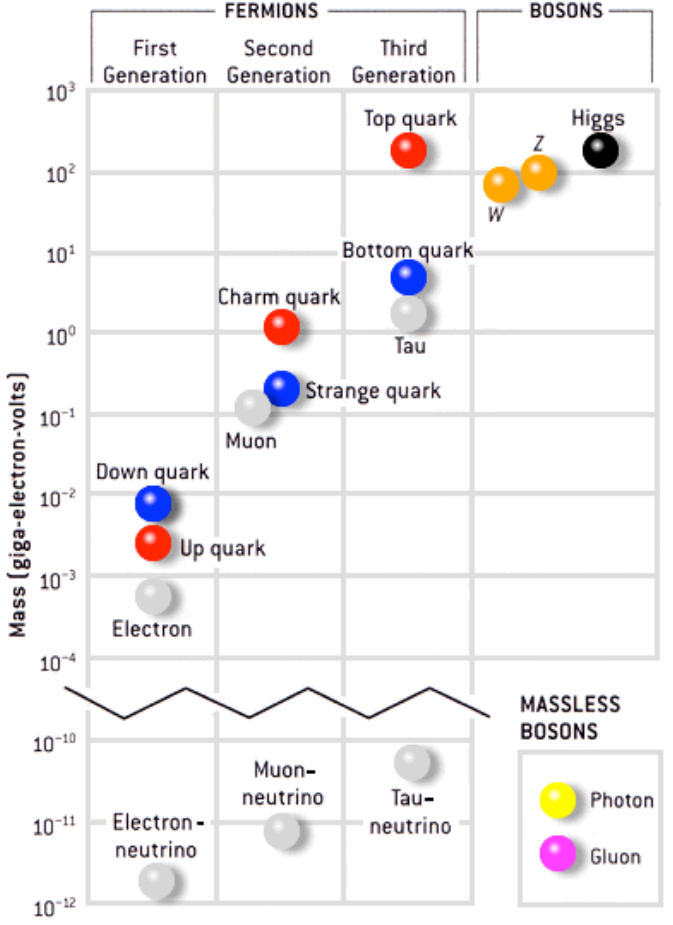
Long-lived particles: The experiments

Vasiliki A. Mitsou

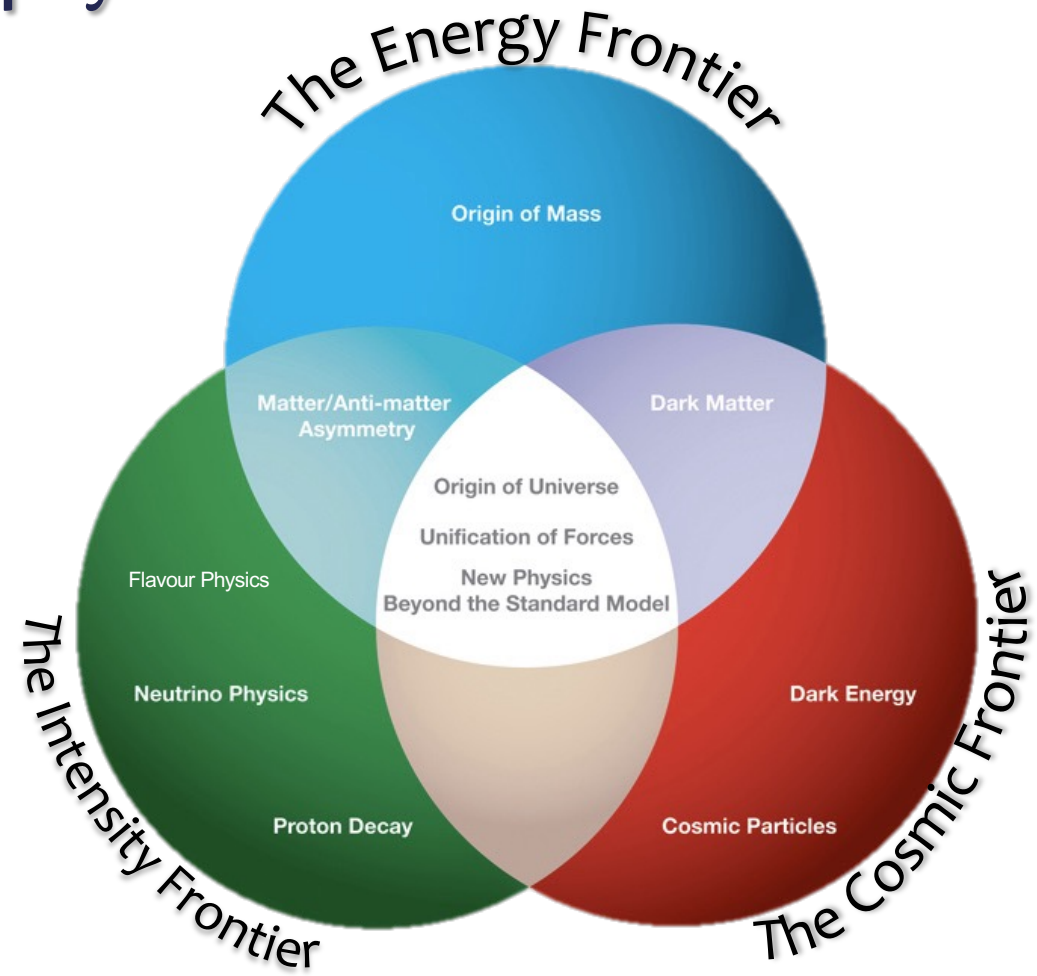
Standard Model (of Particle Physics)

- Content and forces of Universe at a fundamental level summarised in **Standard Model (SM)**
- SM describes well the experimental data so far
- However, important open issues exist
  - Origin of mass
  - Grand unification
  - Gravitation
  - Dark Matter – Dark Energy
  - Neutrino masses
  - Matter ↔ antimatter asymmetry
  - **Observed anomalies**
  - …

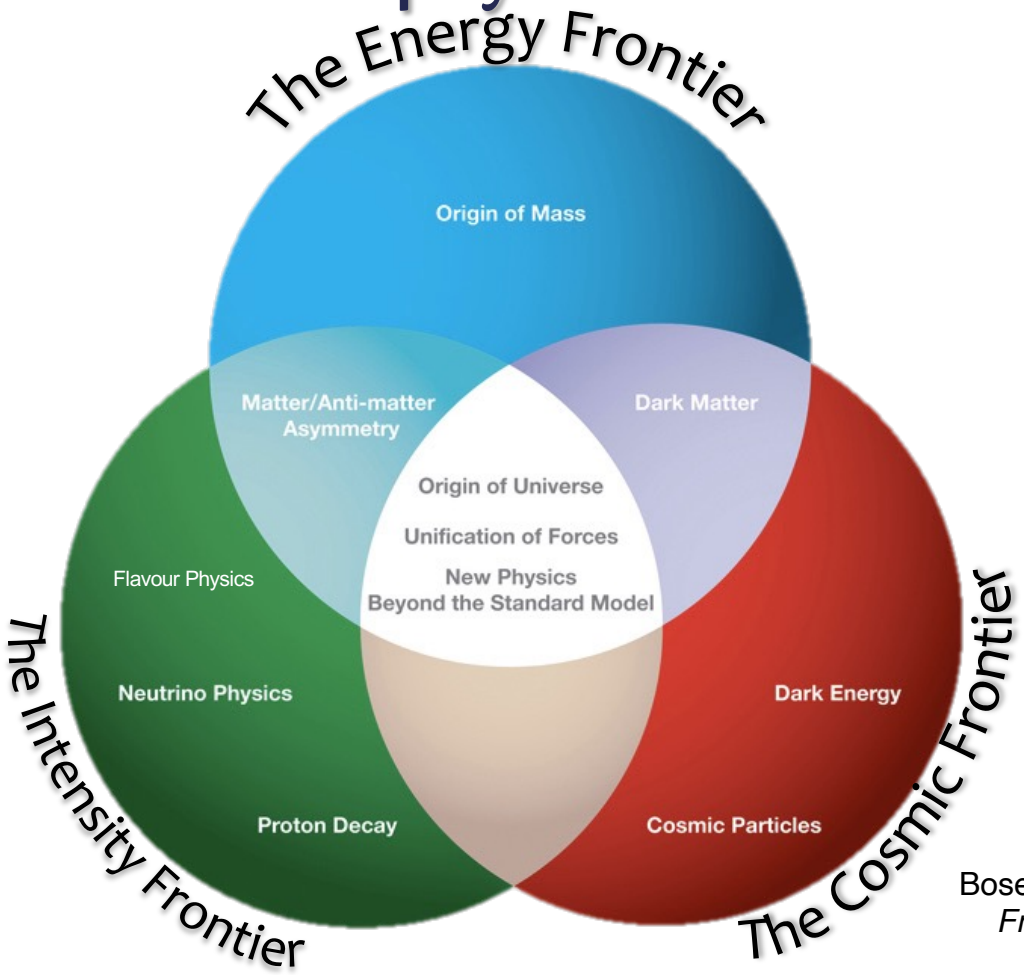


Need for physics beyond the SM (BSM)

Search for physics BSM in three frontiers



Search for physics BSM in three frontiers – LHC



The Energy Frontier

↓

Large high-energy colliders

↓

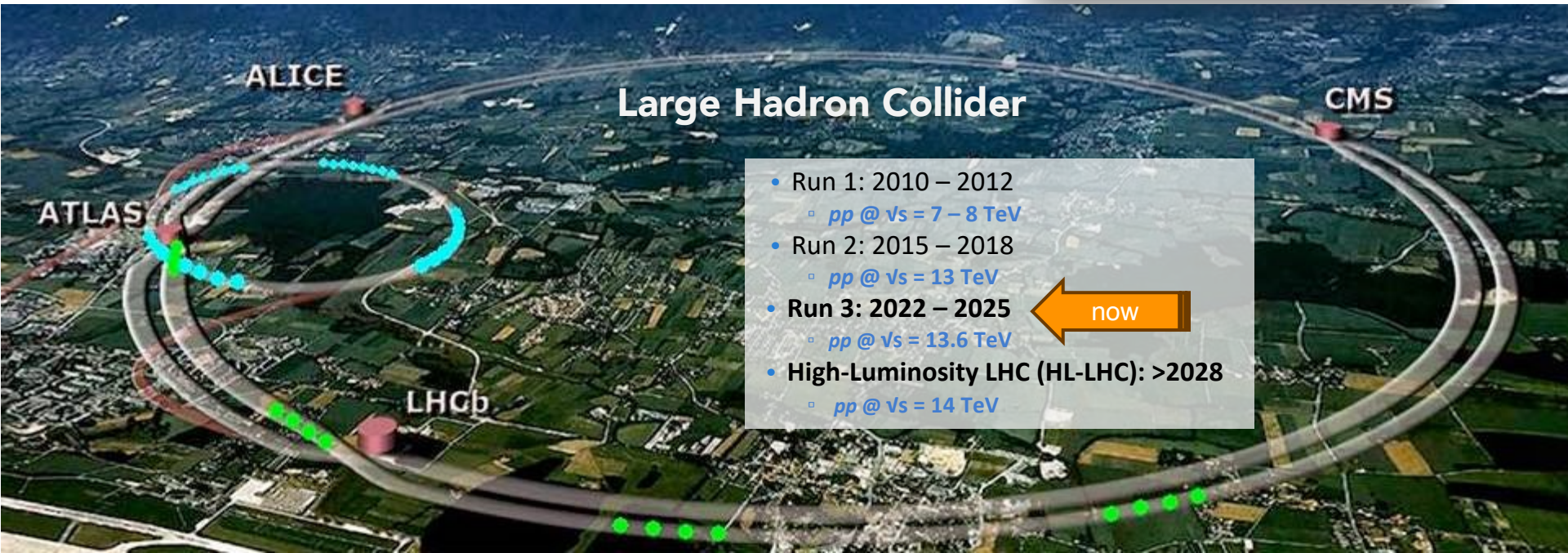
LHC

Bose *et al*, *Physics Beyond the Standard Model at Energy Frontier*, Contribution to Snowmass 2021, arXiv:2209.13128

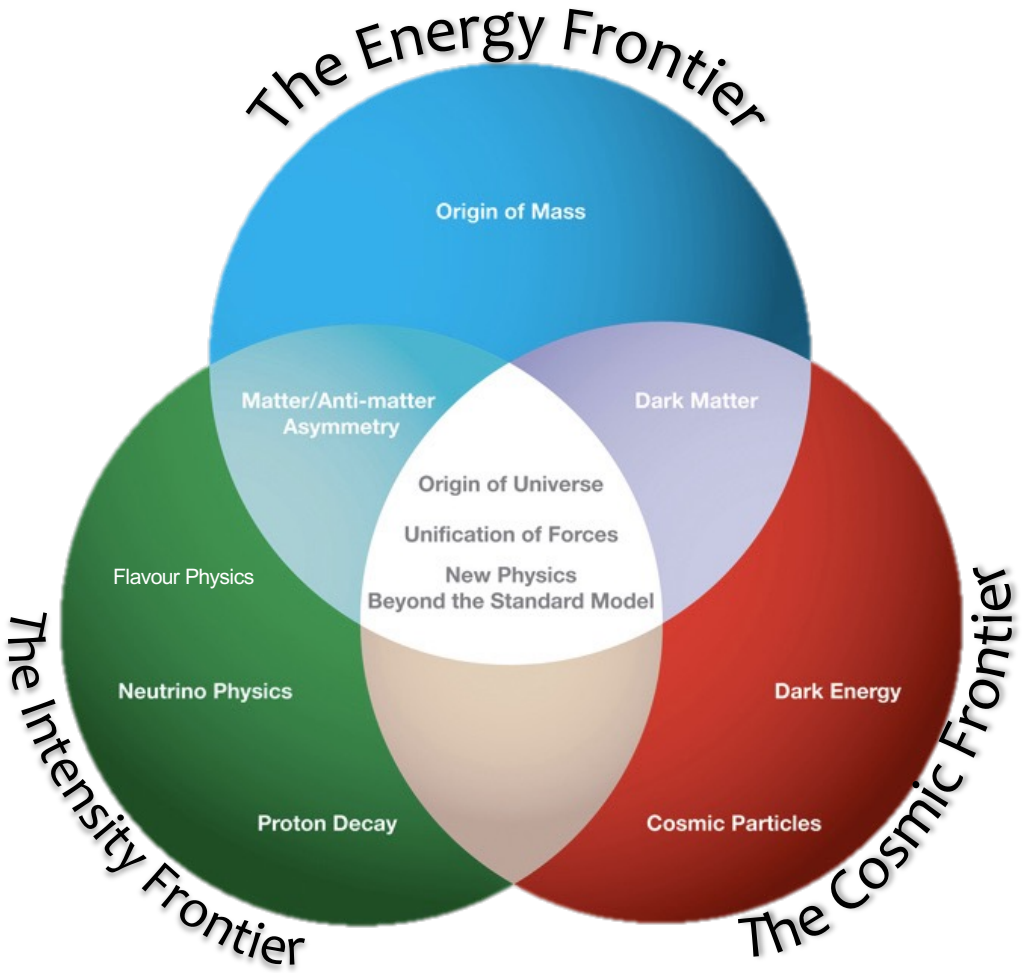
Large Hadron Collider – LHC

Most powerful particle collider to date

Designed to address open issues of SM



The three frontiers

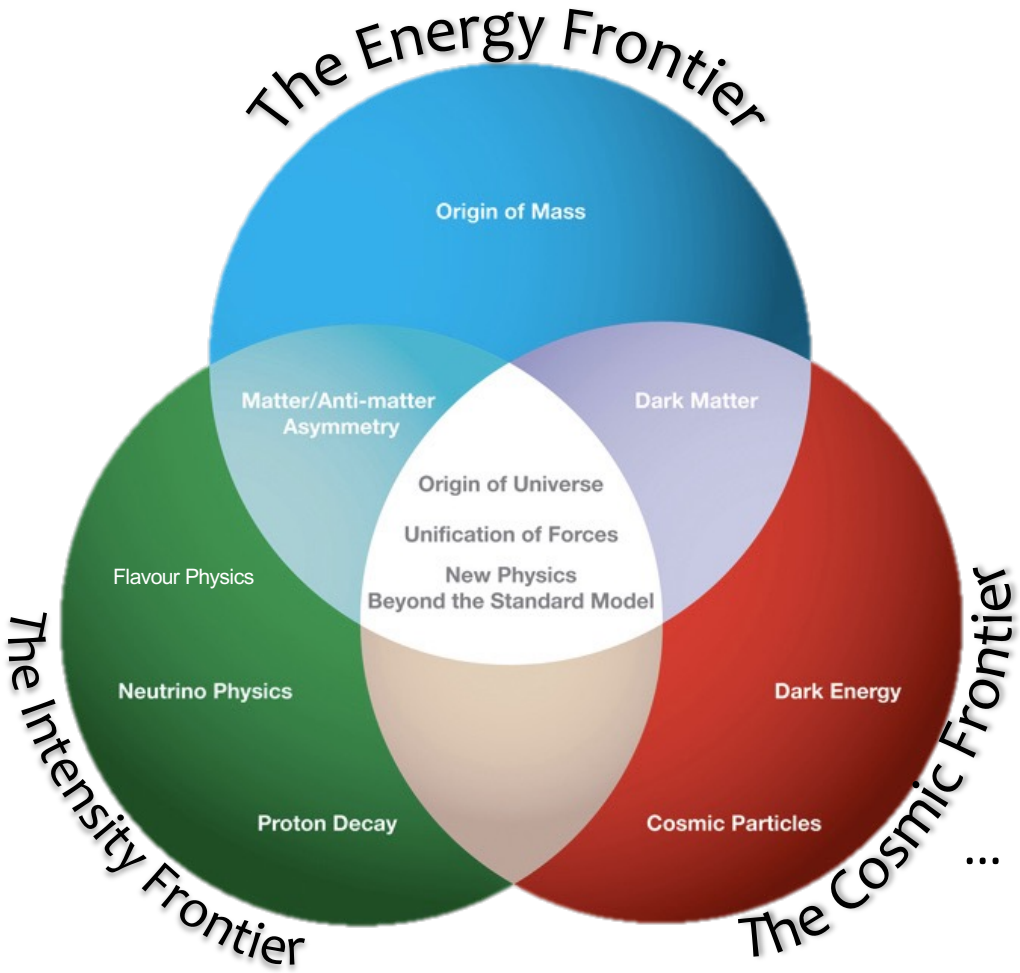


Up to now, no direct evidence of BSM physics has been observed*

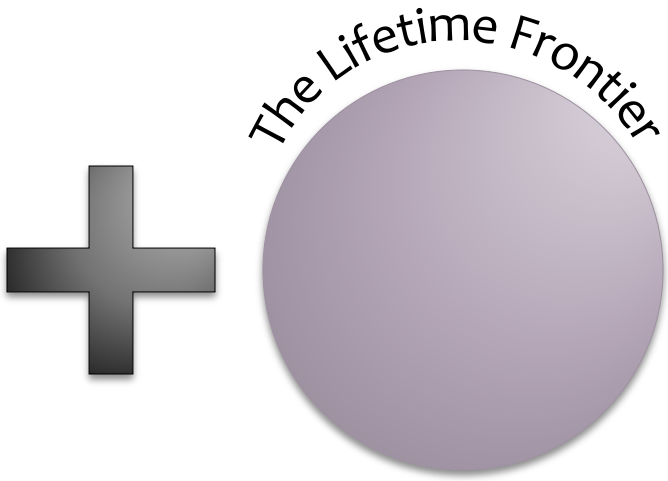
1. Is the mass scale beyond the LHC reach?
2. Is the mass scale within LHC's reach, but we are not looking at the right final states?

* Apart from intriguing anomalies

The ~~three~~ *four* frontiers



… Is the mass scale within LHC's reach, but we are not looking at the right final states?



… look for **Long-Lived Particles (LLPs)**

Mechanisms leading to (BSM) LLPs

Small couplings

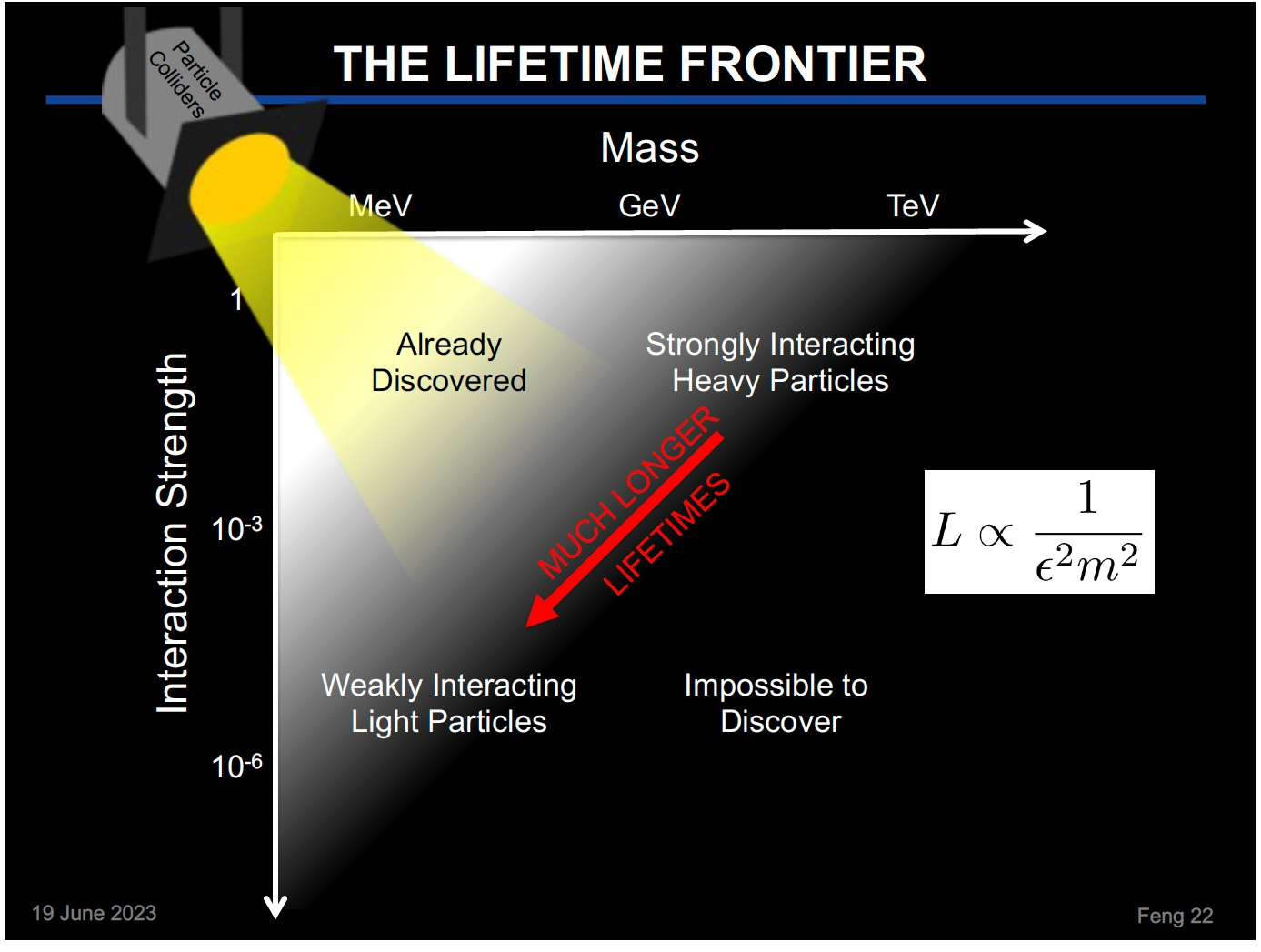
- R-parity violating SUSY with $\lambda \ll 1$
- gravitational coupling in GMSB SUSY

Limited phase space

- e.g. SUSY spectra with small mass splitings
- maybe due to a nearly conserved symmetry

Decays though a heavy, off shell particle

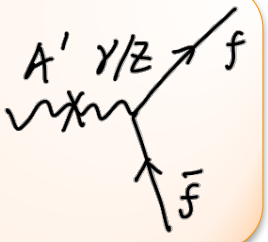
- gluinos and squarks in split SUSY, $\Gamma_{\text{gluino}} \sim m_{\text{gluino}}^5 / m_{\text{squark}}^4$
- heavy neutral leptons decaying to neutrinos



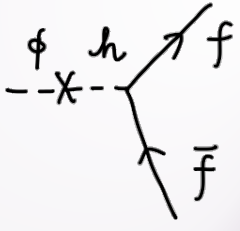
Jonathan Feng, CERN Colloquium

Feebly Interacting Particles (FIPs)

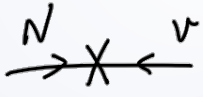
Dark vectors ("Dark Photons")
- adding U(1) gauge group to SM, kinetic mixing with γ/Z



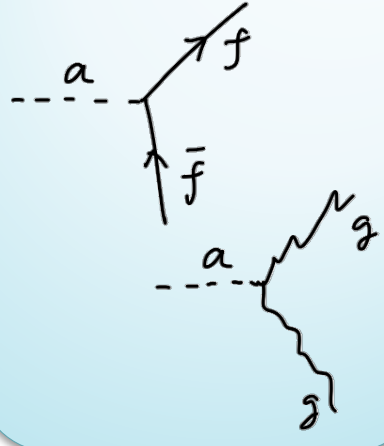
Dark scalars ("Dark Higgs")
- neutral singlet scalers that couple to the SM Higgs field

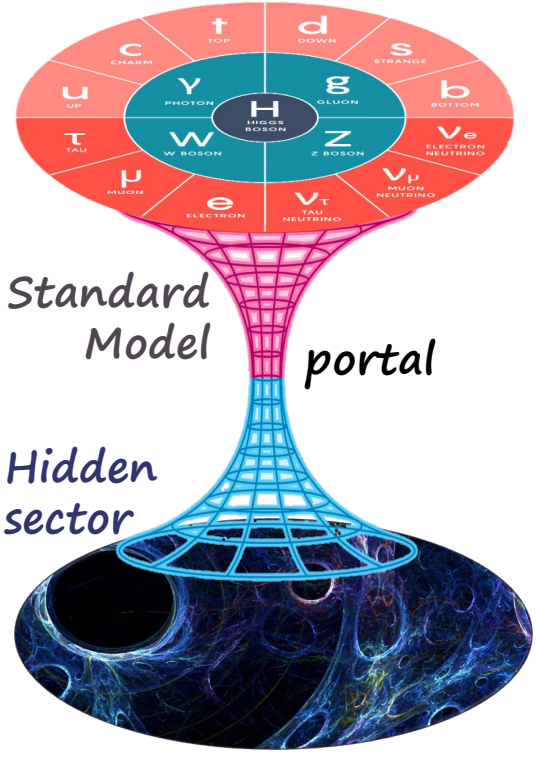


Heavy neutral leptons ("sterile neutrinos")
- explain SM ν masses (seesaw), DM, BAU



Axion-like particles ("ALPs")
- solution of the strong CP problem





☞ Juliette's talk on Wednesday

"Strongly" interacting heavy LLPs

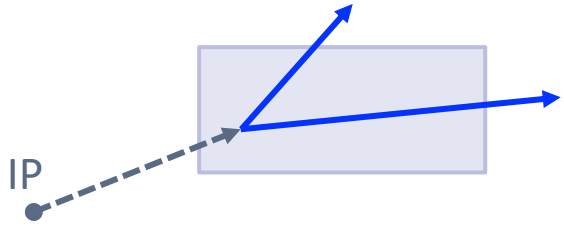
- *LLPs are not only about FIPs*
- Conservation of a parity ⇒ stable particle, e.g. LSP in SUSY
- Models motivated by and having implications for cosmology
  – dark matter
- Scenarios with extra dimensions have similarities to SUSY
- Dirac electric charge quantisation ⇒ magnetic monopoles
- High Electric Charge Objects (HECOs)
  - finite-sized objects (Q-balls)
  - condensed states (strangelets)
  - radiative neutrino models [Martin Hirsch et al, 2021]
  - microscopic black holes (through their remnants)
- …

Some results from such LLPs will follow

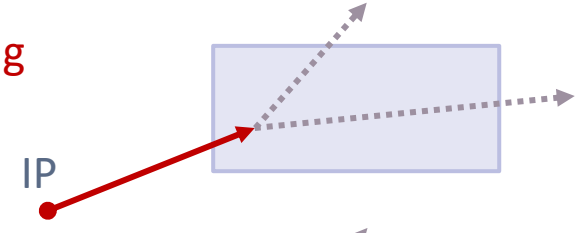
Classes of signatures

LLP decays IN the detector

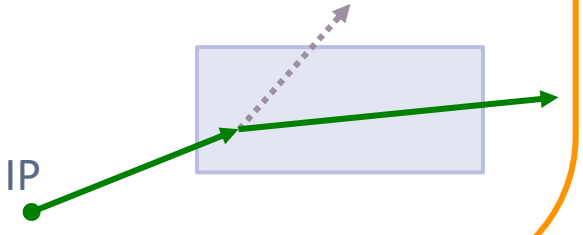
Displaced vertex (DV)



Disappearing track

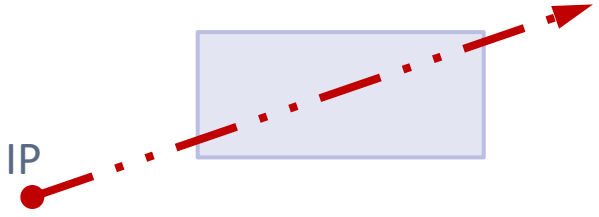


Kink

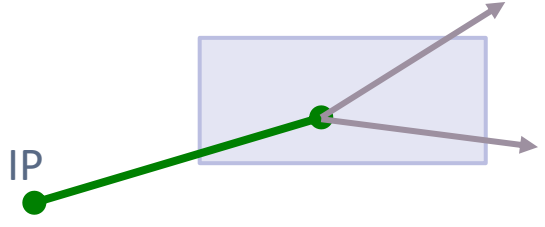


LLP induces anomalous ionisation

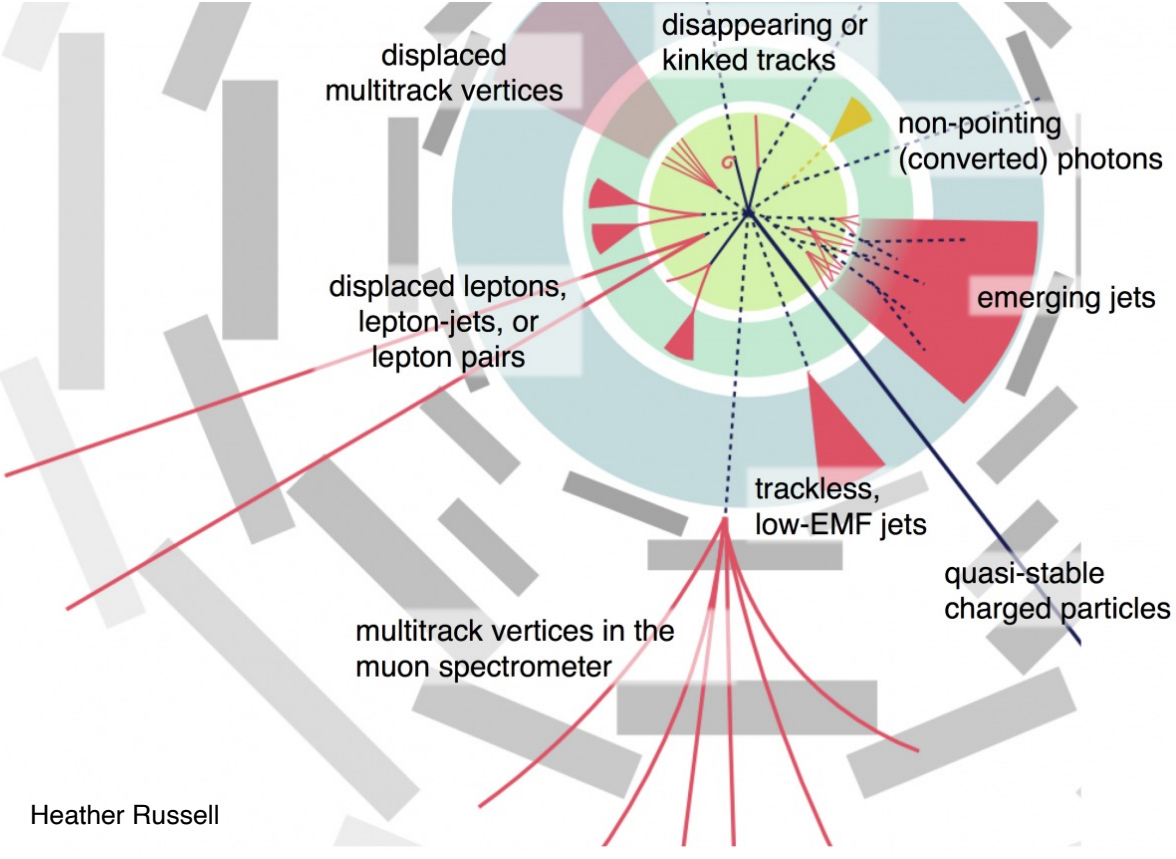
- highly ionising states (HIPs)
- millicharged particles (mCPs)



- if a HIP stops in detector, can decay later and detected *asynchronously*



LLPs at ATLAS & CMS



Huge amount of handles to constrain LLPs

- Unconventional tracks
- Large energy deposits
- Velocity measurements for slow-moving LLPs
- Displaced/non-pointing vertices and objects
  - limited by detector size
  - but, remember exponential nature of decays

ATLAS, CMS and LHCb as LLP detectors

- Although LHC main experiments not optimised for LLP detection, many related results keep coming
- Several challenges… and clever ideas to overcome them

☞ Flavia's talk this afternoon

Trigger

- Conventional trigger menu assumes SM particles produced at IP and are MIPs
- MET triggers or a hard lepton etc. is an option
- Dedicated triggers developed and deployed
- see, e.g. *New LLP triggers in LHC Run 3,* arXiv:2110.14675

Reconstruction

- Standard tracking may miss LLPs
  - IP constraint
  - disappearing track
  - magnetic monopole bending in solenoid field
- Specialised tracking difficult
- Not impossible, e.g. large-radius tracks

Backgrounds

- Neither standard or SM
- Beam induced, cosmics, fragments, timing issues, …
- Hard to simulate → data-driven estimation

ATLAS, CMS and LHCb as LLP detectors

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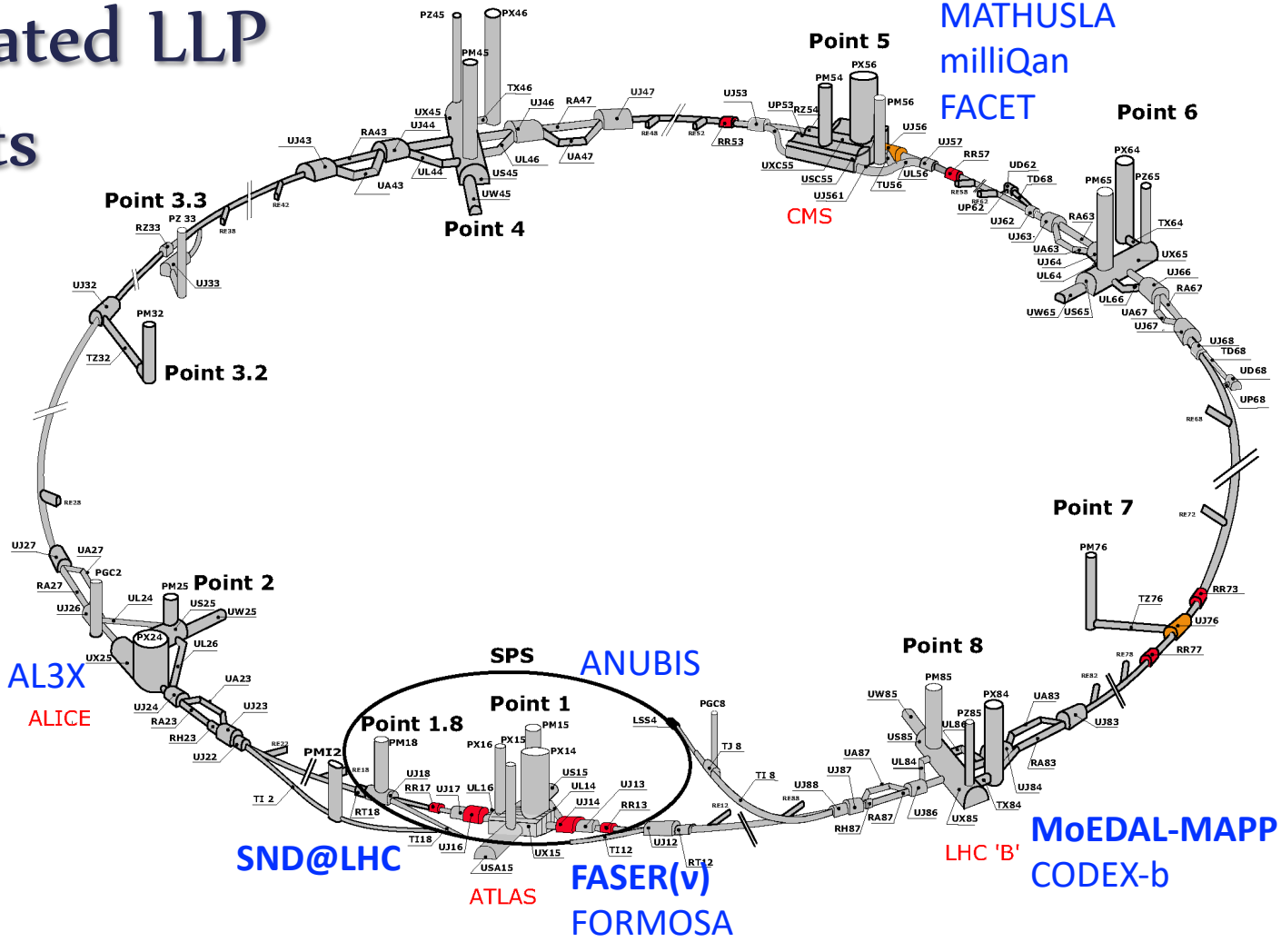
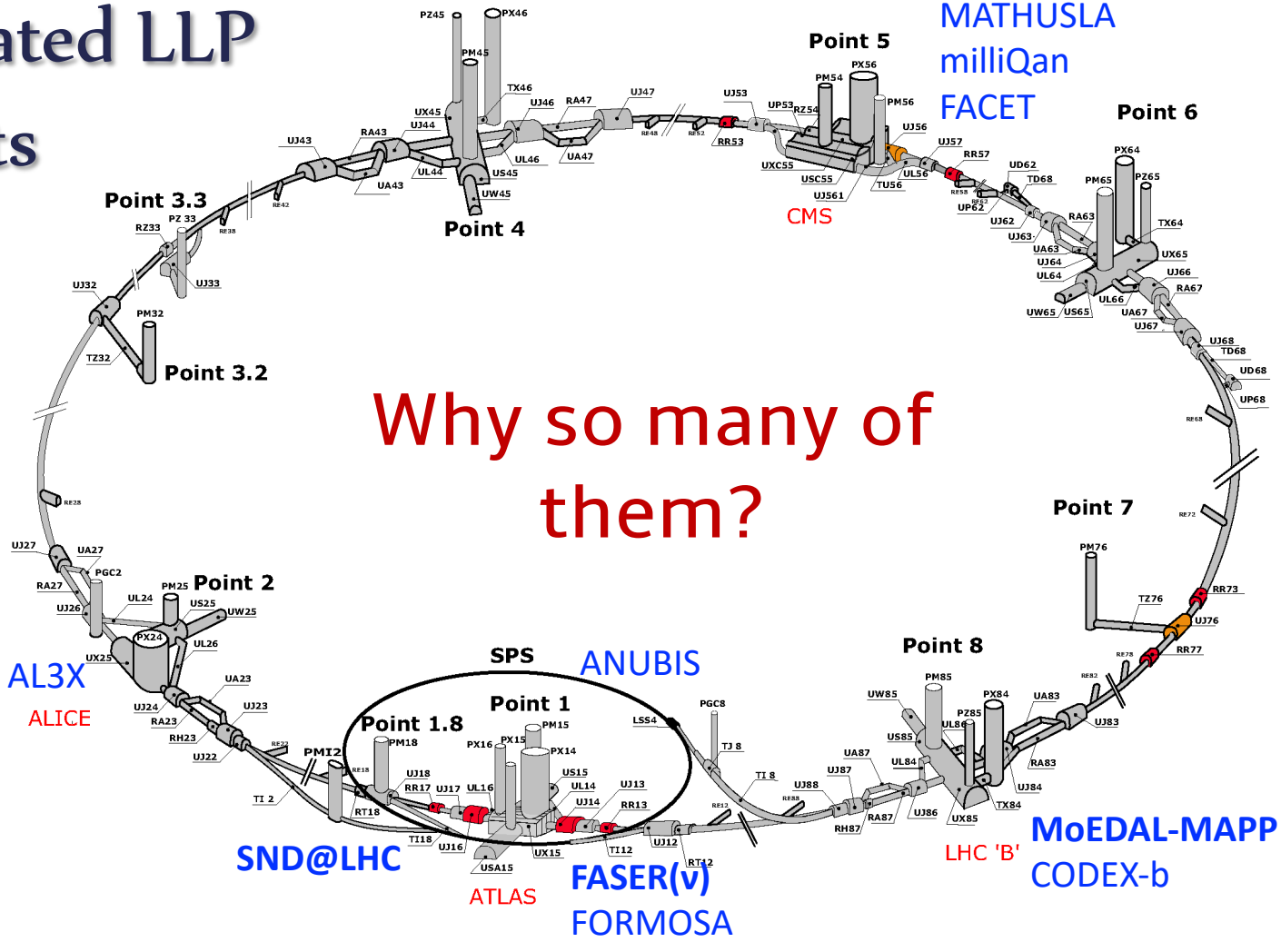
LLP-specific experiments are needed!

LHC dedicated LLP experiments

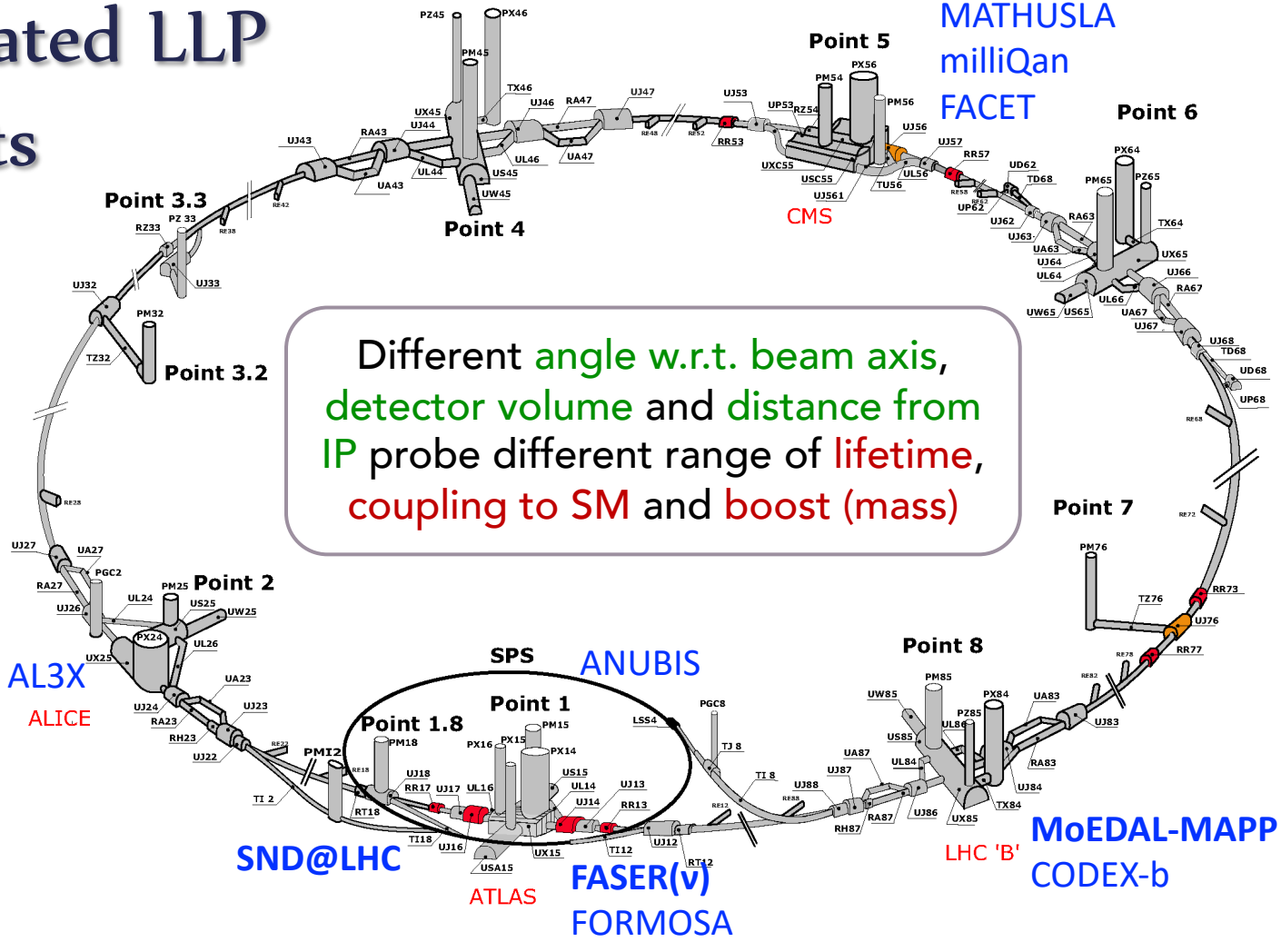


LHC dedicated LLP experiments



Why so many of them?

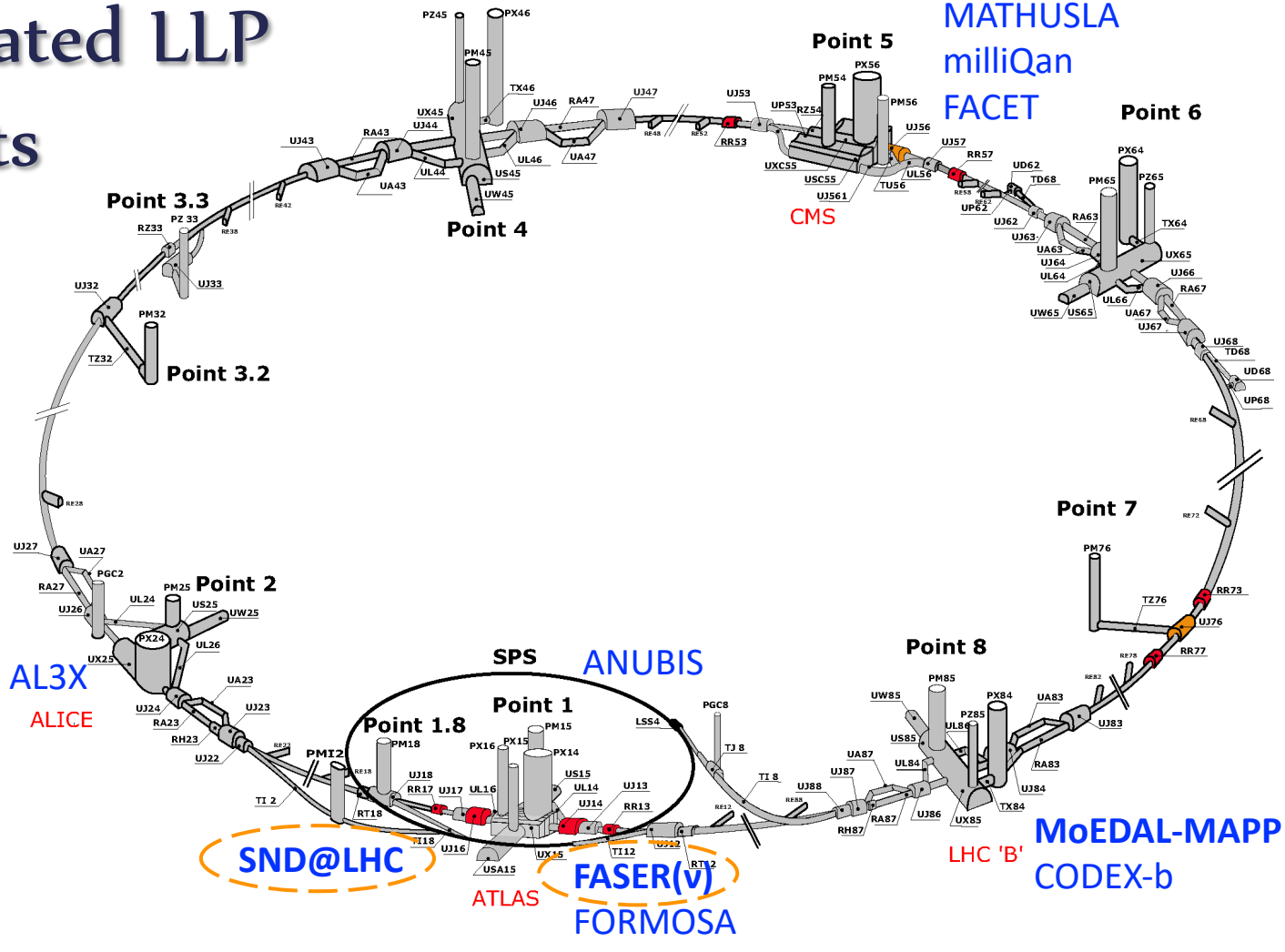
LHC dedicated LLP experiments



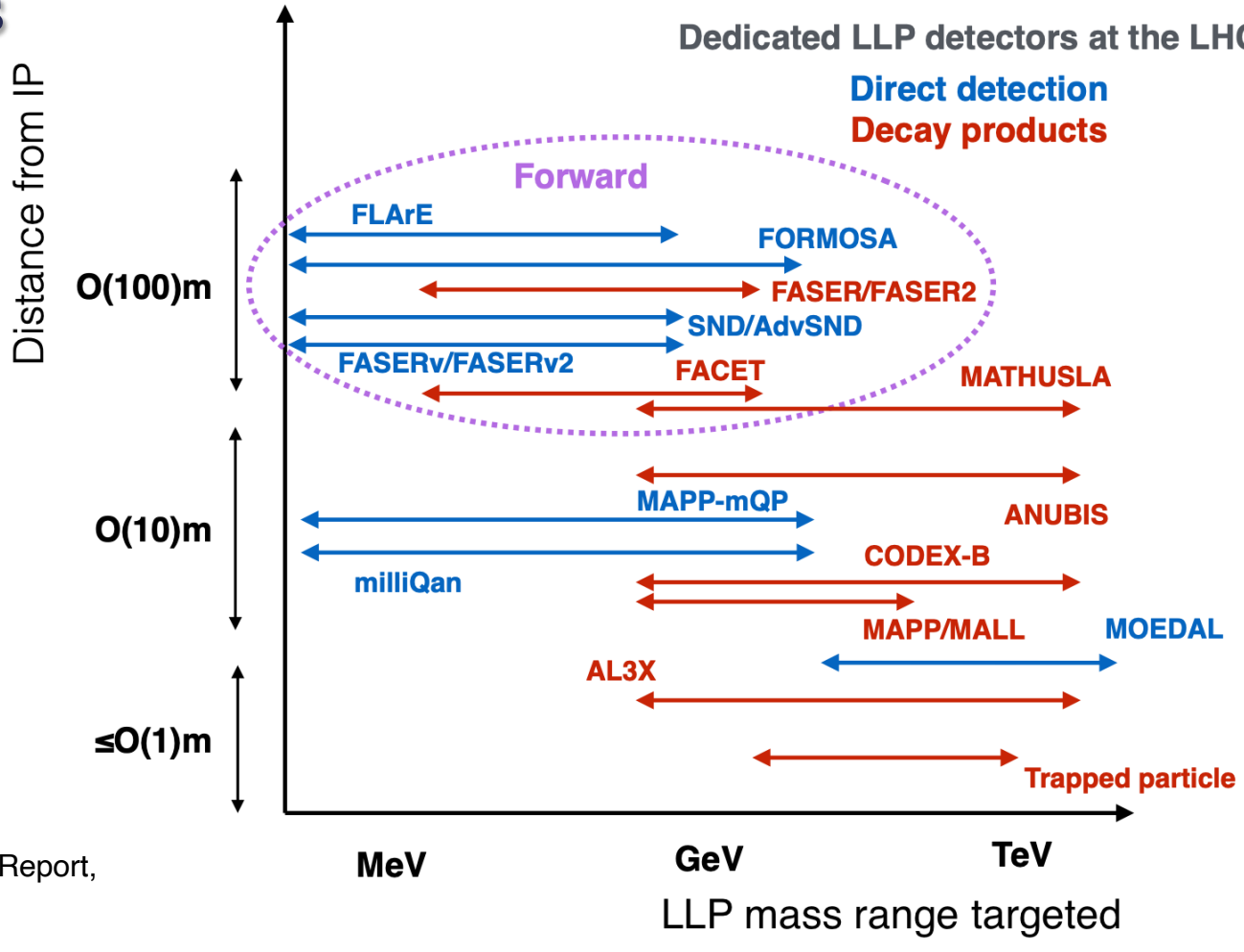
Different angle w.r.t. beam axis, detector volume and distance from IP probe different range of lifetime, coupling to SM and boost (mass)

LHC dedicated LLP experiments

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



Lifetime–mass summary



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

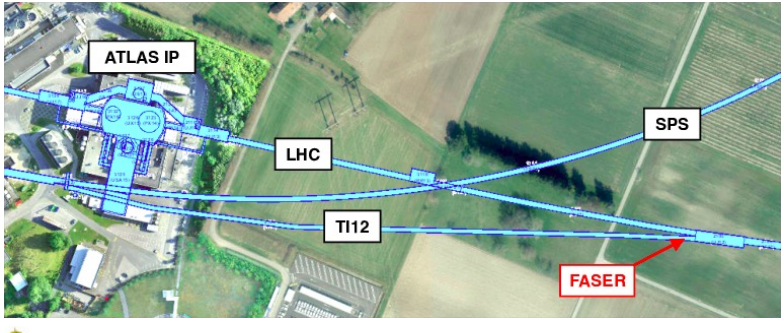
FASER

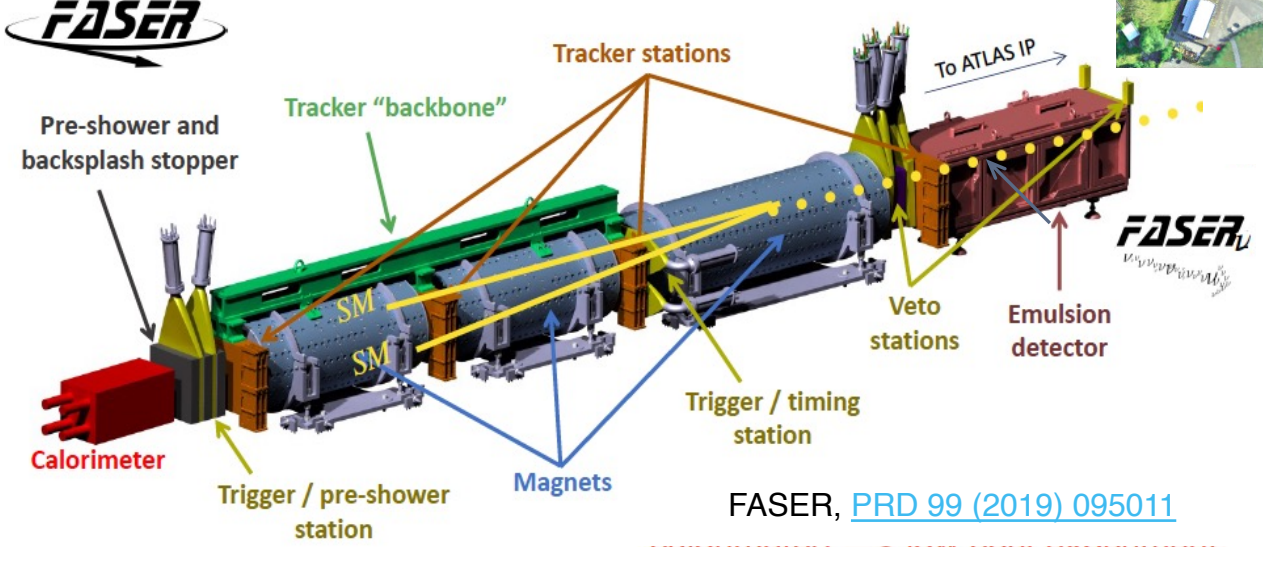
Forw**A**rd **S**earch Expe**R**iment at the LHC

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

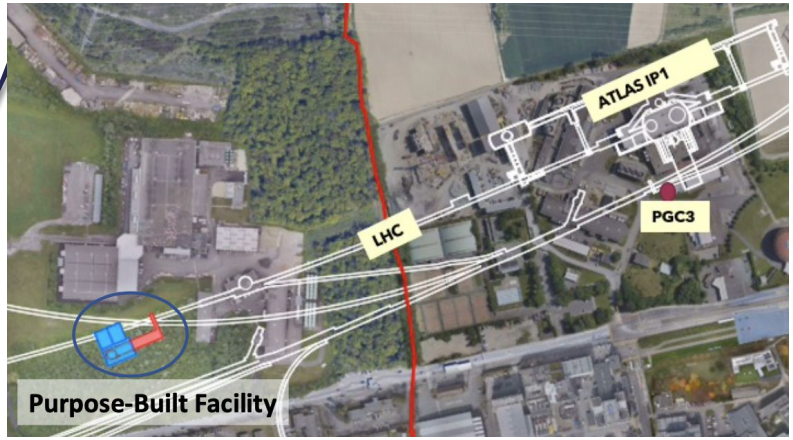
Upgrade:

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

☞ Florian's talk on FASER on Friday

FPF – Forward Physics Facility

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

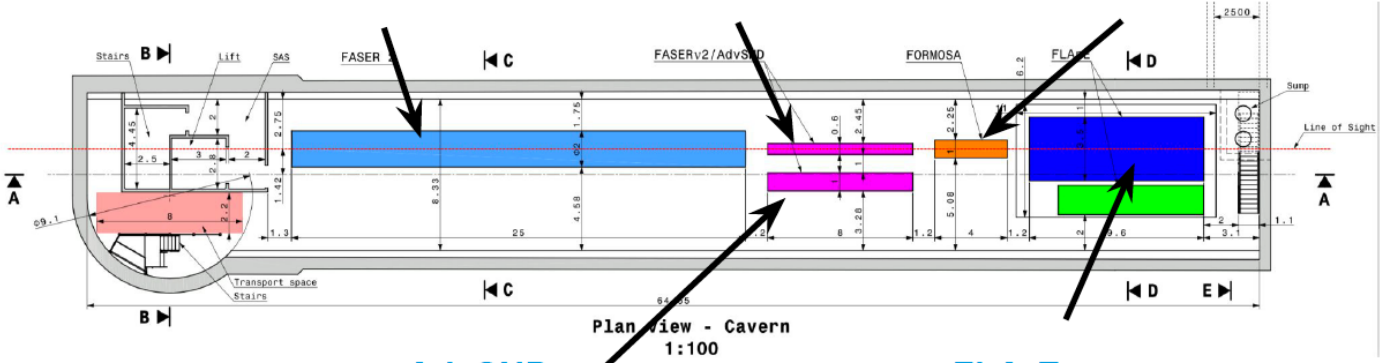


620-685 m west of the ATLAS IP

FASER2
magnetized spectrometer for BSM searches

FASERv2
emulsion-based neutrino detector

FORMOSA
plastic scintillator array for BSM searches



AdvSND
electronic neutrino detector

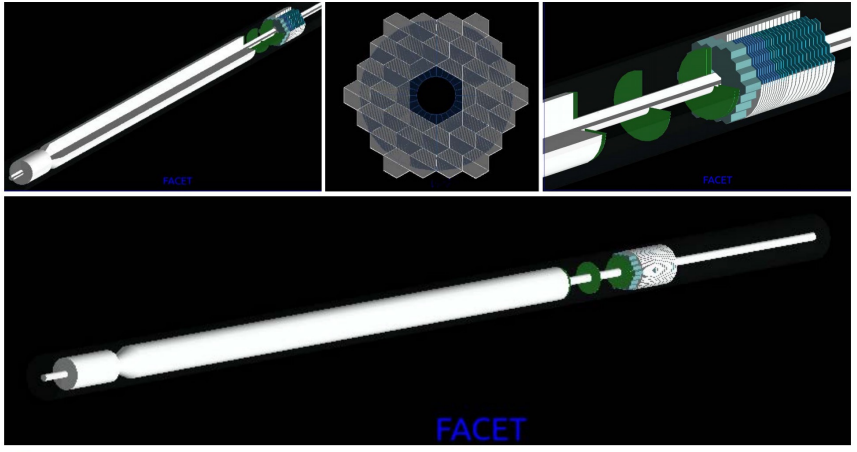
FLArE
LAr based neutrino detector

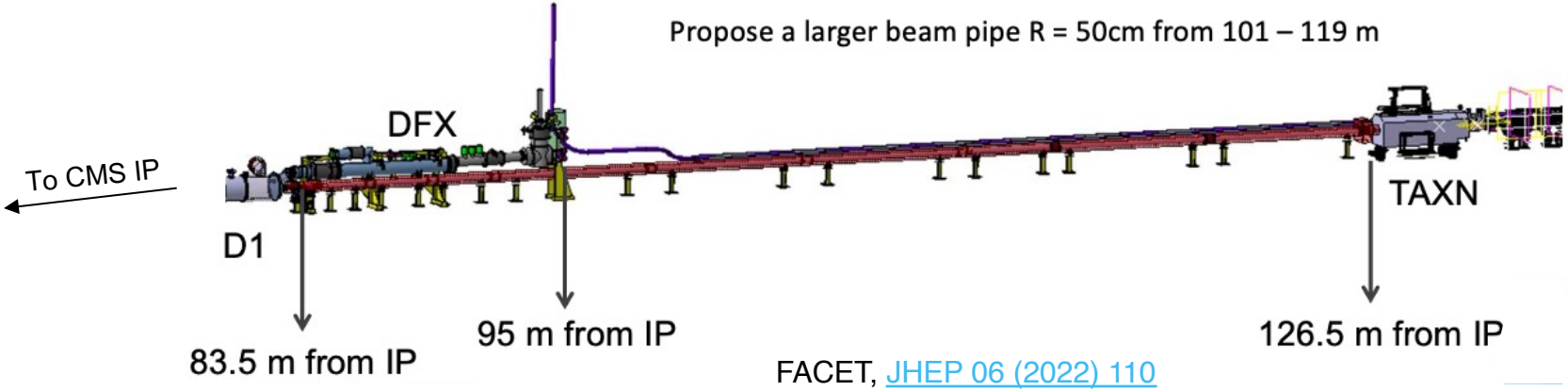
FPF Paper Phys.Rept. 968 (2022) 1

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

FACET – Forward-Aperture CMS ExTension

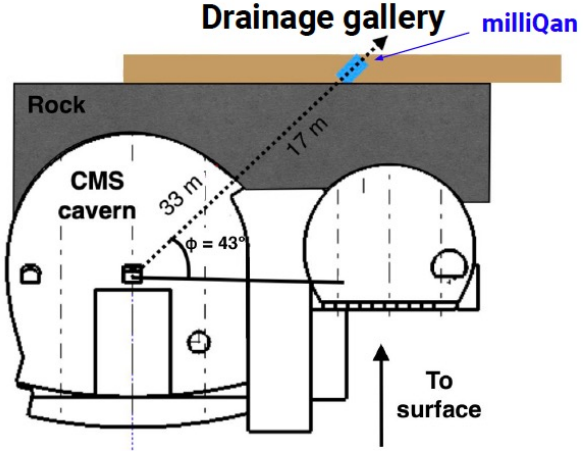
- Multi-particle spectrometer at z ~ +100 m from the IP5 (CMS)
- Detector will have a radius of ~50 cm and coverage **6 < η < 8**
- Much closer to the IP and much larger decay volume than FASER
- Aiming for operation in HL-LHC





FACET, JHEP 06 (2022) 110

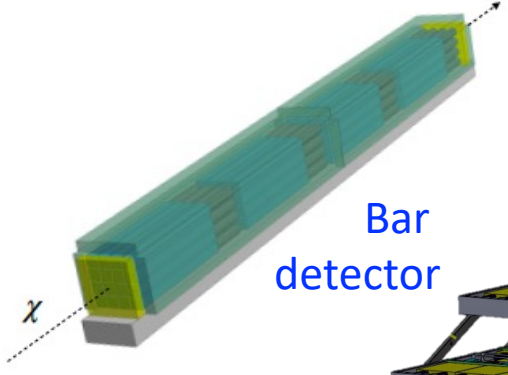
THE MILLIQAN EXPERIMENT



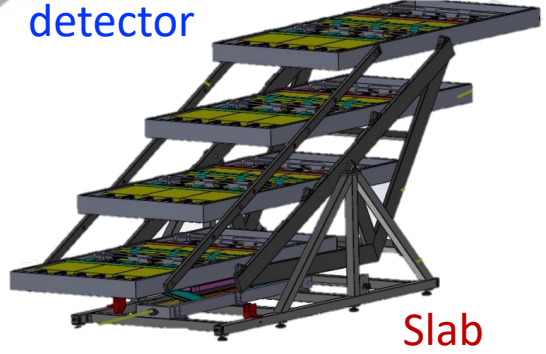
milliQan demonstrator

- ~1% prototype of the full detector
- first mCP constraints at LHC [PRD 102 (2020) 032002]

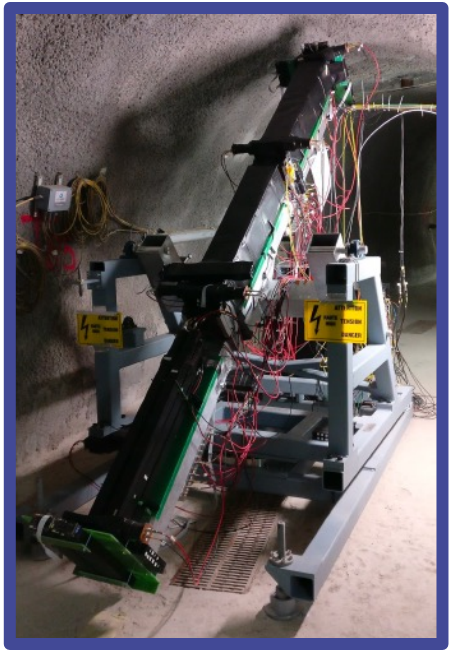
Expected to collect ~30 fb^{-1} in 2023 run



Bar detector



Slab detector



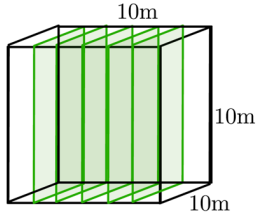
- Bar detector
  - 0.2 m × 0.2 m × 3 m plastic scintillator bars
  - surrounded by active μ veto shield
- Slab detector
  - 40 cm × 60 cm × 5 cm scintillator slabs
  - increased reach for heavier mCPs

milliQan, PRD 104 (2021) 032002

CODEX-b

A COmpact Detector for EXotics at LHCb

- **Resistive plate chambers**: fast, precise, cheap for large area
- Behind 3.2 m thick concrete shielding
  - very low SM background
  - effectively zero background with passive Pb shield
- Can integrate into LHCb trigger



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

CODEX-b

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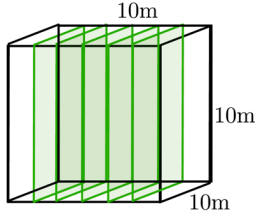
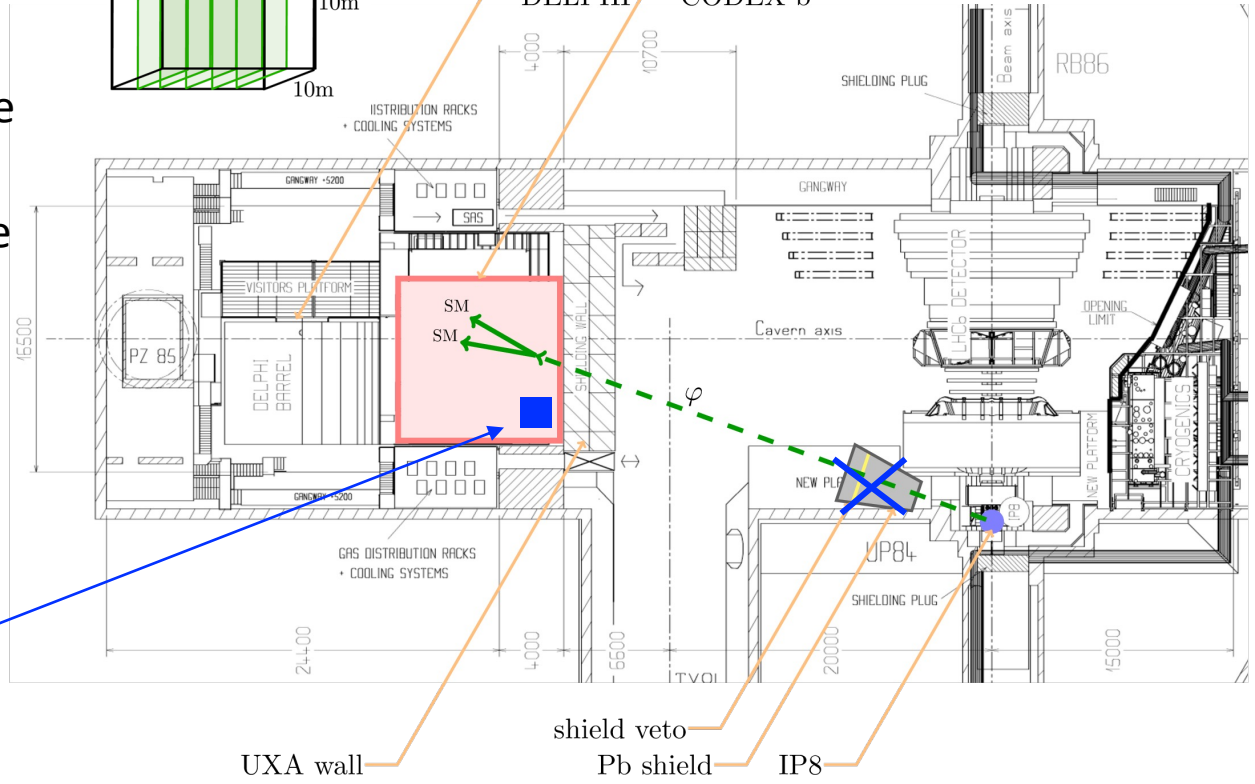
- Can integrate into LHCb trigger
- CODEX-β demonstrator (2×2×2 m^3) for Run-3



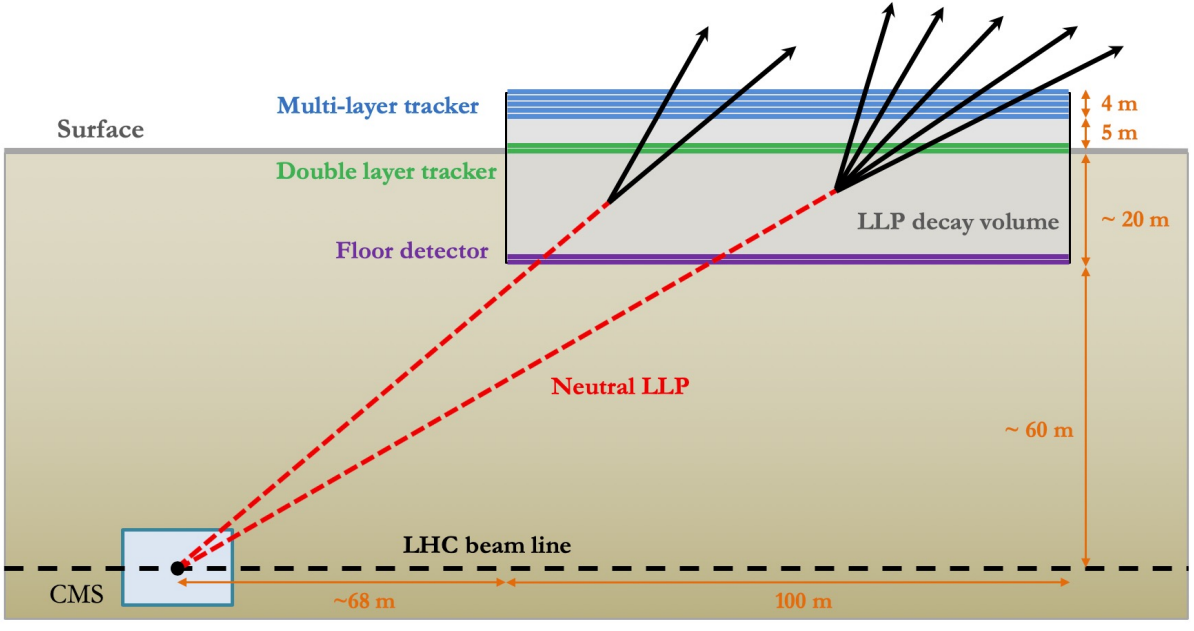
CODEX-b EoI Eur.Phys.J.C 80 (2020) 1177



MATHUSLA

MAsive Timing Hodoscope for Ultra Stable neutraL pArticles

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



MATHUSLA,
LoI arXiv:1901.04040,
arXiv:2009.01693

MATHUSLA

MAsive Timing Hodoscope for Ultra Stable neutraL pArticles

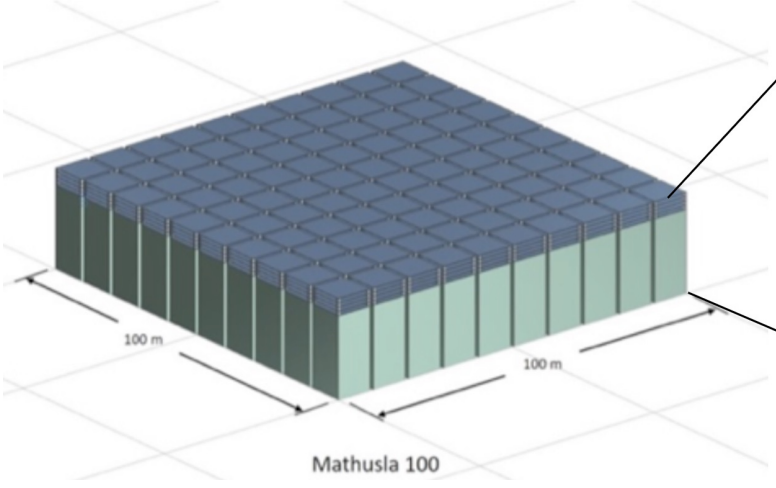
MATHUSLA, LoI arXiv:1901.04040, arXiv:2009.01693

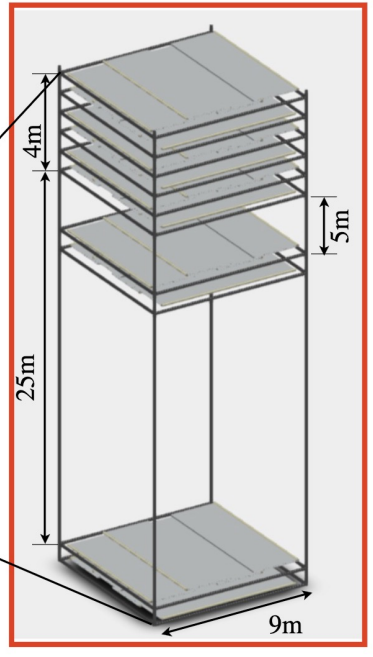
Modular design (100 modules of 9×9×30 m^3)

- Assembly time line not governed rigidly by HL-LHC beam schedule
- Data taking can start after installation of first module

Current status:

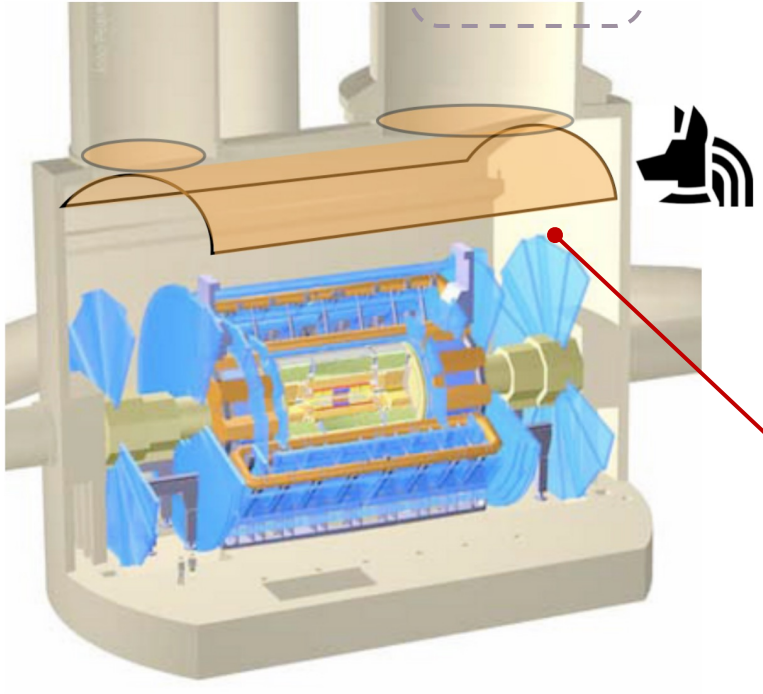
- Detector technology studied extensively
- Small lab-scale prototype units under construction
- CDR in preparation





ANUBIS AN Underground Belayed In-Shaft search experiment

proANUBIS: 180 cm × 100 cm × 100 cm BIS78 RPC triplet being commissioned in cavern to measure background rates



proANUBIS

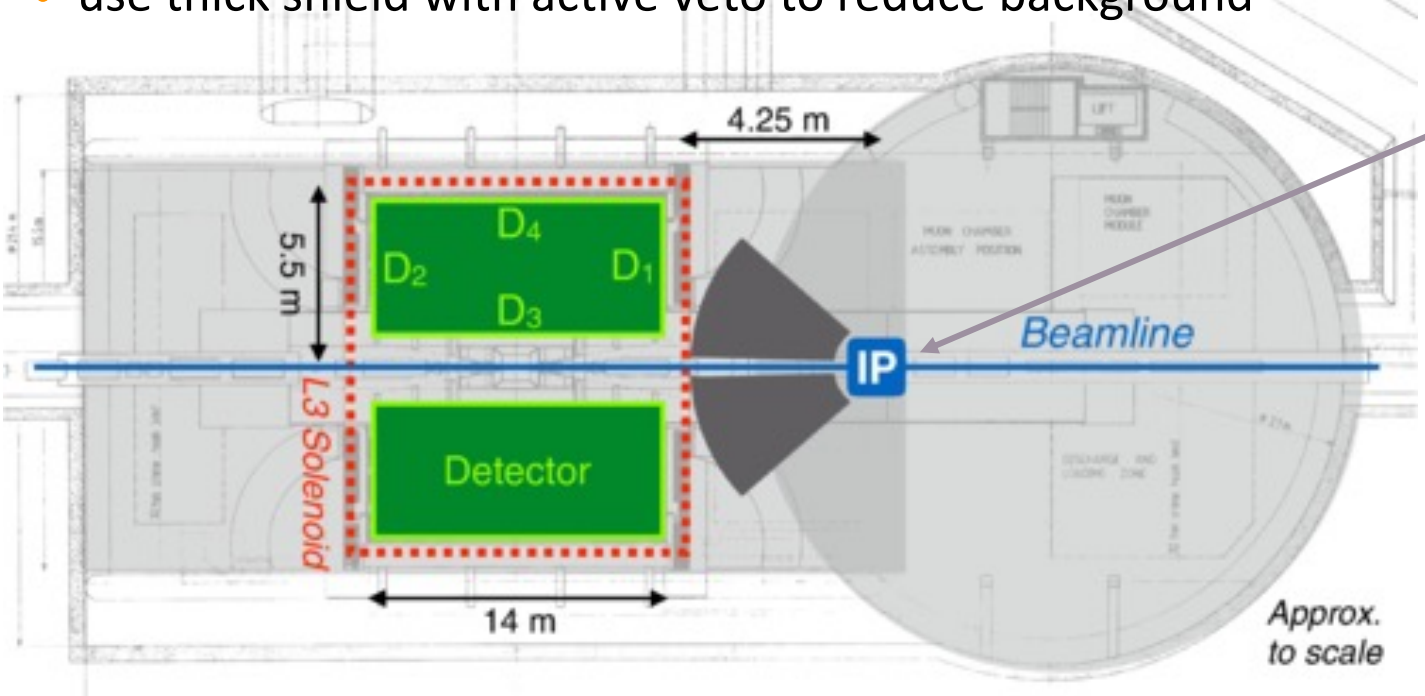
- Relies on existing technology for ATLAS muon system: BIC78 resistive plate chambers
- Latest ANUBIS proposal is to instrument ATLAS ceiling instead of shaft:
  - wider solid angle implies gain in sensitivity despite proximity to IP
  - sensitivity to $c\tau \sim 10^6$ m or so: not quite to BBN limit, but 4 orders of magnitude improvement over ATLAS reach alone

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 HL-LHC ends

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

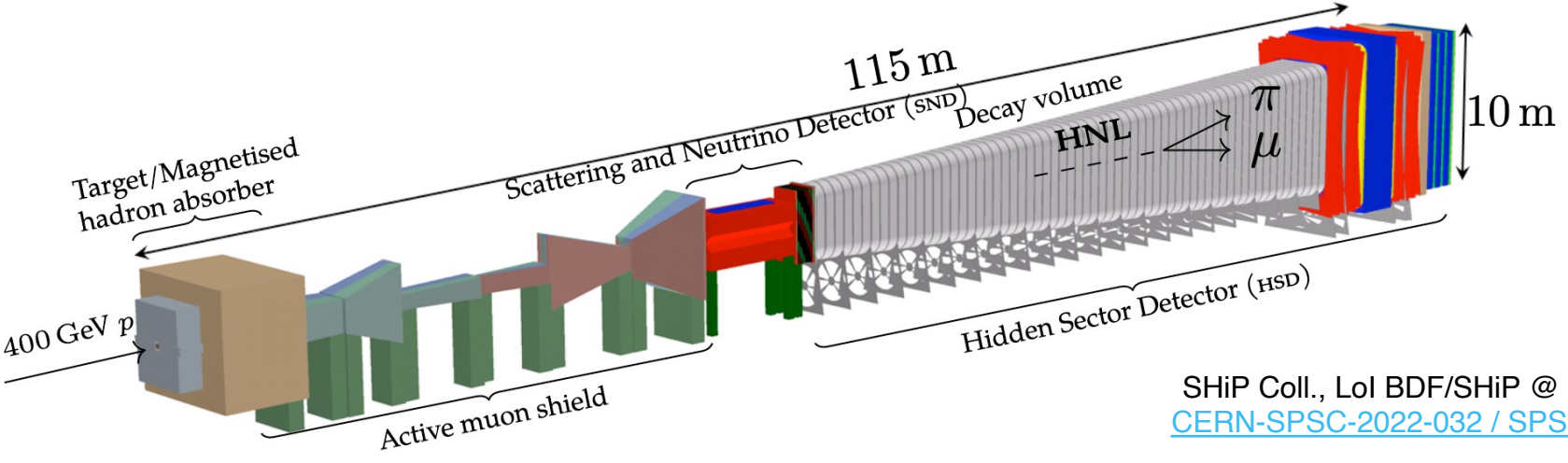


ALICE interaction point moved by 11.25 m outside magnet to allow LLPs to travel before decaying

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

SHiP – Search for Hidden Particles

- Beam dump experiment at SPS with 400-GeV *p* and 4×10^{19} PoT per year
- Originally designed for dedicated new beamline with a new experimental cavern (ECN4)…
- …now fully re-optimised for the *existing* ECN3 cavern
- Preliminary results indicate sensitivity at ECN3 equally good as in proposed ECN4

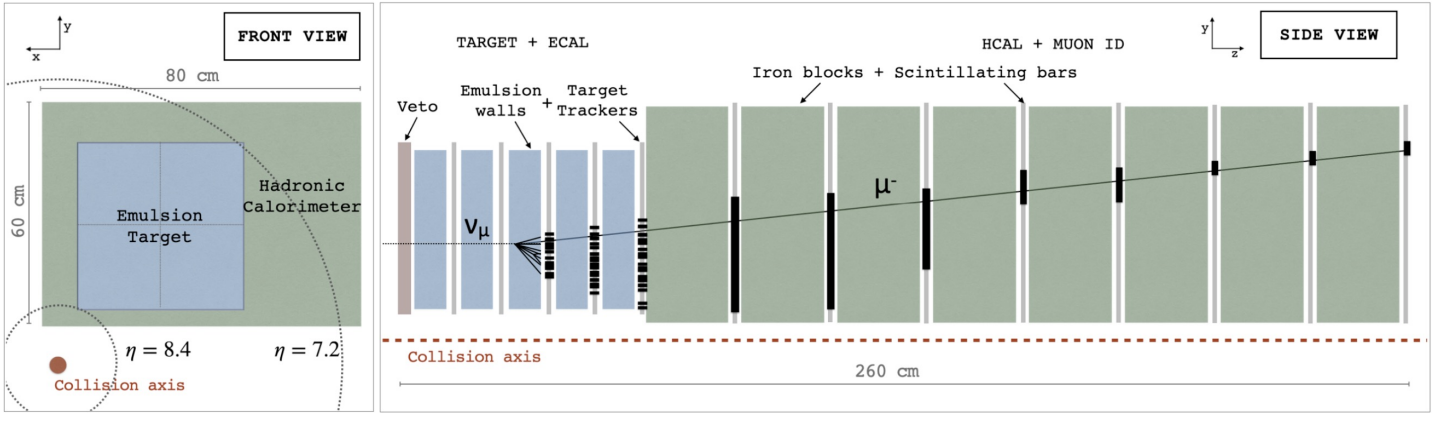


SHiP Coll., LoI BDF/SHiP @ ECN3, CERN-SPSC-2022-032 / SPSC-I-258

SND@LHC – Scattering and Neutrino Detector at the LHC

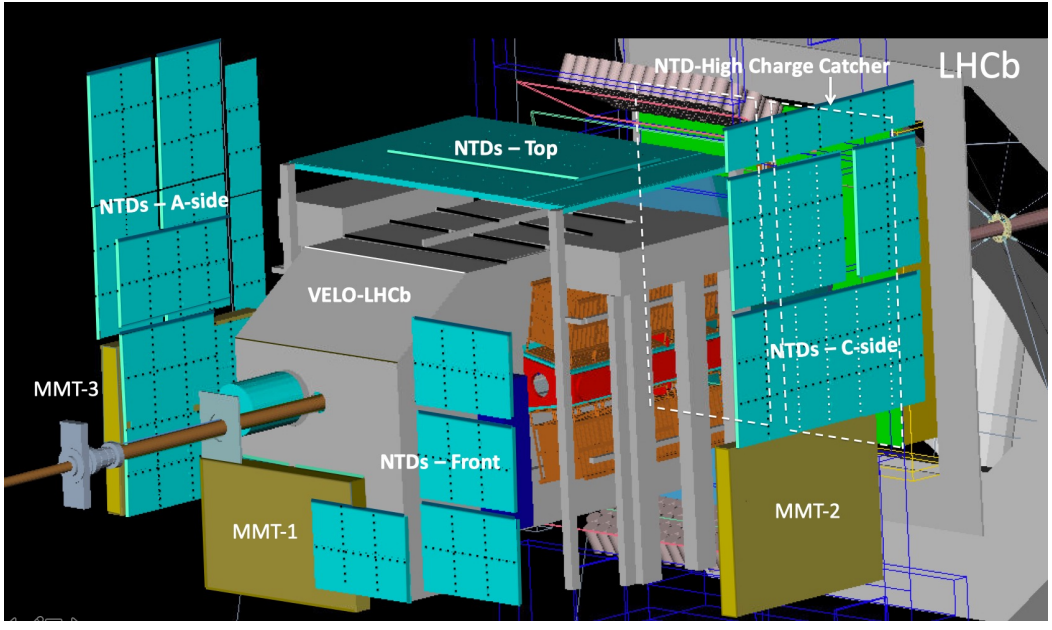
- Compact and stand-alone experiment designed to measure neutrinos produced at the LHC and search for FIPs in the unexplored range of **7.2 < η < 8.6**
- Good spatial resolution of the SND@LHC emulsion → decays into two charged particles may be distinguished from ν scattering events
- Recently, **first ν_μ events** have been observed [Phys.Rev.Lett. 131 (2023) 031802]
- AdvSND: extension of SND@LHC to run during HL-LHC
  - 1. $\text{AdvSND}_{\text{far}}$ (to be located at FPF)
  - 2. $\text{AdvSND}_{\text{near}}$ (to be located much closer and cover LHCb η range)

~480 m from IP1 (ATLAS)



SND@LHC collab., arXiv: 2210.02784

MoEDAL – Monopole & Exotics Detector At LHC



- IP8 – LHCb VELO cavern
- Optimised for detecting **highly ionising particles**
- Sole LHC experiment using passive detectors ➜ no trigger, no readout
  - nuclear track detectors
  - magnetic monopole trappers

Design unlike any other collider experiment

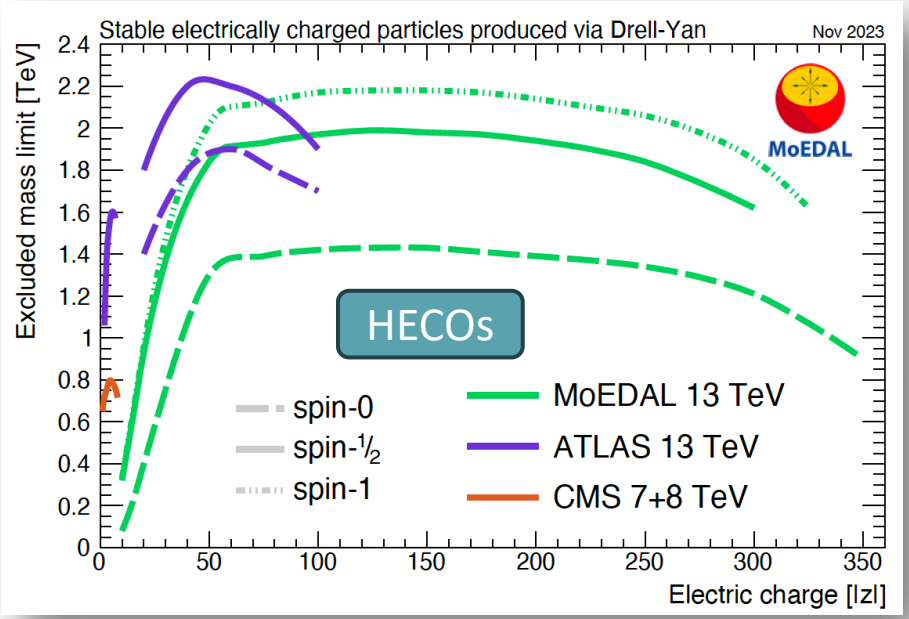
- **Permanent** physical record of new physics
- **No** Standard Model physics backgrounds

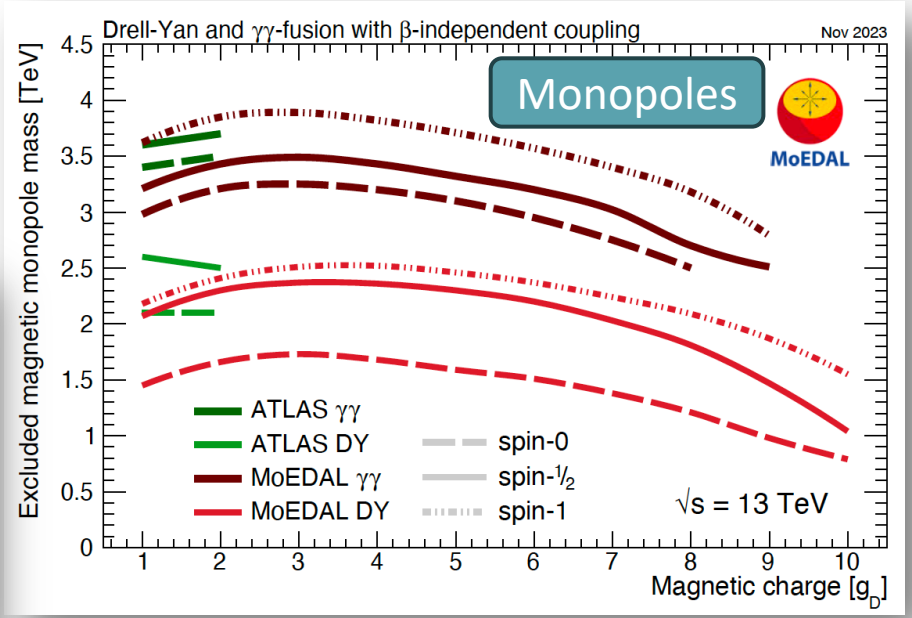
MoEDAL physics program
Int. J. Mod. Phys. A29 (2014) 1430050

Search for magnetic monopoles & HECOs

NEW

MoEDAL sole contender in **high magnetic charges**





Complementarity with ATLAS

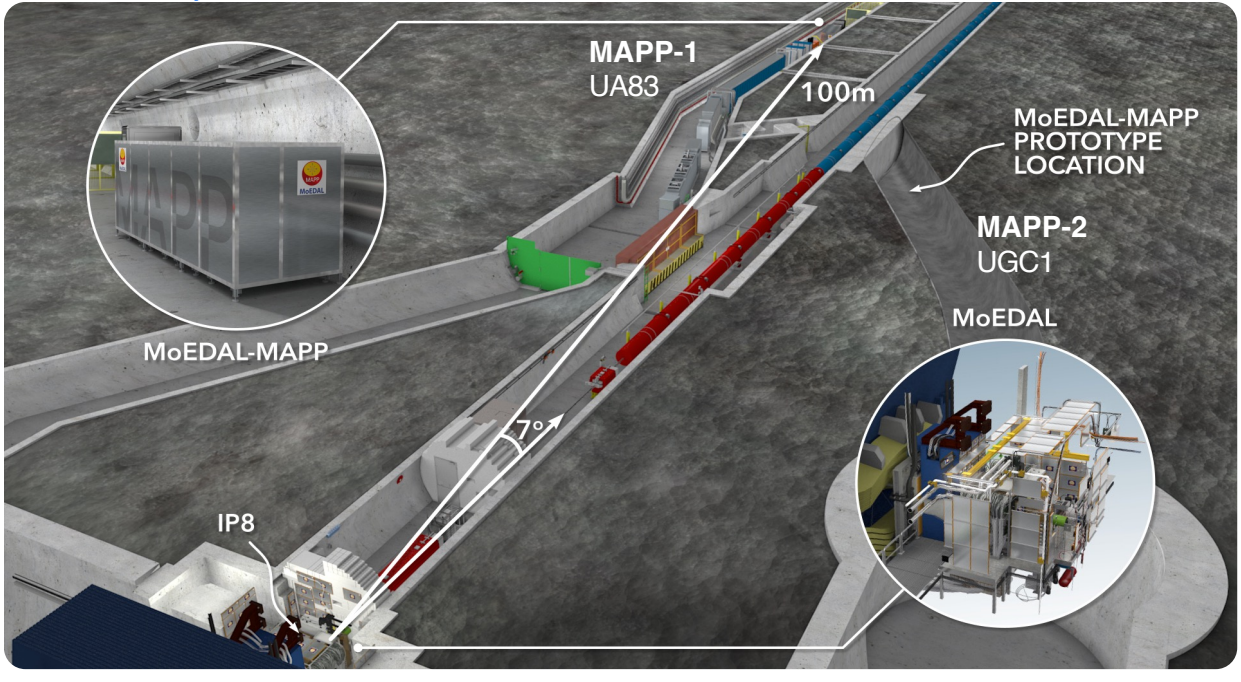
MoEDAL, *Search for highly ionizing particles in pp collisions at the LHC Run-2 using the full MoEDAL detector,* arXiv:2311.06509 [hep-ex]

MAPP: MoEDAL Apparatus for Penetrating Particles

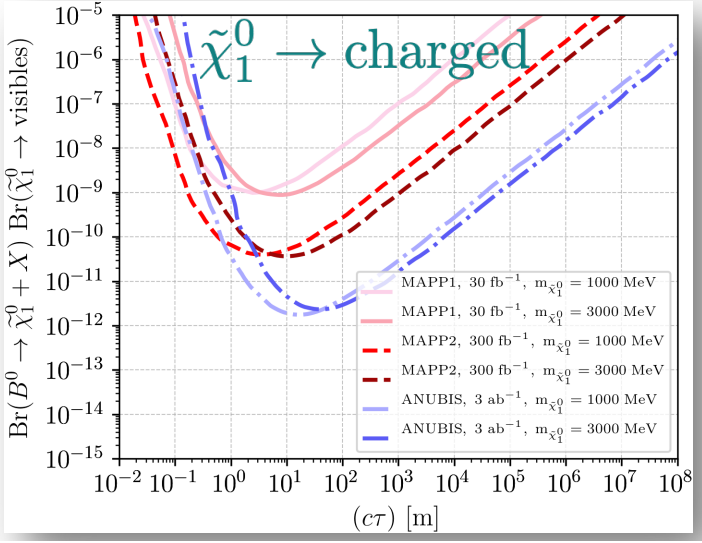
- **MAPP-mQP:** sensitive to low ionisation induced by millicharged particles
  - Phase-1 installation in UA83 is underway
  - 400 scintillator bars (10×10×75 cm^3) in 4 sections readout by PMTs
  - protected by hermetic VETO counter system
- **MAPP-LLP:** sensitive to LL neutral particles through visible decays
- **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



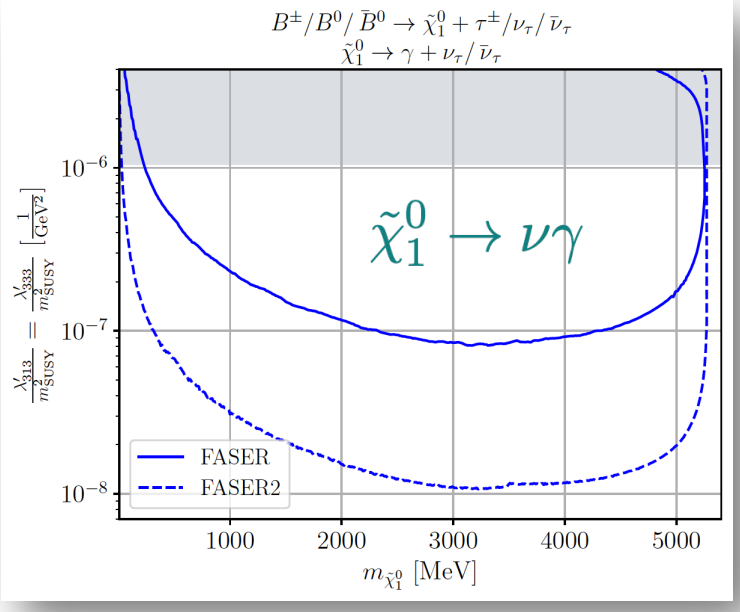
R-parity violating supersymmetry



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



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

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

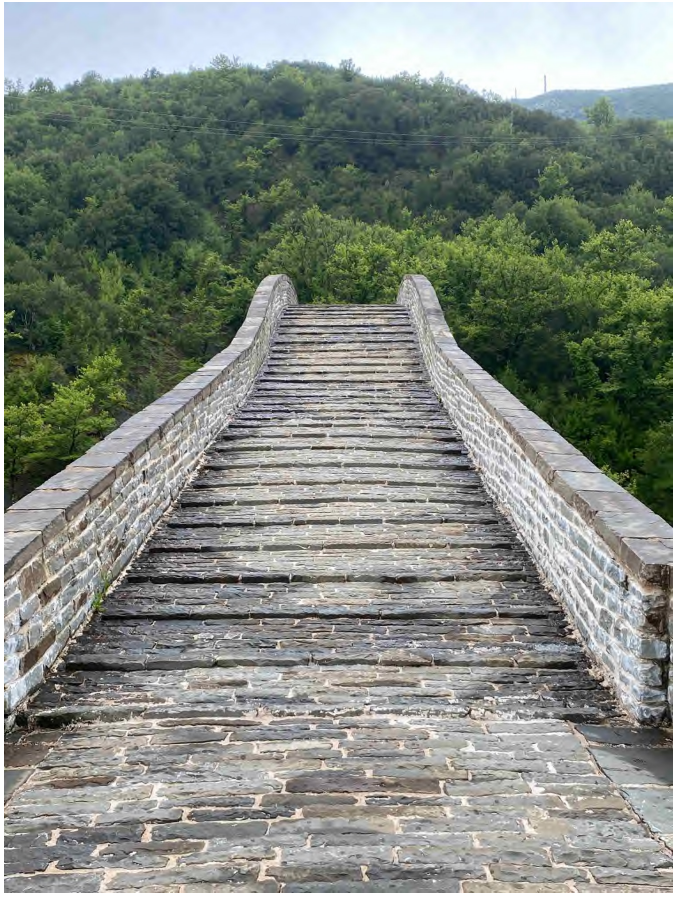
HNLs ↔ RPV SUSY: recasting of results [e.g. Dreiner, Köhler, Nangia, Schürmann, Wang, JHEP 08 (2023) 058]

Beyond LHC: beam-dump, neutrino, … experiments

SUBMET, FerMINI, GAZELLE, DAMSA, MiniBooNE, DUNE + many more not covered here…

Summary & outlook

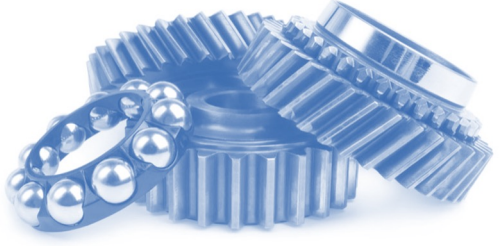
- Ever increasing interest in **long-lived particle** searches at the LHC (and not only…)
- FIPs serve as a "bridge" between our observable world and possible hidden sectors
- MoEDAL, a detector optimised for *highly ionising* particles, entered the FIPs arena with **MAPP**
- Many dedicated experiments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



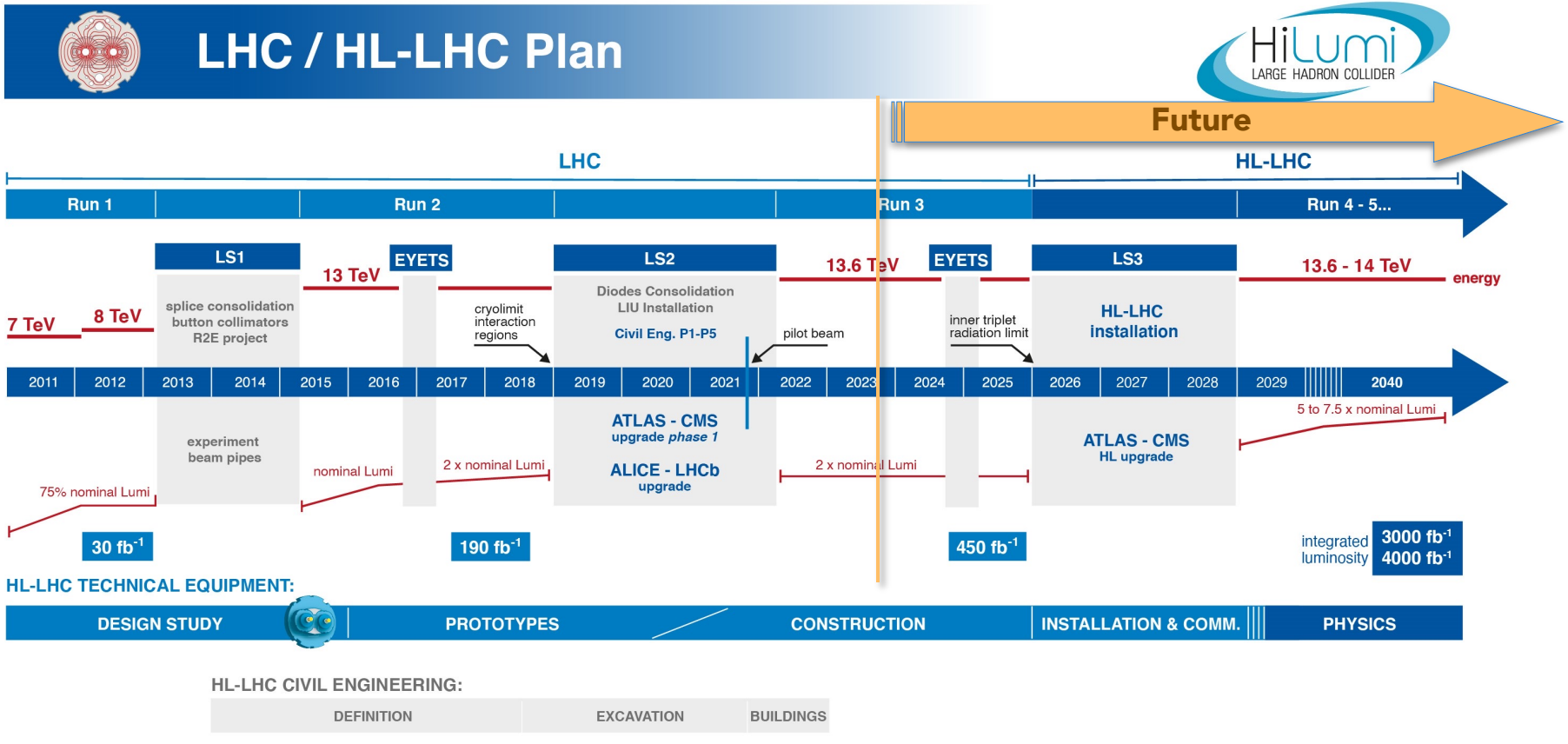
Further reading

- LHC-LLP Community whitepaper – J.Phys.G 47 (2020) 090501
- Physics Beyond Collider at CERN – BSM Report, J.Phys.G 47 (2020) 010501
- FIPs 2022 Workshop Report, arXiv:2305.01715
- Lee, Ohm, Soffer, Yu, *Collider Searches for Long-Lived Particles Beyond the Standard Model,* Prog.Part.Nucl.Phys. 106 (2019) 210-255
- Knapen & Lowette, *A guide to hunting long-lived particles at the LHC*, arXiv:2212.03883
- VAM, *LHC experiments for long-lived particles of the dark sector*, MG16 proc. arXiv:2111.03036
- LLP13 – 13th Workshop of the LLP Community, June 2023

Spares



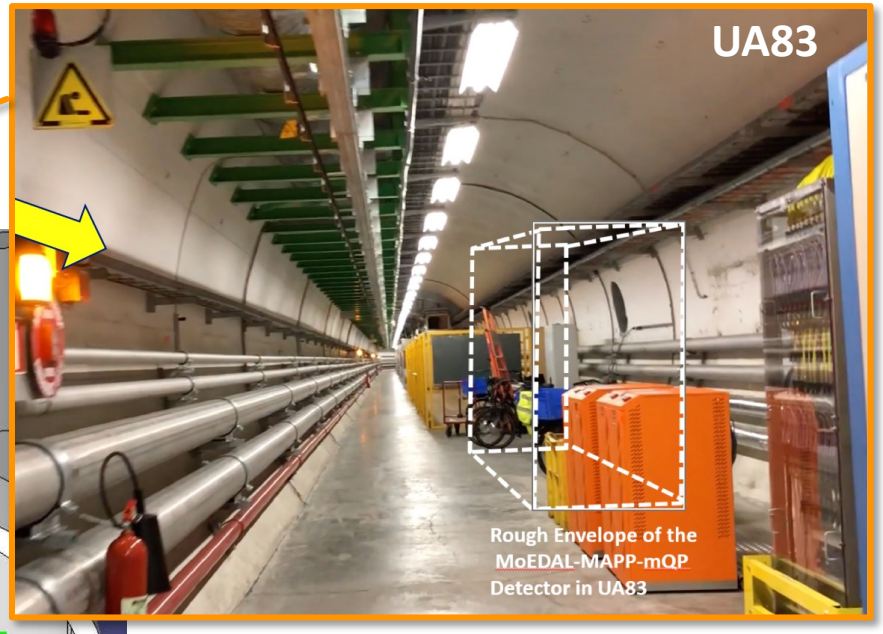
LHC & High Luminosity LHC (HL-LHC)

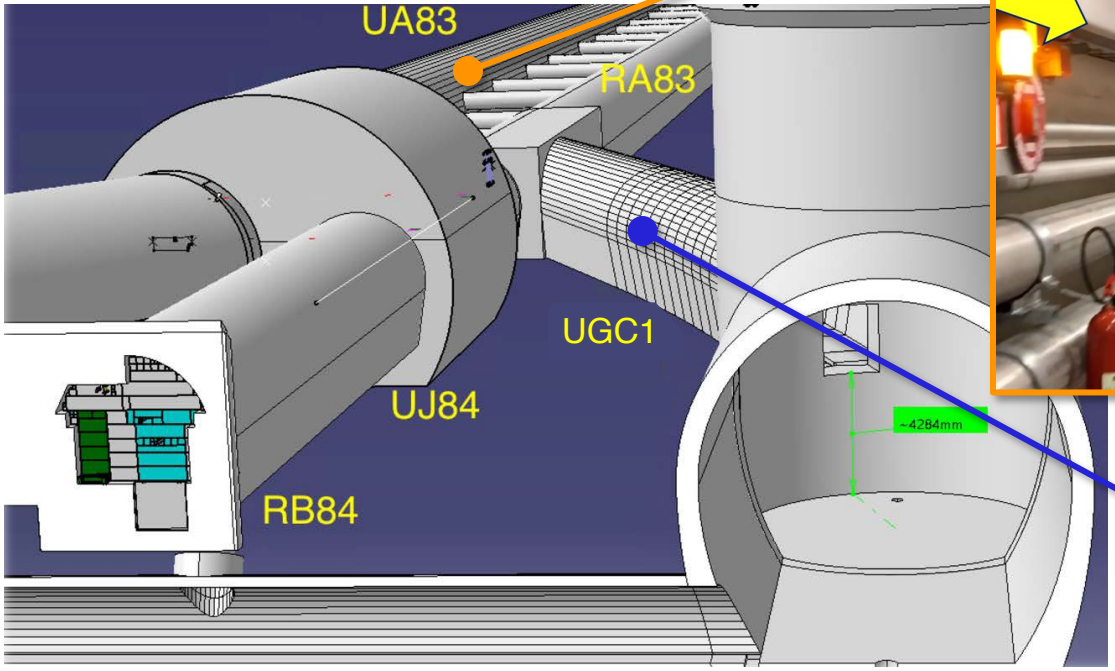


MAPP locations

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

UA83

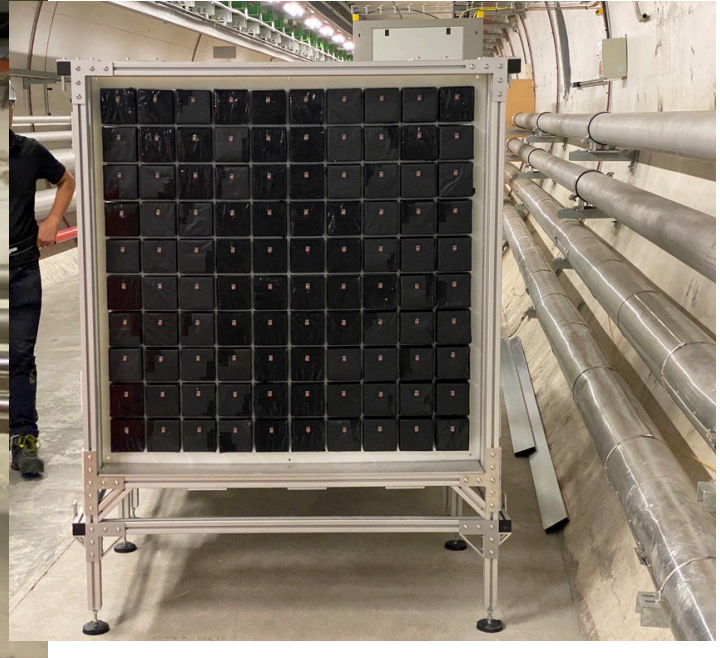




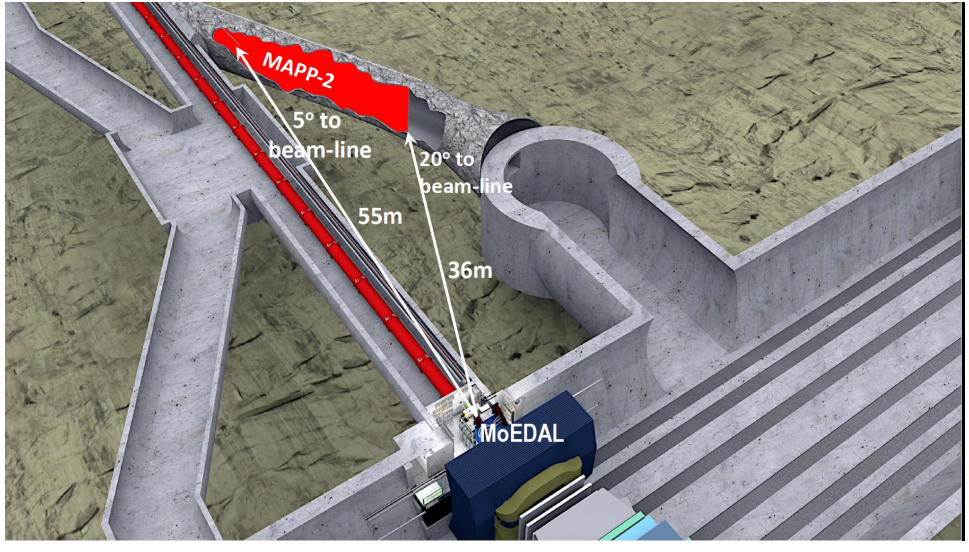
- mQP 2017 prototype location
- Extensive engineering required
- To be ready for MAPP LLP during HL-LHC

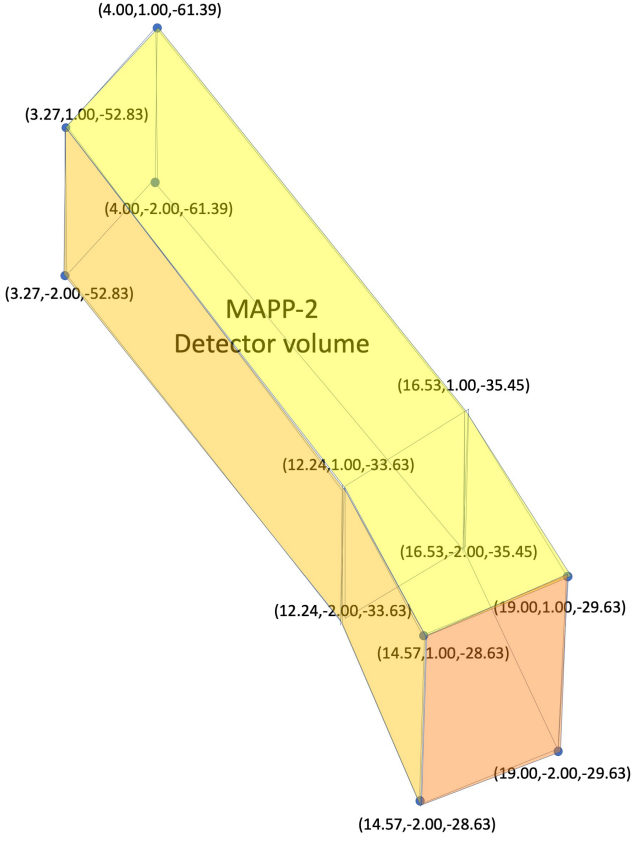
UGC1

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]