Quick Overview of the SBN Programme at Fermilab

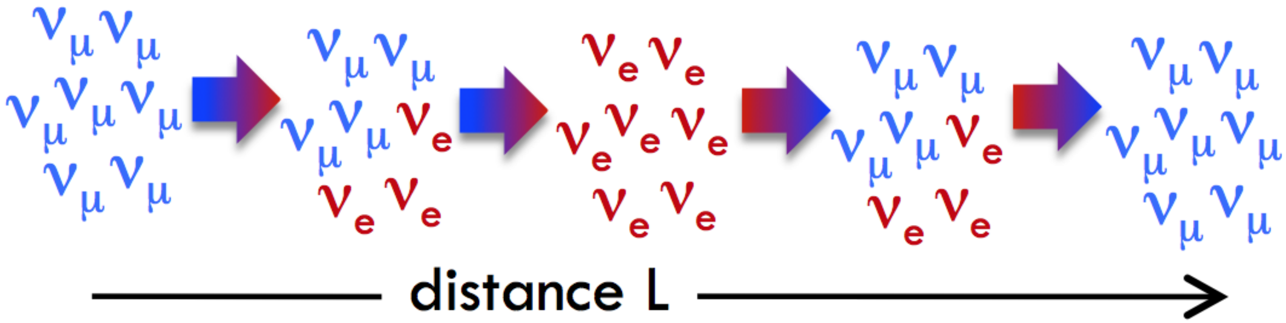
Andrzej M. Szelc

University of Edinburgh

Introduction

- Brief reminder about why we care about short baselines
- Liquid Argon Time Projection Chambers – why do they help us at short baselines
- Short Baseline Neutrino Programme
  - MicroBooNE
  - SBND
  - ICARUS
- Summary

Neutrino Oscillations



- We know three neutrino flavors: ν_e, ν_μ **and** ν_τ
- In oscillation experiments we measure how one type of neutrino changes into another.
- We can do this by detecting the new neutrinos **(appearance)** or registering the loss of original **(disappearance)**.

Oscillations are only possible if neutrinos have mass!

"amplitude" "frequency"

$$P(\nu_x \to \nu_y) = sin^2(2\theta) sin^2(1.27\Delta m^2 \frac{L(km)}{E(GeV)})$$

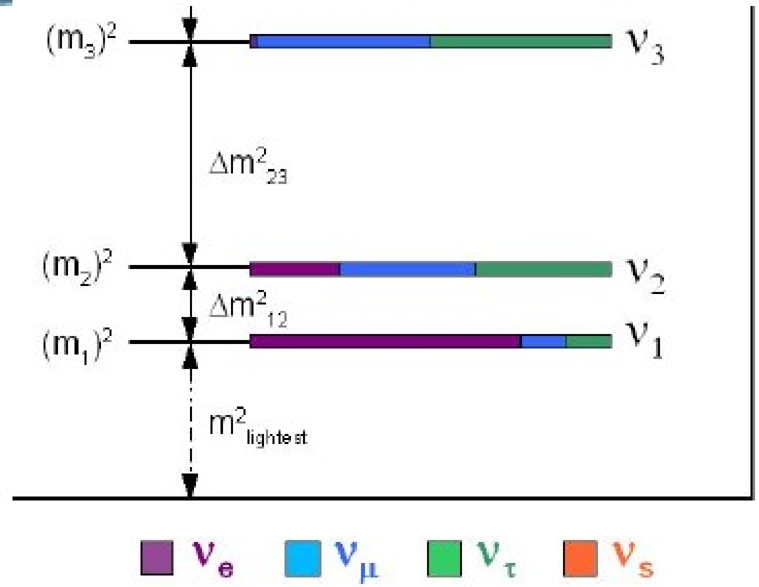
The Current State of Neutrino Knowledge

$$
U = \underbrace{\overset{23}{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}}_{\text{Atmospheric}}
\underbrace{\overset{13}{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}}_{\text{Reactor/Interference}}
\underbrace{\overset{12}{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}}_{\text{Solar}}
$$

$\mu \Rightarrow \tau$ $\qquad$ $\mu \Leftrightarrow e$ $\qquad$ $e \Leftrightarrow \mu$

θ_{13} was first measured fairly recently.

Unknown: δ_{CP} phase and the mass ordering,



“Known” neutrino physics

Δm^2_{21} $[10^{-5}\text{eV}^2]$	7.56 ± 0.19
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (NO)	2.55 ± 0.04
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (IO)	2.49 ± 0.04
$\theta_{12}/°$	$34.5^{+1.1}_{-1.0}$
$\theta_{13}/°$	$8.44^{+0.18}_{-0.15}$
$\delta/°$	252^{+56}_{-36}
$\sin^2\theta_{23}/10^{-1}$ (NO)	$4.30^{+0.20}_{-0.18}$
$\theta_{23}/°$	41.0 ± 1.1
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.96^{+0.17}_{-0.18}$
$\theta_{23}/°$	50.5 ± 1.0

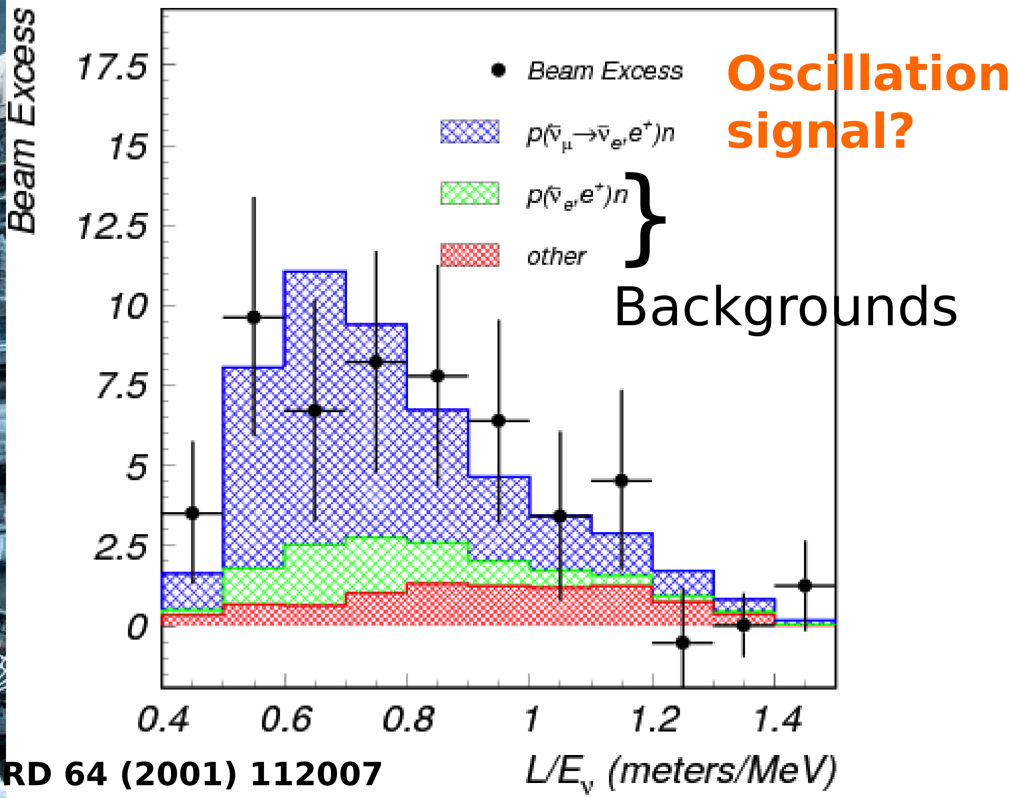
Salas, Forero, Ternes, Tortola, Valle: 2017

Open Questions

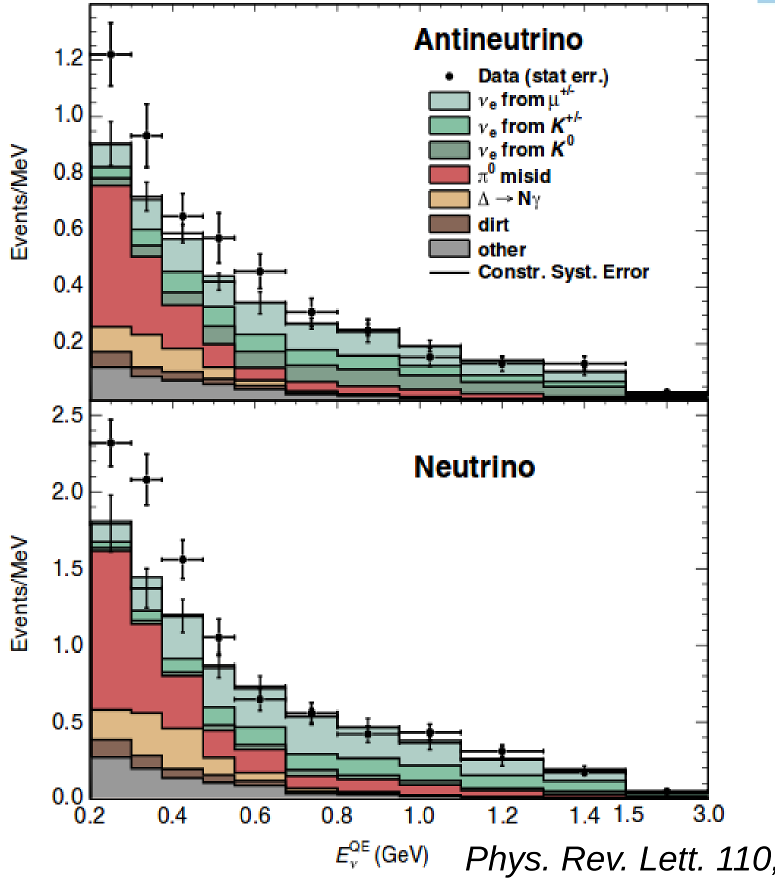
- The questions below, are what is currently driving the field of experimental neutrino physics

- how much do neutrinos weigh? ***- what is the nature of the ν?***	β decay and $0\nu\beta\beta$ decay
- which neutrino is the heaviest and which is the lightest (MH)? ***- do neutrinos violate CP?***	long-baseline neutrinos
- is our picture correct? ***- are there more than 3 kinds of neutrinos?***	short-baseline neutrinos

Accelerator Anomalies



PRD 64 (2001) 112007



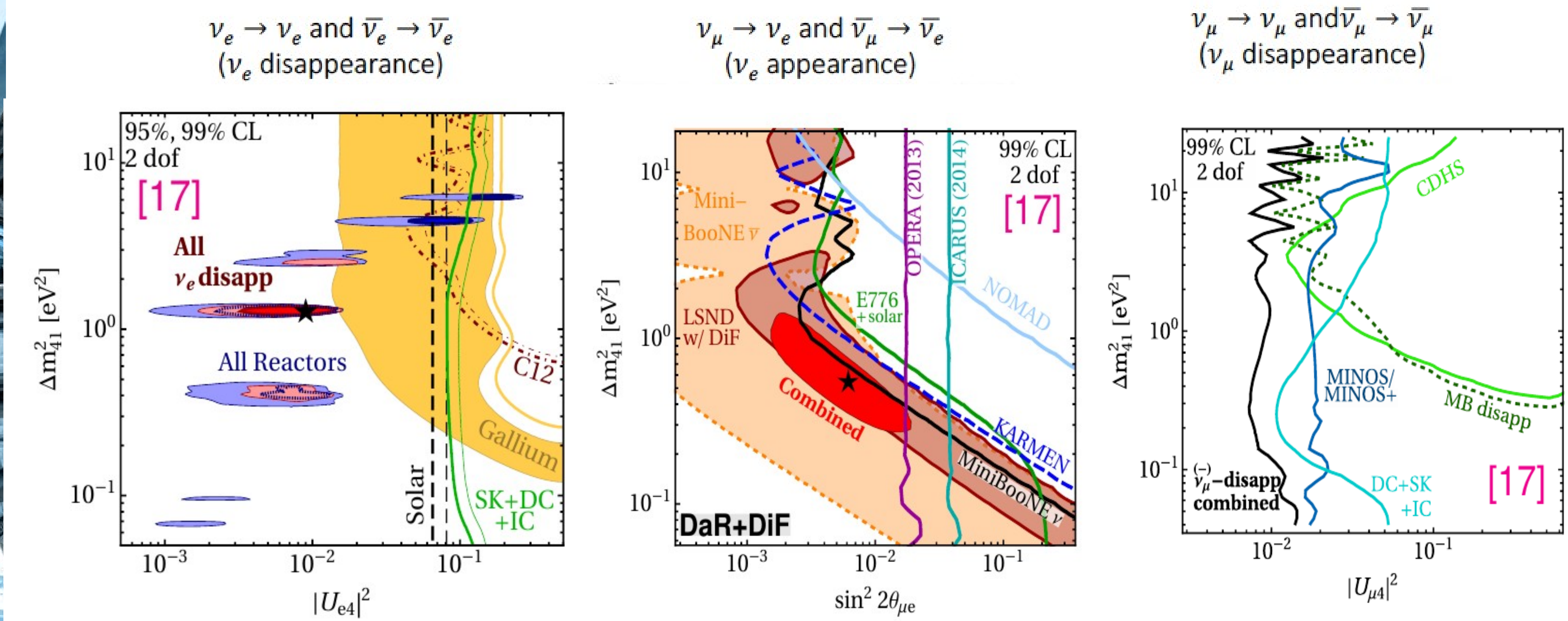
Phys. Rev. Lett. 110, 161801 (2013)

Two neutrino experiments: LSND and MiniBooNE observed signals compatible with oscillations with $\Delta m^2 \simeq 1$ eV^2

~Compatible hints from reactor experiments, and radioactive source measurements.

Global Fits

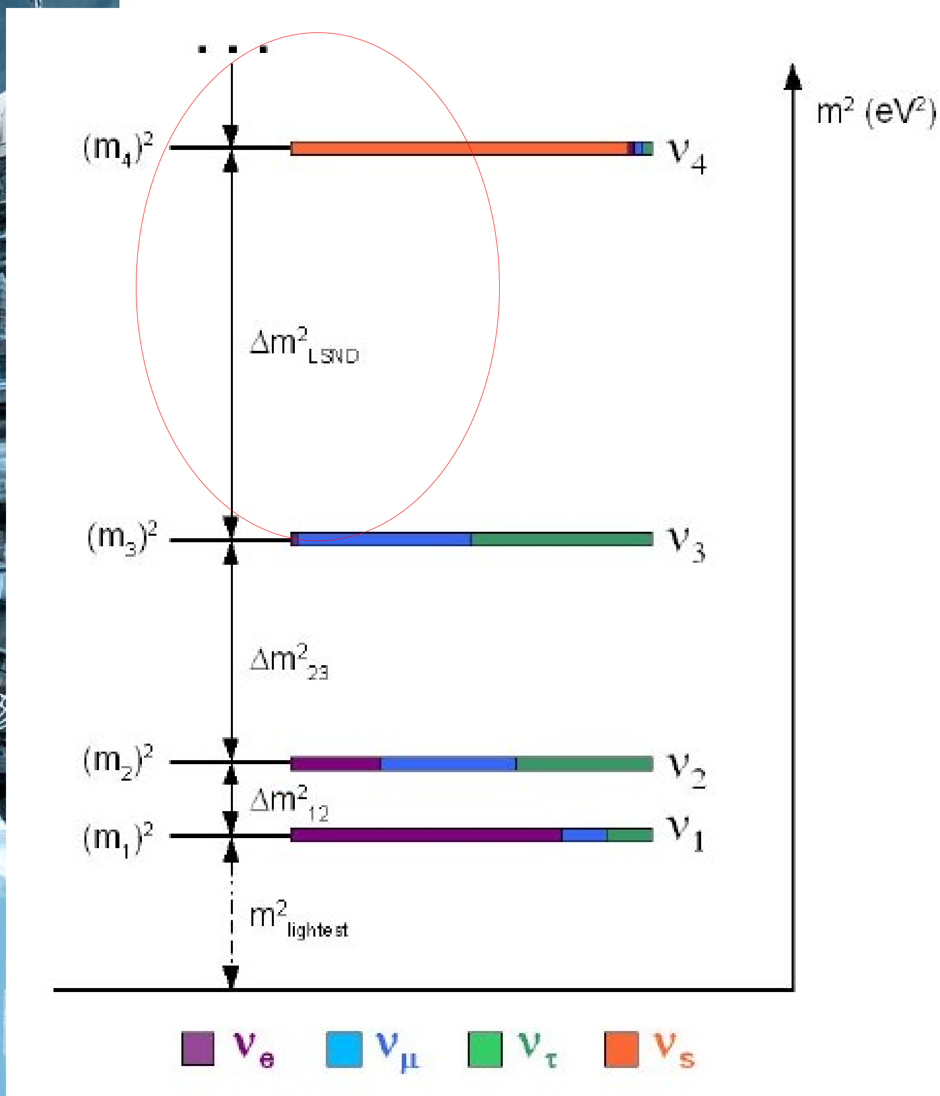
Dentler, Hernández-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, arXiv:1803.10661.



Tension with experiments that observe no signal, especially recent measurements by **IceCube and MINOS+** leads to significant constraints on possible sterile neutrino parameters. But recent IceCube measurements also show hints!

Several measurements released since these global fits (mainly reactor searches).

Why is this a problem/opportunity?



If we are indeed seeing oscillations with $\Delta m^2 \sim 1 eV^2$

Then this cannot fit in with the previous oscillation measurements - need a new neutrino state.

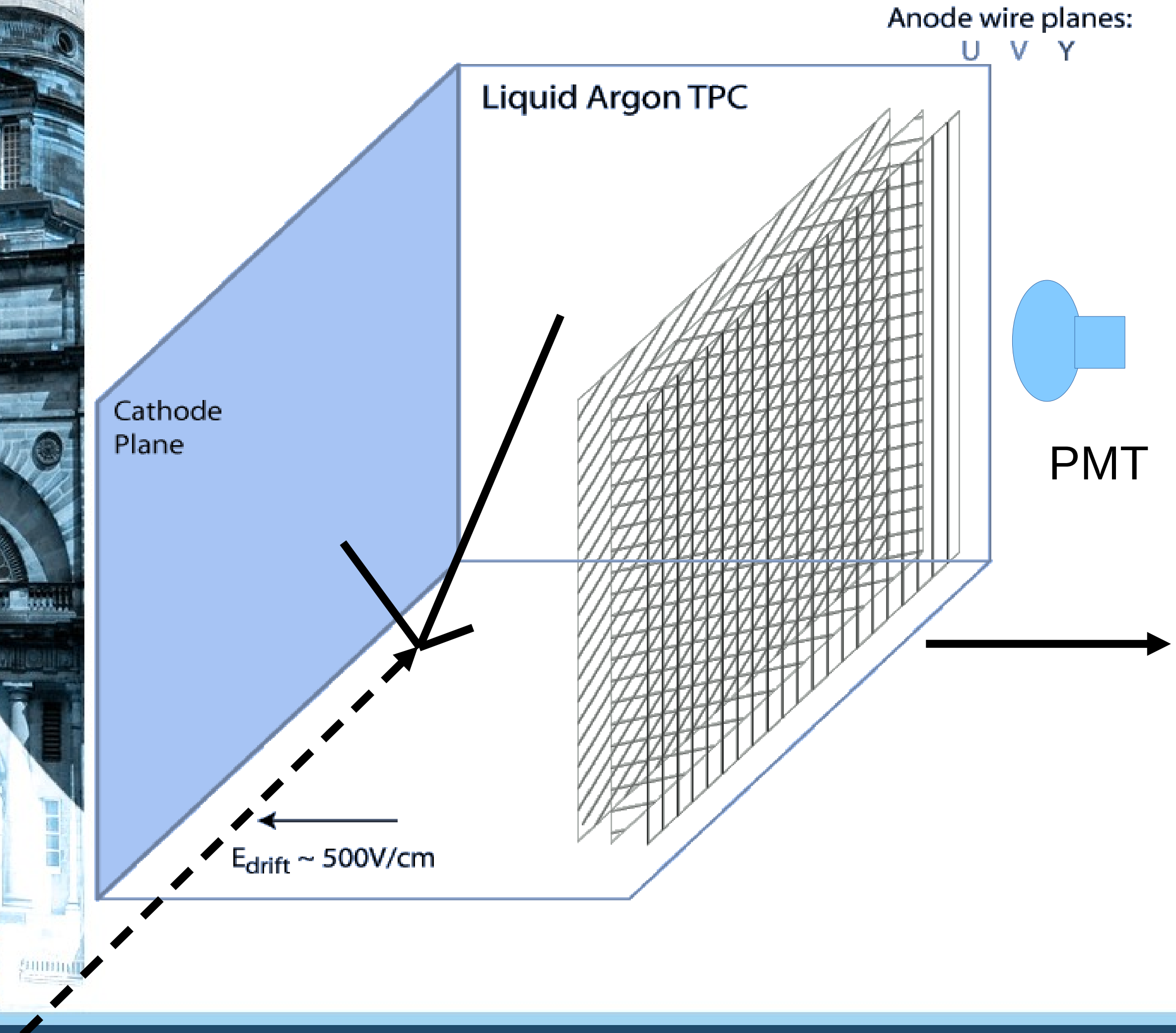
The new neutrino state must be sterile.

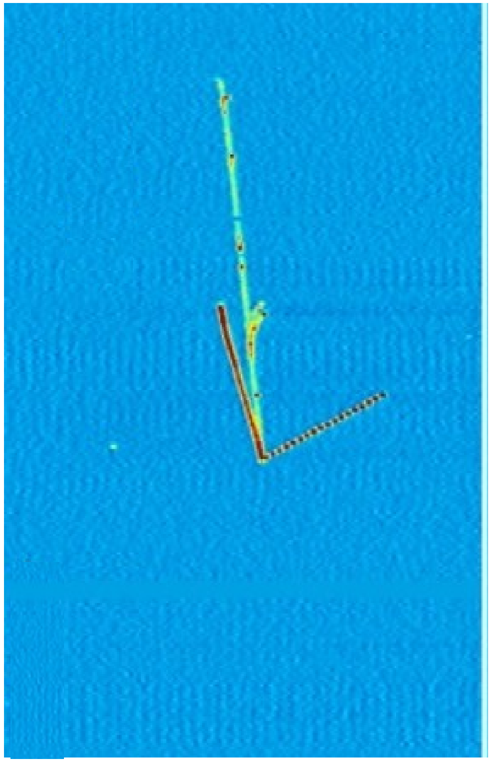
Clear Sign of New Physics Beyond the Standard Model if found.

LArTPCs

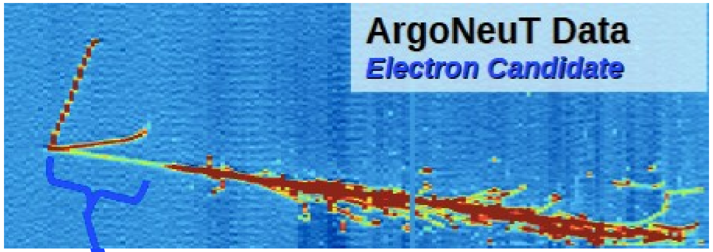
The University of Edinburgh

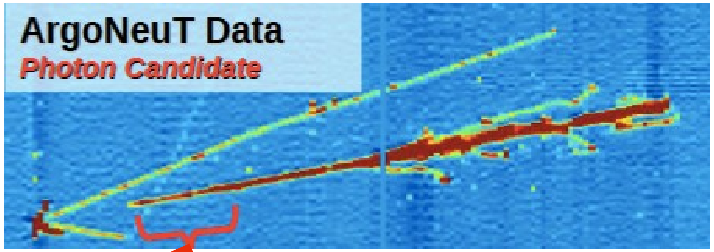
Liquid Argon Time Projection Chambers (LArTPCs)

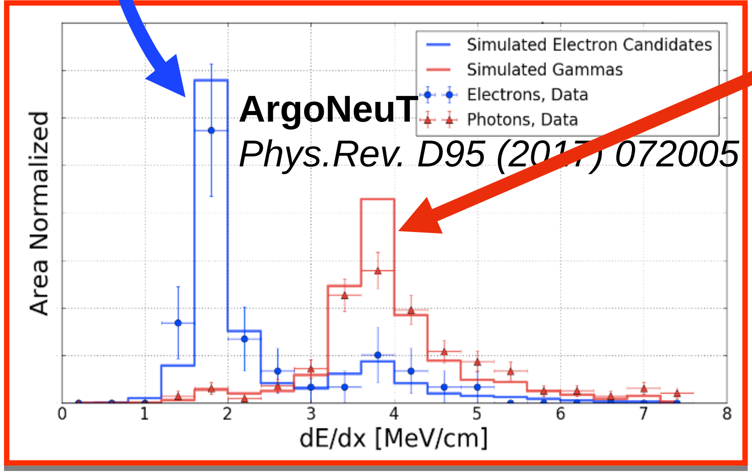




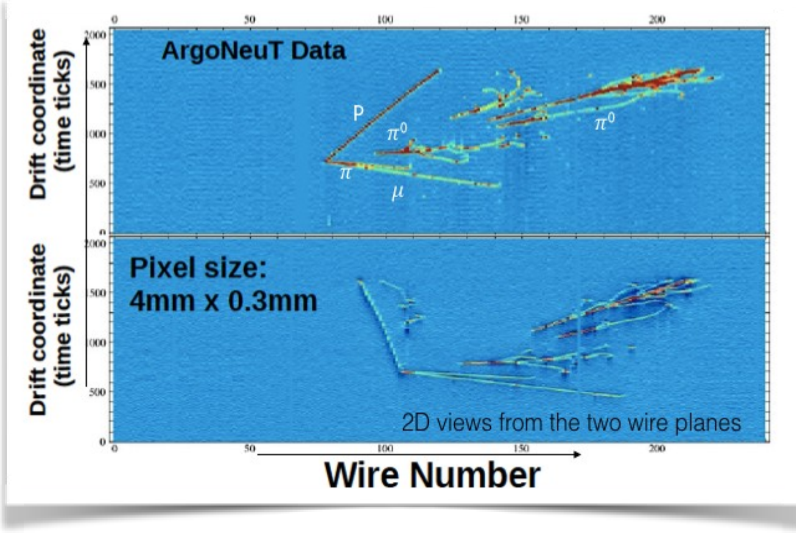
Electron / photon separation





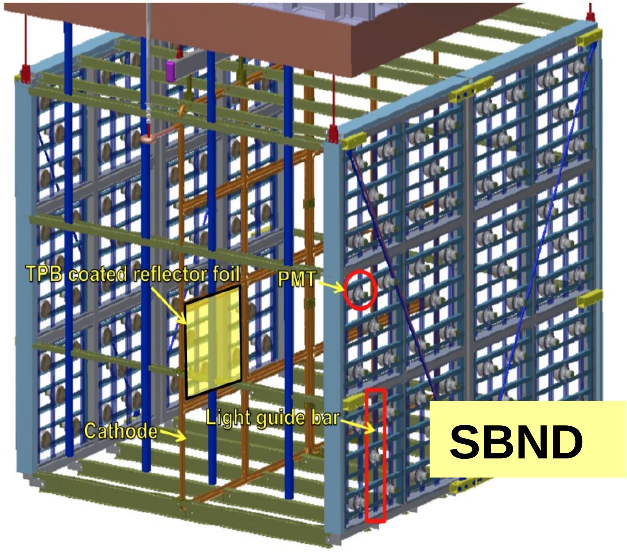


Double handle: topology and dE/dx



The LArTPC is an excellent tool for electron/photon separation

LArTPC detectors in the SBN programme



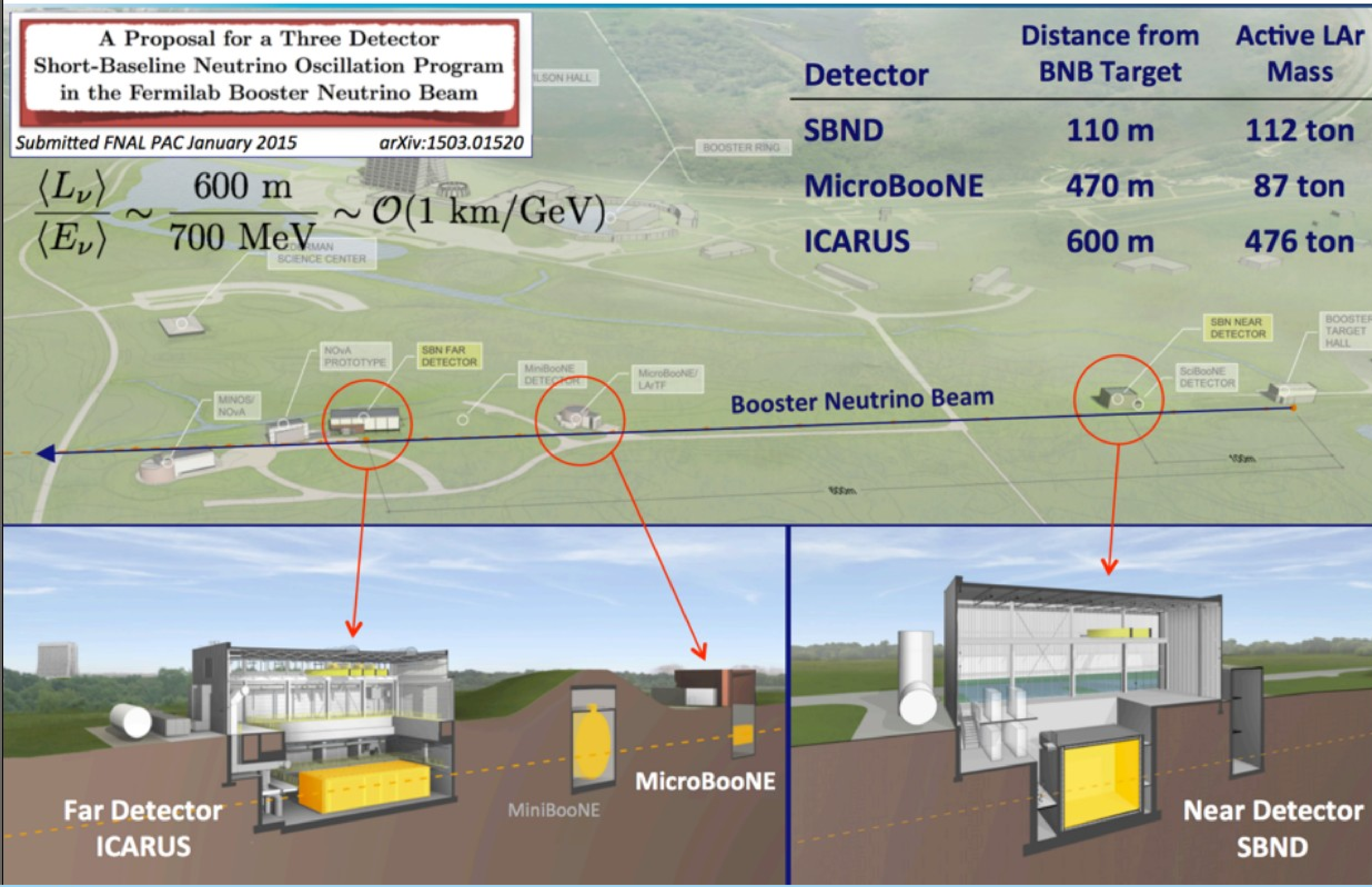
SBN Programme

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

Submitted FNAL PAC January 2015 *arXiv:1503.01520*

$$\frac{\langle L_\nu \rangle}{\langle E_\nu \rangle} \sim \frac{600\ \text{m}}{700\ \text{MeV}} \sim \mathcal{O}(1\ \text{km/GeV})$$

Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton



The University of Edinburgh

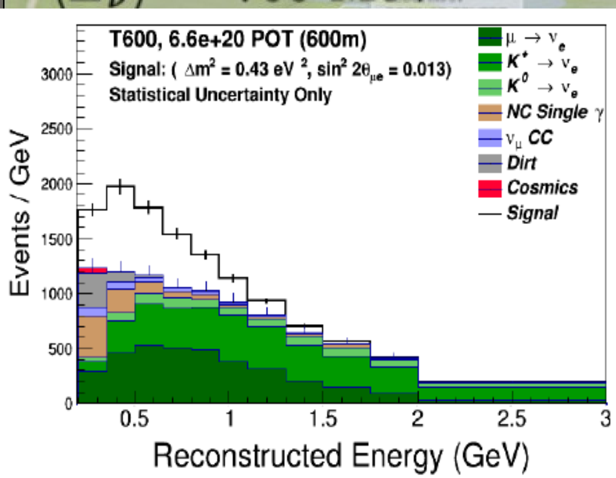
SBN Oscillations

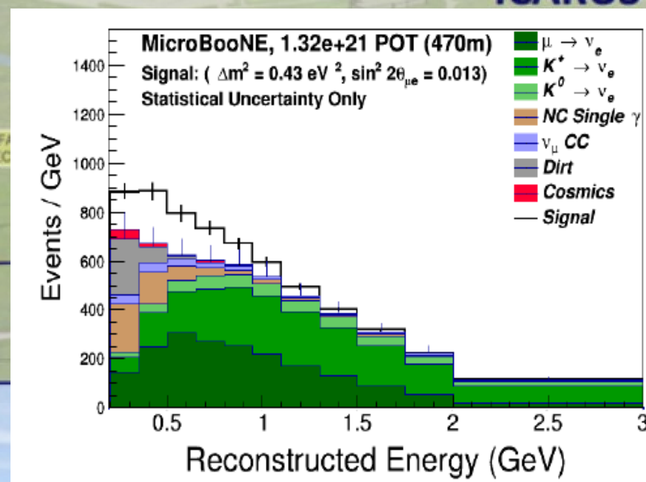
A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam

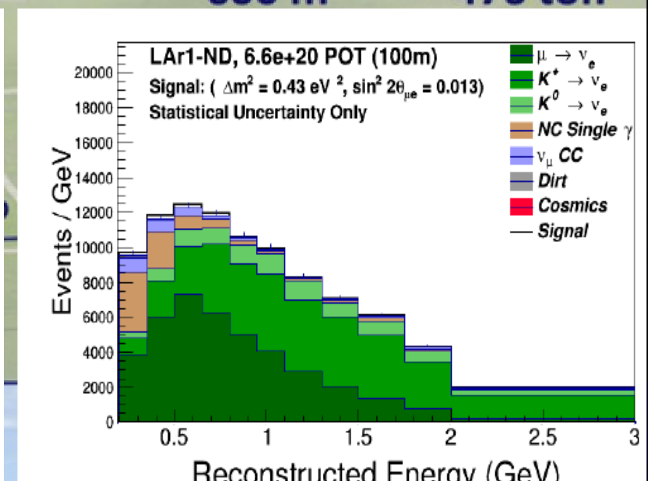
Submitted FNAL PAC January 2015 *arXiv:1503.01520*

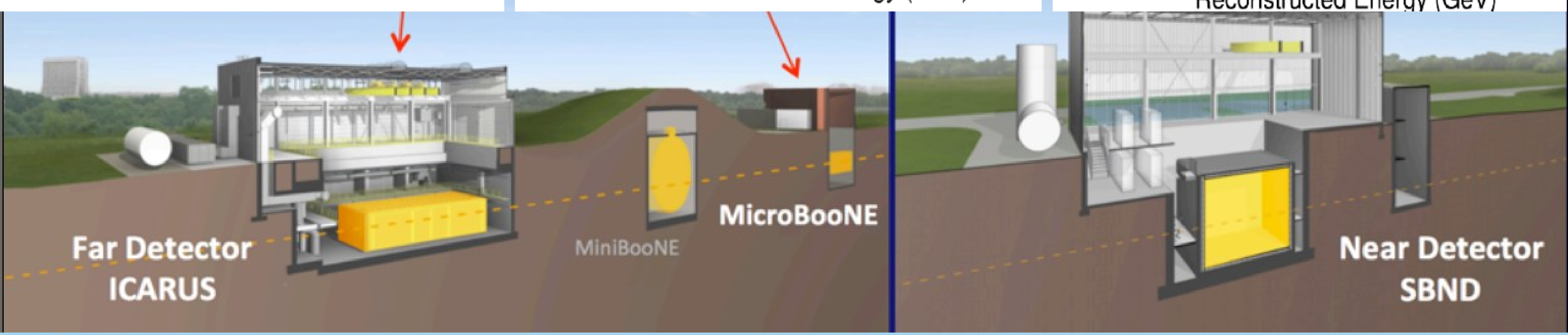
$$\frac{\langle L_\nu \rangle}{\langle E_\nu \rangle} \sim \frac{600\ \mathrm{m}}{700\ \mathrm{MeV}} \sim \mathcal{O}(1\ \mathrm{km/GeV})$$

Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton

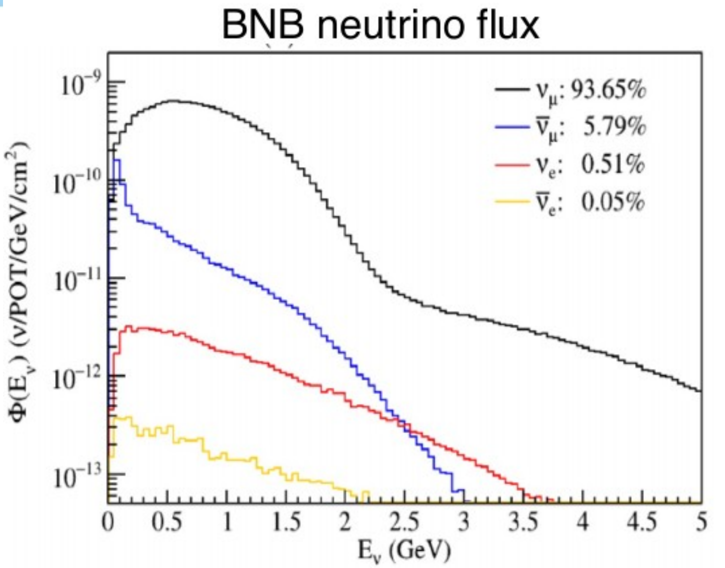






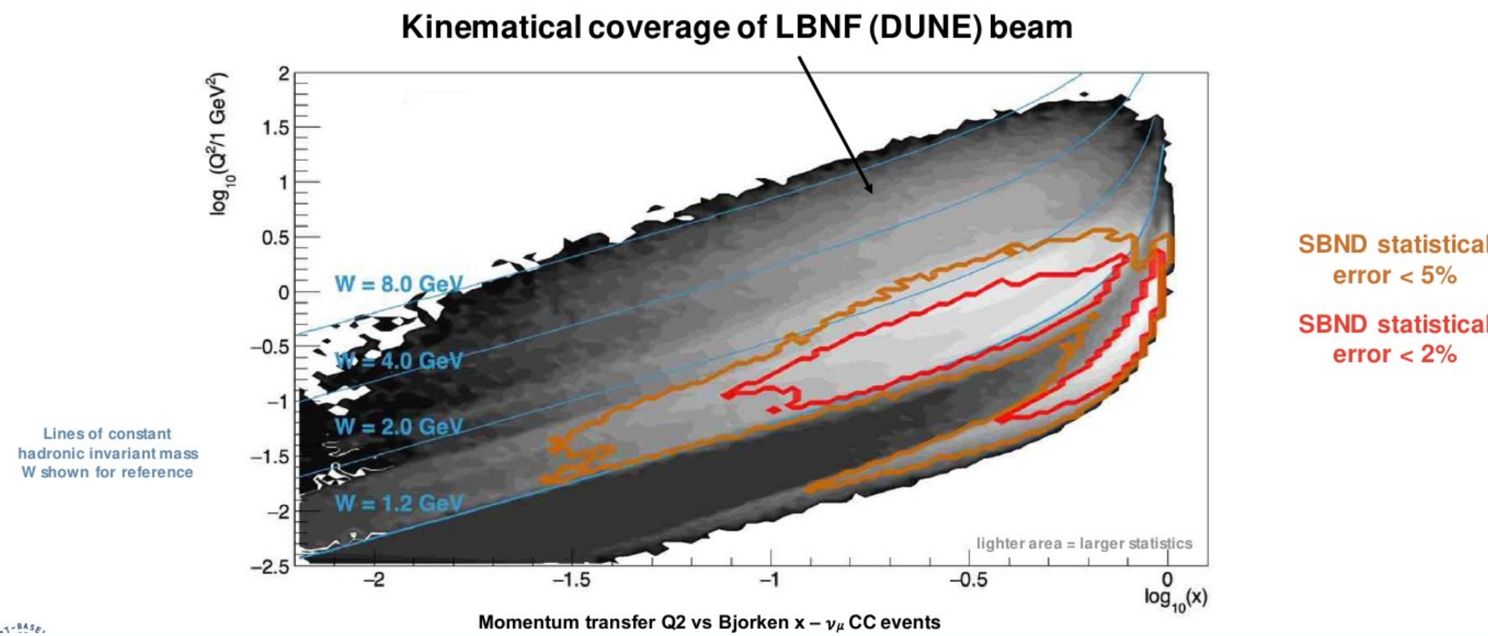


BNB Beamline



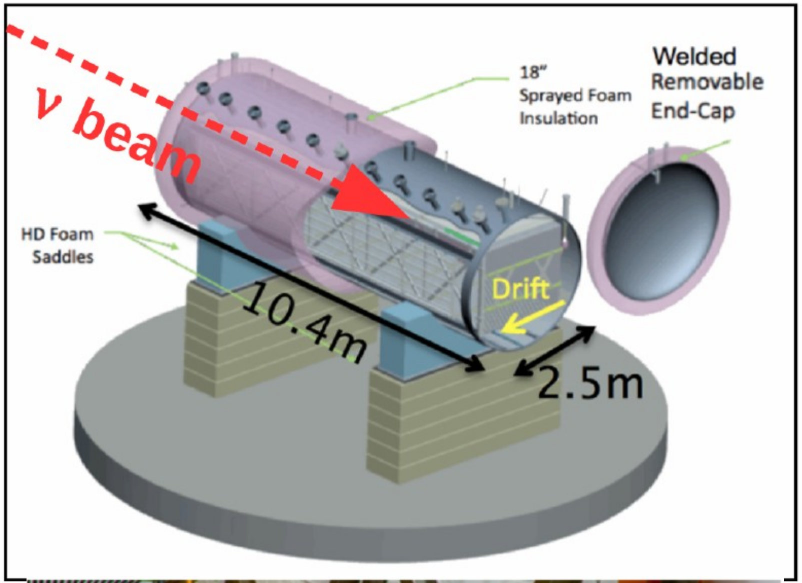
Lower energy that DUNE beam, low electron neutrino content.

But can probe large parts of DUNE kinematically interesting areas.



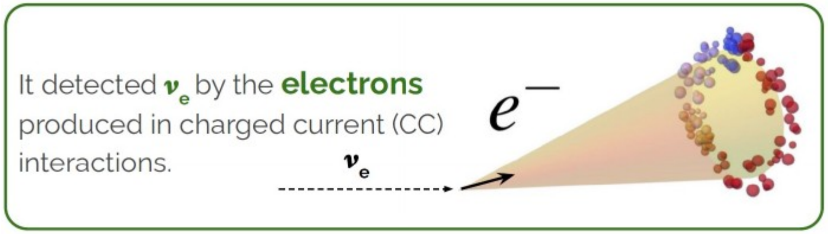
MicroBooNE at a glance

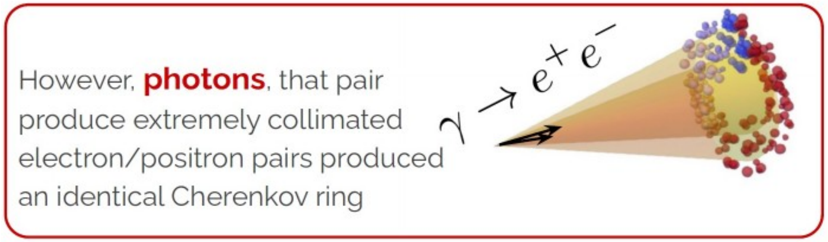
- 170 tons of LAr (90 tons active).
- Longest running LArTPC in a neutrino beam.
- Over 8000 wires (3mm pitch).
- 32 8'' PMTs serve as light collection system.
- A large number of crucial R&D in LArTPC operation.
- Large number of physics measurements coming out now.

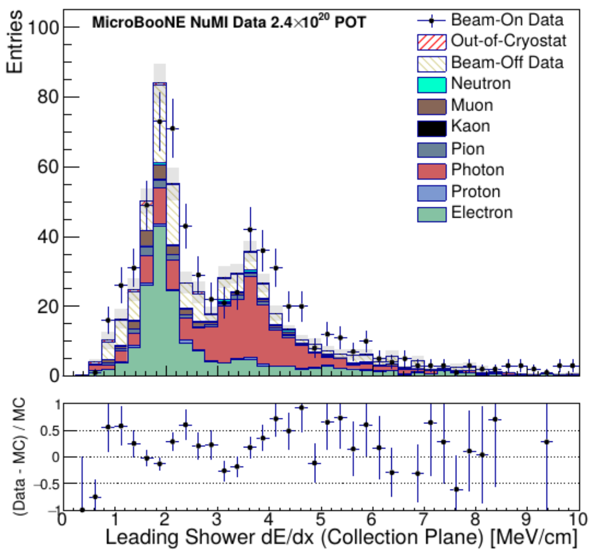


Understanding the Low Energy Excess

- Main goal of MicroBooNE was to understand the nature of LEE observed by MiniBooNE.
- LArTPCs can identify whether excess due to electrons (supporting oscillation hypothesis) or photons.
- First MicroBooNE results focussed on ~50% of the acquired data.

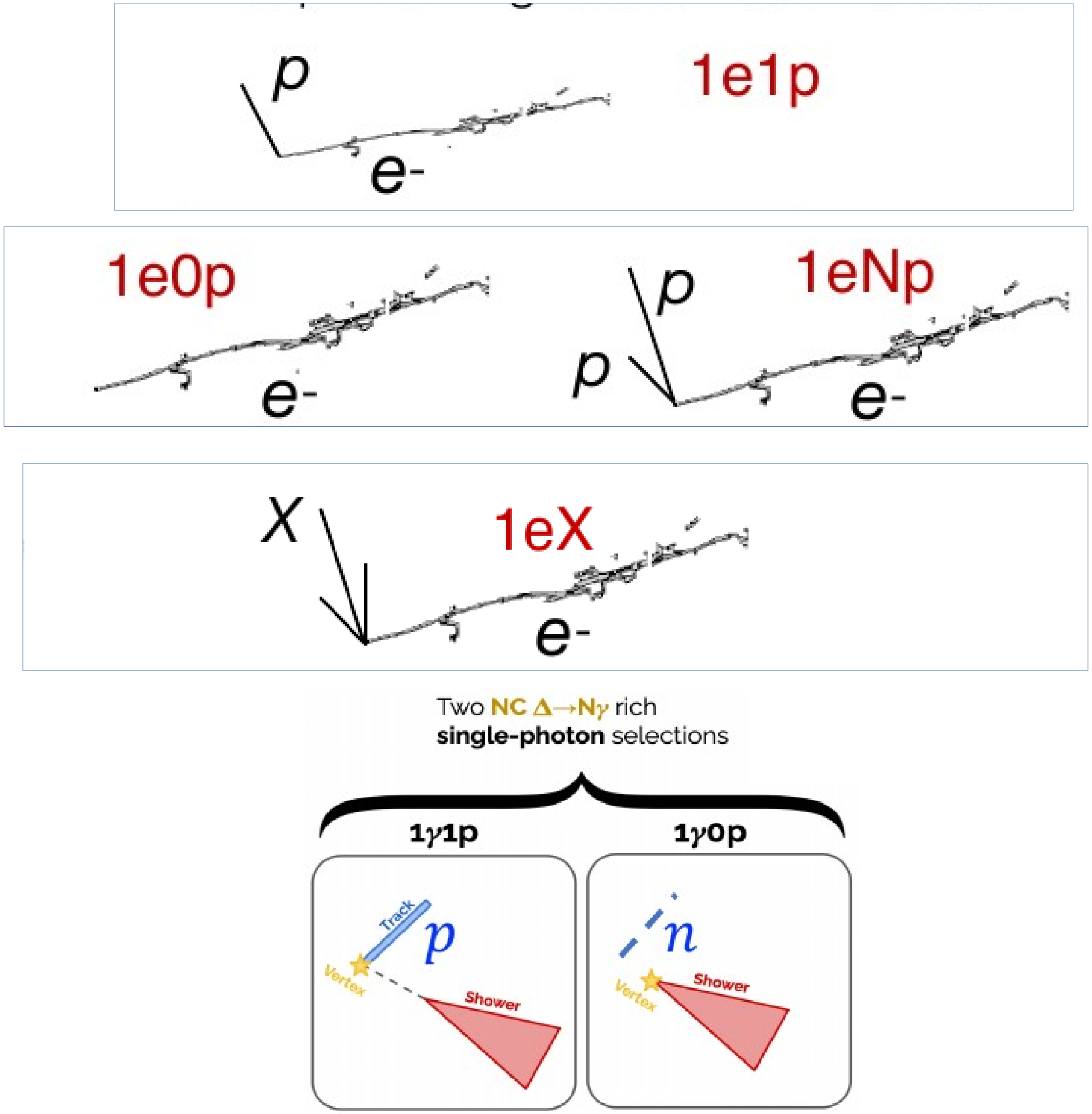






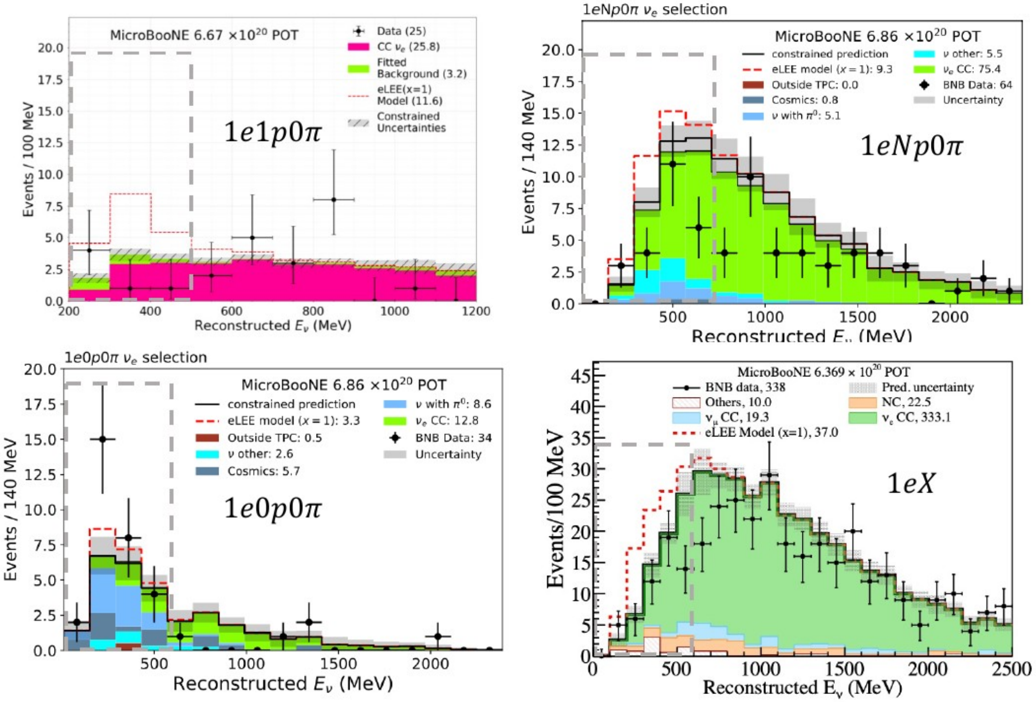
LEE Analyses

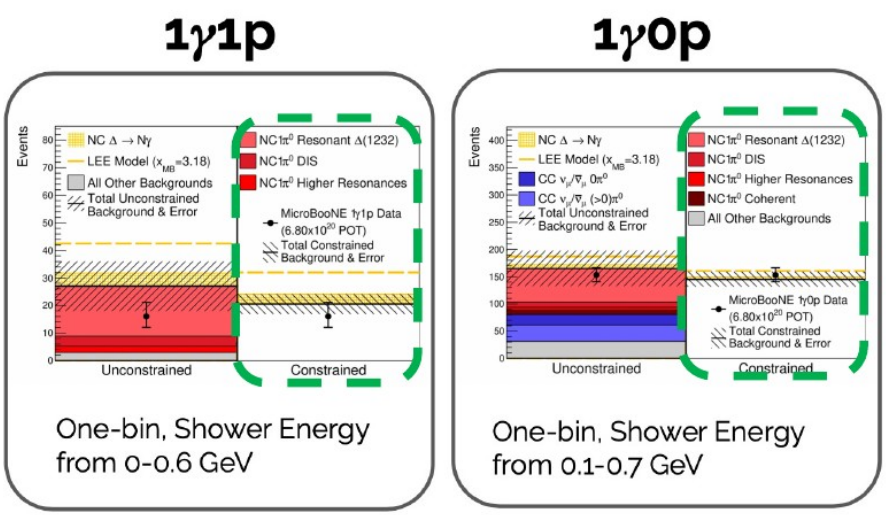
- Three parallel analyses using different reconstruction chains and channels
- One analysis searching for photon events.
- Data blinded and only opened in October 2021.

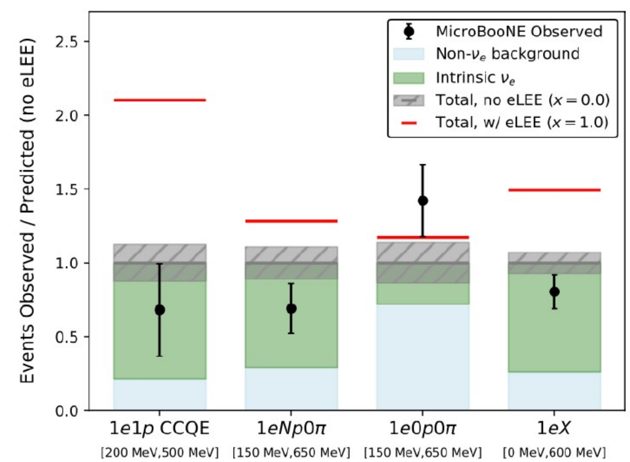


LEE results

- No significant excess observed.
- Disfavor pure ν_e excess as a sole source of MiniBooNE excess at 3 level
- Disfavor pure NC Δ radiative decay as a so source of MiniBooNE excess at about 2σ leve
-

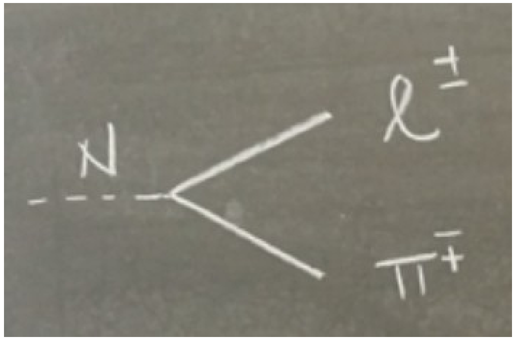




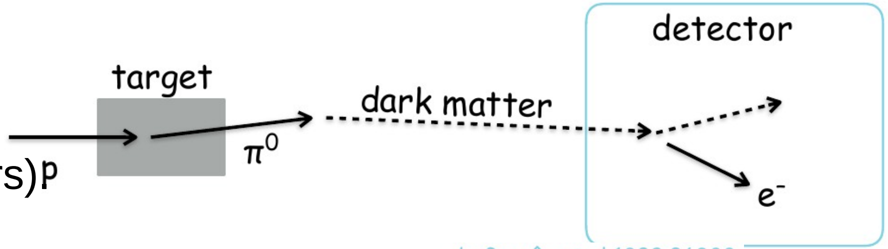


Alternative explanations: What can we look for?

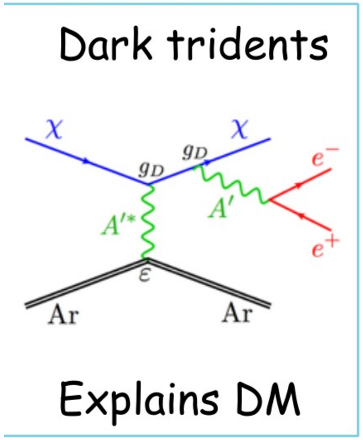
- Decays:
  - e+/e-, mu+/mu-
  - Others, e.g. mu+pi
- Scattering off of electrons:
  - Single e shower
- Scattering/up-scattering off of nuclei
  - e+/e-
  - Photons (or very forward e+/e- pairs)
- Other signatures:
  - Small bumps/faint tracks e.g. in milicharged particles

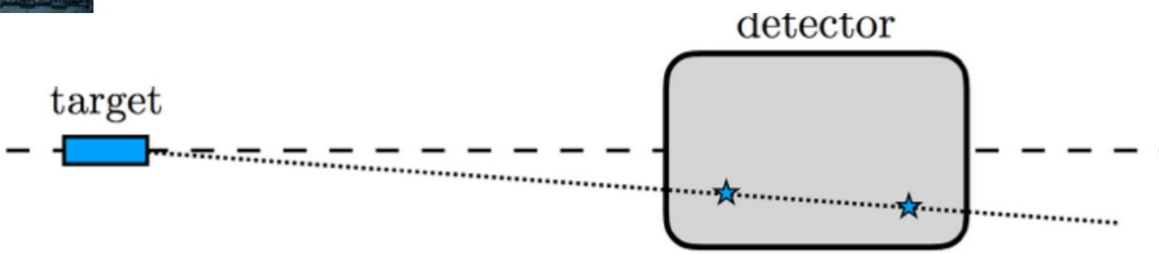


Images from P. Machado



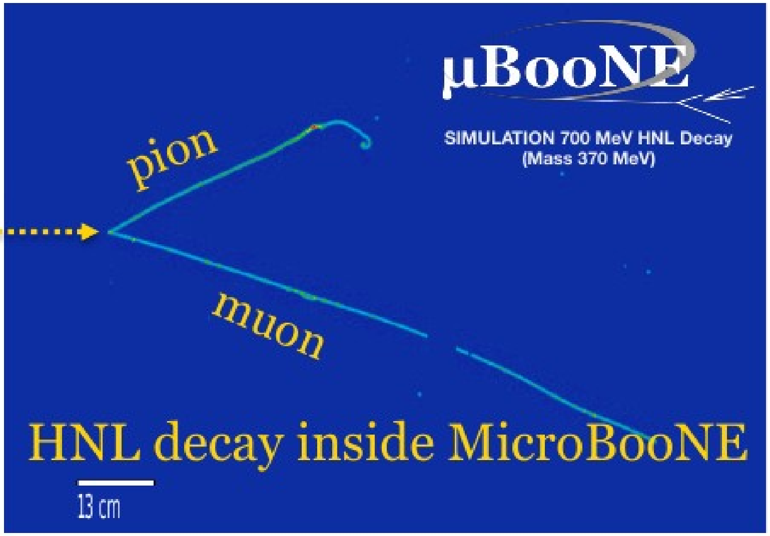
de Gouvêa et al 1809.06388



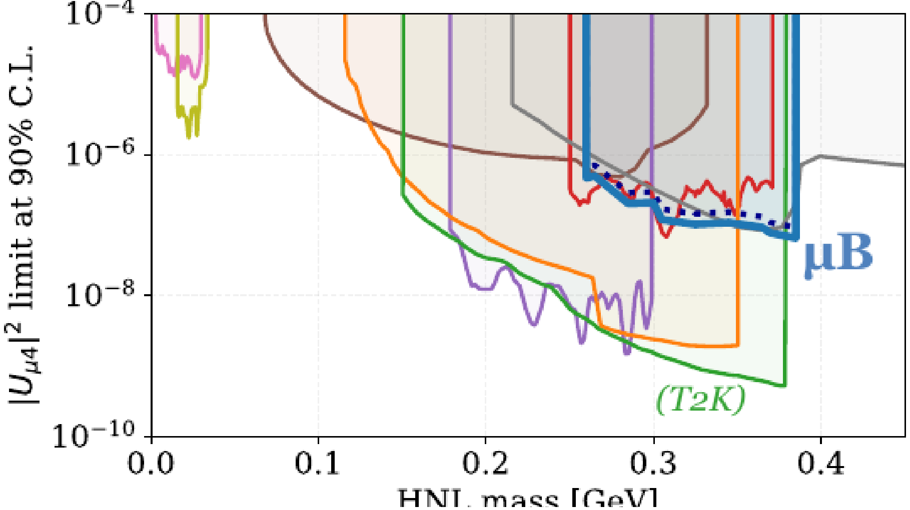


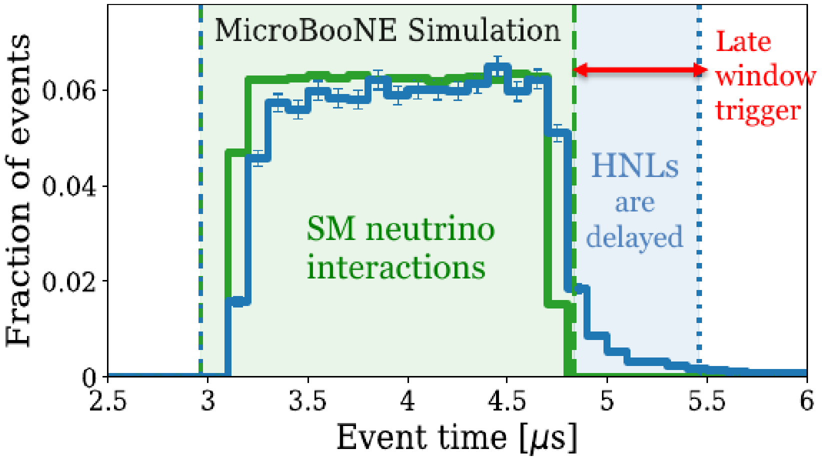
MicroBooNE BSM searches

- First HNL search in a LArTPC.
- Trigger modified to select heavier particles.



MicroBooNE, Phys.Rev.D 101, 052001 (2020)

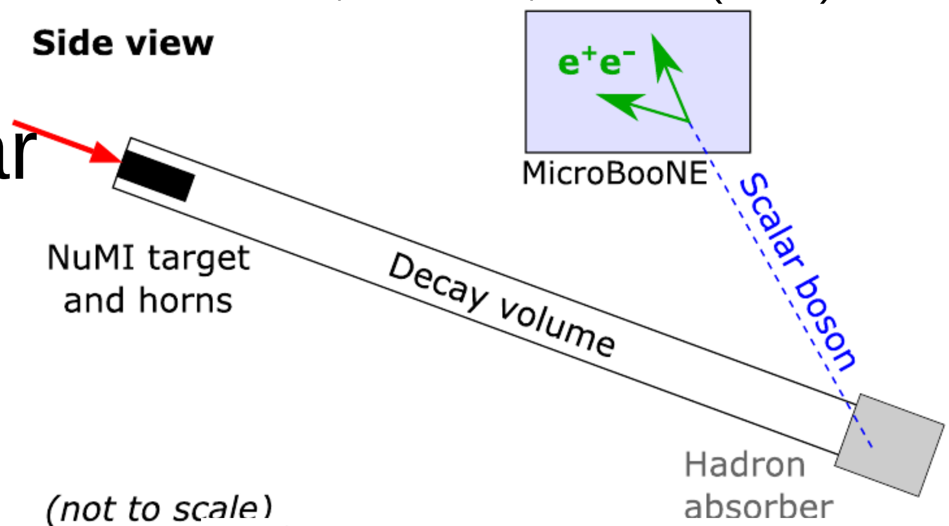


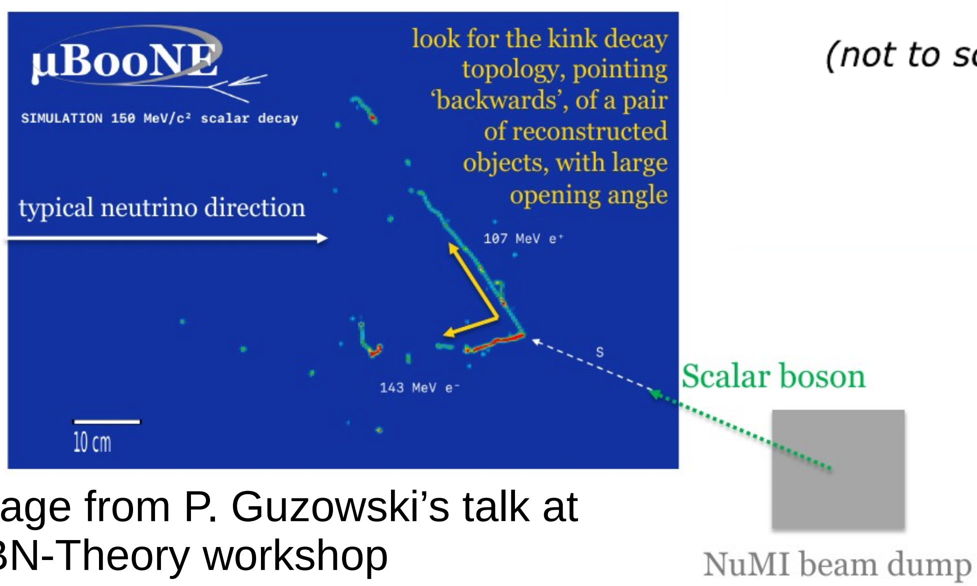


MicroBooNE BSM pt. 2

- Searching for e^+e^- pairs from decays of scalar bosons (m<200MeV).

MicroBooNE, PRL 127, 151803 (2021)





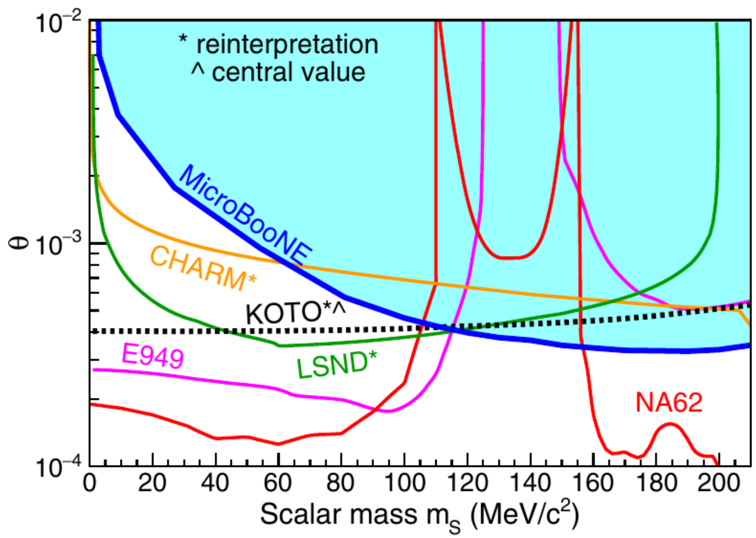
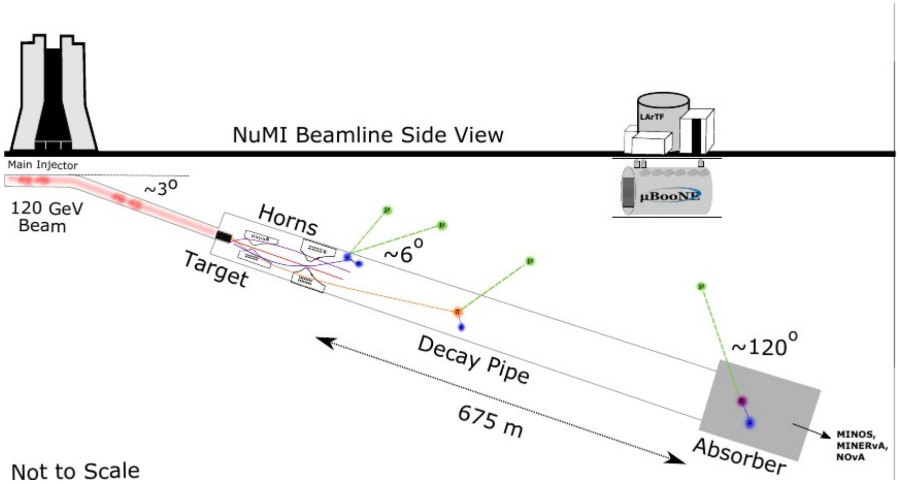
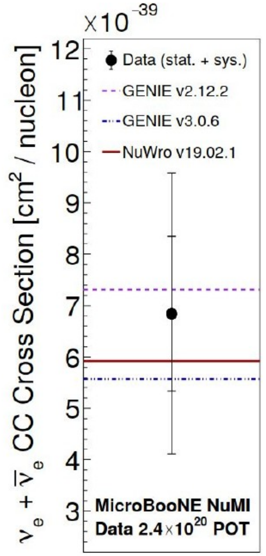


Image from P. Guzowski's talk at SBN-Theory workshop

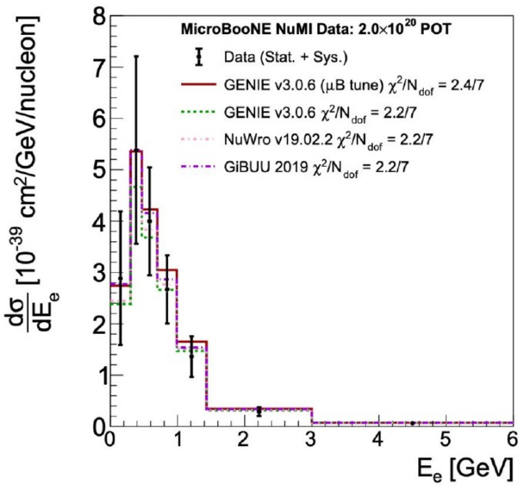
electron-neutrino cross-section

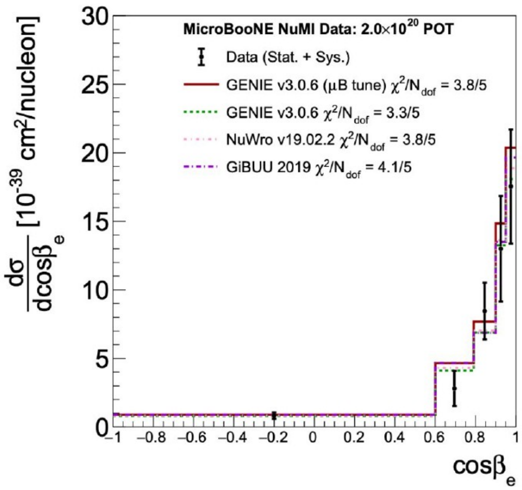


- NuMI beam is off-axis at MicroBooNE – has a higher electron neutrino content.

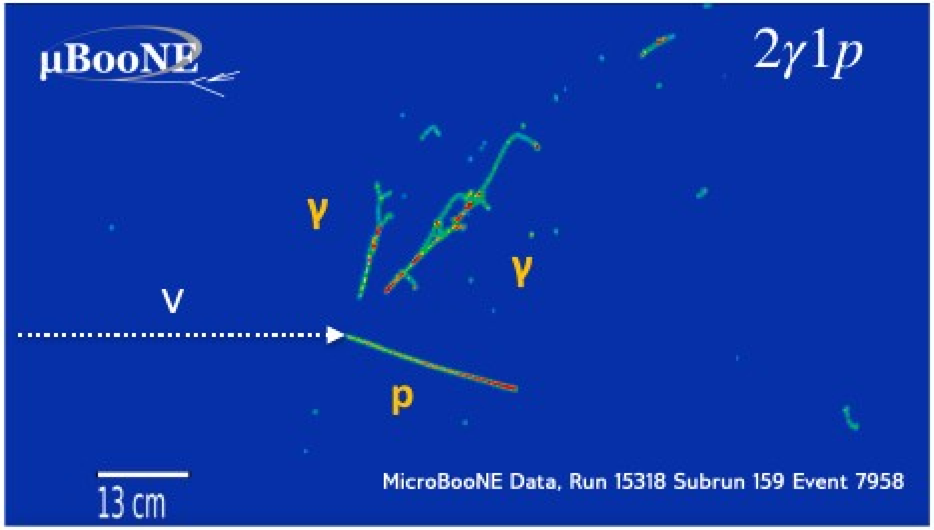


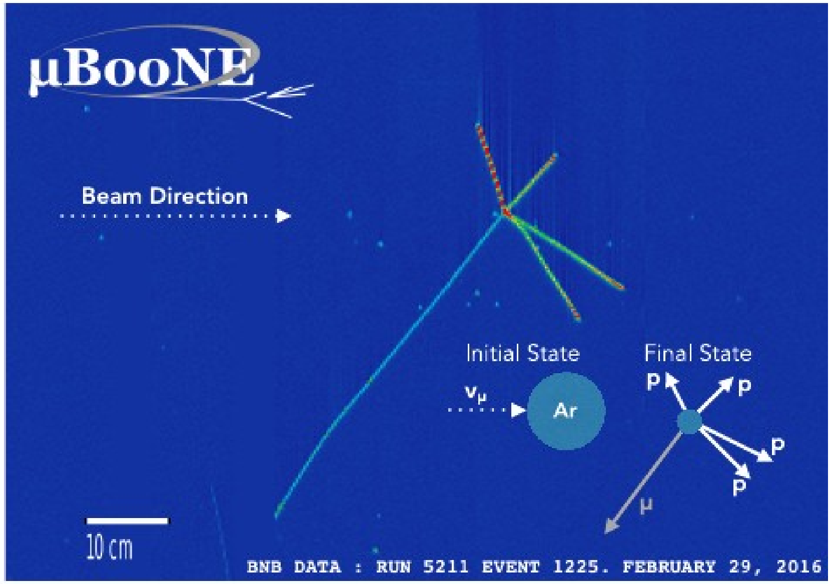
Largest sample of electron-neutrino interactions on argon to-date.





Multitude of other Cross-sections





Publications

Phys. Rev. D 102, 112013 (2020)
ν_μ CC 0π (≥1)p

Phys. Rev. D 104, 052002 (2021)
Total $\nu_e + \bar{\nu}_e$ CC inclusive

Phys. Rev. D 105, L051102 (2022)
Differential $\nu_e + \bar{\nu}_e$ CC inclusive

Phys. Rev. Lett. 128, 151801 (2022)
Energy-dependent ν_μ CC inclusive

Phys. Rev. D 105, 072001 (2022)
MicroBooNE GENIE Tune

arXiv:2205.07943, submitted to PRD
Total NC $1\pi^0$

Since 2020

SBND – the near detector

The Short-Baseline Near Detector (SBND), will be located closest to the source of neutrinos.

It will characterize the beam before oscillations occur and address one of the dominant systematic uncertainties.

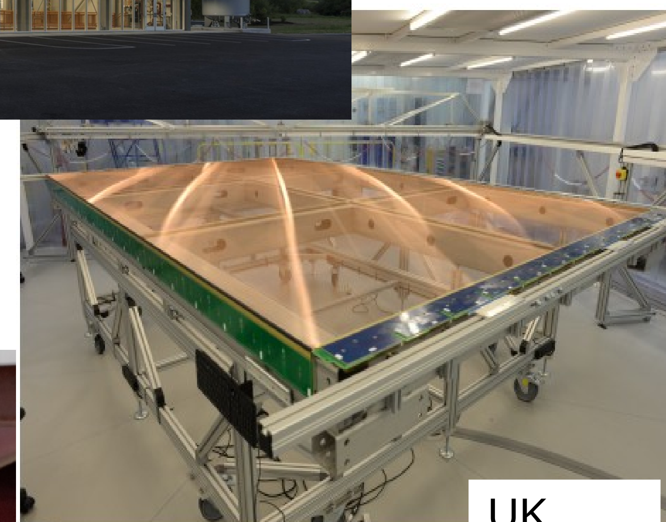
Planned start of operation mid 2023.

SBND at a glance

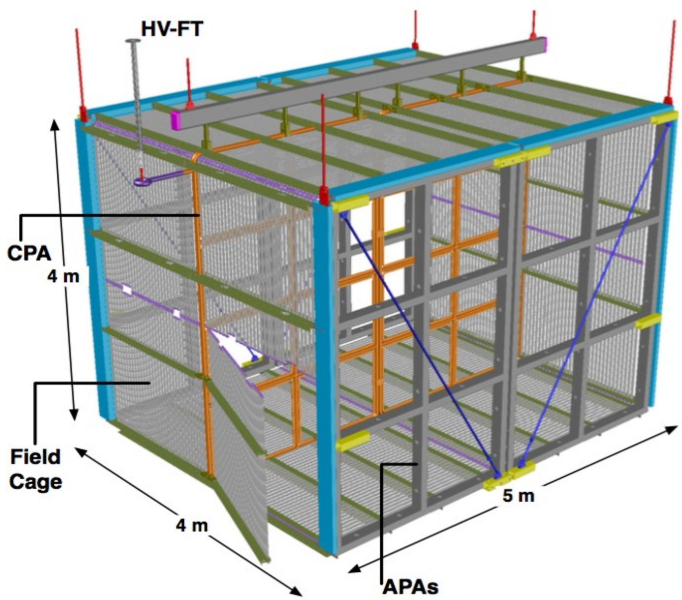
112-ton (active volume) in two Liquid Argon Time Projection Chambers.

4x4x5m Active Volume.

- TPC fully assembled.
- cryostat finished, waiting for endcap.



UK APA

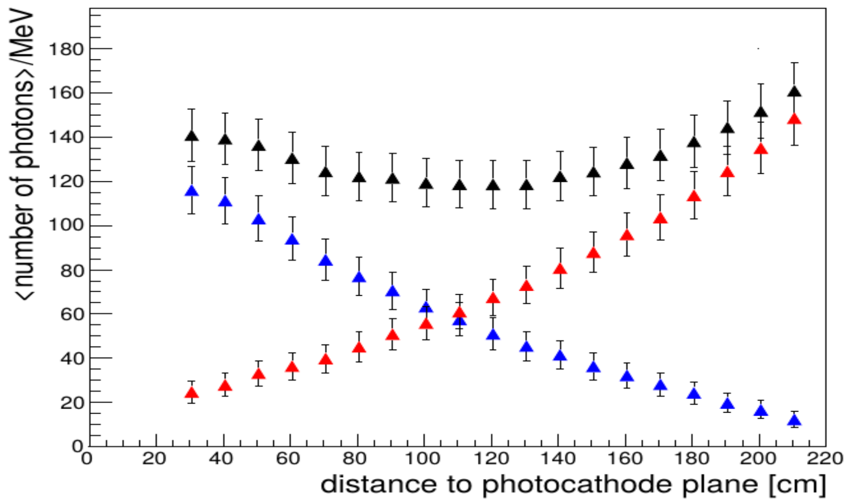


SBND TPC

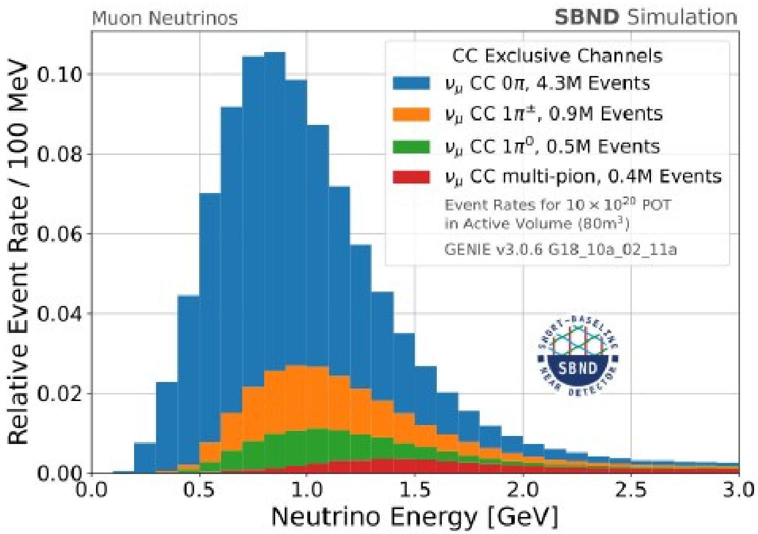

Cold electronics
Field Cage
Field Cage
Cold electronics
APA
CPA
APA
Drift distance
Drift distance
SBND TPC completed in June 2022

Enhancing Light Collection

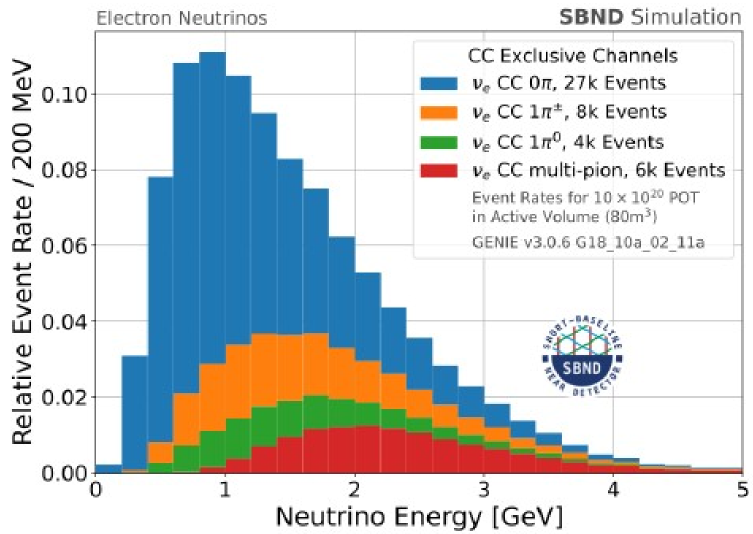
- Adding wavelength-shifting surface at the cathode recovers a large fraction o light that would normally be lost.
- Enhancement expected especially at low energies.
- Produced WLS coated area ($38m^2$) in a detector to date (SBND).



SBND cross sections



1.5M ν_μ CC events in 1 year

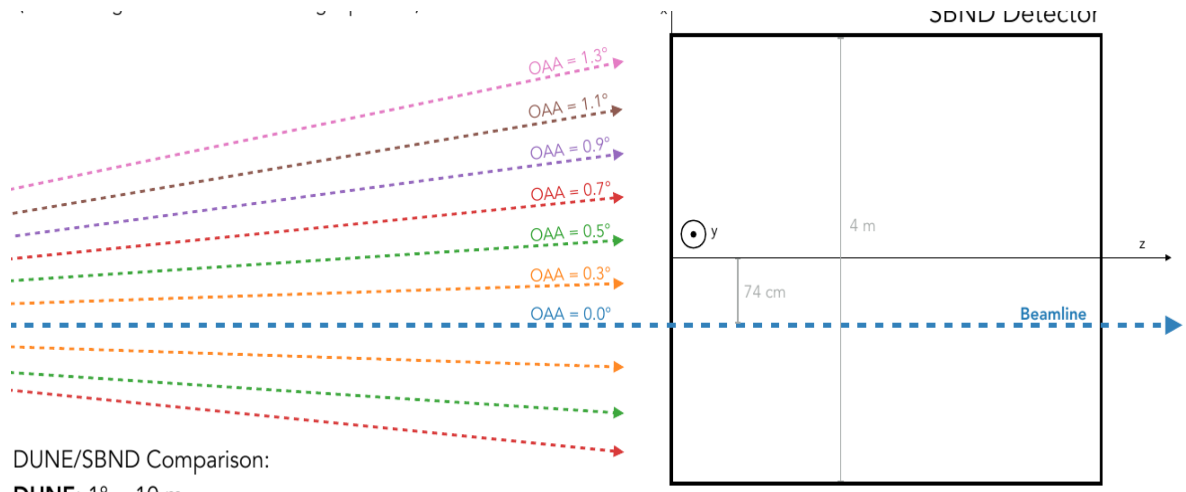


12k ν_e CC events in 1 year

- Due to proximity to the beam, will see enormous (by neutrino standards) number of events.
- Around 5000 neutrinos/day

Proximity to beam - PRISM

Closeness to beam target provides additional handle to differentiate between focused /unfocussed events.



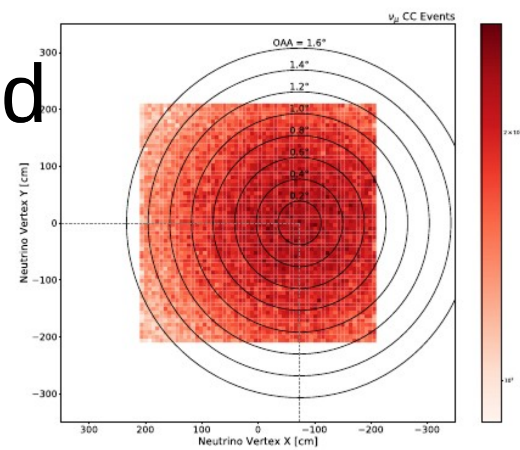
DUNE/SBND Comparison:

DUNE: 1° ≈ 10 m

SBND: 1° ≈ 2 m

Muon-neutrinos CC Events

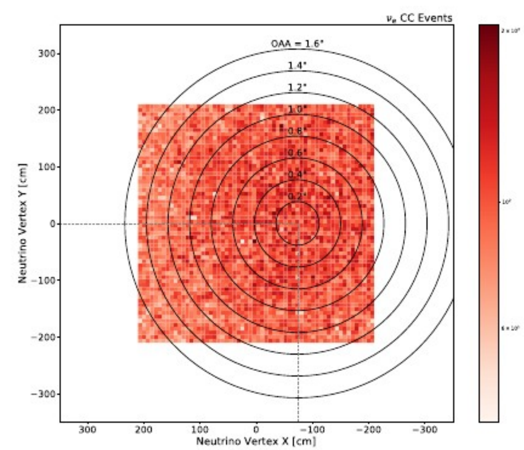
peak coincident with the on-axis position



Electron-neutrinos CC Events

distribution is almost constant

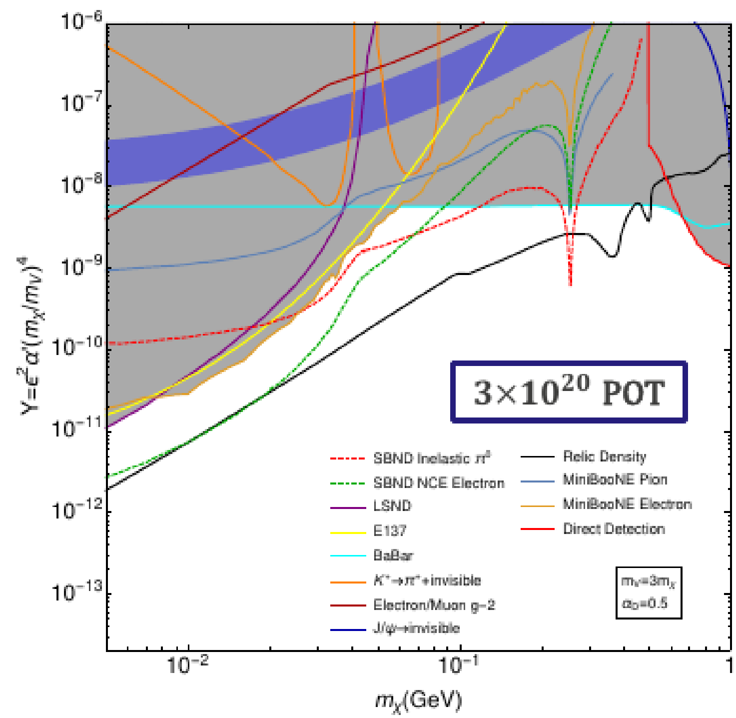
(angular distribution of ν_e is wider due to three-body decay)



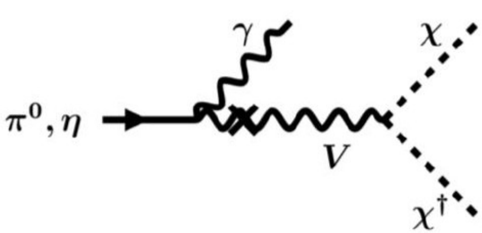
docdb#22196

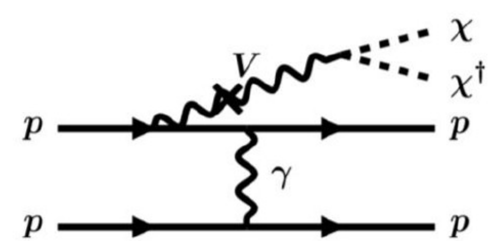
BSM searches in SBND

- SBND will also be able to look for sub-GeV DM candidates.
- A variety of channels: electron scattering, tridents, HNL decays.
- LArTPC is an excellent tool to resolve new topologies if they are there.
- This is in rapid development.

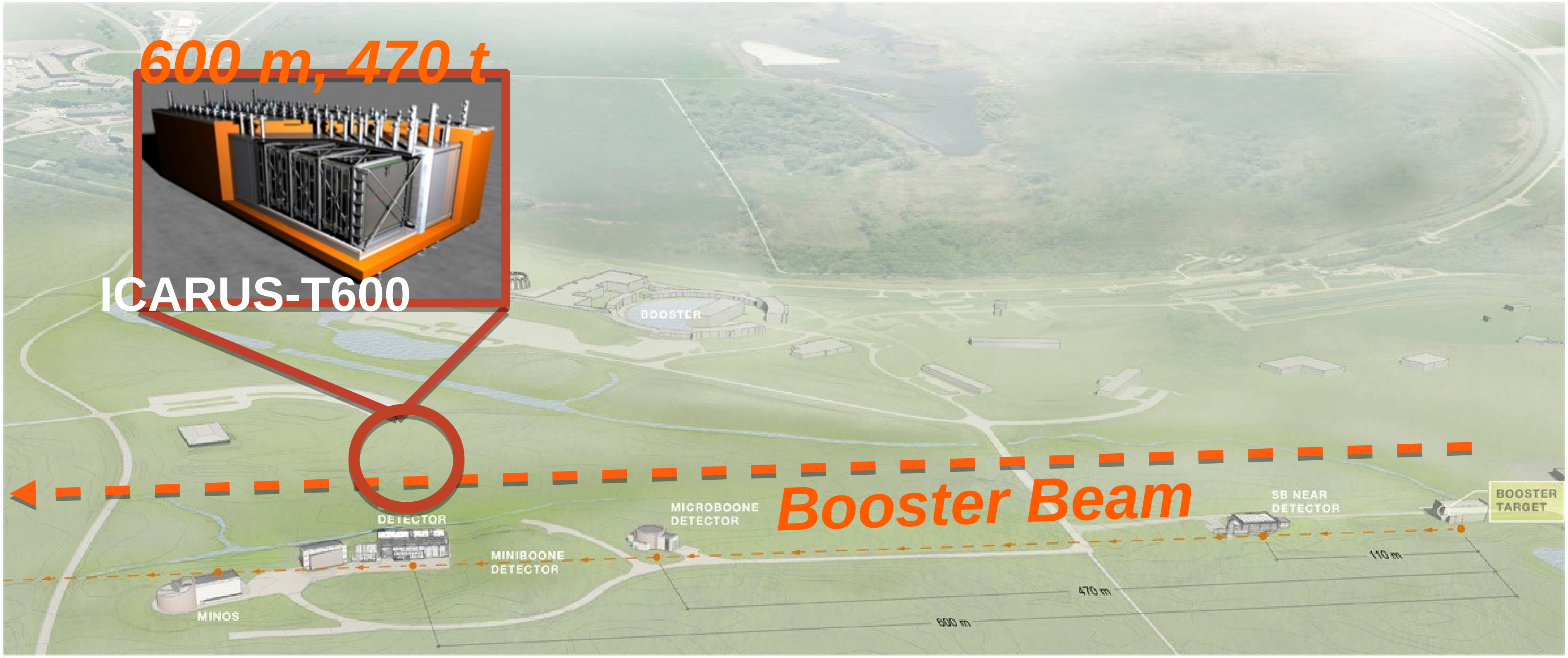


Vector Portal Light Dark Matter





ICARUS – The far detector



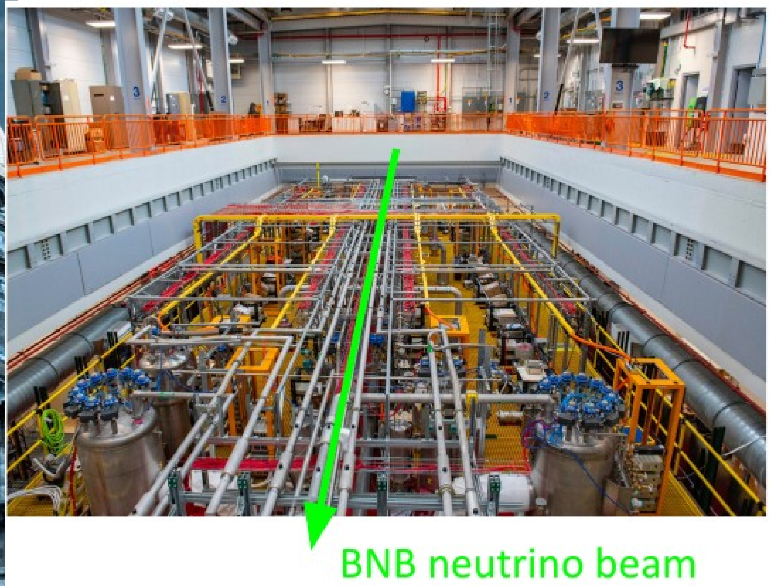
Given its large mass and relatively large distance from the source the ICARUS-T600 will have high sensitivity to neutrino oscillation effects.

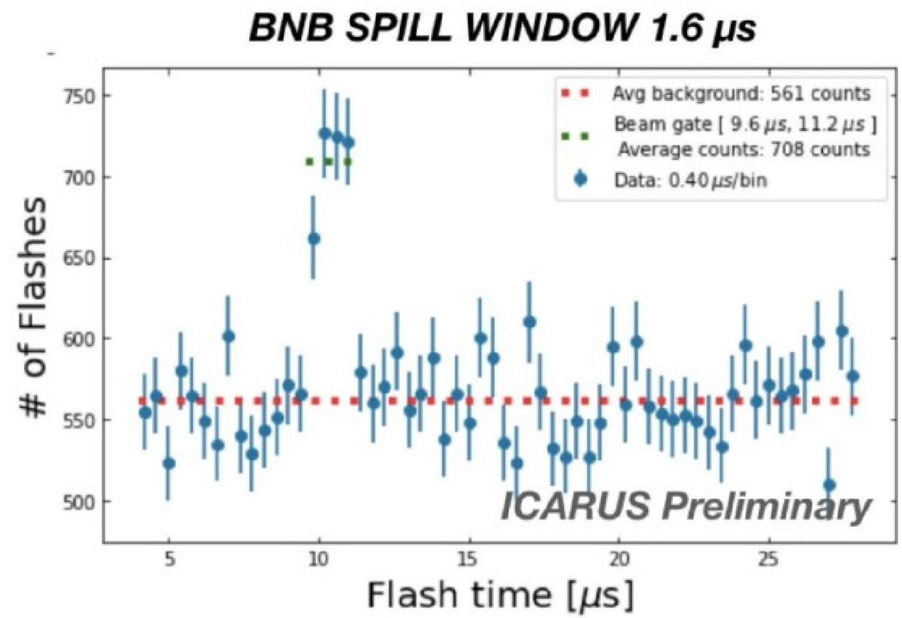
ICARUS

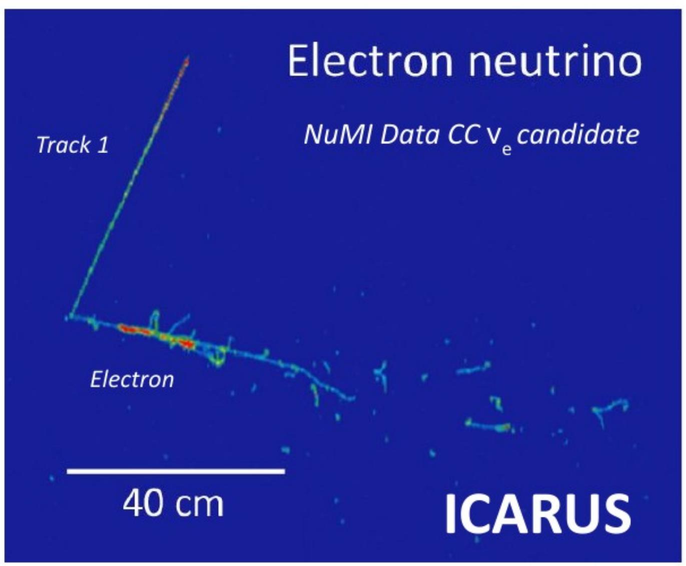
The ICARUS T600, after a succesful Run at Gran Sasso on the CNGS beam was transported to CERN for Refurbishment and then to Fermilab.

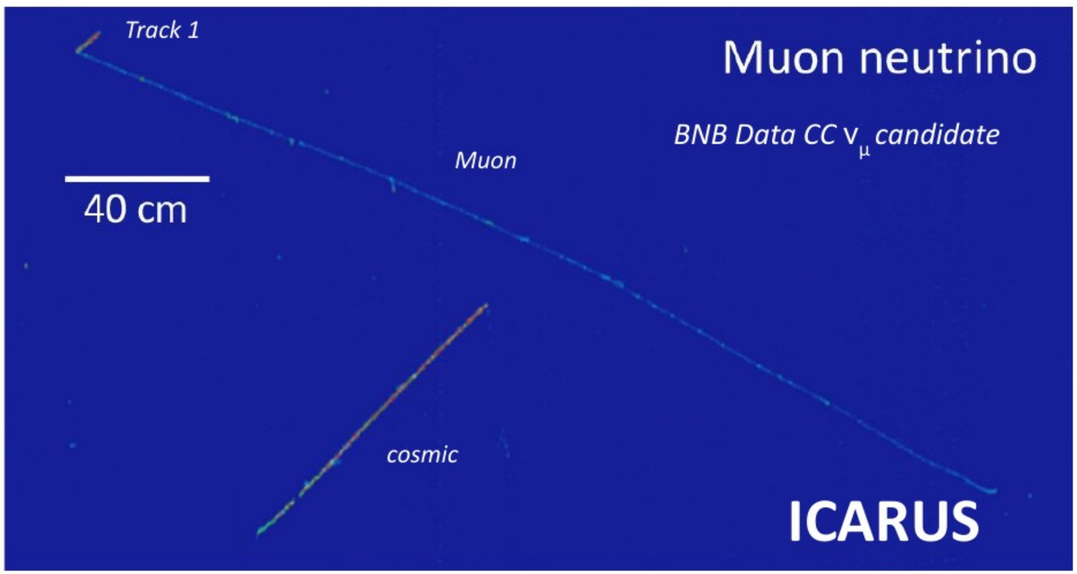
- Two cryostats: 760t total LAr mass / 476t active.
- Two TPCs per cryostat, with a common central cathode.
- Has been cool with liquid argon for over a year now.
- Calibration campaign ongoing

ICARUS- calibration







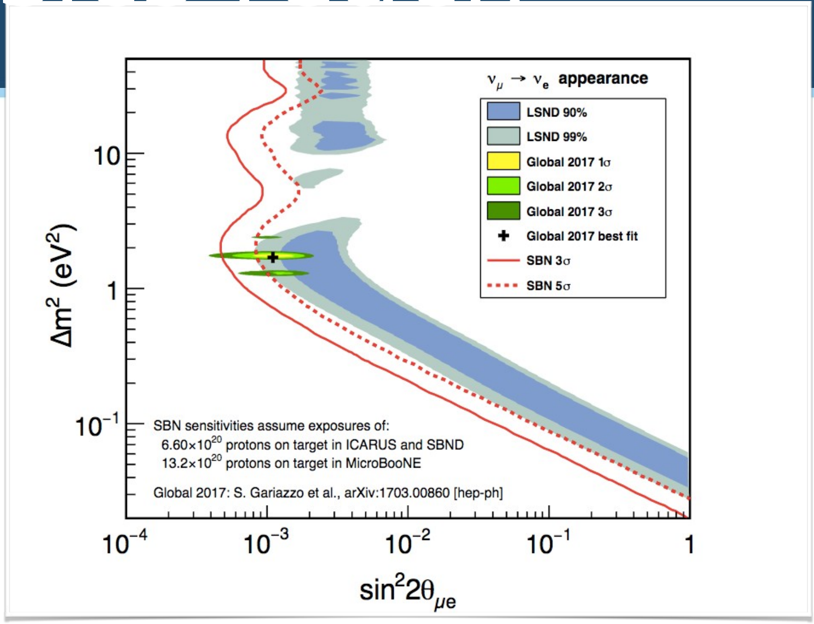


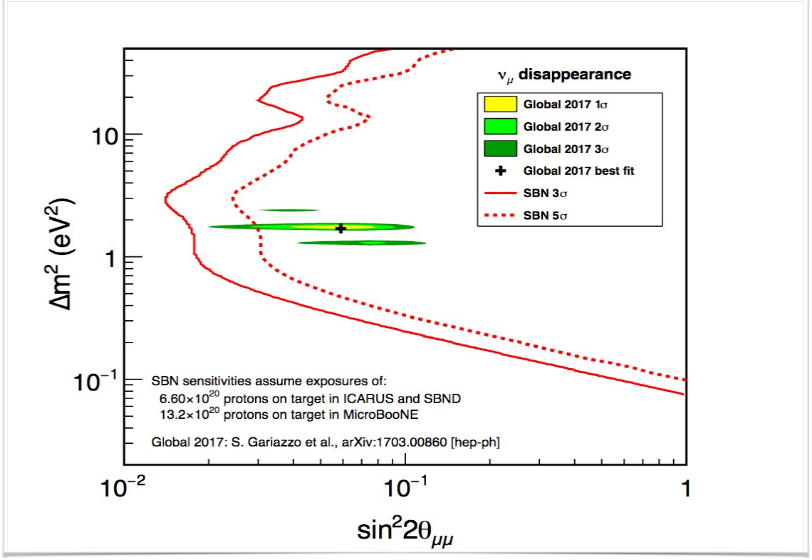
SBN Physics reach

Constraints on the flux and cross-sections from the near detector lead to a powerful combined exclusion region.

LSND parameter space excluded at 5σ.

In addition, SBN can also perform ν_μ disappearance searches. Would confirm an oscillation interpretation of any observed ν_e appearance signal.





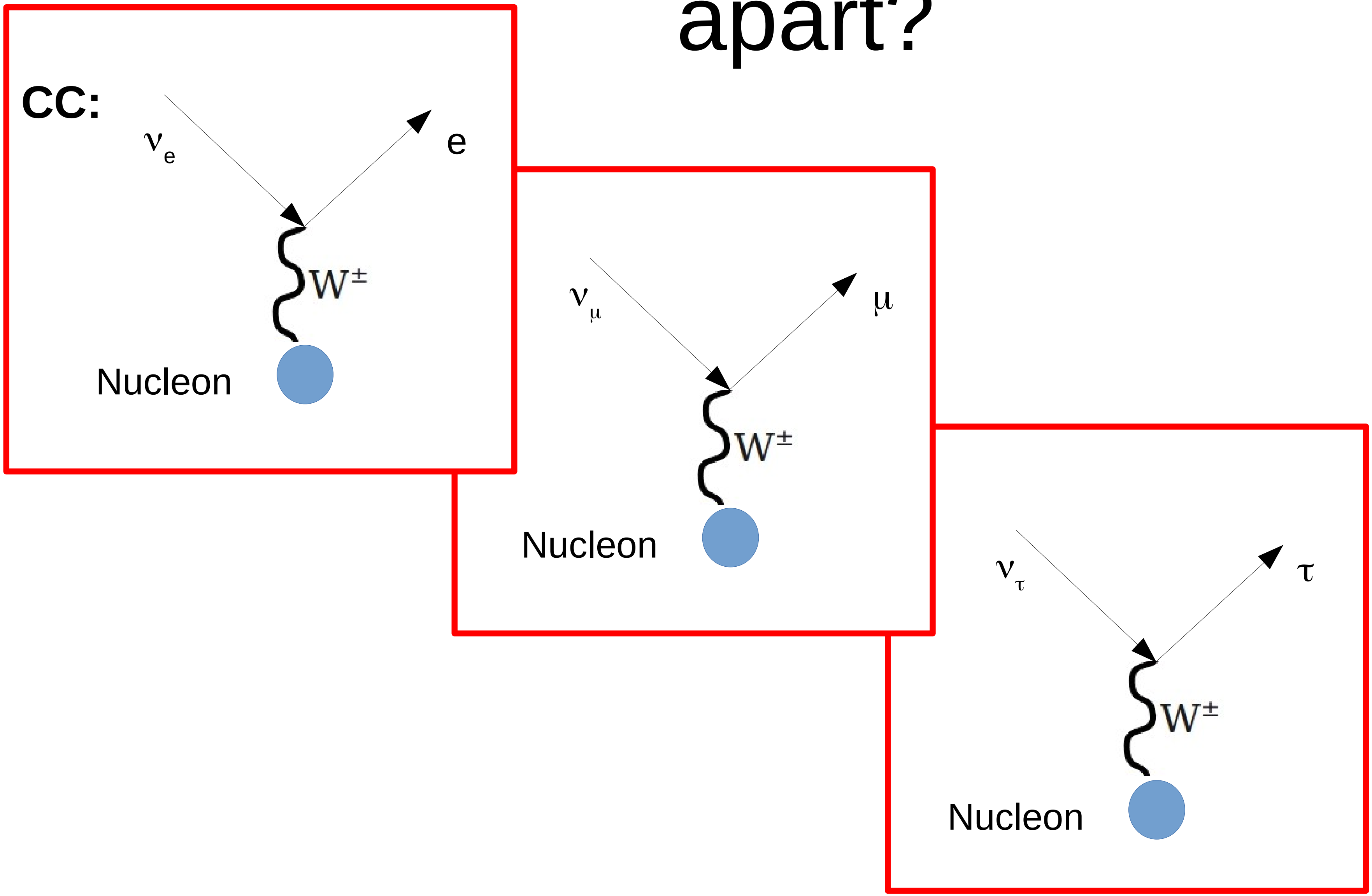
Fit from S. Gariazzo et al., arXiv:1703.00860

Summary

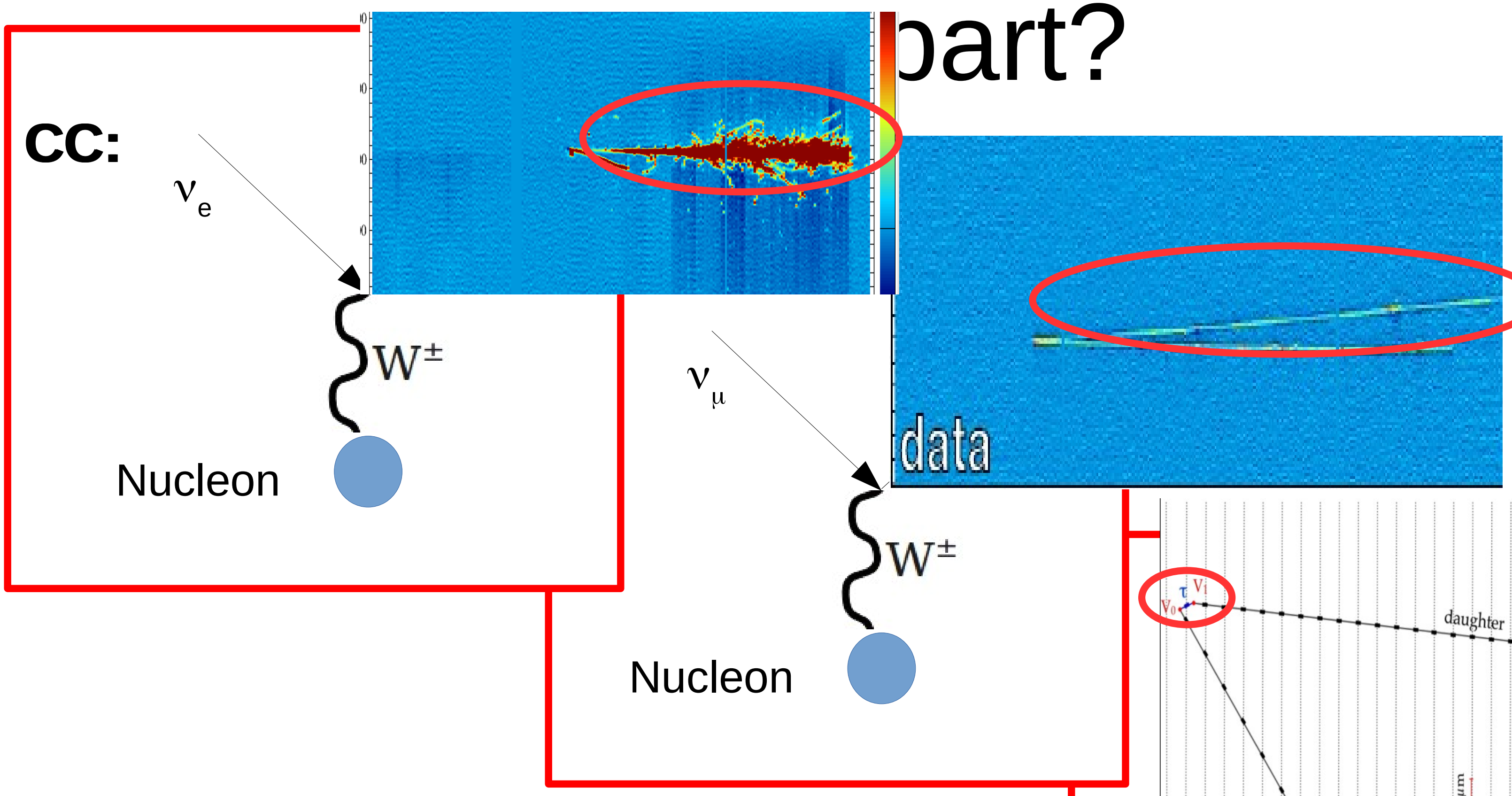
- SBN Programme is developing the technology and the physics measurements for DUNE.
- MicroBooNE already acquired a large data-set.
- ICARUS is currently in calibration phase
- SBND will start operation next year.

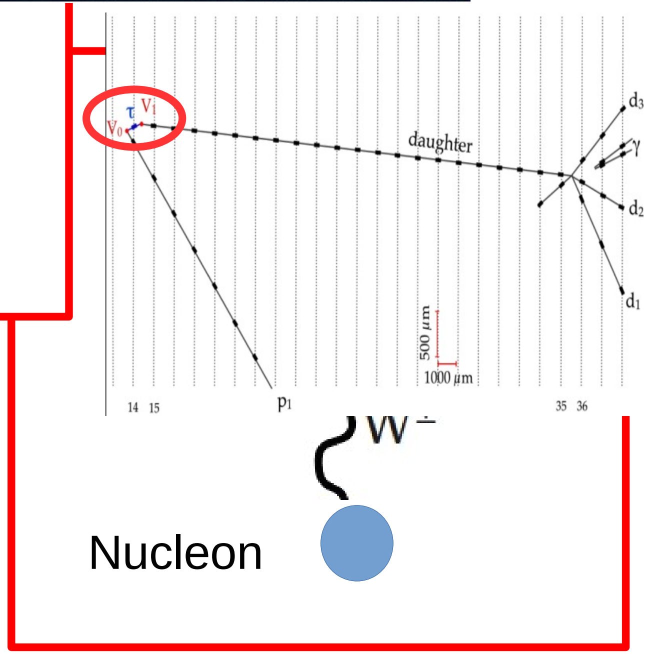
Back up

How do we tell neutrinos apart?



How do we tell neutrinos apart?





Neutrinos can also interact via Neutral Current (NC) or Elastic Scattering (ES) – but then we cannot tell which neutrino it was!