Looking Forward to Millicharged Dark Sectors at the LHC

Based on arXiv:2010.07941 [SF, F. Kling & Y. Tsai]

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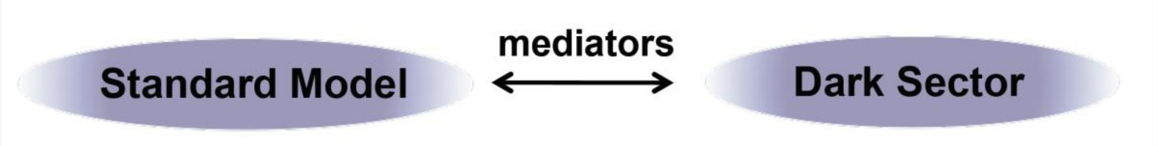
2021 CAP Congress – PPD – Candidates for Dark matter and Dark sector II

OUTLINE

- Motivation for milliCharged Particles (mCPs)
- Dedicated experiments: milliQan to search for MCP
- Other experimental probes: Proton Fixed-Targets / Neutrino Experiments
- FORMOSA: Probing mCPs at the LHC forward physics region
- Millicharged Strongly Interacting Dark Matter

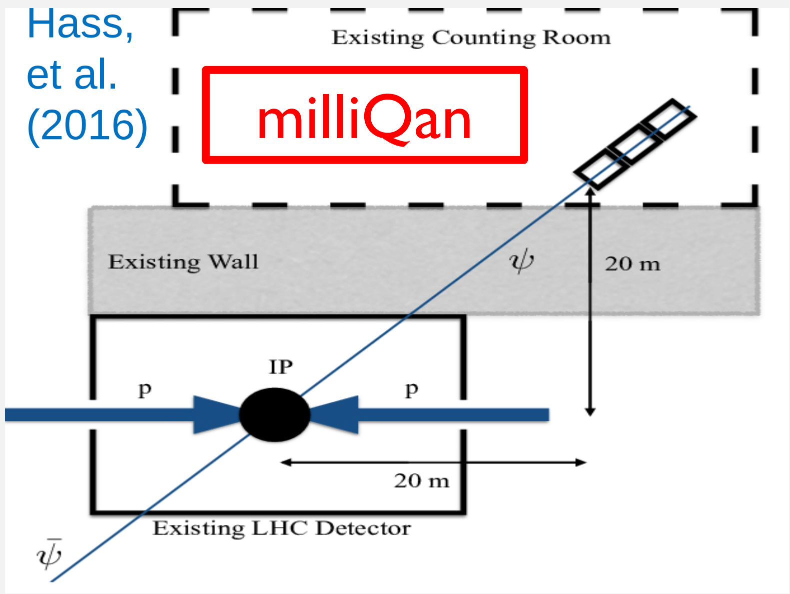
New physics in a dark sector

- Empirical evidence for new physics, e.g. neutrino mass, dark matter, points to a **Dark Sector**
- Particles from a dark sector **weakly interacting** with ordinary matter through a dark mediator are viable dark matter candidates

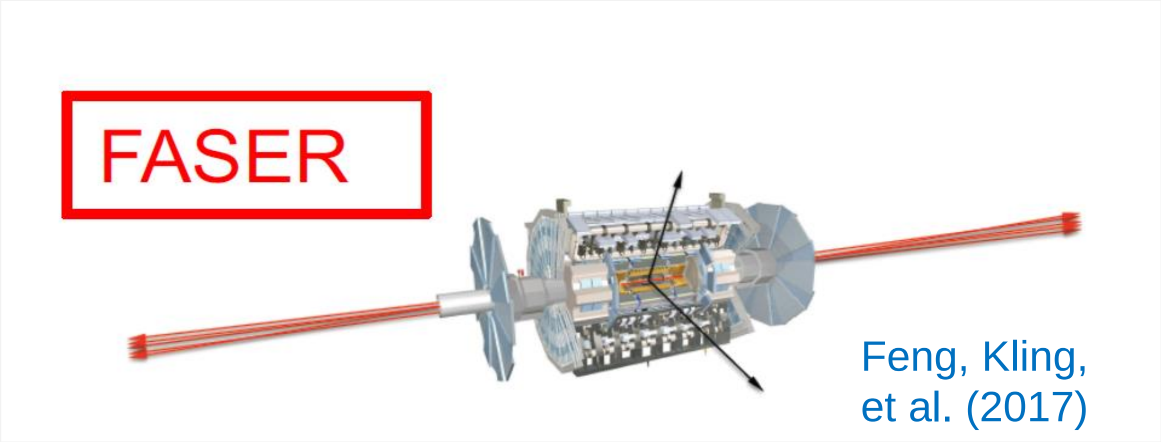


- Examples of proposed experiments @LHC

Searches for millicharged particles



Searches for long lived particles



Fractionally Charged Particles

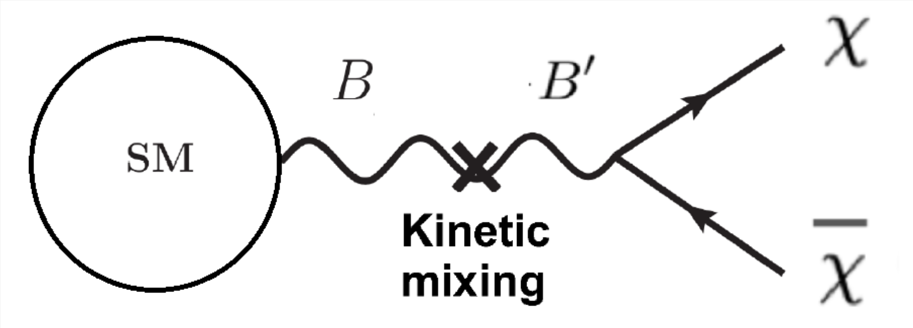
- Fractionally (or irrationally) charged under SM U(1) hypercharge

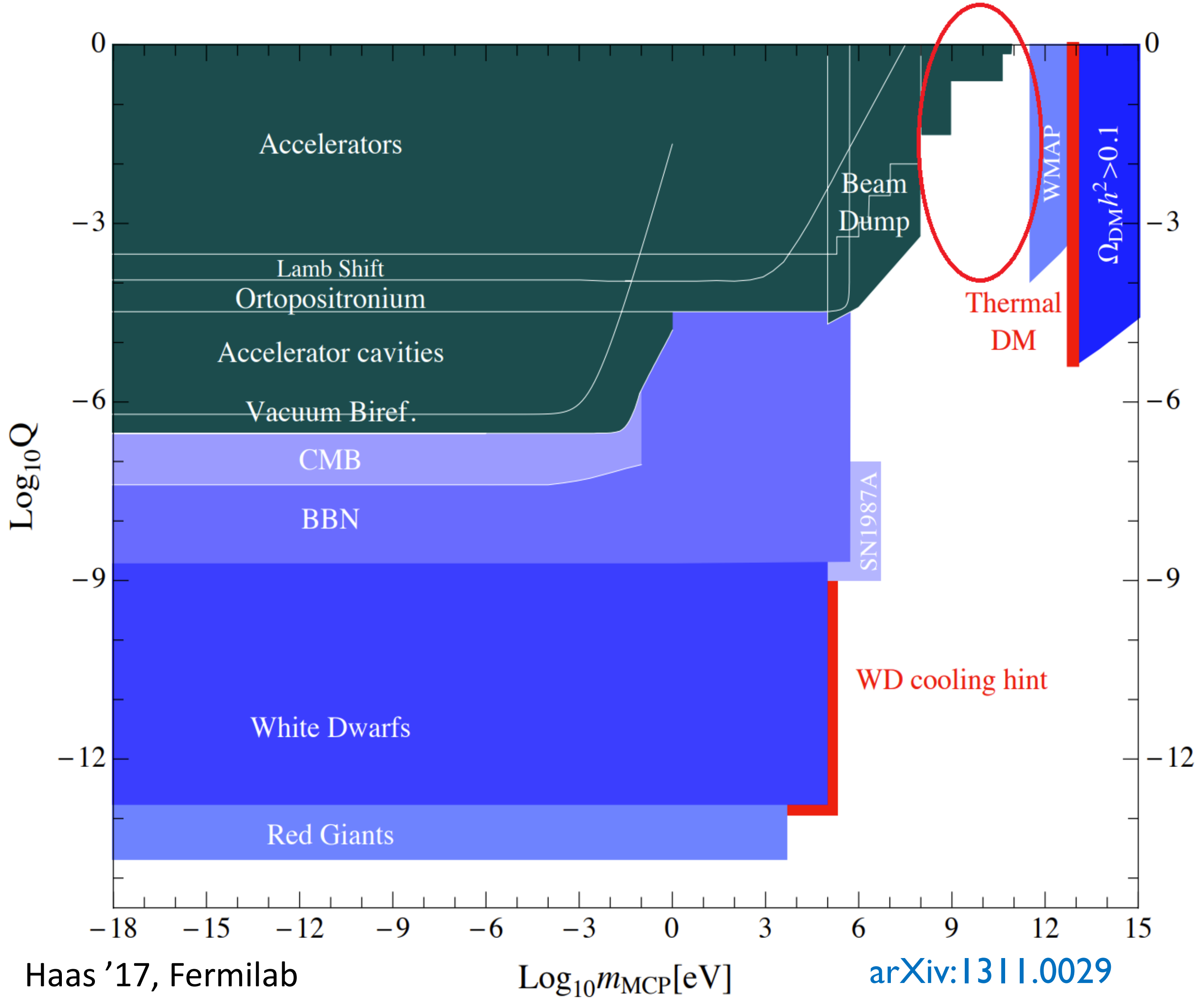
$$\mathcal{L}_{\mathrm{MCP}} = \bar{\chi}(i\not{\partial} - \epsilon' e \not{B} - m_\chi)\chi$$

- Can just consider this Lagrangian terms by themselves (no extra mediator, i.e., dark photon)

- Vector Portal **Kinetic Mixing**: [Holdom, '85]
- Millicharged particle (mCP) can be a **low-energy consequence** of **massless dark photon** (a new $U(1)'$ gauge boson) coupled to **a new fermion** (become MCP)

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} - \frac{1}{4}B'_{\mu\nu}B'^{\mu\nu} - \frac{\kappa}{2}B'_{\mu\nu}B^{\mu\nu} + \bar{\chi}(i\not{\partial} - e'\not{B}' - m_\chi)\chi$$





Haas '17, Fermilab

arXiv:1311.0029

Searches for milli-charged particles

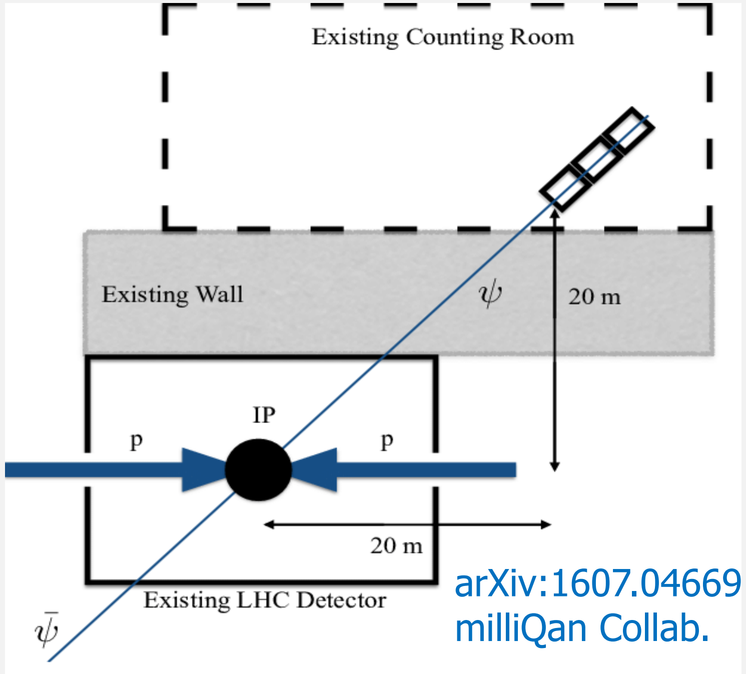
Strong constraints below m_e:

- Astrophysics – Cooling & energy loss bounds from stars, SN, etc.
- Cosmology: Bounds from BBN and CMB on N_{eff}

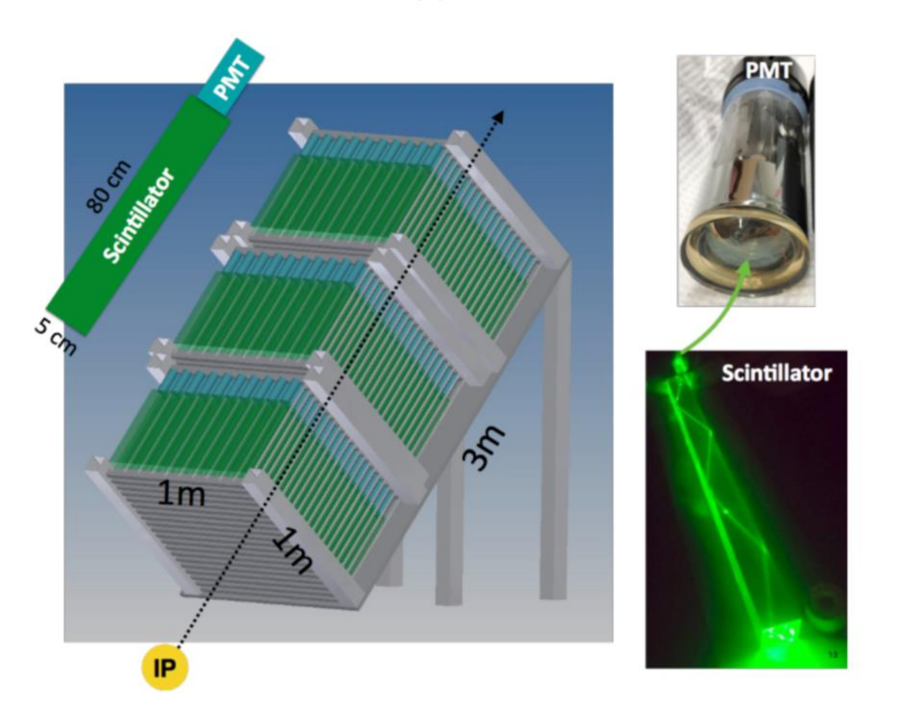
- Accelerators: direct constraints from SLAC mQ, LEP, etc.
- The SM backyard at 0.1 GeV to 100 GeV

Dedicated mCP detector: milliQan @LHC

- Heavier mCP, 0.1 to 100 GeV can be probed at the LHC
- A three-layer scintillator detector at 33 m from CMS IP, at Transverse Region
- Triple Coincidence in small time window ~ 15 ns

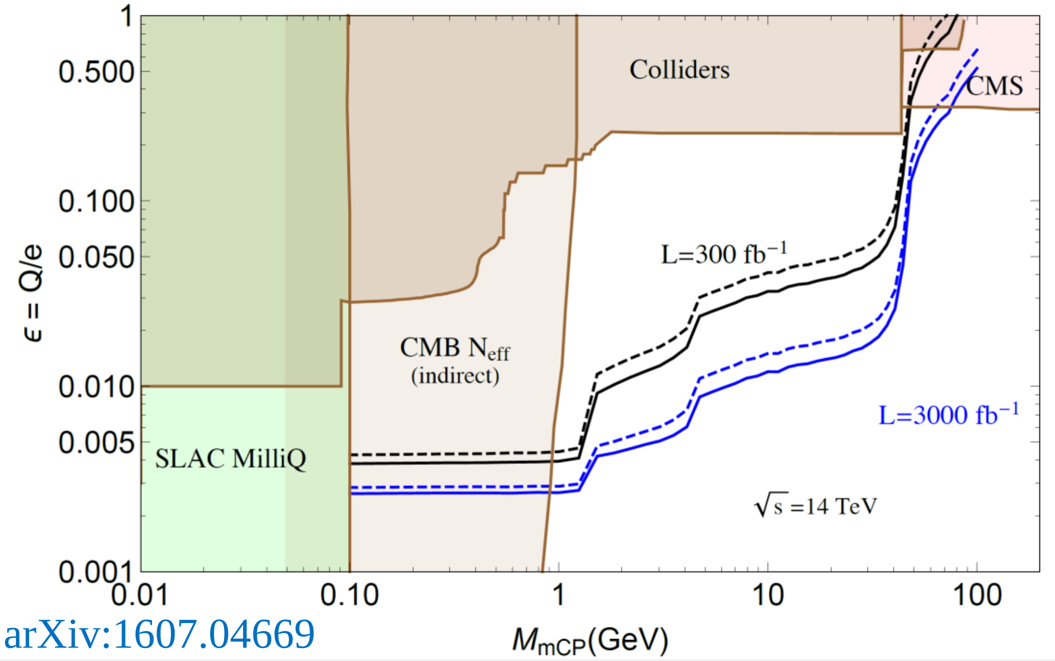


arXiv:1607.04669
milliQan Collab.



Sensitivity to MCPs at Transverse Region

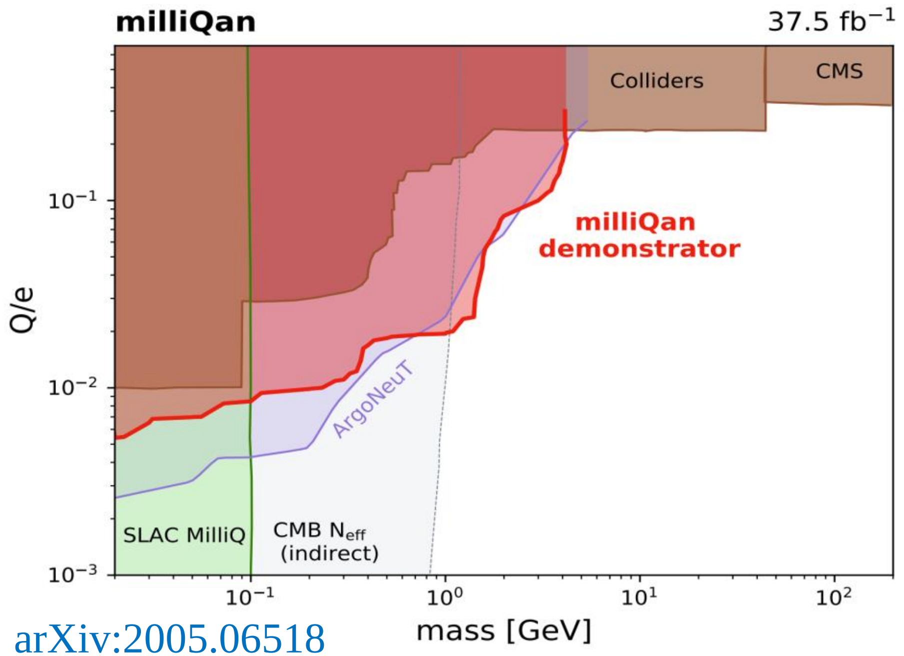
Expected Sensitivity



arXiv:1607.04669

Dominant background:
Cosmic muons & dark current

Proto-milliQan first update!



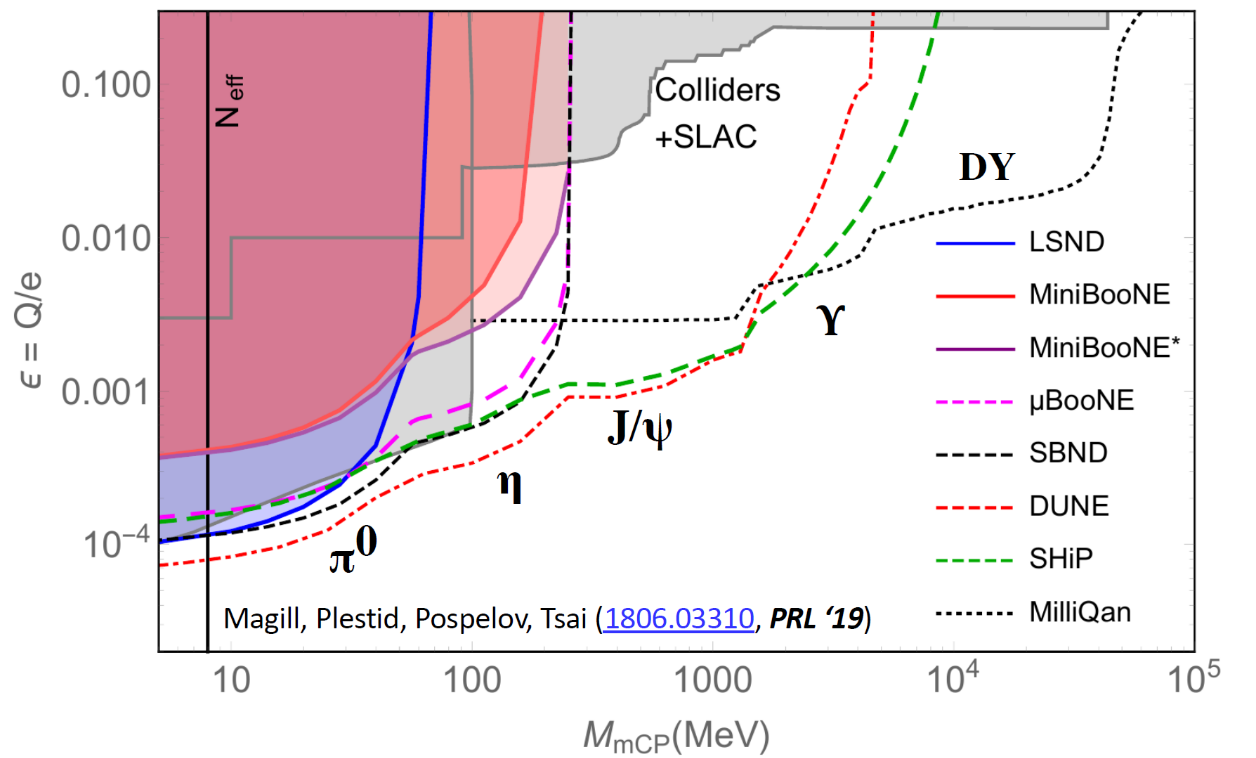
arXiv:2005.06518

Demonstrator ~1% (total of 18 bars) taking data since mid-2017

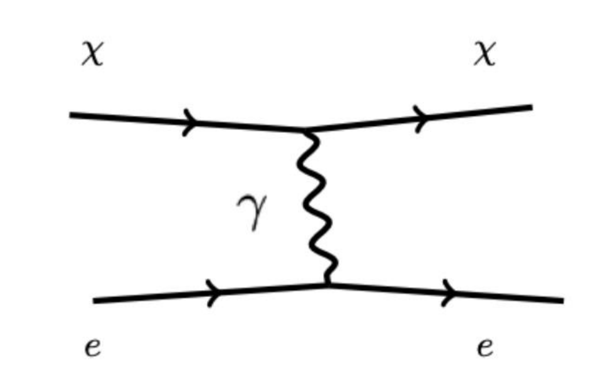
More MilliCharged Particles Hunting

- MCP scattering with electron enjoys **low-momentum transfer**
- Sensitivity greatly enhanced by accurately **measuring low energy**

MCP in neutrino Experiments



Detection: Electron Scattering



Similar topology:
deNiverville, Pospelov, Ritz, '11,
Batell, Pospelov, Ritz, et al. '14

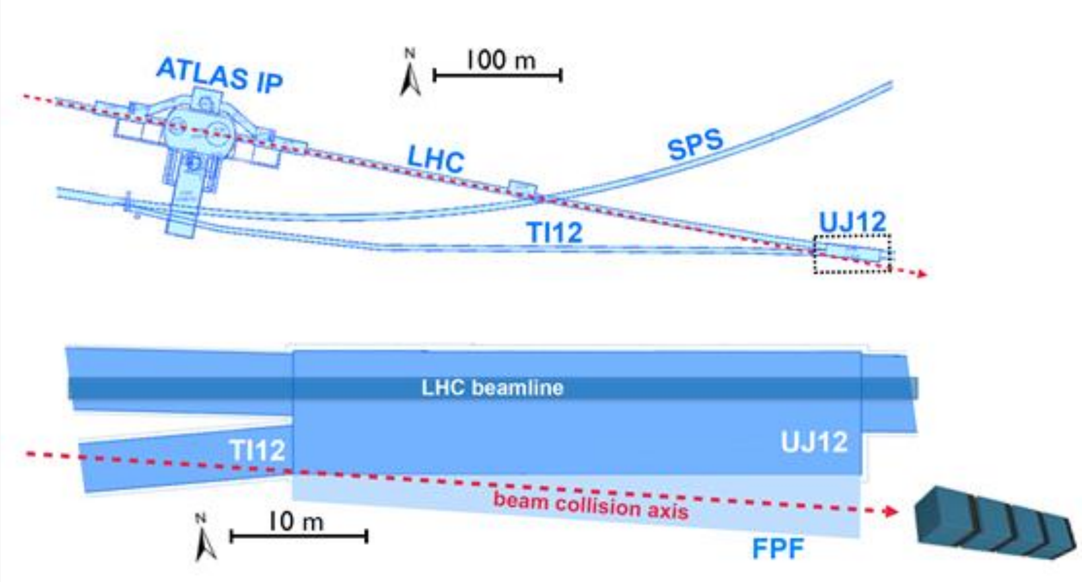
$$\sigma_{e\chi} \propto \frac{\epsilon^2}{E_e^{\min} - m_e}$$

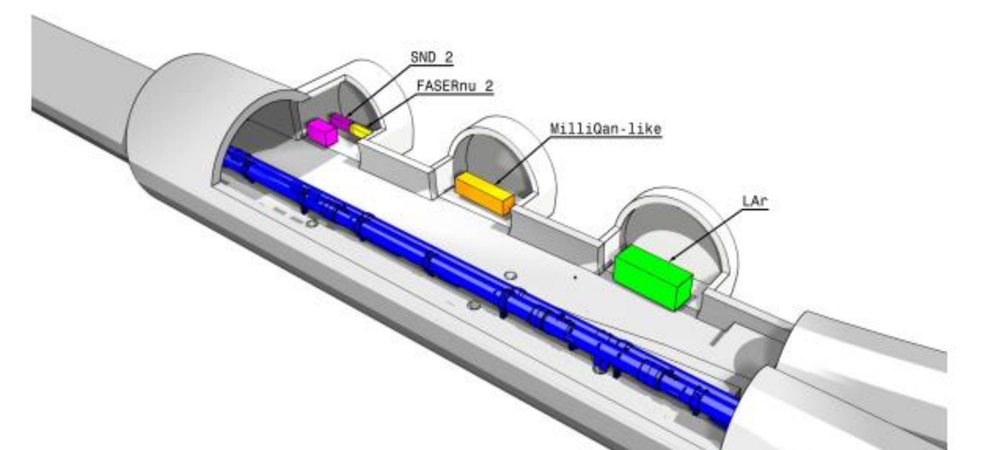
High-Intensity Energy Frontier

- LHC Higgs factory: new physics searches focus on the Central Region (high-pT)

- Instead locate a detector at a few 100 m away along the "collision axis"
  - High flux of light weakly interacting particles at the very Forward Region (along the π, K, D, B decays)
  - A very **energetic beam-dump experiment**!

- Motivates a small and inexpensive detector: **FORMOSA: FOR**ward **M**icr**O**charge **S**e**A**rch



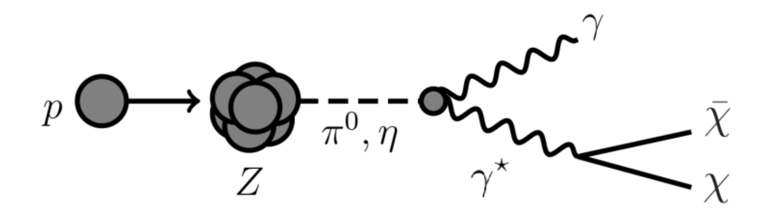


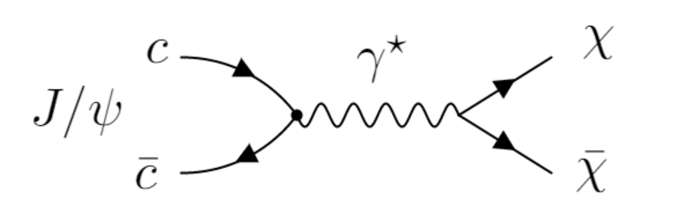
Forward Physics Facility

Existing UJ12 cavern at FPF can house FORMOSA

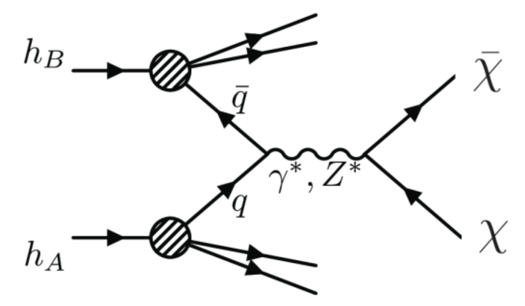
mCP Production Channels

- Light meson decays
- Importance of heavy vector meson at high mass

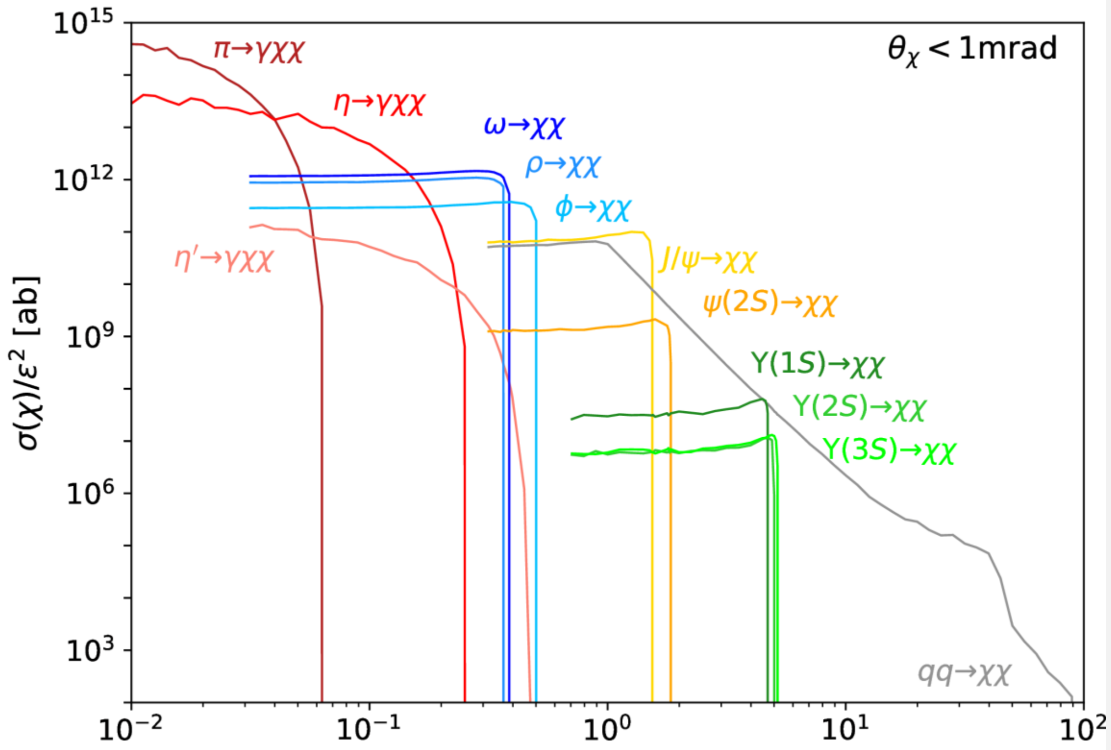




- Drell-Yan



- Enhanced mCP production cross-section compared to the transverse direction



S. F., F. Kling & Y. Tsai '20

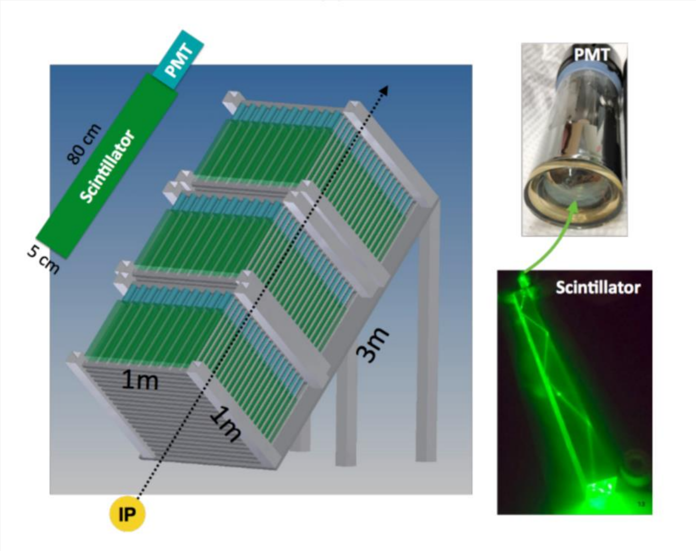
MCP Detection Signature

- Deposition of energy due to ionization

- Average number of photoelectrons (PE):

$$\bar{N}_{\rm PE} \propto L_s \times \langle -\frac{dE}{dx} \rangle \sim \epsilon^2 \times 10^6$$

1 m plastic scintillator bar



- The probability of observing multiple-coincidence of at least one PE in each stack of the scintillator (for reducing the detector background)

$$P_{\rm det.} = (1 - e^{-\bar{N}_{\rm PE}})^n \quad \Longrightarrow$$

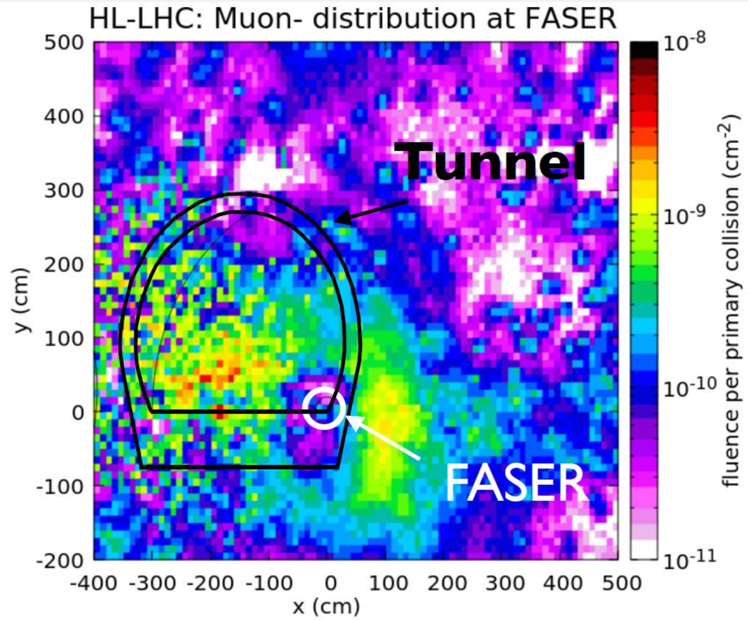
Follows Poisson dist.

Number of signal events $N_\chi \cdot P_{\rm det}$

New Challenge in the Forward Region

Beam related background:

- ❑ **HE muons:** new challenge arises due to large flux of muons (and secondary particles) from the beam collisions
  - FLUKA simulation:
    estimated muon flux ~ one muon every 100 μs



arXiv:1812.09139

❖ Feasible task: implementing an **online-veto of large-PE** events

But this is not the full story …

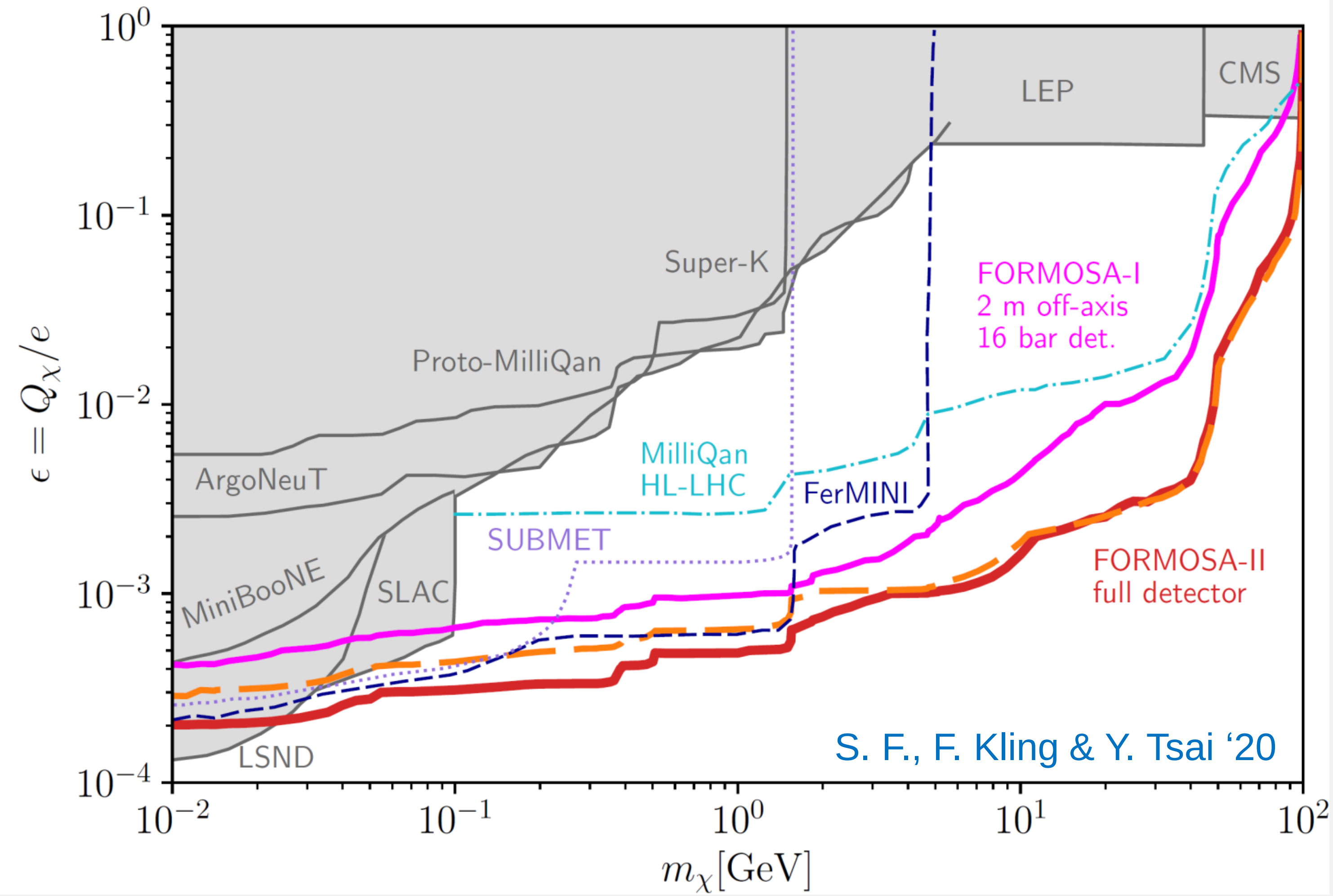
- ❑ **Afterpulses:** small pulses occurring with a delay time of $\delta t \lesssim 10\ \mu s$ after the initial pulse

❖ Remove the afterpulse background by vetoing ~10% of the data

- Better PMTs with reduced afterpulse duration => improve the live-time efficiencies

FORMOSA: Sensitivity

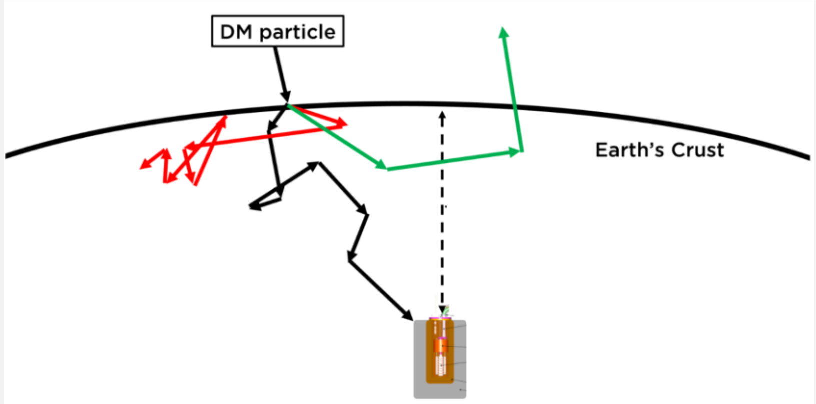
- Two scenarios including placing the detector 2m off-axis.
- Better sensitivity reach in comparison to the full milliQan run.
- More background studies, ideally including in-situ measurements are needed. However, the background can be brought under control.



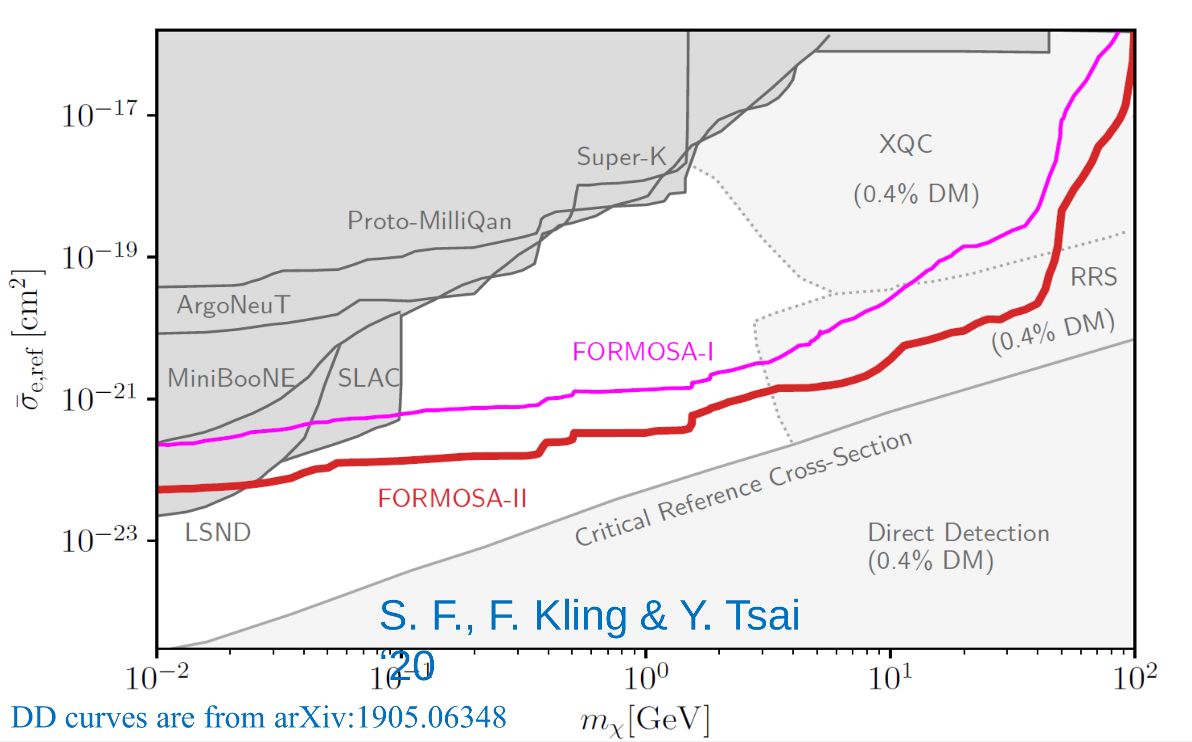
Advantage of enhanced mCP production in the forward direction

Strongly Interacting Dark Matter

- MCPs can account for a fraction of the dark matter (DM) abundance
- If DM-SM interaction is too strong: attenuation of the expected **local dark matter flux** at the underground Direct Detection Experiments
- Loss of sensitivity to DM above some **critical cross section**.



$$\bar{\sigma}_{\mathrm{e,ref}} = \frac{16\pi\alpha^2\epsilon^2\mu_{\chi e}^2}{q_{\mathrm{d,ref}}^4},$$
$$q_{\mathrm{d,ref}} = \alpha m_e$$



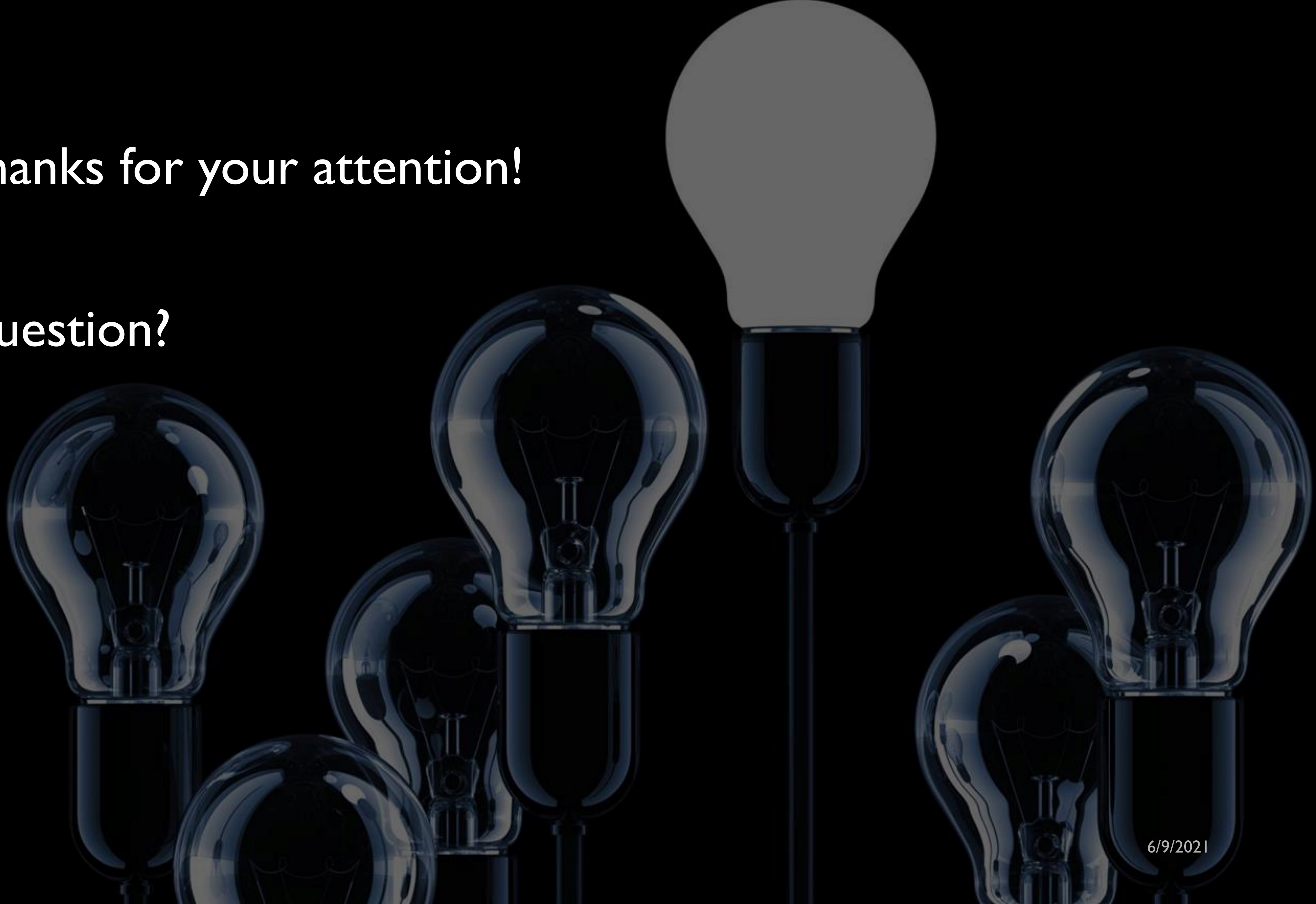
FORMOSA can help cover a large part of the millicharged DM region that is previously unconstrained.

Summary

- Many complementary new experiments at LHC are proposed to search for physics BSM. These experiments are quick, small and inexpensive.
- mCP probes at terrestrial experiments such as colliders, fixed-target experiments as well as astrophysical or cosmological observations have been vastly studied and searched for.
- FORMOSA, a milliQan-like experiment downstream of ATLAS, would take advantage of enhanced mCP production in the forward direction.
- FORMOSA could provide leading sensitivity to MCPs in the 100 MeV to 100 GeV mass window.
- Beam-related backgrounds (from forward muons) become important in the forward direction.
- FORMOSA can help cover a large part of the millicharged DM region that is previously unconstrained.

Thanks for your attention!

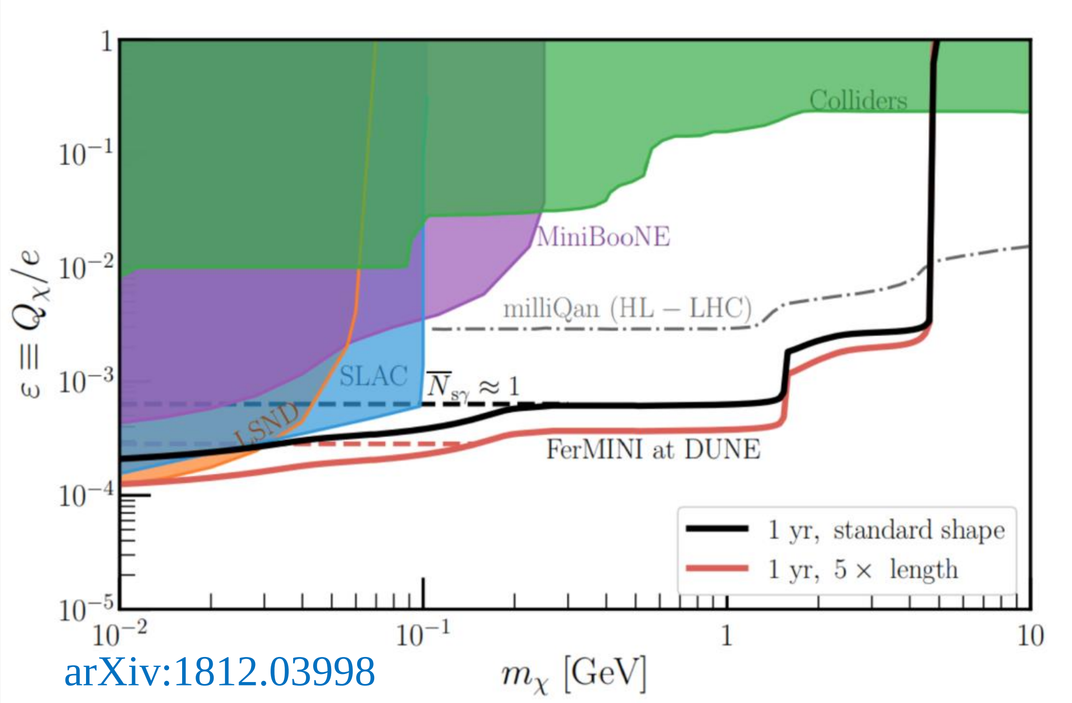
Question?



FerMINI @ DUNE

MCP Produced in Fixed-Target Experiments

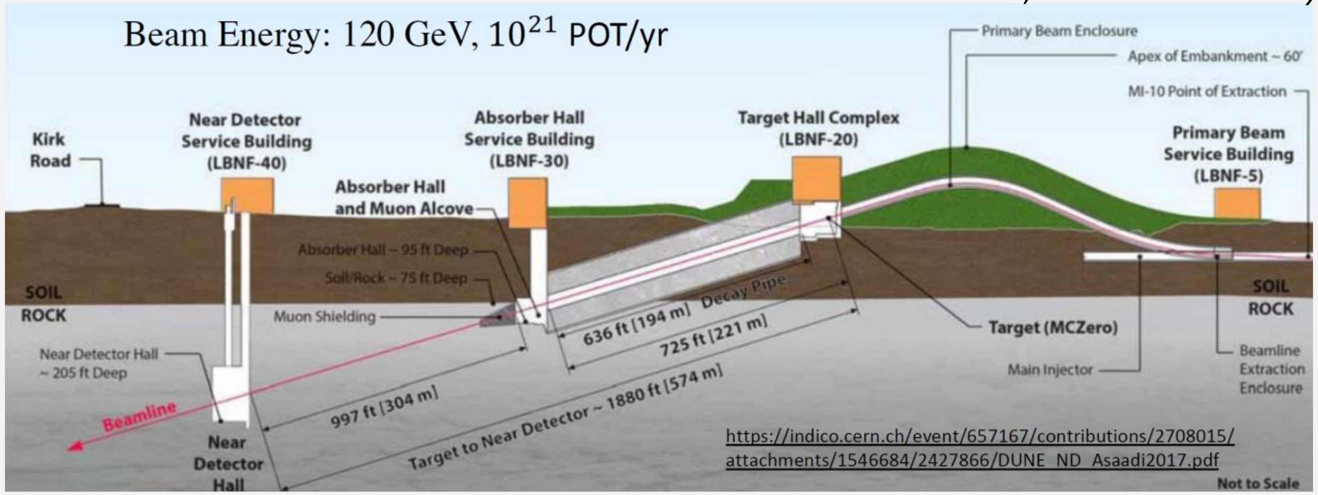
A **Fer**milab Search for **MINI**-charged Particle based on scintillating detectors

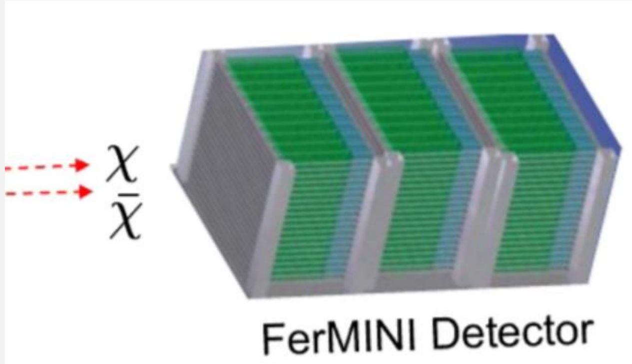


Directly inspired by milliQan concept [Hass, Yavin, et al. '14]

LBNF: Long-Baseline Neutrino Facility

Jonathan Asaadi, *Texas A&M University*

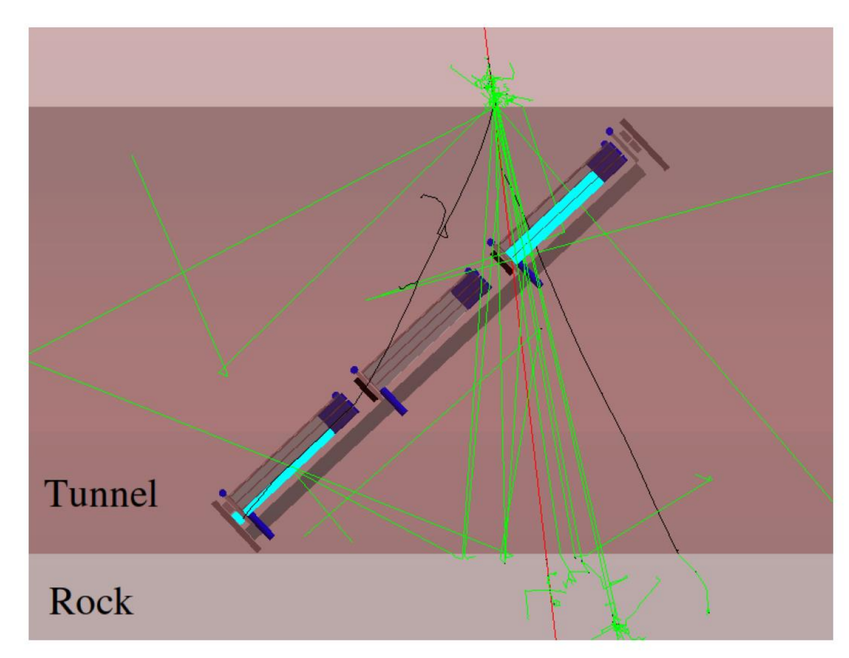




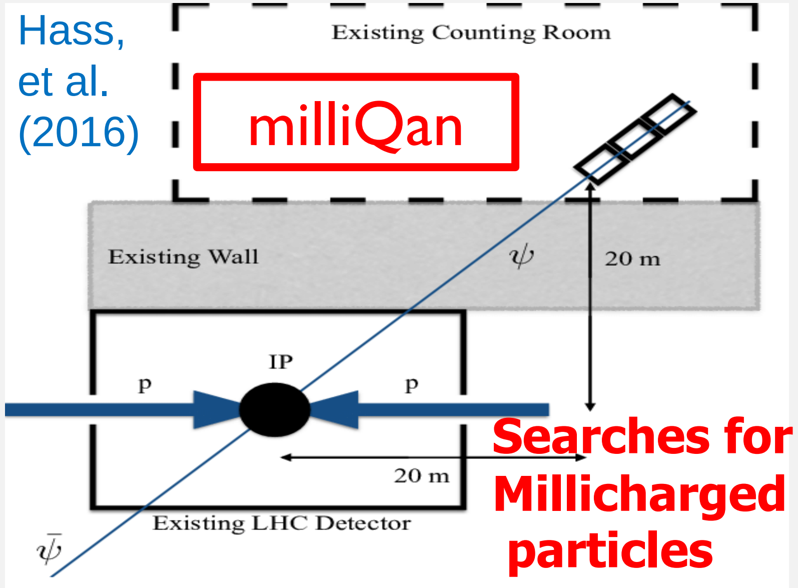
FORMOSA: Beam unrelated background

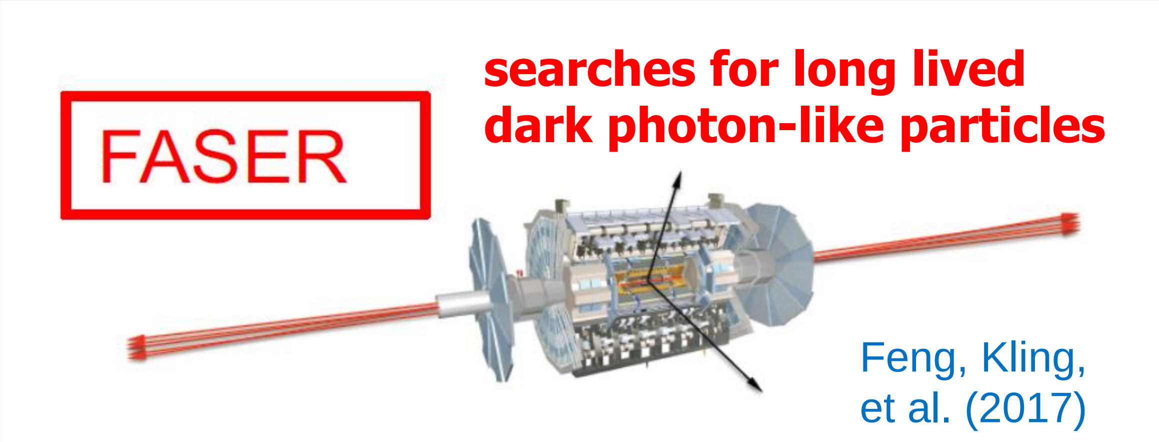
- Cosmic muon & dark current pulses in the PMTs in coincidence ⇒ similar signature to MCPs

❖ Quadruple coincidence can reduce these BG to a negligible level. [milliQan Collaboration ‘20]



Complementary Proposed Experiments @LHC





Long lived weakly interacting neutral particles