# MicroBooNE Electron-Neutrino Cross-Section Results

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on behalf of the MicroBooNE Collaboration



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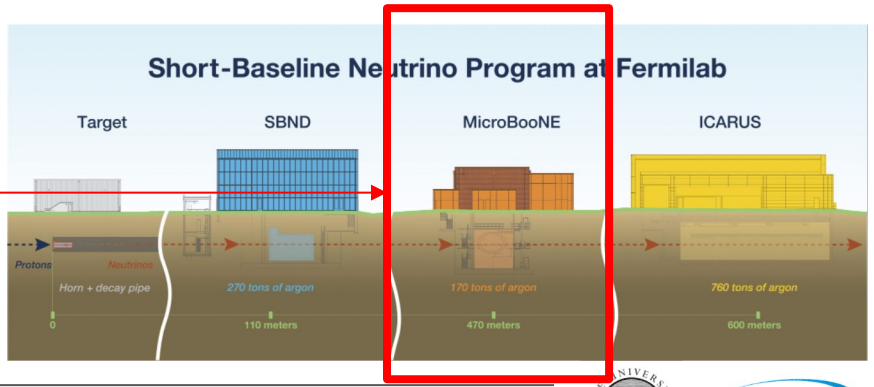
# Importance of the $\nu$-Ar cross section

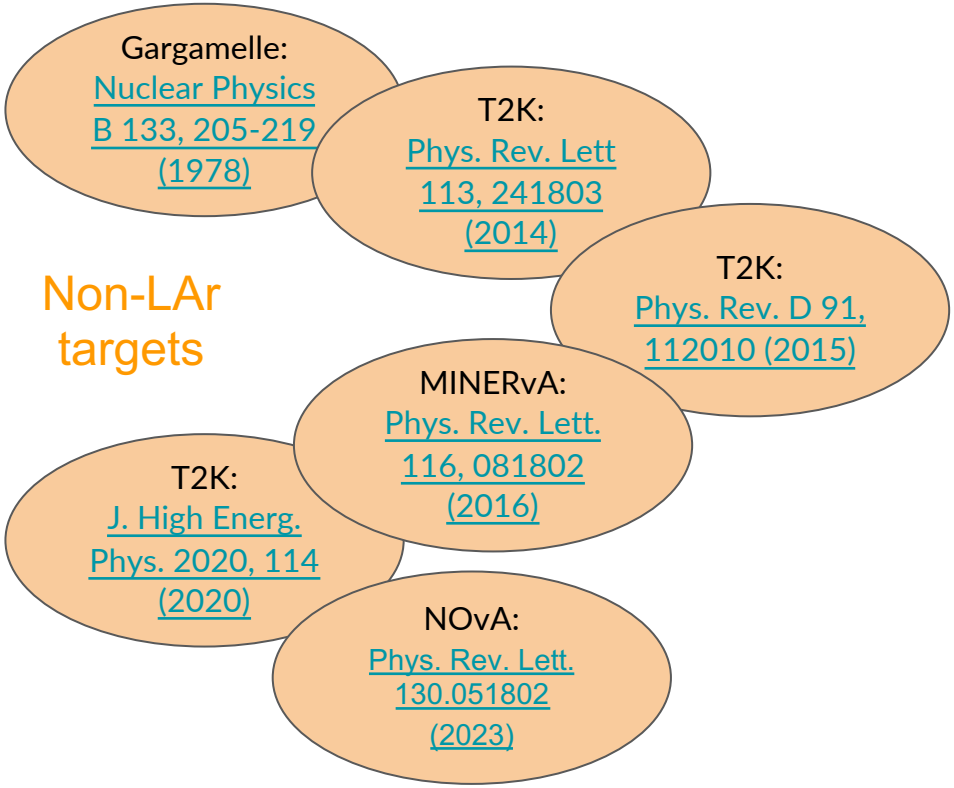
Measuring an **accurate** neutrino cross section is a key information for determining many of the neutrino oscillation parameters with more precision.

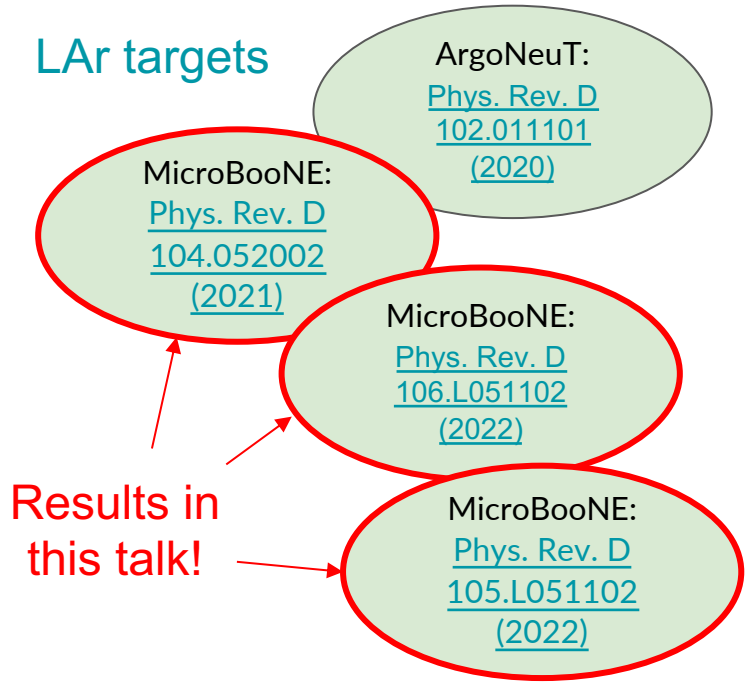
- Long baseline neutrino oscillation experiments' main channel is **$\nu_e$ appearance in a $\nu_\mu$ beam**
- Current and future neutrinos experiments employ the **Liquid Argon Time Projection Chamber** technology:
  - Deep Underground Neutrino Experiment (DUNE)
  - SBN Programme (SBND + **MicroBooNE** + ICARUS)

This talk will present the results from the MicroBooNE detector

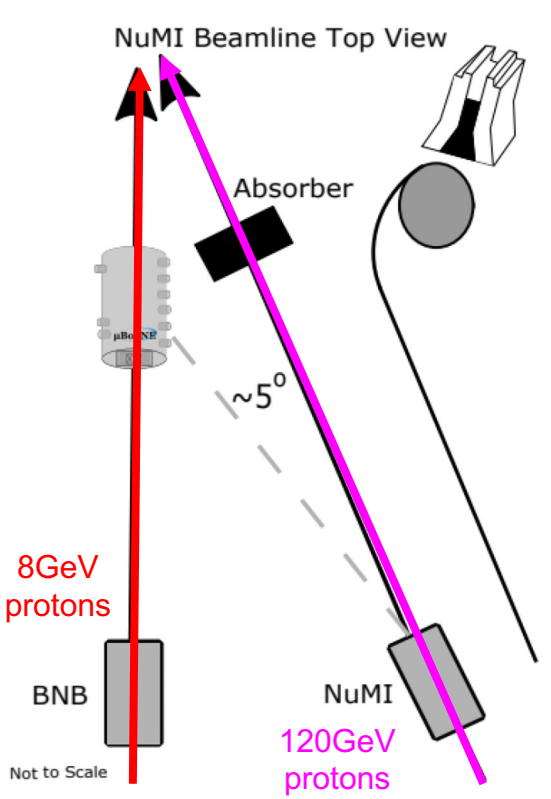


# Current picture of the $\nu_e$ cross section measurements



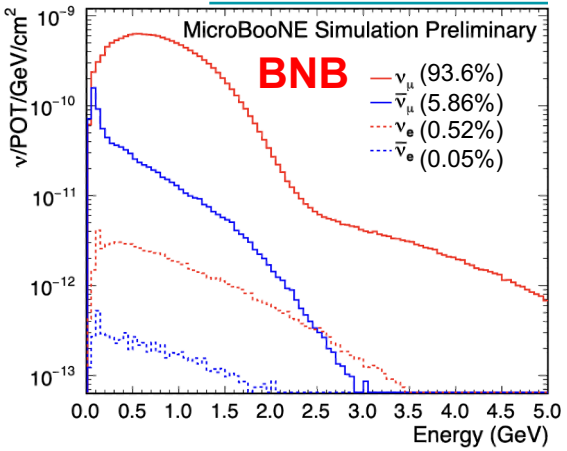
# MicroBooNE's neutrinos: BNB & NuMI



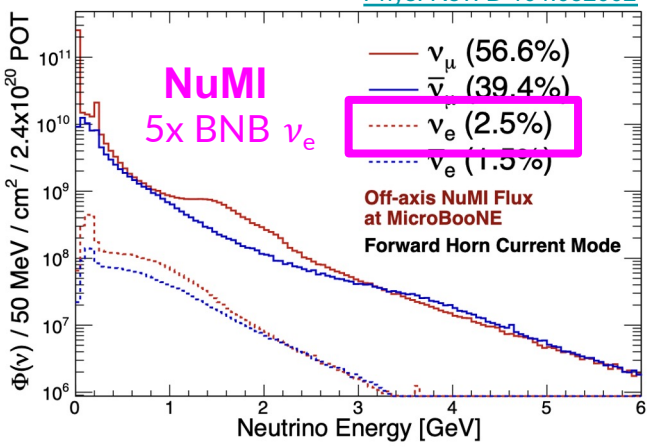

MicroBooNE's privileged location is:

- On-axis to the **Booster Neutrino Beam (BNB)**
- Off-axis to the **Neutrino in the Main Injector (NuMI)** beam

Fermilab-FNAL-Booster-E-0974

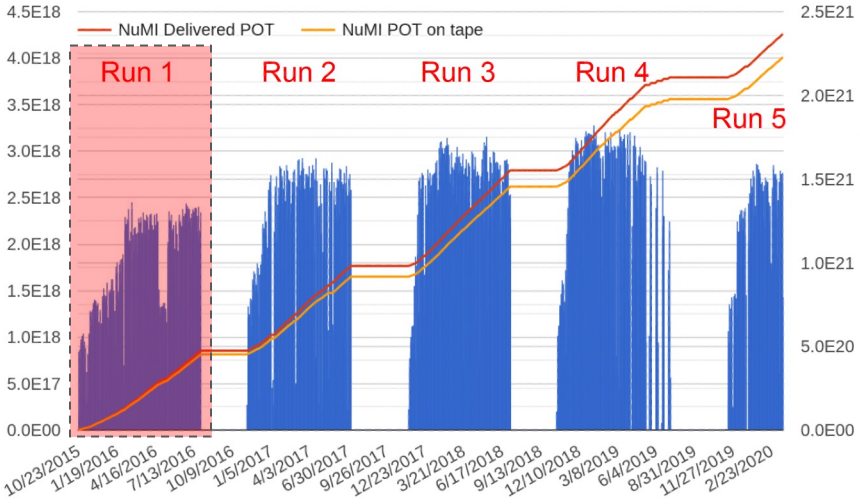



Phys. Rev. D 104.052002



# Five years of neutrino data!

2015 2020




Most of the results in this talk use only NuMI Run 1 data

Longest continuously operating LArTPC!

195 collaborators from 38 institutions!

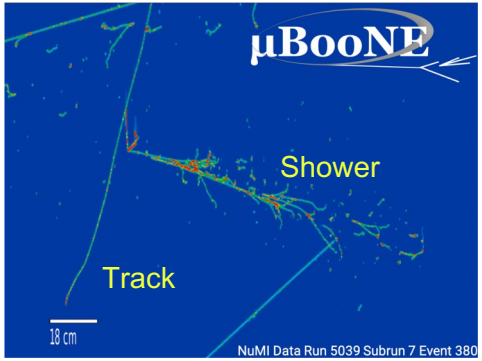
Most of the results in this talk use **NuMI Run 1 data** and will soon be performed using the full MicroBooNE dataset for a larger sample!

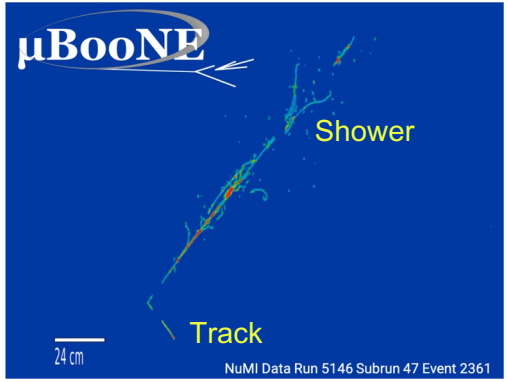
# Liquid Argon Time Projection Chamber

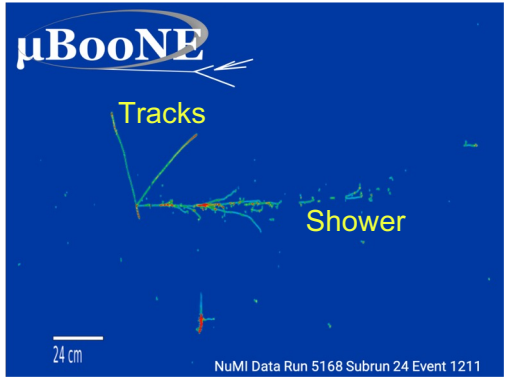
LArTPC talks today @ the Neutrino Physics session:
Miquel Nebot-Guinot (581)
Rodrigo Alvarez-Garrote (637)
Ines Gil Botella (1077)
Richard Diurba (737)
Michael Kirby (738)
Jingyuan Shi (1057)

The MicroBooNE detector is a Liquid Argon Time Projection Chamber (LArTPC):

- Signature: tracks and showers!
- Milimeter spatial resolution
- Excellent calorimetry
- Electron vs photon-induced showers



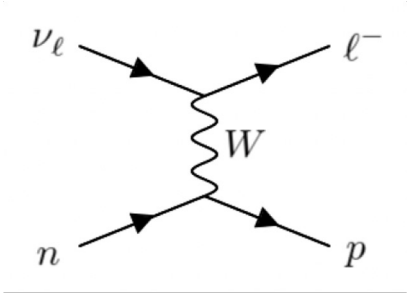



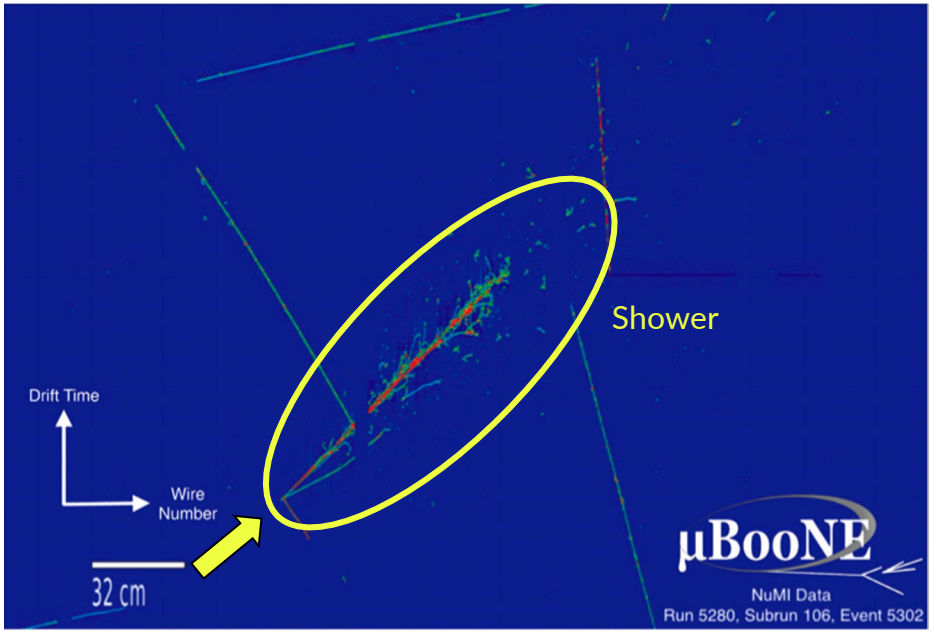

Colour scale is proportional to the amount of deposited energy.

# Signal definition and background removal

All of the results in this talk are **charged-current** cross section measurements, because they allow us to uniquely identify the incoming neutrino flavour by identifying the corresponding produced lepton!

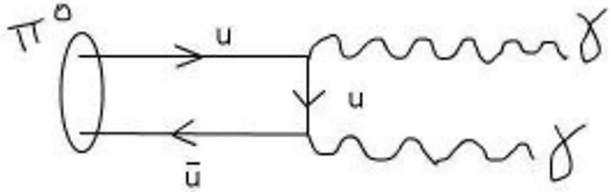



Electron-neutrino charged-current interactions produce an **electron**, whose signature is a **shower**!

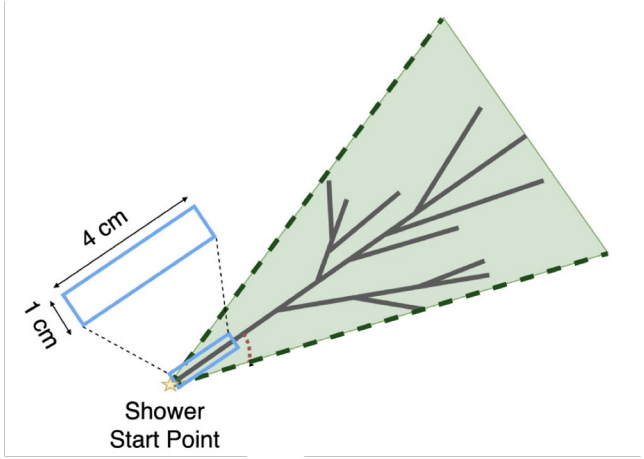


# Main background: $\pi^0$ decays

One of the main backgrounds in $\nu_e$CC searches are neutral pions decay!



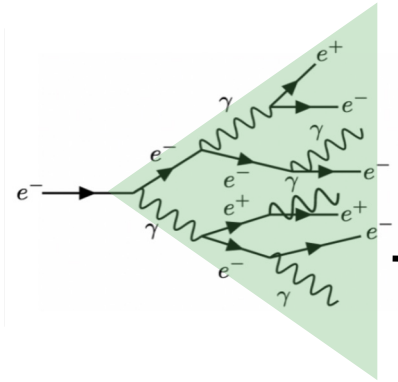

Photons also produce showers in LArTPCs!

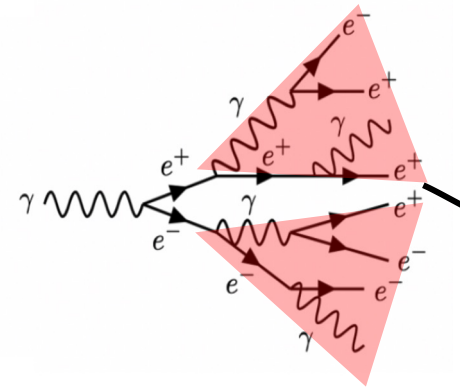



LArTPCs are powerful technologies in distinguishing electron-induced from photon-induced showers, by analysing the first centimeters of the shower!

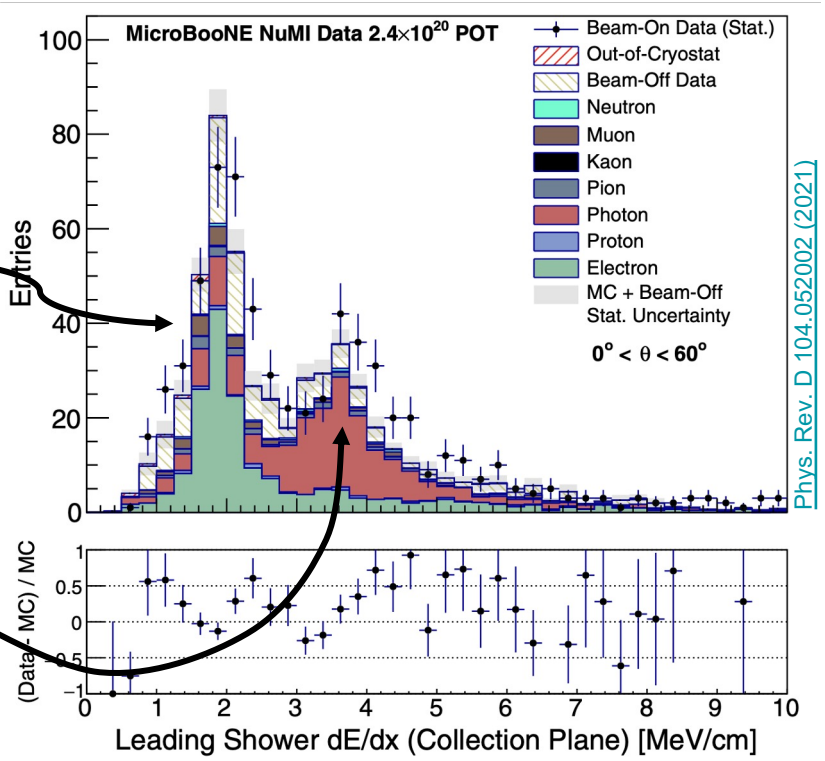
# Electron-photon separation - calorimetry

Method 1:
Measuring the dE/dx of the start of the electromagnetic shower





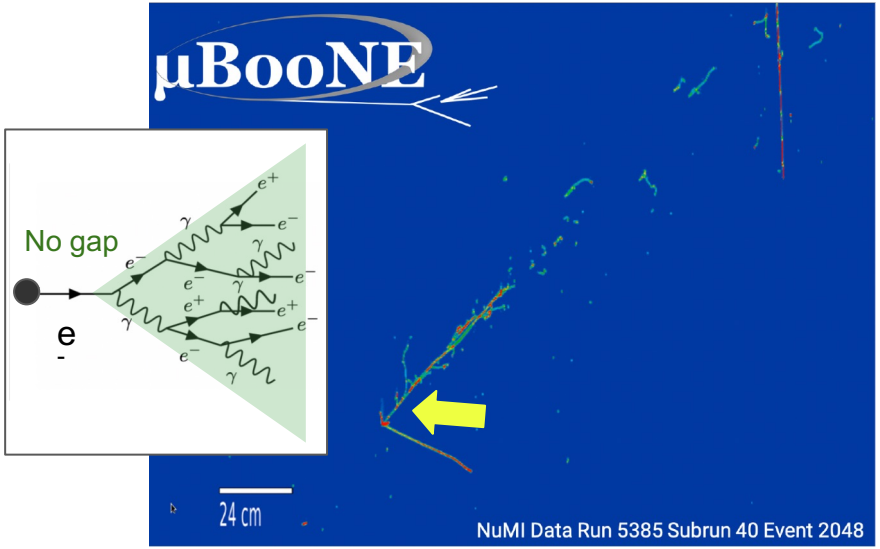
Photon-induced showers are the same as two electron-induced showers!

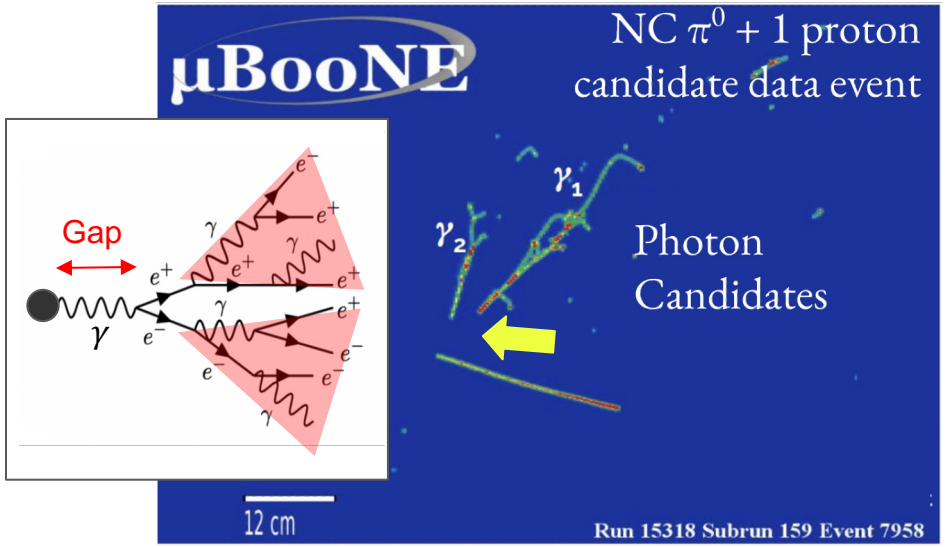


# Electron-photon separation - gap

Method 2:

Measuring the gap between the interaction vertex
and the start of the electromagnetic shower



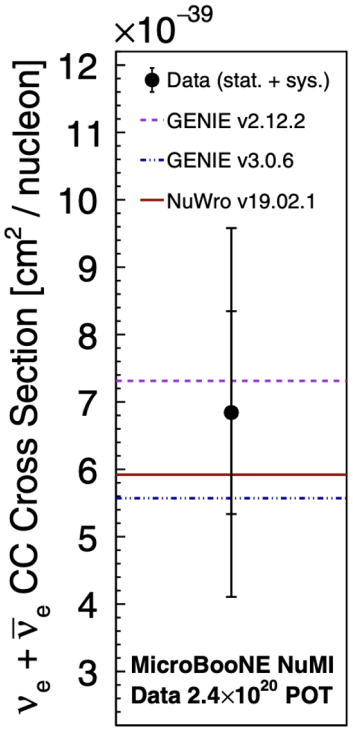
# Cross section results!

**"Measurement of the flux-averaged inclusive charged-current electron neutrino and antineutrino cross section on argon using the NuMI beam and the MicroBooNE detector"**

Phys. Rev. D 104.052002 (2021)

First time that the electron-photon separation technique that the LArTPC offers and a fully automated analysis chain is used!

**214 selected** $\nu_e$ and $\bar{\nu}_e$ CC events in data, using less than ⅕ of the available **NuMI beam**




Mean flux energy of 905 MeV, calculated by integrating the flux from 250 MeV.

$$\langle\sigma\rangle = 6.84 \pm 1.51(\text{stat}) \pm 2.33(\text{sys}) \times 10^{-39} \frac{\text{cm}^2}{\text{nucleon}}$$

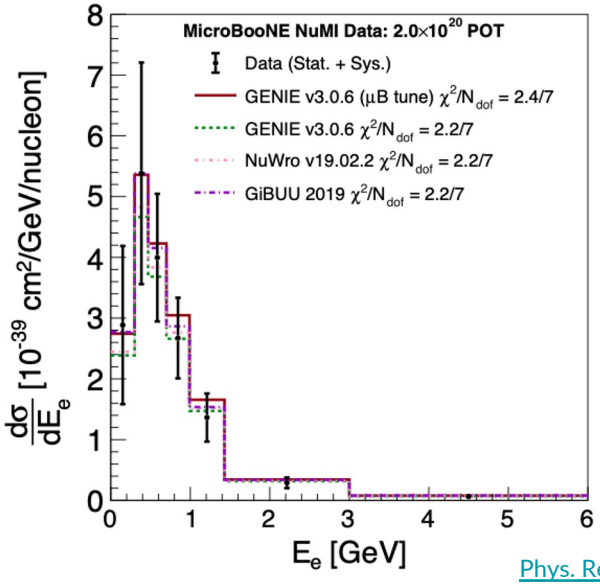
**"First measurement of inclusive electron-neutrino and antineutrino charged current differential cross sections in charged lepton energy on argon in MicroBooNE"**

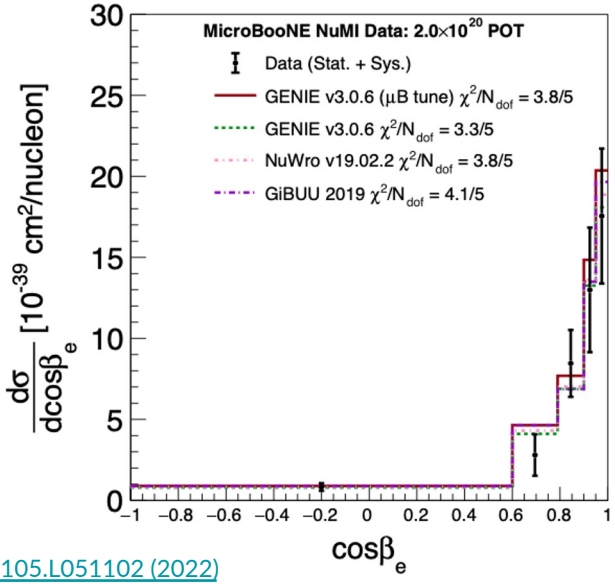
Phys. Rev. D 105.L051102 (2022)

This analysis uses **NuMI beam** data operated in neutrino mode: 2.0x10$^{20}$POT

**243 selected** events in data, **largest sample to date**!

First differential $\nu_e$CC cross-section measurement in **charged lepton energy**!




Phys. Rev. D 105.L051102 (2022)

**"Differential cross section measurement of charged current $\nu_e$ interactions without final-state pions in MicroBooNE"**

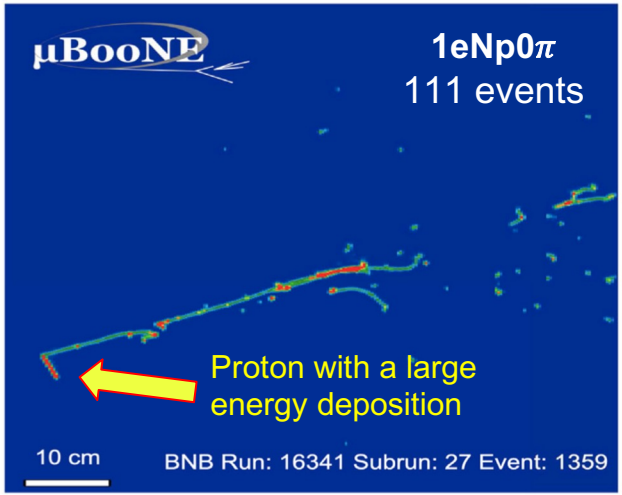
Phys. Rev. D 106.L051102 (2022)

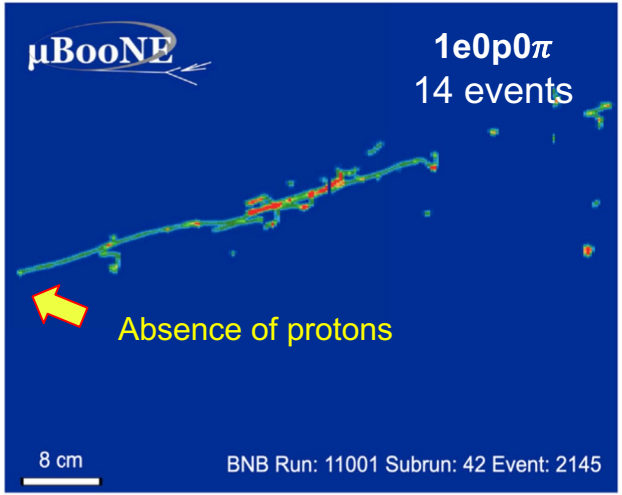
Neutrinos coming from the **BNB beam**: **6.86x10$^{20}$ POT**

**First analysis using data from all five runs of MicroBooNE!**

Signal definition: True $\nu_e$ CC, $KE_e$> 30 MeV, $KE_\pi$< 40 MeV and no $\pi^0$

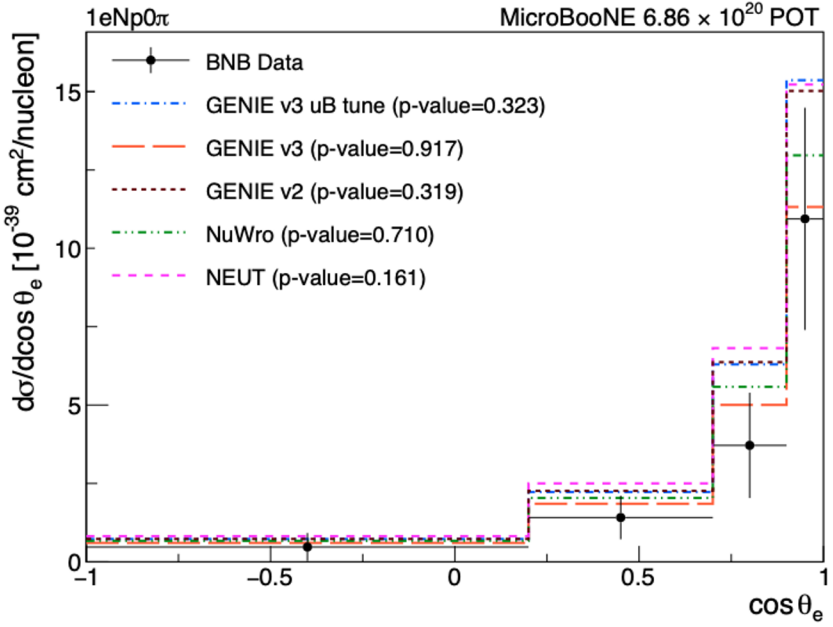
1. If $KE_p \geq$ 50 MeV ⇒ event classified as **1eNp0$\pi$**
2. Else if $KE_p$< 50 MeV or no protons, $E_e^{reco}$>0.5GeV, cos$\theta_e$>0.6 ⇒ event classified as **1e0p0$\pi$**

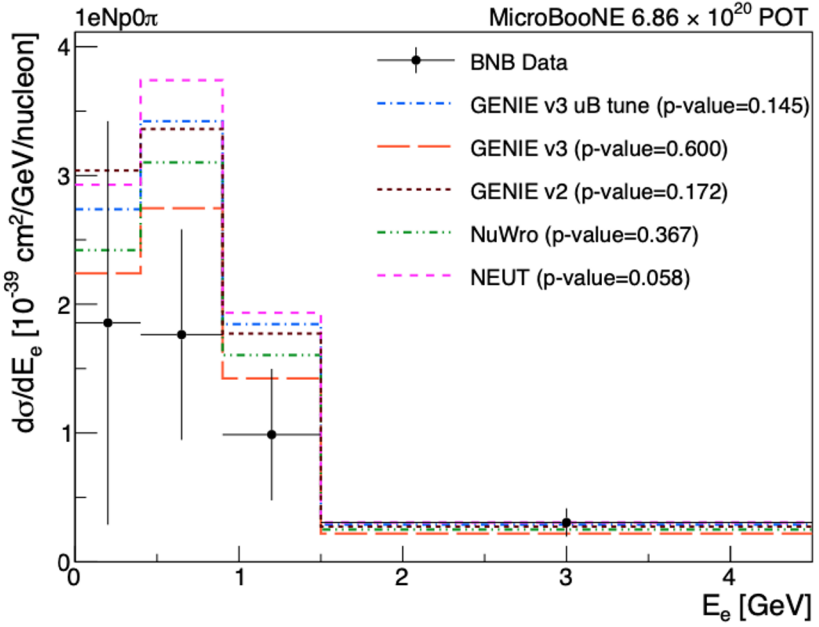


## "Differential cross section measurement of charged current $\nu_e$ interactions without final-state pions in MicroBooNE"

Phys. Rev. D 106.L051102 (2022)



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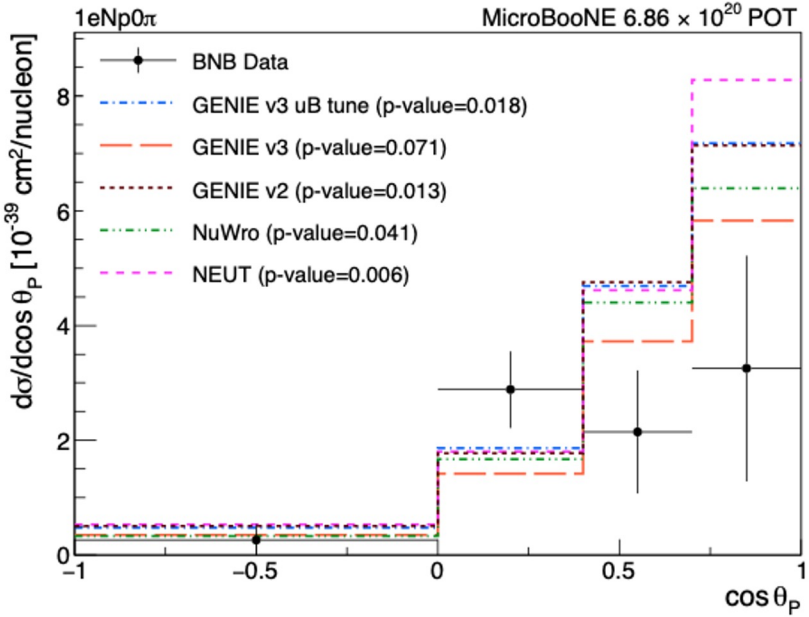
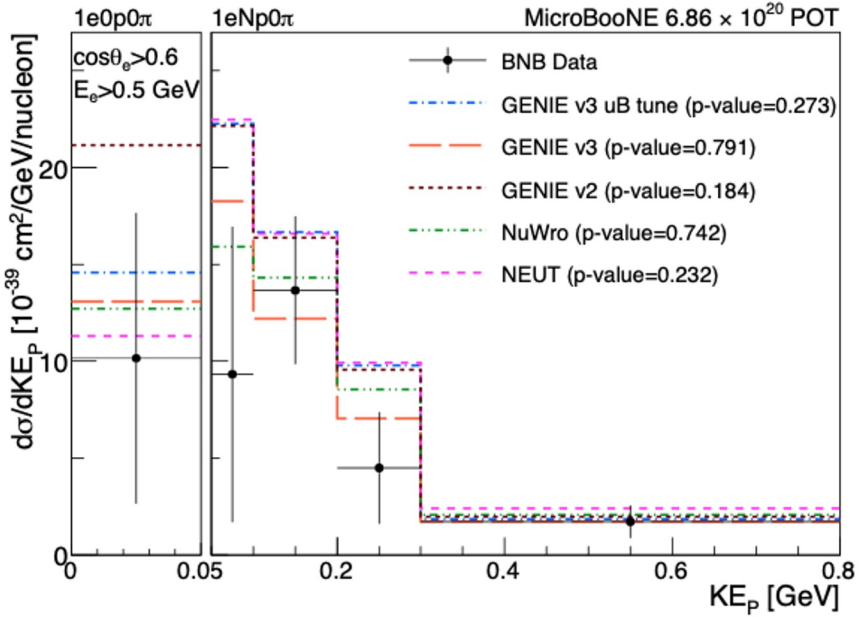


# Updated NuMI flux

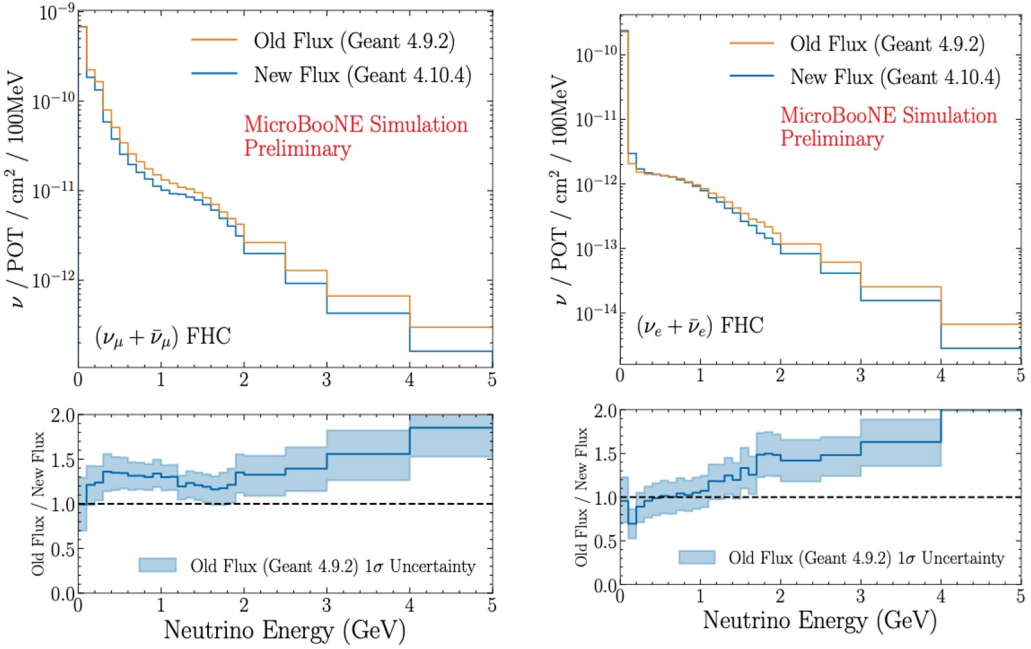
# Updated NuMI flux at MicroBooNE

Close investigation motivated by a geometry bug found simulating the neutrino flux

Main updates:

- Implementation of missing shielding from the GDML description of the NuMI beamline
- Significant improvement of hadron production modelling in Geant 4.10
- Small impact on-axis

Ongoing NuMI analyses paused during investigation and are being updated to use new NuMI flux




Updated NuMI flux at MicroBooNE
More details in MICROBOONE-NOTE-1129-PUB

# Published cross-section measurements

Results covered today!

**CC inclusive**

- 1D $\nu_\mu$ CC inclusive @ BNB, Phys. Rev. Lett. 123, 131801
- 1D $\nu_\mu$ CC $E_\nu$ @ BNB, Phys. Rev. Lett. 128, 151801
- 3D CC $E_\nu$ @ BNB, arXiv:2307.06413
- 1D $\nu_e$ CC inclusive @ NuMI, Phys. Rev. D104, 052002, Phys. Rev. D105, L051102
- 2D $\nu_\mu$ CC0pNp inclusive @ BNB, arXiv:2402.19216, arXiv:2402.19281

**Pion production**

- $\nu_\mu$ NC$\pi^0$ @ BNB, Phys. Rev. D 107, 012004
- 2D $\nu_\mu$ NC$\pi^0$ @ BNB, arXiv:2404.10948
- $\nu_\mu$ CC$\pi^0$ @ BNB, arXiv:2404.09949

See more results later today!

Muon neutrino inclusive and pionless channels, Richard Diurba, 17:00

Muon neutrinos with pions in the final state and rare processes, Michael Kirby, 17:15

**CC0π**

- 1D $\nu_e$ CCNp0π @ BNB, Phys. Rev. D 106, L051102
- 1D & 2D $\nu_\mu$ CC1p0π transverse imbalance @ BNB, Phys. Rev. Lett. 131, 101802, Phys. Rev. D 108, 053002
- 1D & 2D $\nu_\mu$ CC1p0π generalized imbalance @ BNB, Phys. Rev. D 109, 092007
- 1D $\nu_\mu$ CC1p0π @ BNB, Phys. Rev. Lett. 125, 201803
- 1D $\nu_\mu$ CC2p @ BNB, arXiv:2211.03734
- 1D $\nu_\mu$ CCNp0π @ BNB, Phys. Rev. D102, 112013
- 2D $\nu_\mu$ CCNp0π @ BNB, arXiv:2403.19574

**Rare channels & novel identification techniques**

- η production @ BNB, Phys. Rev. Lett. 132, 151801
- Λ production @ NuMI, Phys. Rev. Lett. 130, 231802
- Neutron identification, arXiv:2406.10583

# Ongoing cross section measurements

Much more data available!!!

**CC inclusive**

- $\nu_\mu$ CC inclusive @ **NuMI**
- **$\nu_e$** /$\nu_\mu$ ratios @ BNB, **NuMI**
- 3D $E_\nu$, $E_\mu$, hadronic energy @ **NuMI** & BNB
- **anti-$\nu_e$** @ **NuMI**

**Pion production**

- $\nu_\mu$ CC1$\pi^+$ @ BNB, **NuMI**
- $\nu_\mu$ CCN$\pi$ @ **NuMI**
- 1D $\nu_\mu$ CC$\pi^0$ @ BNB
- 2D $\nu_\mu$ CC/NC $\pi^0$ @ BNB
- 2D **$\nu_{e,\mu}$** NC$\pi^0$ @ BNB

**CC0π**

- 2D $\nu_\mu$ CC1p0π Generalized Kinematic Imbalance @ BNB
- $\nu_\mu$ CC0π inclusive @ BNB
- 2D $\nu_\mu$ CCNp0π @ BNB
- 1D **$\nu_e$** CC0πNp @ **NuMI**
- 1D $\nu_\mu$ NC1p0π @ BNB

**Rare & novel channels**

- $\nu_\mu$ CC Kaon @ BNB, **NuMI**
- MeV-scale Physics in MicroBooNE
- Neutrons @ BNB

NuMI analyses are being updated to use the new NuMI flux!

There are many ongoing electron-neutrino cross-section measurements!

# Conclusions

Electron-neutrino cross-section measurement is one of the key studies to better understand neutrino oscillations!

MicroBooNE offers an unique and privileged condition to perform electron-neutrino cross-section measurements!

We have published three $\nu_e$CC cross-section measurements!

- The results are not affected by the updated NuMI flux
- All of them are statistically limited
- We want to use our full NuMI dataset to make higher stat measurements
- There is more to learn and much more that we can learn with the full dataset

Stay tuned for more electron-neutrino cross-section measurements with MicroBooNE!

# Thank you!

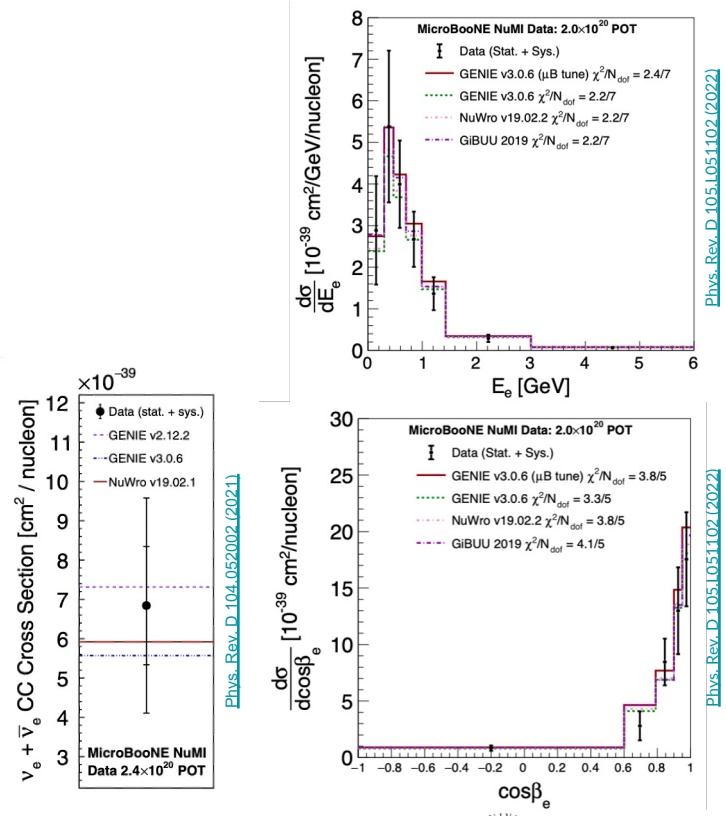
# Back-up slides

# Updated NuMI flux at MicroBooNE: validation

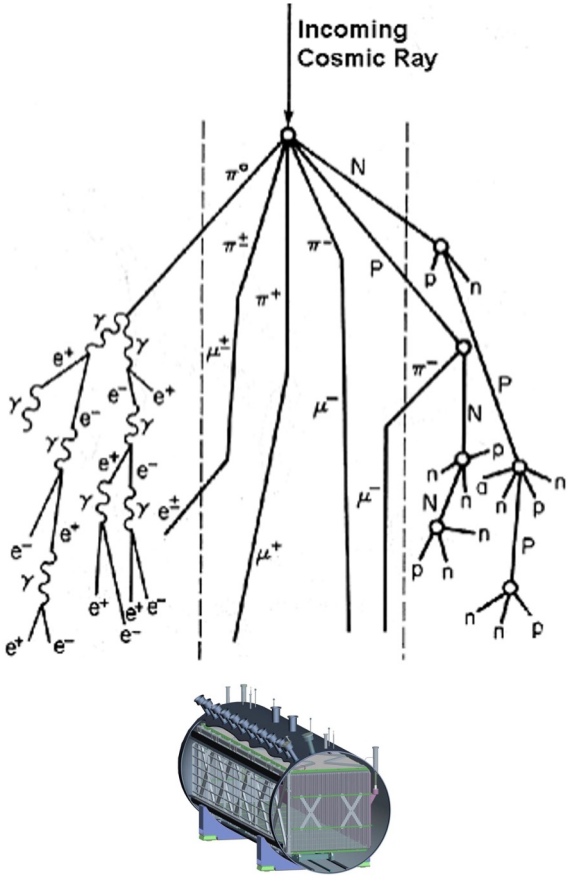
Published NuMI results (Phys. Rev. D 104.052002 and Phys. Rev. D 105.L051102) not affected by the updated NuMI flux!

Fake studies were done suggesting that our electron-neutrino cross-section measurements are not sensitive to the difference between flugg (without flux bug) and dk2nu, two flux predictions, and therefore not sensitive to the changes due to the updated NuMI flux

Ongoing analyses are being updated to use the new NuMI flux!



# Main background: Cosmic rays




MicroBooNE is a **surface detector** and therefore has a large cosmic ray contamination in data!

Cosmic ray rejection is necessary in every neutrino analysis!

1. **Flash-matching**: beam-induced neutrino events are in-time with the neutrino beam spill, most of the cosmic rays are not
2. **Containment**: tracks should have initial and final points inside the detector, otherwise event is rejected