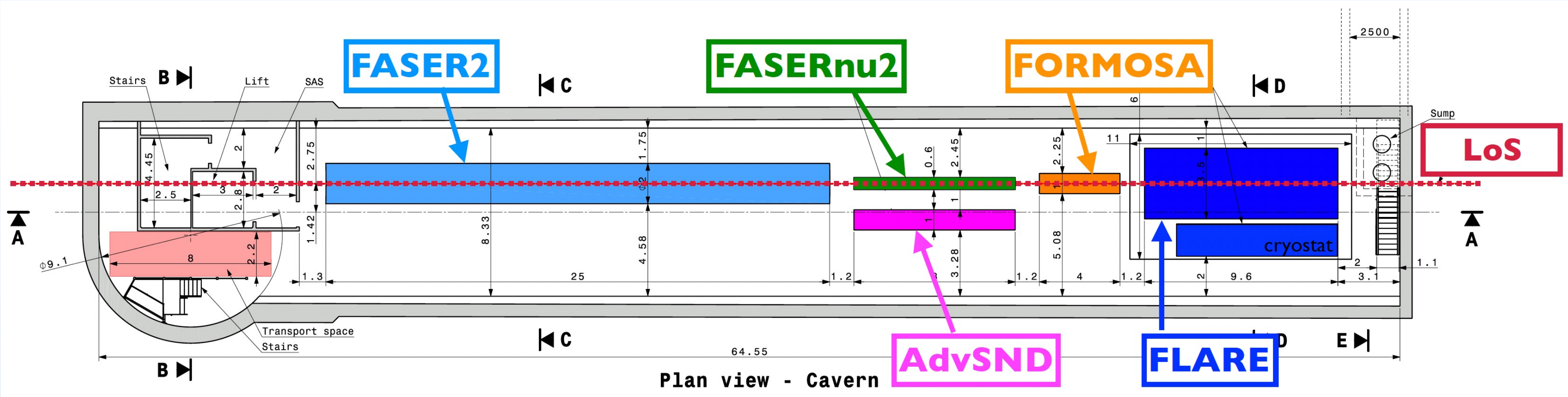


From Felix Kling, See, also, https://arxiv.org/pdf/2109.10905.pdf

Millicharge Particle Searches at FLArE

Yu-Dai Tsai

University of California, Irvine

My works on [Inspire](); Contact: [yt444@cornell.edu]() or [yudait1@uci.edu]()

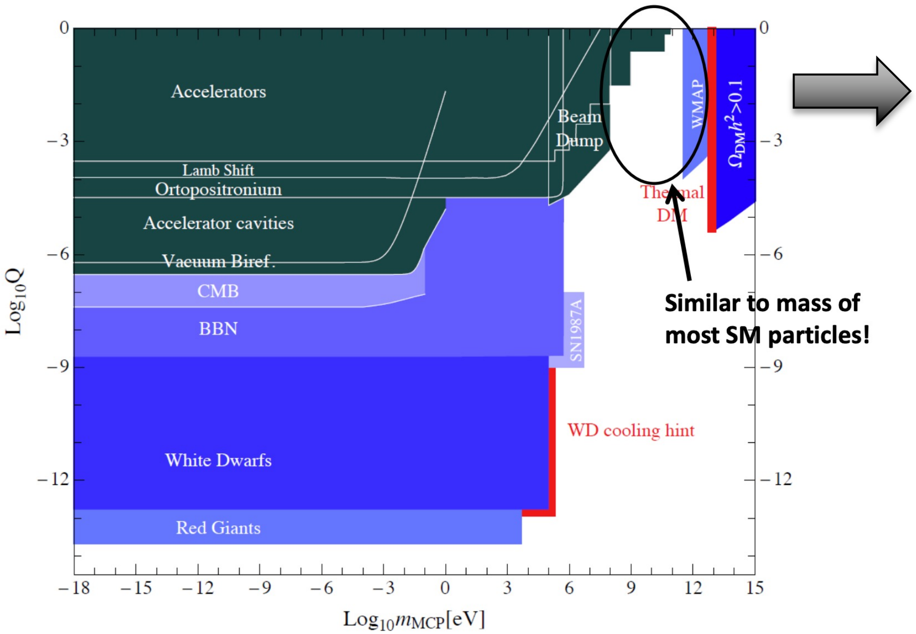
Mostly based on **Kling, Kuo, Trojanowski, Tsai,** [**arXiv:2205.09137**]()

I am in Snowmass, Colorado now and will be in Snowmass, Seattle

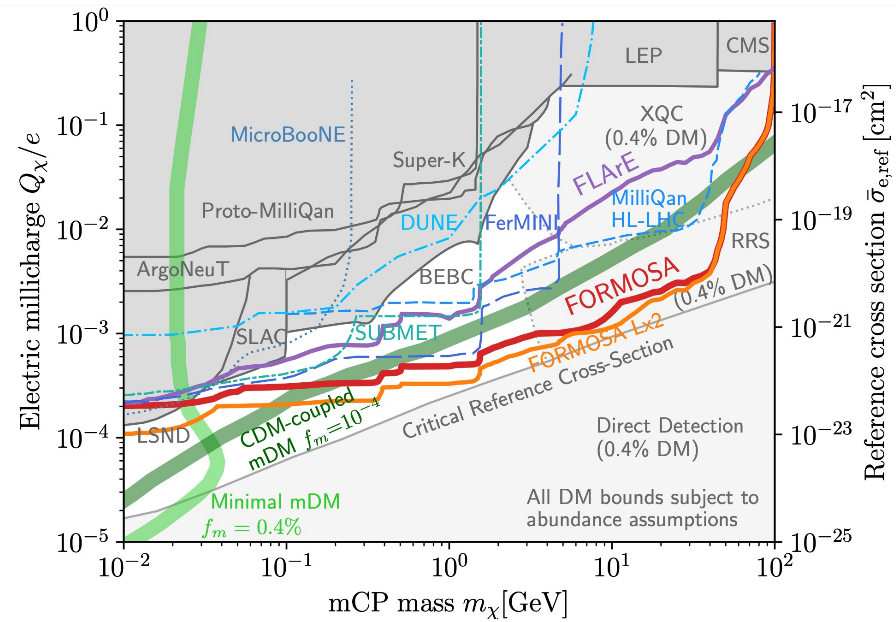
Outline

- millicharged particles & dark matter
- Search methods at FPF
- Signatures at FLArE
- Discussions, future directions, and potential projects

Tremendous Progress in Millicharge Studies



Andy Haas, Fermilab, 2017



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

- For millicharges, recent efforts led by **milliQan**,

  followed by, e.g, **neutrino experiments**, **FerMINI, SUBMET, FORMOSA, FLArE**
- **EDGES** rejuvenated millicharged & strongly interacting dark matter

Millicharged Particles (mCP) is an important benchmark model

RF06 Classification; **PBC** Benchmark

Benchmarks in Final State x Portal Organization

	DM Production	Mediator Decay Via Portal	Structure of Dark Sector
Vector	*m_χ vs. y [m_A/m_χ=3, α_D=.5]* **$m_{A'}$ vs. y** [α_D=0.5, 3 m_χ values] ~~m_χ vs. α_D [$m_{A'}/m_\chi$=3, y=y_{fo}]~~ m_χ vs. m_A [α_D=0.5, y=y_{fo}] *Millicharge m vs. q*	$m_{A'}$ vs. ϵ [decay-mode agnostic] ***$m_{A'}$ vs. ϵ [decays]***	**iDM m_χ vs. y [$m_{A'}/m_\chi$=3, α_D=.5] (anom connection)** **SIMP-motivated cascades [slices TBD]** $U(1)_{B-L / \mu-\tau / B-3\tau}$ (DM or SM decays)
Scalar	m_χ vs. sinθ [λ=0, fix m_S/m_χ, g_D] (thermal target excluded 1512.04119, should still include) Note secluded DM relevance of S→SM of mediator searches	*m_S vs. sinθ* [λ=0] *m_S vs. sinθ* [λ=s.t. Br(H→ss ~10^{-2})]?	Dark Higgsstrahlung (w/vector) scalar SIMP models Leptophilic/leptophobic dark Higgs
Neutrino	e/μ/τ a la1709.07001	*m_N vs. U_e* *m_N vs. U_μ* *m_N vs. U_τ* Think more about reasonable flavor structures	Sterile neutrinos with new forces
ALP	m_χ vs. fq/l [λ=0, fix m_a/m_χ, g_D] (thermal target excluded) What about f_γ, f_G?	*m_a vs. f_γ* *m_a vs. f_G* *m_a vs. f_q=f_l* *m_a vs. f_W*	FV axion couplings

Bold = BRN benchmark, *italic=PBC benchmark.* others are new suggestions. Underline=CV benchmarks that were not used in BRN

PBC: The Physics Beyond Colliders initiative at CERN

Theory overview &
Connections to cosmic observations

Yu-Dai Tsai, UC Irvine, 2022

Theoretical Motivations

- **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 some SM $U(1)_Y$ charge assignments)
- MCP (not confined) is predicted by some Superstring theories:
  Wen, Witten, Nucl. Phys. B 261 (1985) 651-677
  https://www.youtube.com/watch?v=AmUI2qf9uyo (watch 15:50 to 17:28)
- Link to **string compactification** and **quantum gravity** (Shiu, Soler, Ye, PRL '13)
- Conservatively, testing if e/3 is the minimal charge
- Simply a search for particles with **{mass, electric charge}** = $\{m_\chi, \epsilon e\}$

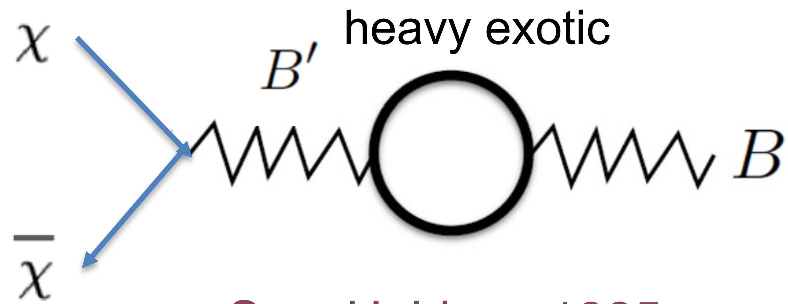
$\epsilon = Q_x/e$

mCP Model

- A particle fractionally (or irrationally) charged under SM U(1) hypercharge $$\mathcal{L}_{\text{MCP}} = i\bar{\chi}(\not{\partial} - i\epsilon' e \not{B} + M_{\text{MCP}})\chi$$
- 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** (cool).
- 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**
  - easily compatible with **Grand Unification Theory**

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'.

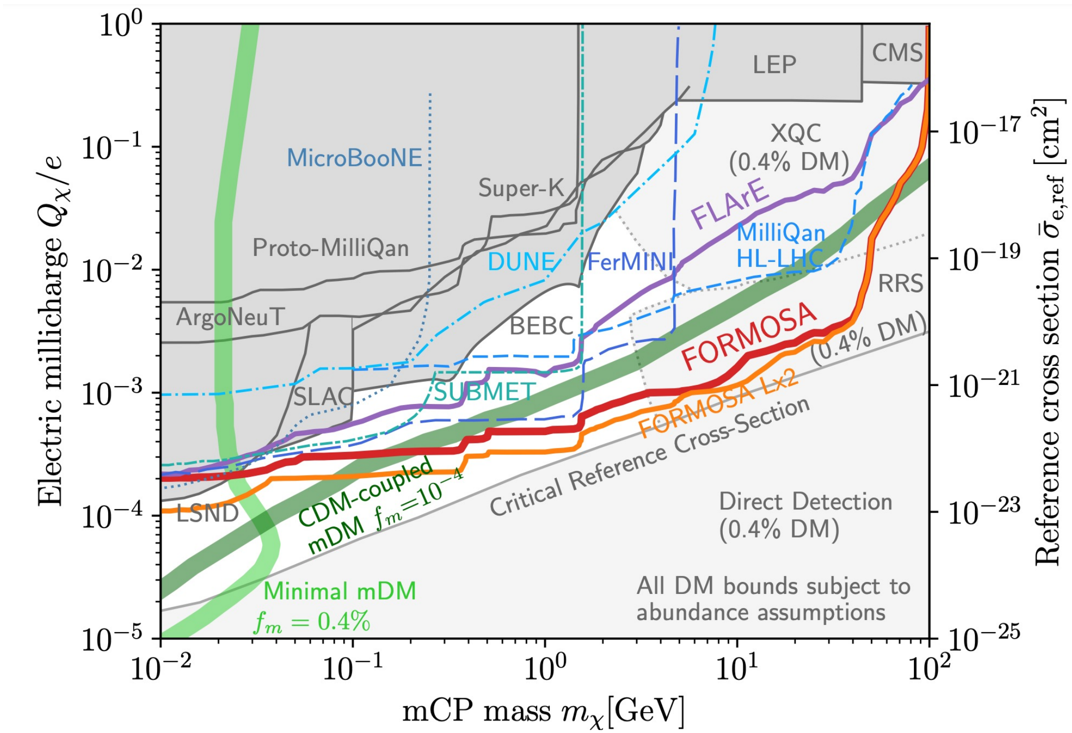
- Millicharged particle (MCP) can be a **low-energy consequence** of **massless dark photon** (a new U(1) gauge boson) coupled to **a new fermion (become MCP** in a convenient basis.)

What if dark matter (DM) is millicharged

Strongly Interacting Dark Matter

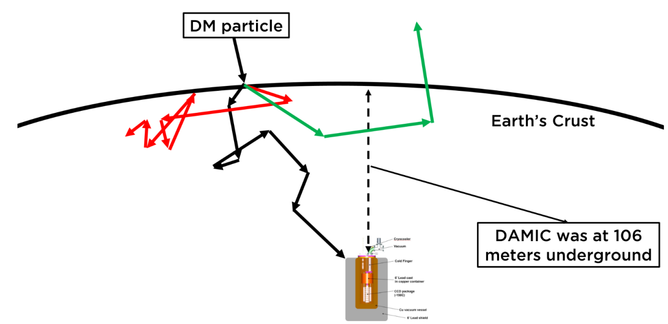
MCP / LDM with ultralight dark photon mediators

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



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

- We will add this figure with all the projections to the Snowmass White Paper
- **Can add this to new milliQan papers**

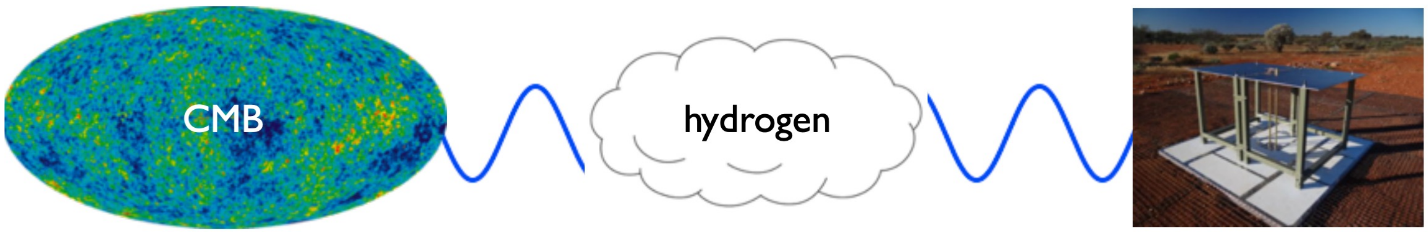


DMATIS (Dark Matter ATtenuation Importance Sampling), Mahdawi & Farrar '17

- Here we plot the **critical reference cross-section** see 1905.06348 (Emken, Essig, Kouvaris, Sholapurkar)
- **Accelerator probes can help close the Millicharged SIDM window!**
- Cosmic-ray production & Super-K detection 2002.11732

Dark Matter May have Small Charge?

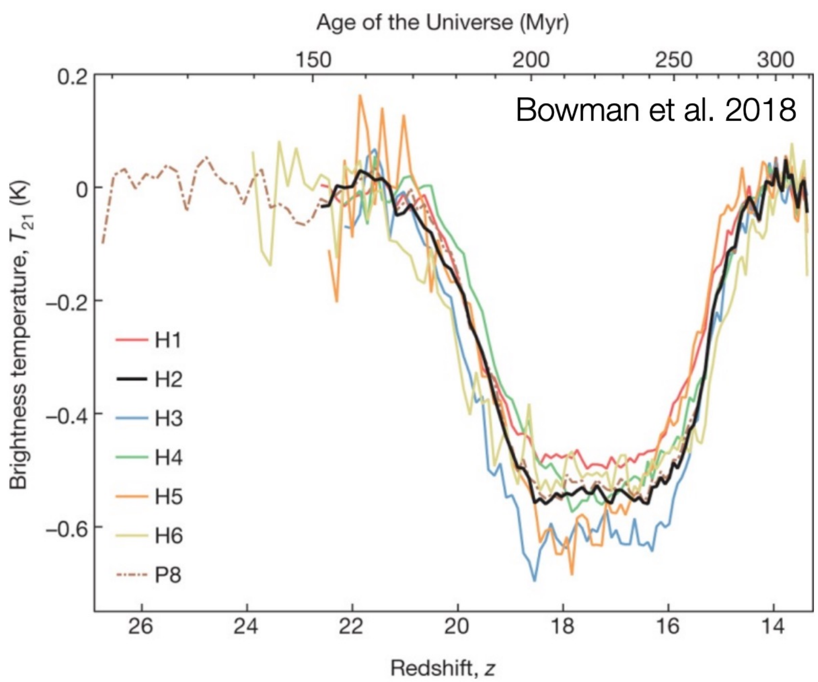
T_γ T_S δT_b



Adapted from J. Pritchard

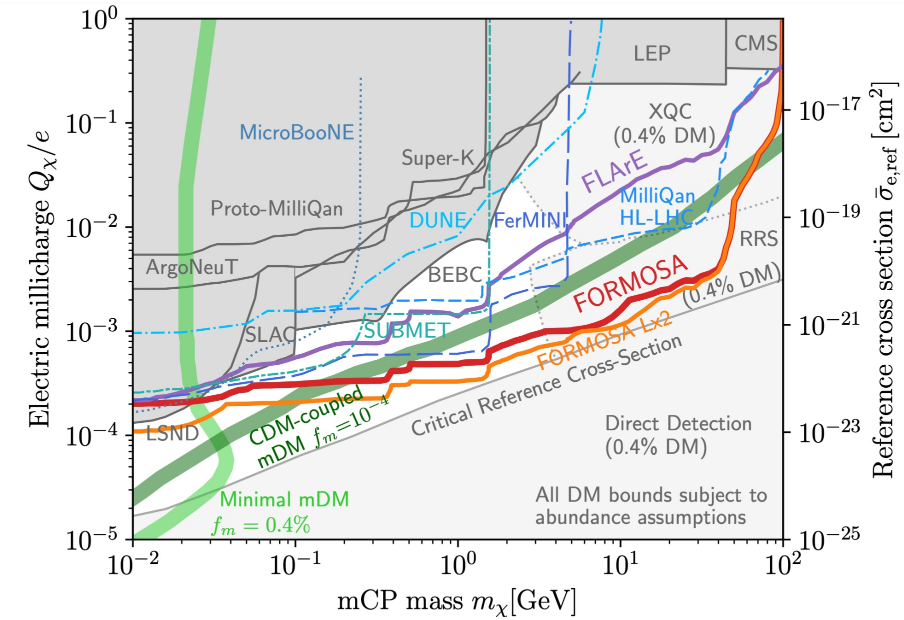
From Jordan Mirocha (UCLA)

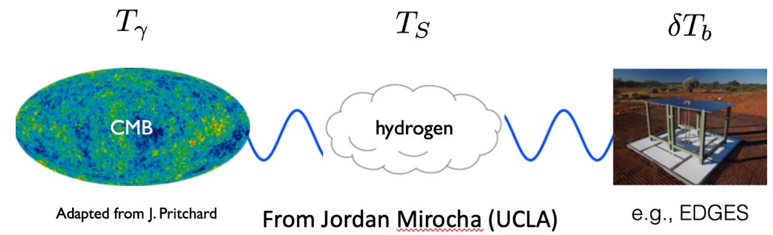
e.g., EDGES



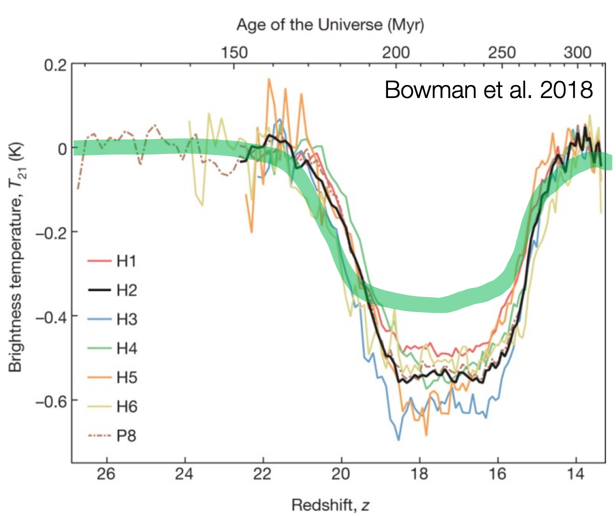
- EDGES collab., Nature, (2018); Barkana, Nature, (2018), more refs listed in the end
- The result is still **heavily debated!!!**
- Millicharged dark matter has strong effects!
- Rekindle the interests in **mCP dark matter**

EDGES & Millicharged Dark Matter





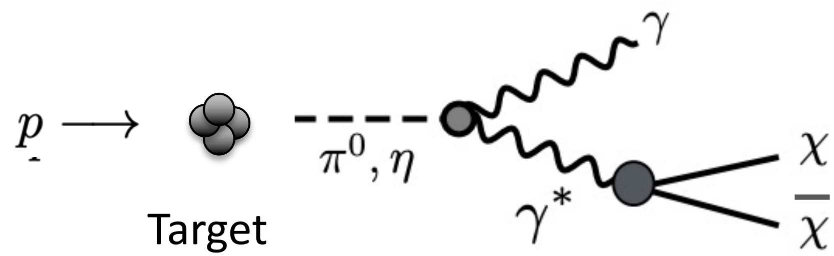
- EDGES gives another hint of dark matter property, just like small-scale structure
- **Can add this to new milliQan papers**
- Connecting to **cosmology** & **dark matter** direct-detection folks
- Demonstrate to **them the power of accelerator probes** & **milliQan-type detectors**
- See Liu, Outmezguine, Redigolo, Volansky, '19 for the 10^{-4} curve



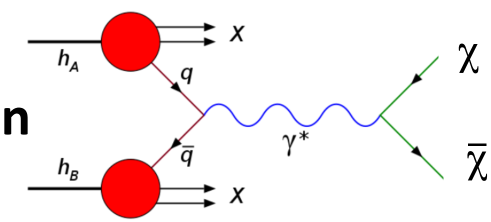
General Search Methods @ FPF

Production of MCP

- ❑ **Production: Meson Decays**



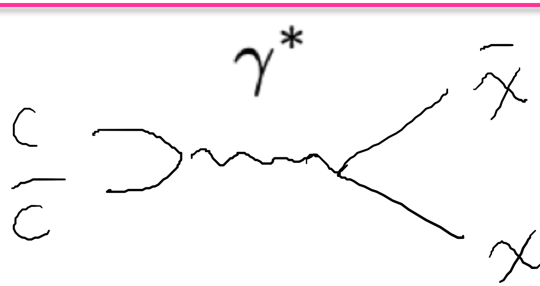
- ❑ **Production: Drell-Yan**



Important for LHC Searches

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

J/ψ



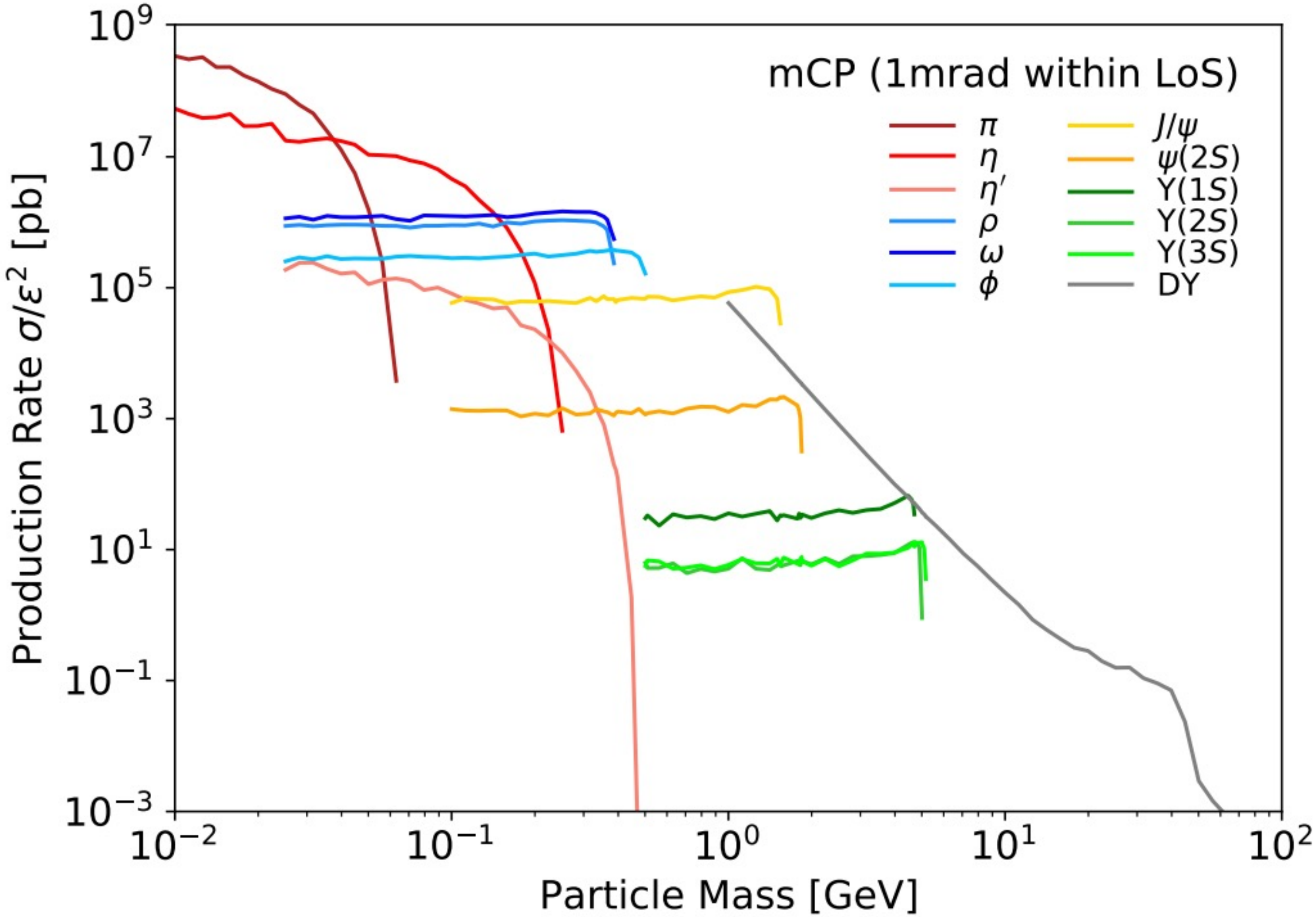
$BR(\pi^0 \rightarrow 2\gamma) = 0.99$

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

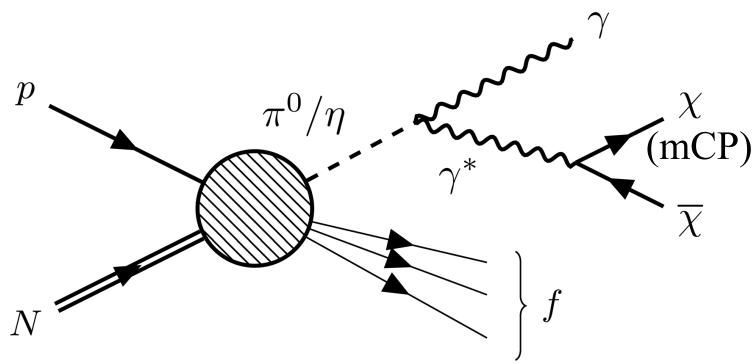
$BR(\pi^0 \rightarrow e^- e^+) = 6 * 10^{-6}$

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

Production channels of MCP

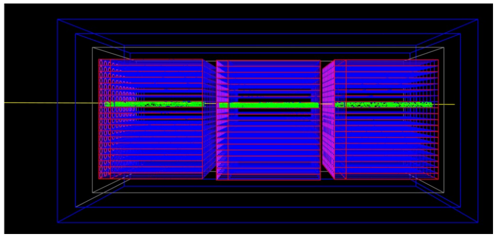


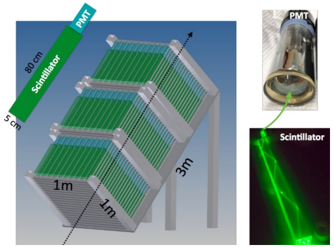
Search Methods: Scattering & Scintillation



(A) **Scintillation Study:** **FORMOSA, etc**

~ eV-level energy exchange

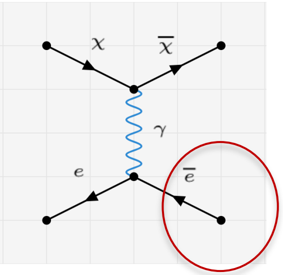


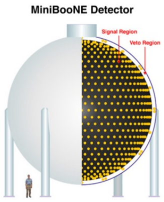


e.g., Haas, Hill, Izaguirre, Yavin, 1410.6816
milliQan design, 1607.04669 (MilliQan Collaboration)

(B) **"Hard" Electron Scattering:** **FLArE, etc**

~ energy exchange set by detector threshold



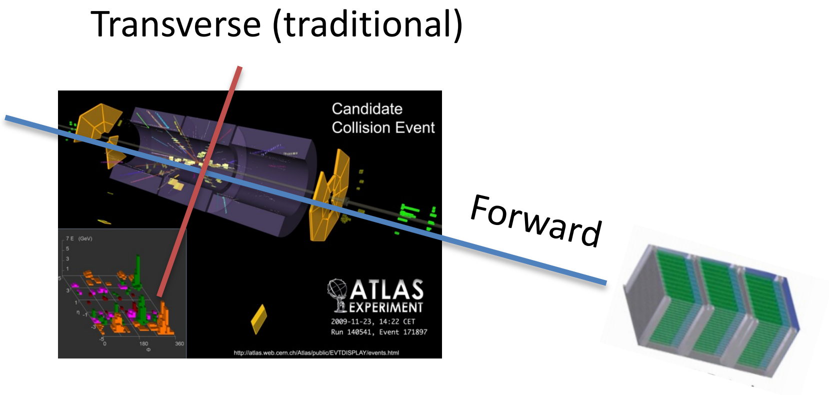


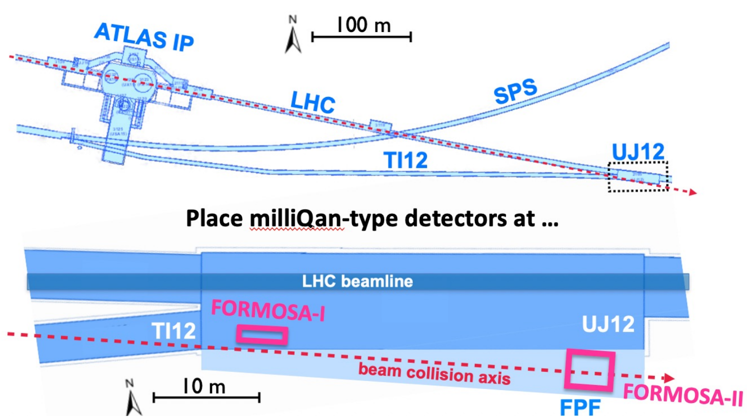
e.g.neutrino Detector
MiniBooNE (arXiv:0806.4201)

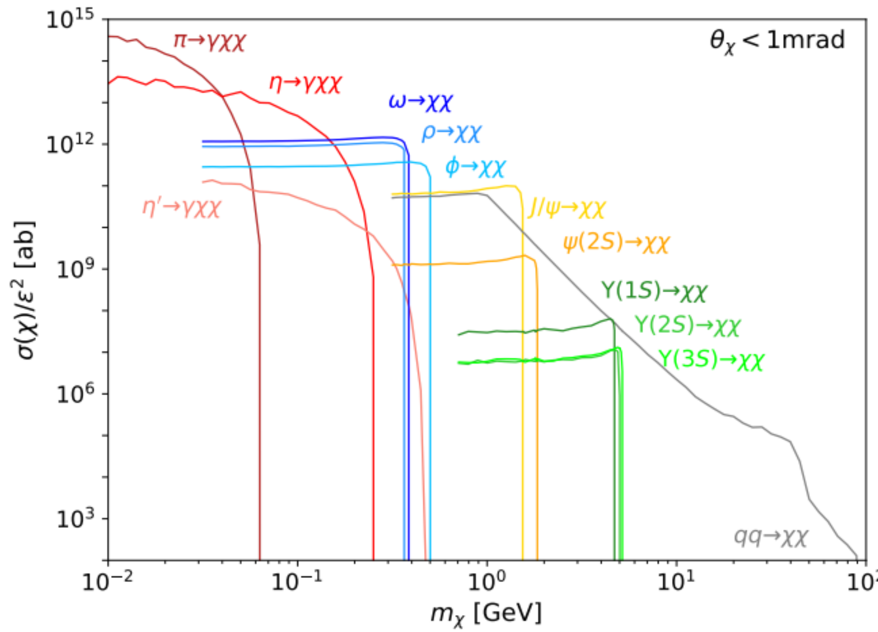
FORward MicrOcharge SeArch (FORMOSA)

FORward MicrOcharge SeArch, FORMOSA

Foroughi-Abari, Kling, **Tsai**, 2010.07941, *PRD 21*

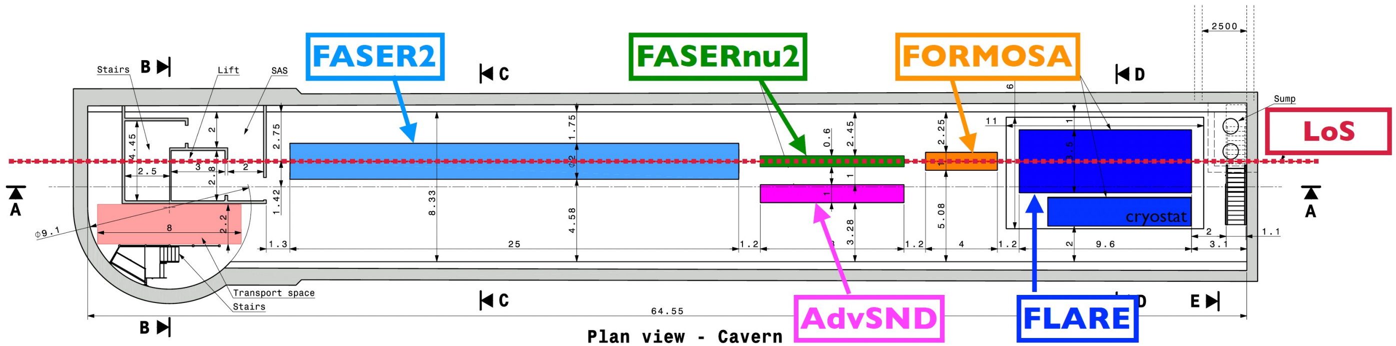


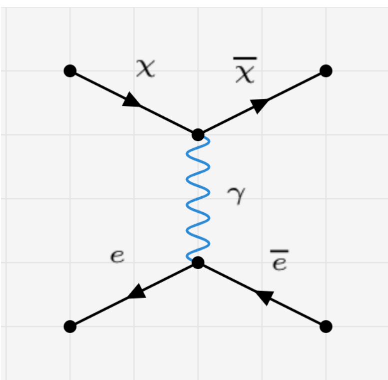




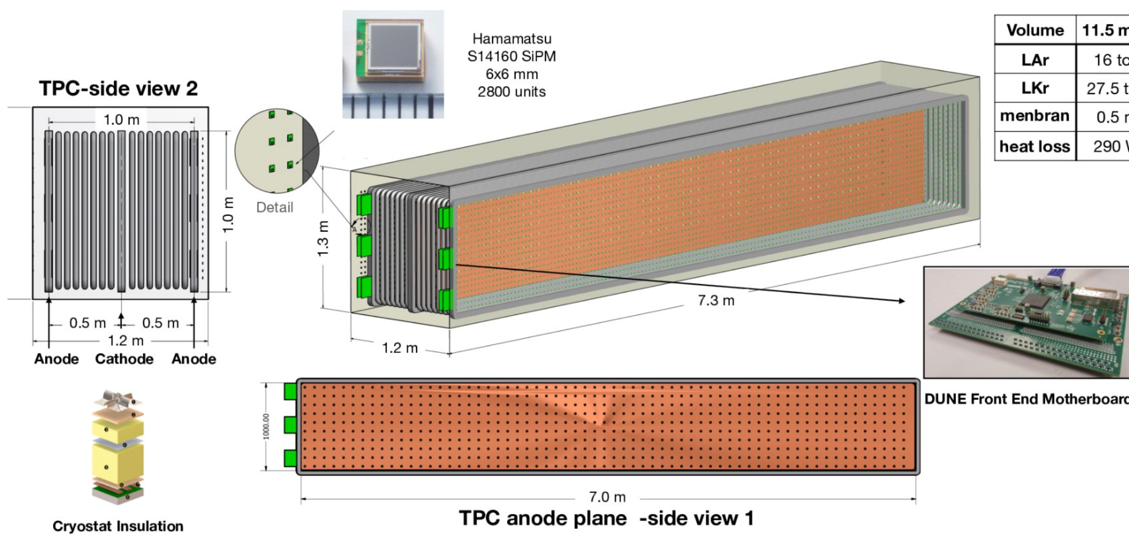
Productions: meson decays + Drell-Yan process

Forward Liquid Argon Experiment (FLArE)





FLArE Detector Preliminary Sketch



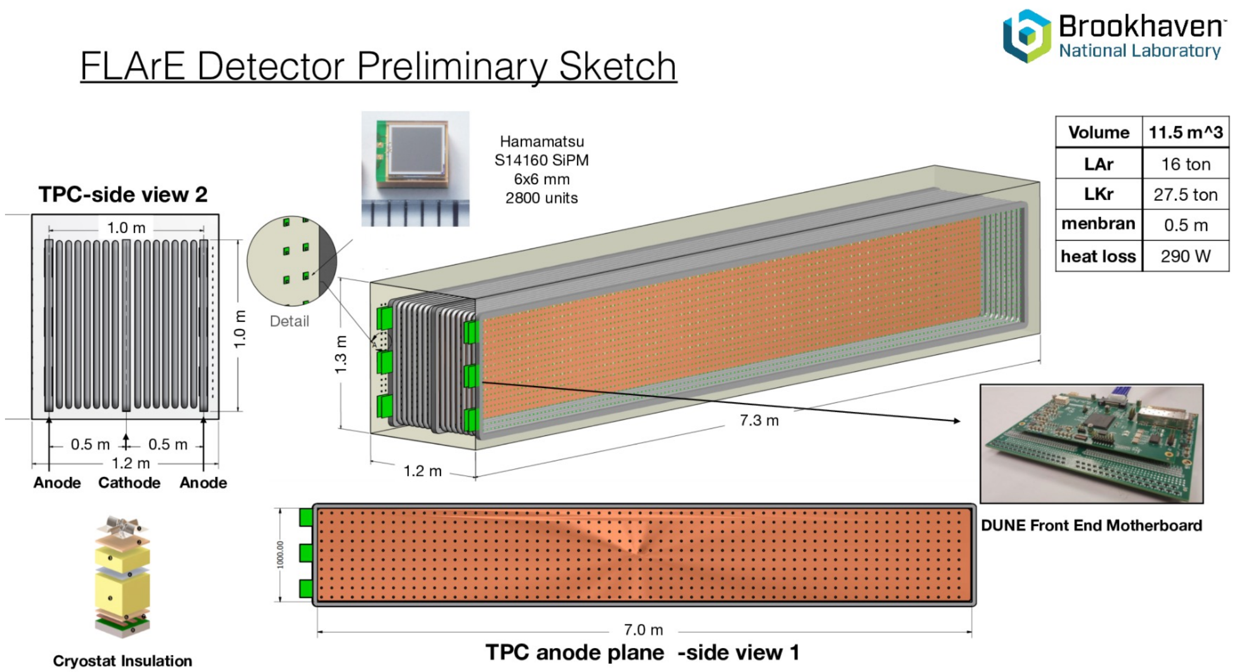
Volume	11.5 m^3
LAr	16 ton
LKr	27.5 ton
menbran	0.5 m
heat loss	290 W

Batell, Feng, Trojanowski, PRD 21

Liquid Argon Detector lead by Diwan@BNL

FLArE Signatures & Sensitivities

FLArE Configuration



$$\text{FLArE}: \quad \Delta = 7\,\text{m}, \quad S_T = (1\,\text{m} \times 1\,\text{m}),$$

- distance L = 620 m away from the ATLAS IP; 10-tonne FLArE detector
- where Δ is the detector length along the beam collision axis and S_T is its transverse area.
- One can also easily consider FLArE-100 (ton) sensitivity with Δ = 30 m and S_T = (1.6 m × 1.6 m), with our phenomenological setup.

Signatures at FLArE

1) Single hit scattering signal (similar to DM signal)

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

$\leftarrow$ $E_{R,\mathrm{single}}$

$$\text{Cut:}\ \ 30\ \mathrm{MeV}\,(300\ \mathrm{MeV}) \lesssim E_{R,\mathrm{single}} \lesssim 1\ \mathrm{GeV},$$

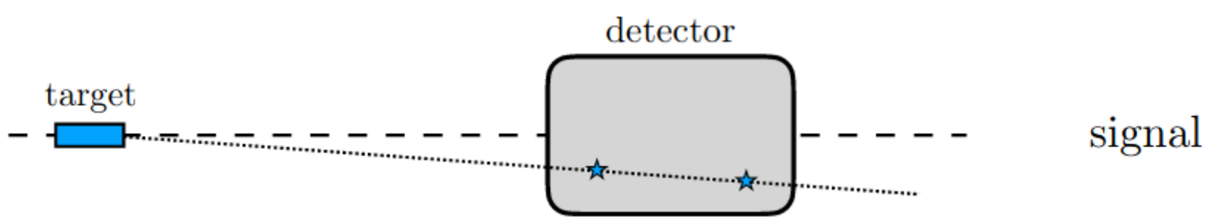
- The lower cut of 30 MeV corresponds to the assumed LArTPC detector capabilities to study soft electron tracks, cf. DUNE CDR, v2.
- The upper energy threshold of 1 GeV allows for suppressing neutrino-induced backgrounds while maintaining the signal rate.

Signatures at FLArE

2) Double-hit Signature

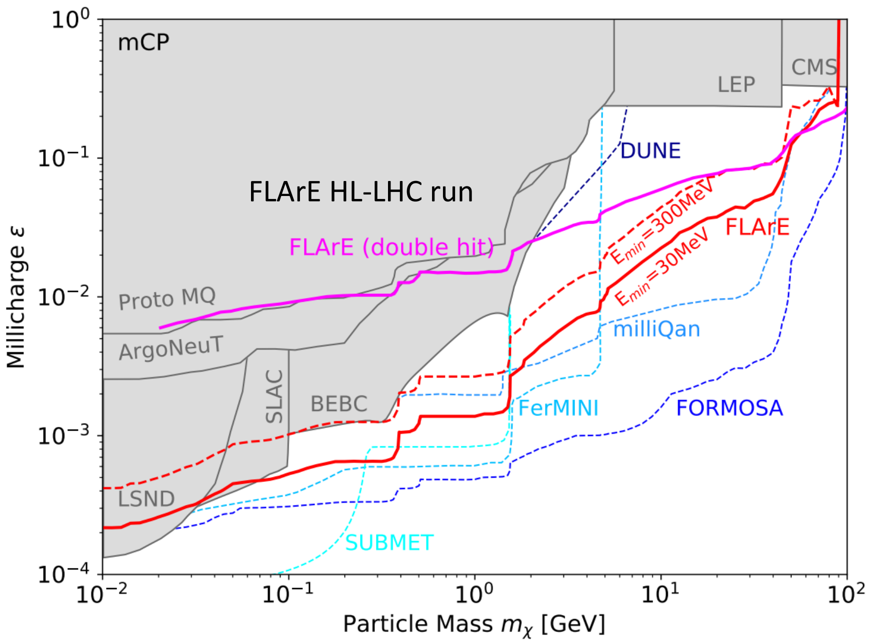
- Allows us to consider MeV-energy scattering, using double-hit requirement to reduce background

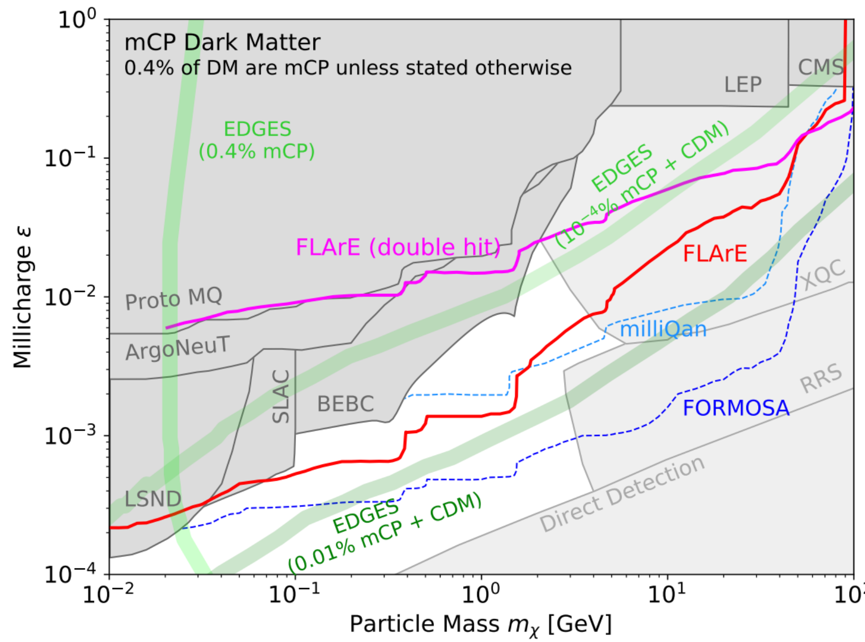
$$5\ \text{MeV} \lesssim E_{R,\text{double}} \lesssim 1\ \text{GeV},$$



Harnik, Liu, Palamara, JHEP 19

Sensitivity Plots





FLArE reach using the single-hit: $30\ \text{MeV}\,(300\ \text{MeV}) \lesssim E_{R,\text{single}} \lesssim 1\ \text{GeV},$

& double-hit signature: $5\ \text{MeV} \lesssim E_{R,\text{double}} \lesssim 1\ \text{GeV},$

Both consider 3 MCP events & assume 100% signal detection efficiency
will discuss how to reduce the background.

Background Discussions

mCP Backgrounds

1. Neutrino-induced backgrounds

2. Muon-induced backgrounds

3. Other backgrounds

- Batell, Feng, Trojanowski, PRD 21
- Kling, Kuo, Trojanowski, Tsai, arXiv:2205.09137

Neutrino-induced backgrounds

- low-energy neutrinos produced more isotropically at the LHC
- Incident neutrinos in the far-forward region typically of order $E\nu \sim 200 - 300$ GeV, see Bai et al, JHEP 20.

- Single-hit: $30 \text{ MeV} \, (300 \text{ MeV}) \lesssim E_{R,\text{single}} \lesssim 1 \text{ GeV},$

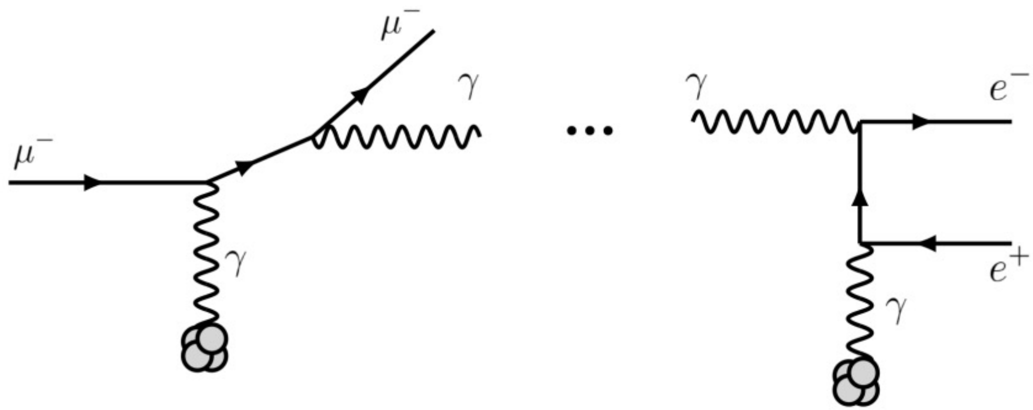
  $<$ O(1) expected neutrino-induced background events in FLArE
  (DM searches has high-energy cut 20 GeV, and has ~ 20 backgrounds)

- Double-hit: $5 \text{ MeV} \lesssim E_{R,\text{double}} \lesssim 1 \text{ GeV},$

  results in even-lower/no neutrino events.

- We use far-forward neutrino fluxes and spectra obtained using the fast neutrino flux simulation in Kling & Nevay, PRD 21 & use GENIE to study neutrino interactions for the above conclusion.

Muon-induced backgrounds



- Batell, Feng, Trojanowski, PRD 21

- A background to the mCP signal if the electron or positron has an energy below the detection threshold energy, and the other has the correct kinematics to pass the selection cuts.

- In addition to muon-bremsstrahlung, such backgrounds can arise in direct electron-positron pair production, $\mu\,N \rightarrow \mu\, e^{+}\, e^{-}\, N$.

Muon-induced backgrounds

To suppress the rate of muons traveling through the FPF:

1. A dedicated **sweeper magnet** to deflect forward-going muons before they reach the experimental facility (see FPF whitepapers, 2109.10905 & 2203.05090). May be feasible for a sweeper magnet to eliminate all muons with energies below 100 GeV from the detector region.

2. **Active front veto** + coincidence timing information.

LArTPV provide active time information, with expected time resolution of LArTPC detectors is at the level of O(ms), and additional light collection system to go beyond the LArTCP capability (arXiv:2109.10905).

For more detailed discussions, see Batell, Feng, Trojanowski, PRD 21 & FPF whitepapers, 2109.10905 & 2203.05090

Other Backgrounds

Other background sources, include

- ambient gamma-ray activity
- intrinsic radioactivity
- electronic noise

- see ArgoNeuT, PRD ’19 for the discussions of LArTPC mCP backgrounds

Important notes to emphasize:

- ArgoNeuT considered MeV-level threshold, so bgs like electronic noises are large and dominant. **We raise our single hit threshold to 30 MeV to have proper EM showers detectable in LArTPCs**

1. ArgoNeuT is very small, 47(w) × 40(h) × 90(l) cm^3, harder to fiducialized & don’t have additional light readout system or magnet
2. But ArgoNeuT has MINOS ND to provide muon information
3. ArgoNeuT is 100 m underground, reduced cosmic-ray events

Other Similar Scattering Searches

EM Form-Factor Dark Sector

In the EFT framework, lowest orders SM photon coupled to dark sector particles χ carrying EM form factors up to dim-6

$$\mathcal{L}_\chi \supset \epsilon e \bar{\chi}\gamma^\mu \chi A_\mu + \frac{1}{2}\mu_\chi \bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu} + \frac{i}{2} d_\chi \bar{\chi}\sigma^{\mu\nu}\gamma^5 \chi F_{\mu\nu}$$

Dim-4 millicharged

Dim- 5 Magnetic dipole moment (MDM)

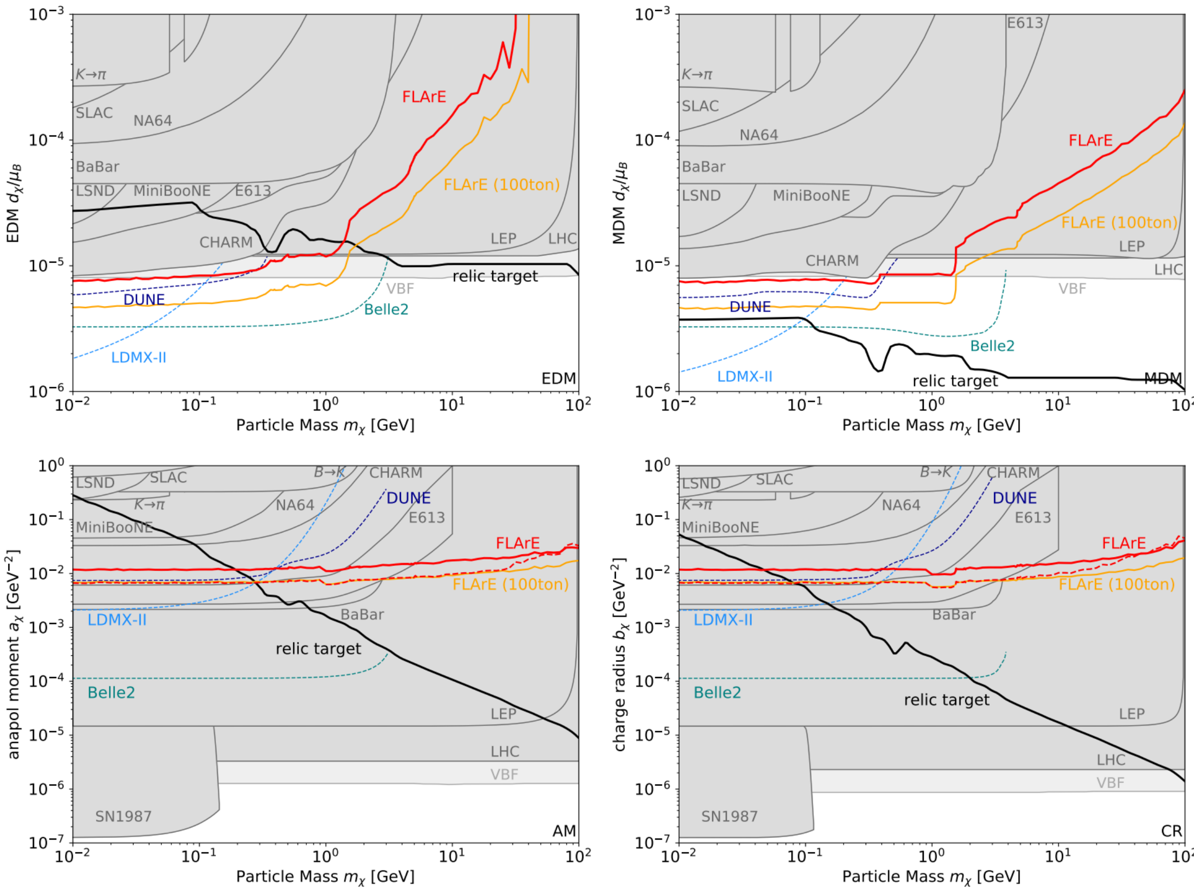
Dim- 5 electric dipole moment (EDM)

$$- a_\chi \bar{\chi}\gamma^\mu\gamma^5\chi\partial^\nu F_{\mu\nu} + b_\chi \bar{\chi}\gamma^\mu\chi\partial^\nu F_{\mu\nu}\,, \quad \sigma^{\mu\nu} \equiv i[\gamma^\mu, \gamma^\nu]/2.$$

Dim-6 anapole moment (AM)

Dim-6 charge radius (CR)

EM Form-Factor Dark Sector



$$\text{mCP:}\quad \frac{d\sigma}{dE_R} = \frac{4\pi\alpha^2\epsilon^2}{E_\chi^2} \times \left(\frac{E_\chi^2}{2m_e E_R^2} - \frac{m_\chi^2}{4m_e^2 E_R}\right),$$

$$\text{MDM:}\quad \frac{d\sigma}{dE_R} = \frac{\alpha\mu_\chi^2}{E_\chi^2} \times \left(\frac{m_\chi^2}{2m_e} + \frac{E_\chi^2}{E_R}\right),$$

$$\text{EDM:}\quad \frac{d\sigma}{dE_R} = \frac{\alpha d_\chi^2}{E_\chi^2} \times \left(-\frac{m_\chi^2}{2m_e} + \frac{E_\chi^2}{E_R}\right),$$

$$\text{AM:}\quad \frac{d\sigma}{dE_R} = \frac{\alpha a_\chi^2}{E_\chi^2} \times \left(2m_e E_\chi^2 + E_R m_\chi^2\right),$$

$$\text{CR:}\quad \frac{d\sigma}{dE_R} = \frac{\alpha b_\chi^2}{E_\chi^2} \times \left(2m_e E_\chi^2 - E_R m_\chi^2\right).$$

assume that $E_\chi \gg m_e, m_\chi, E_R$ and $E_R \gg m_e$.

mχ >> GeV the theory foes beyond the EFT validity regime for the couplings to $F_{\mu\nu}$, one should consider hypercharge field strength $B_{\mu\nu}$ instead of $F_{\mu\nu}$.

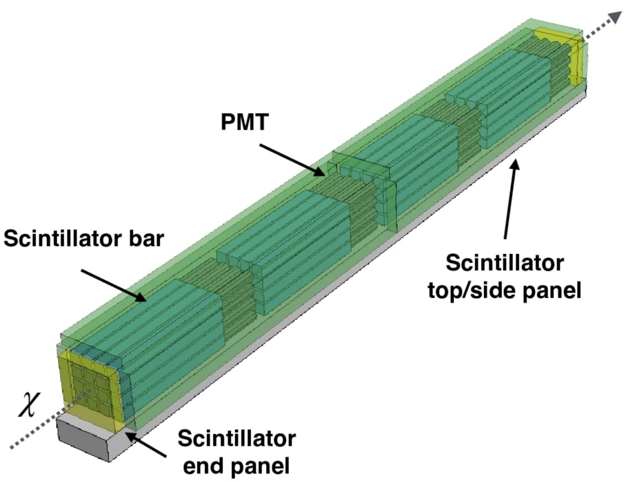
We comment on consequences of employing the hypercharge couplings in arXiv: 2205.09137

Discussion: using FLArE like a milliQan/FORMOSA?

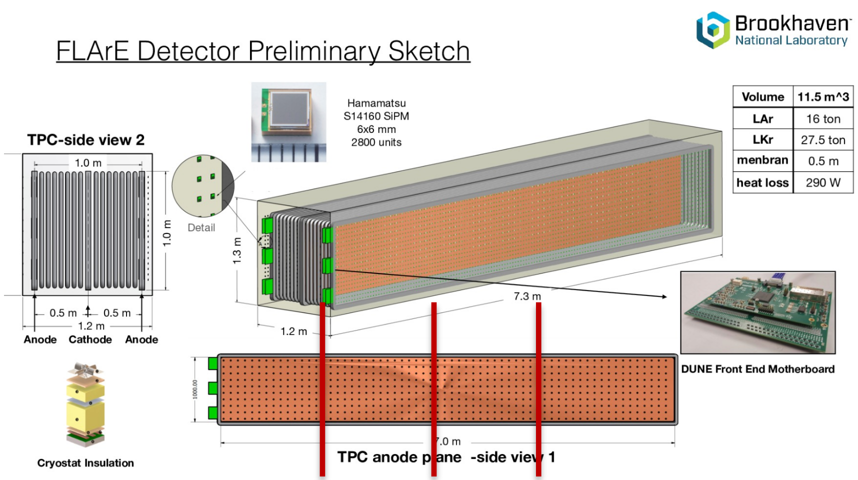
Based on discussion among Milind & Jonathan+ arXiv:2205.09137 authors

FLArE mCP Scintillation Signature?

- Study the sub-detector threshold track of mCPs, not the electrons, and **use FLArE like a milliQan/FORMOSA?**



milliQan Collaboration, PRD '21



$$\text{FLArE}: \quad \Delta = 7\,\text{m}, \quad S_T = (1\,\text{m} \times 1\,\text{m}),$$

Yu-Dai Tsai, UC Irvine, 2022

Some Interesting Future Directions

- FORMOSA + FLArE Synergy
  (similar to MINOS + ArgoNeuT)

- Scintillation Searches at FLArE?

- Gas Argon (TPC) Detector?
  Discuss with DUNE ND experts

- Quirks in FLArE or FORMOSA?

Thank you!

Thanks for the opportunities to present.

Happy to discuss more!

These are subjects with wide range of studies. Please contact me if you think your work should be featured in slides.