Accelerator Probes of Light Dark Scalars

Based on 2004.14515 [SF & A. Ritz '20]

Saeid Foroughi-Abari

University of Victoria

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Overview

1. Motivations to new physics BSM
2. Hidden sector portals
3. Probing Higgs portal at fixed target experiments
4. Existing constraints & future projection on dark scalars
5. Light scalars production & sensitivity reach at LSND

Empirical Evidence for Physics BSM

Dark Matter

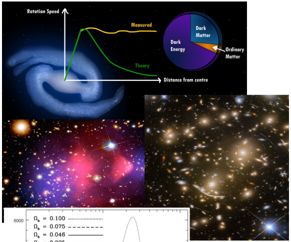
CMB power spectrum
Cluster and galactic rotation curves
Gravitational lensing

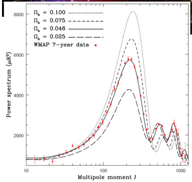
Neutrino Oscillations & Mixing

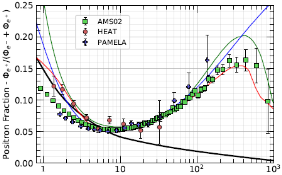
mixing between the flavor and mass eigenstates of neutrinos
Sterile neutrinos

Anomalies, e.g. the cosmic ray excess

Observations of the e^+ excess by PAMELA & AMS II $\Rightarrow$ Potential hint of enhanced DM annihilation mediated by light force carriers

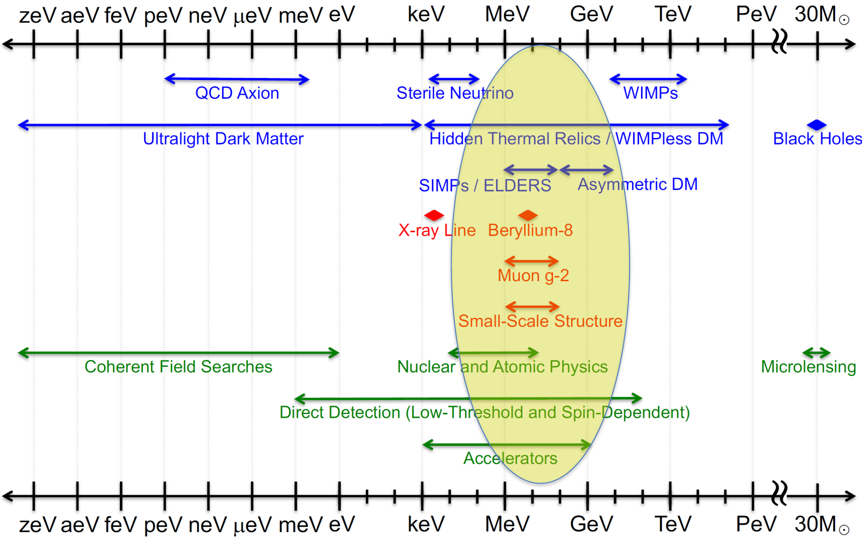






[Cosmic rays – PDG '19]

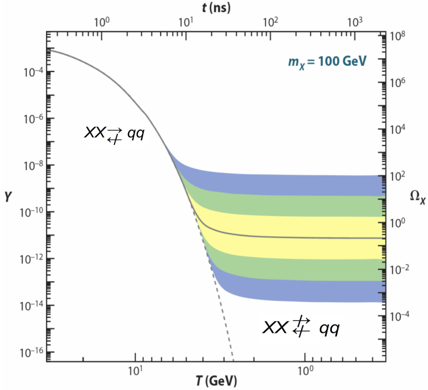
Dark Matter Candidates, Anomalies, and Search Techniques



Thermal Freeze out & WIMP Scenario

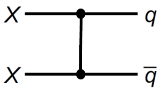
Assume a new heavy particle χ is initially in thermal equilibrium: $\chi\bar{\chi} \to q\bar{q}$

- As the Universe cools and expands:



- It turns out that the relation between Ω_χ and annihilation strength is wonderfully simple:

$$\Omega_X \propto \frac{1}{\langle\sigma v\rangle} \sim \frac{m_X^2}{g_X^4}$$



- For $m_\chi \sim$ GeV - TeV and $g_\chi \sim \mathcal{O}(1) \quad \Rightarrow \quad \Omega_\chi \sim 0.1$

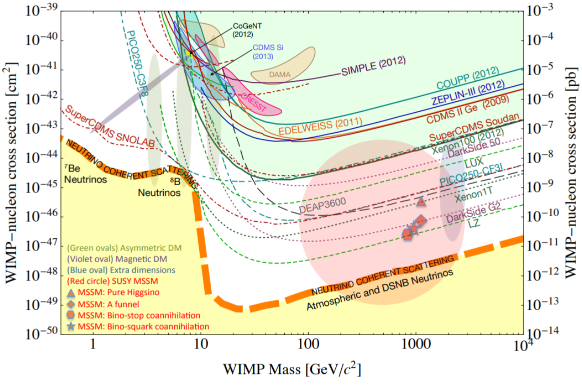
$\Omega_\chi \simeq 0.1200 \pm 0.0012$ [Planck Collab., '18]

WIMP-like (thermal relic) DM

For sub-GeV DM:

$m_e < m_{\mathrm{DM}} < m_{\mathrm{had}}$

a high intensity relativistic beam is advantageous, as direct detection sensitivity drops due to recoil thresholds

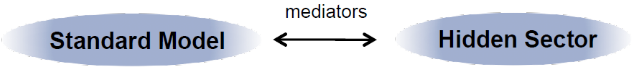


[Snowmass Summary; Cushman et al. '13]

$$\Omega_\chi h^2 \propto \frac{1}{<\sigma v>} \;,\; \sigma_{\mathrm{ann}} \propto \frac{m_{\mathrm{DM}}^2}{M_{\mathrm{mediator}}^4}$$

Viable thermal relic density for a sub-GeV WIMP requires new annihilation channels through light states as part of a hidden sector [Pospelov et al '07]

EFT for a (neutral) hidden sector

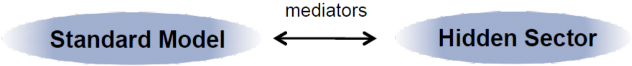


$$\mathcal{L}_{mediation} = \sum_{n=k+l-4} \frac{\mathcal{O}_k^{(\mathrm{SM})}\mathcal{O}_l^{(\mathrm{med})}}{\Lambda^n} \sim \mathcal{O}_{\mathrm{portals}} + \mathcal{O}(\frac{1}{\Lambda})$$

Generic interactions are irrelevant (dimension > 4), but there are three UV-complete relevant or marginal “portals” to a neutral hidden sector

- Vector portal: $\mathcal{L} = -\frac{\epsilon}{2\cos\theta_w} B^{\mu\nu} F'_{\mu\nu}$ [Okun; Holdom; Foot et al]
- Higgs portal: $\mathcal{L} = -H^\dagger H(AS + \lambda S^2)$ [Patt & Wilczek]
- Neutrino portal: $\mathcal{L} = y_N \bar{L} H N$

(Minimal) Higgs portal and light scalars



$$\mathcal{L} \supset -ASH^\dagger H$$

- A potential extension of the Higgs sector
- Consider the DM scenario $m_S < 2m_{DM}$
  The light scalar S acts as a force mediator between fermionic DM and SM
- Interested in sub-GeV mass range:

Induced couplings after EWSB

$$\mathcal{L} \supset -\theta S \left(\frac{m_f}{v} \bar{f} f + g_{S\gamma\gamma} F_{\mu\nu} F^{\mu\nu} + g_{SNN} \bar{N} N + \cdots \right)$$

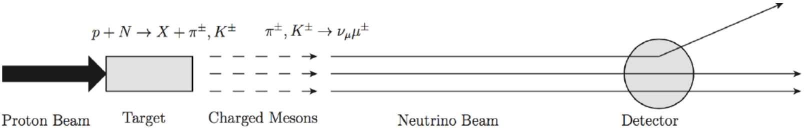
$\theta \simeq Av/m_h^2 \ll 1$

$g_{S\gamma\gamma} = \frac{\alpha}{8\pi v} F_\gamma(m_S)$

$g_{SNN} \sim 1.2 \times 10^{-3}$

Fixed target probes - Neutrino Beams

- Ability to probe the hidden sector experimentally?
- Advantage of fixed targets compare to colliders [Batell, pospelov, Ritz '09]
- Long-Baseline Neutrino Experiments: ν beams generated by high-intensity proton sources directed on fixed targets reach the (near) detector set up.

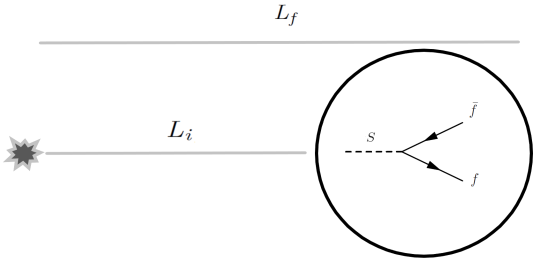


- Consequence of a HS: production of a high intensity "new weakly coupled light mediator beam" followed by the decay (or recoil) in the detector [Batell et al '09, '14]

  $\Rightarrow$ an additional contribution to events

Analysis

- Number of S produced under the Higgs portal scenario?
- Probability that a produced S mediator will reach the detector?
  $P_{\rm decay} = e^{-L_i/\gamma\beta\tau} - e^{-L_f/\gamma\beta\tau}$
- How likely is that the decay $S \to l^+l^-, \pi\pi, KK, \ldots$ produce an event?
  Number of events: $N_S \times P_{\rm det}$,
  $P_{\rm det} \sim \left(\frac{\gamma^2 \Omega_{lab}}{4\pi}\right) \times P_{\rm decay} \times \epsilon_{\rm eff}$

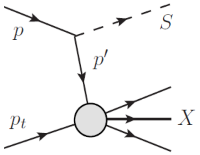


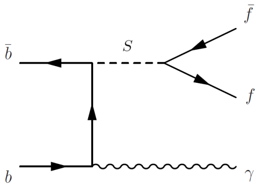
Fixed target probes - Scalar production modes

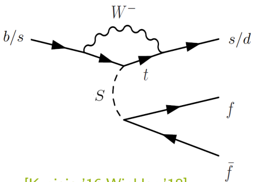
- Direct production
  $p+A \to S+X$ e.g. bremsstrahlung
  $N_S = \sigma N_{\text{POT}} \left(\frac{N_A \rho L}{A} \right)$
- Secondary hadronic decays
  $p+A \to H+X \Rightarrow H \to S+X$
  $N_S = N_H \times \text{Br}_{H \to SX}$

The most **relevant processes**: flavor changing rare B and K meson decays + radiative Υ decays.

$B \to K + S$ for $m_S < m_B - m_K$ $\quad$ $K \to \pi + S$ for $m_S < m_K - m_\pi$



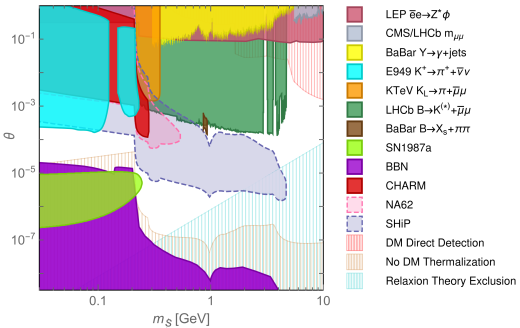




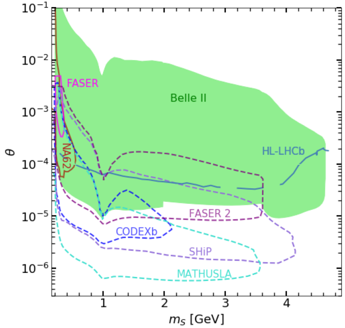
[Krnjaic '16;Winkler '18]

Constraints on dark scalars through Higgs Portal

[Winkler '18]



[Westhoff '19]



@ E949 & NA62 (kaon-mode): Rare decay measurement of $K^+ \to \pi^+ \nu\bar{\nu}$, interpret as $K^+ \to \pi^+ S$.

@ CHARM: Bounds on ALP $(S \to l^+ l^-)$

@ LHCb & Belle: Visibly decaying of S contributes to $B \to K l^+ l^-$ (bump hunt)

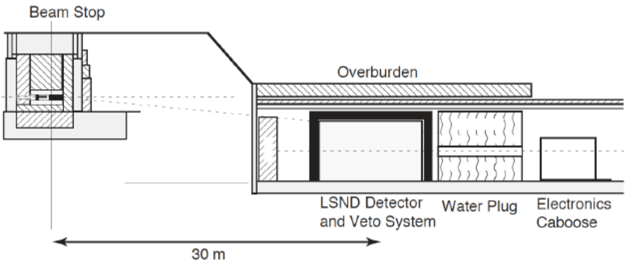
Fixed target probes - Light scalars at LSND

LSND

- largest POT datasets of any fixed target experiment $\sim 10^{23}$
- provide important constraints on the dark photon $N_{A'}^{(\pi)} \sim \epsilon^2 N_\pi$ (low mass)

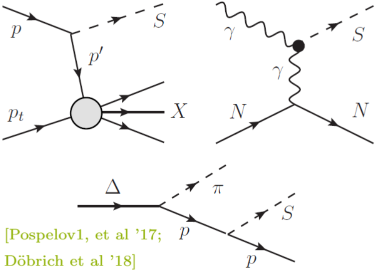
Kinematics

- 800 MeV proton beam impacting a thick target
- At LSND: π and Δ are the relevant hadronic dof.
  K and B mesons are not kinematically accessible.



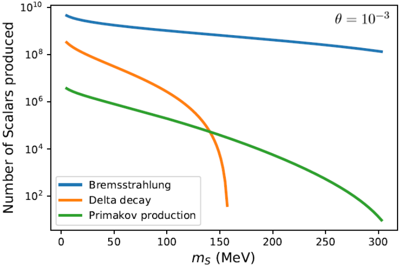
Light scalar production at LSND

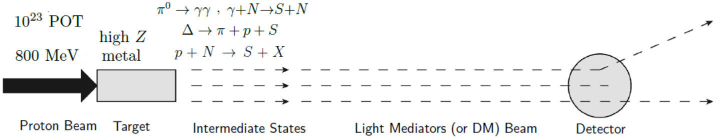
- Proton bremsstrahlung as the dominant production mode



[Pospelov1, et al '17; Döbrich et al '18]

- Normalized production rate [SF, Ritz '20]



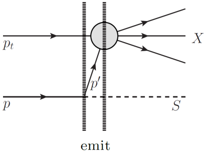


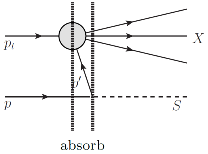
Proton bremsstrahlung - splitting function

OFPT

Approximate the rate in terms of the pp cross-section and a calculable sub-process [Altarelli, Parisi] [Boiarska '19]

Two possible time orderings exchanging the intermediate state p':





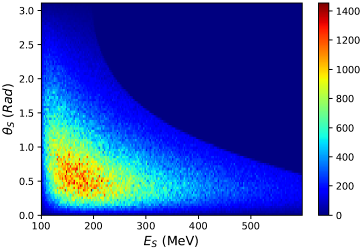
$$\mathcal{M}^{\rm emit} = \frac{\mathcal{M}_{p\to p'S}\mathcal{M}_{pp'\to X}}{2E_{p'}(E_p - E_S - E_{p'})}$$

$$\mathcal{M}^{\rm absorb} = \frac{\mathcal{M}_{p\to p'X}\mathcal{M}_{pp'\to S}}{2E_{p'}(E_S - E_p - E_{p'})}$$

$$\mathcal{M}^{emit} \gg \mathcal{M}^{absorb}$$

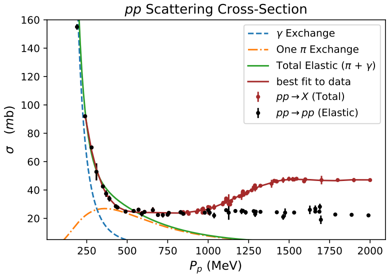
$$\frac{d\sigma_{pp_t\to SX}}{dz dp_T^2} \approx P_S^{\rm split}(z, p_T)\sigma_{pp}(s')$$

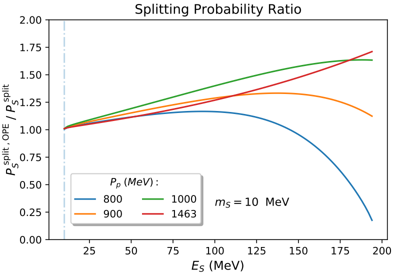
Verified that this condition is satisfied to a few percent for LSND kinematics if $z \in [0, 0.5]$ and $p_T < 300$ MeV



$pp \to ppS$ via OPE - complementary approach

- Modelling of pp scattering at sub-relativistic beam energies via One Pion-Exchange. Additional processes (e.g. two pion exchange) become important for $P_p \gtrsim 600$-700 MeV.
- Inelastic contribution to σ_{pp} via Δ-resonance important at moderately relativistic beam proton. [PDG '06]
- At low P_p: the rate calculation agrees with the splitting probability of the proton to emit S via OPE at the $\mathcal{O}(1)$ level. [SF, A. Ritz '20]



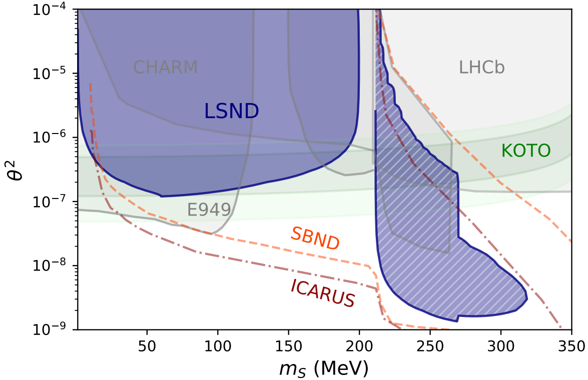


Neutrino backgrounds at LSND (may skip)

- LSND Collab. analysis:
  $\nu_e + {}^{12}C \rightarrow e^- + X$
  $\nu_\mu + {}^{12}C \rightarrow \mu^- + p + X$
- Assumption: $e^+e^-(\mu^+\mu^-)$ pairs produced are indistinguishable from single electrons (muons)
- Kinematic cuts:
  $60 < E_S < 200$ MeV for e^-
  $160 < E_S < 600$ MeV for μ^-
  efficiency ~ 0.1
- Number of beam-excess events < 20
- Br$(S \rightarrow l^+l^-) \simeq 1$

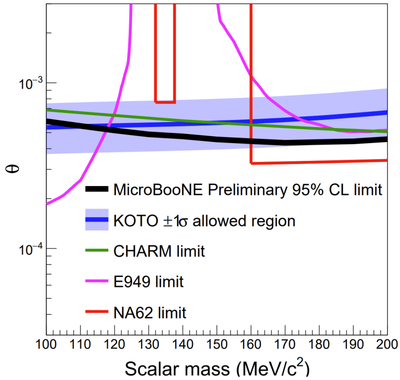
Sensitivity at LSND

The leading constraint in a small window in scalar mass from 120 to 180 MeV & from $2m_\mu$ up to 320 MeV. [SF, A. Ritz '20]



- KOTO provides sensitivity through the neutral decay channel $K_L \to \pi^0 \nu \bar{\nu}$

Search for mono-energetic scalars from the NuMI hadron absorber and decaying to electron-positron pairs. [MicroBooNE Collab. '20]



Upper limit on the scalar–Higgs mixing angle θ for masses in the range 100-200 MeV.

Conclusion

- Light sub-GeV thermal relics are difficult to probe using conventional direct detection experiments.
- High-luminosity fixed target experiments provide impressive sensitivity to new light weakly coupled degrees of freedom.
- Revisited: the minimal model of scalar singlet coupled to the SM through the Higgs portal, decaying visibly to leptons for masses below 350 MeV.
- Proton bremsstrahlung is found to be the dominant S production mechanism at LSND beam energies.
- LSND experiment imposes the leading constraints within two mass windows between $m_S \sim 150$ and 350 MeV.
- Among the possible future analyses is the NA62 at CERN which provides greater sensitivity to $K^+ \to \pi^+ + invisible$ at low S mass.
- (SBN) program at Fermilab could also provide new sensitivity to the Higgs portal. [Batell et al '20]

Looking Forward to Millicharged Dark Sectors

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

Saeid Foroughi-Abari

University of Victoria

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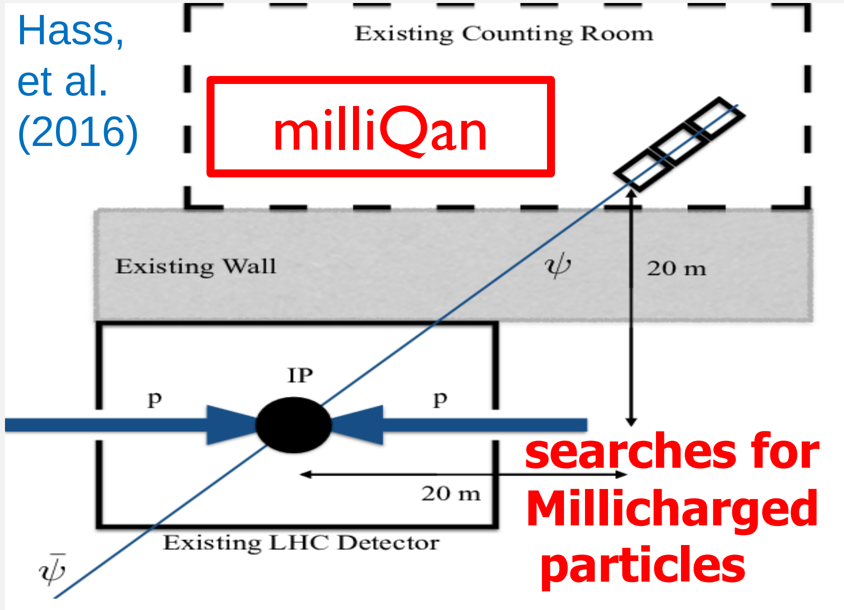
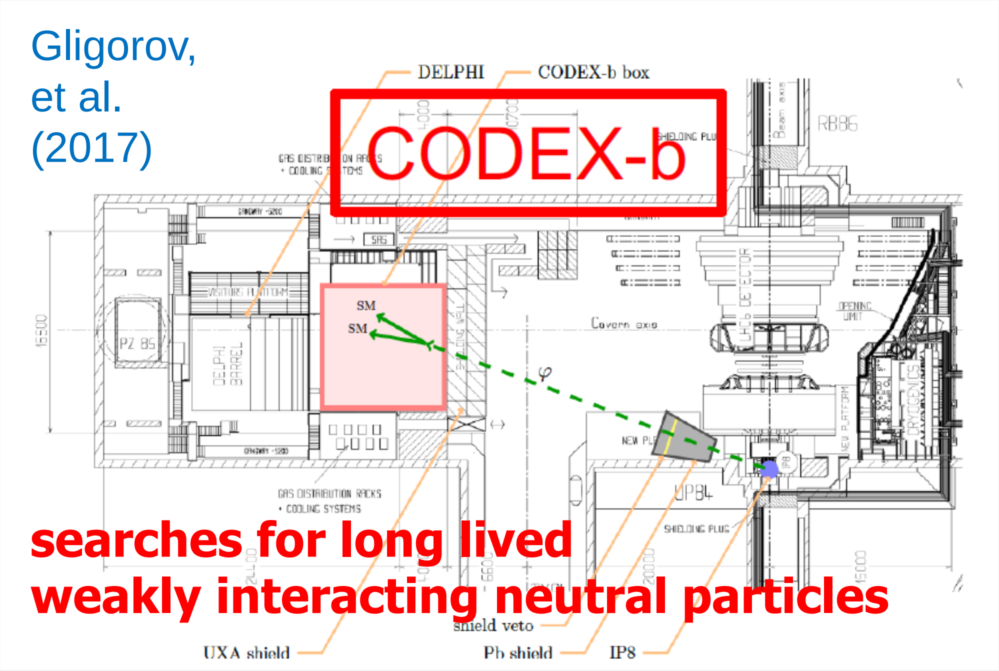
Some of the slides I present are drawn from talks given by **Yu-Dai Tsai**

OUTLINE

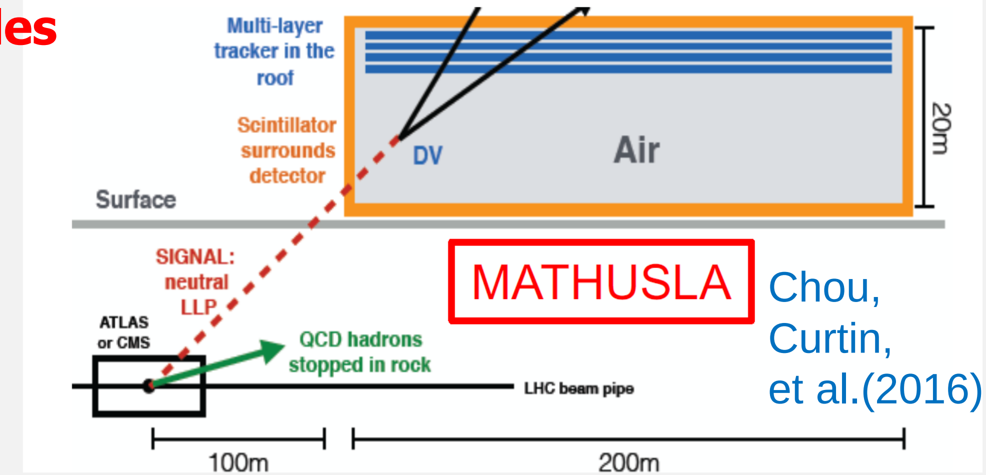
- Intro (models) of millicharged particles (MCP)
- Dedicated experiments: MilliQan & FerMINI to search for MCP
- FORMOSA: Probing MCP at the LHC forward physics region
- Other experimental probes: Proton Fixed-Targets / Neutrino Experiments
- Millicharged Strongly Interacting Dark Matter

Complementary Proposed Experiments @LHC





searches for long lived weakly interacting neutral particles



Why study MeV – GeV+ dark sectors?

- MeV – GeV+ Dark Sector are motivated by **thermal freeze-out DM** & **anomalies**

We don't need to search in the dark!

- Some anomalies involving MeV - GeV+ explanations

- Muon g-2 anomaly
- LSND & MiniBooNE anomaly
- EDGES result
- KOTO anomaly
- Proton charge radius anomaly (resolved?)

⋮

- Below ~ MeV there are also strong astrophysical/cosmological bounds that are hard to avoid.

Fractionally Charged Particles

- Is electric charge **quantized** and why?
- Fractionally (or irrationally) charges are allowed under SM U(1) hypercharge

$$\mathcal{L}_{\text{MCP}} = \bar{\chi}(i\partial\!\!\!/ - \epsilon' e B\!\!\!/ - m_\chi)\chi$$

Naively **violating** the empirical charge quantization

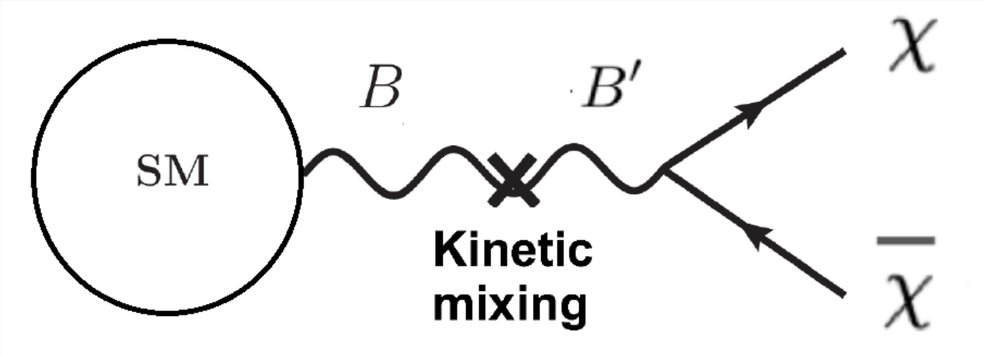
- Can just consider these Lagrangian terms by themselves (no extra mediator, i.e., dark photon)

- Could account for (sometimes fractional) **dark matter (DM) relic abundance**
- A small fraction of the DM as MCP can potentially (used for the cooling of gas temperature to) explain **EDGES anomaly**: [EDGES collab., (2018); Barkana, (2018)]
  - Observation of anomalous absorption of 21 cm spectrum

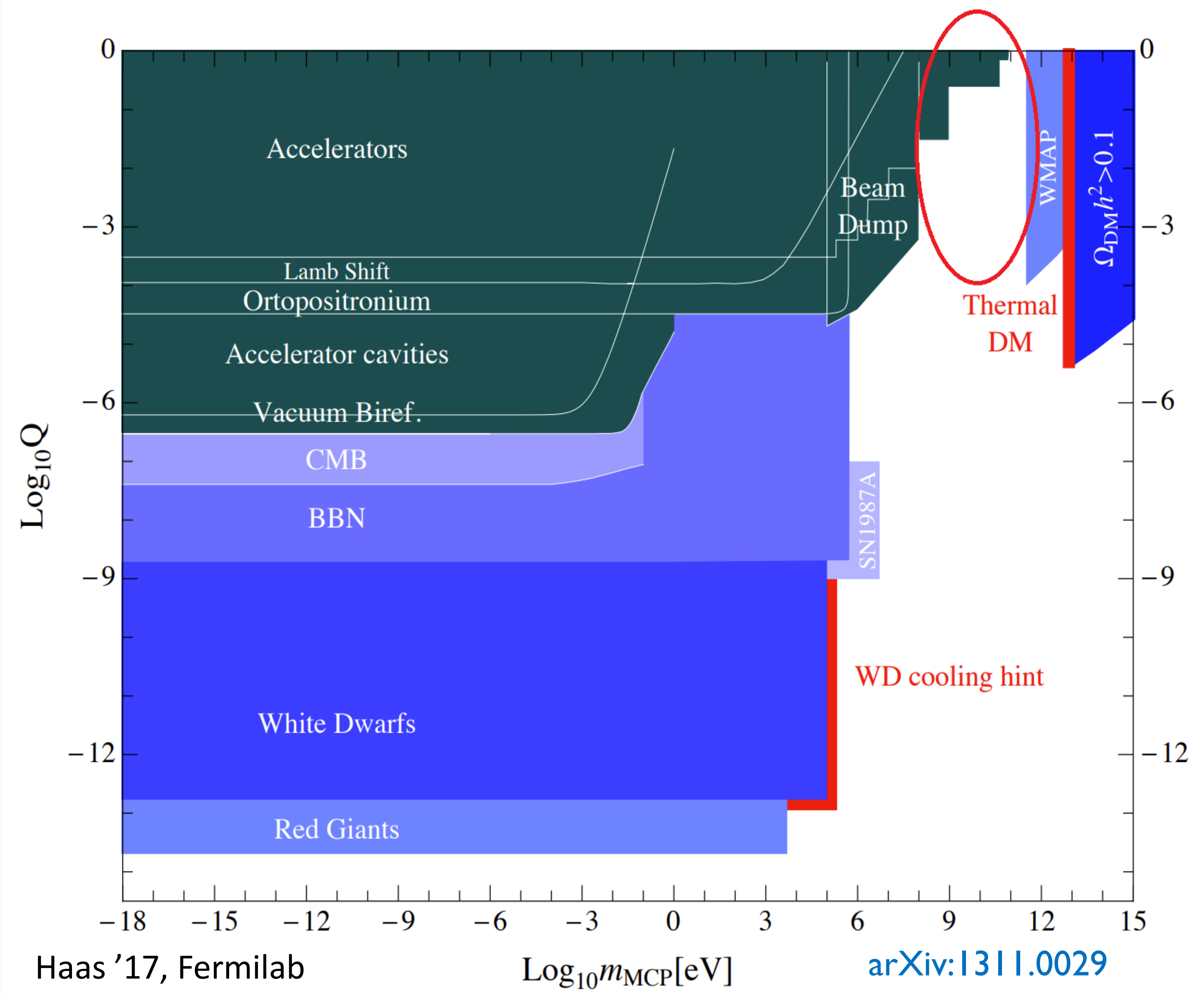
Kinetic Mixing and MCP Phase

- This could arise from 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)

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4} B'_{\mu\nu} B'^{\mu\nu} - \frac{\kappa}{2} B'_{\mu\nu} B^{\mu\nu} + \bar{\chi}(i\partial\!\!\!/ - e' B\!\!\!/' - m_\chi)\chi$$



Searches for milli-charged particles

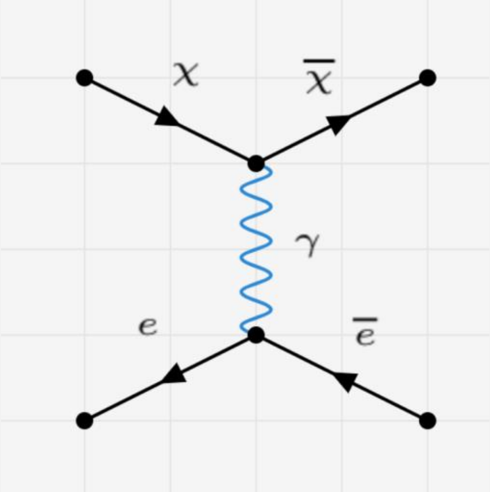


MCP is one of the simplest dark-sector test models for accelerator experiments

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

MCP Detection Signature



- **"Hard" (MeV-level)** electron elastic scattering

e.g., MCP in neutrino experiments [Pospelov, et al. 1806.03310]

- **Ionization (eV-level):** ~ very low-energy scattering

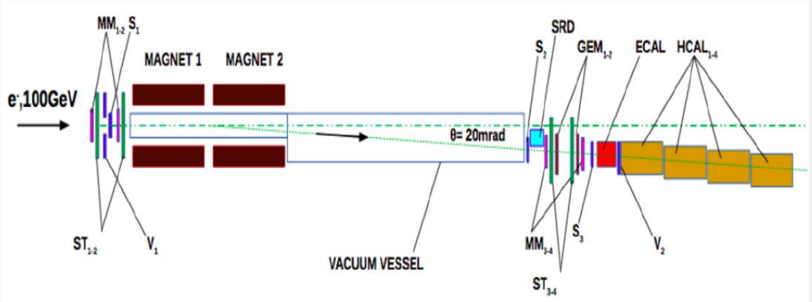
➢ MilliQan: arXiv:1410.6816,

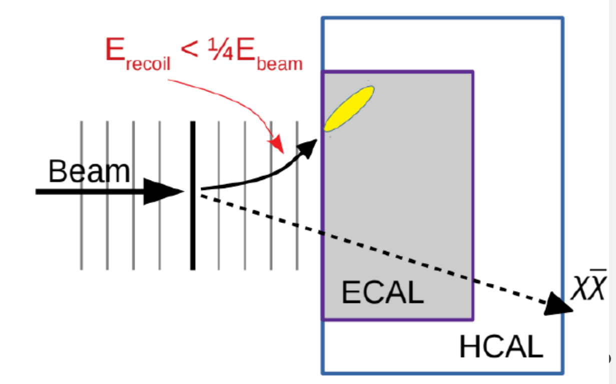
➢ FerMINI: arXiv:1812.03998

$$\left\langle -\frac{dE}{dx} \right\rangle \propto \epsilon^2$$

- **Missing** energy/momentum/monophoton/Z decay

1710.00971
(NA64 collab.)

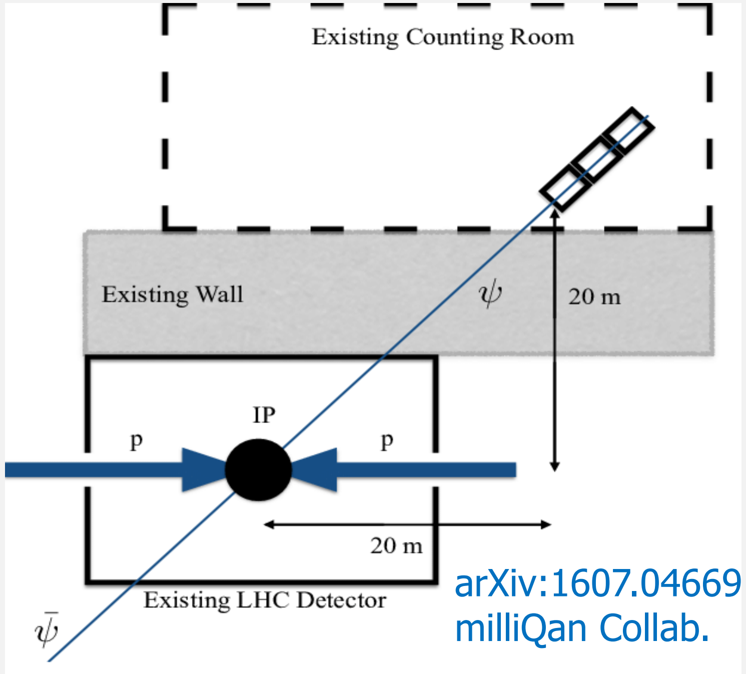




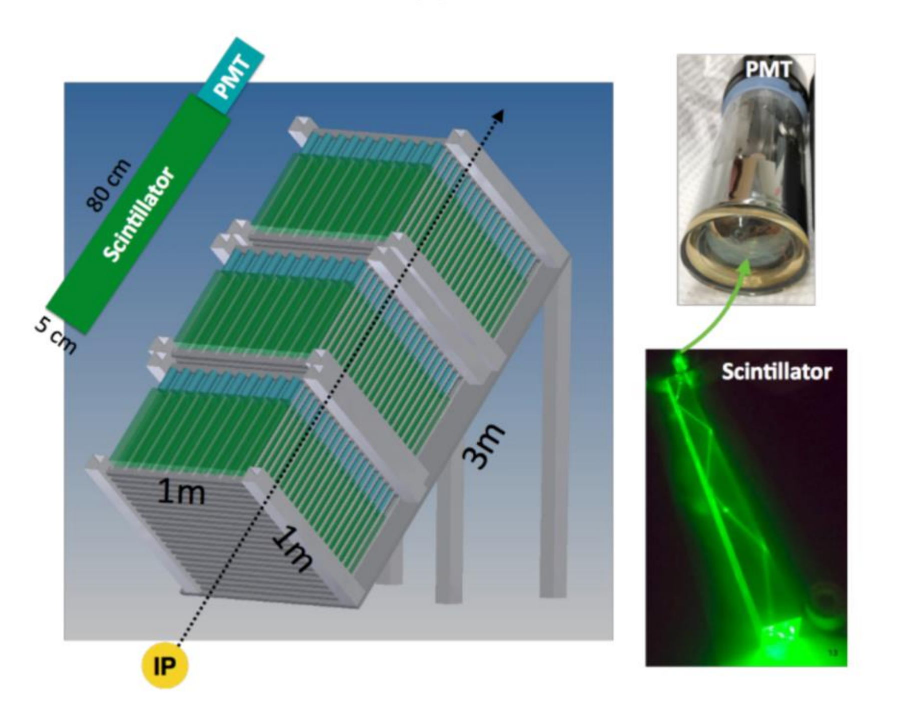
1808.05219
(LDMX collab.)

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 Regin
- Triple Coincidence in small time window ~ 15 ns

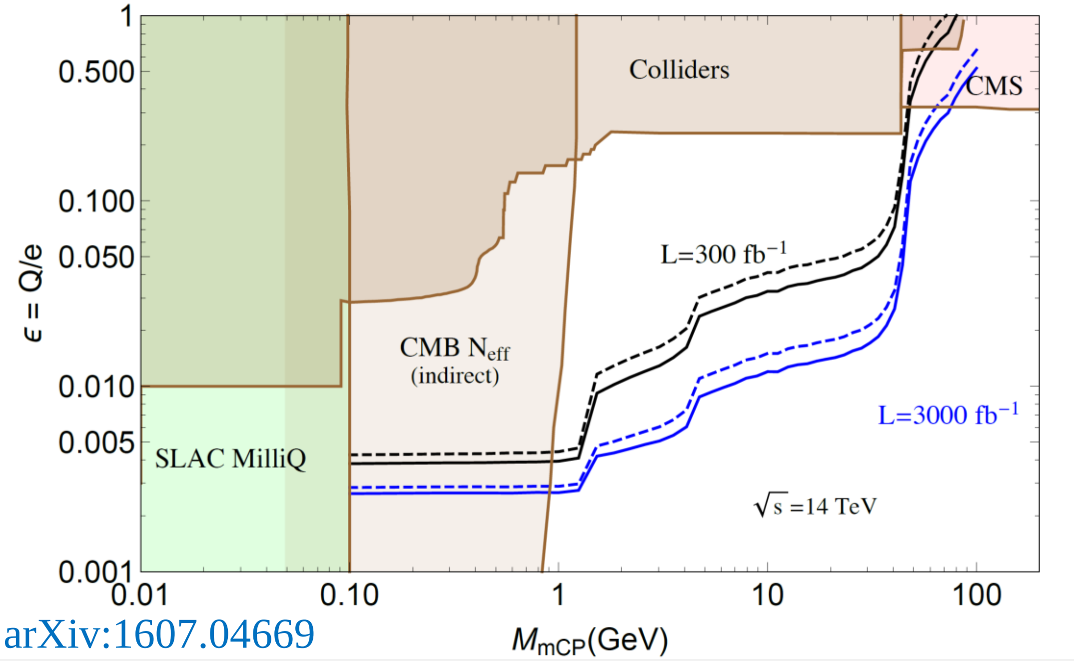


arXiv:1607.04669
milliQan Collab.



Sensitivity to MCPs at Transverse Region

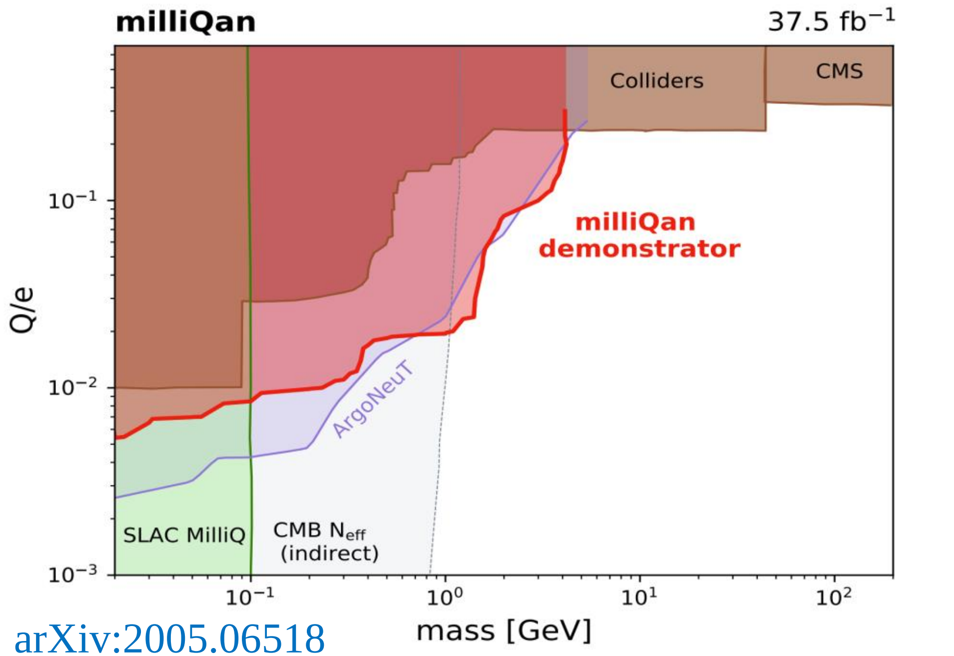
Expected Sensitivity



arXiv:1607.04669

Dominant background:
Cosmic muons & dark current

Proto-milliQan first update!



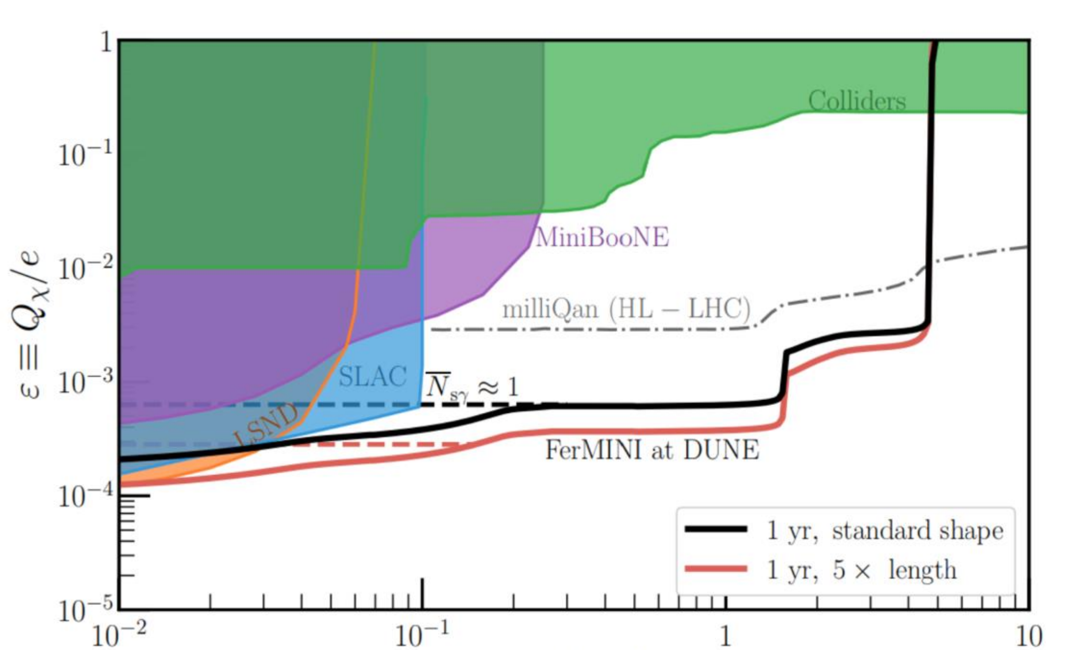
arXiv:2005.06518

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

FerMINI @ DUNE

MCP Produced in Fixed-Target Experiments

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

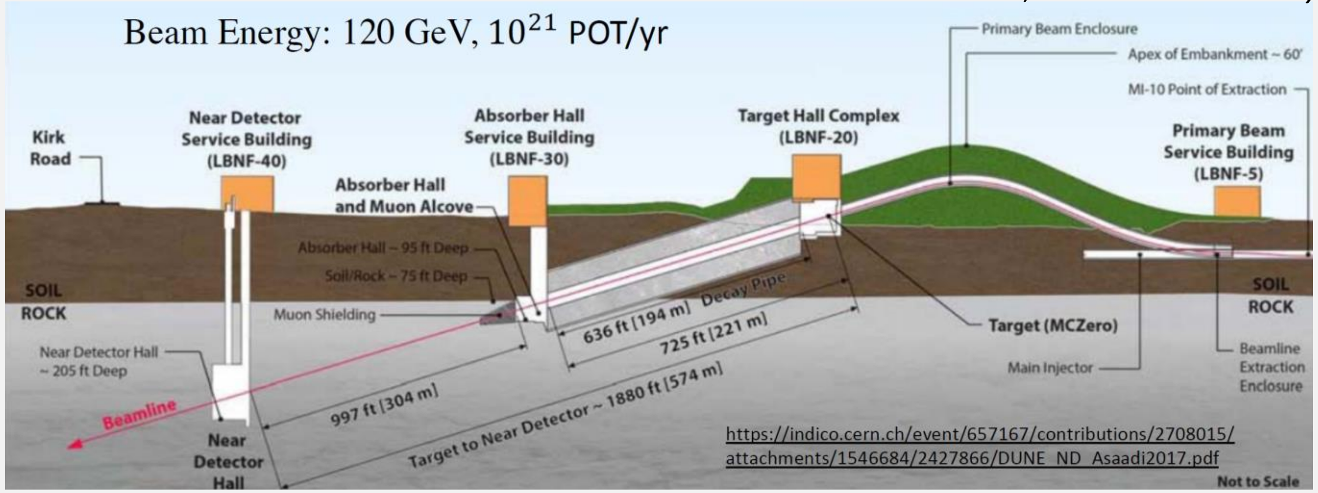


arXiv:1812.03998

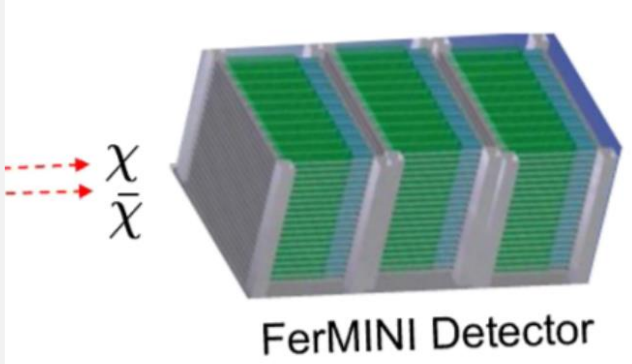
Directly inspired by milliQan concept [Hass, Yavin, et al. '14]

LBNF: Long-Baseline Neutrino Facility

Jonathan Asaadi, *Texas A&M University*



https://indico.cern.ch/event/657167/contributions/2708015/attachments/1546684/2427866/DUNE_ND_Asaadi2017.pdf

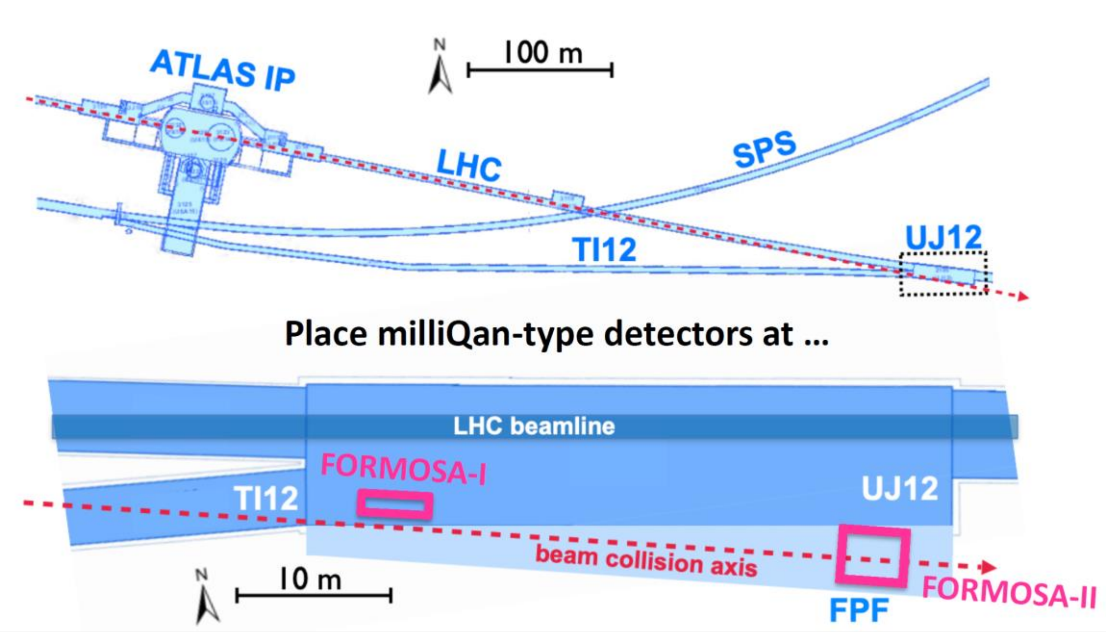


High-Intensity Energy Frontier

- Despite the focus of the LHC Higgs factory on Central Region (isotropic production)
- High flux of light dark sector (weakly interacting) particles could be achieved at the LHC Forward Region
- View the detector located at ~ 500 m away along the "collision axis" after beam curves as a very energetic beam-dump experiment!

- Motivates a small and inexpensive detector:

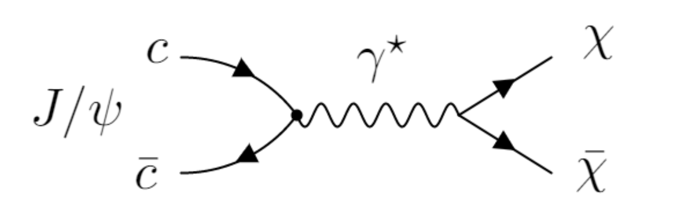
FORMOSA: FORward **M**icr**O**charge **S**e**A**rch

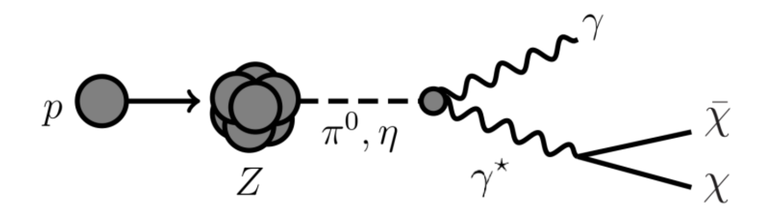


Existing UJ12 cavern at Forward Physics Facility (FPF) can house FORMOSA

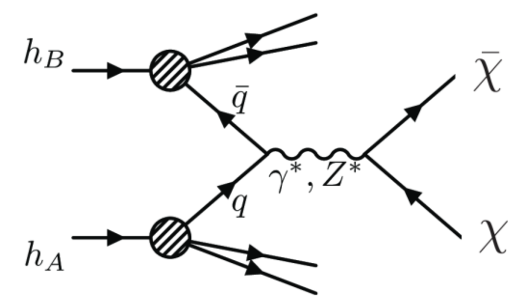
MCP Production Channels

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

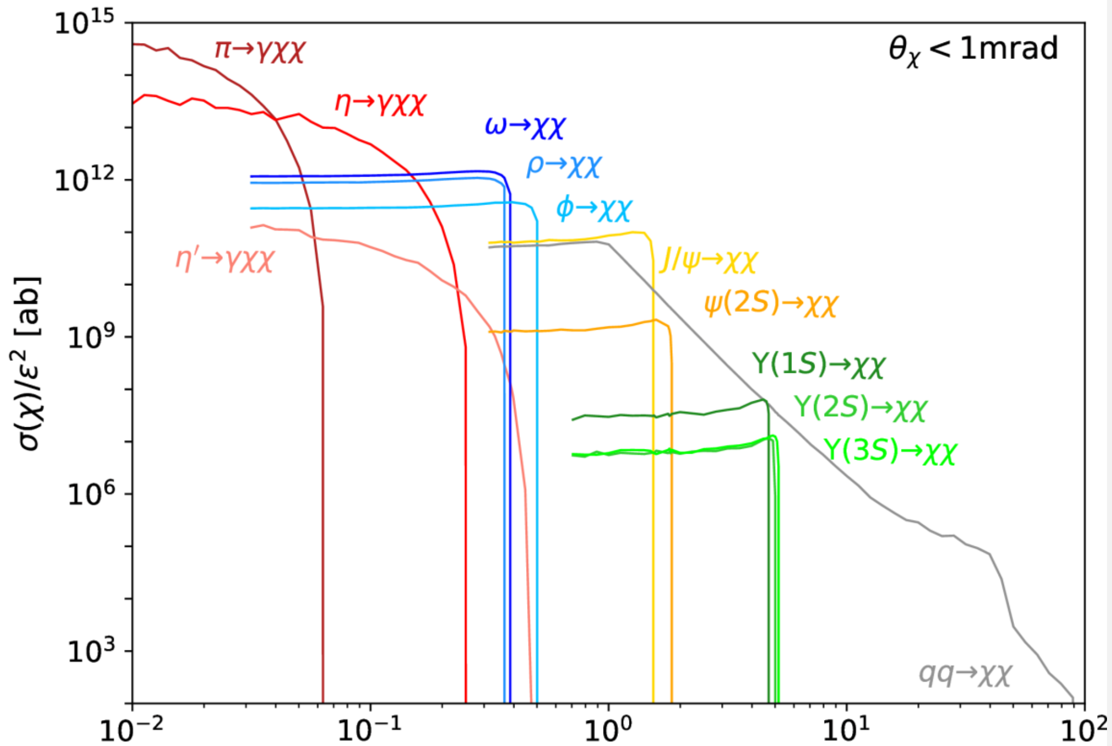




- Drell-Yan direct production



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



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

MCP Detection: Ionization

- Deposition of energy due to ionization

$$\langle -\frac{dE}{dx} \rangle \sim 2\,\epsilon^2\,\mathrm{MeV/cm}$$ Typical mass stopping power

- Average number of photoelectrons (PE):

$$\bar{N}_{\mathrm{PE}} \propto L_s \times \langle -\frac{dE}{dx} \rangle \sim \epsilon^2 \times 10^6$$ 1 m plastic scintillator bar

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

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

Follows Poisson dist.

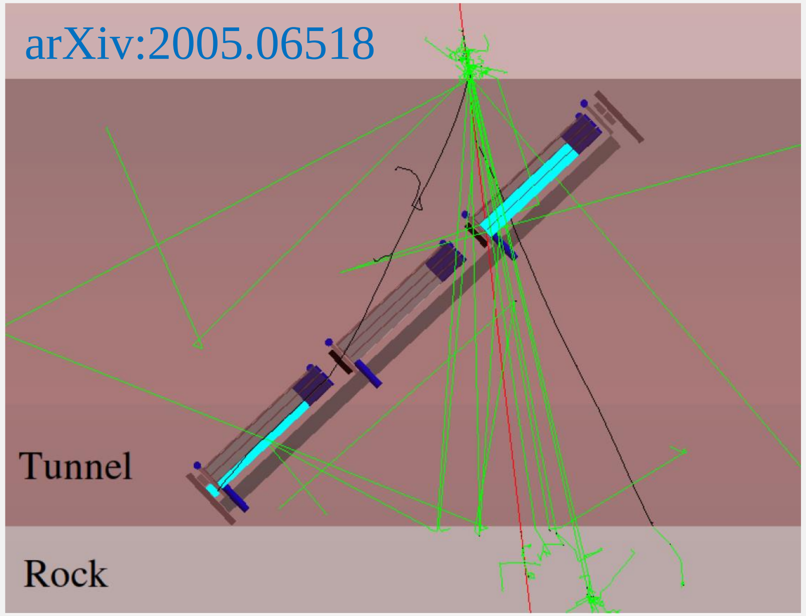
Total number of signal events $N_\chi \cdot P_{\mathrm{det}}$

FORMOSA: Expected Background

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]



Simulated cosmic ray shower event

Background from the beam pipe

❖ Use the panel veto-shields + reconstruct the events to be pointing to the ATLAS IP

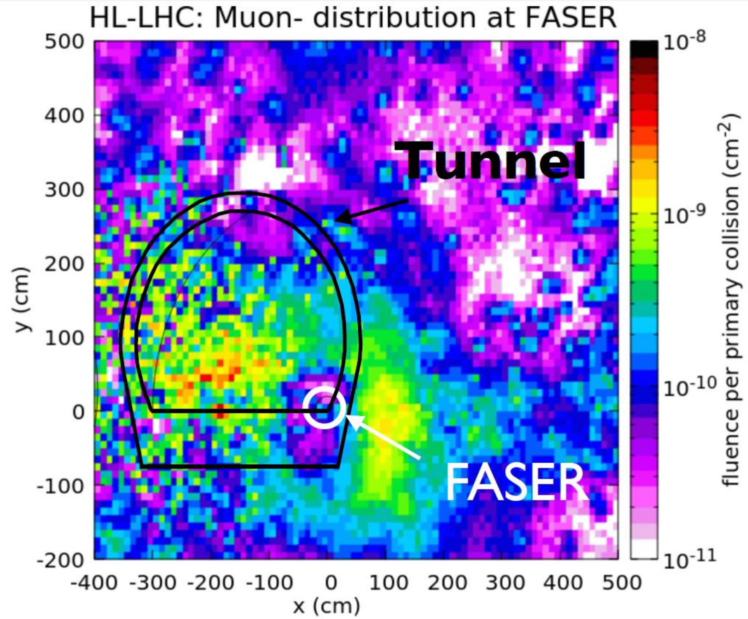
A New Challenge in the Forward Region

Beam related background:

- New challenge arises due to large flux of HE muons (and secondary particles) from the beam collisions

- FLUKA simulation performed by CERN STI group
  estimated muon flux < ~ 1 Hz/cm2 **~ one muon every 100 μs**

- Feasible task: implementing an **online-veto of large-PE** events
  - ensures a high signal efficiency



arXiv:1812.09139

But this is not the full story …

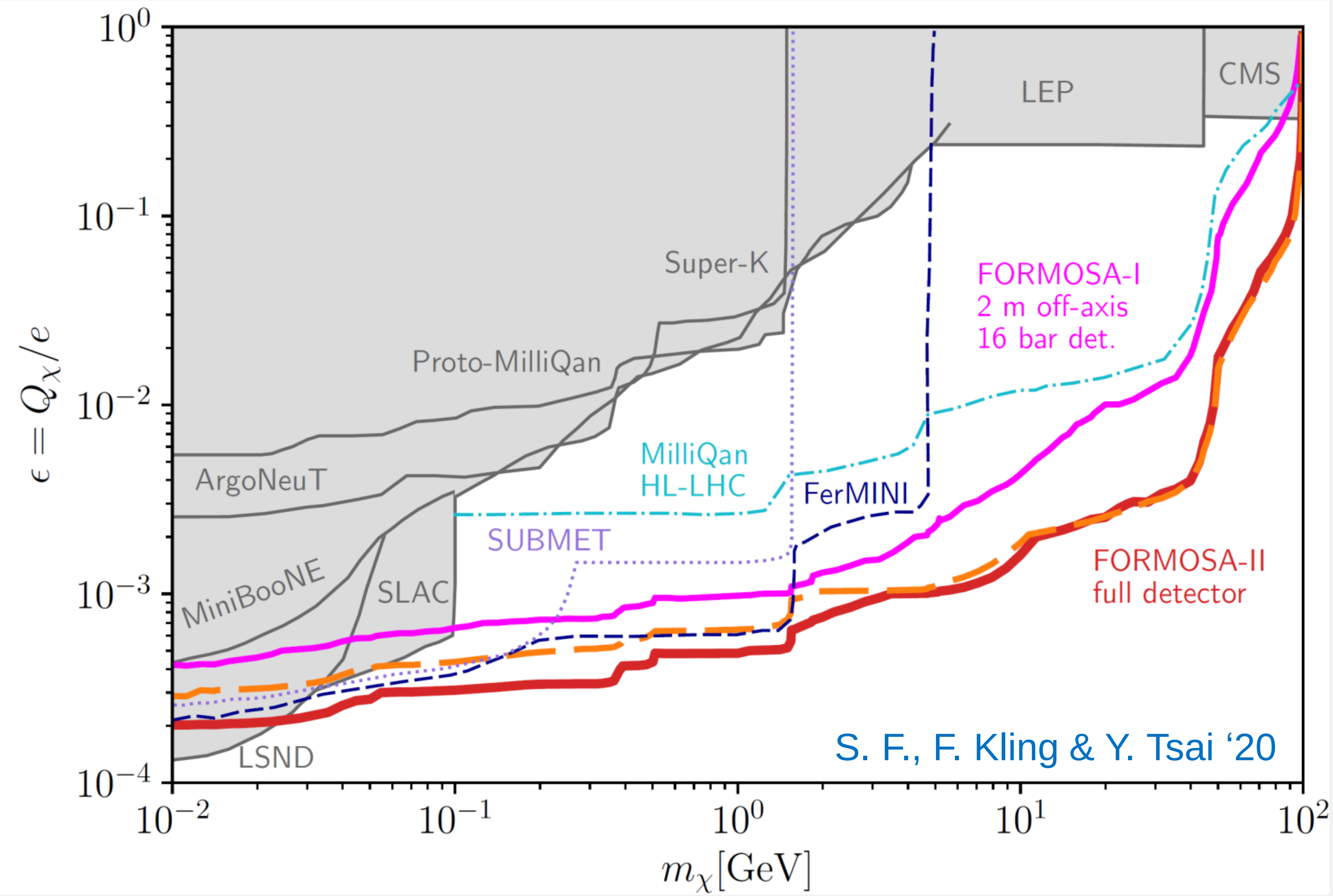
- Afterpulses: small pulses occurring with a delay time of $\delta t \lesssim 10\ \mu s$ after the initial pulse

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

- Considering better PMTs with reduced afterpulse duration can also 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.

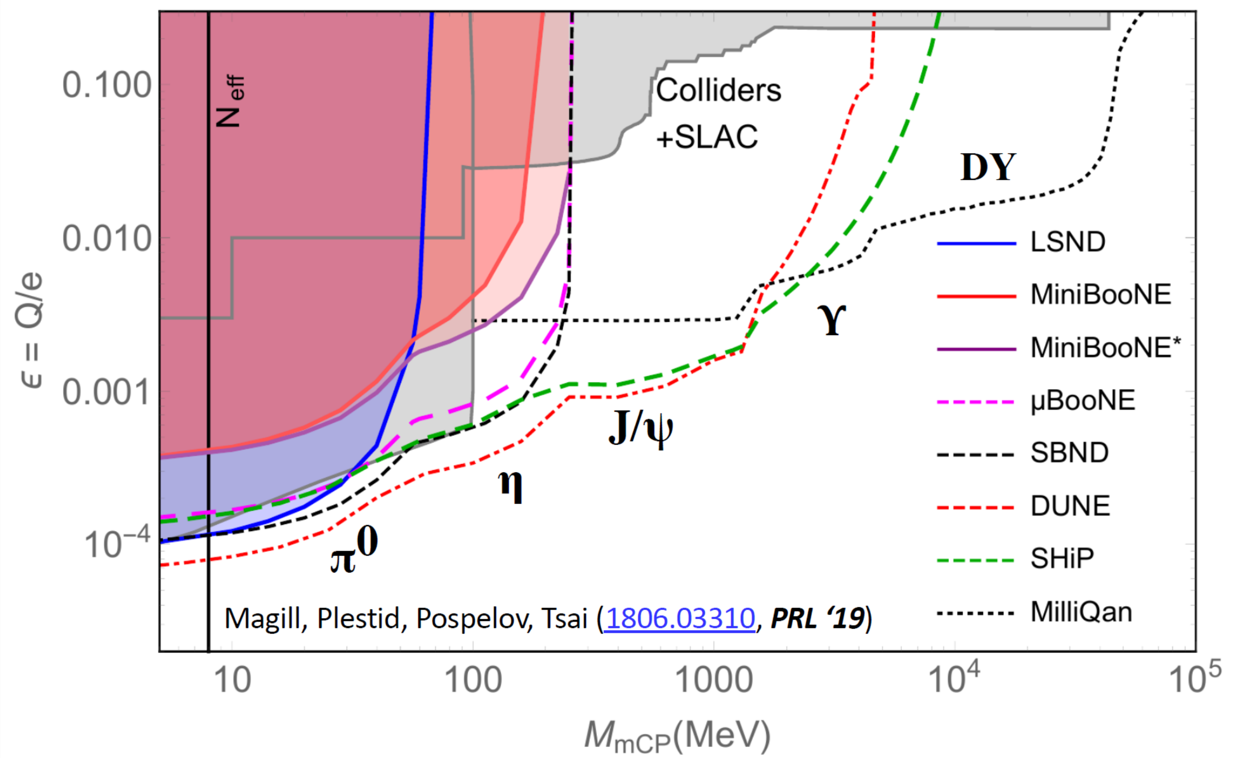


Advantage of enhanced MCP production in the forward direction

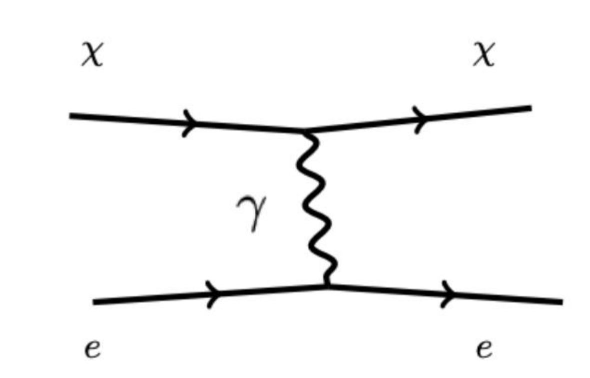
More Millicharged Particles Hunting

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

MCP in neutrino Experiments



Detection: Electron Scattering

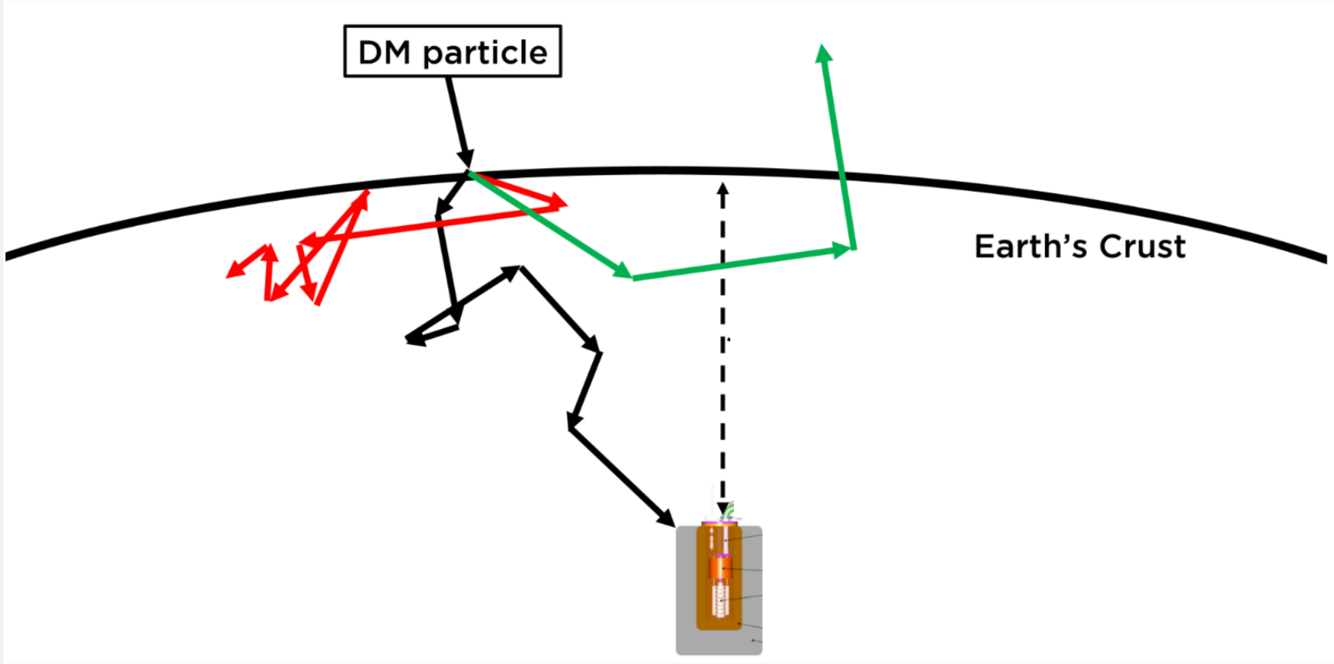


Similar topology:
deNiverville, Pospelov, Ritz, '11,
Batell, Pospelov, Ritz, et al. '14

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

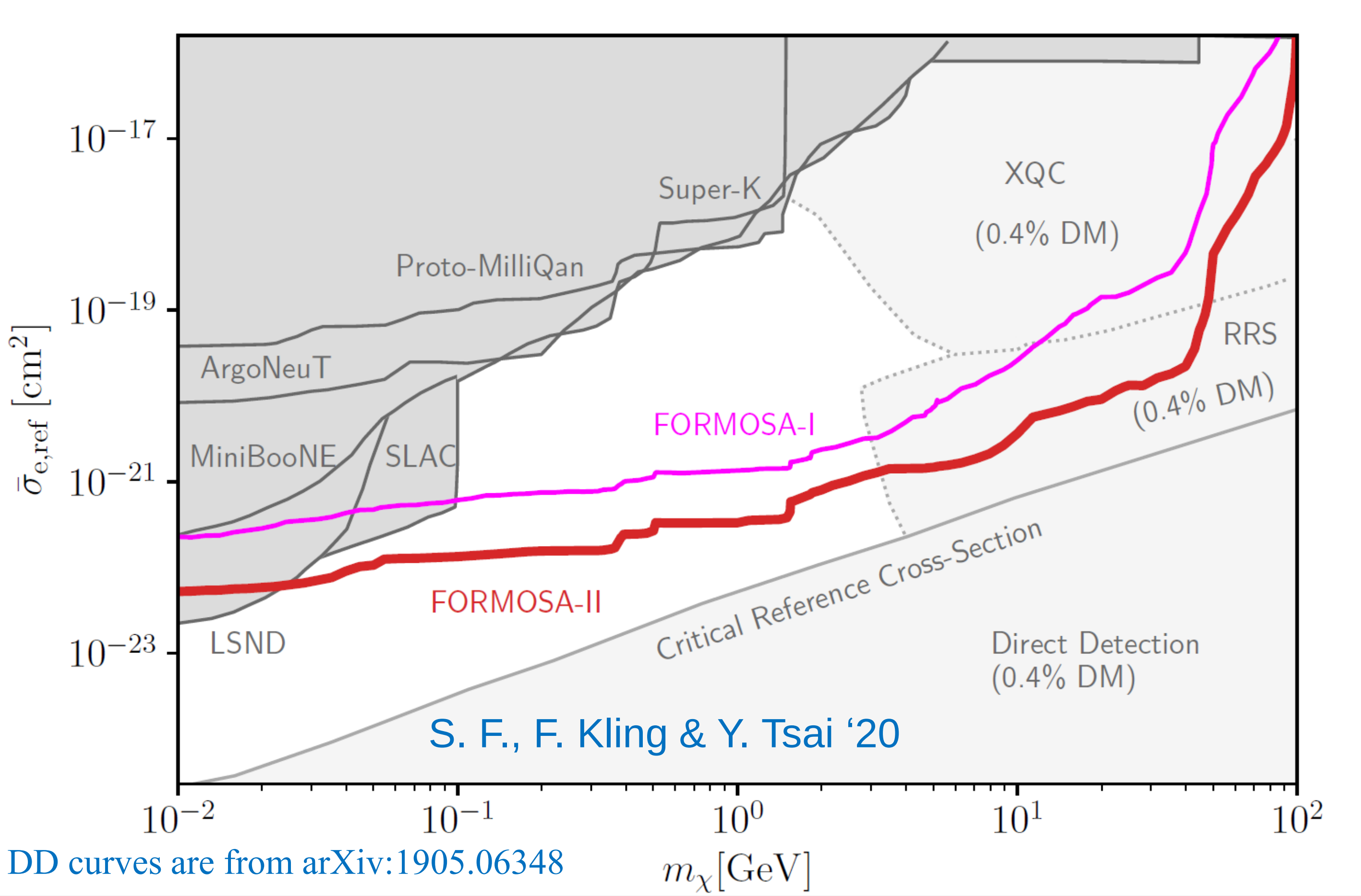
Strongly Interacting Dark Matter

- 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 dark matter above some **critical cross section**.



Probe of Millicharged Dark Matter

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



DD curves are from arXiv:1905.06348

Reference Cross-section for MCP-Electron Scattering (Direct Detection)

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

$$q_{d,ref} = \alpha m_e$$

Summary

- 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 placed ~ 500 downstream from ATLAS, would take advantage of enhanced MCP production in the forward direction using scintillator-based detectors
- FORMOSA can help cover a large part of the millicharged DM region that is previously unconstrained in the 100 MeV to 100 GeV mass window.
- Beam-related backgrounds associated with the sizable flux of forward muons, such as PMT afterpulses, become important in the forward direction.

THANK YOU FOR YOUR ATTENTION! ANY QUESTIONS?