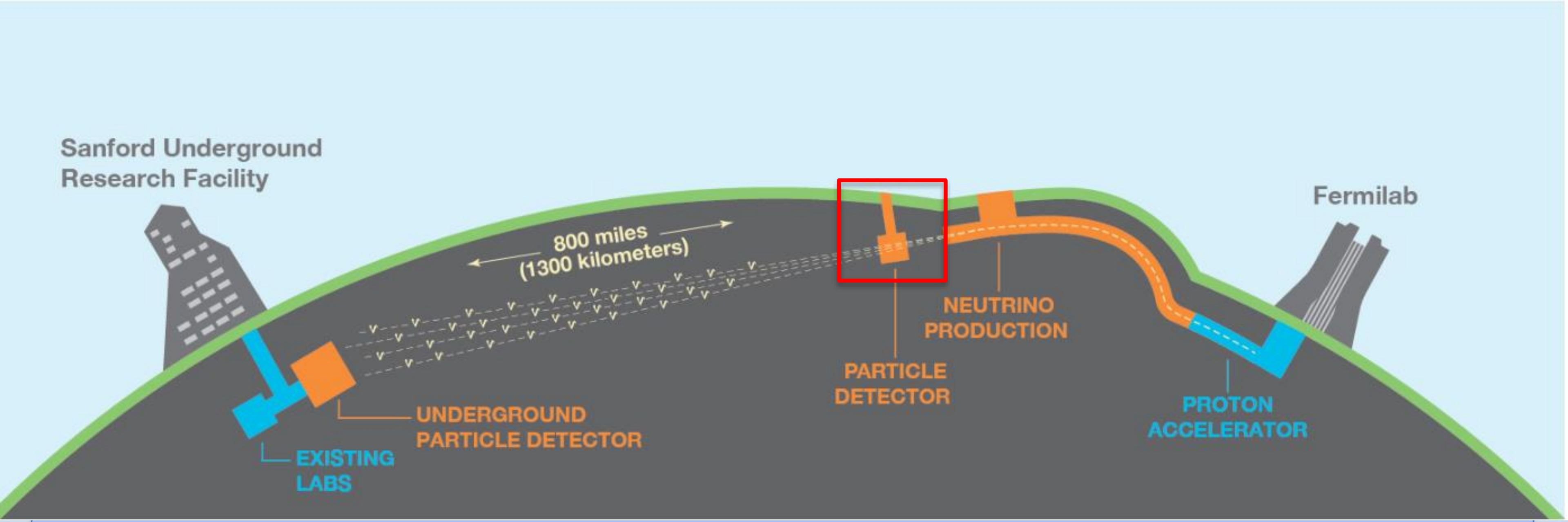


Dark Sectors in FerMINI & Neutrino Experiments: Millicharged Particles

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

New Physics in Neutrino Experiments

⋮

- **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 Neutrino 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 New Papers OUT!
Happy to talk about these during the coffee break.

Yu-Dai Tsai,
Fermilab

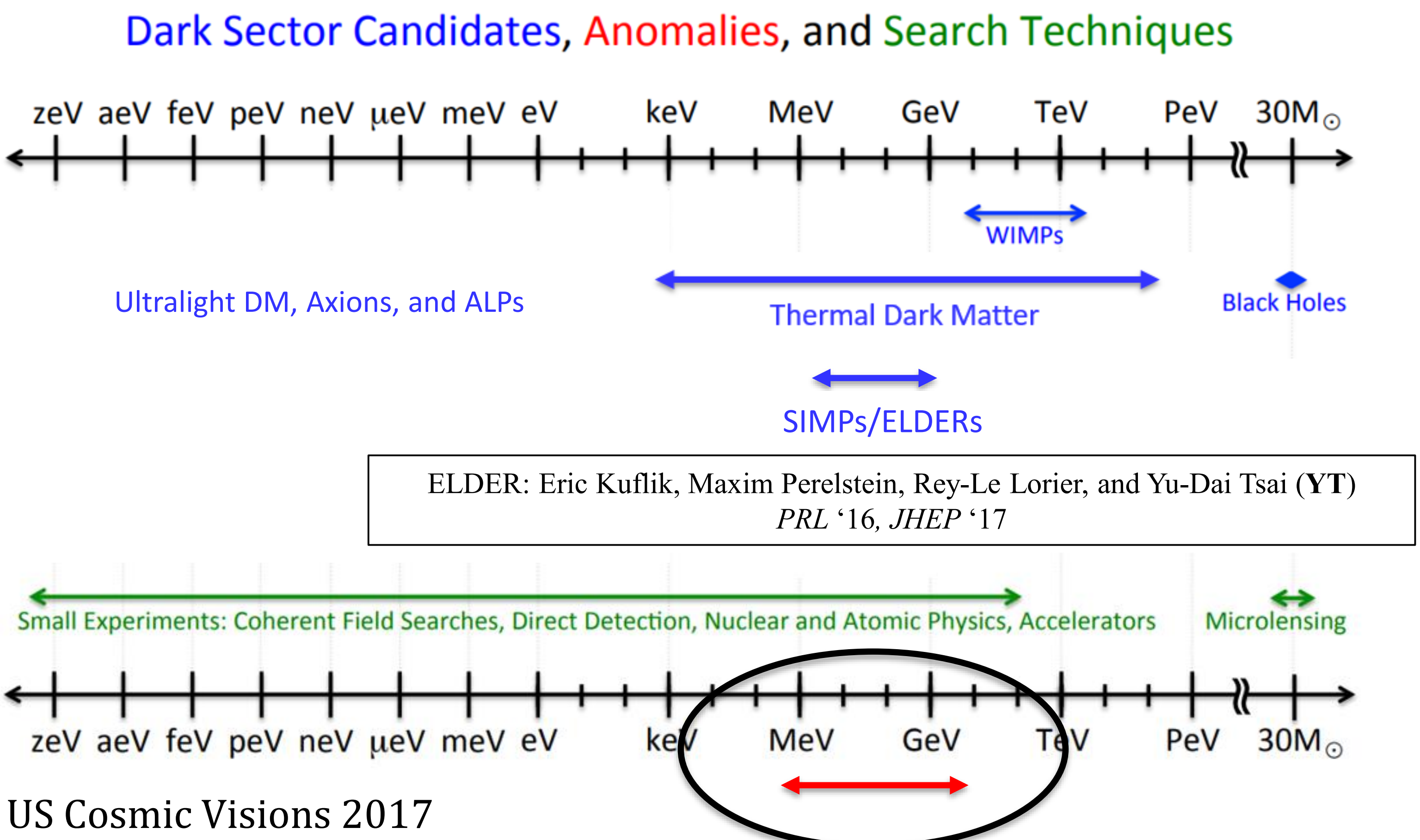
Outline

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

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

Neutrino & Fixed-Target (FT) Experiments

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 Fixed-Target 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
- 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 detection / indirect detection

different

Cosmology: N_{eff}, 21 cm, etc: assume cosmo history

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 without DM abundance assumption**

New Physics in Neutrino Experiments

⋮

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⋮

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Yu-Dai Tsai,
Fermilab

New Physics in Neutrino 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**)

Yu-Dai Tsai,
Fermilab

⋮

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

Millicharged Particles

Is electric charge quantized?
Other Implications

Yu-Dai Tsai, Fermilab, 2019

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)

Millicharged Particle: Models

mCP Model

- Small charged particles under U(1) hypercharge

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

- 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

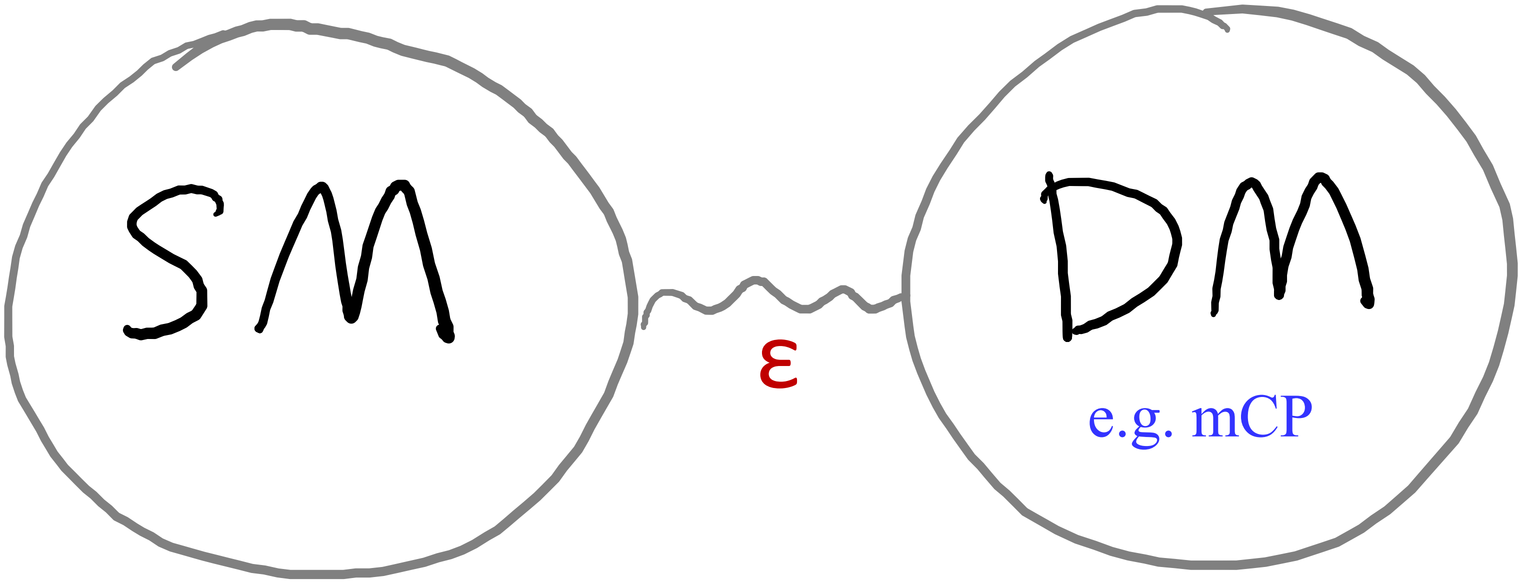
(SM: Standard Model)

See, Holdom, 1985

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

- 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 Notes

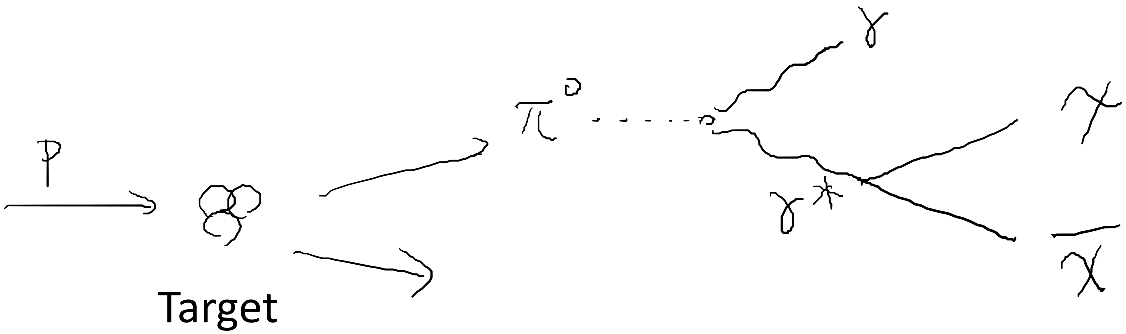
- Won't get into details, but it's **interesting to find "pure" MCP, that is WITHOUT a massless dark photon** (massless dark photon is subject to strong dark radiation constraints, see Cui's talk)
- More **violent violation of the charge quantization** (not generating millicharge through kinetic mixing)
- Testing some GUT models, and **String Compactifications** (!!) see Shiu, Soler, Ye, arXiv:1302.5471, PRL '13 for more detail.

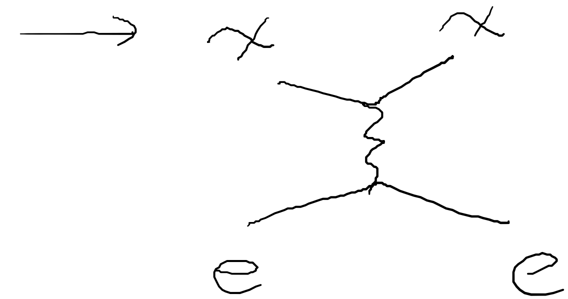
Some Reference of **MCP DM and constraints**. See, e.g.,

McDermott, **Yu**, Zurek, arXiv: 1011.2907; Berlin, **Hooper**, Krnjaic, McDermott, arXiv:1803.02804; Bhoonah, **Bramante**, Elahi, Schon, arXiv: 1806.06857; Kovetz, Poulin, Gluscevic, **Boddy**, Barkana, Kamionkowski, arXiv:1807.11482

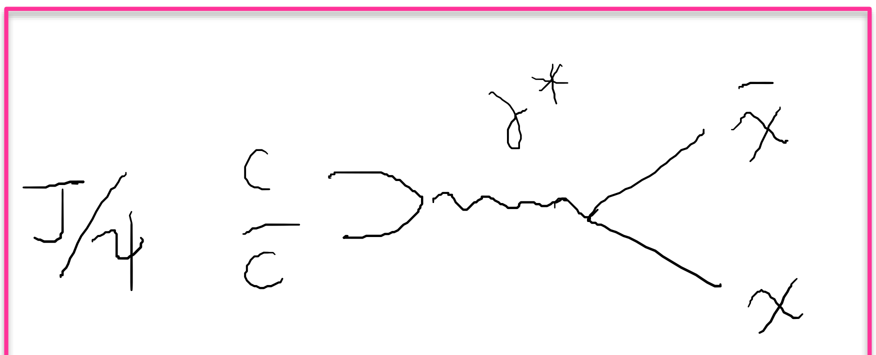
Millicharged Particle: Signature

MCP (or general light DM): production & detection





- ❑ production:
  meson decays
- ❑ detection:
  scattering electron



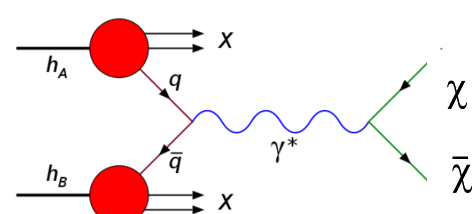
BR($\pi^0 \to 2\gamma$) = 0.99

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

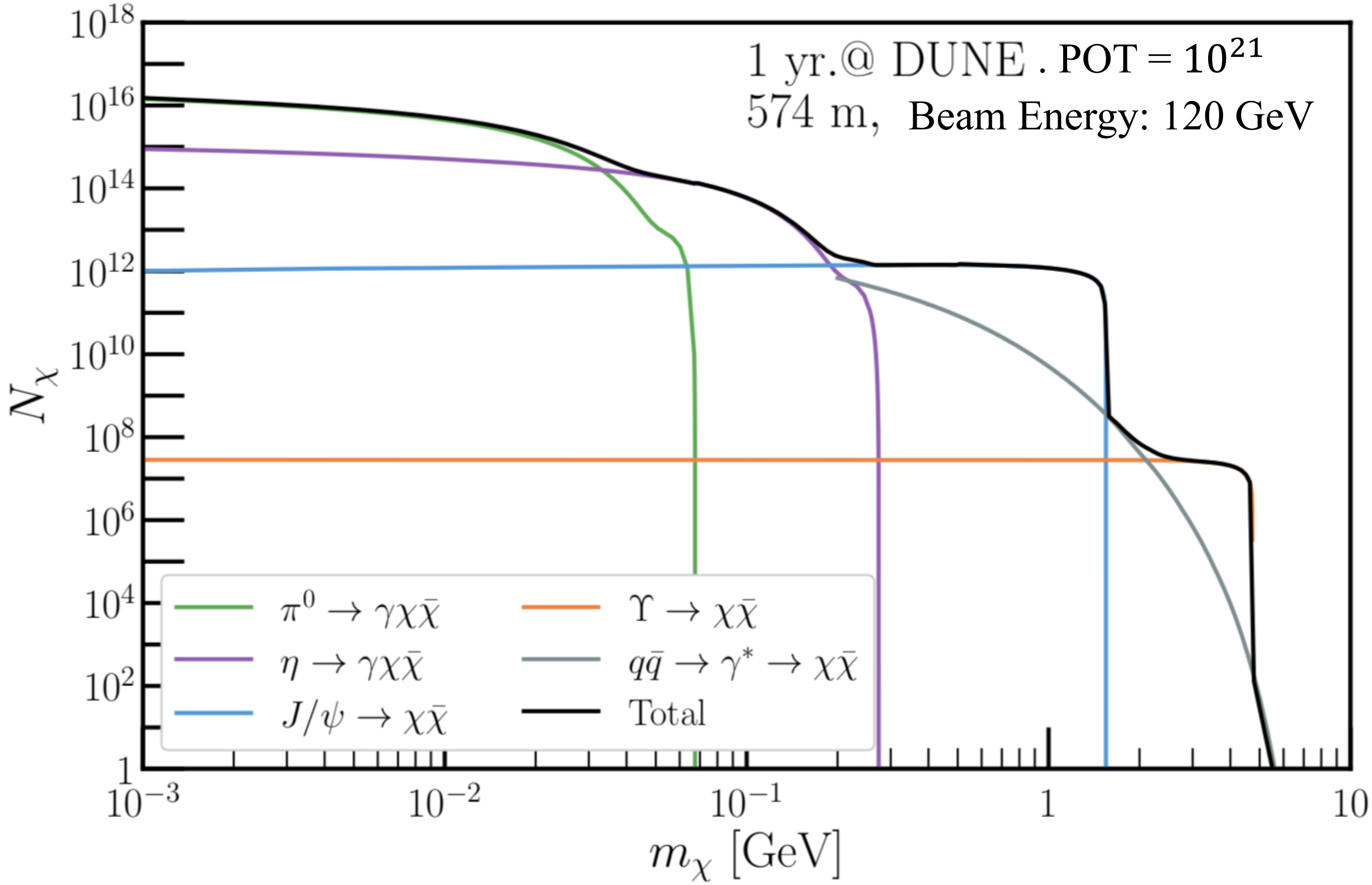
BR($\pi^0 \to e^- e^+$) = $6 * 10^{-6}$

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



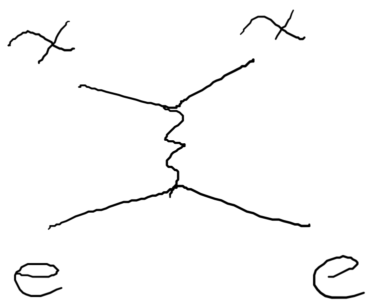
- We use PYTHIA to generate neutral meson Dalitz or direct decays from the pp collisions and rescale by considering, $\mathrm{BR}(\mathcal{M} \to \chi\bar{\chi}) \approx \epsilon^2 \times \mathrm{BR}(\mathcal{M} \to X e^+ e^-) \times f\left(\frac{m_\chi}{M}\right)$,
- M: mass of the parent meson, X:additional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

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

- 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

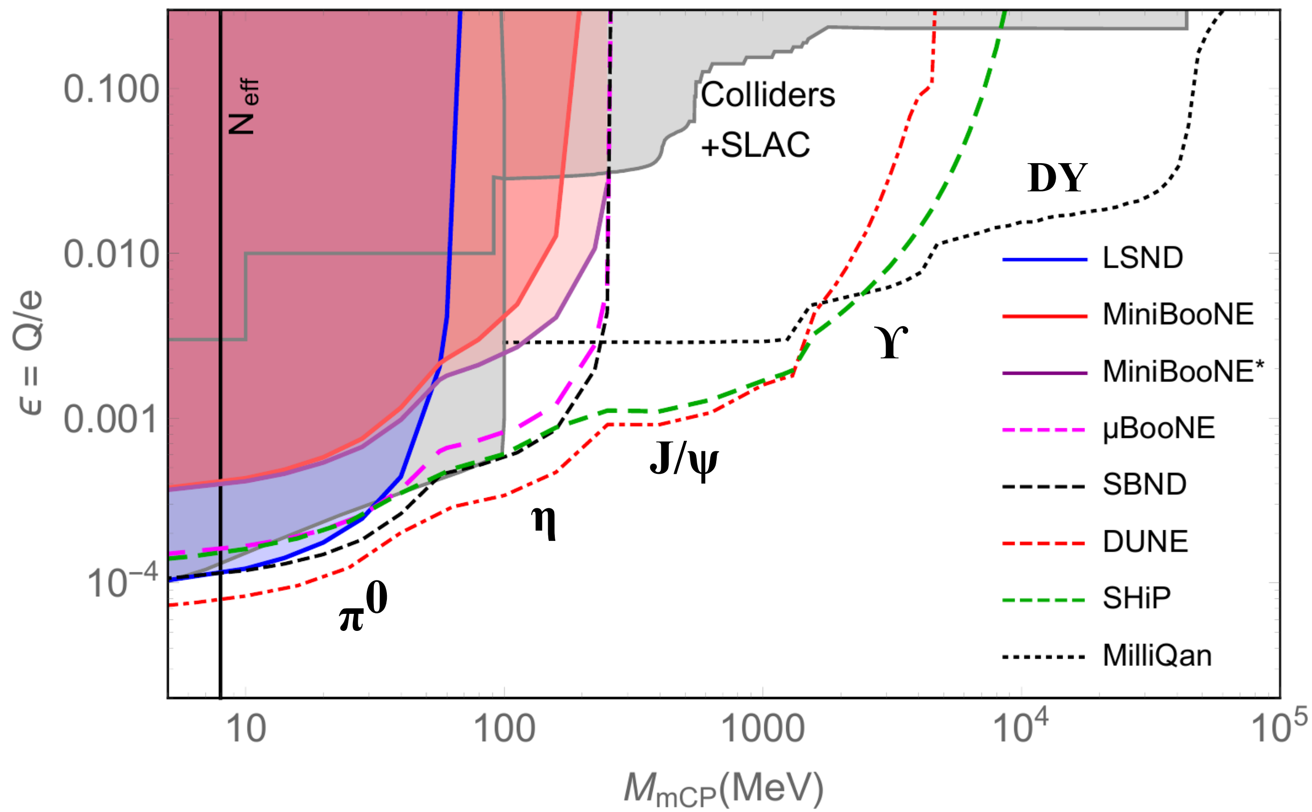
- **signal events** s_{event}

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

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 [$\times 10^{20}$] π^0	η	$A_{\text{geo}}(m_\chi)[\times 10^{-3}]$ 1 MeV	100 MeV	Cuts [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 dark matter run where a cut of cos θ > 0.99 effectively reduces backgrounds to zero [Dharmapalan, MiniBooNE, (2012)]).
- Efficiency of 0.2 for Cherenkov detectors, 0.5 for nuclear emulsion detectors, and 0.8 for liquid argon time projection chambers.

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

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

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

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,** $\boldsymbol{E_{e,\,R,min}}$ **cut**, etc
- One should consider **multi-scattering!** (Harnik, Liu, ArgoNeuT)

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

FerMINI as an example

FerMINI:

Putting dedicated Minicharge Particle Detector (milliQan-type)
@ 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

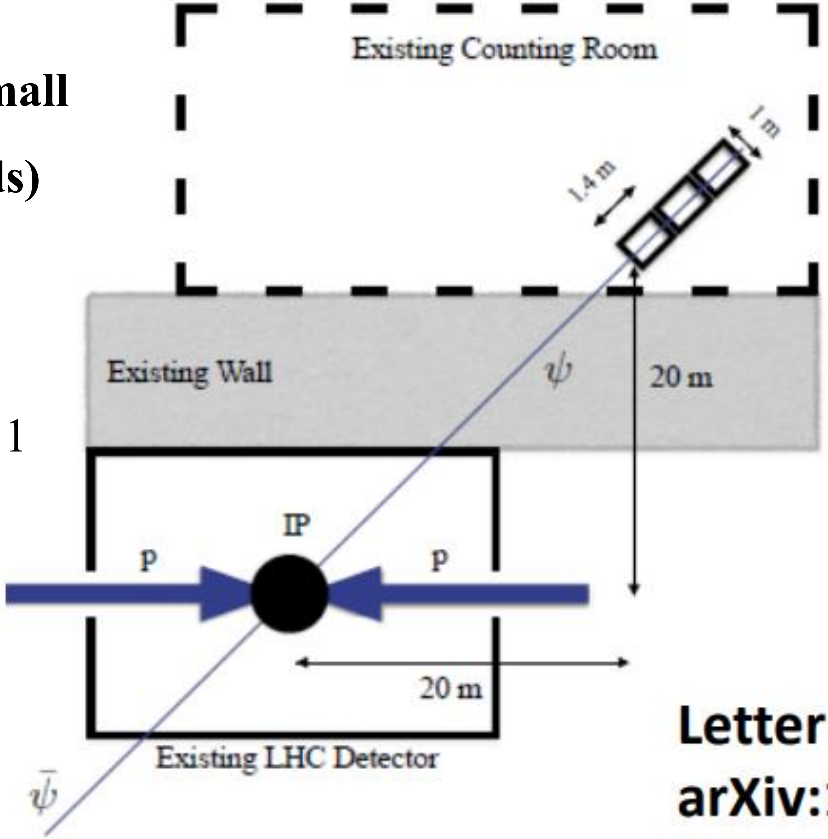
Austin Ball, Jim Brooke, Claudio Campagnari, Albert De Roeck, Brian Francis, Martin Gastal, Frank Golf, Joel Goldstein, **Andy Haas, Christopher S. Hill, Eder Izaguirre**, Benjamin Kaplan, Gabriel Magill, Bennett Marsh, David Miller, Theo Prins, Harry Shakeshaft, David Stuart, Max Swiatlowski, **Itay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

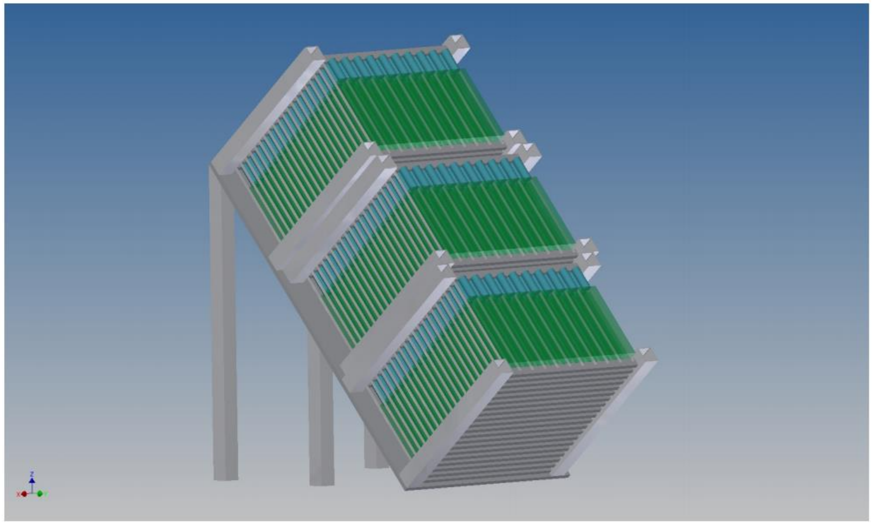
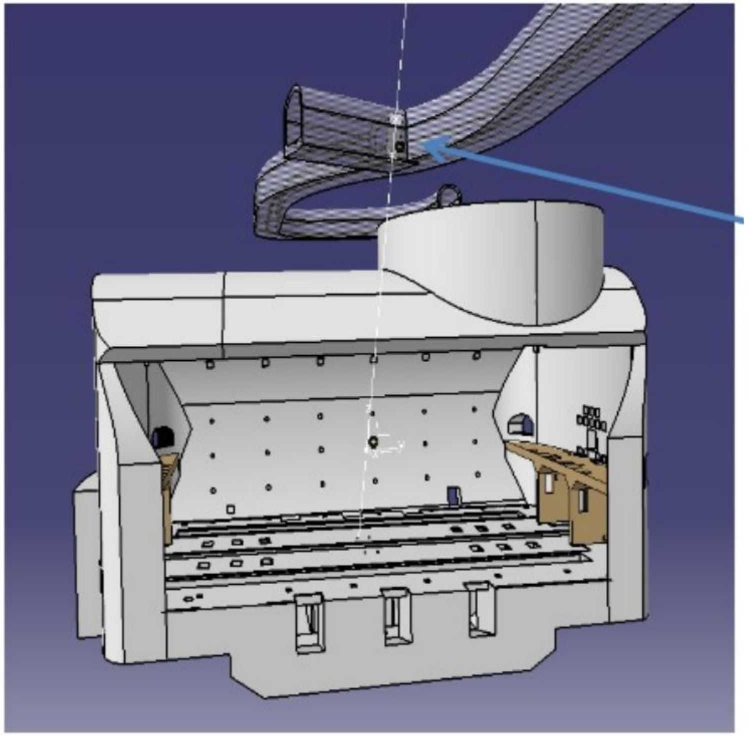


Figure from 1607.04669 (milliQan LOT)

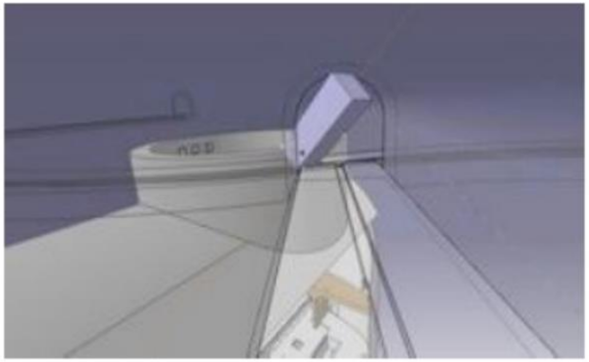
MilliQan: Location!

- 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

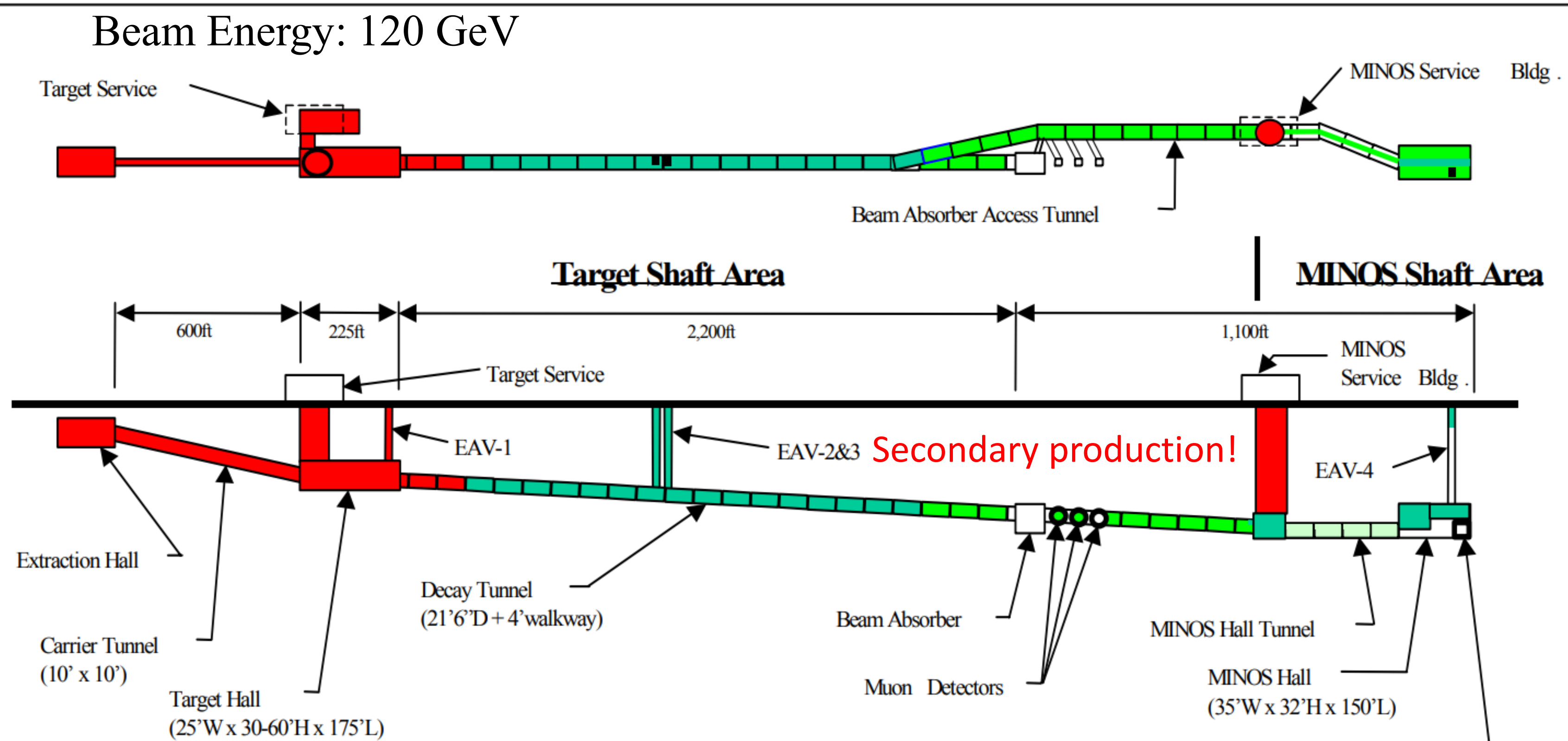
Andrew Haas, Fermilab (2017)

FerMINI:

A Fermilab Search for MINI-charged Particle

Kelly, **YT**, 1812.03998

Site 1: NuMI Beam & MINOS ND Hall

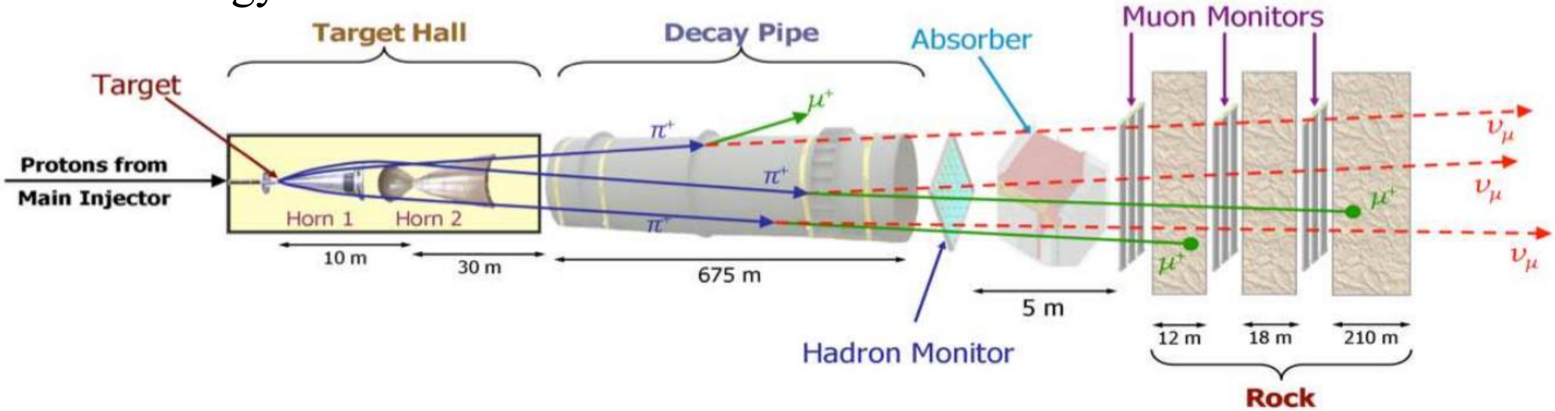


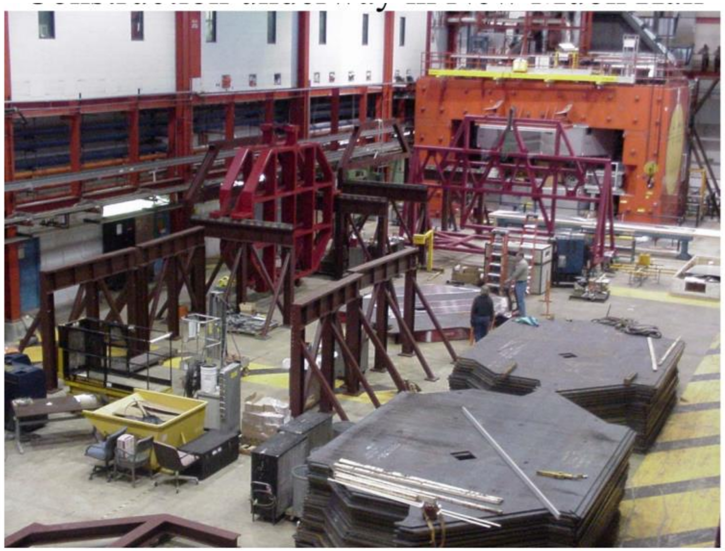
http://www.slac.stanford.edu/econf/C020121/overhead/S_Childr.pdf

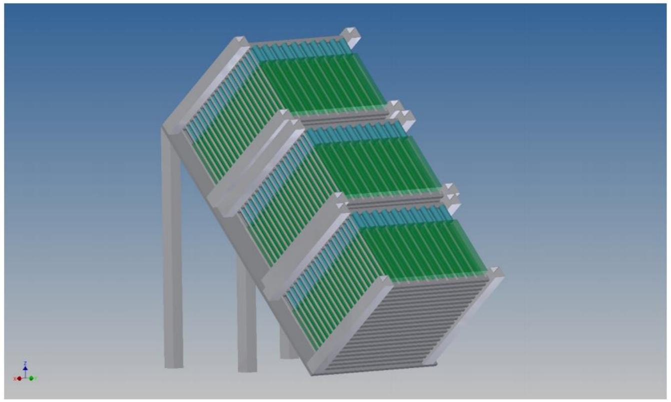
NuMI: Neutrinos at the Main Injector
MINOS: Main Injector Neutrino Oscillation Search
ND: Near Detector

FerMINI @ NuMI-MINOS Hall

Beam Energy: 120 GeV

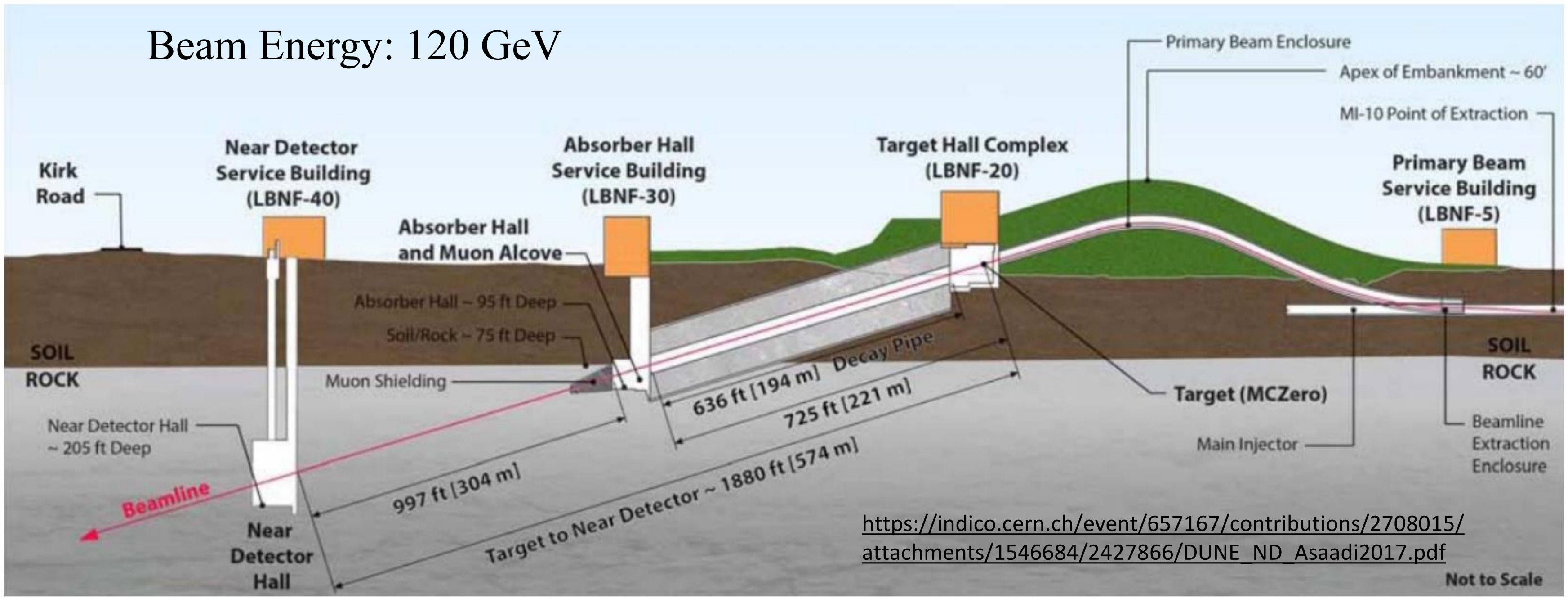






Site 2: LBNF Beam & DUNE ND Hall

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

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

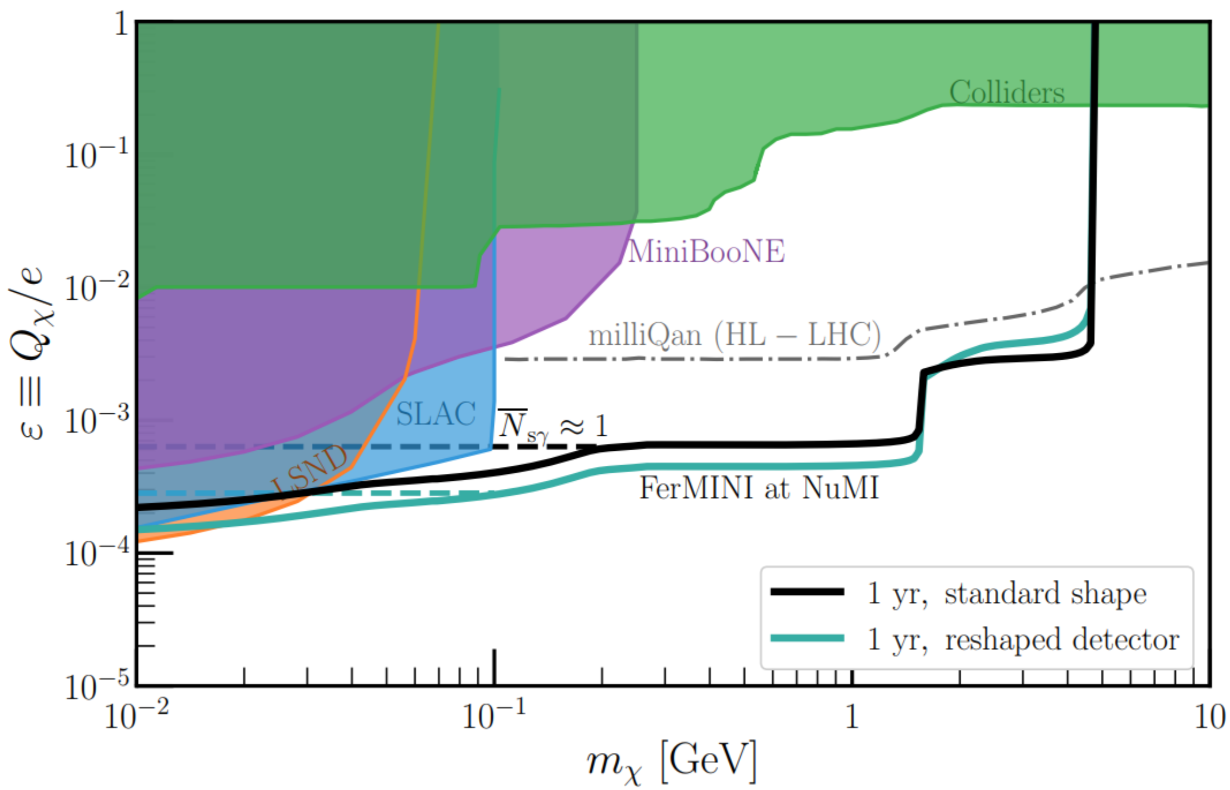
- We will discuss two major **detector backgrounds** and the **reduction technique**
- **SM charged particles from background radiation (e.g., cosmic muons):**
  - Offline veto of events with > 10 PEs
  - Offset middle detector
- **Dark current: triple coincidence**

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

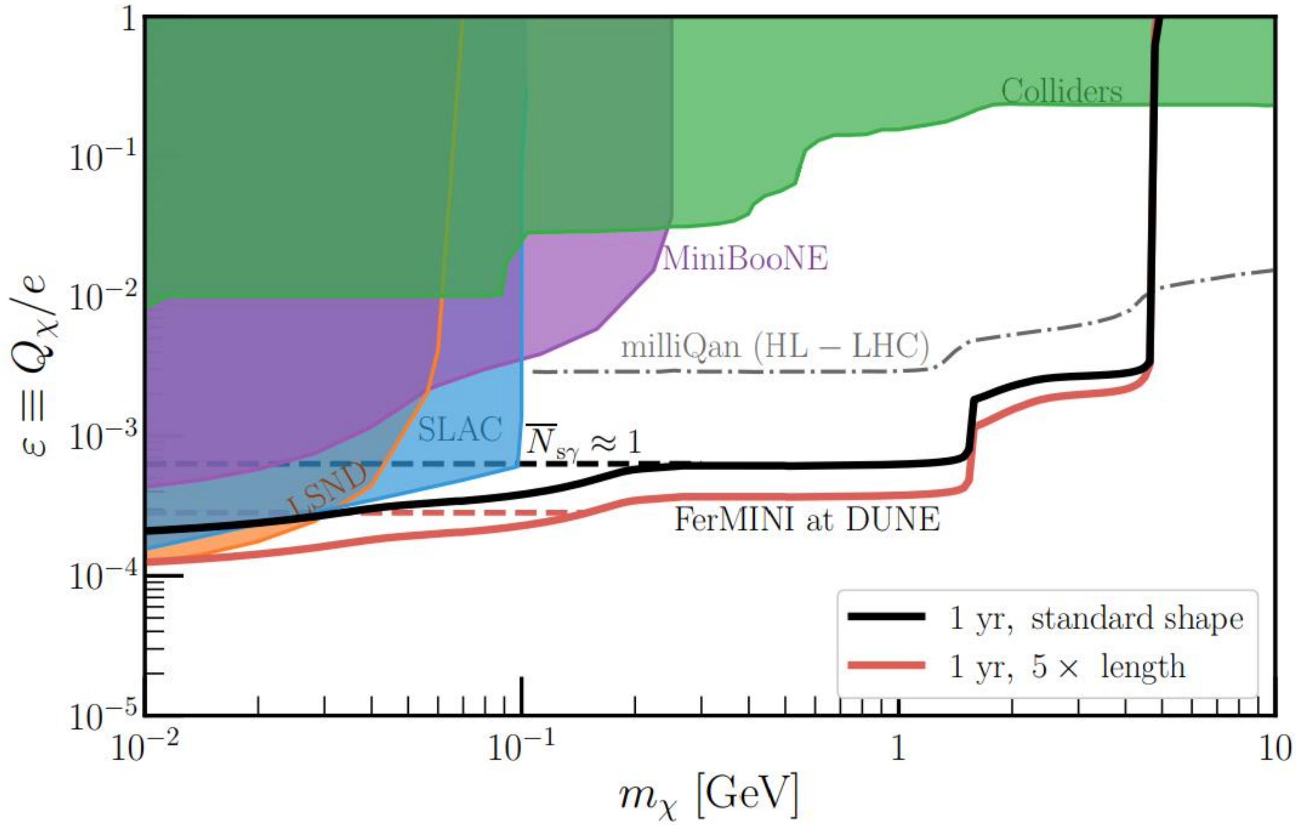
FerMINI @ MINOS



- Had meeting with **milliQan members**, got their support
- Recruting 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

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

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. 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 $\mathbf{10^{-5}}$
   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 Collaboration (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!

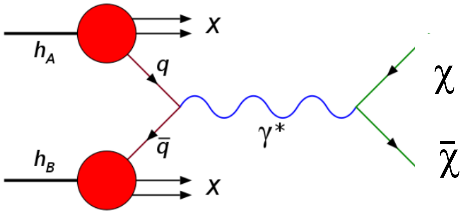
Thanks for the nice conference!

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, 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].]

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	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, see arXiv:1812.03998