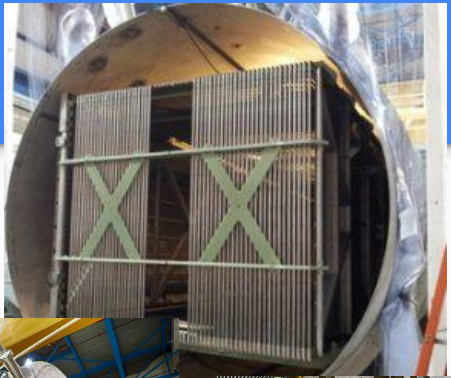
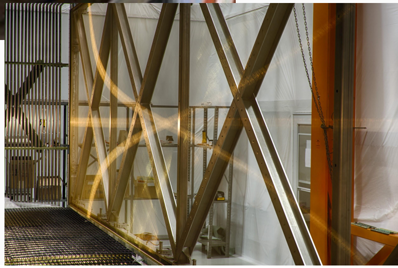
Investigating the MiniBooNE excess using MicroBooNE's data

Nicolò Foppiani - Harvard University
On behalf of the MicroBooNE collaboration

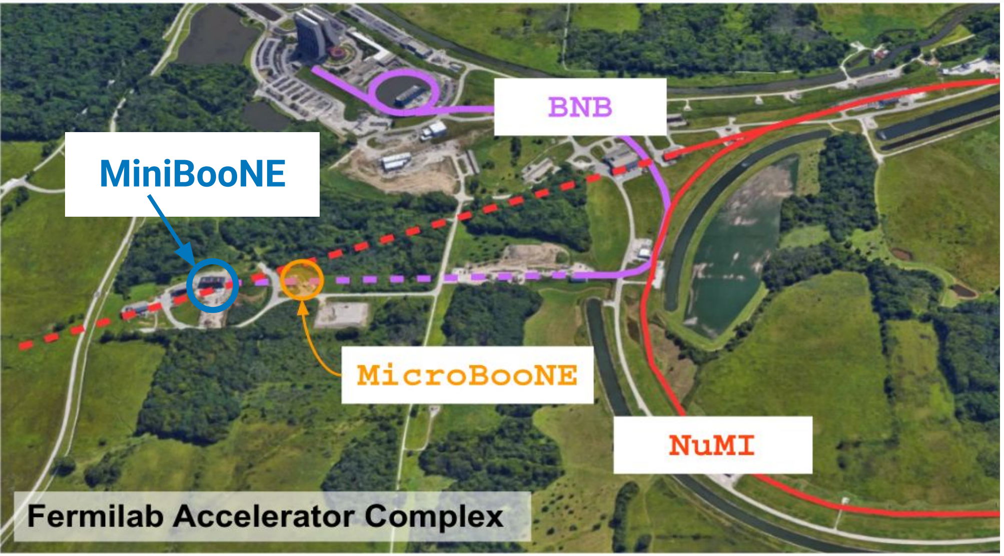
Lake Louise Winter institute
February 23rd, 2022

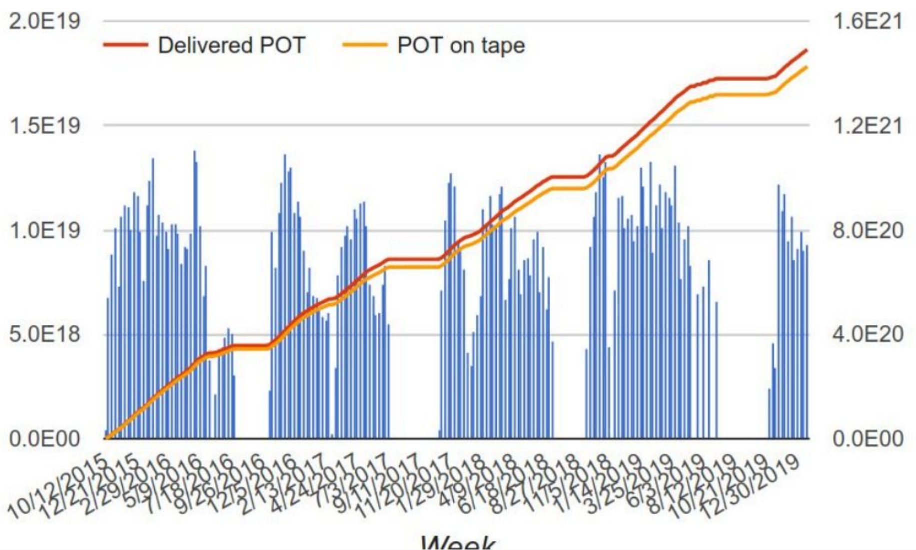
The MicroBooNE detector





- Located at Fermilab, close to MiniBooNE
- Longest running large-scale Liquid Argon Time Projection Chamber
- O(500K) ν interactions collected



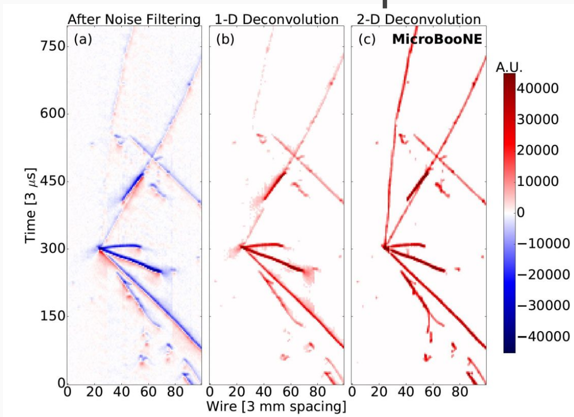


MicroBooNE physics reach

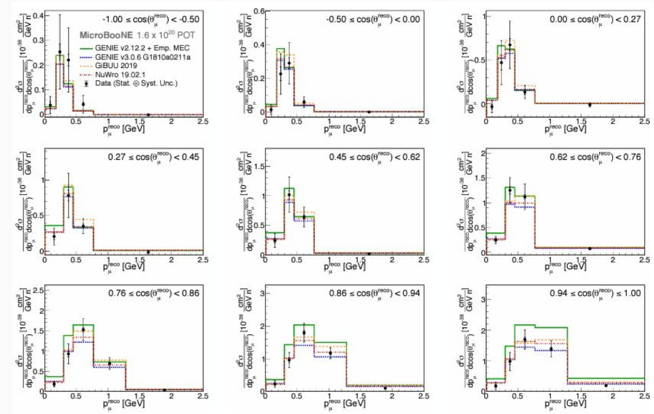
See Kirsty's talk for more info!

LArTPC development

JINST 15, P03022 (2020)
JINST 13, P07006 (2018)
JINST 13, P07007 (2018)



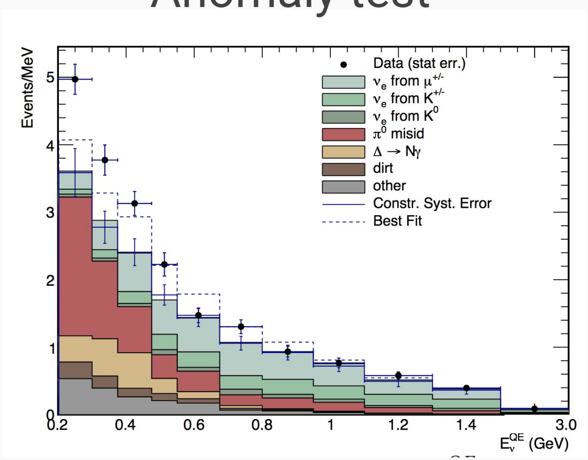
ν-Ar cross sections



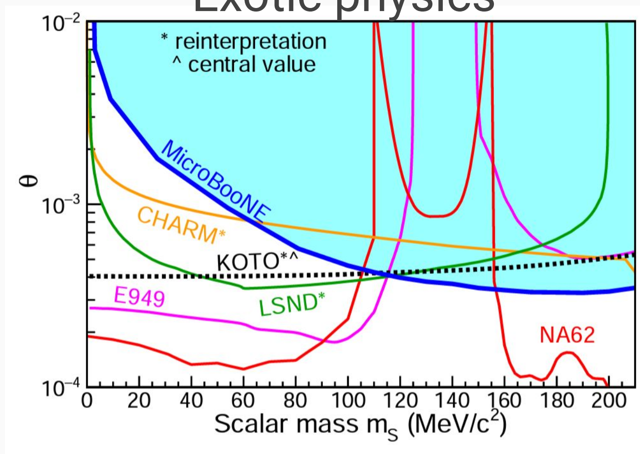
Phys. Rev. D99, 091102(R) (2019)
Phys. Rev. Lett. 125, 201803 (2020)
Phys. Rev. Lett. 125, 201803 (2020)

Anomaly test

arXiv:2110.14054, submitted to PRL
arXiv:2110.13978, submitted to PRD
arXiv:2110.14065, accepted by PRD
arXiv:2110.14080, submitted to PRD
arXiv:2110.00409, accepted by PRL



Exotic physics



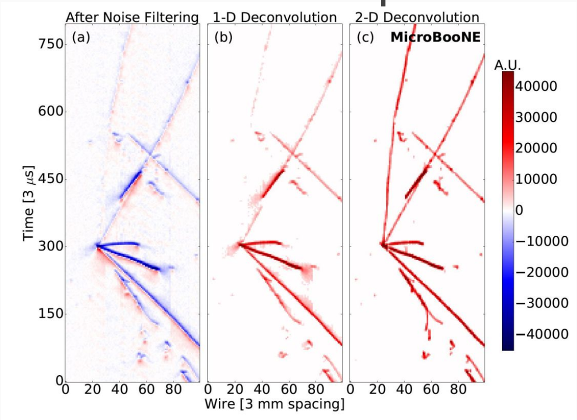
Phys. Rev. D101, 052001 (2020)
Phys. Rev. Lett. 127, 151803 (2021)

MicroBooNE physics reach

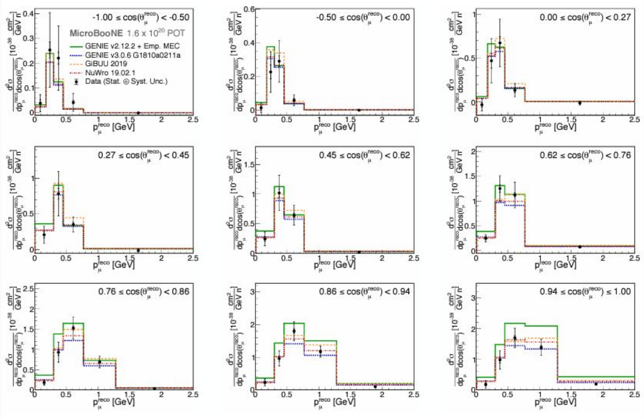
See Kirsty's talk for more info!

LArTPC development

JINST 15, P03022 (2020)
JINST 13, P07006 (2018)
JINST 13, P07007 (2018)



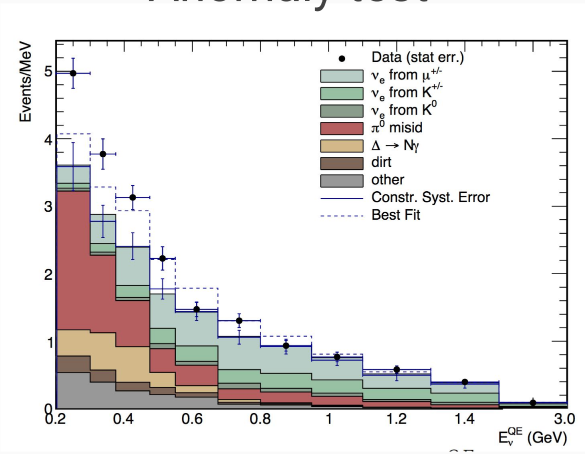
ν-Ar cross sections



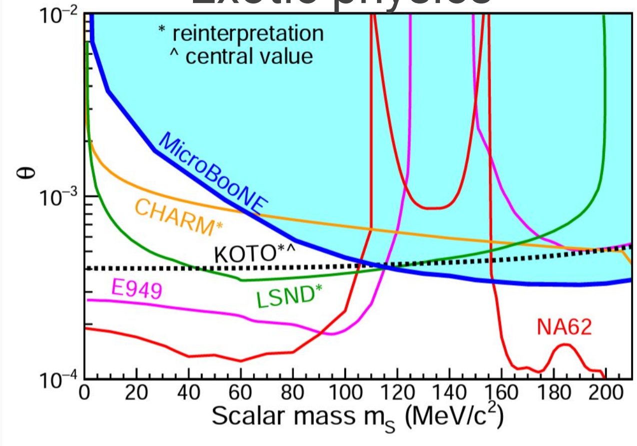
Phys. Rev. D99, 091102(R) (2019)
Phys. Rev. Lett. 125, 201803 (2020)
Phys. Rev. Lett. 125, 201803 (2020)

Anomaly test

arXiv:2110.14054, submitted to PRL
arXiv:2110.13978, submitted to PRD
arXiv:2110.14065, accepted by PRD
arXiv:2110.14080, submitted to PRD
arXiv:2110.00409, accepted by PRL



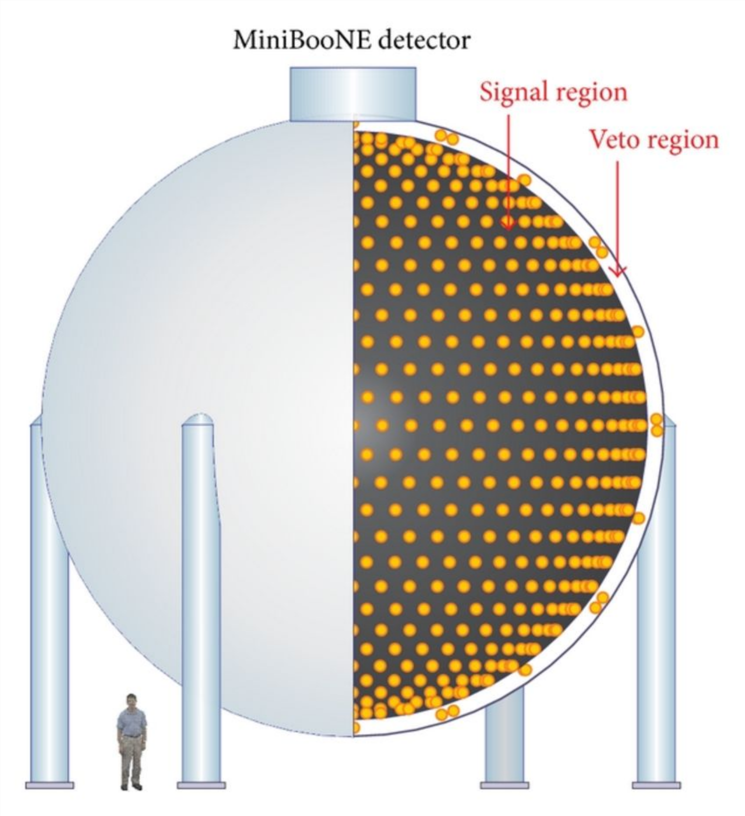
Exotic physics

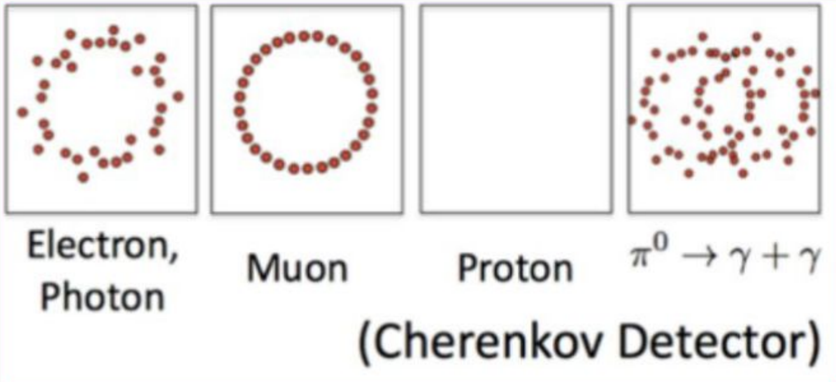


Phys. Rev. D101, 052001 (2020)
Phys. Rev. Lett. 127, 151803 (2021)

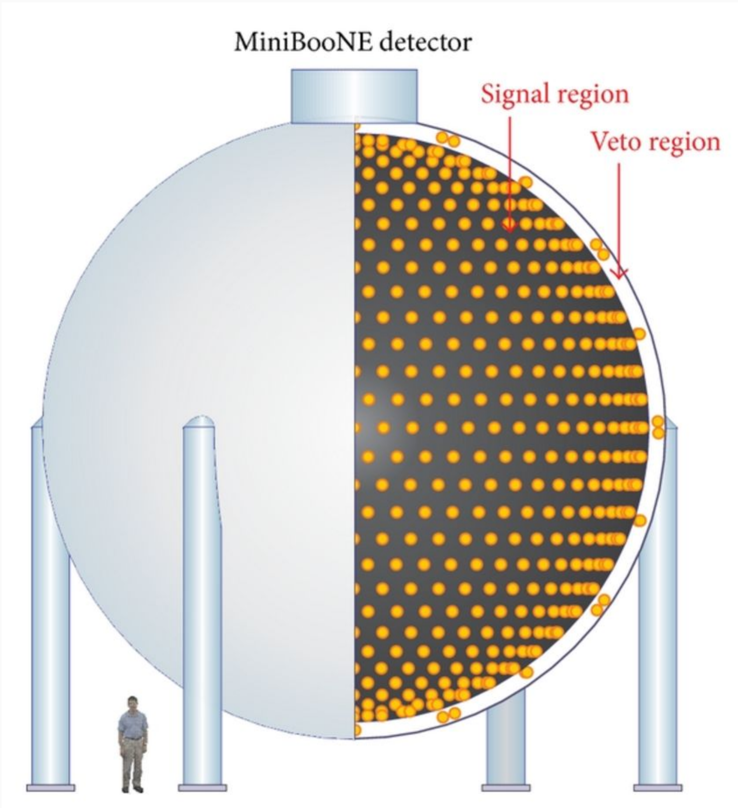
A closer look at MiniBooNE

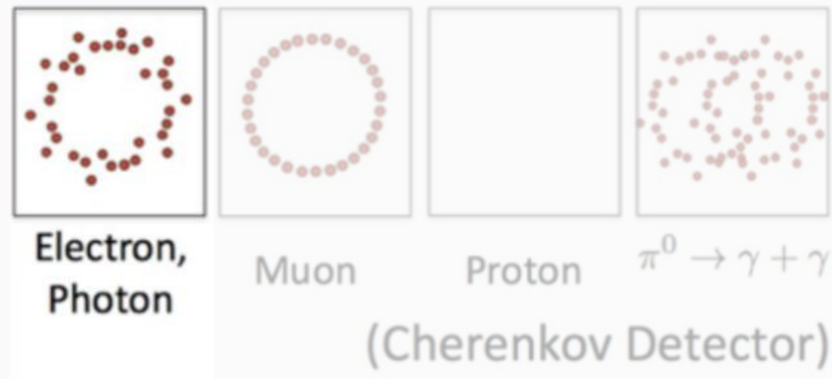
See Kirsty's talk for more info!

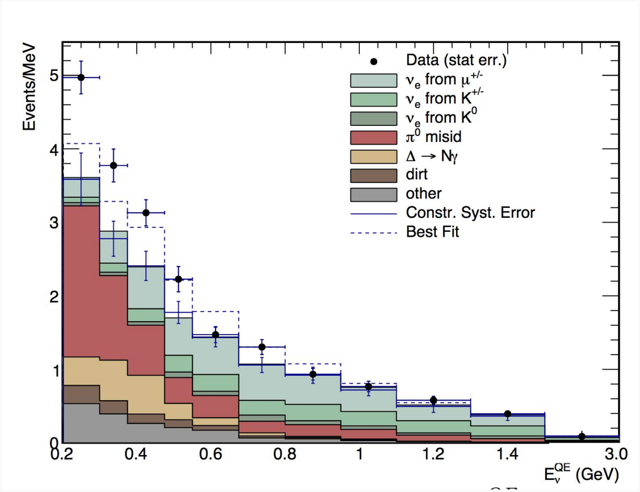




A closer look at MiniBooNE

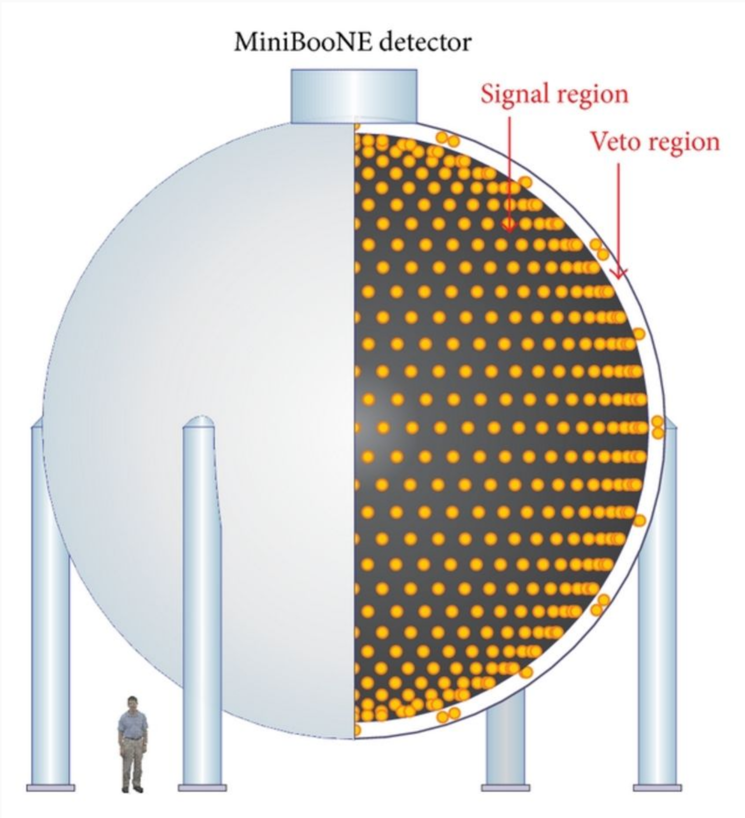


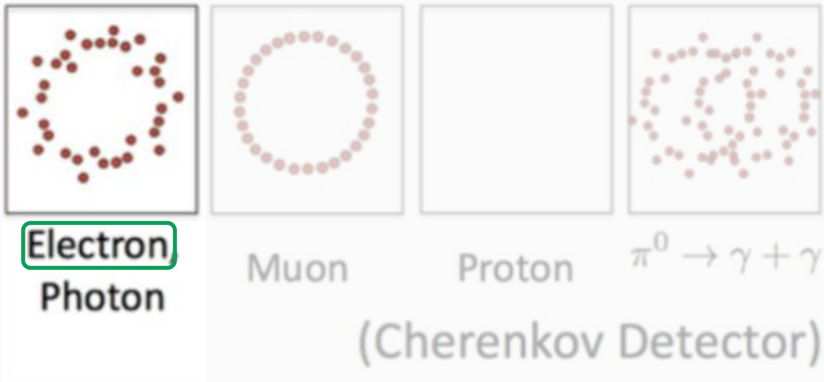


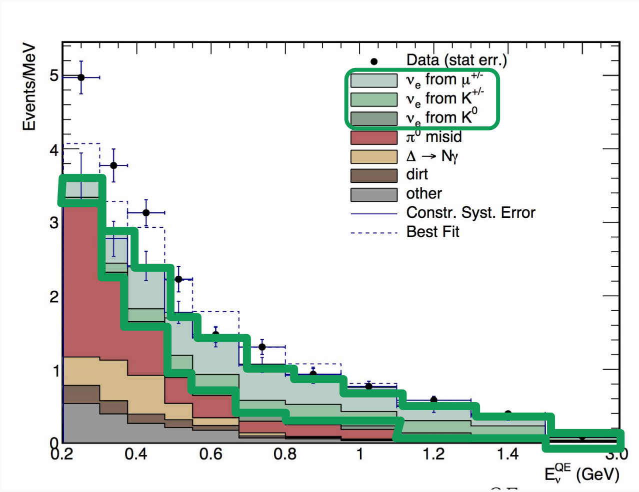


Phys. Rev. Lett. 121, 221801 (2018)

A closer look at MiniBooNE

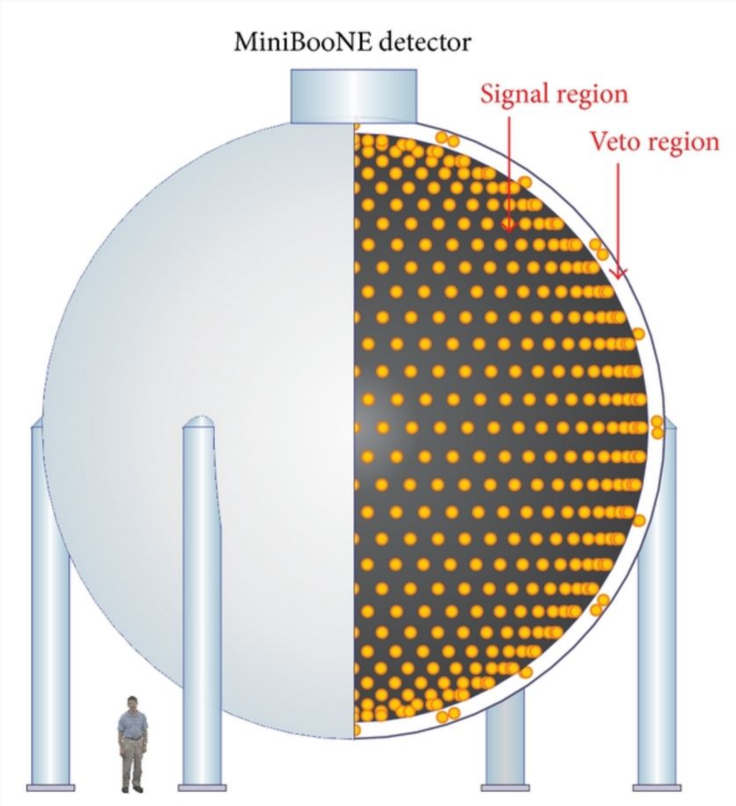


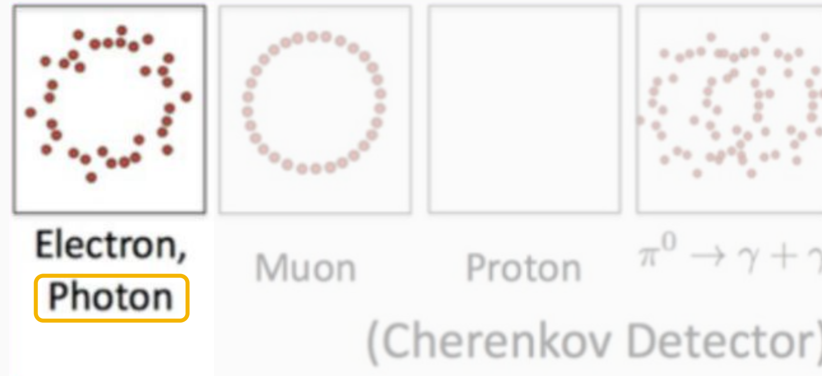


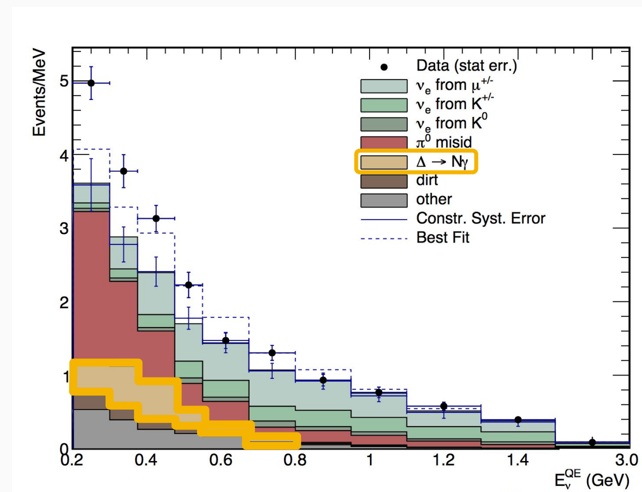


[Phys. Rev. Lett. 121, 221801 (2018)]

A closer look at MiniBooNE

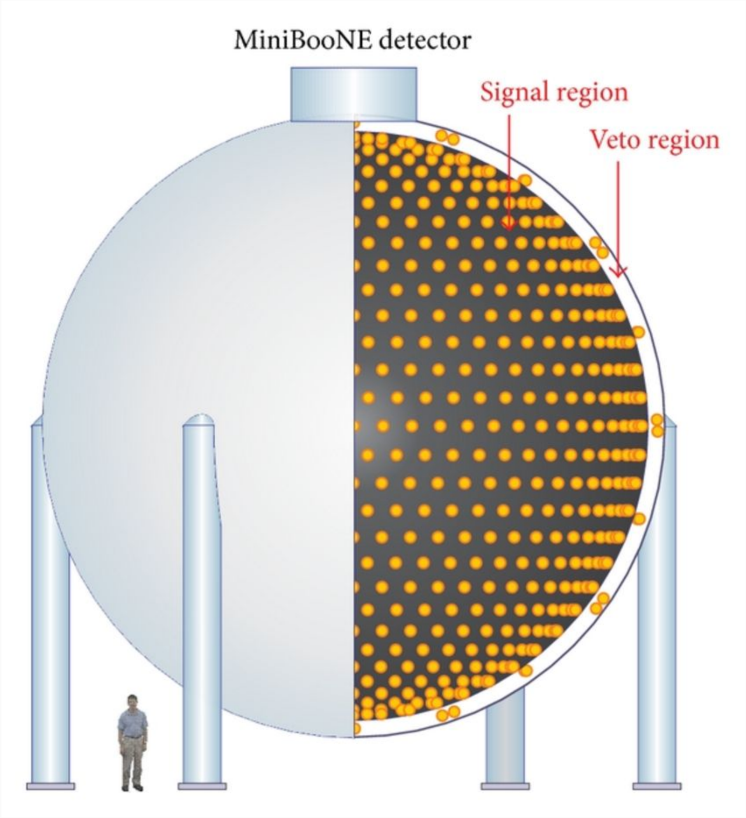


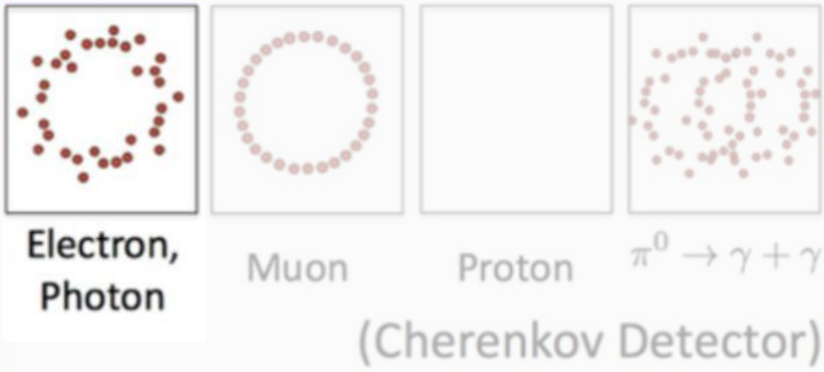


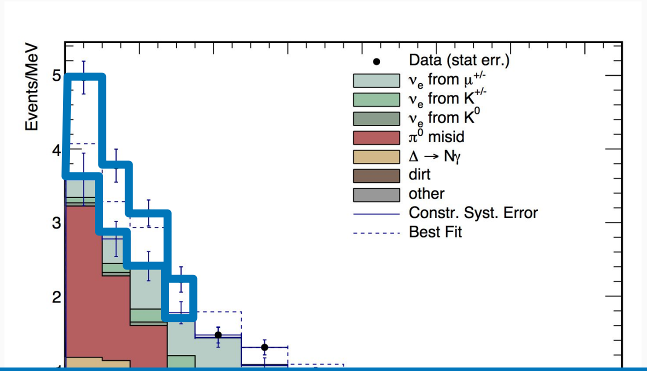


Phys. Rev. Lett. 121, 221801 (2018)

A closer look at MiniBooNE



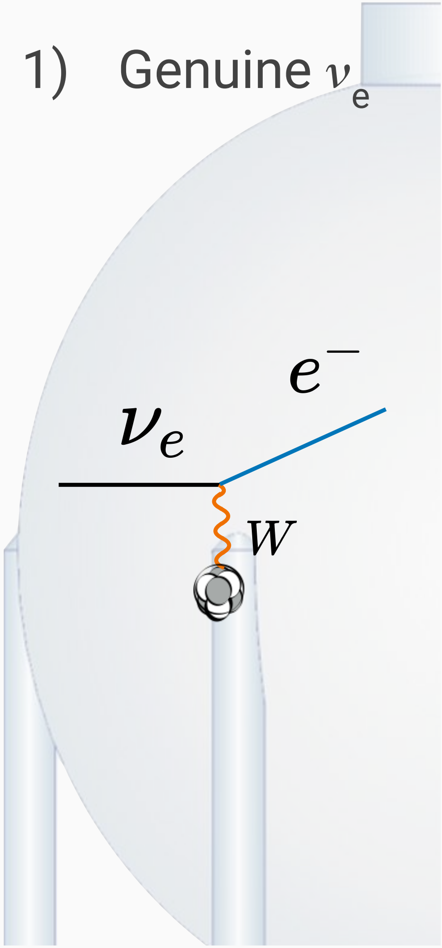




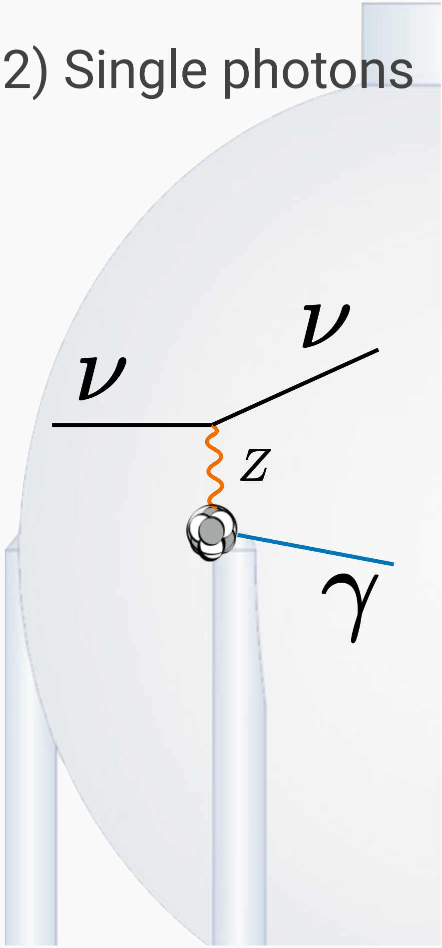
What is responsible for the excess?
About 200 events, significance of 4.5σ

Interpreting the MiniBooNE excess

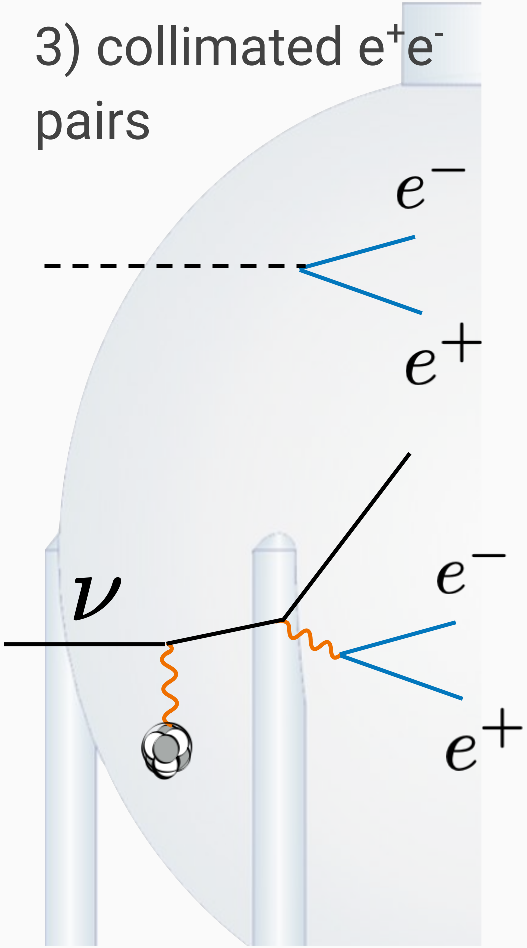
1) Genuine ν_e



2) Single photons

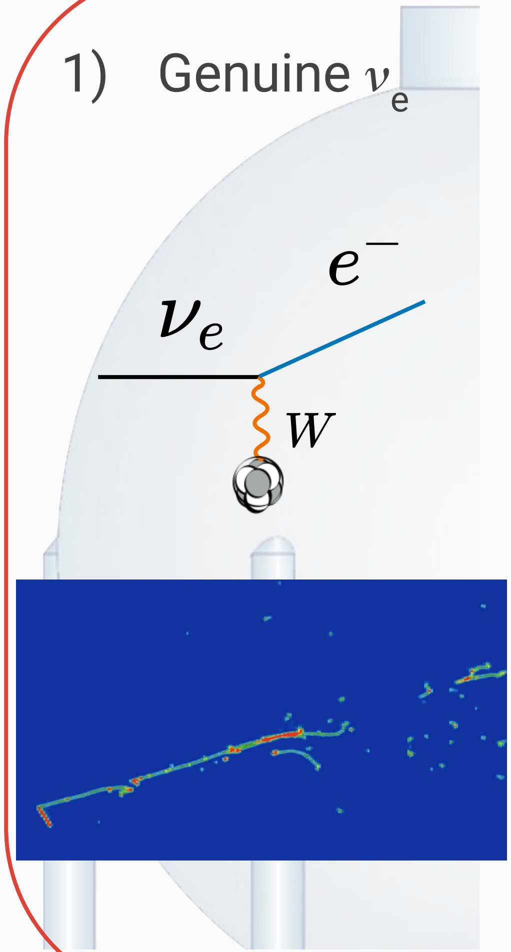


3) collimated e^+e^- pairs

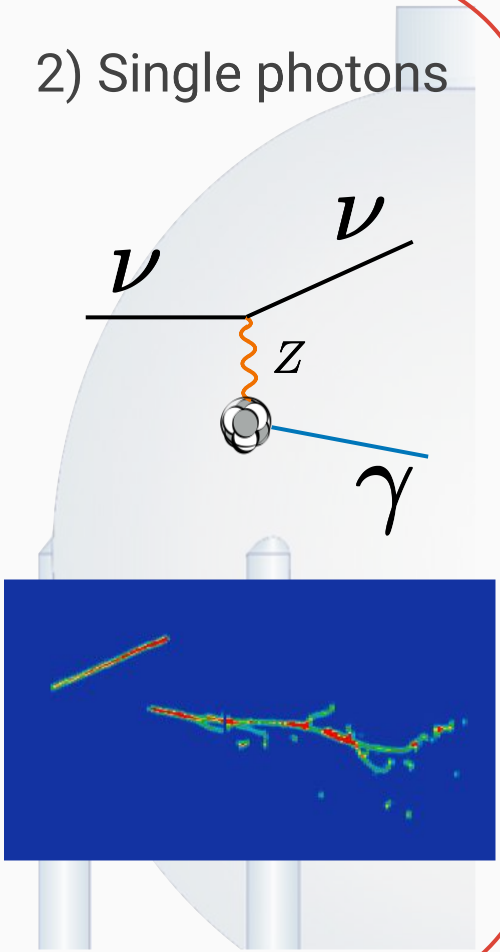


Interpreting the MiniBooNE excess

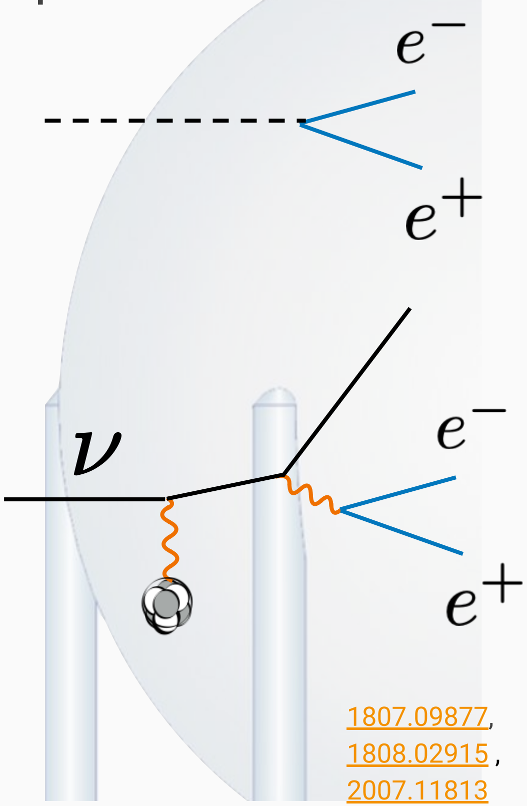
1) Genuine ν_e



2) Single photons



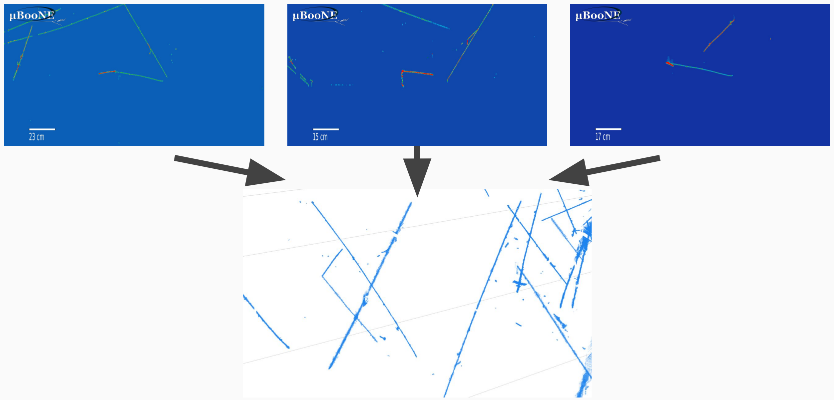
3) collimated e^+e^- pairs



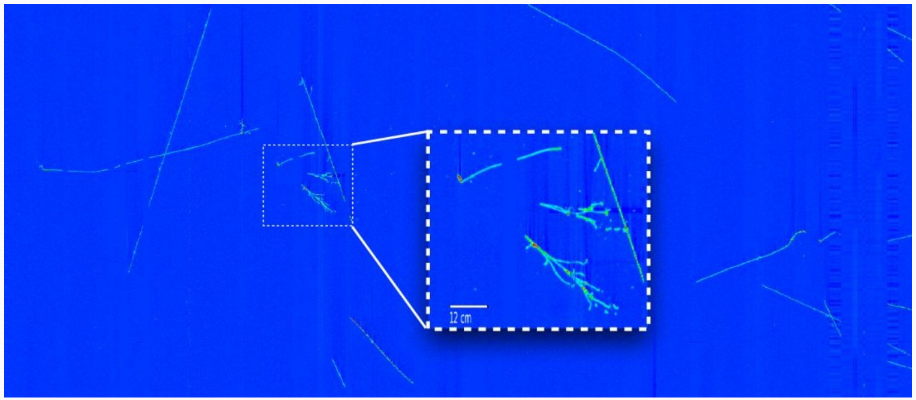
1807.09877, 1808.02915 , 2007.11813

General analysis structure

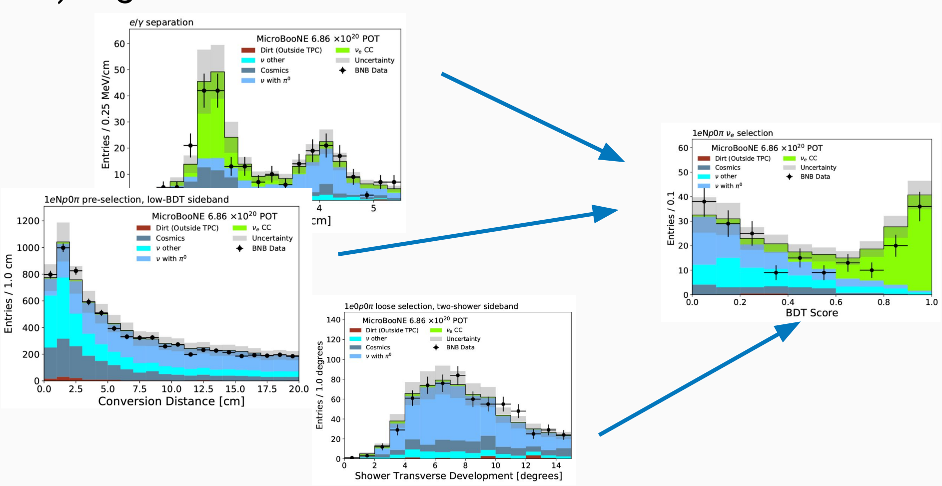
1) From 2D to 3D



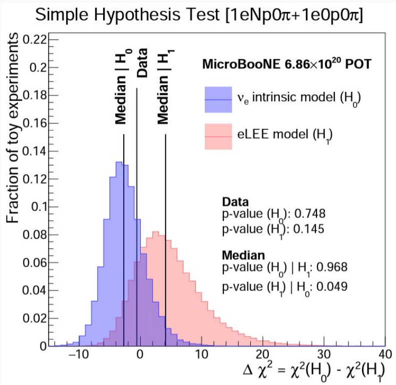
2) Identification of neutrino candidate



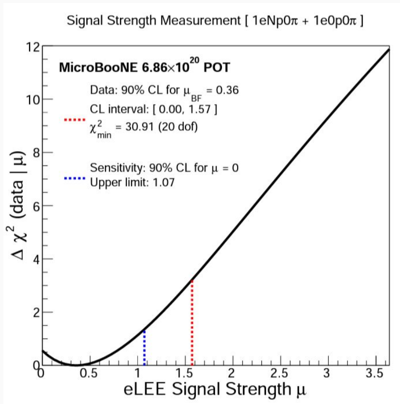
3) High level variables and event selection



4) Statistical analysis and hypothesis testing



(c) 1eNp0π +1e0p0π



Three reconstruction frameworks

Pandora Eur. Phys. J. C78, 1, 82 (2018)

- ➔ Algorithmic
- ➔ 2D hits
- ➔ 2D clusters
- ➔ 3D recostruction

Deep-learning based Phys. Rev. D103, 052012 (2021) Phys. Rev. D103, 092003 (2021)

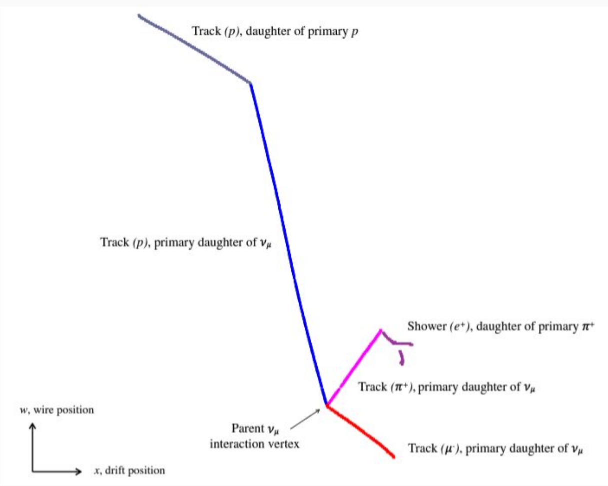
- 2D image is the basic ingredient
- Convolutional networks

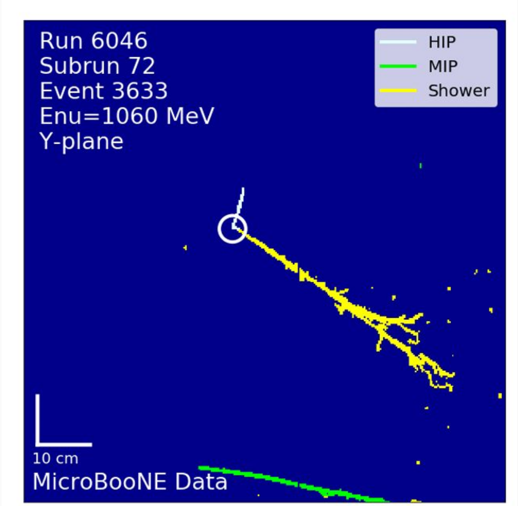
Wire-Cell

arXiv:2110.13961

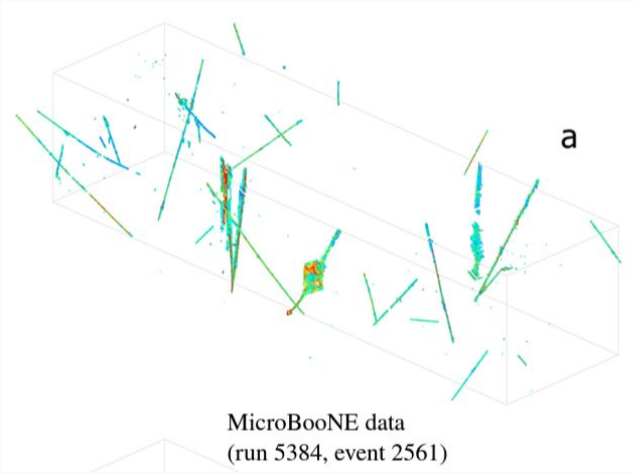
arXiv:2101.05076

- 3d tomography - natively in 3d



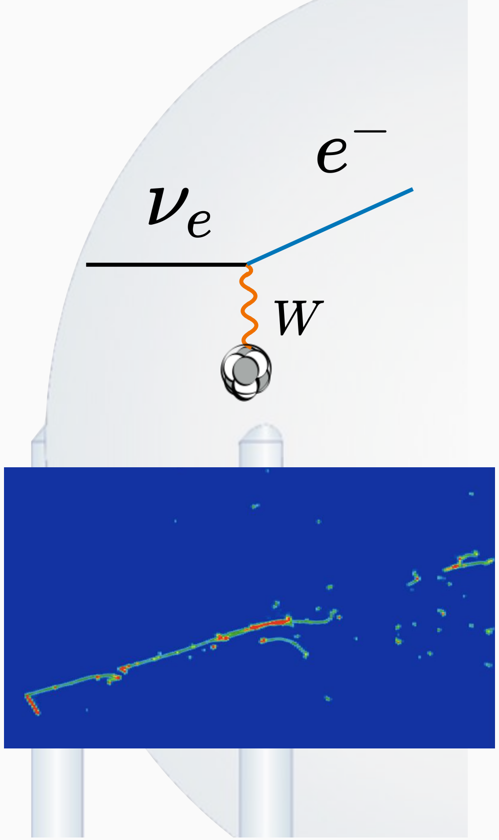


(b)

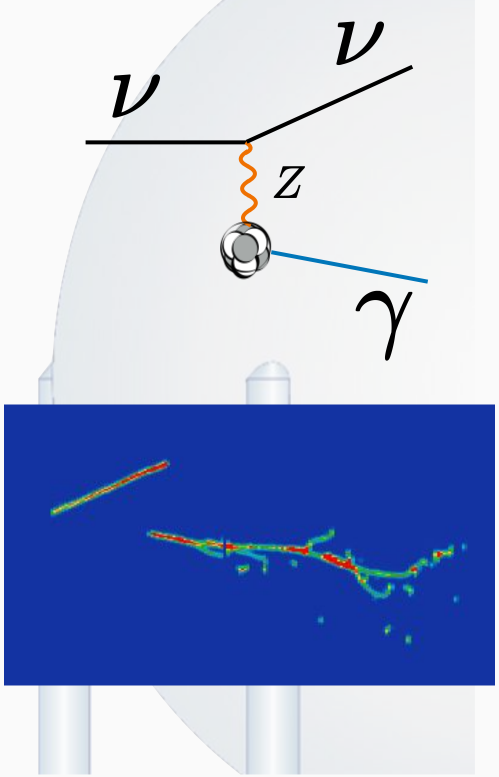


Interpreting the MiniBooNE excess

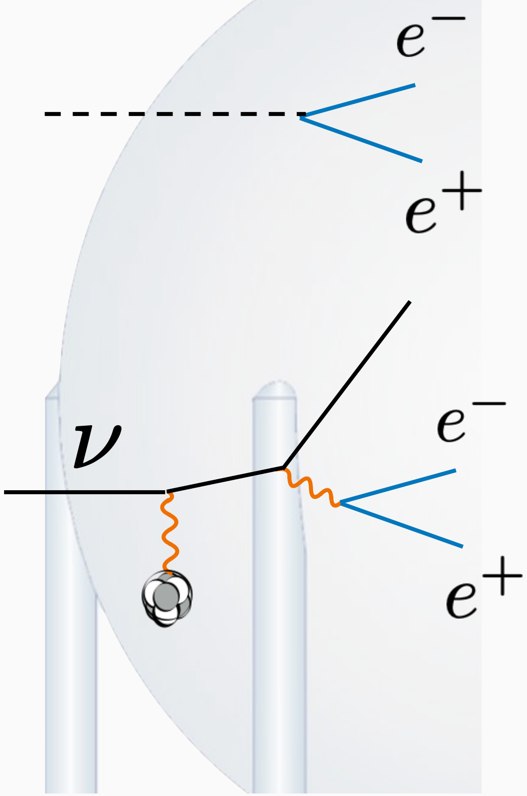
1) Genuine ν_e



2) Single photons



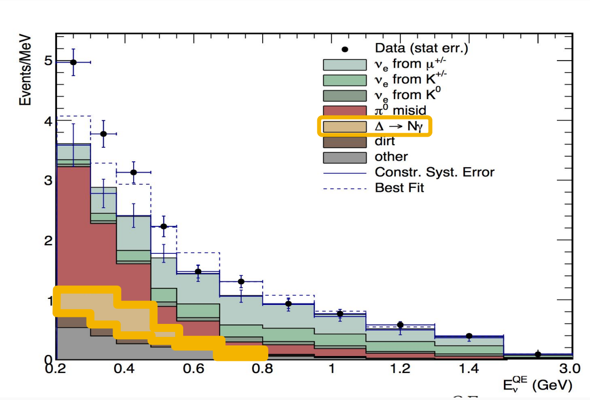
3) collimated e^+e^- pairs

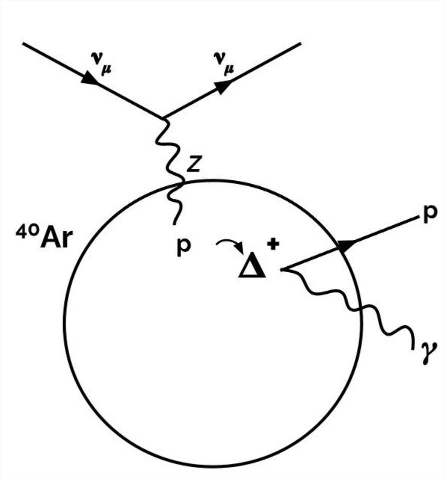


Single photon signal: Δ radiative decay

arXiv:2110.00409, accepted by PRL

- Standard model process
- ν + N -> Δ -> N + γ
- Never measured in neutrino interactions
- Br(Δ(1232)$\rightarrow$Nγ) < 1% from theory
- In 3 years of data expected 125 events





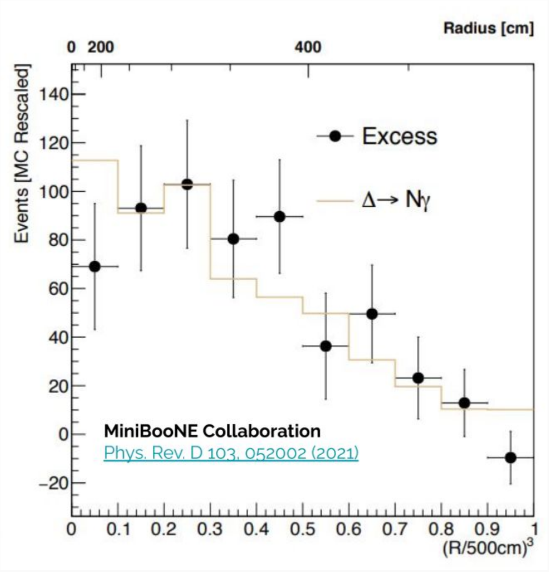
MiniBooNE reports that scaling this process by 3.18 reproduces the excess.

Signal = 3.18 x Δ^{theory}(1232)

- Δ(1232) -> Nγ

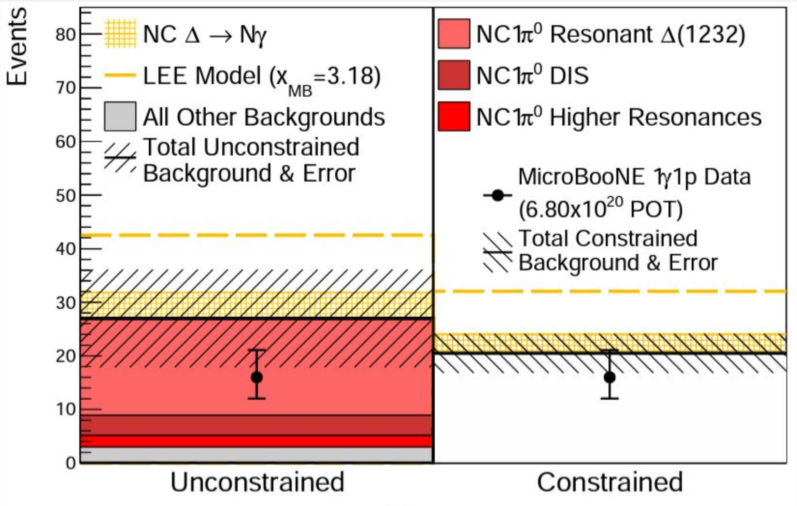
Main background = NCπ^0

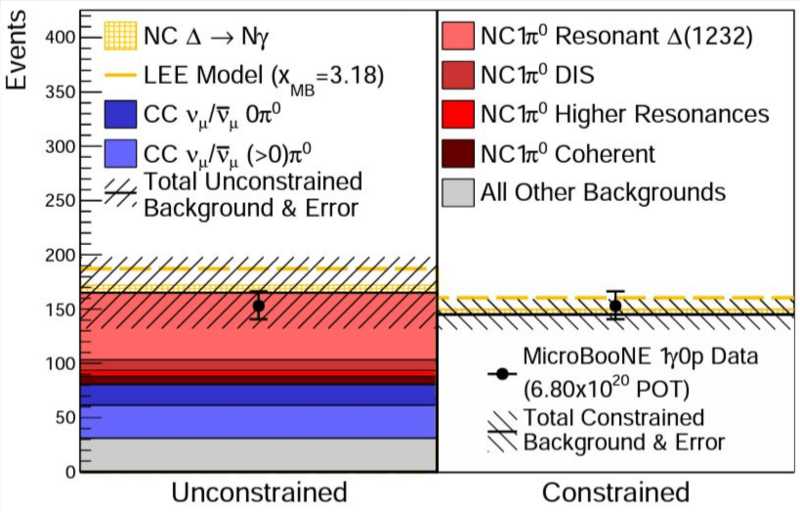
- π^0->$\gamma\gamma$, one γ missing

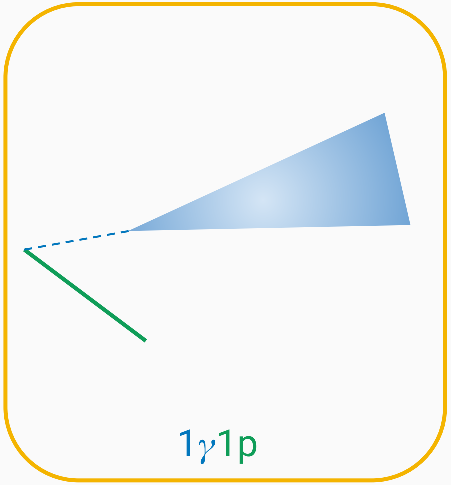


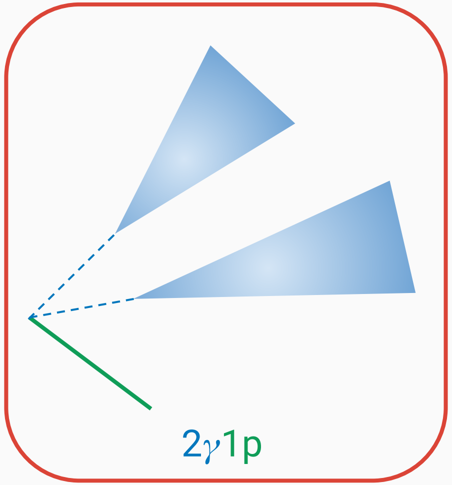
Single photon analysis

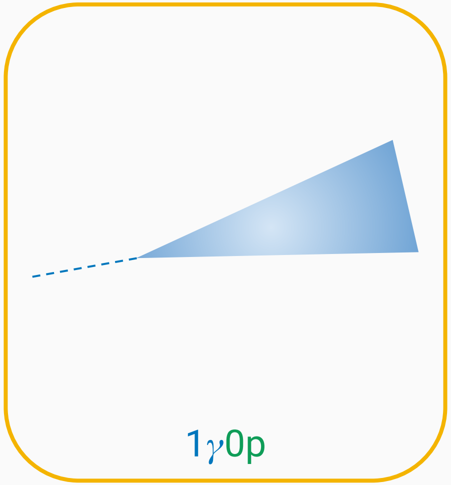
arXiv:2110.00409, accepted by PRL

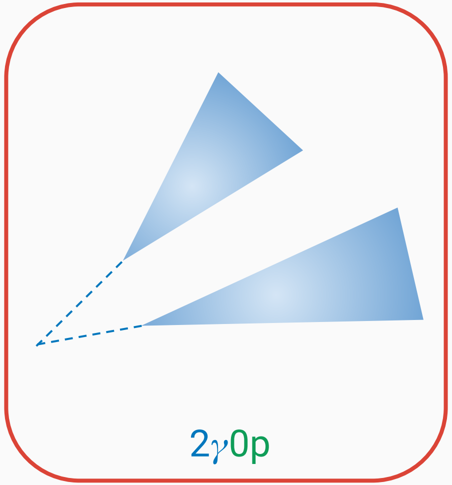






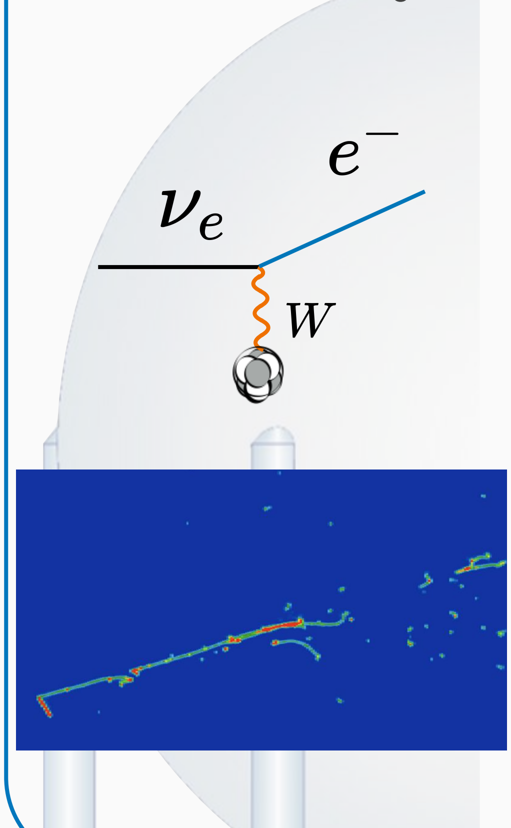




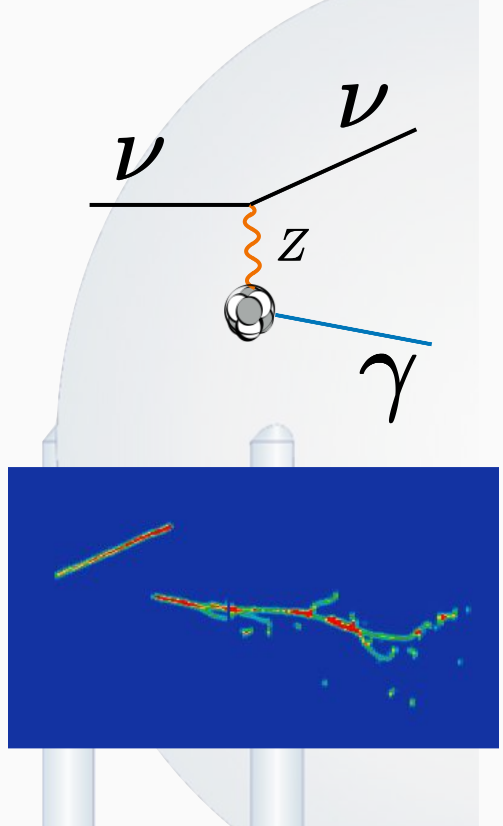


Interpreting the MiniBooNE excess

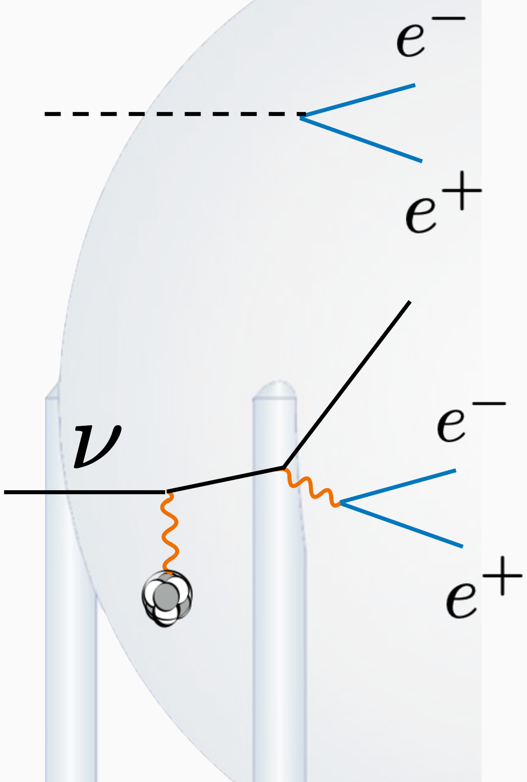
1) Genuine ν_e



2) Single photons

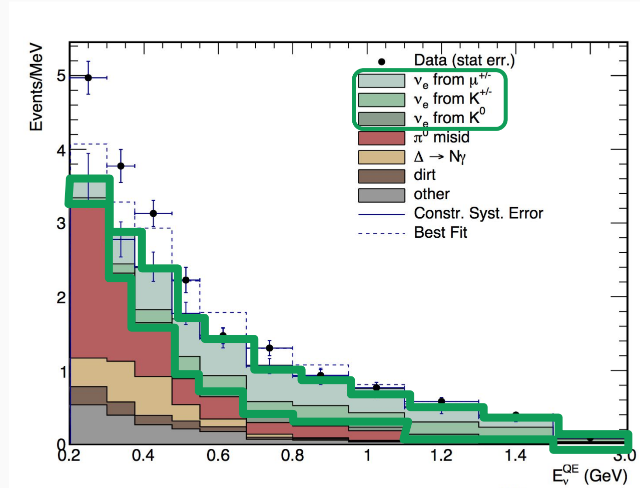


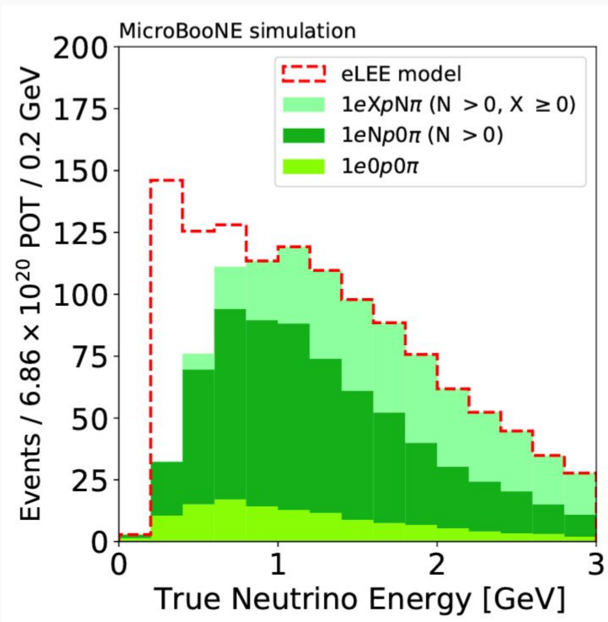
3) collimated e^+e^- pairs



Electron neutrino signal

Two possible models for a ν_e signal:
- 3+1 sterile neutrino
- **Scaling of the beam**



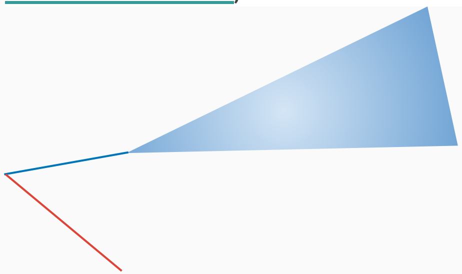


MicroBooNE's eLEE model:

- Unfold MiniBooNE excess to true energy
- Consider it as an additional component to the beam
- Propagate to MicroBooNE

Three complementary ν_e analyses

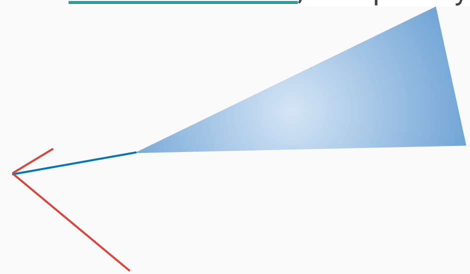
arXiv:2110.13978, submitted to PRD



1e 1p 0π - QE-like

- ➔ Mostly at low E
- ➔ required consistency E_ν^{calo} and $E_\nu^{inferred}$ under QE

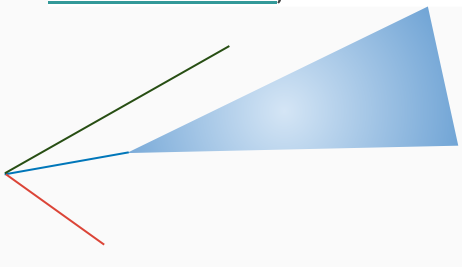
arXiv:2110.14065, accepted by PRD



1e Xp 0π - pionless

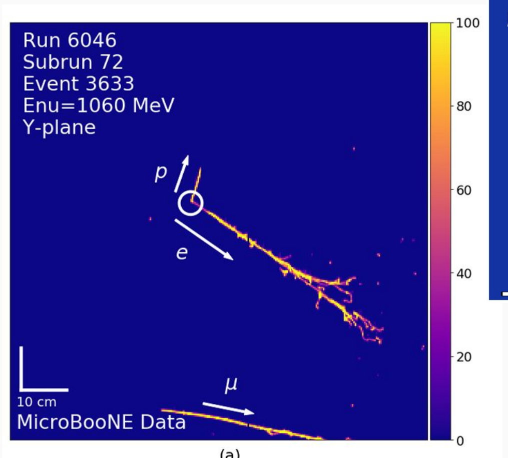
- ➔ Low to medium E
- ➔ Two channels: 0p and Np>0

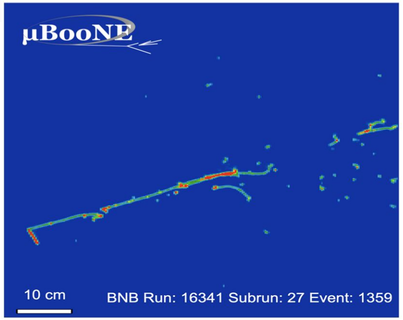
arXiv:2110.13978, submitted to PRD

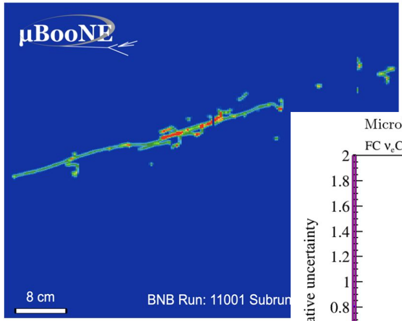


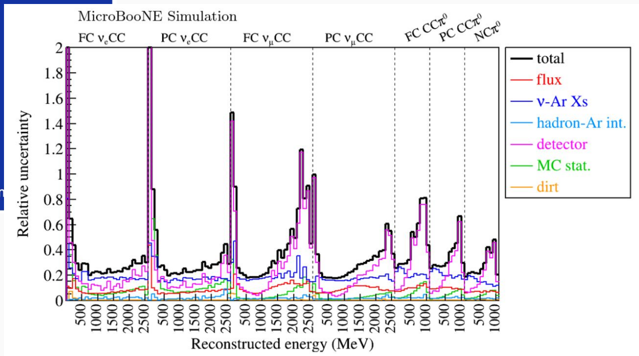
1e X - inclusive

- ➔ Benefits from high statistics
- ➔ seven channel fit with multiple sidebands



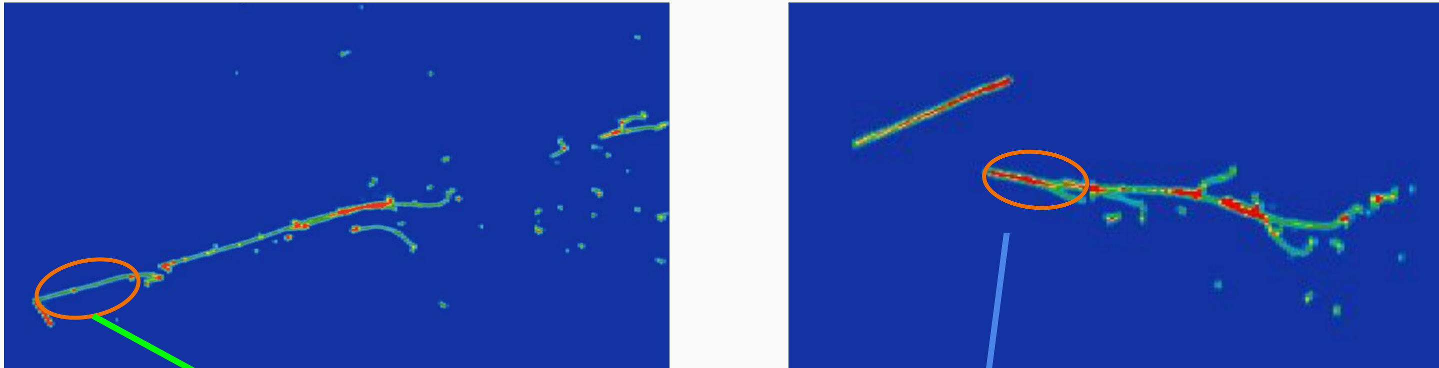






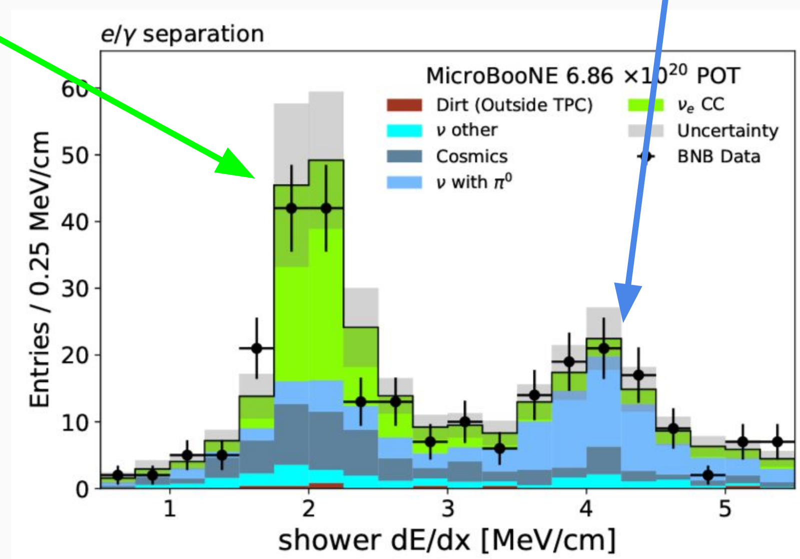
electron/photon separation: dE/dx

Examples and plot from arXiv:2110.14065, accepted by PRD



dE/dx at the start of the shower:

- e^- ~ 2 MeV/cm
- γ ~ 4 MeV/cm

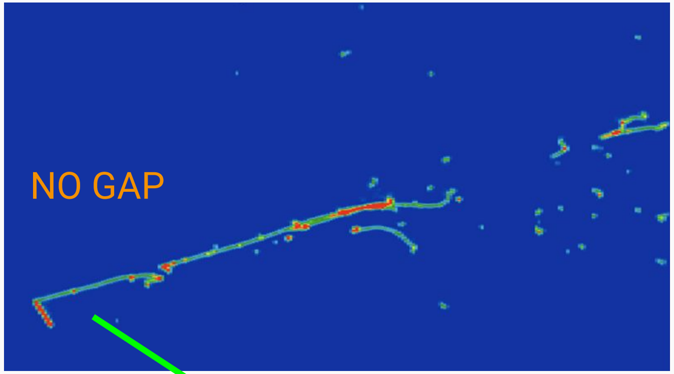


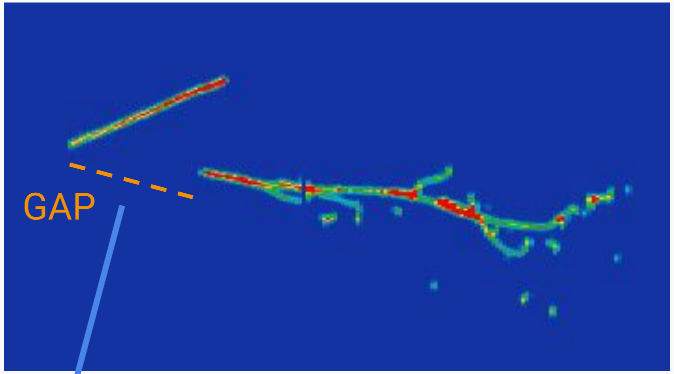
Experimentally:

➔ Median value in the first 4 cm

electron/photon separation: conversion distance

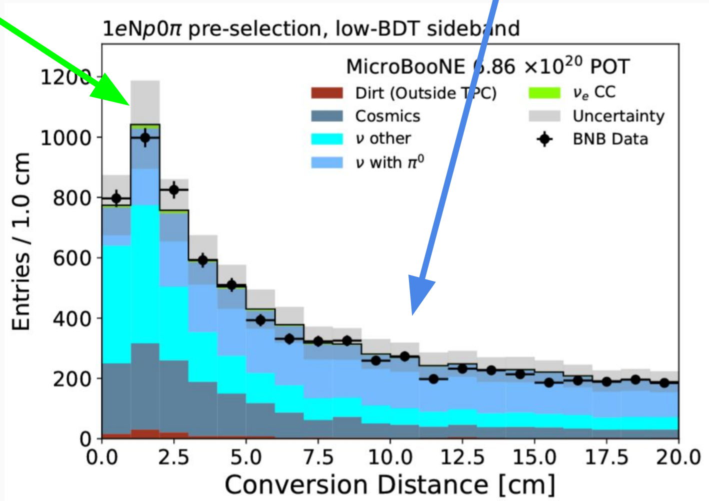
Examples and plot from arXiv:2110.14065, accepted by PRD





Theoretically:

- Photon conversion distance ~ 26 cm



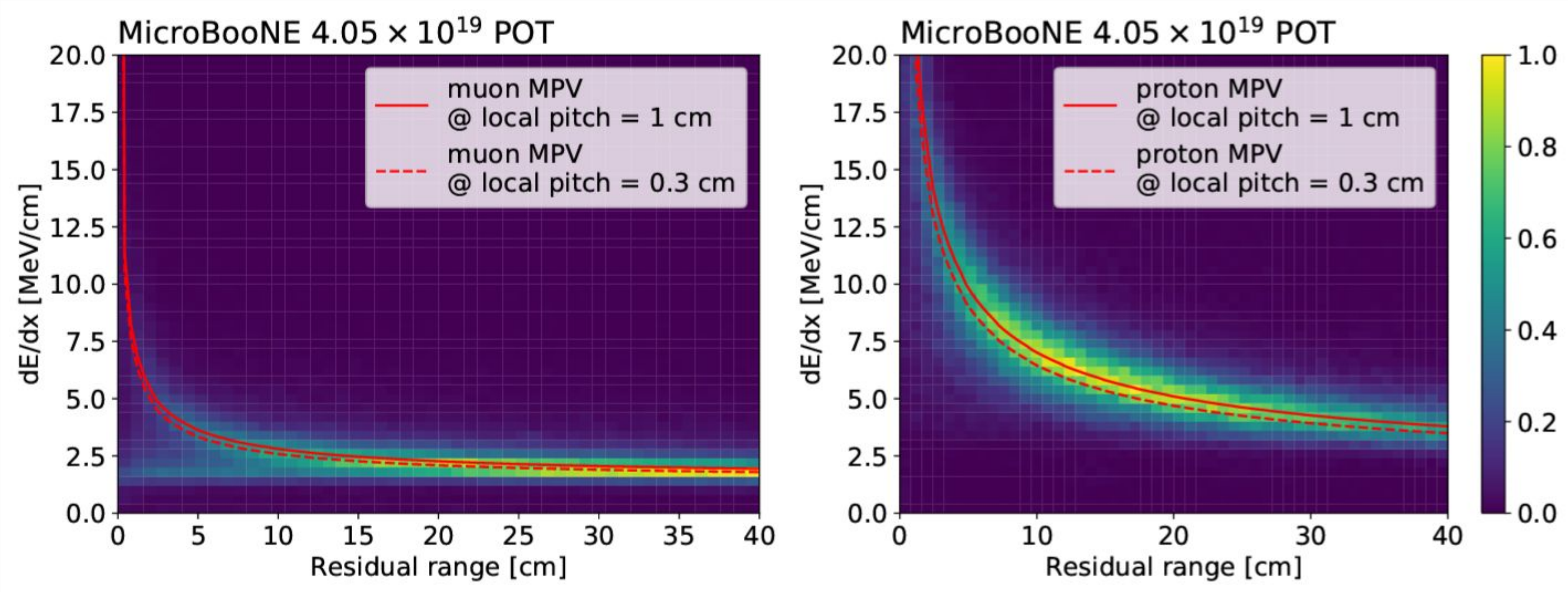
Experimentally:

➔ Vertex-shower start gap

Proton/muon separation: track profile

LAr TPC allow precise calorimetry and identification of the **Bragg Peak:**

- Deposited charge in a hit -> ΔQ -> ΔE
- 3D reconstruction -> Δx
- Reconstruction of local dE/dx along the particle trajectory

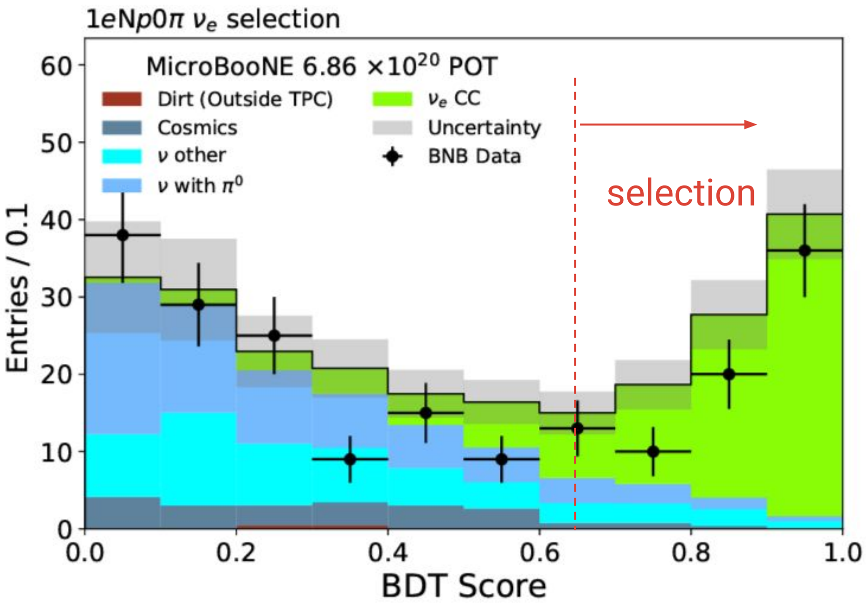


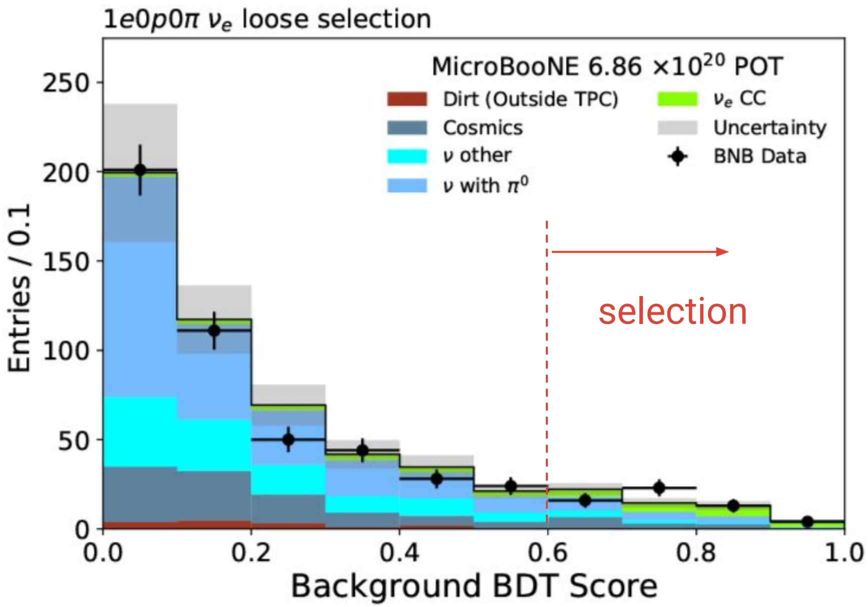
Background rejection strategy

Examples and plot from arXiv:2110.14065, accepted by PRD

All the high-level variables are combined in a BDT:

- ➔ Classification of ν_e from the other background - mostly ν with π^0
- ➔ No weight on energy, no use of kinematics related variables
- ➔ Cut on BDT score is chosen to provide high purity





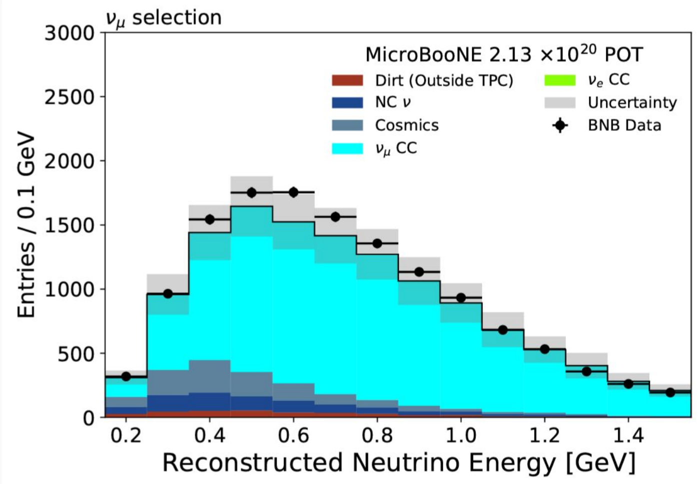
Constraint of systematic uncertainties

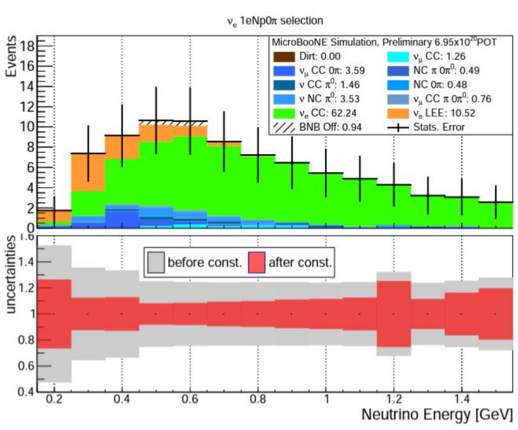
Examples and plot from
arXiv:2110.14065, accepted by PRD

ν_e and ν_μ share the same systematic uncertainties:

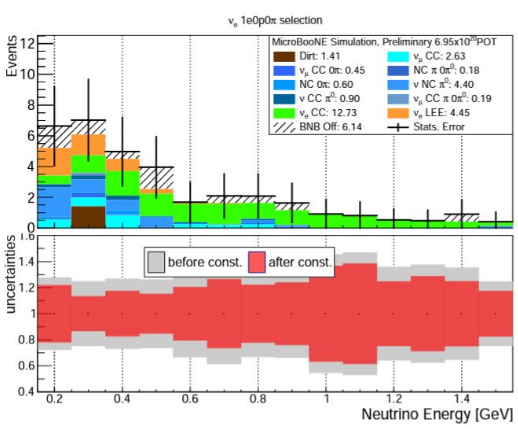
- Flux: same hadronic production
- Cross section: same ν-Ar interaction model

Selection of ν_μ is used as a constraint





(a) 1eNp0π selection



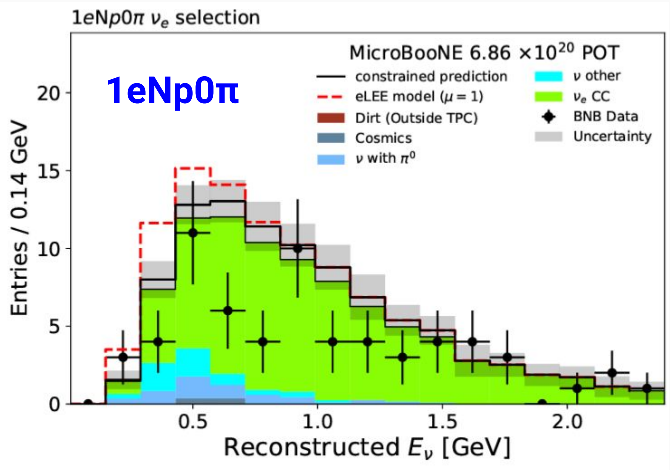
(b) 1e0p0π selection

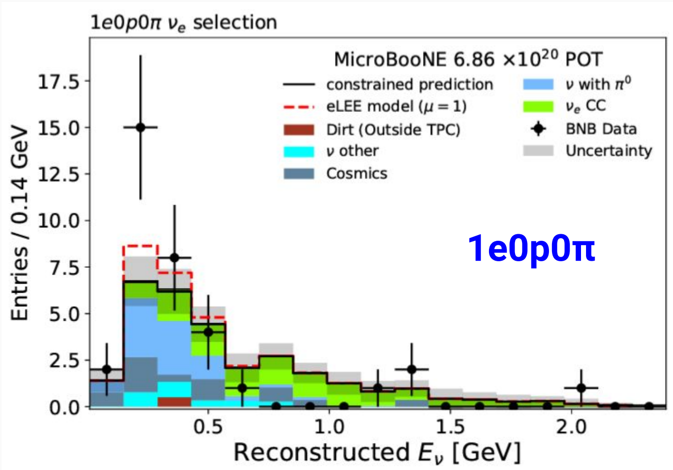
One large covariance matrix between ν_e and ν_μ selections

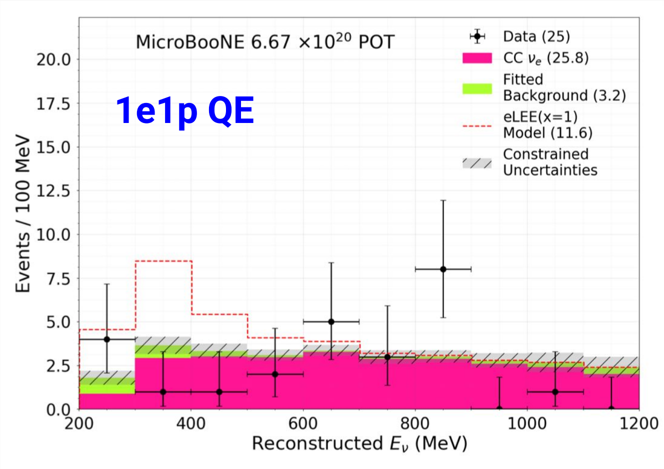
- Profile over the ν_μ data
- Obtain updated central value and covariance for the ν_e selection

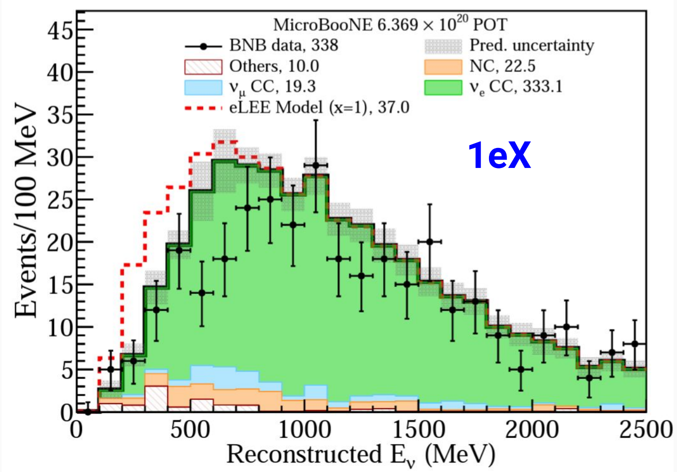
Reconstructed energy spectra

arXiv:2110.14054, submitted to PRL





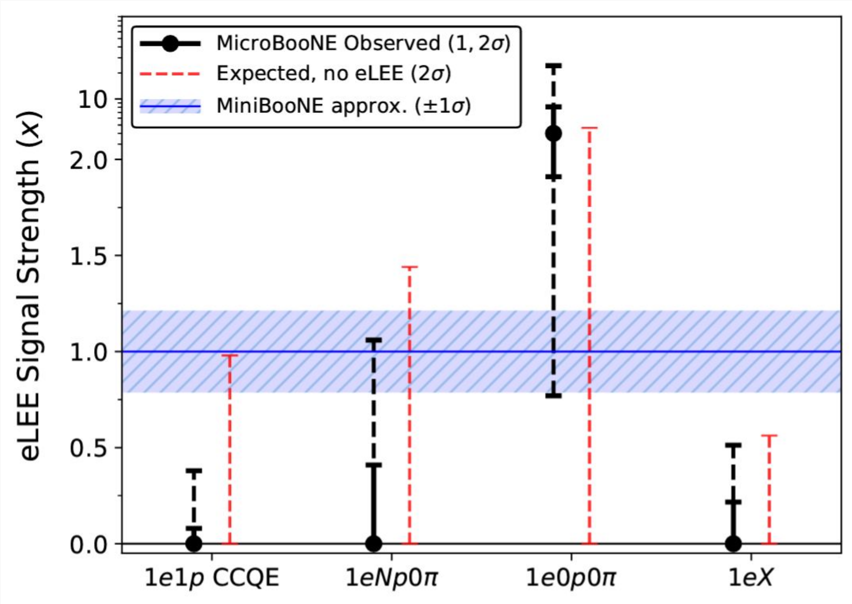




Interpretation

Overall, no clear evidence for an excess of ν_e interactions

Ruling out this explanation of MiniBooNE at the ~2σ level



Conclusions (1)

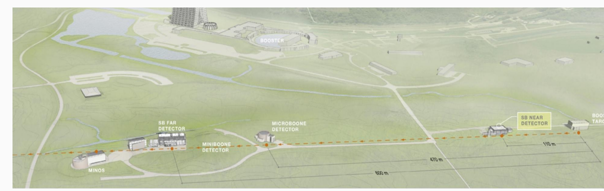
Short baseline anomalies is a BIG open puzzle in neutrino physics…

…the more experiments, the more pieces that do not quite fit.

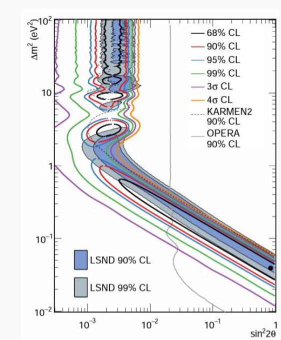
Conclusions (2)

MicroBooNE:

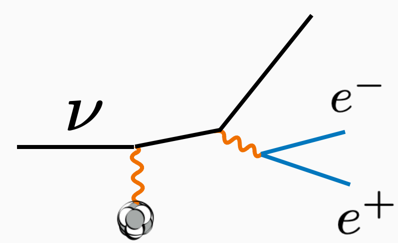
- **strongly pushed forward the development of LAr TPCs**
- **probed the most intuitive explanations for the MiniBooNE excess**
- **Many other physics results - publication list**



The next steps:

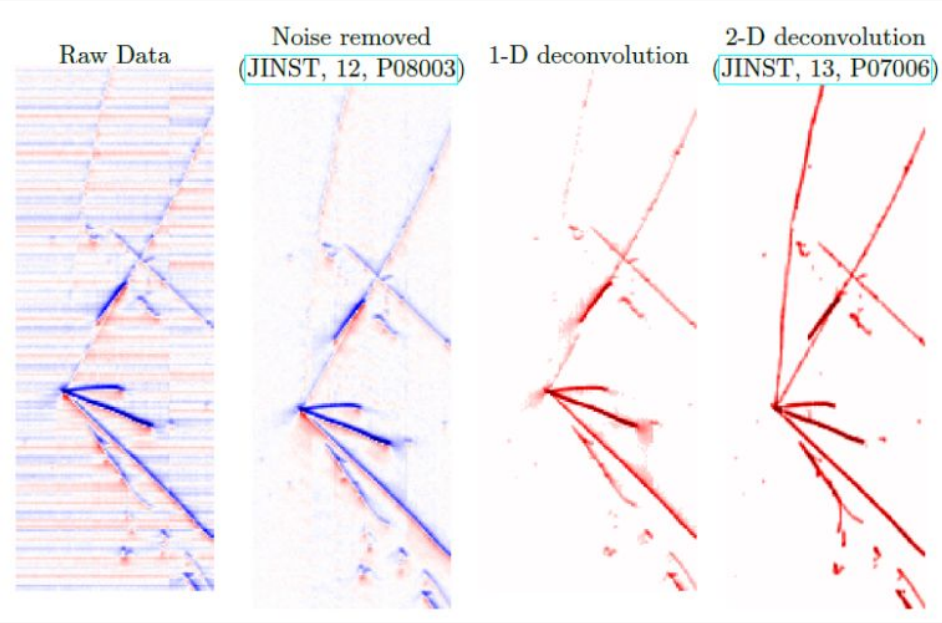


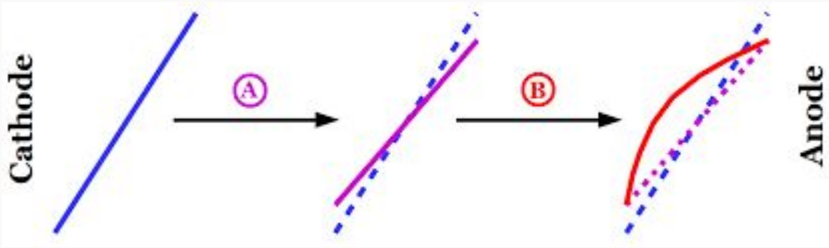
- The SBN program: 3 detectors better than 1!
- Full 3+1 osc analysis
- Searching for a larger set of signatures: e^+e^-

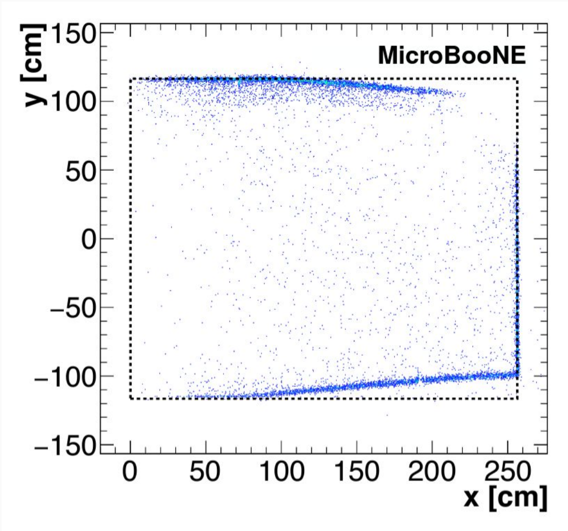


Thank you for your attention!

Detector understanding and modelling





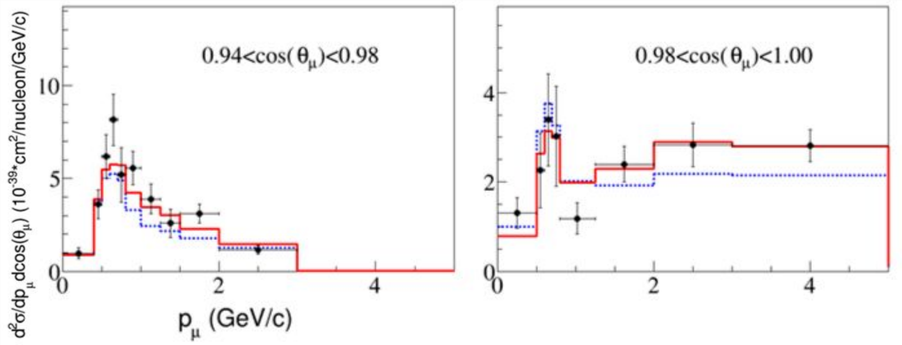


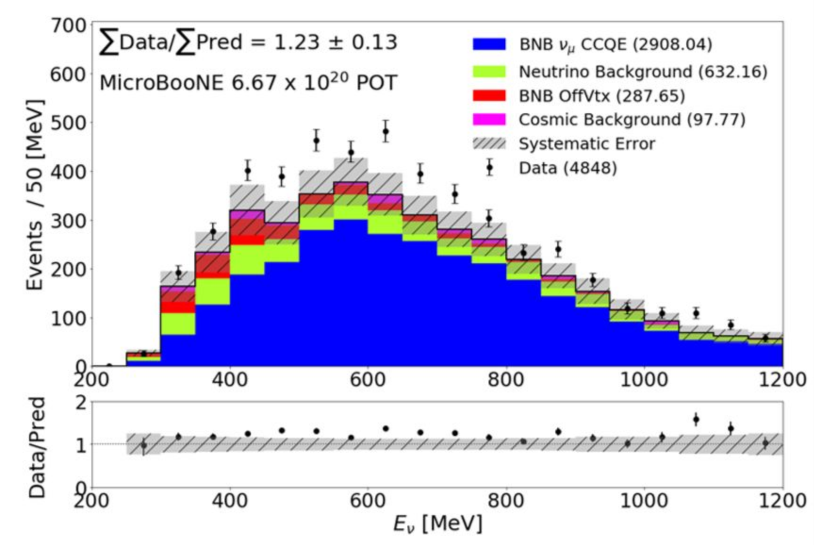
- Noise removal
- deconvolution of signals from induced charge on neighboring wires

- Track distortion induced by non-uniformity of the electric field

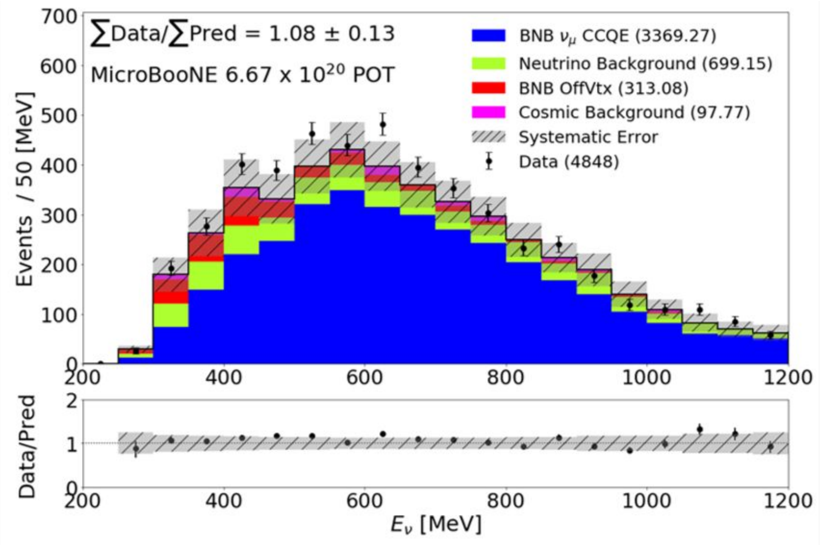
Neutrino interaction generator

- Tailored GENIE Tune
- Using external data (T2K ND280) at similar energy and similar processes
- In-situ constraints applied later





Before TUNE

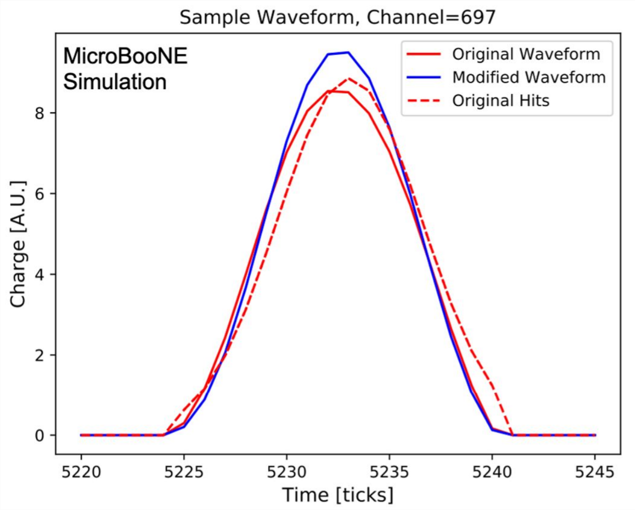


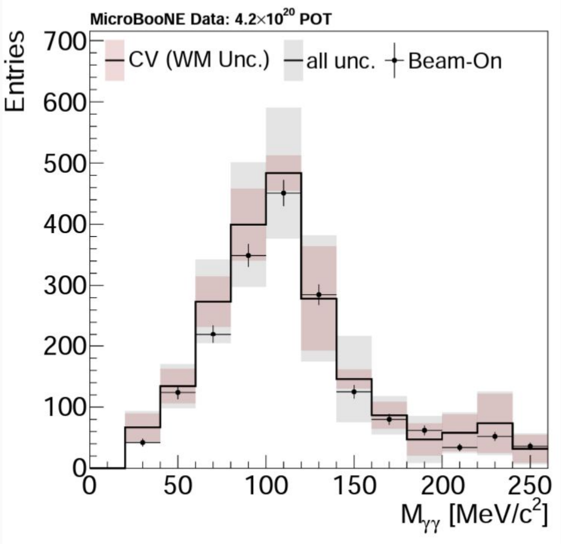
After TUNE

Detector systematics

Detector systematics are treated by varying the reconstructed waveforms

- ➔ Good trade-off between accurate description and computational time
- ➔ Main effect is on calorimetry, less on topology





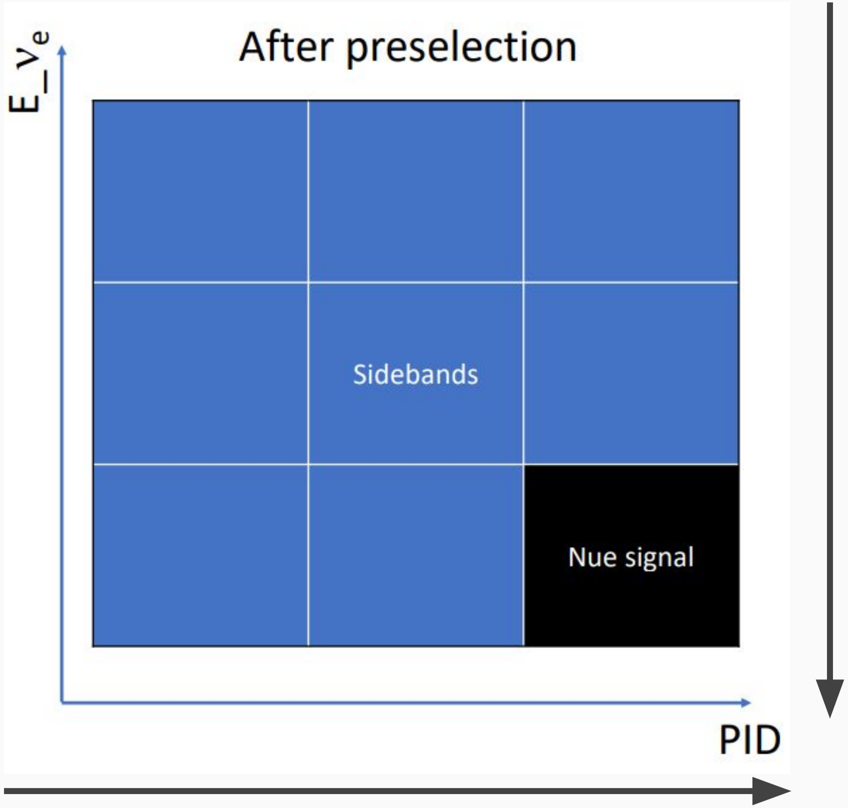
This propagates to analysis variables

- Clear effect on the ones more dependent on calorimetric information
- Red is detector systematics, grey is all systematics

Unblinding the data

Blind analysis:

1) Freeze analysis based on small portion of open data
2) Look at the whole datasets in sidebands
3) Progressively closer to the signal box

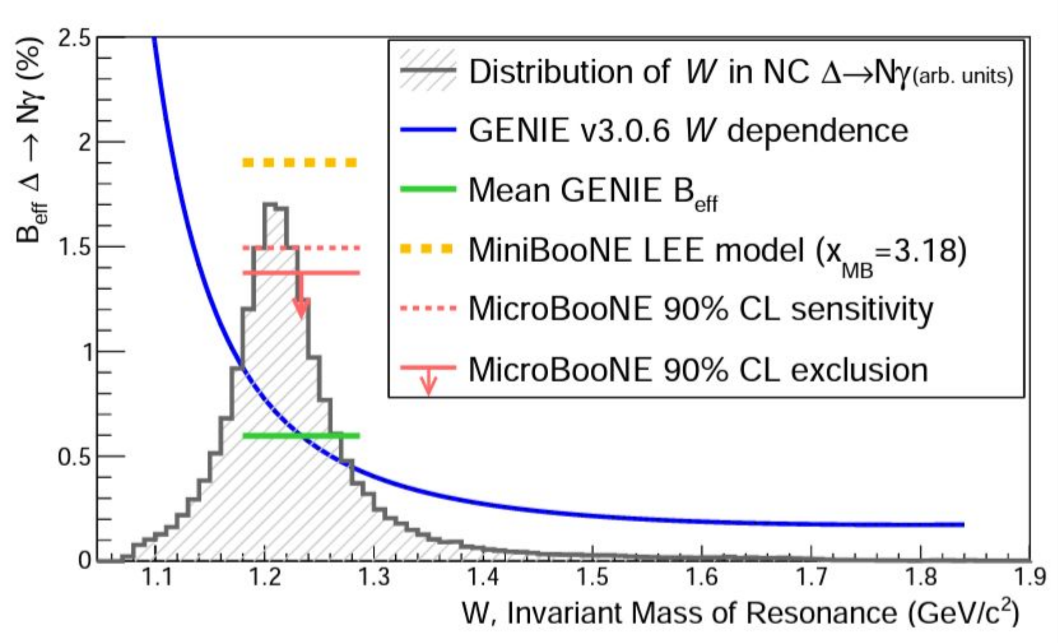


Reconstruct and measure ν_e at progressively lower energies

Check the distribution of the backgrounds at progressively larger PID, using BDT scores and box cuts

Single photon results

arXiv:2110.00409, accepted by PRL

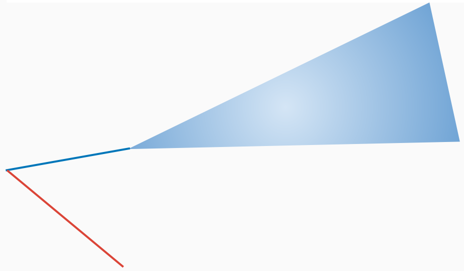


Fit for x_{Δ} - scaling factor for Δ radiative decay:

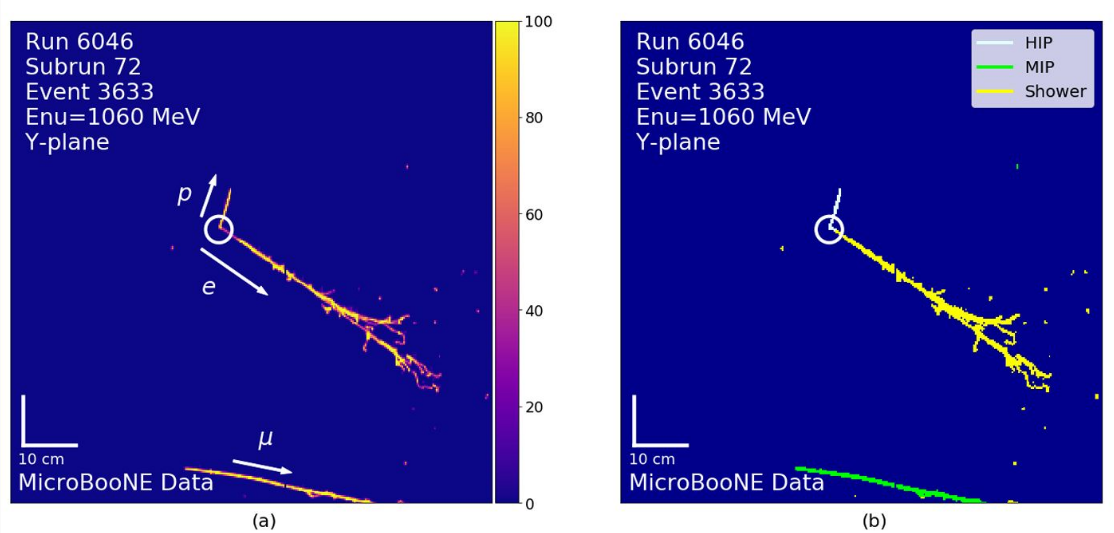
- Best-fit = 0
- Confidence interval = [0, 2.3]
- Exclude single photon hypothesis at 94.8% CL

QE-like analysis

arXiv:2110.13978, submitted to PRD



1e 1p 0π - QE-like



QE-like signature:

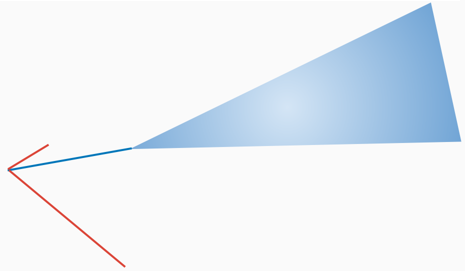
➔ required consistency between E_ν^{calo} and $E_\nu^{inferred}$ under QE hypothesis

Using Deep-learning based reconstruction:

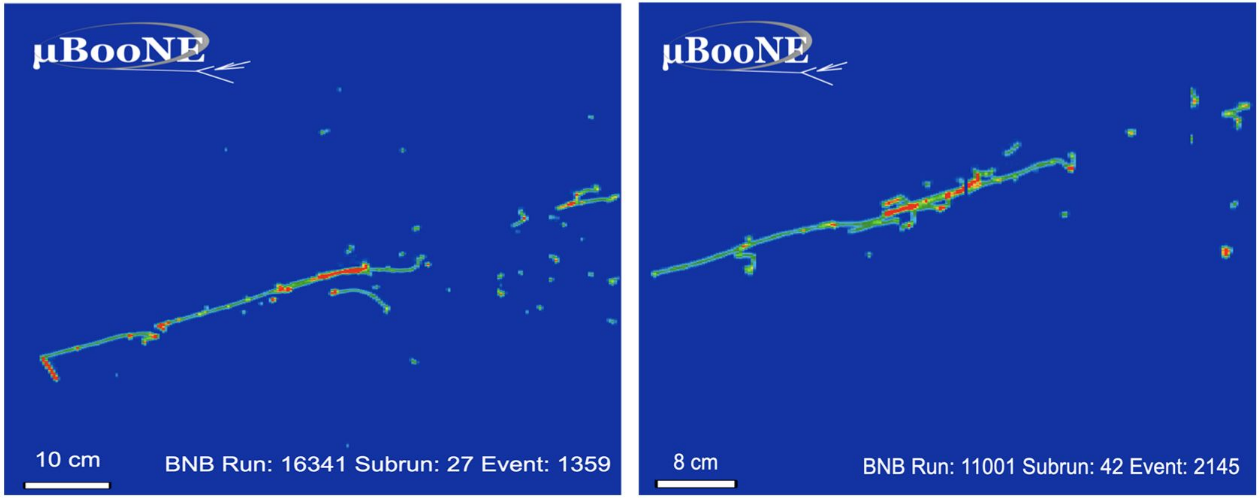
- **Pixel labelling** using Sparse Networks
- Multi-particle identification using **Convolutional** Networks

Pionless analysis

arXiv:2110.14065, accepted by PRD



1e Xp 0π - pionless



Two different sub-channels:

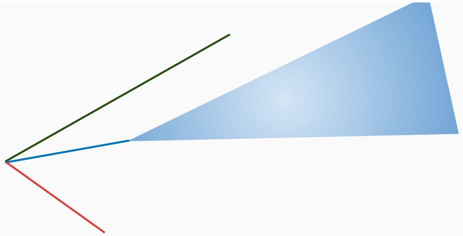
- ➔ X > 0 protons
- ➔ 0 protons

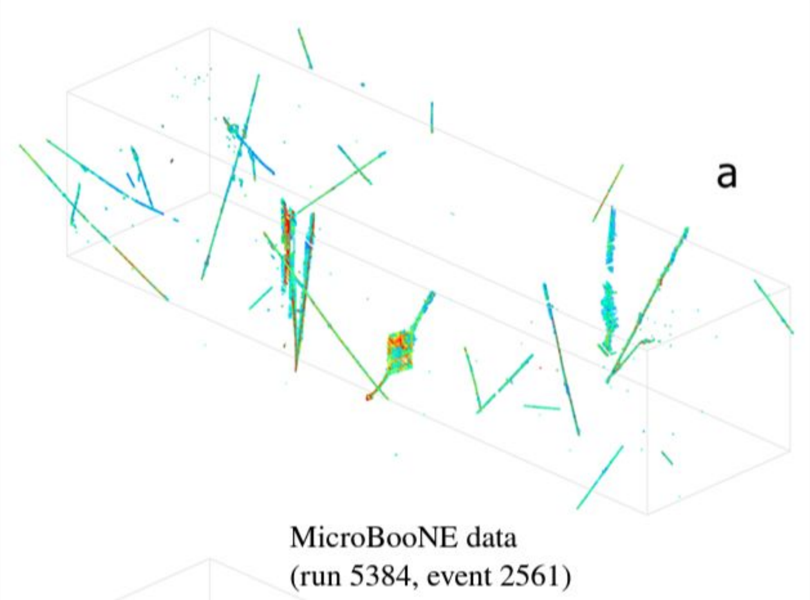
Using Pandora reconstruction framework:

- **Selection based on topology**
- **No use of the event kinematics in the selection to not bias analysis towards low energy**

Inclusive analysis

arXiv:2110.13978, submitted to PRD





1e X - inclusive

Inclusive analysis benefit from high statistics;
- seven channel fit with multiple sidebands

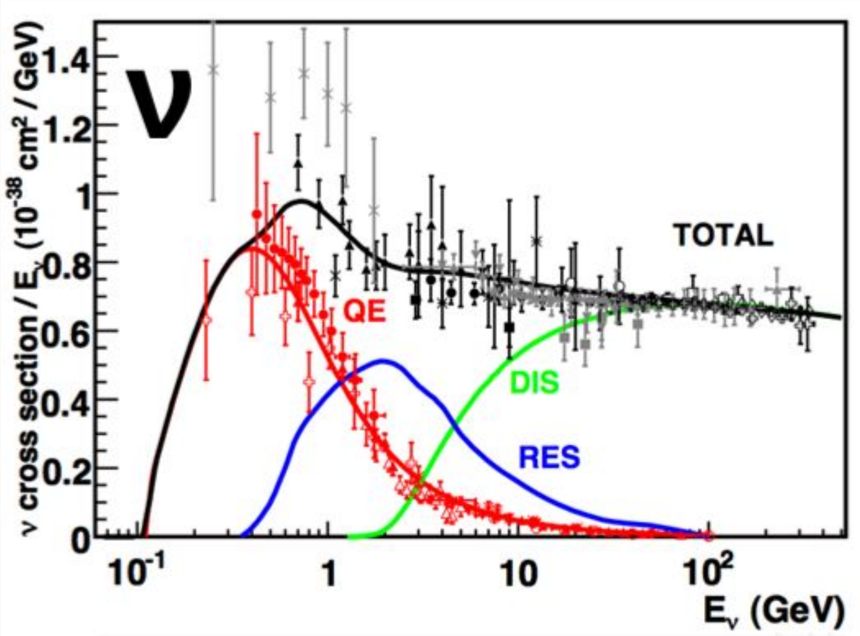
Wire-Cell tomography 3D imaging:

- **Reconstruct directly in 3D space**

Different interaction processes at different energies

Quasi elastic:

- $\nu_e + n \rightarrow e^- + p$
- Two particles final state - one track & one shower



Deep inelastic scattering:

- Multi-hadron final states

Resonant and Meson-exchange-current:

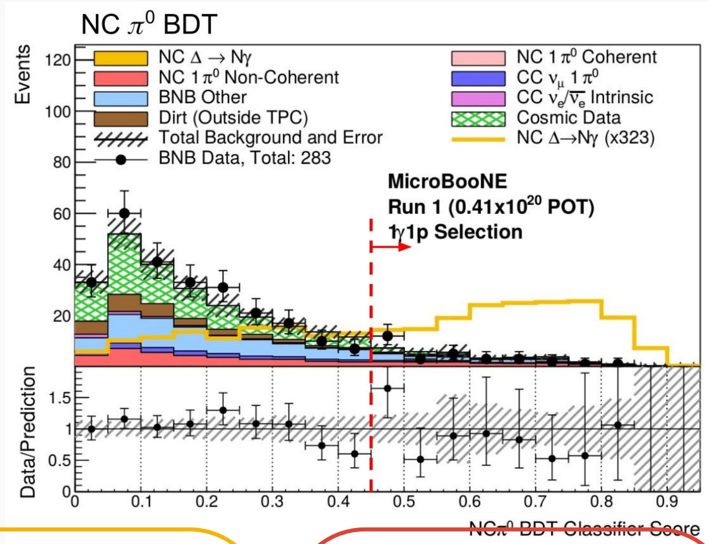
- $\nu_e + N \rightarrow e^- + \pi + N'$ and $\nu_e + n + p \rightarrow e^- + p + p$
- Single pion or 2-proton production

Event selection and analysis channels

arXiv:2110.00409, accepted by PRL

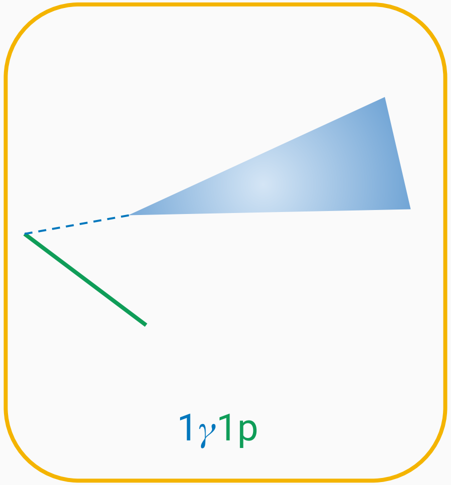
For this analysis:

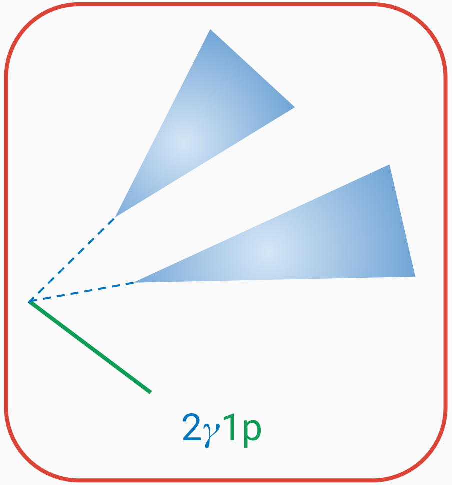
- Signal = 3.18 x Δ(1232) -> Nγ
- Main background = π^0->$\gamma\gamma$, one missing

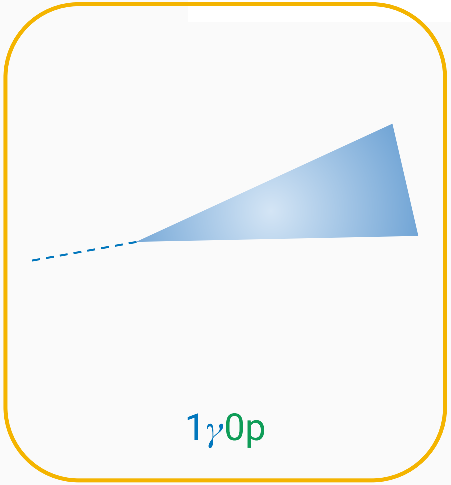


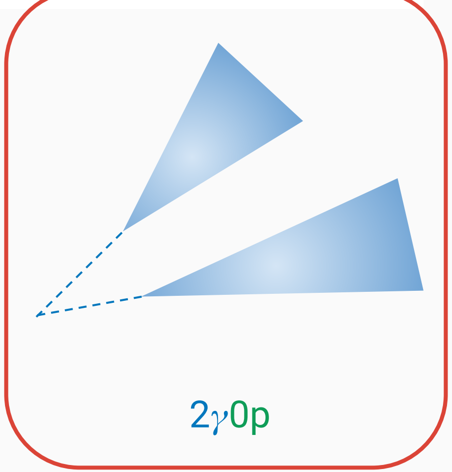
➔ BDT combines high-level information to reject most backgrounds

➔ 4 analysis channels: 2 signal and 2 constraining background









Reconstructed energy spectra

arXiv:2110.14054, submitted to PRL