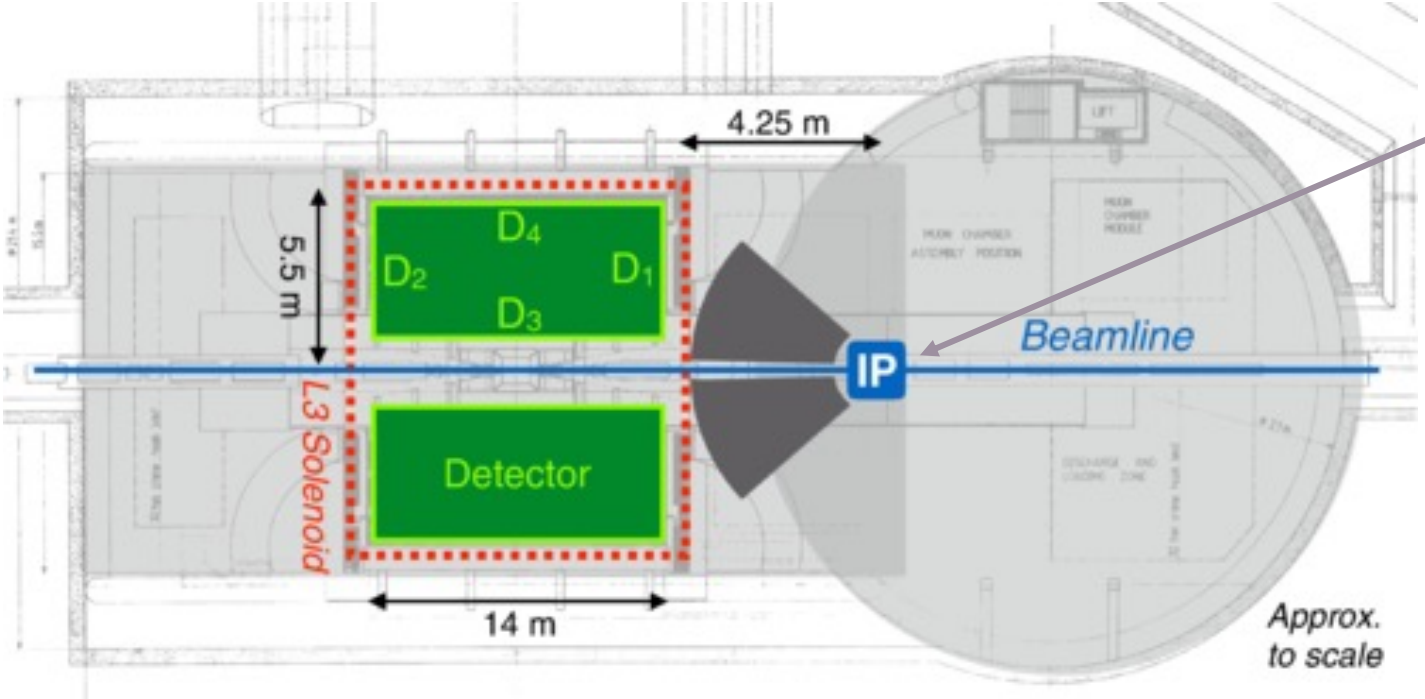
- Four evenly spaced tracking stations with a cross-sectional area of 230 m^2 each
- Tracking stations same RPC technology as ATLAS layers
- 180 cm × 100 cm × 100 cm BIS78 RPC triplet dubbed **proANUBIS** being commissioned to measure background rates

Bauer, Brandt, Lee, Ohm, arXiv:1909.13022

AL3X – A Laboratory for Long-Lived eXotics

In the unlikely event that ALICE finishes its physics program before the end of HL-LHC

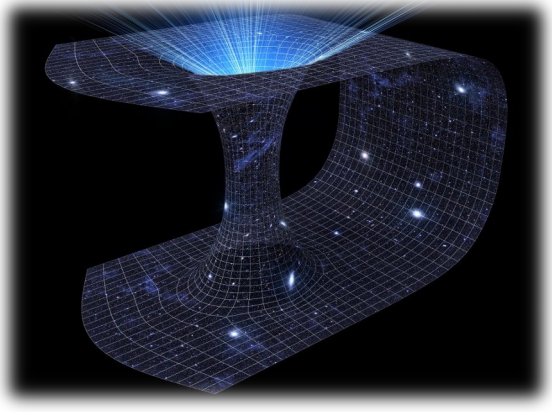
- reuse the L3 magnet and (perhaps) the ALICE TPC for LLP searches
- use thick shield with active veto to reduce background



ALICE interaction point moved by 11.25 m outside magnet to allow LLPs to travel before decaying

Gligorov, Knapen, Nachman, Papucci, Robinson,
PRD 99 (2019) 015023

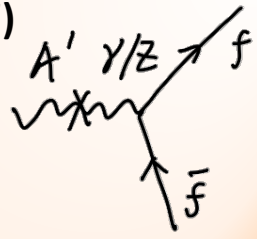
Sensitivity to portal models



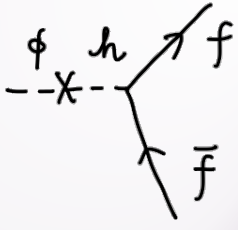
Credit: General Electric

Hidden sector – Feebly Interacting Particles (FIPs)

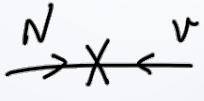
Dark vectors ("Dark Photons")
- adding U(1) gauge group to SM, kinetic mixing with γ/Z
- light neutral meson decays, millicharged particles



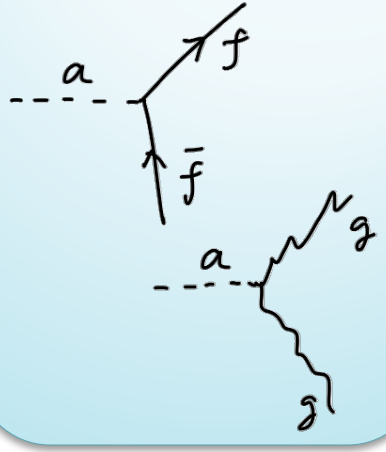
Dark scalars ("Dark Higgs")
- neutral singlet scalers that couple to the SM Higgs field
- produced in penguin decays of K, D, B mesons

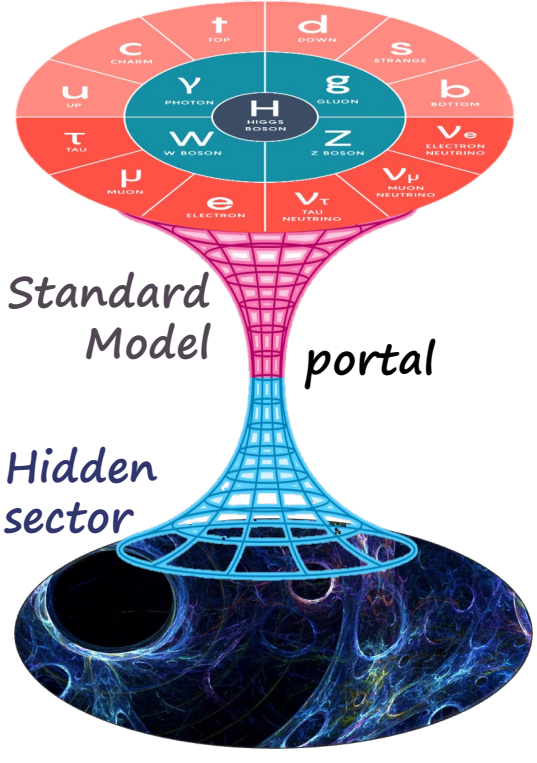


Heavy neutral leptons ("sterile neutrinos")
- explain SM ν masses (seesaw), DM, BAU
- weak semi-leptonic decays of hadrons, W, Z

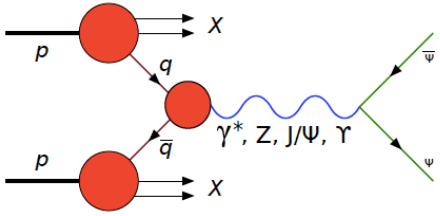


Axion-like particles ("ALPs")
- solution of the strong CP problem
- generalisation of the axion model in MeV-GeV mass range

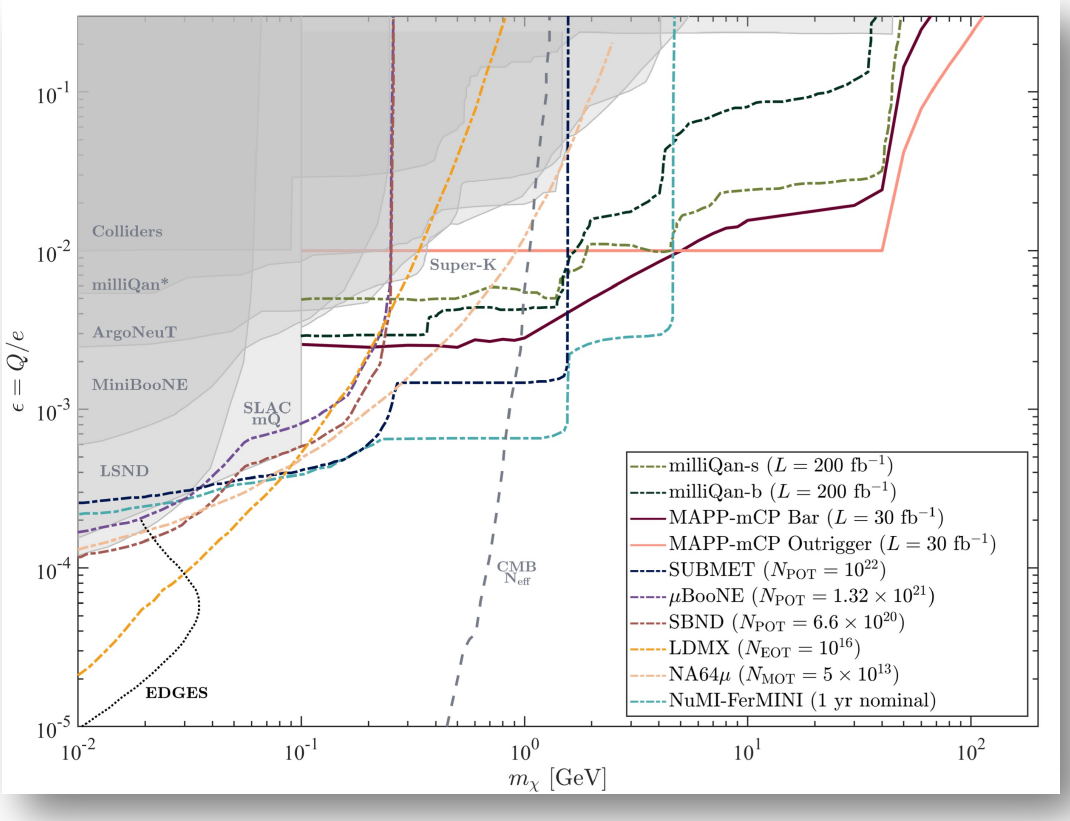




Millicharged particles and dark photons



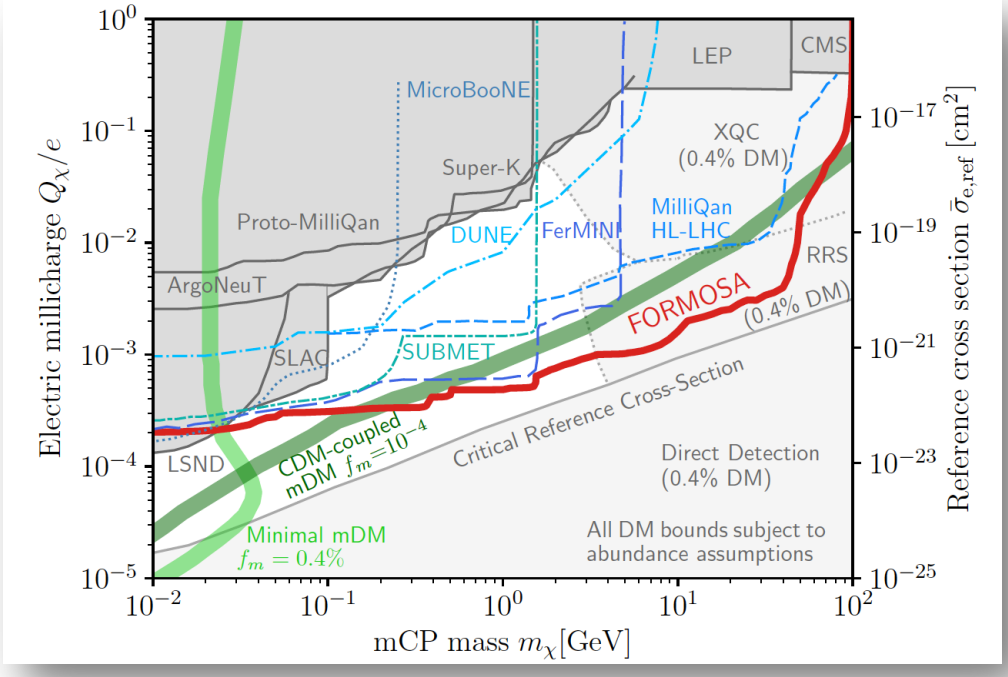
- mCP generated by **massless dark photon**, kinetically mixed with SM, that couples to χ and induces millicharge of χ
- Production through meson decays also posible
  - only Drell-Yan production shown here
- Moreover, MAPP sensitive to **heavy neutrino** with large **electric dipole moment**, experimentally similar to mCP [Frank et al, Phys.Lett.B 802 (2020) 135204]



MoEDAL contribution to Snowmass, arXiv:2209.03988

Millicharged strongly interacting DM (mSIDM)

- mCPs can account for a fraction of dark matter abundance
- mSIDM characterised by a large "reference cross section"
- Particle flux attenuated through interactions in the Earth's atmosphere and crust
- Can escape detection by conventional underground direct-detection detectors
- FORMOSA can help close the mSIDM window



FPF Paper Phys.Rept. 968 (2022) 1

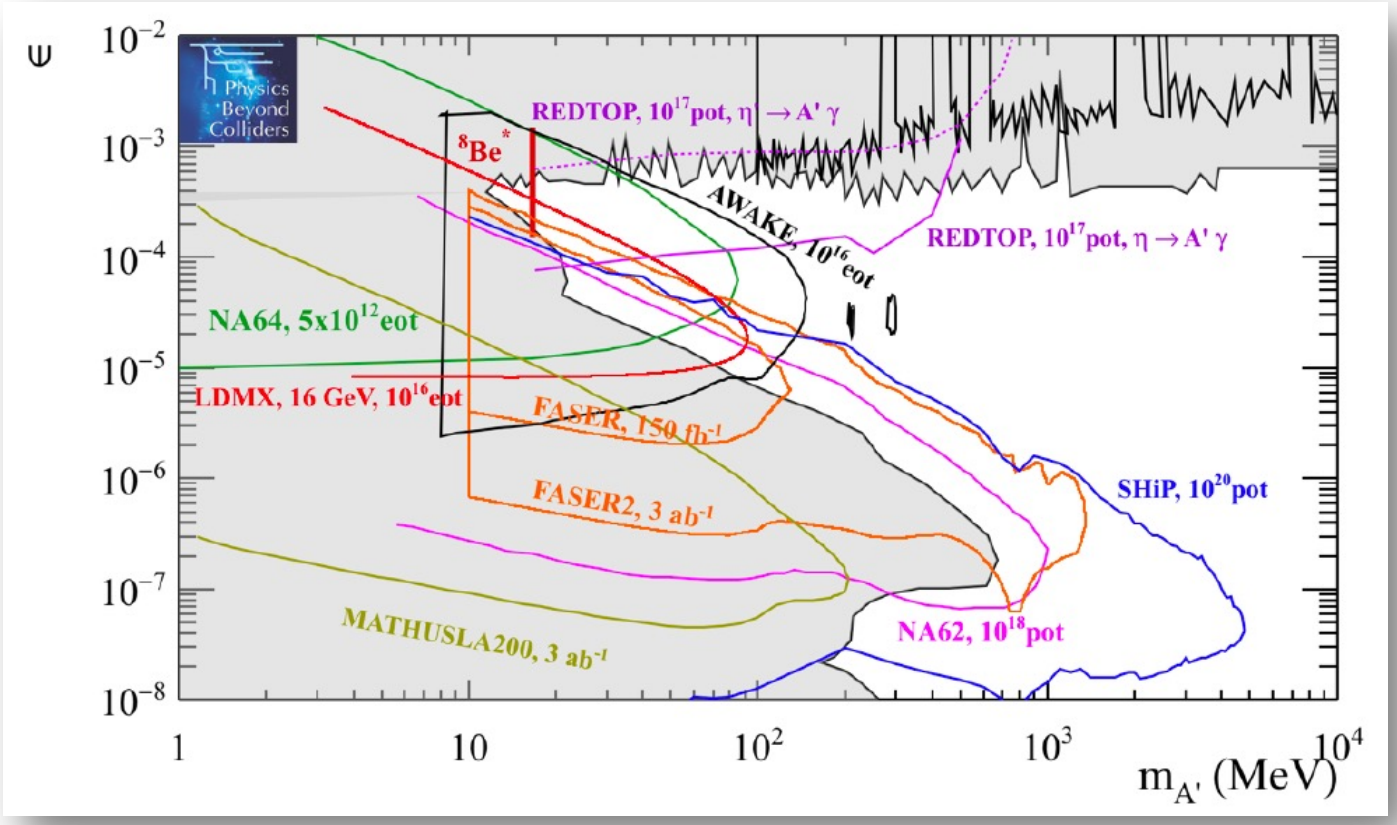
Emken, Essig, Kouvaris, Sholapurkar, JCAP 09 (2019) 070

Foroughi-Abari, Kling, Tsai, PRD 104 (2021) 035014

FORMOSA: Scintillator-based detector to be hosted in FPF

Minimal dark photon model

- Adding a new hidden U(1) with massive gauge field A'_μ, the *dark photon*
- DM assumed to be either heavy or contained in a different sector
- Dark photon decays to SM states (*visible* decays)
- $m_{A'}$: dark photon mass
- ϵ : coupling of dark photon with the standard photon

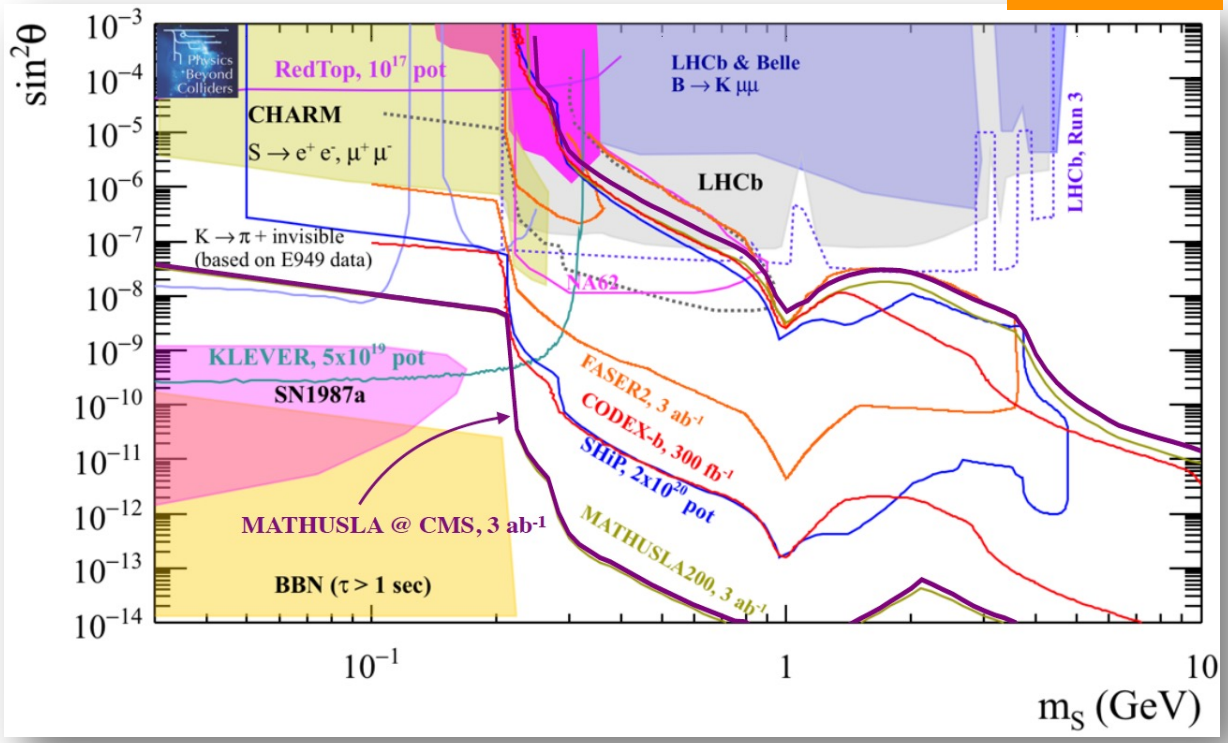


PBC–BSM Report, J.Phys.G 47 (2020) 010501

Scalar portal – dark Higgs

$$\mathscr{L} = \mathscr{L}_{SM} + \mathscr{L}_{DS} + \mu^2 S^2 - \frac{1}{4}\lambda_S S^4 - \epsilon_H S^2 |H|^2$$

μ≠0, λ≠0

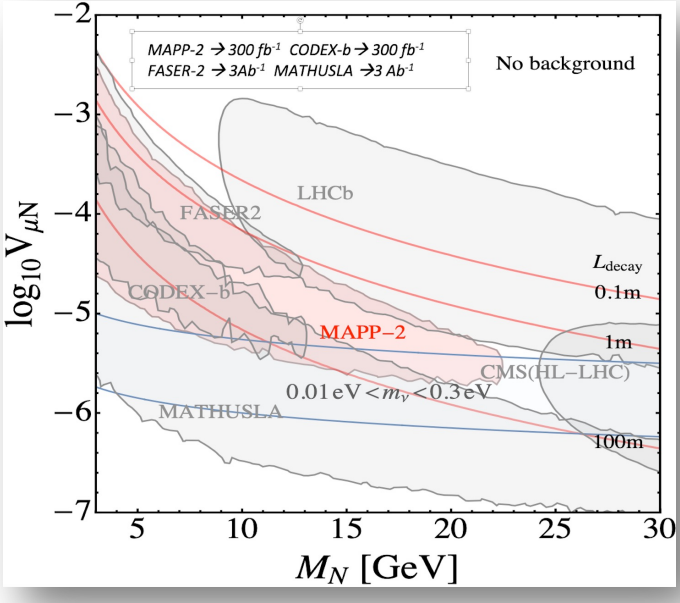


- Dark Higgs ϕ mixing with SM H^0 through θ ≪ 1, leading to exotic $B \to X_s\phi$ decays with $\phi \to \ell^+\ell^-$
- BR(h → SS) ≈ 10^{-2} assumed for complementarity to H → inv. LHC searches

MATHUSLA Snowmass contribution, arXiv:2203.08126

Heavy neutral leptons

$U(1)_{B-L}$ HNL scenario

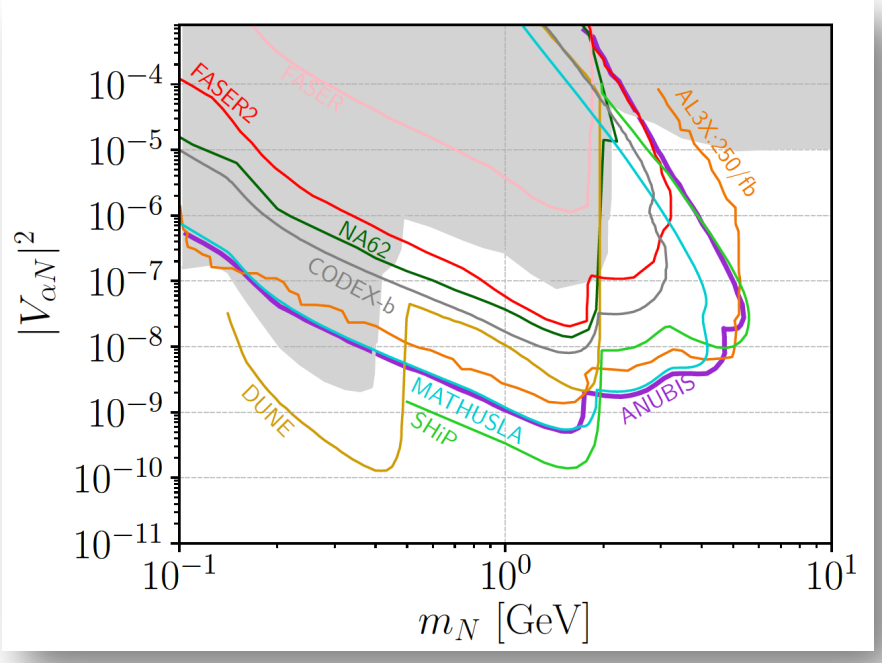


Pair production of RH neutrinos from decay of additional neutral Z' boson in gauged B-L model

MoEDAL Snowmass paper, arXiv:2209.03988

See also, Deppisch et al, PRD 100 (2019) 035005

minimal HNL scenario

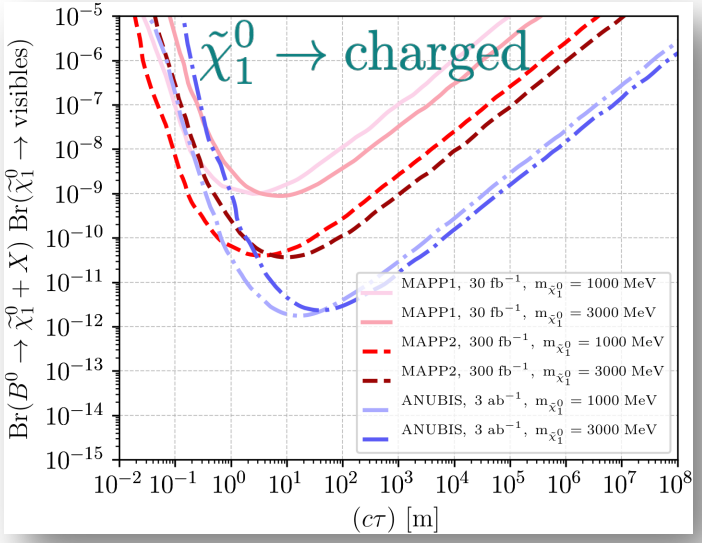


Hirsch & Wang, Phys.Rev.D 101 (2020) 055034

- Production and decay mediated by active-sterile neutrino mixing
- For simplicity, only one species of HNL considered
- Mainly produced from on-shell decays of D-mesons, B-mesons, W, Z, Higgs, t

R-parity violating supersymmetry

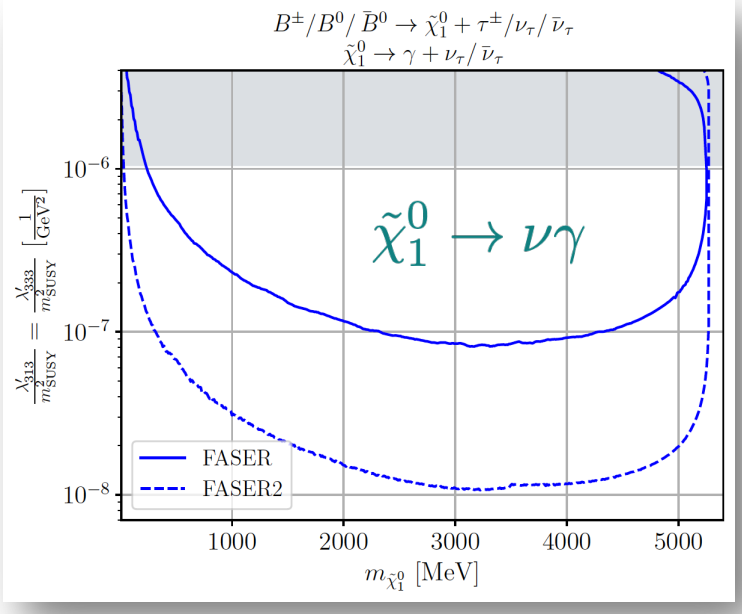
If RPV coupling, λ, λ', λ'' small enough, the (N)LSP may be long lived



Dreiner, Günther, Wang, PRD 103 (2021) 075013

λ'_P for production	λ'_{131}
λ'_D for decay	λ'_{112}
Produced meson(s)	$B^0,\ \bar{B}^0$
Visible final state(s)	$K^{\pm} + e^{\mp},\ K^{*\pm} + e^{\mp}$
Invisible final state(s) via λ'_P	None
Invisible final state(s) via λ'_D	$(K_L^0, K_S^0, K^*) + (\nu_e, \bar{\nu}_e)$

RPV couplings

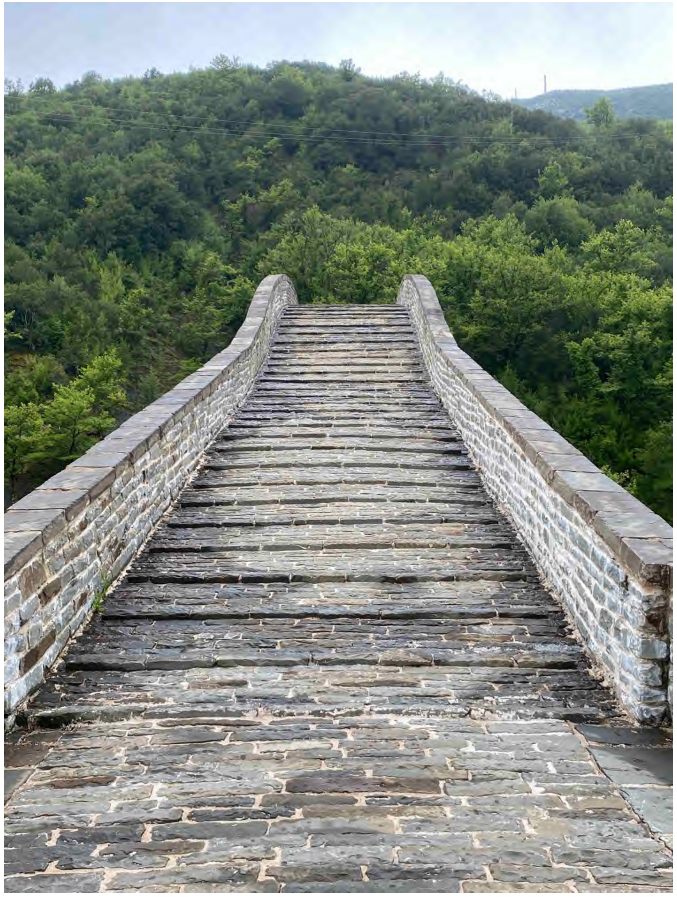


- Sub-GeV $\tilde{\chi}_1^0$ produced via meson M decays: M → $\tilde{\chi}_1^0$ + ℓ/ν
- Single photon highly boosted

Dreiner, Köhler, Nangia, Wang, JHEP 02 (2023) 120

Summary & outlook

- Ever increasing interest in **long-lived particle** searches at the LHC (and not only…)
- FIPs serve as a "bridge" between our observable world and possible hidden sectors
- Dedicated complementary LHC experiments proposed, under construction or running
- MoEDAL, a detector optimised for *highly ionising* particles, entered the FIPs arena with **MAPP**
- New results expected in LHC Run 3

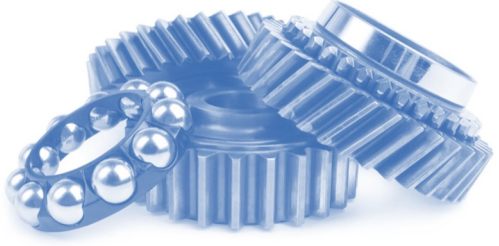


Further reading & workshops

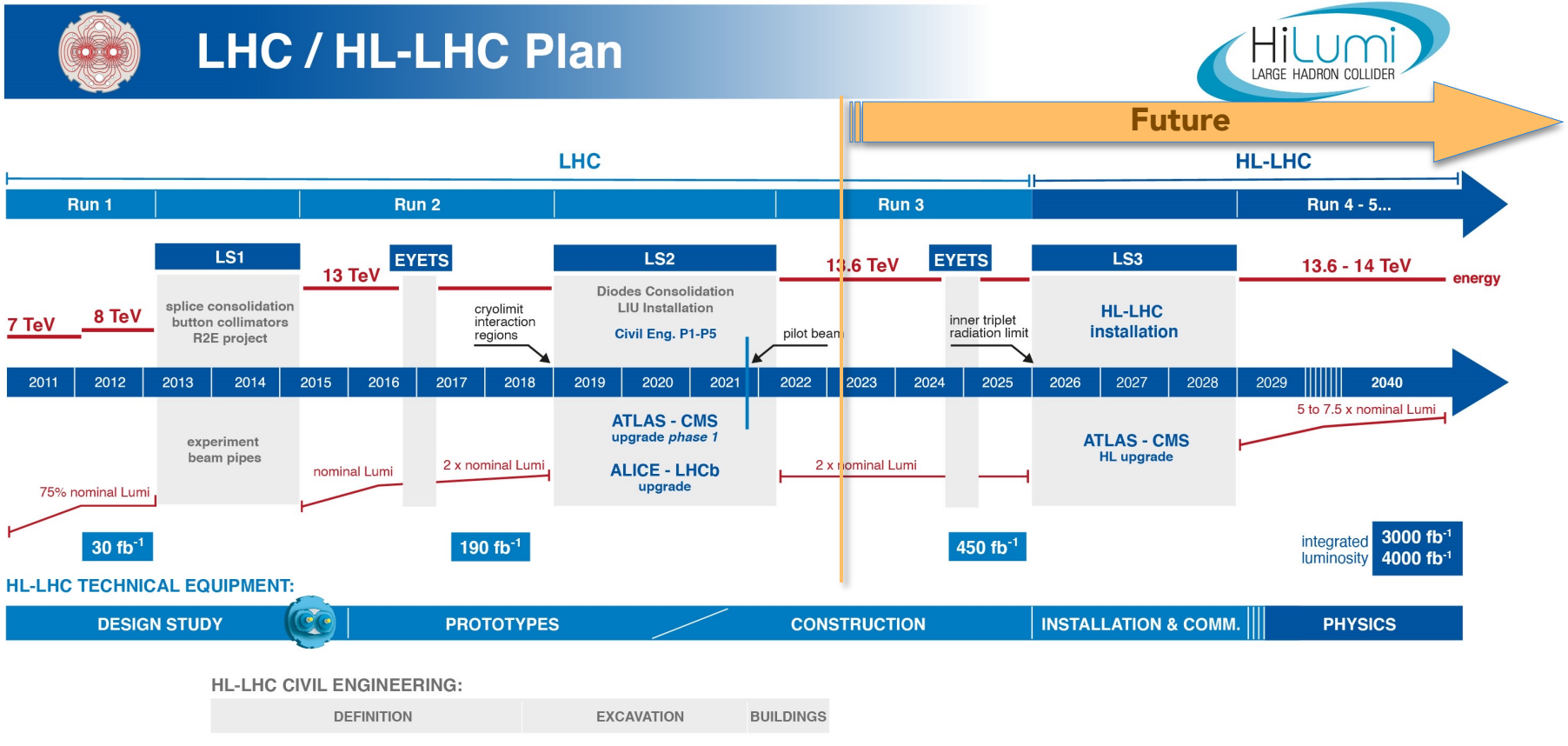
- LHC-LLP Community whitepaper – J.Phys.G 47 (2020) 090501
- Physics Beyond Collider at CERN – BSM Report, J.Phys.G 47 (2020) 010501
- FIPs 2020 Workshop Report, Eur.Phys.J.C 81 (2021) 1015
- VAM, Review on LLP experiments, MG16 proc. arXiv:2111.03036
- 12th workshop of the LHC LLP Community, Oct-Nov 2022
- FIPs 2022 Workshop, Oct 2022

NEW

Spares



LHC & High Luminosity LHC (HL-LHC)

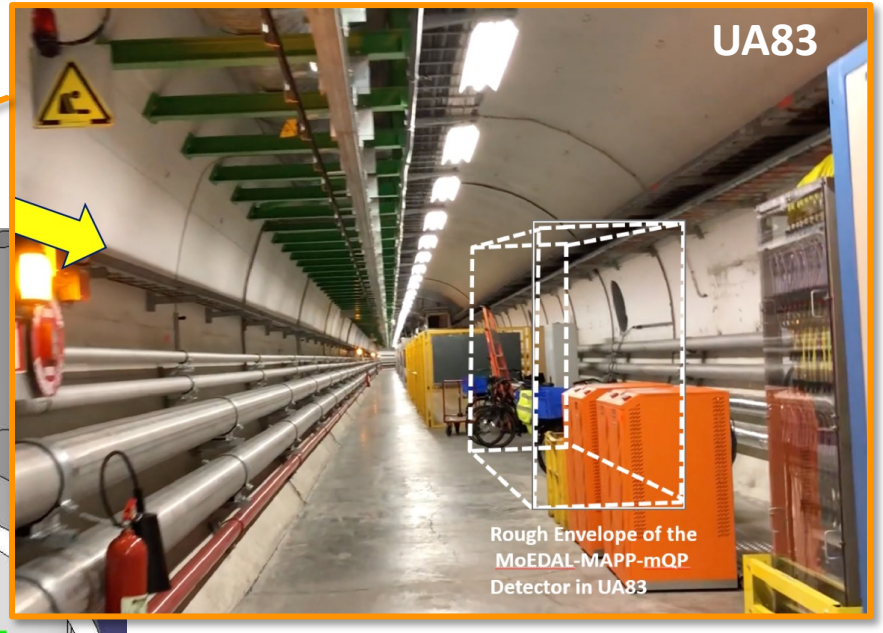


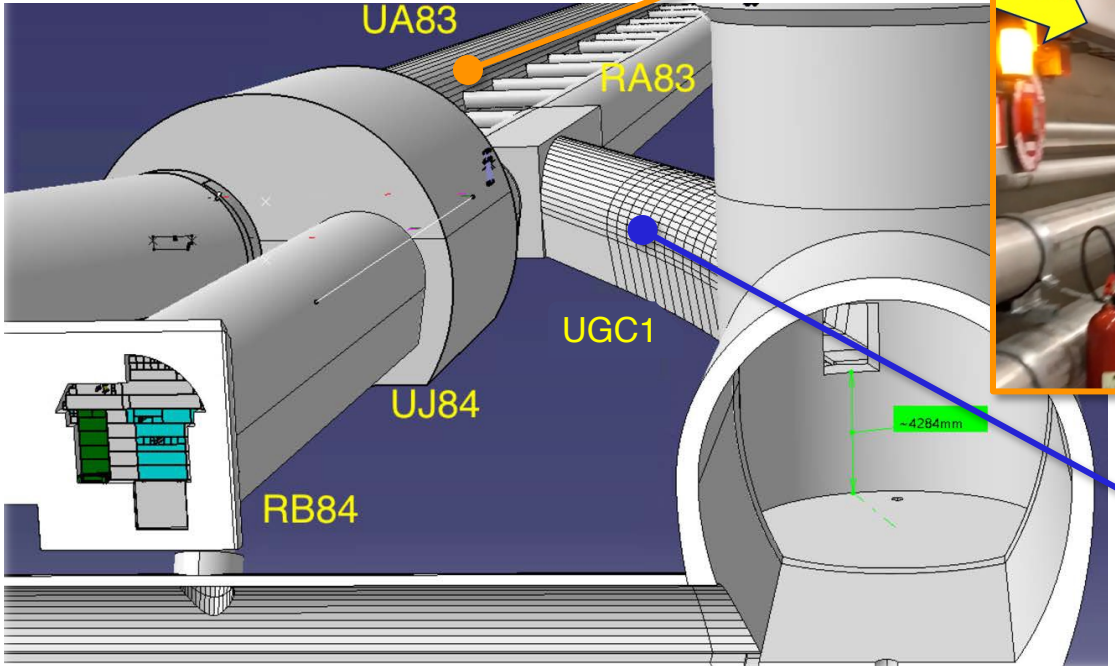
MAPP locations

MoEDAL

- mQP location
- 100 m from IP8 at ~7° to the beam
- Easily accessible gallery, already fitted out
- Access independent from LHCb

UA83

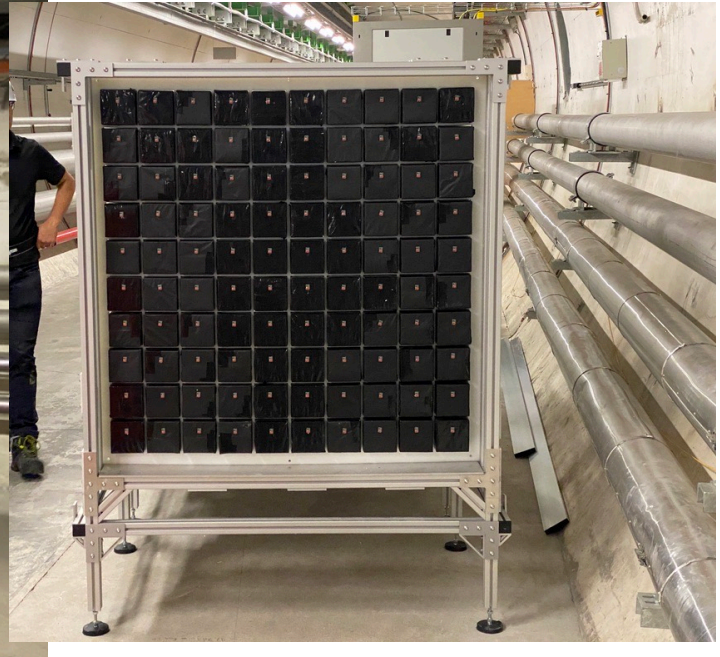




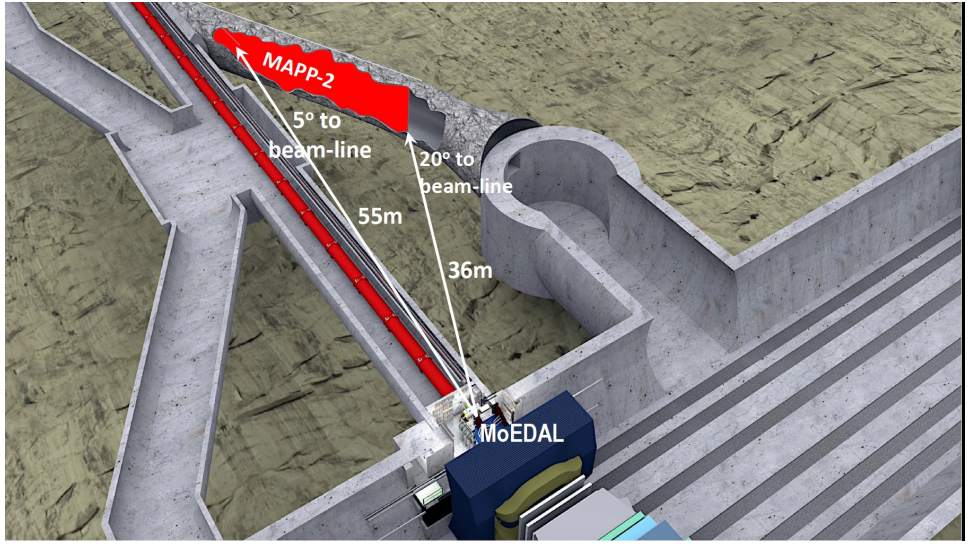
- mQP 2017 prototype location
- Extensive engineering required
- To be ready for MAPP LLP during HL-LHC

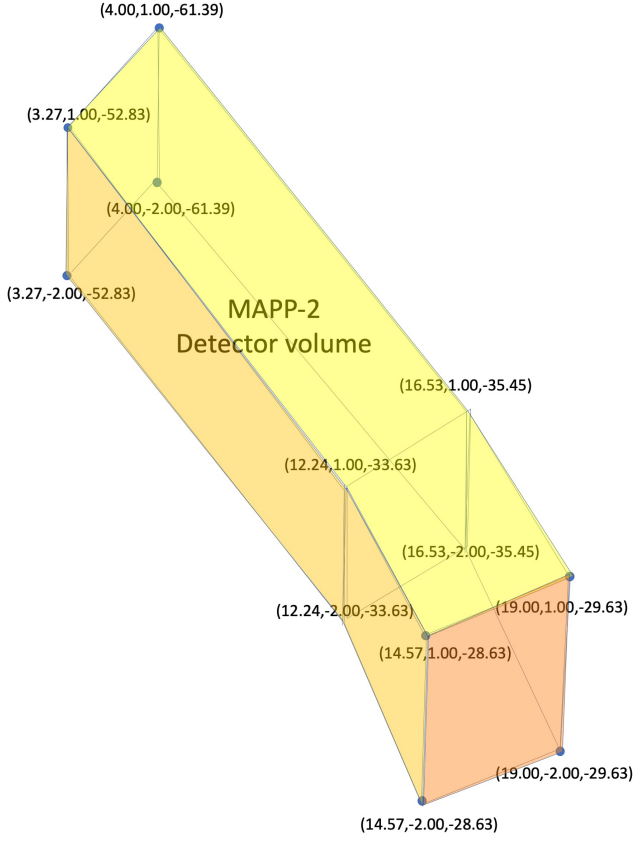
UGC1

MAPP-mQP Phase-1 installation



Phase-2: MAPP-2 for HL-LHC

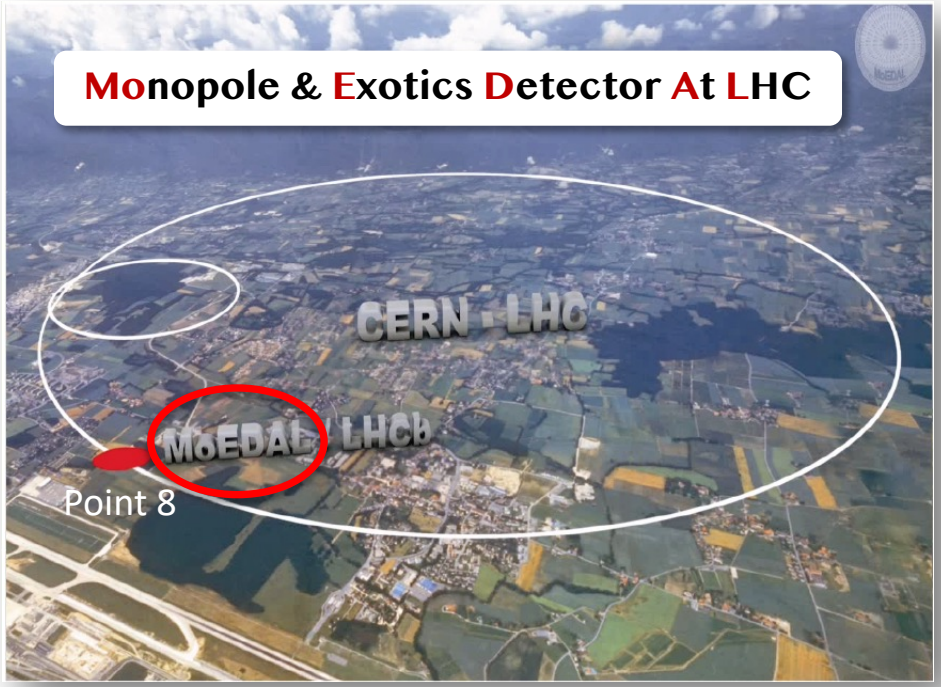




- The UGC1 gallery will be prepared during Long Shutdown 3 prior to HL-LHC
- MAPP-2 detector extends to the full length of the UGC1 gallery

MoEDAL contribution to Snowmass Study, arXiv:2209.03988 [hep-ph]

MoEDAL Collaboration



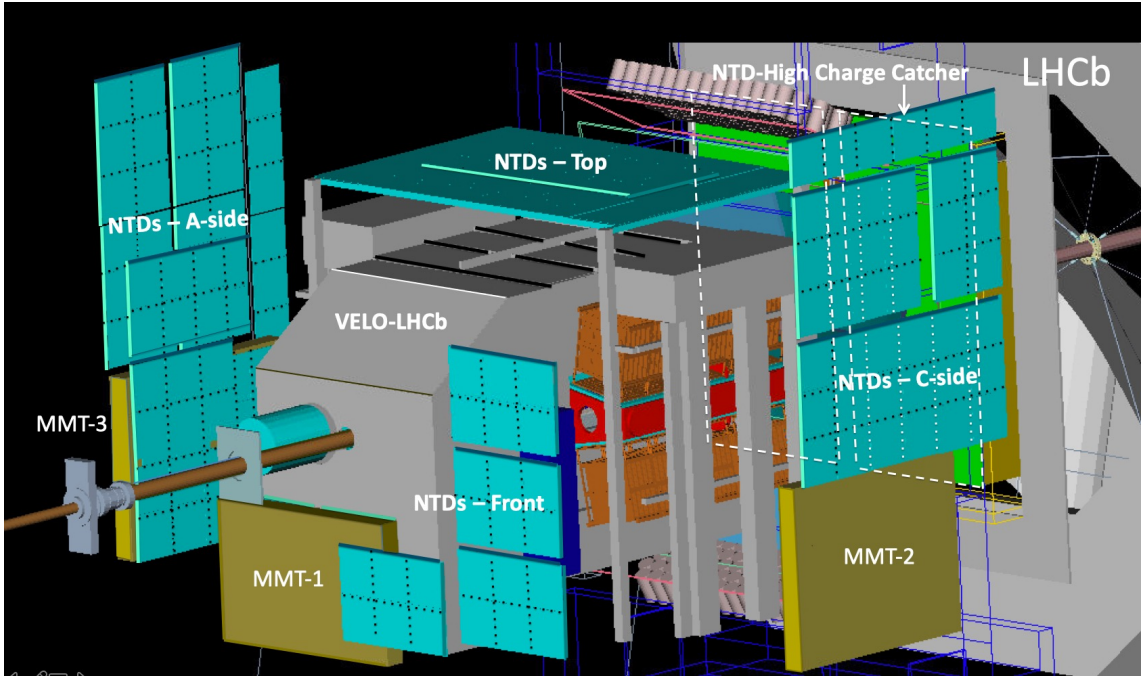
~70 physicists from 21 institutions

UNIVERSITY OF ALABAMA
UNIVERSITY OF ALBERTA
INFN & UNIVERSITY OF BOLOGNA
UNIVERSITY OF BRITISH COLUMBIA
HELSINKI INSTITUTE OF PHYSICS
UNIVERSITY OF MONTREAL
CERN
CONCORDIA UNIVERSITY
IMPERIAL COLLEGE LONDON
KING'S COLLEGE LONDON
NATIONAL INSTITUTE OF TECHNOLOGY, KURUKSETRA
TECHNICAL UNIVERSITY IN PRAGUE
QUEEN MARY UNIVERSITY OF LONDON
INSTITUTE OF SPACE SCIENCE, ROMANIA
INSTITUTE FOR RESEARCH IN SCHOOLS, CANTERBURY
CENTER FOR QUANTUM SPACETIME, SEOUL
TRACK ANALYSIS SYSTEMS Ltd, BRISTOL
TUFT'S UNIVERSITY
VAASA UNIVERSITIES
IFIC VALENCIA
UNIVERSITY OF VIRGINIA

MoEDAL

LHC's first dedicated *search* experiment
(approved 2010)

Baseline MoEDAL detector



- Mostly **passive detectors**; no trigger; no readout
- Permanent physical record of new physics
- No Standard Model physics backgrounds

THREE DETECTOR TECHNOLOGIES

① Nuclear Track Detectors
- **Low-threshold NTD** array $z/\beta > \sim 5\text{-}10$
- High Charge Catcher NTD (**HCC-NTD**) array $z/\beta > \sim 50$

② Monopole Trapping detector (**MMT**) – aluminum bars

③ **TimePix** radiation background monitor