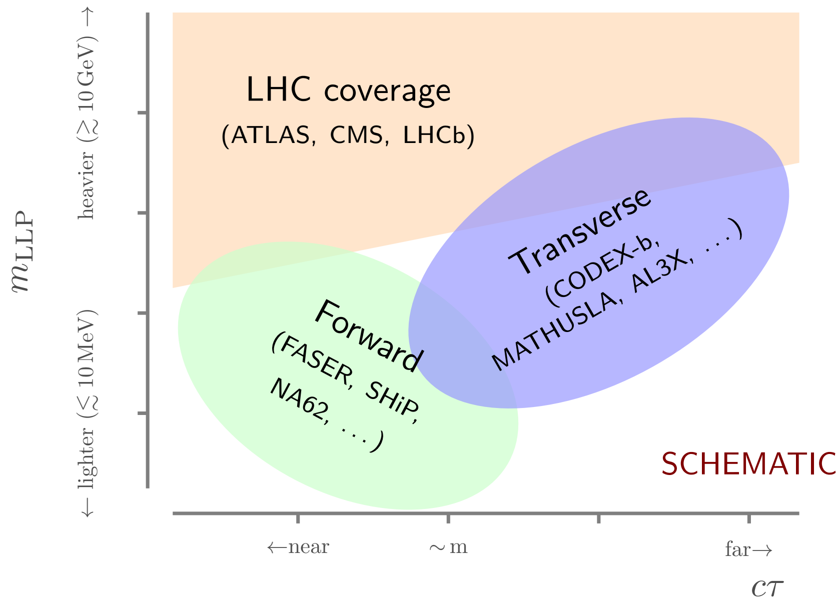
LHC dedicated experiments for long-lived particles (LLPs)

Vasiliki A. Mitsou

LLP Round Table
6th Red LHC workshop
9-11 May 2022, IFT, Madrid, Spain

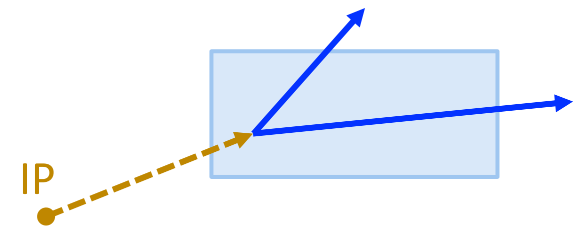
The lifetime frontier



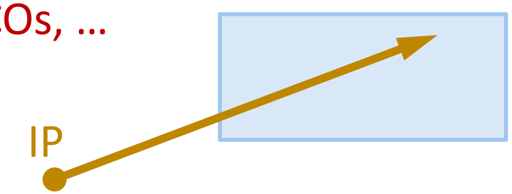
CODEX-b EoI, EPJC 80 (2020) 1177 [arXiv:1911.00481]

- LHC main experiments also sensitive to LLPs, however limited by trigger, timing, large backgrounds
- Variety in signatures and lifetime require designing dedicated experiments for LLPs

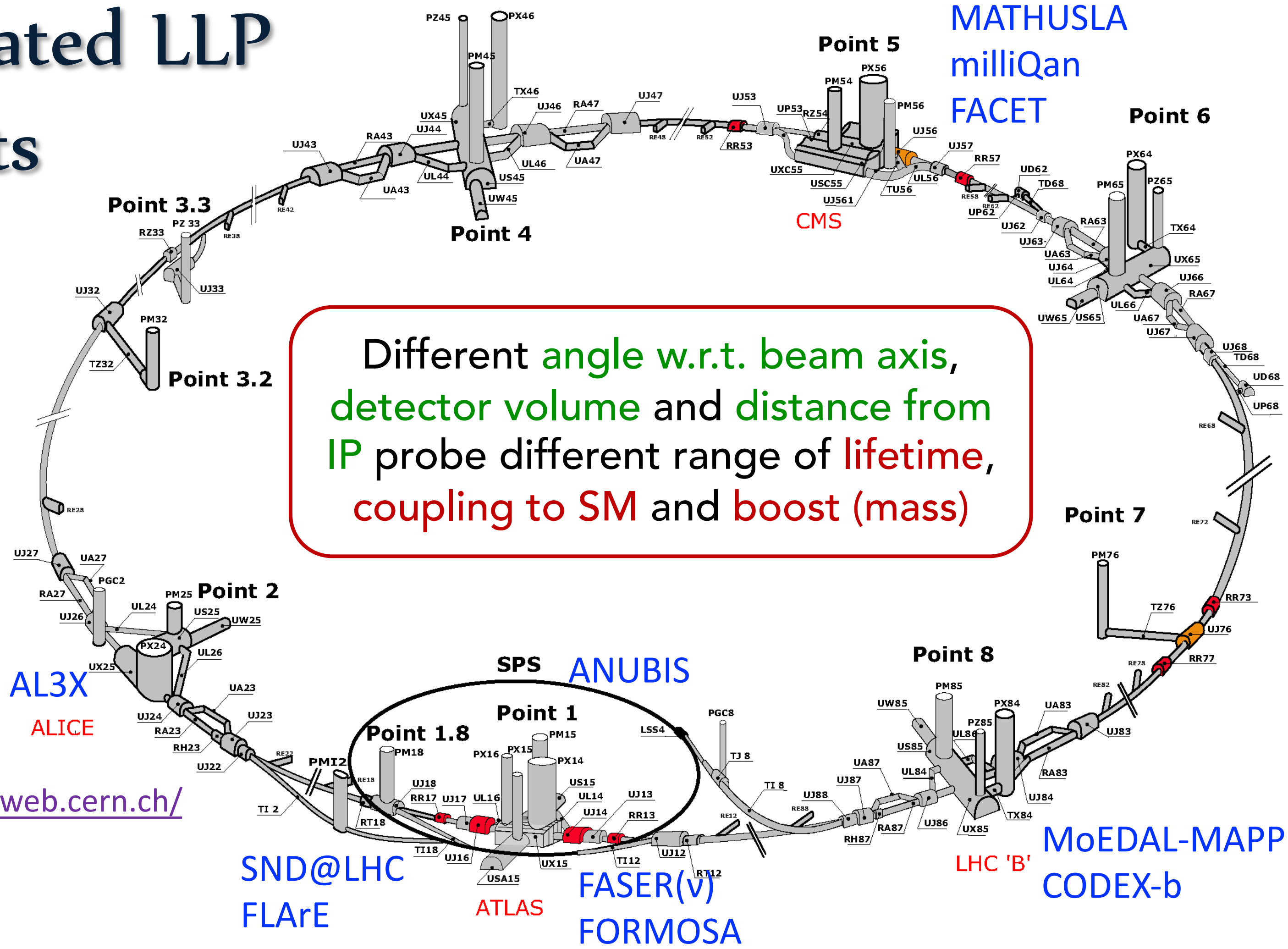
LLPs may decay to visible particles → displaced vertices



LLPs may induce anomalous ionisation, e.g. millicharged particles, magnetic monopoles, HECOs, …



LHC dedicated LLP experiments

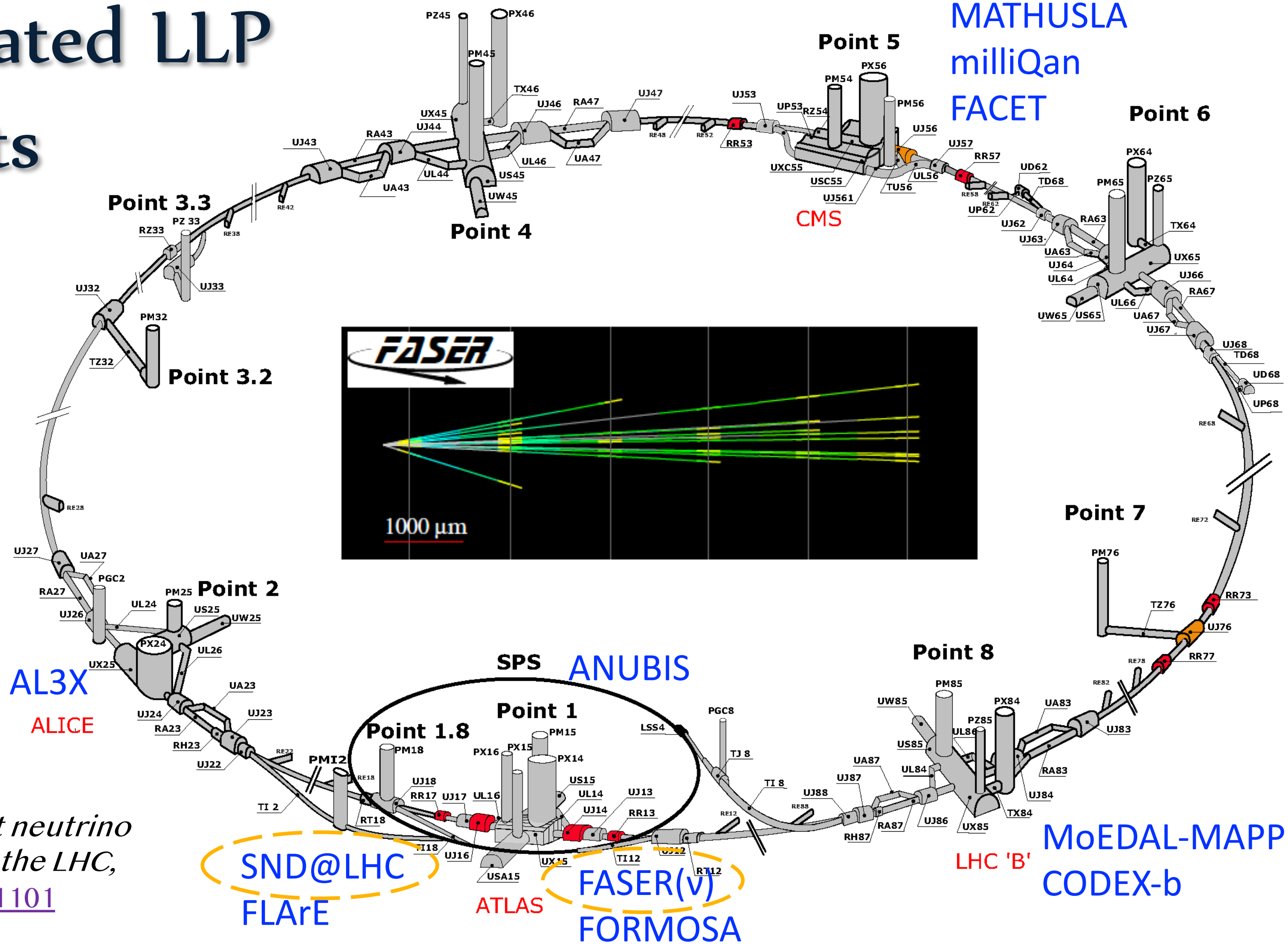


Different angle w.r.t. beam axis, detector volume and distance from IP probe different range of lifetime, coupling to SM and boost (mass)

LHC-LLP Community
https://longlivedparticles.web.cern.ch/

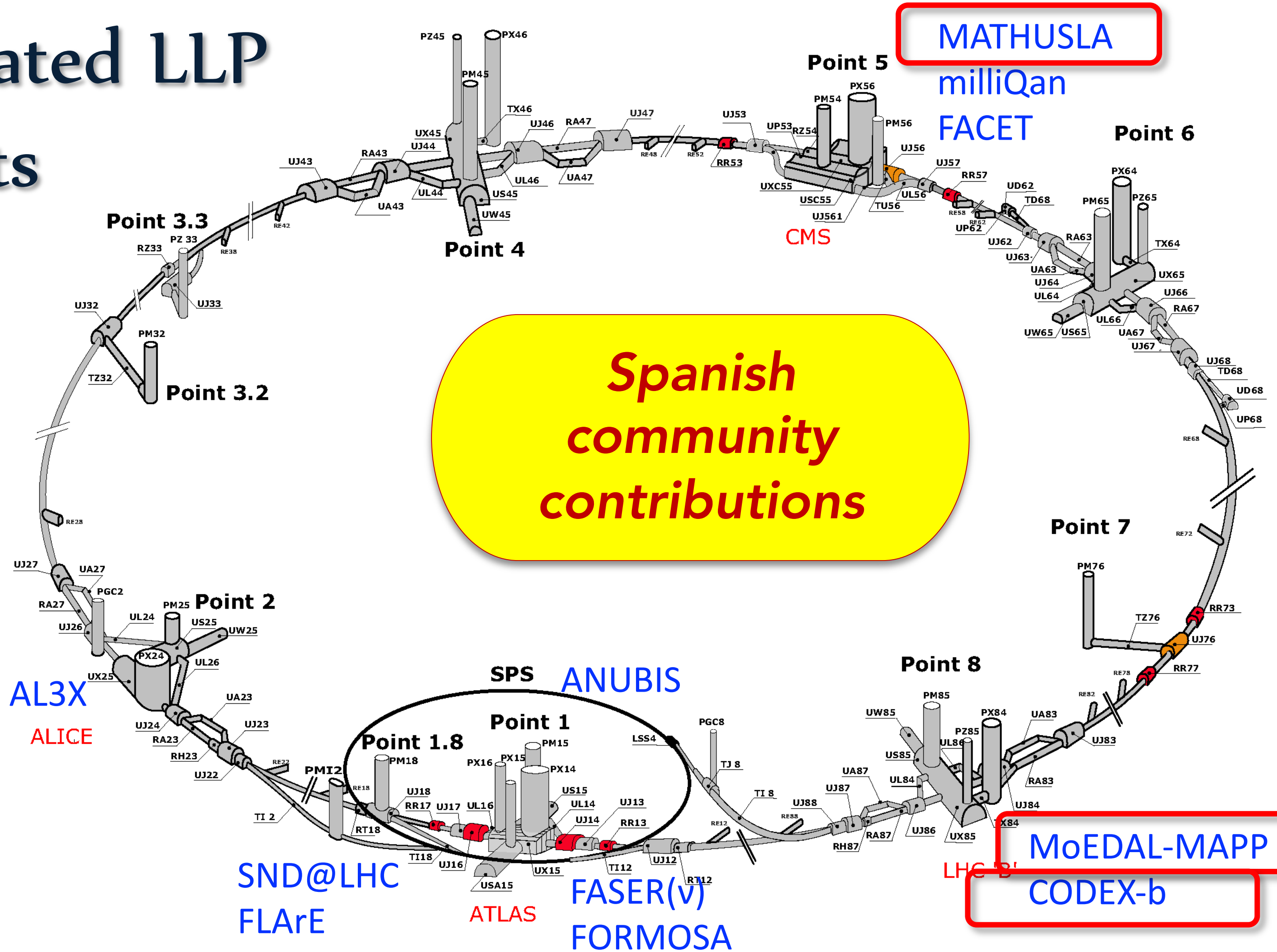
LHC dedicated LLP experiments

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



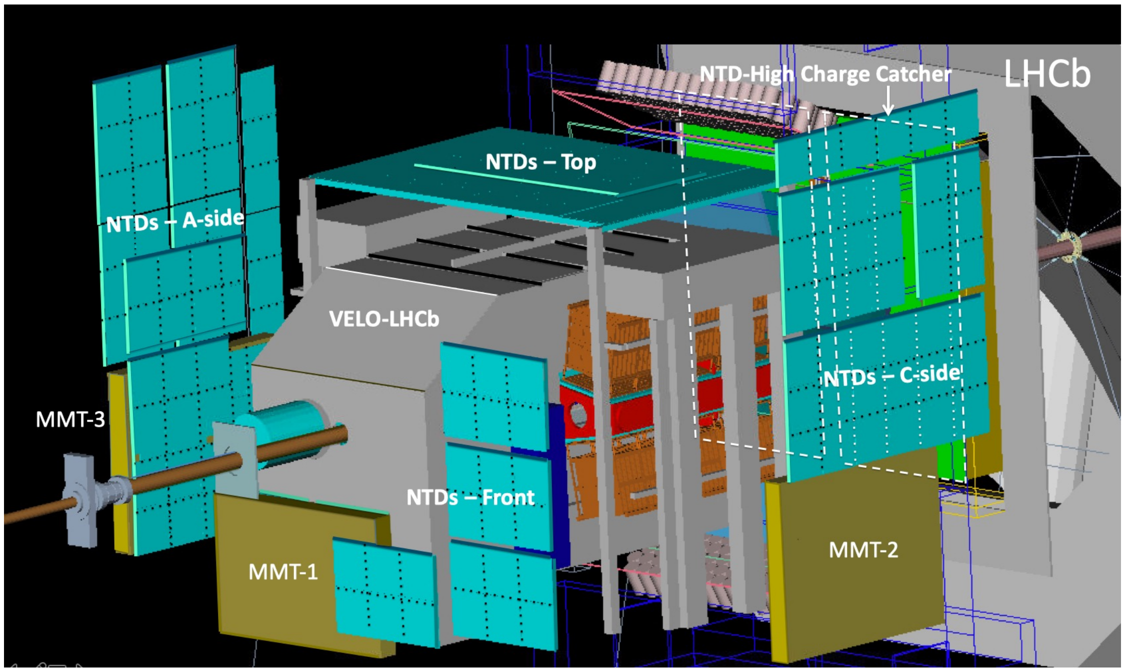
FASER Collaboration, *First neutrino interaction candidates at the LHC*, Phys.Rev.D 104 (2021) L091101

LHC dedicated LLP experiments



MoEDAL – Monopole & Exotics Detector At LHC

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



Optimised for **highly ionising particles** – magnetic & electric charges

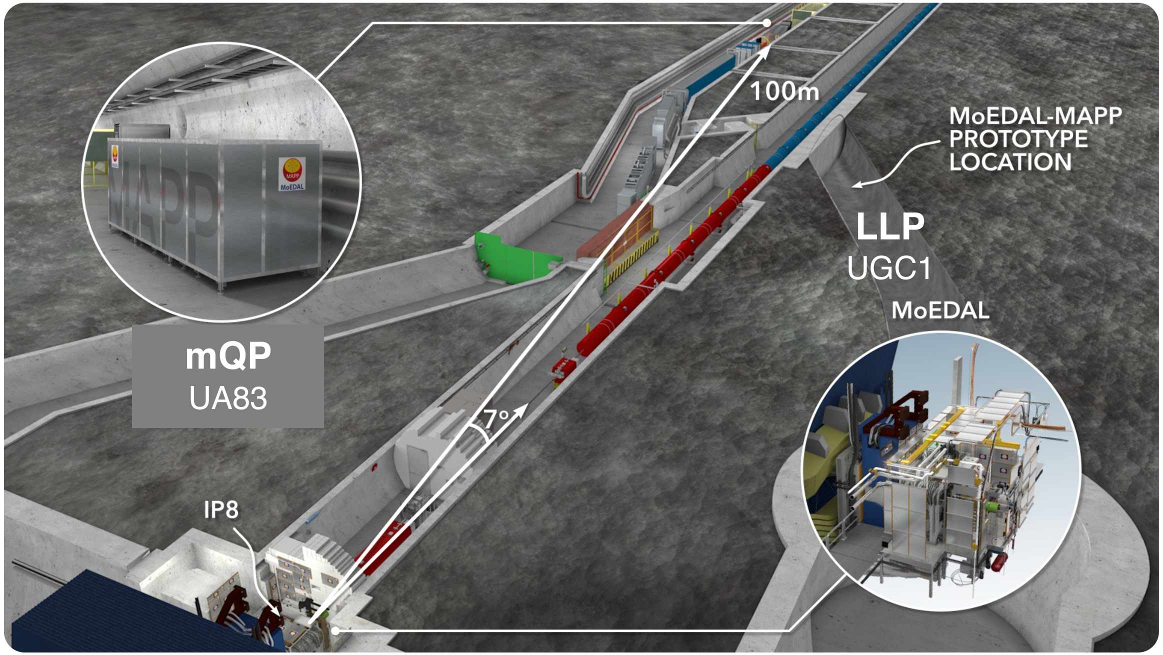
- magnetic monopoles
- SUSY sleptons & R-hadrons
- doubly charged Higgs
- ν mass models
- KK extra dimensions
- D matter
- black-hole remnants

More info in: VAM, CERN EP Seminar, March 22nd, 2022

☞ *VAM's talk on MoEDAL in the afternoon*

MAPP – MoEDAL Apparatus for Penetrating Particles

1. **MAPP-mQP:** Core millicharged particle detector
   - particles with charges ≪ ***1e*** leaving a trace of low ionisation
2. **MAPP-LLP:** Very long-lived weakly interacting neutral particle detector



MAPP Phases

- Phase-1: mQP → Run-3
  Approved by CERN Research Board on Dec 1st 2021
- Phase-2: mQP + LLP → HL-LHC

Pinfold, Phil.Trans.Roy.Soc.Lond.A 377 (2019) 20190382

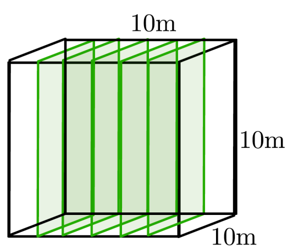
CODEX-b

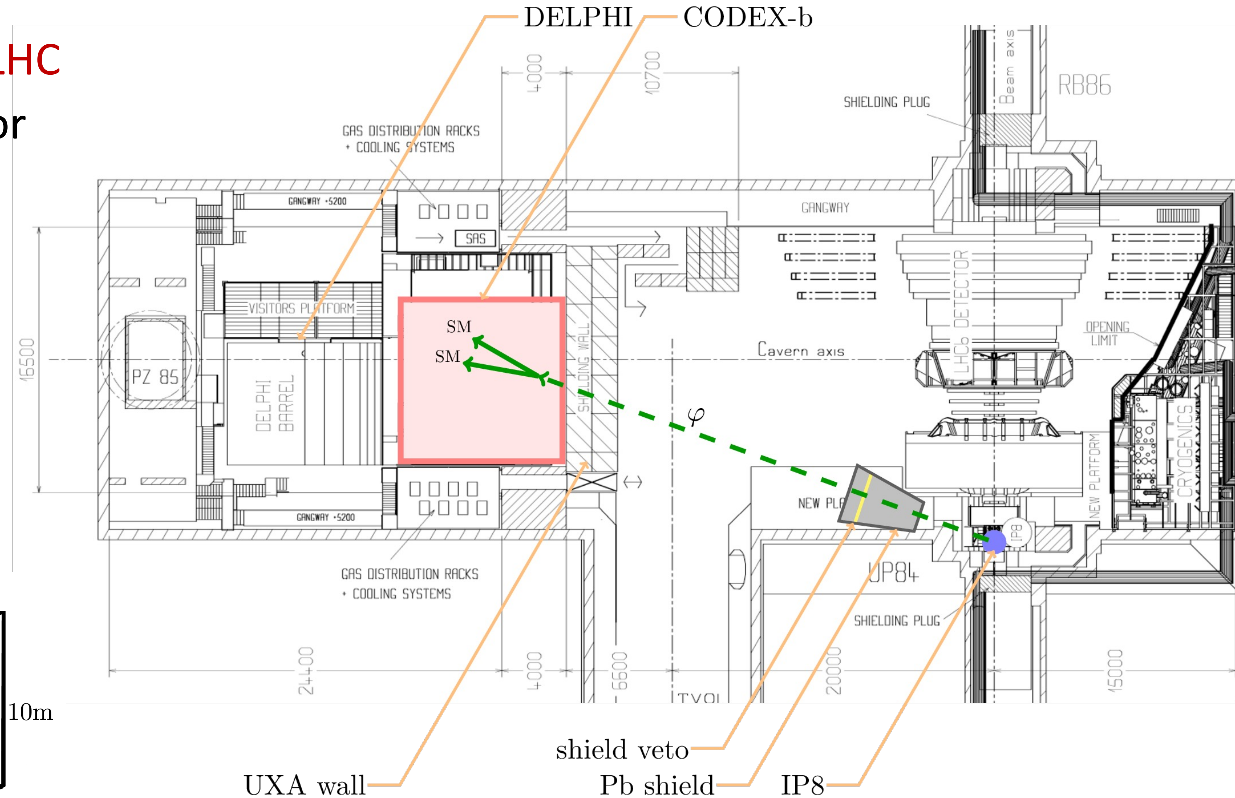
A COmpact Detector for EXotics at LHCb

Expression of interest: arXiv:1911.00481

IGFAE
Instituto Galego de Física de Altas Enerxías

- Transverse detector at the LHC
- **RPCs**: fast, precise, cheap for large area
- 6 RPC layers at 4 cm intervals on each box face with 1 cm granularity
- Integration with LHCb trigger-less readout
- CODEX-β demonstrator ($2\times2\times2$ m^3) planned for Run-3



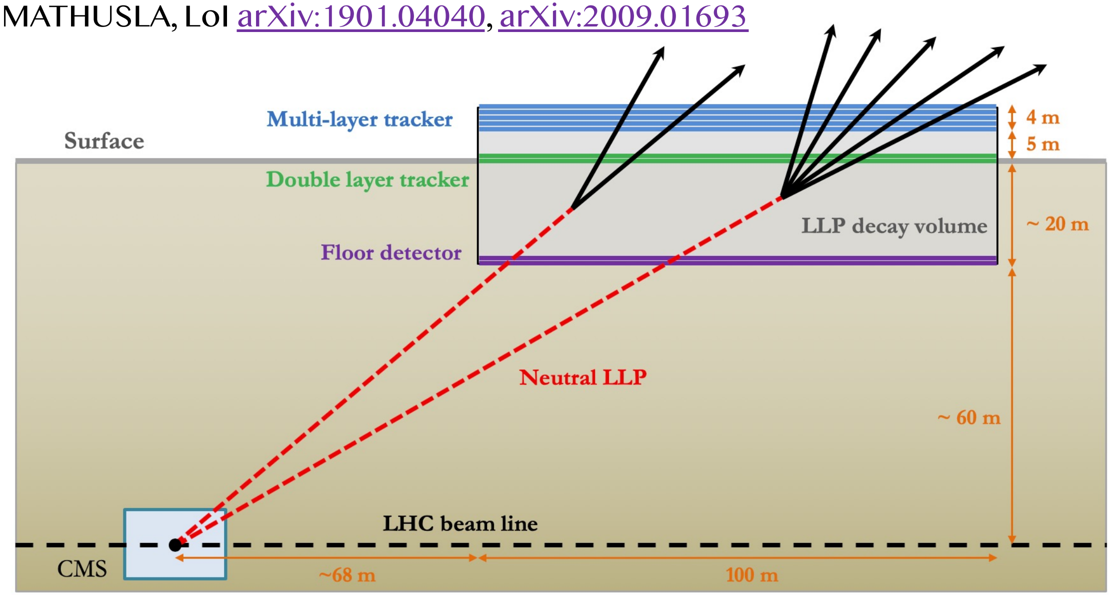


MATHUSLA

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

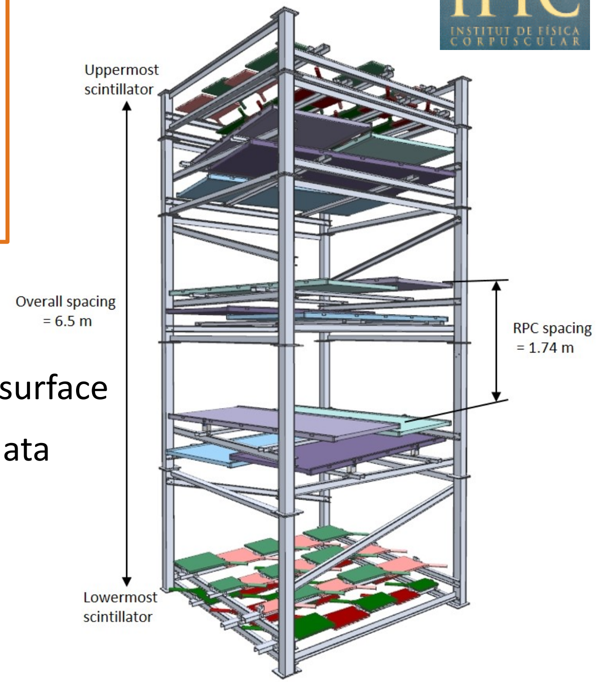
MATHUSLA, LoI arXiv:1901.04040, arXiv:2009.01693



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

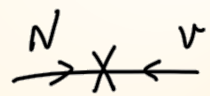
2018 data



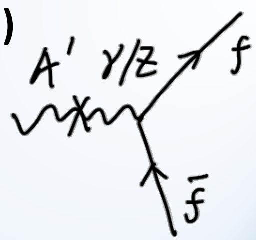
MATHUSLA, Nucl.Instrum.Meth.A 985 (2021) 164661 arXiv:2005.02018

Hidden sector & long-lived particles

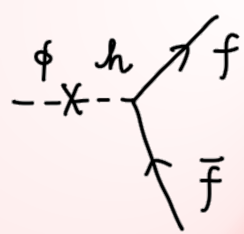
Heavy neutral leptons ("sterile neutrinos")
- explain SM ν masses (seesaw), DM, BAU
- weak semi-leptonic decays of hadrons, W, Z



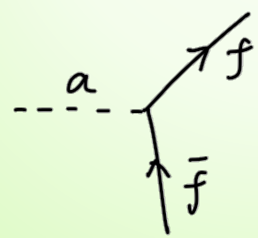
Dark vectors ("Dark Photons")
- adding U(1) gauge group to SM, kinetic mixing with γ/Z
- light neutral meson decays, milli-charged particles

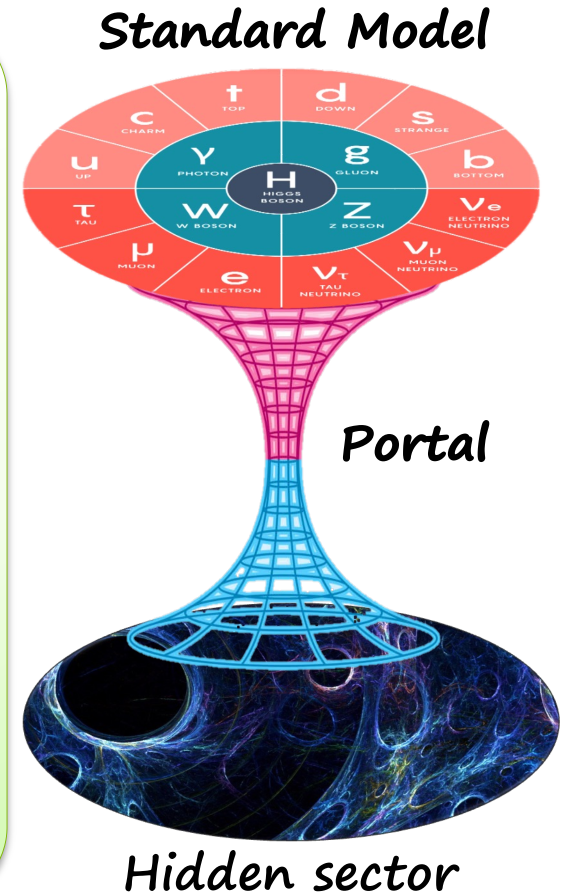


Dark scalars ("Dark Higgs")
- neutral singlet scalers that couple to the SM Higgs field
- produced in penguin decays of K, D, B mesons



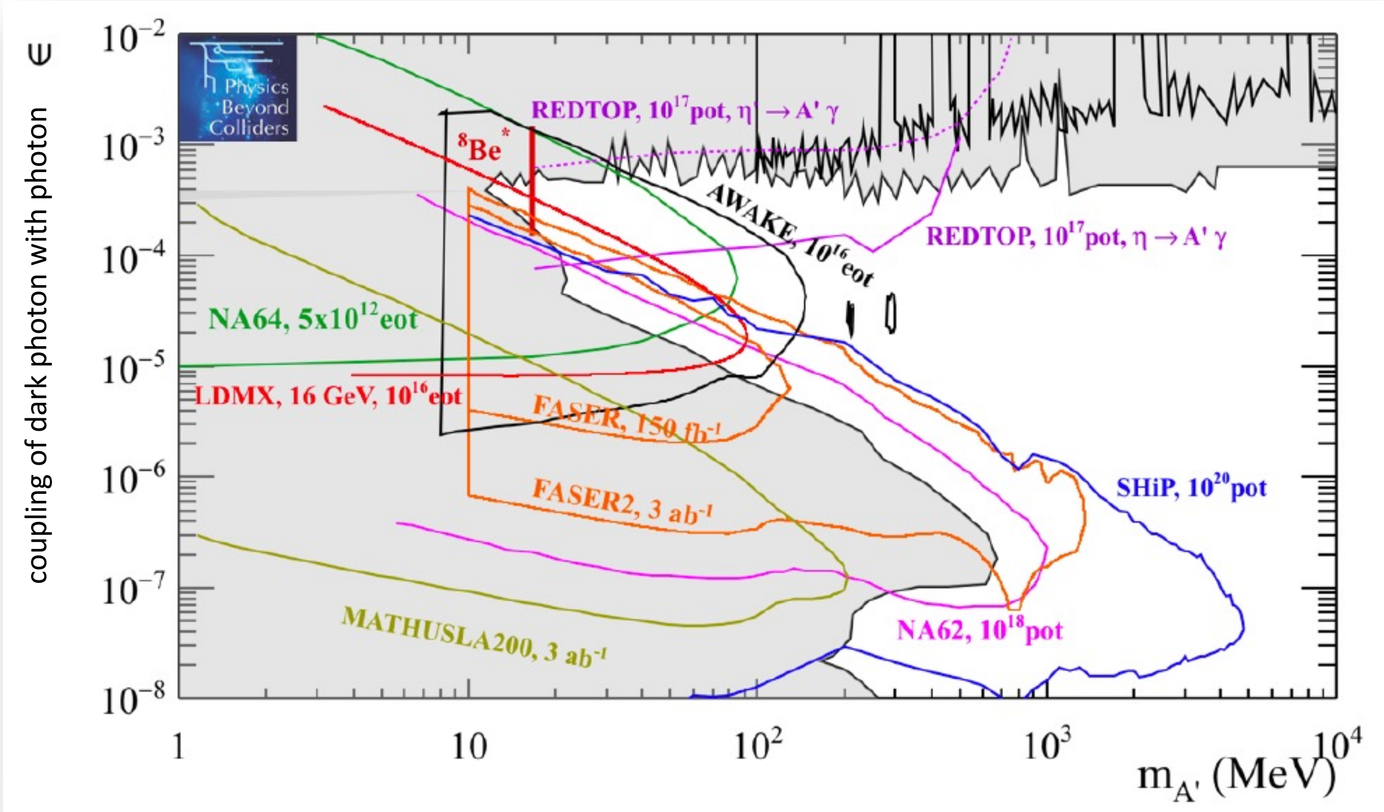
Axion-like particles ("ALPs")
- solution of the strong CP problem
- generalisation of the axion model in MeV-GeV mass range





Example: minimal dark photon model

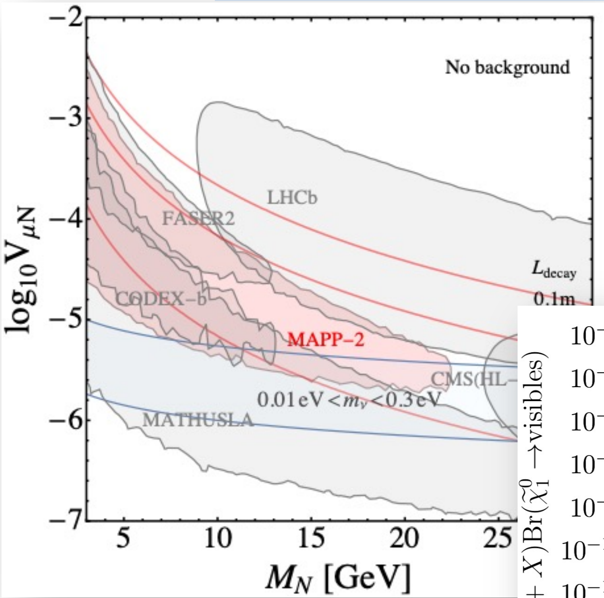
- Adding a new hidden U(1) with massive gauge field A'_{μ}, the *dark photon*
- DM assumed to be either heavy or contained in a different sector
- Dark photon decays to SM states (*visible* decays)



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

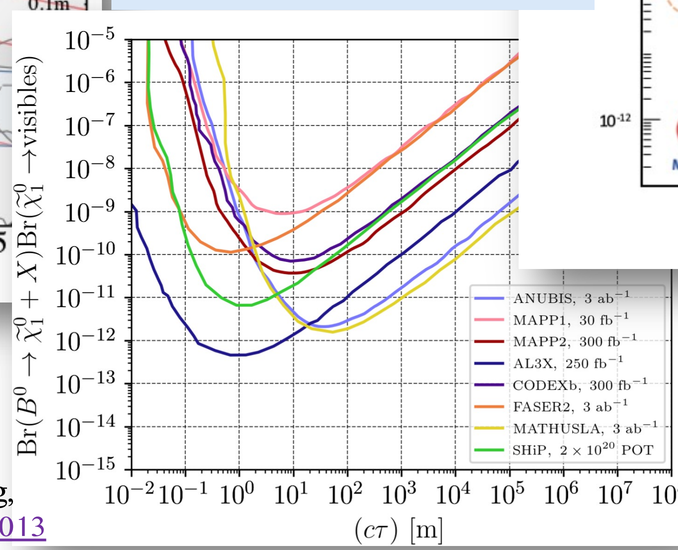
LLPs predicted in many theoretical scenarios

Heavy neutrinos $pp \to Z' \to N\bar{N}$



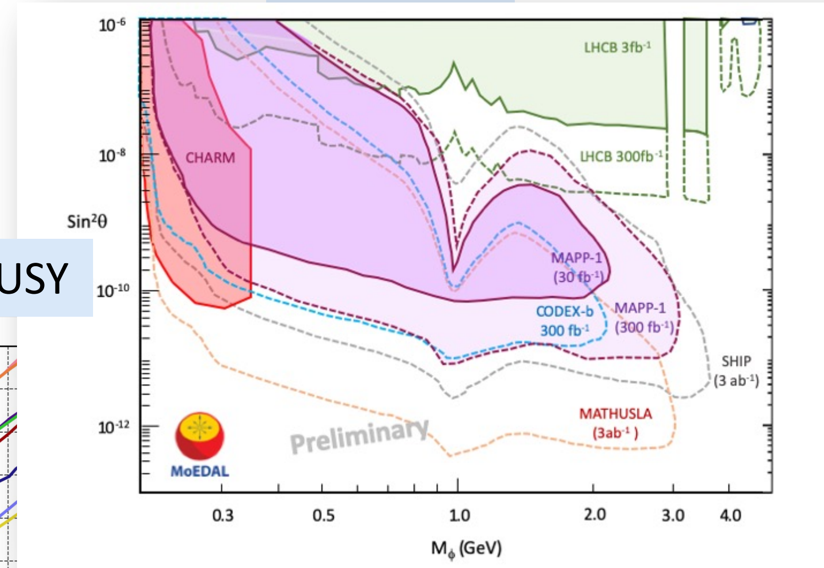
Deppisch, Kulkarni, Liu, Phys.Rev.D 100 (2019) 035005

R-parity violating SUSY



Dreiner, Günther, Wang, Phys.Rev.D 103 (2021) 075013

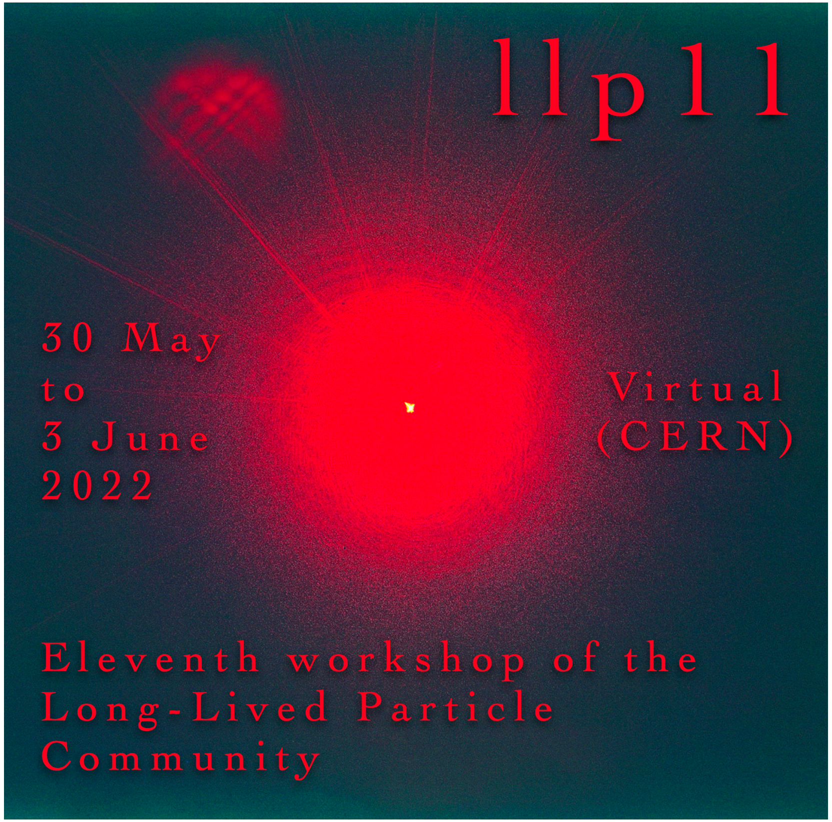
Dark Higgs



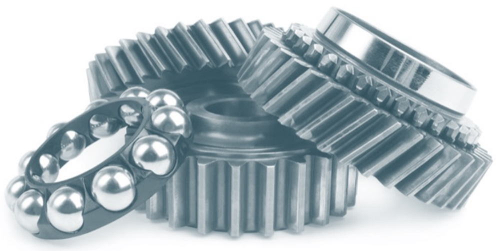
adopted from Gligorov, Knapen, Papucci, Robinson, Phys.Rev.D 97 (2018) 015023

Further reading

- LHC LLP whitepaper – J.Phys.G 47 (2020) 090501 [arXiv:1903.04497]
- Physics Beyond Collider at CERN – BSM Report J.Phys.G 47 (2020) 010501
- Feebly-Interacting Particles: FIPs 2020 Workshop Report, arXiv:2102.12143
- VAM, *LHC experiments for long-lived particles of the dark sector*, arXiv:2111.03036
- 11th Workshop of the LHC LLP Community, May-June 2022
  - Registration still open!

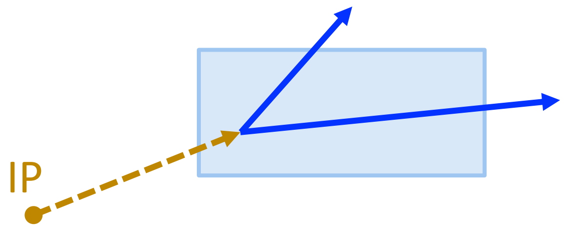


Spares

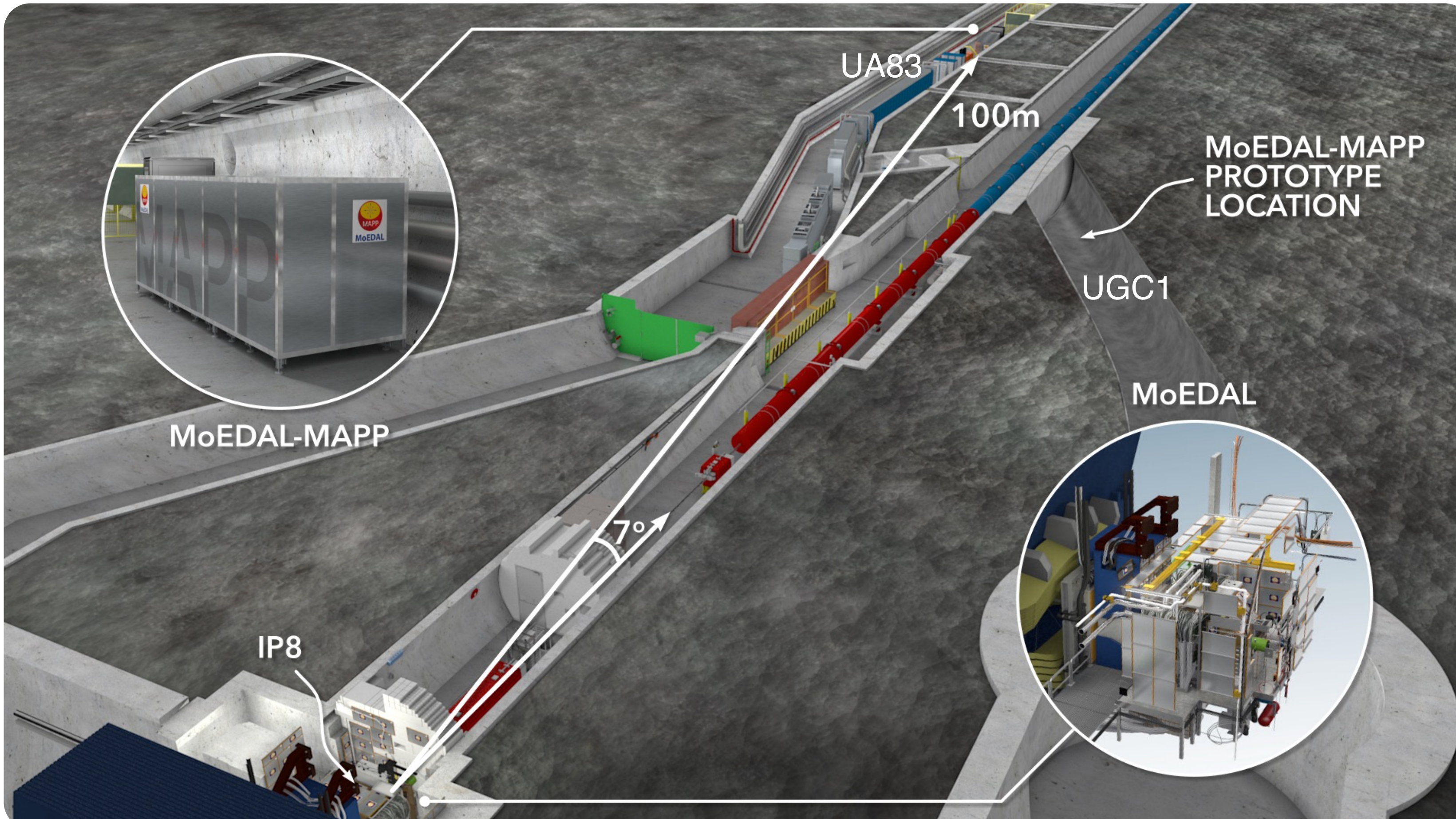


Long-lived neutral particles decaying in detector volume

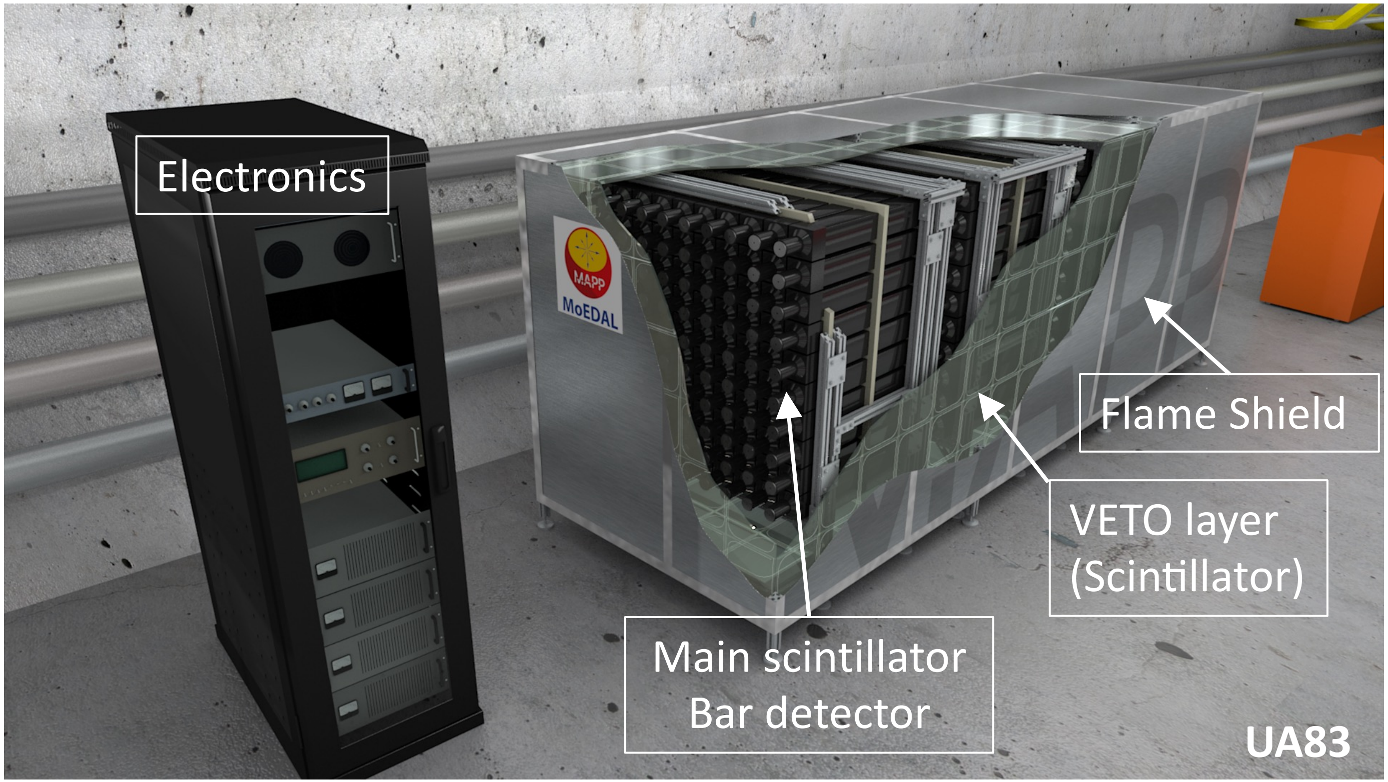
- MoEDAL-MAPP
- FASER
- CODEX-b
- MATHUSLA
- AL3X
- ANUBIS
- FACET



MAPP location



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

MAPP-mQP Phase-1 installation

MoEDAL

complete section

MAsive Timing Hodoscope for Ultra Stable neutraL pArticles

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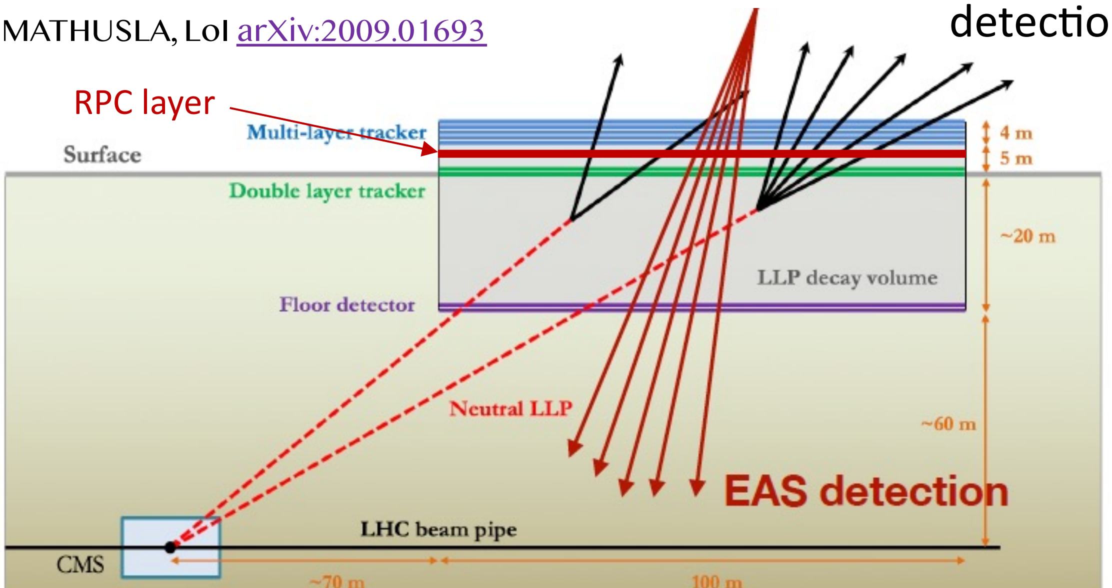
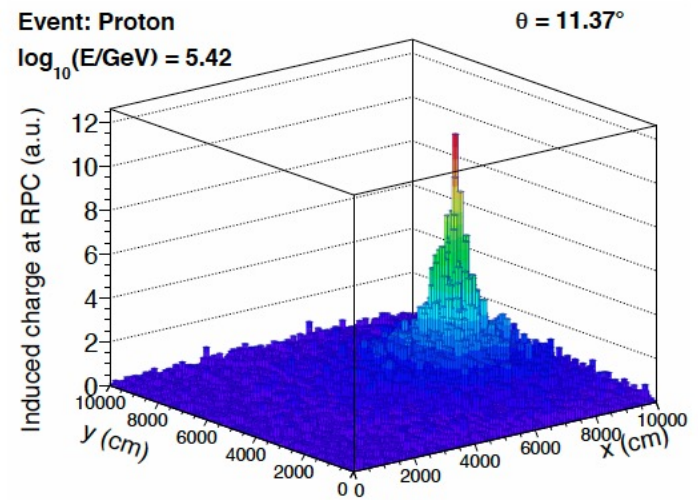
MATHUSLA, LoI arXiv:2009.01693



Indirect detection of cosmic rays through extensive air showers (EAS)

- Adding an RPC layer to the MATHUSLA detector would significantly enhance EAS detection

Charge density at the RPC



FASER

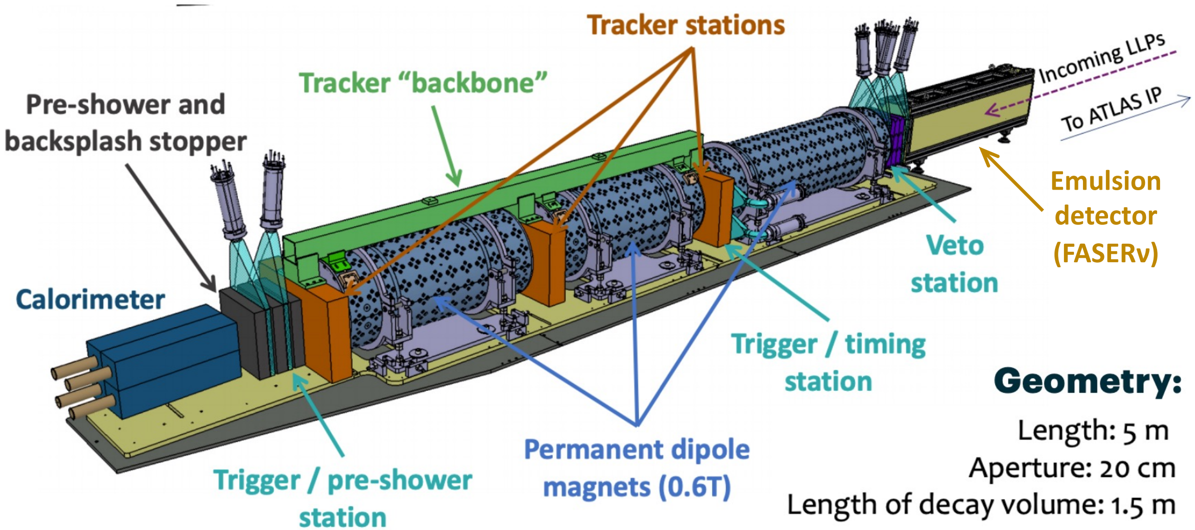
Forw**A**rd **S**earch **E**xpe**R**iment at the LHC

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

FASER will be situated along the beam collision axis line of sight (LOS) in TI12 tunnel

- ~480 m from IP1 (ATLAS)
- after beams start to bend
- a few meters from the LHC beamline
- transverse radius of 10 cm covering the mrad regime (η > 9.1)

FASER, Phys.Rev.D 99 (2019) 095011 arXiv1811.12522

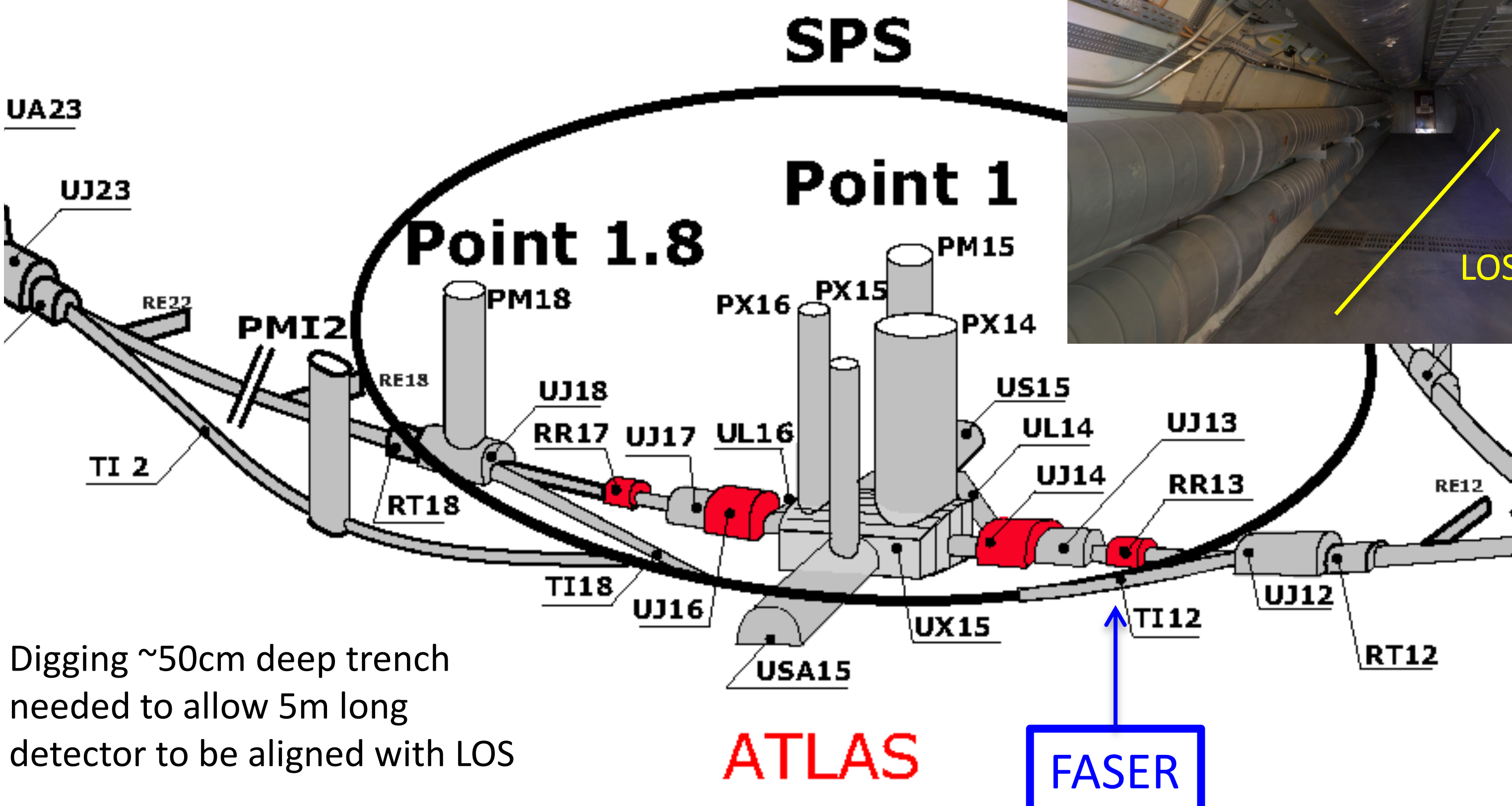


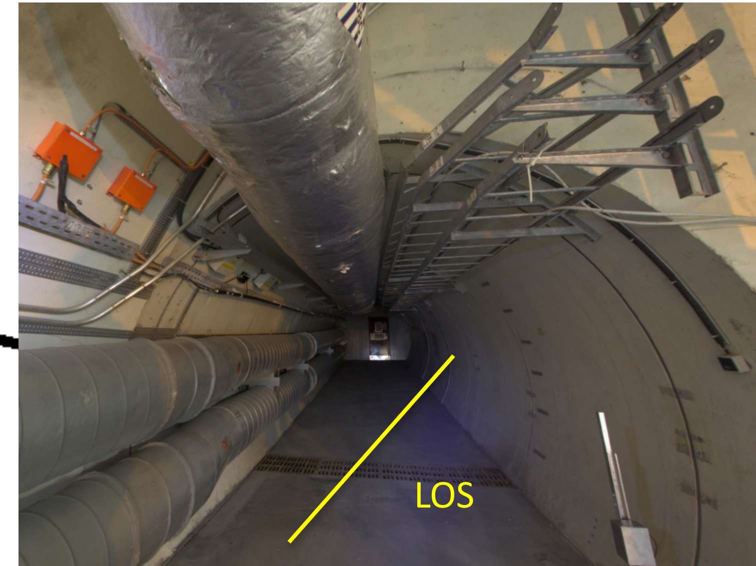
Geometry:

Length: 5 m
Aperture: 20 cm
Length of decay volume: 1.5 m

- **FASERν** To detect and measure collider neutrinos
  First neutrino interaction candidates at the LHC, arXiv:2105.06197
- **FASER2** for HL-LHC with a larger radius of ~1 m

FASER location: TI12

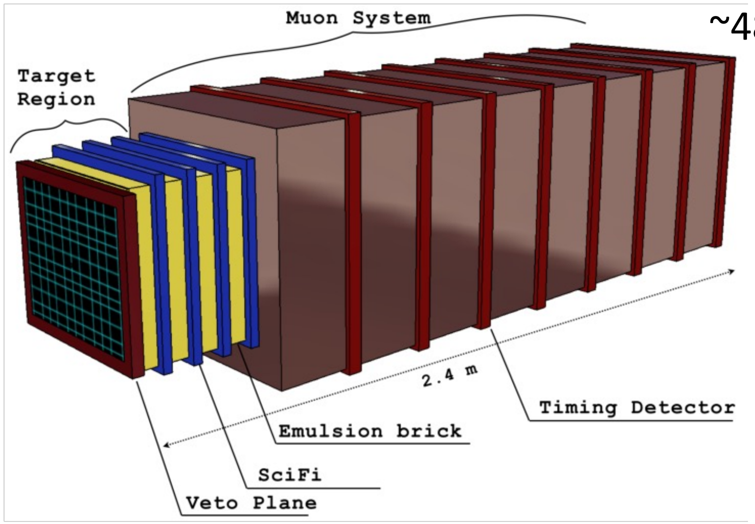




Digging ~50cm deep trench needed to allow 5m long detector to be aligned with LOS

SND@LHC – Scattering and Neutrino Detector at the LHC

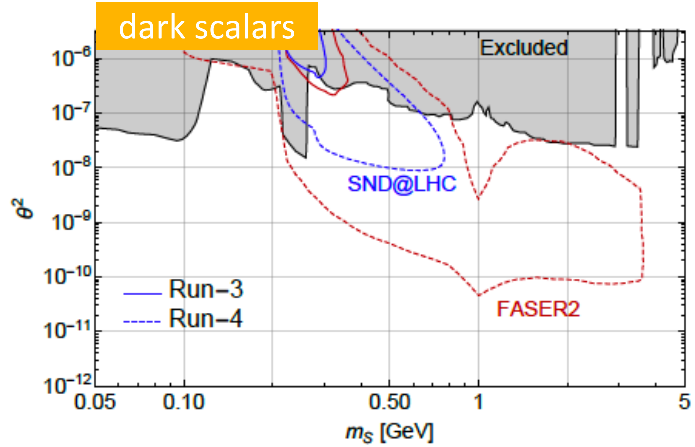
- Compact and stand-alone experiment designed to measure neutrinos produced at the LHC and search for FIPs in the unexplored range of **$7.2 < \eta < 8.6$**
- Detector will be a small-scale prototype of the SHiP experiment SND

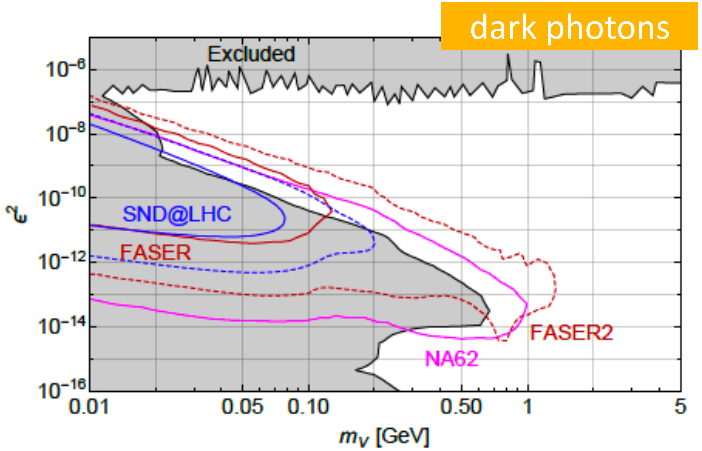


~480 m from IP1 (ATLAS)

Good spatial resolution of the SND@LHC emulsion
→ decays into two charged particles may be distinguished from ν scattering events

SHiP collab., arXiv:2002.08722

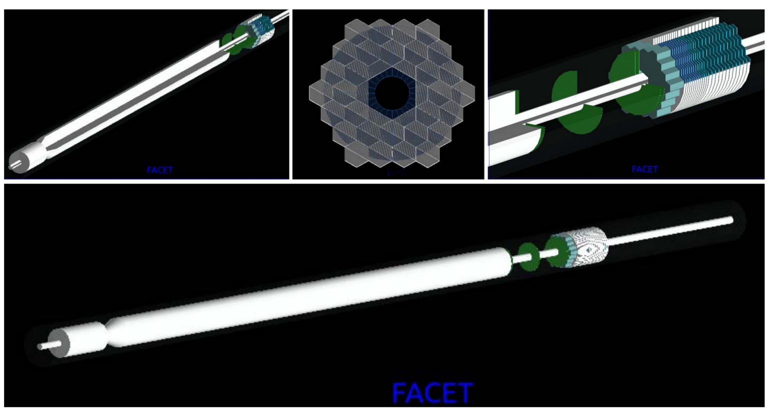


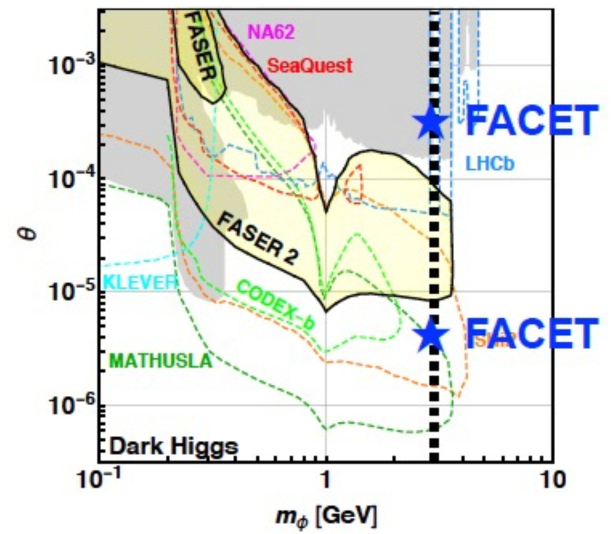


Boyarsky et al., arXiv:2104.09688

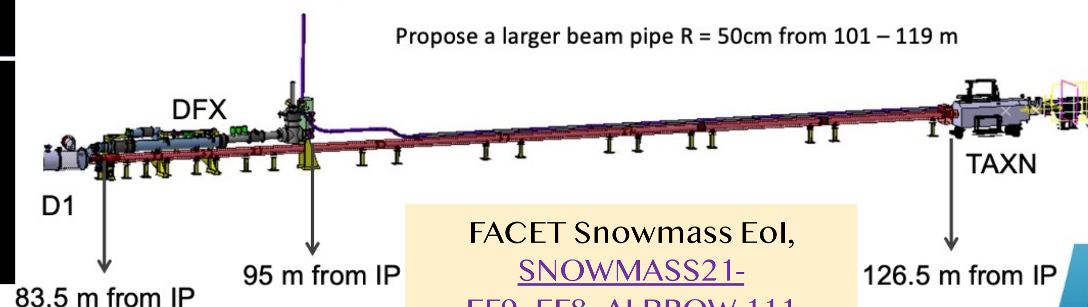
FACET – Forward-Aperture CMS ExTension

- Multi-particle spectrometer
  - at z ~ +100 m from the IP5 (CMS)
  - radius of ~50 cm and coverage 6 < η < 8
- Much closer to the IP and much larger decay volume than FASER
- If approved, FACET will operate in HL-LHC





Adapted from Phys.Rev.D 99 (2019) 095011 arXiv1811.12522



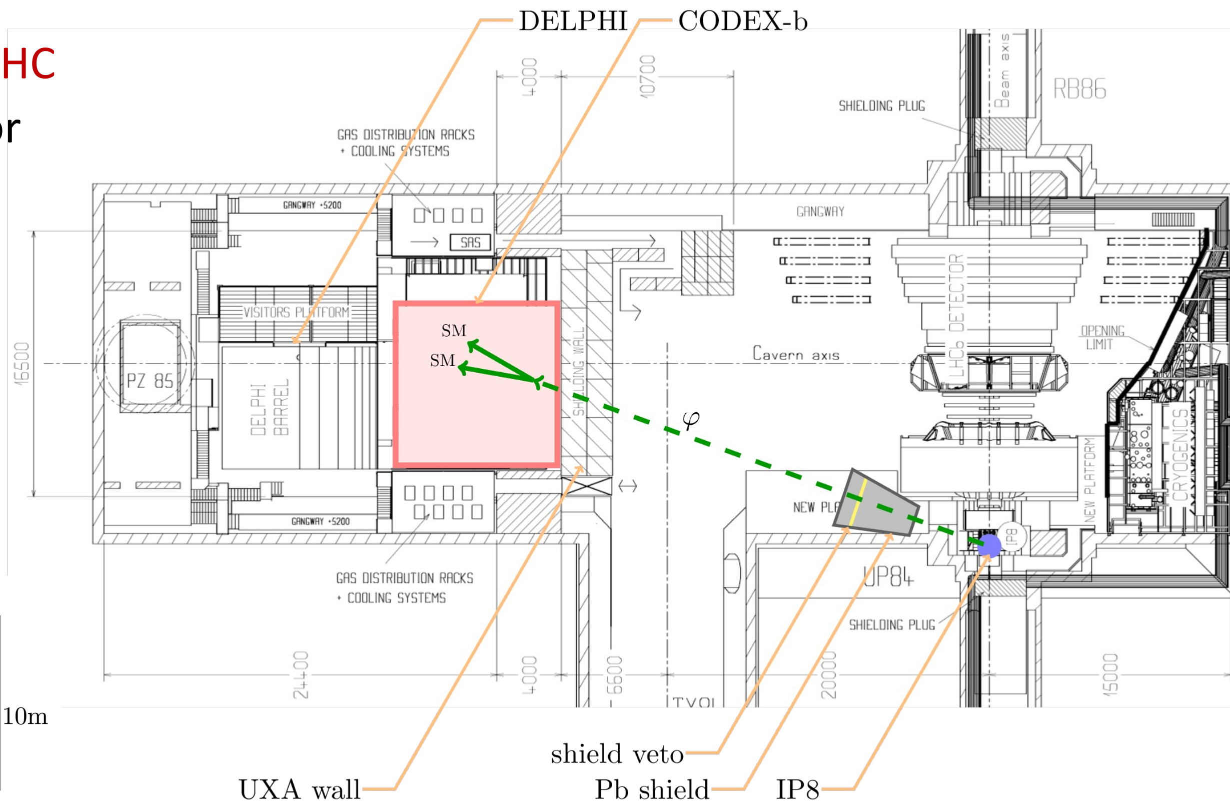
FACET Snowmass EoI, SNOWMASS21-EF9_EF8_ALBROW-111

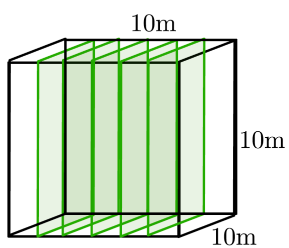
CODEX-b

A COmpact Detector for EXotics at LHCb

Expression of interest: arXiv:1911.00481

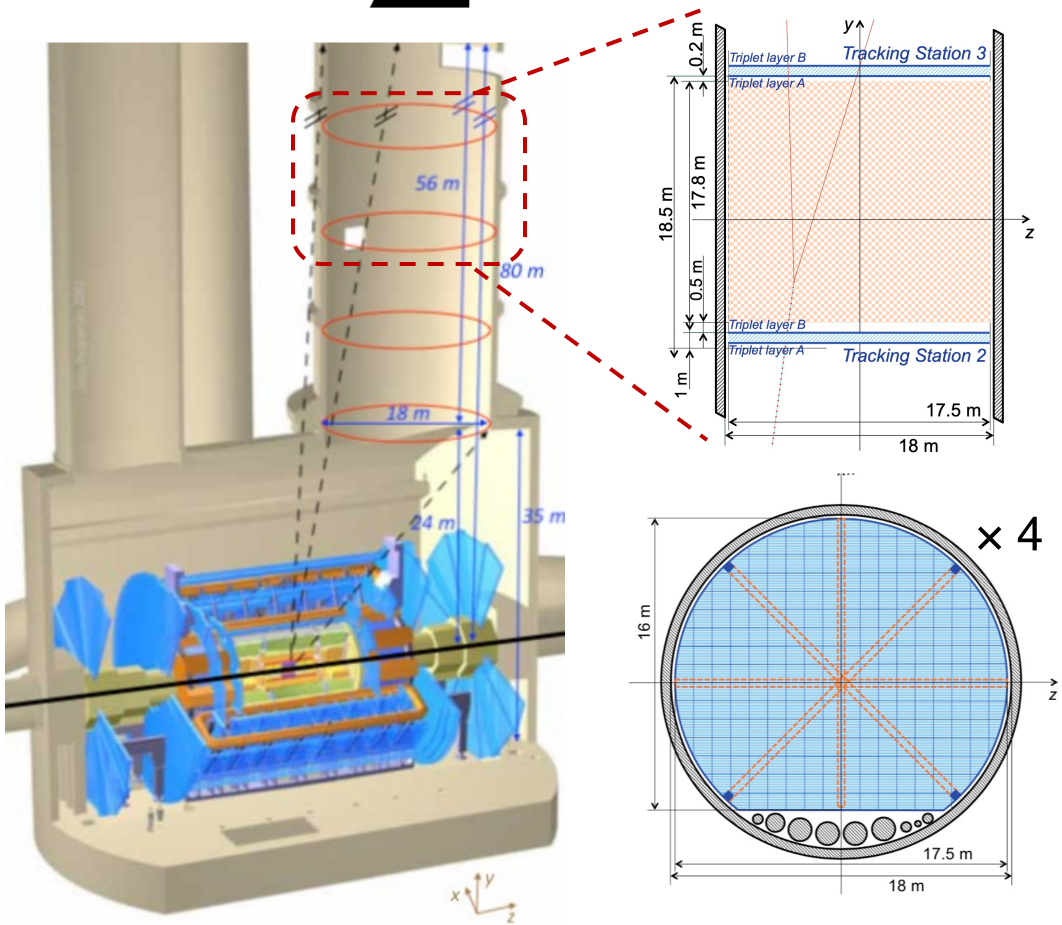
- Transverse detector at the LHC
- **RPCs**: fast, precise, cheap for large area
- 6 RPC layers at 4 cm intervals on each box face with 1 cm granularity
- Integration with LHCb trigger-less readout
- CODEX-β demonstrator ($2\times2\times2$ m^3) planned for Run-3





ANUBIS

AN Underground Belayed In-Shaft search experiment



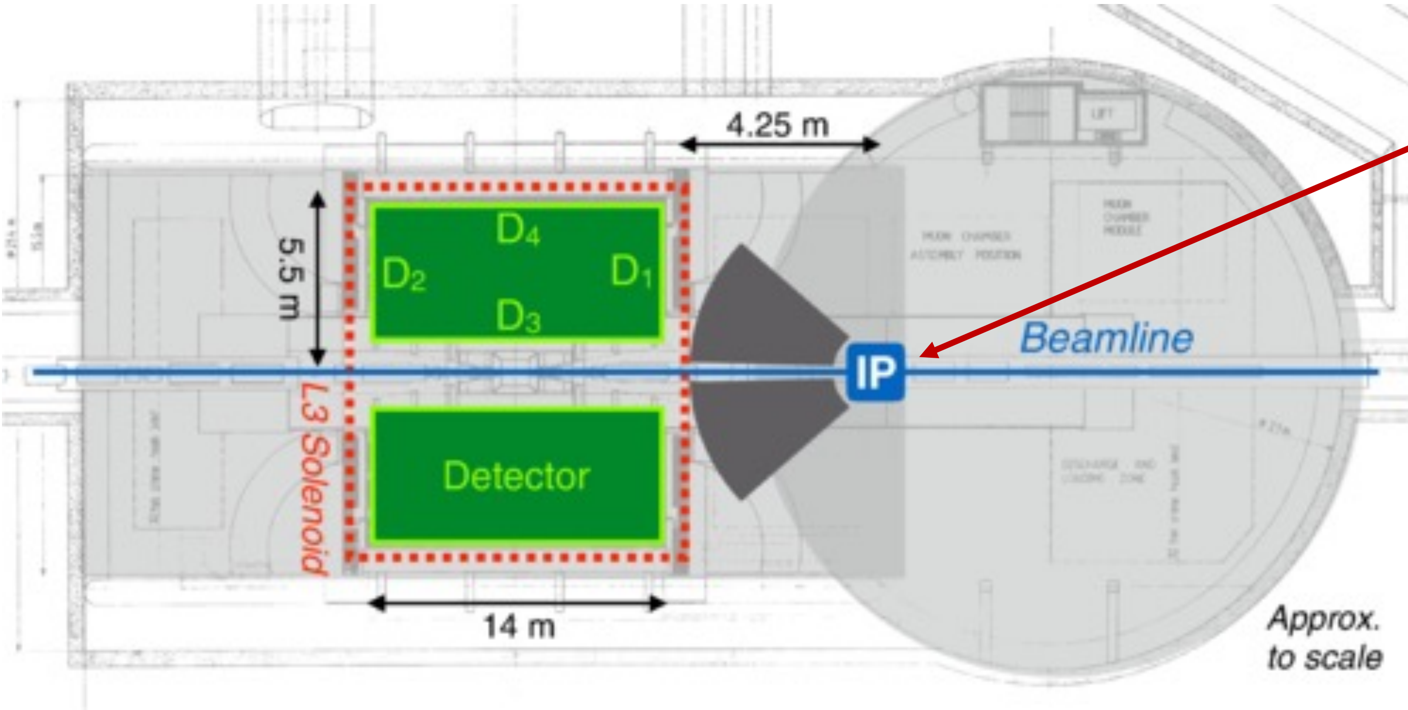
- Four evenly spaced tracking stations with a cross-sectional area of 230 m^2 each
- Tracking stations same RPC technology as new ATLAS layers
- ATLAS can be used as an active veto of SM activity
- Projective decay volume optimises acceptance for different lifetimes
- Planning to install a demonstrator for Run 3

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

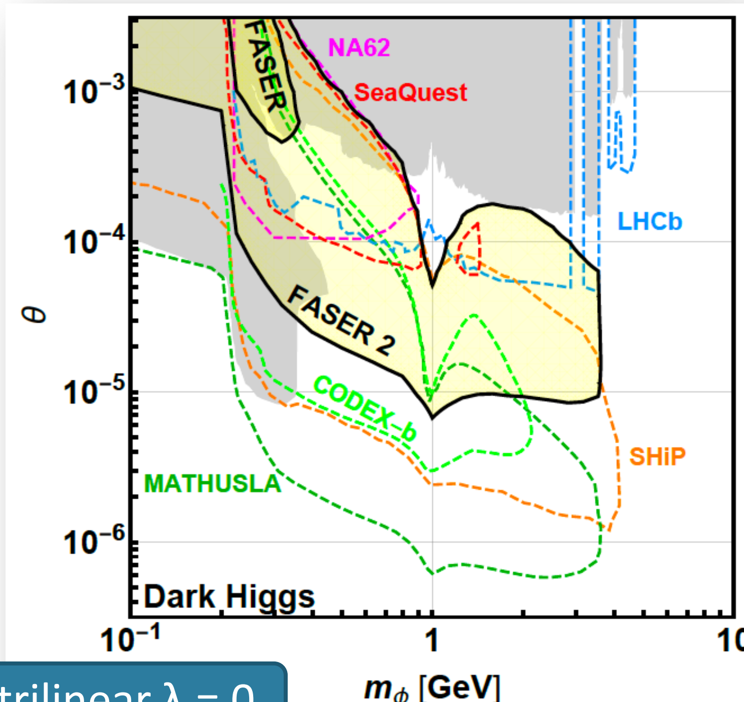
Gligorov, Knapen, Nachman, Papucci, Robinson, [Phys. Rev. D 99 (2019) 015023]

Scalar portal – dark Higgs

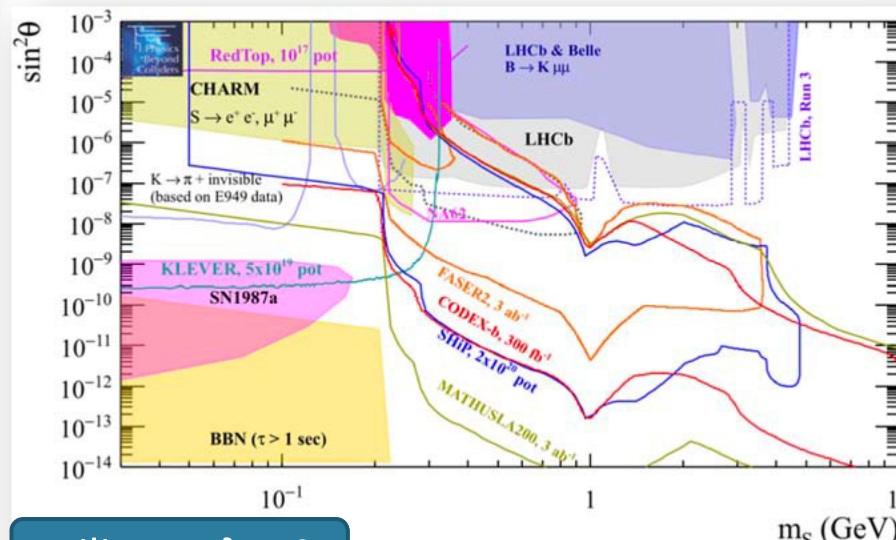
$$\mathscr{L} = \mathscr{L}_{SM} + \mathscr{L}_{DS} + \mu^2 S^2 - \frac{1}{4}\lambda_S S^4 - \epsilon_H S^2 |H|^2$$

- At loop level S can induce flavour-changing transitions, e.g. lead to decays K → πS, B → K(*)S, etc
- Coupling constant λ can lead to pair-production of S
- BR(h → SS) ≈ 10^{-2} assumed for complementarity to H → inv. LHC searches

FASER, arXiv:1901.04468



trilinear λ = 0

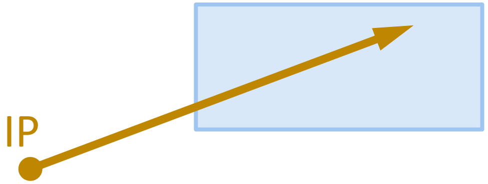


trilinear λ ≠ 0

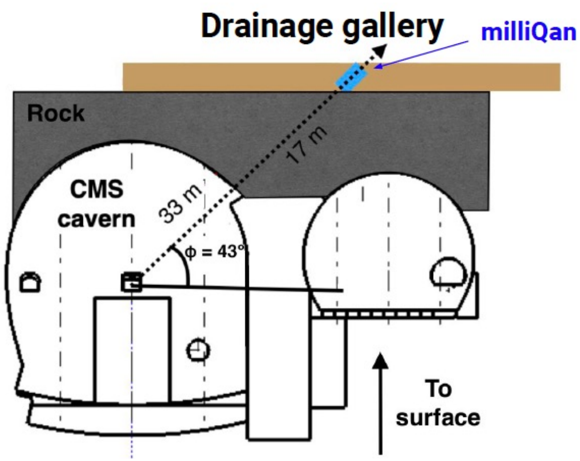
PBC–BSM Report, J.Phys.G 47 (2020) 010501

Milli-charged particles

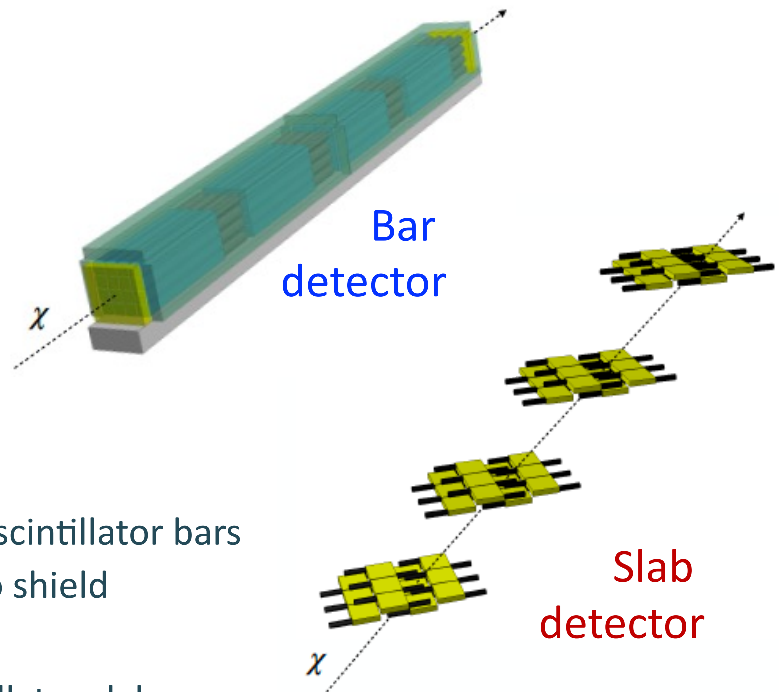
- milliQan
- MAPP-mQP
- FORMOSA



Detector & demonstrator



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



Two detectors for Run-3:

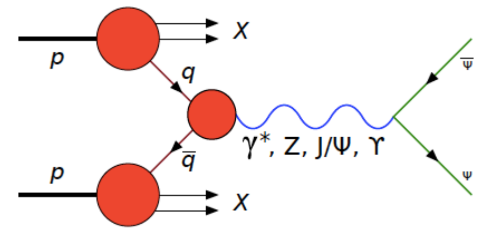
- Bar detector
  - 0.2 m × 0.2 m × 3 m plastic scintillator bars
  - surrounded by active μ veto shield
- Slab detector
  - 40 cm × 60 cm × 5 cm scintillator slabs
  - increased reach for heavier mCPs

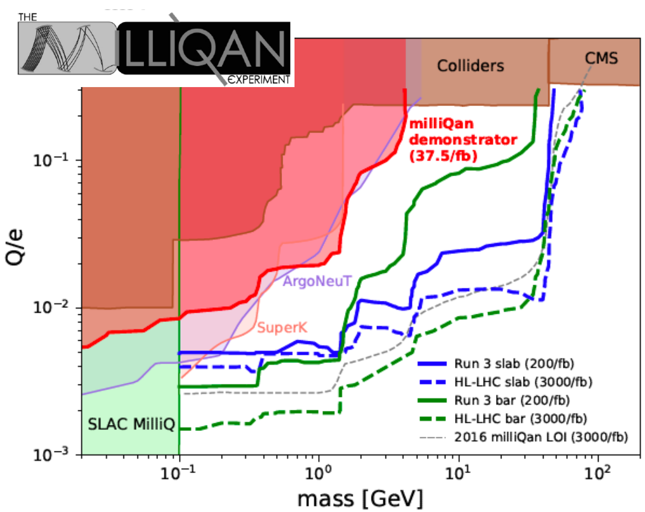
milliQan, arXiv:2104.07151

milliQan, PRD 102 (2020) 032002 [arXiv:2005.06518]

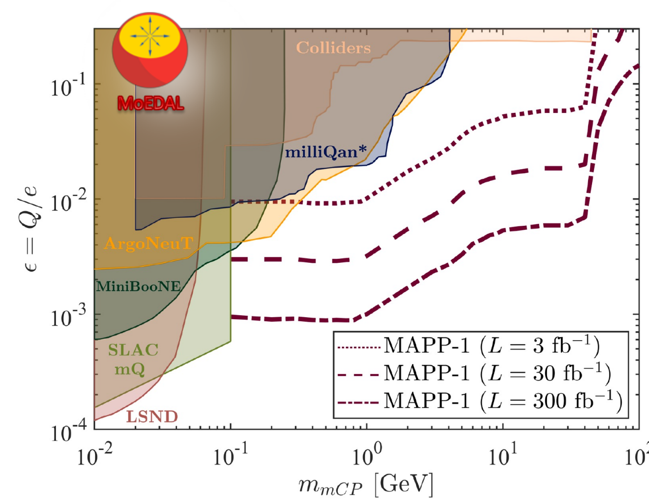
Millicharged particles in dark QED

- New massless U(1) gauge field of a dark photon A' (via kinetic mixing) and a massive fermionic field ψ are added to the SM
- Field A' redefinion ➔ coupling between ψ and SM hypercharge γ/Z
- Field ψ (mCP) is charged under hypercharge with a *fractional charge* proportional to mixing parameter ϵ





milliQan, arXiv:2104.07151



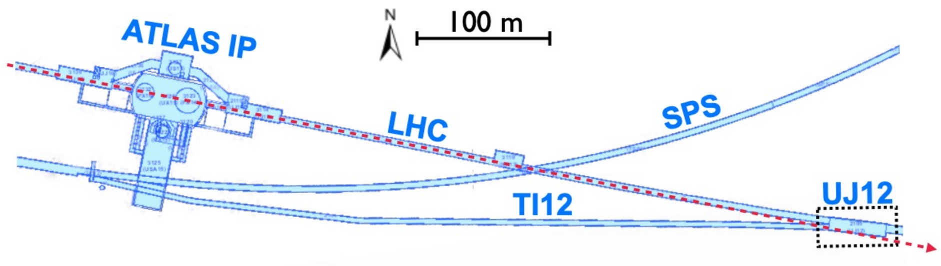
M. Staelens, PhD thesis, U. Alberta

MAPP-mQP & **milliQan** expect low mass (0.1-1 GeV) sensitivity to mCP with **Q ~ 10^{-3}e**

Increased reach for both mass and charge expected with FORMOSA experiment

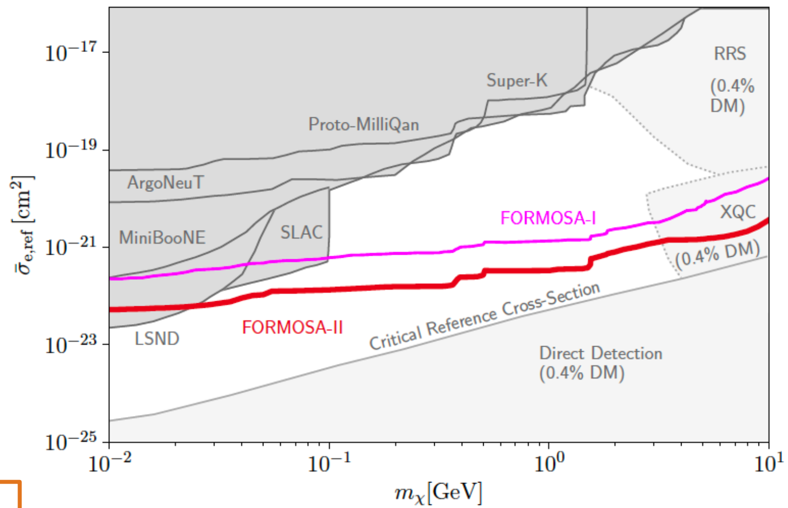
FORMOSA – FORward MicrOcharge SeArch

- Scintillator-based detector to be hosted in the LHC Forward Physics Facility (FPF), an expanded UJ12 hall
- Propose to start in Run 3 by moving the milliQan demonstrator to UJ12



Strongly interacting dark matter (SIDM)

- DM-SM Interaction too strong that attenuation stop the particles from reach the direct detection detector [Emken, Essig, Kouvaris, Sholapurkar, JCAP09(2019)070 1905.06348]
- DM is millicharged in the limit of zero dark-photon mass
- SIDM in the sub-GeV scale



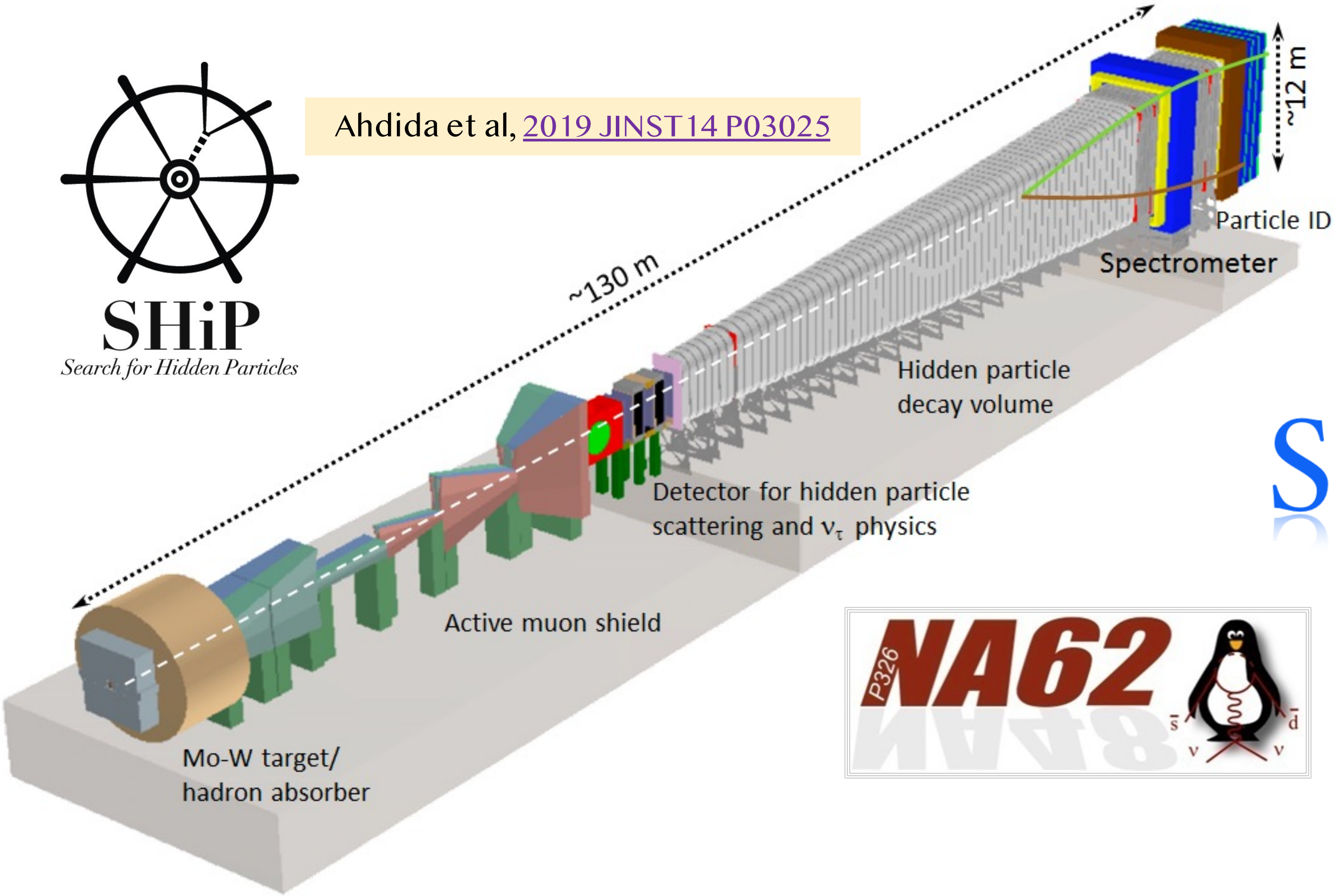
Foroughi-Abari, Kling, Tsai, arXiv:2010.07941

FORMOSA can help close the millicharged SIDM window

Beyond LHC: beam-dump, neutrino, … experiments

SHiP
Search for Hidden Particles

Ahdida et al, 2019 JINST 14 P03025



NA64

SoLid

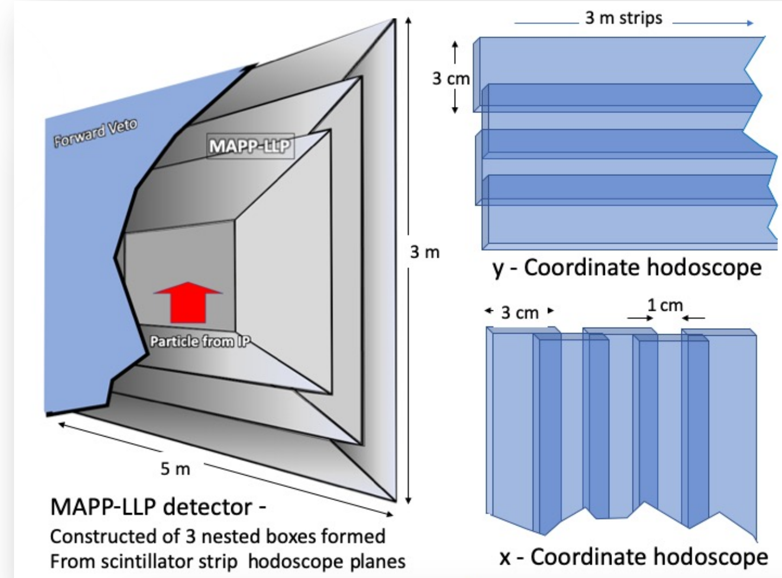
P326 NA62

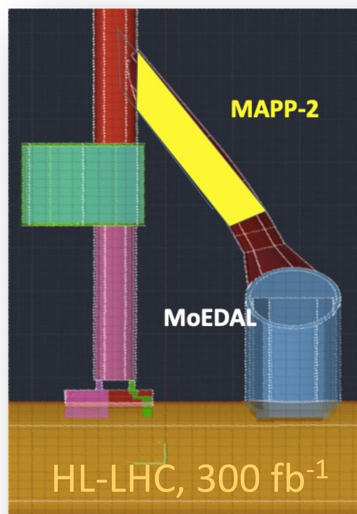
SeaQuest E906

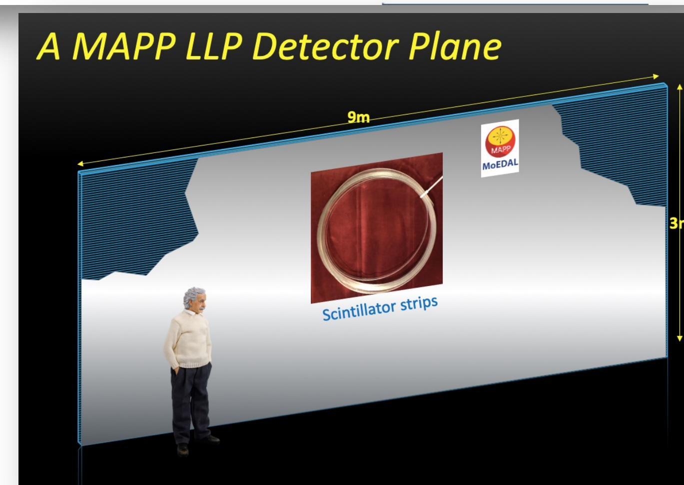
+ many more …

The MAPP-LLP detector

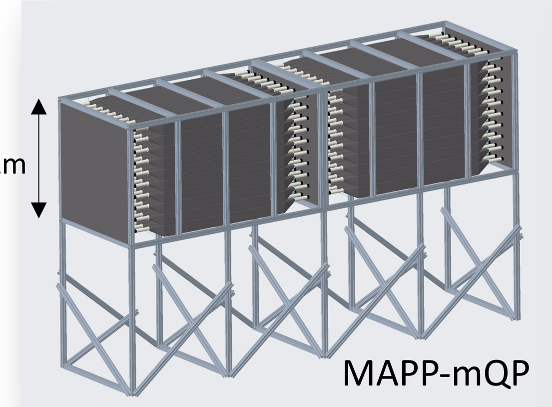
- “Box-within-a-box” or “Russian Doll” structure to detect charged tracks from neutral-particle decay
- The readout structure are scintillator strips in an *x-y* configuration readout by SiPMs
  - resolutions ~1cm × 1cm on each hit
- Using SiPM, fast scintillator and picoTDC chips MAPP plan to have 500 ps or better timing resolution

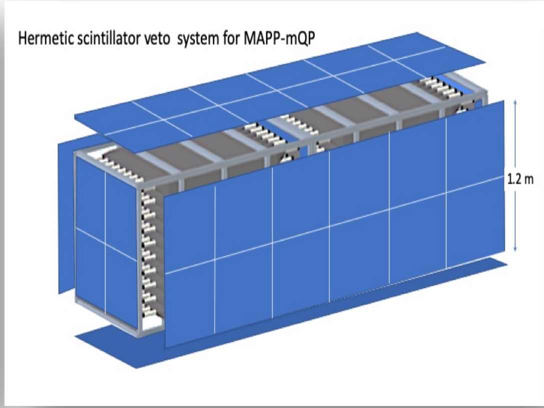


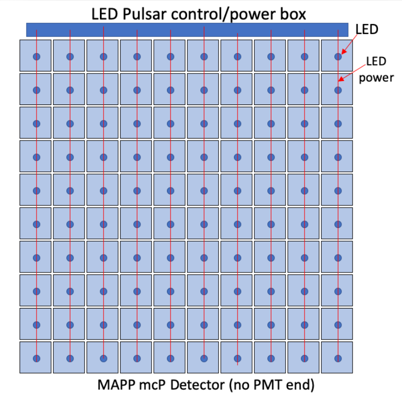




The MAPP-mQP detector







- 100 × (10 cm × 10 cm × 75 cm) scintillator bars in 4 lengths, 2 lengths/section readout by 4 low noise 3.1" PMTs, in coincidence
- No background from dark counts and radiogenic backgrounds
- Calibration by pulsed blue LEDs + neutral density filter

Prototype mQP installed in 2017
- 3×3 bars (~30×30 cm)
- ~10% of full detector

Millicharged particles in dark QED

- Introduce new, hidden U(1) with a massless field A', a "dark photon" that couples to a massive "dark fermion" ψ'

$$\mathcal{L}_{\text{dark-sector}} = -\frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\psi}'(\gamma^\mu\partial_\mu + ie'\gamma^\mu A'_\mu + iM_{\text{mCP}})\psi' - \frac{\kappa}{2}A'_{\mu\nu}B^{\mu\nu}$$

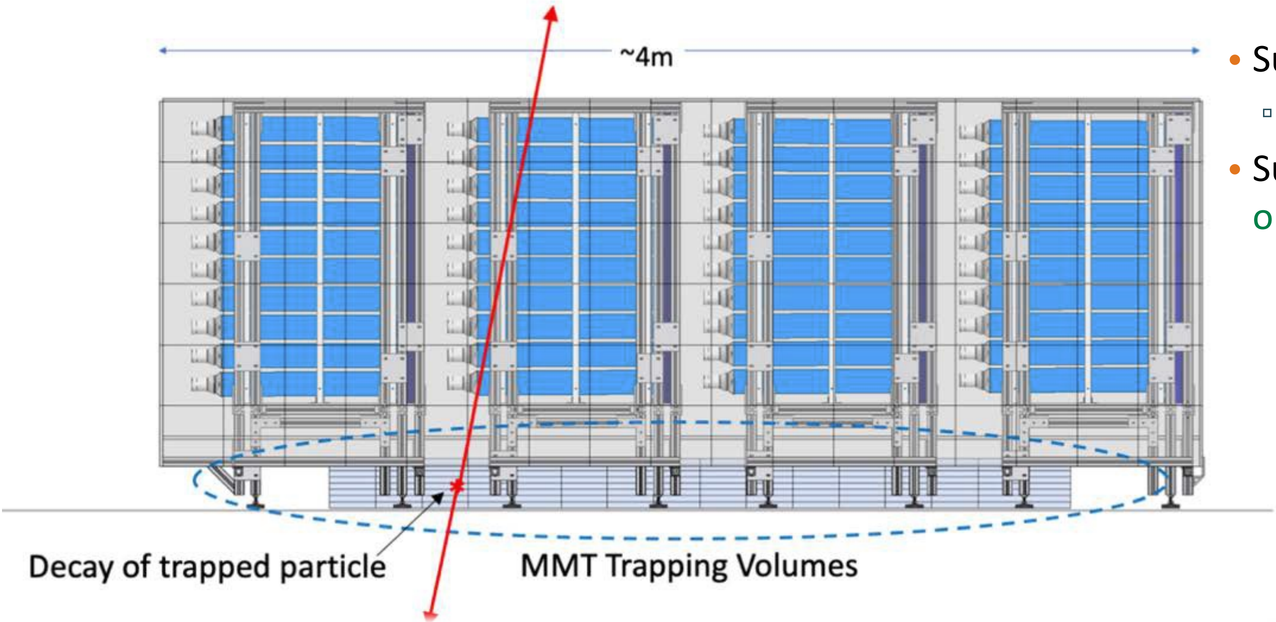
massless "dark photon" — "dark fermion" with mass M_{mCP}, charge e' — mixing term (κ << 1)

- ψ' has mass M_{mCP}, charge under the new U(1) of e' and field strength $A'_{\mu\nu}$
- ψ' couples to γ and Z with $\kappa e'\cos\theta_W$ & $-\kappa e'\sin\theta_W$, respectively
- ψ' acts as a field with a charge of $\kappa e' = e/\cos\theta_w \ll 1$ ☜ milli-charge

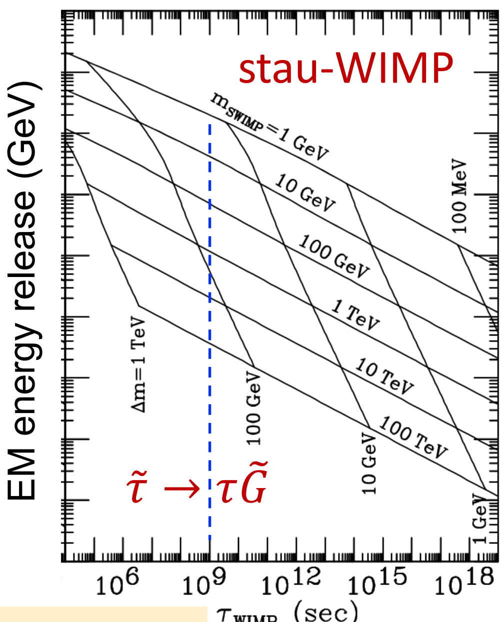
Holdom, Phys. Lett. B166 (1986) 196

Milli-charged particles are a natural consequence of extra U(1) with massless gauge field

Extremely Long-Lived Charged Particles with MAPP-mQP



- SuperWIMP model for cold dark matter
  - WIMP → SM + SWIMP
- SuperWIMP particles may explain the observed lithium under-abundance



- MAPP-mQP can be used to monitor MoEDAL's exposed trapping detector for the decays of electrically charged trapped particles
  - exposed trapping volumes moved directly underground to UA83
  - lifetimes longer than 10 years can be probed

Feng, Rajaraman, Takayama, Phys. Rev. D 68, 063504 (2003)