FORMOSA: Millicharged Particles in the LHC Forward Region

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Driving Questions

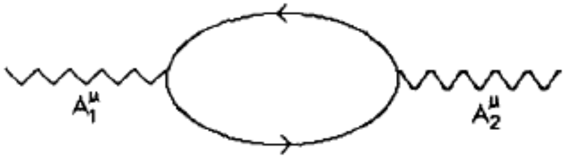
1) Why do we care about millicharged particles?

2) How can we search for millicharged particles?

3) What's the sensitivity for a detector in the forward region?

Why do we care about millicharged particles?

(millicharged particle = mCP)



[Source: B. Holdom 1986]

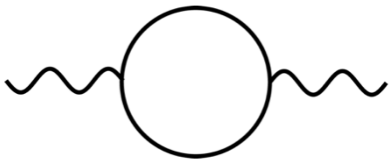
Dark EM as a portal into the dark sector

(also massless)

Standard model

(What we know)

A



A'

SM

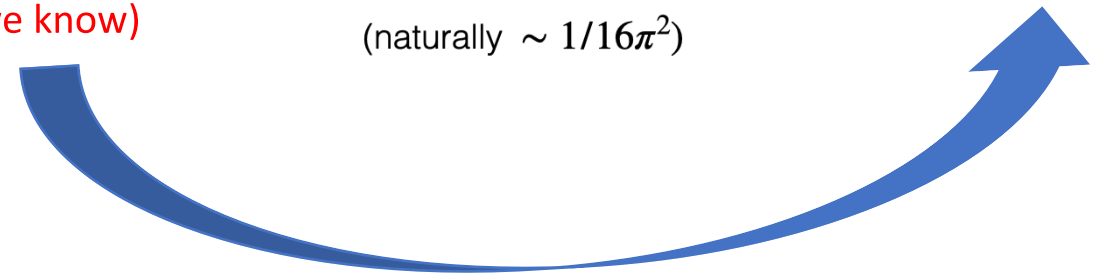
$\kappa \sim 10^{-3} - 10^{-2}$

(naturally $\sim 1/16\pi^2$)

dark sector

Dark sector

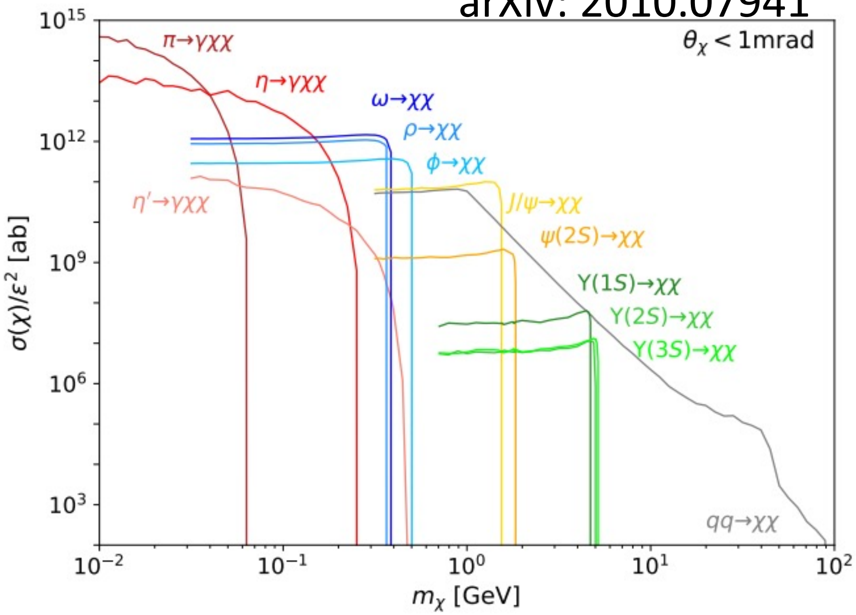
(What may solve SM anomalies)

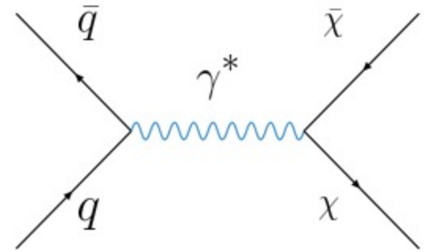


This mixing provides a portal to the dark sector

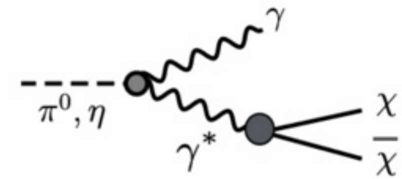
Production of millicharged candidates

arXiv: 2010.07941

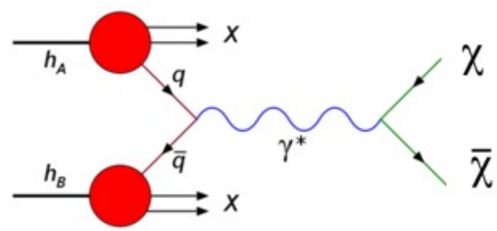




Meson decays



Dalitz decays



Drell-Yan

For more on meson production in the LHC forward region: arXiv:1811.12522v3

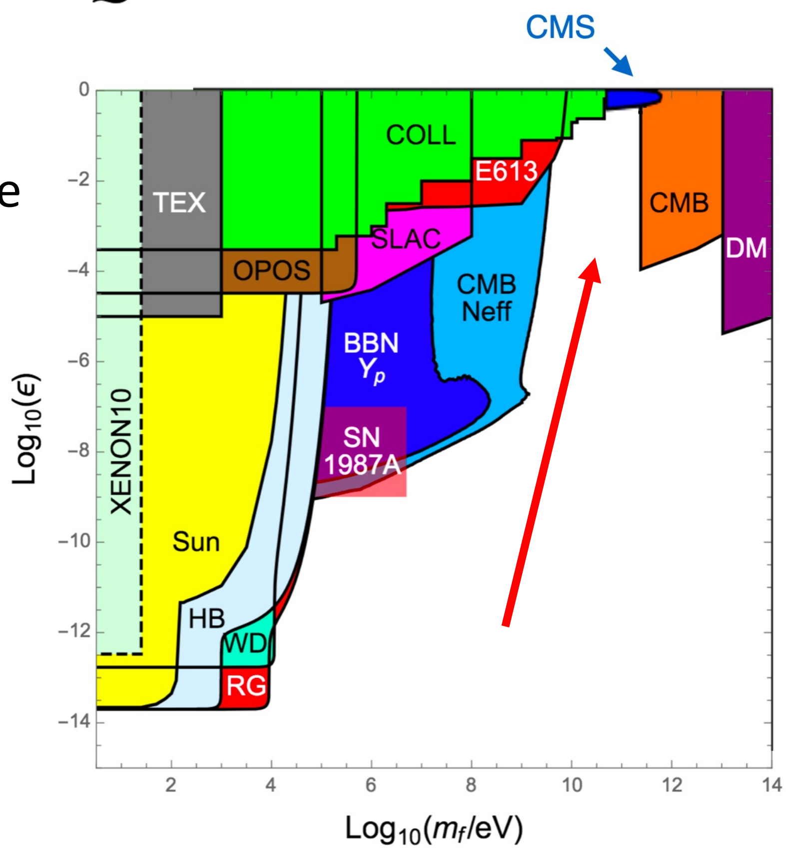
Processes are model independent!
Depend only on the mass and charge of the mCP

Current phase space need

- There are many ways to search for mCPs
- There's a gap in the sensitivity ~1GeV
  - mCPs could be produced copiously at the LHC in this region
  - General purpose detectors don't have the sensitivity for ϵ<1/3
    - dE/dx goes as Q^2
    - E.g. CMS
- **We need dedicated detectors!**
- This is where FORMOSA and MilliQan come in!

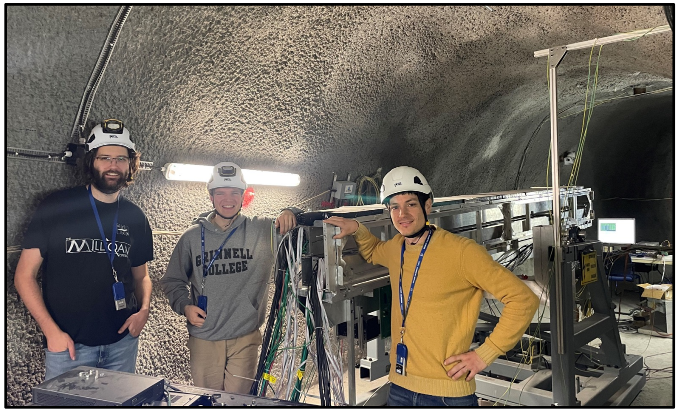
$Q = \epsilon e$

arXiv:1511.01122



How can we search for millicharged particles?

The MilliQan detector, a starting point!

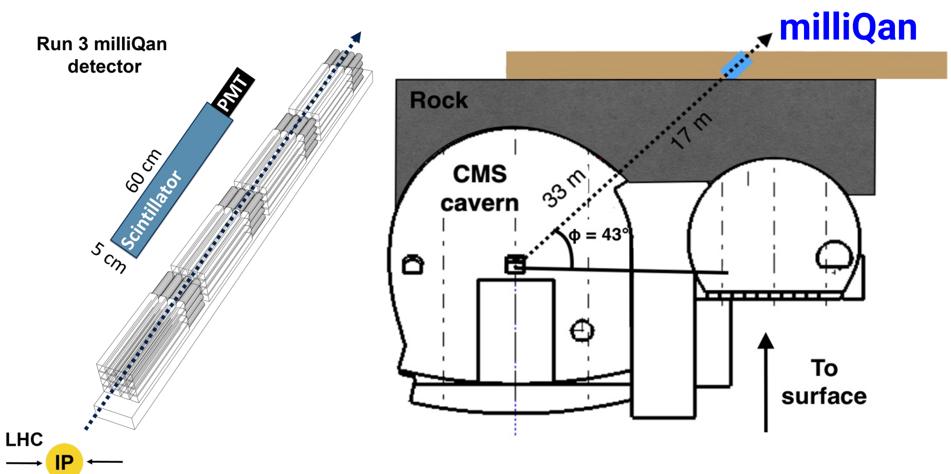


Located in the central region

- Separated with 17m of rock
- Angled downward towards the CMS interaction point

Currently operational!

- Has been taking stable data for physics and commissioning this LHC run



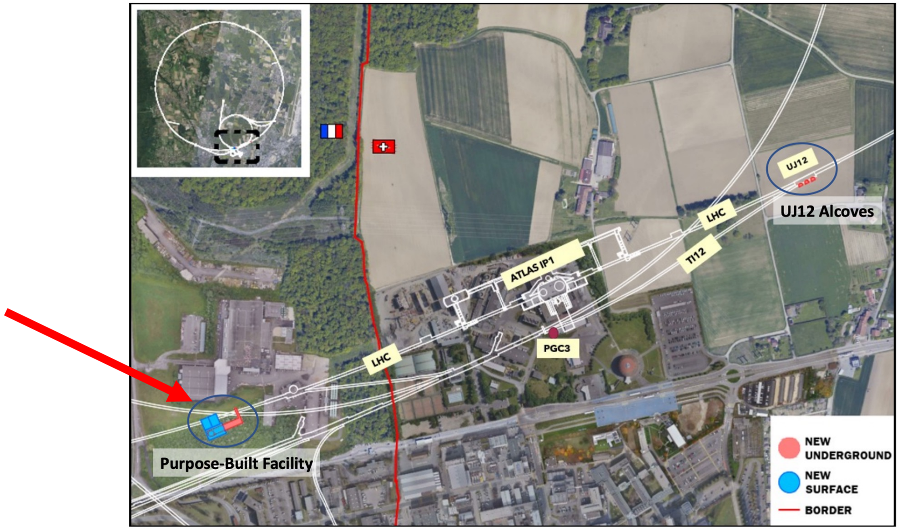
Signal of only a few photons per layer

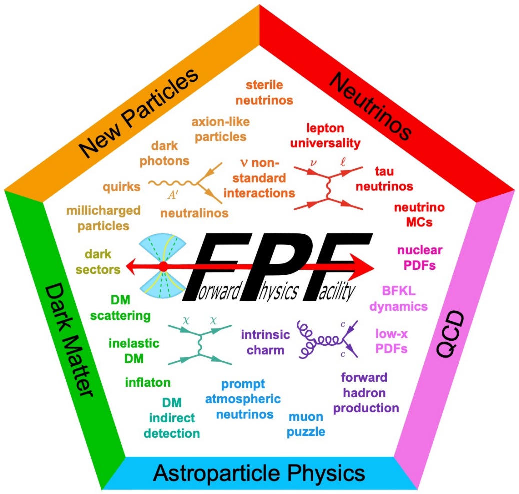
- Need sensitivity in low-energy region
  - Long scintillator bars help provide that!

A hit in all 4 layers indicates a potential candidate!

- Eliminates the uncorrelated background events
- E.g. dark rate → spontaneous thermal emission of an electron from the photocathode
- Such backgrounds would otherwise dominate our signal

Moving forward





Forward Physics Facility is proposed to provide comprehensive coverage of the forward BSM and SM phenomena at the LHC

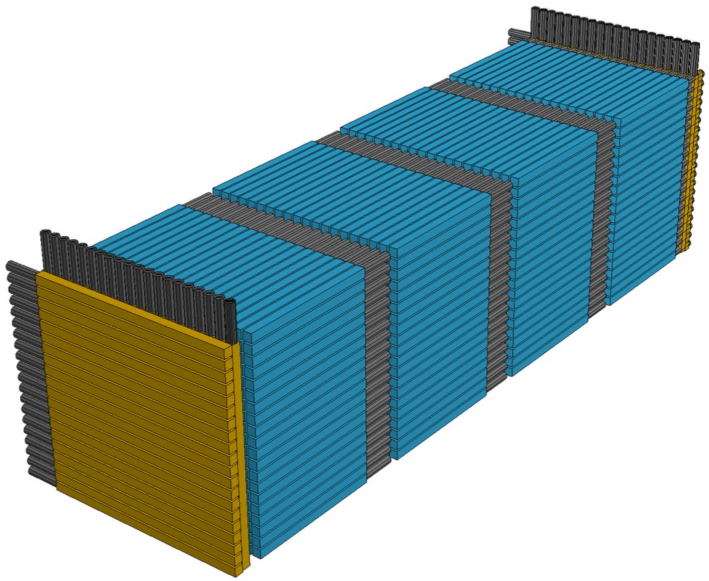
- 600m from ATLAS interaction point
- Ideal location for forward mCP detector, FORMOSA
- Greater mCP sensitivity in the forward region
  - ~250x higher mCP production cross section

Building out of MilliQan…FORMOSA

10x10x4 array of Eljen EJ-200 plastic scintillator bars

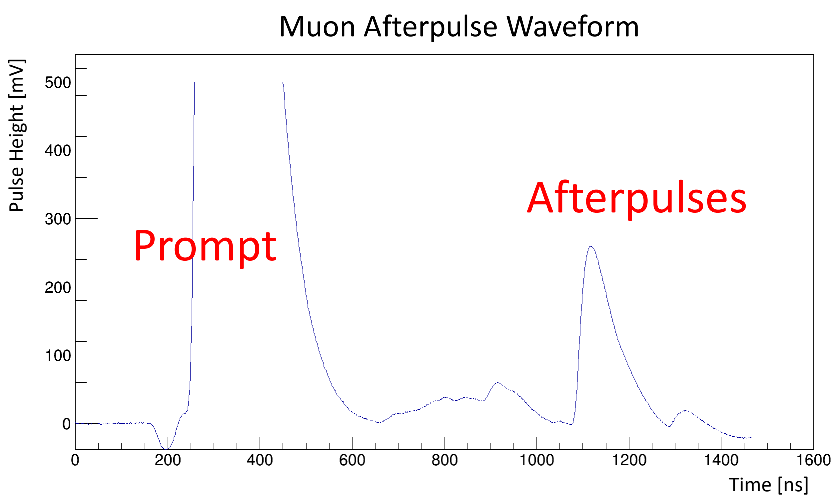
- Bars mounted to Hamamatsu R7725 PMTs
- Segmented beam-muon panels on the front and back

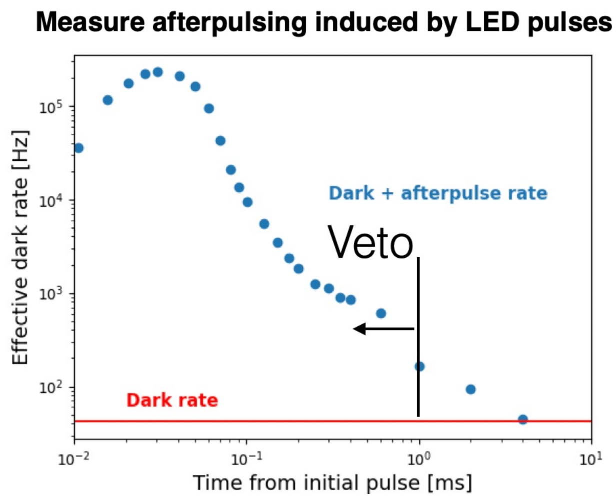
- Similarly for quadruple coincidence for signal
  - A hit in each layer
- Can incorporate high-performance scintillator
  - CeBr3 has a factor of ~30 higher photon yield/cm
  - Allows for lower charge sensitivity



FORMOSA Detector

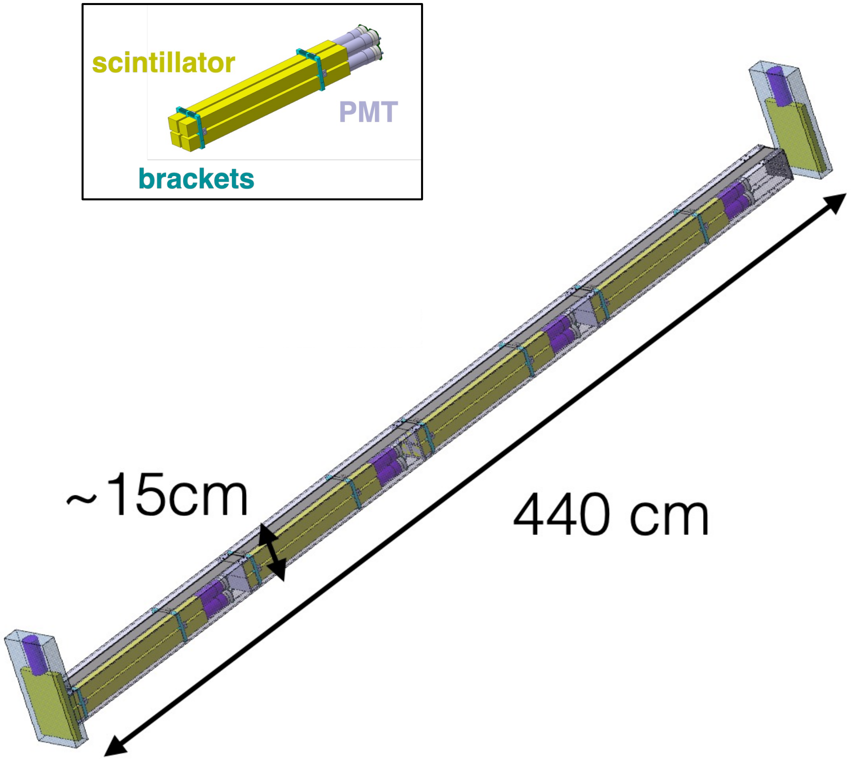
Challenge of being in the forward region





- Through-going beam muons deposit much energy in the scintillators.
  - Causes "afterpulsing"
  - I.e. ionization of the gas in the PMT → ions drift towards dynodes
  - This is our primary background
- Can veto these by cutting on time relative to initial pulse
- **We will study this with the FORMOSA demonstrator!**

FORMOSA Demonstrator in FASER cavern



FORMOSA Demonstrator

2x2x4 array of Eljen EJ-200 plastic scintillator bars

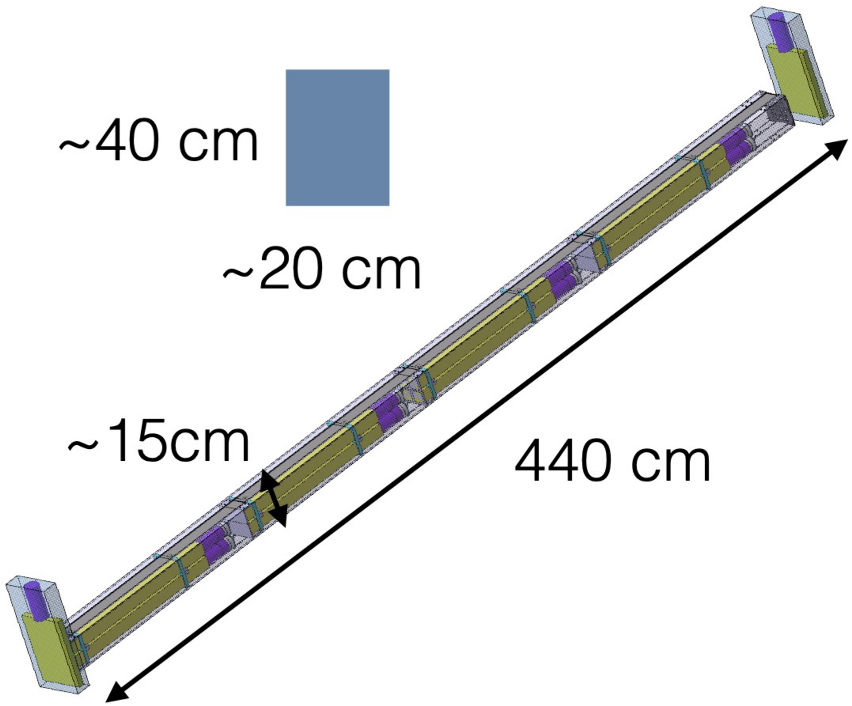
- Mounted to Hamamatsu R7725 PMTs
- Scintillator panels on front and back to identify beam muons

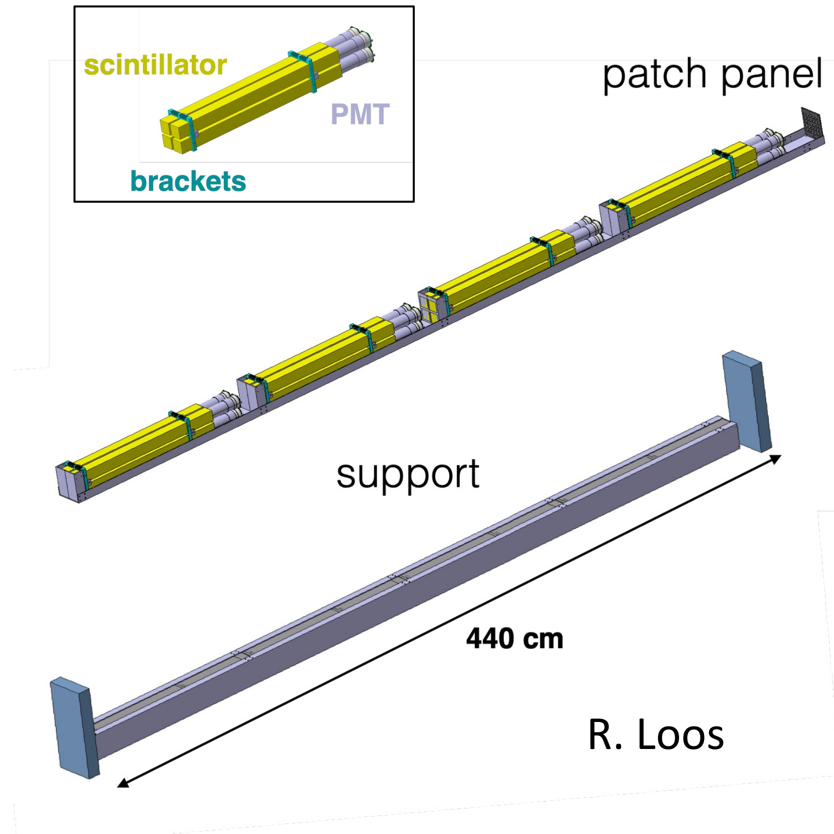
To be proof of concept

- Better understand backgrounds: beam muons, cosmic muons, dark rate, etc.
- Determine feasibility of searching for millicharged particles in forward region
- Determine if any design changes need to be made

- Currently under construction and will be installed early 2024

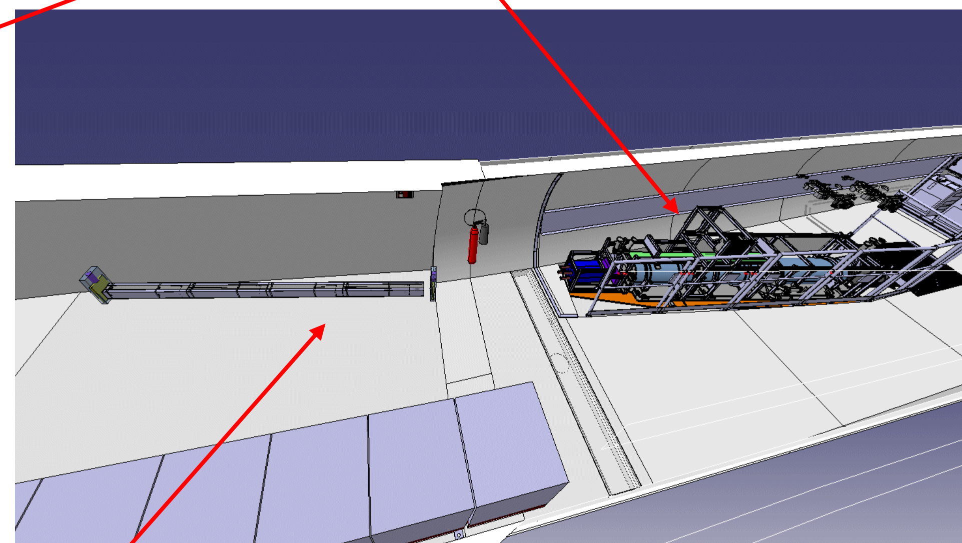
The structural design





To be deployed in the FASER cavern

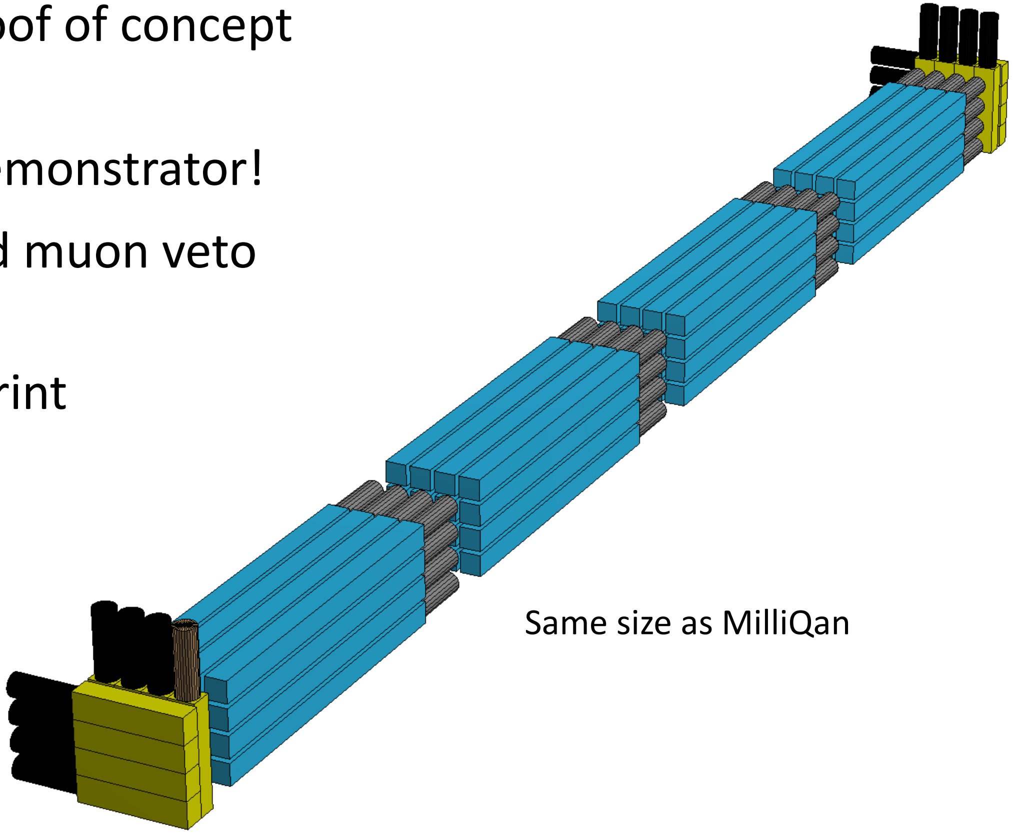
FASER



Demonstrator

An extension of the demonstrator…

- Can be implemented after proof of concept is established
- Makes search feasible with demonstrator!
- Can study having a segmented muon veto panel
- Only a small increase in footprint



Same size as MilliQan

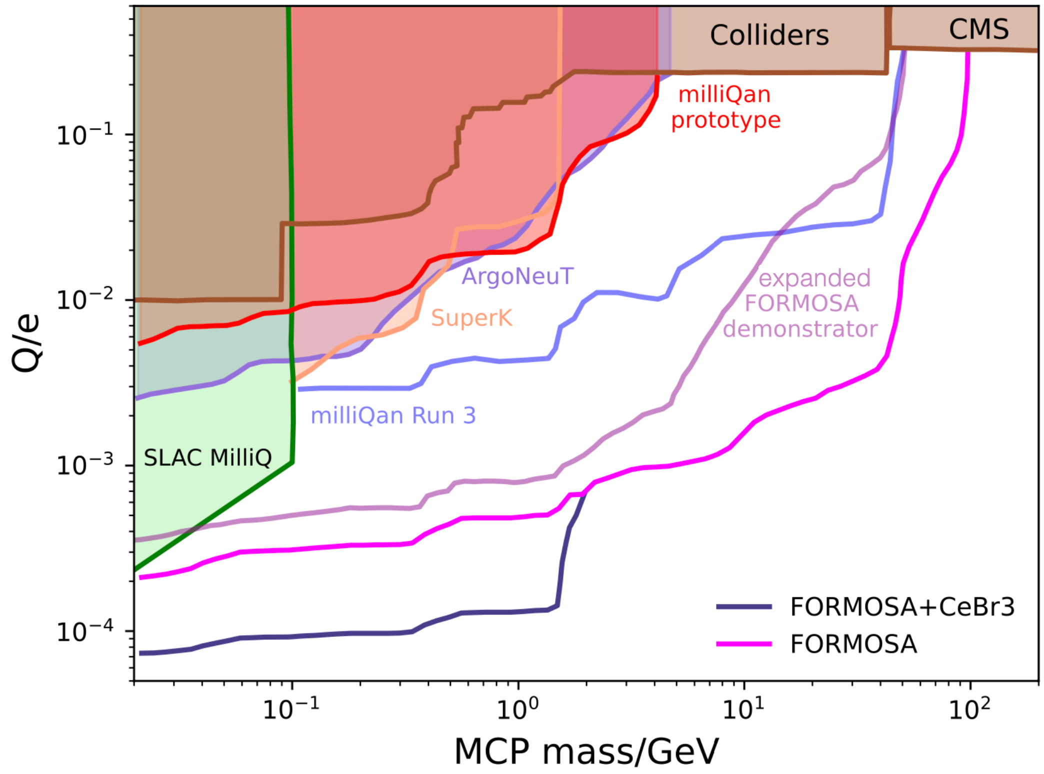
Current status

- We have all the scintillator bars and PMTs necessary for construction of the demonstrator
- Wrapping of scintillator bars underway
- Currently assessing the dark rate of the new PMTs and performing source calibrations
- FORMOSA has many potential opportunities along the whole process
  - Construction, analysis, testing, triggers, hardware, etc.

For undergrads too!

What’s the sensitivity for a detector in the forward region?

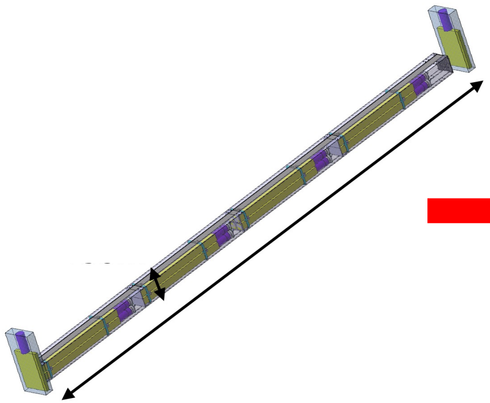
The advantage of being in the forward region!

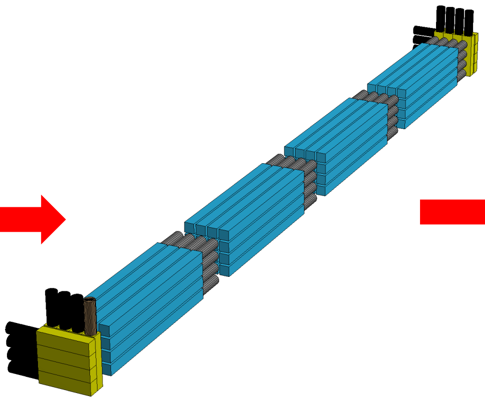


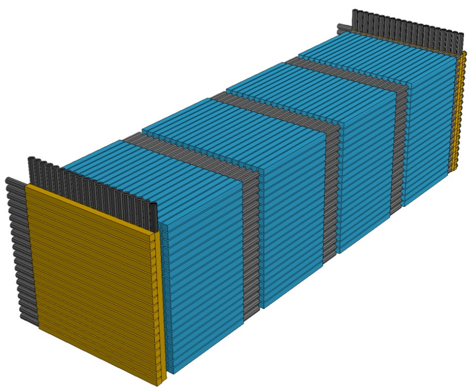
Charge range: ~(10^{-4} to 0.1)e   Mass range: ~(0.01-100)GeV

Progress Summary

- Timeline
  - Construction of demonstrator is ongoing!
  - Beginning of 2024: Demonstrator installation
  - End of 2024-Early 2025: Expanded demonstrator
  - 2028-2032: Full FORMOSA
- Phenomenology paper to be published within two months







Thank you!

This speaker is supported with funding from the Department of Energy.

Backup

Lagrangians/Gauge Transformation

- Add details about the gauge transformation that gets the Lagrangian we care about.

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} - \frac{\kappa}{2}A'_{\mu\nu}A^{\mu\nu}$$

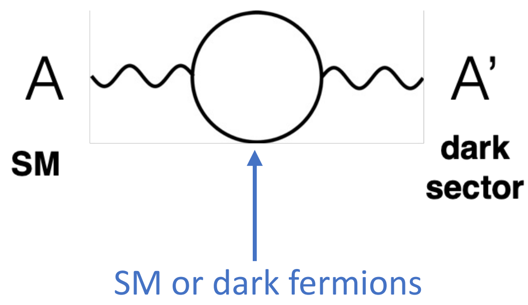
$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} - \frac{\kappa}{2}A'_{\mu\nu}A^{\mu\nu} + i\bar{\psi}(\not{\partial} + ie'A' + iM_{mCP})\psi$$

$$A' \to A' - \kappa A$$

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\psi}(\not{\partial} + i\kappa e'A + ie'A' + iM_{mCP})\psi$$

Theoretical Motivation

- Propose another electromagnetism in the dark sector
  - Suppose it's governed by a U(1) group, call it U'(1)
  - U(1) will have the standard charge (e)
  - **U'(1) will have some other fundamental charge (e')**
  - Fermions in this theory could have ±e, ± e', both, or neither
  - This gives a **coupling between our photon (A) and a new, dark photon (A')** via virtual pairs of fermions with both charges



- The Lagrangian:

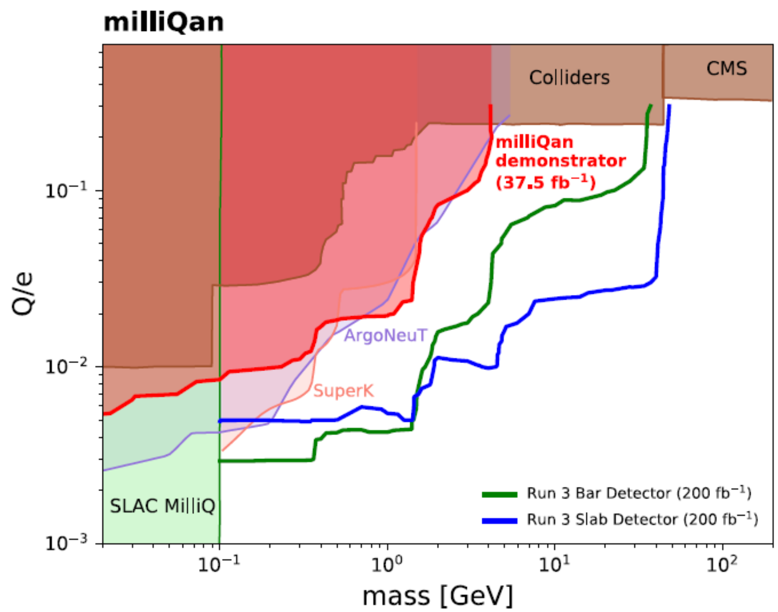
$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\psi}(\not{\partial} + i\kappa e' A + ie' A' + iM_{mCP})\psi$$

Millicharged coupling to the photon

Millicharged coupling to the **dark** photon

[Source: B. Holdom 1986]

The Sensitivity of MilliQan Detectors



Charge range: ~(0.001-0.1)e

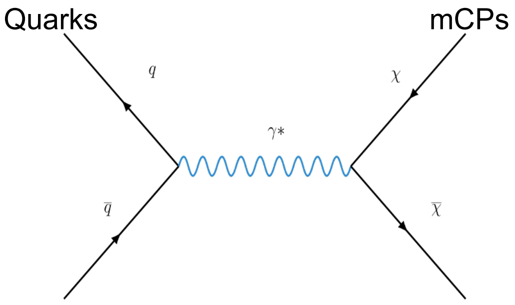
Mass range: ~(0.1-100)GeV

Bar Detector sensitive to a larger charge range.

Slab Detector sensitive to a larger mass range.

By what processes can we detect these?

- Standard electromagnetic interactions!
- Millicharged particles couple electromagnetically to the standard model photon
  - Charge of κe
  - κ should be in the range of 0.1 – 0.001 otherwise current colliders would have found something (e.g. 0.5e)
  - https://cds.cern.ch/record/2841994/files/EXO-19-006-pas.pdf
- Thus, we can use standard charged-particle techniques!
- $\frac{dE}{dx} \sim Q^2$ for millicharged candidates with a mass greater than 100MeV
  - Ionization is the primary energy loss mechanism
  - Given by the Bethe-Bloch equation



[Source: A. Haas et al. 2015]

CeBr3 Scintillator Added