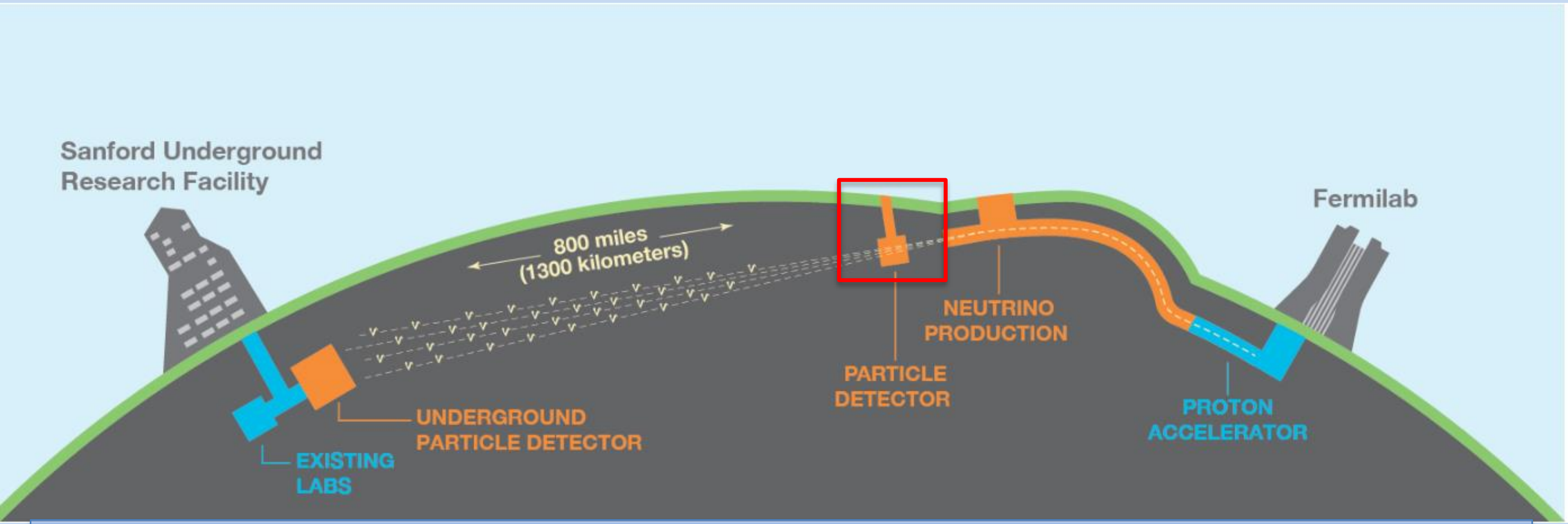


Energy Frontier of the Intensity Frontier: Millicharged Particle in Neutrino Exps. and FerMINI

Yu-Dai Tsai, **Fermilab (WH674W) / U. Chicago**

with Magill, Plestid, Maxim Pospelov (1806.03310, ***PRL '19***)

with Kelly (1812.03998, submitted to *PRL*)

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

TEAM MCP!

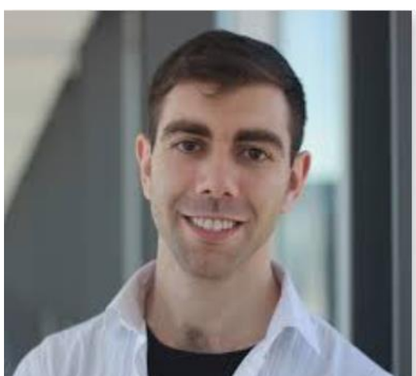
Maxim Pospelov
Minnesota / Perimeter

Yu-Dai Tsai
(Presenting)
Fermilab / U.Chi

Arguelles, MIT

Hostert, Durham

Team Dark Neutrino



Gabriel Magill
McMaster

Ryan Plestid
McMaster

Kevin Kelly
Fermilab

Outline

- **Motivations**
- **Millicharged Particle (MCP) & Proton Fixed-Target Experiments**

I) **Sensitivity Reach @ DUNE near detector (LAr-TPC ND)**
(and other neutrino detectors)

II) **Sensitivity Reach @ FerMINI setup** (adding a low-cost detector in the ND complex, further extend MCP sensitivity)

- **Discussion**

Yu-Dai Tsai,
Fermilab

Thanks for the invitation!

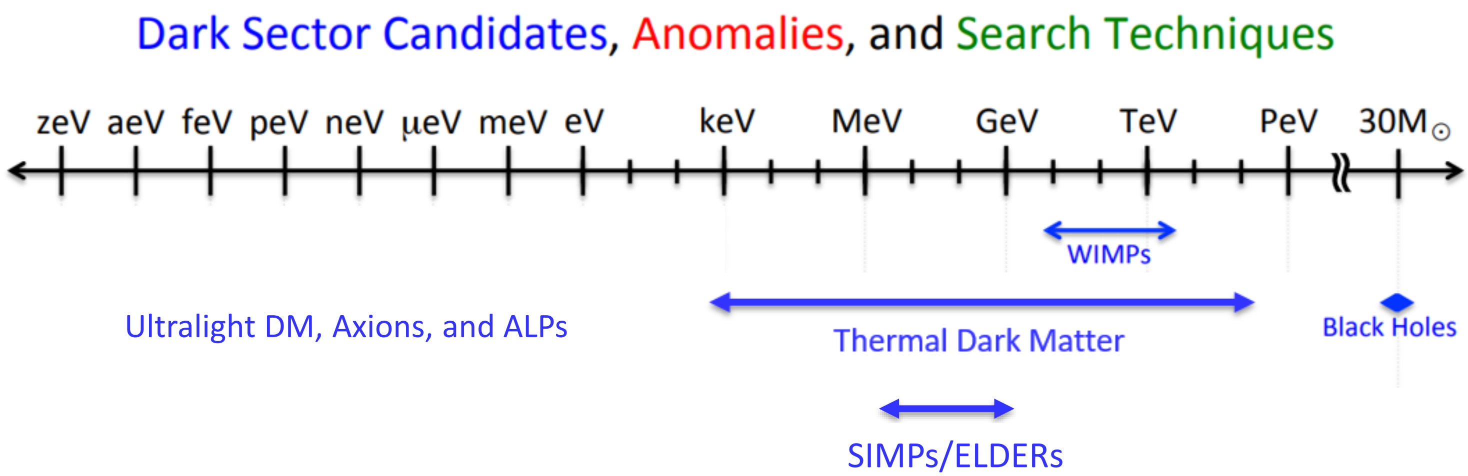
Neutrino & Proton Fixed-Target (FT) Experiments:

Natural habitats for signals of

weakly interacting / long-lived / hidden particles

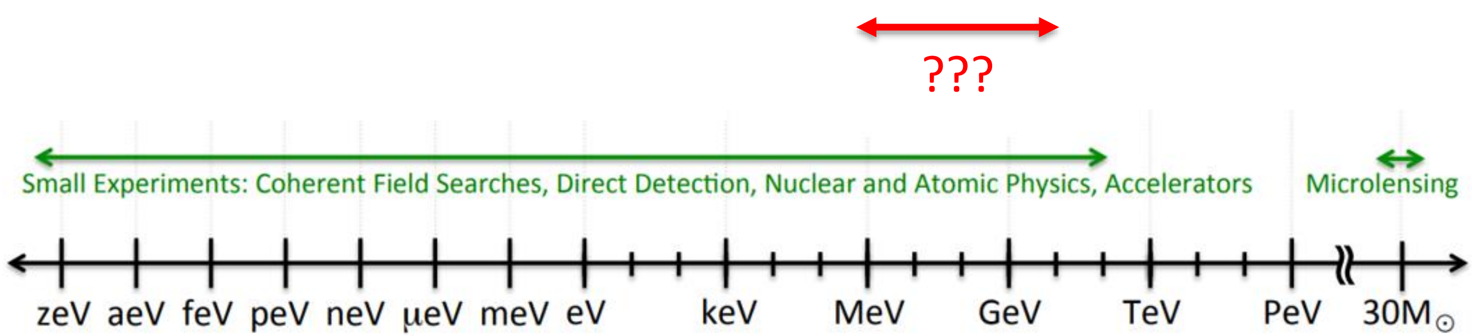
But why? Why MeV - GeV+?

Dark Matter/Hidden Particles Exploration



US Cosmic Visions 2017

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



- Proton fix-target/neutrino experiments are **important for MeV ~ 10 GeV!**

Hidden Particles in Neutrino Experiments

- Neutrinos are weakly interacting particles. Just like **Millicharged particles**
- High statistics, e.g. DUNE plans $\sim 10^{22}$ Protons on Target (POT)
- Shielded/underground: low background (e.g. solar ν programs)
- Many of them existing and many to come: **strength in numbers**
- Produce hidden particles (from the beam!) without **DM-abundance or cosmological history assumptions**: more "direct" than astrophysics/cosmological probes.
- Relatively high energy (LBNF/NuMI: 120 GeV; SPS: 400 GeV)

Not all bounds are created with equal assumptions

"Assumptions" ⟶

Or, how likely is it that theorists would be able to argue our ways around them

Accelerator-based: Collider, Fixed-Target Experiments
Some other ground based experiments

techinical ↓

Astrophysical productions (not from ambient DM): energy loss/cooling, etc:
Rely on modeling/observations of (extreme/complicated/rare) astro systems

Dark matter direct/indirect detection: abundance, velocity distribution, etc (reveal true story of DM)

} different

Cosmology: assume cosmological history, species, etc

Signals of discoveries grow from anomalies

Maybe nature is telling us something so we don't have to search in the dark? ~~(systematics?)~~

Some anomalies involving MeV-GeV+ Explanations

⋮

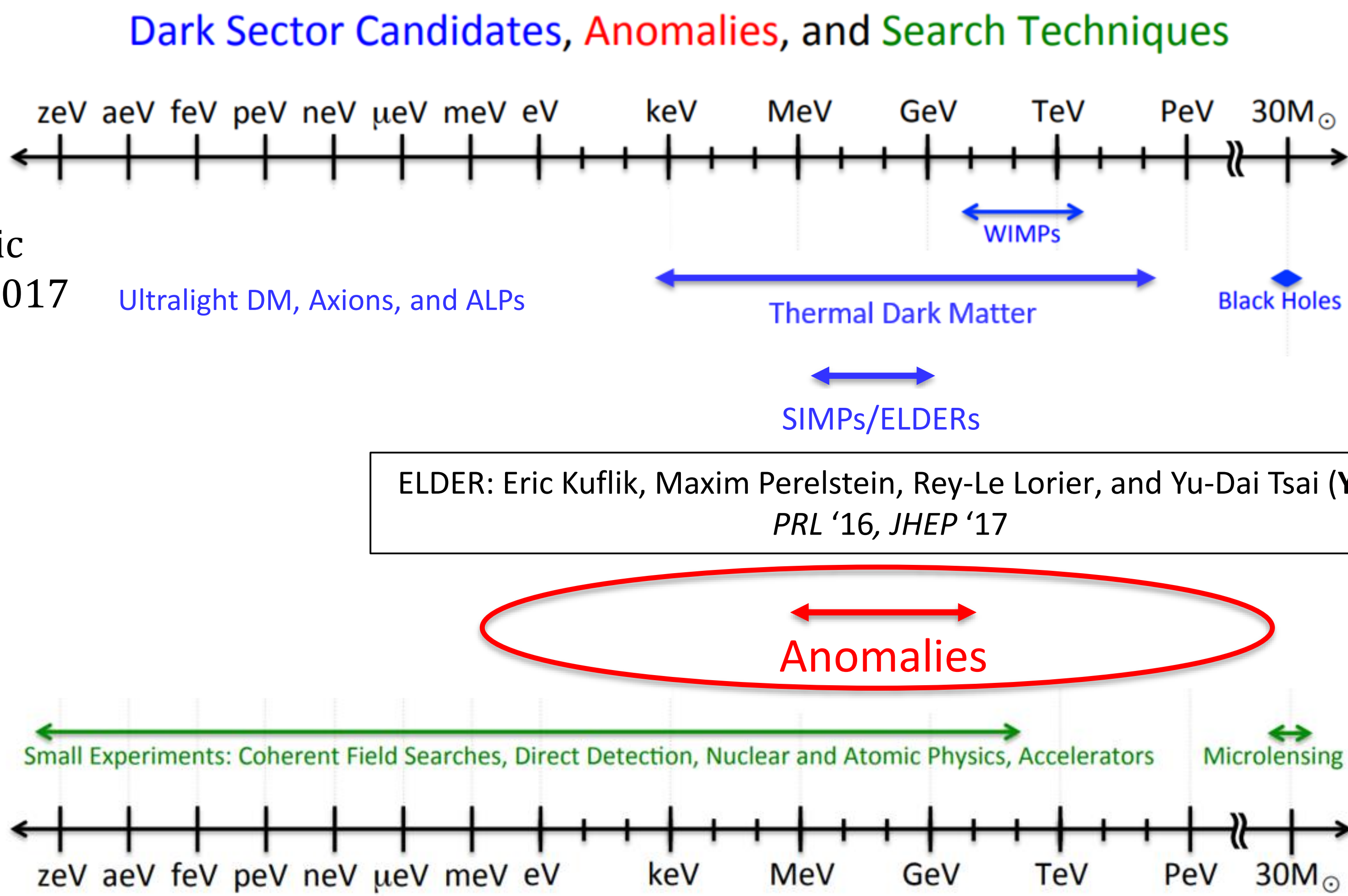
- **Muon g-2**
- **Proton charge radius anomaly**
- **LSND & MiniBooNE anomaly**
- **EDGES result**

⋮

Below ~ MeV there are also **strong astrophysical/cosmological bounds**

Dark Matter/Hidden Particles Exploration

US Cosmic Visions 2017



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

- Proton fix-target/neutrino experiments are **important for MeV ~ 10 GeV!**
- Many **anomalies & anomaly explanations** in this range!

Anomaly & **New Physics** in Neutrino FT Experiments

⋮

1) **Light Scalar** & Dark Photon at Borexino & LSND

   Pospelov & **YT**, *PLB '18*, 1706.00424 (**proton charge radius anomaly**)

2) **Dipole Portal Heavy Neutral Lepton**

   Magill, Plestid, Pospelov & **YT** , *PRD '18*, 1803.03262

   (**Short-baseline LSND/MiniBoonE anomalies**) **See Ian's talk for more!**

3) **Millicharged Particles** in Neutrino Experiments

   Magill, Plestid, Pospelov & **YT**, *PRL '19*, 1806.03310

   (**EDGES 21-cm measurement anomaly**)

⋮

MeV – GeV + anomalies: Not just search in the dark

⋮

4) **Millicharged Particles** in **FerMINI Experiments**

   Kelly & **YT,** 1812.03998

   (**EDGES Anomaly**)

5) **Dark Neutrino** at Scattering Experiments**: CHARM-II & MINERvA**

   Argüelles, Hostert, **YT**, 1812.08768

   (**MiniBooNE Anomaly**) **Also see Pedro/Ian's talk for more!**

⋮

Two new papers OUT!
Happy to chat

Millicharged Particles

Electric charge quantization?

Other implications (dark sector, etc)

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

Finding Minicharge

- **Is electric charge quantized?** A long-standing question!
- U(1) allows arbitrarily small (any real number) charges.
  Why don't we see them in electric charges?
  Motivates Dirac quantization, Grand Unified Theory (GUT), etc, to explain such quantization
- A test to see if **e/3 is the minimal charge**
- MCP could have natural link to **dark sector** (dark photon, etc)
- Could account for dark matter (DM) (WIMP or Freeze-in scenarios)

- Used for the cooling of gas temperature to explain the **EDGES result** [EDGES collab., Nature, (2018), Barkana, Nature, (2018)].
  A small fraction of the **~ MeV-100 MeV DM as MCP** to explain the EDGES anomalous 21-cm absorption spectrum

Millicharged Particle: Models

mCP Model

- Small charged particles under U(1) hypercharge

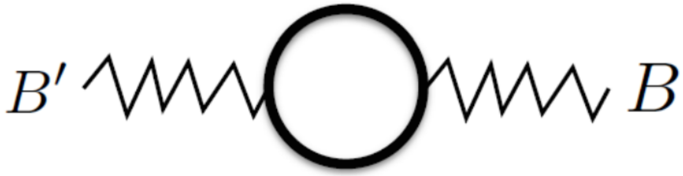
$$\mathcal{L}_{\mathrm{mCP}} = i\bar{\psi}(\partial\!\!\!/ - i\epsilon' e B\!\!\!/ + M_{\mathrm{mCP}})\psi$$

- Can just consider these Lagrangian terms by themselves (no extra mediator, i.e., dark photon), one can call this a “pure” MCP

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

Kinetic Mixing and MCP Phase

- Coupled to new dark fermion



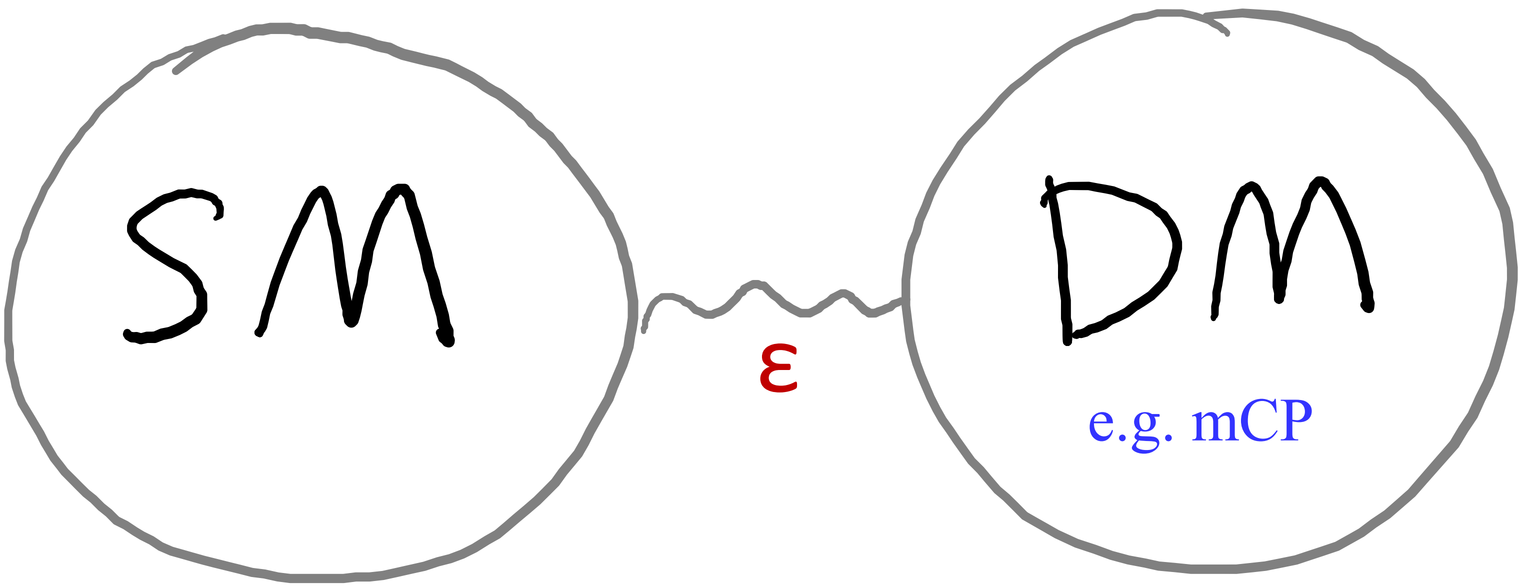
(SM: Standard Model)

See, Holdom, 1985

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

- New Fermion ψ charged under U(1)’
- Field redefinition into a more convenient basis for massless B', $B' \to B' + \kappa B$
- 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



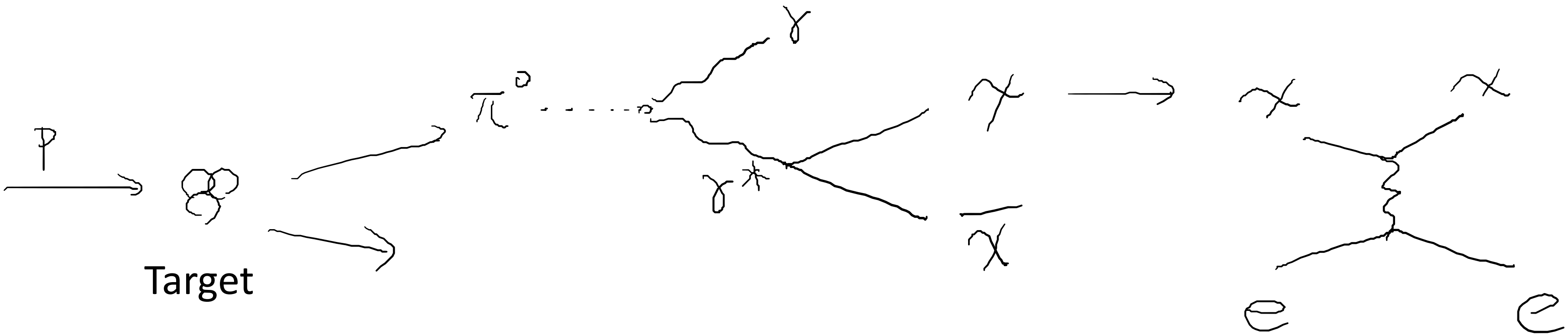
Yu-Dai Tsai, Fermilab

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
- There are additional motivations to search for "pure" MCP!

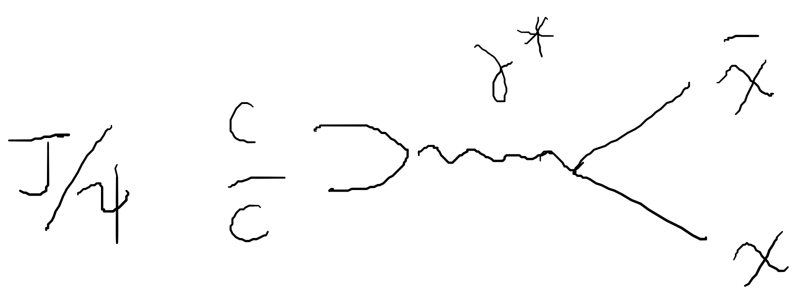
Millicharged Particle: Signature

MCP (or general light DM): production & detection



- production:
  meson decays

- detection:
  scattering electron



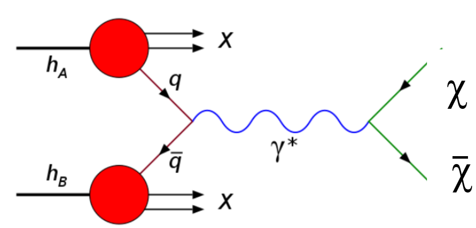
BR($\pi^0 \rightarrow 2\gamma$) = 0.99

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

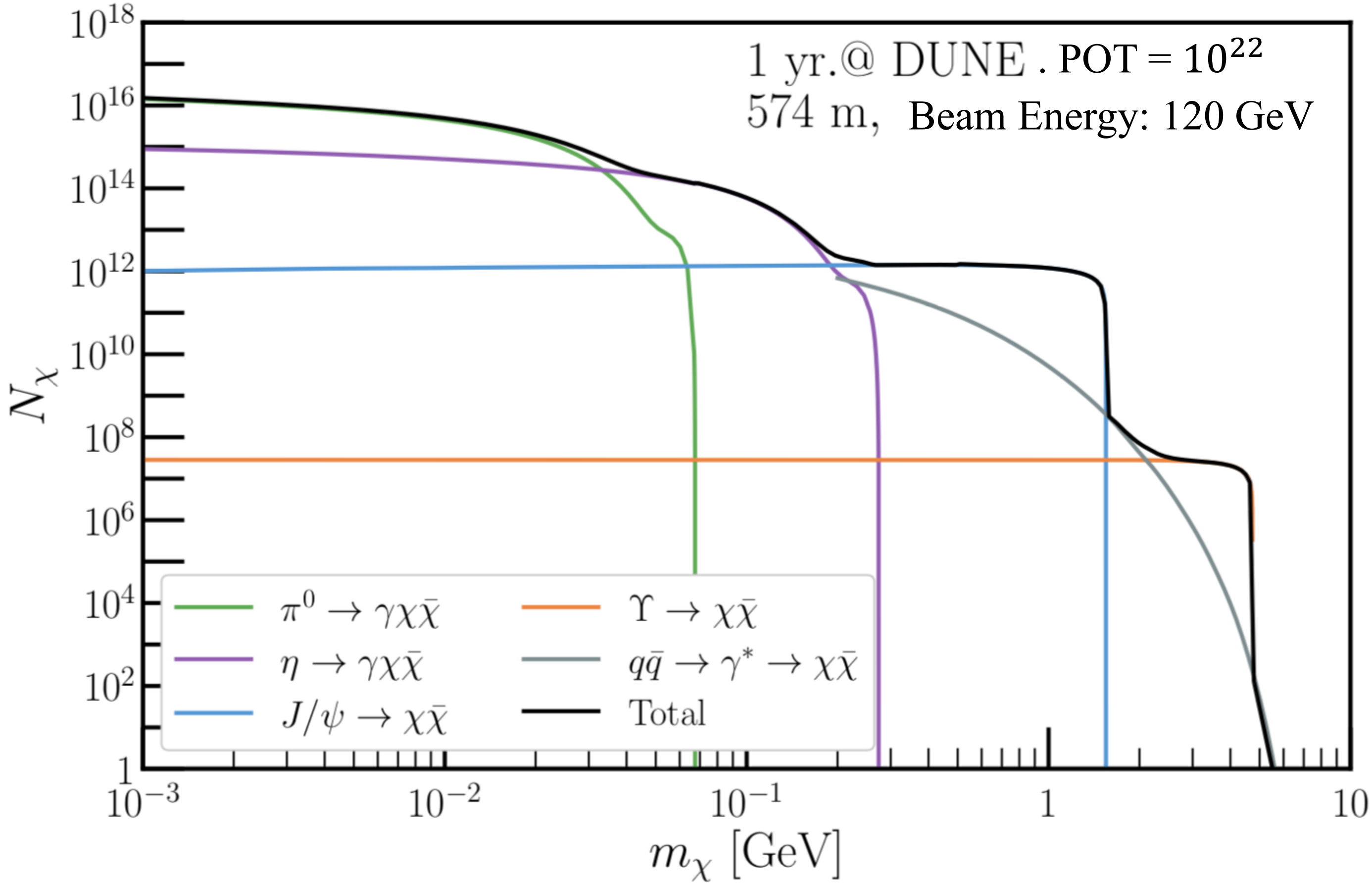
BR($\pi^0 \rightarrow e^- e^+$) = $6 * 10^{-6}$

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

- **Heavy mesons are important for higher mass mCP's in high enough beam energy**
- **Important and often neglected!**



MCP Production/Flux



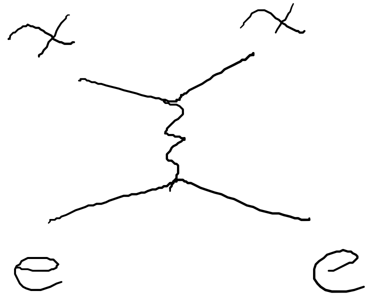
- We use PYTHIA to generate neutral meson Dalitz or direct decays from the pp collisions and rescale by considering, $\mathrm{BR}(\mathcal{M} \to \chi\bar{\chi}) \approx \epsilon^2 \times \mathrm{BR}(\mathcal{M} \to X e^+ e^-) \times f\left(\frac{m_\chi}{M}\right)$,
- M: mass of the parent meson, X:additional particles, $f(m_\chi/M)$: phase space factor
- We also include Drell-Yan production for the high mass MCPs (see arXiv:1812.03998)

MCP Detection: electron scattering

- **Light mediator:** the total cross section is dominated by the small Q^2 contribution, we have $\sigma_{e\chi} = 4\pi\, \alpha^2 \varepsilon^2 / Q_{min}{}^2$.
- 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

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

- Sensitivity greatly enhanced by accurately **measuring low energy electron recoils** for mCP's & light dark matter - electron scattering,
- See e.g., Magill, Plestid, Pospelov, **YT**, 1806.03310 & deNiverville, Frugiuele, 1807.06501 (for sub-GeV DM)



MCP @ Neutrino Detectors

MCP Signals in Neutrino Detector

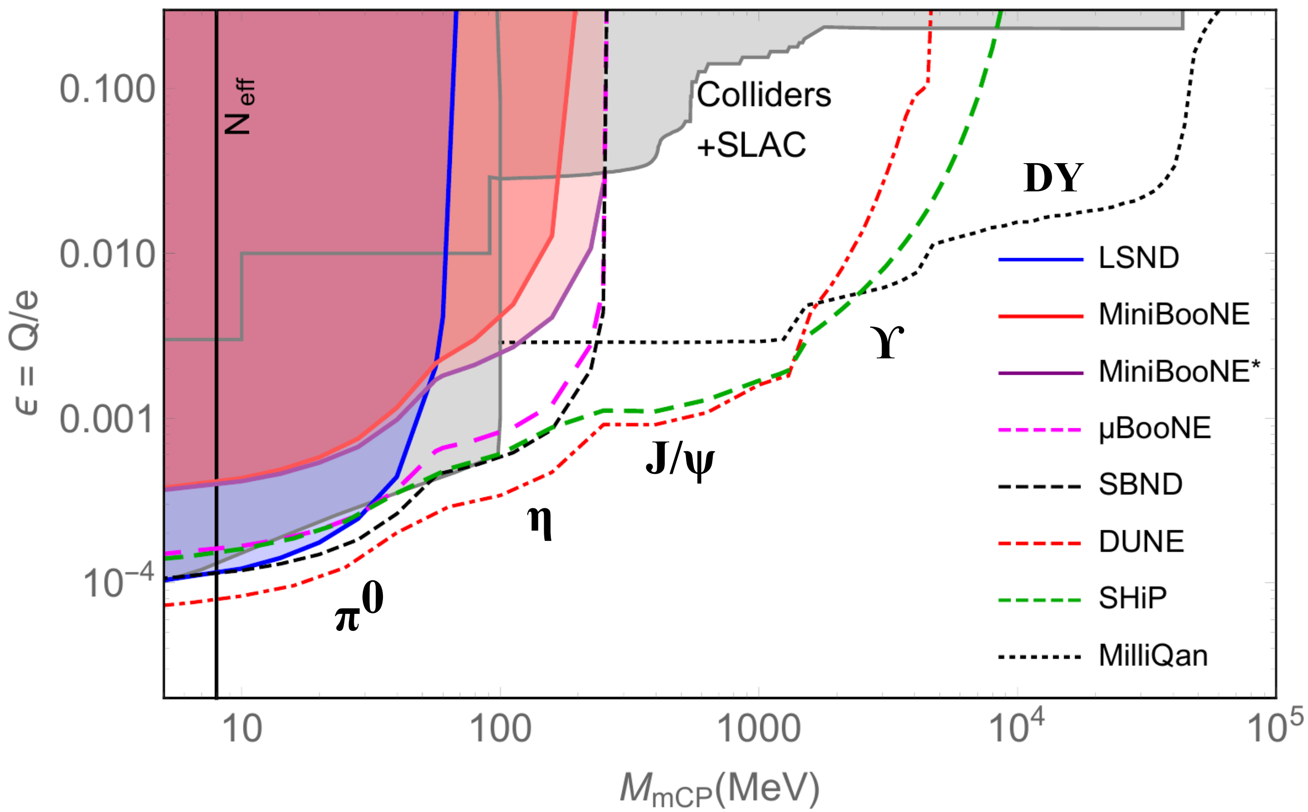
- **signal events** n_{event}

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

detection efficiency

- $N_\chi(E_i)$: number of mCPs with energy E_i arriving **at the detector**.
- N_e: **total number of electrons** inside the active volume of the detector
- Area: active volume divided by the average length traversed by particles inside the detector.
- $\sigma_{e\chi}(E_i)$: **detection cross section consistent** with the angular and recoil cuts in the experiment
- Here, $n_{\text{event}} \propto \varepsilon^4$. ε^2 from N_χ and ε^2 from $\boldsymbol{\sigma}_{\text{ex}}$
- Throughout this paper, we choose a credibility interval of $1 - \alpha = 95\%$ (~ 2 sigma)
- Roughly, $\varepsilon_{sensitivity} \propto E_{e,R,min}^{1/4}\ Bg^{1/8}$

Preview: Sensitivity and Contributions



- 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).

Background for Future Measurements

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

1) From neutrino fluxes (calculable),

[i.e. **νe** → **νe** and **νn** → **ep**], **greatly reduced by maximum electron recoil energy cuts E_e(max), because no low Q^2 enhancement (through W/Z, not γ)**

2) Other sources such as beam related: dirt related events, mis-id particles external: cosmics, multiply a factor of the neutrino-caused background to account for these background

3) More on background control: **Harnik, Liu, Ornella,1902.03246**

MeV-Scale Physics in Lar-TPC: **ArgoNeuT, 1810.06502 (Ivan Lepetic +)**

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
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
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/pixel spacing** is assumed to be around **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/pixels. **DUNE LArTPC ND**, **Using CDR config.** 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)

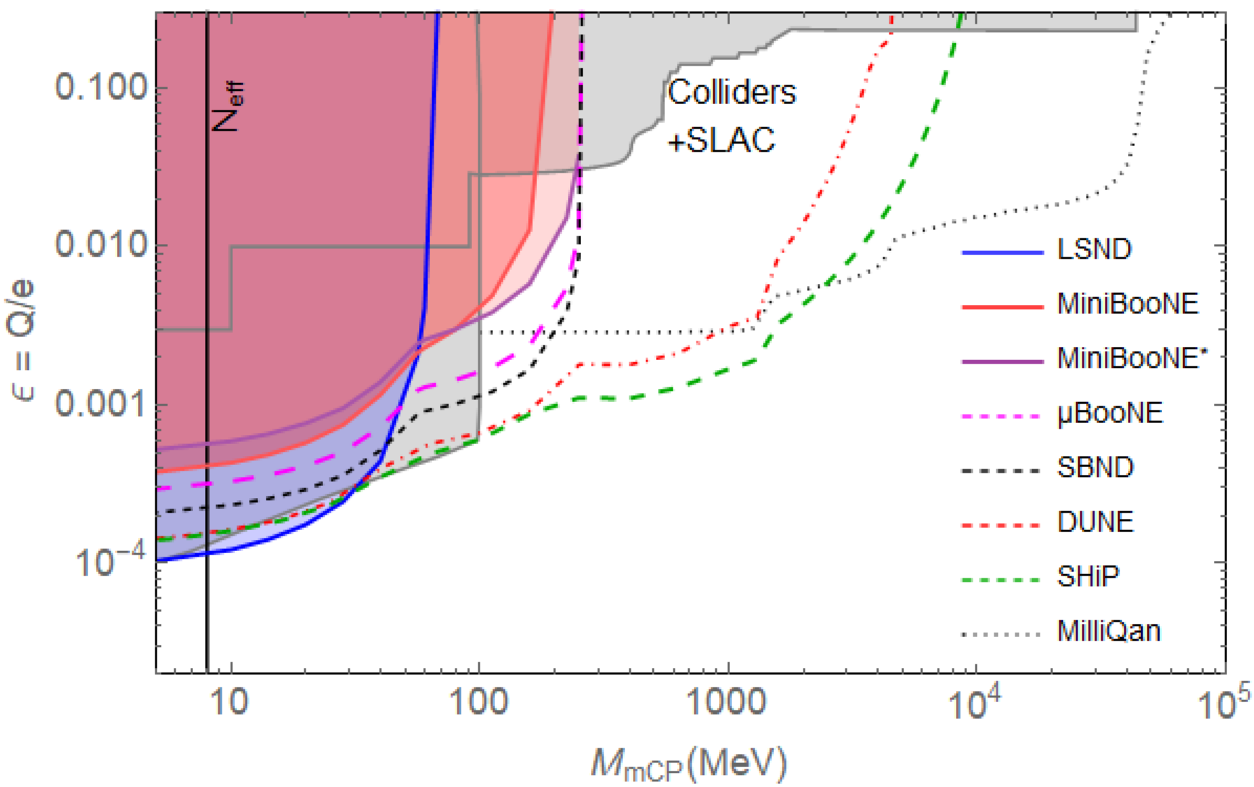
- **LSND**: hep-ex/0101039. Measurement of **electron-neutrino electron elastic scattering**

- **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 (see Bishai's talk).
  Electron recoil analysis
  $\cos\theta > 0$ 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)]).

- We did not include their timing cuts in our calculations, since they were optimized by the MiniBooNE collaboration

More Conservative Cuts on Threshold



Exp. (Beam Energy, POT)	N $[\times 10^{20}]$		$A_{geo}(m_\chi)[\times 10^{-3}]$		Cuts [MeV]		
	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 with lighter mediator

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

  - Signature favor **low electron-recoil energy threshold**

  - ν background reduced by **max electron-recoil energy cuts**
- For more involved analysis (with your help): including **realistic background, $E_{e,\,R,min}$ cut**, etc, with Animesh, Albert, Jae, Yun-Tse on realistic analysis on different experiments.

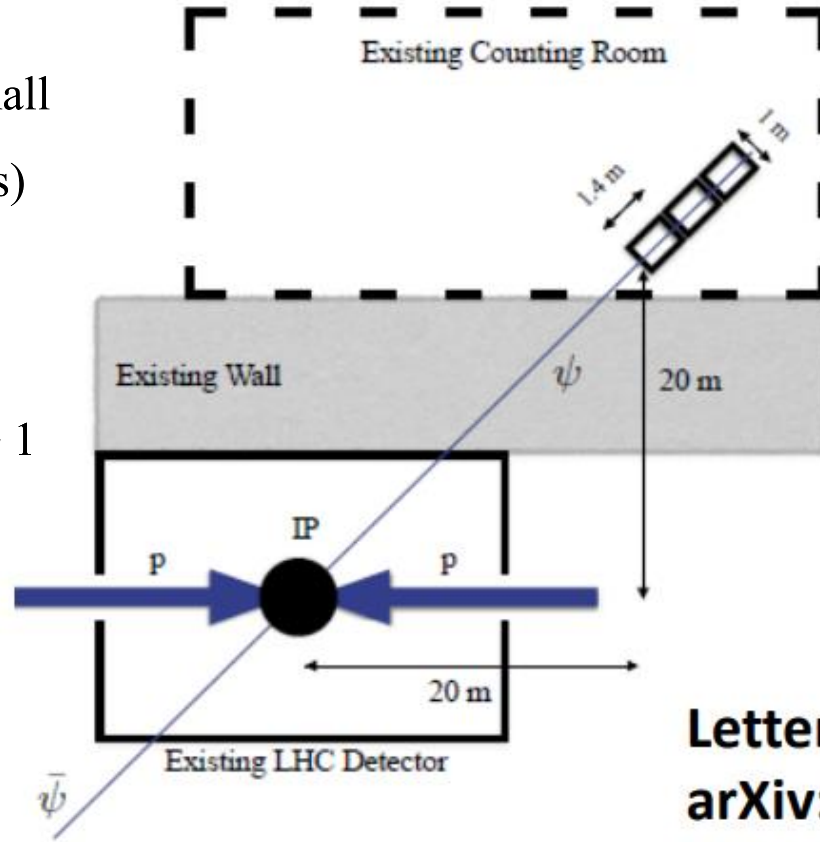
FerMINI Proposal:

Putting milliQan-Type Minicharged Particle Detector
in the Fermilab Beamlines: **NuMI** or **LBNF**
Independent from the DUNE ND MCP probe

Yu-Dai Tsai, Fermilab

MilliQan Detector: 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)

- **A. Haas, C. S. Hill, E. Izaguirre, I. Yavin, arXiv:1410.6816, PRD '15**
- **ArXiv:1607.04669, Letter of Intent (LOT)**

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)**.

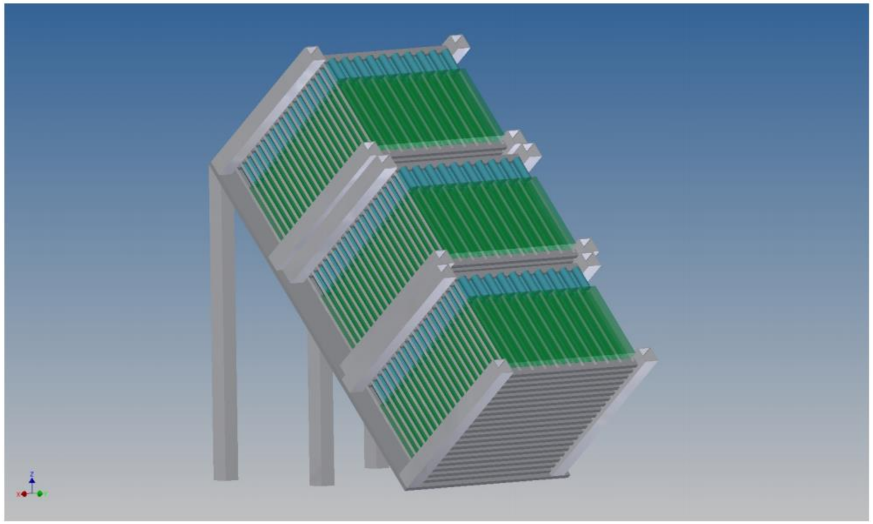


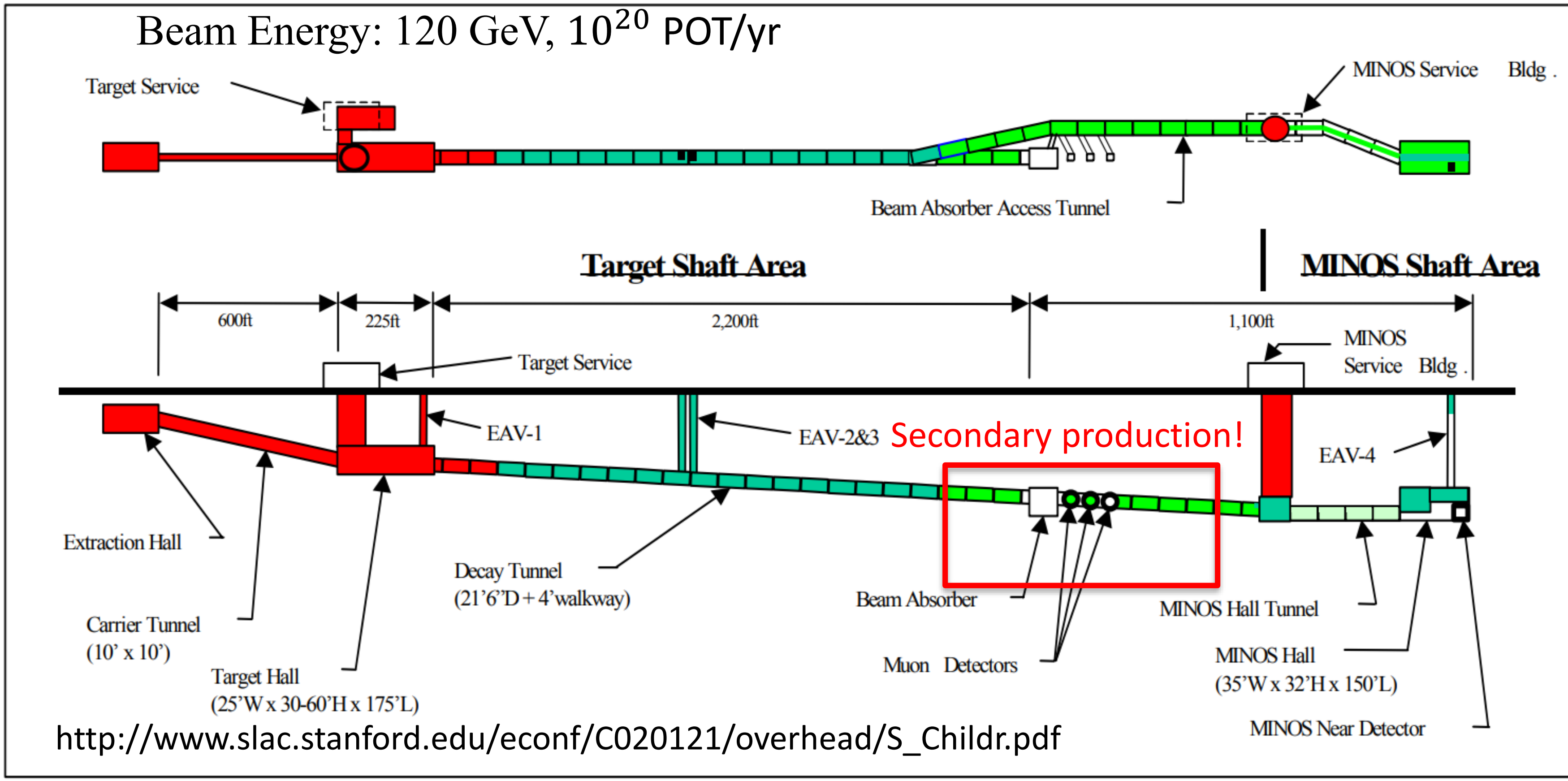
Figure from 1607.04669 (milliQan LOT)

FerMINI:

A Fermilab Search for Minicharged Particle

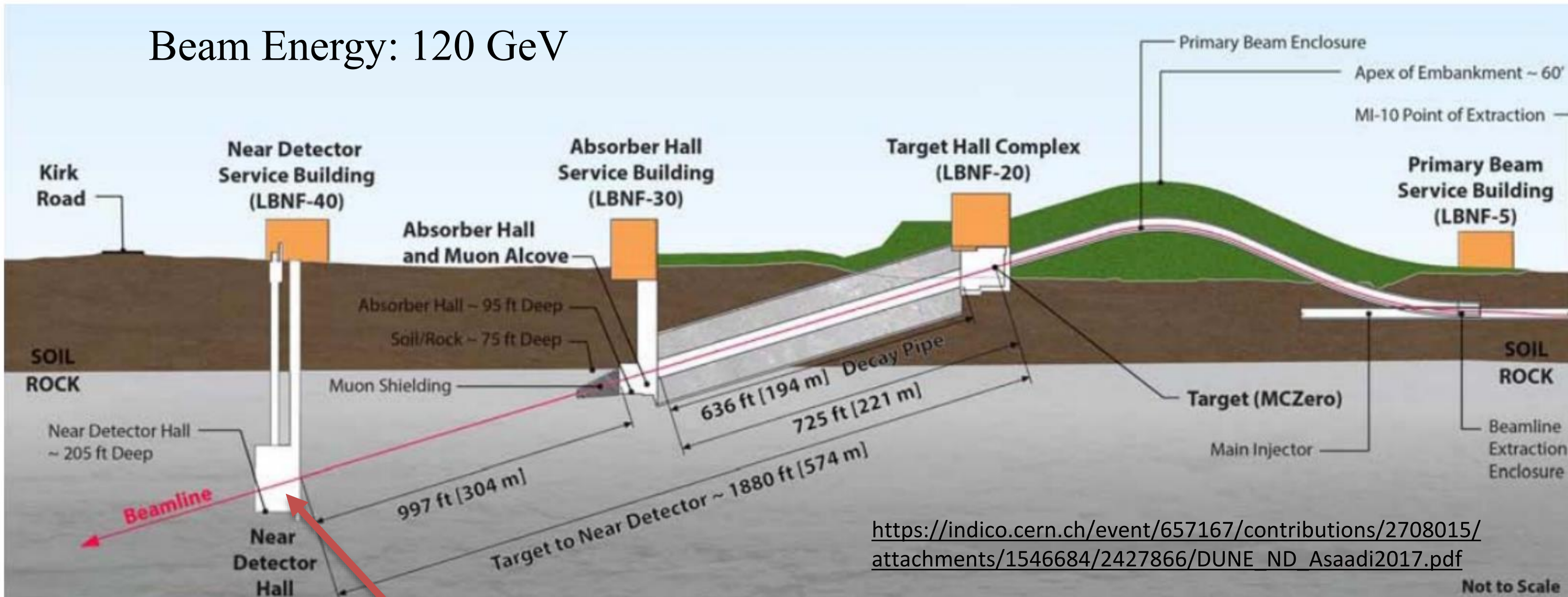
Yu-Dai Tsai, Fermilab, ytsai@fnal.gov

Site 1: NuMI Beam & MINOS ND Hall



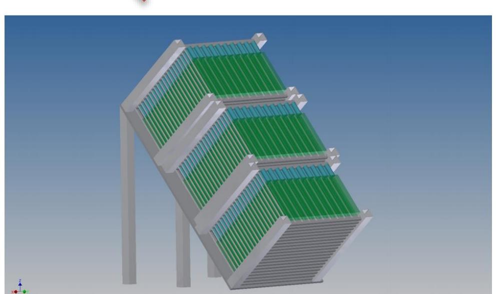
NuMI: Neutrinos at the Main Injector (**See Todd's talk**)
MINOS: Main Injector Neutrino Oscillation Search, ND: Near Detector
(**MINERvA**: Main Injector Experiment for v-A is also here)

Site2: LBNF Beam & DUNE ND Hall

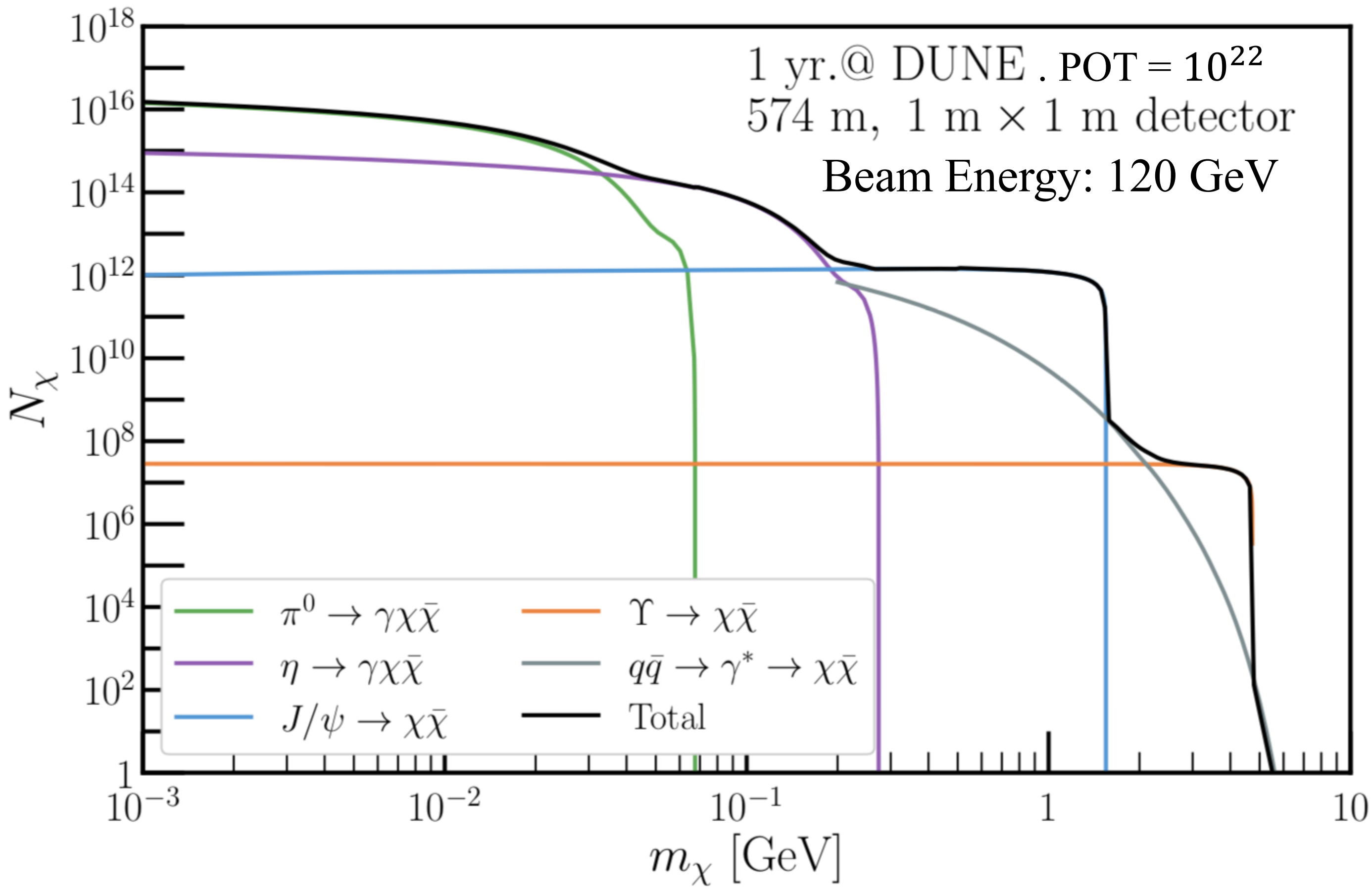


https://indico.cern.ch/event/657167/contributions/2708015/attachments/1546684/2427866/DUNE_ND_Asaadi2017.pdf

Jonathan Asaadi – University of Texas Arlington



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

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

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

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

Background

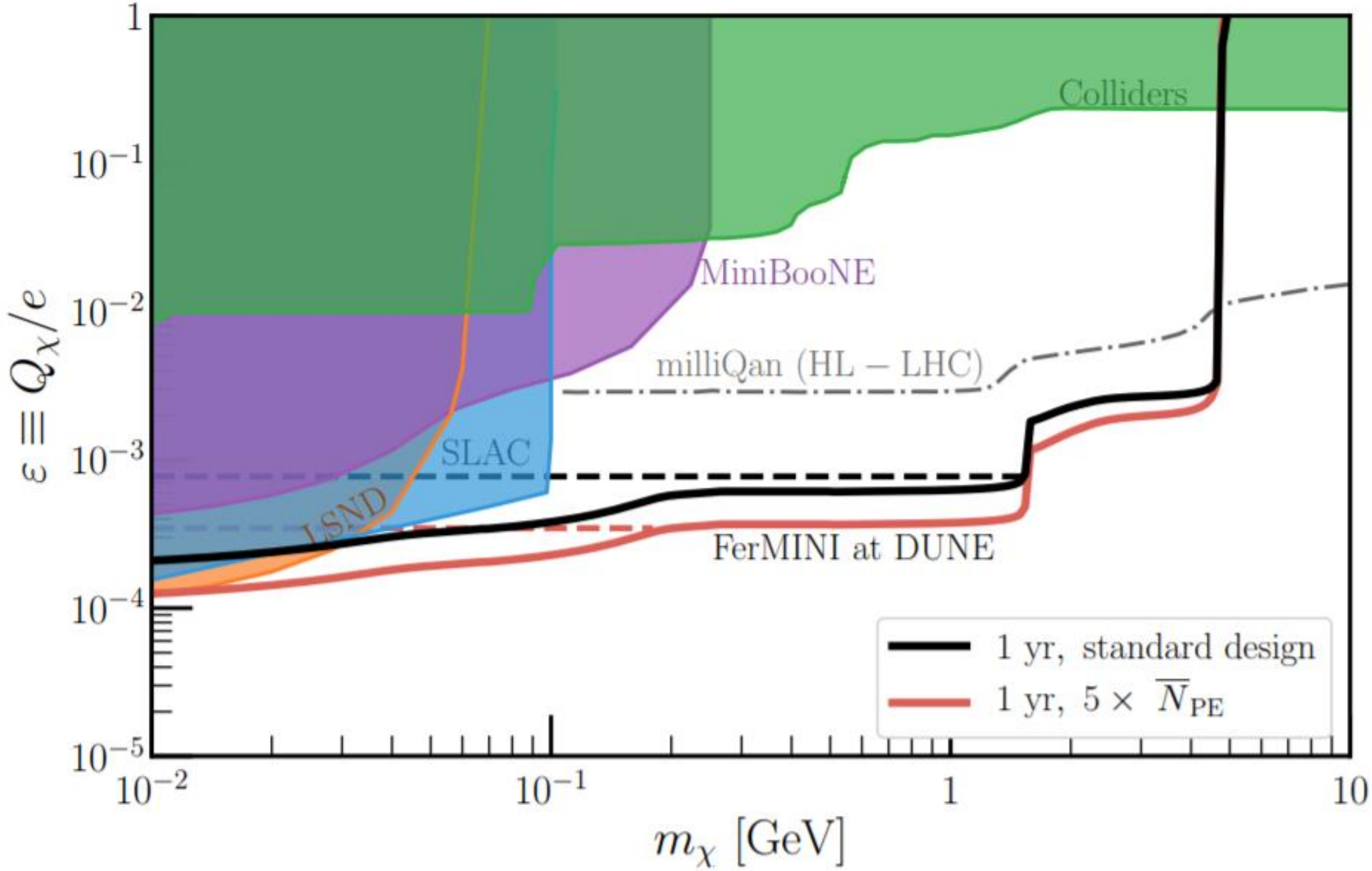
- We will discuss two major **detector backgrounds** and the **reduction technique**
- **SM charged particles from background radiation (e.g., cosmic muons):**

  - Offline veto of events with > 10 PEs

  - Offset middle detector
- **Dark current: triple coincidence**

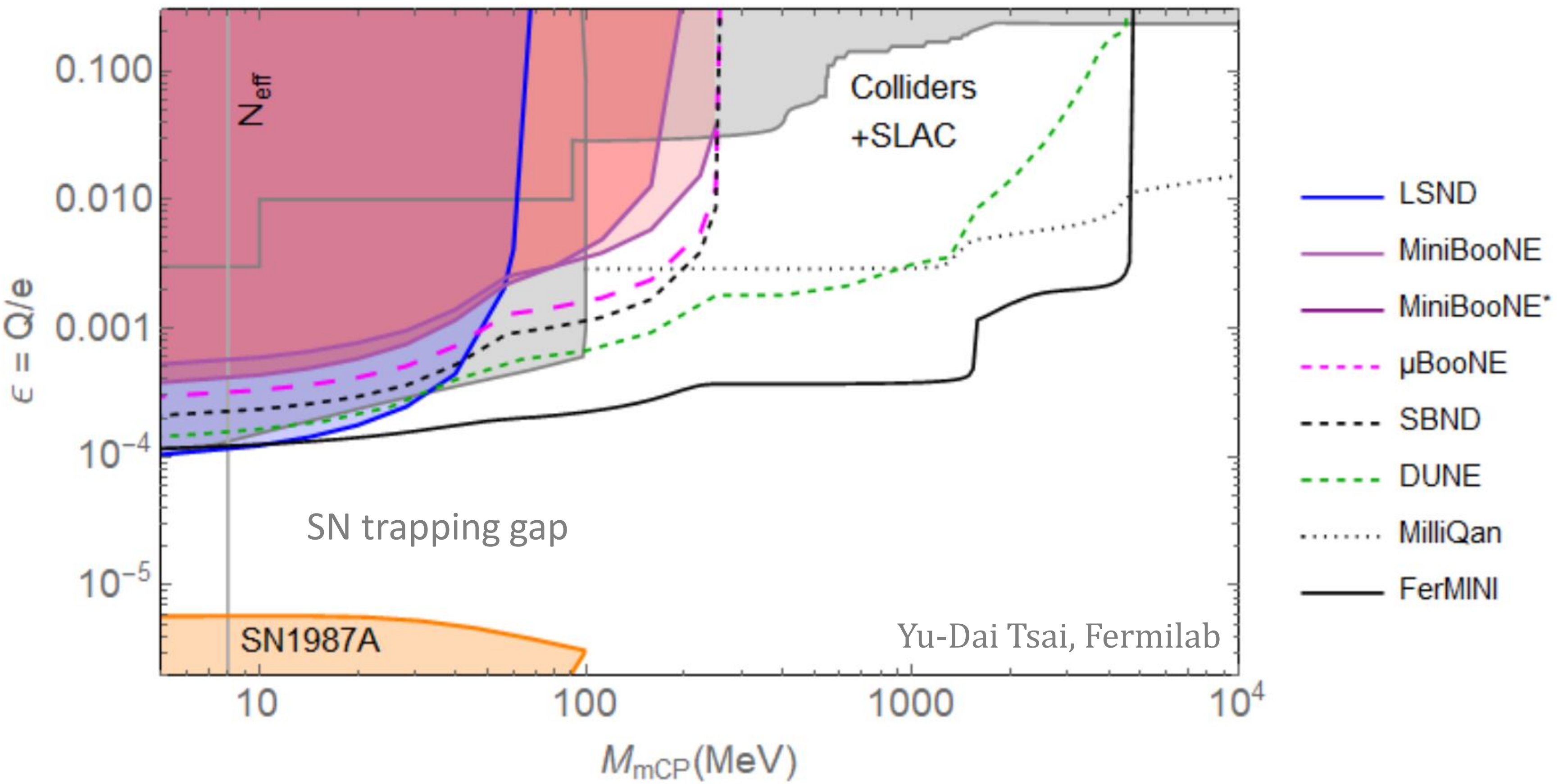
  ~ **300 events** in one year of trigger-live time

FerMINI @ DUNE



NuMI/MINOS Hall is a viable alternative site

Compilation



One can **combine the MCP detector with neutrino detector** to improve sensitivity or reduce background

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

1. LHC entering long shutdown

2. Can develop at NuMI/MINOS and then move to DUNE

3. NuMI operating, shutting down in 5 years (DO IT NOW!)

4. Sensitivity better than milliQan for MCP below 5 GeV and don’t have to wait for HL-LHC

JOIN THE PROPOSAL! ytsai@fnal.gov

Yu-Dai Tsai, Fermilab

Alternative Detector Setup & New Ideas

- **Combine with neutrino detector**: behind, in front, or sandwich them: **mixed signature**
- Combine with **DUNE PRISM**: moving up and down
- **FerMINI+DUNE 3DST**
- **Better scintillator material**
- **Can search for millicharged quarks, fermions with small electric dipole**
- New ideas from you are welcomed!

Looking Ahead

- Exploring **Energy Frontier of the Intensity Frontier** (complementary to and **before HL-LHC upgrade**)
- Near-future (and almost free) opportunity (**NuMI Facility, SBN program, DUNE Near Detector**, etc.)
- Other new **low-cost alternatives/proposals (~ $1M)** to probe hidden particles and new forces **(FerMINI is just a beginning!)**
- **Dark sectors in neutrino telescopes**
- **Cosmology-driven models!**

Thank You

Thanks for the invitation again!

Backup Slides

Dark Current Background @ PMT

- **Major Background Source!**
- dark-current frequency to be $\boldsymbol{v_B}$**= 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

(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].]

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
  We did not include their timing cuts in our calculations, since they were optimized by the MiniBooNE collaboration to the signal's timing profile.

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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	$\mathrm{g\ mol^{-1}}$
K	$4\pi N_A r_e^2 m_e c^2$ (Coefficient for dE/dx)	$0.307\,075\ \mathrm{MeV\ mol^{-1}\ cm^2}$
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., νμ from the beam striking the detector (or nearby rock) and producing a muon

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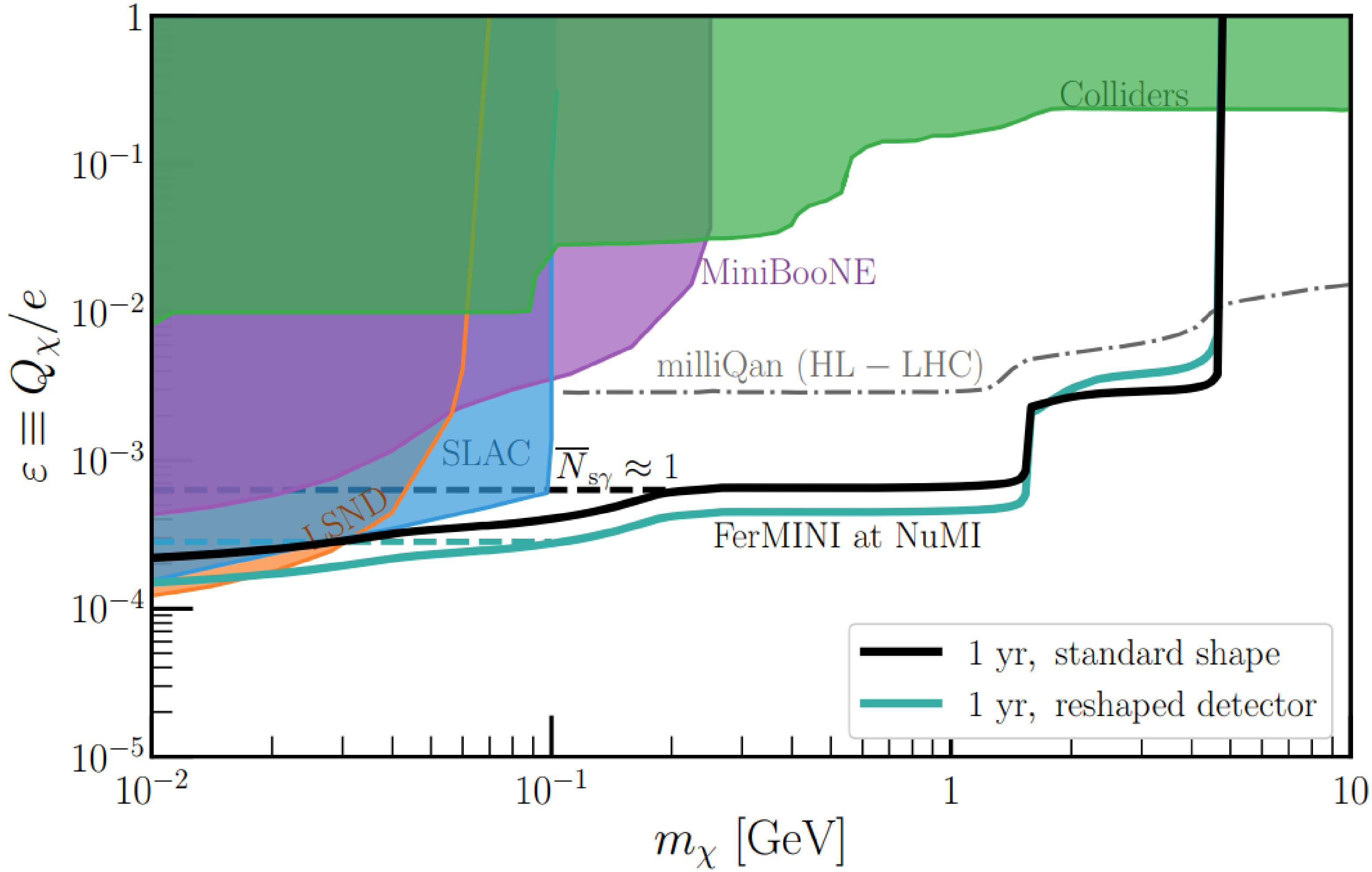
Beam Related Background:

- 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.

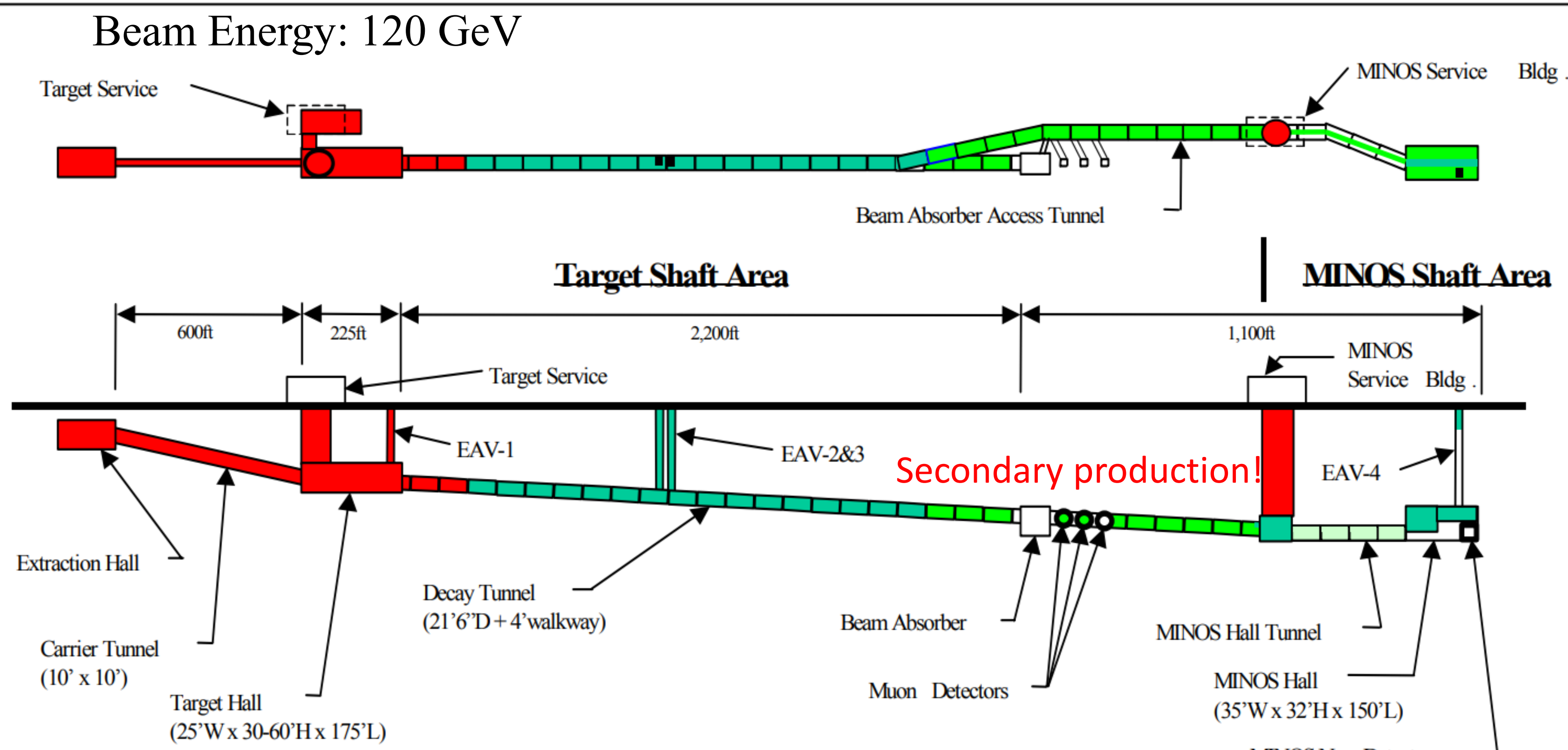
FerMINI: Increasing scintillation photons

- 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



NuMI Beam & MINOS ND Hall

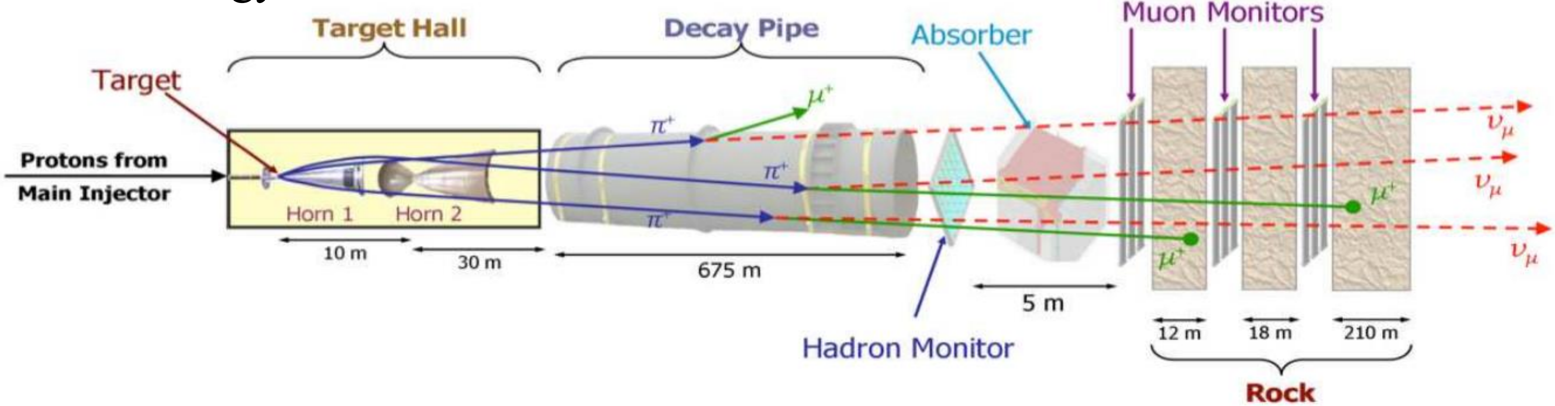


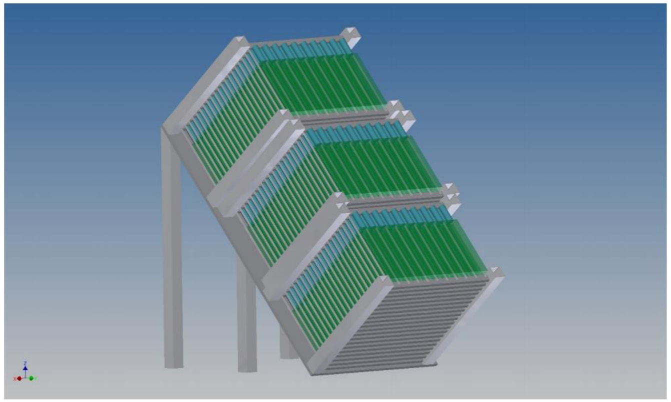
http://www.slac.stanford.edu/econf/C020121/overhead/S_Childr.pdf

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

FerMINI @ NuMI-MINOS Hall

Beam Energy: 120 GeV





FerMINI: Discussions & Alternative Designs

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

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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Summary Table

Exp. (Beam Energy, POT)	N [$\times 10^{20}$] π^0	η	$A_{\text{geo}}(m_\chi)[\times 10^{-3}]$ 1 MeV	100 MeV	Cuts [MeV] E_e^{min}	E_e^{max}	Bkg
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
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

- $\varepsilon \propto E_{e,R,min}^{1/4}\, Bg^{1/8}$
- **DUNE LArTPC ND, Using CDR configuration**
  Efficiency of 0.2 for Cherenkov detectors, 0.5 for nuclear emulsion detectors, and 0.8 for liquid argon time projection chambers.