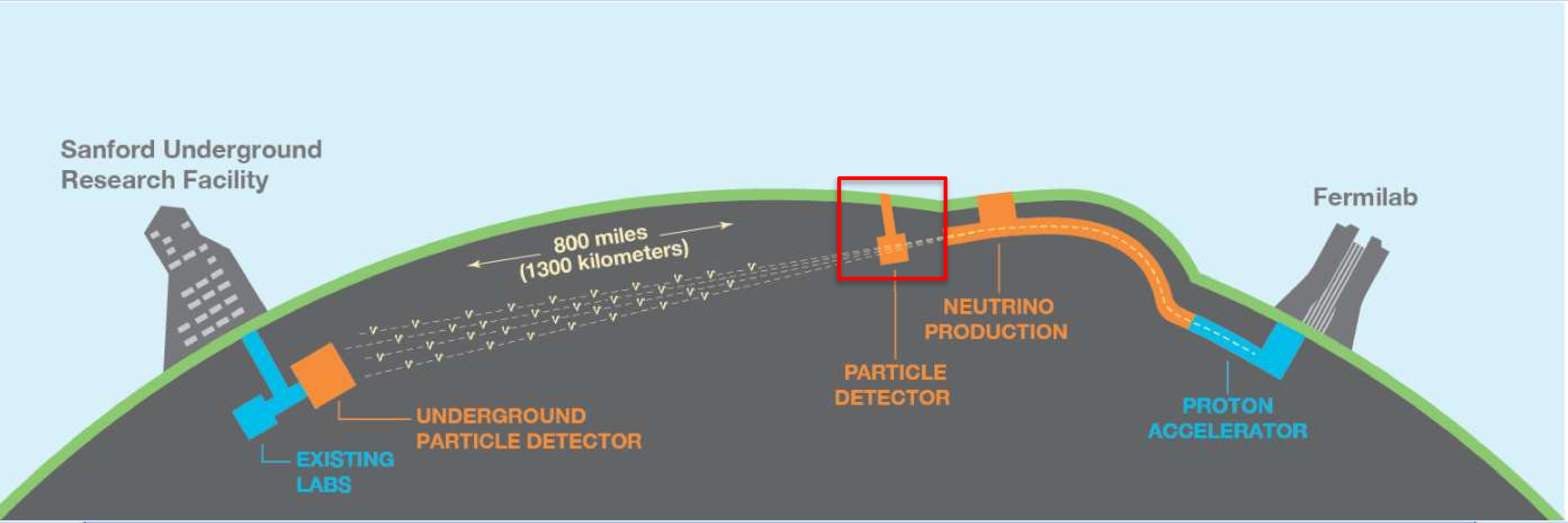


Fixed-Target Minicharge Searches: FerMINI and Neutrino Experiments

Yu-Dai Tsai, **Fermilab** , ytsai@fnal.gov

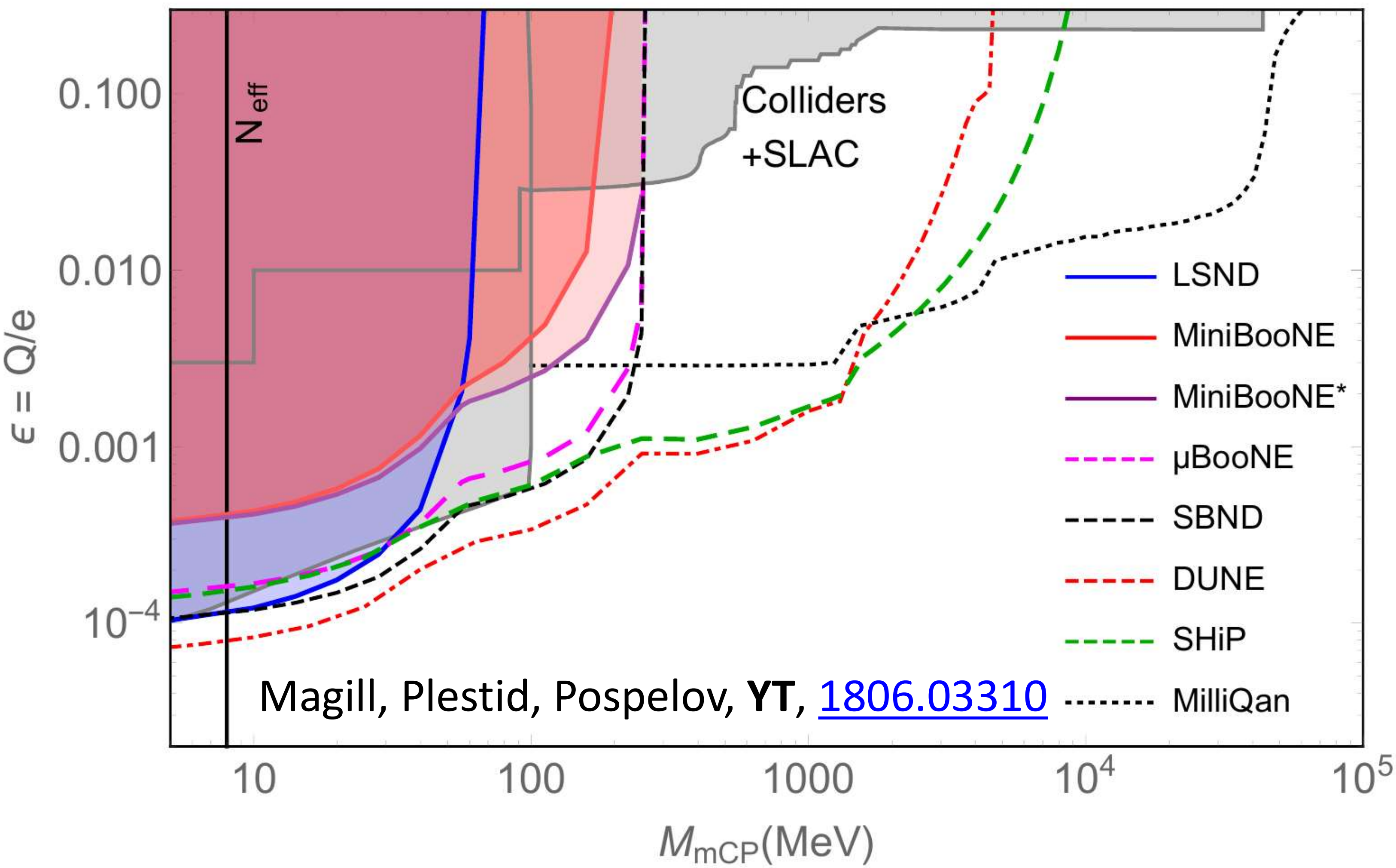
+ Gabriel Magill, Ryan Plestid, Maxim Pospelov (1806.03310, **PRL '18**)

with Kevin Kelly (1811.xxxxx, coming out this week!)

Outline

- Motivations
- Millicharged Particle (mCP) & Proton Fixed-Target Experiments
- Bounds & Sensitivity Reaches @ Neutrino Detectors
- Bounds & Sensitivity Reaches @ FerMINI (Preliminary)
- Discussion

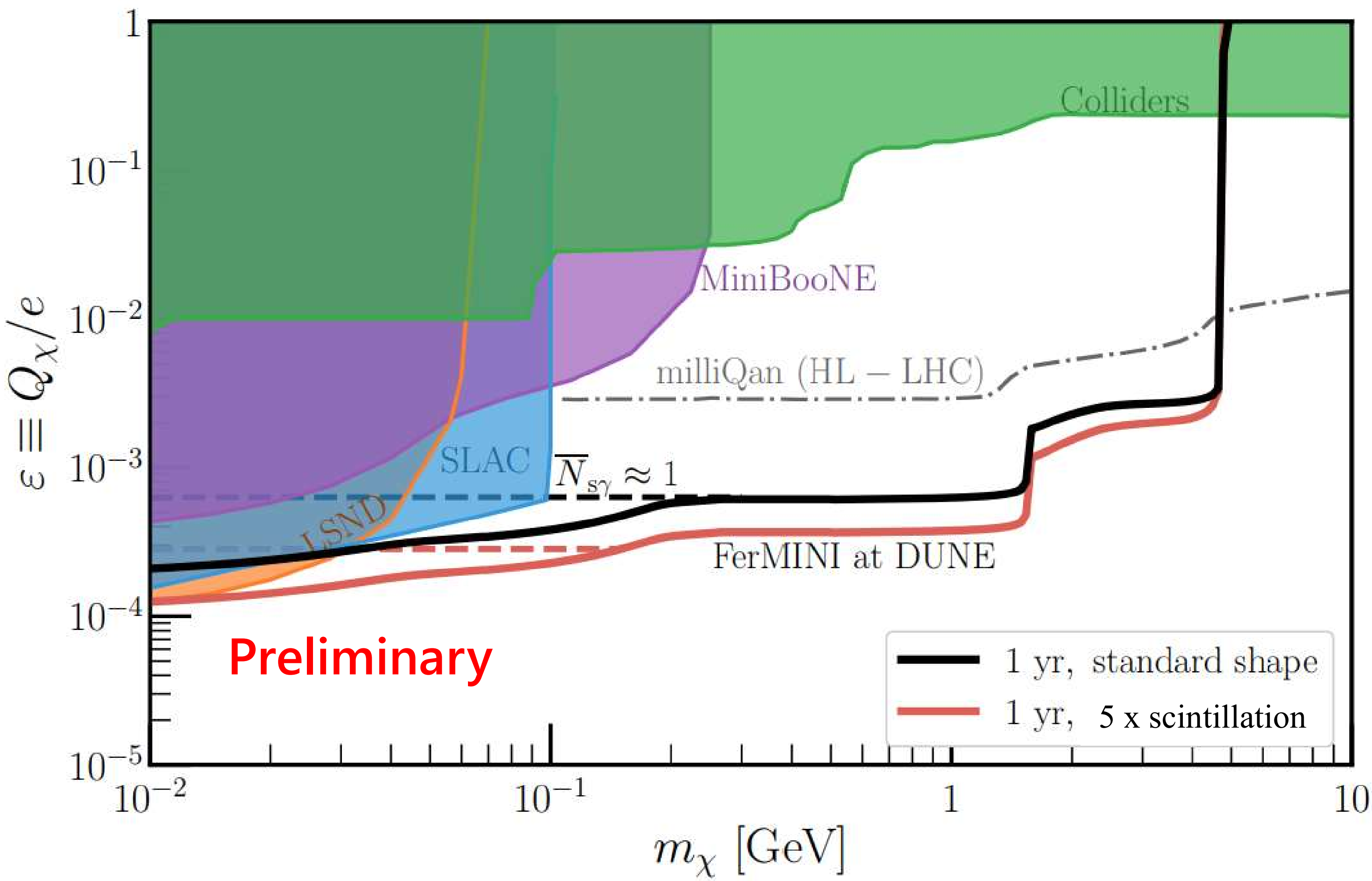
Preview @ Neutrino Detectors



- **Solid: current bounds**
- **Dashed: future sensitivity**
- **General review on other bounds:**

Andy Haas, Fermilab, 2017

Preview @ FerMINI



- **Solid shades: current bounds**
- **Solid curves: projections**
- **Dot-Dashed: milliQan projection**
- **(High Luminosity LHC)**

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, to explain charged quantization

- Searching for millicharge is a test of **e/3 charge quantization**

- MCP could have natural link to **dark sector** (e.g. dark photon)

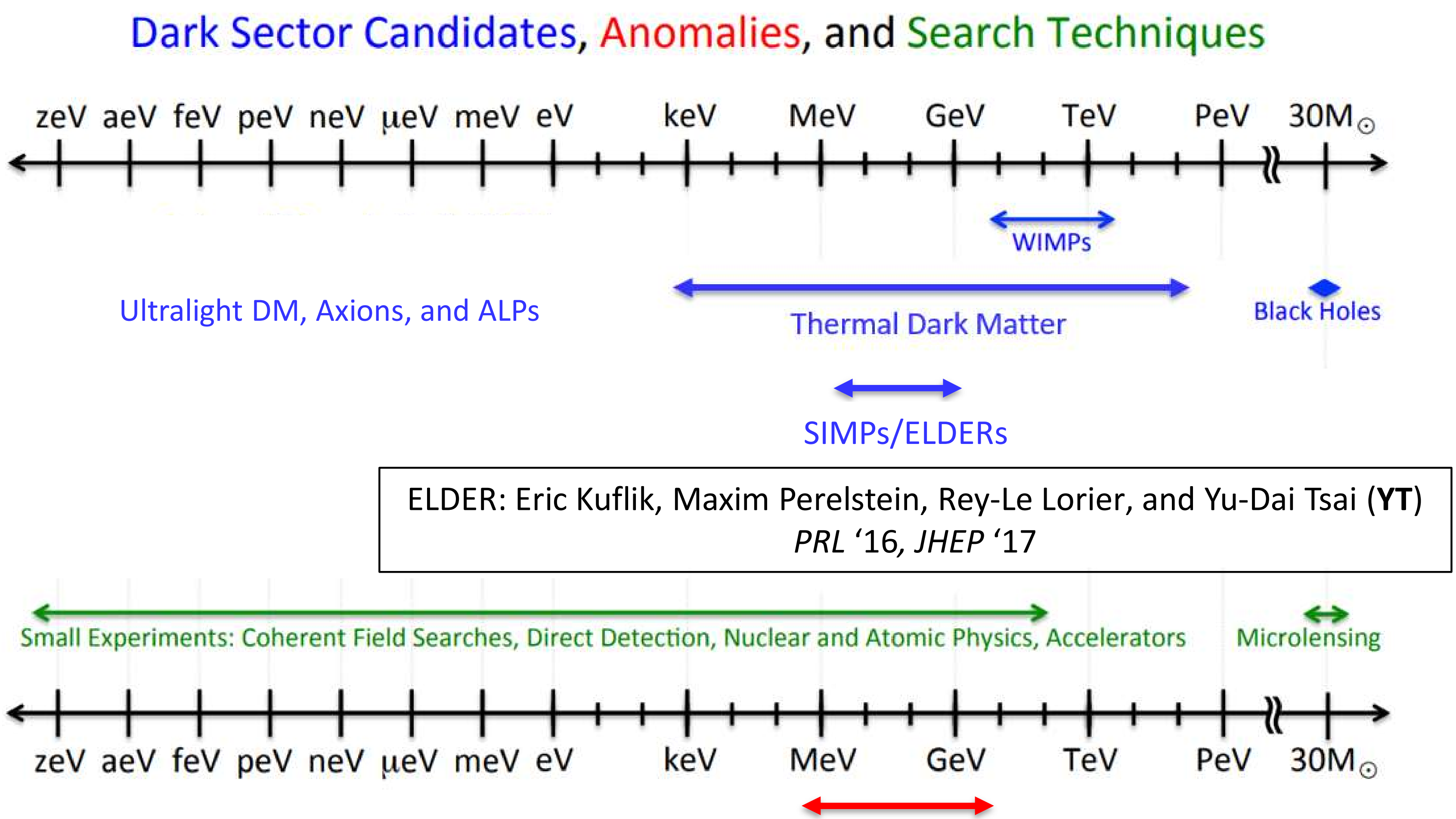
- Could account for dark matter (DM) (WIMP-like or other scenarios)

- 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



US Cosmic Visions 2017

- Proton fix-target/neutrino experiments are important for MeV ~ 10 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, …

⋮

Yu-Dai Tsai, Fermilab

Anomalies and Tests for MeV-GeV Explanations

⋮

Proton charge radius anomaly

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

  (Pospelov & **YT,** 1706.00424)

LSND/MiniBooNE excess

- **Dipole Portal Heavy Neutral Lepton**

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

- **New Constraints on MiniBooNE Excess Explanations**

  (Carlos Arguelles, **Matheus Hostert**, in progress)

EDGES anomaly

- **Millicharged Particles** in Neutrino Experiments

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

Further inspired by …

deNiverville, Pospelov, Ritz, ’11,

Kahn, Krnjaic, Thaler, Toups, ’14 …

⋮

Millicharged Particle: Models

mCP Model

- Small charged particles under U(1) hypercharge

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

- 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 Grand Unification Theory
  - I will not spend too much time on the model

Kinetic Mixing

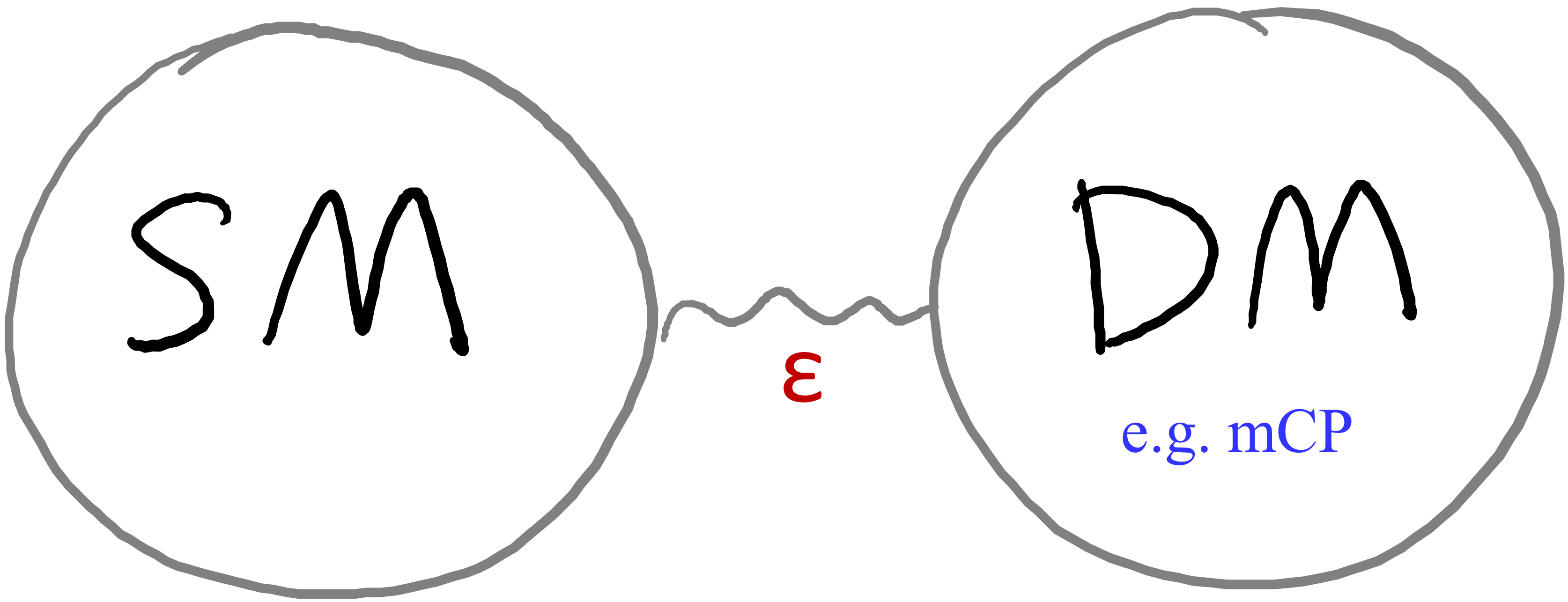
See, Holdom, 1985

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

- 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



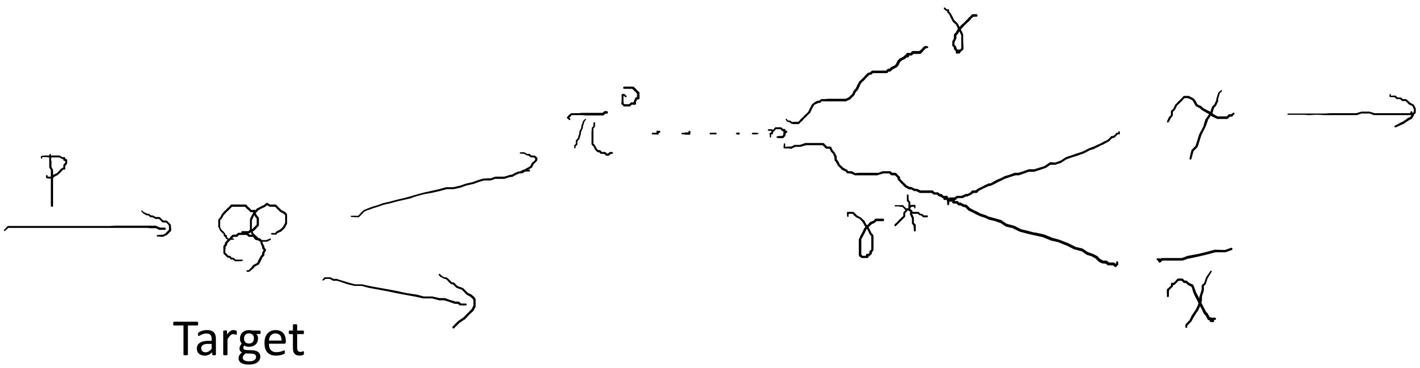
Yu-Dai Tsai, Fermilab, 2018

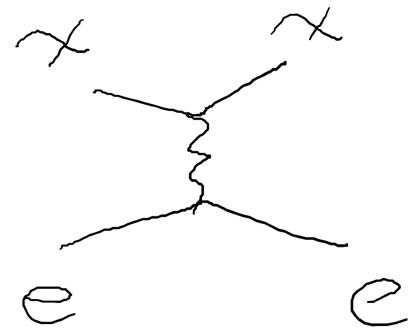
IMPORTANT NOTE

- 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

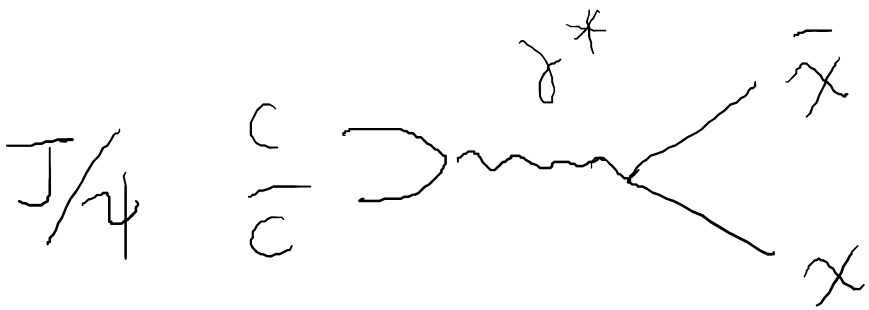
MCP: production & detection @ neutrino detector





- production:
  meson decays

- detection:
  scattering electron



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

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

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

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

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

MCP Signals

- **signal events** s_{event}

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

detection efficiency

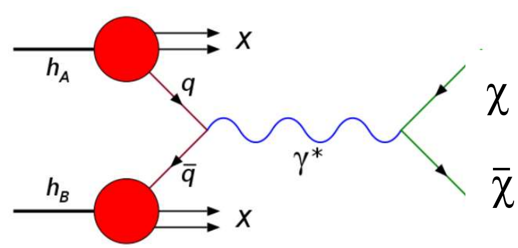
- $N_\chi(E_i)$ represents the number of mCPs with energy E_i arriving at the detector. $N_\chi(E_i)$ is a function of both the **branching ratio** and **geometric losses** which can vary significantly between experiments
- N_e: **total number of electrons** inside the active volume of the detector
- 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, *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**.



https://en.wikipedia.org/wiki/Drell%E2%80%93Yan_process

(detail) Meson Production Details

- 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.
- Calibrated with existing data [e.g. NA50, EPJ '06, nucl-ex/0612012, Herb et al., PRL '77]. and simulations from other groups [e.g. deNiverville, Chen, Pospelov, and Ritz, Phys. Rev. D95, 035006 (2017), arXiv:1609.01770 [hepph].]

MCP Detection

- Detection signature: **elastic scattering with electrons**.
- Look for single-electron events
- **Electron scattering as a detection signal** has a **low- Q^2 enhancement** (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 $\sigma_{e\chi} = 4\pi\, \alpha^2\varepsilon^2/{Q_{min}}^2$.
- In the lab frame, Q^2 can be expressed in terms of 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

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

Yu-Dai Tsai, Fermilab, 2018

MCP Detection

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

- 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 Bound/Sensitivity

- **signal events s_{event}**

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

- Here, $s_{event} \propto \varepsilon^4$. ε^2 from N_x and ε^2 from $\boldsymbol{\sigma}_{ex}$
- 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 $\alpha = \Gamma(1 + n, b + s_{event})/\Gamma(1 + n, b)$, 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?**
- Consider two classes of backgrounds:

  1) From neutrino fluxes (calculable),

     [i.e. **νe** → **νe** and **νn** → **ep**], sum over the neutrino 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

(1) Background Reduction

Imposing the maximum electron recoil energy cuts E_e(max) for neutrino-caused backgrounds

- 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.

(2) Estimation of Other Background

- Liquid Argon Time Projection Chamber **(LArTPC)** can use **timing information as vetoes to reduce backgrounds.**
- 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 decrease 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

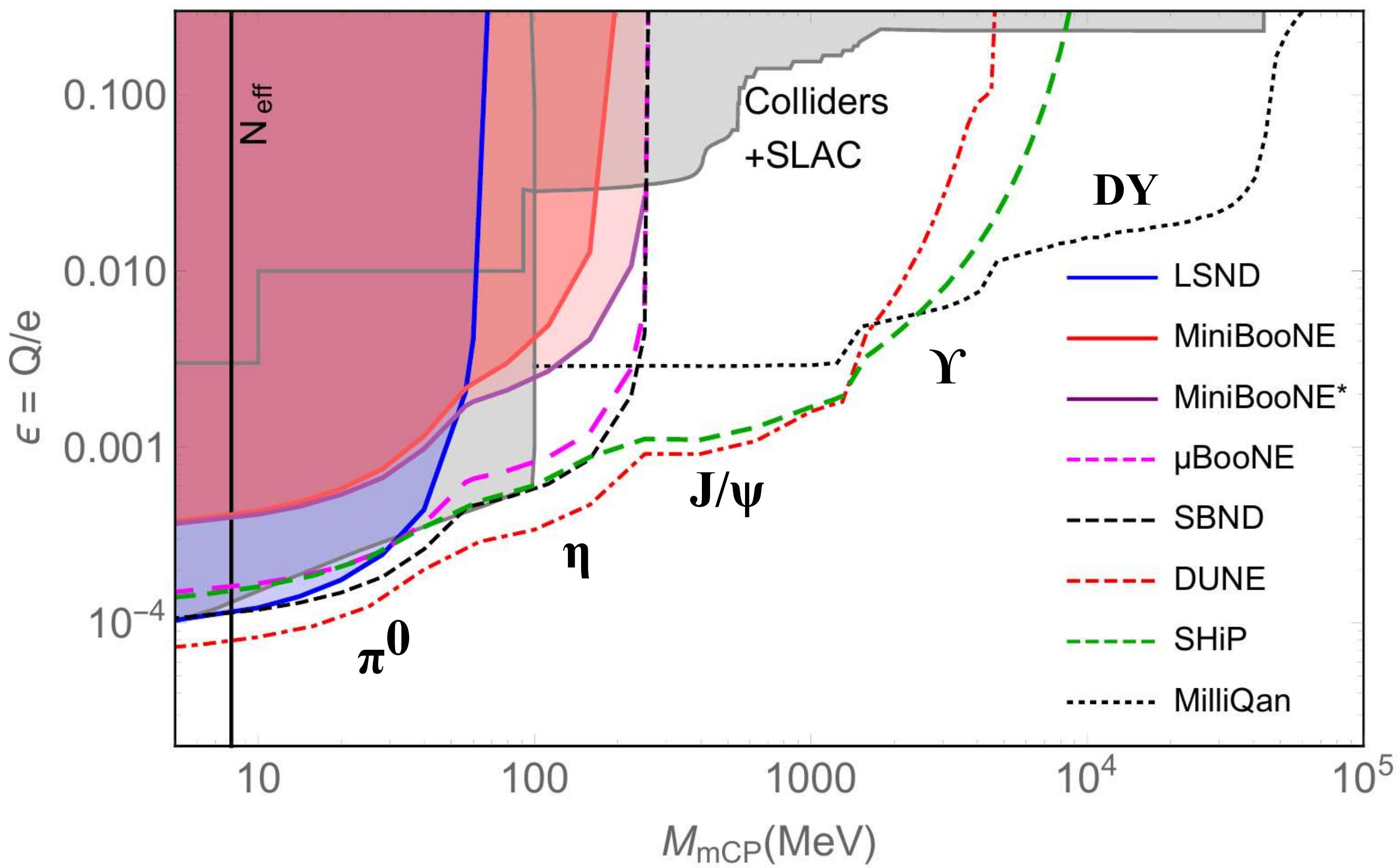
Exp. (Beam Energy, POT)	N [$\times 10^{20}$] π^0	η	$A_{\rm geo}(m_\chi)$[$\times 10^{-3}$] 1 MeV	100 MeV	Cuts [MeV] $E_e^{\rm min}$	$E_e^{\rm max}$	Bkg
Existing							
LSND (0.8 GeV, 1.7×10^{23})	130	—	20	—	18	52	300
mBooNE (8.9 GeV, 2.4×10^{21})	17	0.56	1.2	0.68	130	530	2k
mBooNE* (8.9 GeV, 1.9×10^{20})	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

- $\varepsilon \propto E_{e,R,min}^{1/4}\, Bg^{1/8}$
- $\cos\theta > 0$ is imposed (*except for at MiniBooNE's dark matter run where a cut of $\cos\theta > 0.99$ 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.

(Detail) 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 $\mathbf{2.4 \times 10^{21}}$ **POT** for which we take the **single electron background to be** $\mathbf{2.0 \times 10^{3}}$ events and the **measured rate to be** $\mathbf{2.4 \times 10^{3}}$
- **MiniBooNE* (DM run)**: arXiv:1807.06137 (came out after our v1). **Electron recoil analysis** We did not include their timing cuts in our calculations, since they were optimized by the MiniBooNE collaboration to the signal's timing profile.

Contributions & Other Bounds



- MilliQan: Haas, Hill, Izaguirre, Yavin, (2015), + (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).

Summary Table

Exp. (Beam Energy, POT)	N [$\times 10^{20}$]		$A_{geo}(m_\chi)[\times 10^{-3}]$		Cuts [MeV]		
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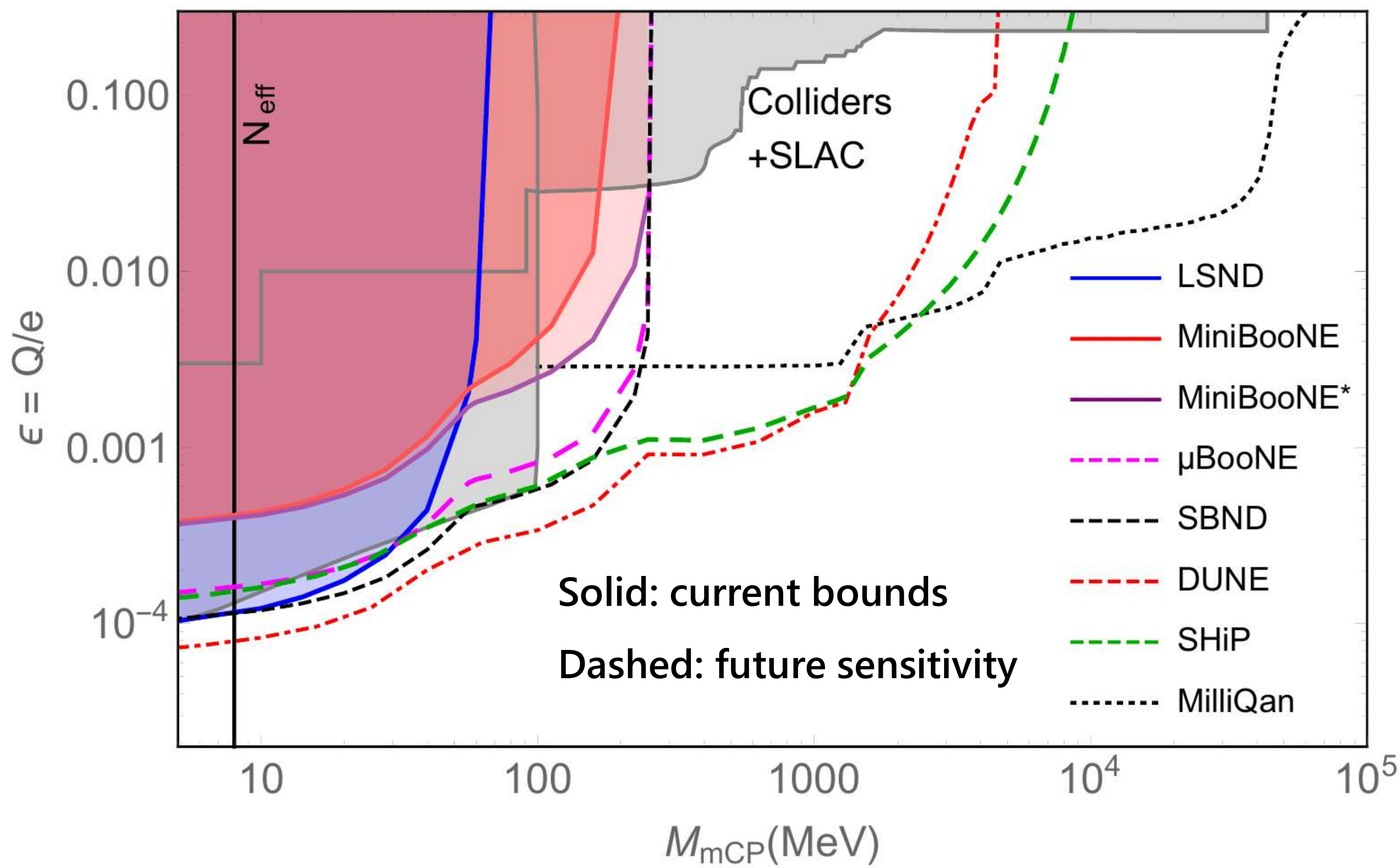
mBooNE* (8.9 GeV, 1.9×10^{20})	1.3	0.04	1.2	0.68	75	850	0
μBooNE (8.9 GeV, 1.3×10^{21})	9.2	0.31	0.09	0.05	2	40	16
SBND (8.9 GeV, 6.6×10^{20})	4.6	0.15	4.6	2.6	2	40	230
DUNE (80 GeV, 3.0×10^{22})	830	16	3.3	5.1	2	40	19k
SHiP (400 GeV, 2.0×10^{20})	4.7	0.11	130	220	100	300	140

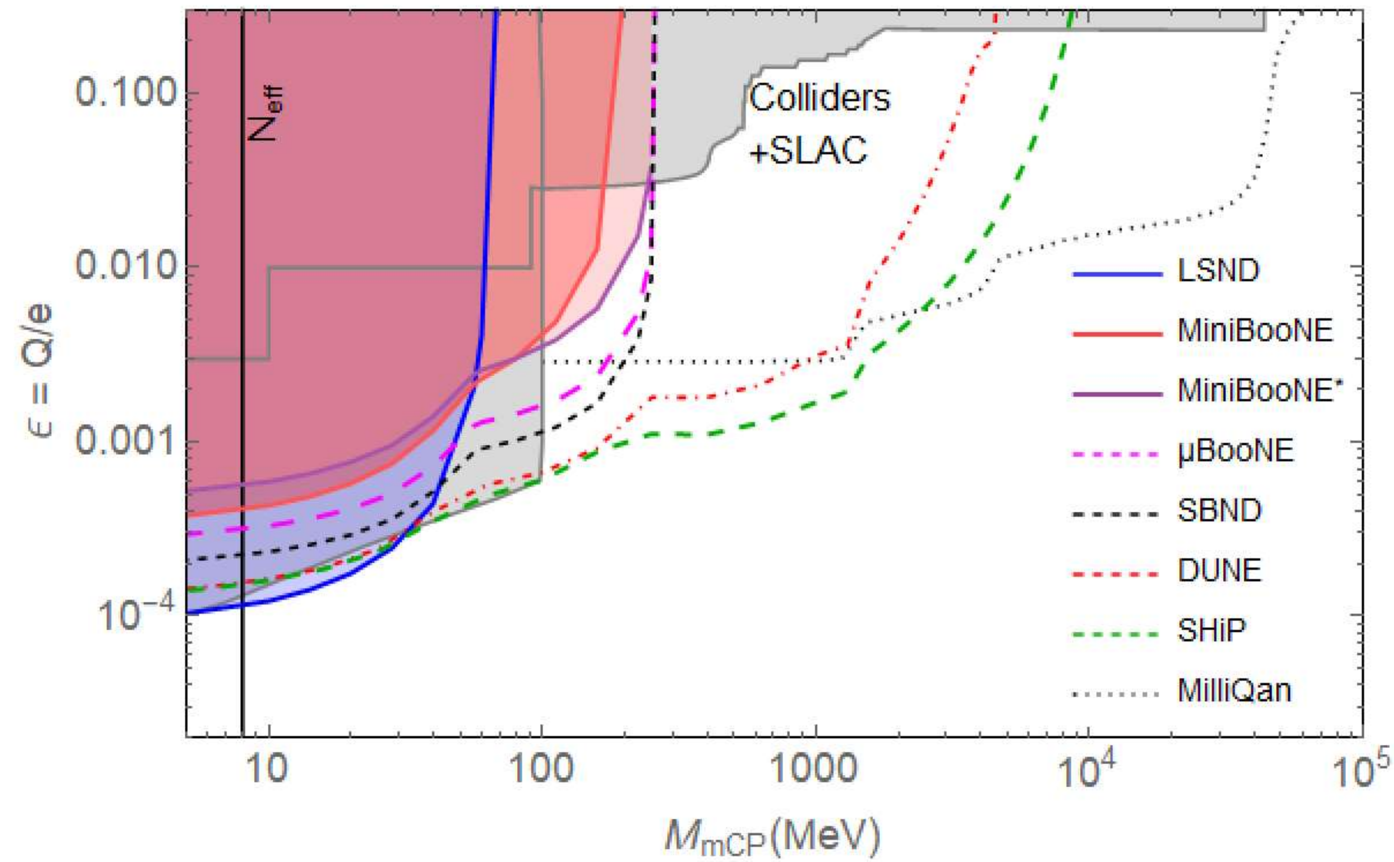
- $\varepsilon \propto E_{e,\,R,min}^{1/4}\, Bg^{1/8}$
- At **LArTPC**, the **wire spacing is about 3 mm**, the ionization stopping power is approximately **2.5 MeV/cm**: electrons with total energy larger than at least **2 MeV** produce tracks long enough to be reconstructed across two wires.

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

More Conservative Cuts on Threshold



	N $[\times 10^{20}]$		$A_{geo}(m_\chi)[\times 10^{-3}]$		Cuts [MeV]		
Exp. (Beam Energy, POT)	π^0	η	1 MeV	100 MeV	E_e^{min}	E_e^{max}	Bkg
μBooNE (8.9 GeV, 1.3×10^{21})	9.2	0.31	0.09	0.05	30	70	20
SBND (8.9 GeV, 6.6×10^{20})	4.6	0.15	4.6	2.6	30	70	200
DUNE (80 GeV, 3.0×10^{22})	830	16	3.3	5.1	30	70	19k

Remarks

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

  - Production from **heavy neutral mesons** are important (sometimes neglected in literature)

  - Signature favor **low electron-recoil energy threshold**
- For more realistic analysis (with your help): including realistic **background, $E_{e,\,R,min}$ cut**, etc

FerMINI Proposal:

Putting milliQan-Type Minicharged Particle Detector

@ Fermilab Beamlines: NuMI or LBNF

Yu-Dai Tsai, Fermilab, 2018

MilliQan at CERN

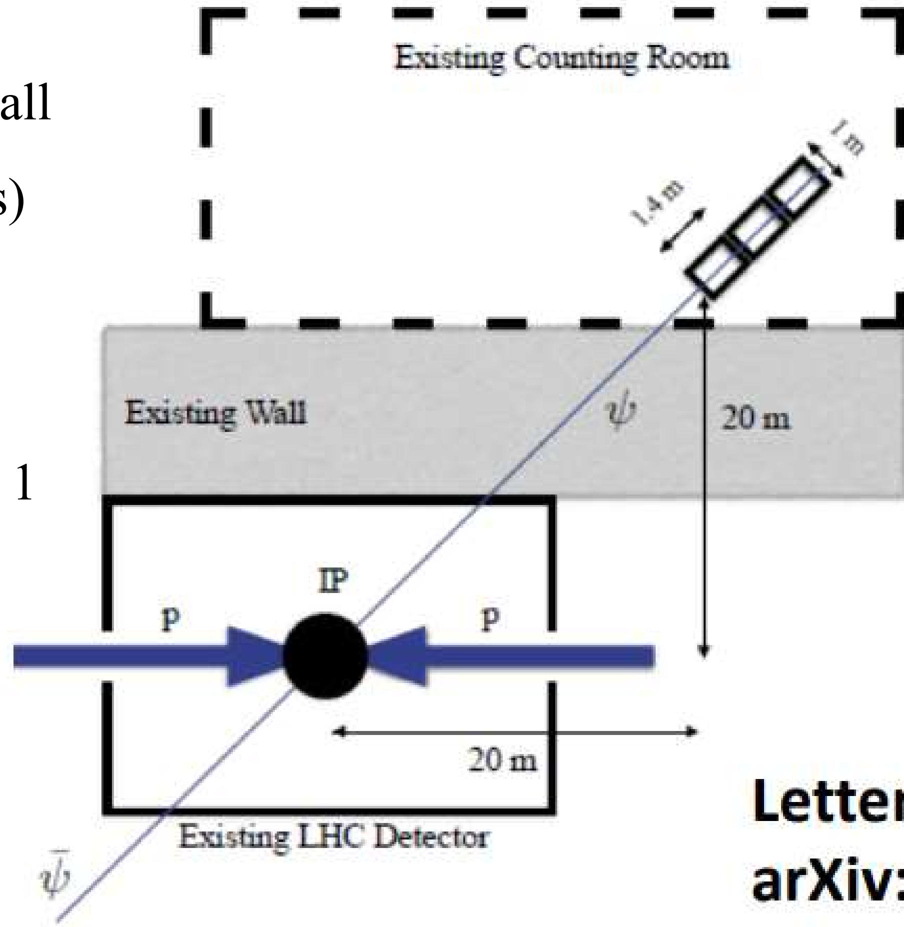
Austin Ball, Jim Brooke, Claudio Campagnari, Albert De Roeck, Brian Francis, Martin Gastal, Frank Golf, Joel Goldstein, **Andy Haas, Christopher S. Hill, Eder Izaguirre**, Benjamin Kaplan, Gabriel Magill, Bennett Marsh, David Miller, Theo Prins, Harry Shakeshaft, David Stuart, Max Swiatlowski, **Itay Yavin**

arXiv:1410.6816, PRD '15

arXiv:1607.04669, Letter of Intent (LOT)

MilliQan: General Idea

- Require triple incidence in small time window (15 nanoseconds)
- With Q down to 10^{-3} e, each MCP produce averagely ~ 1 photo-electron observed per ~ 1 meter long scintillator



Letter of intent: arXiv:1607.04669

Andrew Haas, Fermilab (2017)

MilliQan: Design

- Total: 1 m × 1 m (transverse plane) × 3 m (longitudinal) plastic scintillator array.
- Array oriented such that the long axis points at the CMS **Interaction Point**.
- The array is subdivided into 3 sections each containing 400 5 cm × 5 cm × 80 cm scintillator bars optically coupled to high-gain photomultiplier **(PMT)**.
- A **triple-incidence within a 15 ns time window** along longitudinally contiguous bars in each of the 3 sections will be required in order to reduce the **dark-current noise (the dominant background)**.

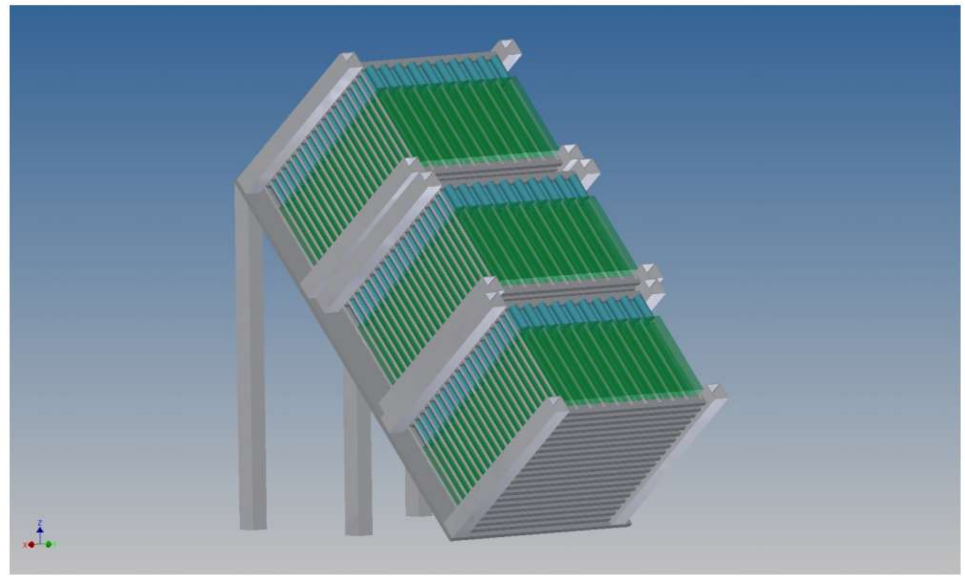
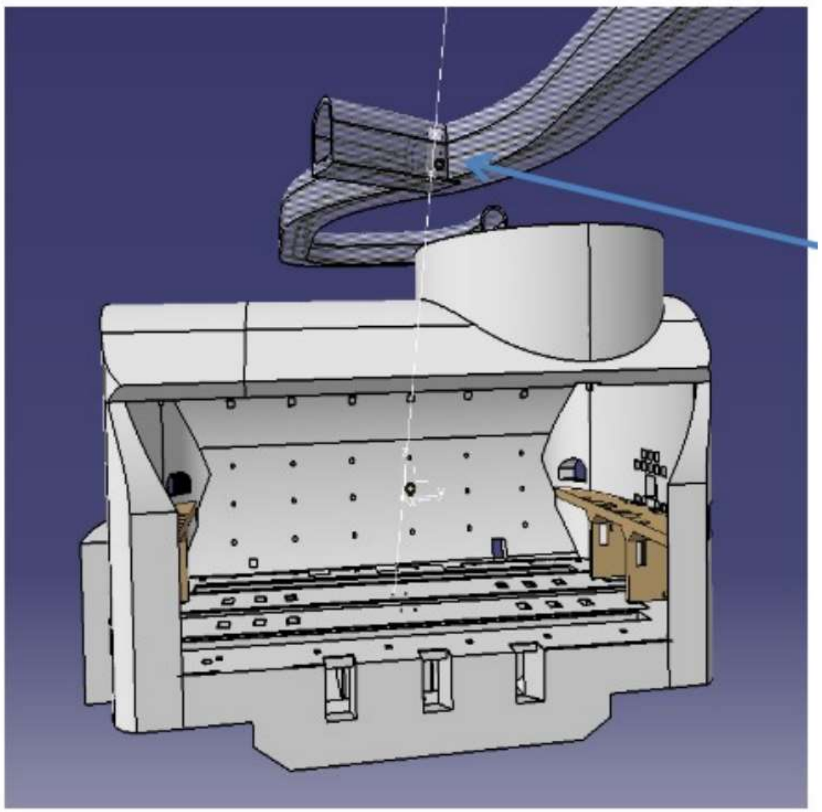


Figure from 1607.04669 (milliQan LOT)

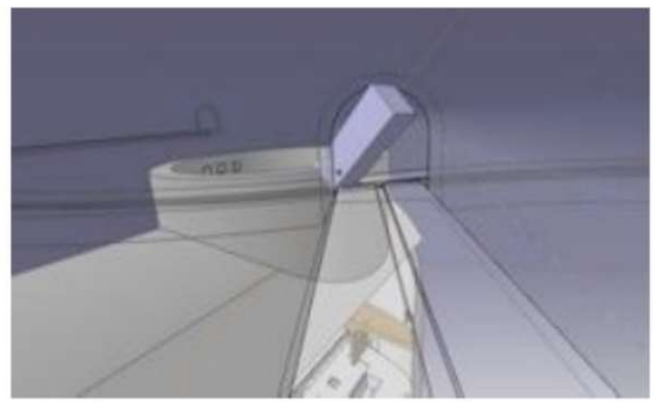
MilliQan: Location!

- Placed in CMS "drainage gallery" above the detector

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



Beam backgrounds shielded by 14m of rock



30m from interaction point

Small angle from vertical

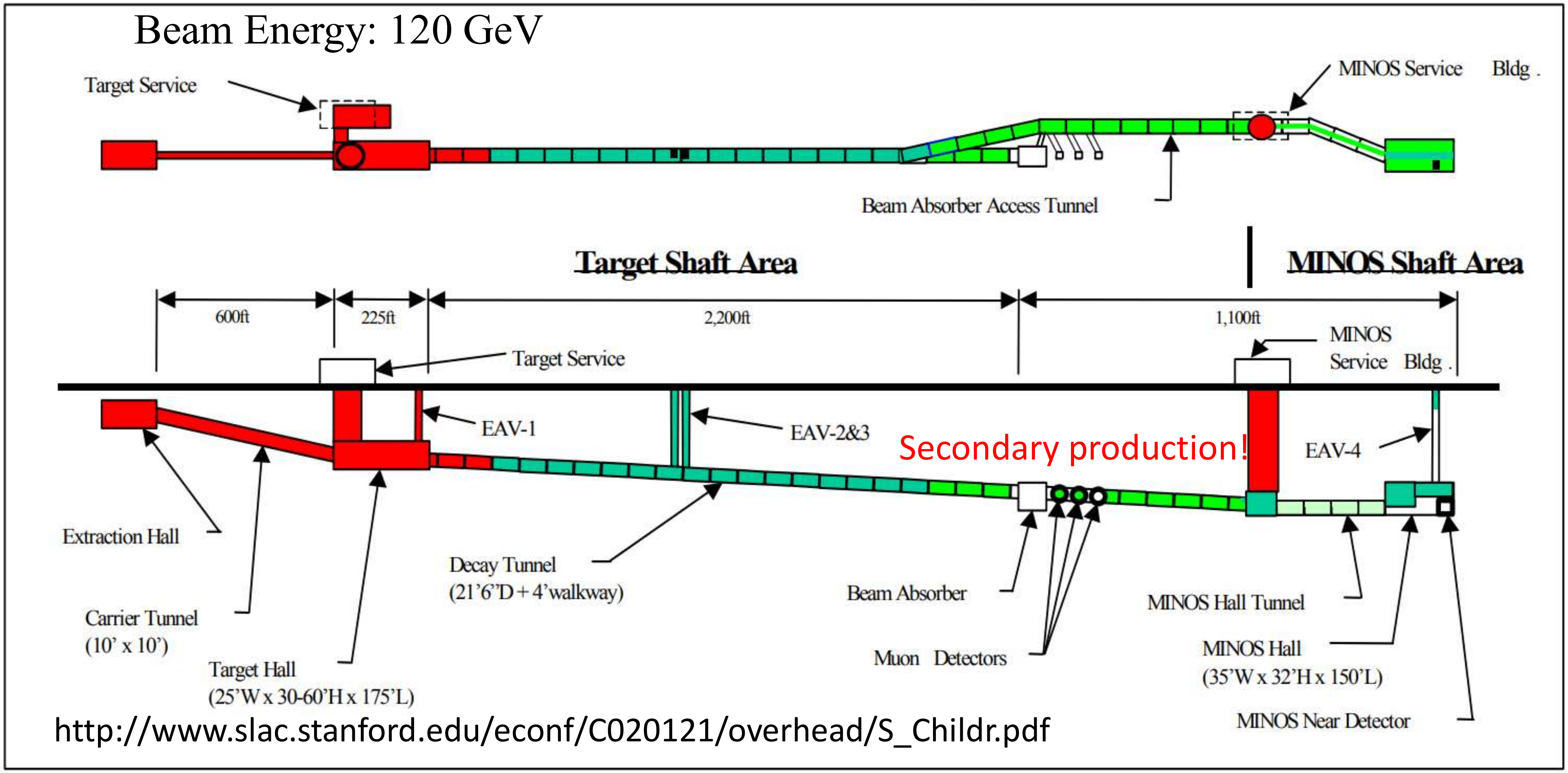
Andrew Haas, Fermilab (2017)

FerMINI:

A Fermilab Search for Minicharged Particle

Kevin Kelly & Yu-Dai Tsai

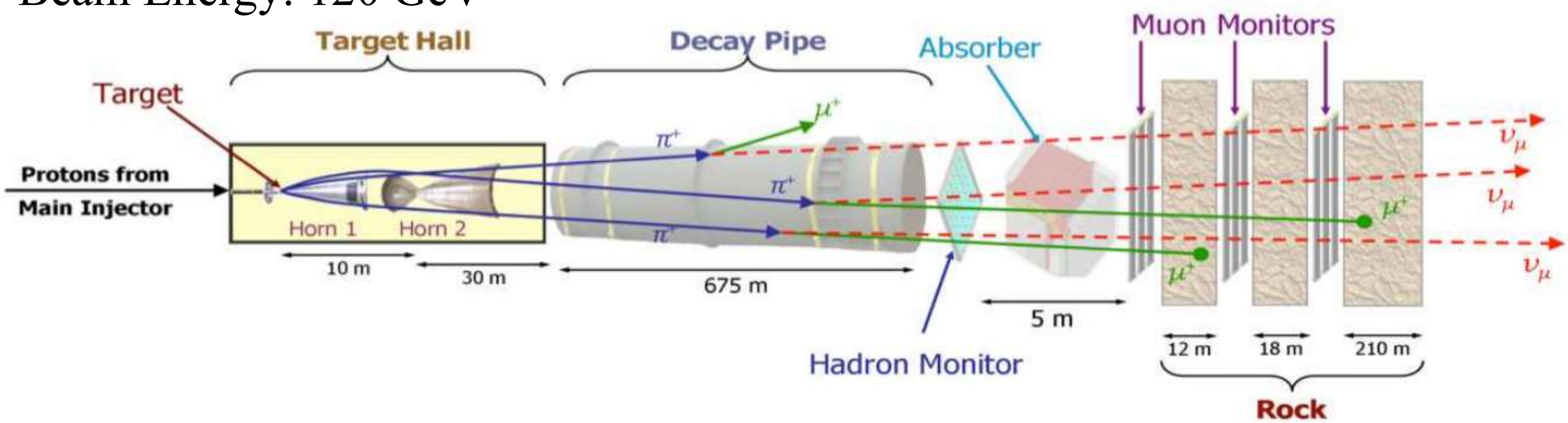
NuMI Beam & MINOS ND Hall

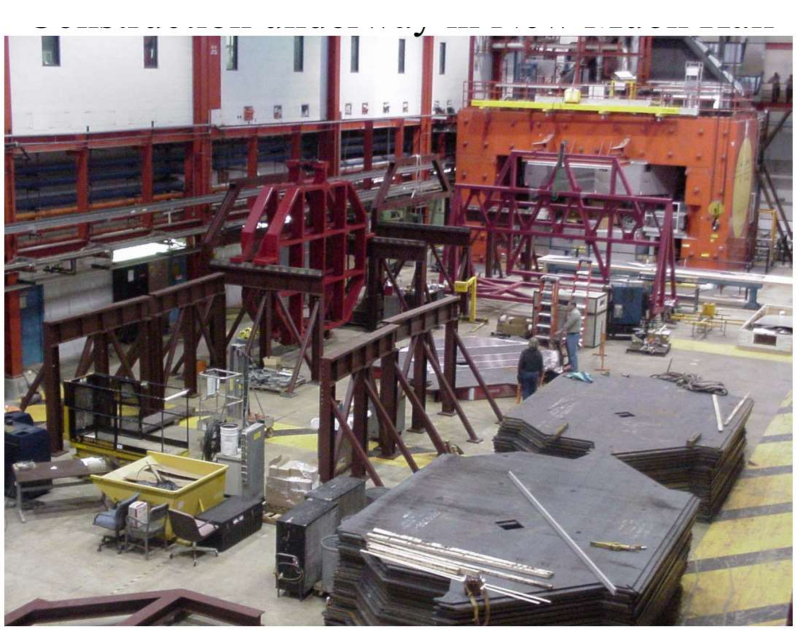


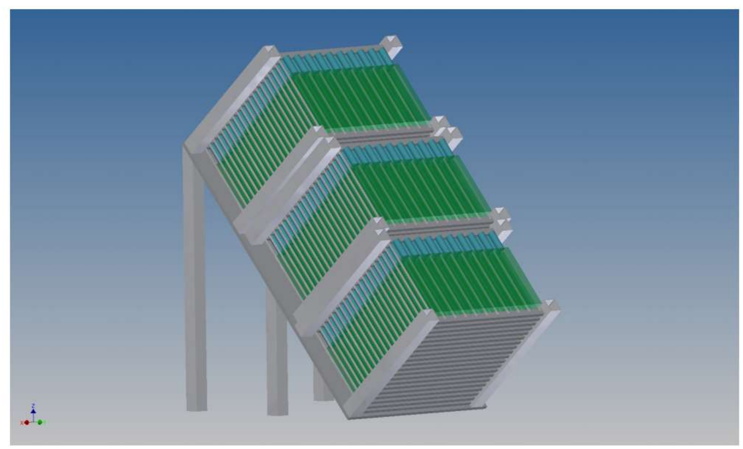
NuMI: Neutrinos at the Main Injector
MINOS: Main Injector Neutrino Oscillation Search

FerMINI @ NuMI-MINOS Hall

Beam Energy: 120 GeV

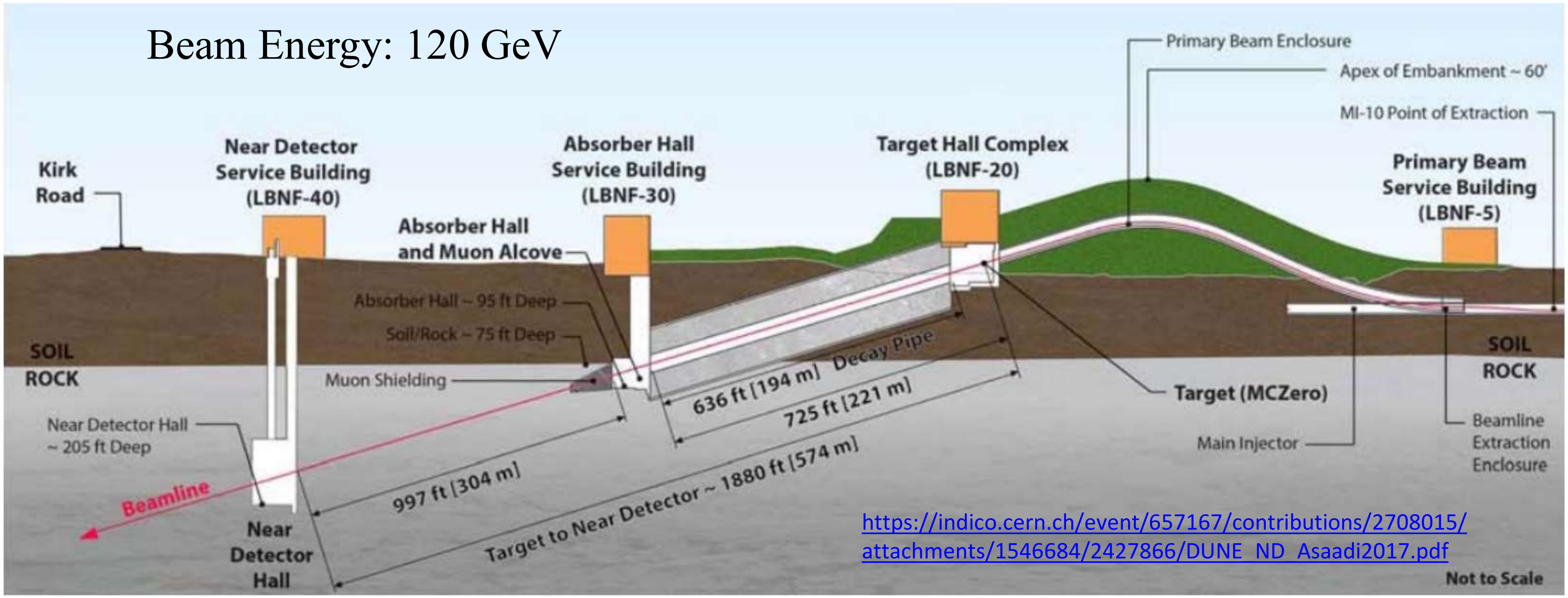






LBNF Beam & DUNE ND Hall

Beam Energy: 120 GeV



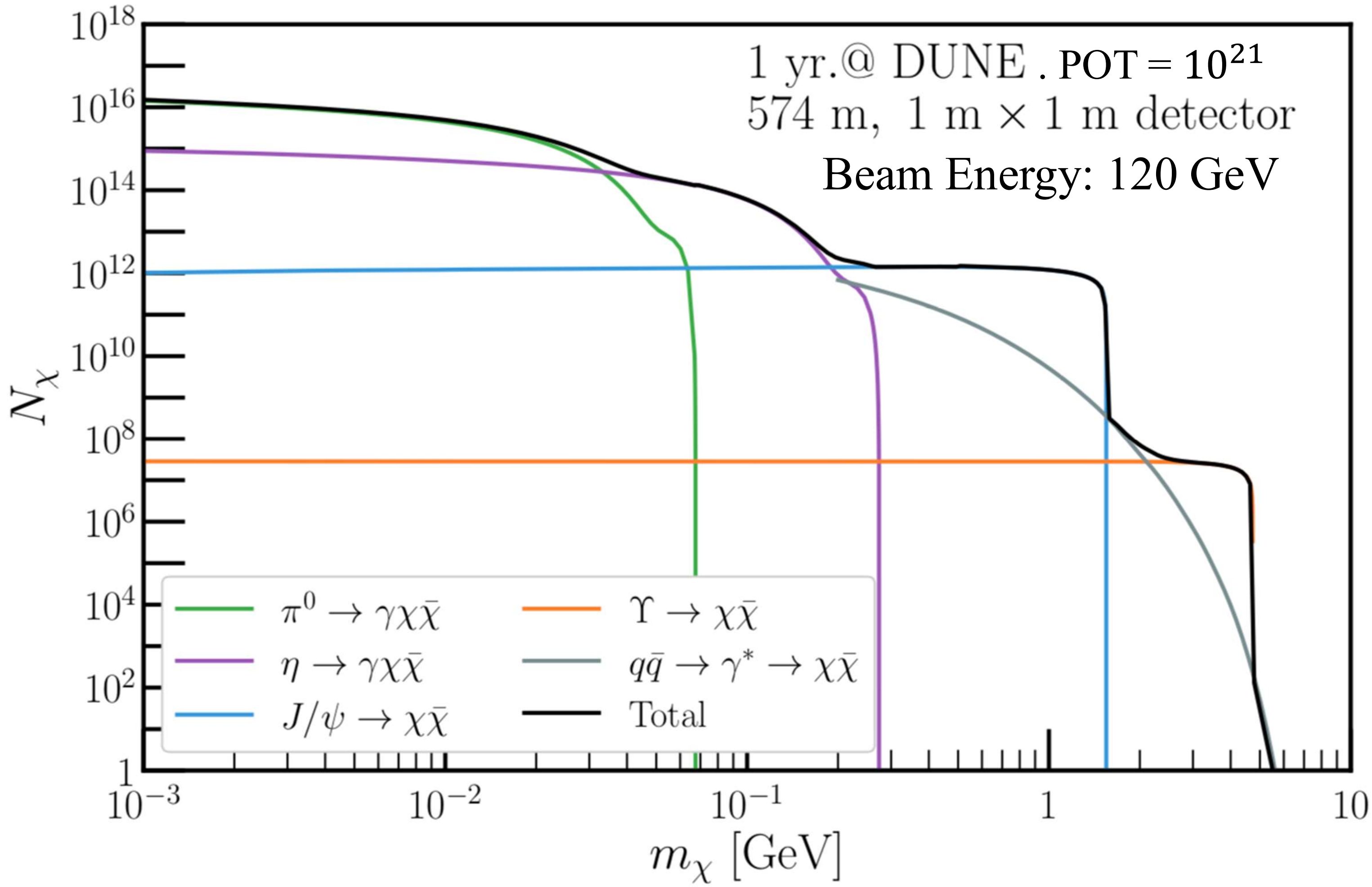
https://indico.cern.ch/event/657167/contributions/2708015/attachments/1546684/2427866/DUNE_ND_Asaadi2017.pdf

Jonathan Asaadi – University of Texas Arlington

Explore **new physics opportunities** in the near detector!

Let's SPLASH the PONDD!

MCP Production/Flux



- We use PYTHIA to generate neutral meson Dalitz or direct decays from the pp collisions and rescale by considering, $\mathrm{BR}(\mathcal{M} \to \chi\bar{\chi}) \approx \epsilon^2 \times \mathrm{BR}(\mathcal{M} \to X e^+ e^-) \times f\left(\frac{m_\chi}{M}\right),$
- M: mass of the parent meson, X:additional particles, $f(m_\chi/M)$: phase space factor
- We also include Drell-Yan production for the high mass MCPs.

Signature: Triple Incidence

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

$$N_{PE} \simeq \rho_{scint} \times \left\langle -\frac{dE}{dx} \right\rangle \times l_{scint} \times LY \times e_{det}.$$

  - LY: light yield
  - e_{det}: detection efficiency

$N_{PE} \sim \epsilon^2 \times 10^6$, so $\epsilon \sim 10^{-3}$ roughly gives one PE in 1 meter scintillation bar

- Based on Poisson distribution, zero event in each bar correspond to $P_0 = e^{-N_{PE}}$, so the probability of seeing triple incident of one or more photoelectron is: $P = \left(1 - e^{-N_{PE}}\right)^3,$

- $N_{x,detector} = N_x \times$ **P .**

Number of photoelectrons (PEs)

- For moderately small epsilon and heavy enough MCP (>> electron mass), one can use Bethe equation to estimate average energy loss.

$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] .$$

z	charge number of incident particle	
Z	atomic number of absorber	
A	atomic mass of absorber	g mol^{-1}
K	$4\pi N_A r_e^2 m_e c^2$ (Coefficient for dE/dx)	0.307 075 MeV mol^{-1} cm^2
I	mean excitation energy	eV (*Nota bene!*)
$\delta(\beta\gamma)$	density effect correction to ionization energy loss	

$$W_{\max} = \frac{2 m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2} .$$

- M: charged particle mass
- For very small epsilon (related to the finite length effect), one have to consider **most probable energy deposition & consider landau distribution** for the energy transfer.

Background:
Detector & Beam Related

Detector Background

- We will discuss two major **detector backgrounds** and the **reduction technique**
- **SM charged particles from background radiation (e.g., cosmic muons):**
  offline veto + offset middle detector
- **Dark current: triple incidence**
- See 1607.04669 (milliQan LOT)

Reduce background from SM

- Reduce background from **SM charged particles**
- **Offline-vetoes of large-PE events: Offline veto of events with > 10 PEs** Background events (such as **cosmic muons**) produce a large number of PEs (typically > 10^3 PEs) would be vetoed.
- **Offset the middle detector array**: Charged standard model particles skimming the edge, producing only a low number of PE. **Offsetting the middle detector, or making it slightly smaller/larger**, would prevent these types of events from producing signature in all three arrays.
- These would also reduce the **charged particles directly or indirectly from the beam**, e.g., vμ from the beam striking the detector (or nearby rock) and producing a muon

Dark Current Background @ PMT

- **Major Background!**
- We take the dark-current frequency to be v_B= 500 Hz for estimation. (from 1607.04669, milliQan L.O.T.)
- For each tri-PMT set (each connect to the three connected scintillation bar), the background rate for triple incidence is $\boldsymbol{v_B^3}$ **Δt^2 = 2.8 x $\mathbf{10^{-8}}$ Hz**, for **Δt = 15 ns.**
- There are 400 such set in the nominal design.
- The total background rate is 400 x 2.8 x 10^{-8} ~ 10^{-5} Hz
- ~ **300 events** in one year of trigger-live time

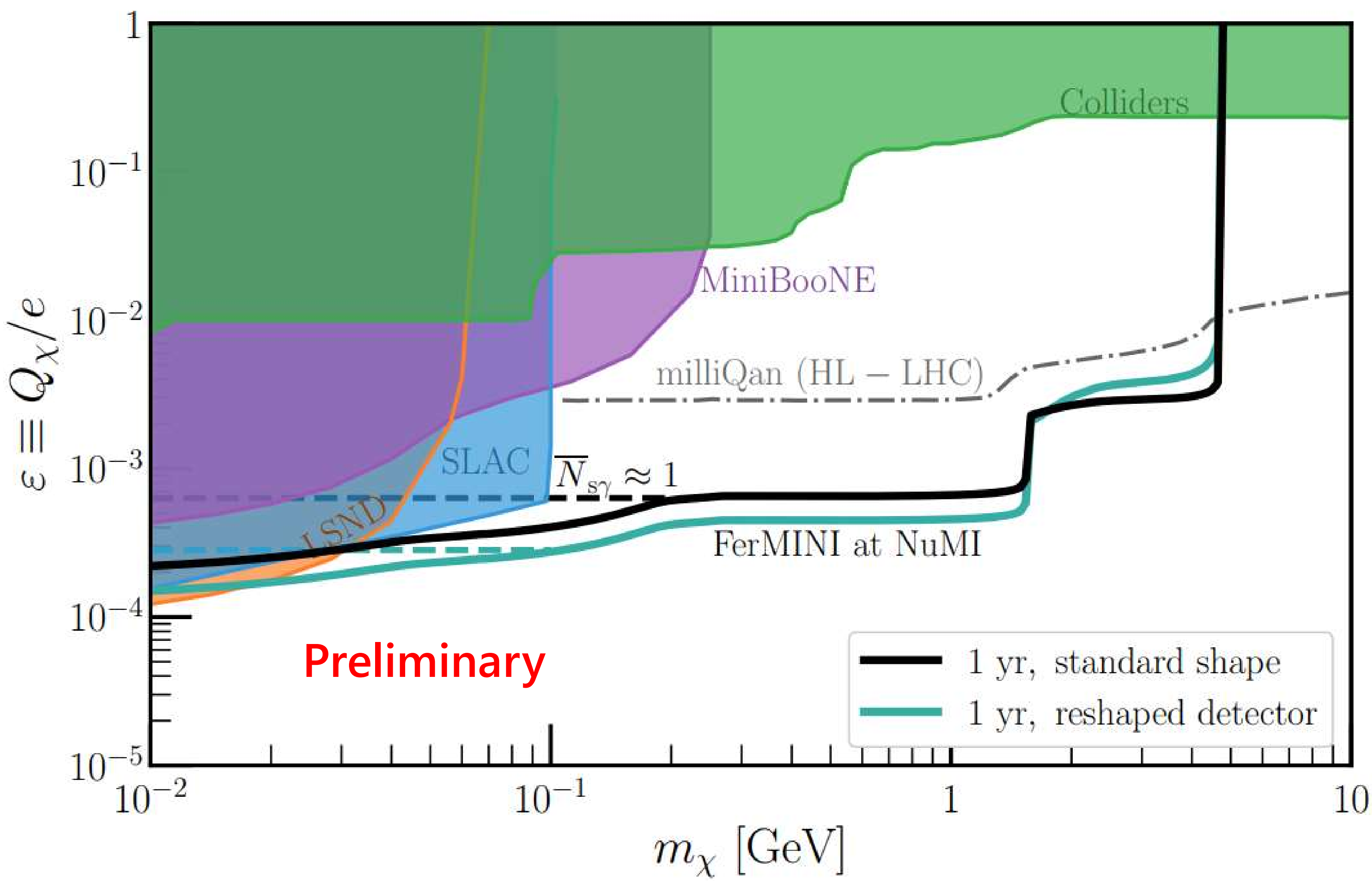
Beam Related Background:

- Beam produced charged particle went through several shielding already, including **absorber and rocks.**
- Each beams have **muon monitors.**
- **Determine the SM charged particle rate on site**
- Remaining beam / dirt / rock produced charged particle: **vetoed similar to the previous veto of cosmic muons.**
- Neutrino produced background: **O**$(\mathbf{10^{-19}})$, negligible.
- To be conservative, we assume the **beam related background** $\approx$ **dark current background** for our sensitivity determination.

FerMINI: Increasing scintillation photons

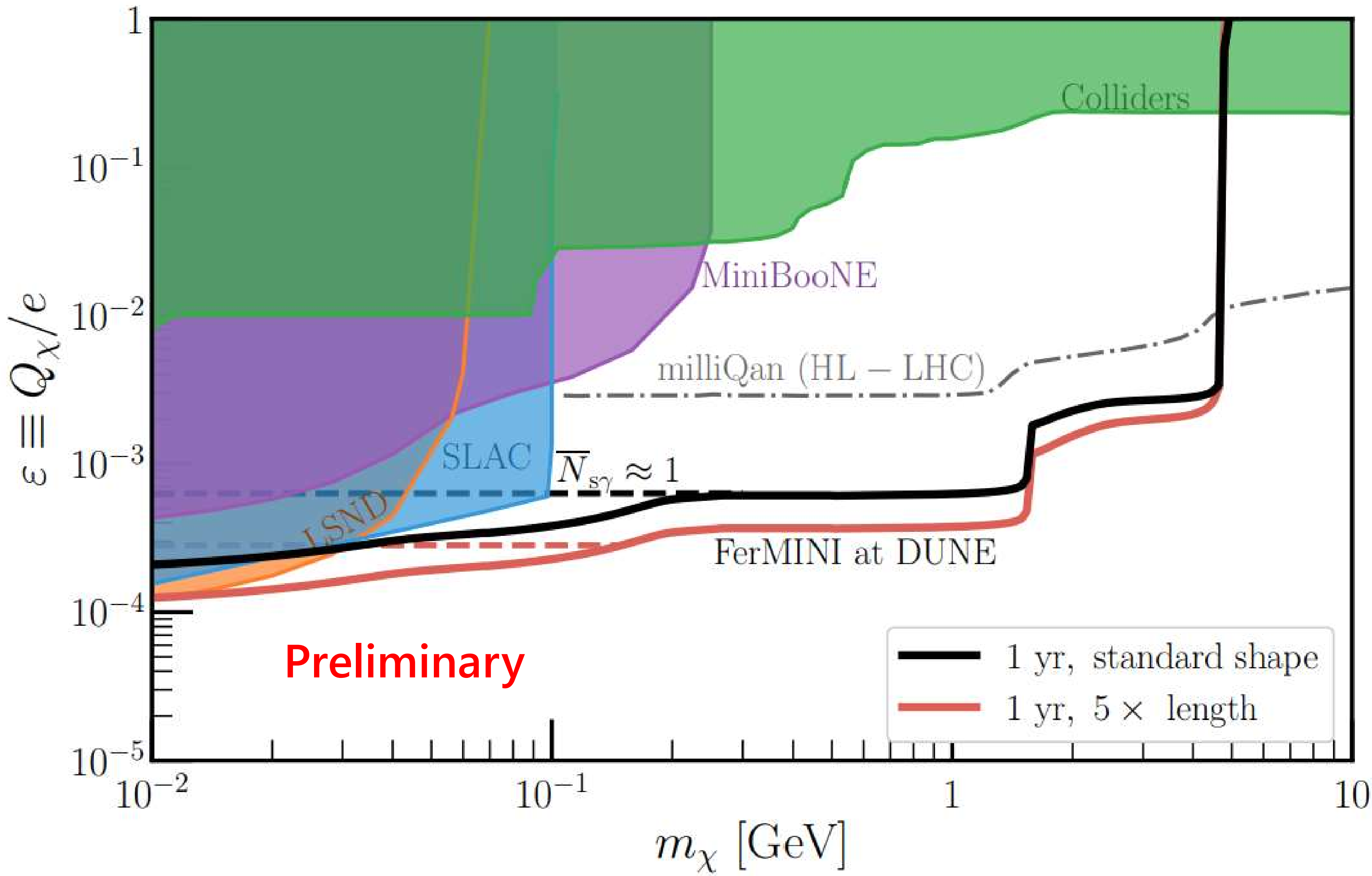
- Elongating the scintillator bar does not affect the background from dark current (basically determined by the number of PMTs)
- So we estimate the sensitivity of FerMINI at DUNE for **five times larger scintillation capability**
- And estimate the sensitivity of FerMINI at NuMI for **five time more scintillation capability** but **five times less scintillator bar-PMT sets** (actually reduce dark current background!)

FerMINI @ MINOS



Yu-Dai Tsai, Fermilab, 2018

FerMINI @ DUNE



Detection Limitation: $N_{photon} \leq 1$

- **Define: ε_{low} as $N_{sintilator\ photon}$ = 1**
- **Roughly around or below this, one really have to worry about scintillator performance**
- **One can elongate the scintillator or consider alternative materials to help.**

Material	Photons/keV	Density (g/cm^3)	* Length needed (cm)	Speed (ns)	Cost for 5x5 cm ($)	Notes
Plastic BC408	10	1.03	145	~2	~200	Current choice
NaI	38	3.67	11	~230	~800	Slow, fragile
LaBr3(Ce)	63	5.08	5	~16	~3000	Radioactive
Liquid Xe	62	2.95	8	~2 / ~34	~1000?	Cryogenic, ultraviolet

- Andy Haas, Fermilab, 2017

* Length needed to get 3 photons for charge 1/1000 e

FerMINI: Discussions & Alternative Designs

Advantages:
Timeliness, Low-cost, Movable, Tested, Easy to Implement, …

1. LHC entering long shutdown
2. NuMI operating, shutting down in 5 years (DO IT NOW!)
3. Bring millicharged glory (back?) to Fermilab/America
4. DUNE ND design still underway
5. Can develop at NuMI/MINOS and then move to DUNE
6. Sensitivity better than milliQan for low-mass MCP and don't have to wait for HL-LHC

...

Alternatives (Straightforward)

1. Quadruple incidence: further background reduction, sacrifice event rate but potentially gain better control of background, reduce the background naively by **10^{-5}**

1. Basically zero background experiment?

2. Different lengths for each detectors

3. Different materials:

Material	Photons/keV	Density (g/cm^3)	* Length needed (cm)	Speed (ns)	Cost for 5x5 cm ($)	Notes
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Other "Brand New" Ideas …

- **Combine with neutrino detector**: behind, in front, or sandwich them
- Combine with **DUNE PRISM**: moving up and down
- **FerMINI+DUNE 3DST**
- …
- New ideas from you are welcomed!

Thank You!
Let's splash the PONDD!

Backup Slides

Other Constraints

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

MCP Existing 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)

$$\sin^2\theta_W = 1 - (m_W/m_Z)^2 = 0.2223(21).$$

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

Some Derivation of dE/dx

$$\frac{d\sigma_R(W;\beta)}{dW} = \frac{2\pi r_e^2 m_e c^2 z^2}{\beta^2} \frac{(1-\beta^2 W/W_{\max})}{W^2},$$

r_e classical electron radius

$$\frac{d\sigma_B(W;\beta)}{dW} = \frac{d\sigma_R(W,\beta)}{dW} B(W).$$

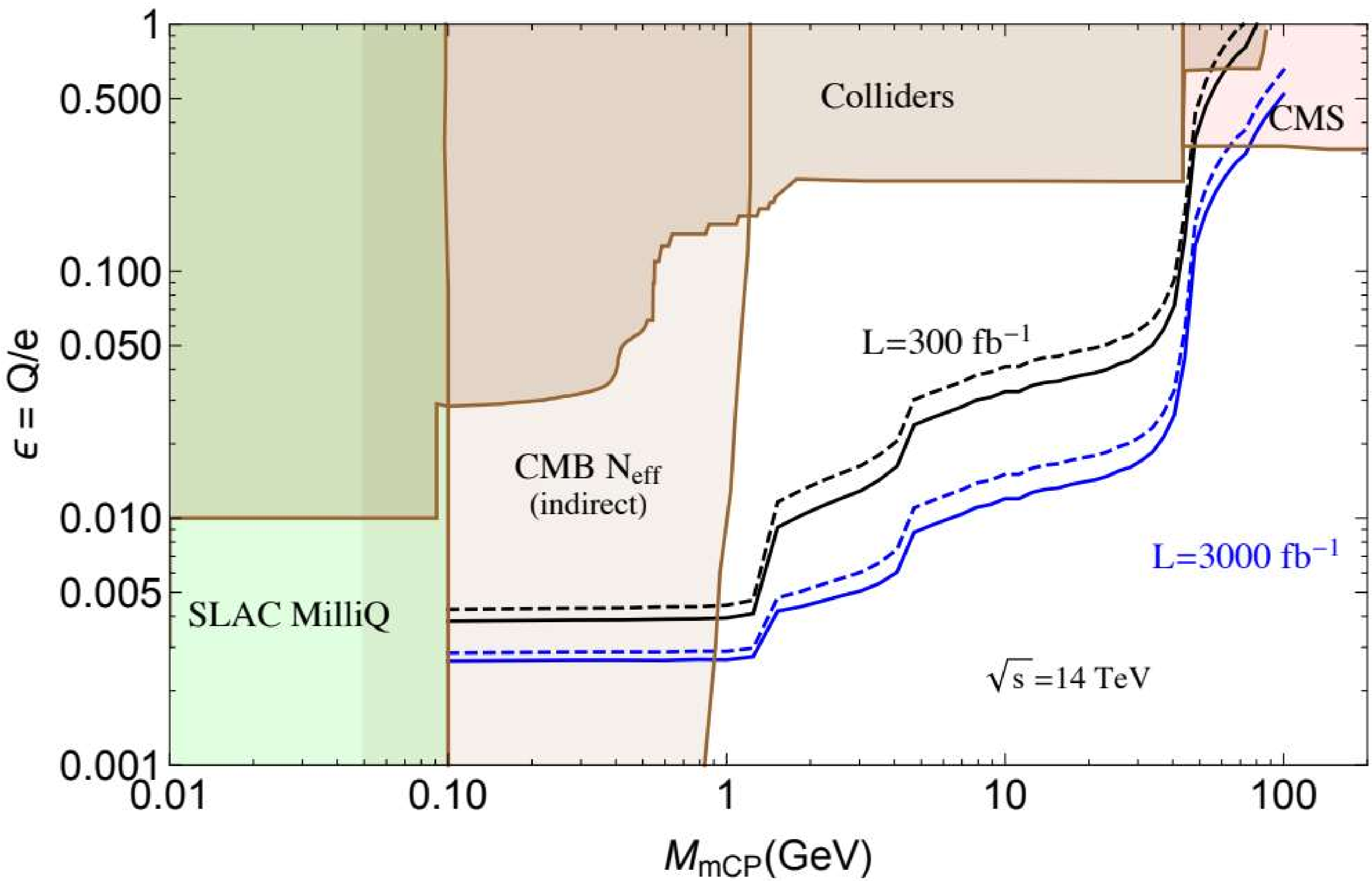
In matter electrons are not free. W must be finite and depends on atomic and bulk structure. Electronic binding is accounted for by the correction factor B(W). After integration:

$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right].$$

$$W_{\max} = \frac{2 m_e c^2 \, \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}.$$

- Maximum energy transfer: determined kinematically

Dark Photon MCP vs "Pure" MCP



Deadtime Veto!

- **Deadtime veto of small after-pulses**: Whenever a pulse enters a photo-multiplier, there are smaller after-pulses that are generated. These small after-pulses occur **within approximately 10 μs, falling within the digitization deadtime** of the readout board and will thus be vetoed.

MilliQan Detector

- Array of plastics scintillators and PMTs, see single photo-electrons from traversing mCPs

The Scintillator

- A MIP with $Q = 1e$ deposits $\sim$ 2 MeV/cm in a material with a density of 1 g/cm^3
- For a plastic scintillator, energy deposits result in $\sim 10^4$ photons / MeV
- Putting it together, 2×10^6 photons would be liberated in a 1m long bar

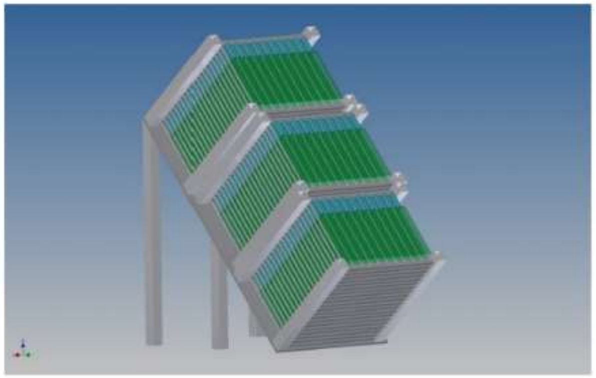
The PMT

- On average 1/3 of photons successfully hit the PMT
- The quantum efficiency of the PMT is $\sim$25%
- Thus, the overall efficiency is 10%,
  i.e. one photo electron (PE) for every 10 liberated photons

mCP's

- The deposited energy is proportional to Q^2
- For a mCP with $Q = 2.2 \times 10^{-3}e$, we expect 1 PE per bar

Andrew Haas, Fermilab (2017)



Other Probes of the similar regime

- LDMX: Berlin, Blinov, Krnjaic, Schuster, Toro, 18
- NA64: arXiv:1810.06856
- Reactor Probe (lower mass range)
- BEPC:
- …

A bit details of the dE/dx calculation

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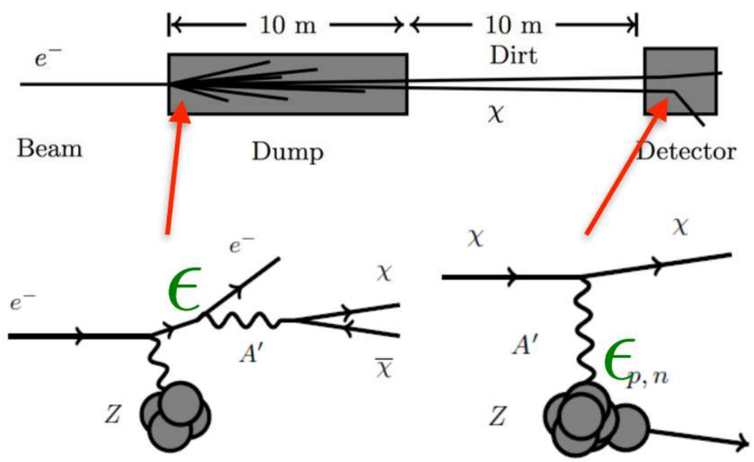
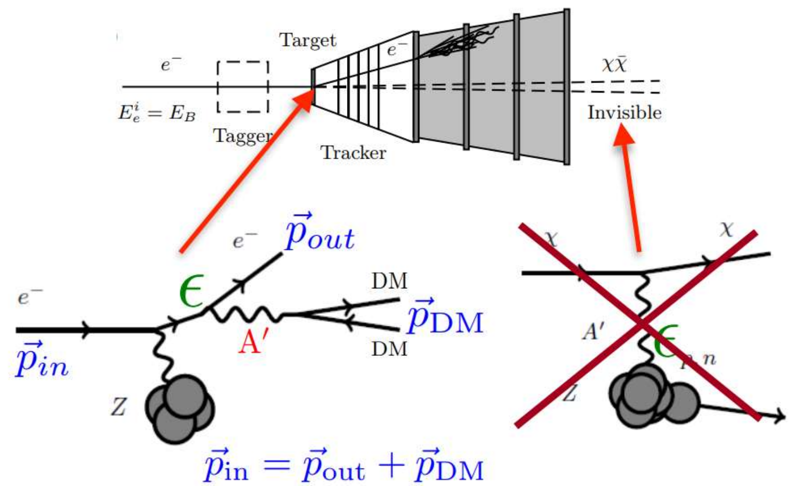
LDMX @ SLAC

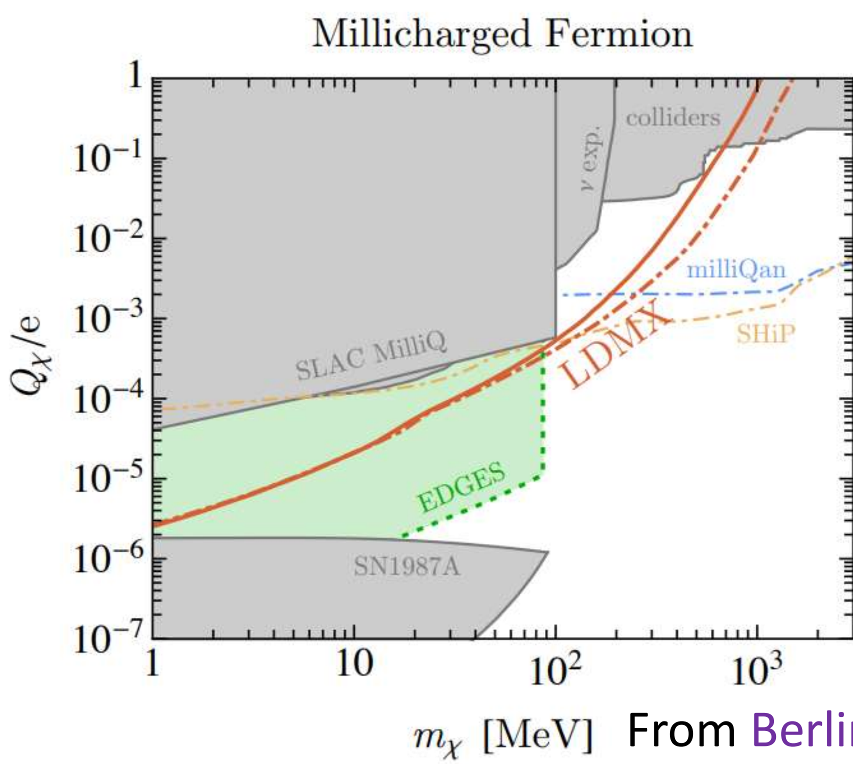
beam dump



missing momentum



Tim Nelson, for LDMX, 2017



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

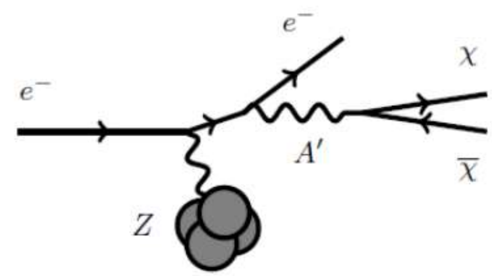
BDX @ BNL

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

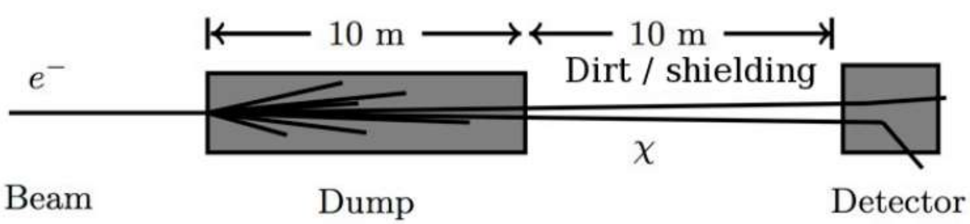
- High-energy, high-intensity e^- beam impinging on a dump
- χ particles pair-produced radiatively, trough A' emission

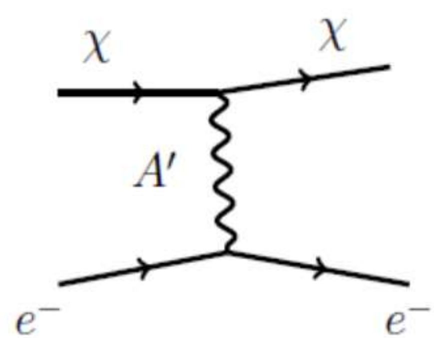


χ detection

- 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