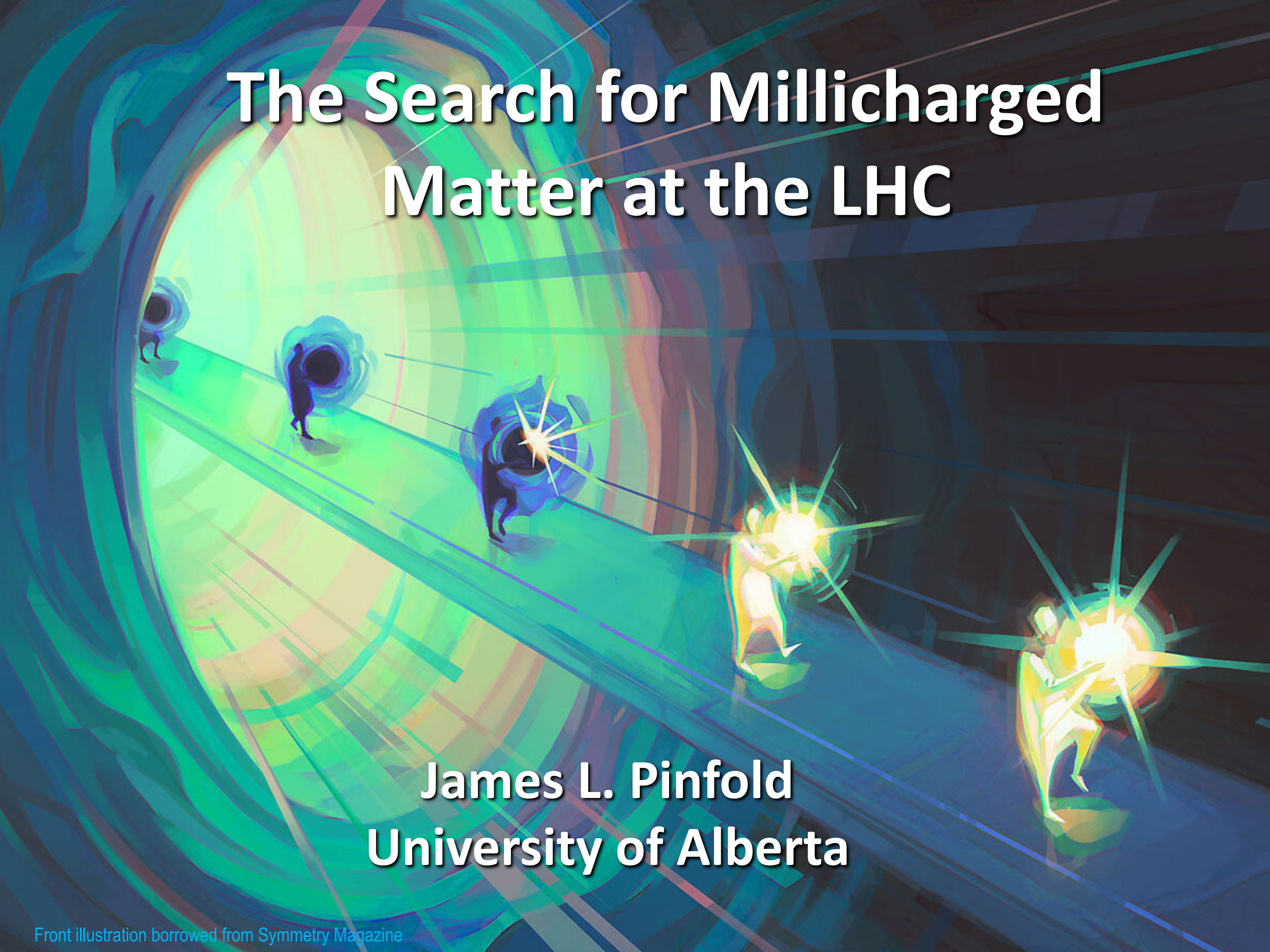
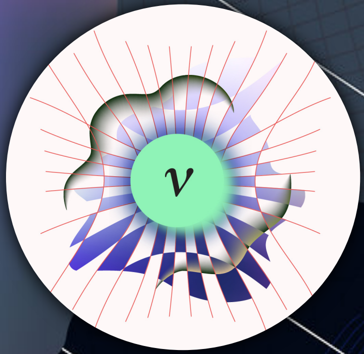


The Search for Millicharged Matter at the LHC

James L. Pinfold
University of Alberta

Front illustration borrowed from Symmetry Magazine

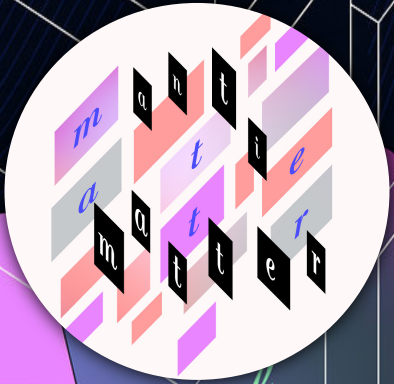
Problems with the Standard Model



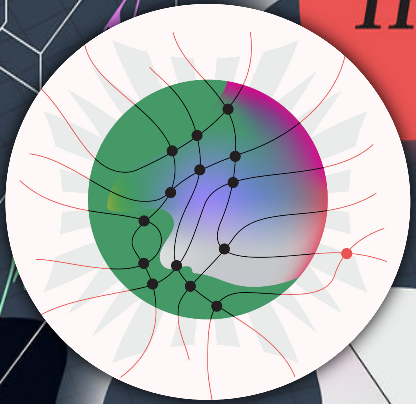
Why do neutrinos have mass?

What is Dark Matter?

What is the nature of Dark Energy?



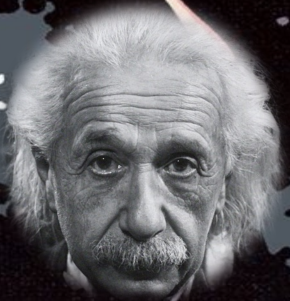
Origin of the Universe’s baryon symmetry

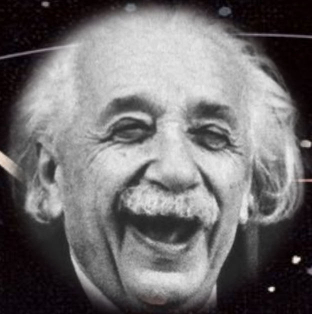


Where does gravity fit in?

This implies a more fundamental theory underlying the SM

Why No New Physics Yet at the LHC?



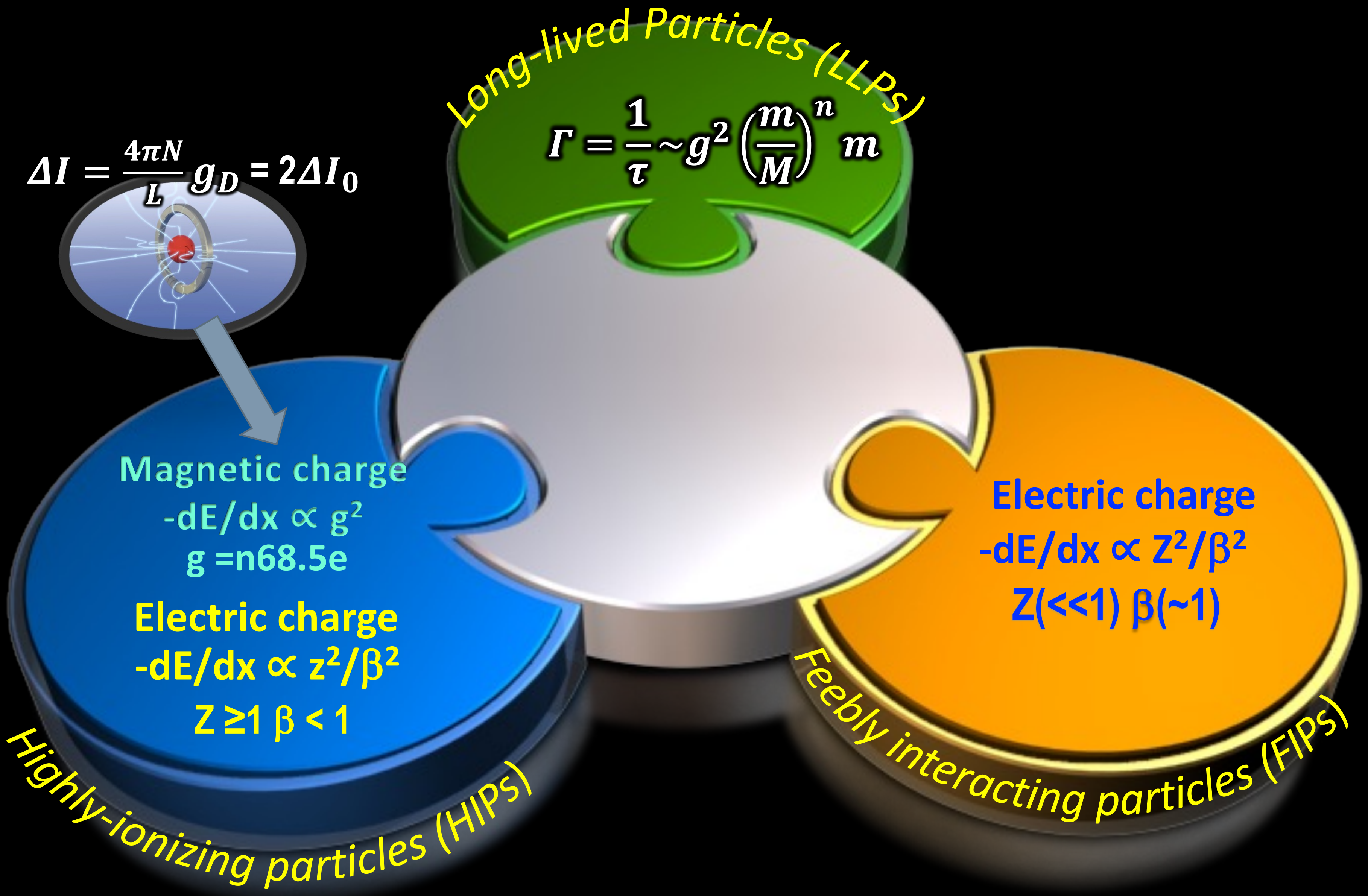


- *The Standard Model is it - there is no New Physics*
- *The mass scale of the new physics is beyond the LHC's reach*

- ***The mass scale is within LHC's reach, but final states are elusive to direct search***

The Avatars of New Physics

for which ATLAS & CMS are not optimized



Long-lived Particles (LLPs)

$$\Gamma = \frac{1}{\tau} \sim g^2 \left(\frac{m}{M}\right)^n m$$

$$\Delta I = \frac{4\pi N}{L} g_D = 2\Delta I_0$$

Magnetic charge

$-dE/dx \propto g^2$

$g = n68.5e$

Electric charge

$-dE/dx \propto z^2/\beta^2$

$Z \geq 1 \ \beta < 1$

Highly-ionizing particles (HIPs)

Electric charge

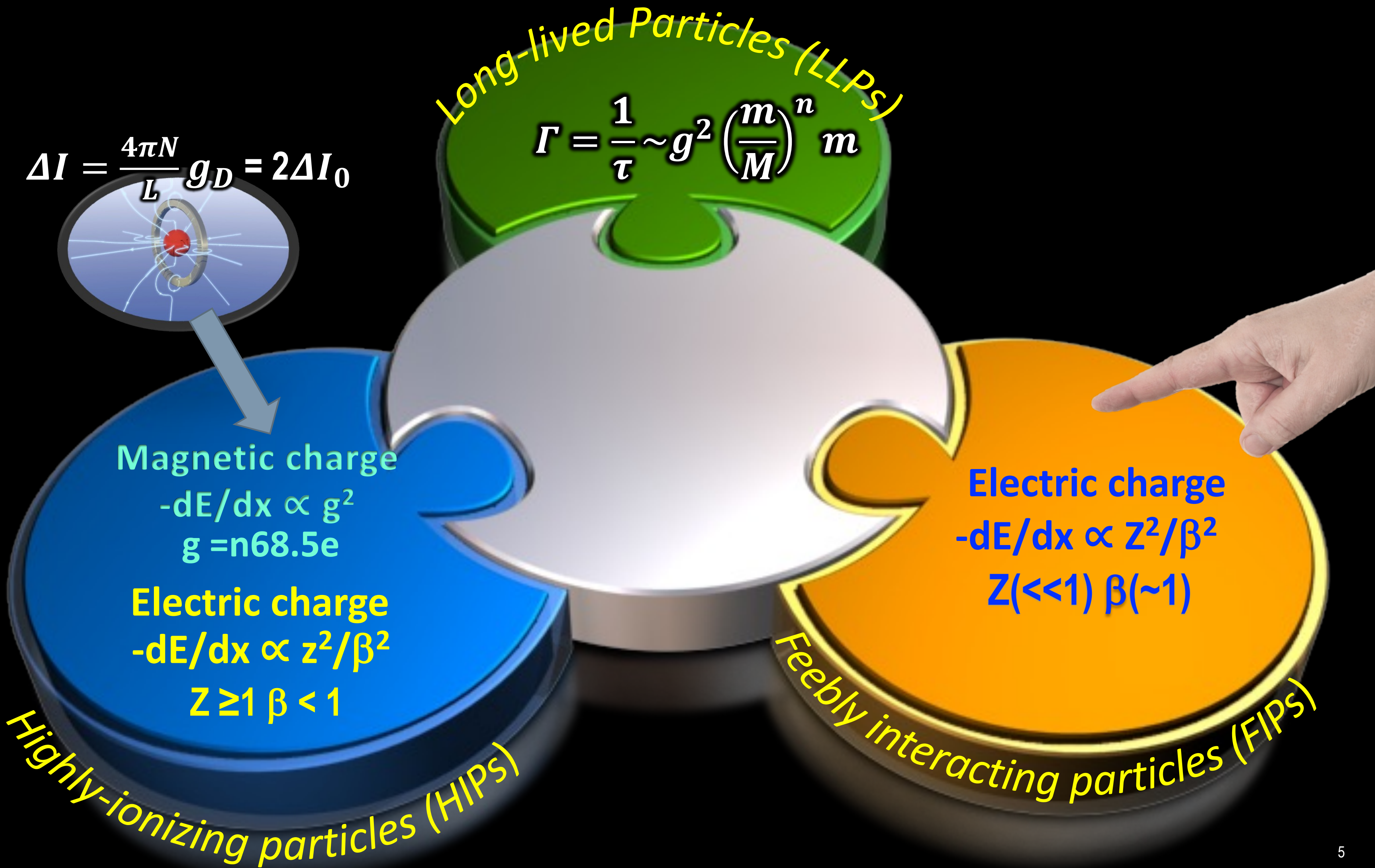
$-dE/dx \propto Z^2/\beta^2$

$Z(<<1) \ \beta(\sim 1)$

Feebly interacting particles (FIPs)

The Avatars of New Physics

for which ATLAS & CMS are not optimized



Long-lived Particles (LLPs)

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Magnetic charge

-dE/dx ∝ g^2

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Electric charge

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Z ≥1 β < 1

Highly-ionizing particles (HIPs)

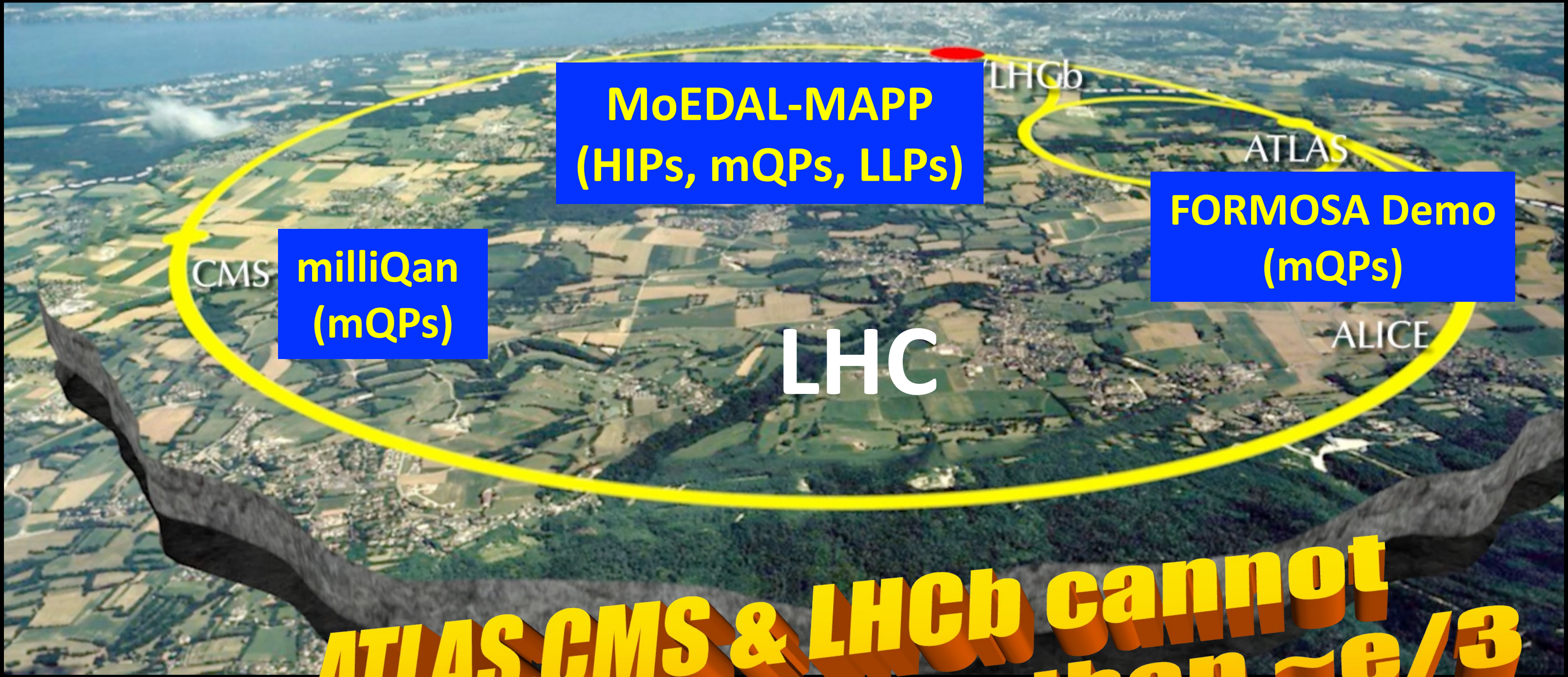
Electric charge

-dE/dx ∝ Z^2/β^2

Z(<<1) β(~1)

Feebly interacting particles (FIPS)

LHC'S Search for milli-charged Matter at Run-3



MoEDAL-MAPP (HIPs, mQPs, LLPs)

milliQan (mQPs)

FORMOSA Demo (mQPs)

ATLAS,CMS & LHCb cannot Detect charges less than ~e/3

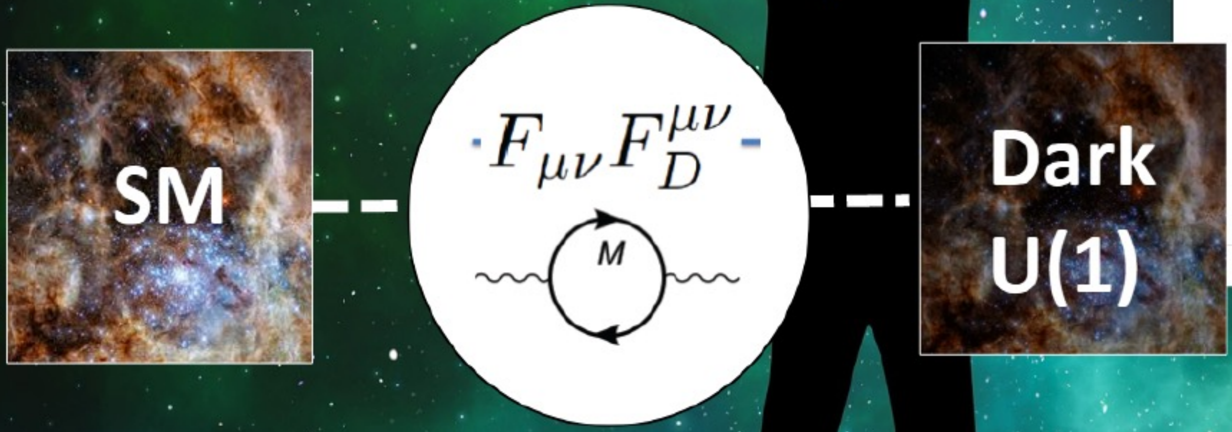
Search technique using plastic scintillator det. pioneered at SLAC by Prinz et al, PRL 81:1175,'98

Mapping the Dark Sector

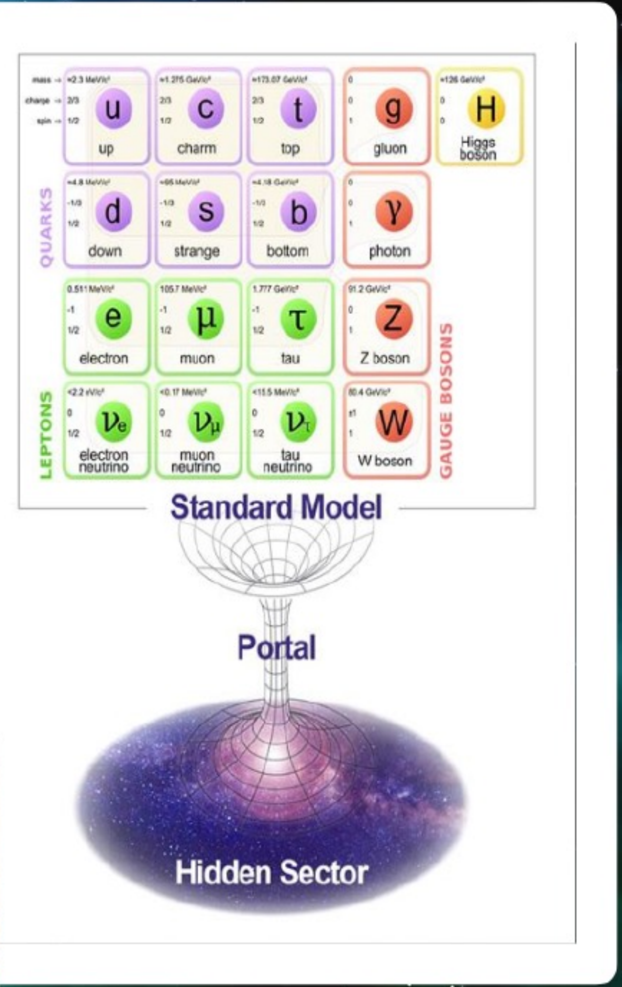
The main evidence for dark matter is gravitational. What are the "likely" non-gravitational interactions?

To detect a dark sector, we must know how it interacts with us.

- *Interactions between the two sectors are via mediator particles through so-called "portal interactions" — in this case, the vector portal:*



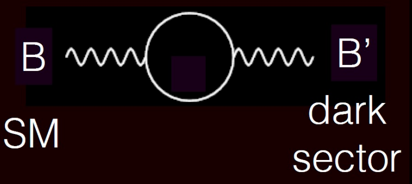
Mediator particles



A Model for Millicharged Particles

"Dark EM" **Mixing of dark photon and SM photon**

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}B'_{\mu\nu}B^{\mu\nu\prime} - \frac{\kappa}{2}B'_{\mu\nu}B^{\mu\nu} + i\bar{\psi}(\partial\!\!\!/ + ie'B\!\!\!/' + iM_{\rm mCP})\psi$$



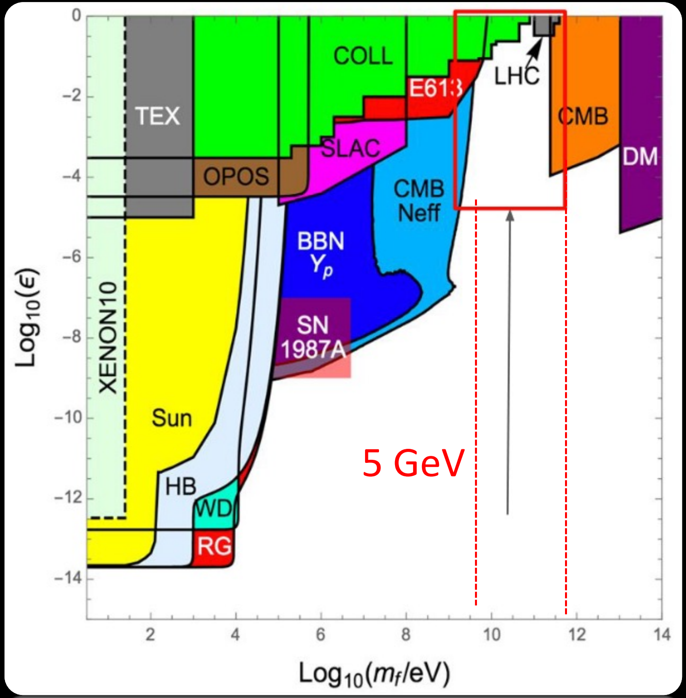
- *Consider a dark sector containing a massless U(1) gauge field, B'*
- *Introduce kinetic mixing κ between B' & SM hypercharge B ($\kappa \sim \alpha/\pi \sim 10^{-3}$)*
- *Redefine, B' → B' + κB to get rid of the mixing term and generate hypercharge for a new fermion:*

$$\mathscr{L} = \mathscr{L}_{SM} - \frac{1}{4}B'_{\mu\nu}B'^{\mu\nu} + i\overline{\psi}(\partial + \underbrace{i\kappa e'B}_{} + ie'B' + iM_{mCP})\psi$$

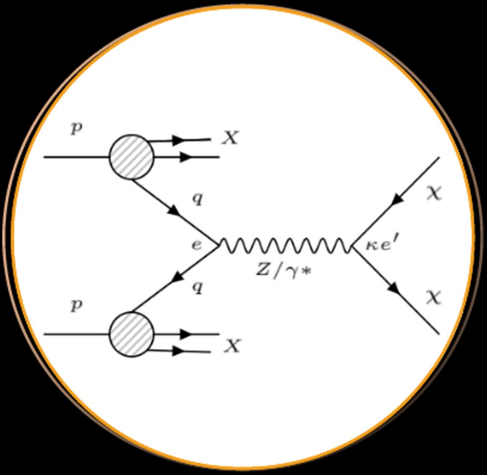
- *The new fermion has small EM charge: a milli-charged particle (mCP)*
- *The mCP ψ couples to the photon with a charge $\kappa e'\cos\vartheta_{W.}$ The fractional charge in units of the electric charge is therefore $\epsilon \equiv \kappa e'\cos\vartheta_W/e$.*

Production of Milli-charged at Colliders

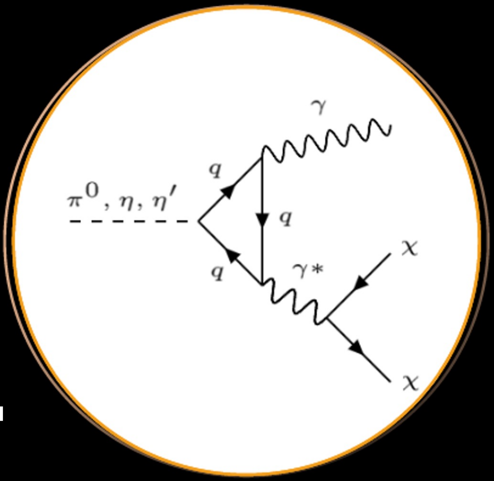
mCPs arise naturally from the dark sector via the Vector Portal/Dark Photon



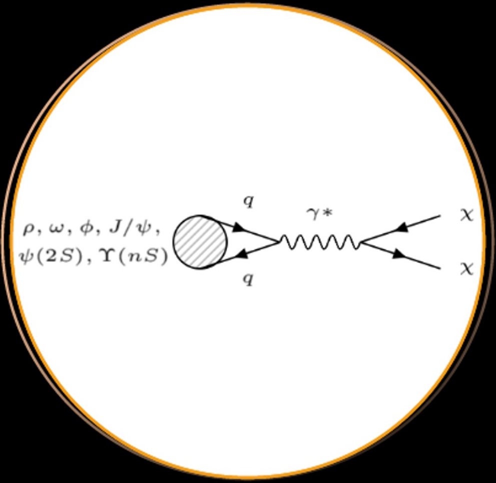
The Sweet Spot
arXiv:1511.01122



DRELL-YAN

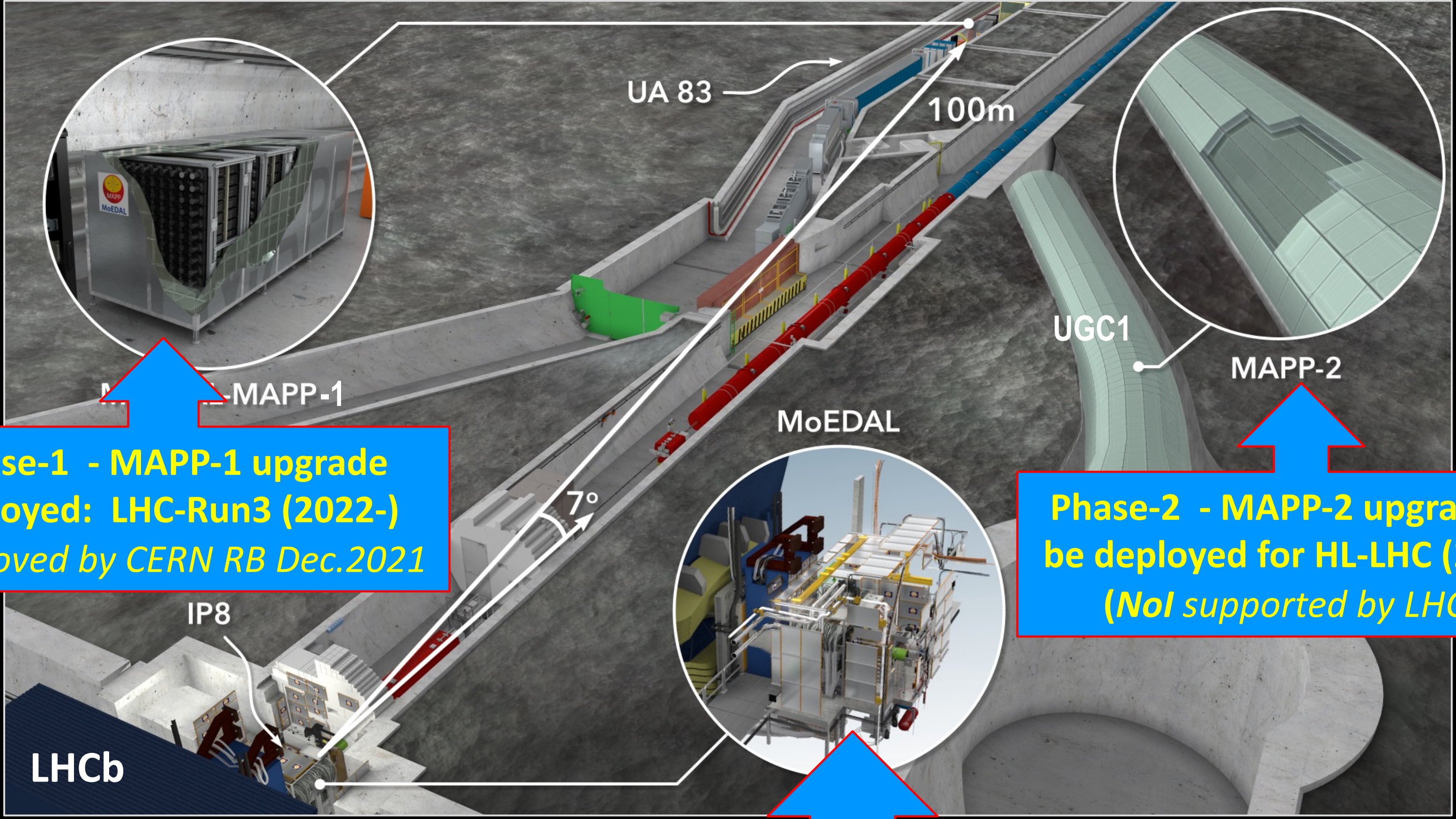


DALITZ DECAYS



DIRECT DECAYS

MoEDAL-MAPP a > 25 Year Project

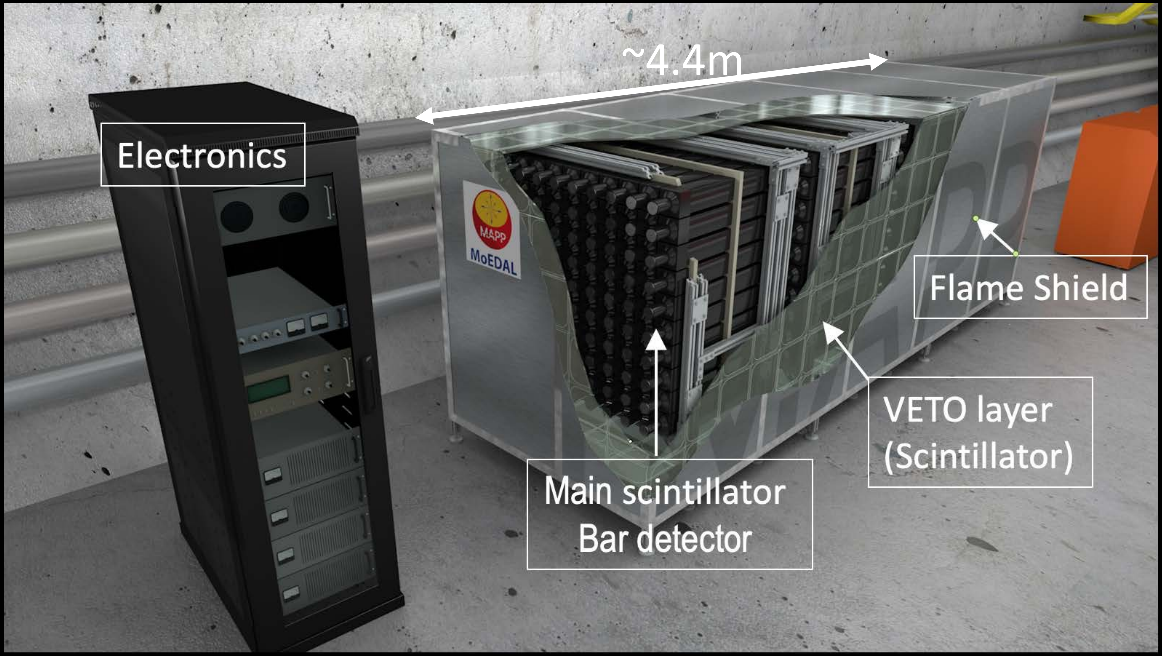


Phase-1 - MAPP-1 upgrade deployed: LHC-Run3 (2022-)
(Approved by CERN RB Dec.2021

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

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

MoEDAL's MAPP-1 Detector at UA83

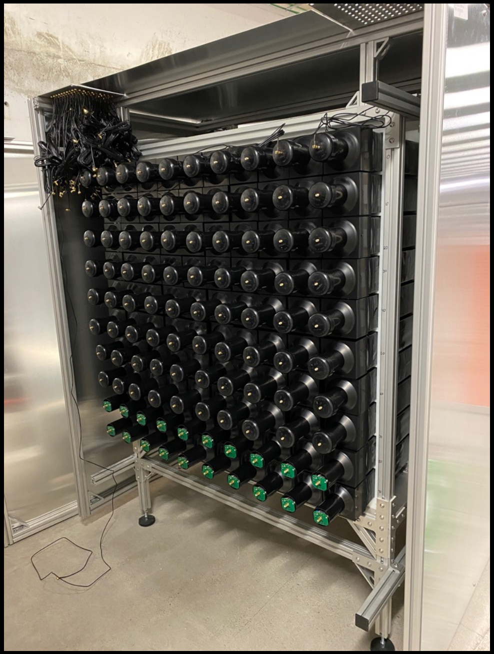


- *400 scintillator bars (10 x 10 x 75 cm^3) in 4 sections each readout by a low dark count PMT - with a hermetic VETO counter system & LED calibration*
- *The detector is ~100 m from IP8 in the UA83 tunnel, the centre of the detector makes a ~7 deg. angle with the beam-line.*
  - *The overburden is comprised of 110m of sedimentary rock*
  - *On average there is ~45 m of rock/concrete between IP8 & MAPP-1*

MAPP Installation in UA83

Electronics rack

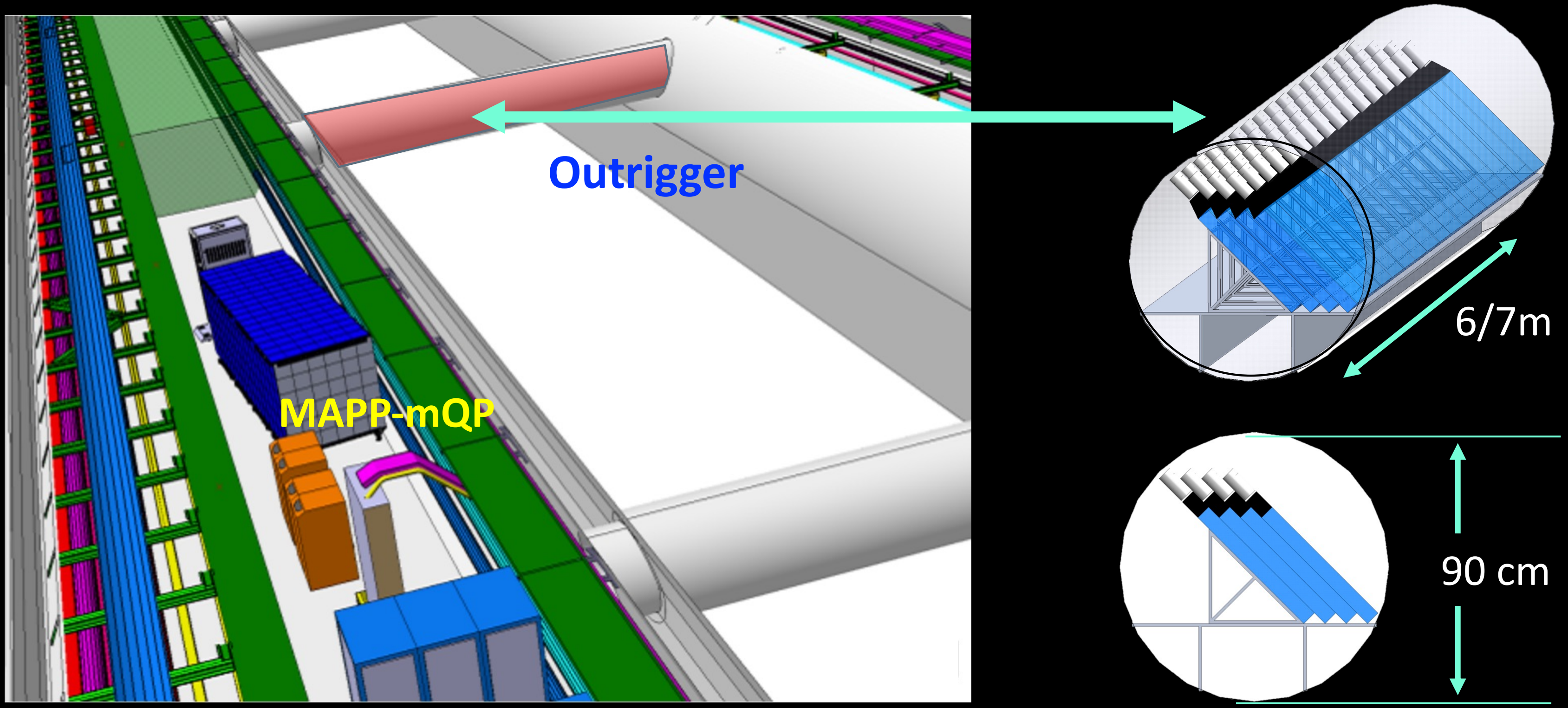
MAPP-1 with flame shield



One sector of MAPP-1

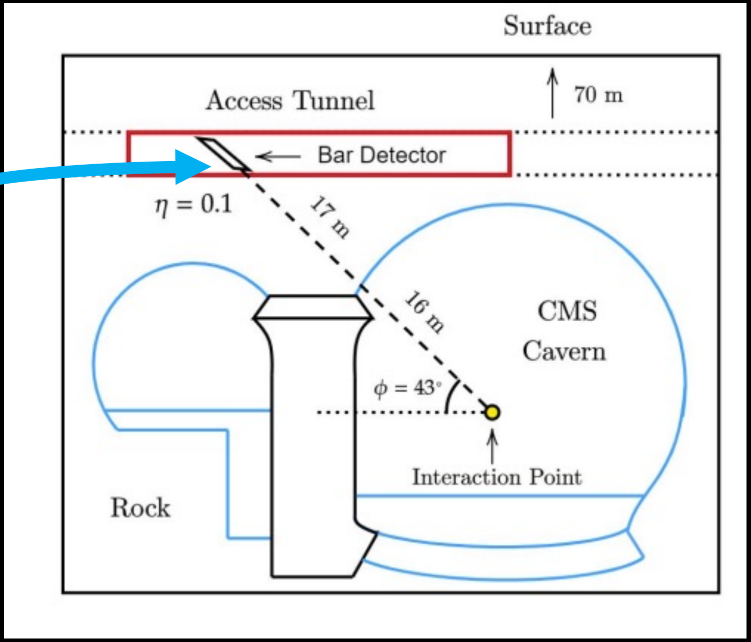
- *This detector is currently being installed in the UA83 tunnel parallel to the the LHC beam tunnel – data taking to start in the spring of 2024.*

The MAPP Outrigger Detector Upgrade



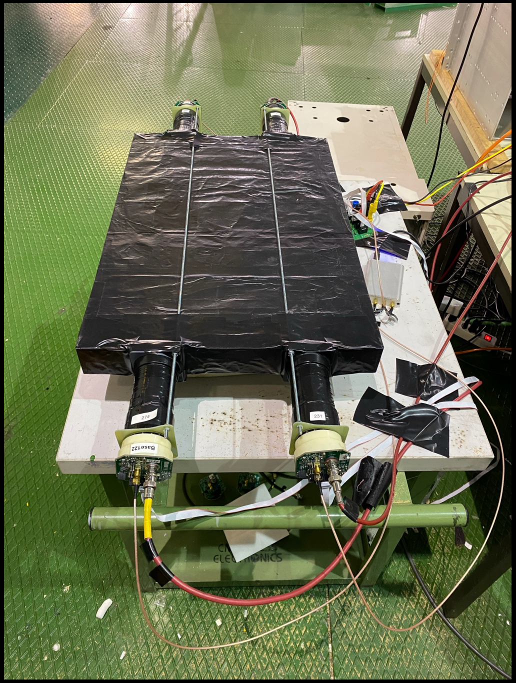
- *The outrigger detector for the MAPP-mQP is designed to improve its sensitivity at larger masses and millicharged.*
  - *Phase-1 (for 2024) - The basic unit of the outrigger is a 60 cm x 30 cm x 5 cm plate readout by a PMT on a light guide. These basic units are combined in 4 layer, 6/7m long, ~80 detector array that fill the ducts joining UA83 and the beam-line tunnel*
  - *Phase-2 (for 2025) – The Outrigger detector will be doubled in size using two additional ducts*

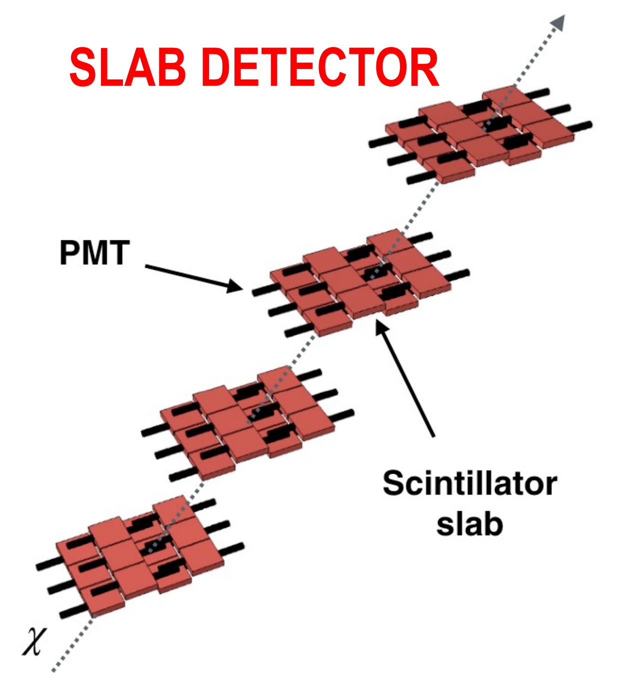
milliQan LHC Run-3 Bar Detector

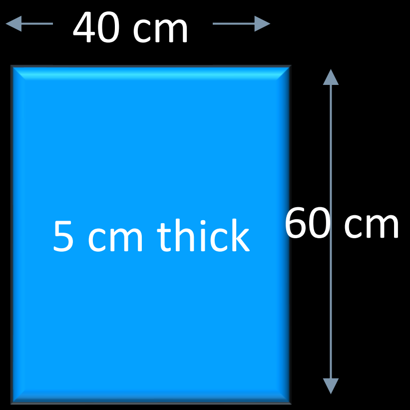


- *4 sections of 4 x 4 plastic scintillator bars (5 x 5 x 60 cm^3) with veto*
  - *Trigger formed from a 4-fold coincidence of low noise PMTs*
- *milliQan is situated 70m underground, 31 m from CMS IP, with 17m rock shield from the IP*
  - *LED system for calibration and monitoring*
- *Actively taking data to commission and calibrate the detector, expect physics data taking in the coming weeks*

milliQan LHC Run-3 Slab Detector



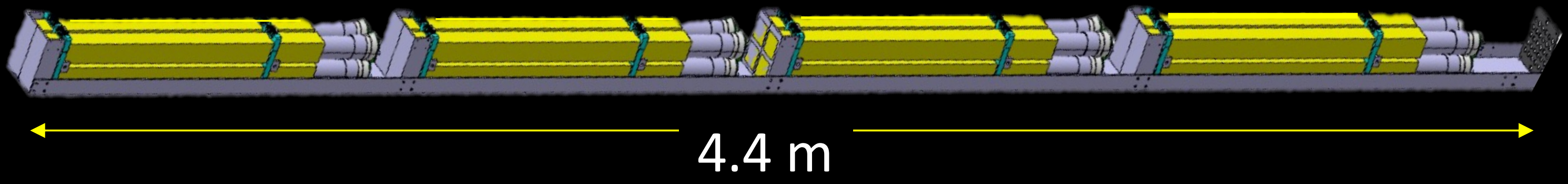




Slab detector element

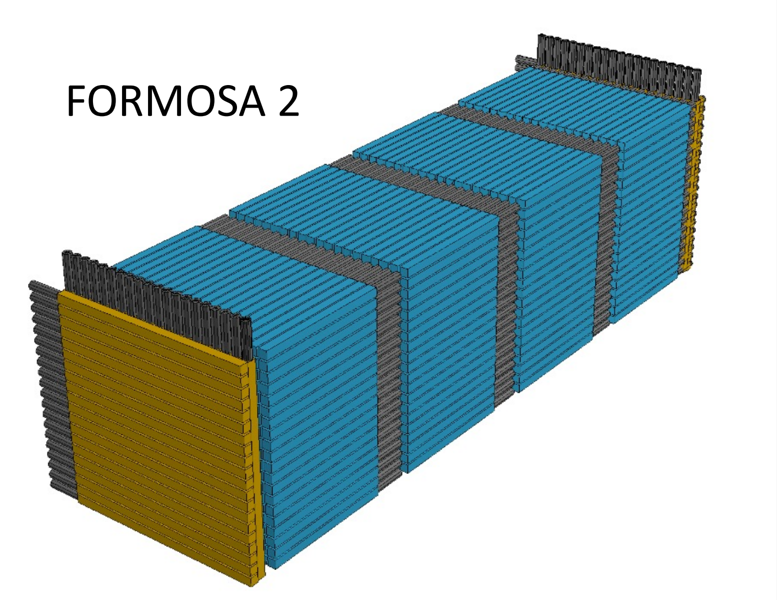
- *4 layers of slabs, thinner scintillator with larger active area*
- *Improve sensitivity for milli-charged particle with large mass (>~1GeV)*
- *Each layer has 3✕4 slabs*
- *Each slab has 4 PMTs attached to increase light collection efficiency*
- *Same PMT amplification and LED calibration system as bar detector*

FORMOSA Demonstrator – Run 3

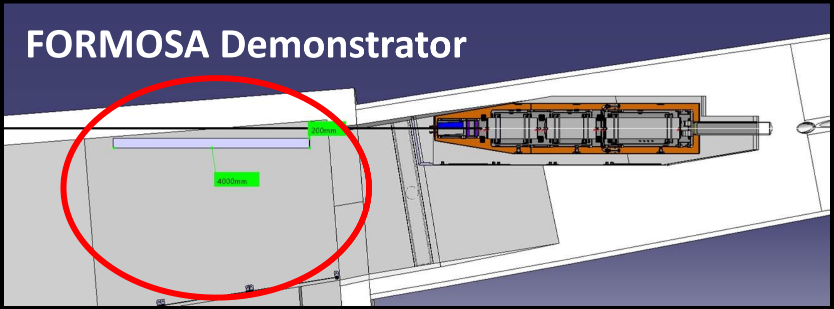


- *Four layers of 2x2 bars (each bar 5 cm x 5cm x 60 cm) attached to PMTs. Panels at the front and back for muon veto*
- *PMTs from a line of four bars placed in coincidence*

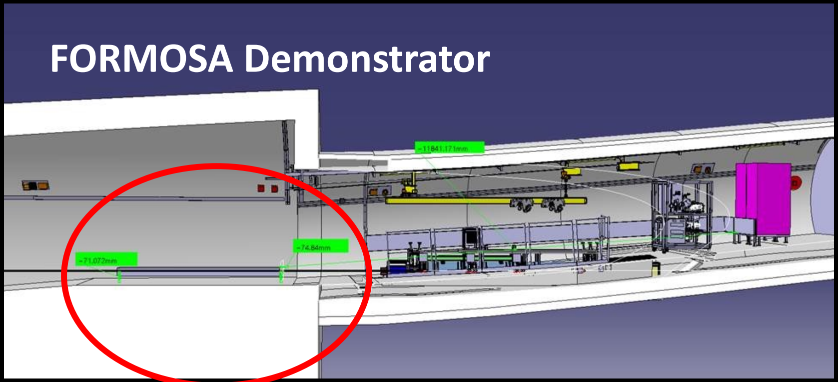
- *FORMOSA-2*
- *Much larger detector planned for HL-LHC*
- *Four sections of 20 x 20 bars each bar 5cm x 5cm x 60 cm^3*
- *Deployed along side FASER-2 at the Forward Physics Facility*



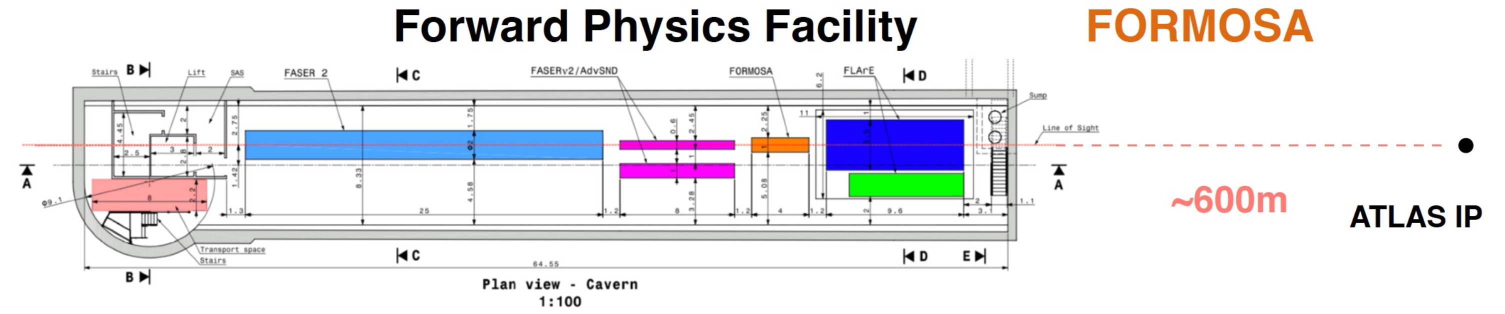
FORMOSA Demonstrator Location



FORMOSA Demonstrator



FORMOSA Demonstrator



FORMOSA planned position at HL-LHC

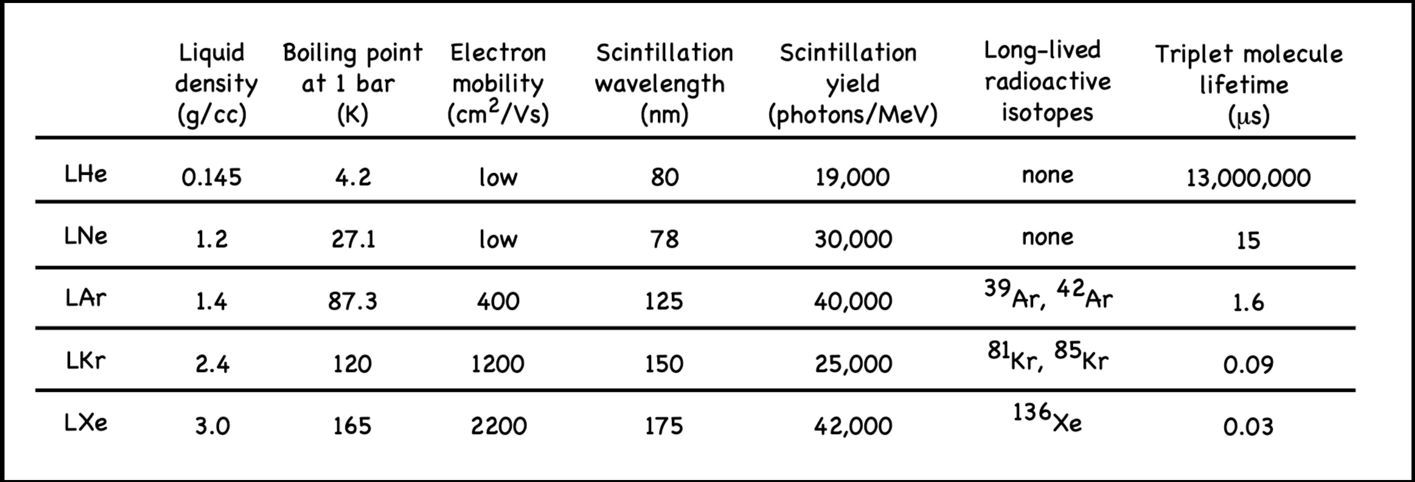
A Summary of Detector Properties

Experiment (IP)	Scintillator bars (size in cms)	Sections (sens. area/ length)	PMTs	Dist. from IP (angle to beam.)	Over-Burden/ Rock From IP	Auxiliary Detector? (slabs size cm/ #slabs)
MAPP (LHCb)	**400 x (10 x 10 x 75)**	**4 ($1m^2/4.4m$)**	**400**	**100m (7 deg.)**	**110 m/ ~45 m**	**Outrigger (30 x 60/160)**
milliQan (CMS)	**64 x (5 x 5 x 60)**	**4 ($0.04m^2/4.4m$)**	**64**	**31m (43 deg.)**	**70m/ 17m**	**Slab detector (40 x 60/48)**
FORMOSA Demo.	**16 x (5 x 5 x 60)**	**4 ($0.01m^2/4.4m$)**	**16**	**400m (0 deg.)**	**88m/ 100m**	**No Auxiliary detector**

- *The three detectors cover three different regions of pseudorapidity in a complementary way.*
- *All are planning to run at Run-3 and HL-LHC*

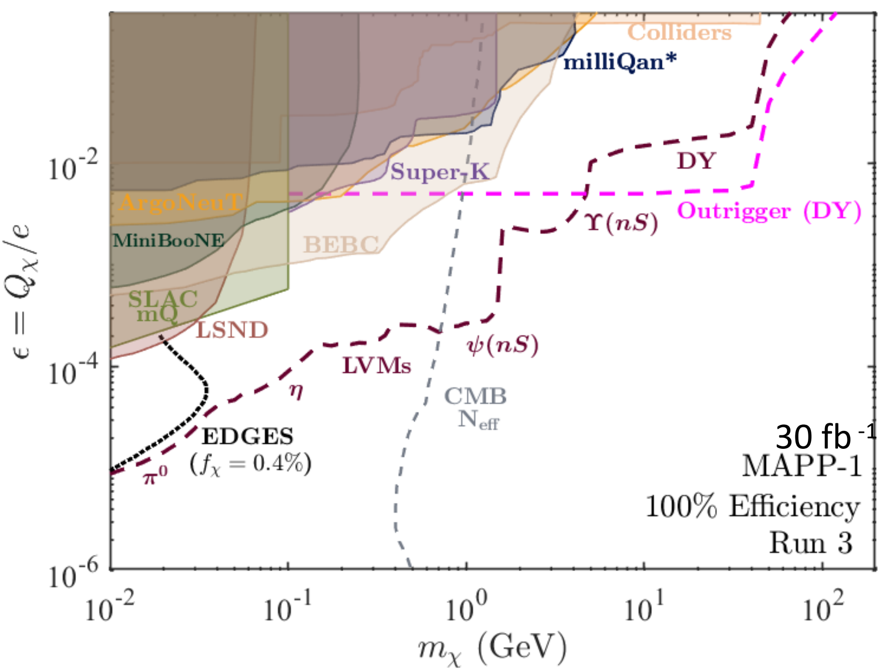
Increasing Experimental Sensitivity?

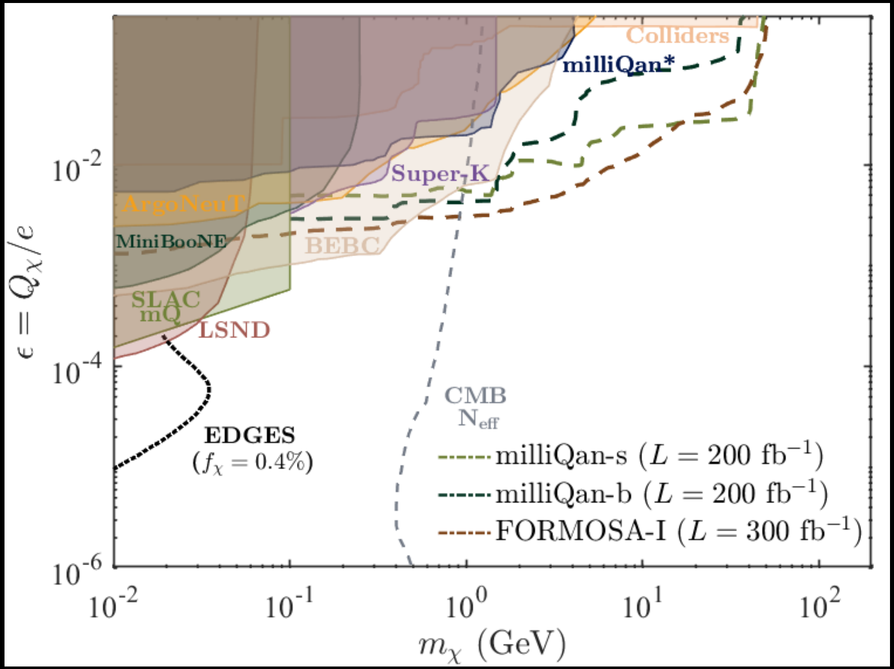
- *The sensitivity limit of existing experiments at the LHC is ~10^{-3}e set by the light output of regular plastic scintillator (BC408) of ~10K photons/MeV*
- *We could improve sensitivity by using use higher light output scintillators:*
    - *LANTHANUM BROMIDE [$LaBr_3$(Ce)]: light output 30K ph/MeV, decay time 20ns. CONS: it has internal activity, currently available in size up to 3" dia. X 3" lng*
    - *SCINTCLEAR^{TM} (SrI_2(Eu)): light output 90K ph/MeV, emission matches SiPM sens. CONS: long decay time ~3μs, currently available in size up to 2.5" dia. X 4" lng.*
- *Liquid noble gases also have high scintillation light output than plastic, but WLS needed to match sensitivity of currently available PMTs*



	Liquid density (g/cc)	Boiling point at 1 bar (K)	Electron mobility (cm^2/Vs)	Scintillation wavelength (nm)	Scintillation yield (photons/MeV)	Long-lived radioactive isotopes	Triplet molecule lifetime (μs)
LHe	0.145	4.2	low	80	19,000	none	13,000,000
LNe	1.2	27.1	low	78	30,000	none	15
LAr	1.4	87.3	400	125	40,000	^{39}Ar, ^{42}Ar	1.6
LKr	2.4	120	1200	150	25,000	^{81}Kr, ^{85}Kr	0.09
LXe	3.0	165	2200	175	42,000	^{136}Xe	0.03

Physics Reach at Run-3



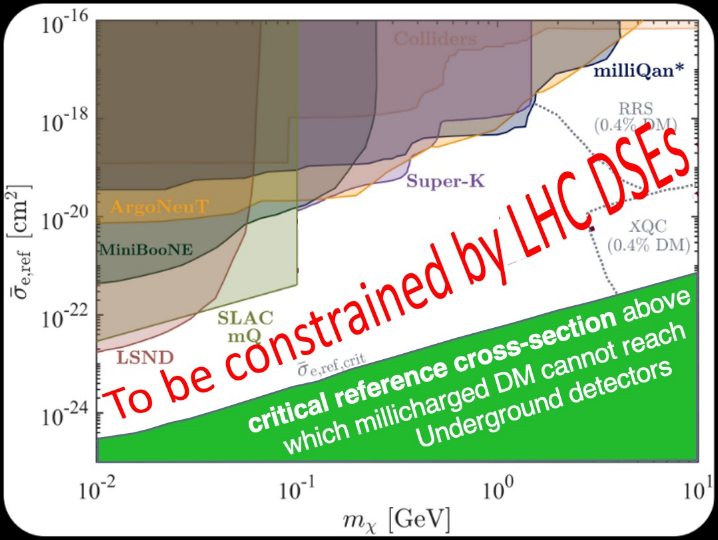


- *(LEFT) The fiducial sensitivity of the MAPP-1 detector and Outrigger assuming 100% detector efficiency*
  - *Estimates with MAPP-1 detector efficiency estimates incorporated, due out in arXiv in a month or two.*
- *(RIGHT) The sensitivity of the milliQan-s, milliQan-b and FORMOSA-1 (demonstrator) with detector efficiency estimates incorporated*

Plots provided by Michael Staelens

mCPs - an Answer to the EDGES Anomaly?

95% C.L. for mCPs projected onto the mC-SIDM scenario, assuming 0.4% of the DM to be mCPs



To be constrained by LHC DSEs

critical reference cross-section above which millicharged DM cannot reach Underground detectors

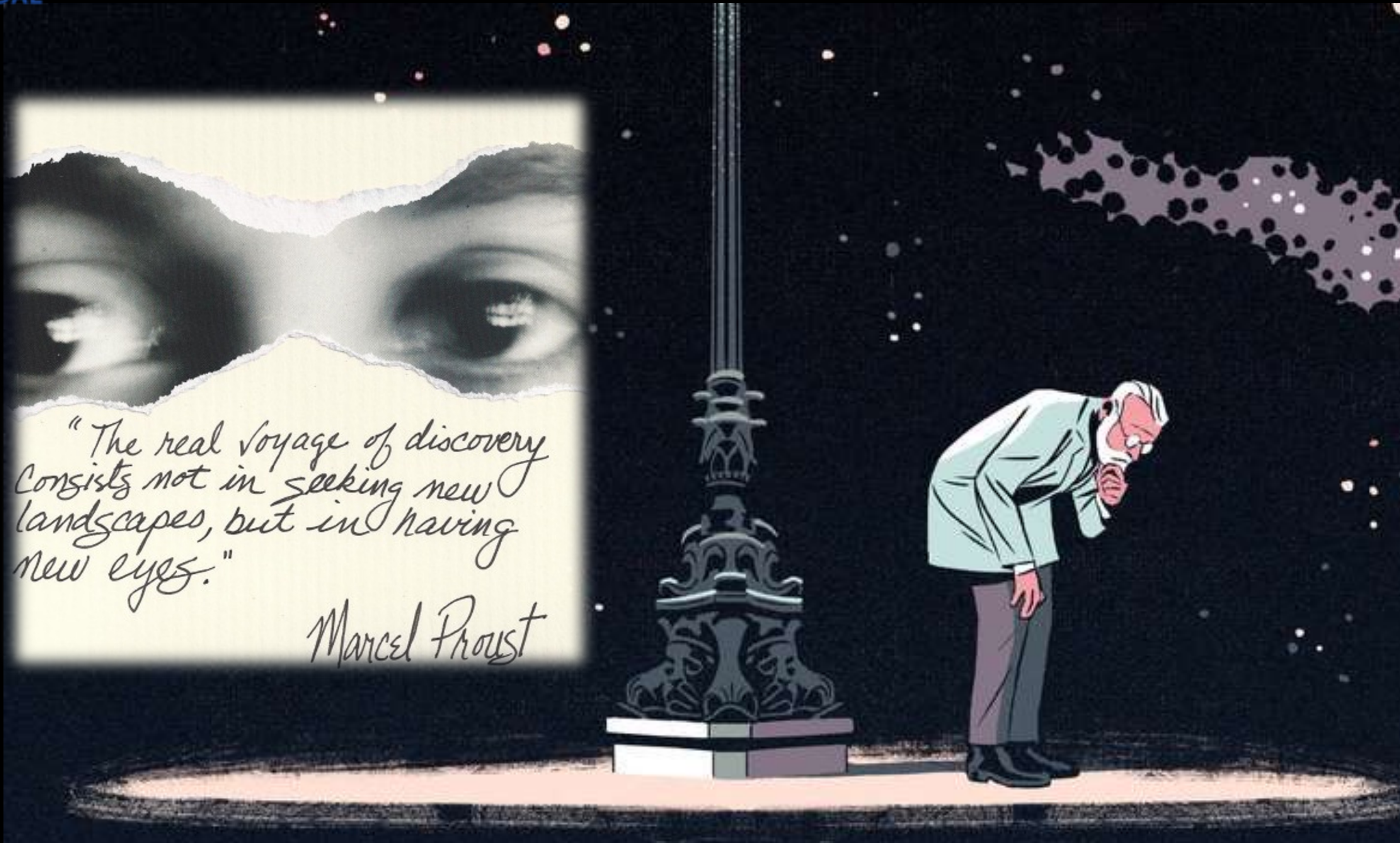
Minicharged Strongly-Interacting DM (mC-SIDM)

Phys. Rev. D **104**, 035014 (2021); *Phys. Rev. D* **102**, 115032 (2020); *JCAP* **2018(10)**, 007 (2018); *JCAP* **2019(09)**, 070 (2019)

(**EDGES**) is a radio telescope - the Murchison Radio-astronomy Observatory - in Western Australia.

- *In 2018, the EDGES Expt. reported the detection of an anomaly in the 21-cm H absorption spectrum indicating more absorption than expected. For this, either cooling of the H gas or radiative heating of the CMB is necessary.*
  - *A resolution of the anomaly involves introducing a small mini-charged component of DM, feebly interacting with H gas thru Coulomb interactions, leading to its cooling*
  - *One group (PRD 98 103529, 2018) suggested that 0.4% fraction of DM composed of mCPs would be sufficient to solve the problem as well as being cosmologically allowed*

Concluding Remarks



"The real voyage of discovery consists not in seeking new landscapes, but in having new eyes."

Marcel Proust

With dedicated detectors as our new eyes we hope to reveal physics beyond the SM illumination at the LHC and the FCC