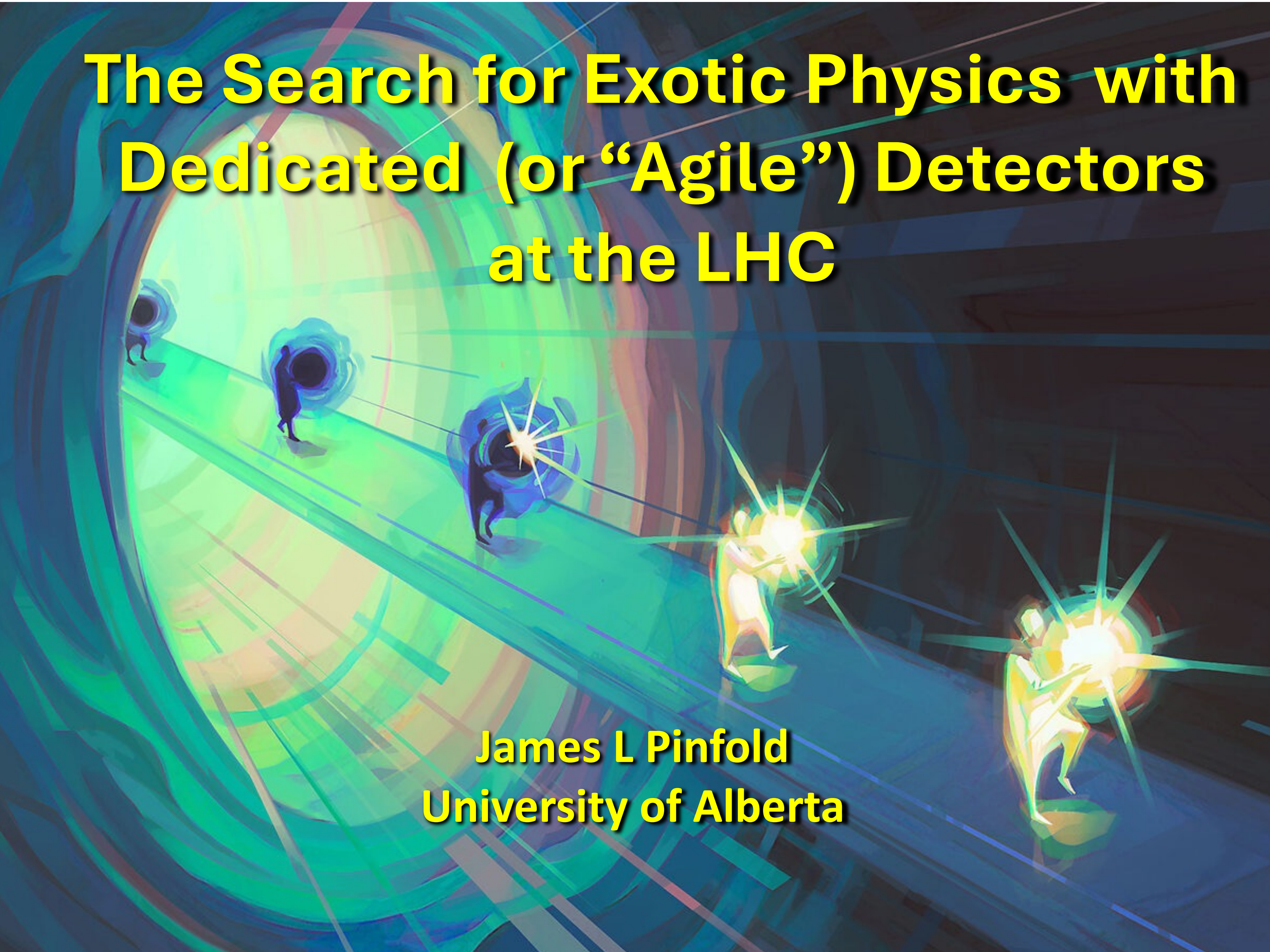
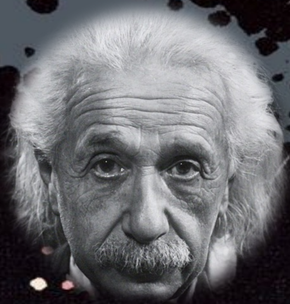
The Search for Exotic Physics with Dedicated (or “Agile”) Detectors at the LHC



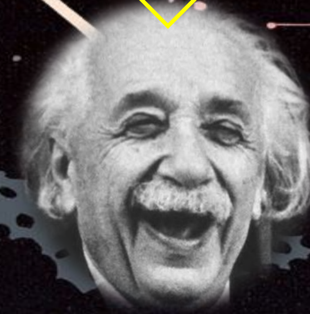
James L Pinfold
University of Alberta

Why No New Physics Yet at the LHC?

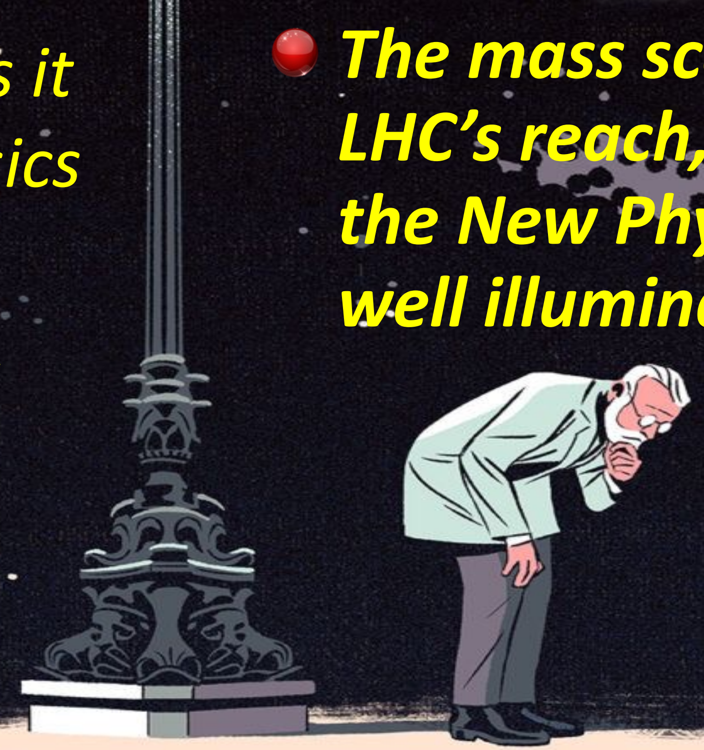


- *The Standard Model is it - there is no New Physics*
- *The mass scale of the new physics is beyond the LHC's reach*

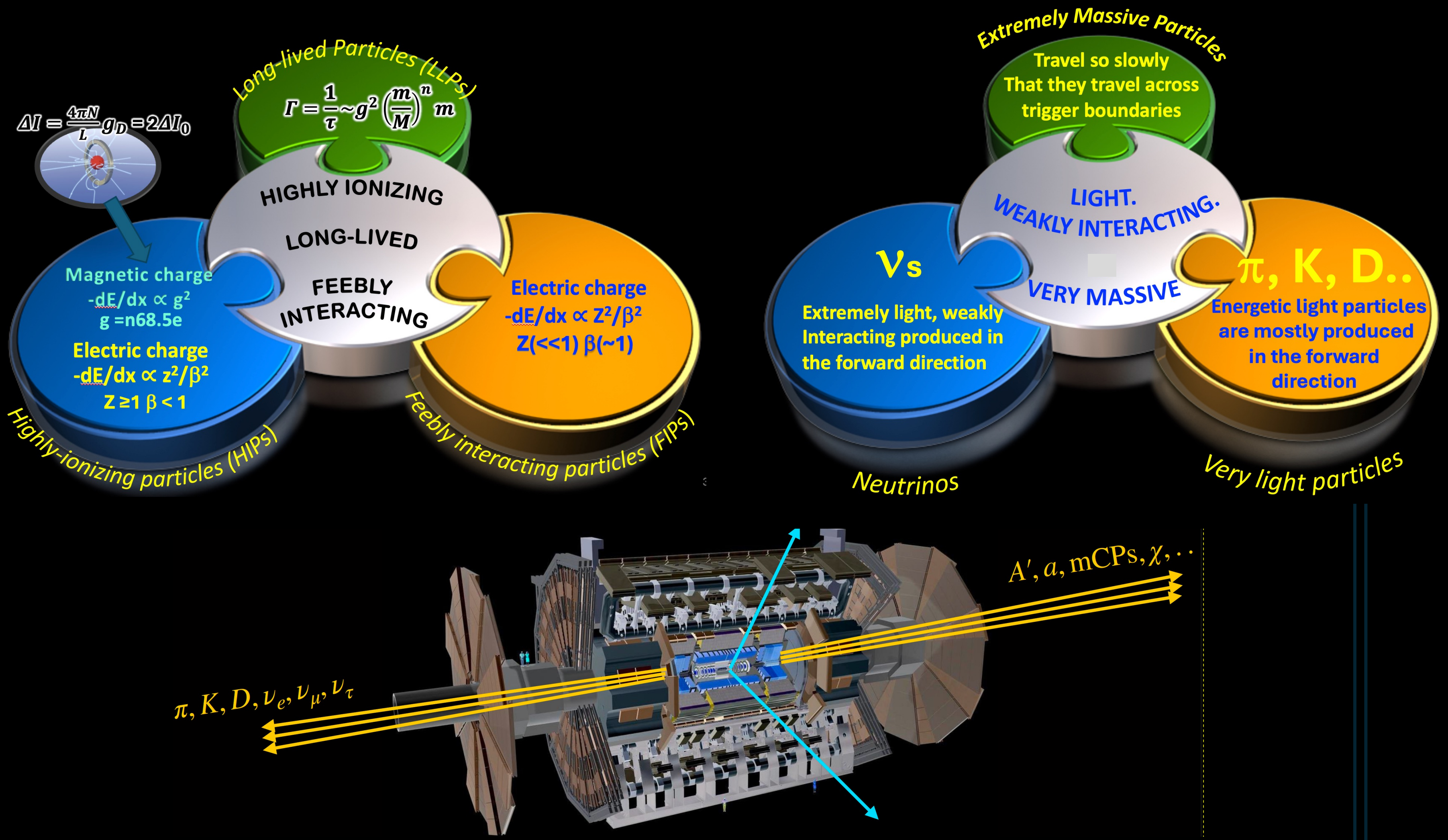
Another answer



- ***The mass scale is within LHC's reach, but perhaps the New Physics is not well illuminated!***



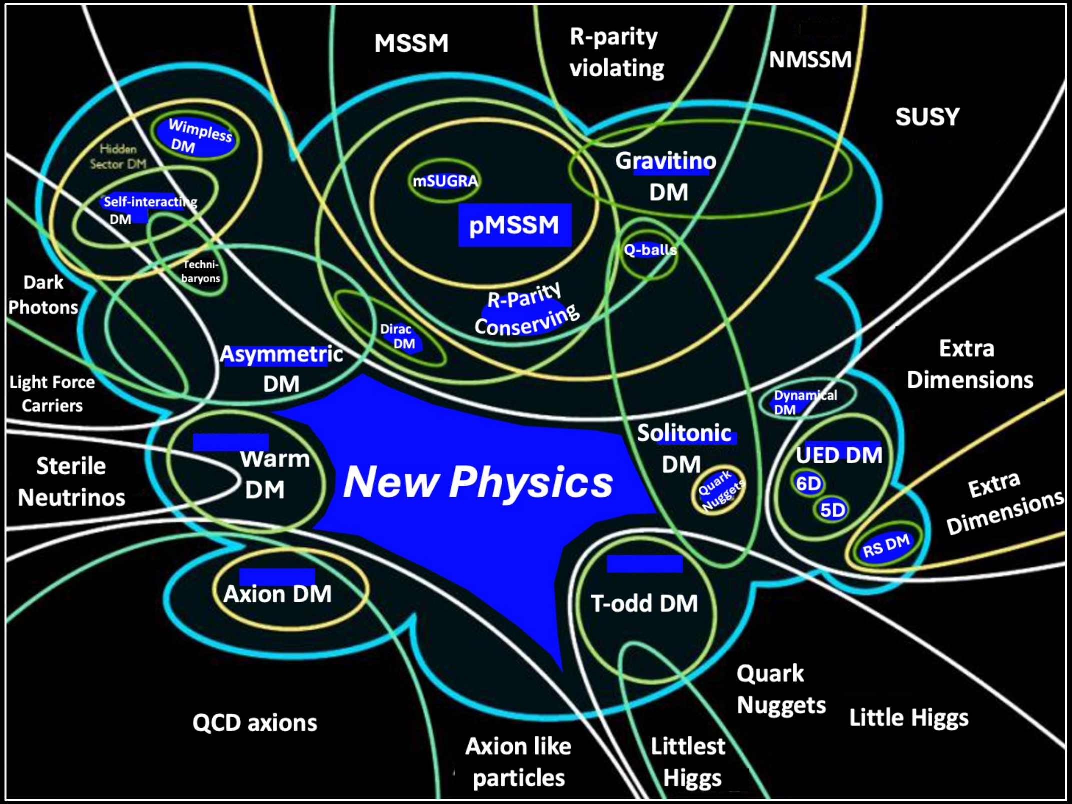
Physics for which ATLAS & CMS is not Optimized

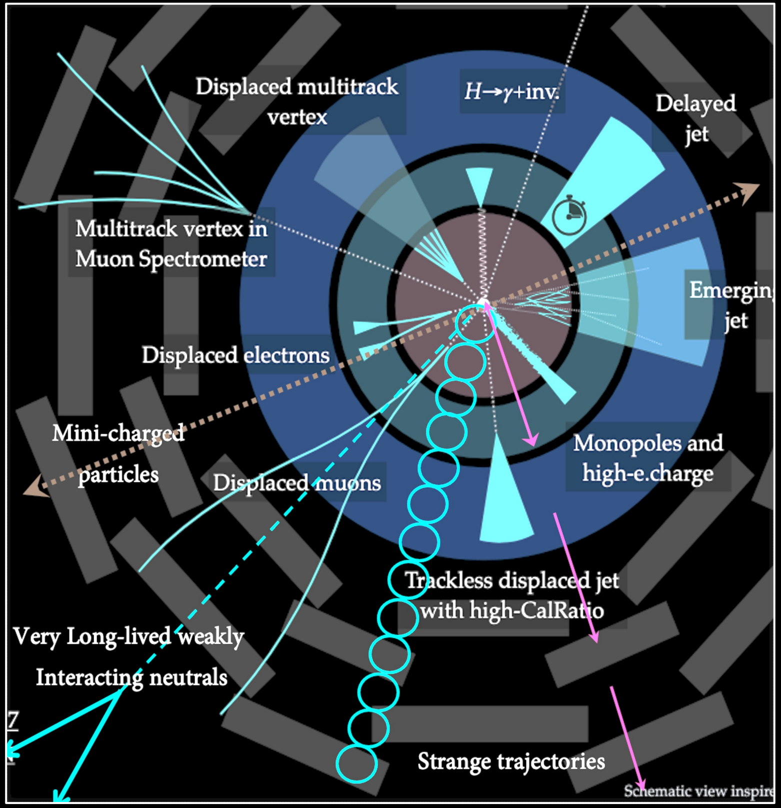


Blind spots in the Forward Direction of ATLAS & CMS

TOTEM and AFP

New Physics and Its Signatures





Scenarios

Signatures

Often not ATLAS & CMS friendly!

Dedicated Search, or "Agile," Detectors at the LHC

The beginning……

N·H
ELSEVIER

Nuclear Physics B (Proc. Suppl.) 78 (1999) 52–57

NUCLEAR PHYSICS B
PROCEEDINGS
SUPPLEMENTS
www.elsevier.nl/locate/npe

Searching for Exotic Particles at the LHC with Dedicated Detectors.

J. L. Pinfold, [a*]

[a]Centre for Subatomic Research, University of Alberta,
Edmonton, Alberta T6G 2N4,Canada

The LHC will open up a new energy regime where it may be possible to observe physics beyond the Standard Model. Therefore the search for exotic phenomena, such as: magnetic monopoles, massive stable particles; slowly decaying exotic particles; highly penetrating particles; and, free quarks and gluons, will be an important part of the LHC physics program. We propose that the search strategy for exotics planned for the main LHC detectors be extended with modest dedicated experiments designed to enhance the physics reach of the LHC. We shall use two examples to illustrate this thesis. First, a passive, plastic track-etch detector "ball" designed to detect highly ionizing particles and measure their Z/β. Such a detector is currently the subject of a Letter of Intent to the LHCC from the MOEDAL collaboration. Another (active) small acceptance detector – protected by shielding and monitoring an extended decay zone – specifically designed to detect massive stable particles and detect slowly decaying particles, is described. The use of such a detector at the LHC, has recently been proposed.

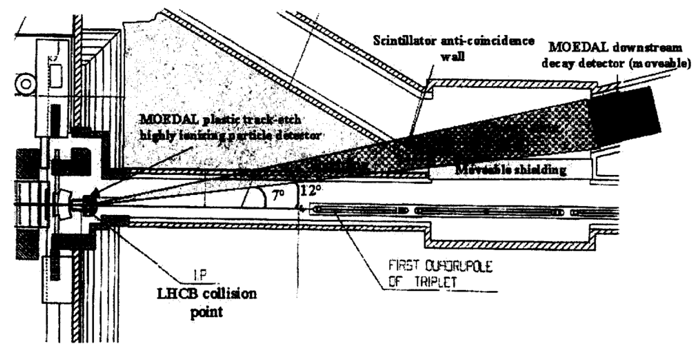


Figure 1. A schematic view of a detector for heavy stable and quasi-stable exotic particles. The detector is deployed in this case in the region UJ84 behind a minimum of 16m of rock/concrete shielding with a decay zone of similar length. The MOEDAL passive detector for highly ionizing particles is also shown deployed around the LHCB vertex chamber.

MoEDAL was the first such experiment, approved by CERN in 2010

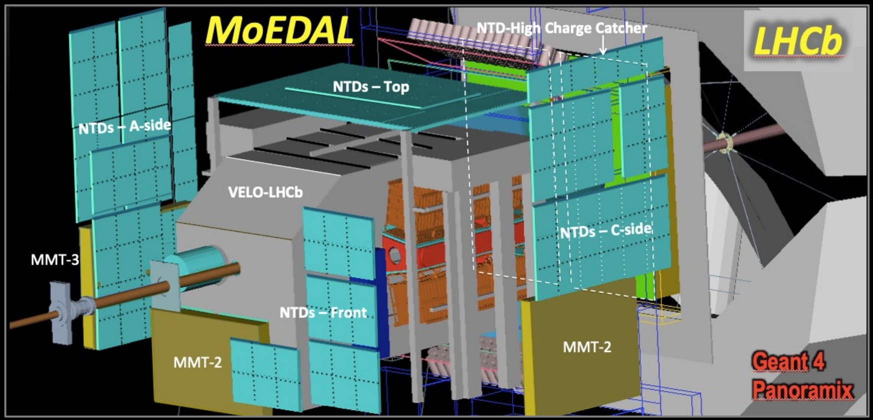
The Caste of "Agile" Detectors Today

Highly Ionizing Particles (HIPs)

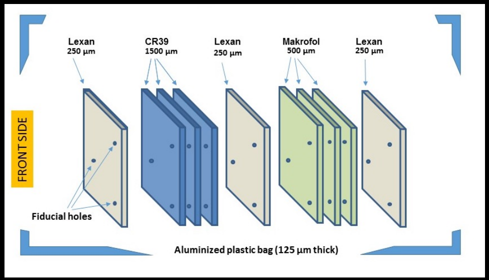
Eg Magnetic Monopoles, Dyons, Q-balls, Strangelets, Black-Hole Remnants, Doubly Charged Higgs, Massive Slowly Moving Charged Particles, Multiply Charged Particles, etc.

The Phase-0 MoEDAL Detector

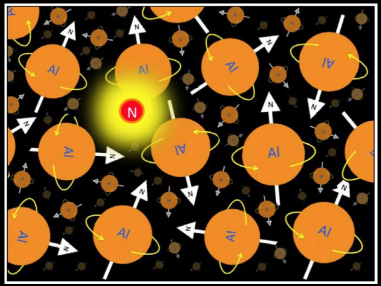
LHC's 1st dedicated search expt. –upgraded for Run-3 with higher eff. & lower thresholds



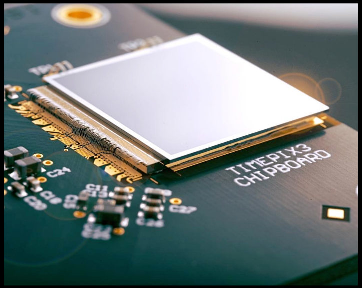
Searching for HIP avatars of new physics



NUCLEAR TRACK DETECTOR Plastic array (185 stacks, 12 m^2) – Like a big Camera



TRAPPING DETECTOR ARRAY A tonne of Al to trap Highly Ionizing Particles for analysis



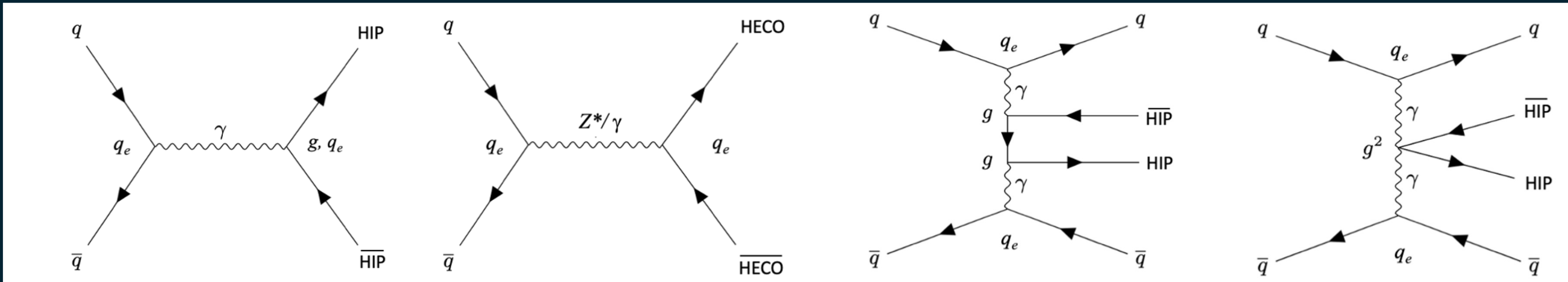
TIMEPIX Array a digital Camera for real time radiation monitoring

NO TRIGGER

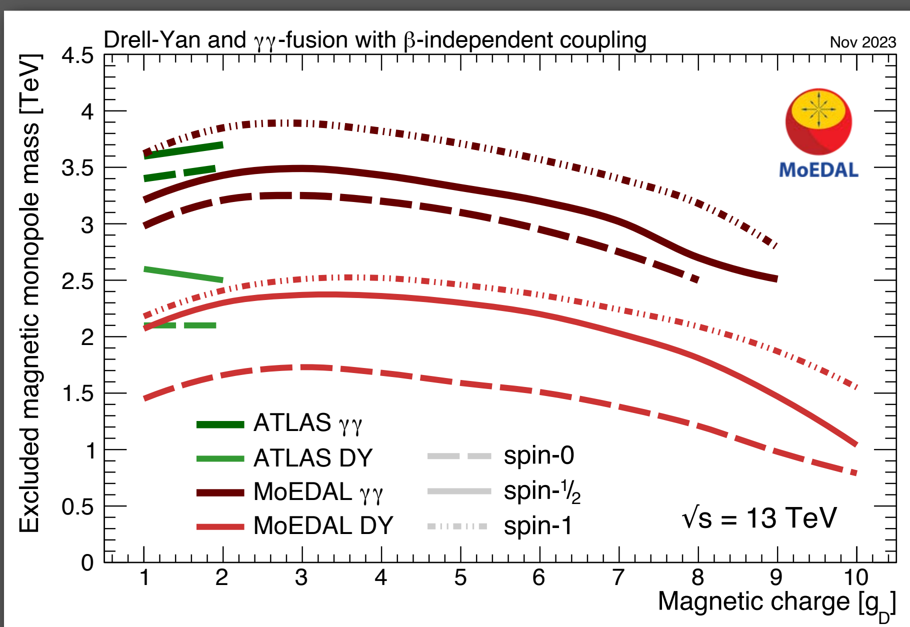
NO SM BACKGROUNDS

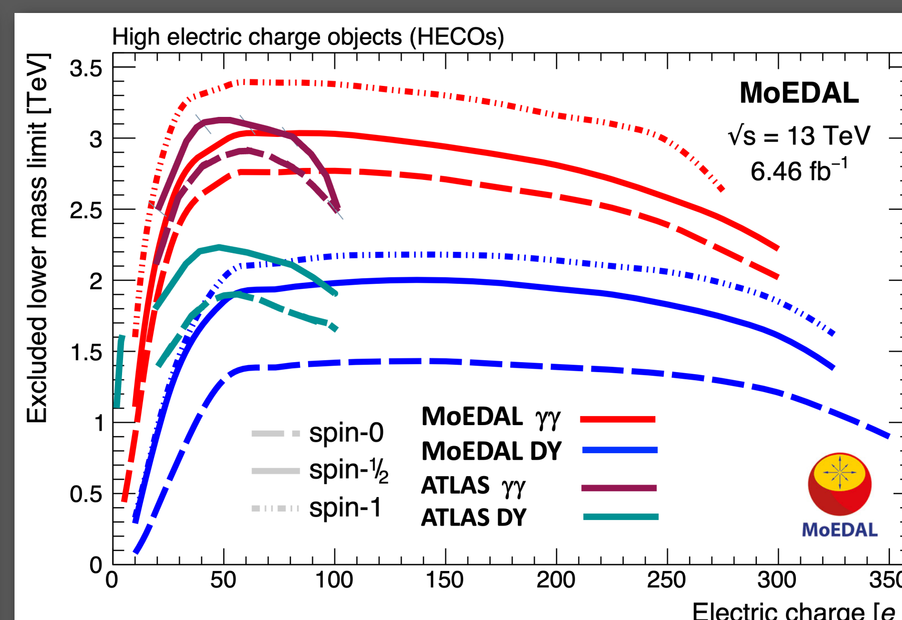
PERMANENT RECORD

Recent Results from HIP Search



(a) DY production of spin 0, ½, 1 HIPs (b) DY production of spin ½ HECOs (c) Four-vertex PF process (d) Three-vertex PF process



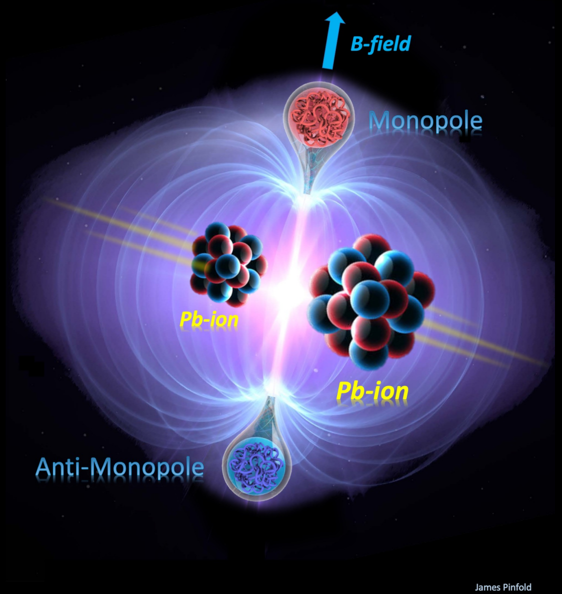


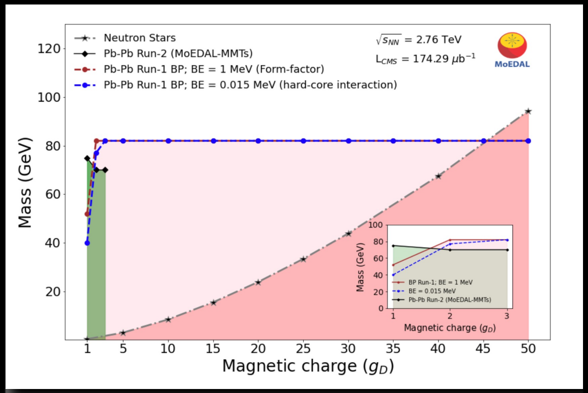
MAGNETIC MONOPOLES (MMs) **HIGHLY ELECTRICALLY CHARGED OBJECTS**

- *MoEDAL e-Print: 2311.06509 [hep-ex]….to be published in PRL*

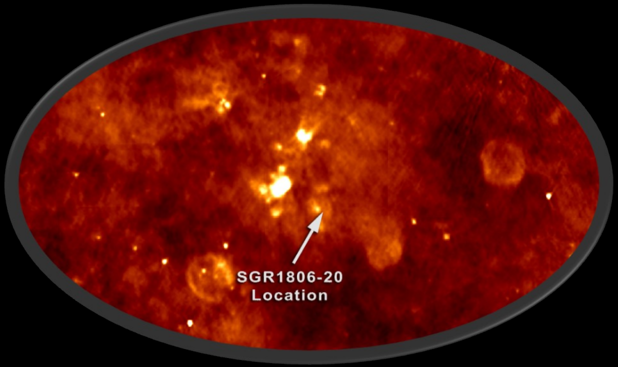
Schwinger Production of Monopole Pairs

Nature 602 (2022) 7895, 63-67 (Run-1)   arXiv:2402.15682v1, 24 Feb 2024 to be published in PRL





Monopole mass limits of 80 GeV placed on monopoles with charge as high as 45 Dirac Charges

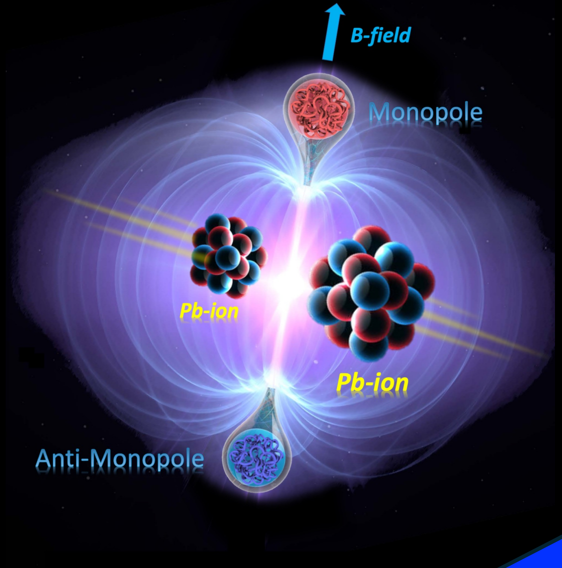


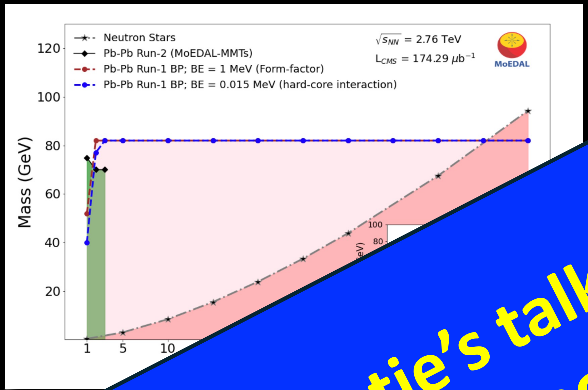
Magnetar 1806-20 surface field is ~10^{11}T versus 10^{16} T for UPC of Pb-ions at the LHC

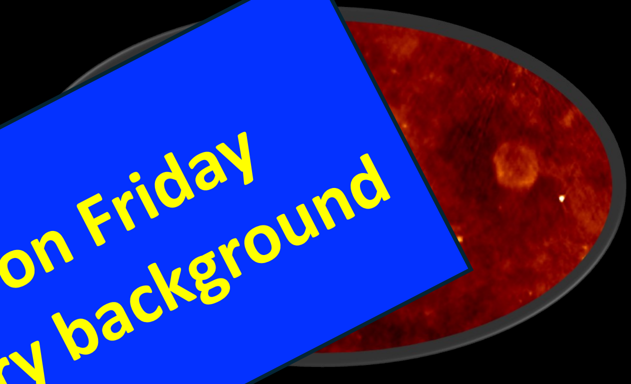
- *MoEDAL performed the 1st search for Schwinger Pair production of monopole–anti-monopole pairs in a super-strong magnetic field (as much as 10^{16} T) created in UPC of Pb-ions at the LHC*
  - *The most recent study used a SQUID magnetometer to search for monopoles trapped in the CMS beampipe*
- *The Schwinger production of composite MMs is NOT exponentially suppressed by a factor of e−O(500) as is MM production using DY or gg production modes.*
- ***Thus, this may well be the first search ever sensitive to composite monopoles***

Schwinger Production of Monopole Pairs

Nature 602 (2022) 7895, 63-67 (Run-1)   arXiv:2402.15682v1, 24 Feb 2024 to be published in PRL







…tar 1806-20 surface field is … 10^{11} T versus 10^{16} T for UPC of Pb-ions at the LHC

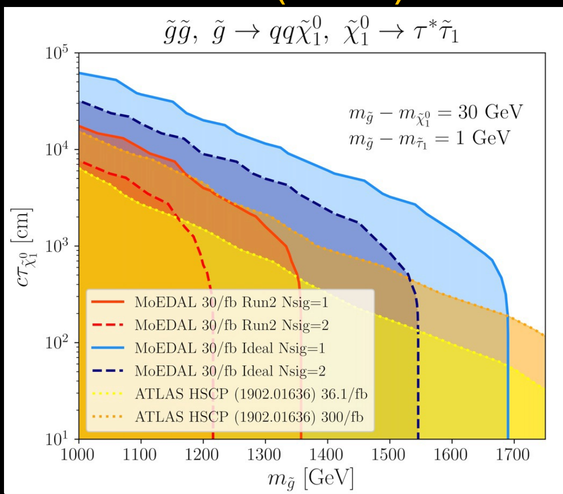
See Professor Arttu Rajantie's talk on Friday (plenary session 13) for a great theory background

- *MoEDAL p… …inger Pair production of monopole–anti-… …magnetic field (as much as 10^{16} T) cr… …LHC*
  - *T… …d a SQUID magnetometer to search for monopoles trapped in t… …pe*
- *The Sch… …r production of composite MMs is NOT exponentially suppressed by a factor of e−O(500) as is MM production using DY or gg production modes.*
- ***Thus, this may well be the first search sensitive to composite monopoles***

Searching for Long-Lived HIPS

Due to the absence of trigger, timing & SM backgrounds, MoEDAL can relax selection requirements + increase sensitivity to charged, SUSY LLPs

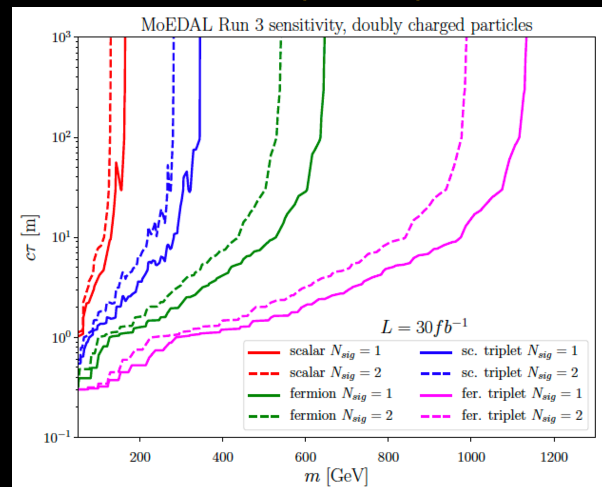
EPJC 80 (2020) 431



MoEDAL can cover the long-lifetime region at Run-2/3 for gluinos, stops, sleptons & charginos

SLEPTONS

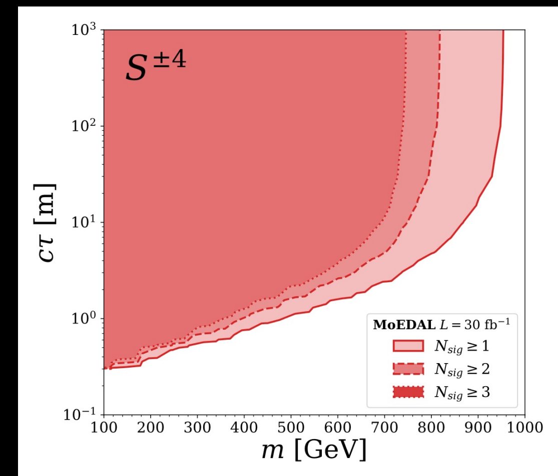
EPJC 80 (2020) 572



Authors added doubly charged scalars & fermions in various SU(2)L rep's, to the SM particle content .

DOUBLY CHARGED

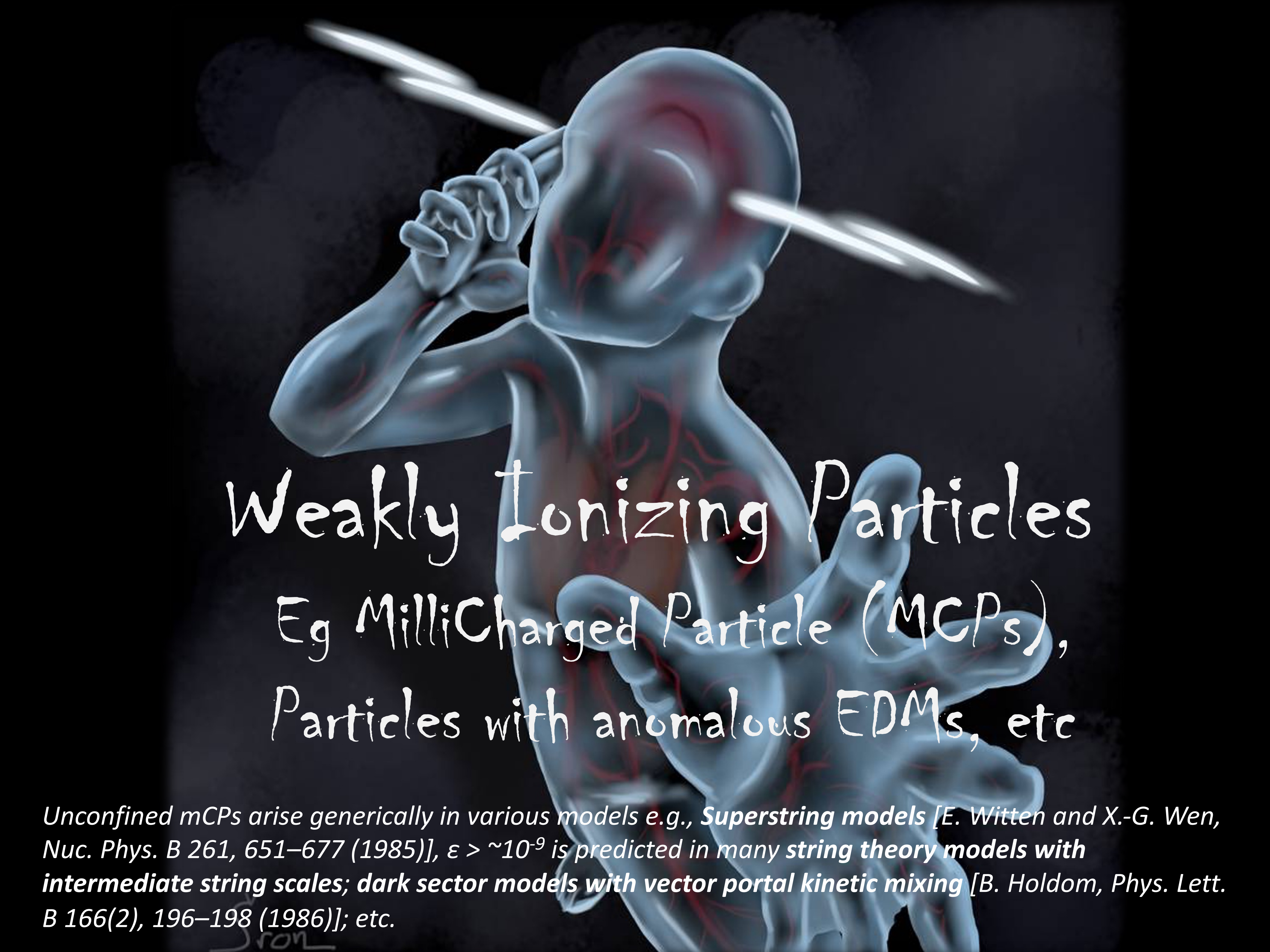
EPJC 81 (2021) 697



In this class of neutrino mass models, the SM is extended with two scalar fields, and 3 pairs of vector-like fermions.

2,3 and 4 CHARGED

- *If sufficiently slow moving, even singly or multiply ($\lesssim$10e) charged particles may leave a track in NTDs*
- *Supersymmetry offers such long-lived states: sleptons, R-hadrons, charginos*
- *Multiply charged scalars or fermions are, for example, predicted in several neutrino mass models.*



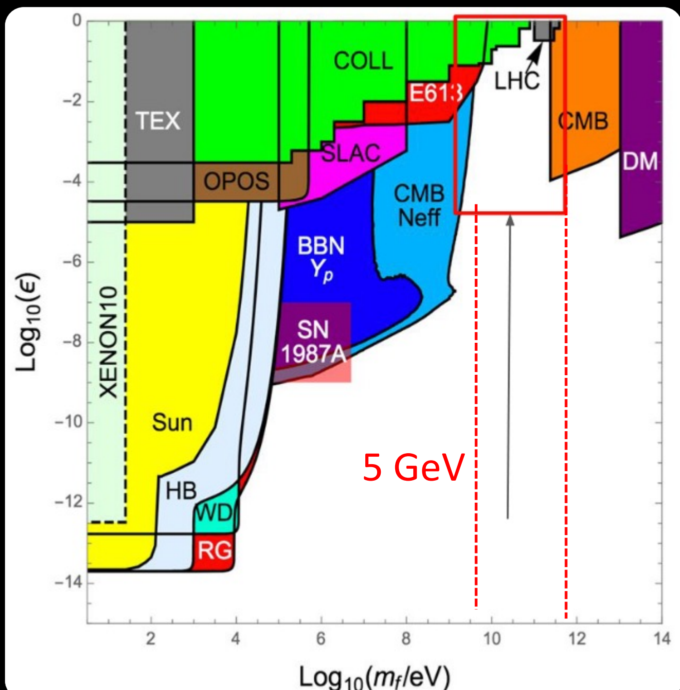
Weakly Ionizing Particles

Eg MilliCharged Particle (MCPs), Particles with anomalous EDMs, etc

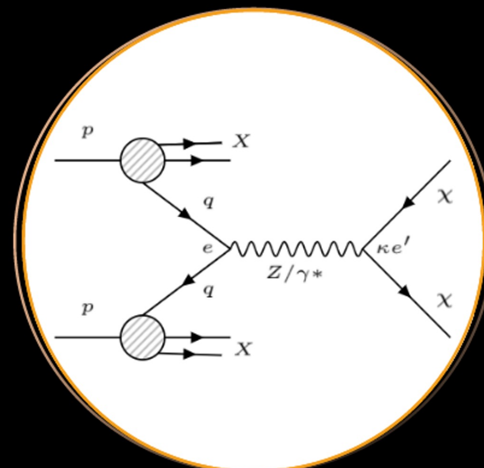
Unconfined mCPs arise generically in various models e.g., ***Superstring models*** *[E. Witten and X.-G. Wen, Nuc. Phys. B 261, 651–677 (1985)], $\varepsilon > \sim 10^{-9}$ is predicted in many* ***string theory models with intermediate string scales; dark sector models with vector portal kinetic mixing*** *[B. Holdom, Phys. Lett. B 166(2), 196–198 (1986)]; etc.*

Production of Milli-charged at Colliders

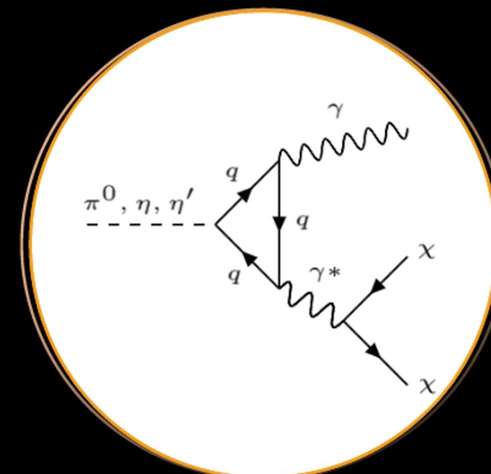
mCPs arise naturally from the dark sector via the Vector Portal/Dark Photon



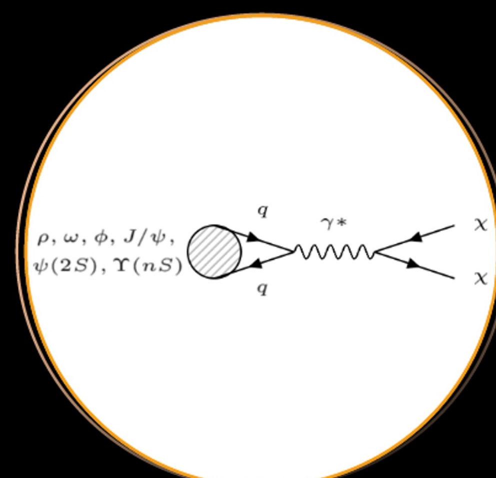
The Sweet Spot
arXiv:1511.01122



DRELL-YAN

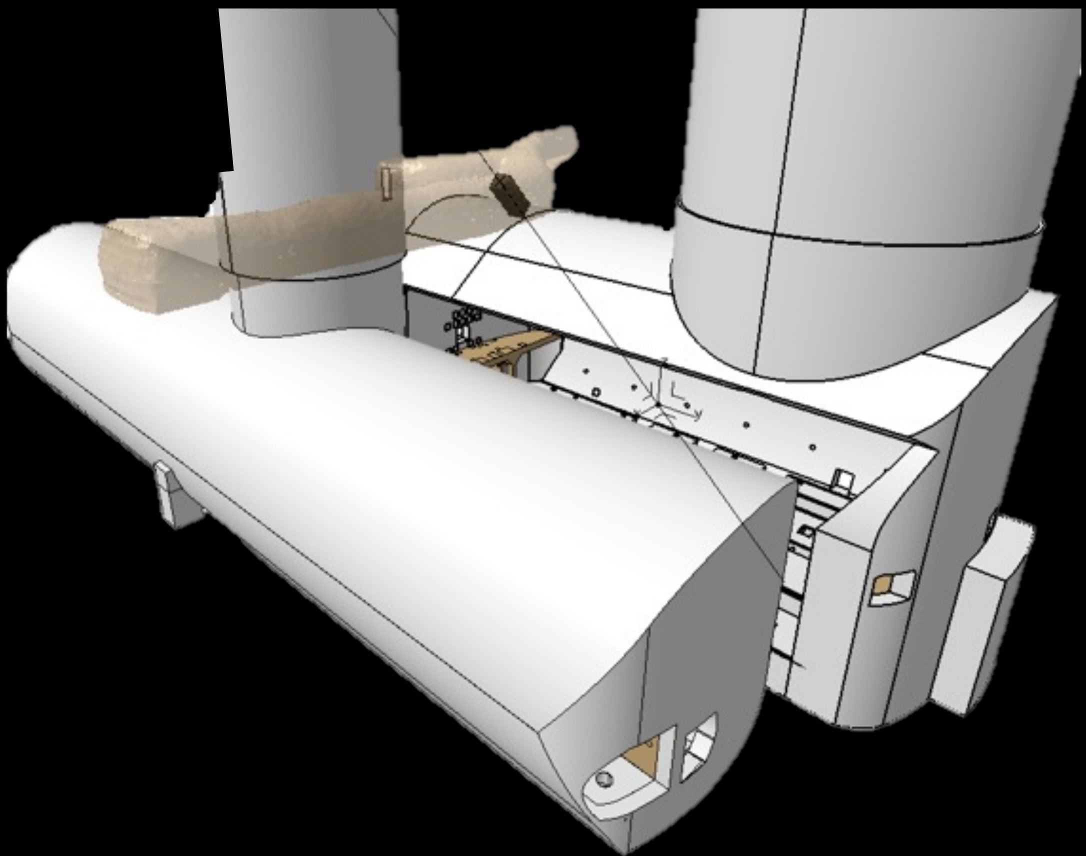


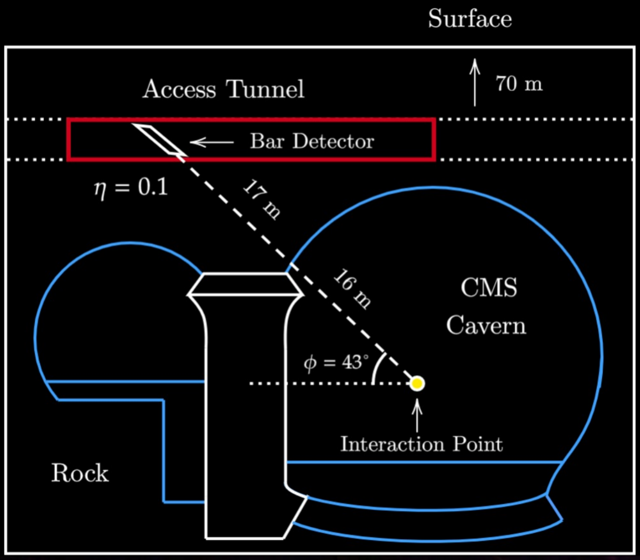
DALITZ DECAYS



DIRECT DECAYS

milliQan

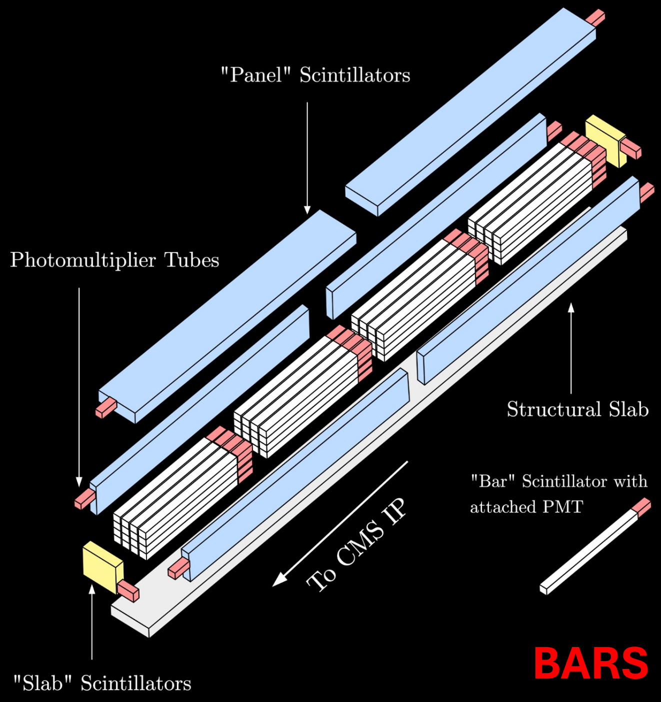


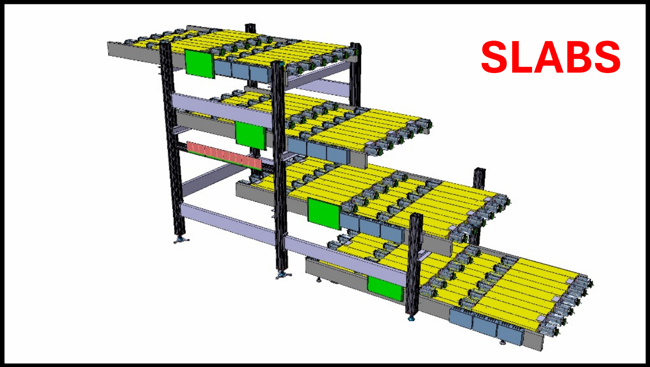


- *milliQan is located 80m underground*
- *33m (17m of rock) from the the CMS collision*
- *At η ~ 0.1, Φ = 43°,*

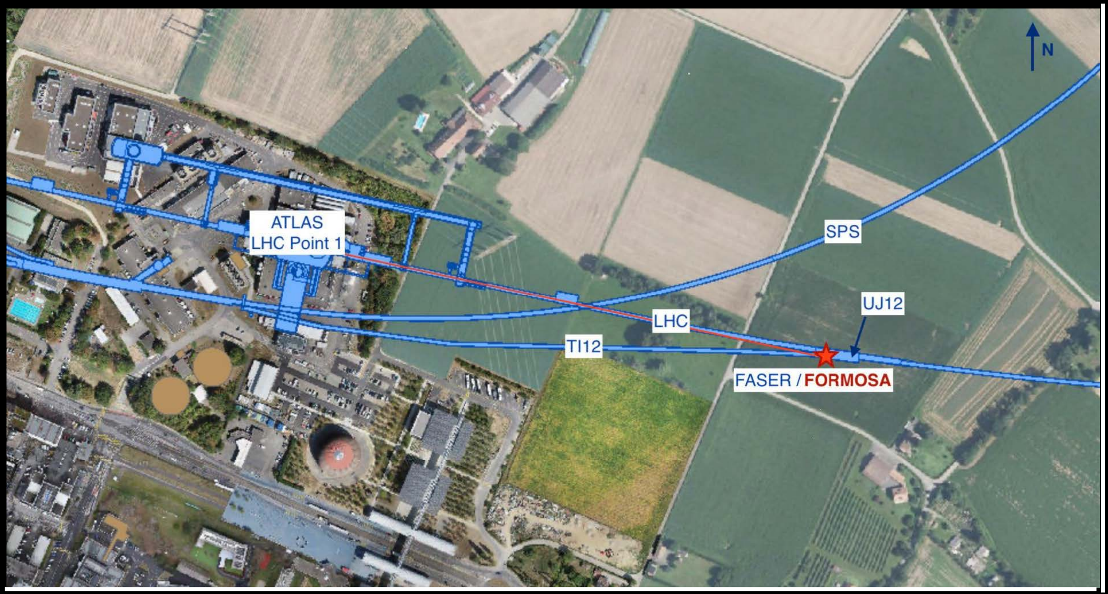
milliQan "Bar" Detector

- **Basic design:**
  - 64 scintillator bars (60 x 5 x 5 cm^3) attached to PMTs arranged in 4 layers, pointing at CMS IP
  - 6 Veto slabs on top and sides of detector to reject external backgrounds
  - 2 Veto panels on front and back of detector
- Above 1.4 GeV, mCP production is rarer; acceptance is limiting factor
- "Slab Detector" Improves acceptance for Q >~0.01e and higher mass (> 1.4 GeV)
  - Uses four layers of twelve 40 x 60 x 5 cm plastic scintillator slabs

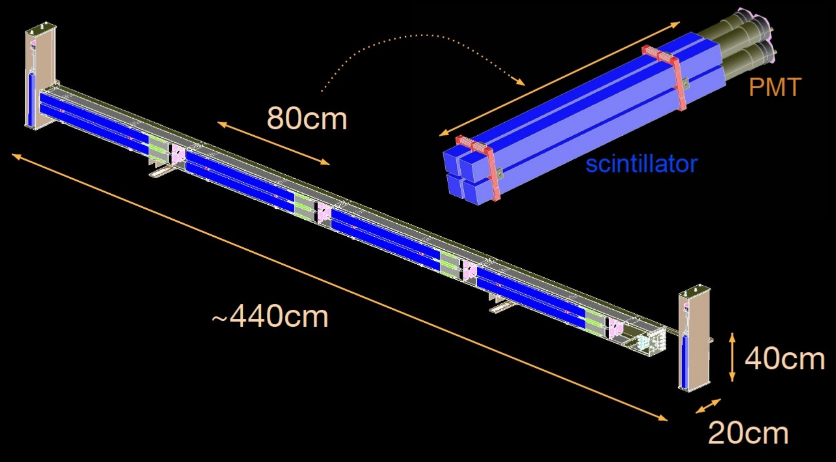




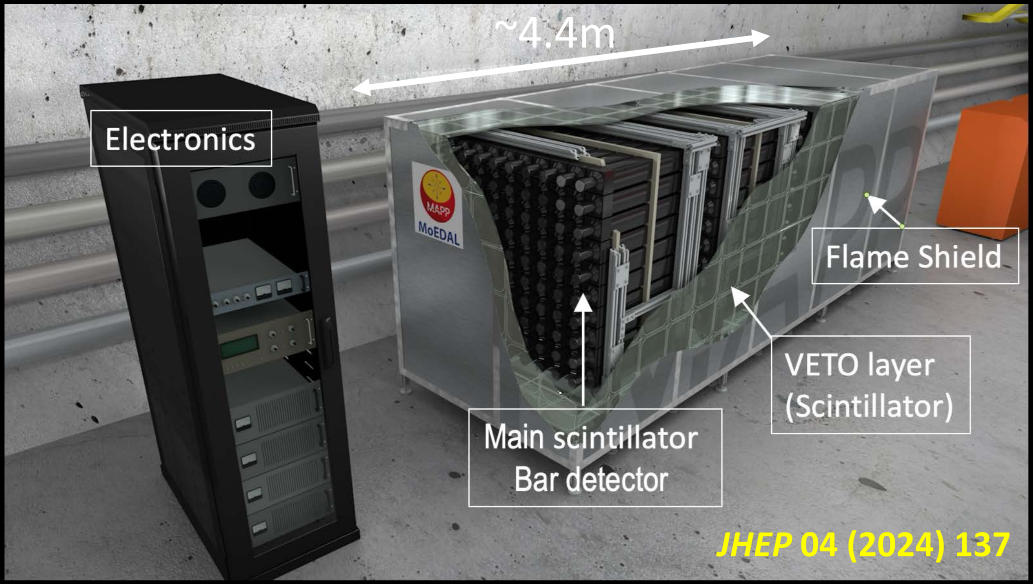
FORMOSA-1 (Demonstrator)



- *FAR FORWARD- Installed in the UJ12 cavern behind FASER ~500m from IP*
- *4 layers of 2x2 scintillator bar arrays with PMTs*
  - *5x5x80 cm bars*
- *2 veto panels with PMTs*
  - *20x40x2.5 cm panels*

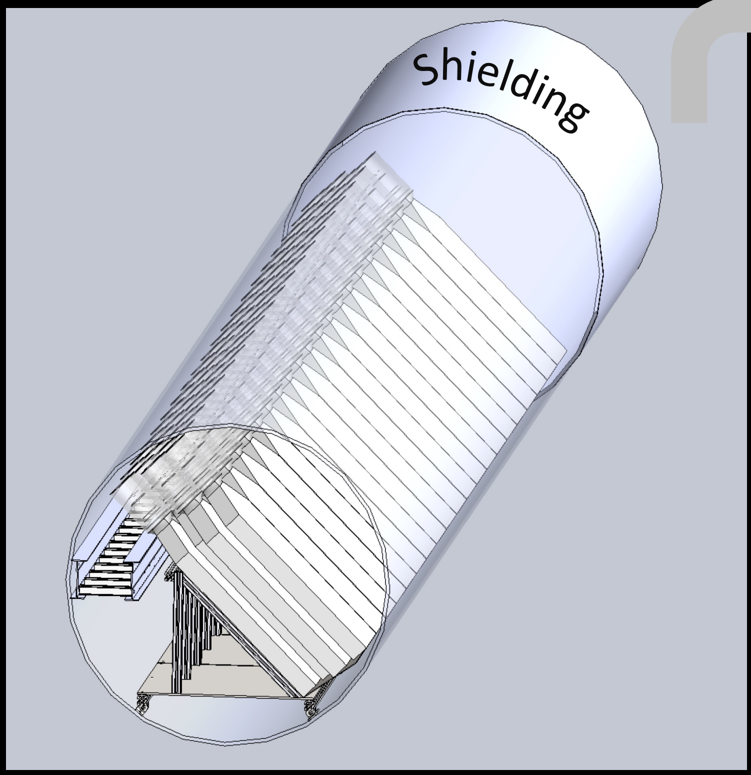


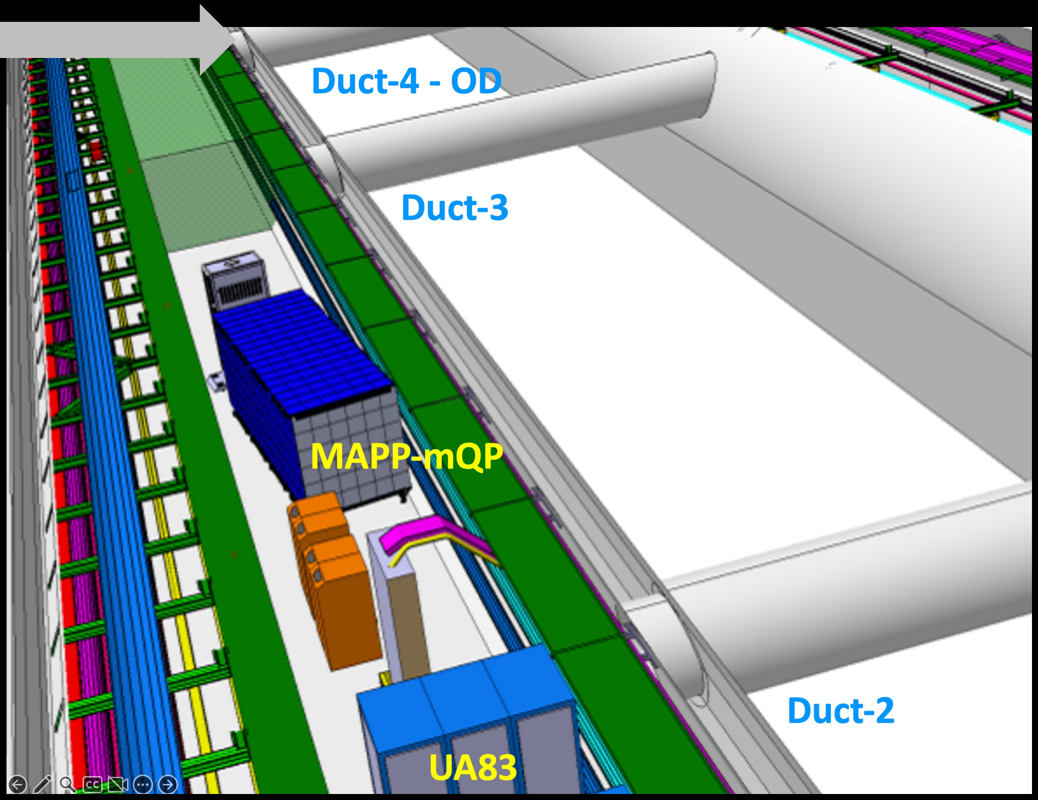
MoEDAL's MAPP-1 Detector at UA83



- *The detector is ~100 m from IP8 in the UA83 tunnel, the centre of the detector makes a ~7 deg. angle with the beam-line. It consists of:*
  - *400 scintillator bars (10 x 10 x 75 cm^3) in 4 sections readout by low dark count PMTs - with a hermetic VETO system & LED calibration*
  - *The overburden is comprised of 110m of sedimentary rock /concrete*
  - *On average there is ~45 m of rock/concrete between IP8 & MAPP-1*
- *MAPP-1 is sensitive to:*
  - *Milli-charged (10^{-3}e) particles*
  - *Long-lived neutral particles & very long-lived charged particles (using MoEDAL's MMTs)*

The MAPP-1 Outrigger

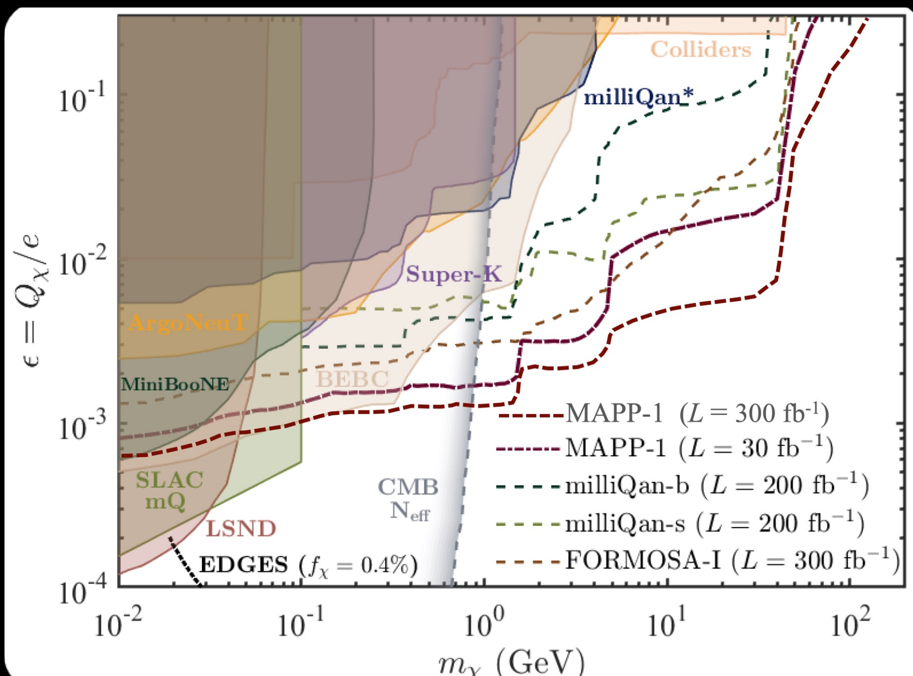


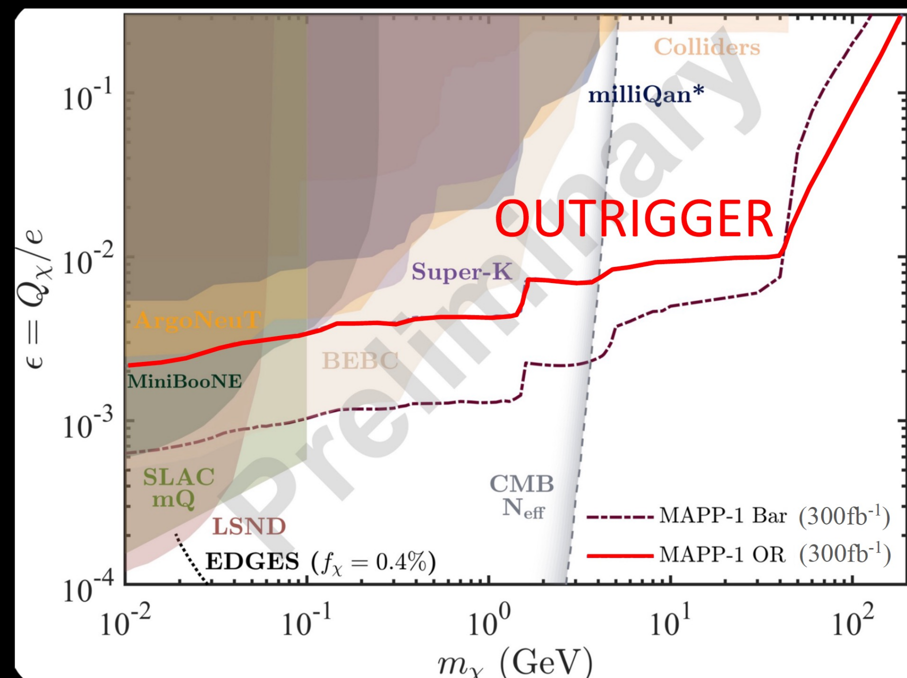


- *OUTRIGGER- A proposed extension of the MAPP bar detector to improve the overall reach for higher mass mCPs (for charges $\epsilon \gtrsim 10^{-2}e$)*
  - *At HL-LHC extends reach from 130 GeV to 200 GeV*
- *4 scintillator planes (each comprised of 20 60 cm x 30 cm x 5 cm sub-planes angled at 45 degrees) readout by coincident PMTs – an effective area of ~2.6m^2*

Sensitivity to mCPs at the LHC

Realistic Detector efficiency has been incorporated into plots

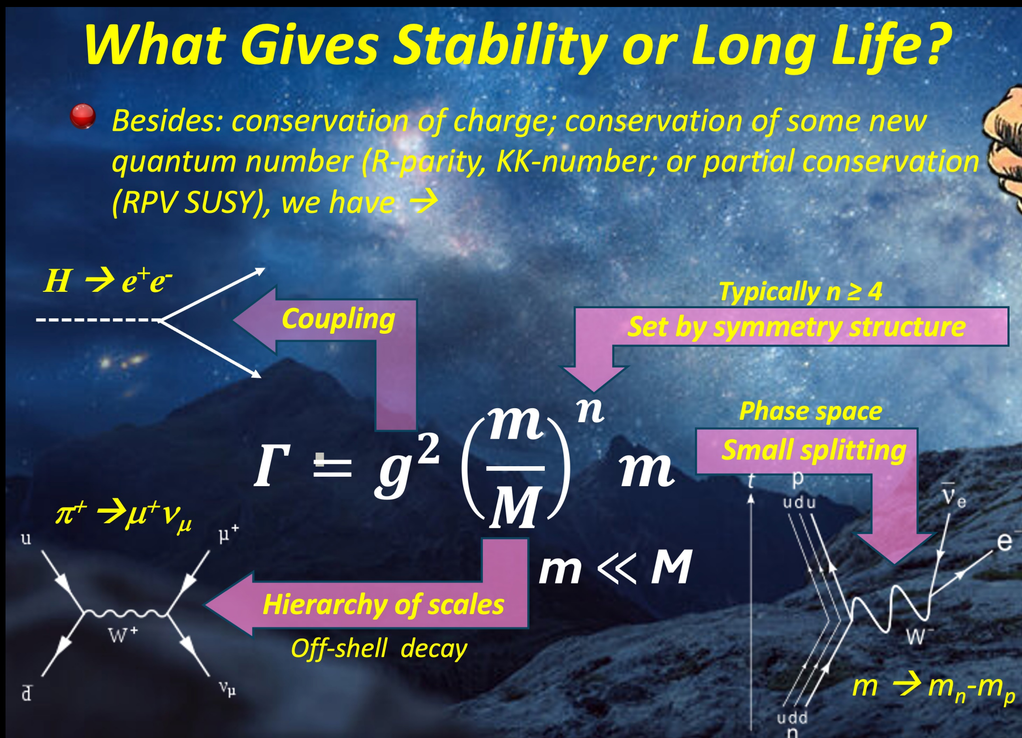




milliQan—Phys. Rev. D 104, 032002 (2021); FORMOSA—Phys. Rev. D 104, 035014 (2021); MAPP-1 -- JHEP 2024, 137 (2024)

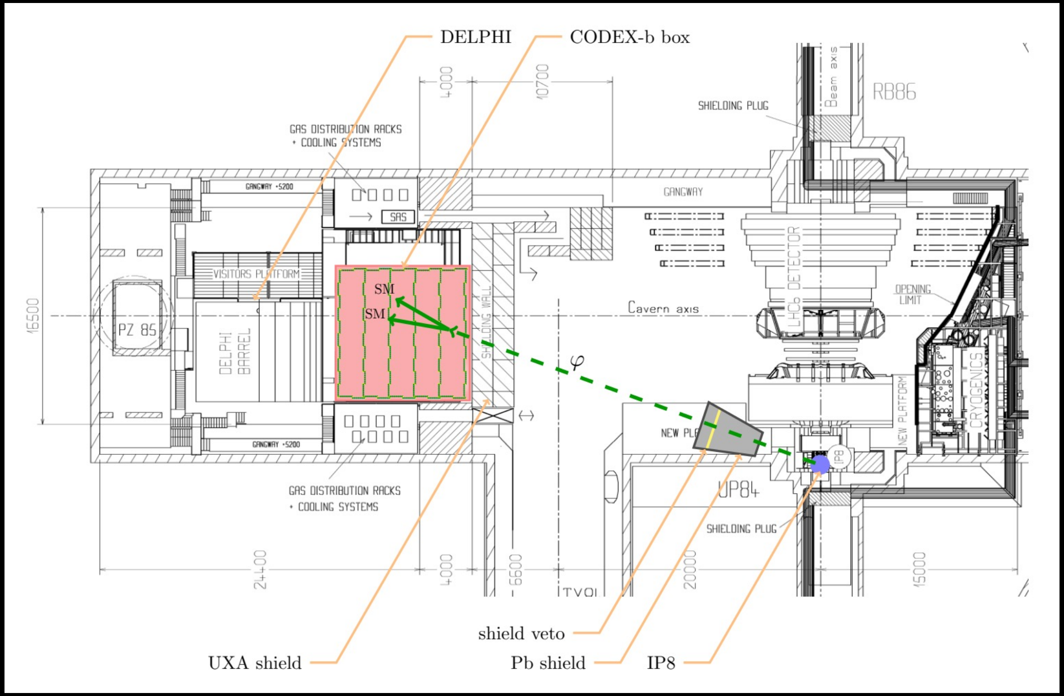
- *The 95% CL exclusion Limits for MAPP-1 for mCPs produced by DY mech. + direct decays of heavy quarkonia, light vector mesons & single Dalitz decays of PS mesons.*
- *Sensitivity can be improved to $\epsilon \sim 10^{-4}e$ with inorganic scintillators (eg $CeBr_3$)*

Long Lived Particles

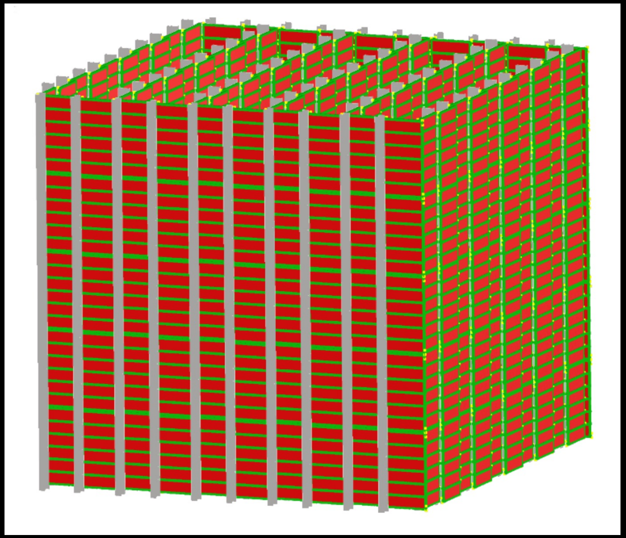


Ubiquitous in Beyond Standard Model Physics

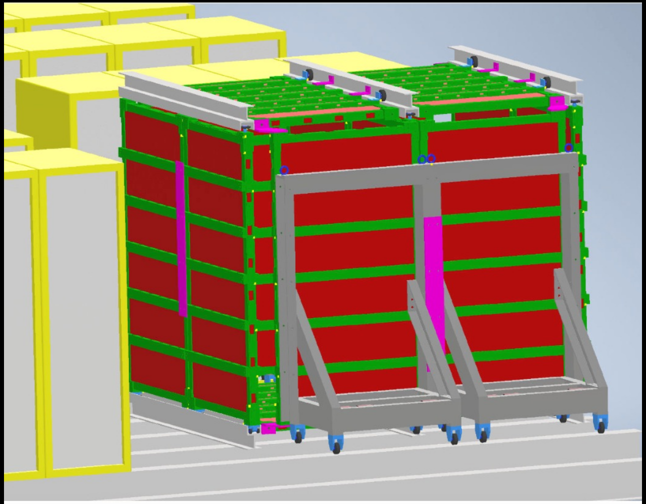
CODEX-b and CODEX-β



- *Transverse long-lived particle detector.*
- *Located at LHC interaction point 8, next to the LHCb detector.*
- *10m cube of resistive plate chambers (RPCs).*
- *CODEX-β is a demonstrator for CODEX-b which is 2 x 2 x 2 m^3 – it is approved with construction in 2024 year end shutdown of the LHC*



CODEX-b a 10 m cube



CODEX-β a 2 m cube

CODEX-b the Future?

- *LHCb to start using underground servers for run 4*
- *Original LHCb detector design can't fully be used*
- *Simulations show partial installations still yield similar reconstruction efficiencies*
- *Details on new design still need to be ironed out*
- *Meanwhile CODEX-β will run with 1/125th of the volume of CODEX-b*

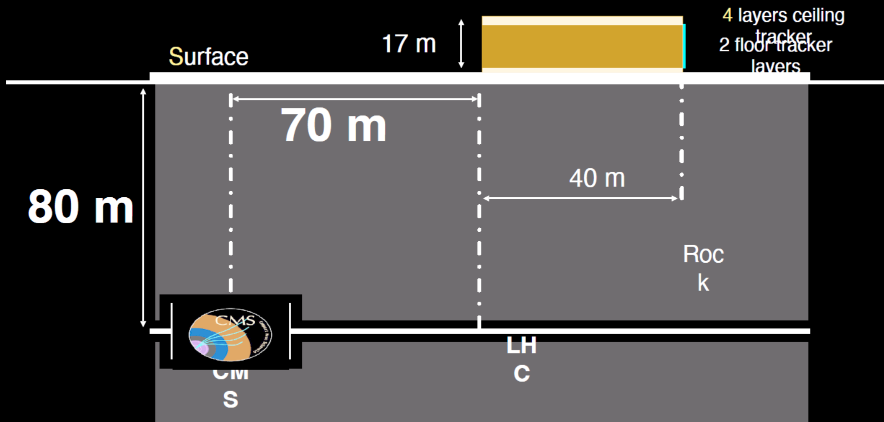
MATHUSLA at the HL-LHC

MAssive Timing Hodoscope for Ultra Stable neutraL pArticles

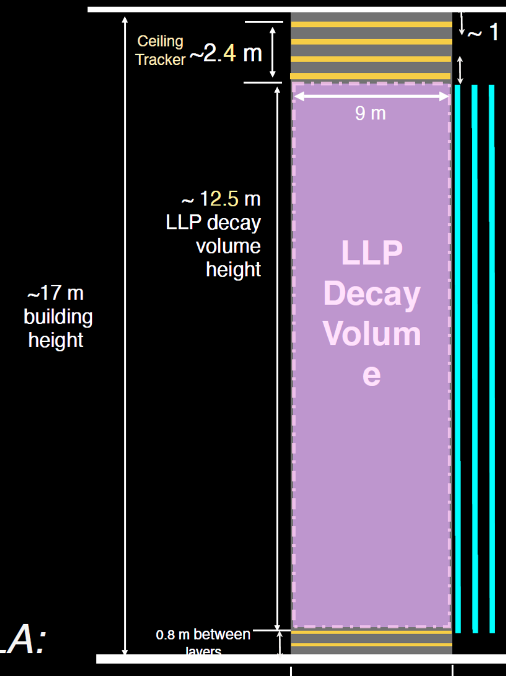
NEW DESIGN

40 m x 40 m x 17 m

Tracking – extruded scintillator bars with WLS fibre readout

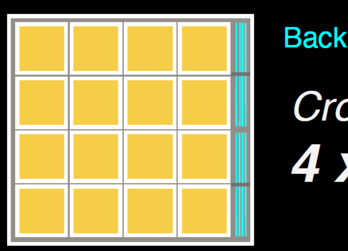


Side view



Adding tracking layers along back modules improves signal efficiency by ~30%

Back tracker made of same planes as ceiling tracking layers with same ~0.8 m separation



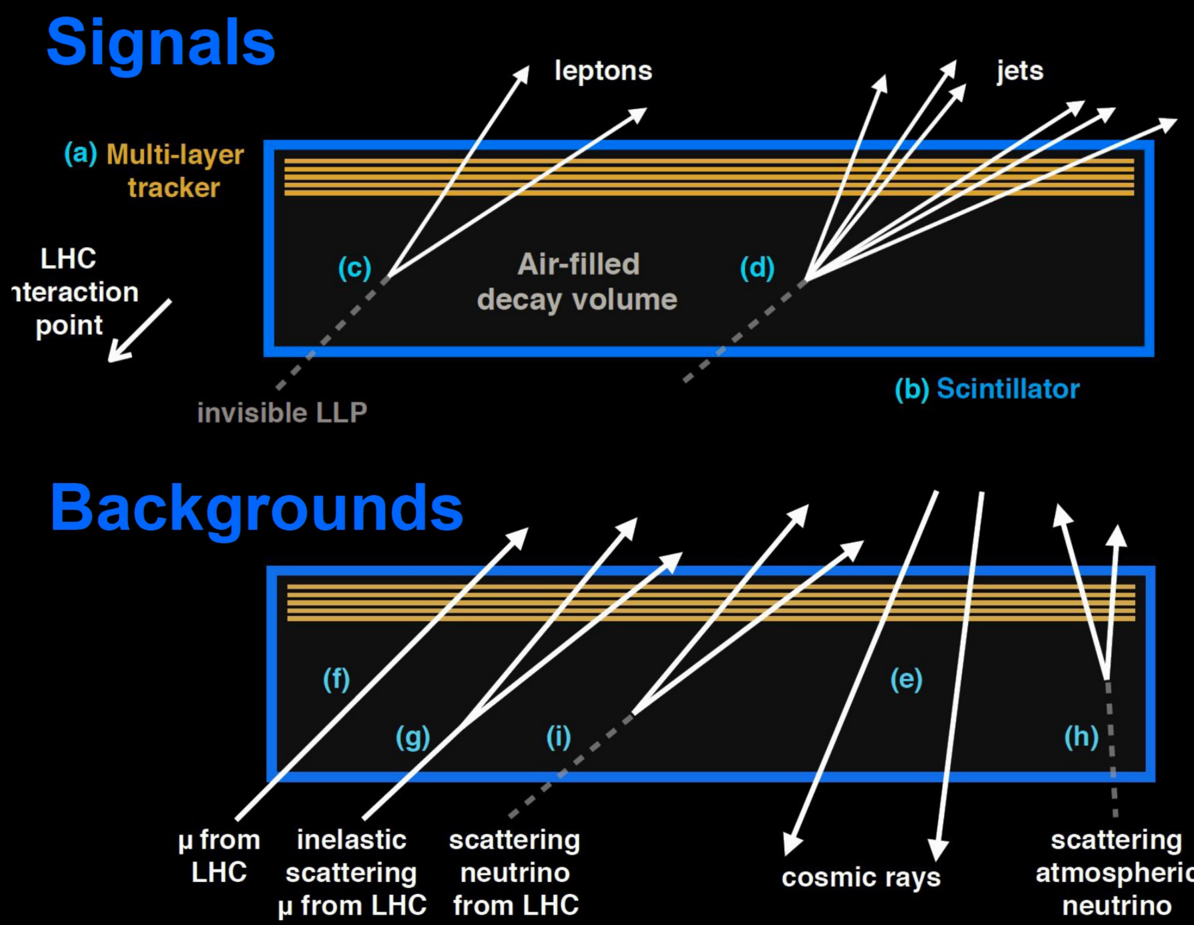
Cross-section of MATHUSLA:

4 x 4 grid of 9 x 9 m² modules with ~1 m gap

9 x 9 m² module Vertical structure

DOE funding problems result in reduction in detector size from 100 x 100 x 25 m³

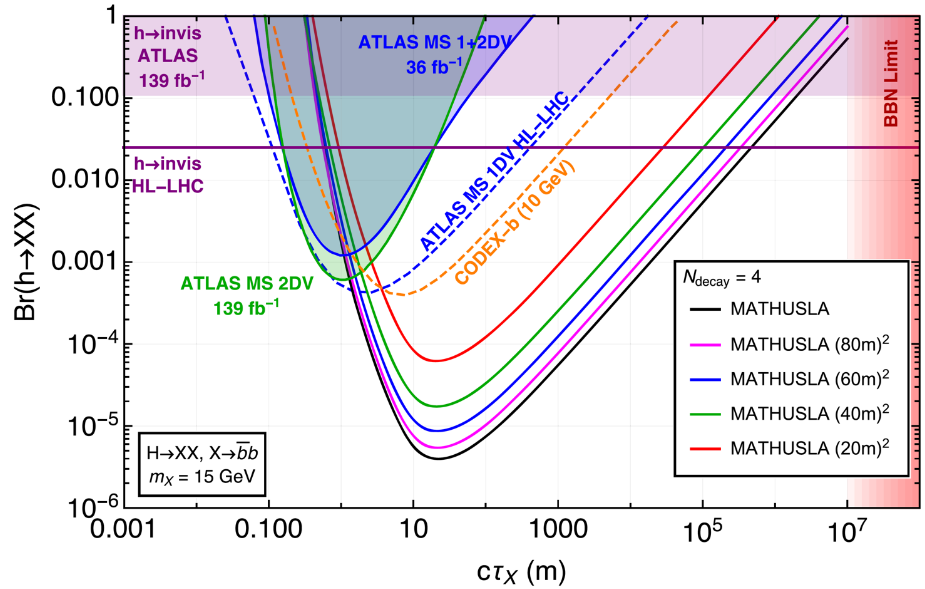
MATHUSLA – Signal & Backgrounds

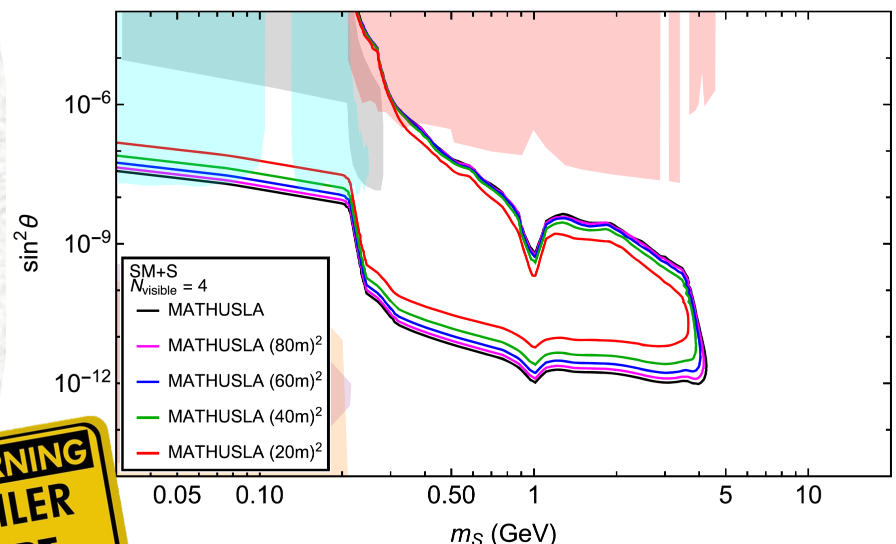


- *MATHUSLA cannot measure momentum or energy, but*
- *MATHUSLA+CMS: This allows further determination of LLP production mode, mass range and spin*

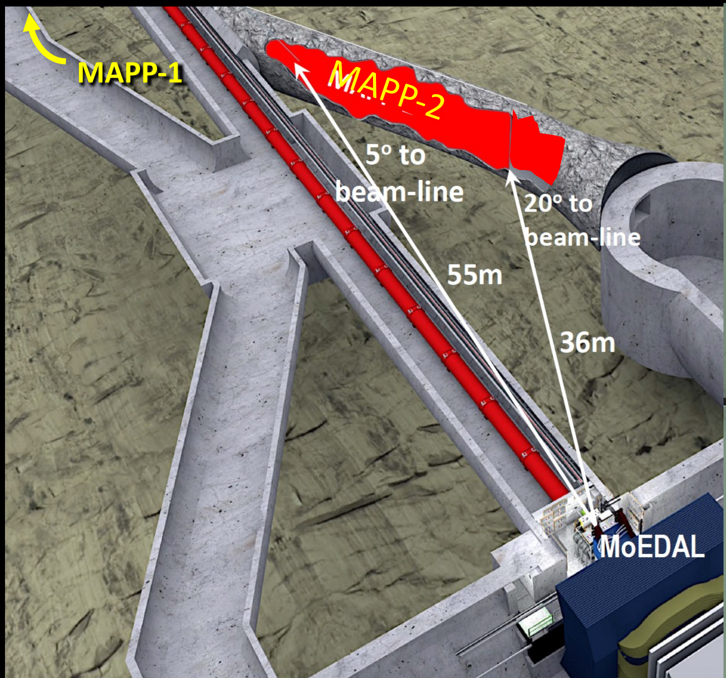
Sensitivity

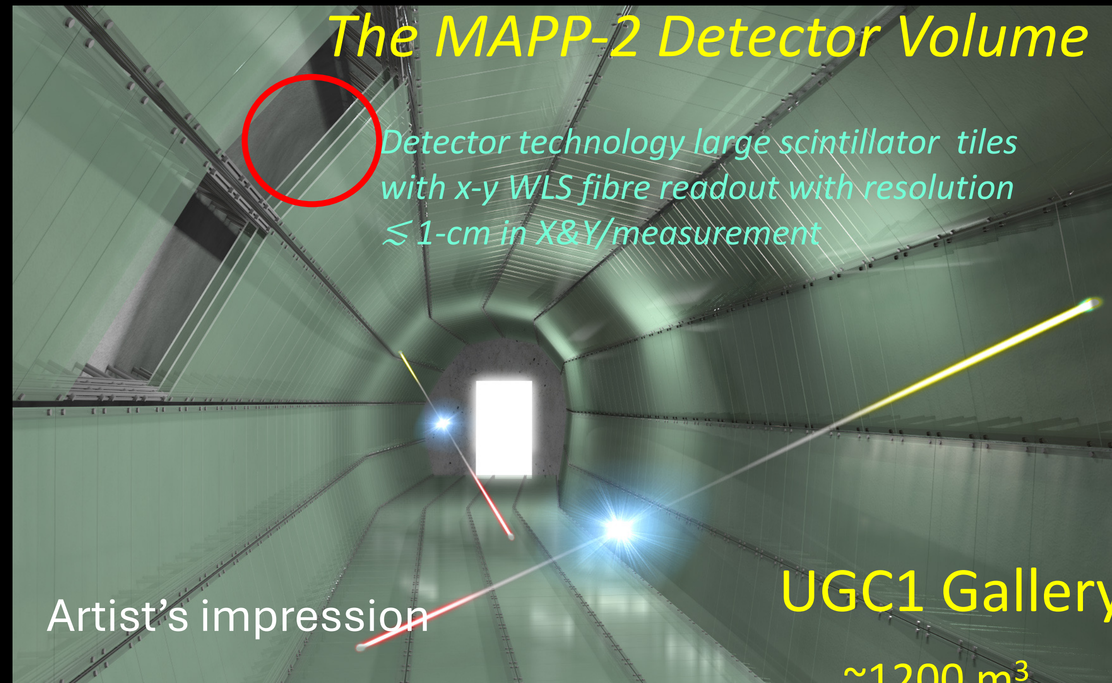
- *Primary physics case: hadronically decaying O(10-100 GeV) LLPs. e.g., LLPs in exotic Higgs decays.*
    - *Secondary physics case: GeV-scale LLPs. e.g, scalar LLPs in the SM+S model*
- *Sensitivity scales roughly with volume.*
    - *Previous baseline 100 x 100 x 25m^3 = 2.5 x 10^5 m^3(decay volume (MATHUSLA-100). 40m x 40m x 13m*
    - *However, the new baseline (MATHUSLA-40) 40 x 40 x 13 m^3 = 2 x 10^{4}m^3 has reduced reach by roughly a factor of ten*





MAPP-2 for HL-LHC at Intermediate η





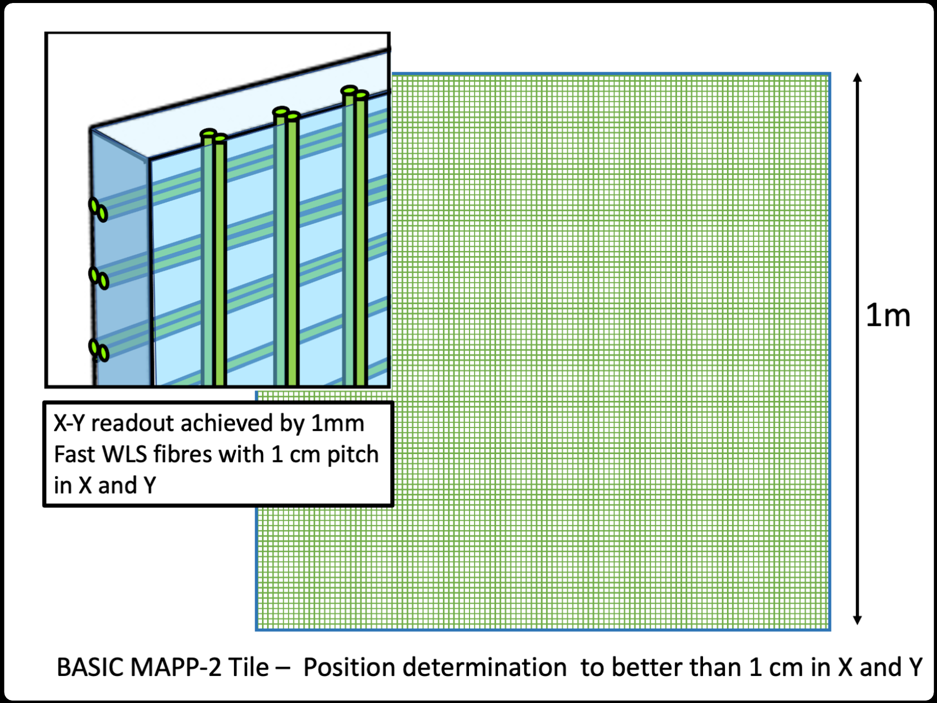
- *The MAPP-2 detector would be deployed 100 m UG in the UGC1 gallery 55 m to 33 m from IP8 (LHCb) – protected by ~33-36m of rock*
- *The MAPP-2 detector fills the UGC1 gallery*
  - *The tracking detectors would form 3 or 4 hermetic containers defining an OPEN DECAY ZONE for greater sensitivity to photons of lower energy*
- *Designed to be sensitive to decays to **charged particles & photons (down to ofo 100 MeV)***

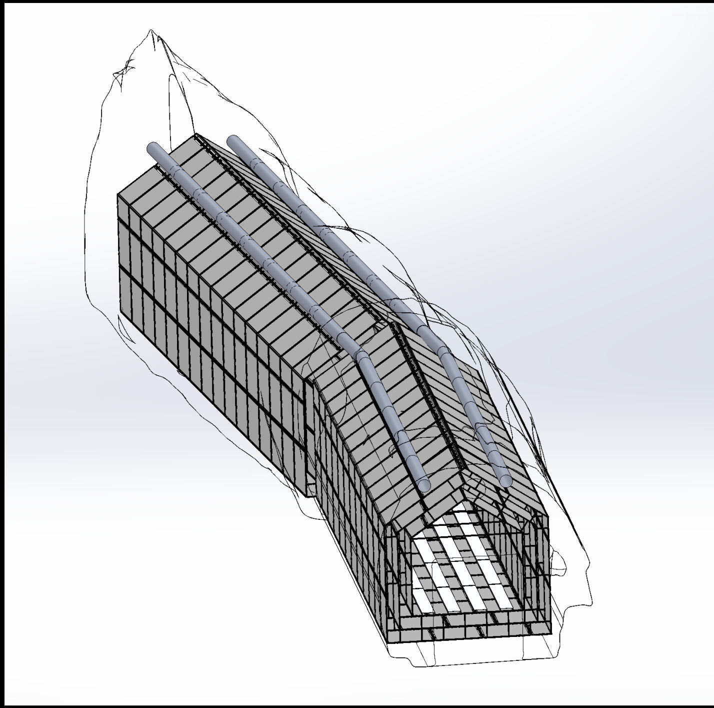
UGC1 Refurbishment

Safety Requirement	Cost	Cost + Contingency
Fire Detection Emergency Red phone	21,000 CHF 11,200 CHF	23,100 CHF (10 %) 11,760 CHF (5 %)
Electrical Safety	48,200 CHF	53,000 (10 %)
Civil Engineering	151, 000 CH F	166,100 CHF (10 %)
HVAC	45,000 CHF	54,000 CHF (20%)
Access and work at height at UGC1	10,000 CHF	11,000 CHF (10 %)
Radiation Protection Patrol & Access System Requirement	45,000 CHF 4,500 CHF	49,500 CHF (10 %) Patrol System 4,725 CHF (5 %) Sector door
TOTAL	335,900 CHF	373,185 CHF

- *Civil work ~$0.4 million*
- *MAPP-2 Detector cost ~$3-4 million*
- *Funding requested for work in 2026 awarded in 2025 (if successful)*
- *TP under construction (NoI given)*

The MAPP-2 LLP Detector
Different than the Rest





- *The basic detector element is a ~1 m^2 scintillator plate readout in 2-D by WLS fibres - most other LHC LLPs use RPCs → **No gas problems***
- *WLS Fibres are readout by SiPMs, with fibre pitch of 1cm in X and Y.*
  - *Gives us the ability to construct vertices to σ ~ 0.5 mms in X, Y and Z.*
  - *Provides two hit resolution for charge tracks and photons of a few cms.*

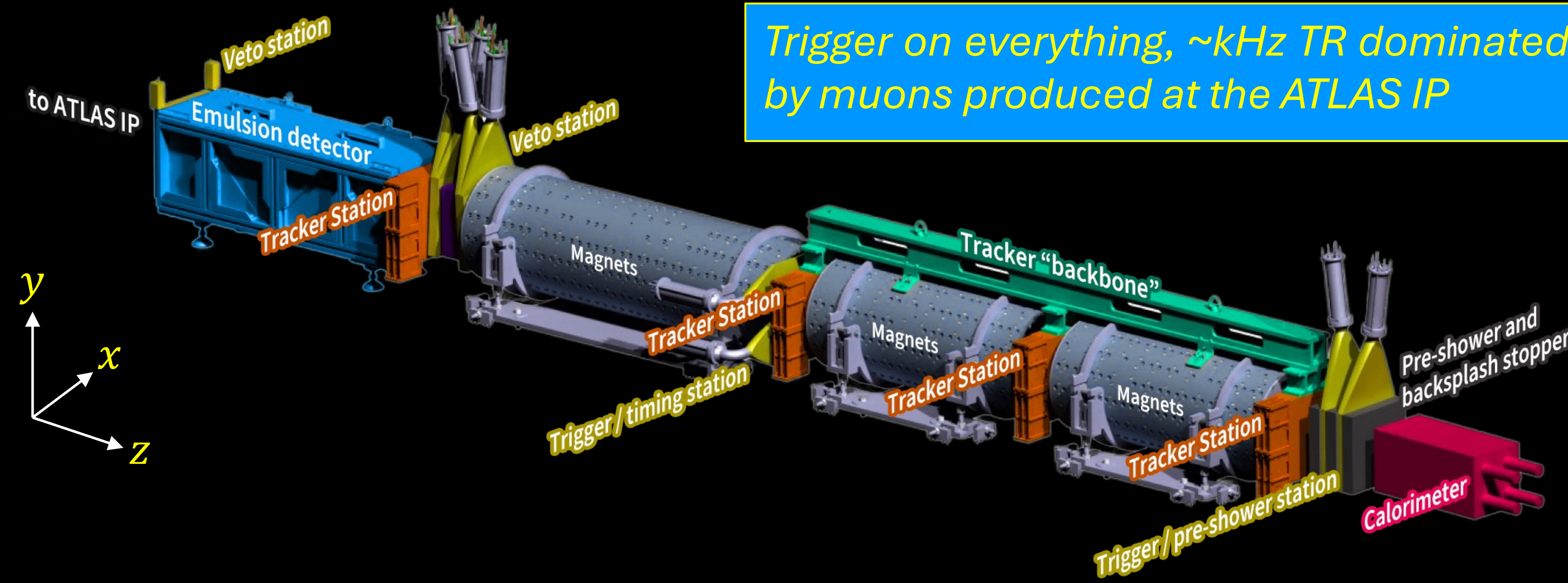
FASER

(ForwArd Search ExpeRiment at the LHC)

- 480m from ATLAS IP
- 88 m underground,
- 100 m of rock & concrete protection from ATLAS IP

The FASER Detector

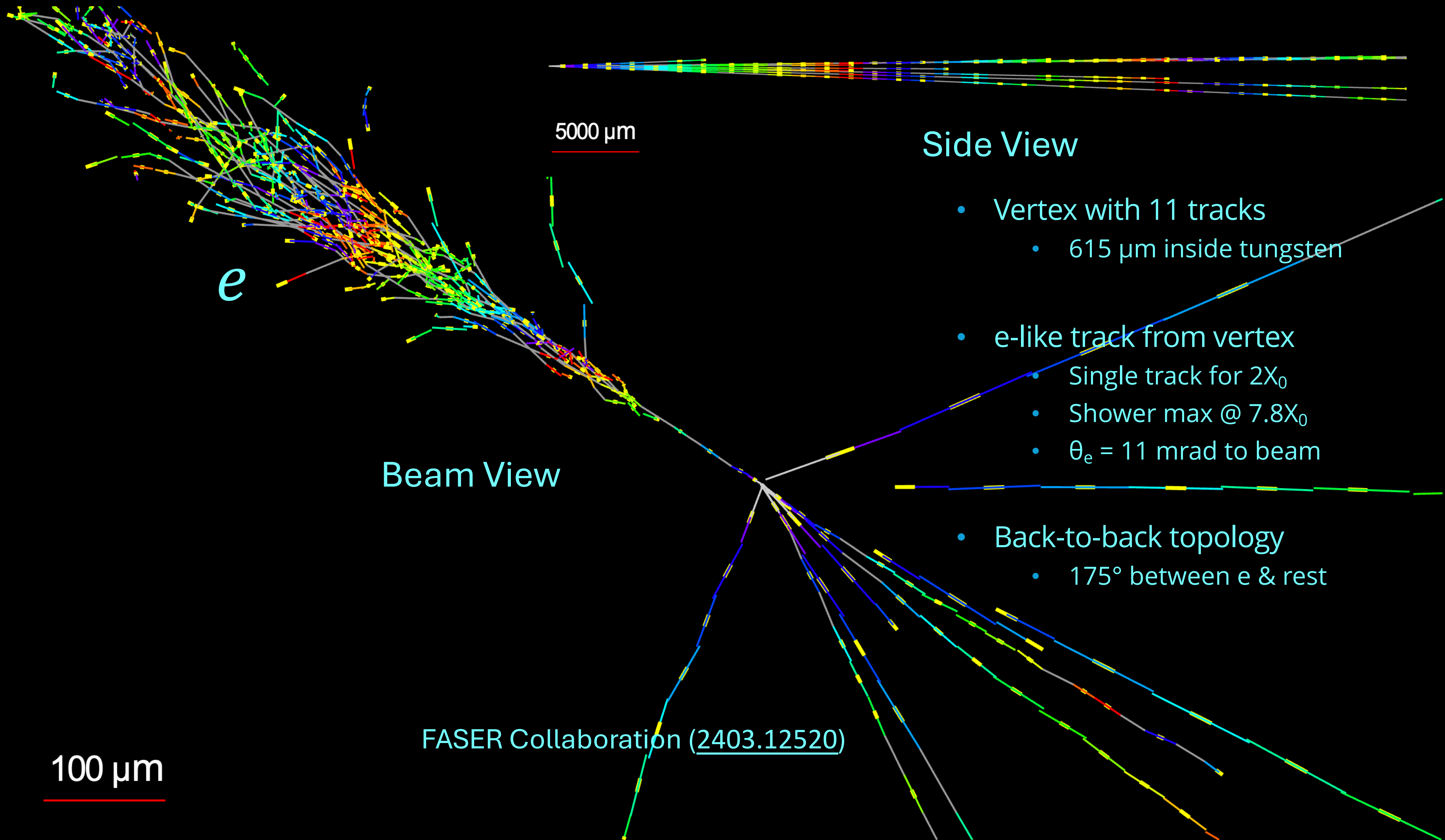
- **Detector:**- Total length ~ 5 m, decay volume: R = 10 cm, L = 1.5 m.
  - 3 permanent dipole magnets, Halbach design,
  - Tracker: 4 stations x 3 layers x 8 mod. = 96 ATLAS SCT modules. Resolution = 16 μm in y, 820 μm in x.
  - Calorimeter: 2 x 2 LHCb ECAL modules.
  - Scintillators: 4 stations, multiple layers, each 2 cm thick, 4-layer veto
- **FASER ν:** 770 interleaved sheets of tungsten + emulsion. 1 m long, 1.1 ton total mass. Micron-level spatial resolution,.



Trigger on everything, ~kHz TR dominated by muons produced at the ATLAS IP

Neutrinos from Emulsion in FASERν

- *The discovery analysis did not even use the emulsion data! With the emulsion, we have now observed the first collider electron neutrinos, including the "Pika-ν" event, the highest energy (1.5 TeV) electron neutrino from a lab source.*

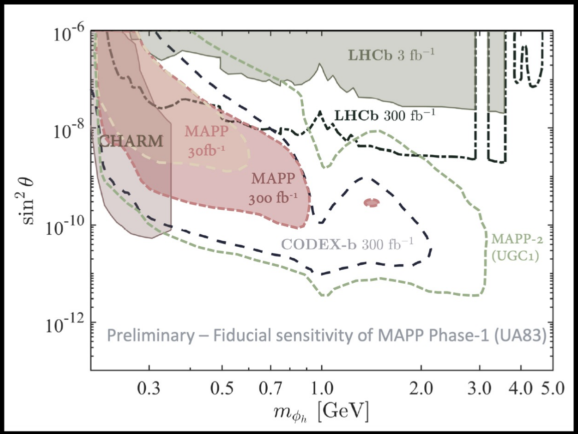


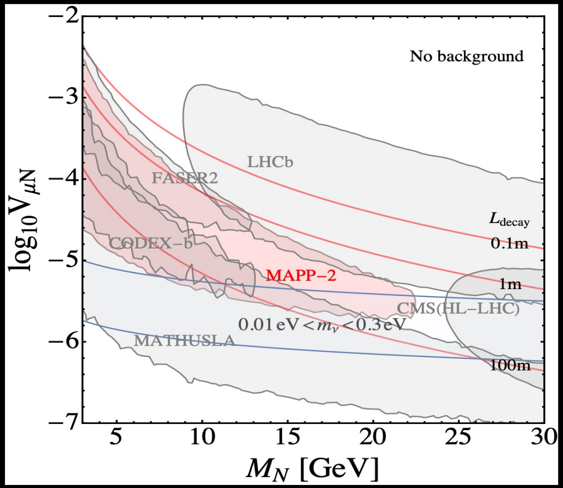
Side View

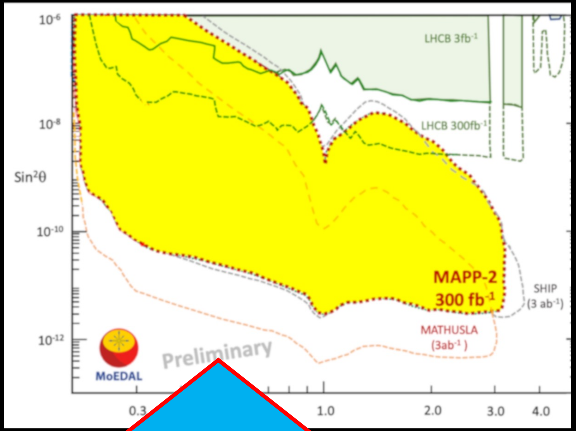
- Vertex with 11 tracks
  - 615 μm inside tungsten
- e-like track from vertex
  - Single track for $2X_0$
  - Shower max @ $7.8X_0$
  - θ_e = 11 mrad to beam
- Back-to-back topology
  - 175° between e & rest

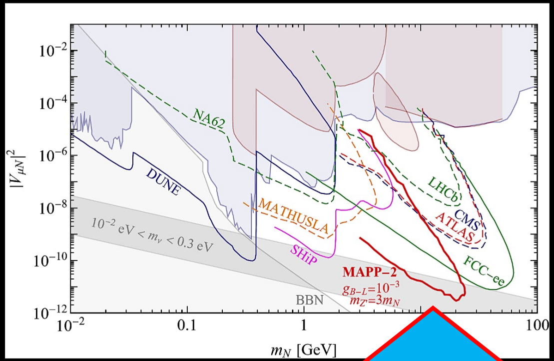
FASER Collaboration (2403.12520)

Sensitivity – Two Baseline Scenarios









arXiv:2110.09392v1 [hep-ph] Oct 2021
Phys. Rev. D, 97:015023, Jan. 2018.

This benchmark involves the decay of dark Higgs where the dark Higgs mixing portal allows the inclusive B decays, $B \to X_s\varphi_h$, (φ_h is a light CP–even scalar that mixes with the SM Higgs) & $\varphi_h \to \mu^+\mu^-$) with mixing angle $\vartheta \ll 1$.

Frank Deppisch. To be published in EPJ-ST,
Phys. Rev. D100 (2019), 035005.

Pair production of right-handed neutrinos from the decay of an additional neutral Z^0 boson in the gauged B-L model. V_{mN} is the active-sterile mixing parameter.

New LHC Facilities for “Agile” Experiments Defined in Latest SNOWMASS Process

DOI: 10.5281/zenodo.4009641

FERMILAB-FN-1167-T
29 September 2020

SNOWMASS 2021 LETTER OF INTEREST

FORWARD PHYSICS FACILITY

Roshan M. Abraham,[1] Henso Abreu,[2] Yoav Afik,[2] Sanjib K. Agarwalla,[3] Juliette Alimena,[4] Luis Anchordoqui,[5] Claire Antel,[6] Akitaka Ariga,[7] Tomoko Ariga,[8] Carlos A. Argüelles,[9] Kento Asai,[10] Weidong Bai,[11] Pouya Bakhti,[12] Akif B. Balantekin,[13] Victor Baules,[14] Brian Batell,[15] James Beacham,[16] John F. Beacom,[4,17,18] Nicole F. Bell,[19] Florian Bernlochner,[20] Atri Bhattacharya,[21] Tobias Boeckh,[20] Kyrylo Bondarenko,[22] Jamie Boyd,[22] Lydia Brenner,[22] Mauricio Bustamante,[23] Franck Cadoux,[6]

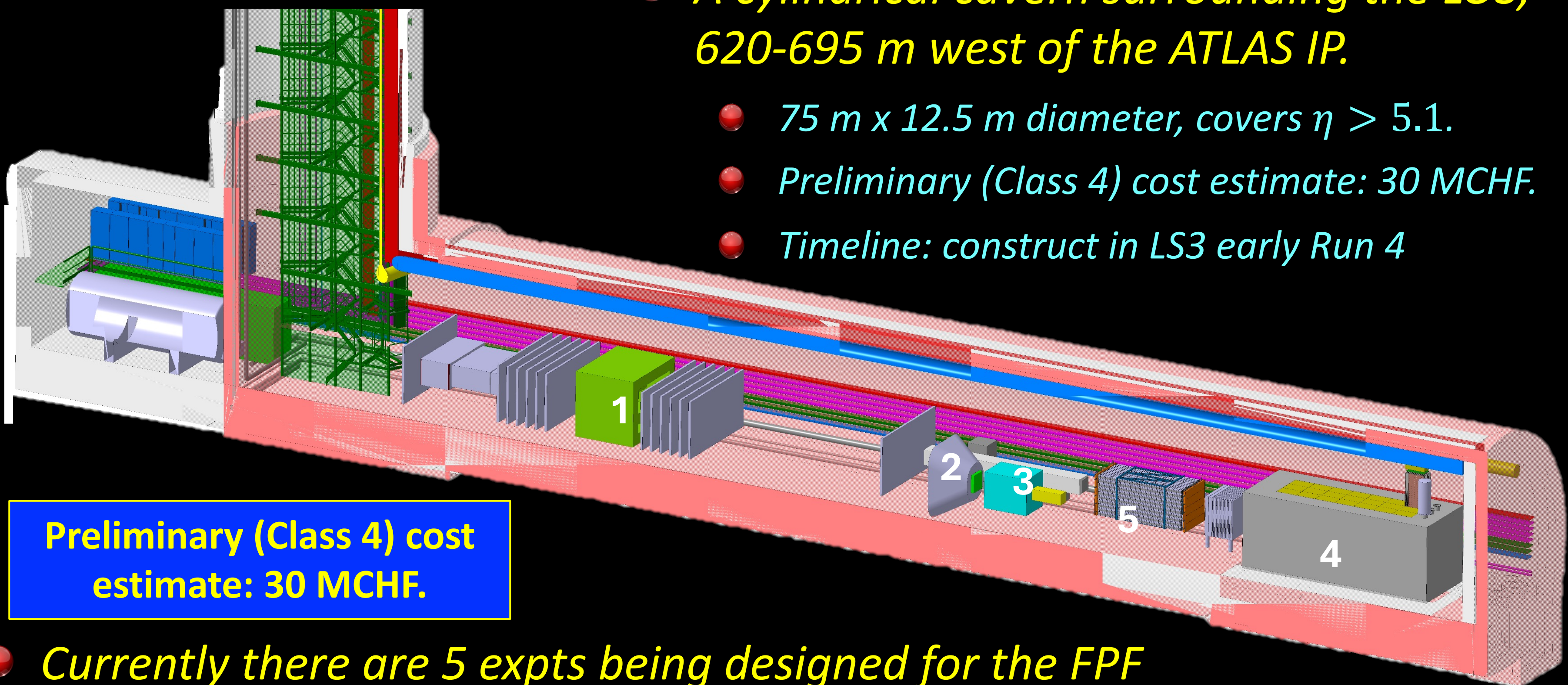
MoEDAL-MAPP – an LHC Dedicated Detector Search Facility

B. Acharya,[1,*] J. Alexandre,[1] P. Benes,[2] B. Bergmann,[2] S. Bertolucci,[3] A. Bevan,[4] H. Branzas,[5] P. Burian,[2] M. Campbell,[6] S. Cecchini,[3] Y. M. Cho,[7] M. de Montigny,[8] A. De Roeck,[6] J. R. Ellis,[1,9,†] M. El Sawy,[6,‡] M. Fairbairn,[1] D. Felea,[5] M. Frank,[10] J. Hays,[4] A. M. Hirt,[11] P. Q. Hung,[12] J. Janecek,[2] M. Kalliokoski,[13] A. Korzenev,[14] D. H. Lacarrère,[6] C. Leroy,[15] G. Levi,[16] A. Lionti,[14] A. Margiotta,[16] R. Masełek,[17] A. Maulik,[3,8] N. Mauri,[16] N. E. Mavromatos,[1,§] M. Mieskolainen,[18] L. Millward,[4] V. A. Mitsou,[19] E. Musumeci,[19]

Submitted to the Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021)

Forward Physics Facility

- *A cylindrical cavern surrounding the LOS, 620-695 m west of the ATLAS IP.*
  - *75 m x 12.5 m diameter, covers $\eta > 5.1$.*
  - *Preliminary (Class 4) cost estimate: 30 MCHF.*
  - *Timeline: construct in LS3 early Run 4*

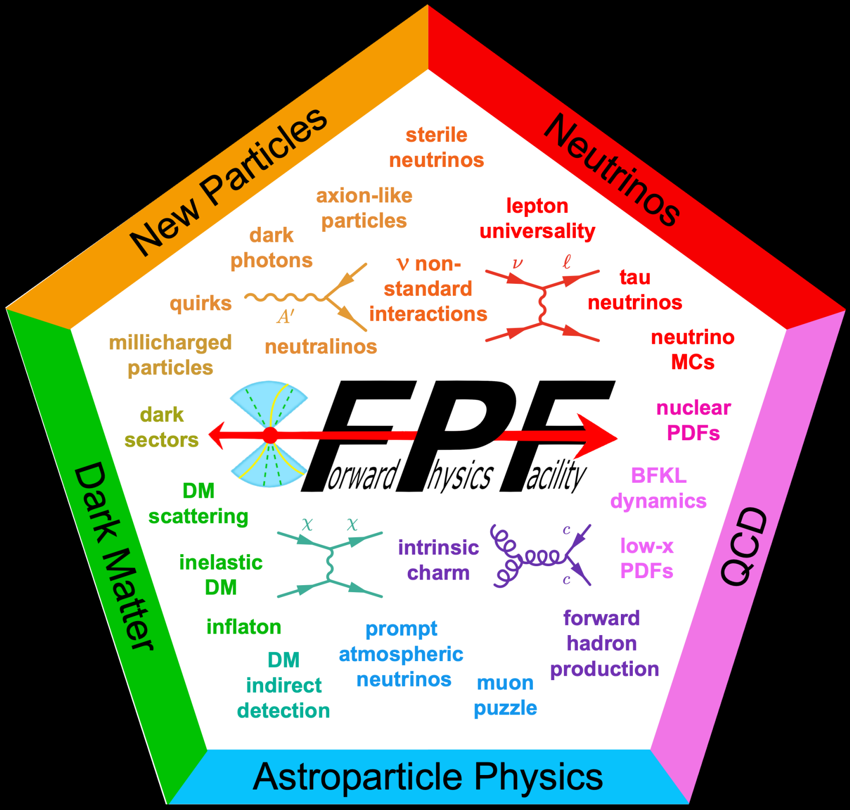


Preliminary (Class 4) cost estimate: 30 MCHF.

- *Currently there are 5 expts being designed for the FPF*
  - ***FASER2:** magnetized spectrometer for BSM searches (1)*
  - ***FASERn2**: 10-ton emulsion-based neutrino detector (2)*
  - ***advSND:** dedicated neutrino detector covering complementary rapidity region (3);*
  - ***FLArE**: 10-ton LArTPC neutrino detector +McP detector (4)*
  - ***FORMOSA-2**: scintillator array for BSM searches (successor to MilliQan) (5)*

1st Results and the Future

- *First Direct Observation of Collider Neutrinos with FASER at the LHC, PRL, 2303.14185*
- *Observation of Collider Muon Neutrinos with SND@LHC, PRL, 2305.09383*
- *Search for Dark Photons at FASER, CERN-FASER-CONF-2023-001, PLB, 2308.05587*
- *Observation of High-Energy Electron Neutrinos with FASERν, CERN-FASER-CONF-2023-002*
- *Search for U(1)B-L Gauge Bosons at FASER, PLB, 2308.05587*
- *First Measurement of the ν_e and ν_μ Interaction Cross Sections at the LHC with FASERν, 2403.12520*
- *Search for ALPs in Photonic Final States with FASER CERN-FASER-CONF-2024-001*



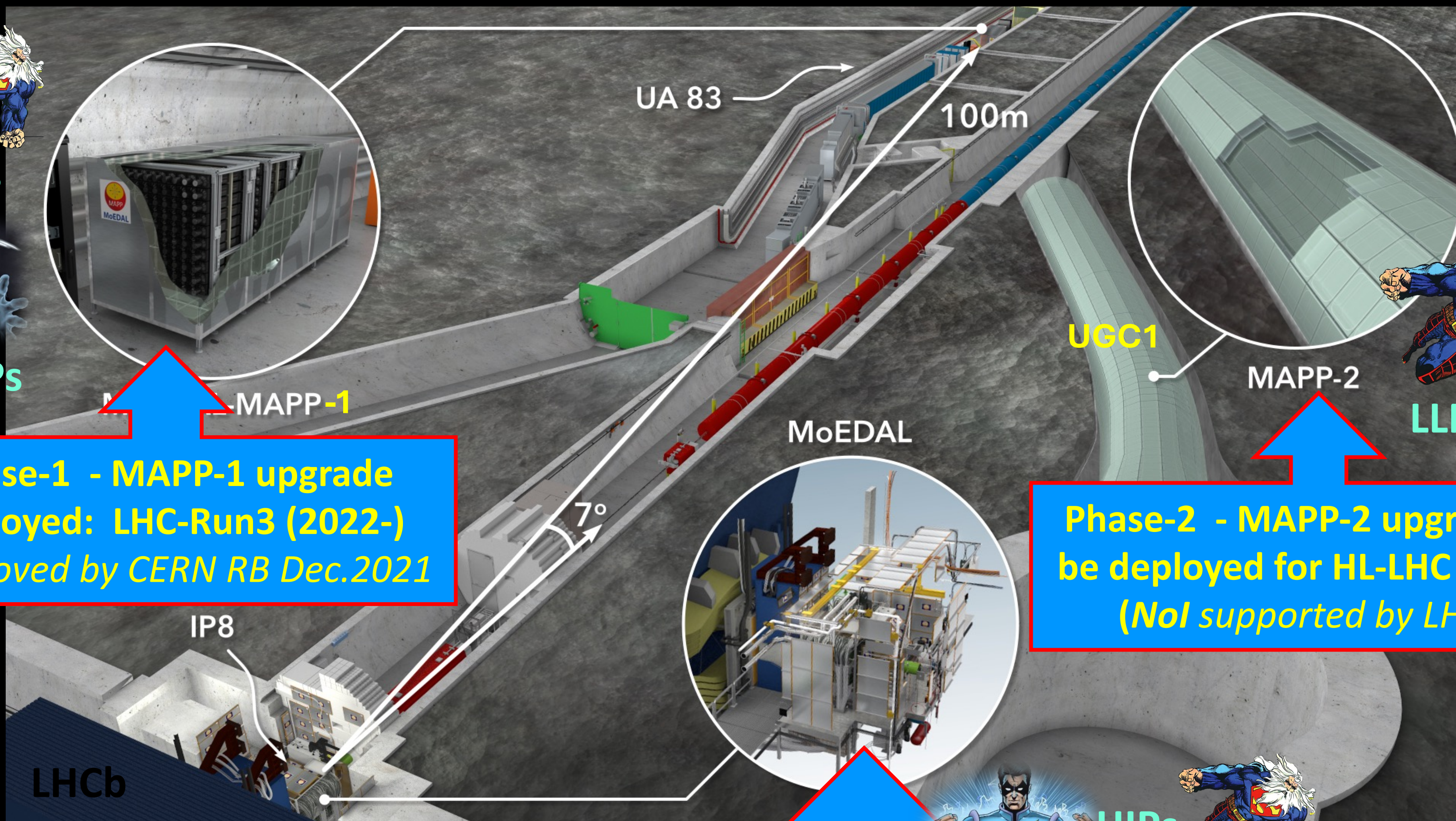
- **June 2024: Document on the Facility to be submitted to the PBC.**
- **Early 2025: LOI to be submitted to the LHCC.**
- **March 2025: input to be submitted to European Strategy Update.**

The MoEDAL-MAPP Facility

MoEDAL

LLPs

FIPs



Phase-1 - MAPP-1 upgrade deployed: LHC-Run3 (2022-)
(*Approved by CERN RB Dec.2021*

LLPs

Phase-2 - MAPP-2 upgrade to be deployed for HL-LHC (2027-)
(***NoI** supported by LHCC)*

HIPs

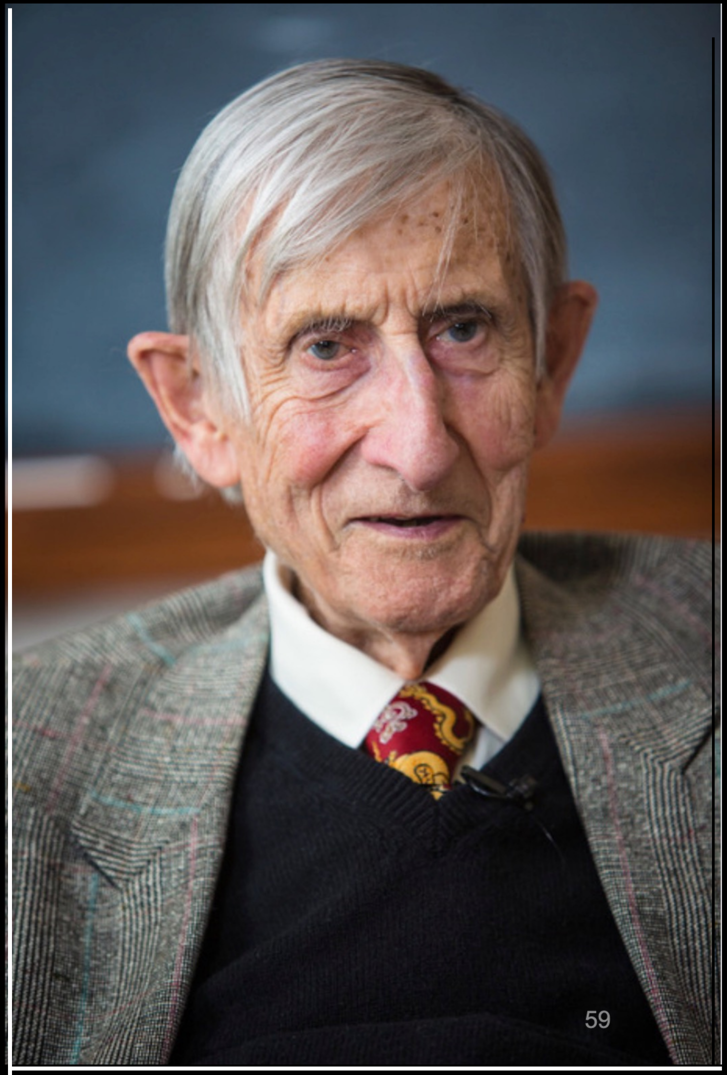
LLPs

Phase-0 - MoEDAL Detector deployed for LHC-Run-1& 2 (2010 - 18) and Phase-1 - Run-3 (2022 -)
(Approved by CERN RB in 2010 & reapproved for LHC's Run-3 in Dec. 2021

Final Words

"New directions in science are launched by new tools much more often than by new concepts."

- Freeman Dyson



- ***The Dedicated, or "Agile" Search Detectors at the LHC discussed here are the <u>new tools</u> now being used to in the search for physics beyond the SM at the LHC***