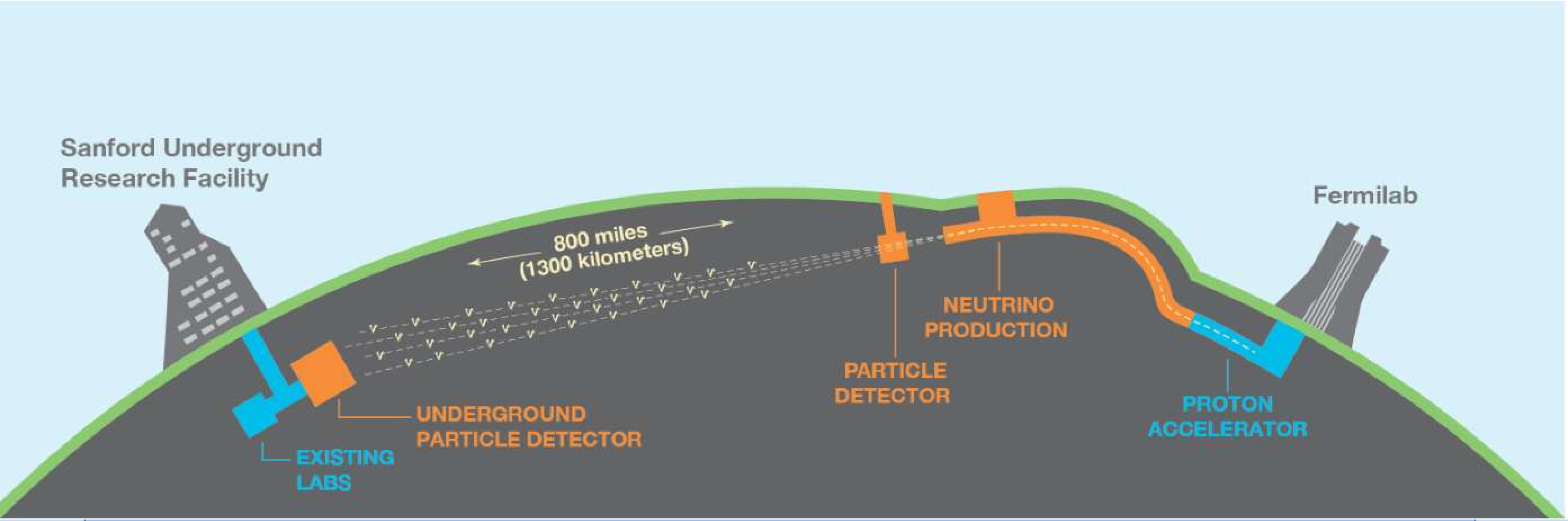


Millicharged Particles in Neutrino Experiments

arXiv:1806.03310 (submitted to PRL)

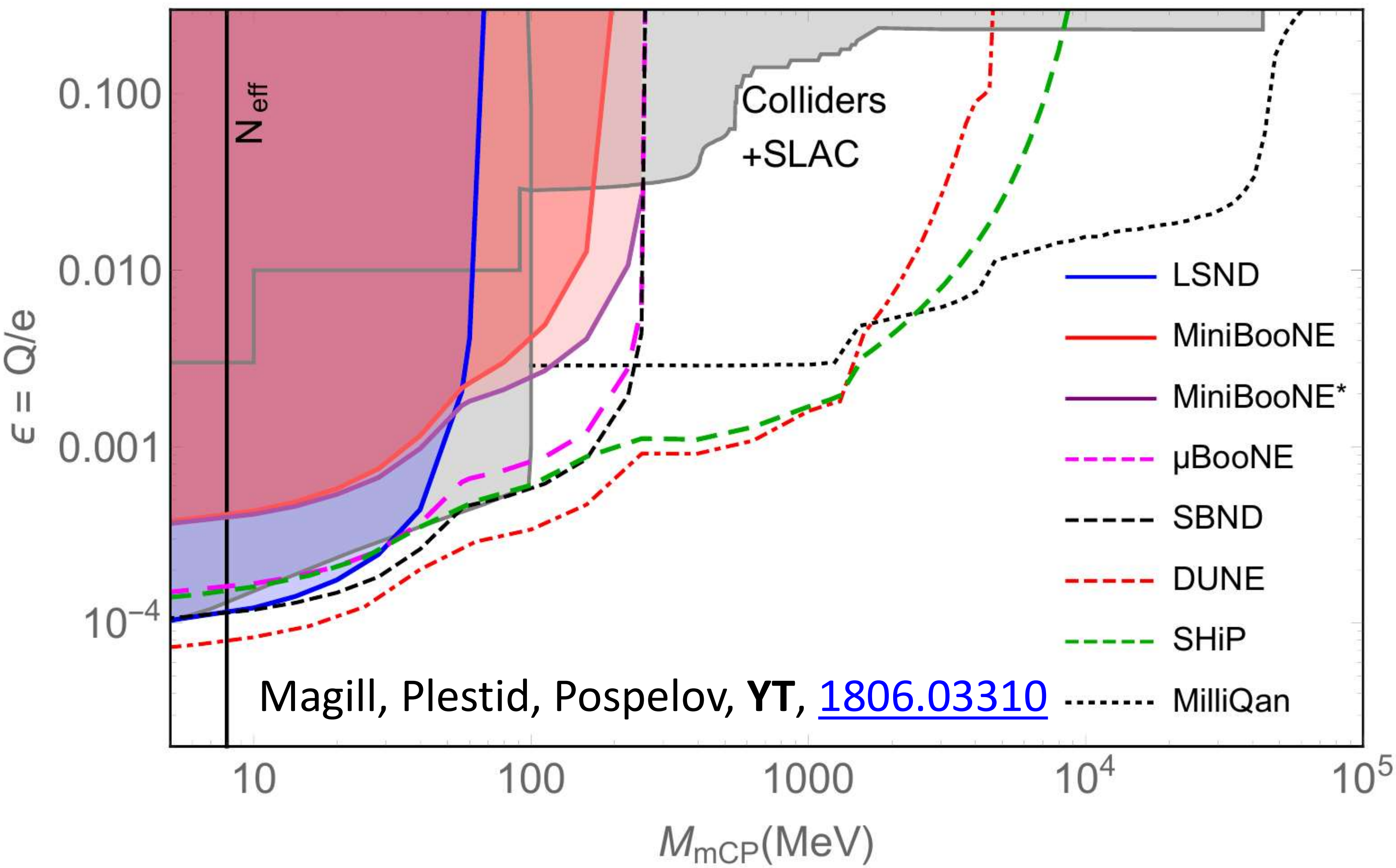
Yu-Dai Tsai, **Fermilab**

with Gabriel Magill, Ryan Plestid, and Maxim Pospelov

Outline

- **Motivations**
- **Millicharged Particle (mCP) & Neutrino Experiments**
- **Bounds & Sensitivity Reaches**
- **Discussion**

Preview



- **Solid: current bounds**
- **Dashed: future sensitivity**

- **General review on other bounds:**

Andy Haas, Fermilab, [2017]

Millicharged Particles

Is electric charge quantized?
Other Implications

Finding Minicharge

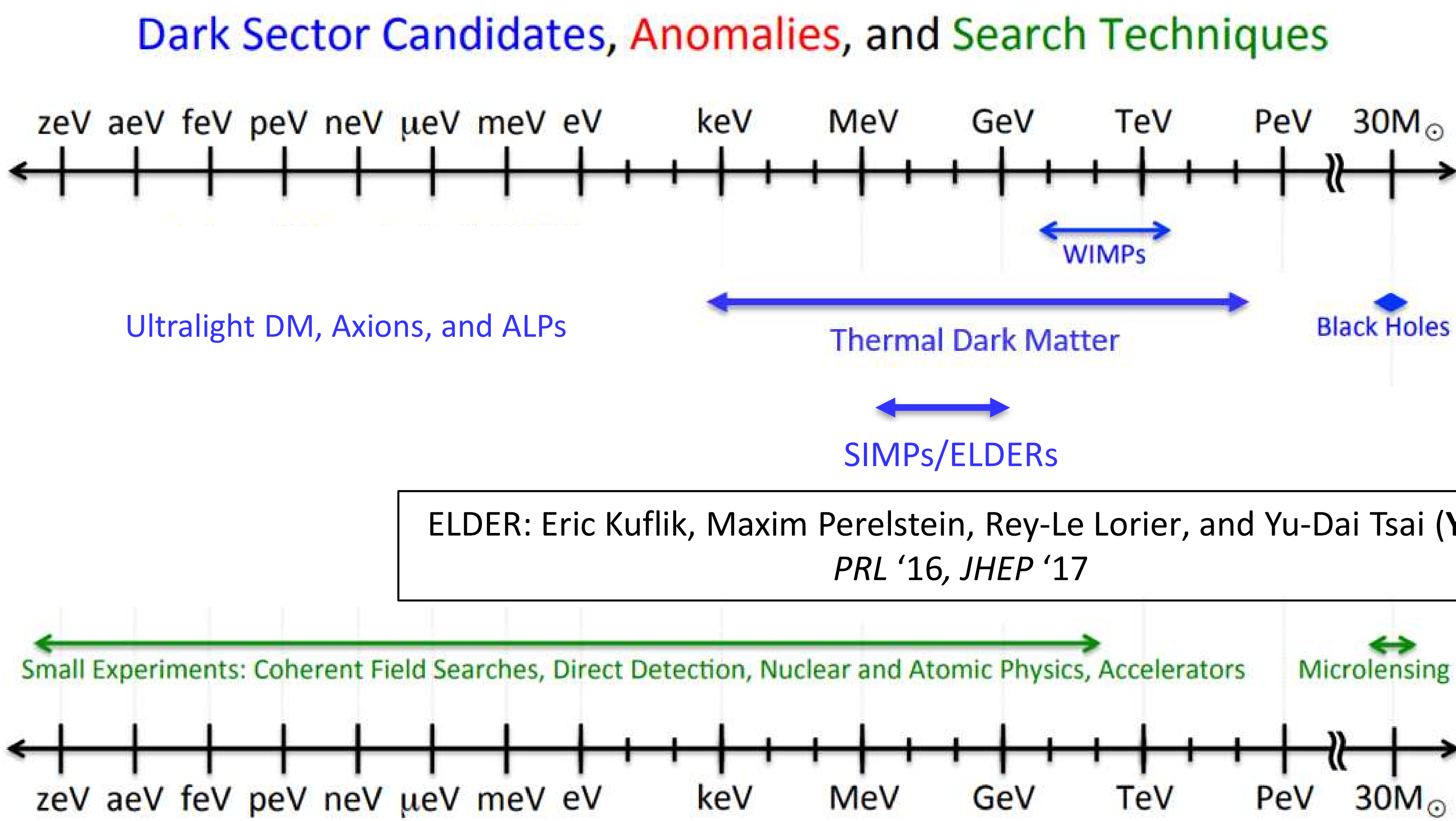
- **Is electric charge quantized?**
- U(1) group allows arbitrarily small charges. Why don't we see them in electric charges? This motivated Dirac monopole, Grand Unified Theory (GUT), etc
- Practically, searching for millicharge is a test of **e/3 charge quantization**, and this could imply something more significant
- Could have natural link to **dark sector** (e.g. dark photon)
- Could account for DM (WIMP-like or other scenarios)

\- Used to explain the cooling of gas temperature to explain the EDGES result [EDGES collab., Nature, (2018), Barkana, Nature, (2018)]. Only ~ 1% of the DM allowed to explain the "anomaly" given other constraints

Neutrino Experiments

- Neutrinos are weakly interacting particles. Just like **Millicharged particles**
- High statistics, e.g. LSND has 10^{23} Protons on Target (POT)
- Shielded/underground: low background (e.g. solar ν programs)
- There are many of them existing and many to come: **strength in numbers**
- Produce hidden particles without DM assumptions: more "direct" than cosmology/astrophysics probes, DM direct detections, etc.

Dark Matter/Hidden Particles Exploration



ELDER: Eric Kuflik, Maxim Perelstein, Rey-Le Lorier, and Yu-Dai Tsai (**YT**)
PRL '16, *JHEP* '17

US Cosmic Visions 2017

- Proton fix-target/neutrino experiments are important for MeV ~ GeV!
- Golowich and Robinett, PRD 87
- Babu, Gould, and Rothstein, PLB 94
- Gninenko, Krasnikov, and Rubbia, PRD 07, …

ν Hopes for New Physics: Personal Trilogy

⋮

- **Light Scalar/Dark Photon** at Borexino & LSND

  (Pospelov & **YT,** 1706.00424)

- **Dipole Portal Heavy Neutral Lepton**

  (Magill, Plestid, Pospelov & **YT,** 1803.03262)

- **Millicharged Particles** in Neutrino Experiments

  (Magill, Plestid, Pospelov & **YT,** 1806.03310)

Inspired by …

deNiverville, Pospelov, Ritz, ’11,

Kahn, Krnjaic, Thaler, Toups, ’14, …

⋮

ν Hopes for New Physics & Anomalies

⋮

- **Light Scalar**/Dark Photon at Borexino & LSND

  Proton charge radius anomaly

- **Dipole Portal Heavy Neutral Lepton**

  LSND/MiniBooNE anomaly

- **Millicharged Particles** in Neutrino Experiments

  EDGES 21-cm measurement anomaly

We can chat about these over coffee

⋮

Yu-Dai Tsai, Fermilab

Millicharged Particle: Models

mCP Model

- Small charged particles under U(1) hypercharge

$$\mathcal{L}_{\rm mCP} = i\bar{\psi}(\partial\!\!\!/ - i\epsilon' e B\!\!\!/ + M_{\rm mCP})\bar{\psi}$$

- Can just consider this effective lagrangian term by itself (no extra mediator, i.e., dark photon)

- Or this could be from Kinetic Mixing
  - give a nice origin to this term
  - an example that gives rise to **dark sector**
  - easily compatible with GUT
  - I will not spend too much time on the model

Kinetic Mixing

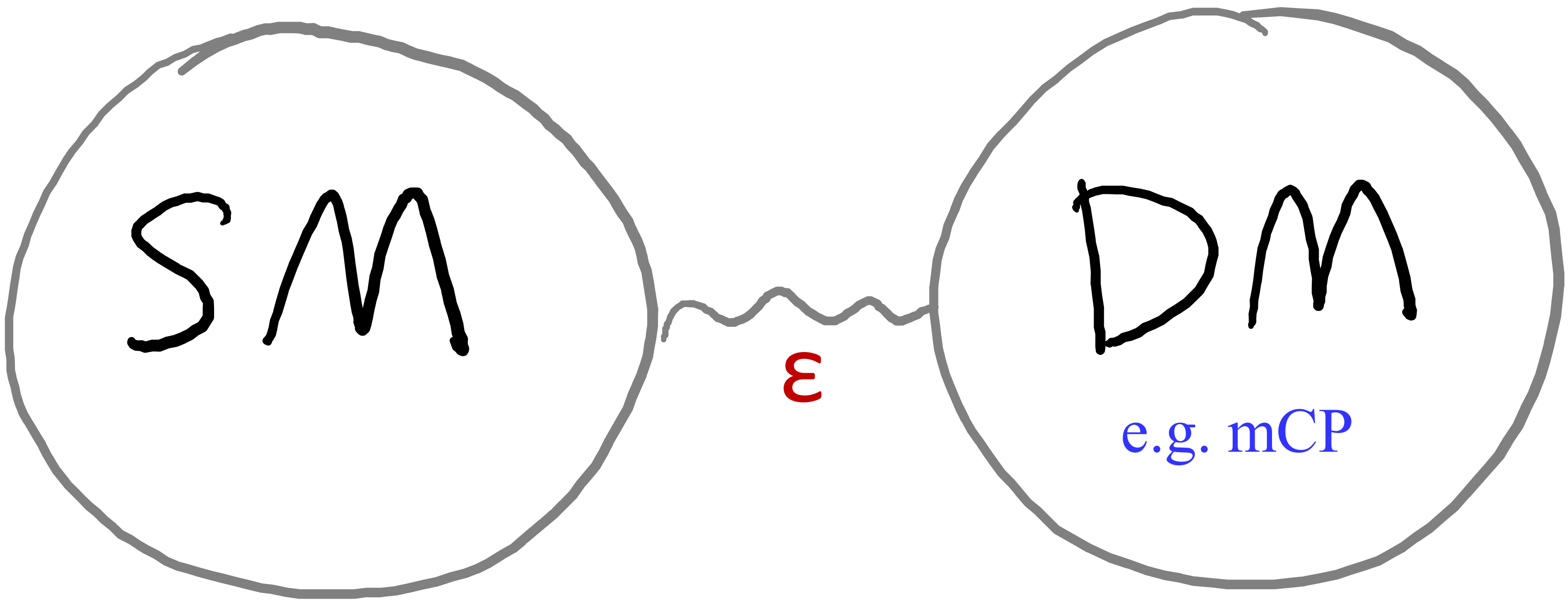
See, Holdom, 1985

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

- Field redefinition into a more convenient basis for massless B', $B' \to B' + \kappa B$
- Getting rid of the mixing term, B' decouple from SM
- After EWSB the new fermion acquires an small EM charge Q (the charge of mCP ψ):

$$Q = \kappa e' \cos\theta_W. \quad \epsilon \equiv \kappa e' \cos\theta_W / e.$$

The Rise of Dark Sector

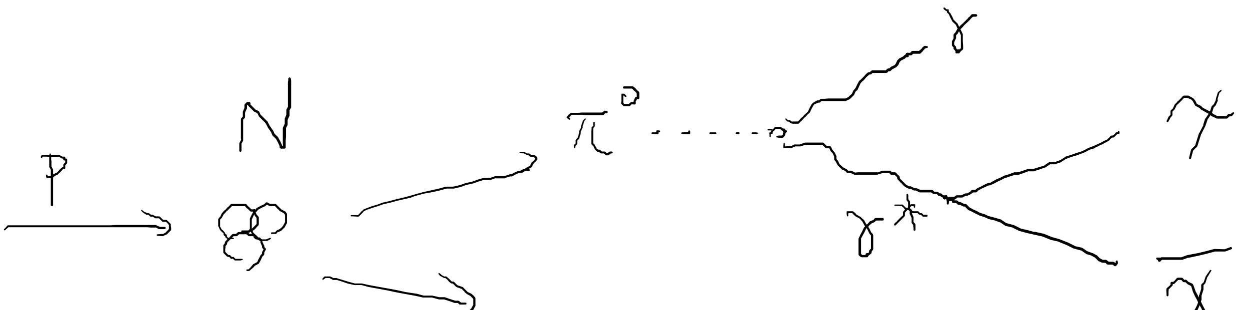


IMPORTANT NOTE

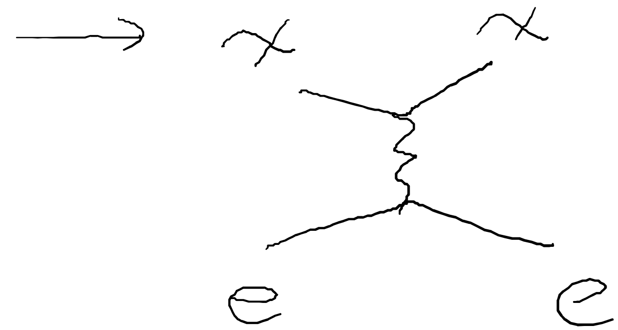
- Our search is simply a search for particles (fermion χ) with {mass, electric charge} = $\{m_\chi, \epsilon e\}$
- Minimal theoretical inputs/parameters
- **mCPs do not have to be DM in our searches**
- The bounds we derive **still put constraints on DM as well as dark sector scenarios.**
- Not considering bounds on dark photon (not necessary for mCP particles)
- Similar bound/sensitivity applies to scalar mCPs

Millicharged Particle: Signature

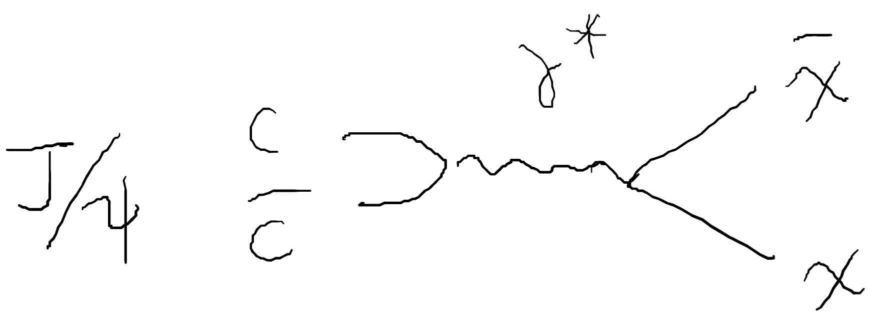
MCP: production & detection



Target



- production: meson decays
- detection: scattering electron



Heavy measons are important for higher mass mCP's in high enough beam energy

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

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

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

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

MCP Signals

- **signal events** s_{event}

$$sig \simeq \sum_{\text{Energies}} N_\chi(E_i) \times \frac{N_e}{\text{Area}} \times \sigma_{e\chi}(E_i;\ m_\chi) \times \mathcal{E}.$$

detection efficiency

- $N_\chi(E_i)$ represents the number of mCPs with energy E_i arriving at the detector. $N_\chi(E_i)$ is a function of both the **branching ratio** and **geometric losses** which can vary significantly between experiments
- N_e: **total number of electrons** inside the active volume of the detector
- Area: the active volume divided by the average length traversed by particles inside the detector.
- $\sigma_{e\chi}(E_i)$ is the **detection cross section consistent** with the angular and recoil cuts in the experiment

MCP productions

- For **η** & **π^0**, Dalitz decays: $\pi^0/\eta \rightarrow \gamma\, \chi\, \bar{\chi}$ dominate
- For **J/ψ** & **Y**, direct decays: J/ψ, Y $\rightarrow \chi\, \bar{\chi}$ dominate.
  Important for high-mass mCP productions!
- The branching ratio for a meson, $\mathscr{M}$, to mCPs is given roughly by

$$\mathrm{BR}(\mathcal{M} \to \chi\bar{\chi}) \approx \epsilon^2 \times \mathrm{BR}(\mathcal{M} \to X e^+ e^-) \times f\left(\frac{m_\chi}{M}\right),$$

- M: the mass of the parent meson, X:any additional particles, $f(m_\chi/M)$: phase space factor as a function of m_χ/M.
- Also consider **Drell-Yan production of mCP** from **q q-bar annihilation**.

MCP Detection

- Detection signature: **elastic scattering with electrons**.
- Look for single-electron events
- **The dominance of electron scattering as a detection signal** is related to the **low- Q^2 sensitivity of the scattering cross section.** (Q^2 is the squared 4-momentum transfer)
- Explicitly, in the limit of small electron mass, we have

$$\frac{\mathrm{d}\sigma_{e\chi}}{\mathrm{d}Q^2} = 2\pi\alpha^2\epsilon^2 \times \frac{2(s - m_\chi^2)^2 - 2sQ^2 + Q^4}{(s - m_\chi^2)^2 Q^4}.$$

MCP Detection

- Integrate over momentum transfers, the total cross section will be dominated by the small Q^2 contribution, we have $\sigma_{e\chi} = 4\pi\, \alpha^2 \varepsilon^2 / Q_{min}{}^2$.
- We can relate Q_{min} in the lab frame to the recoil energy of the electron via $Q^2 = 2m_e\,(E_e - m_e)$.
- An experiment's **recoil energy threshold**, $E_e{}^{(min)}$ sets the scale of the detection cross section

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

MCP Detection

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

- Sensitivity to mCPs can be greatly enhanced by accurately **measuring low energy electron recoils**
- An important feature for **search strategies at future experiments for mCP's and LDM-electron scattering**
- Demonstrated in

  Magill, Plestid, Pospelov, **YT**, 1806.03310 &

  (for sub-GeV DM) deNiverville, Frugiuele, 1807.06501

MCP Signals Recap

$$sig \simeq \sum_{\text{Energies}} N_{\chi}(E_i) \times \frac{N_e}{\text{Area}} \times \sigma_{e\chi}(E_i;\ m_{\chi}) \times \mathcal{E}.$$

Detection efficiency

- $sig \propto \varepsilon^4$
- For most of the mCP parameter space under consideration, **electromagnetic decays of mesons** provide the dominant flux contribution
- **Drell-Yan production (DYP) dominates for the large mCP masses** that are only accessible at **DUNE** and **SHiP**.
- For DYP, we integrate over the full production phase-space using **MSTW parton distribution functions** [Martin, Stirling, Thorne, Watt, 2009]

MCP Bound/Sensitivity

- **signal events** s_{event}

$$sig \simeq \sum_{\text{Energies}} N_\chi(E_i) \times \frac{N_e}{\text{Area}} \times \sigma_{e\chi}(E_i;\ m_\chi) \times \mathcal{E}.$$

- Our sensitivity curves are obtained by performing a standard sensitivity analysis [PDG, PLB 2010]:
- Given a number of background events b and data n, the number of signal events s_{event} . The $(1 - \alpha)$ credibility level is found by solving the equation $\alpha = \Gamma(1 + n, b + sup)/\Gamma(1 + n, b)$, where $\Gamma(x, y)$ is the upper incomplete gamma function.
- Throughout this paper, we choose a credibility interval of $1 - \alpha = 95\%$ (~ 2 sigma)
- Roughly, $\varepsilon_{sensitivity} \propto E_{e,\,R,min}^{1/4}\ Bg^{1/8}$

Background Estimation for Future Measurements

- Single-electron background for ongoing/future experiments for **MicroBooNE, SBND, DUNE, and SHiP?**
- We consider two classes of backgrounds:

  1) Coming from neutrino fluxes (calculable)

     [i.e. **ve** → **ve** and **vn** → **ep**], we sum over the neutrino-flux contributions from each collaboration and account for the detection efficiencies.

  2) Other sources such as

     beam related: **dirt related events**, **mis-id particles**

     external: **cosmics**, etc

Background Reduction

- For neutrino-caused backgrounds, large background reduction is obtained by **imposing the maximum electron recoil energy cuts E_e(max)**.
- This do not significantly affect the mCP signal (which is dominated by low electron recoils from low-Q^2), but significantly reduce charged and neutral current neutrino backgrounds.

Estimation of Other Background

- **Liquid Argon Time Projection Chamber (LArTPC) can use timing information as vetoes to reduce backgrounds,** Therefore, we multiply our neutrino induced backgrounds by a factor of **10 for LArTPC detectors (MicroBooNE, SBND, and DUNE)**
- For a nuclear emulsion chamber detector, we times a factor of **25 for the background (SHiP)**;
- These increase in the backgrounds decreases our sensitivity to ε by $20 - 30\%$
- **Our results can be easily revised for different background assumptions,** roughly, $\varepsilon \propto Bg^{1/8}$.

Summary Table

	Exp. (Beam Energy, POT)	N [$\times 10^{20}$]		$A_{\rm geo}(m_\chi)$[$\times 10^{-3}$]		Cuts [MeV]		
		π^0	η	1 MeV	100 MeV	$E_e^{\rm min}$	$E_e^{\rm max}$	Bkg
Existing	LSND (0.8 GeV, 1.7×10^{23})	130	—	20	—	18	52	300
	mBooNE (8.9 GeV, 2.4×10^{21})	17	0.56	1.2	0.68	130	530	2k
	mBooNE* (8.9 GeV, 1.9×10^{20})	1.3	0.04	1.2	0.68	75	850	0
Future	μBooNE (8.9 GeV, 1.3×10^{21})	9.2	0.31	0.09	0.05	2	40	16
	SBND (8.9 GeV, 6.6×10^{20})	4.6	0.15	4.6	2.6	2	40	230
	DUNE (80 GeV, 3.0×10^{22})	830	16	3.3	5.1	2	40	19k
	SHiP (400 GeV, 2.0×10^{20})	4.7	0.11	130	220	100	300	140

- $\varepsilon \propto E_{e,\,R,min}^{1/4}\, Bg^{1/8}$
- cos θ > 0 is imposed (∗except for at MiniBooNE's dark matter run where a cut of cos θ > 0.99 effectively reduces backgrounds to zero [Dharmapalan, MiniBooNE, (2012)]).
- efficiency of 0.2 for Cherenkov detectors, 0.5 for nuclear emulsion detectors, and 0.8 for liquid argon time projection chambers.

Recasting Existing Analysis: LSND, MiniBooNE, and MiniBooNE* (DM Run)

- **LSND**: hep-ex/0101039. Measurement of **electron-neutrino electron elastic scattering**
- **MiniBooNE**: arXiv:1805.12028.
  Electron-Like Events in the MiniBooNE Short-Baseline Neutrino Experiment, combines data from both **neutrino and anti-neutrino runs** and consider a sample of **2.4×10^{21}POT** for which we take the **single electron background to be 2.0×10^{3}** events and the **measured rate to be 2.4×10^{3}**
- **MiniBooNE* (DM run)**: arXiv:1807.06137 (came out after our v1).
  Electron recoil analysis, details see talk by Dr. Remington
  We did not include their timing cuts in our calculations, since they were optimized by the MiniBooNE collaboration to the signal's timing profile.

Summary Table

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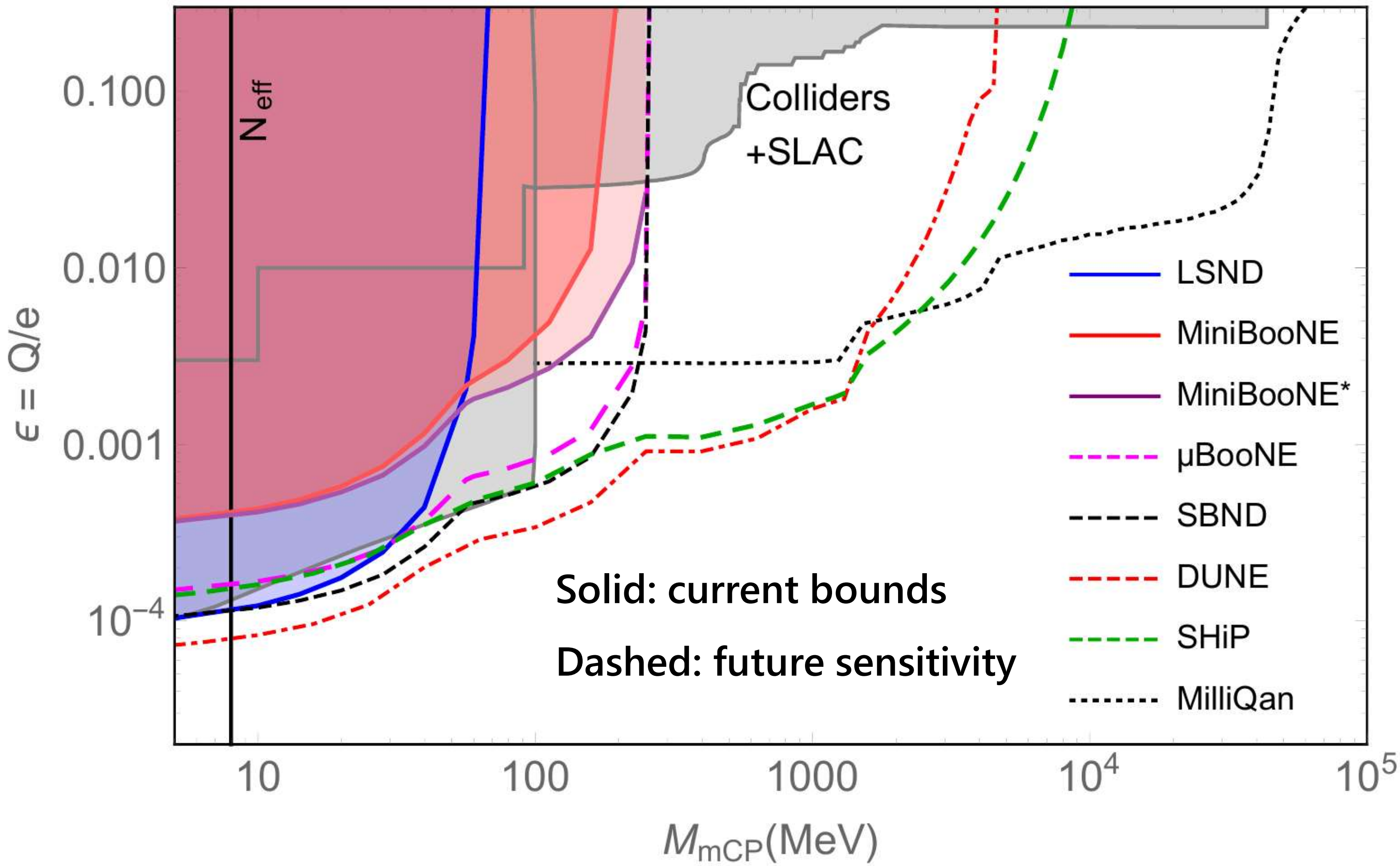
SHiP (400 GeV, 2.0×10^{20})	4.7	0.11	130	220	100	300	140

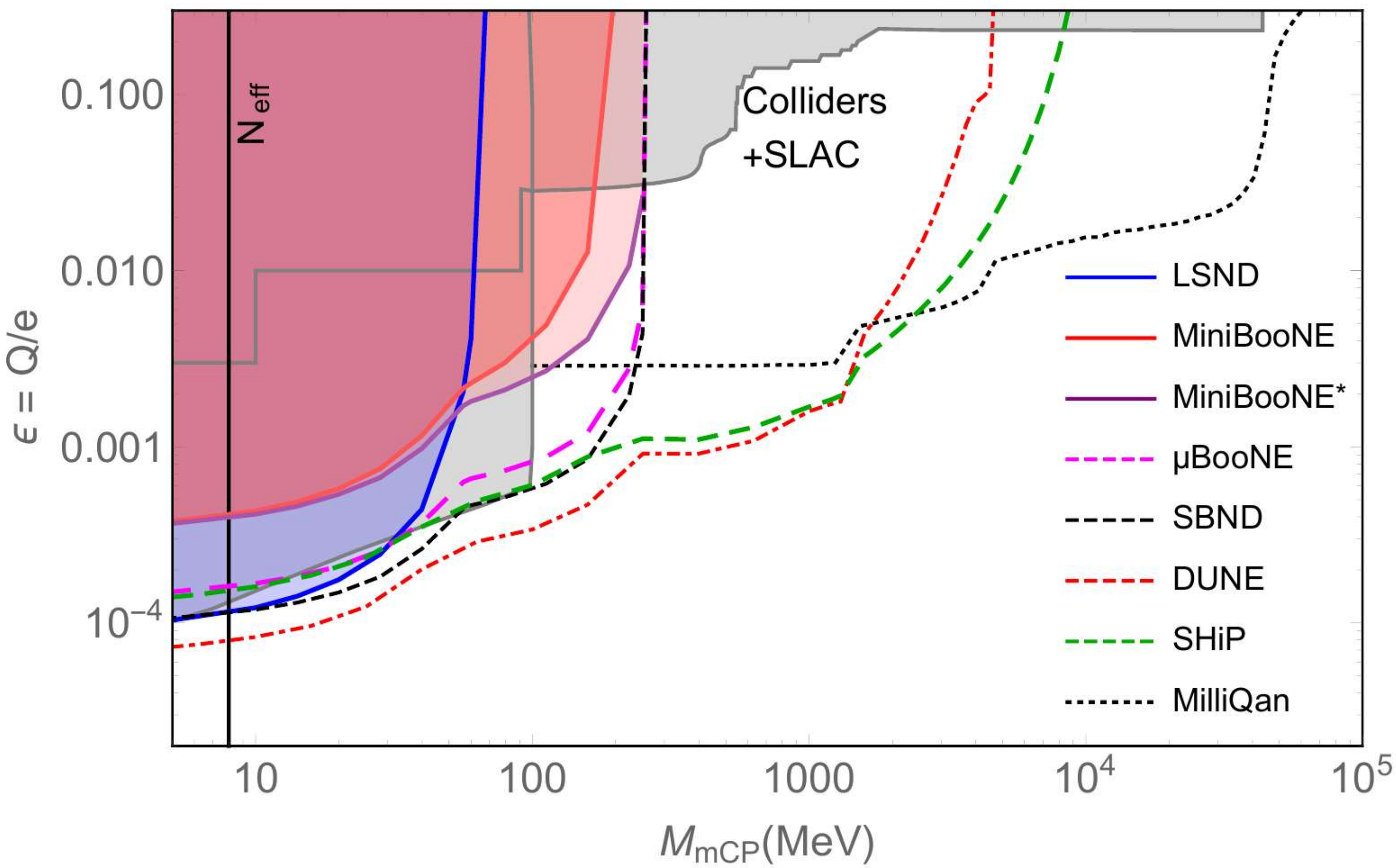
- $\varepsilon \propto E_{e,\,R,min}^{1/4}\ Bg^{1/8}$
- At **LArTPC**, the **wire spacing is about 3 mm**, the ionization stopping power is approximately **2.5 MeV/cm**: electrons with total energy larger than at least **2 MeV** produce tracks long enough to be reconstructed across two wires.

Probes of mCPs



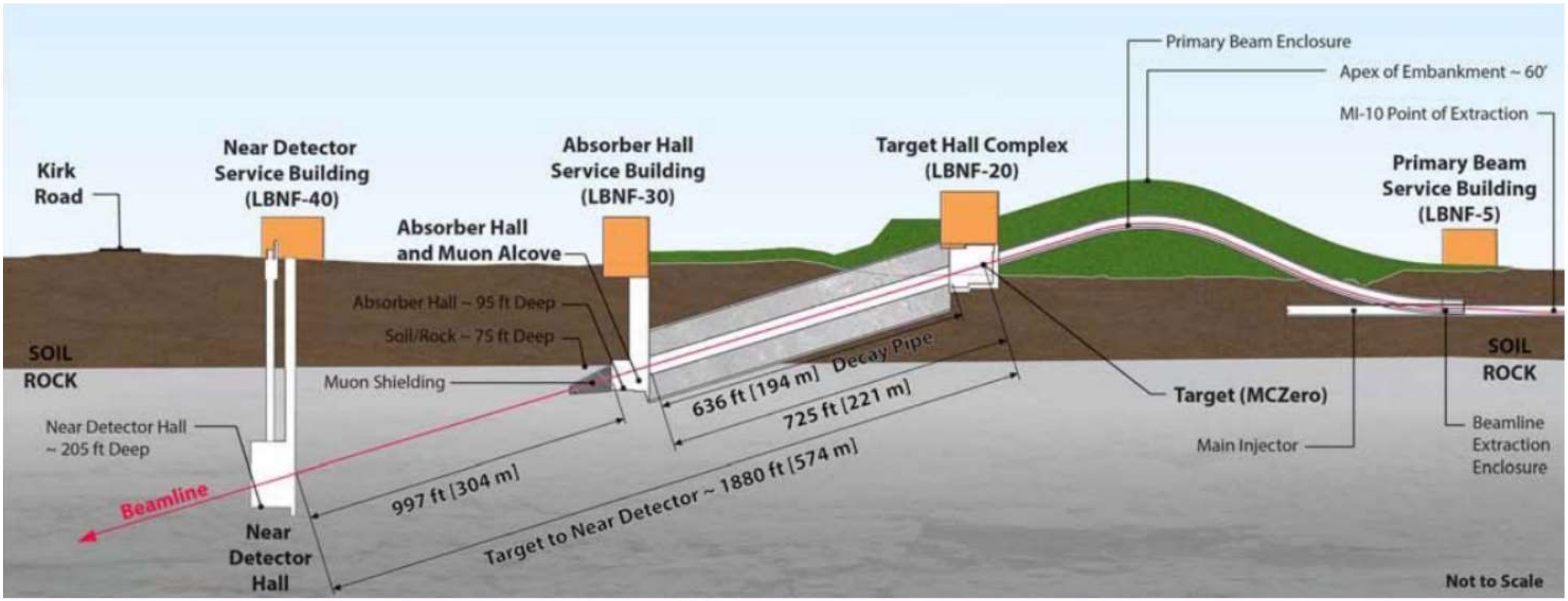
- Heavy neutral meson production turns on in large enough beam energy. Extend mCP mass above 200 MeV
- $\varepsilon \propto E_{e,R,min}^{1/4}\, Bg^{1/8}$ for future experiments

Existing Bounds & MilliQan



- MilliQan: Haas, Hill, Izaguirre, Yavin, 15, + (LOT arXiv:1607.04669)
- N_{eff}: Bœhm, Dolan, and McCabe, (2013)
- Colliders/Accelerator: Davidson, Hannestad, Raffelt 2000 + refs within.
- SLAC mQ: Prinz el al, PRL (1998); Prinz, Thesis, (2001).

DUNE Near Detector



Remarks and Outlook

- Out technique can be applied to more generic **light dark matter** and other **weakling interacting particles**
- For **MCP**, and generically **light dark matters**

  - Production from **heavy neutral mesons important**

  - Signature favor **low electron-recoil energy threshold**
- Discussing with **DUNE/SBN experimentalists** about realistic background, $E_{e,\,R,min}$ cut, and better simulation (adding **heavy mesons**)
- Sensitivity (along with other new physics scenarios) from **NuMI beam in off-axis detectors**? High energy, lower neutrino background, but also lower statistics (Yun-Tse Tsai, **YT**, + … just started)

To Do List

- **Millicharged particles in electron-based experiments** (electron collisions + fixed target experiments), (Blinov, Krnjaic, **YT**, in progress) including BaBar, Belle II, BDX, etc.

  (LDMX sensitivity set by Berlin, Blinov, Krnjaic, Schuster, Toro, 18

  soon after our paper

- A lot more to do! Let's chat more during the coffee time.

Thank You!

Thanks for the conference!

MCP Exisiting bounds

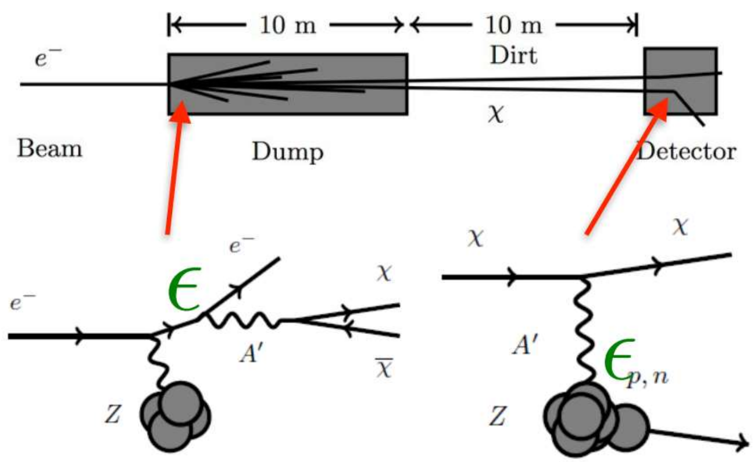
- A recent analysis looking for low ionizing particles in **CMS** excluded particles: charge ±e/3 for MmCP < 140 GeV & particles:charge ±2e/3 for MmCP < 310 GeV [CMS, PRD (2013)].
- mCP coupling to the Z is suppressed by sin(θW)

$$\sin^2 \theta_{\mathrm{W}} = 1 - (m_{\mathrm{W}}/m_{\mathrm{Z}})^2 = 0.2223(21).$$

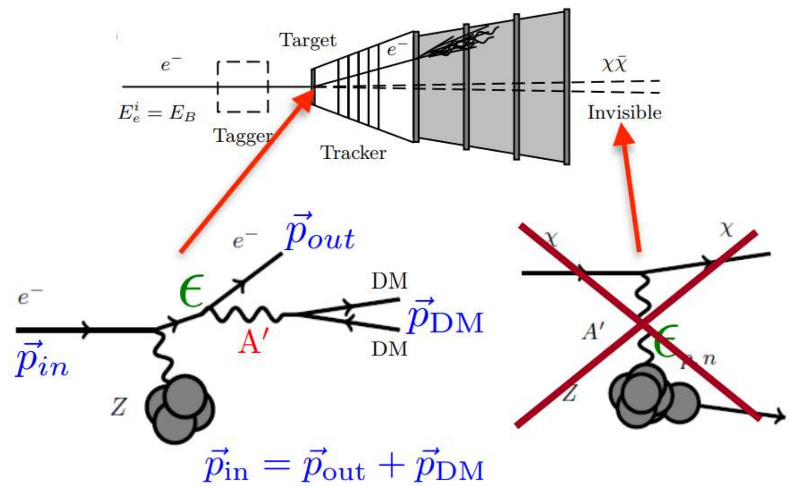
- **LEP invisible Z width**: mCP not contribute more than the 2σ width at LEP. [Davidson, Hannestad, Raffelt, 2000]: $\epsilon < 0.24 \quad m_\epsilon > 45 \text{ GeV},$

LDMX @ SLAC

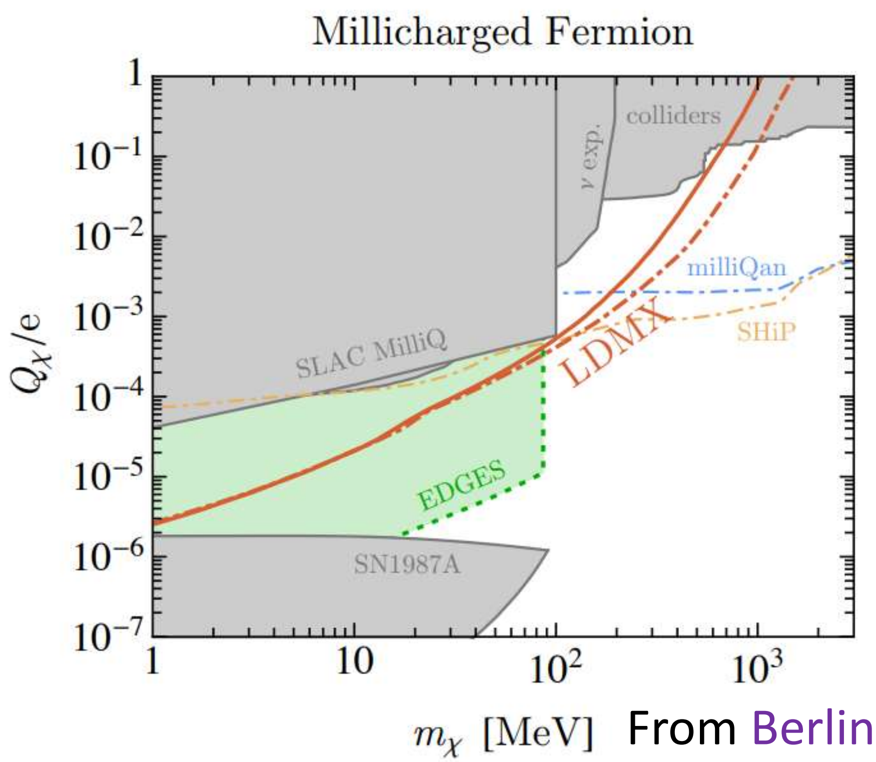
beam dump



missing momentum



Tim Nelson, for LDMX, 2017

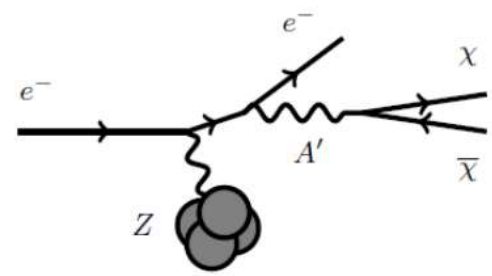


From Berlin, Blinov, Krnjaic, Schuster, Toro, 18

BDX @ BNL

Beam Dump eXperiment: Light Dark Matter (LDM) direct detection in a e^- beam, fixed-target setup[1]

LDM parameters space:
M'_A, M_χ, ε, α_D
$M'_A \simeq 10 \div 1000$ MeV
$M_\chi \simeq 1 \div 100$ MeV



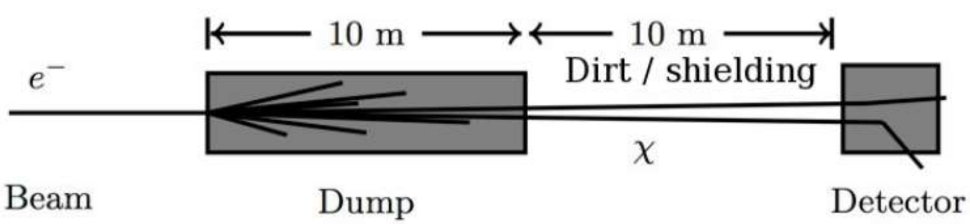
χ production

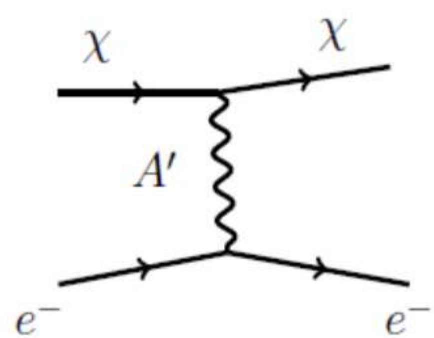
- High-energy, high-intensity e^- beam impinging on a dump
- χ particles pair-produced radiatively, trough A' emission

χ detection

- Detector placed behind the dump, $\simeq 20m$
- Neutral-current χ scattering on atomic e^- trough A' exchange,recoil releasing visible energy
- Signal: high-energy EM shower, $E > .3$ GeV

Number of events scales as: $N \propto \frac{\alpha_D \varepsilon^4}{m_A^4}$





Andrea Celentano, INFN-Genova, 2017

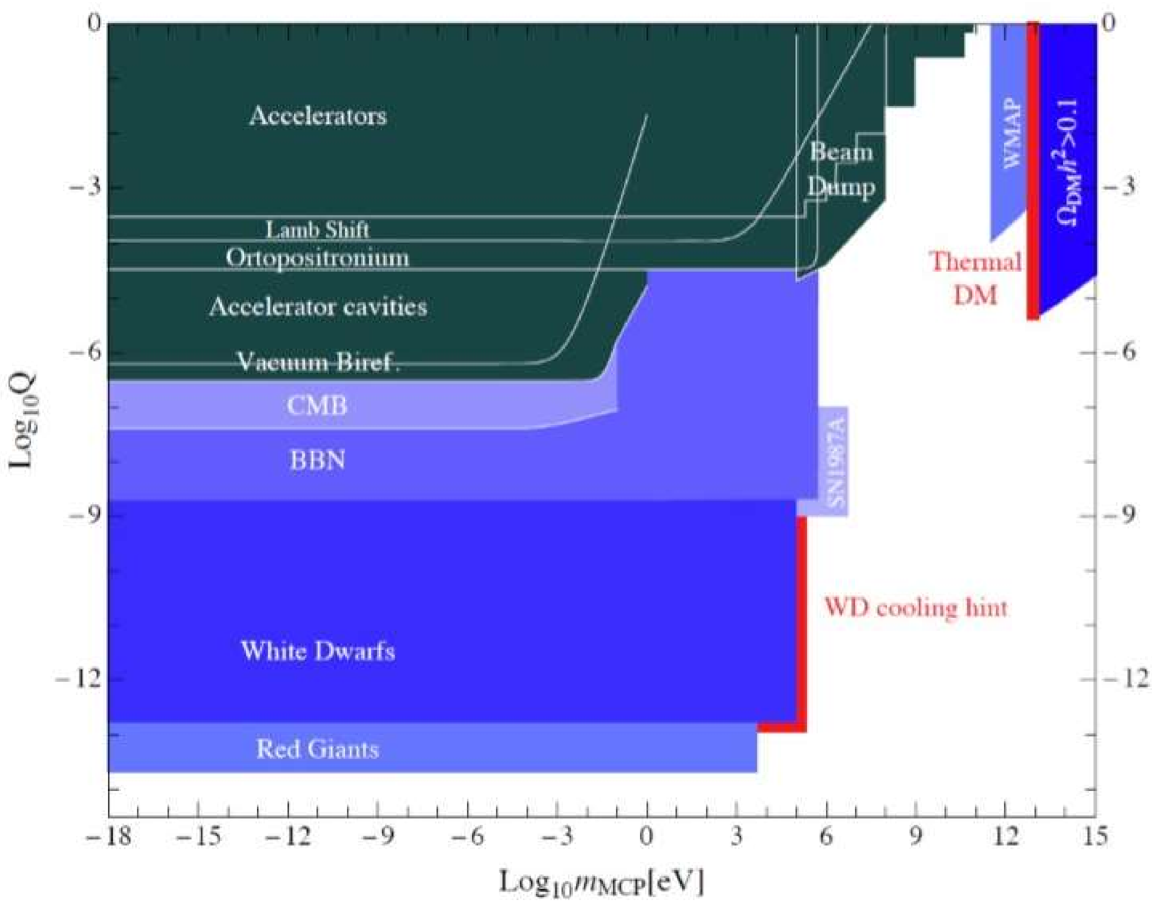
Meson Production List!

- At LSND, the π0 (135 MeV) spectrum is modeled using a Burman-Smith distribution
- Fermilab's Booster Neutrino Beam (BNB): π0 and η (548 MeV) mesons. π0's angular and energy spectra are modeled by the **Sanford-Wang distribution**. η mesons by the Feynman Scaling hypothesis.
- SHiP/DUNE: pseudoscalar meson production using the **BMPT distribution**, as before, but use a beam energy of 80 GeV
- J/ψ (3.1 GeV), we assume that their energy production spectra are described by the distribution from **Gale, Jeon, Kapusta, PLB '99**, nucl-th/9812056.
- Upsilon, Y (9.4 GeV): Same dist. , normalized by data from HERA-B, I. Abt et al., PLB (2006), hep-ex/0603015.

Meson Production Check!

- Using this, we have reproduced the Pb rates in [NA50, EPJ '06, nucl-ex/0612012] for J/Ψ, and for Υ, we reproduced the Pt rates in [Herb et al., PRL '77].

Other Broader Constraints



- Andy Haas, Fermilab, 2017
- **Beware of the different assumptions**

$Br(o-Ps \to \text{invisible}) < 4.2 \times 10^{-7}$ (90% C.L.) Badertscher et al, PRD (2007)

$\delta E = E(2S_{1/2}) - E(2P_{1/2}) \quad \delta E_{\mathrm{VP}} \simeq -\frac{\alpha^5 m_e}{30\pi}\left(\frac{m_e}{\mu}\right)^2 \varepsilon^2 .$ Gl¨uck, Rakshit, Reya, PRD (2007)

Other Constraints

- Astrophysics: Cooling/energy loss bounds from stars and SN
- Cosmology: BBN/CMB Neff
- Laboratory:
- Invisitble decay of ortho-positronium
- Lamb Shift
- Accelerators: E613, ASP, LEP, etc
- Andy Haas, Fermilab, 2017

MCP production

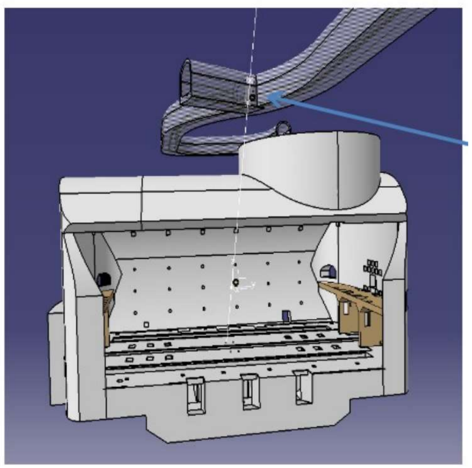
- **Significant branching ratios of electromagnetic decays to lepton pairs** implies an corresponding **decay to pairs of mCPs**, resulting in a significant flux of mCPs, even with small charges.
- Fixed target neutrino experiments: produce neutrinos from **weak decays of charged pions.** Similar spectrum of $\boldsymbol{\pi^0}$ is produced (inferred by comparing the production of π^0 and π^+ in pp and pn collisions ([Teis et al, 1996]), or by using counting arguments on the number of production [Norbury & Townsend, NIM B, 2007].
- For large enough beam energies, other neutral mesons (e.g. **η, Y, J/ψ**) are also produced.

Backup: MilliQan at CERN

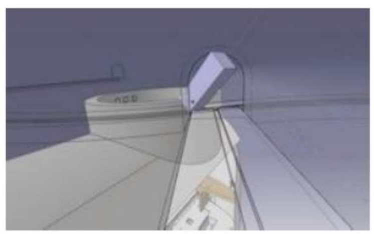
MilliQan Brief Review

- ~ 1 photo-electron observed per 1 long scintillator
- Require triple incidence in time window
- Moving in CMS "drainage gallery" at P5

- "Drainage Gallery" - an interlocked tunnel above CMS Point 5



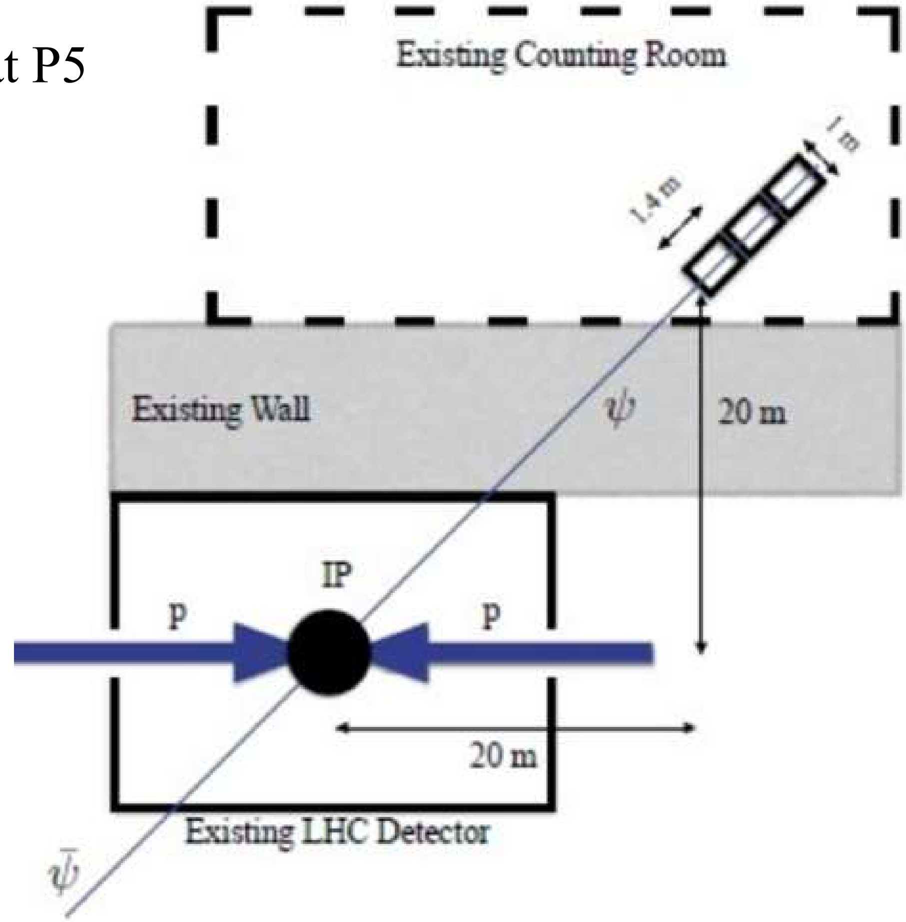
Beam backgrounds shielded by 14m of rock



30m from interaction point

Small angle from vertical

Andrew Haas, Fermilab (2017)



- MilliQan: Haas, Hill, Izaguirre, Yavin, 15, + (LOT arXiv:1607.04669)