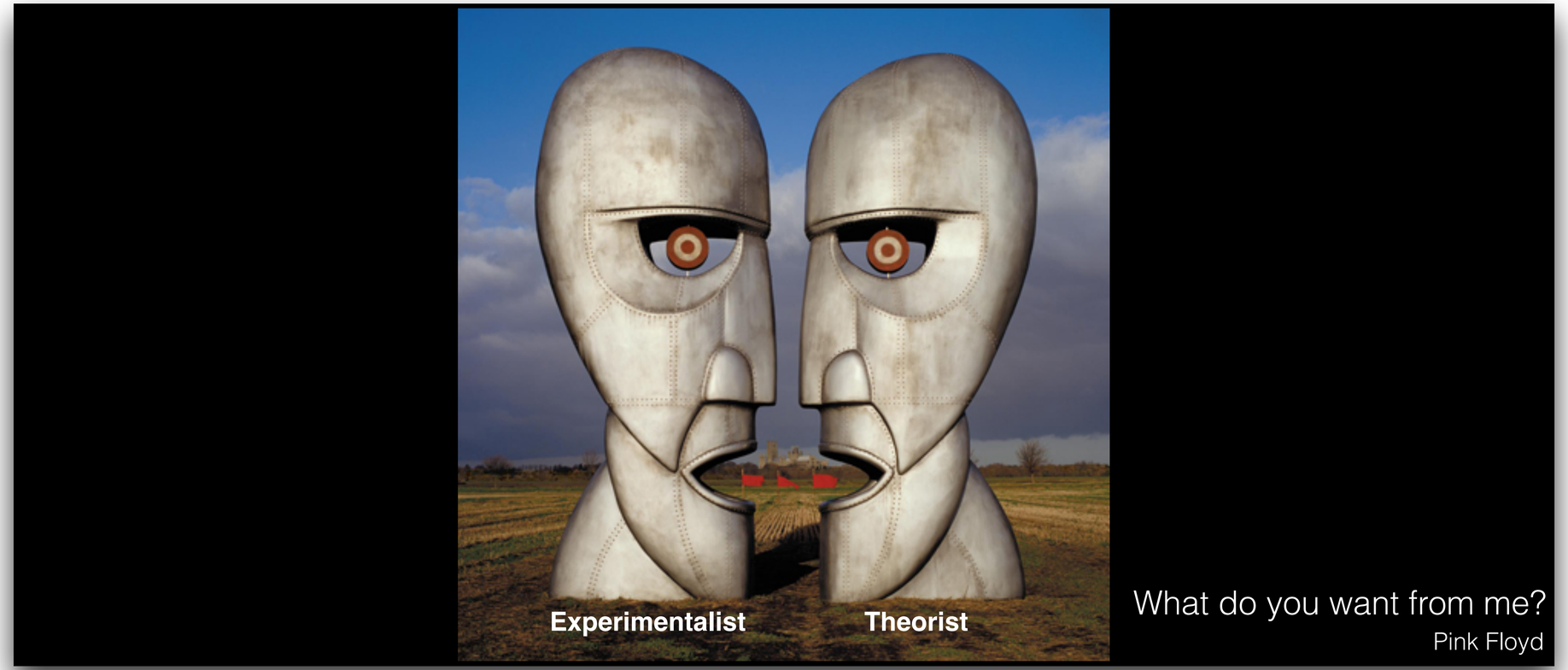


Experimental needs from theory: New Physics

Neutrino Theory Network Workshop
Fermilab
June 23rd 2022

Ornella Palamara
Fermilab & Yale University

Outline

Beyond the Standard Model Physics with Neutrinos.

A successful history of experiment-theory joint projects*.

Some examples, including physics from “empty” events…

Experimental needs from theory ⟷ Theory needs from experiments.

Many thanks to my amazing theorist colleagues who
made me a big fan of BSM Physics!

Disclaimer

* Examples are from personal experience! Focus on Short-Baseline LAr TPC detectors.
Apologies for not covering others.

What is BSM?

We know there **needs** to be physics beyond the standard model.

We have **no idea** of what and where that is.

In the search for new physics, we have many places to look.

A reach science program to explore the unknown!

For a given experiment, search in many diverse signal regions for new models.

Close collaboration between theory and experimental groups is critical!

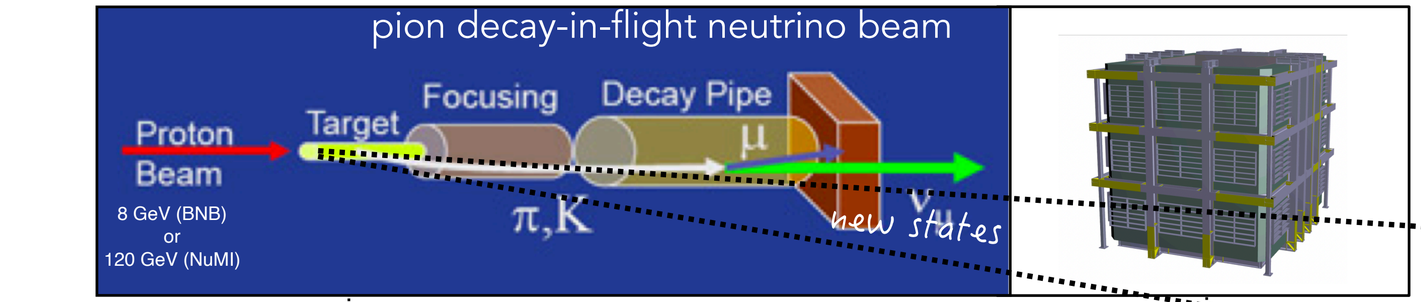
Where to study New Physics?

- New physics searches have been the domain of high-energy colliders (Large Hadron Collider (LHC) @ Cern, Tevatron @ FNAL) for decades.

- Increasing interest for similar/complementary opportunities to explored in neutrino experiments!
  - The BSM models accessible are specific to the neutrino source used.

As a case study, Short-Baseline **Liquid Argon Time Projection Chamber** (LArTPC) detectors on **accelerator neutrino beam** at Fermilab are considered.

Why BSM in SBL LAr TPC Neutrino Experiments?



BSM states can be produced.
Complementary to colliders.

The combination of

- **High-intensity proton beams (high intensity neutrino beams)** coupled with
- **Large mass LAr TPC detectors** close to the beam target, with
  - Event imaging
  - Fine granularity calorimetry and particle identification
  - Good timing resolution
  - Low energy threshold

opens up unprecedented opportunities to probe signatures for

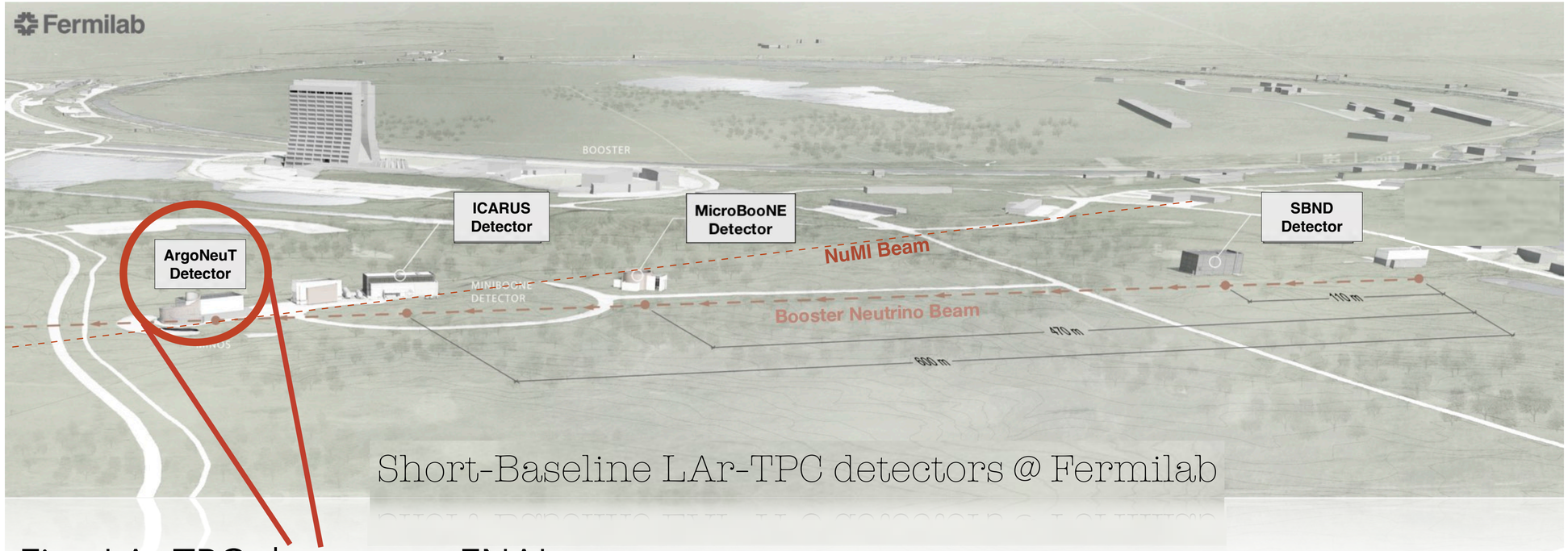
New Physics scenarios in the neutrino sector and beyond

Several targets of opportunity to complement the neutrino program.

Modifications to the neutrino oscillation paradigm
(effects of BSM physics on neutrino oscillation)

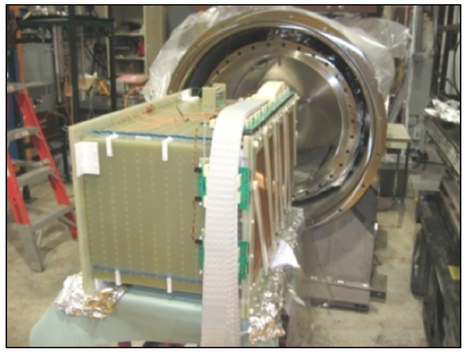
Novel experimental signatures
produced in the beam target

Short-Baseline LAr TPC detectors at Fermilab: ArgoNeuT

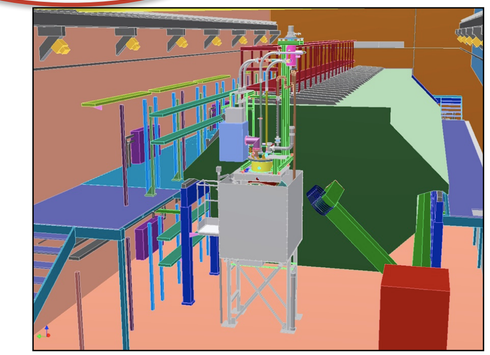


First LAr TPC detector at FNAL

5 months data taking in 2009-2010 !!!

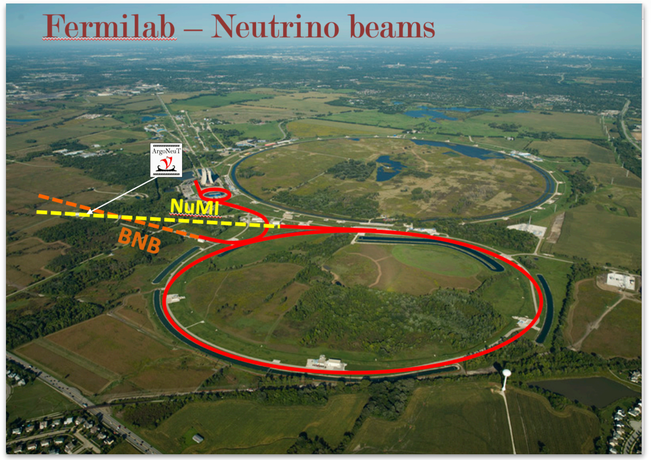


0.24 tons active volume LAr TPC

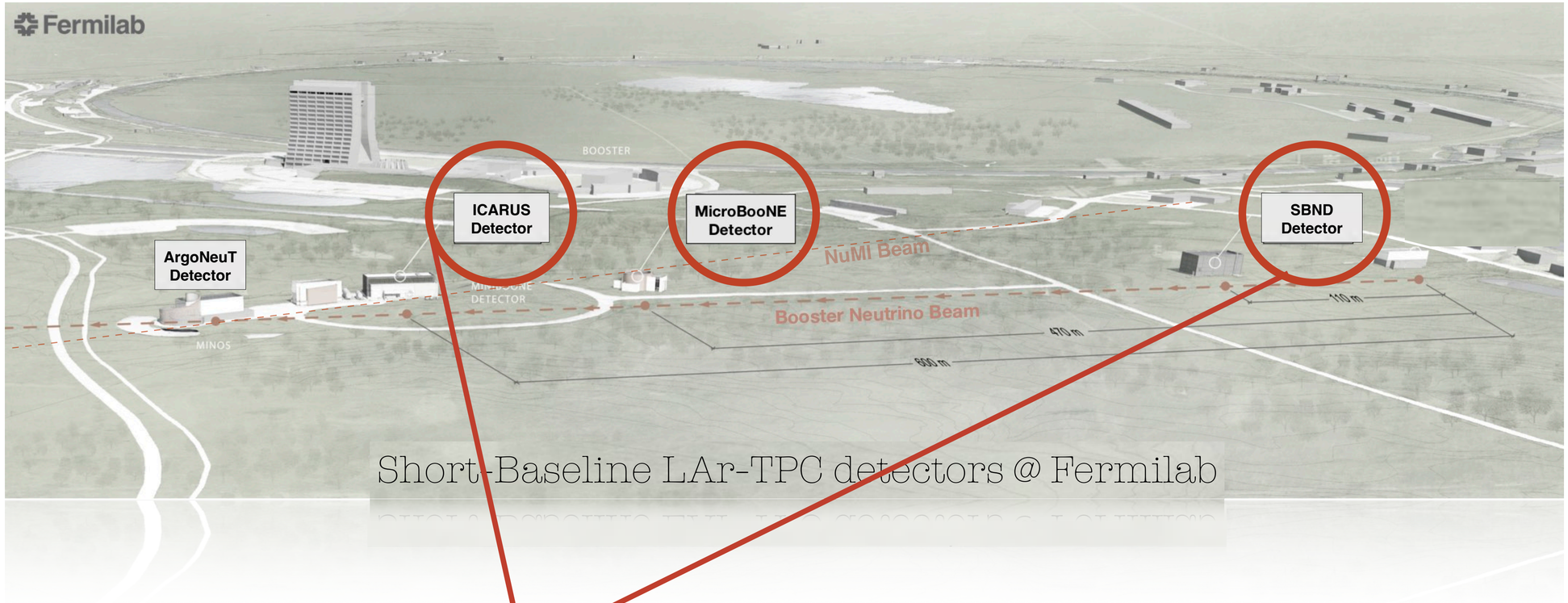


100 m underground, in front of the MINOS ND, ~ 1km from target

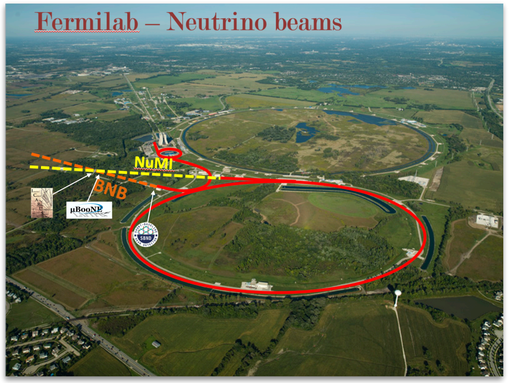
On-axis on NuMI <E_ν>≃4 GeV



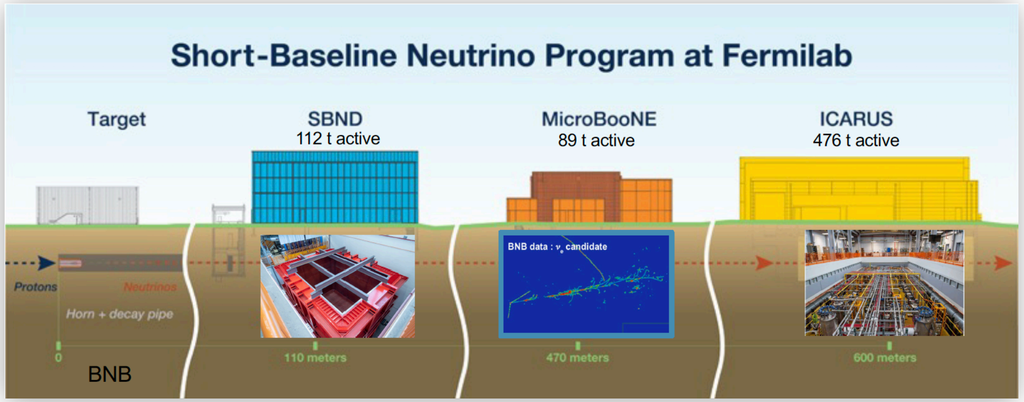
Short-Baseline LAr TPC detectors at Fermilab: SBN detectors



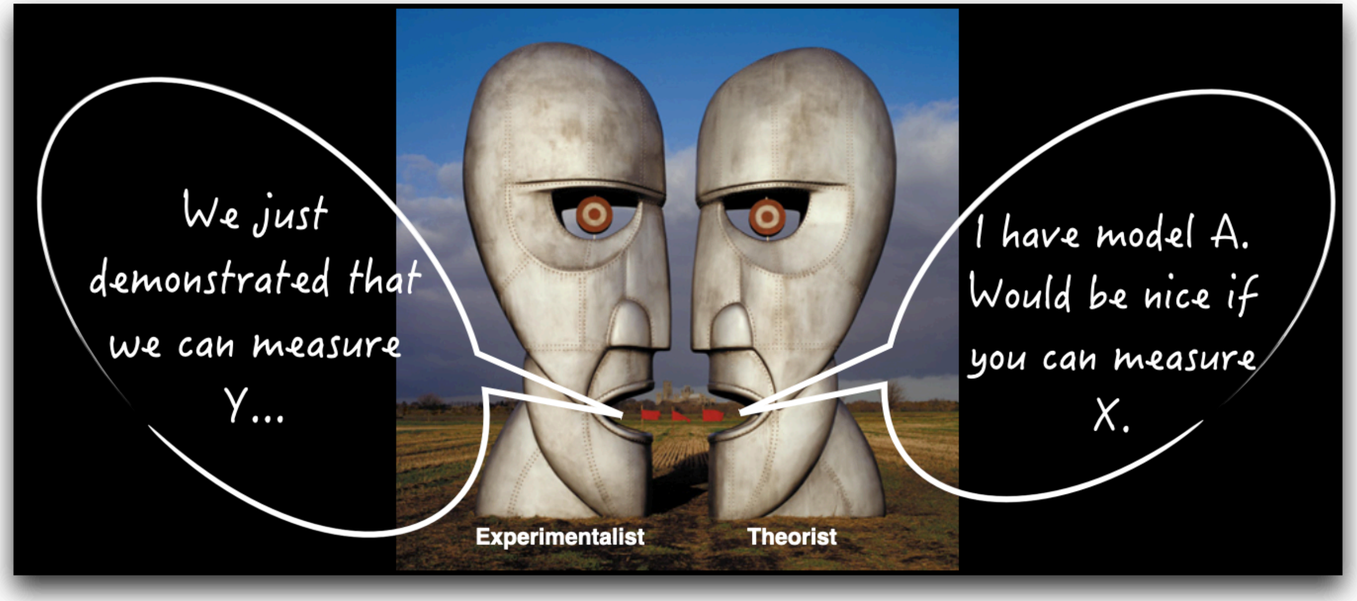
Two other detectors to form the Short-Baseline (SBN) program.



On-axis on BNB (<E_ν>≃4 GeV) and off-axis on NuMI (MicroBooNE, ICARUS)



A bridge between theory and neutrino experimental program



Fermilab is an ideal place to develop this program

Some informal discussion between neutrino experimentalists and theorists turned into the **SBN-Theory working group**, organized by P. Machado (started in 2018 - a joint experiment+theory effort).

Goal: to exploit possibilities to enrich the physics program of LAr TPC neutrino experiments with New Physics scenarios.

Direct, regular and continued collaboration turned in several **successful projects** [a few examples in the following slides]!

SBN-Theory working group meetings

Informal meetings (slides+backboard!!)

Discuss experimental capabilities of LAr TPC detectors, current status of event reconstruction, thresholds and resolution.

Discuss models for New Physics to be studied in LAr TPC neutrino experiments.

Theorists to better know how the LAr TPC technology works and experimentalists to better know what to look for.

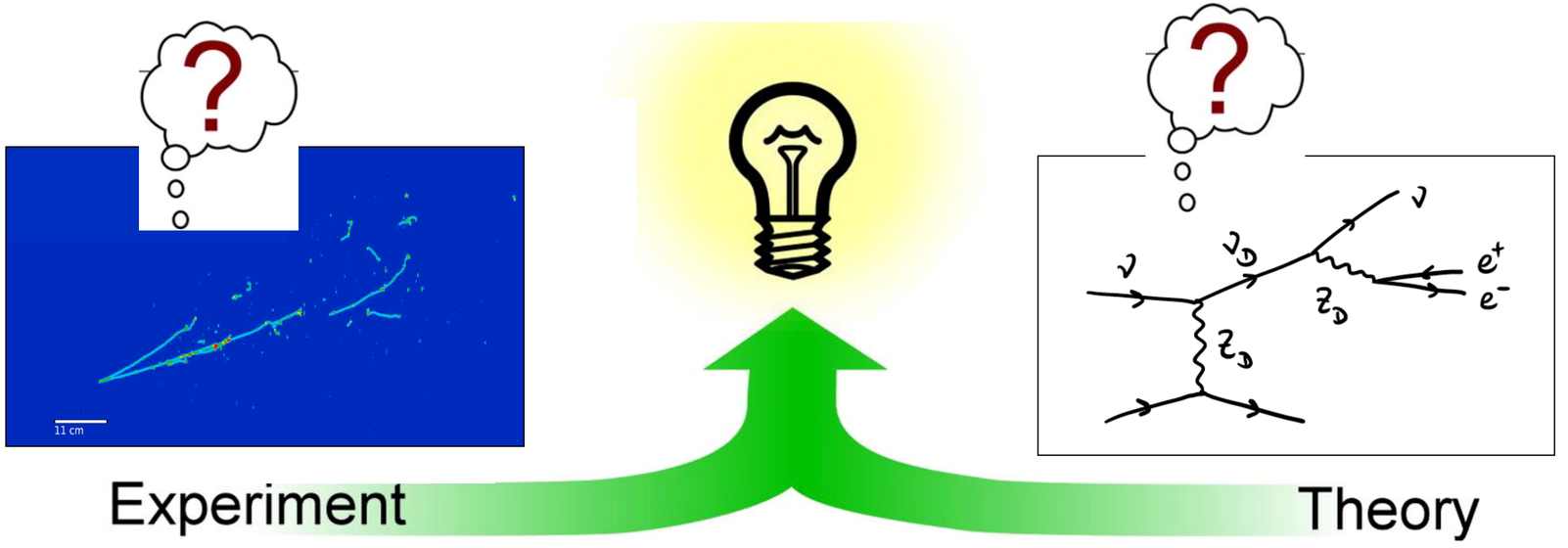
Work **side-by-side** on various projects, understanding signal and background.

Organizer: Pedro Machado

87 people in the SBN-TH mailing list

30+ participants in each meeting.

Clearly a lot of interest in the community!

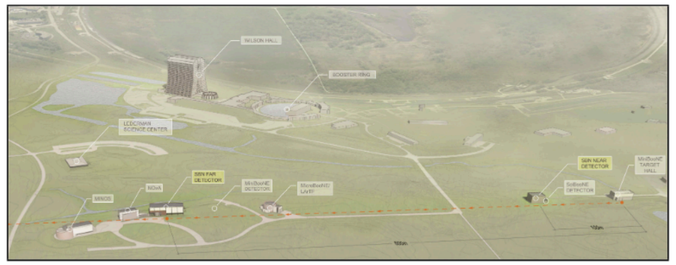


SBN program: not only oscillation physics!

The Short-Baseline Neutrino program proposal (**2014**) only mentioned about another possible search for "New Physics":

"SBN will also be able to search for sub-GeV dark matter *(mass less than a few hundred MeV) by* running in beam-dump mode*, where the 8 GeV proton beam is steered above the beryllium target and into the 50 m (or 25 m) downstream absorber.*

A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam



The ICARUS, SBND and MicroBooNE collaborations
arXiv:1503.01520, January 2014

Designed for **Sterile Neutrino** searches
Same neutrino beam, nuclear target and detector technology: reducing systematic uncertainties to the % level

It is an evolving landscape!

Alternative potential explanations to the SBL neutrino anomalies from more recently emerging new physics scenarios from theory.

Joint experiment+theory effort evolved into a review paper (**2019**), where a range of ideas [now under active development] for using the SBN detectors and beam to search for signatures of **New Physics** are discussed!

ANNUAL REVIEWS

Annual Review of Nuclear and Particle Science

The Short-Baseline Neutrino Program at Fermilab

Pedro A.N. Machado,[1] Ornella Palamara,[1] and David W. Schmitz[2]

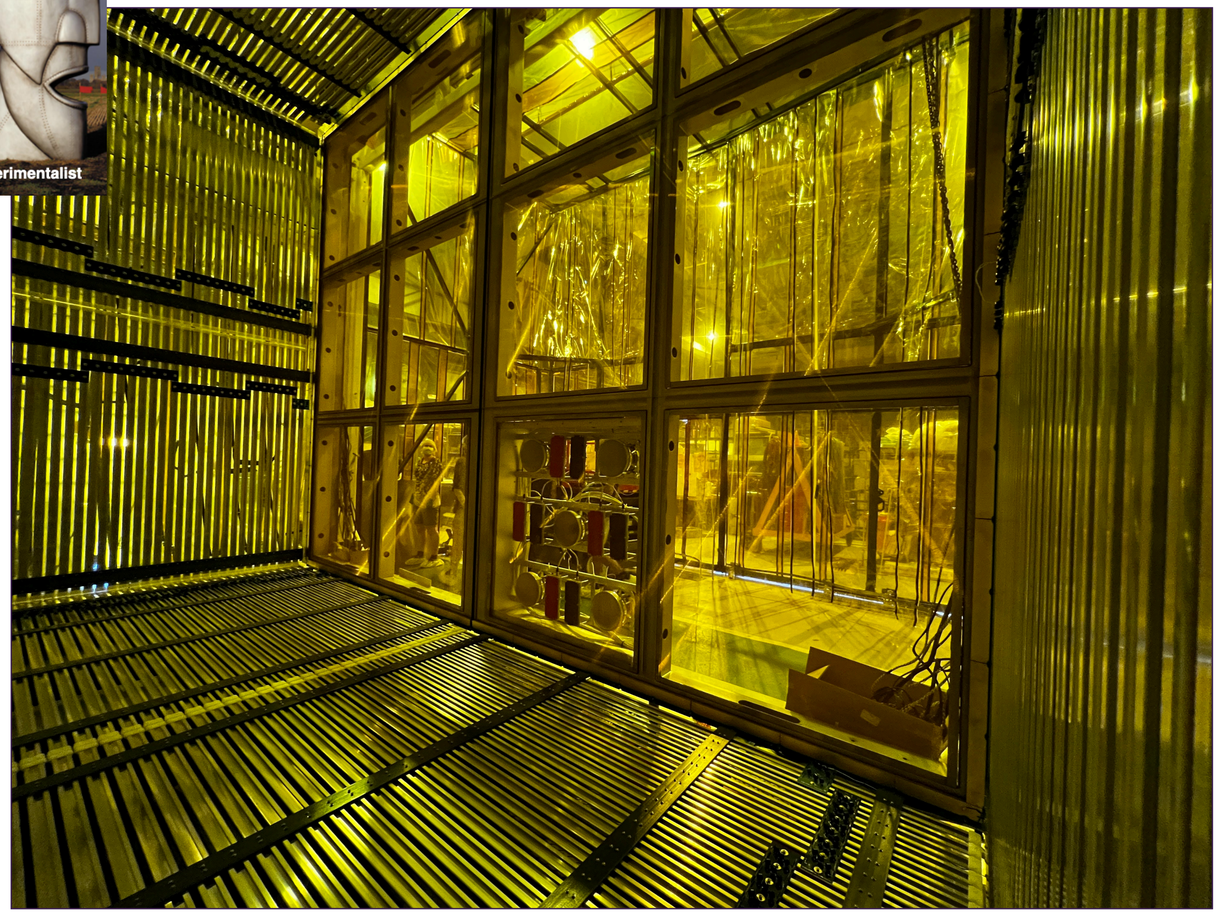
[1]Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

[2]Enrico Fermi Institute and Department of Physics, University of Chicago, Chicago, Illinois 60637, USA; email: dwschmitz@uchicago.edu

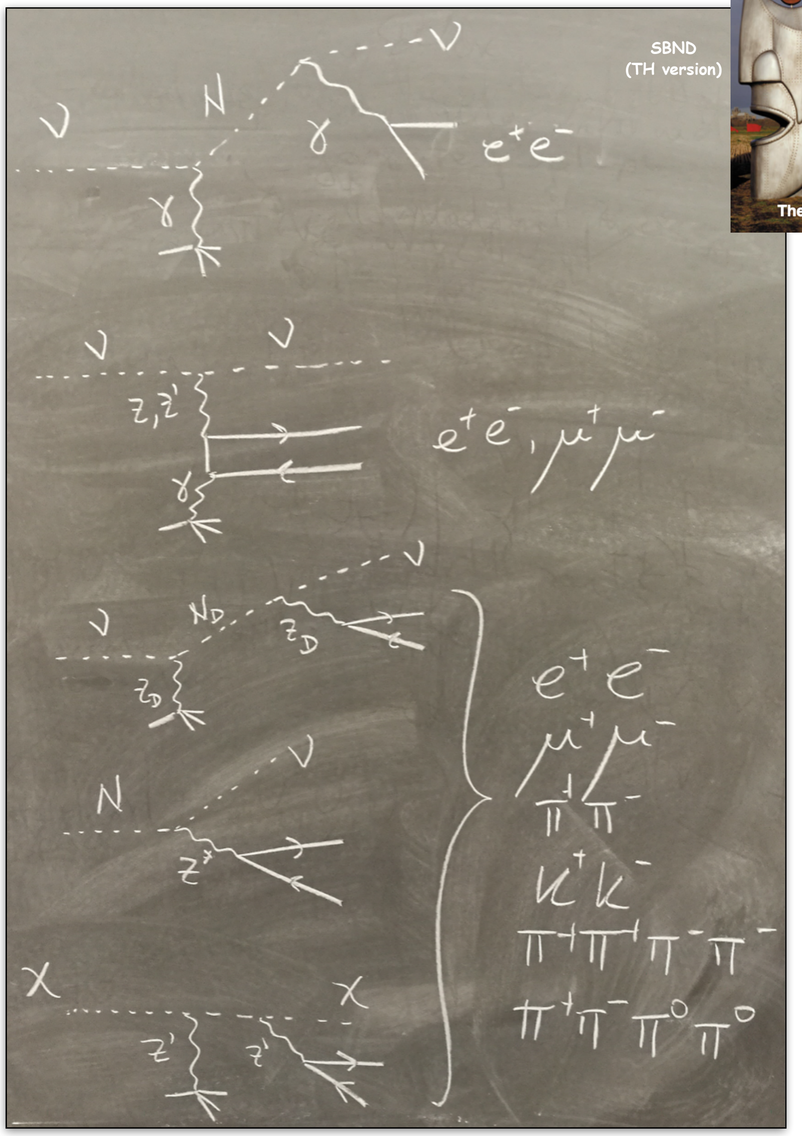
Annu. Rev. Nucl. Part. Sci. 69 363-387 (2019)

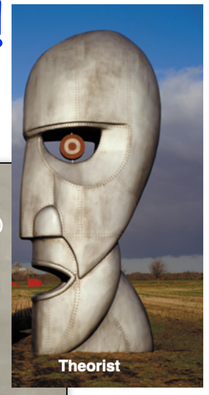
Joint Experiment+Theory: Same perspective from two different angles!

SBND TPC complete last week and
Photon Detection System installation in progress



SBND Theory version

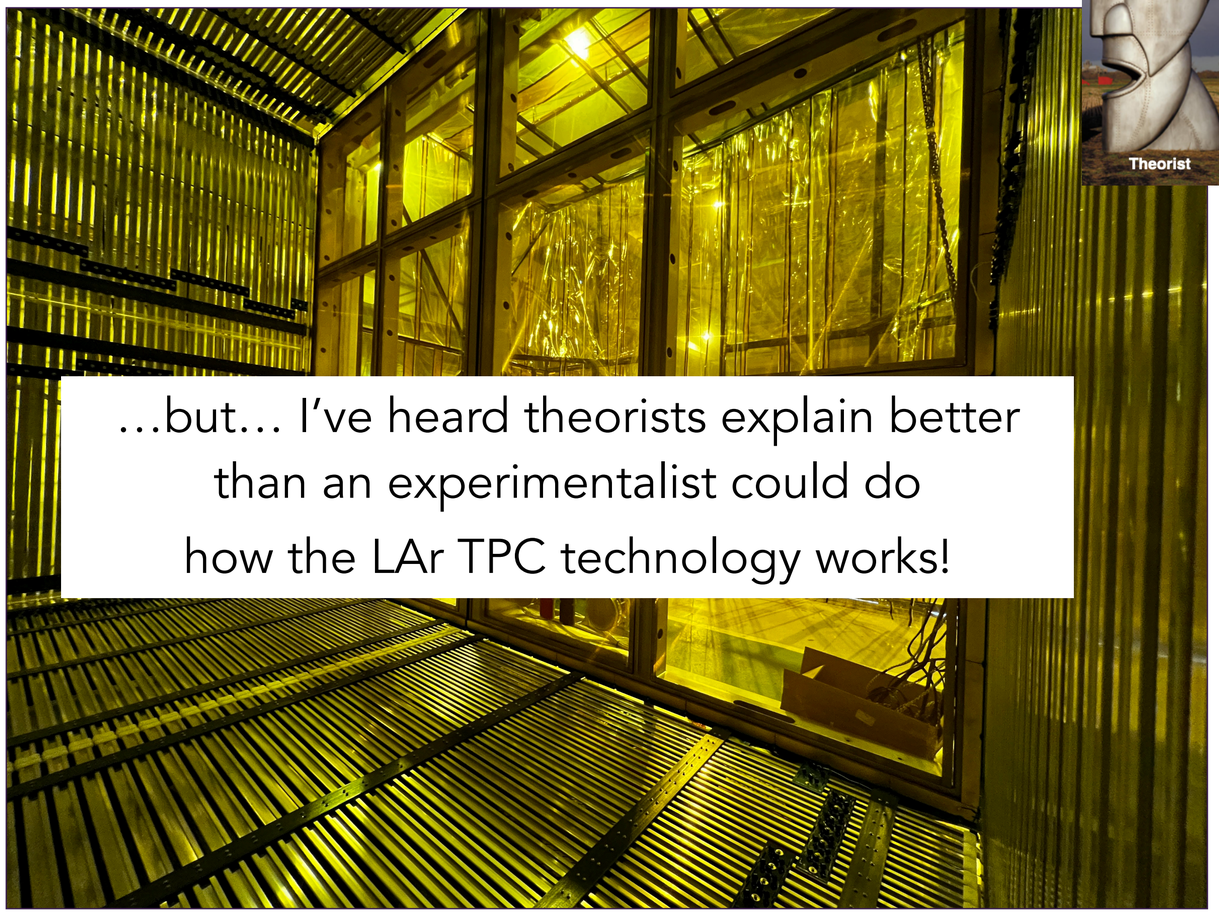




Courtesy of P. Machado, from one of the SBN-Theory WG meetings

Joint Experiment+Theory: Same perspective from two different angles

SBND TPC complete last week and
Photon Detection System installation in progress



…but… I've heard theorists explain better than an experimentalist could do how the LAr TPC technology works!

…and theorist can help us building our detectors!
SBND 2nd APA installation day, Pedro was with us!

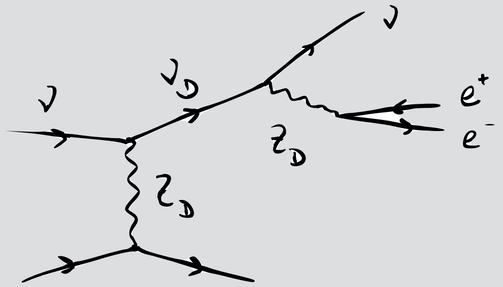
Joint Experiment+Theory projects: BSM searches

Alternative explanations to the MiniBooNE excess and other BSM scenarios

Not an exhaustive list

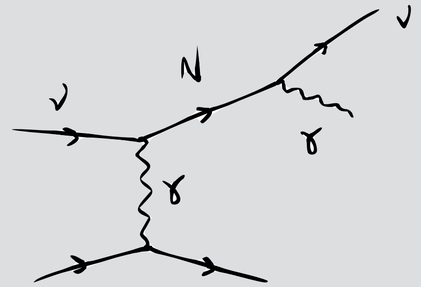
Some diagram credit: Pedro Machado

Dark Neutrinos



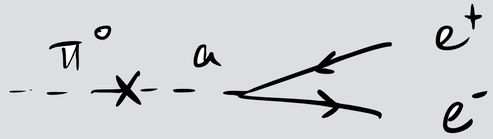
Bertuzzo Jana Machado Zukanovich PRL 2018, PLB 2019
Arguelles Hostert Tsai PRL 2019
Ballett Pascoli Ross-Lonergan PRD 2019
Ballett Hostert Pascoli PRD 2020

Transition Magnetic Moment



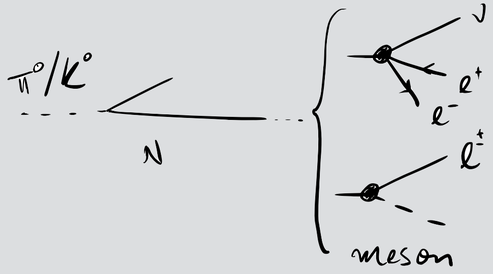
Gninenko PRL 2009
Coloma Machado Soler Shoemaker PRL 2017
Atkinson et al 2021 Vergani et al 2021

Axion-like Particles



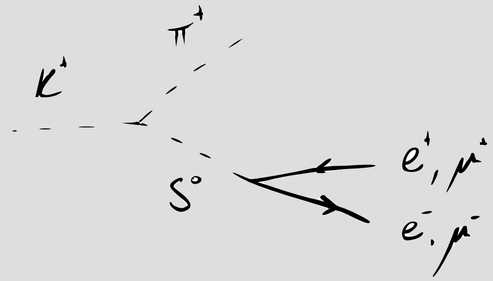
Kelly Kumar Liu PRD 2021
Brdar et al PRL 2021

Heavy Neutral Leptons



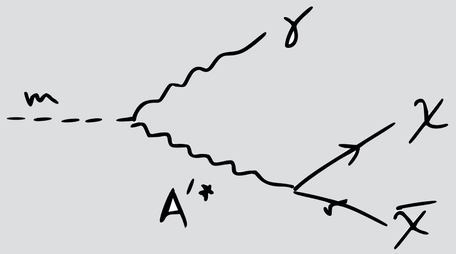
Ballett Pascoli Ross-Lonergan JHEP 2017
Kelly Machado PRD 2021

Higgs Portal Scalar



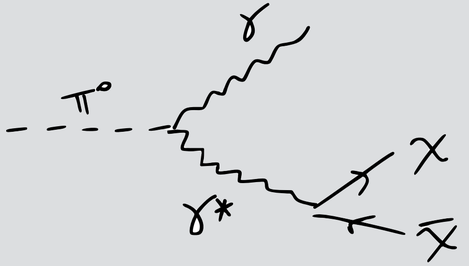
Pat Wilczek 2006
Batell Berger Ismail PRD 2019
MicroBooNE 2021

Light Dark Matter



Romeri Kelley Machado PRD 2019

Millicharged Particles



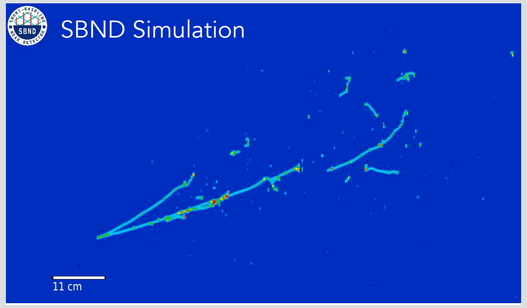
Magill, Plestid, Pospelov, Tsai, PRL 2019
Harnik Liu Palamara, JHEP 2019

Joint Experiment+Theory projects: BSM searches in SBND

Alternative explanations to the MiniBooNE excess and other BSM scenarios

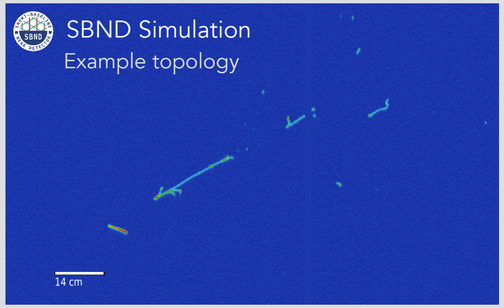
Not an exhaustive list

Dark Neutrinos



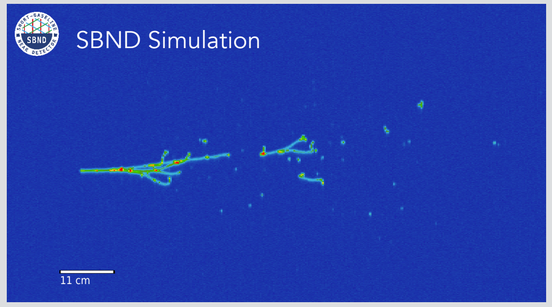
e+e- pair w/ or w/o hadronic activity

Transition Magnetic Moment



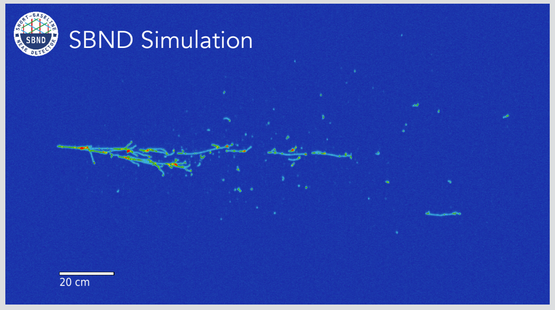
photon shower and hadronic activity

Axion-like Particles



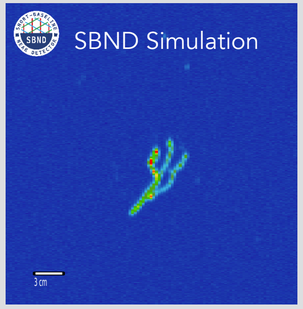
high-energy e^+e^-, $\mu^+\mu^-$

Heavy Neutral Leptons



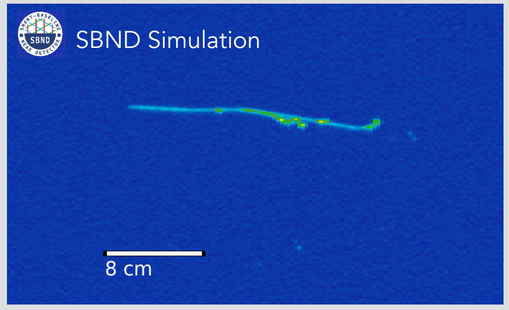
e^+e^-, $\mu^+\mu^-$, $\mu\pi$

Higgs Portal Scalar



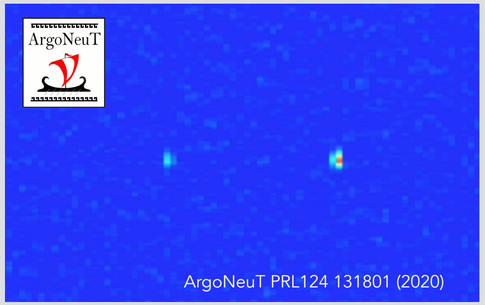
e^+e^-, $\mu^+\mu^-$, no hadronic activity

Light Dark Matter



electron scattering

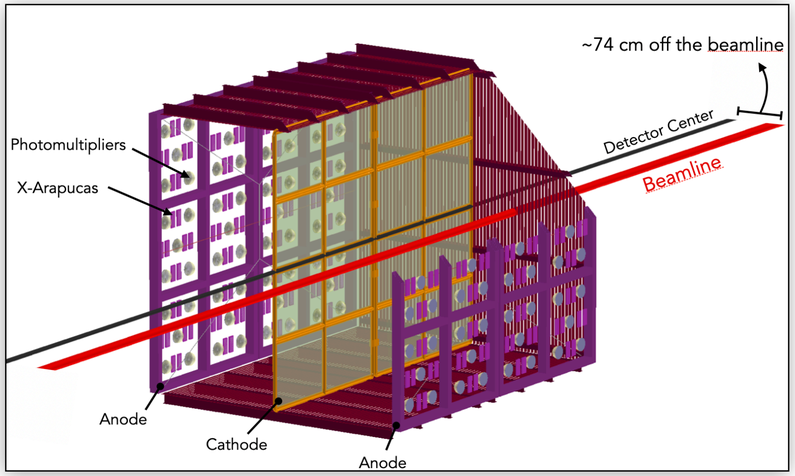
Millicharged Particles

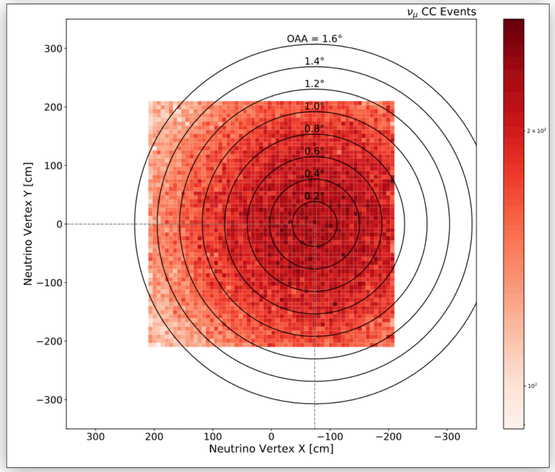


blips/faint tracks

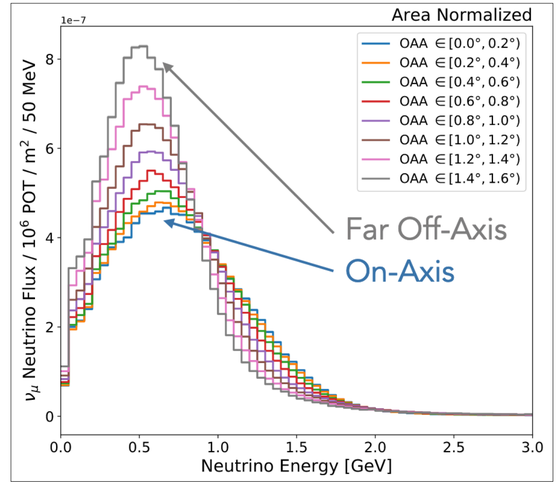
Joint Experiment+Theory projects: SBND-PRISM

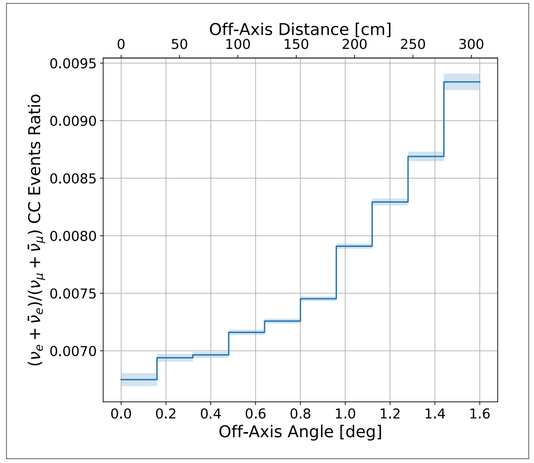
A Slightly Off-Axis Detector close to the neutrino source.
Sampling Multiple Off-Axis Fluxes with the Same Detector.



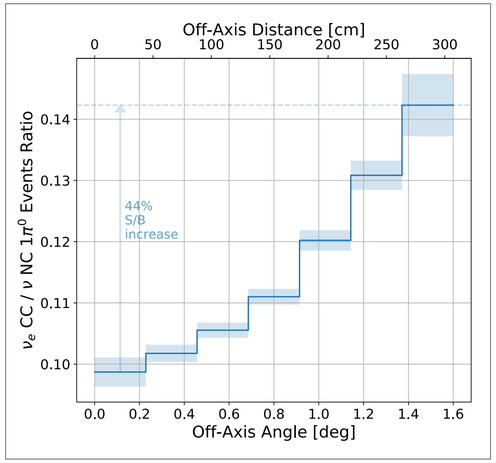


ν_μ flux





ν_e to ν_μ ratio changes moving off-axis



NC π^0 decreases moving off-axis

Exploring physics potentials of SBND-PRISM

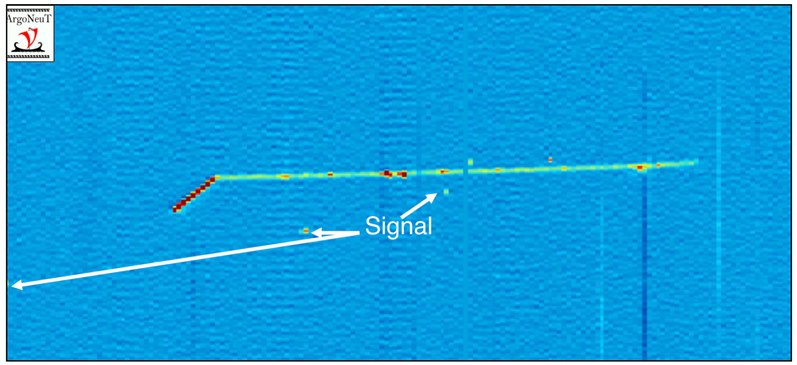
- Further constrain neutrino interactions in oscillation physics→enhance sensitivity to sterile neutrino oscillation.
- Perform targeted neutrino interaction measurements.
- Background reduction moving off-axis.
- Improve sensitivity to probe BSM.

Collaboration with
K. Kelly,
R. Harnik and
P. Machado.

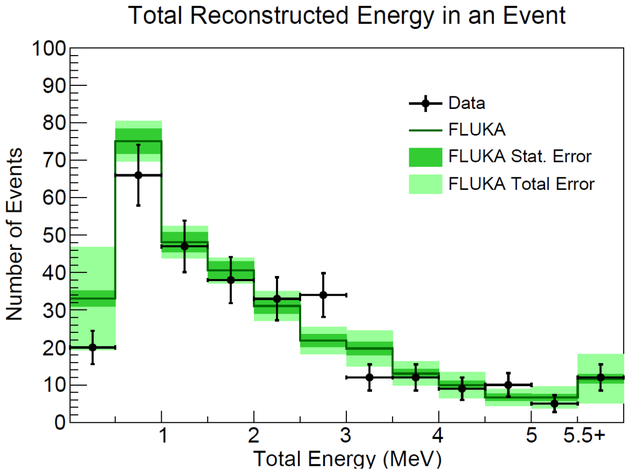
Joint Experiment+Theory projects: search for Millicharged Particles

Motivated by the fact that LAr TPC's have demonstrated to be able to detect and reconstruct

(sub-)MeV energy depositions



300 KeV threshold
In ArgoNeuT



R. Acciarri et al., PRD 99, 012002 (2019)

Topologically separated low-energy depositions are identified as electrons produced by Compton scattering of

- de-excitation photons from the target nucleus and
- photon produced by neutron inelastic interactions

We started a common project, which evolved into two papers:

Theory paper

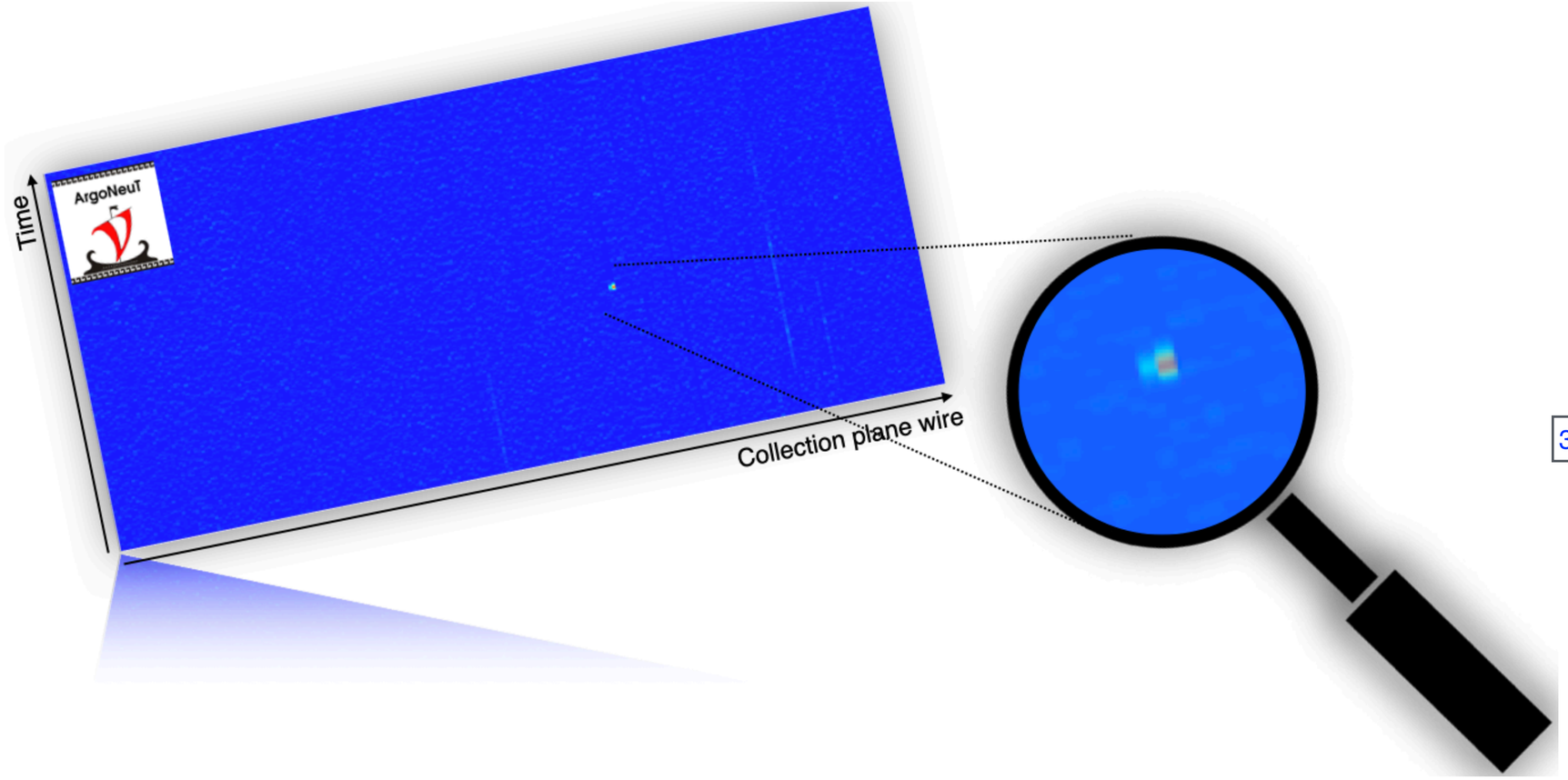
*Roni Harnik, Zhen Liu, and O. P., "**Millicharged particles** in liquid argon neutrino experiments", JHEP 07, 170 (2019)*

ArgoNeuT Collaboration + 2 theorists (R. Harnik and Z. Liu)
R. Acciarri et al., PRL124 131801 (2020)

Experimental paper

Joint Experiment+Theory projects: using "empty" events !

The vast majority of NuMI beam spills delivered did not produce a neutrino interaction within the TPC (due to the limited size of the detector)



5 months of data (2009-2010)
0.24 t LAr TPC detector

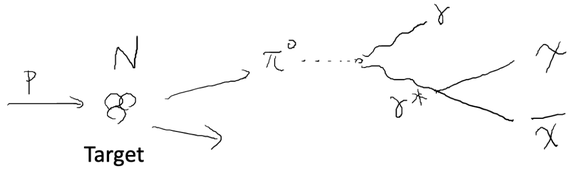
3,259,427 events in 1.0 · 10^{20} protons on target (POT)

~88% have 0 clusters, ~2% have 2 clusters

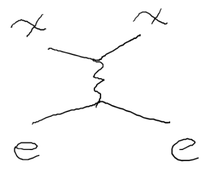
We searched for the possible presence of mCPs in these empty events

Joint Experiment+Theory projects: First search for Millicharged Particles in LAr TPC

mCP have an electric charge $Q=\epsilon \cdot e$ ($\epsilon \ll 1$)

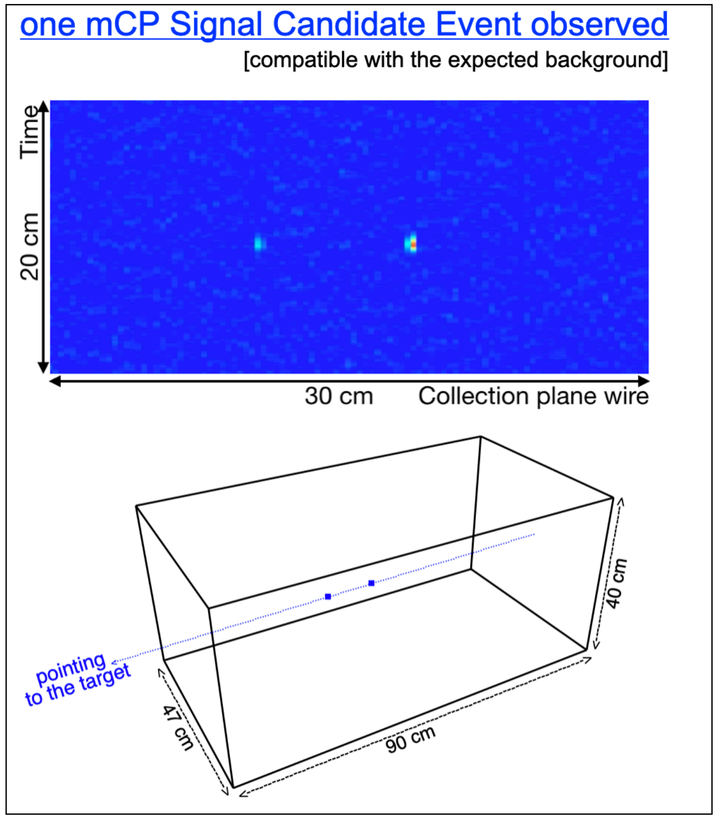


❑ production: meson decays



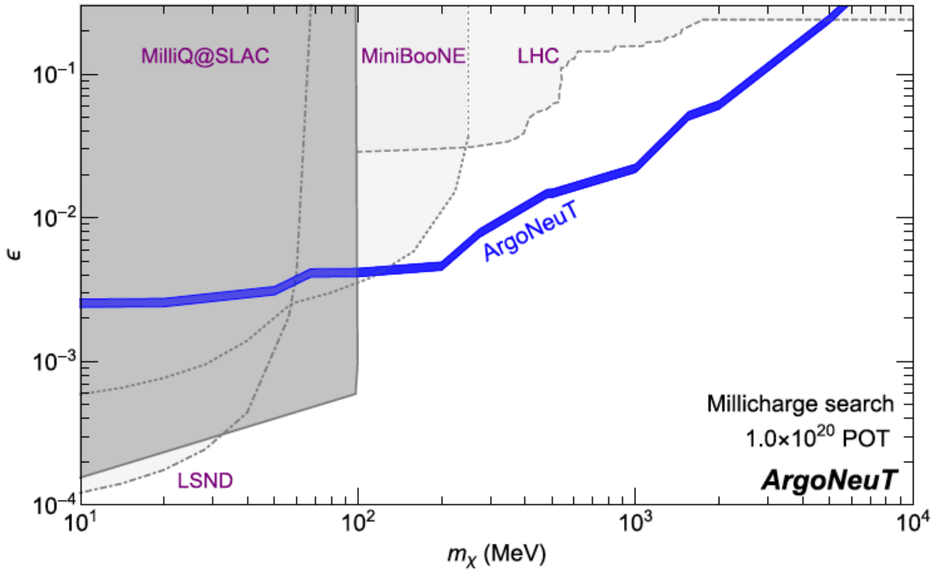
❑ detection: scattering electron

Low energy threshold (300 KeV) is the key!



ArgoNeuT Collaboration + 2 theorists (R. Harnik and Z. Liu)

R. Acciarri et al., PRL124 131801 (2020)



Leading constraints in unexplored parameter region!

Experiment+Theory wine & cheese

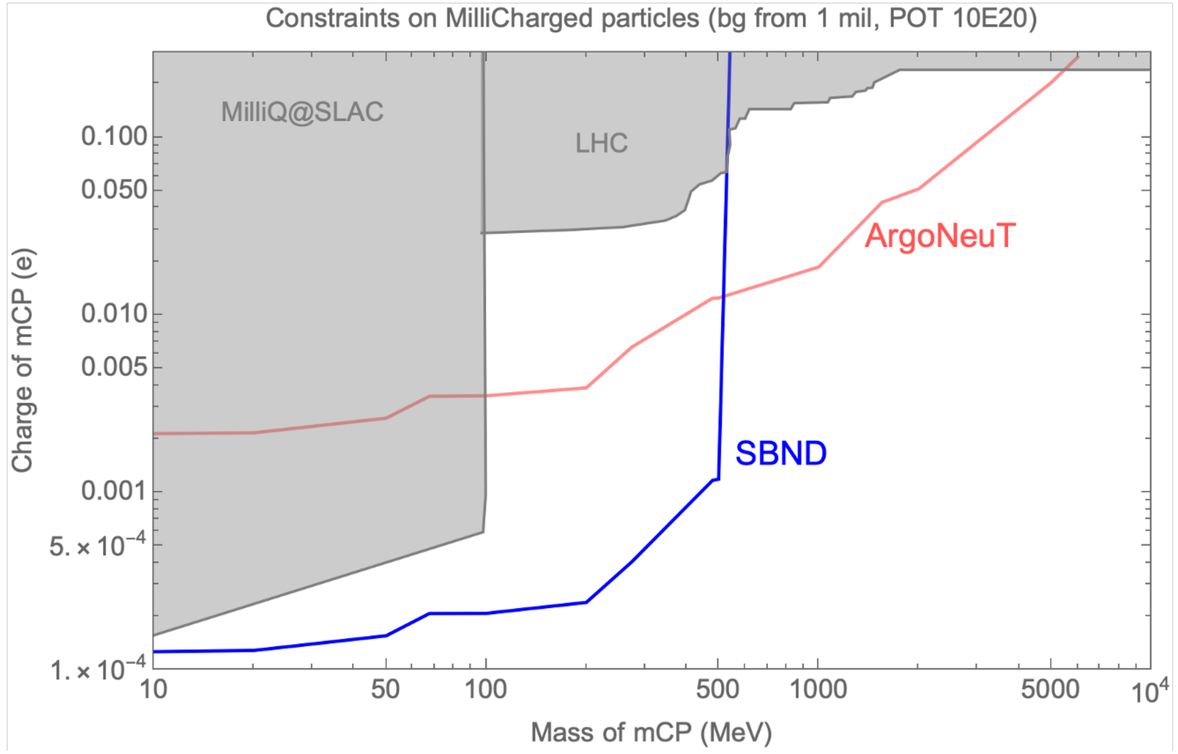
Joint Experiment+Theory projects: First search for Millicharged Particles in LAr TPC

mCP have an electric charge $Q=\epsilon \cdot e$ ($\epsilon \ll 1$)

- production: meson decays

Low energy threshold (300 KeV) is the key!

Work in progress: SBND exclusion limits



Preliminary results from simulation

d Z. Liu), R. Acciarri et al., PRL124 131801 (2020)

s in unexplored parameter region!

Joint Experiment+Theory projects: First search for Heavy Neutral Leptons N $\rightarrow \nu\mu^+\mu^-$ in LAr TPC

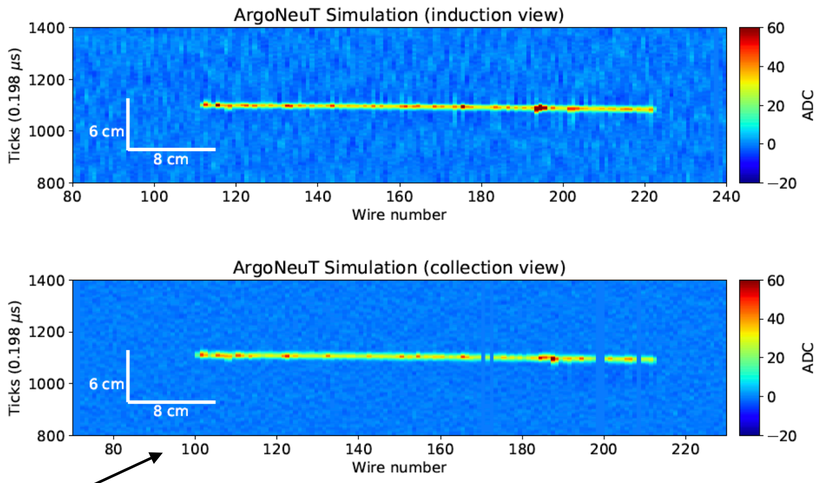
Assuming HNL production predominately from $\tau^\pm$ decay:

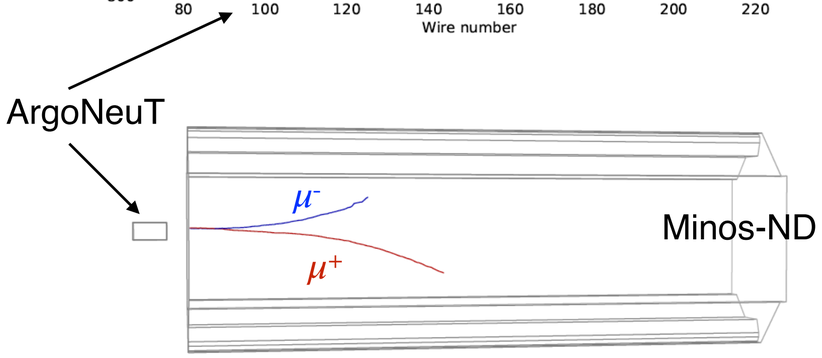
D/D_s decay to τ, that subsequently decay to HNLs

$\tau^\pm \rightarrow N\, X^\pm$ ($X^\pm$ is a SM particle e.g. $\pi^\pm$)

HNL decay (MC)

$N \rightarrow \nu\mu^+\mu^-$

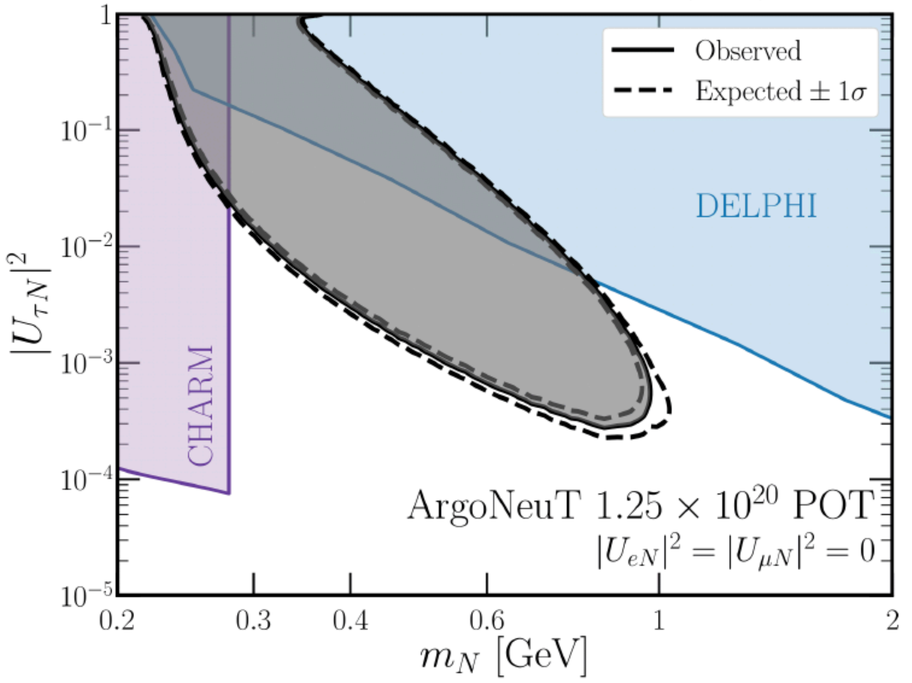




0 events observed in the data

ArgoNeuT Collaboration + 2 theorists (K. Kelly and A. de Gouvêa)

R. Acciarri et al., PRL 127 121801 (2021)



Significant increase in the parameter space exclusion region!

Experiment+Theory wine & cheese

Joint Experiment+Theory projects: First search for ? in LAr TPC

…Coming very soon to arXiv.

Stay tuned!

SBN-Theory mini-workshop

Given the recent exciting developments in Fermilab's SBN Program, we are organizing the special SBN-Theory mini-workshop "**Physics opportunities at the Short Baseline Neutrino Program**" on **December 13-15, 2021**.

The goal of the workshop is to foster collaborations among theorists and experimentalists to discuss future searches in the SBN Program, particularly in the context of the MiniBooNE anomaly, though not limited to it.

As in other SBN-Theory events, this mini-workshop will be informal, focused on the physics and the intersection between theory and experiment.

Organizers: Pedro Machado, Mark Ross-Lonergan, Minerba Betancourt & Andrzej Szelc

Three half-days. Plenty of time for discussions.

Despite the short notice, 100+ person attendance.

Clearly a lot of interest in the community!

- Day 1: Theory - MiniBooNE anomaly and alternative models for the MiniBooNE LEE & discussion session.
- Day 2: Experiment - EM shower and proton reconstruction & discussion session.
- Day 3: Lessons Learned from BSM searches in LAr TPCs and tools/ generators for BSM searches & discussion session.

SBN-Theory mini-workshop

Lively discussions, one of them centered around this table:

The theorist "score-card"

Model	U. Signature	LSND	MB	Reactors	Cosmology	Issues	Score
3+1	Oscillations					Appearance-disappearance tension.	6
(3+1) + inv-ν decay	Damped oscillations					Large couplings. UV model?	4
(3+1) + NSI	Modified matter effects					Large NSI couplings. DeepCore tension.	11
Anomalous matter	Resonant appearance				unknown	Tension with T2K if resonance in E.	9
Large extra dim	Osc with related freqs.				unknown	Same issues as 3+1 or worse.	12
LNV in μ decays	$\mu^+ \rightarrow$ anti-ν_e					Michel params in tension w/ TRIUMF.	8
Lorentz violation	Sidereal time variation				unknown	HE IceCube tension.	10
Dark neutrinos	Upscattering to N $\rightarrow \nu e^+e^-$					MINERvA/CHARM-II/ND280 tension?	**2**
Dipole portal	Upscattering to N $\rightarrow \nu \gamma$					MINERvA/CHARM-II/ND280 tension?	**3**
(3+1) + vis-ν decay	DIF of $\nu_s \rightarrow \nu_e$					Tension with solar antineutrinos.	5
(3+1) + vis decay	DIF of N $\rightarrow \nu \gamma$					Timing at MB.	7
Dark sectors: dark matter	Upscattering to $\chi' \rightarrow \chi e^+e^-$					MINERvA/CHARM-II/ND280 tension?	5
Dark sectors: (pseudo)-scalar	Forward scattering to γ					MINERvA/CHARM-II/ND280 tension?	**1**

Personal vision: a new kind of interaction

Traditional interactions between experimentalists and theorists have revolved around theorists picking up information on data based on experimental presentations in meetings and published papers.

Different approach, promoting **a new kind of interaction**:

Creating **one-on-one interactions** between experimentalists and theorists.

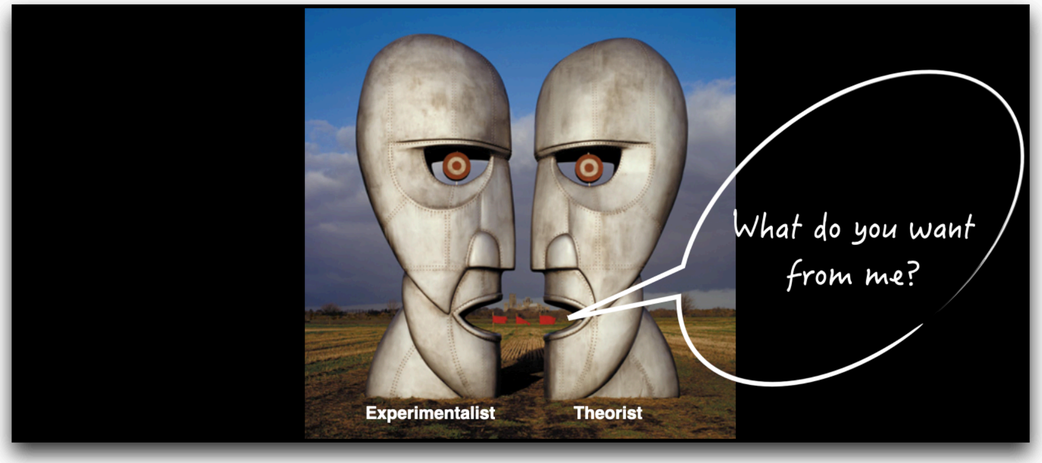
Connecting theorists to capabilities of ongoing and future experiments and experimentalist to BSM models.

Theorists fully involved in the experimental physics discussions in general, and in planning which analyses to undertake in particular.

Frequent, unstructured interactions to propose new searches, and possibly discuss and rapidly interpret new results [of course respecting collaboration rules concerning dissemination of data].

Experimental needs from theory

Collaborations between experimentalists and theorists are of great relevance to the International neutrino physics community, that needs the theory support to strengthen the neutrino experimental measurements, particularly when searching for New Physics.



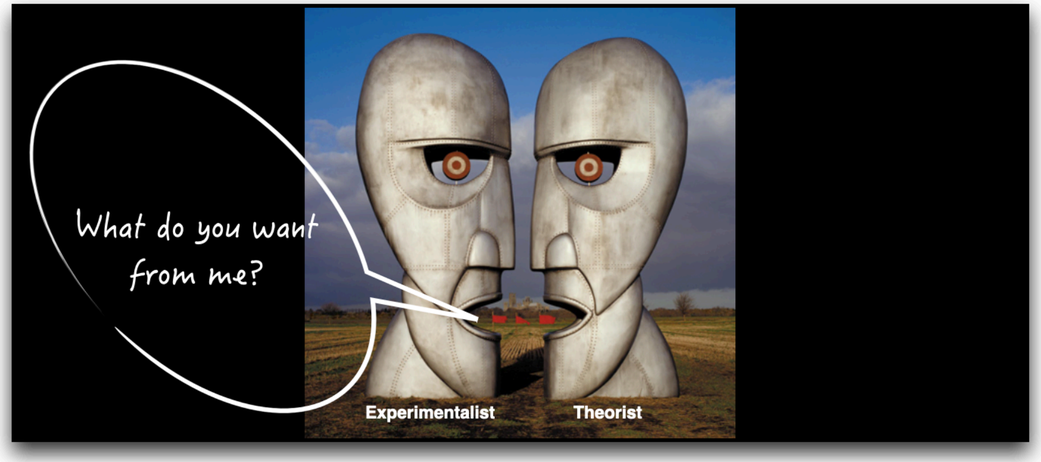
Theorists that enjoy working close to the experiments and engaging in direct collaborations with experimental groups in different areas and have a good understanding of detector performance.

[e.g., e.m. shower reconstruction, angular resolution and reconstruction of hadronic activity]

Theorists' involvement **enriches the scientific output of the experiments** and even **serves to identify new directions**, in connection with specific experiments and emerging technologies.

Theory needs from experiments

Collaborations between experimentalists and theorists are of great relevance to the International neutrino physics community, that needs the theory support to strengthen the neutrino experimental measurements, particularly when searching for New Physics.



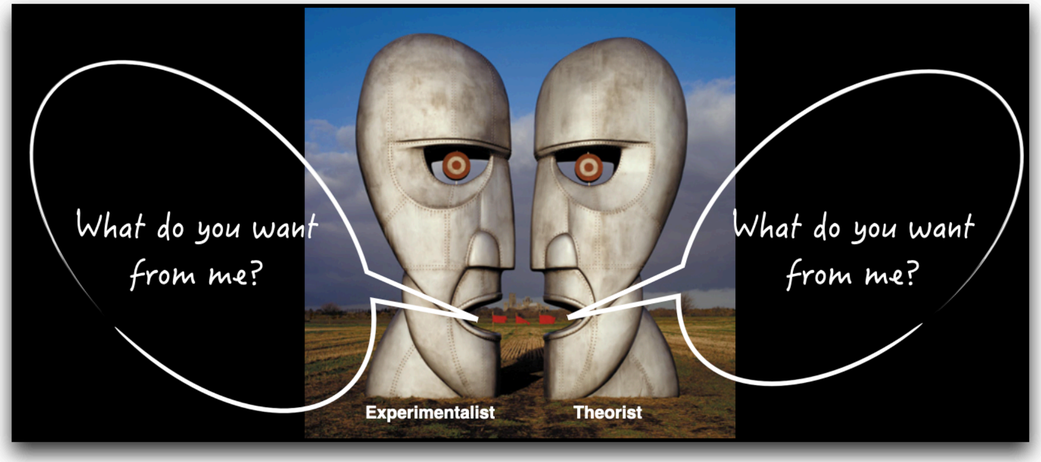
Experimentalists that are willing to have a close understanding of the possible signatures of New Physics.

A robust BSM program requires **automation of theory calculations and tools for BSM**: flexible generators incorporating new physics models (as does the Achilles generator) and possibly implemented directly into the experiment's software framework [same signal and backgrounds processing].

Knowledge of neutrino (background!) cross sections and related uncertainties greatly affect BSM sensitivities. Theorists to help identify measurements to be made to constrain the models.

Many BSM models…ideally, experimentalists may want them grouped into categories, based on event final state topology (e.g. multiple leptons with similar kinematics).

Experimental needs from theory
&
Theory needs from experiments



Strength the theory-experiment collaboration by developing common goals to help enable major discoveries in neutrino physics.

Connections between the BSM phenomenology community and the neutrino cross section community important to estimate sensitivity to BSM.

The **Neutrino Theory Network program**, designed to facilitate collaboration within the theory community and with the experimental community, can have a big impact!

Summary

ArgoNeuT, a small LAr TPC running for 5 months on the NuMI beam produced world leading BSM searches.

Current and next- generation neutrino experiments are fantastic tools to look for New Physics in the neutrino sector and beyond.

Close/direct collaboration between experimentalists and theorists is the key to success!

Create a whole that is greater than the sum of its parts to get the most out of our neutrino programs!

Visit to the SBND detector during the workshop