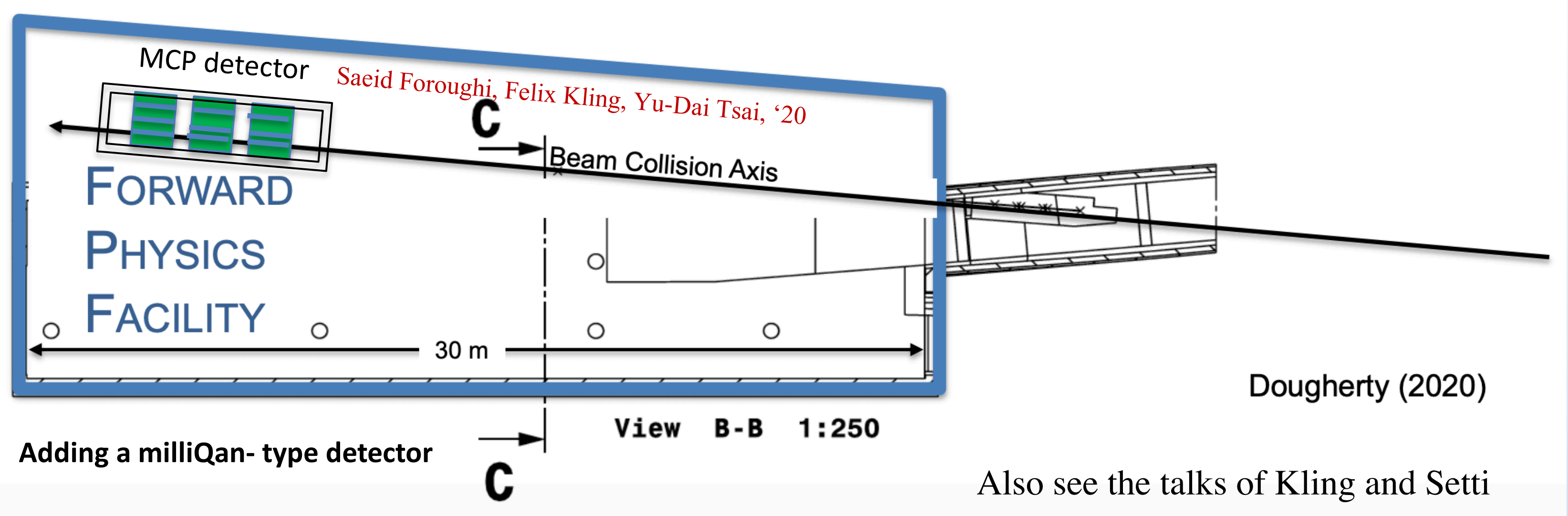


FORMOSA & Forward-DUNE - Looking Forward to Millicharged Dark Sectors and New Neutrino Physics

Yu-Dai Tsai, Fermilab / U Chicago

Saeid Foroughi, Felix Kling, Yu-Dai Tsai, arXiv:2010.07941

"Tau & Heavy Neutrino Electric Dipole Moment," Foroughi, Kling, Tsai, (see link!)

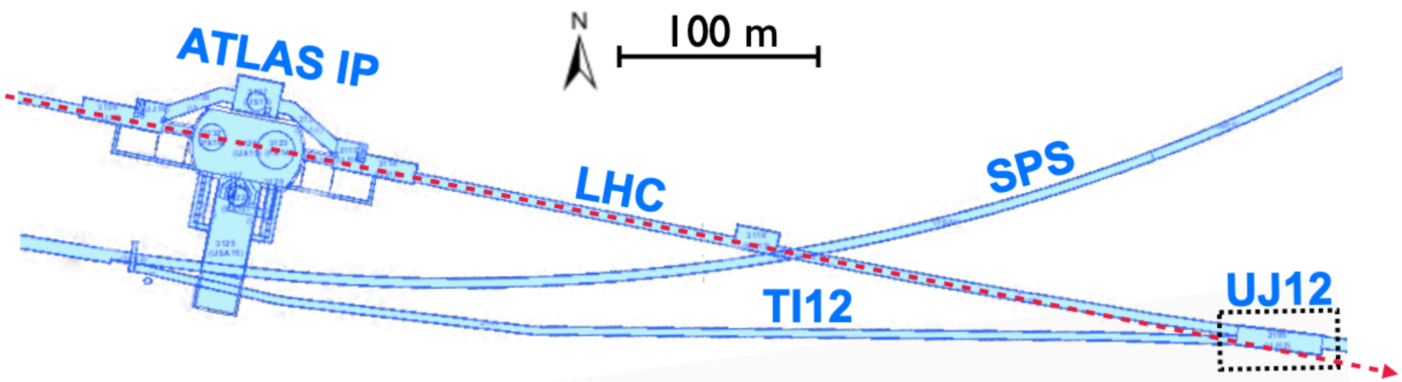
Forward proto-DUNE, Kling, Tsai (+ Feng, Foroughi, Cavanna), one slide

Email: ytsai@fnal.gov; arXiv: https://arxiv.org/a/tsai_y_1.html

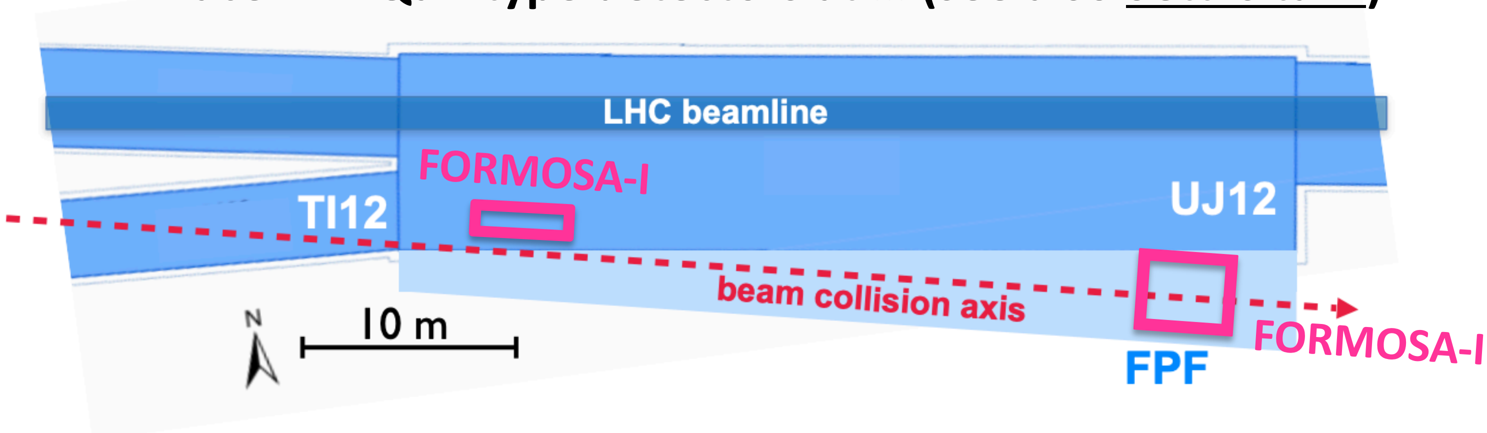
When Energy meets Intensity

- **The High-Intensity Energy Frontier: FPF**
- General LLP: **FASER**
- Specified (MCP): **FORMOSA**
- Neutrino: **FASERν + Forward-DUNE**
- Filling low-mass / high-mass gap (dark sector)
- low-energy / high-energy gap (neutrino)

FORMOSA: FORward MicrOcharge SeArch



Place milliQan-type detectors at … (see also Setti's talk)



Formosa means "beautiful" in Portuguese and is the ancient name of Taiwan

Outline

- Intro of millicharged particles (MCP)
- FORMOSA and its sensitivity reach
- Probing the strongly-interacting millicharged dark matter (SIMDM) window
- New idea: Forward (proto-)DUNE

Millicharged Particle & Dark Matter

Finding Minicharge

- **Is electric charge quantized and why?** A long-standing question!

- SM U(1) allows arbitrarily small (any real number) charges.
  Why don't we see them? Motivates **Dirac quantization, Grand Unified Theory (GUT)**, to explain such quantization
  (anomaly cancellations fix the SM $U(1)_Y$ charge assignments)

- MCP (not confined) is predicted by Superstring theories:
  Wen, Witten, Nucl. Phys. B 261 (1985) 651-677, Youtube: link
  Link to string compactification and quantum gravity (Shiu, Soler, Ye, PRL '13)

- Conservatively, testing if e/3 is the minimal charge

- MCP could have natural link to dark sector (through dark photon, etc)

- Could account for (sometimes fractional) dark matter (DM) abundance;
  Used for the cooling of gas temperature to explain the EDGES anomaly
  [EDGES collab., Nature, (2018); Barkana, Nature, (2018)]. Refs in backup slides.

- Review of Accelerator Probes of MCP: TODAY at 4 pm Central Time! [link]

MCP Model

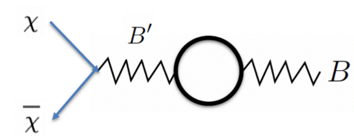
- A particle fractionally (or irrationally) charged under SM U(1) hypercharge, $\mathcal{L}_{\mathrm{MCP}} = i\bar{\chi}(\partial\!\!\!/ - i\epsilon' e B\!\!\!/ + M_{\mathrm{MCP}})\chi$

- ϵ' can in principle be arbitrarily small.

- Can just consider these Lagrangian terms by themselves (no extra mediator, i.e., dark photon). **Completely legal**! Naively **violating the empirical charge quantization**.

- We are simply search for MCP!
  Minimal assumptions = most robust constraints/probes.

- This could come from vector portal **Kinetic Mixing** (Holdom, '85)
  - a nice origin to the above terms
  - help give rise to **dark sectors: a dark photon model**
  - easily compatible with **Grand Unification Theory**
  - see backup slides

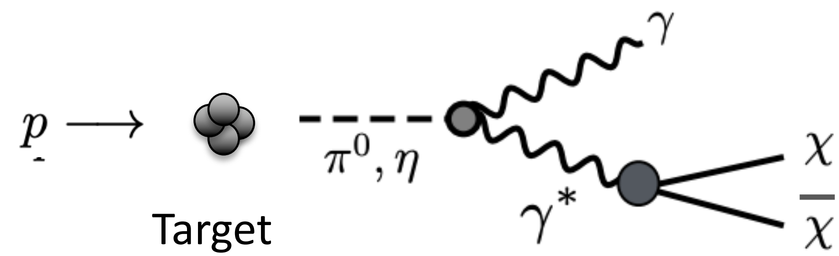


Important Notes!

- Our search is simply a search for particles (**fermion χ**) with **{mass, electric charge}** = $\{m_\chi, \epsilon e\}$
- **Minimal theoretical inputs/parameters** (need **high-energy/intensity machines** to probe in MeV – GeV+ mass regime)
- **Dark photon not necessary for MCP particles** (Neff, Self-Int. could provide extra constraints)
- Similar bound/sensitivity applies to scalar MCPs

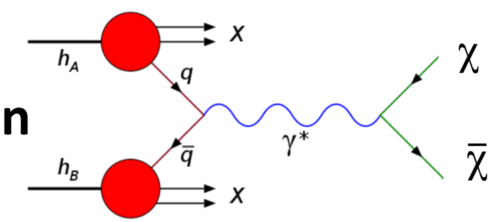
Important Production Channels of MCP

- ❑ **Production: Meson Decays**

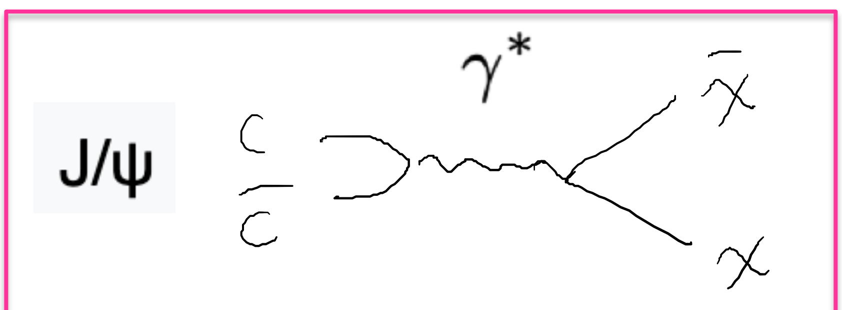


Modified from 1703.06881 (Izaguirre, Kahn, Krnjaic, Moschella)

- ❑ **Production: Drell-Yan**



❑ **Heavy (vector) mesons are important for high-mass mCP's in high-energy beams**



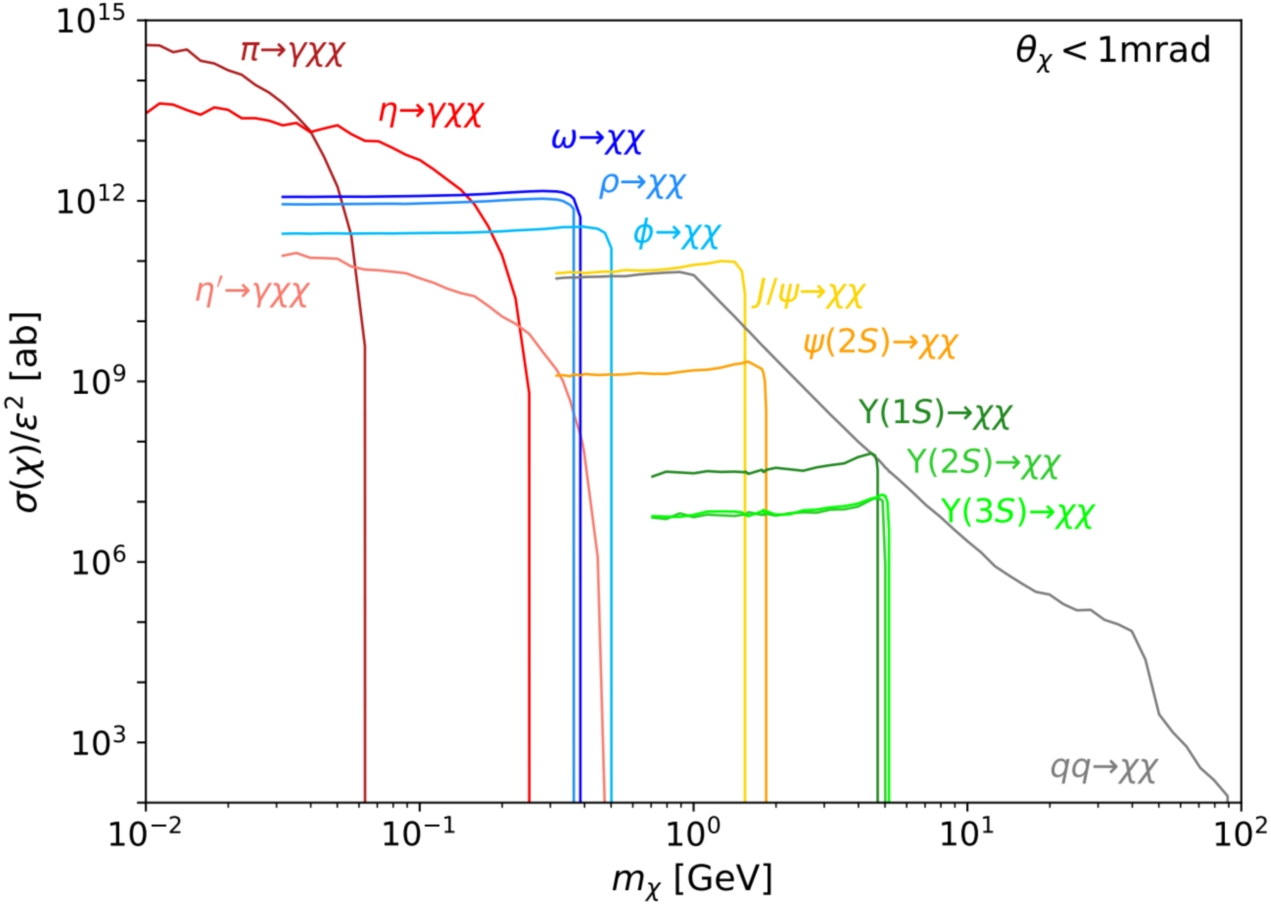
$BR(\pi^0 \to 2\gamma) = 0.99$

$BR(\pi^0 \to \gamma e^- e^+) = 0.01$

$BR(\pi^0 \to e^- e^+) = 6 * 10^{-6}$

$BR(J/\psi \to e^- e^+) = 0.06$

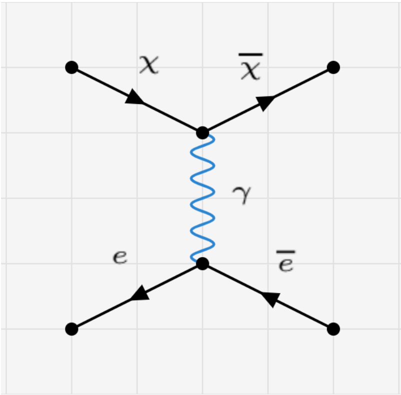
MCP Production/Flux



Saeid Foroughi, Felix Kling, Yu-Dai Tsai, arXiv:2010.07941

Flux much more enhanced comparing to the transverse region

MCP Detection: Ionization or Hard Scattering



- **MCP's & light-mediator scattering:** favors scattering with **small energy transfer**
- **Different from Neutrino (exchange heavy boson), MCP exchange photon**
- **studying ionization / scintillation** or **measuring low-energy electron recoils**
- **Ionization (eV-level):** ~ very low-energy scattering**: (triple / quadruple scintillation)**

  MilliQan: arXiv:1410.6816, Haas, Hill, Izaguirre, Yavin
- "Hard" (MeV-level) electron elastic scattering: (single / double hit)

  see, e.g., Magill, Plestid, Pospelov, **Tsai**, 1806.03310 (MCP in neutrino Experiments)

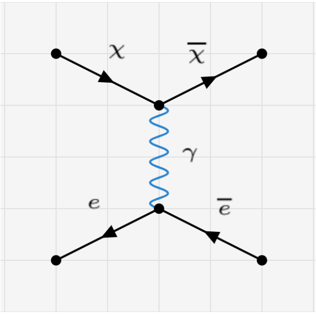
MCP Detection: Electron Scattering

- $\boldsymbol{Q^2}$ is the squared 4-momentum transfer.

- lab frame: $Q^2 = 2m_e\,(E_e - m_e)$, $E_e - m_e$ is the electron recoil energy.
- Expressed in **recoil energy threshold**, $E_e^{(min)}$, we have

$$\sigma_{e\chi} \simeq 2.6 \times 10^{-25}\mathrm{cm}^2 \times \epsilon^2 \times \frac{1\ \mathrm{MeV}}{E_e^{(\mathrm{min})} - m_e}.$$

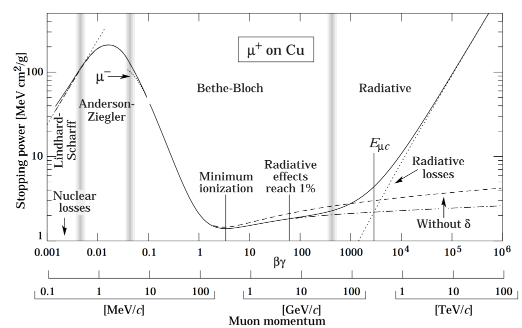
- Sensitivity greatly enhanced by accurately **measuring low energy electron recoils** **for MCP's & light-mediator scattering**



MCP Detection: Ionization

- Want very low momentum transfer**: ionization and scintillation signature**
- Signature proportional to **- dE/dx of the MCP, referred to as energy loss/stopping power**
- Can be approximated with the Bethe-Bloch Formula (various modified versions and detailed considerations.)

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

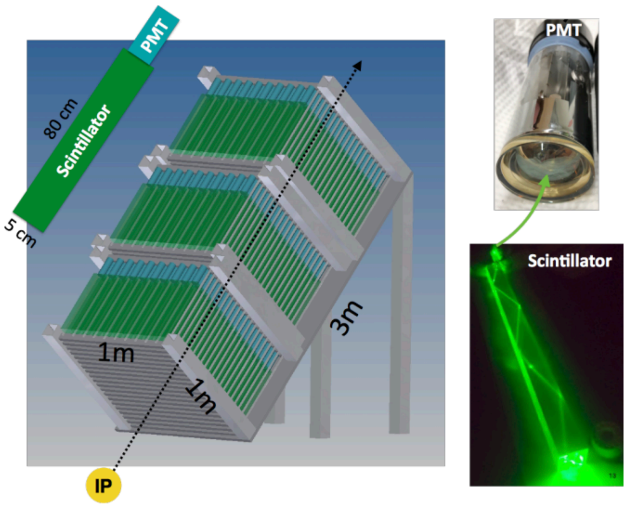


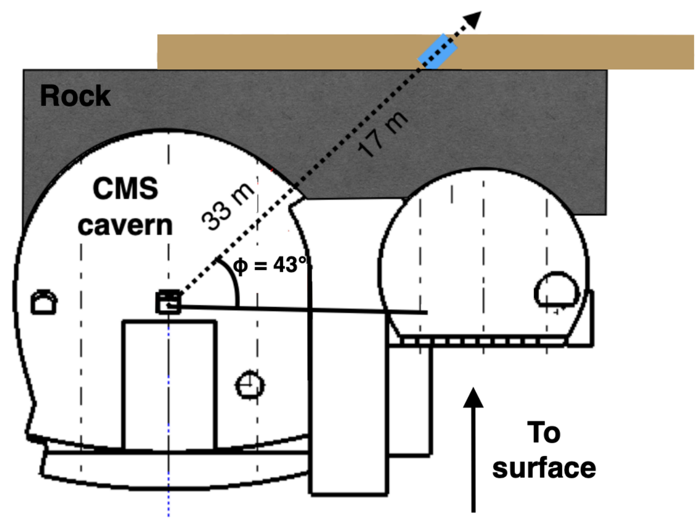
intentionally make the plot small so we don't get into too much details of this.
http://pdg.lbl.gov/2020/reviews

MilliQan

- MilliQan: arXiv:1410.6816, Haas, Hill, Izaguirre, Yavin
- Also will show an update from the milliQan-prototype!
- From milliQan Collaboration:

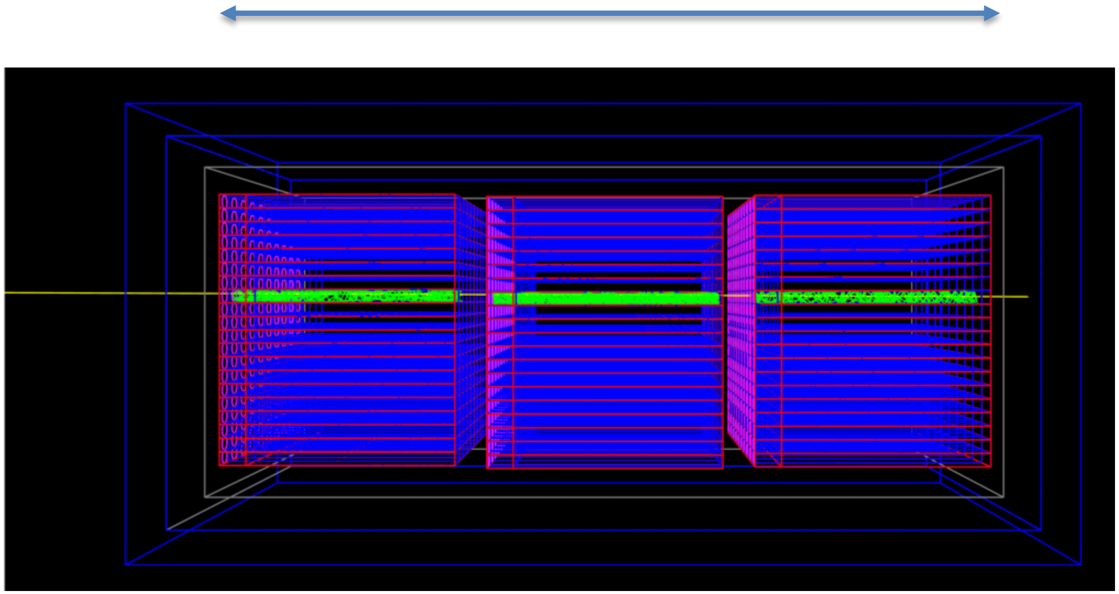
- LOI: 1607.04669
- First result update: 2005.06518 (will get into this more)

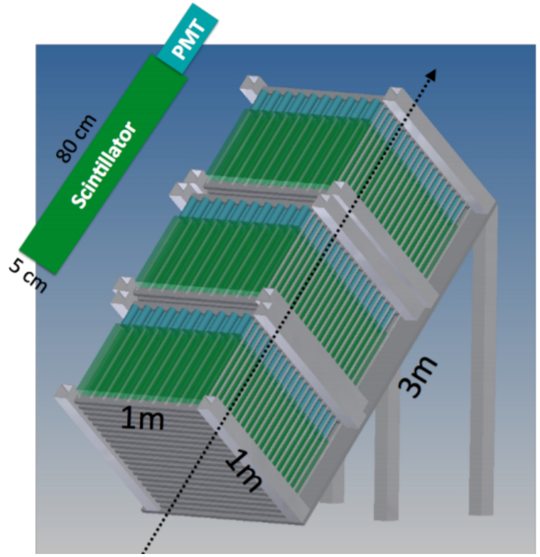


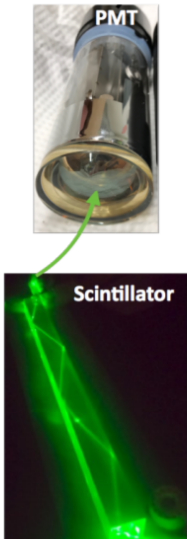


MCP Detector Concept

$$(\Delta t)_{\text{offline}} = 15\,\text{ns}$$







1607.04669, (MilliQan Collaboration)
Ball, Brooke, Campagnari, De Roeck, Francis, Gastal, Golf, Goldstein, **Haas**, **Hill**, **Izaguirre**, Kaplan, Magill, Marsh, Miller, Prins, Shakeshaft, Stuart, Swiatlowski, **Yavin**

Photoelectrons (PE) from Scintillation

- **The averaged number of photoelectron (PE)** seen by the detector from single MCP is:

$$N_{PE} \propto \left\langle -\frac{dE}{dx} \right\rangle \times l_{scint}, \quad \left\langle -\frac{dE}{dx} \right\rangle \propto \epsilon^2.$$

$\langle dE/dx \rangle$ is the "mass stopping power" (PDG 2018)

One can use modified **Bethe-Bloch Formula** to get an approximation

- $\boldsymbol{N_{PE}} \sim \epsilon^2$ x $\mathbf{10^6}$ for **1 - meter plastic scintillation bar**
- $\epsilon \sim \mathbf{10^{-3}}$ roughly gives one PE

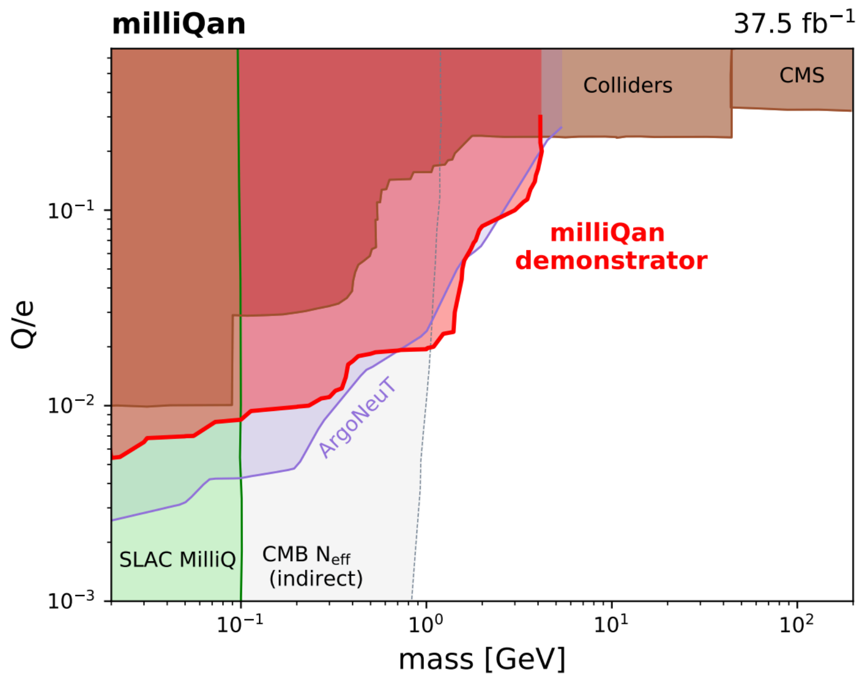
Signature: Triple Coincidence

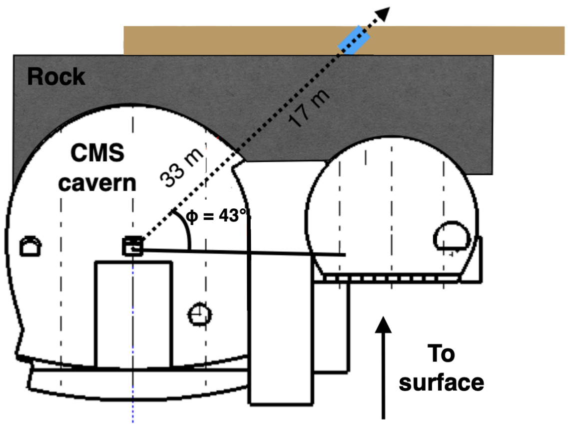
- Based on Poisson distribution, zero event in each bar correspond to $\boldsymbol{P_0} = \boldsymbol{e^{-N_{PE}}}$, so the probability of seeing triple incident of one or more photoelectrons is:

$$P = \left(1 - e^{-N_{PE}}\right)^3$$

- **$\mathbf{N_{x,detector}}$ = $\mathbf{N_x}$ (going through detector)** x **P.**

Proto-milliQan Update!

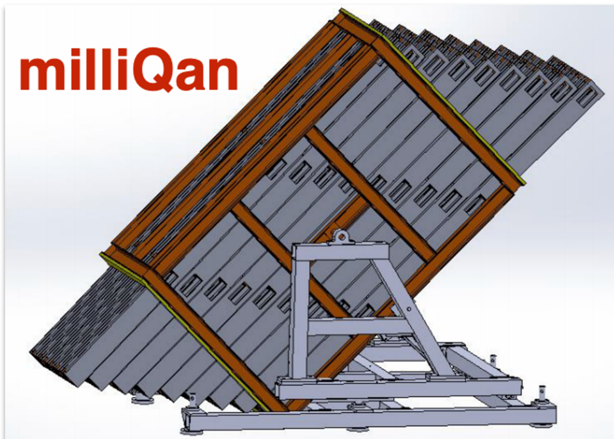




- ~1% of the full milliQan (total of 18 bars)
- LHC ’18 of 37.5 fb−1 at a center-of-mass energy of 13 TeV.
- A prototype scintillator-based detector is deployed to conduct the first search at a hadron collider
- 20 and 4700 MeV is excluded at 95% confidence level for charges between 0.006e and 0.3e

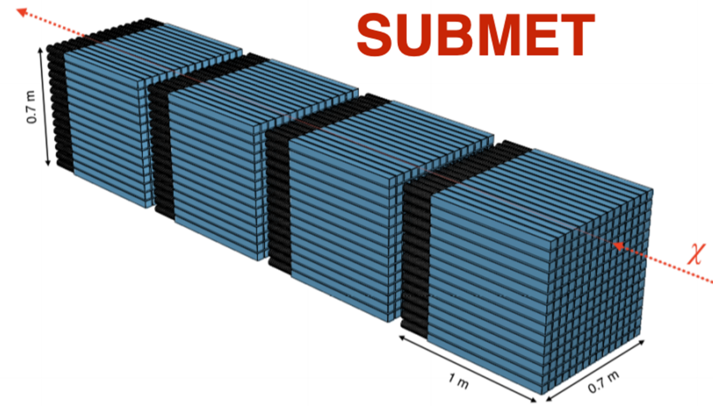
MilliQan prototype: updates on the results
https://arxiv.org/pdf/2005.06518.pdf
(milliQan Collaboration)

Scintillation based detection



LHC with sensitivity for m < ~45 GeV

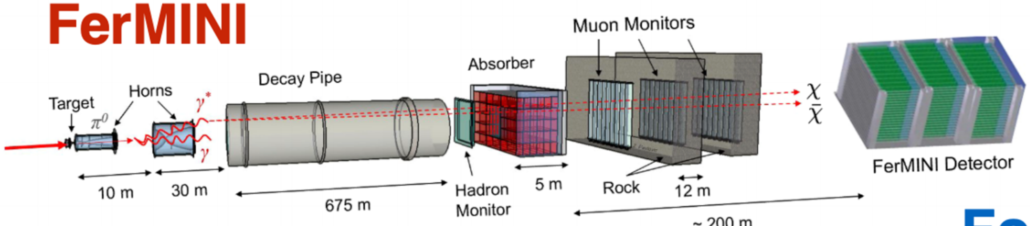
1607.04669



J-PARC with sensitivity for m < ~1.5 GeV

2007.06329

FerMINI



Range of detectors with complementary sensitivity

Fermilab with sensitivity for m < ~5 GeV

1812.03998

For milliQan: proof of concept "demonstrator" installed at CERN

M. Citron mcitron@ucsb.edu 4

Directly from **Matthew Citron**'s talk at NF3 kickoff meeting: link

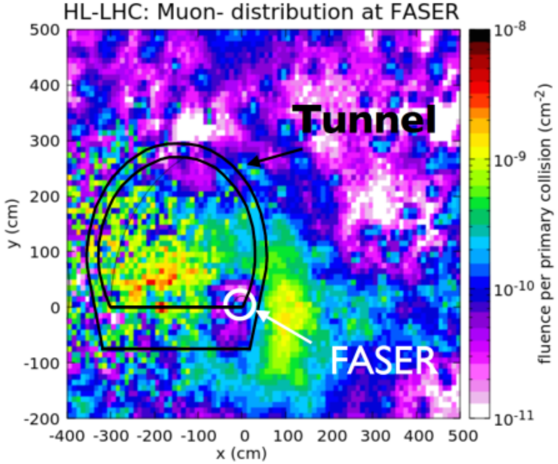
See Snowmass LOI "Sensitivity reach of scintillator-based detectors for millicharged particles" (link)

A New Challenge in the Forward Region

Stronger Beam related background:

- ❑ New challenge arises due to large flux of **High-Energy Muons** (and secondary particles) from the beam collisions
- **FLUKA simulation** performed by CERN STI group estimated muon flux < ~ 1 Hz/cm2 resulting in roughly ~ one muon every **100** μs
- ❖ Feasible task: implementing an **online-veto of large-PE** events

But this is not the full story …

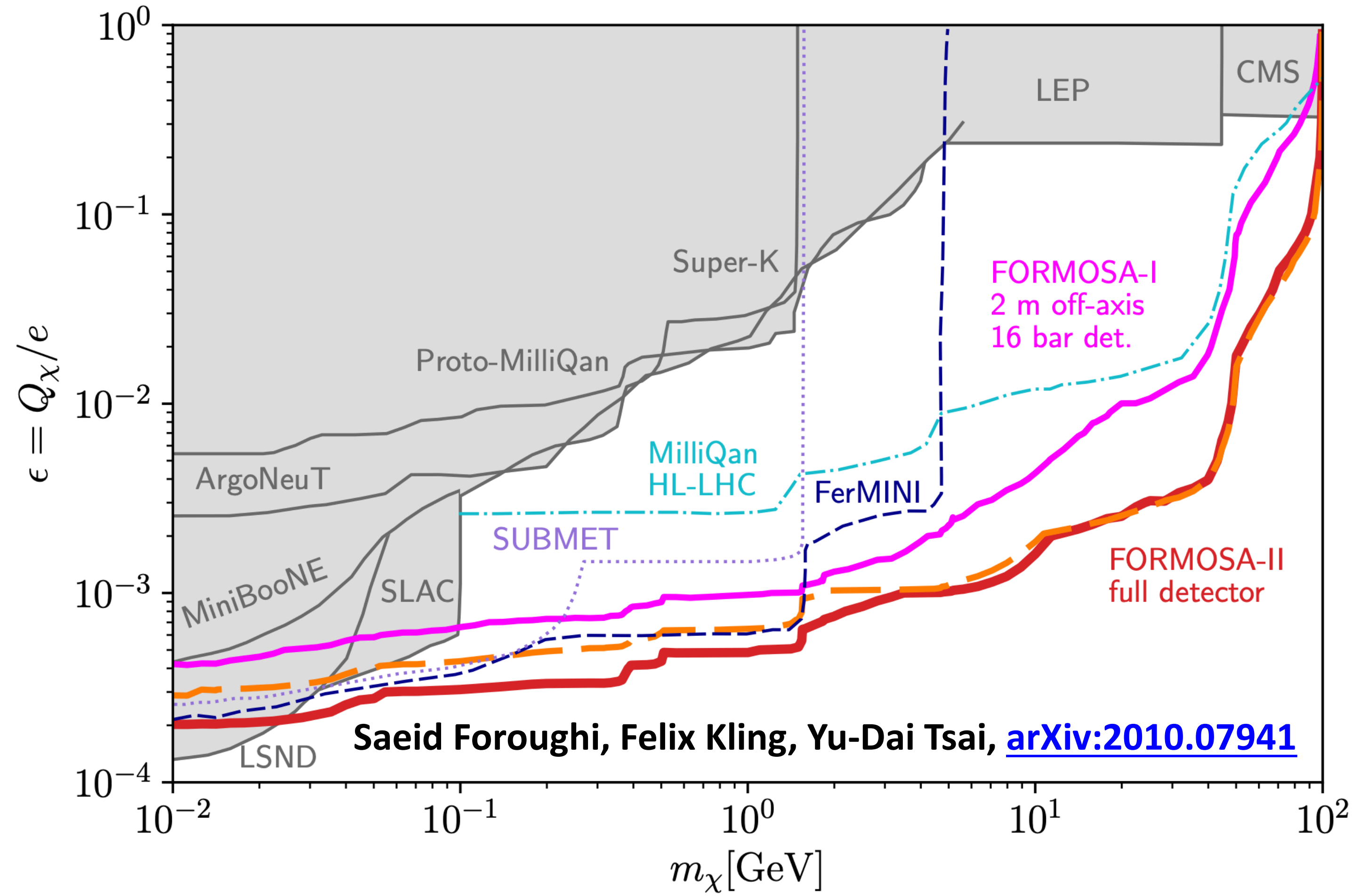


FASER Collaboration, arXiv:1812.09139

- ❑ **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 can also improve the live-time efficiencies

Thank Saeid, Matthew, and Felix for help preparing this slide.

FORMOSA Sensitivity



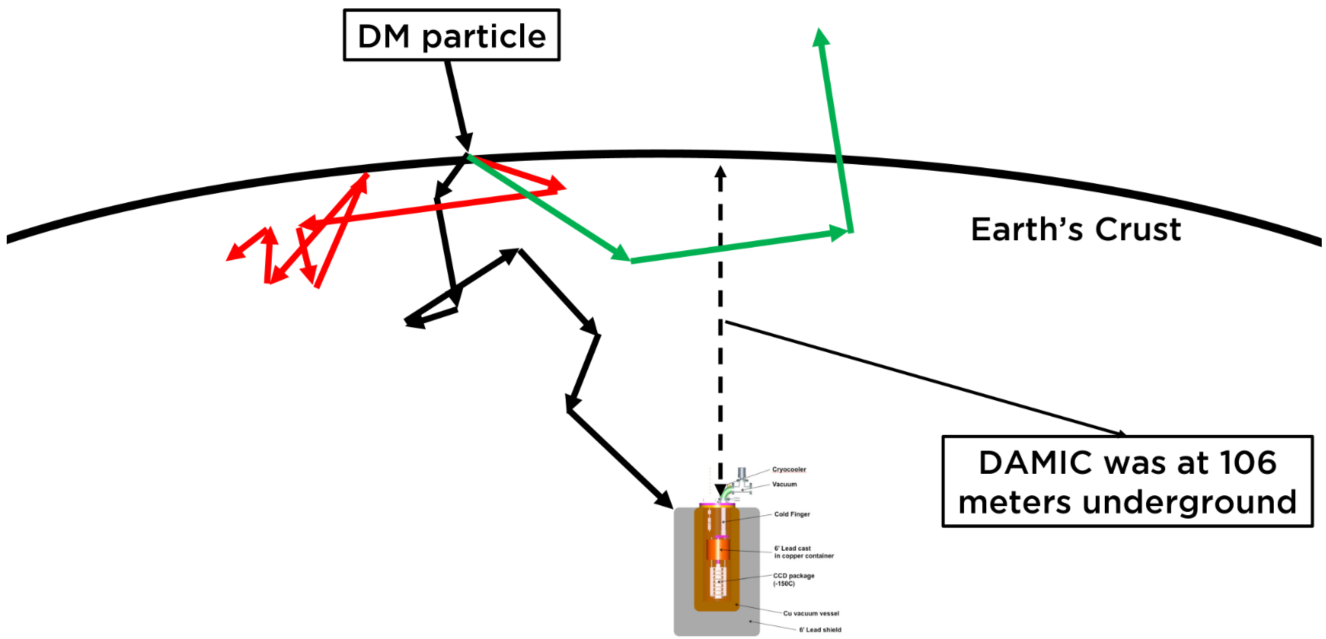
FORMOSA-I: ~ **0.2 m × 0.2 m × 4 m; 4 layers of 16 scintillator bars @UJ12/TI12 tunnel.**

(can use the milliQan demonstrator: ~ **5 cm × 5 cm × 3 m; 3 layers of 6 scintillator bars)**

FORMOSA-II: ~ **1 m × 1 m × 4 m; 4 layers of 400 scintillator bars @ FPF.**

Strongly Interacting Dark Matter

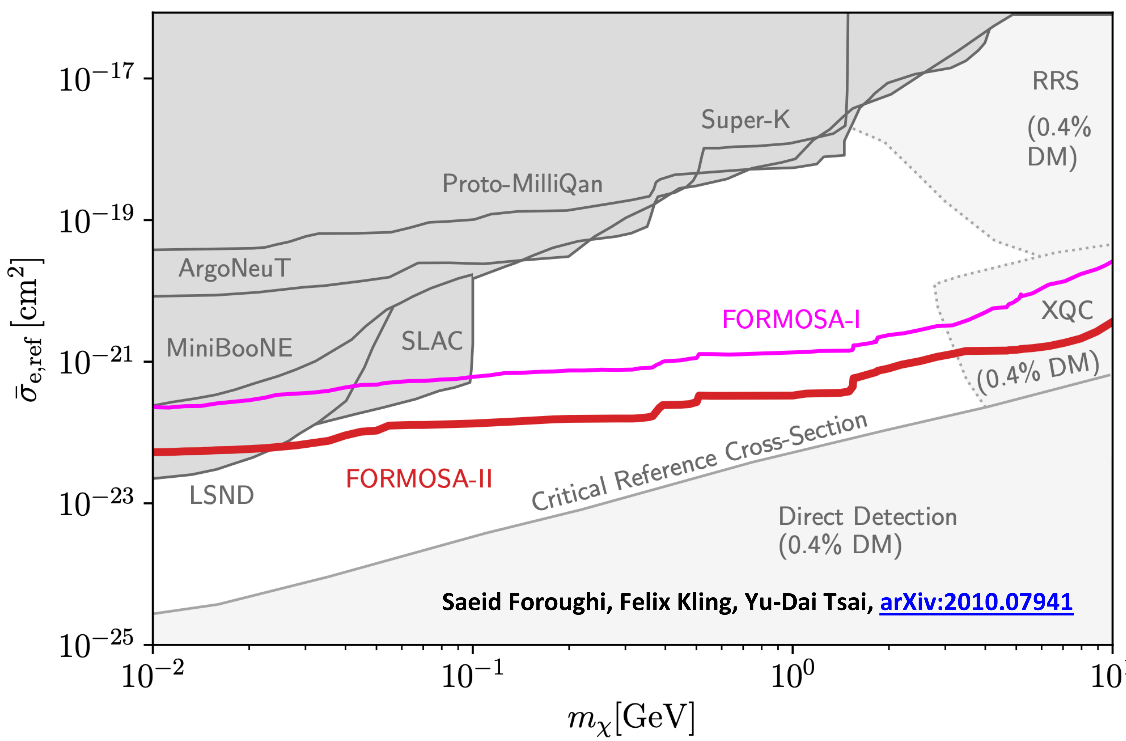
DM-SM Interaction too strong that attenuation stop the particles from reach the direct detection detector



DMATIS (Dark Matter ATtenuation Importance Sampling), Mahdawi & Farrar '17
Also, see Mahdawi & Farrar, arXiv:1804.03073

Probe of Millicharged Dark Matter

$$\bar{\sigma}_e \simeq \frac{16\pi\alpha^2\epsilon^2\mu_{\chi e}^2}{q_{ref}^2}, \; q_{ref} = \alpha m_e$$



- Here we plot the **critical reference cross-section** see 1905.06348 (Emken, Essig, Kouvaris, Sholapurkar)
- Cosmic-Ray Production/Super-K Detection 2002.11732
- **FORMOSA can help close the Millicharged SIDM window!**

Looking Ahead

Action plan:

- Run 3: placing milliQan demonstrator:

  ~ 5 cm × 5 cm × 3 m; 3 layers of 6 scintillator bars @UJ12/TI12 tunnel.

- FORMOSA-I:

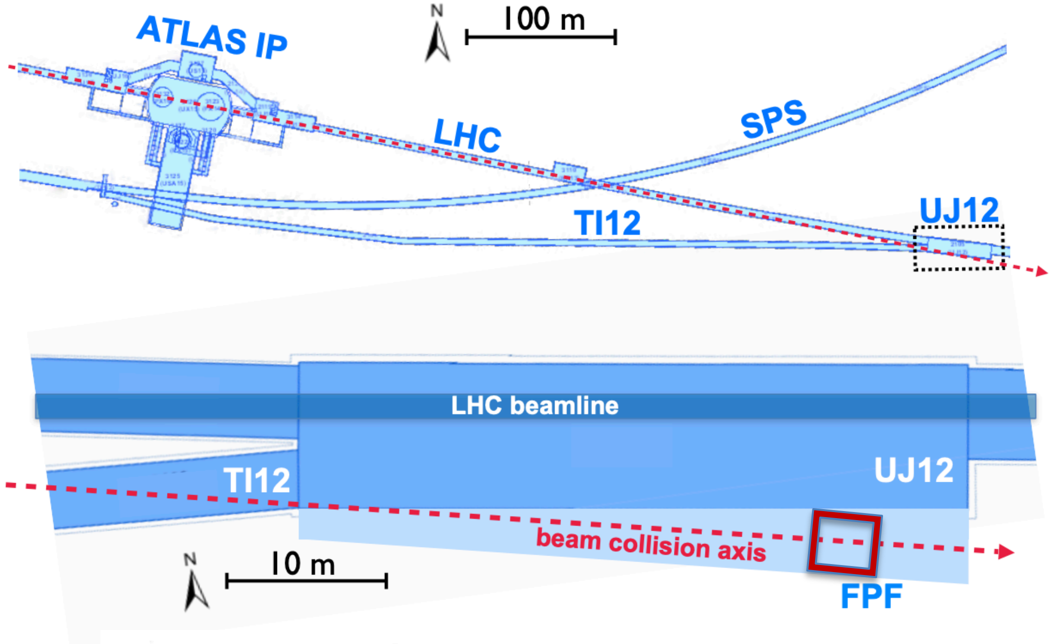
  ~ 0.2 m × 0.2 m × 4 m; 4 layers of 16 scintillator bars @UJ12/TI12 tunnel.

- FORMOSA-II:

  ~ 1 m × 1 m × 4 m; 4 layers of 400 scintillator bars @ FPF.

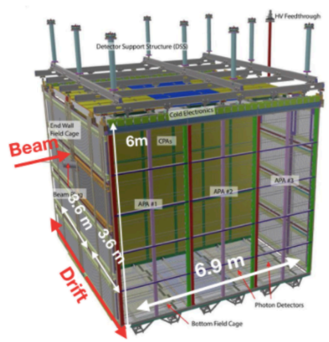
Other new ideas? Neutrino physics?

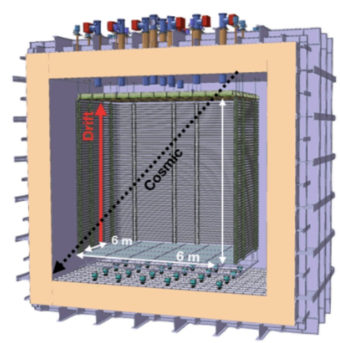
Forward Proto-DUNE (Forward-DUNE!)



New idea!
Kling, **Tsai** (+ Feng, Foroughi, Cavanna)

Single-Phase (SP) liquid argon time projection chamber (LArTPC)
7.2×6.0×6.9 m^3





Duel-Phase (DP) Detector
6 x 6 x 6 m^3 LAr TPC

Figure 3: Left: draft of ProtoDUNE-SP [2]. Right: draft of ProtoDUNE-DP [3]

DUNE Collaboration (arXiv:1706.07081 + arXiv:1409.4405)
Updates, see, e.g. arXiv:1910.10115 & arXiv:2007.06722

Thank you!

Special thanks to my collaborators and the organizers.

Thank Albert for the invitation!

Para uma formosa aventura!

Review: Accelerator Probes of MCP

- HEP/Astro Results Forum talk, “Accelerator Probes on Millicharged Particles and Dark Matter”.
- HEP/Astro Results Forum website: https://sites.google.com/site/lhcresultsforumtalks/
- Link to subscribe to this mailing list: https://utlists.utexas.edu/sympa/subscribe/lhcresultsforum

The relevant literatures are growing fast, please let us know if we miss mentioning your important works.

Backup Slides and Information

More on MCP/DM & 21-cm Cosmology

Some more reference of **Millicharged DM (mDM) and constraints**.

See, e.g.,

McDermott, Yu, Zurek, 1011.2907;

Muñoz, Dvorkin, Loeb, 1802.10094, 1804.01092;

Berlin, Hooper, Krnjaic, McDermott, 1803.02804;

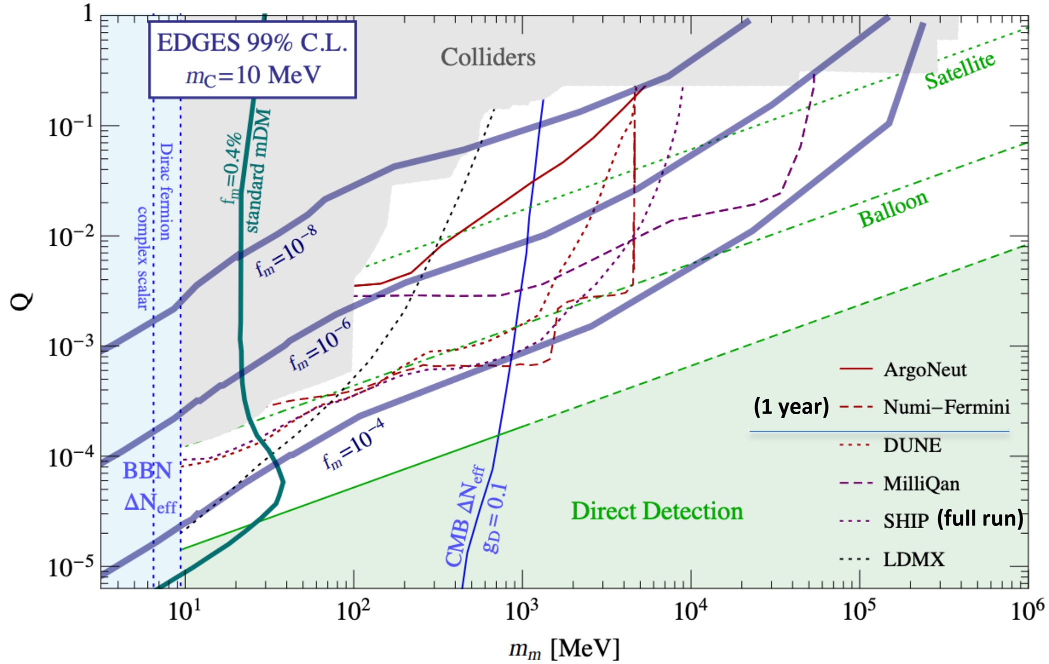
Kovetz, Poulin, Gluscevic, Boddy, Barkana, Kamionkowski, 1807.11482;

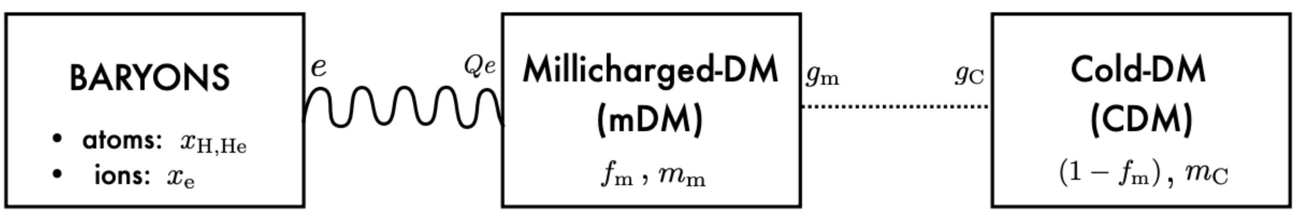
Liu, Outmezguine, Redigolo, Volansky, 1908.06986:

"Reviving Millicharged Dark Matter for 21-cm Cosmology,"

Introduces a long-range force between a subdominant mDM and the dominant cold dark matter (CDM) components. Leads to efficient cooling of baryons in the early universe. Extend the range of viable mDM masses for EDGES explanation to ~ 100 GeV.

MDM as an EDGES Explaner

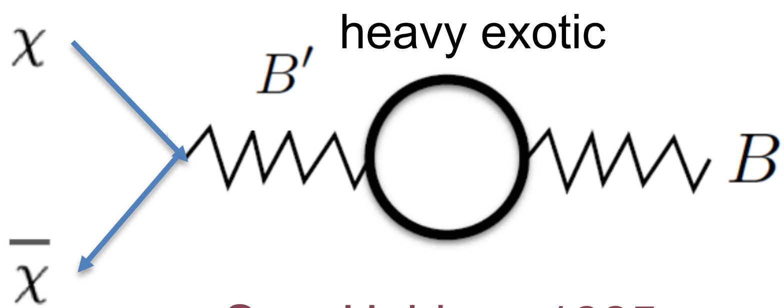




Liu, Outmezguine, Redigolo, Volansky, '19
For more refs, see backup slides

Kinetic Mixing and MCP Phase

- **Coupled to new dark fermion χ**



(SM: Standard Model)

See, Holdom, 1985

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

- New fermion χ charged under new gauge boson B'.

- 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** in a convenient basis.)
- Important Notes: Our search is simply a search for particles (**fermion χ**) with **{mass, electric charge}** = $\{m_\chi, \epsilon e\}$

Accelerator Probes of MCP: Reference

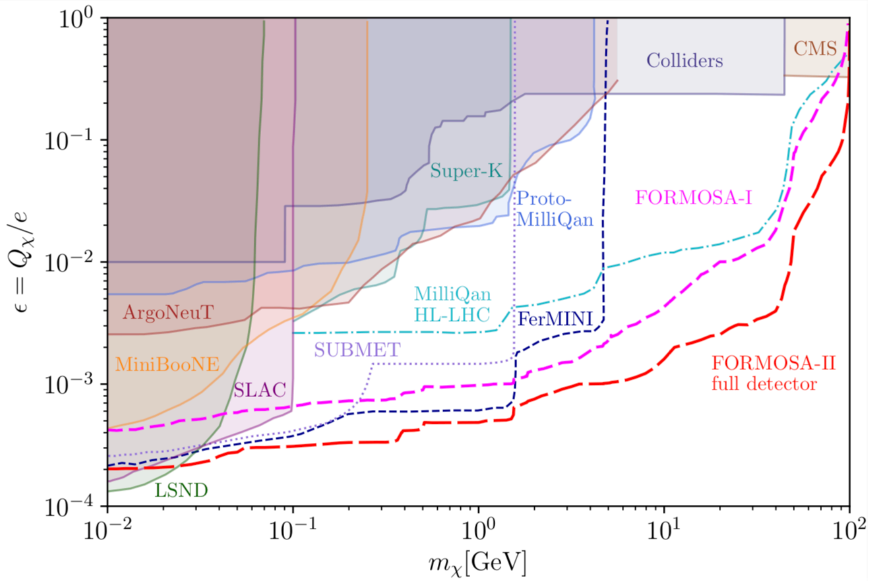
Works from other people and collaborations:

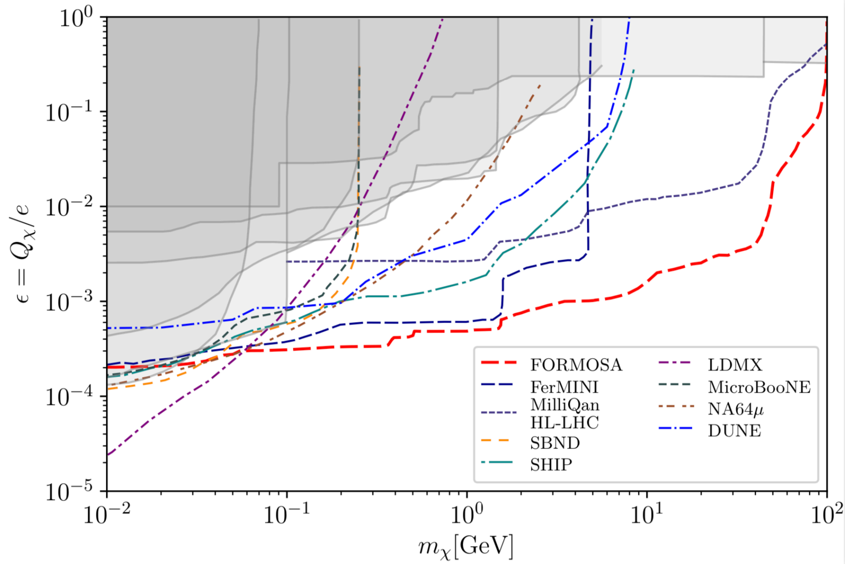
- SLAC mQ (hep-ex/9804008)
- Early collider bounds (LEP+) (hep-ph/0001179)
- Invisible decays of positronium (hep-ex/0609059)
- LHC - CMS (1210.2311)
- milliQan (1410.6816 + 1607.04669 + 2005.06518)
- LDMX MCP probe (1807.01730)
- NA64 MCP Probe (1810.06856)
- LArTPC's (1902.03246) / ArgoNeuT (1911.07996)
- MAPP (conf. proceeding, LHCP 2019)
- Electron colliders (1909.06847)
- SUBMET (2007.06329)
- …

Our works:

- MCPs in neutrino experiments (LSND, MiniBooNE, DUNE) (1806.03310)
- FerMINI (1812.03998), Fermilab today
- Cosmic-Ray production and detection in Super-K (2002.11732)
- Forward MCP Search (coming ~ next week)
- My review talk: https://indico.cern.ch/event/910753/contributions/3831616/

Compilation





- Our search is simply a search for particles (fermion χ) with **{mass, electric charge}** = $\{m_\chi, \epsilon e\}$
- **The result for scalar MCP is similar**
- $\epsilon \equiv Q_\chi/e.$