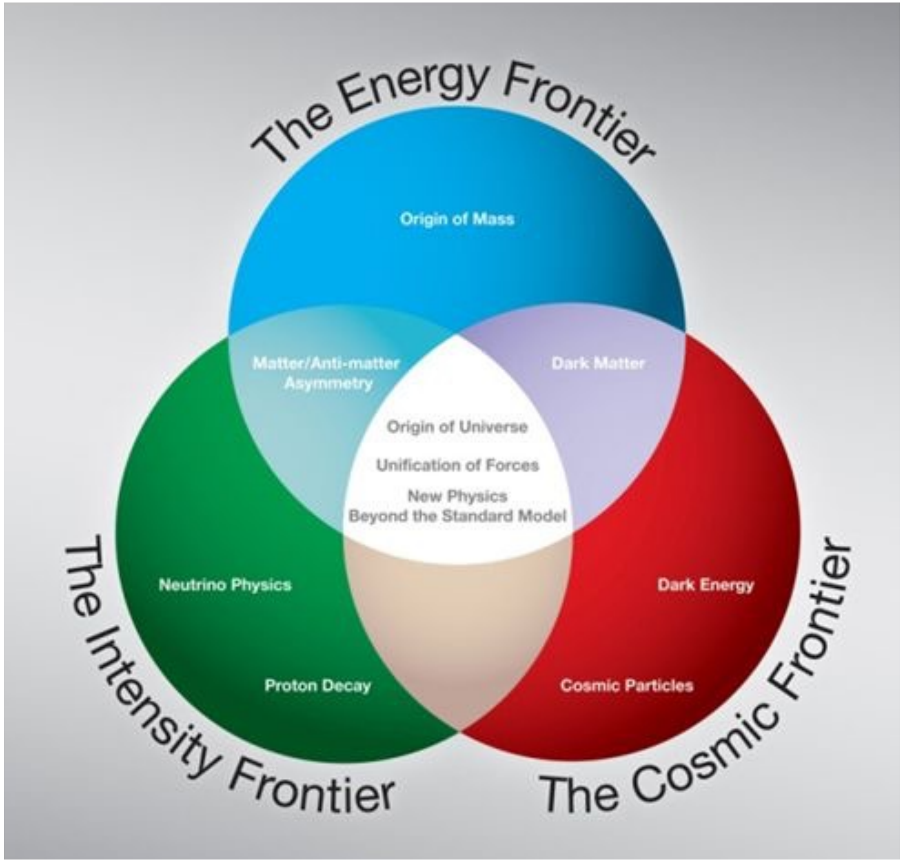
LHC experiments for long-lived particles of the dark sector

Vasiliki A. Mitsou

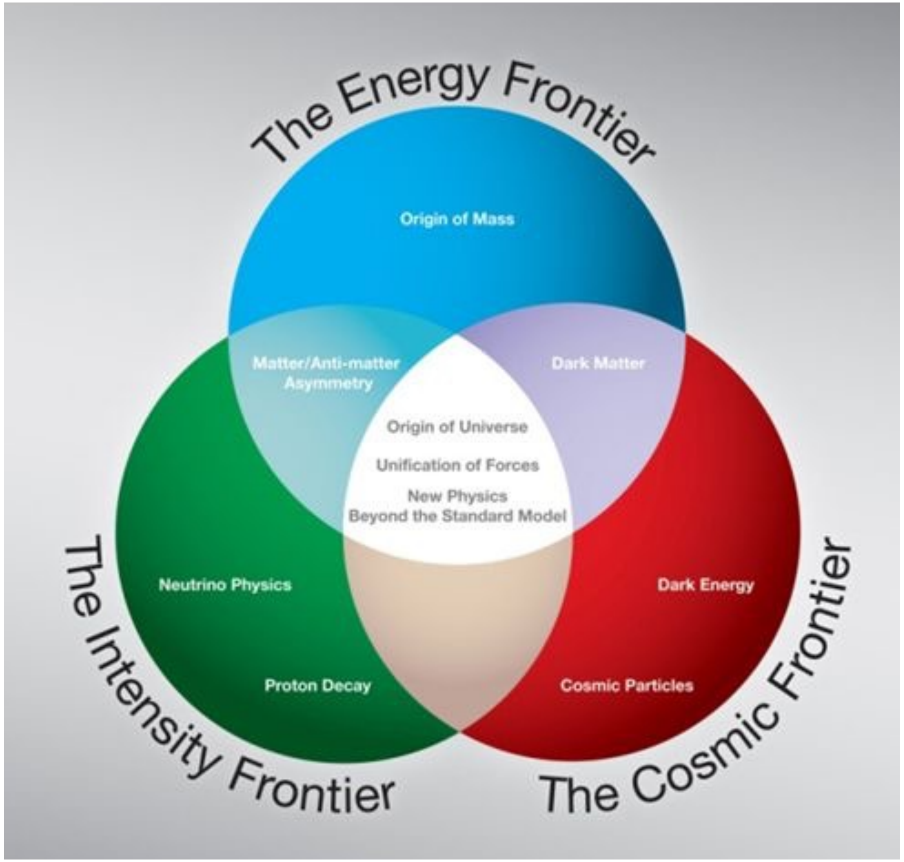
Sixteenth Marcel Grossmann Meeting – MG16

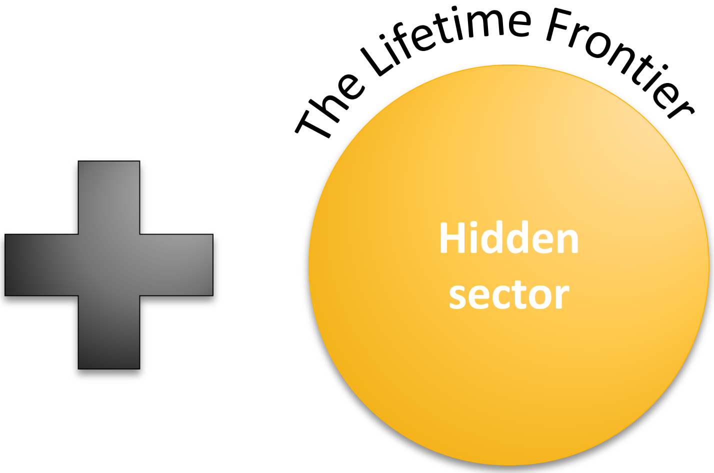
Virtual Meeting - July 5-10, 2021

The three frontiers

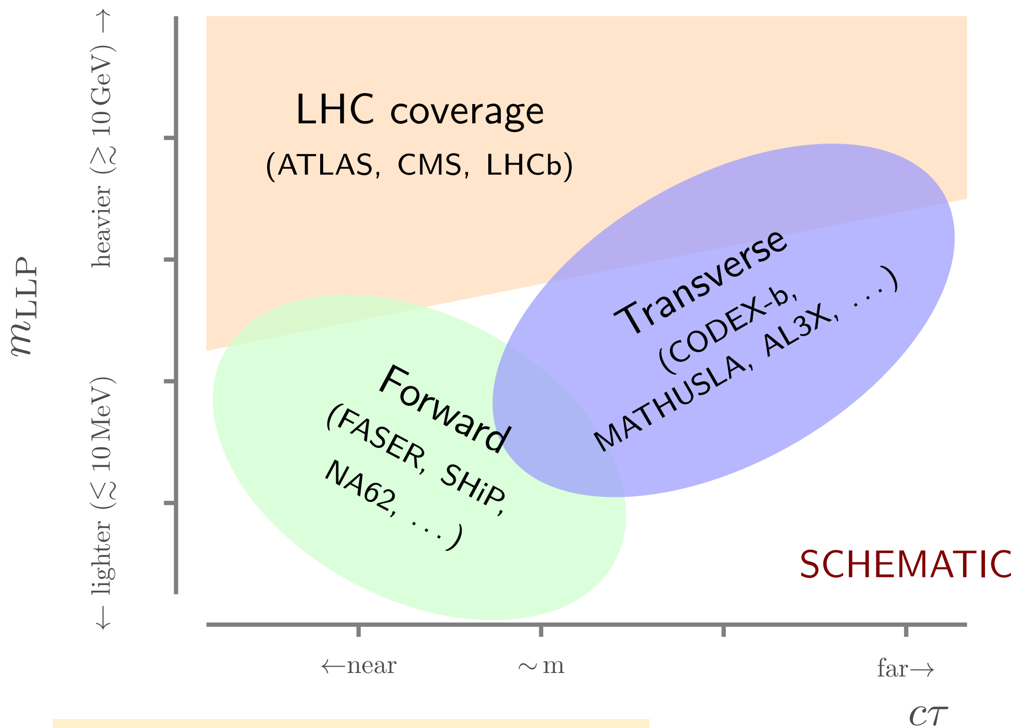


The ~~three~~ *four* frontiers





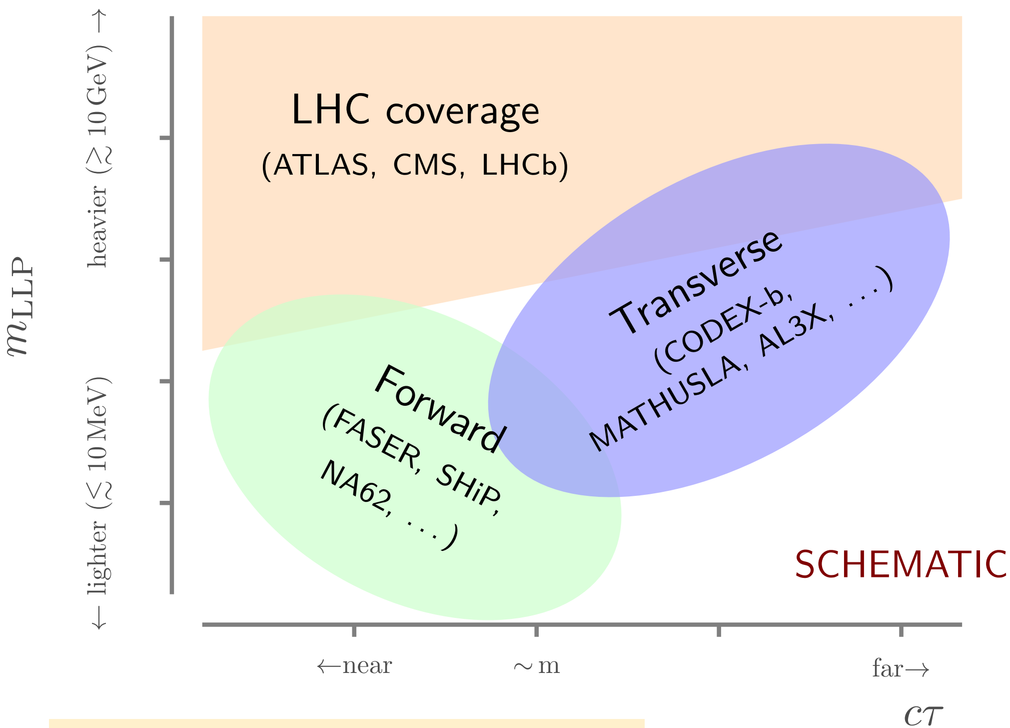
The lifetime frontier



CODEX-b EoI, [EP.JC 80 (2020) 1177]
[[arXiv:1911.00481]]

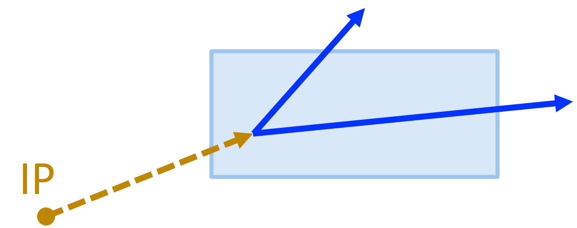
- ATLAS, CMS and LHCb mainly optimised for new particles that decay *promptly* ⇒ *strongly coupled*
- Development of new trigger/reconstruction/analysis strategies allow also probing new *long-lived* particles
- Variety in signatures and lifetime range require designing and building dedicated experiments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

The lifetime frontier

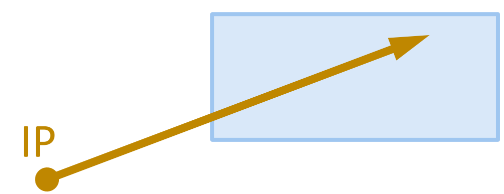


CODEX-b EoI, EPJC 80 (2020) 1177
[arXiv:1911.00481]

LLPs may decay to visible particles
➜ displaced vertices

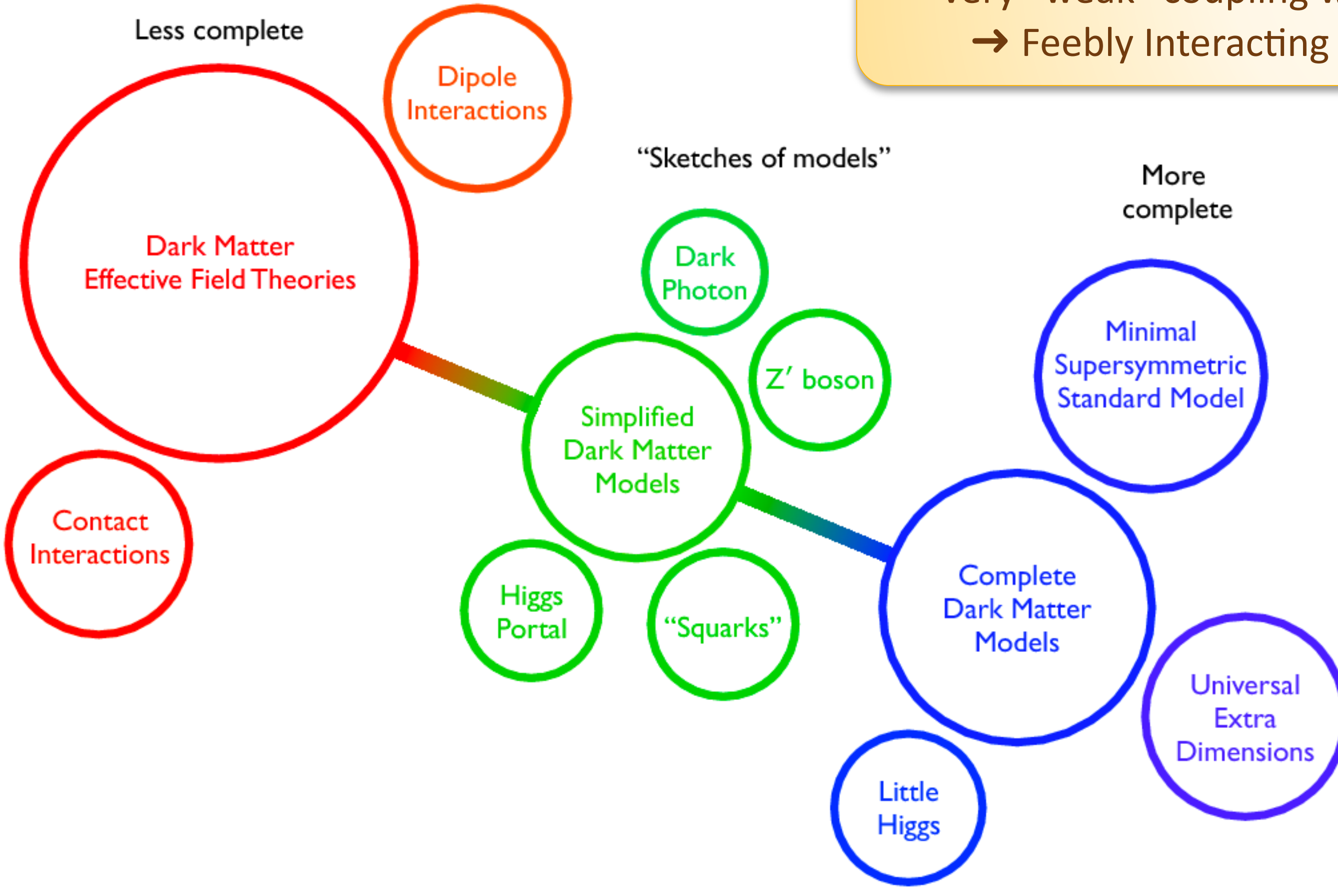


LLPs may induce anomalous ionisation, e.g. millicharged particles



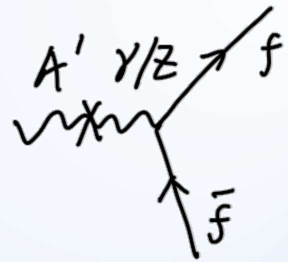
Dark matter models

A new particle may be long-lived due to a very "weak" coupling with SM particles
→ Feebly Interacting Particles (**FIPs**)

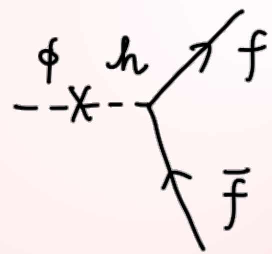


Hidden sectors – dark portal

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



Dark scalars ("Dark Higgs")
- neutral singlet scalars with quartic couplings to the SM Higgs field
- produced in penguin decays of K, D, B mesons

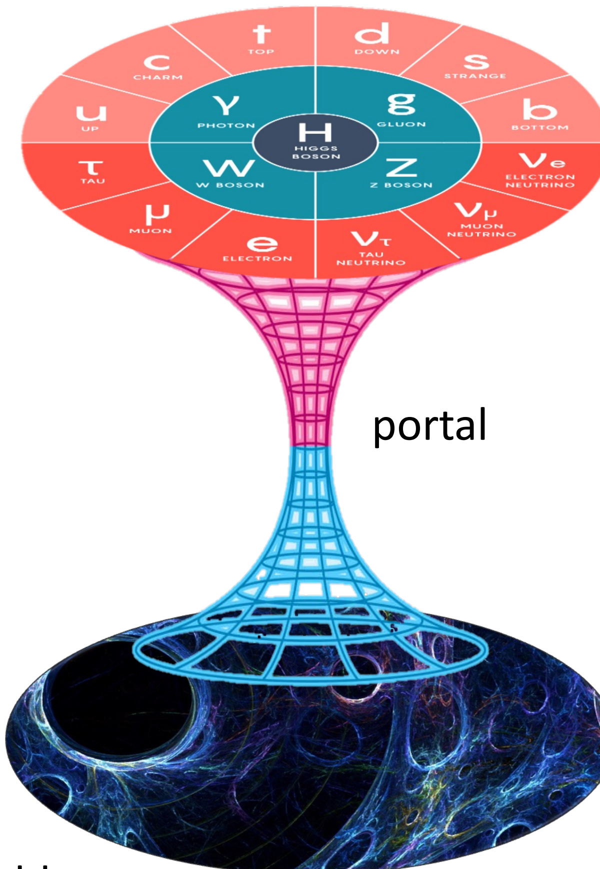


IMPORTANT: Other portals include heavy neutrinos and axion-like particles

➡ here focus is on Dark Matter

For description of models, see: PBC-BSM report, J.Phys.G 47 (2020) 010501

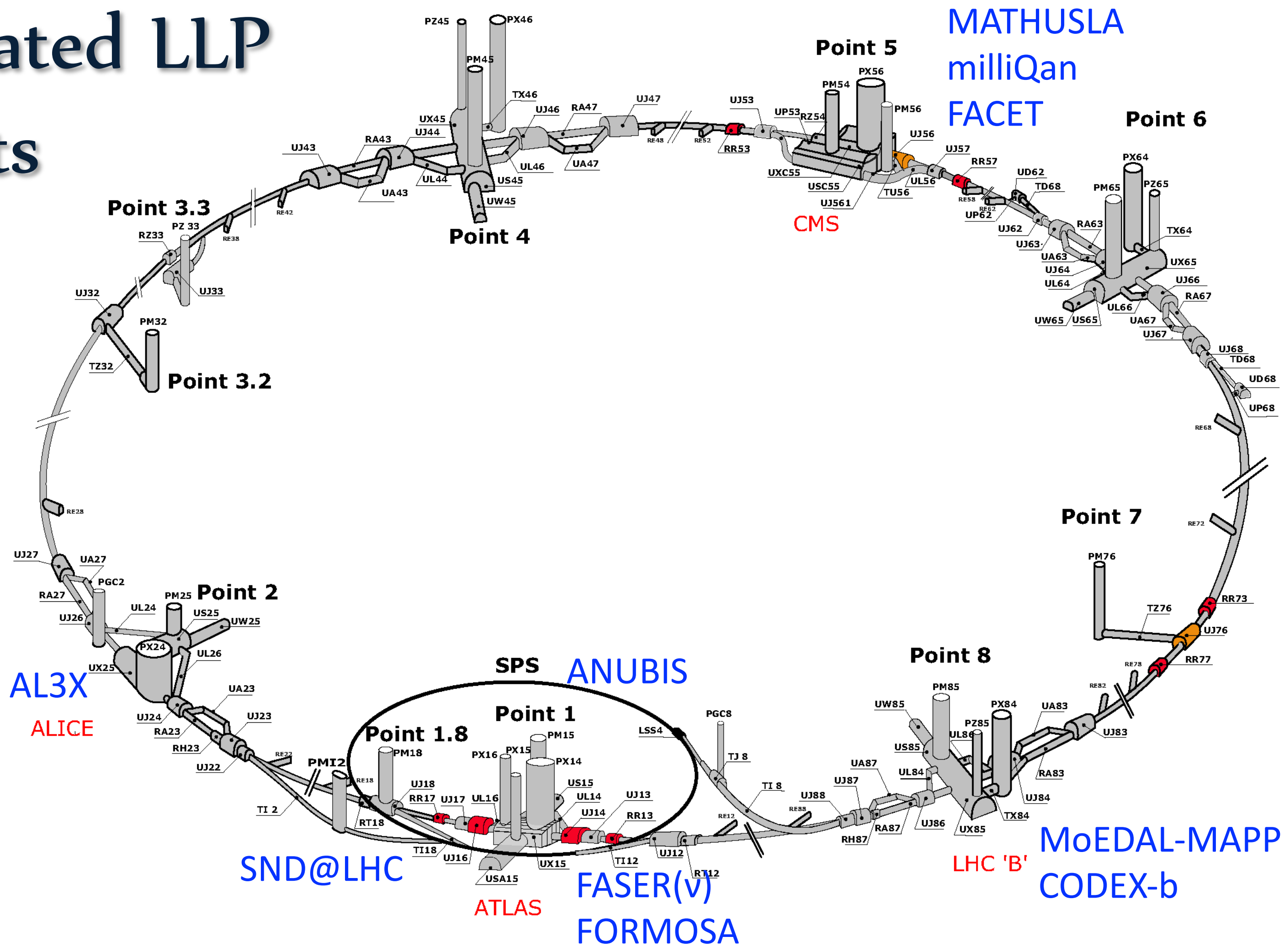
Standard Model



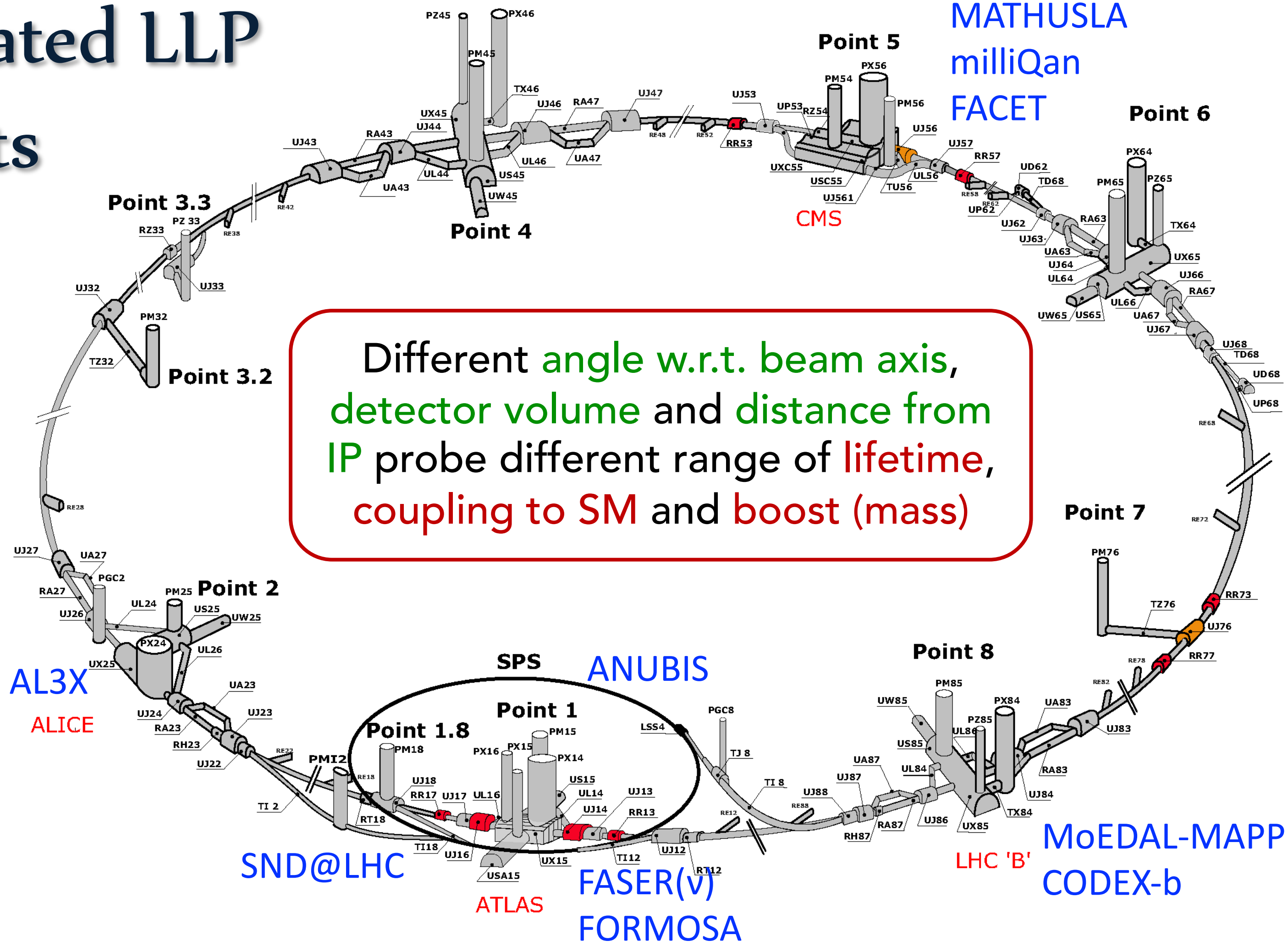
portal

Hidden sector

LHC dedicated LLP experiments



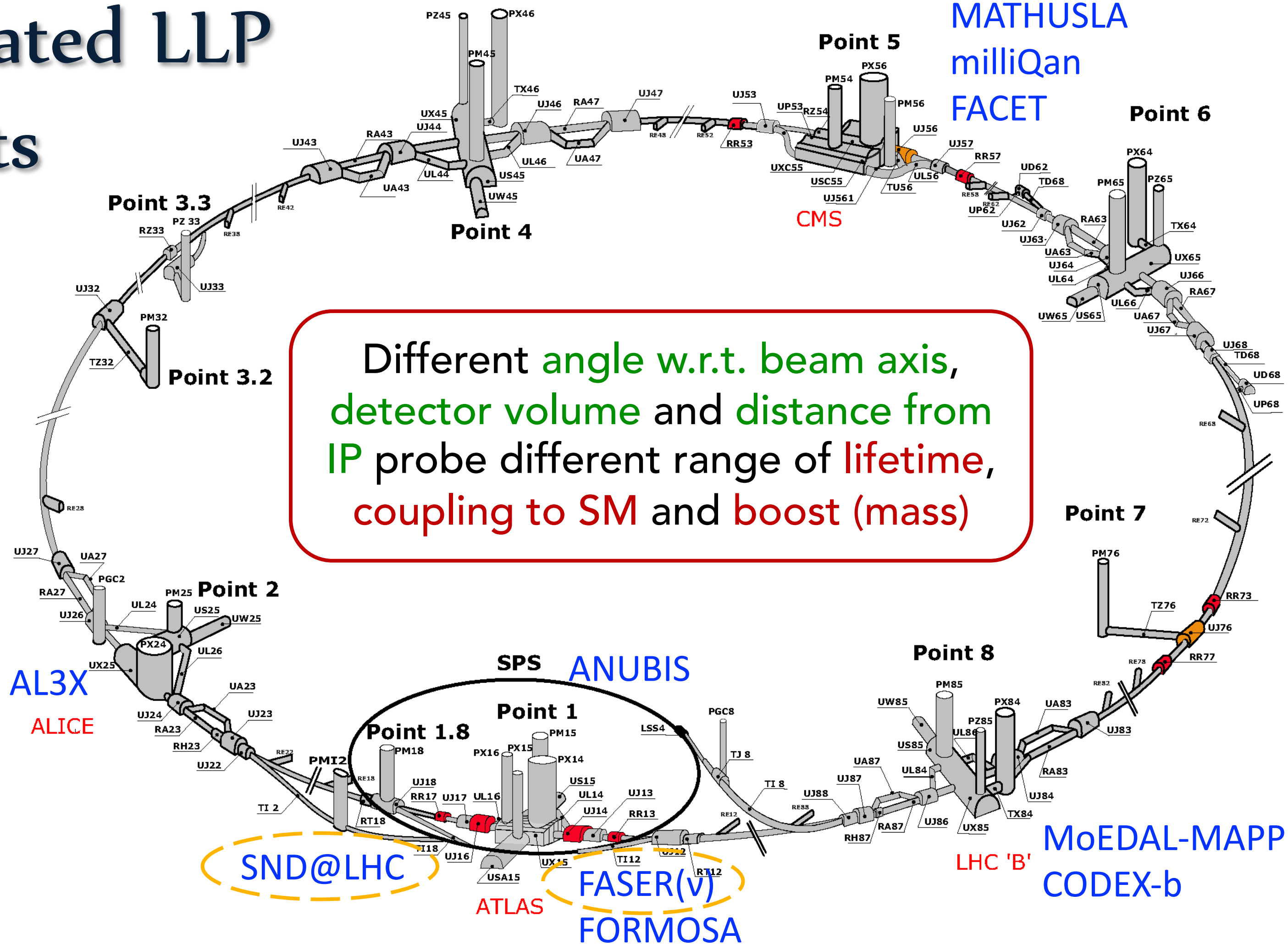
LHC dedicated LLP experiments



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 dedicated LLP experiments

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



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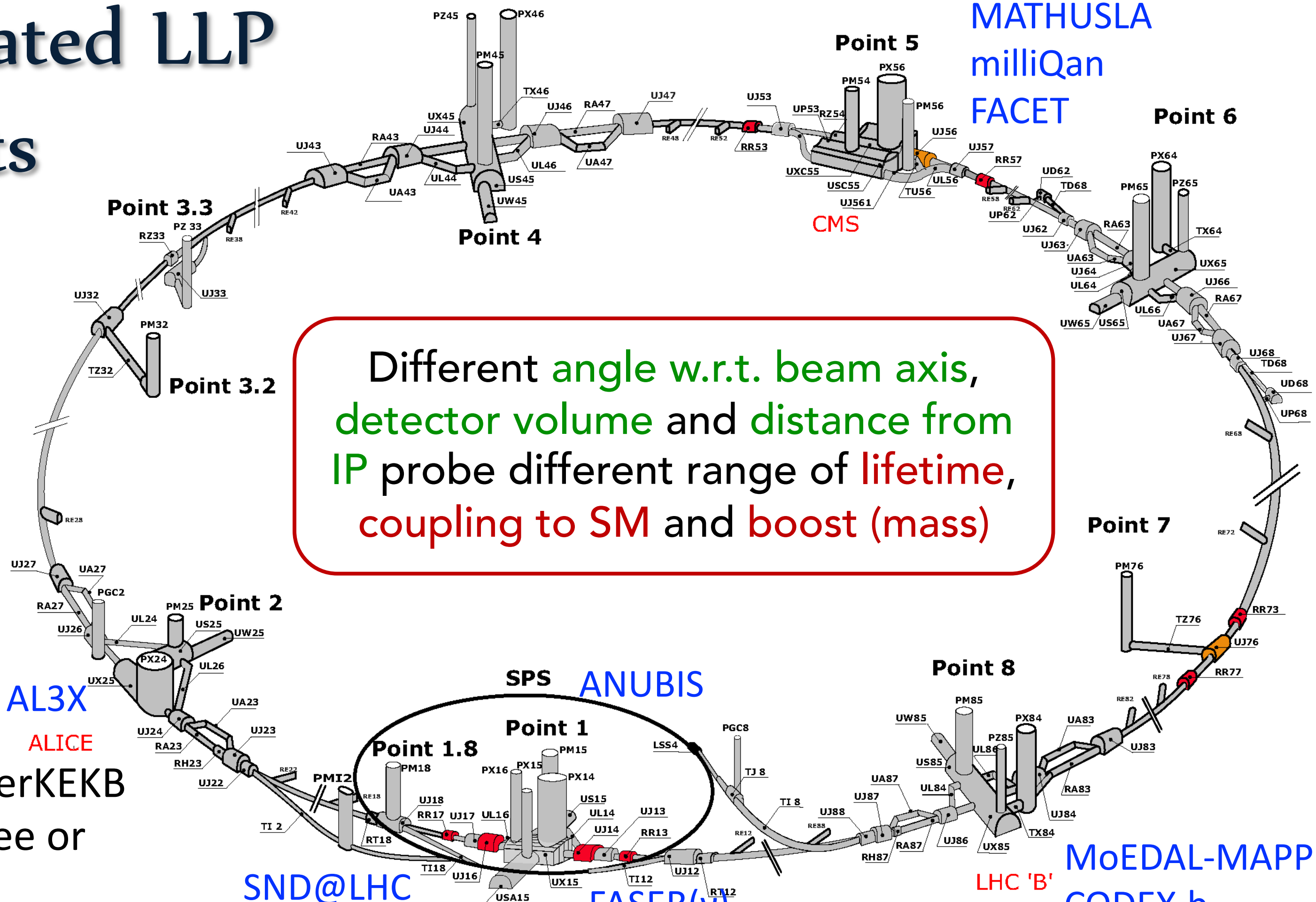
LHC dedicated LLP experiments



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

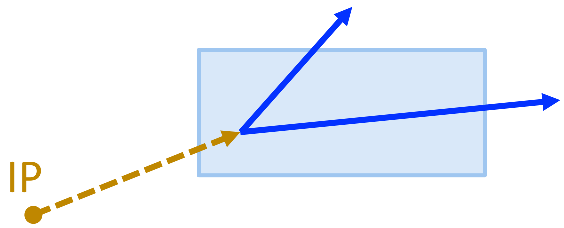
Also non-LHC experiments:

- SHiP
- NA48/2
- NA62
- NA64
- SeaQuest
- Solid
- GAZELLE @ SuperKEKB
- HECATE @ FCC-ee or CEPC

…

Long-lived neutral particles decaying in detector volume

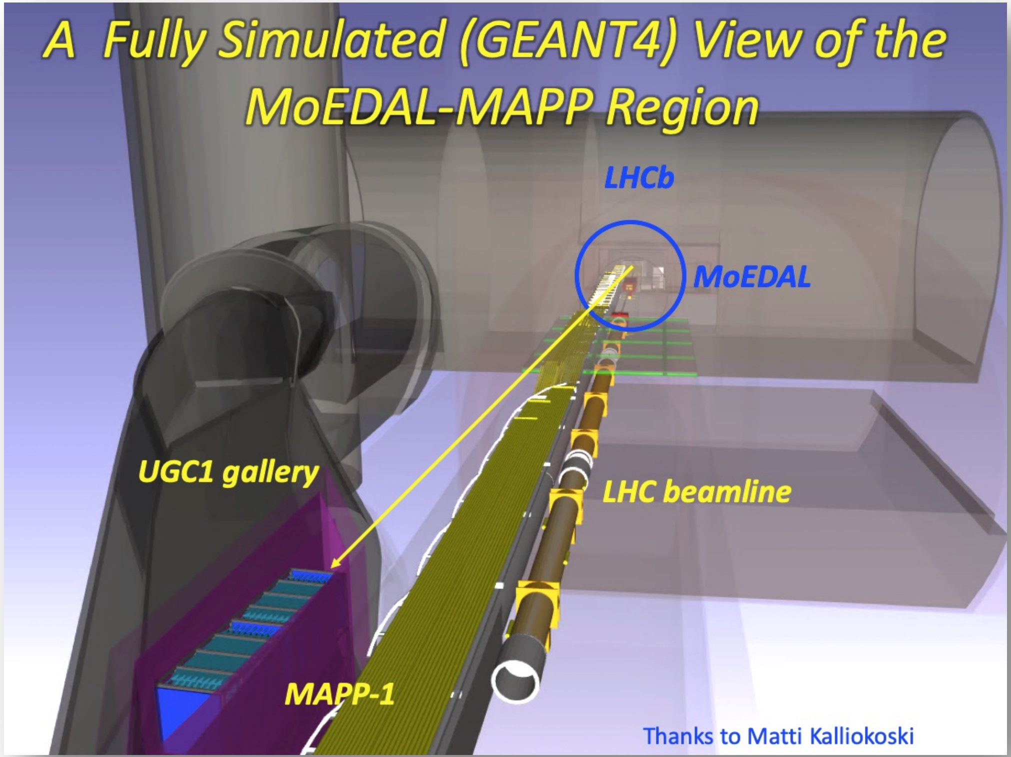
- MoEDAL-MAPP
- FASER
- CODEX-b
- MATHUSLA
- AL3X
- ANUBIS
- FACET



MAPP – MoEDAL Apparatus for Penetrating Particles

Consists of two subdetectors:

- The very long-lived weakly interacting neutral particle detector **MAPP-LLP**
- The core millicharged particle detector **MAPP-mQP**
  - particles with charges $\ll$ ***1e***



- Around 55 m away from interaction point
- At an angle of ~5° from beam axis
- Protected by
  - 100 m of rock overburden
  - 25 m of rock from IP

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

☞ Jim Pinfold's talk on MoEDAL after this talk

FASER

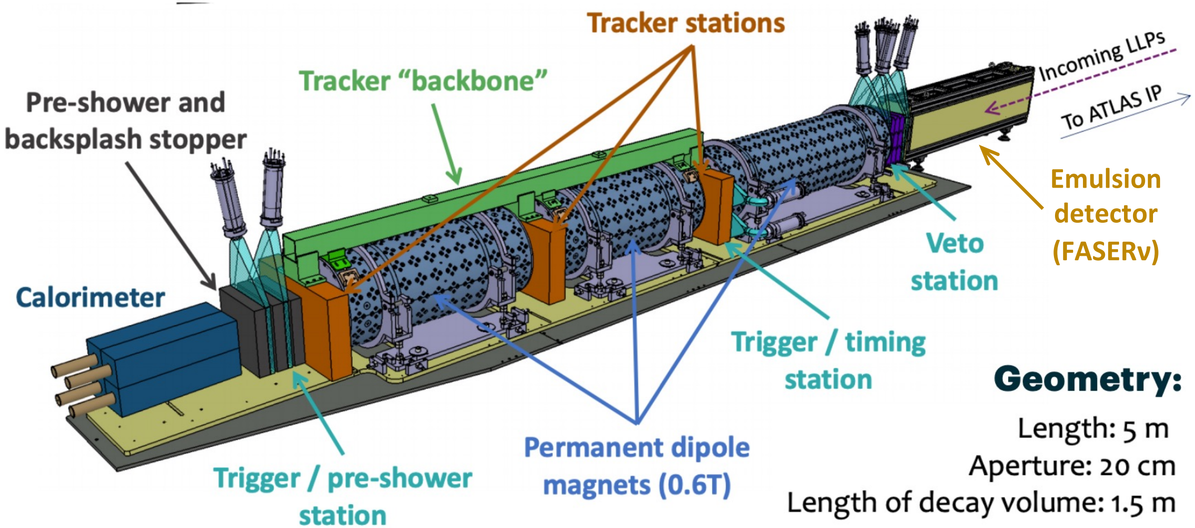
Forw**A**rd **S**earch **E**xpe**R**iment at the LHC

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 ($\eta > 9.1$)

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

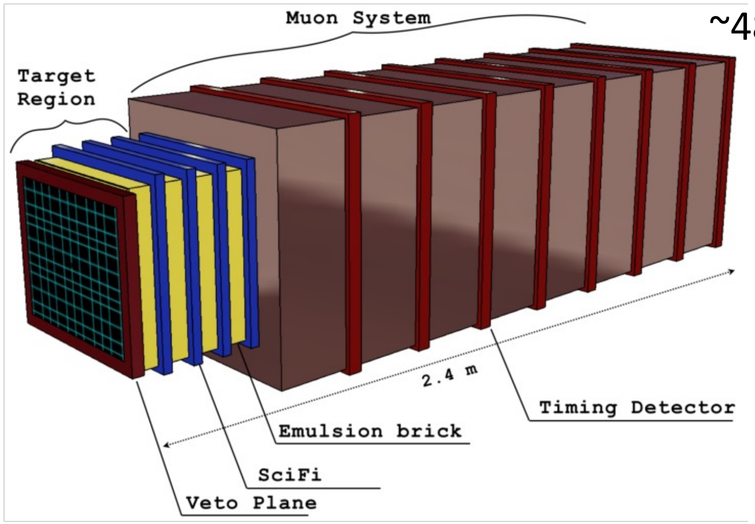


Geometry:
Length: 5 m
Aperture: 20 cm
Length of decay volume: 1.5 m

- **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

SND@LHC – Scattering and Neutrino Detector at the LHC

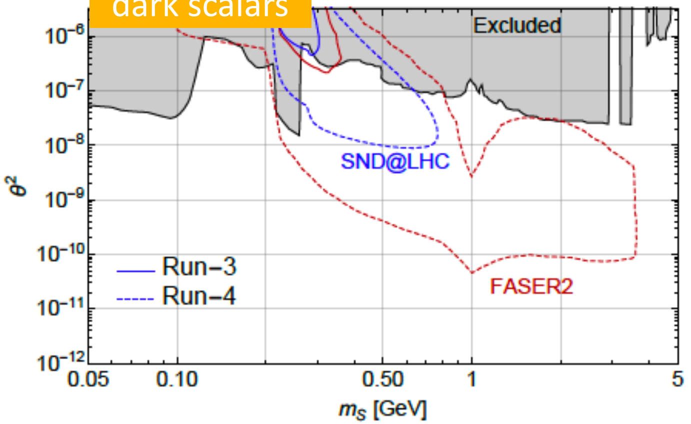
- Compact and stand-alone experiment designed to measure neutrinos produced at the LHC and search for FIPs in the unexplored range of **7.2 < η < 8.6**
- Detector will be a small-scale prototype of the SHiP experiment SND



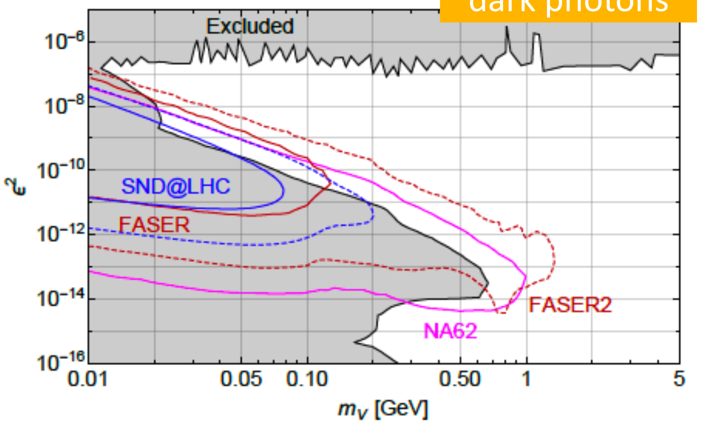
~480 m from IP1 (ATLAS)

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

dark scalars



dark photons

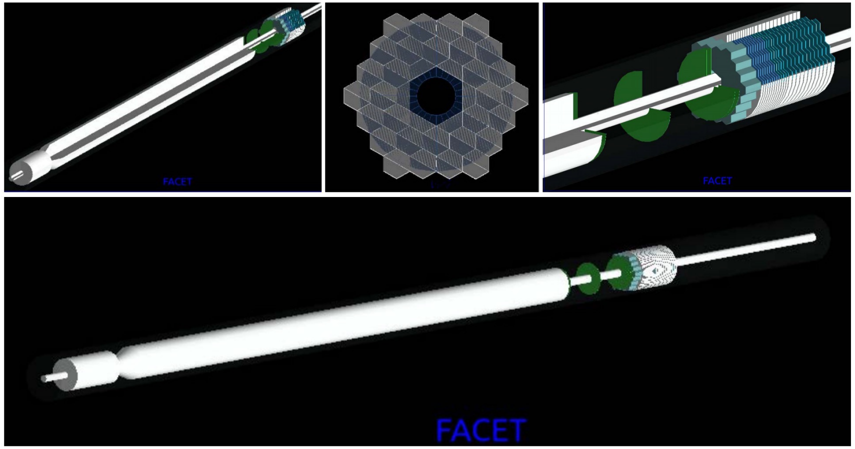


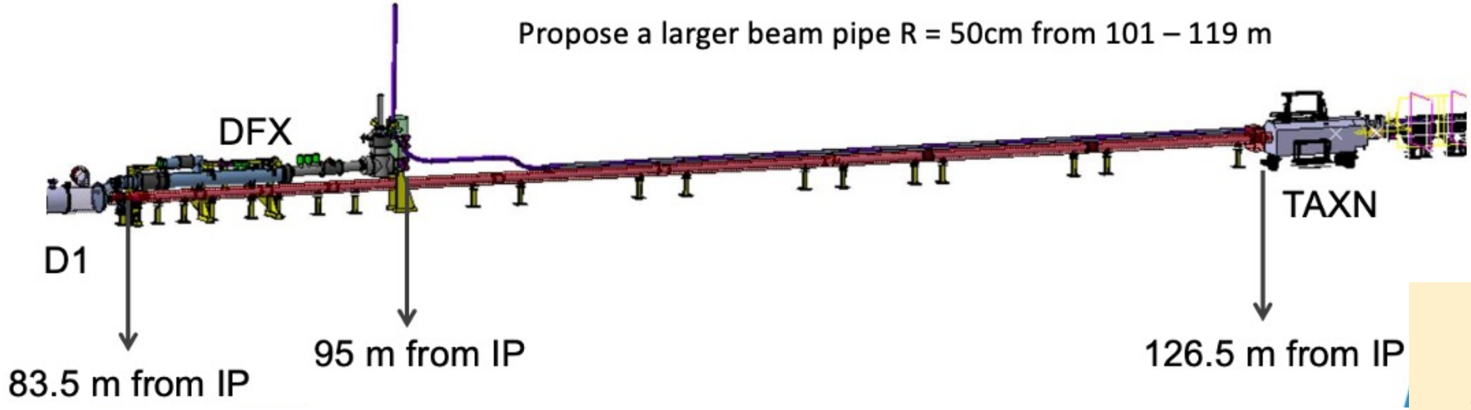
SHiP collab., arXiv:2002.08722

Boyarsky et al., arXiv:2104.09688

FACET – Forward-Aperture CMS ExTension

- Multi-particle spectrometer at z ~ +100 m from the IP5 (CMS)
- 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
- If approved, FACET will operate in HL-LHC





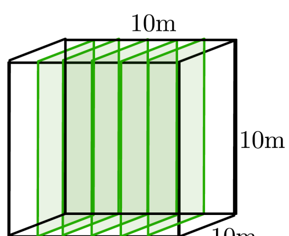
FACET Snowmass EoI, SNOWMASS21-EF9_EF8_ALBROW-111

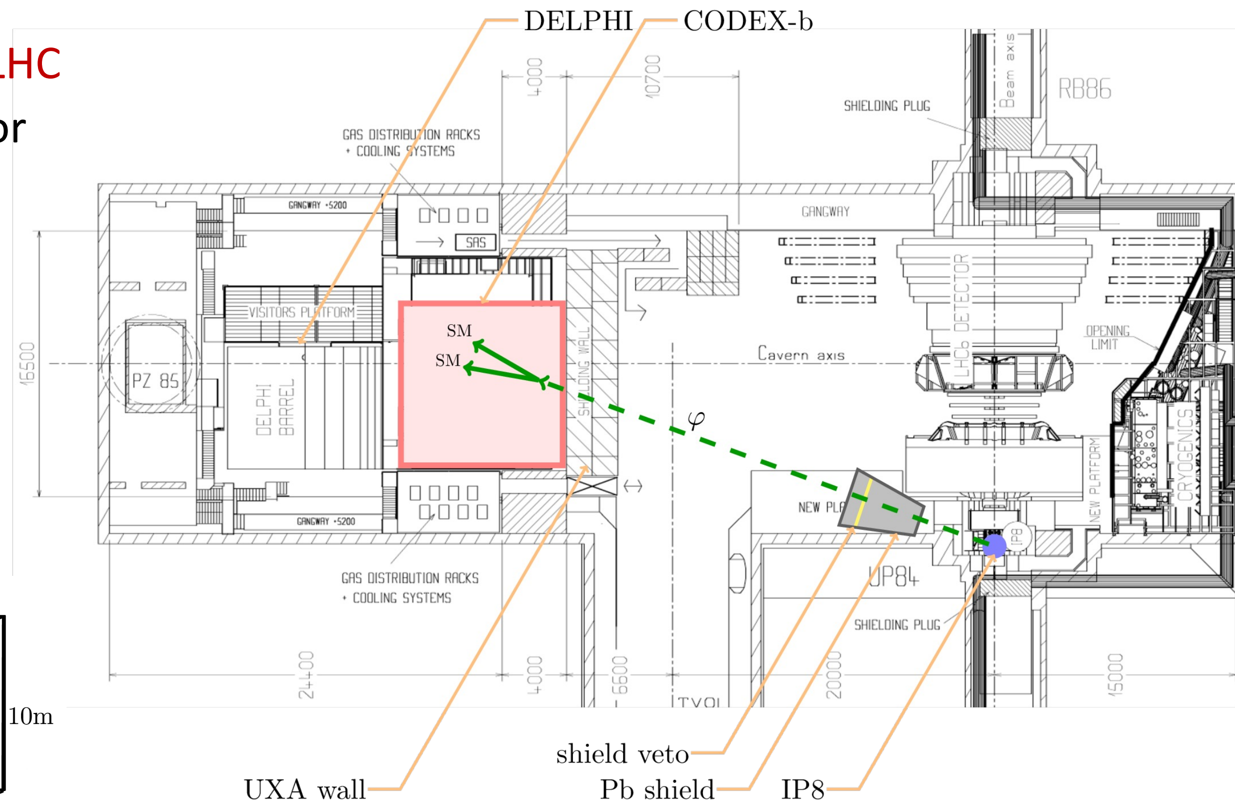
CODEX-b

A COmpact Detector for EXotics at LHCb

Expression of interest: [arXiv:1911.00481](https://arxiv.org/abs/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





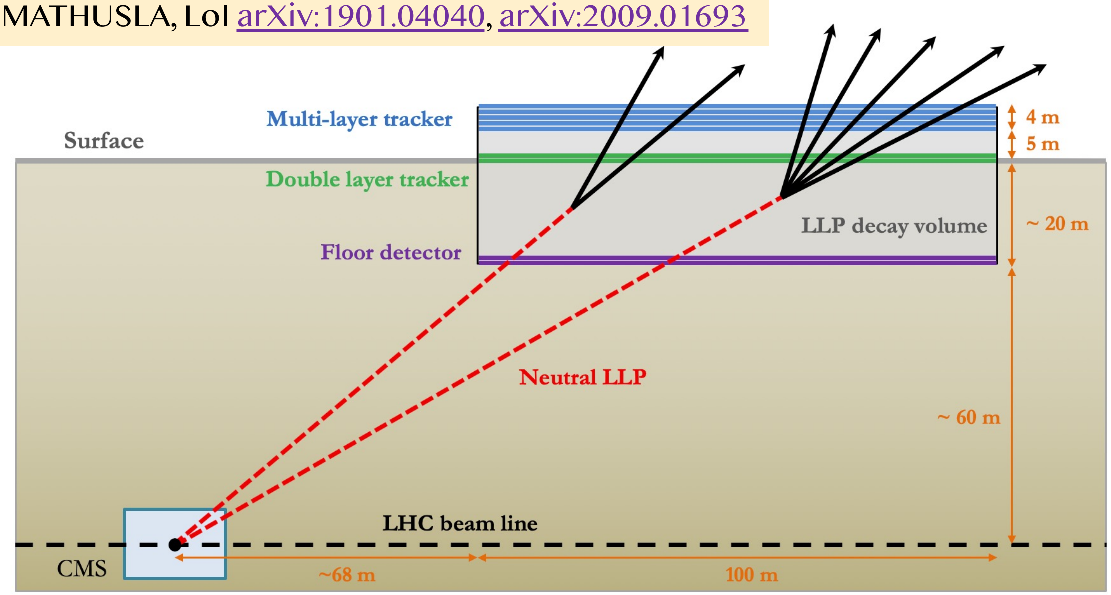
MATHUSLA

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

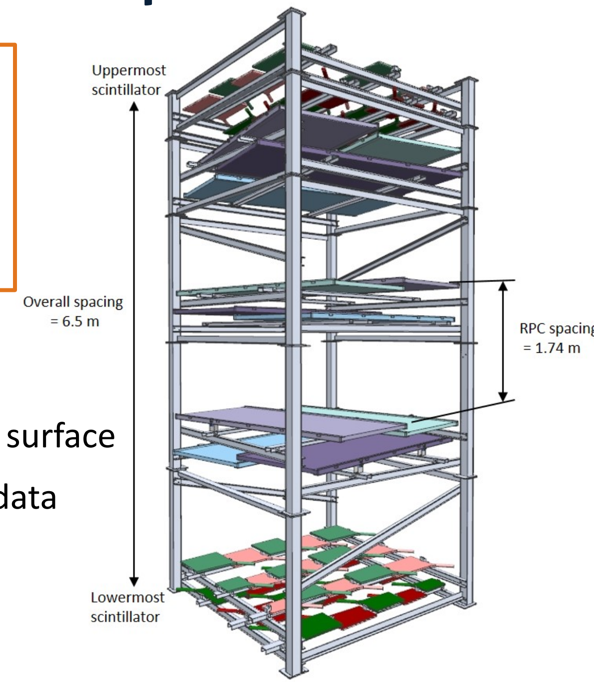
2.5×2.5×6.5 m^3 test stand with eight layers of trackers confirms background assumptions and gives confidence in projected physics reach

MATHUSLA, LoI arXiv:1901.04040, arXiv:2009.01693



ATLAS surface

2018 data



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

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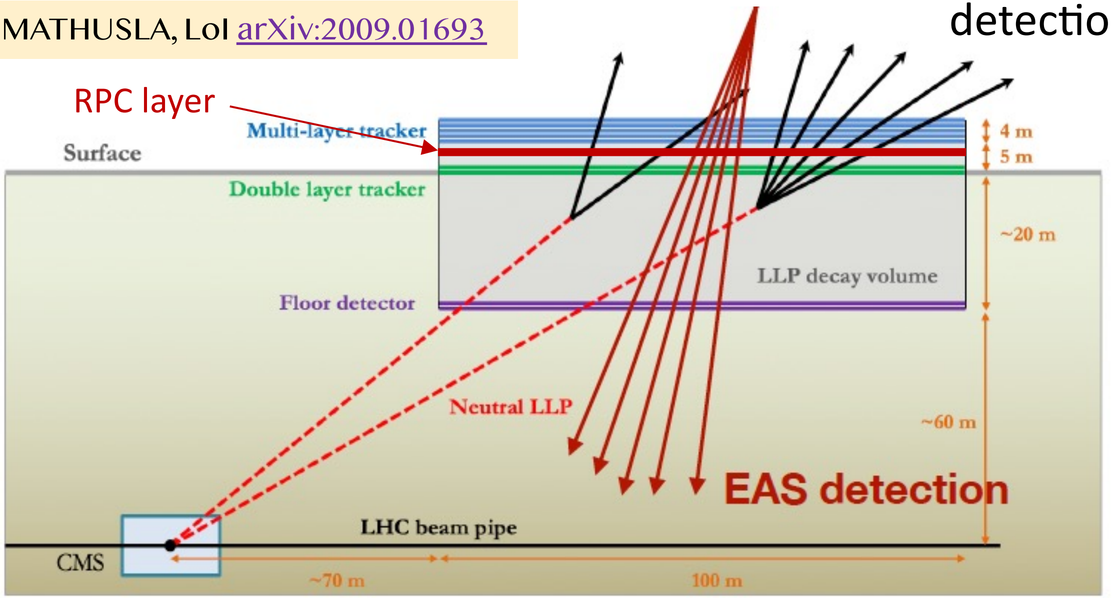
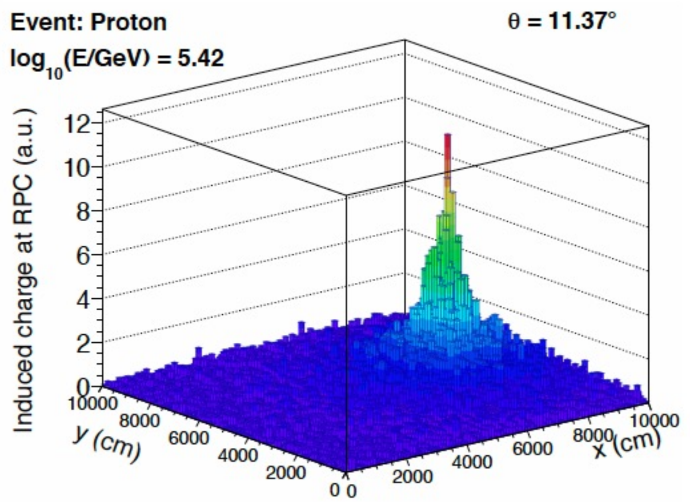
MATHUSLA, LoI arXiv:2009.01693



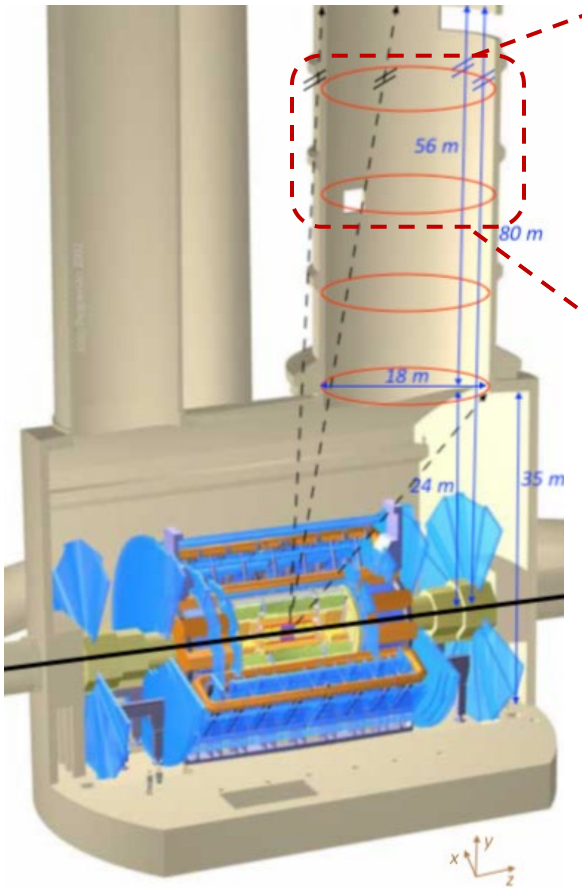
Indirect detection of cosmic rays through extensive air showers (EAS)

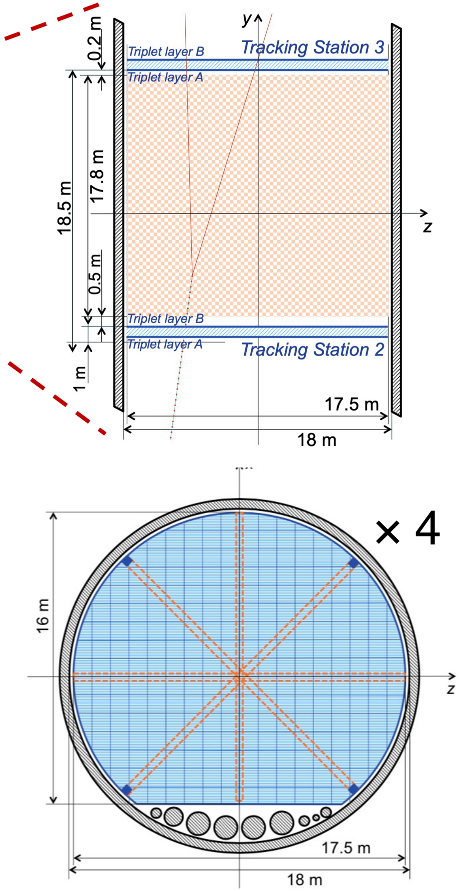
- Adding an RPC layer to the MATHUSLA detector would significantly enhance EAS detection

Charge density at the RPC



ANUBIS AN Underground Belayed In-Shaft search experiment





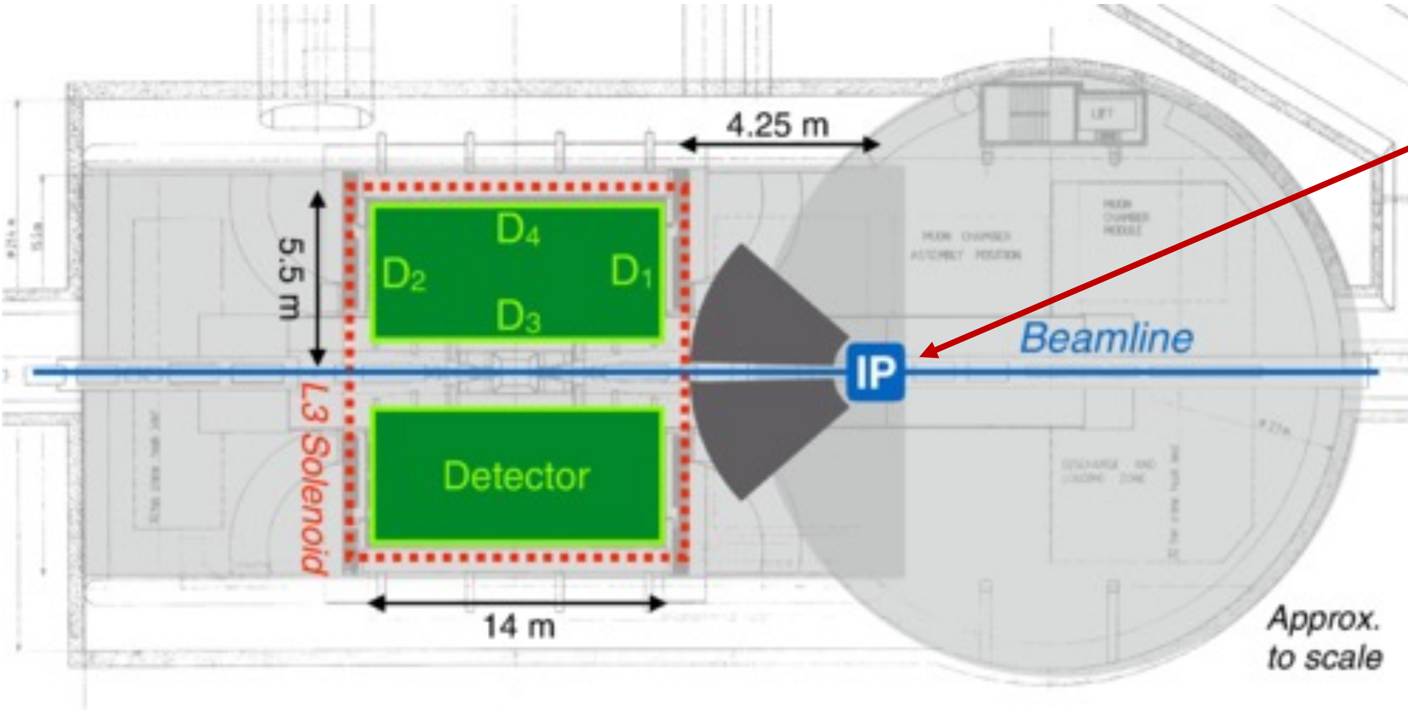
- Four evenly spaced tracking stations with a cross-sectional area of 230 m^2 each
- Tracking stations same RPC technology as new ATLAS layers
- ATLAS can be used as an active veto of SM activity
- Projective decay volume optimises acceptance for different lifetimes
- Planning to install a demonstrator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

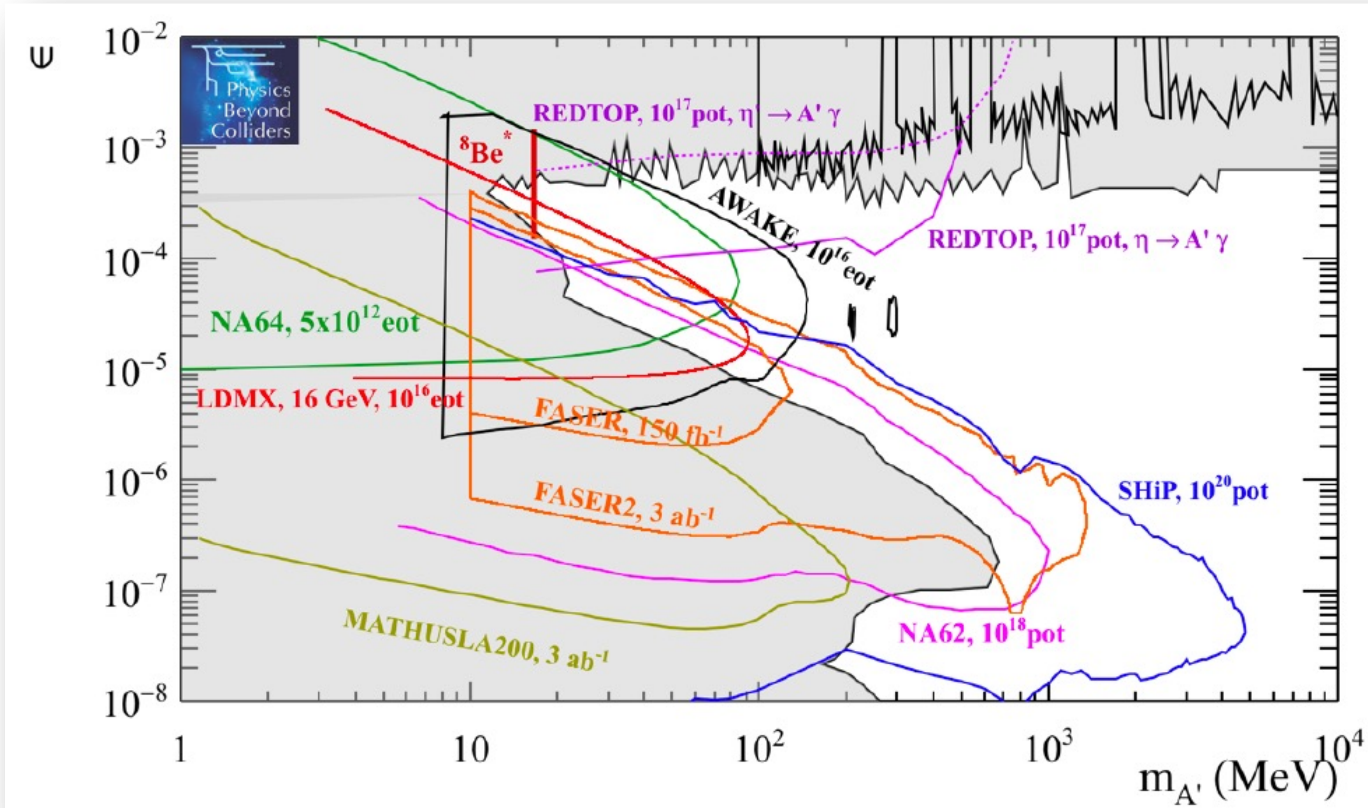


ALICE interaction point moved by 11.25 m outside magnet to allow LLPs to travel before decaying

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

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



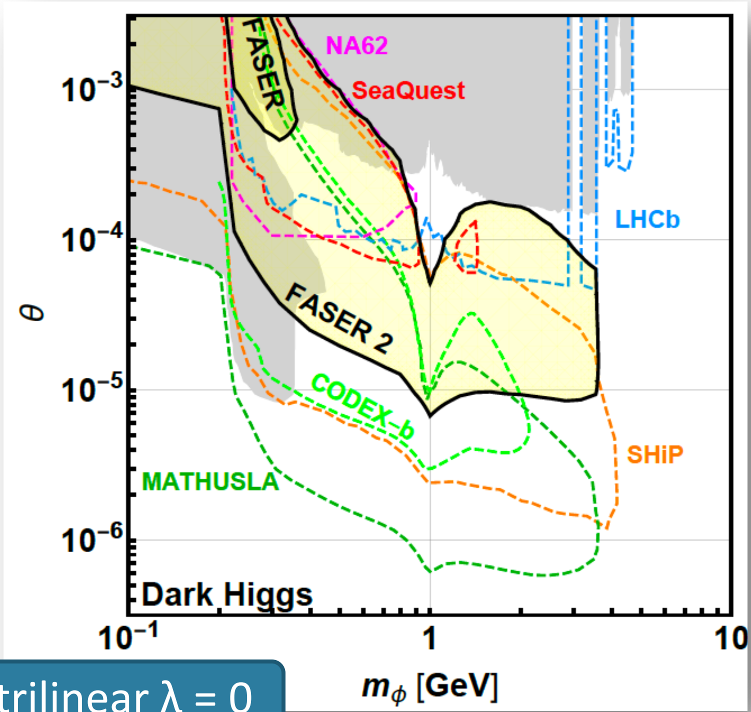
PBC–BSM Report, J.Phys.G 47 (2020) 010501

Scalar portal – dark Higgs

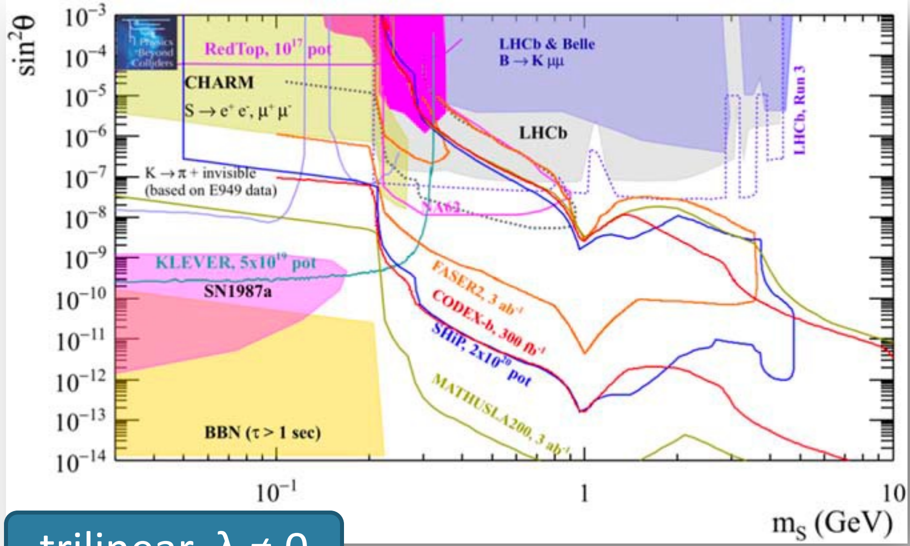
$$\mathscr{L} = \mathscr{L}_{SM} + \mathscr{L}_{DS} + \mu^2 S^2 - \frac{1}{4}\lambda_S S^4 - \epsilon_H S^2 |H|^2$$

- 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

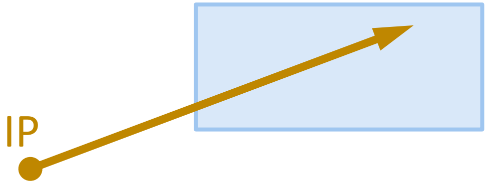


trilinear λ ≠ 0

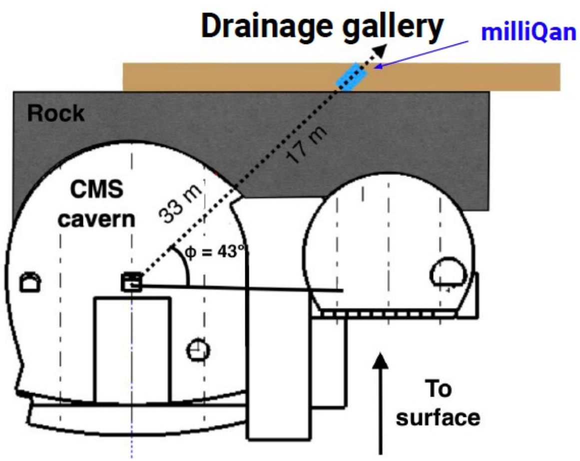
PBC-BSM Report, J.Phys.G 47 (2020) 010501

Milli-charged particles

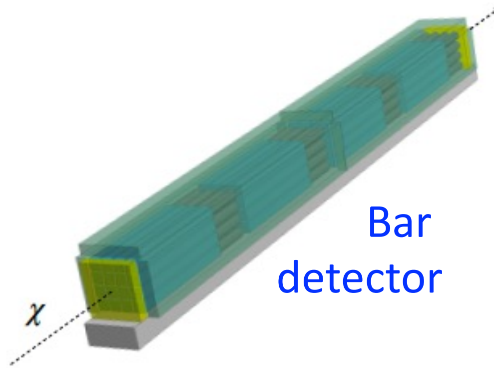
- milliQan
- MAPP-mQP
- FORMOSA



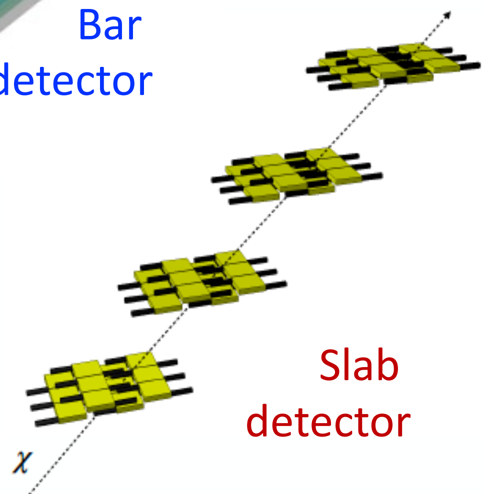
Detector & demonstrator



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



Bar detector



Slab detector

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

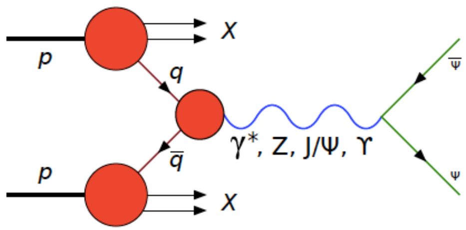
Two detectors for Run-3:

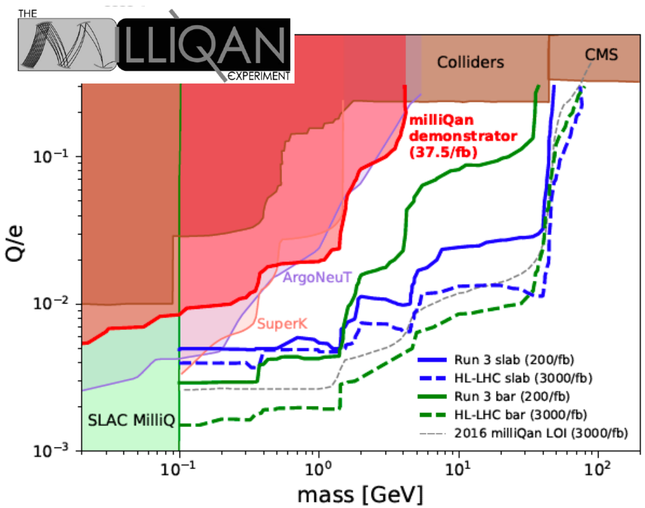
- Bar detector
  - 0.2 m × 0.2 m × 3 m plastic scintillator bars
  - surrounded by active μ veto shield
- Slab detector
  - 40 cm × 60 cm × 5 cm scintillator slabs
  - increased reach for heavier mCPs

milliQan, arXiv:2104.07151

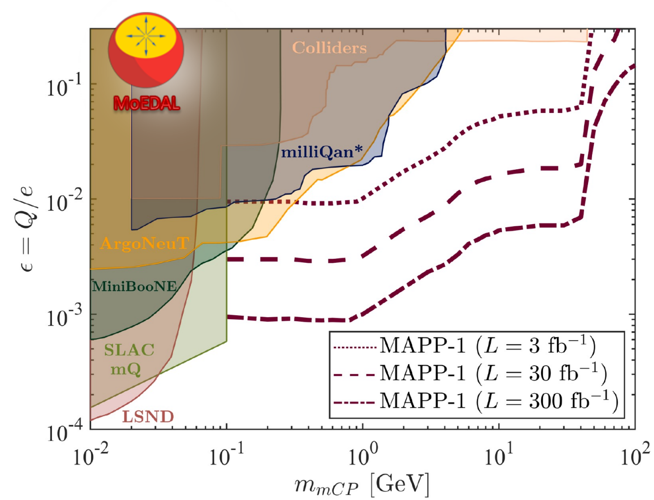
Millicharged particles in dark QED

- 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



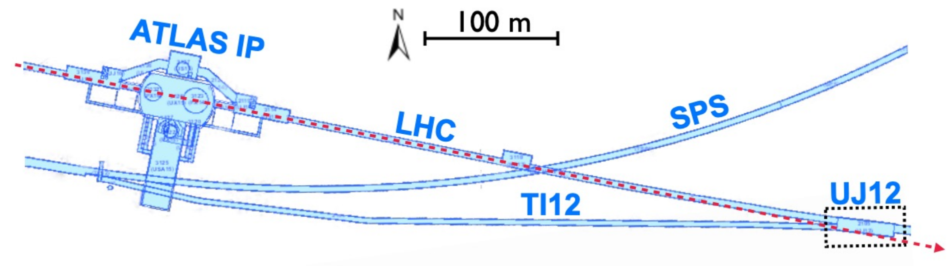
M. Staelens, PhD thesis, U.Alberta

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

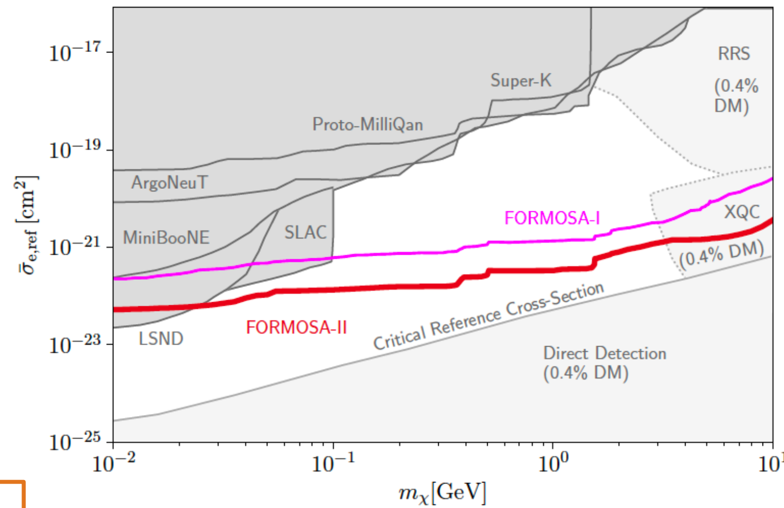
FORMOSA – FORward MicrOcharge SeArch

- 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

Outlook

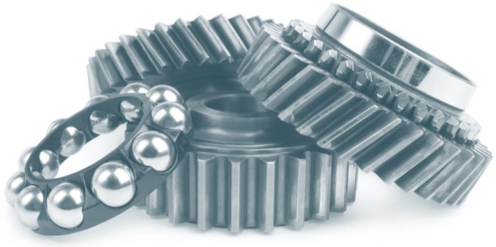
- Ever increasing interest in **long-lived particle** searches at the LHC (and not only…) including the **dark sector**
- Dedicated complementary LHC experiments proposed or under construction
- Several experiments have built small-scale demonstrators to measure backgrounds and provide proof-of-concept

A different perspective on the dark sector – the **long lifetime** – is expected for LHC Run 3 and beyond

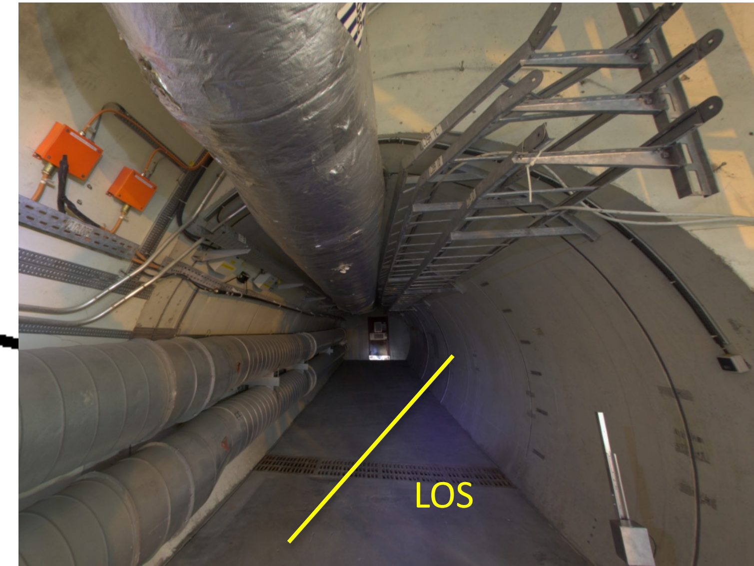
Further reading

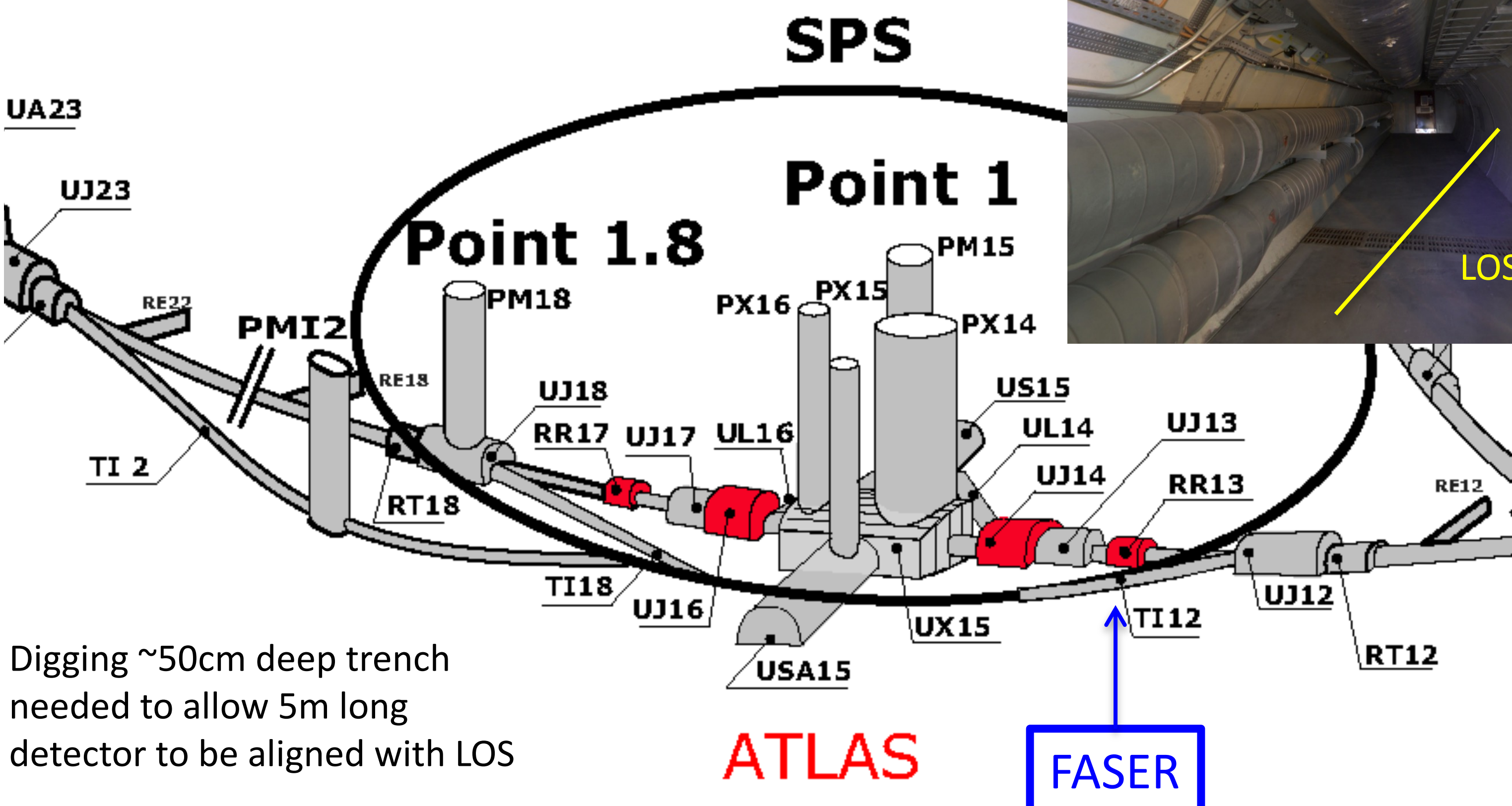
- LHC LLP whitepaper – J.Phys.G 47 (2020) 090501 [arXiv:1903.04497]
- Physics Beyond Collider at CERN – BSM Report J.Phys.G 47 (2020) 010501
- Feebly-Interacting Particles: FIPs 2020 Workshop Report, arXiv:2102.12143
- 9th workshop of the LHC LLP Community, May 2021
- FIPs 2020: Workshop on Feebly Interacting Particles, Aug – Sep 2020

Spares



FASER location: TI12



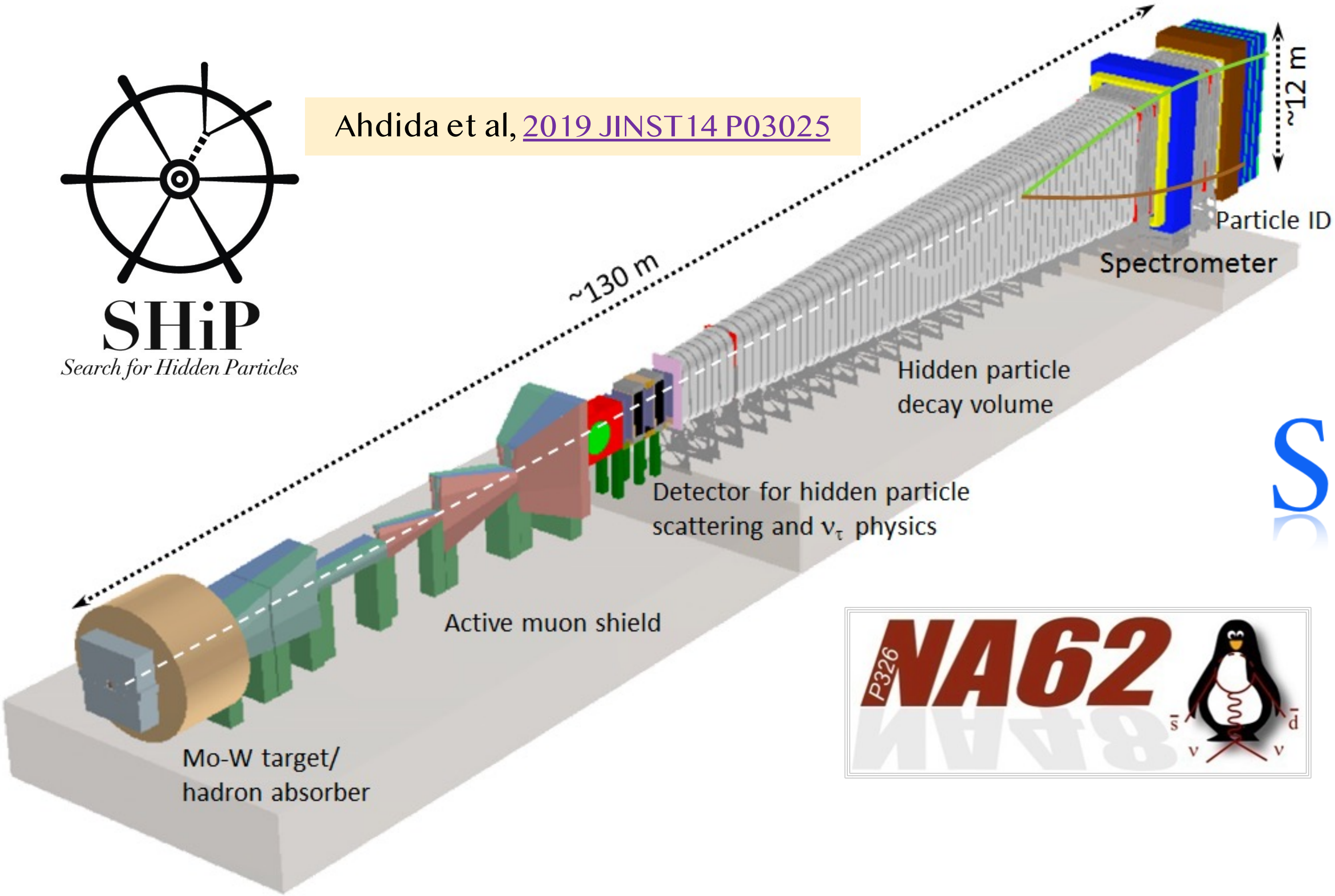


Digging ~50cm deep trench needed to allow 5m long detector to be aligned with LOS

Beyond LHC: beam-dump, neutrino, … experiments

SHiP
Search for Hidden Particles

Ahdida et al, [2019 JINST 14 P03025]



NA64

SoLid

NA62

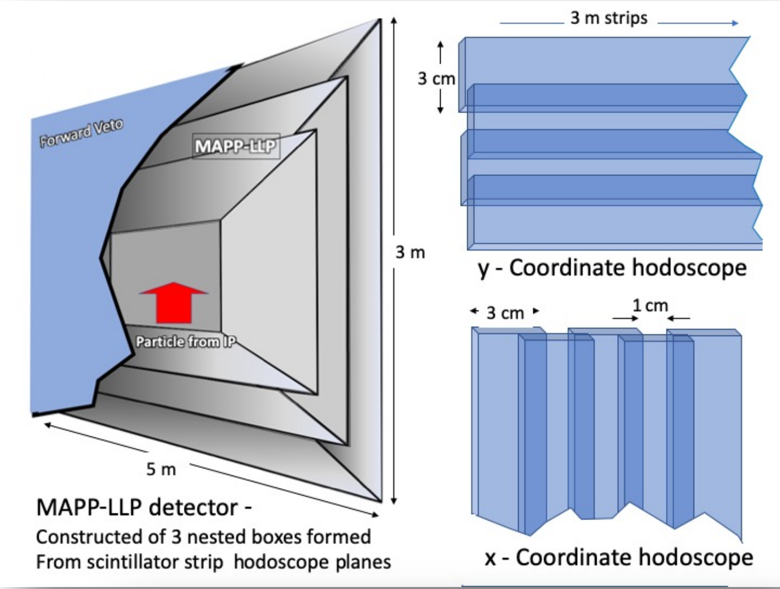
SeaQuest
E906

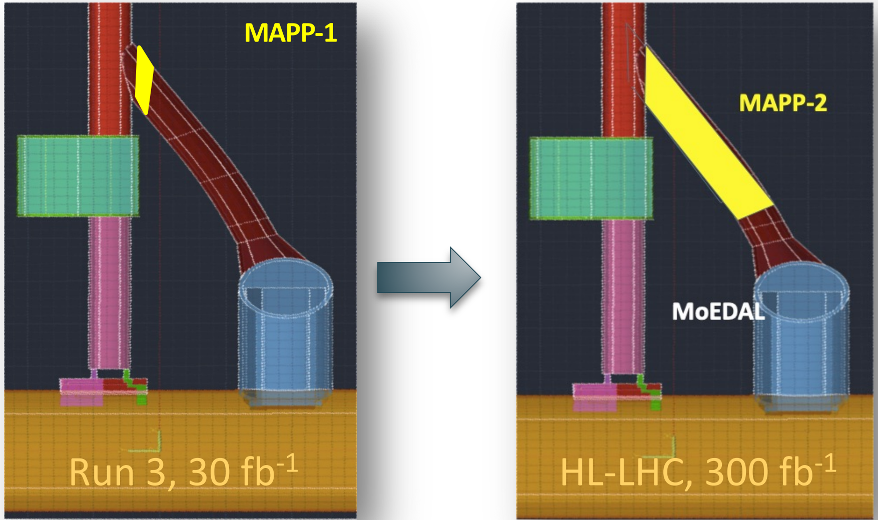
\+ many more …

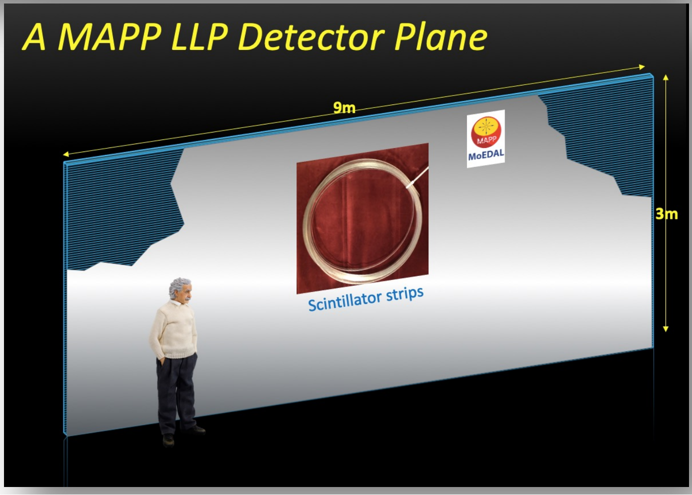
The MAPP-LLP detector

MoEDAL

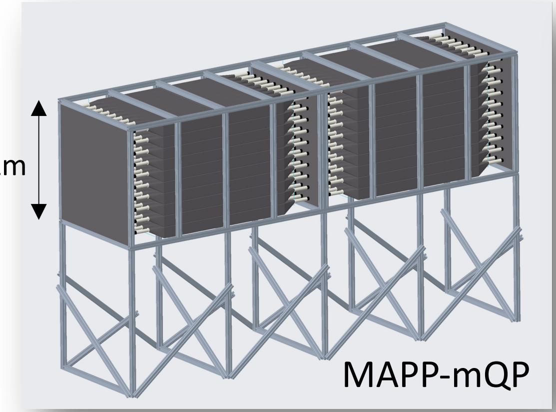
- "Box-within-a-box" or "Russian Doll" structure to detect charged tracks from neutral-particle decay
- The readout structure are scintillator strips in an *x-y* configuration readout by SiPMs
  - resolutions ~1cm × 1cm on each hit
- Using SiPM, fast scintillator and picoTDC chips MAPP plan to have 500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

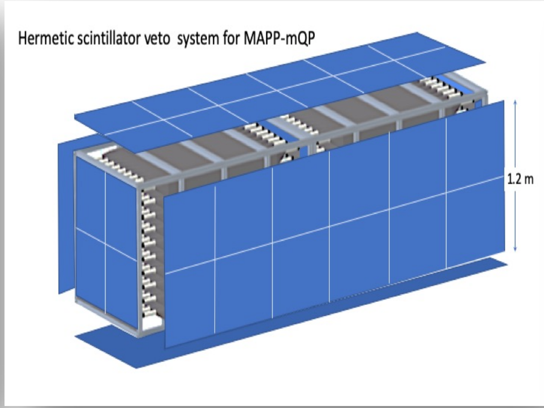


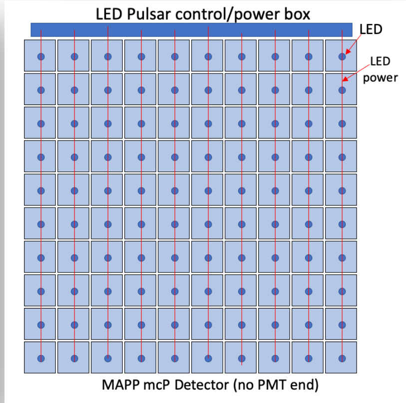




The MAPP-mQP detector







- 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'

$$\mathcal{L}_{\text{dark-sector}} = -\frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + \underbrace{i\bar{\psi}'(\gamma^{\mu}\partial_{\mu} + ie'\gamma^{\mu}A'_{\mu} + iM_{\text{mCP}})\psi'}_{\text{"dark fermion" with mass } M_{mCP}\text{, charge } e'} - \frac{\kappa}{2}A'_{\mu\nu}B^{\mu\nu}$$

massless "dark photon"

mixing term ($\kappa \ll 1$)

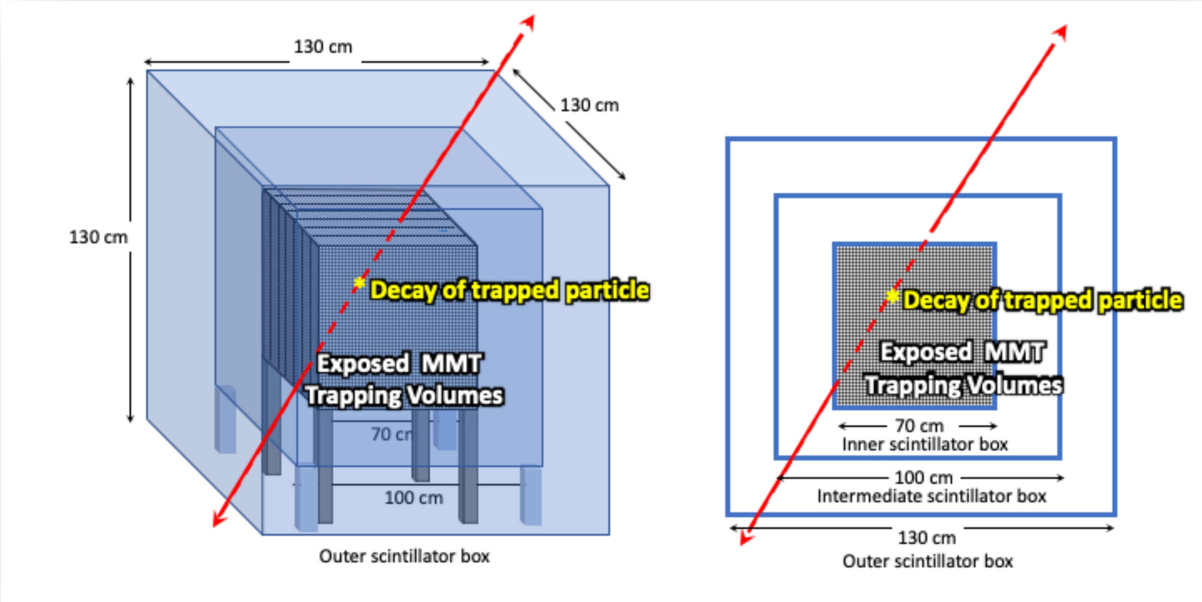
- ψ' has mass M_{mCP} , charge under the new U(1) of e' and field strength $A'_{\mu\nu}$
- ψ' couples to γ and Z with $\kappa e'\cos\theta_W$ & $-\kappa e'\sin\theta_W$, respectively
- ψ' acts as a field with a charge of $\kappa e' = e/\cos\theta_W \ll 1$ ☜ milli-charge

Holdom, Phys. Lett. B166 (1986) 196

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

MALL – MoEDAL Apparatus for very Long Lived particles

- After exposure and SQUID scan, MoEDAL MMTs will be monitored for decaying *electrically charged* particles that may have been trapped in their volume
  - ATLAS & CMS similar analyses in empty bunch crossings for trapped R-hadrons decaying into jets
- Sensitive to charged particles (e, μ, had.) and to photons with energy as small as 1~GeV
- MALL planned to be installed during Run-3 at the UGC1 gallery of IP8



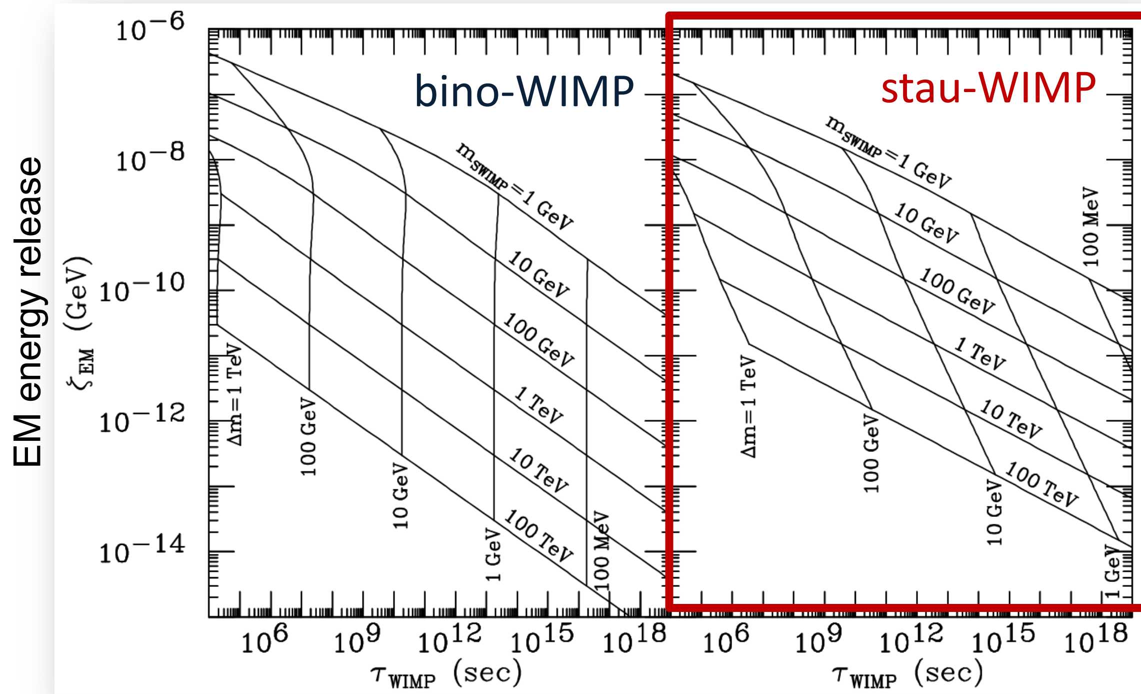
Estimated MALL probed lifetimes ~10 yrs

J. Pinfold, [Universe 5 (2019) no.2, 47]

MALL – physics example

- **SuperWIMP model for cold dark matter, WIMP -> S + SWIMP**
  - S: SM particle, SWIMP=~G
- SuperWIMP particles naturally inherit the desired relic density from the late decays of metastable WIMPs & may explain the observed lithium under-abundance
- For example, a charged slepton NSLP in this scenario the lifetime of a ~150 GeV stau decaying to a ~100 GeV gravitino is $O(10^9\ \text{s})$ i.e. $O(10\ \text{yr})$

$\tilde{\tau} \rightarrow \tau\tilde{G}$

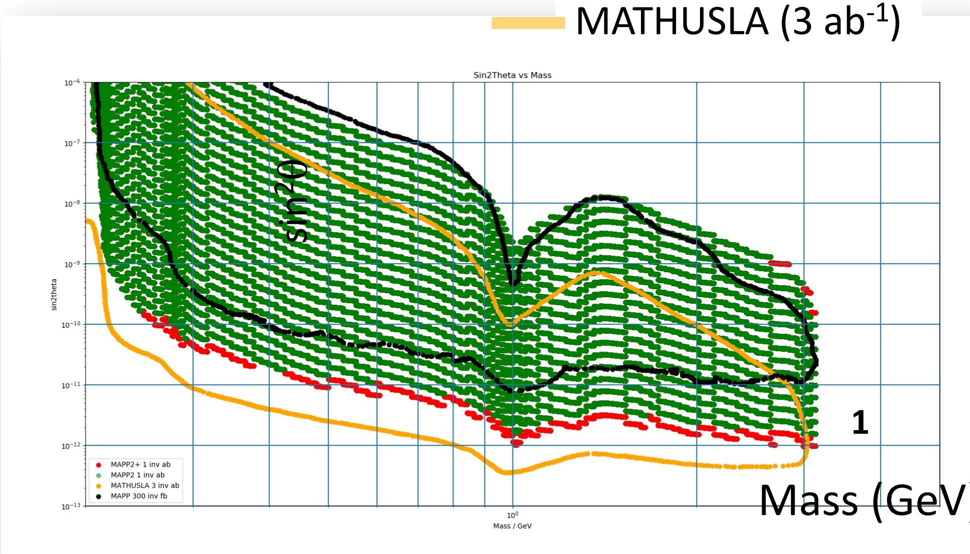


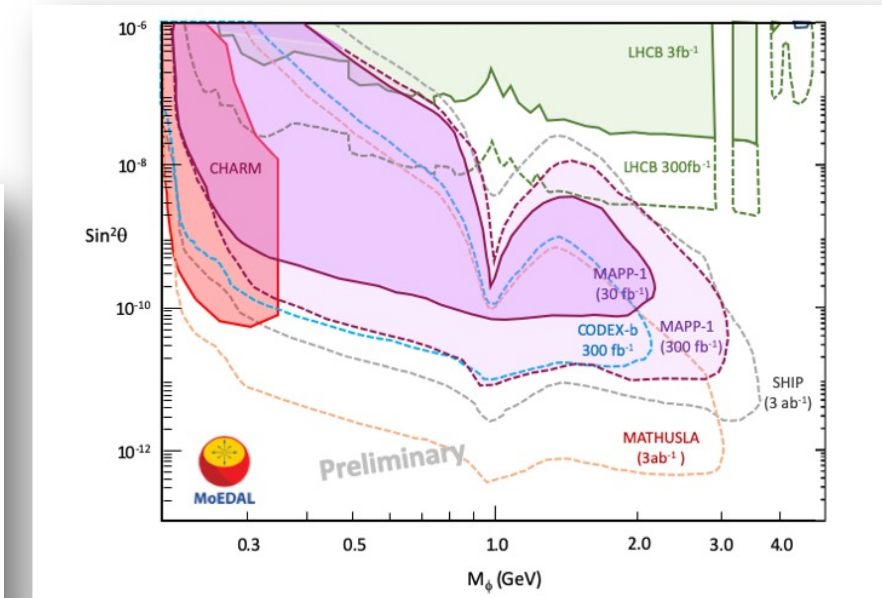
Feng, Rajaraman, Takayama, Phys. Rev. D 68, 063504 (2003)

MAPP-2 – for High Luminosity LHC

Dark Higgs scenario

MAPP-1 (300 fb^{-1})
MAPP-2 (1ab^{-1})
MATHUSLA (3 ab^{-1})



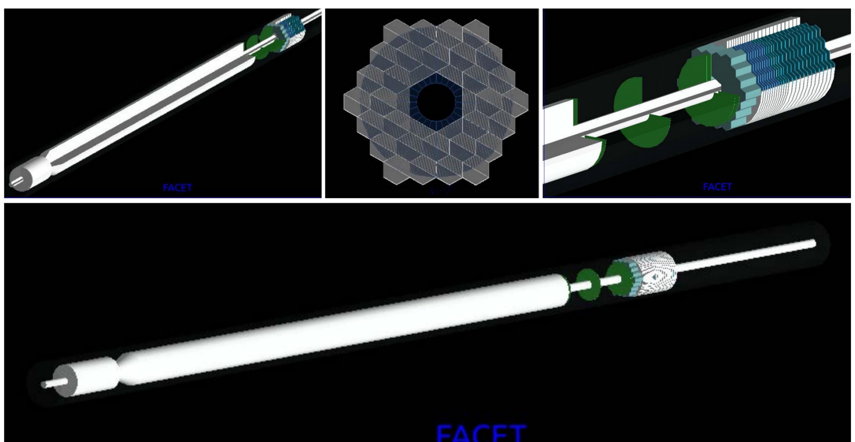


adopted from Gligorov, Knapen, Papucci, Robinson, [Phys.Rev.D 97 (2018) 015023]

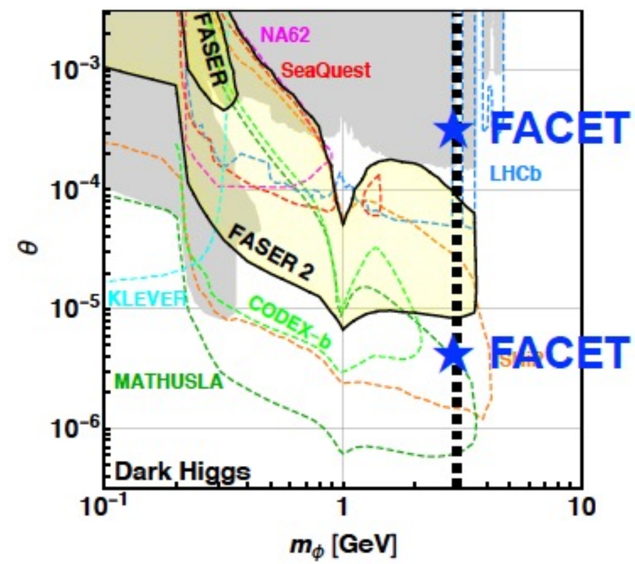
FACET – Forward-Aperture CMS ExTension

- 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
- If approved, FACET will operate in HL-LHC

Initial simulations show good sensitivity



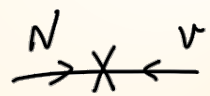
FACET Snowmass EoI, SNOWMASS21-EF9_EF8_ALBROW-111



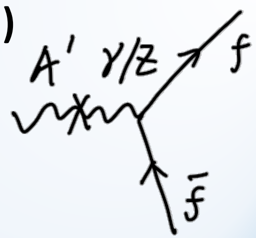
Adapted from Phys.Rev.D 99 (2019) 095011 arXiv1811.12522

Hidden sector

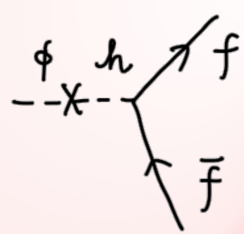
Heavy neutral leptons ("sterile neutrinos")
- explain SM ν masses (seesaw), DM, BAU
- weak semi-leptonic decays of hadrons, W, Z



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