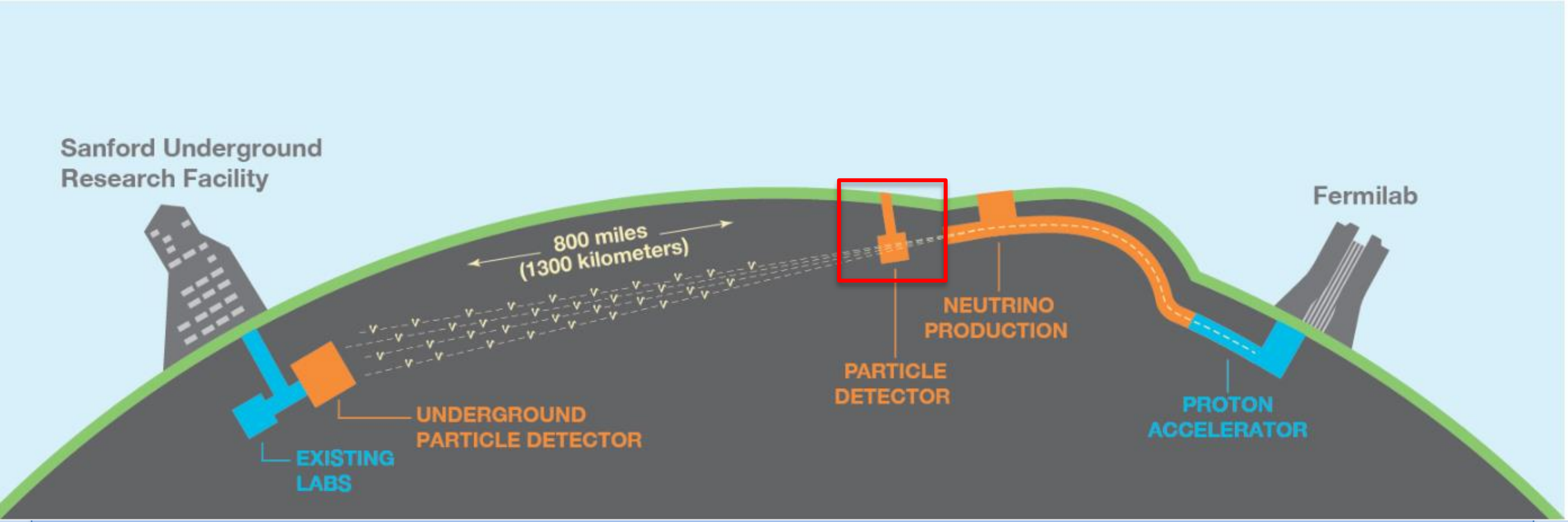


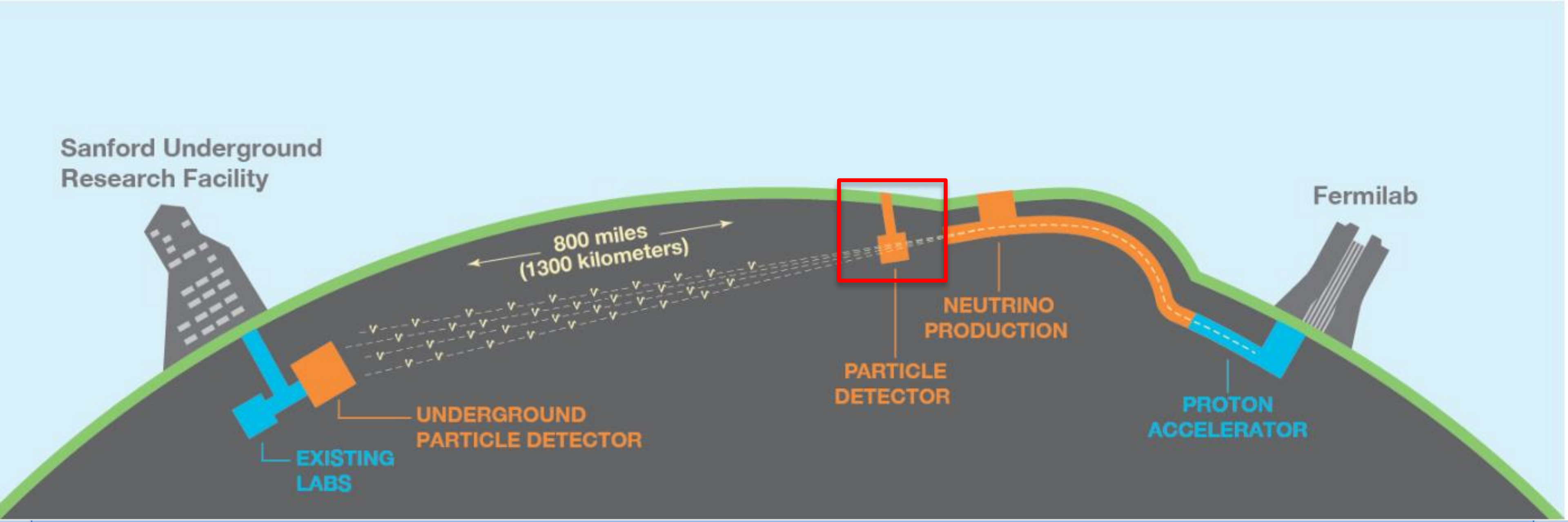
Dark Sectors in FerMINI & Neutrino Experiments: Millicharged Particles

Yu-Dai Tsai, **Fermilab/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



Long-Lived Particles in the Energy Frontier of the Intensity Frontier

- Light Scalar & Dark Photon at Borexino & LSND, 1706.00424 (proton-charge radius anomaly)
- Dipole Portal Heavy Neutral Lepton, 1803.03262 (LSND/MiniBooNE anomalies)
- Dark Neutrino at Scattering Exp: CHARM-II & MINERvA! 1812.08768, (MiniBooNE Anomaly)
- General purpose experiments: coming out soon!

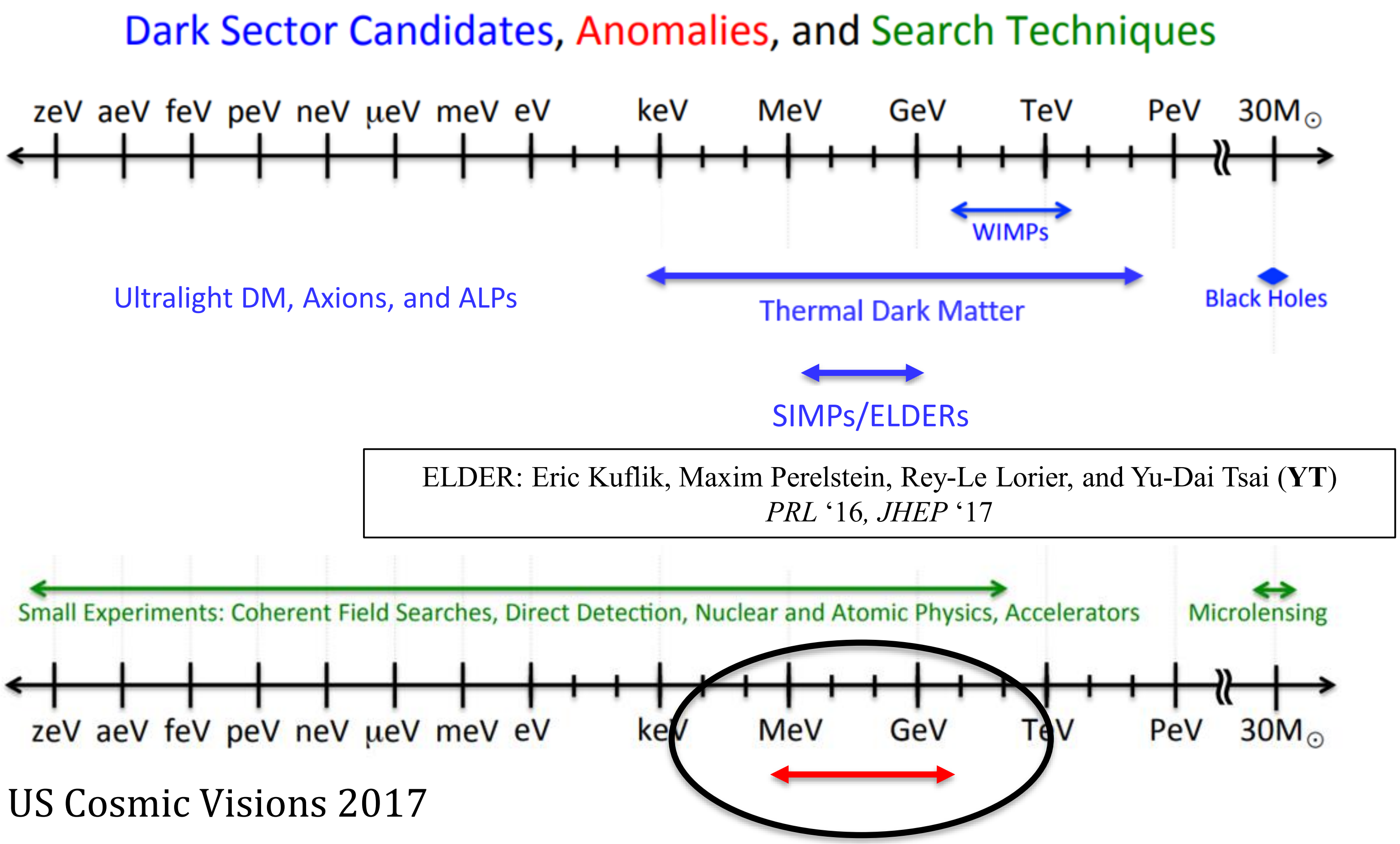
Outline

- **Motivations**
- **Dark Sectors @ Fixed-Target & Neutrino Experiments**
- **Millicharged Particle (mCP)**
- **Bounds & Projections @ Neutrino Detectors**
- **The FerMINI Experiment**
- **Discussion**

Neutrino & Proton Fixed-Target (FT) Experiments:

Some natural habitats for signals of
weakly interacting / long-lived / hidden particles:

Exploration of the Dark Sectors



US Cosmic Visions 2017

- **Astrophysical/cosmological observations** are important to reveal the **actual story of dark matter (DM).**
- **Why Neutrino/FT experiments? And why MeV – GeV+?**

Neutrino & Proton FT Experiments

- Neutrinos are **weakly interacting particles**.
- High statistics, e.g. LSND has 10^{23} Protons on Target (POT)
- Shielded/underground: lower background
- Many of them existing and many to come:

  strength in numbers
- Relatively high energy proton beams on targets exist

  O(100 – 400) GeV (I will compare Fermilab/CERN facilities)
- Produce hidden particles / involve less assumptions

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

Cosmology: assume cosmological history, species, etc

} different

Why study MeV – GeV+ dark sectors?

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**

ν Hopes for New Physics: Personal Trilogy

⋮

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

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

- **Dipole Portal Heavy Neutral Lepton**

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

  (**LSND/MiniBooNE anomalies**)

- **Millicharged Particles** in Neutrino Experiments

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

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

⋮

Inspired by …

deNiverville, Pospelov, Ritz, '11,

Batell, deNiverville, McKeen, Pospelov, Ritz, '14

Kahn, Krnjaic, Thaler, Toups, '14 …

Yu-Dai Tsai,
Fermilab

New Physics in Proton FT Experiments

⋮

- **Millicharged Particles** in **FerMINI Experiments**

  Kelly & **YT,** 1812.03998

  (**EDGES Anomaly**)

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

  Argüelles, Hostert, **YT**, 1812.08768, submitted to *PRL*

  (**MiniBooNE Anomaly**)

Two Recent Papers!
Happy to talk about these during the coffee break.

⋮

Millicharged Particles

Is electric charge quantized?
Other Implications

Finding Minicharge

- **Is electric charge quantized and why?** A long-standing question!
- U(1) allows arbitrarily small (any real number) charges.
  Why don't we see them in e charges? Motivates
  Dirac quantization, Grand Unified Theory (GUT), etc, to explain such quantization (anomaly cancellations fix some SM $U(1)_Y$ charge assignments)
- Testing 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 DM as MCP to explain the EDGES anomaly (severely constrained, see **more reference later**, also see Julian's)

Millicharged Particle: Models

Yu-Dai Tsai, Fermilab, 2019

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

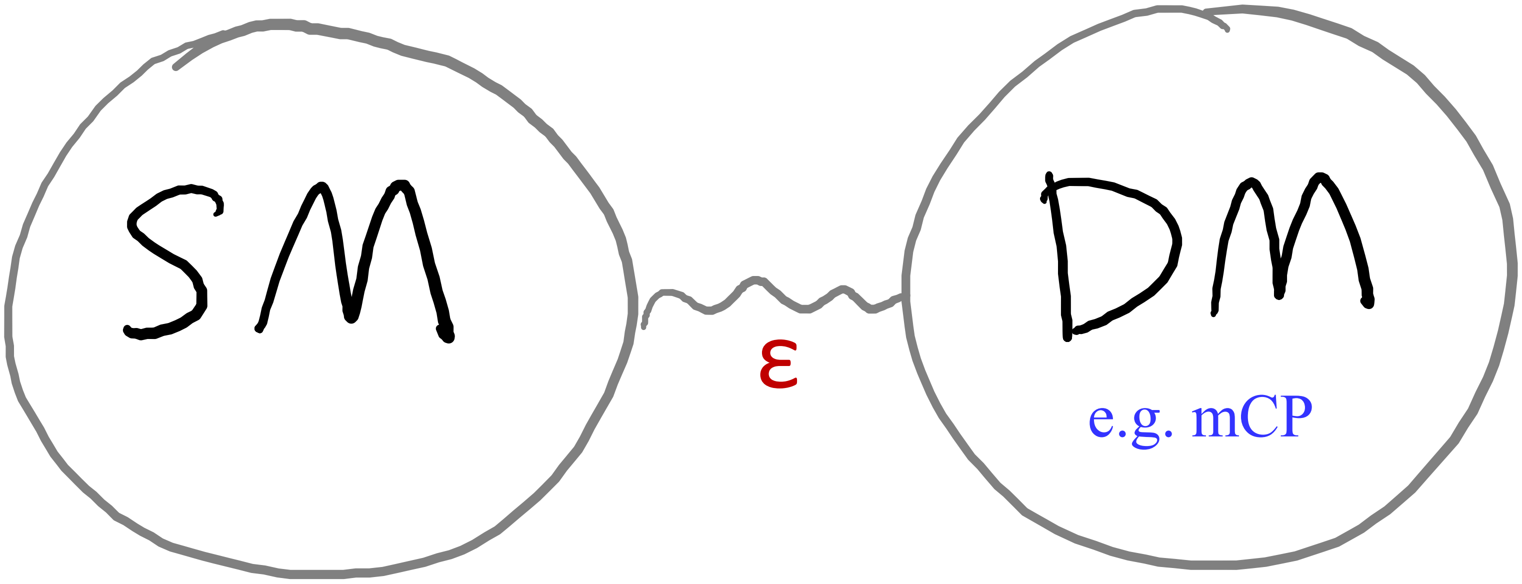
(SM: Standard Model)

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', $B' \rightarrow B' + \kappa B$
- 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, 2019

Important Notes!

- Our search is simply a search for particles (**fermion χ**) with

  {mass, electric charge} = $\{m_\chi, \epsilon e\}$
- **Minimal theoretical inputs/parameters**

  (hard to probe in MeV – GeV+ mass regime)

- **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

Additional Motivations

- Won't get into details, but it's **interesting to find "pure" MCP, that is WITHOUT a massless / light dark photon** (finding MCP in the regime light/massless A' is strongly constraint!)
- More **violent violation of the charge quantization (and GUT, etc)** (if not generating millicharge through kinetic mixing)
- Testing some GUT models, and **String Compactifications** (!!) see Shiu, Soler, Ye, arXiv:1302.5471, PRL '13 for more detail.

Some Reference of **MCP DM and constraints**. See, e.g.,

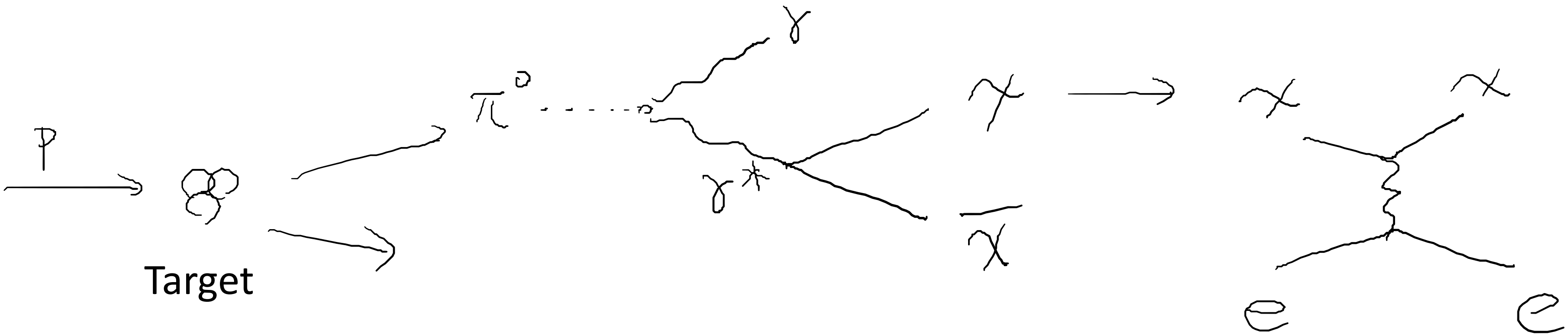
McDermott, Yu, **Zurek**, 1011.2907; **Muñoz**, **Dvorkin**, Loeb, 1802.10094, 1804.01092, Berlin, Hooper, Krnjaic, McDermott, 1803.02804;

Kovetz, Poulin, Gluscevic, Boddy, Barkana, Kamionkowski, arXiv:1807.11482,

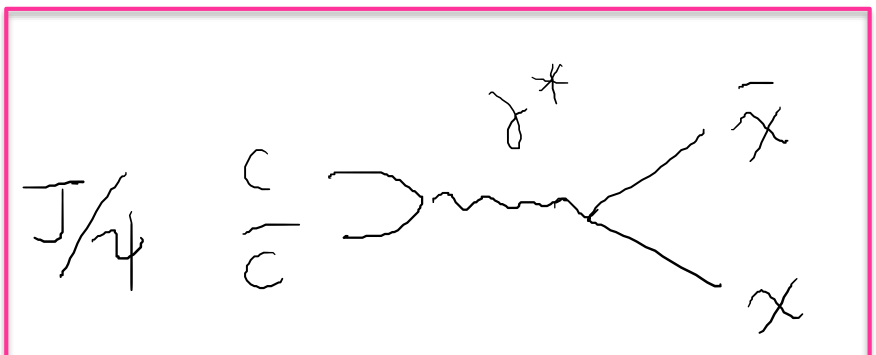
Harnik, **Liu**, Ornella, 1902.03246, **Dvorkin**, **Lin**, Schutz, 1902.08623

Millicharged Particle: Signature

MCP (or light DM with light mediator): production & detection



- production: meson decays
- detection: scattering electron



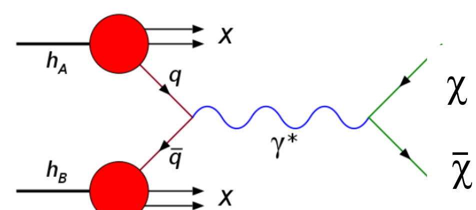
$BR(\pi^0 \to 2\gamma) = 0.99$

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

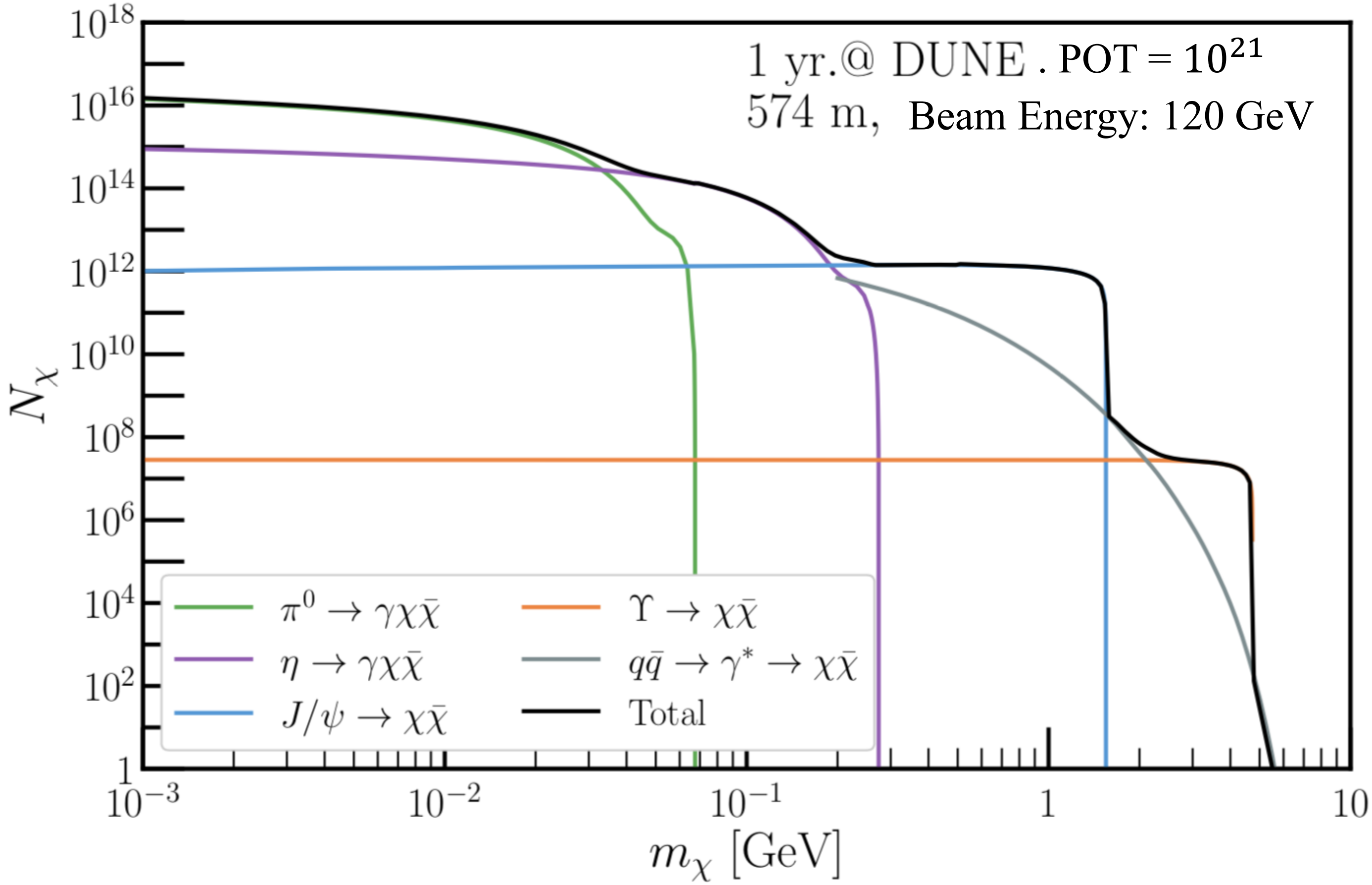
$BR(\pi^0 \to e^- e^+) = 6 * 10^{-6}$

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

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



MCP Production/Flux



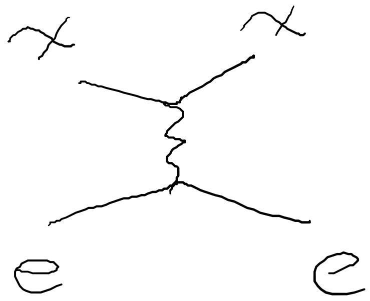
- We use PYTHIA to generate neutral meson Dalitz or direct decays from the pp collisions and rescale by considering, $\mathrm{BR}(\mathcal{M} \to \chi\bar{\chi}) \approx \epsilon^2 \times \mathrm{BR}(\mathcal{M} \to X e^+ e^-) \times f\left(\frac{m_\chi}{M}\right),$
- M: mass of the parent meson, X:additional 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

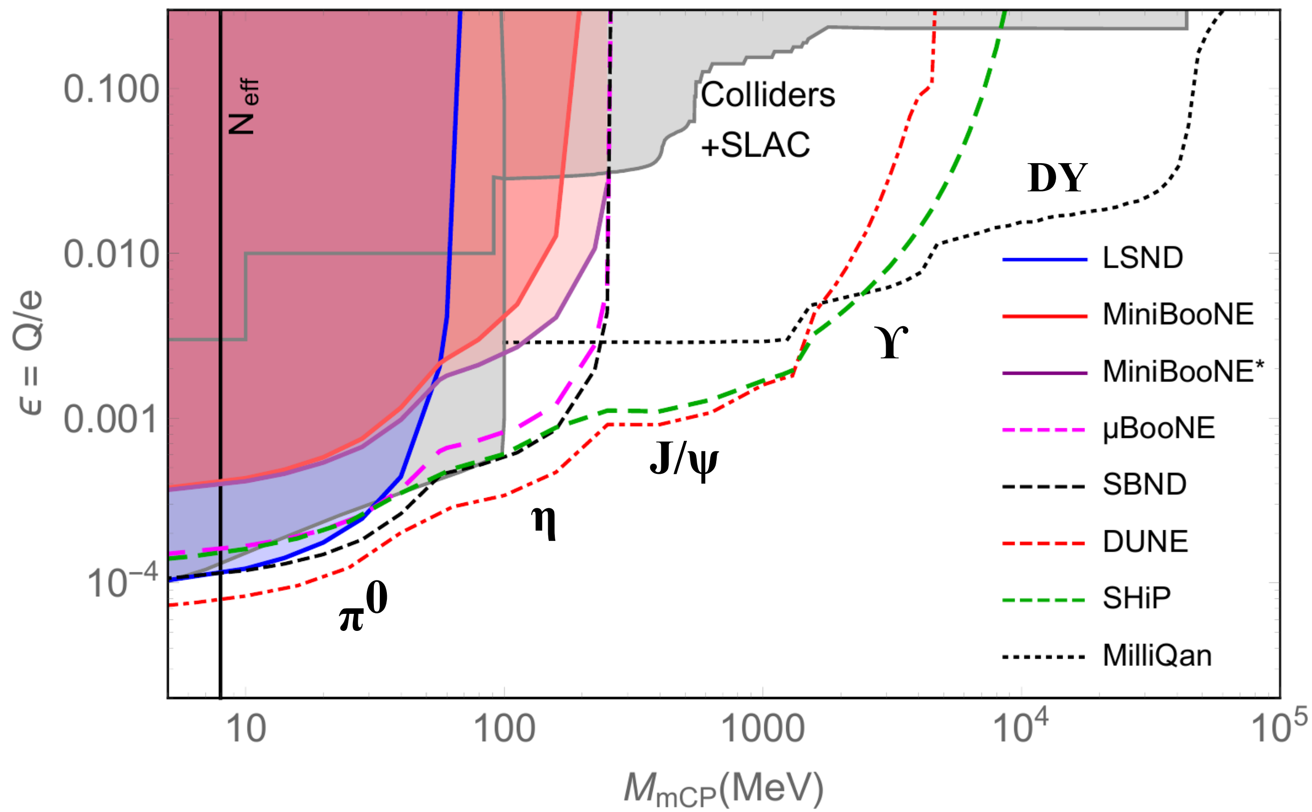
- **signal events** s_{event}

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

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, $s_{event} \propto \varepsilon^4$. ε^2 from N_x and ε^2 from $\boldsymbol{\sigma}_{ex}$
- Throughout this paper, we choose a credibility interval of $1 - \alpha = 95\%$ (~ 2 sigma)
- Roughly, $\varepsilon_{sensitivity} \propto E_{e,\,R,min}^{1/4}\ Bg^{1/8}$

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).

Summary Table

	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
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	0.4
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 DM 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
  $\cos\theta > 0$ 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

Background for Future Measurements

- Single-electron background for ongoing/future experiments for **MicroBooNE, SBND, DUNE, and SHiP?**
- Background discussions:

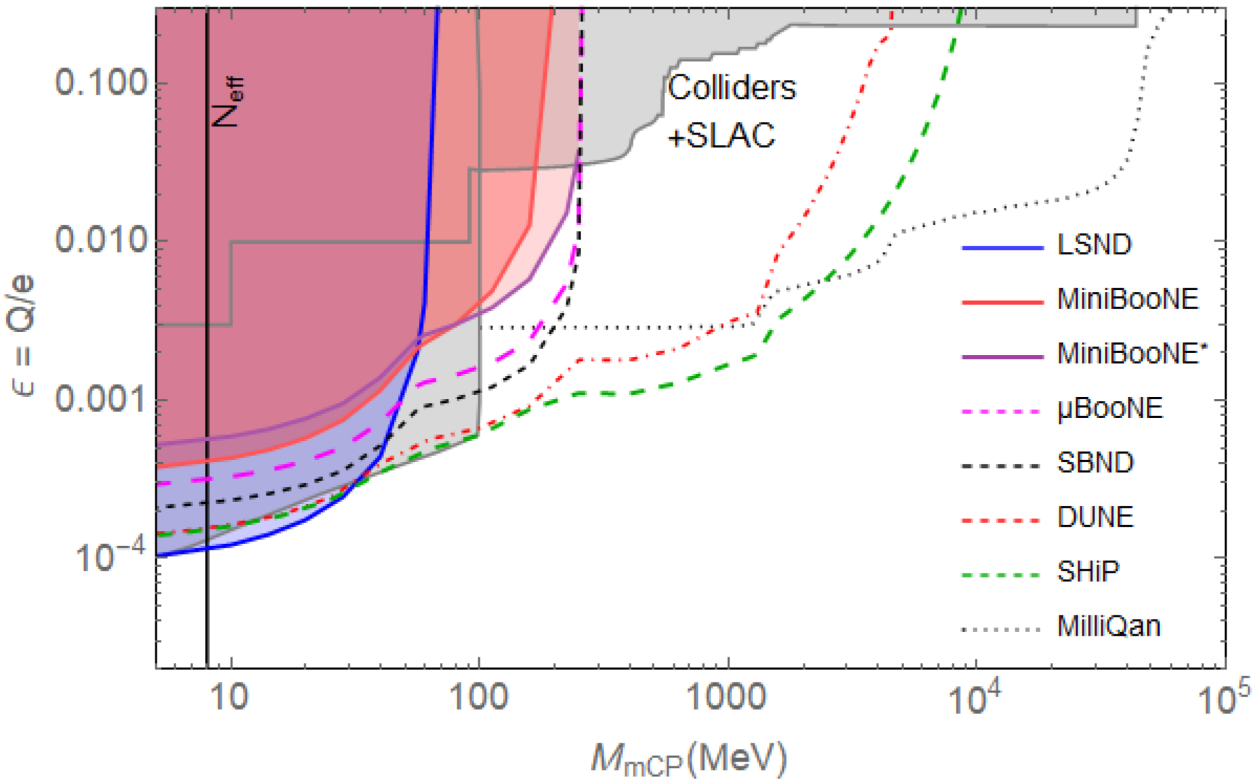
1) From neutrino fluxes (calculable),

[i.e. **νe** → **νe** and **νn** → **ep**], greatly reduced by **maximum electron recoil energy cuts E_e(max)**

2) other: times a factor (10-20) to account for these

3) Harnik, **Liu**, Ornella: multi-scattering, point back to target to reduce the background, **arXiv:1902.03246!**

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

Summary

- Technique can be easily applied to more generic **light dark matter** and other **weakling interacting particles**

  - Production from **heavy neutral mesons** are important

    (very often neglected in literature)

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

- For more realistic analysis: include realistic **background,** $E_{e,\,R,min}$ **cut**, etc

Low-cost Fixed-target Probes of Long-Lived Particles

FerMINI as an example:

more to come!

Yu-Dai Tsai, Fermilab, 2019

FerMINI:

Putting dedicated Minicharge Particle Detector (~1M)
@ Fermilab Beamlines: NuMI or LBNF or @ CERN: SPS

Kelly, **YT**, 1812.03998

(can also probe other new physics scenarios like
small-electric-dipole dark fermions, or quirks, etc)

MilliQan at CERN

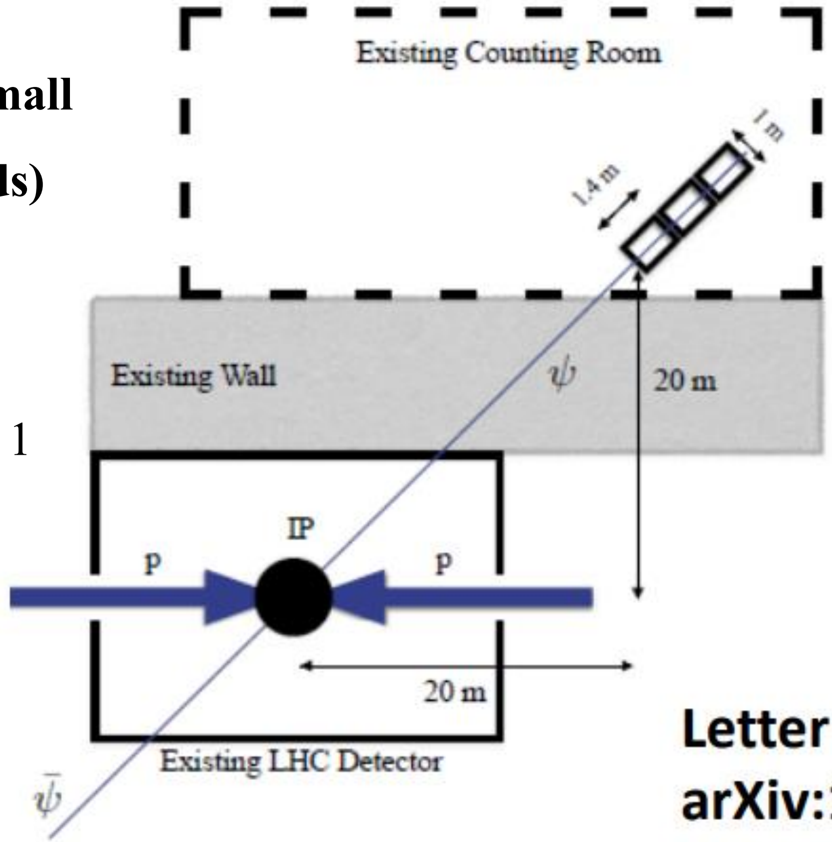
Austin Ball, Jim Brooke, Claudio Campagnari, Albert De Roeck, Brian Francis, Martin Gastal, Frank Golf, Joel Goldstein, **Andy Haas, Christopher S. Hill, Eder Izaguirre**, Benjamin Kaplan, Gabriel Magill, Bennett Marsh, David Miller, Theo Prins, Harry Shakeshaft, David Stuart, Max Swiatlowski, **Itay 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 (P5)**.
- 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 required to reduce the **dark-current noise (the dominant background)**.

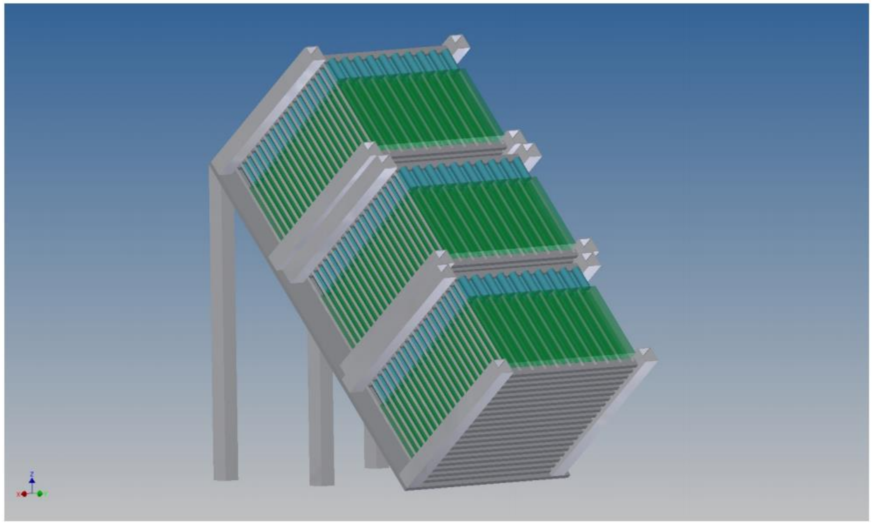


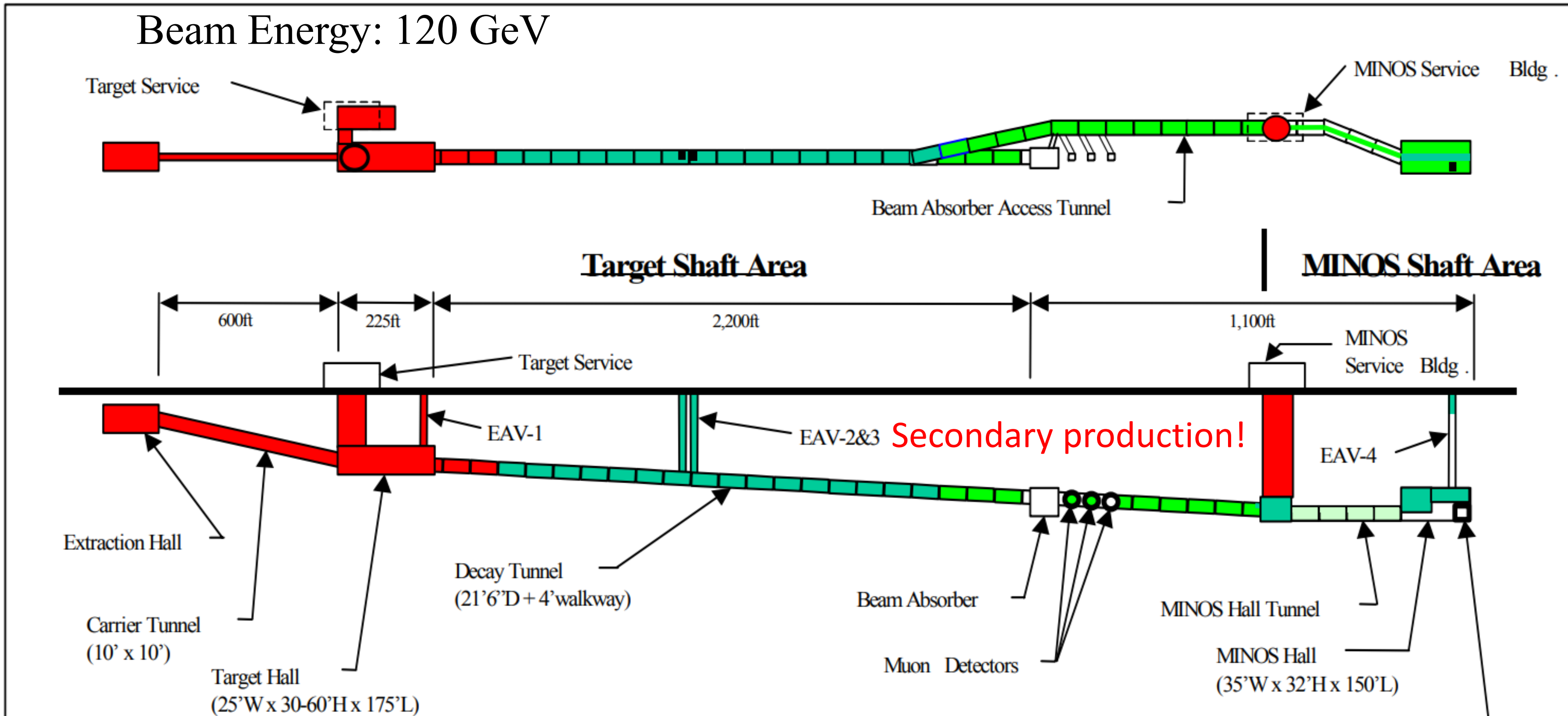
Figure from 1607.04669 (milliQan LOT)

FerMINI:

A Fermilab Search for MINI-charged Particle

Kelly, **YT**, 1812.03998

Site 1: NuMI Beam & MINOS ND Hall

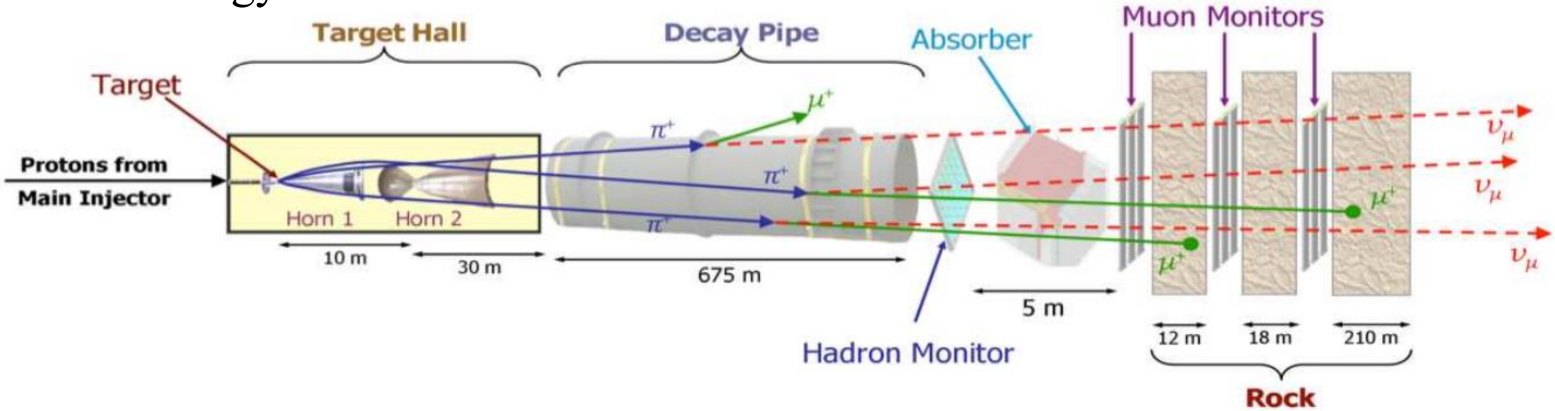


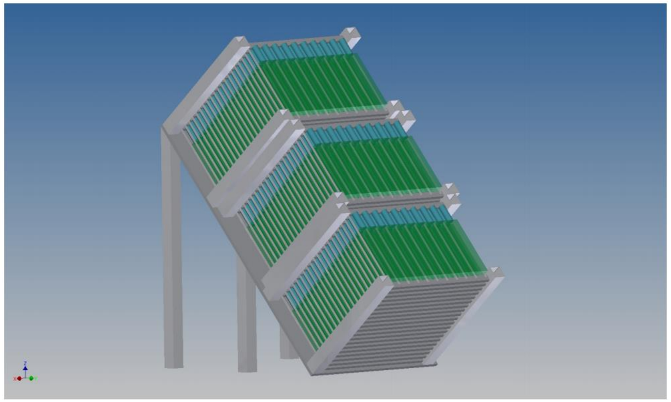
http://www.slac.stanford.edu/econf/C020121/overhead/S_Childr.pdf

NuMI: Neutrinos at the Main Injector
MINOS: Main Injector Neutrino Oscillation Search
ND: Near Detector

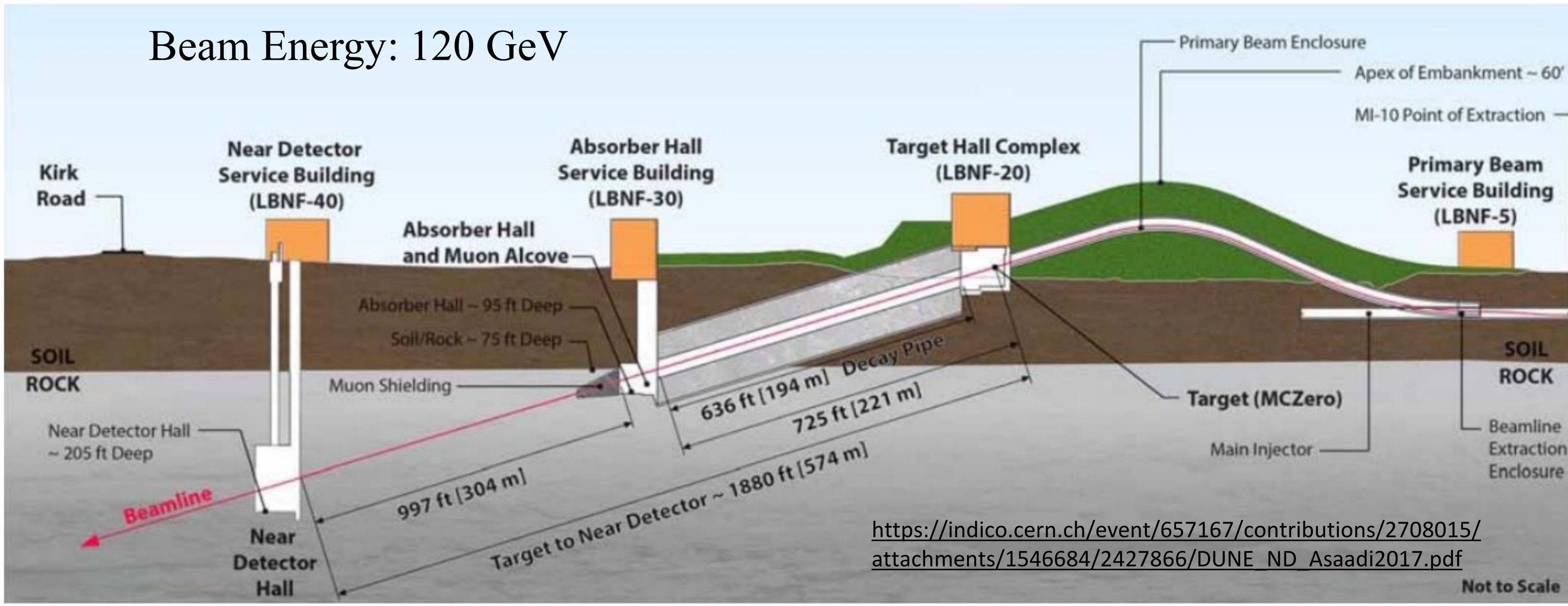
FerMINI @ NuMI-MINOS Hall

Beam Energy: 120 GeV





Site 2: LBNF Beam & DUNE ND Hall



Jonathan Asaadi – University of Texas Arlington

There are many other **new physics opportunities** in the **near detector hall**!

Signature: Triple Coincidence

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

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

- $\langle dE/dx \rangle$ is the "mass stopping power" (PDG 2018)
- LY: light yield
- e_{det}: detection efficiency

$\boldsymbol{N_{PE}} \sim \epsilon^2$ x $\mathbf{10^6}$, $\epsilon \sim \mathbf{10^{-3}}$ roughly gives one PE in one 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 .**

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 of events with > 10 PEs

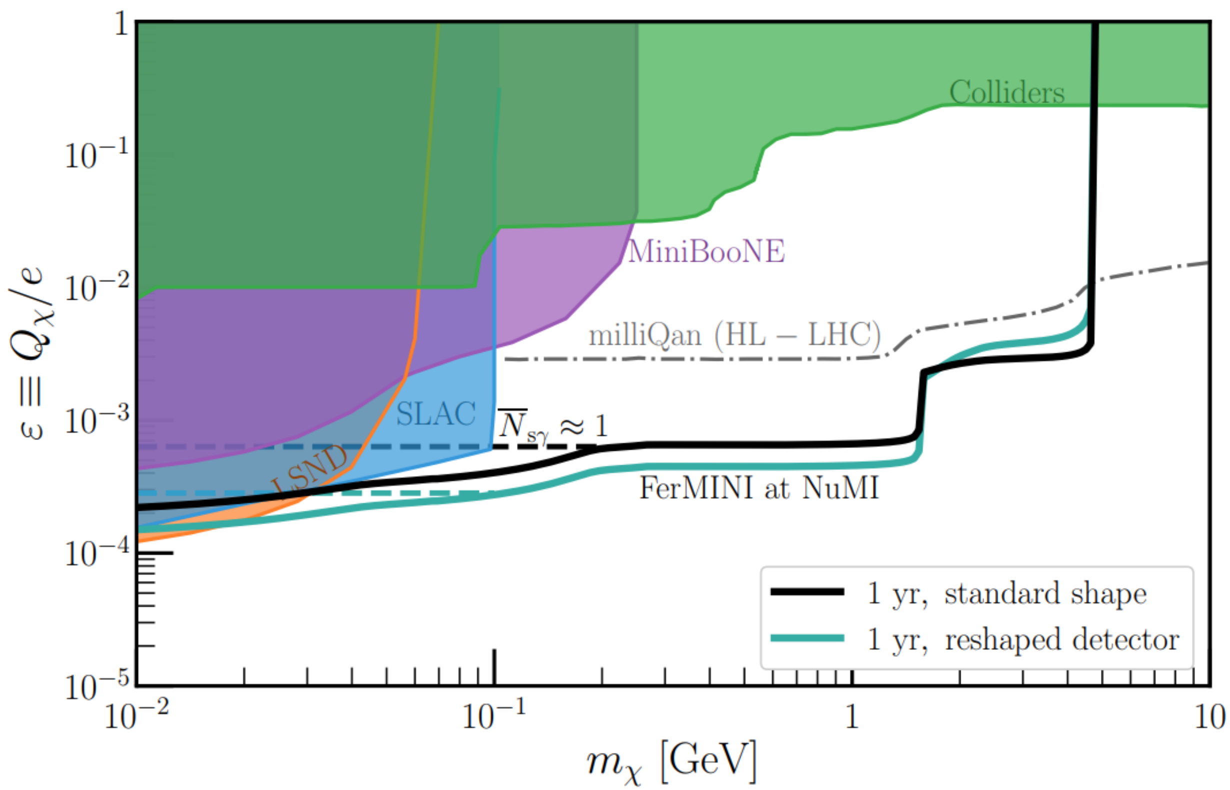
  - Offset middle detector
- **Dark current: triple coincidence**

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

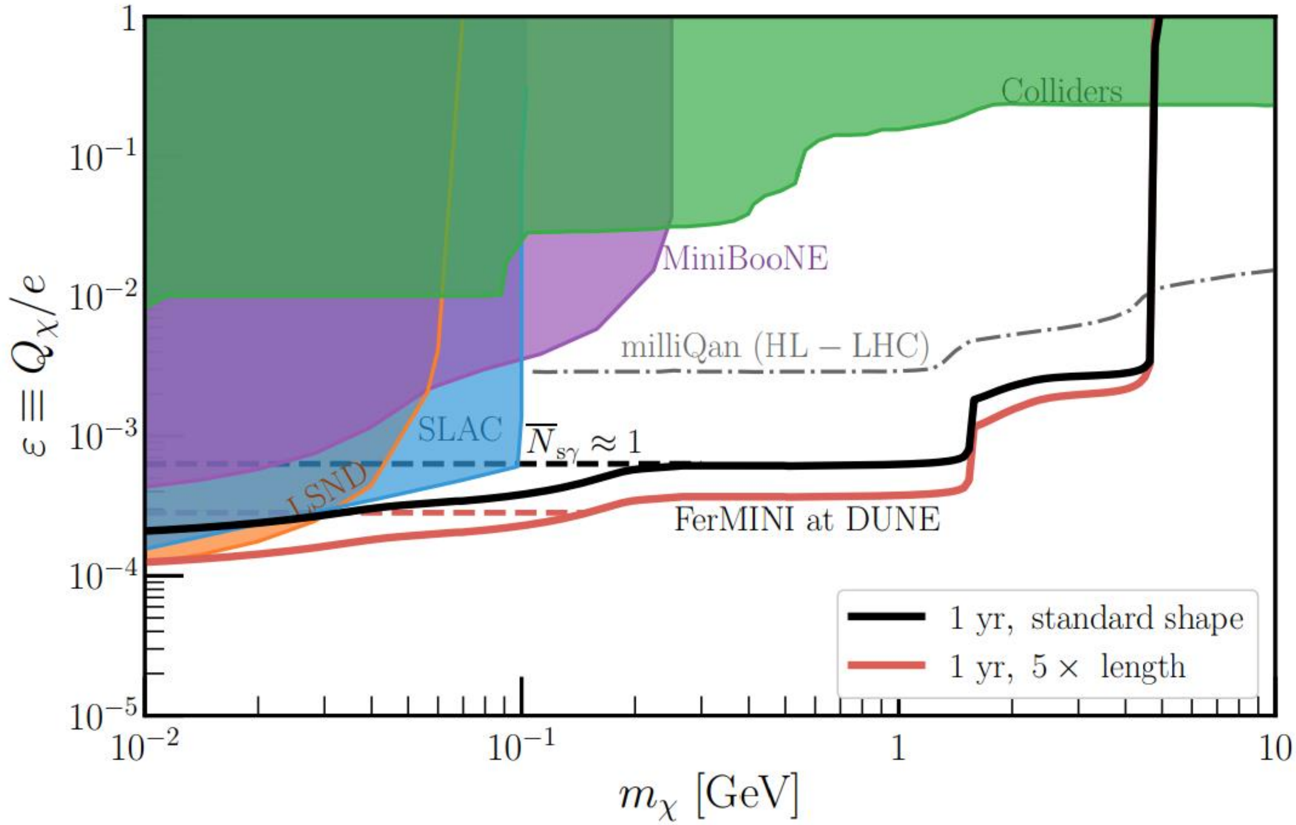
FerMINI @ MINOS



- Got support from **milliQan members**
- Recruiting young experimentalists to take charge of the Fermilab LDRD proposal/experimental Implementation

Yu-Dai Tsai, Fermilab

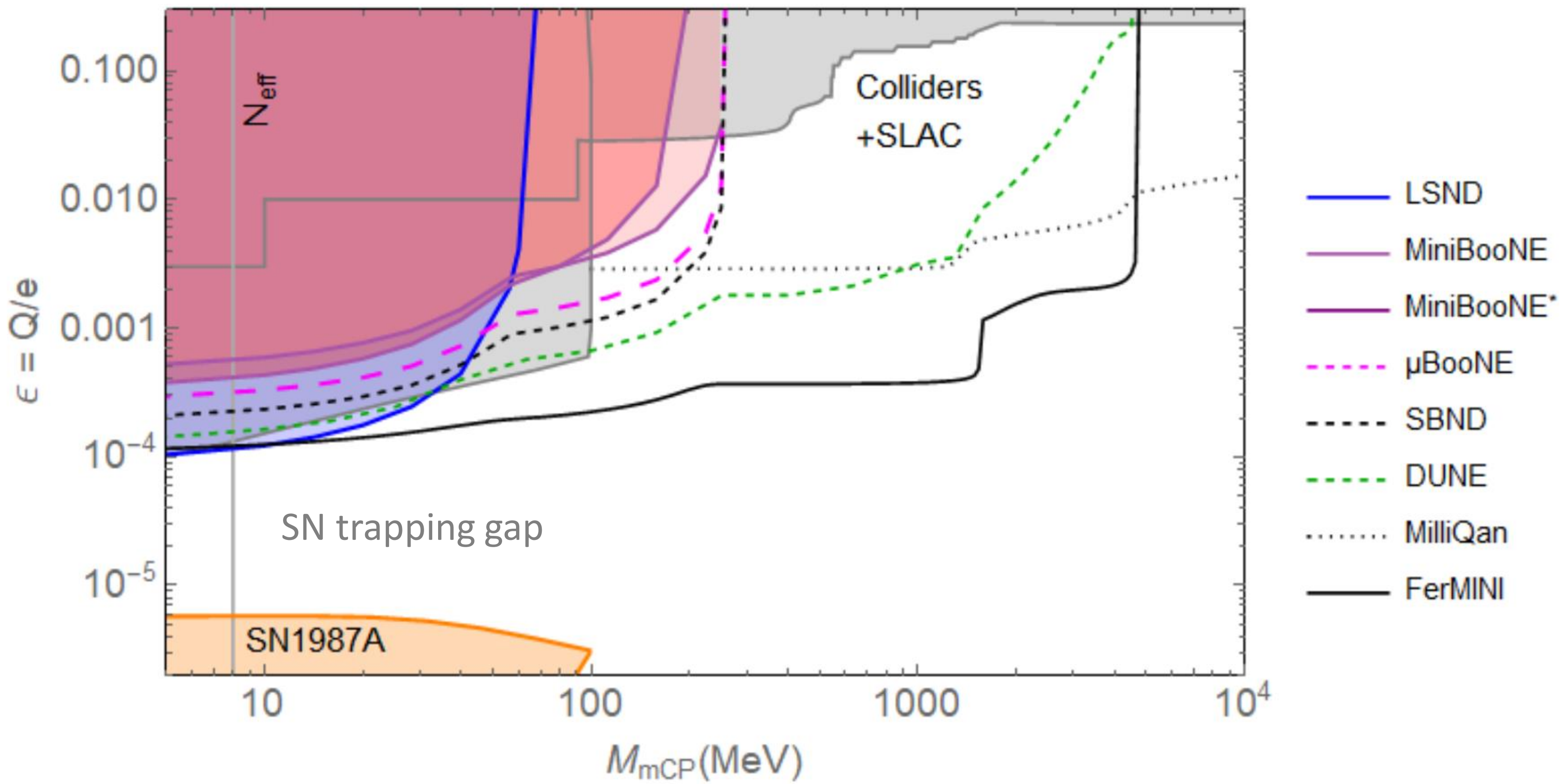
FerMINI @ DUNE



- Scheduled meeting with **DUNE near detector conveners**
- **Try to incorporate it into the near detector proposal**
- Experimentalists like it. **FerMINI is probably happening**

Yu-Dai Tsai, Fermilab

Compilation



Yu-Dai Tsai, Fermilab

NuMI (MINOS) / LBNF (DUNE)
Now and the future bests in POTs

- Fermilab (FT):
- NuMI beam: 1 - 4 x 10^{20} POT/yr (beam: 120 GeV)
  http://www.int.washington.edu/talks/WorkShops/int_06_2b/People/Gran_R/gran-NuMI.pdf
- LBNF beam: 1 - 2 x 10^{21} POT/yr (120 GeV)
  https://indico.fnal.gov/event/12571/contribution/4/material/slides/0.pdf

- CERN SPS (FT): (400 GeV)
- NA62: up to 3 x 10^{18} POT/yr (see Gaia's talk)
- SHiP: up to 10^{19} POT/yr (see Gaia's talk)

- FASER (collider, forward): 10^{16} - 10^{17} POT/yr
  (see Iftah's talk), much higher energy

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! Fermilab! USA!)

3. Broadening the physics case for fixed-target facilities

4. **DUNE near detector design** still underway

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

6. **Sensitivity better than milliQan for MCP up to 5 GeV** and don't have to wait for HL-LHC

7. Synergy between **dark matter**, **neutrino**, and **collider** community

FerMINI:
Alternative Designs
& New Ideas

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}**
   Basically zero dark-current 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
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

New Ideas …

- **Combine with neutrino detector**: behind, in front, or sandwich them
- Combine with **DUNE PRISM**: moving up and down
- **FerMINI + DUNE 3-D scintillation detector (3DST)**
- Combine with **SPS/SHiP facilities**
- Can potentially probe (electric) **dipole portal dark fermion**, **quirks**, etc.
- **Detail Proposal:** Kelly, Plestid, Pospelov, **YT** + milliQan people (ytsai@fnal.gov)

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**
- **Many new papers to come!**

Thank You!
Thanks for the nice conference!

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)**

  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

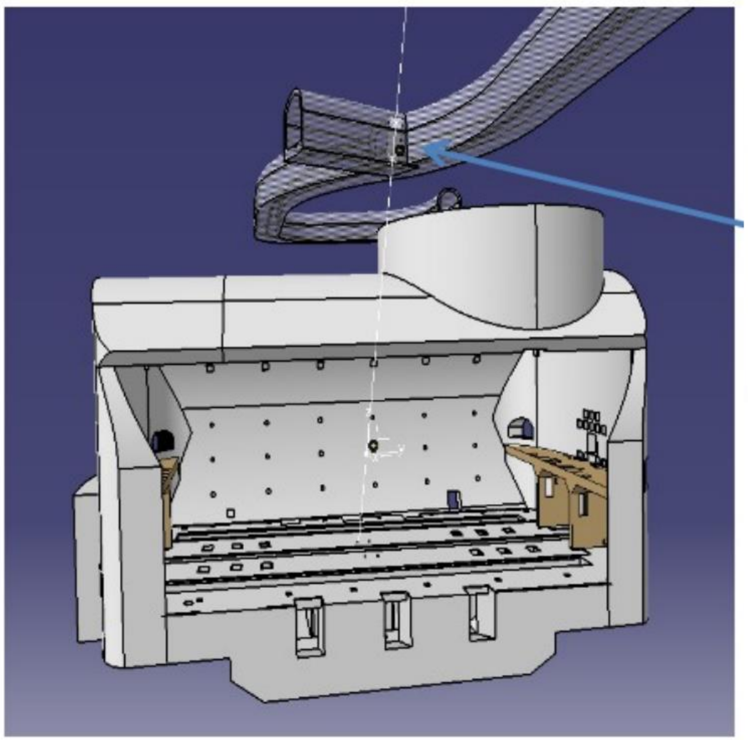
Beam Related Background (can skip)

- Shielding: including **absorber and rocks.**
- Controlled: **muon monitors.**
- **Can determine the SM charged particle rate on site**
- **Vetoed similar to the previous veto of cosmic muons.**
- Neutrino produced hard-scattering background: **O($\mathbf{10^{-19}}$)**, negligible.
- To be conservative, we assume the **beam related background** $\approx$ **dark current background** for our sensitivity determination.
- Based on **SENSEI experience**, beam produced charge background is weaker than cosmic, but of course energy dependence
- Assumed to be at the same level of detector background

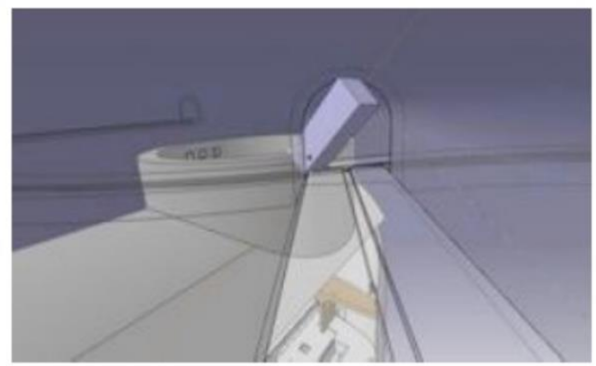
MilliQan: Location!

- 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

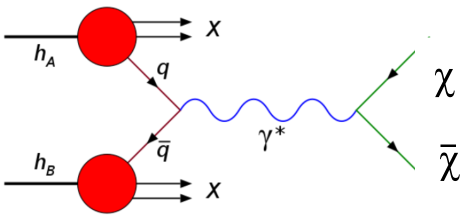
Andrew Haas, Fermilab (2017)

MCP productions

- For **η** & **π^0**, Dalitz decays: $\pi^0/\eta \to \gamma\, \chi\, \bar{\chi}$ dominate
- For **J/ψ** & **Υ**, direct decays: J/ψ, Υ $\to \chi\, \bar{\chi}$ 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, Υ (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].]

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!)

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.**

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

(Detail) dE/dx formula

- 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, see arXiv:1812.03998