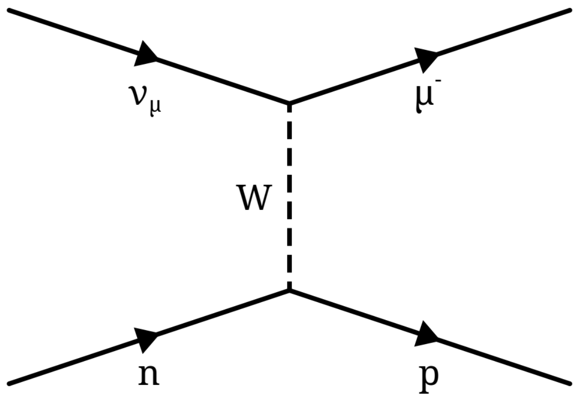
Neutrino angle reconstruction in MicroBooNE for precision atmospheric neutrino oscillations



4/9/2026
BNL seminar

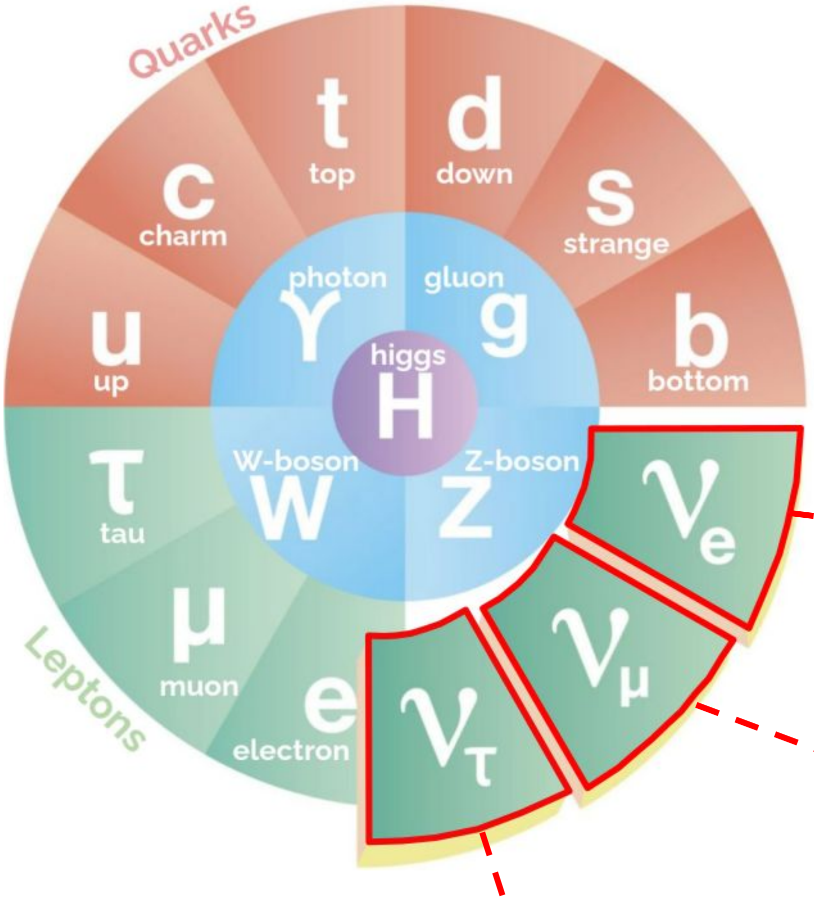
Afroditi Papadopoulou

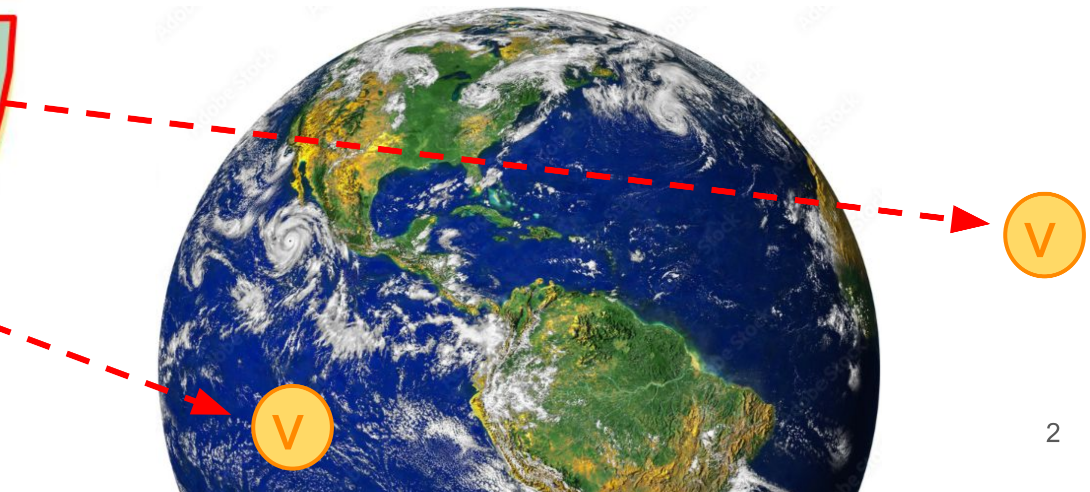
LA-UR-26-22465

µBooNE Los Alamos NATIONAL LABORATORY

Neutrinos 101

- Mysterious particles
- No charge
- Almost massless
- Incredibly hard to observe!





Neutrino states

Flavor states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

What we interact with and can produce/detect

Neutrino states

Flavor states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

What we interact with and can produce/detect

Mass states

$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

What propagates through space and has defined mass

Neutrino states

Flavor states   Mass states

$$\begin{pmatrix}\nu_e \\ \nu_\mu \\ \nu_\tau\end{pmatrix} = \begin{pmatrix}\text{mixing} \\ \text{matrix}\end{pmatrix} \begin{pmatrix}\nu_1 \\ \nu_2 \\ \nu_3\end{pmatrix}$$

Neutrino states

Flavor states　　　　Mass states

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}\text{mixing}\\ \text{matrix}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{-i\delta_{CP}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

$$\theta = \text{mixing angle}$$
$$c_{ij} = \cos\theta_{ij}$$
$$s_{ij} = \sin\theta_{ij}$$

Experimental overview

L: distance (baseline)

E_ν: neutrino energy

Two-neutrino approximation

mass difference

mixing angle

$m_2^2 - m_1^2$

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

Experimental overview

mass difference

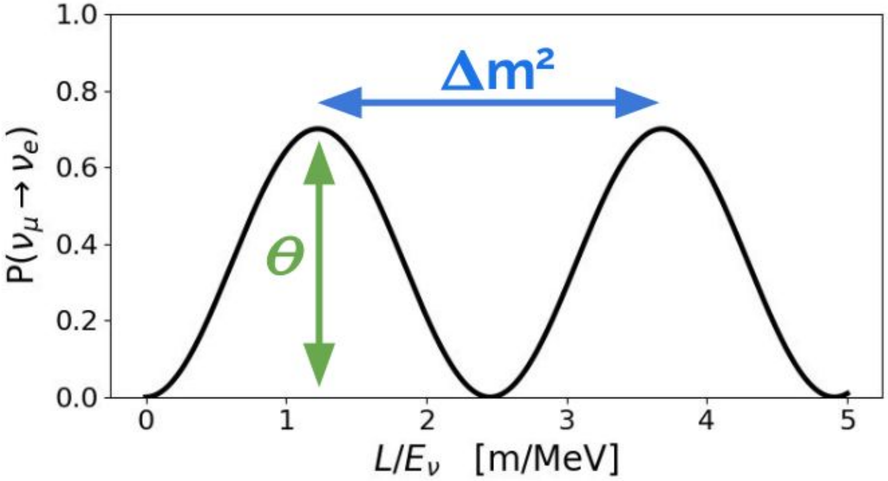
mixing angle

$$P(\nu_\mu \to \nu_e) \approx \underbrace{\sin^2(2\theta)}_{\text{amplitude}} \sin^2 \underbrace{\left(\frac{\Delta m^2 L}{4E_\nu}\right)}_{\text{frequency}}$$

amplitude

frequency

Neutrino "oscillation"



Experimental overview

mass difference

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$$P(\nu_\mu \to \nu_e) \approx \underbrace{\sin^2(2\theta)}_{\text{amplitude}} \sin^2 \underbrace{\left(\frac{\Delta m^2 L}{4E_\nu}\right)}_{\text{frequency}}$$

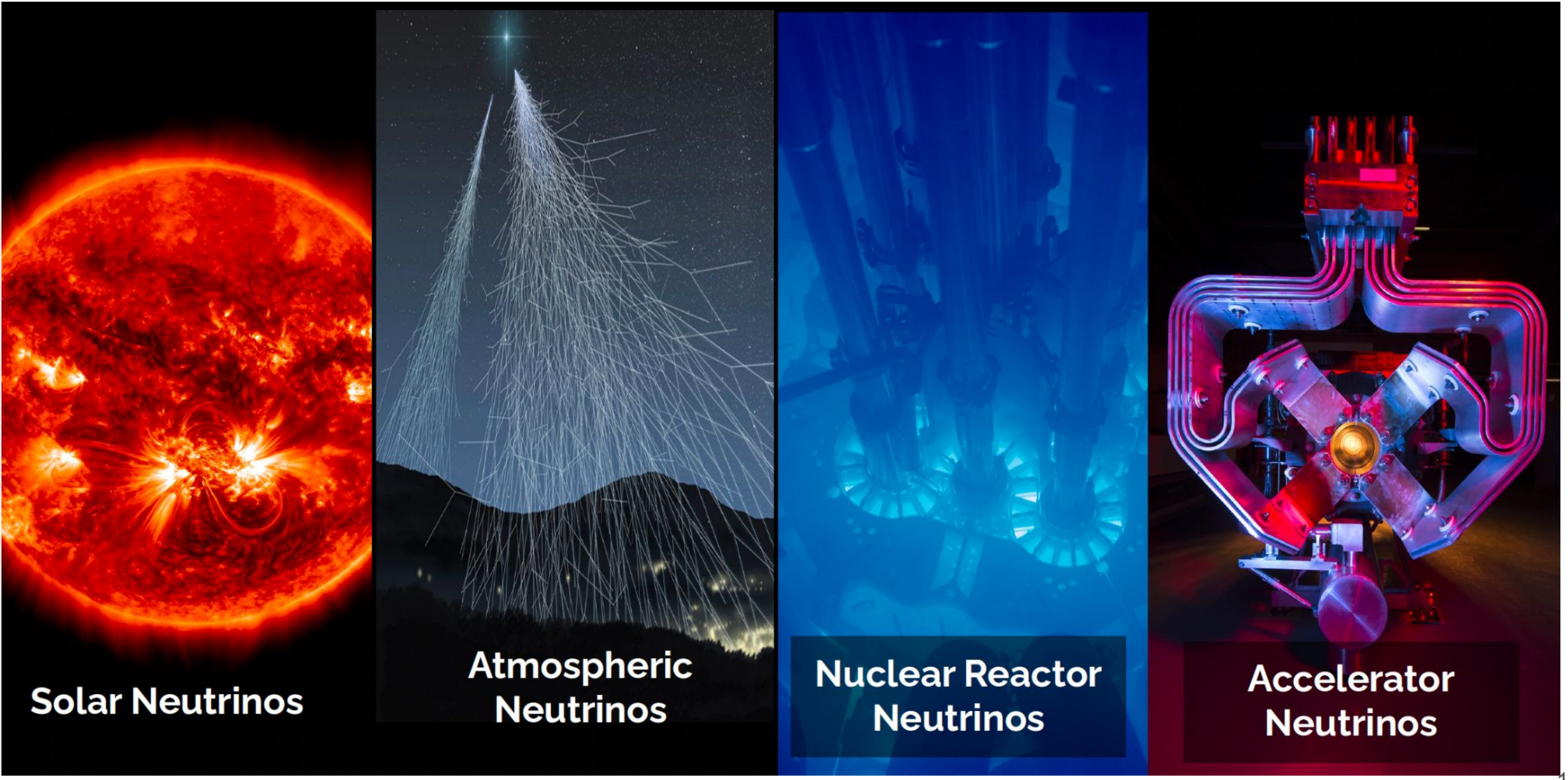
amplitude

frequency

Optimizing baseline L for a given neutrino source of energy E_ν

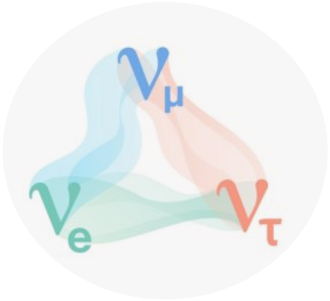
Mass difference Δm^2 and mixing angles θ known to few %-level

Leverage neutrino sources across wide energy spectrum



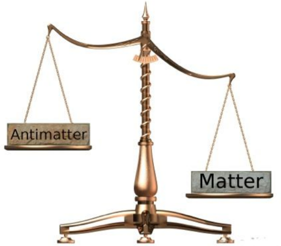
~MeV ~GeV ~MeV ~GeV

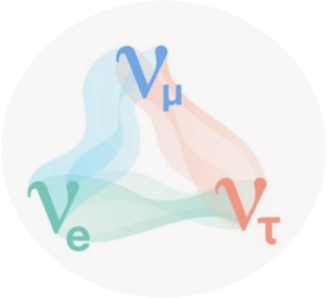
Open questions



Open questions

Charge parity violation





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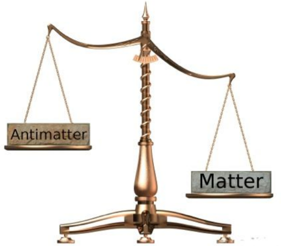
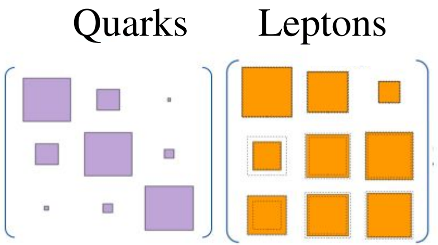
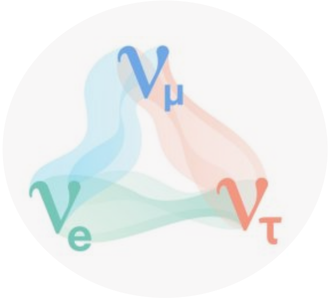


Mixing matrix





Open questions

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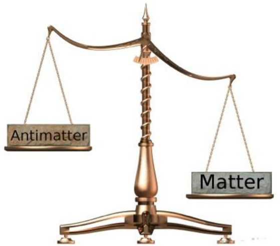
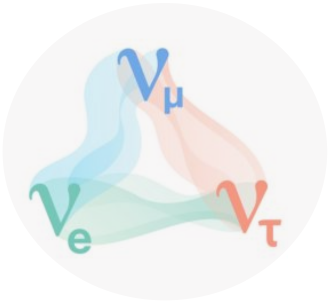
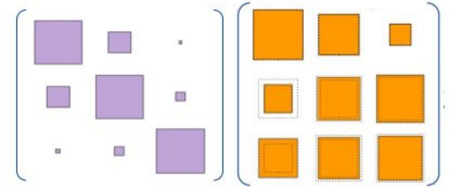


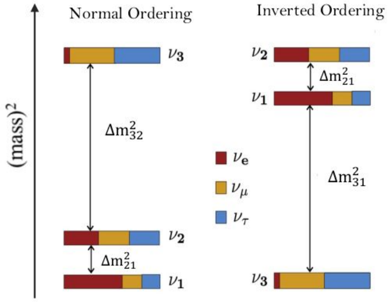


Mixing matrix

Quarks Leptons

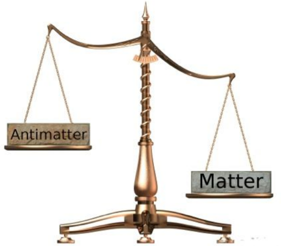


Mass ordering



Open questions

Charge parity violation



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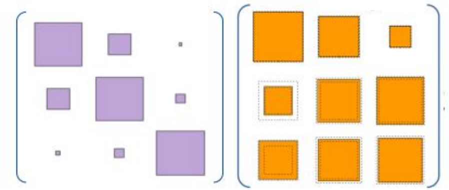
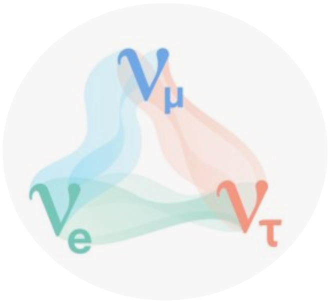
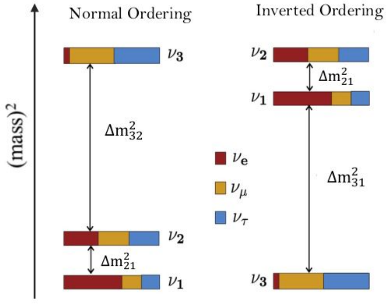




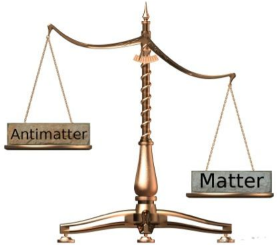
Mass ordering



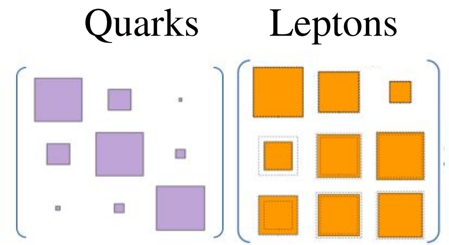
Mass mechanism

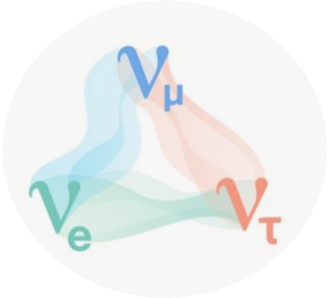
Open questions

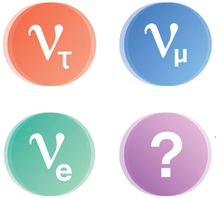
Charge parity violation



Mixing matrix



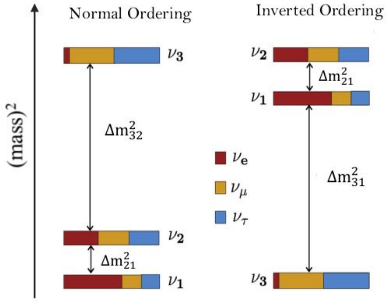




Sterile neutrinos

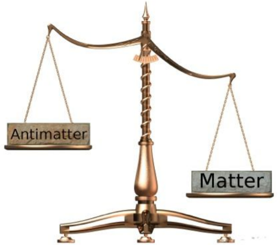
Mass mechanism

Mass ordering

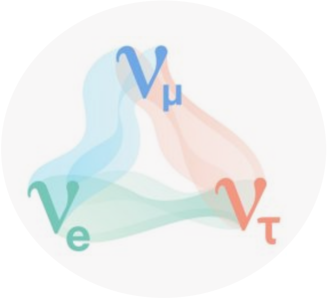


Open questions

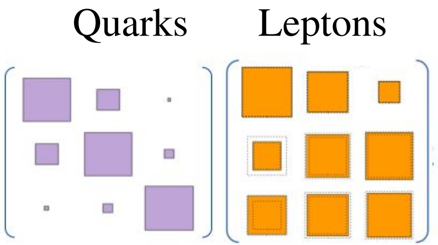
Charge parity violation



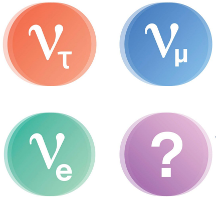
Majorana vs Dirac



Mixing matrix

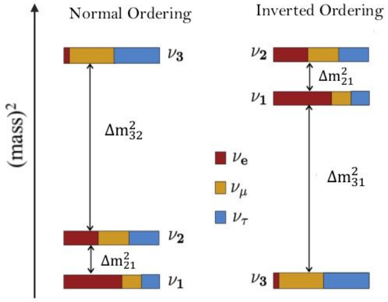


Sterile neutrinos



Mass mechanism

Mass ordering



Open questions

Charge parity violation

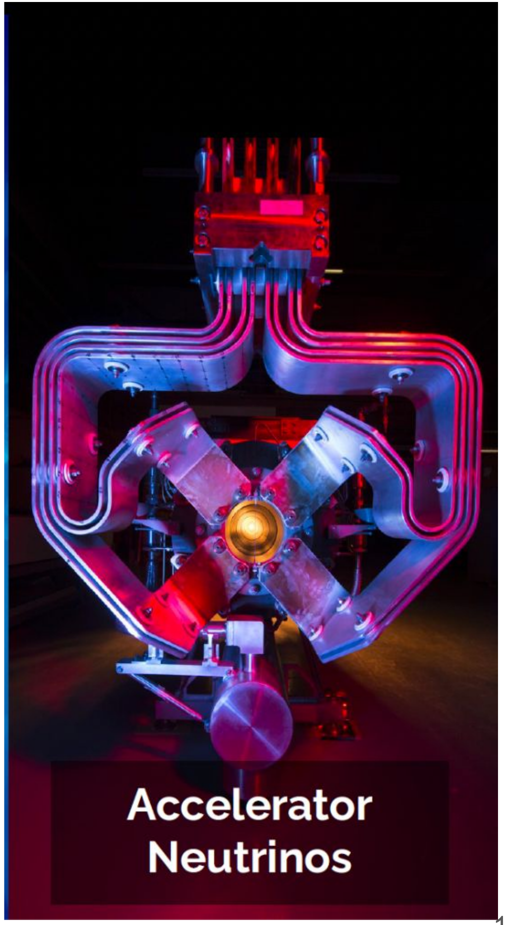
Mixing matrix

Investigated with high-precision neutrino oscillation experiments

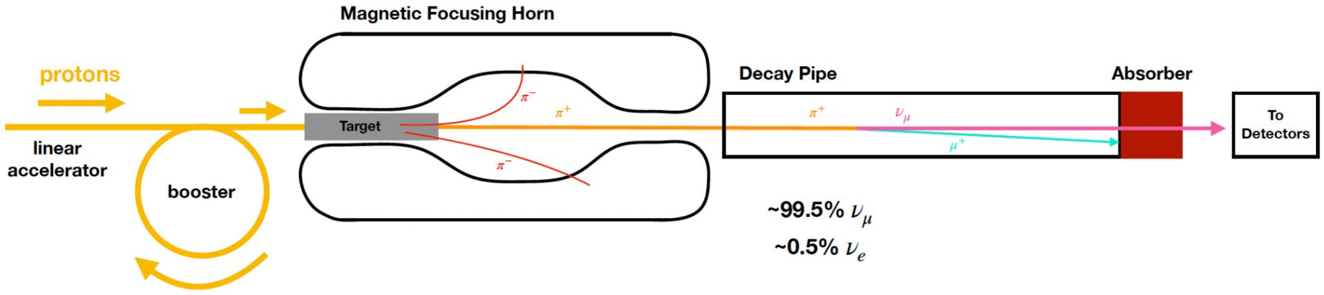
Sterile neutrinos

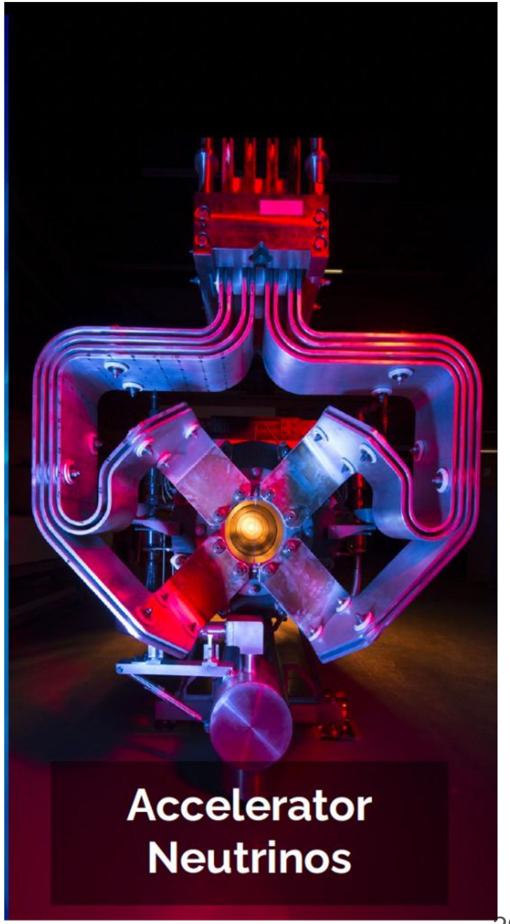
Mass ordering

Commonly used



Commonly used



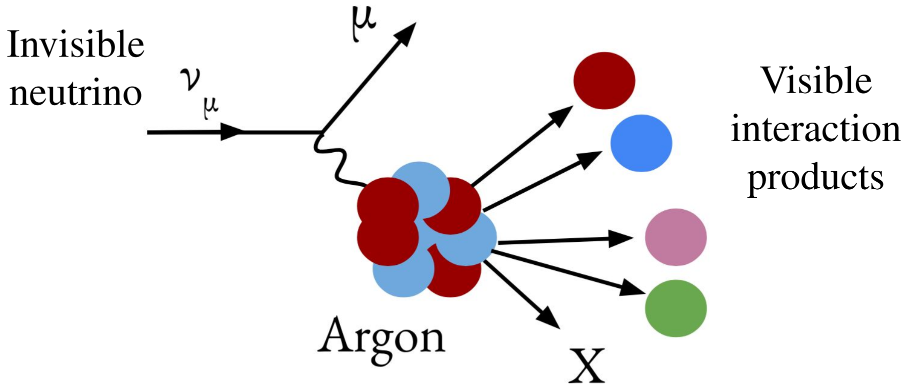


Neutrino oscillation experiments

$N_{ND}^{\mu}(E_{rec})$: Number of events of flavor μ

E_{rec} = Reconstructed ν energy

Near detector



Neutrino flux prediction

Near detector selection efficiency

$$N^{\mu}_{ND}(E_{rec}) \sim \Phi_{ND}(E_\nu)\sigma(E_\nu)\epsilon_{ND}(E_\nu)$$

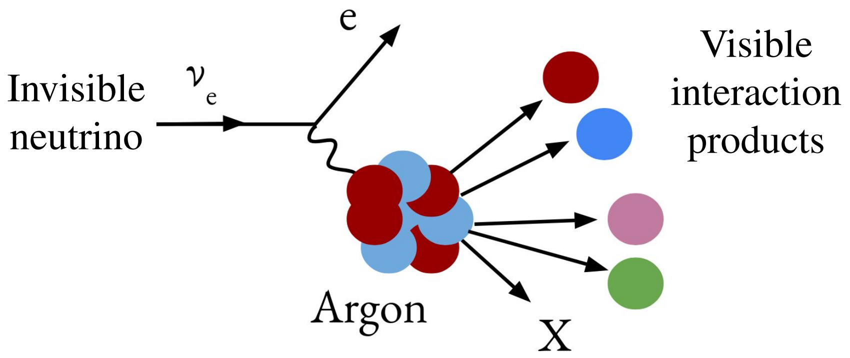
Neutrino cross section model

Neutrino oscillation experiments

$N_{FD}^{e}(E_{rec})$: Number of events of flavor e

E_{rec} = Reconstructed ν energy

Far detector



Neutrino flux prediction

Far detector selection efficiency

$$N^{e}_{FD}(E_{rec}) \sim \Phi_{FD}(L, E_{\nu})\sigma(E_{\nu})\epsilon_{FD}(E_{\nu})P(\nu_{\mu} \rightarrow \nu_{e})$$

Neutrino cross section model

Far detector

Oscillation probability

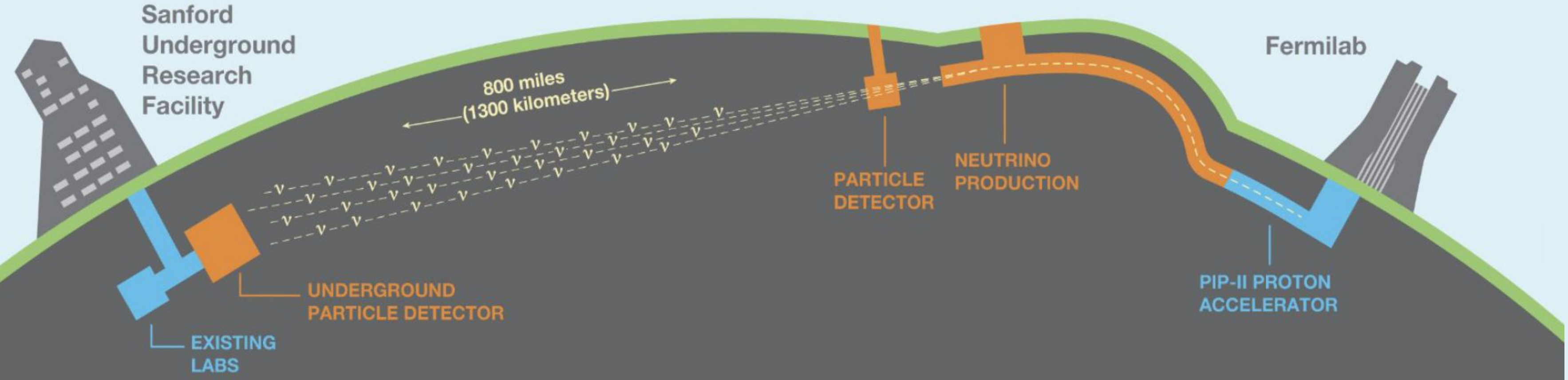
$$N_{FD}^{e}(E_{rec}) \sim \Phi_{FD}(L, E_\nu)\sigma(E_\nu)\epsilon_{FD}(E_\nu)\boxed{P(\nu_\mu \to \nu_e)}$$

mass difference

mixing angle

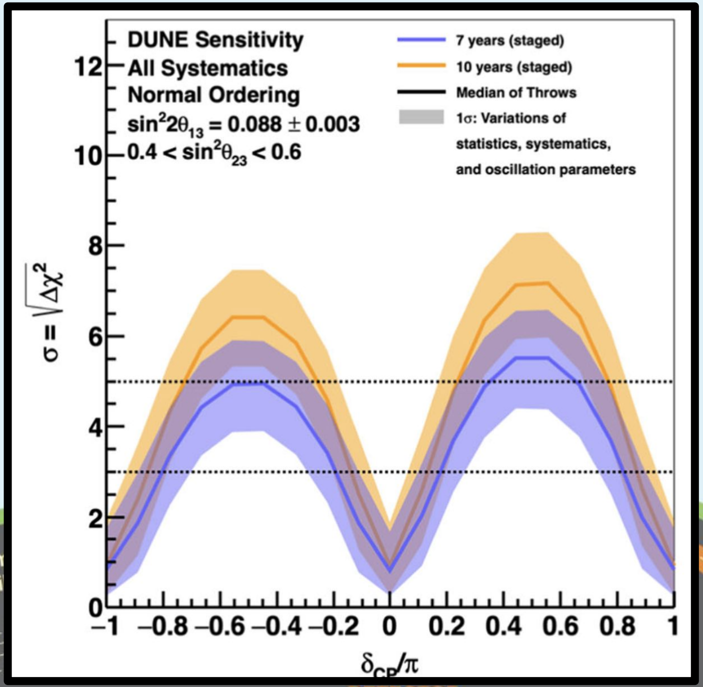
$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

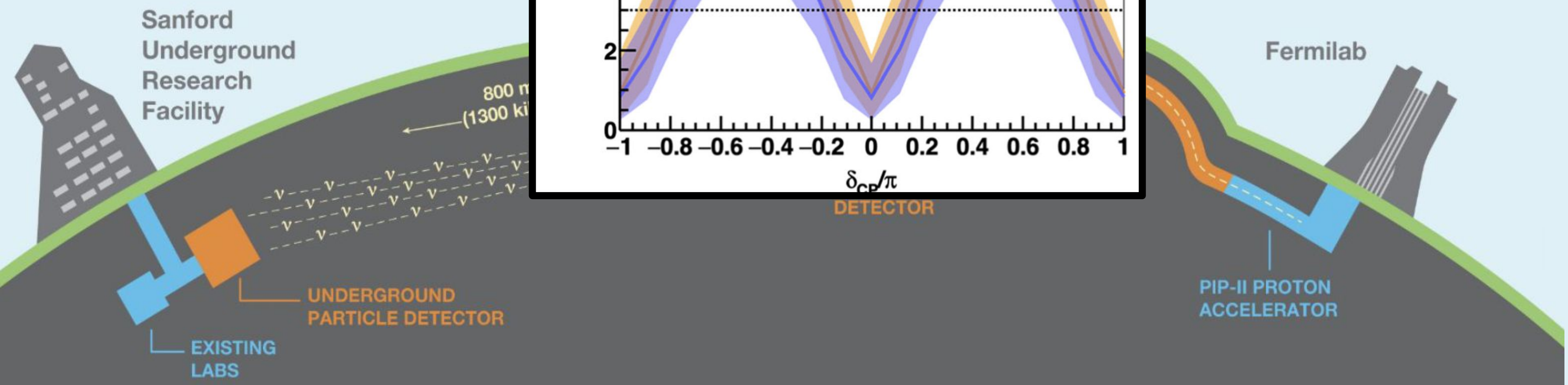
Forthcoming neutrino oscillation experiments aim to perform **high-precision measurements** in the neutrino sector



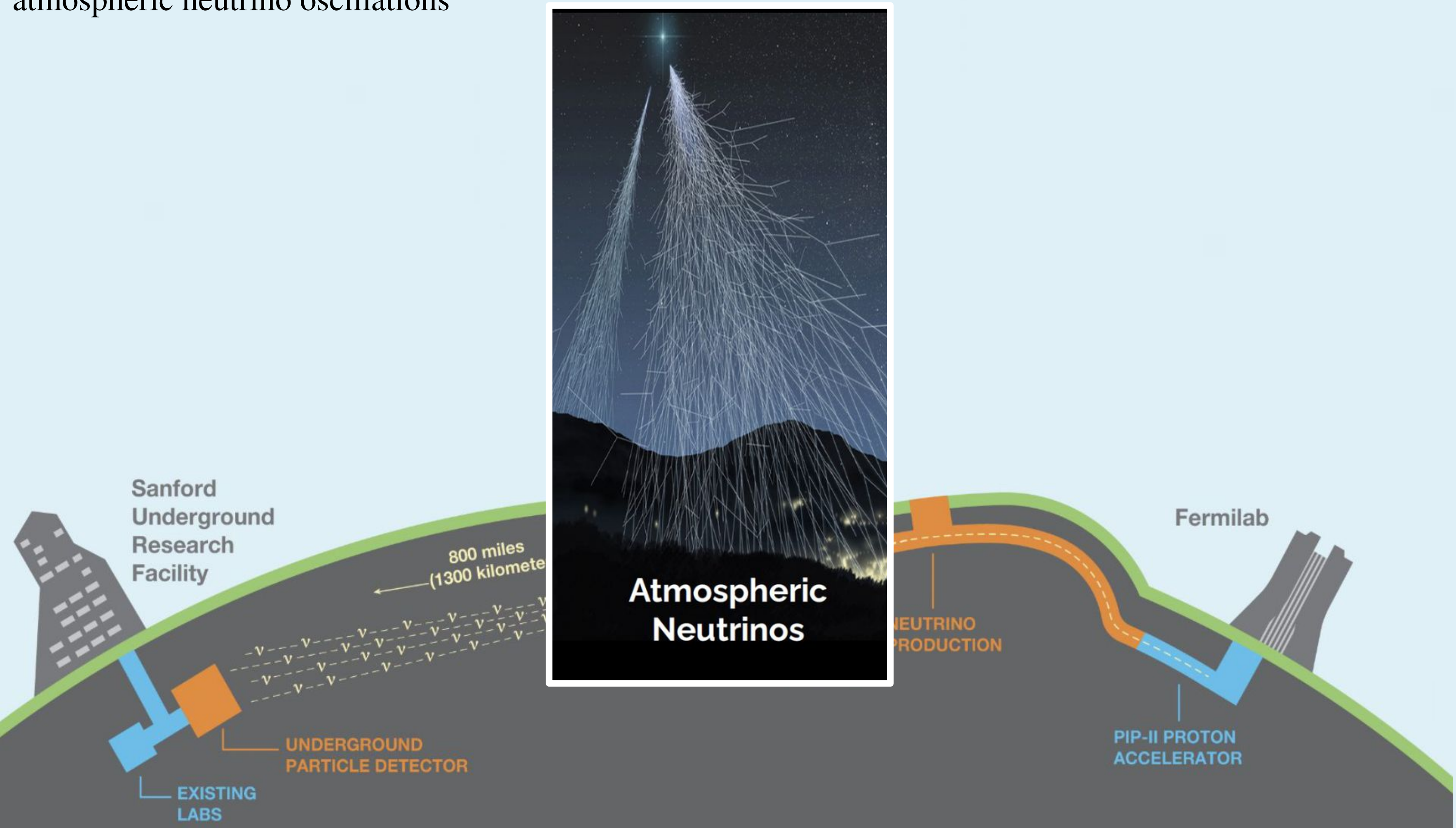
Flagship analysis!

Charge-parity (CP) phase extraction might shed light on matter-antimatter asymmetry in universe





However … **first analyses** will use atmospheric neutrino oscillations



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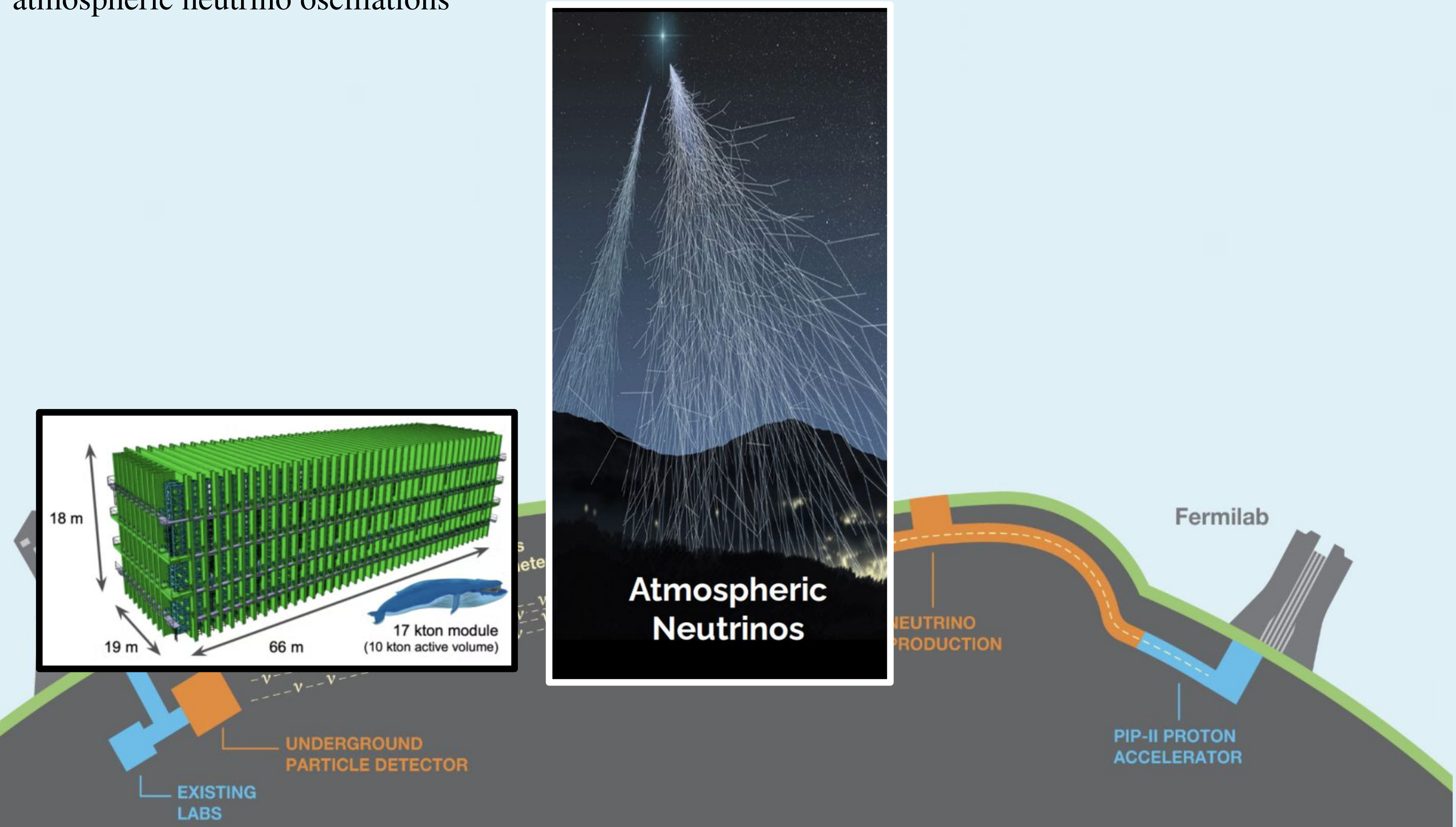
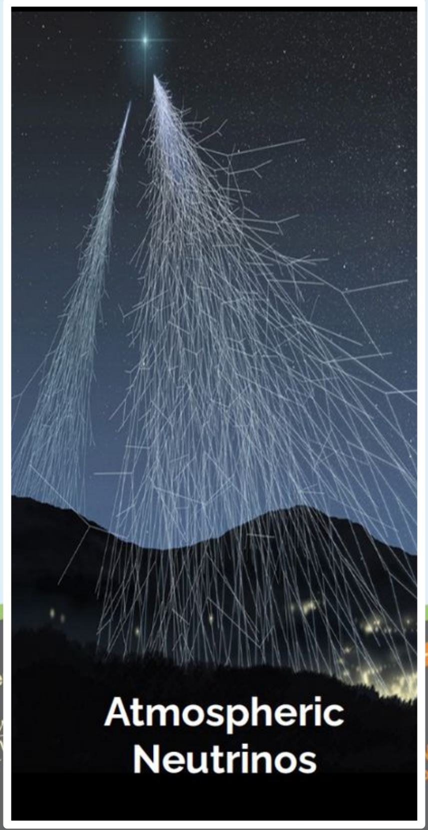


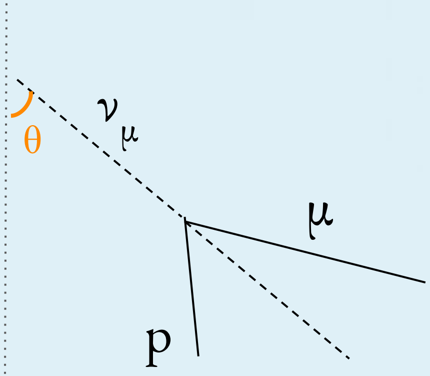
However … **first analyses** will use atmospheric neutrino oscillations

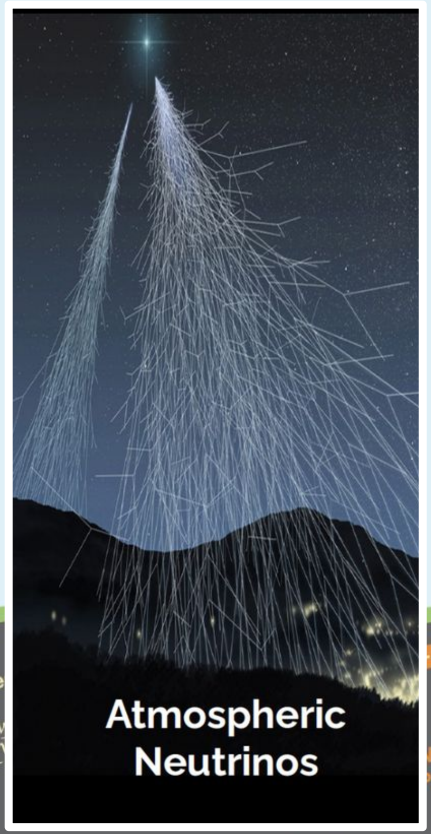
$$\pi^+ \rightarrow \nu_\mu + \mu^+$$
$$\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$$

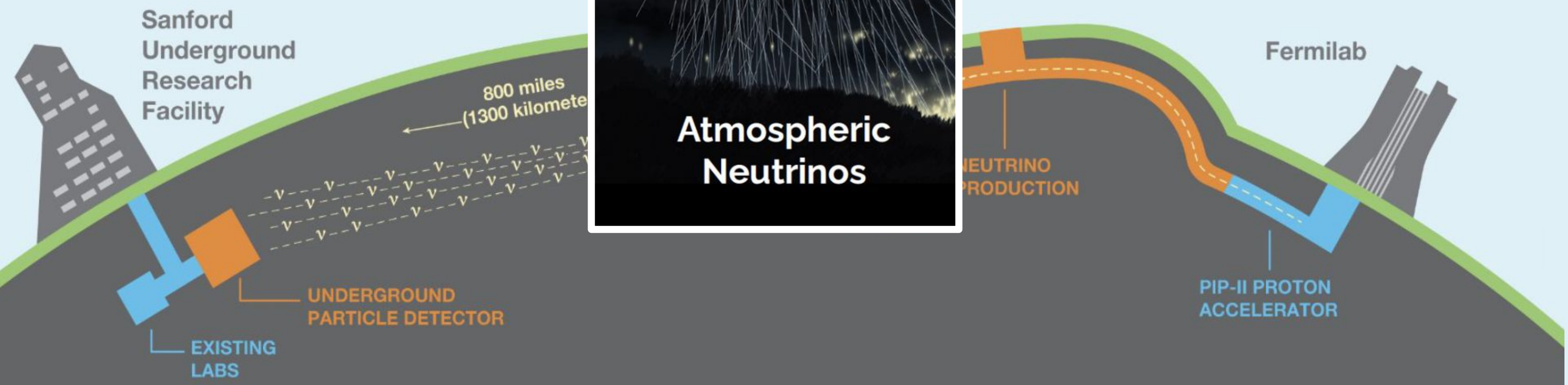
$$\pi^- \rightarrow \bar{\nu}_\mu + \mu^-$$
$$\mu^- \rightarrow \nu_\mu + \bar{\nu}_e + e^-$$



Neutrino direction (θ) needs to be reconstructed with high precision from interaction products

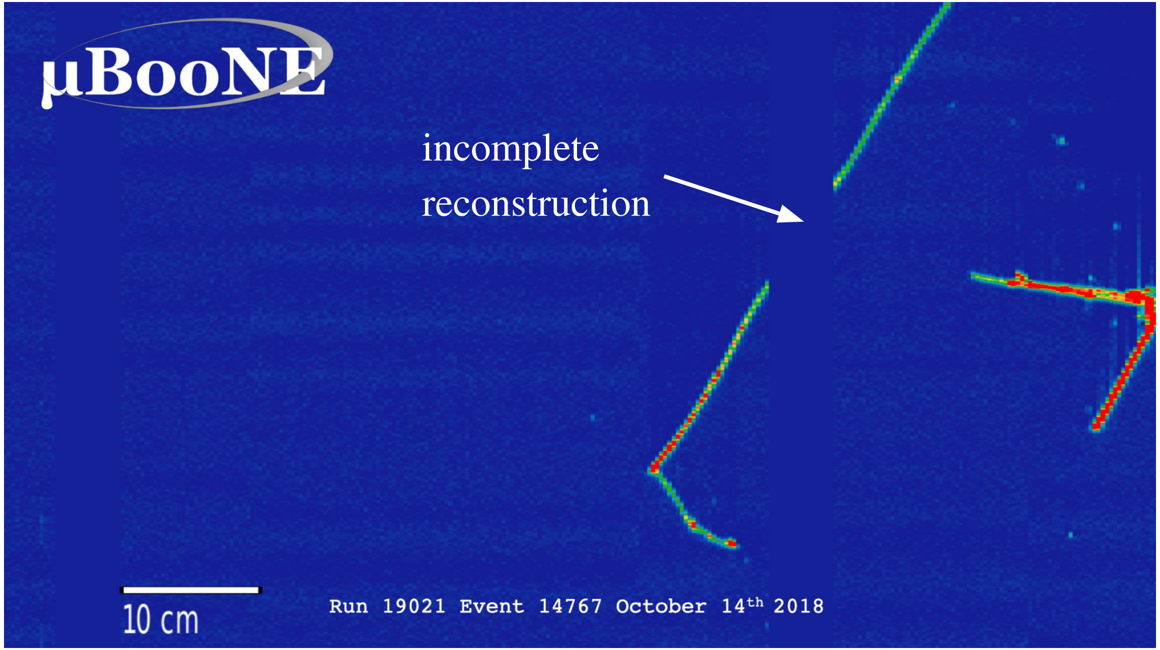






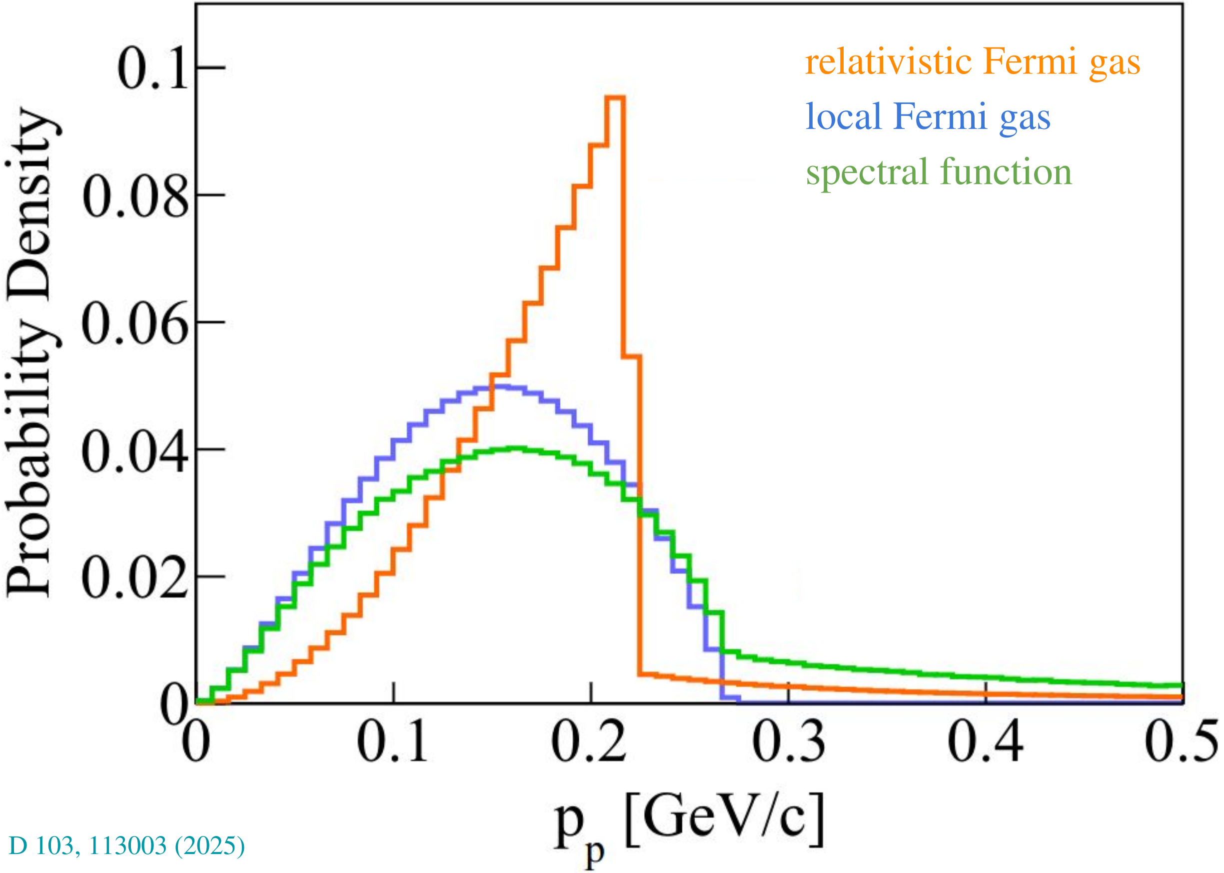
Reconstruction limitations

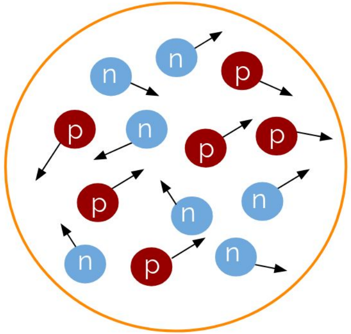
Incomplete reconstruction or non-responsive detector regions



Modeling limitations

Struck nucleon momentum

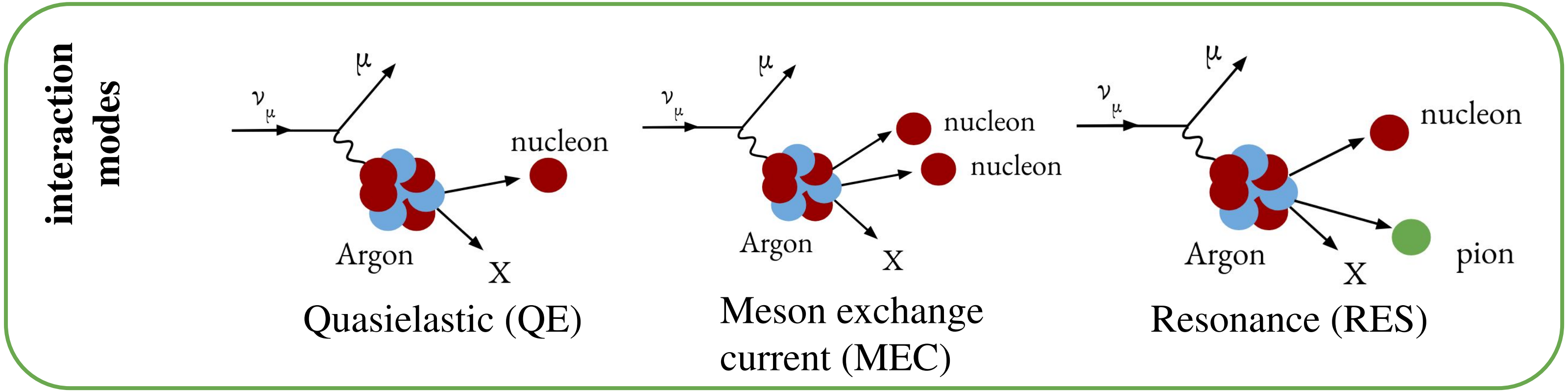




Phys. Rev. D 103, 113003 (2025)

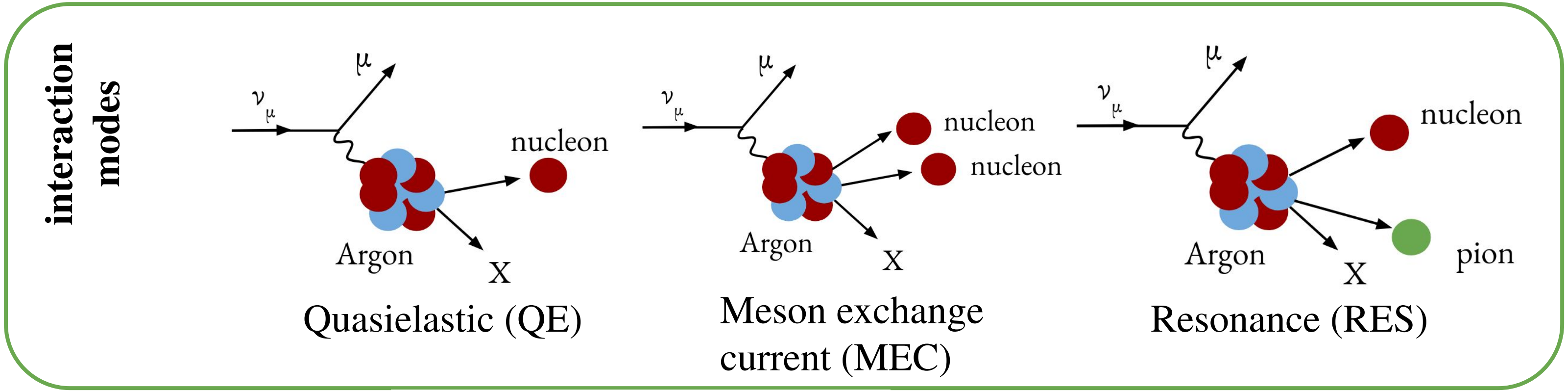
Modeling limitations

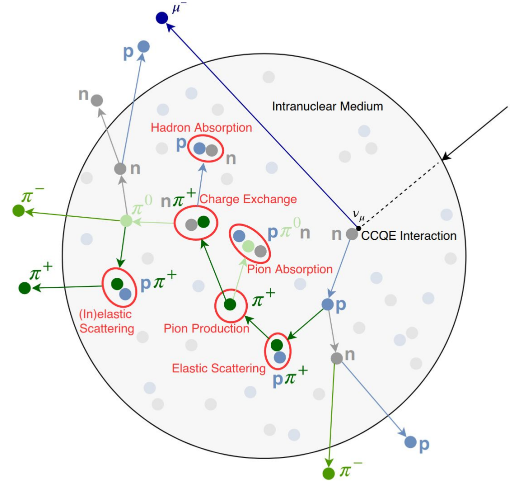
Hadron reinteractions



Modeling limitations

Hadron reinteractions





Modeling limitations

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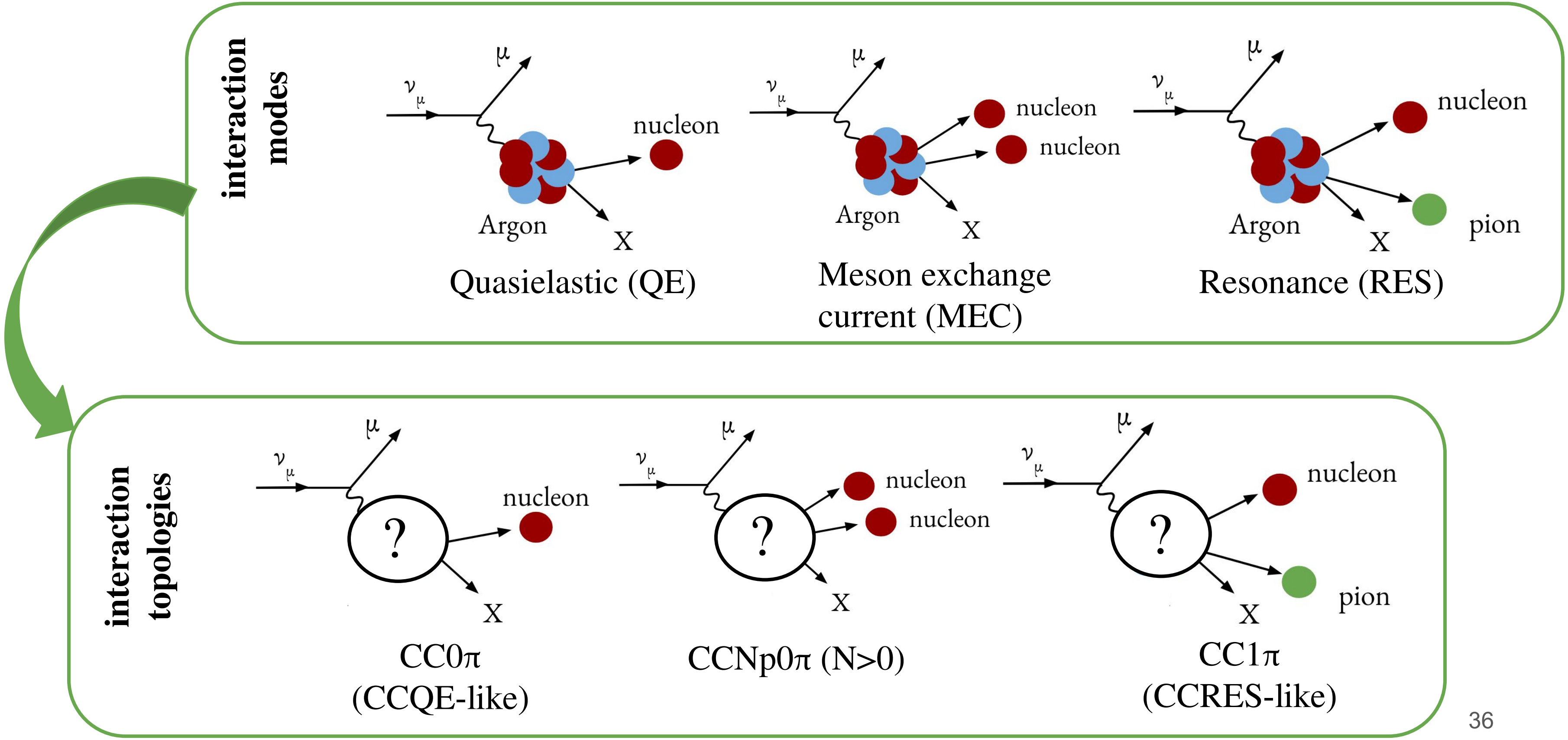
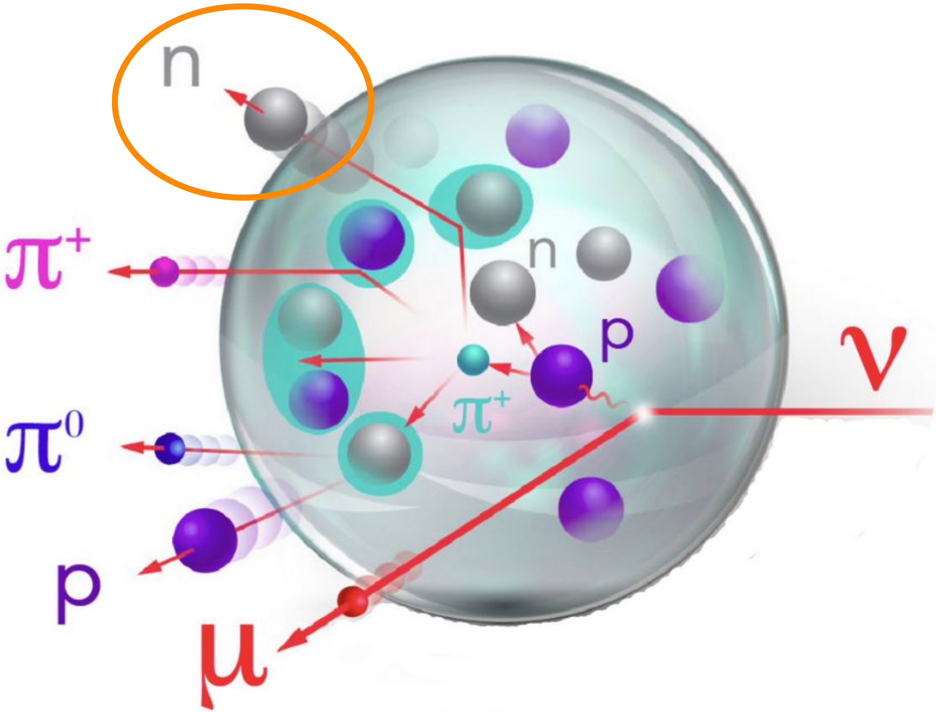


Modeling limitations

Undetectable particles eg neutrons



Nature volume 599, pages 565–570 (2021)

Cannot easily study these effects if our neutrinos are coming from every possible direction ….

Let’s be smart

Let’s be smart

- Use another detector where the neutrino origin is known

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- Treat neutrinos as “atmospheric neutrinos” of unknown origin

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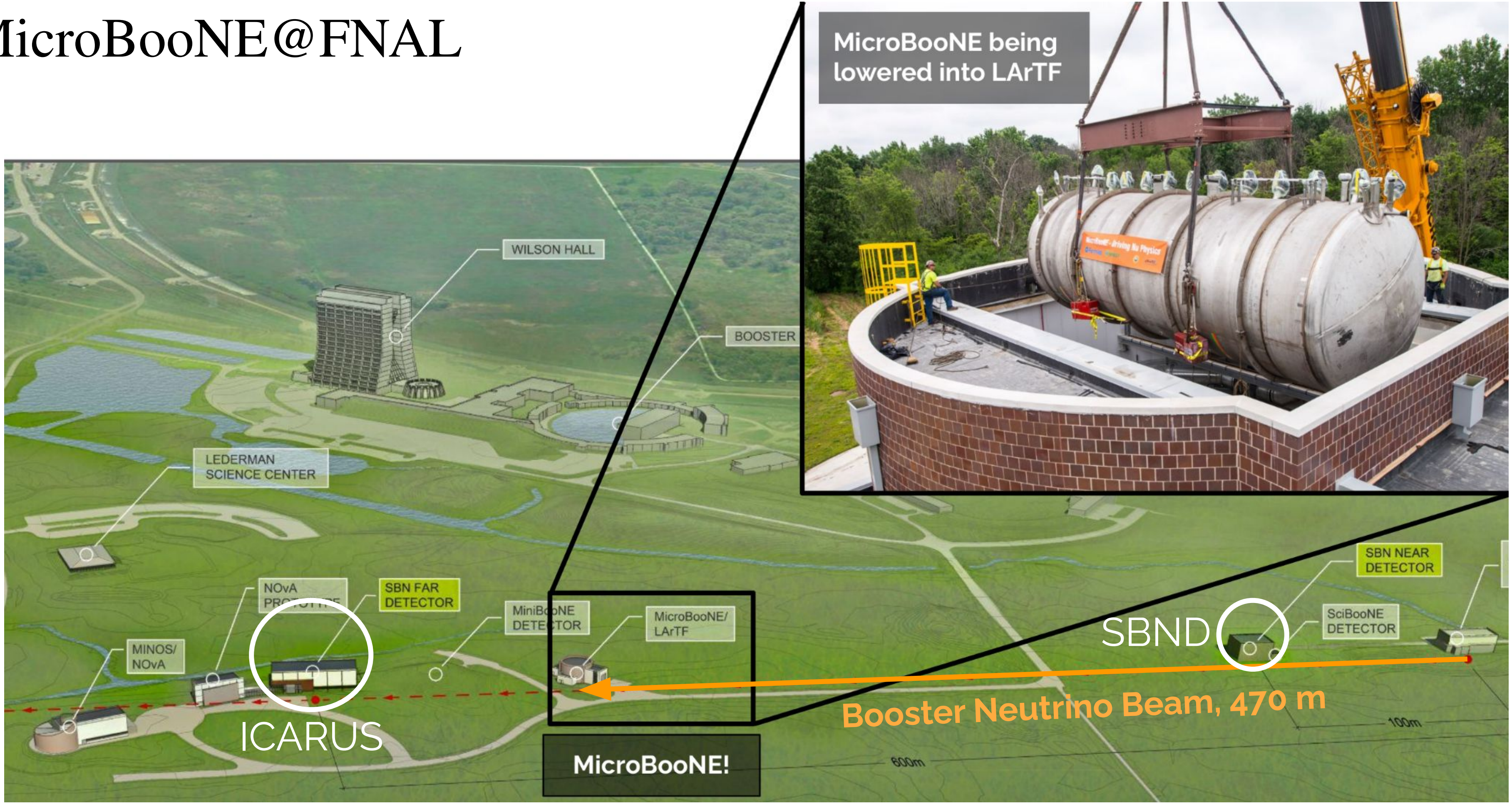
And that brings us to μBooNE !

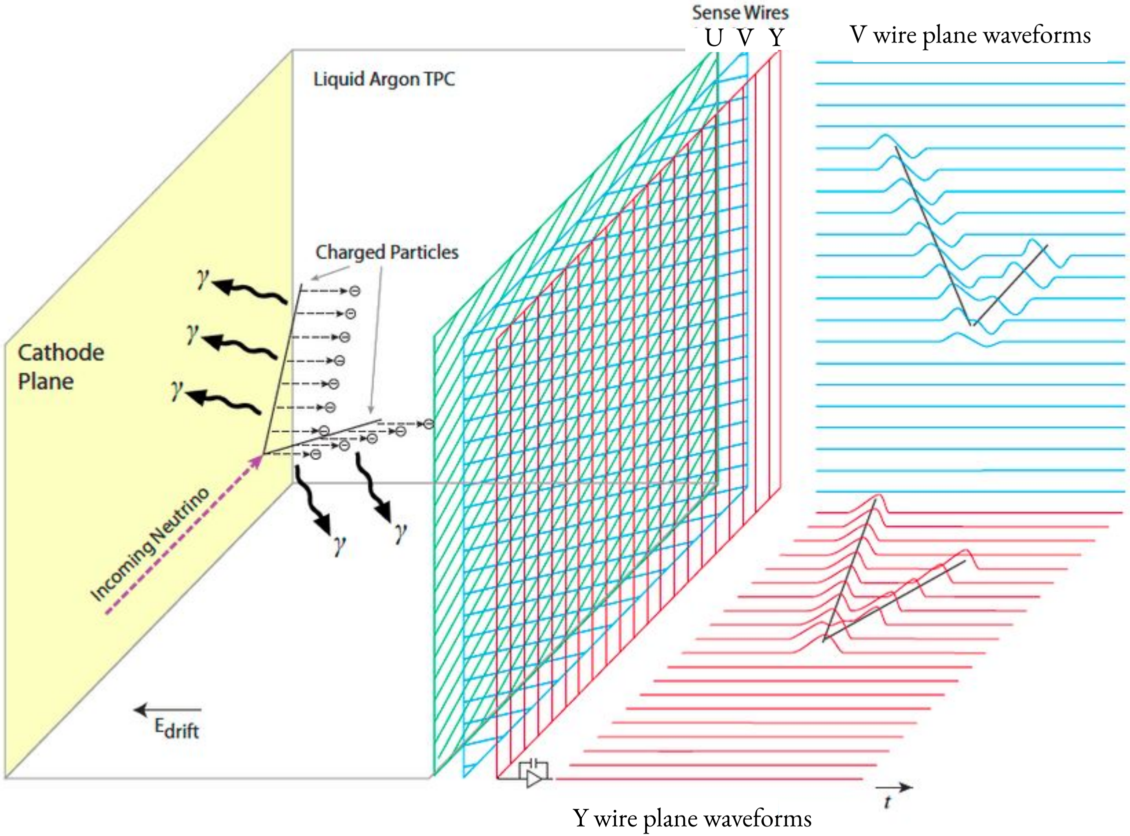
MicroBooNE@FNAL



85 tonne Liquid Argon Time Projection Chamber (LArTPC)

JINST 12, P02017 (2017)

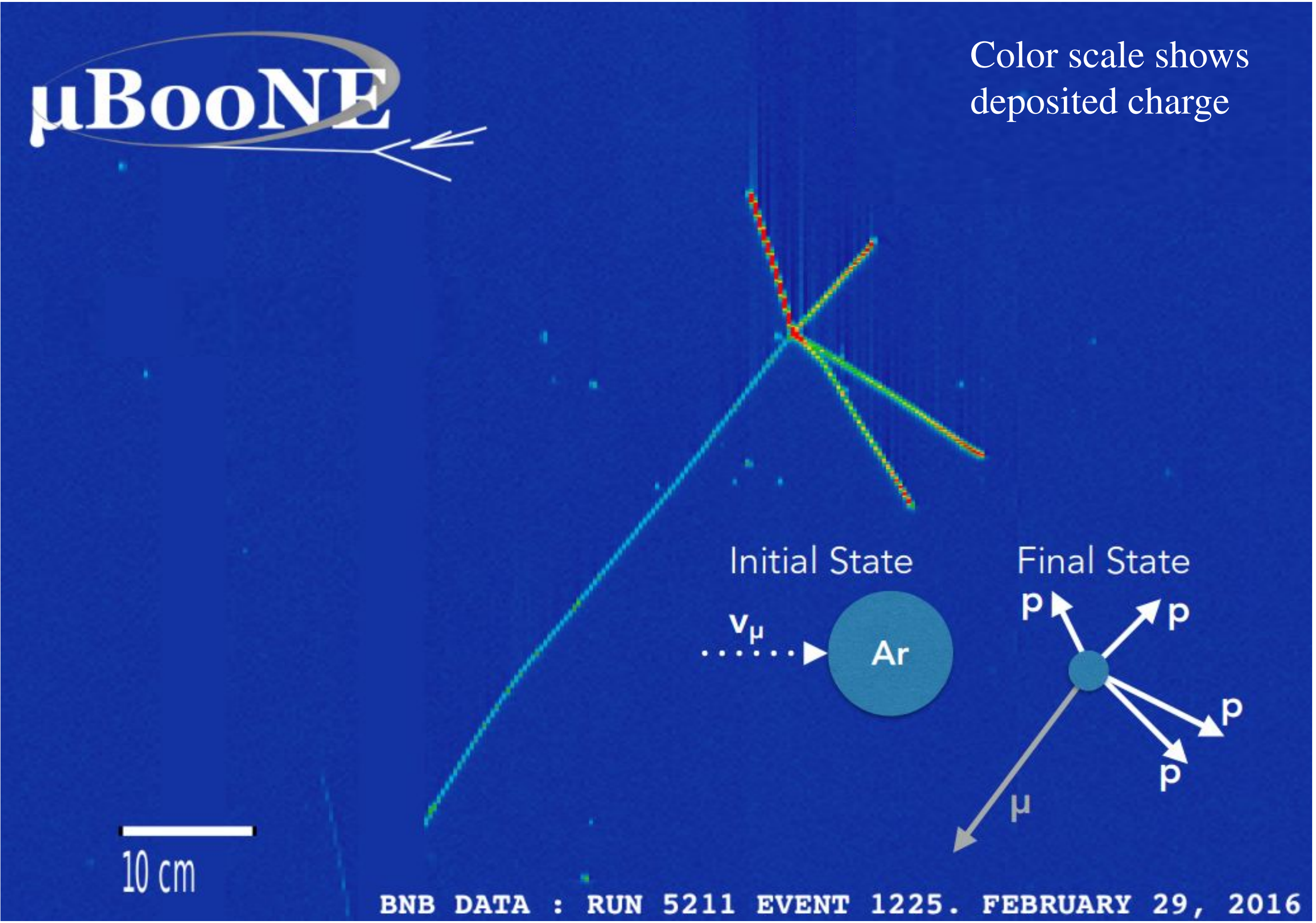
MicroBooNE detector



- 3 wire planes
- 8192 gold coated wires
- 3 mm wire spacing
- 32 PMTs

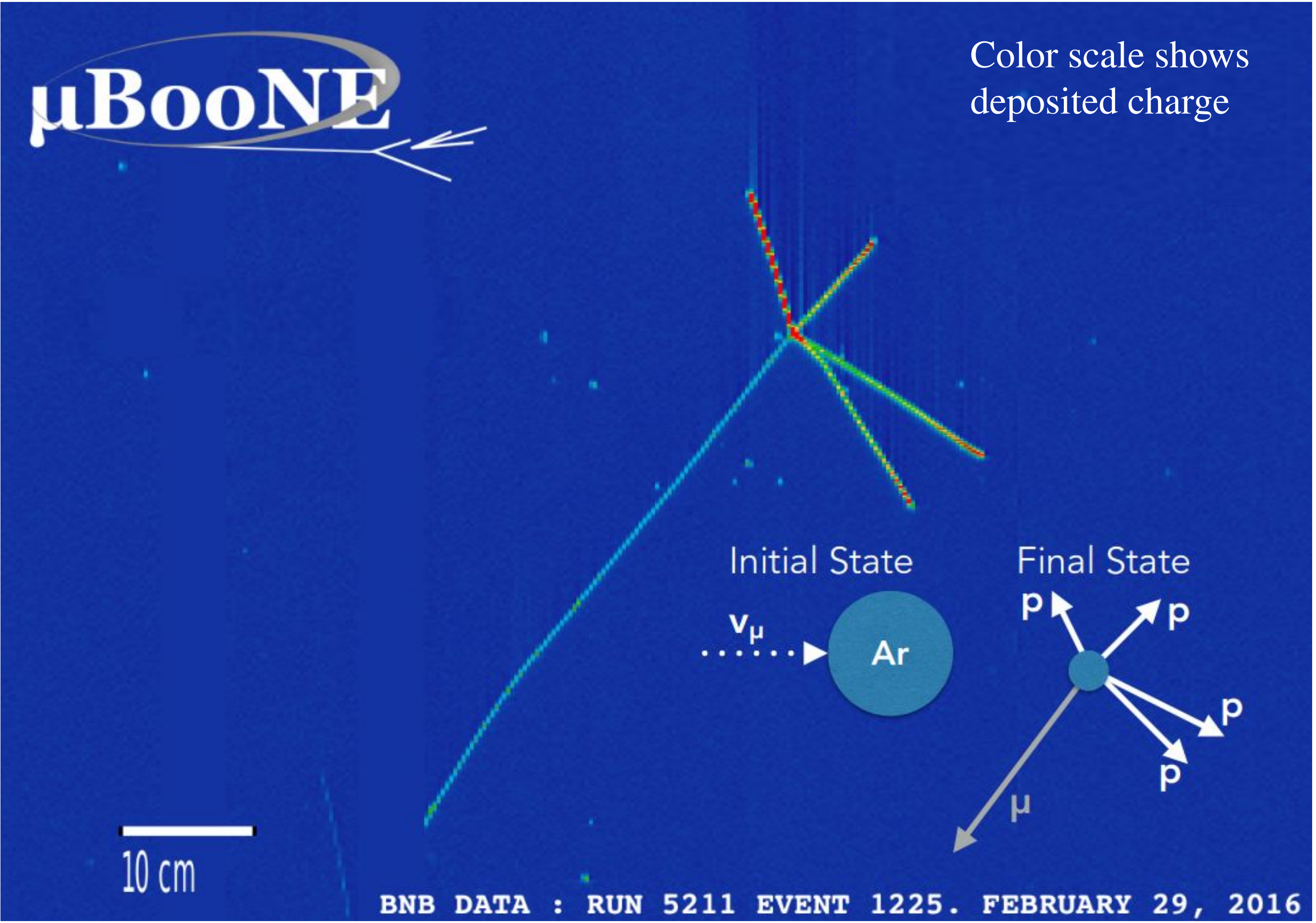
JINST 12, P02017 (2017)

MicroBooNE data events



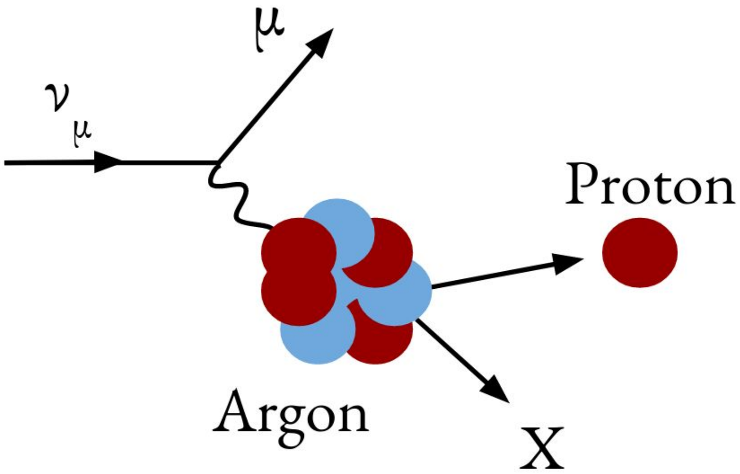
- Excellent spatial resolution
- Low detection thresholds
- Precise calorimetric information
- Powerful particle identification

MicroBooNE data events



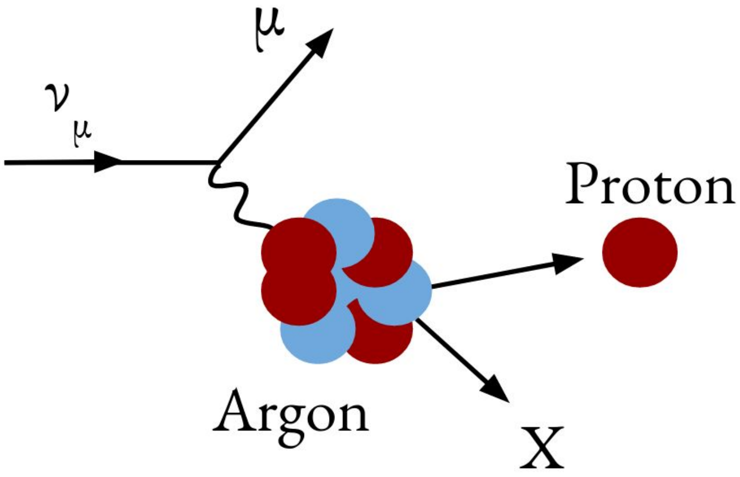
- One of largest available neutrino-argon data sets with ~500k recorded neutrino interactions
- More than 20 released and 30 active MicroBooNE cross section analyses
- Multiple event types investigated

Single-proton knockout events

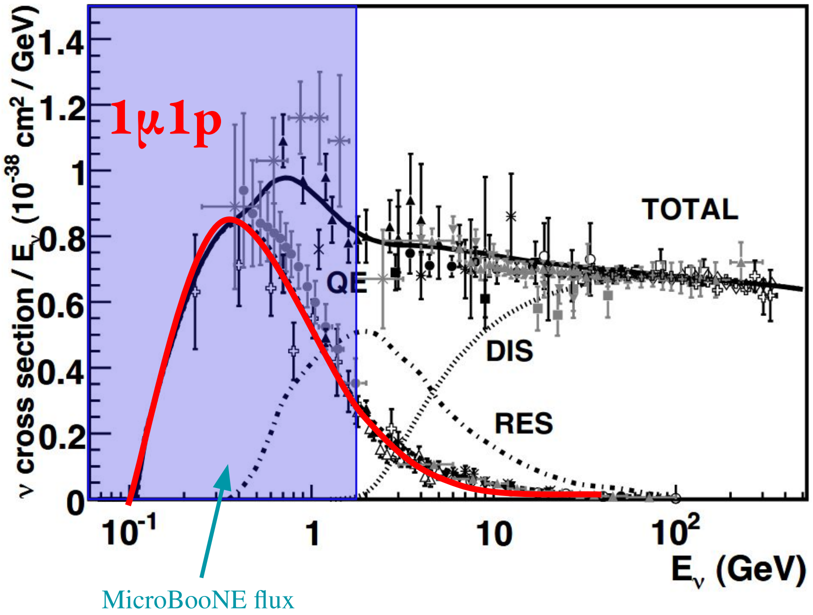


- First-ever neutrino angle reconstruction data-driven study on argon
- Quantified angular reconstruction performance in specific phase-space regions

Why single-proton events?

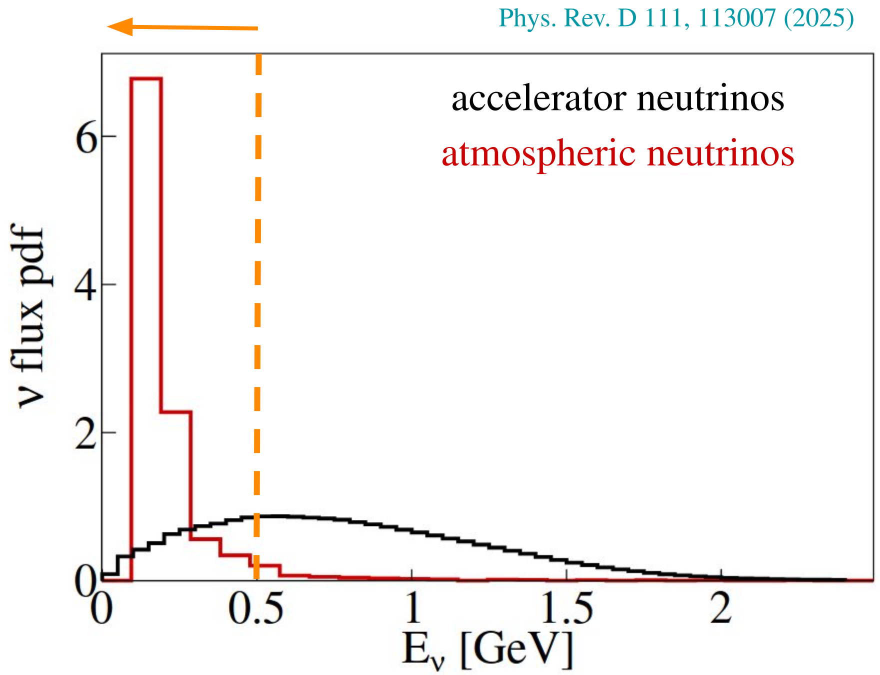


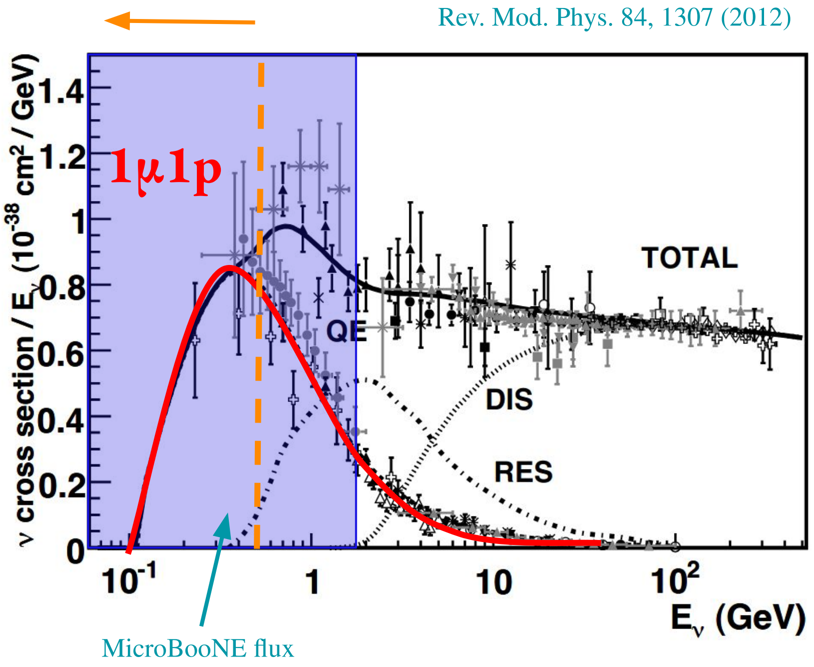
Rev. Mod. Phys. 84, 1307 (2012)



Simple and dominant at relevant energies

Bonus!





Overlap with low energies relevant for atmospheric neutrinos

Signal definition

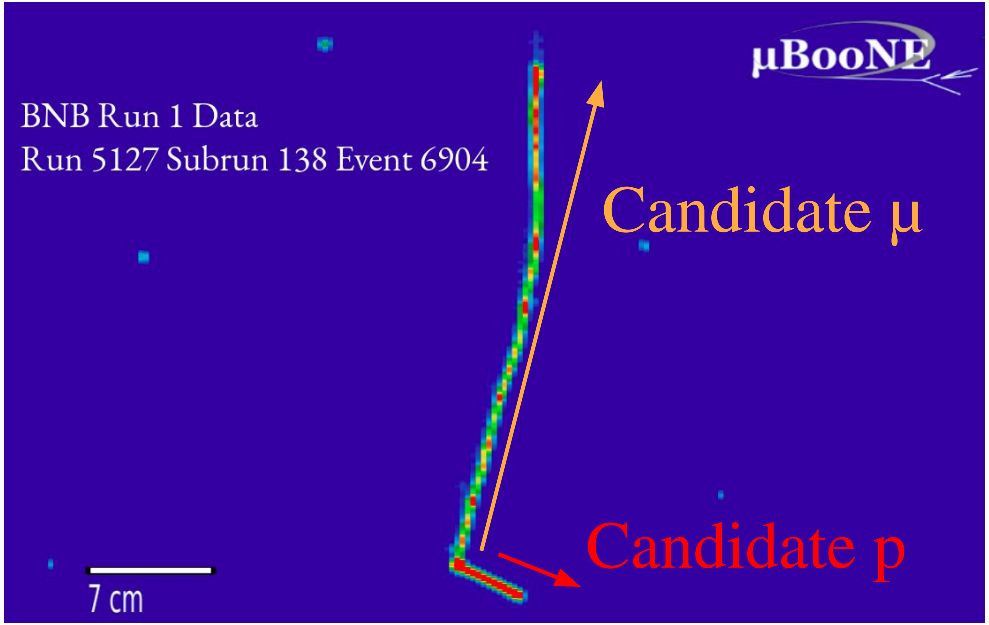
- 1 muon
  $100 < P_\mu < 1200$ MeV/c

- 1 proton
  $300 < P_p < 1000$ MeV/c

- No $\pi^\pm$ with $P_\pi > 70$ MeV/c

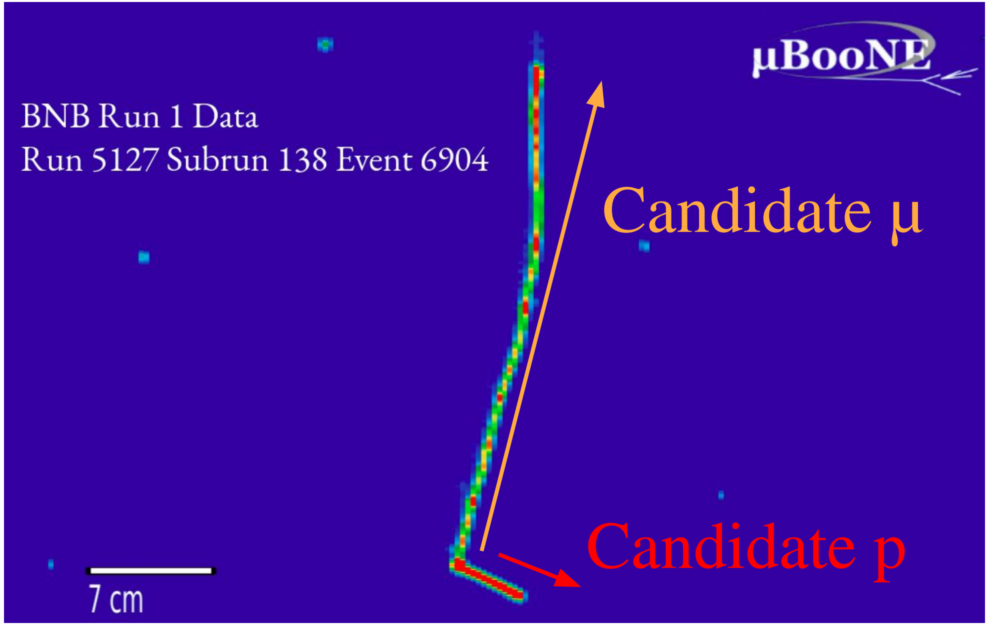
- No π^0/heavier mesons

- Any number of neutrons



Signal definition

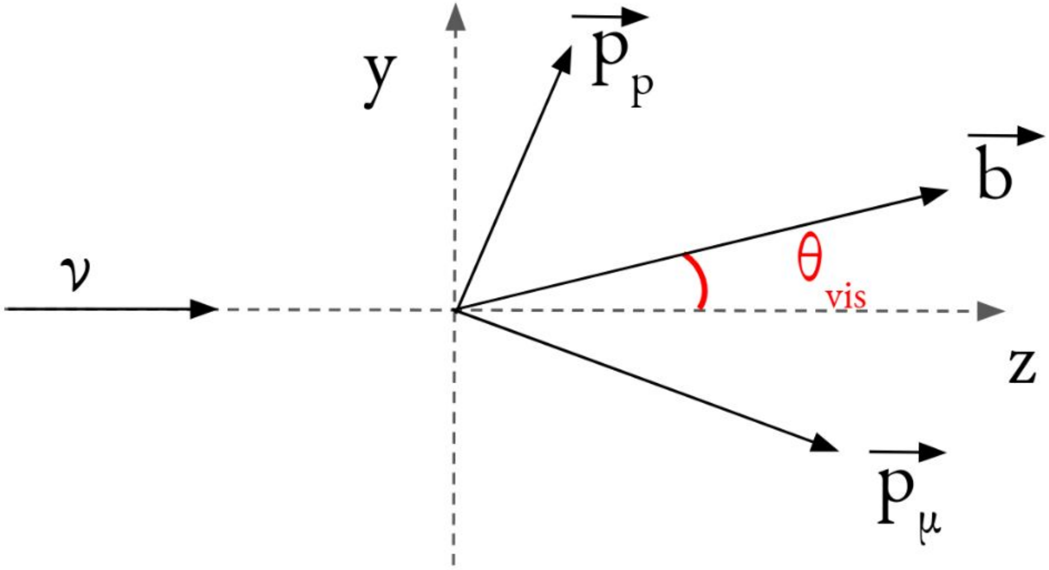
- Using Booster Neutrino Beam (BNB) flux and full MicroBooNE data set
- Fully contained tracks
- 17130 CC1p0π candidate data events
- Purity ~70%
- Efficiency ~10%



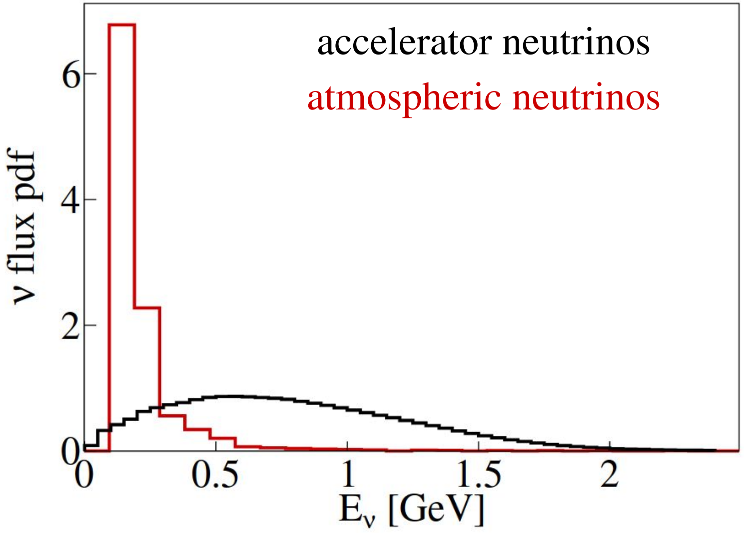
Main observable

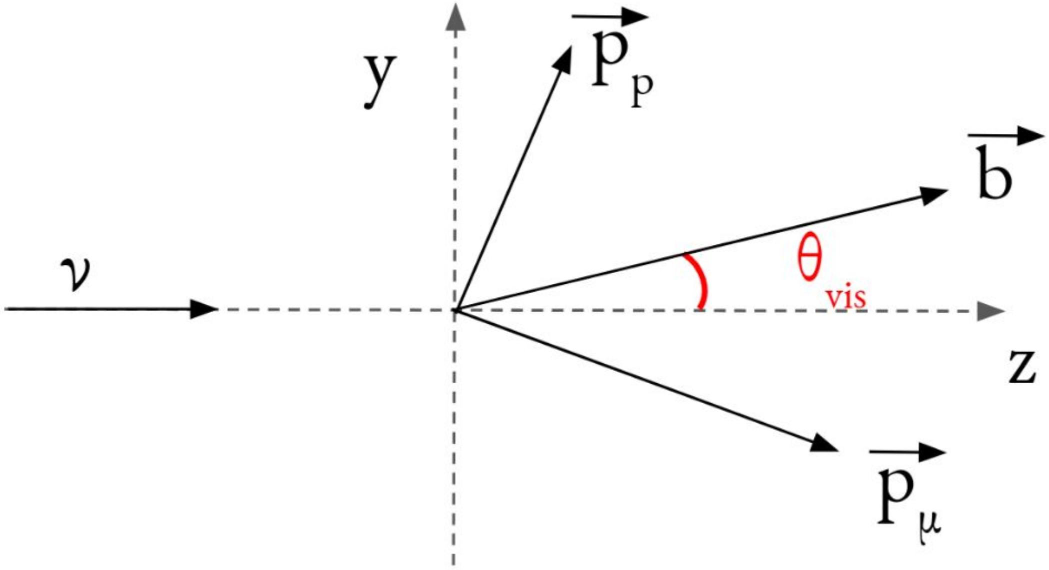
$$\theta_{\text{vis}} = \text{acos}(\frac{\vec{b} \cdot \hat{z}}{|\vec{b}|})$$

with $\vec{b} = \vec{p}_\mu + \vec{p}_p$



Main observable



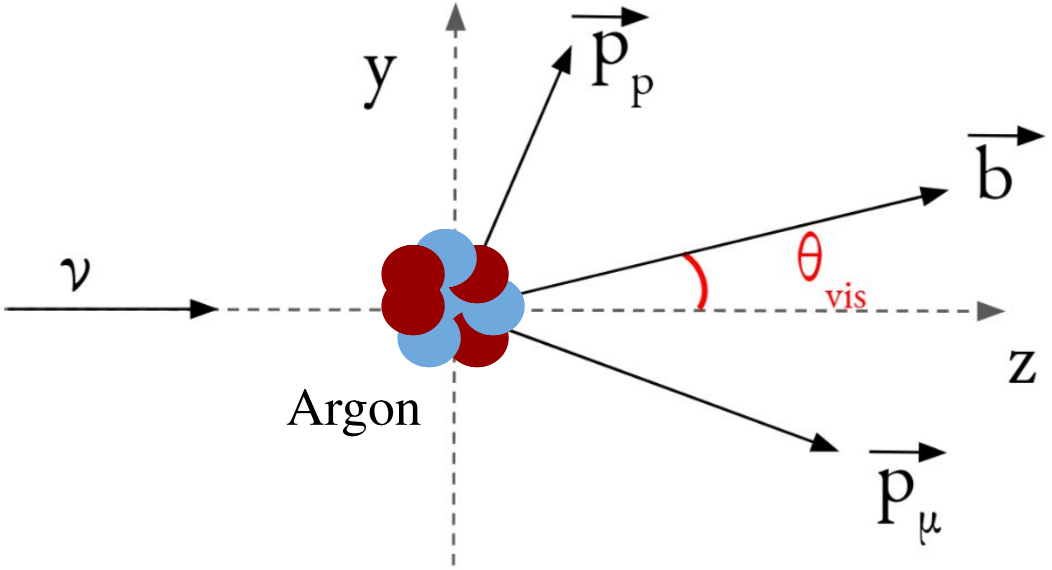


- BNB neutrinos have known origin, unlike DUNE atmospheric neutrinos
- BNB peaks at ~600 MeV and has minimal contributions beyond 2 GeV

Main observable

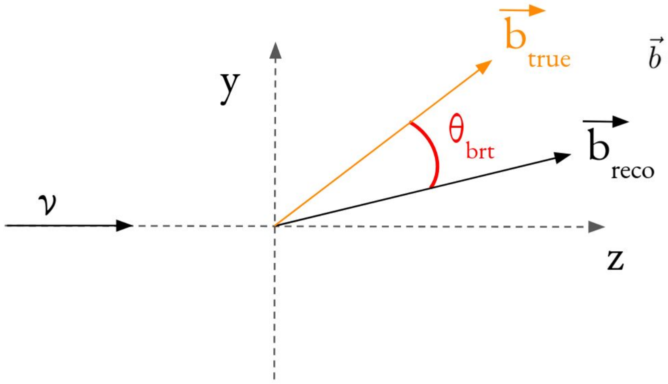
$$\theta_{\text{vis}} = \text{acos}(\frac{\vec{b} \cdot \hat{z}}{|\vec{b}|})$$

$$\text{with } \vec{b} = \vec{p}_\mu + \vec{p}_p$$



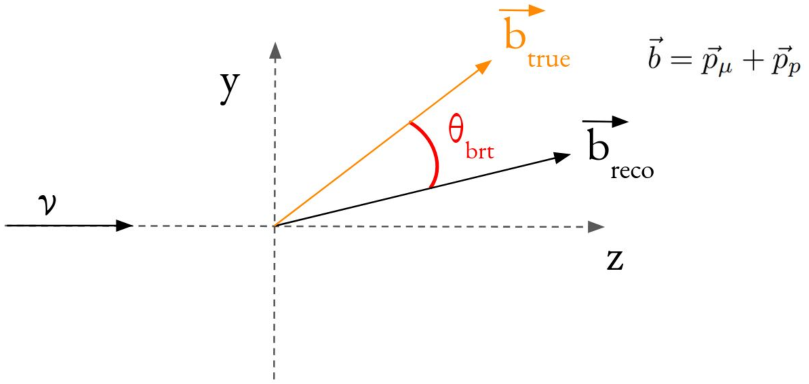
- Reconstructed angle θ_{vis} is **not** expected to be precisely 0° due to detector smearing and nuclear effects that complicate our understanding of neutrino-nucleus interactions

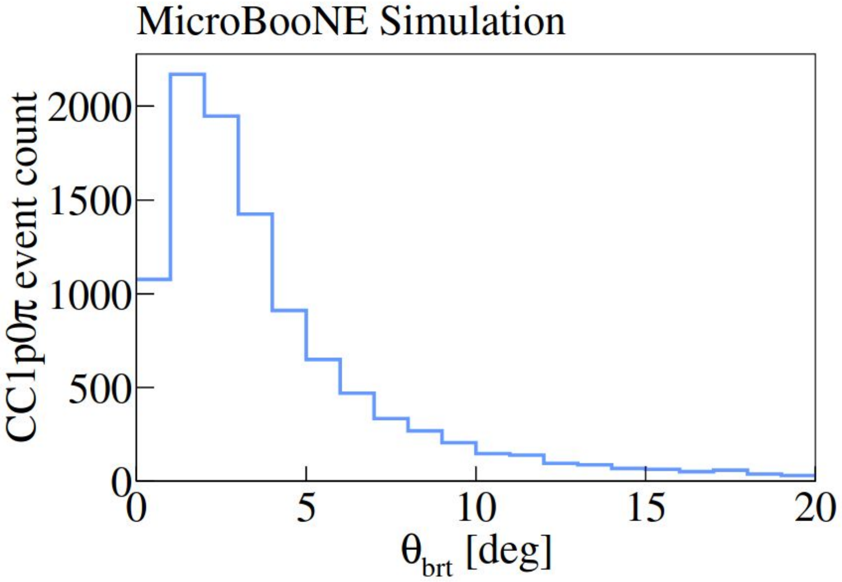
Reconstruction performance



$$\vec{b} = \vec{p}_\mu + \vec{p}_p$$

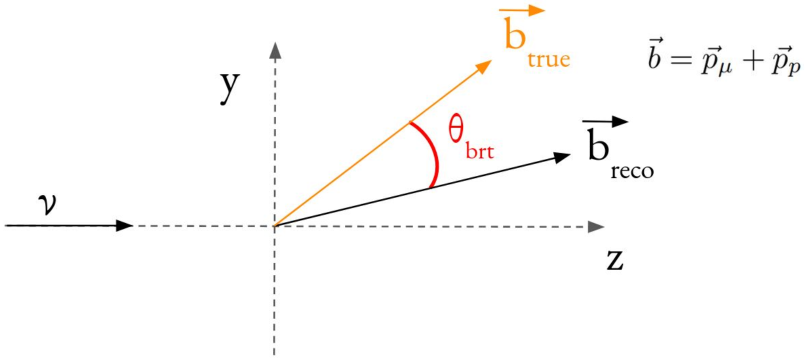
Reconstruction performance

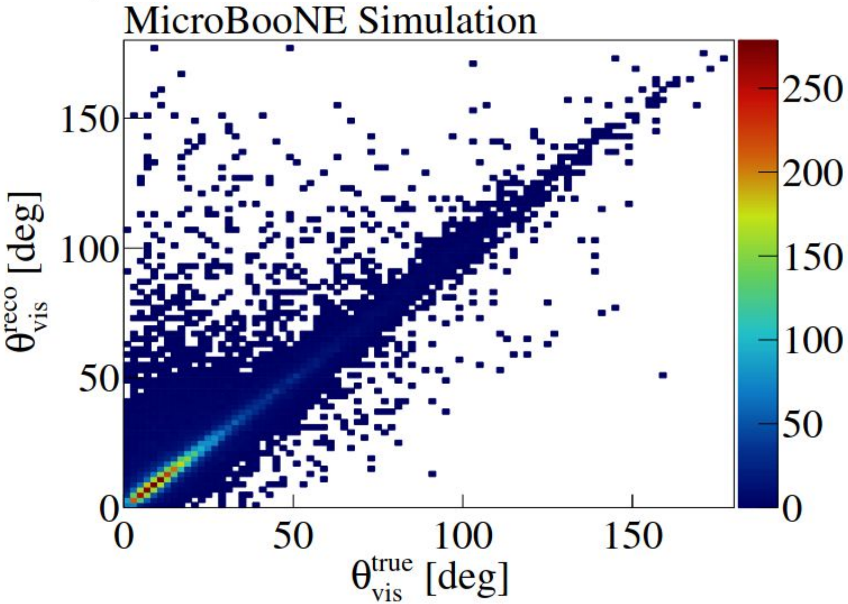


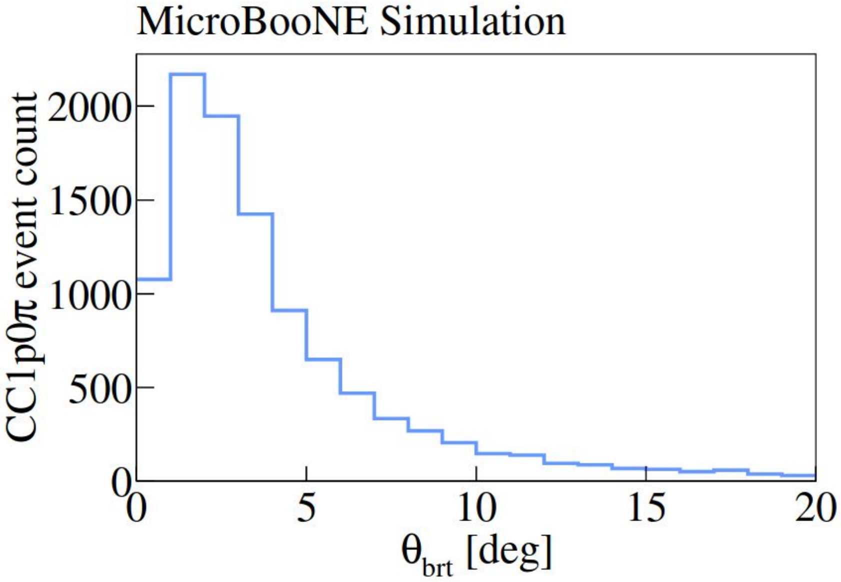


- Most events are reconstructed to better than 5°

Reconstruction performance





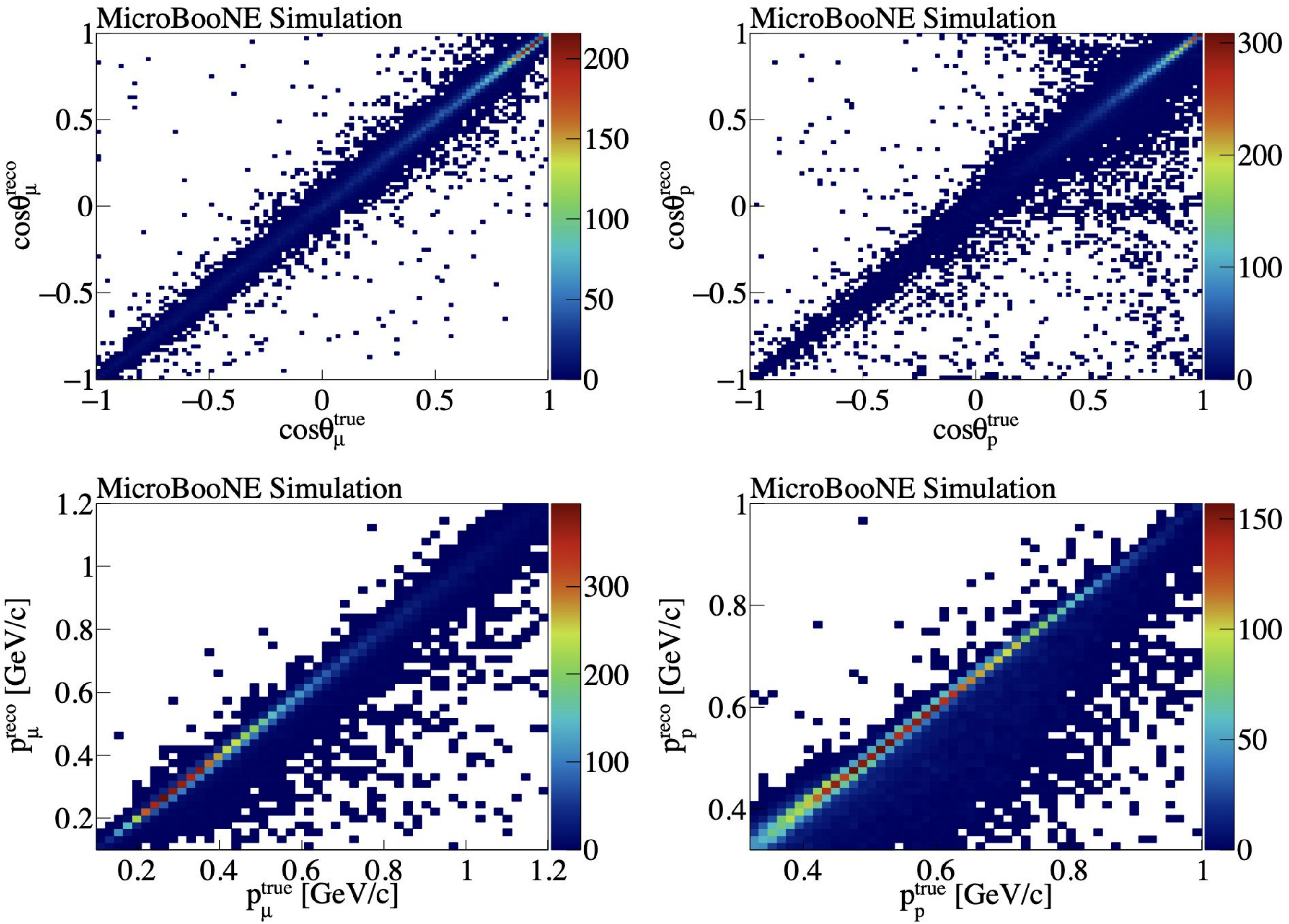


- Most events are reconstructed to better than 5°

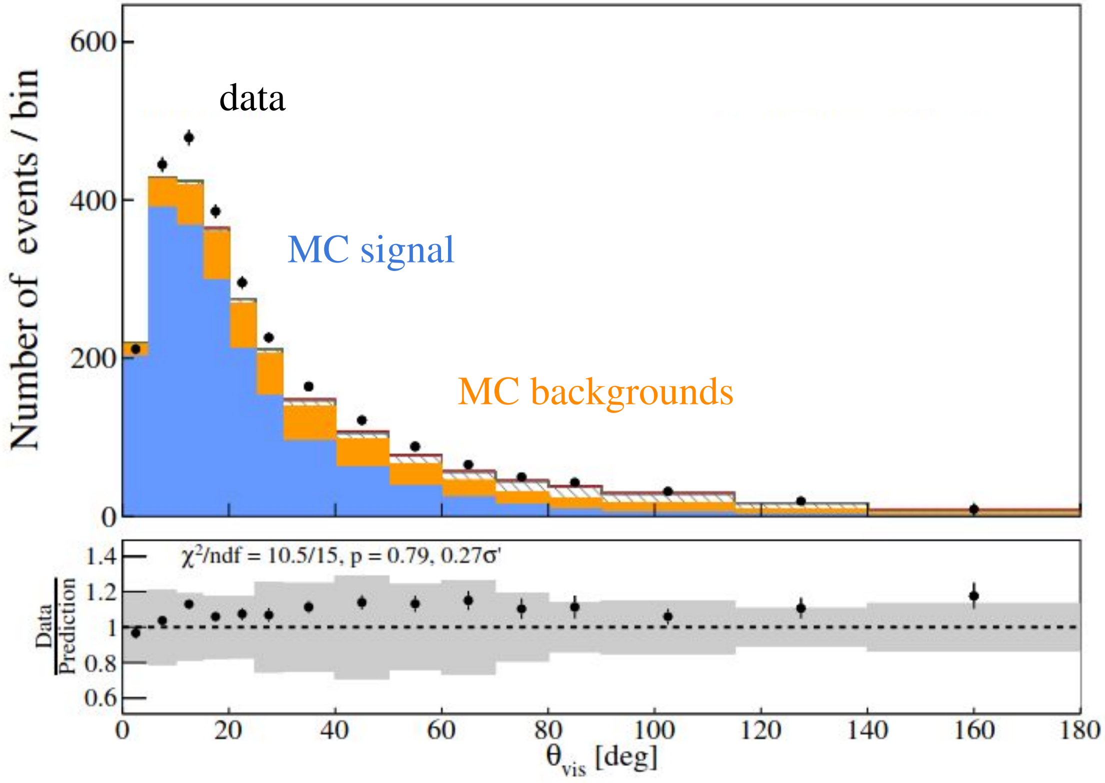
- Very diagonal behavior

Driving force

Excellent muon/proton angle & momentum reconstruction in LArTPCs



θ_{vis} evolution



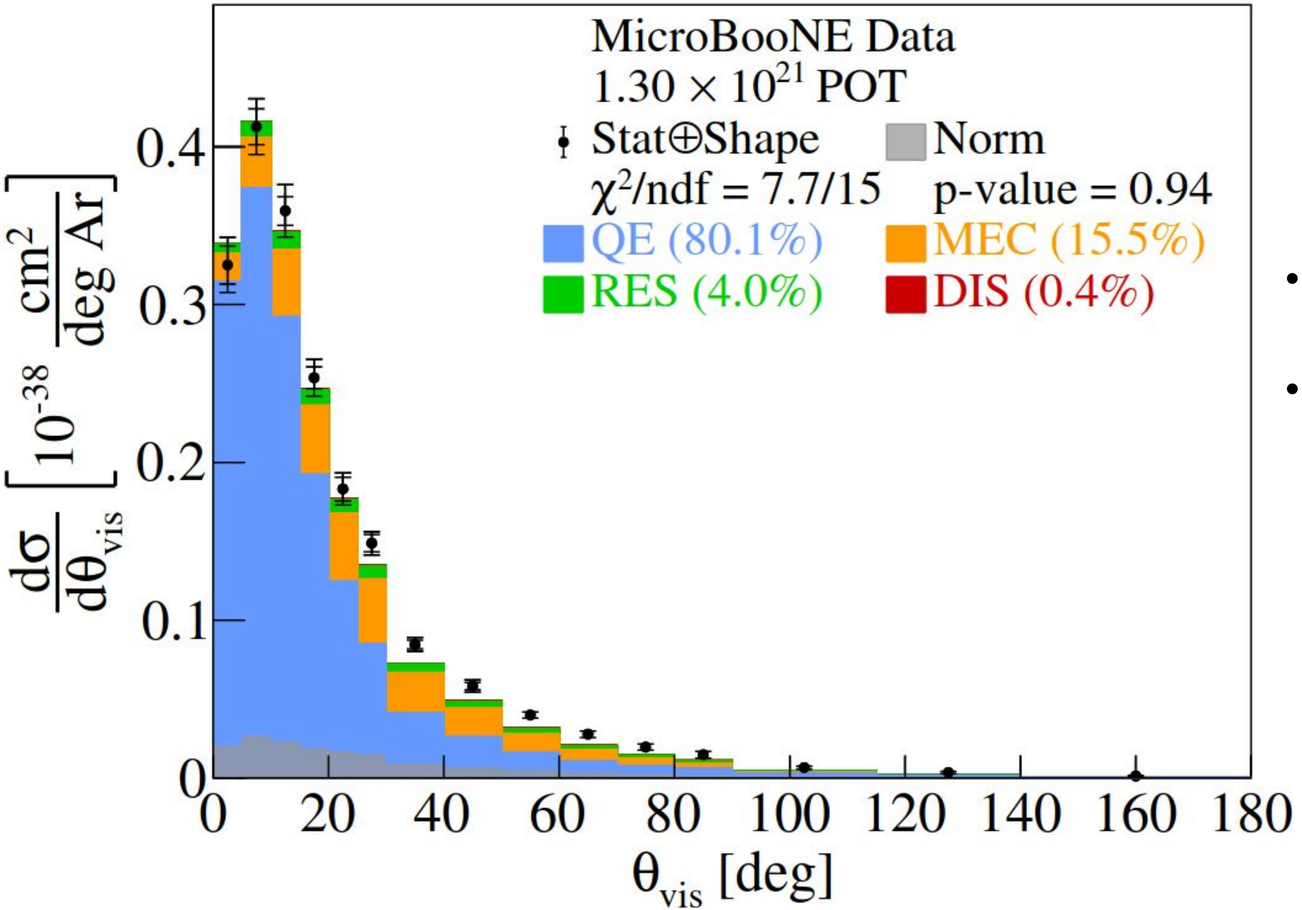
Broad distribution due to detector smearing and nuclear effects

Cross section measurements

Detector smearing effects removed

Nuclear effects still present

Cross section measurements



- Long tail observed
- But still no clear indication of which nuclear effect is dominant

Regions of study

Reconstructed visible energy

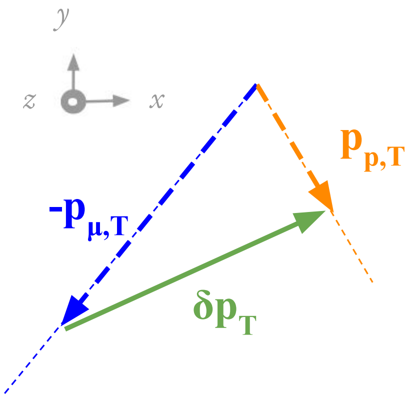
B = 30.9 MeV argon removal energy

$$E_{\text{reco}} = E_\mu + K_p + B$$

Regions of study

$$\delta\vec{p}_T = \vec{p}_{\mu,T} + \vec{p}_{p,T}$$

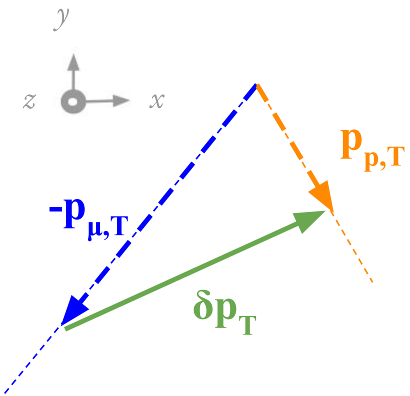
Total struck nucleon momentum



Regions of study

$$\delta\vec{p}_T = \vec{p}_{\mu,T} + \vec{p}_{p,T}$$
$$p_L = p_{\mu,L} + p_{p,L} - E_{\text{reco}}$$

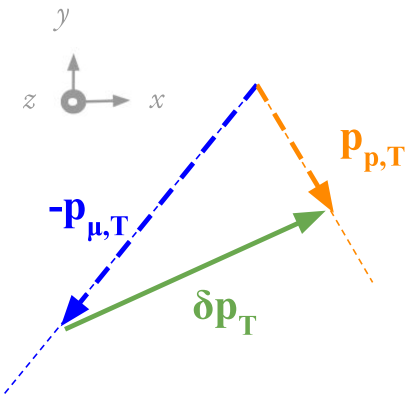
Total struck nucleon momentum

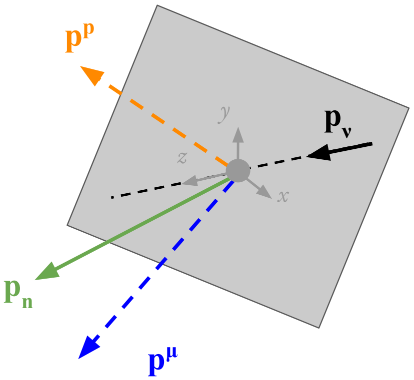


Regions of study

Total struck nucleon momentum

$$\delta\vec{p}_T = \vec{p}_{\mu,T} + \vec{p}_{p,T}$$
$$p_L = p_{\mu,L} + p_{p,L} - E_{\text{reco}}$$
$$p_n = |\vec{p}_n| = \sqrt{p_L^2 + \delta p_T^2}$$





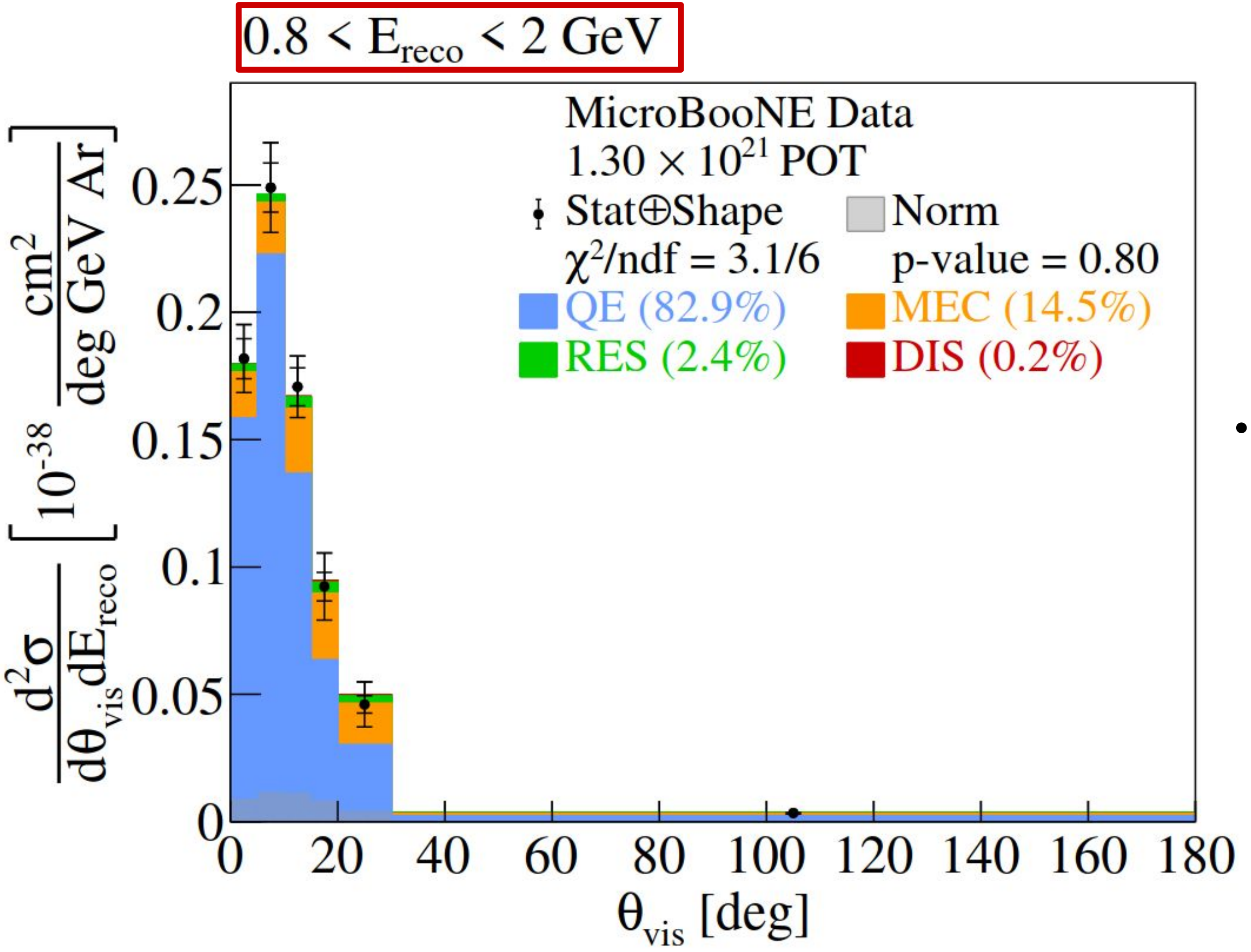
Regions of study

Missing momentum
(new and agnostic to neutrino direction!)

$$\vec{b} = \vec{p}_\mu + \vec{p}_p$$
$$p_{\text{miss}} = E_{\text{reco}} - b$$

Cross section measurements

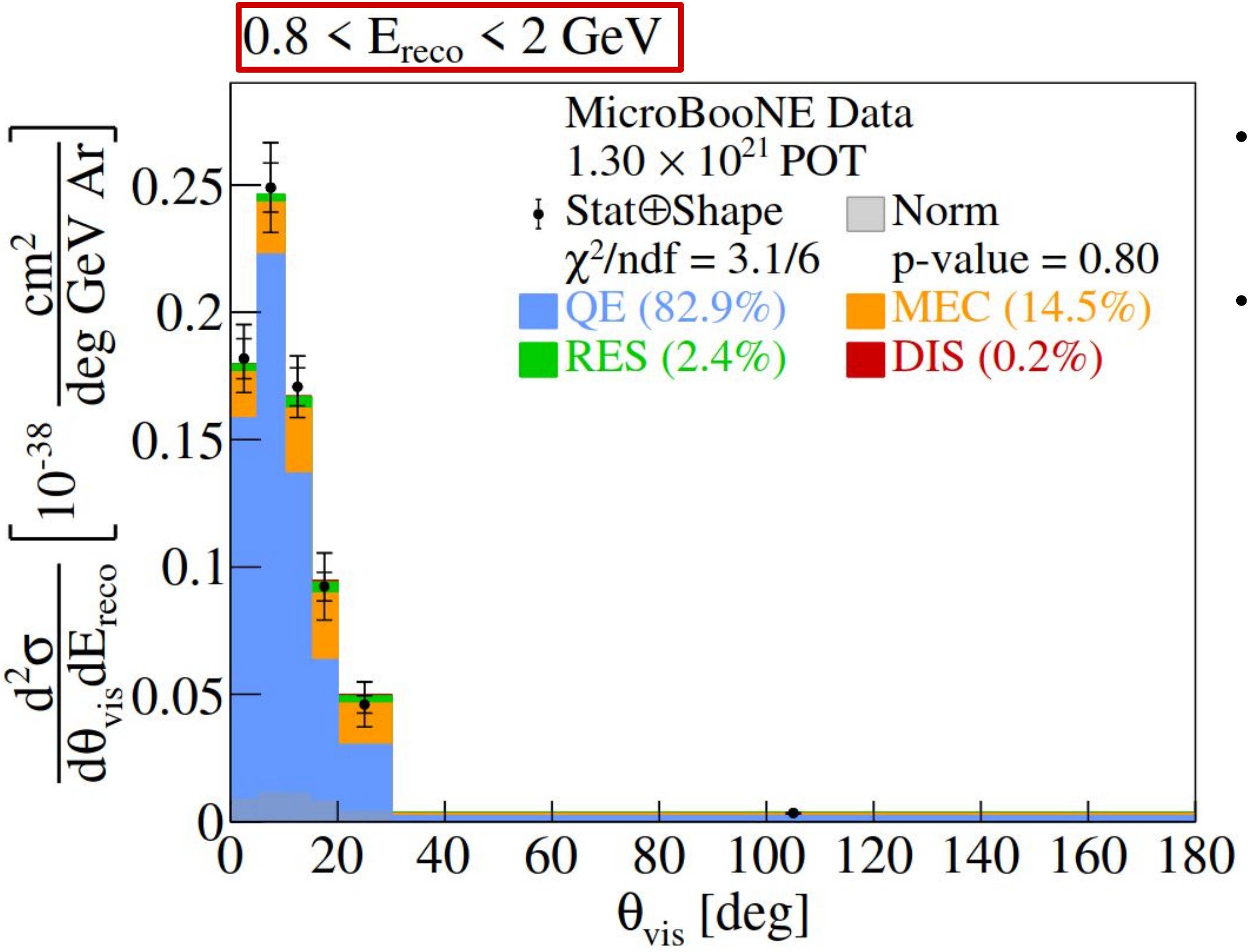
$$E_{\text{reco}} = E_\mu + K_p + B$$



- Depleted tail → less reinteractions or undetected particles

Cross section measurements

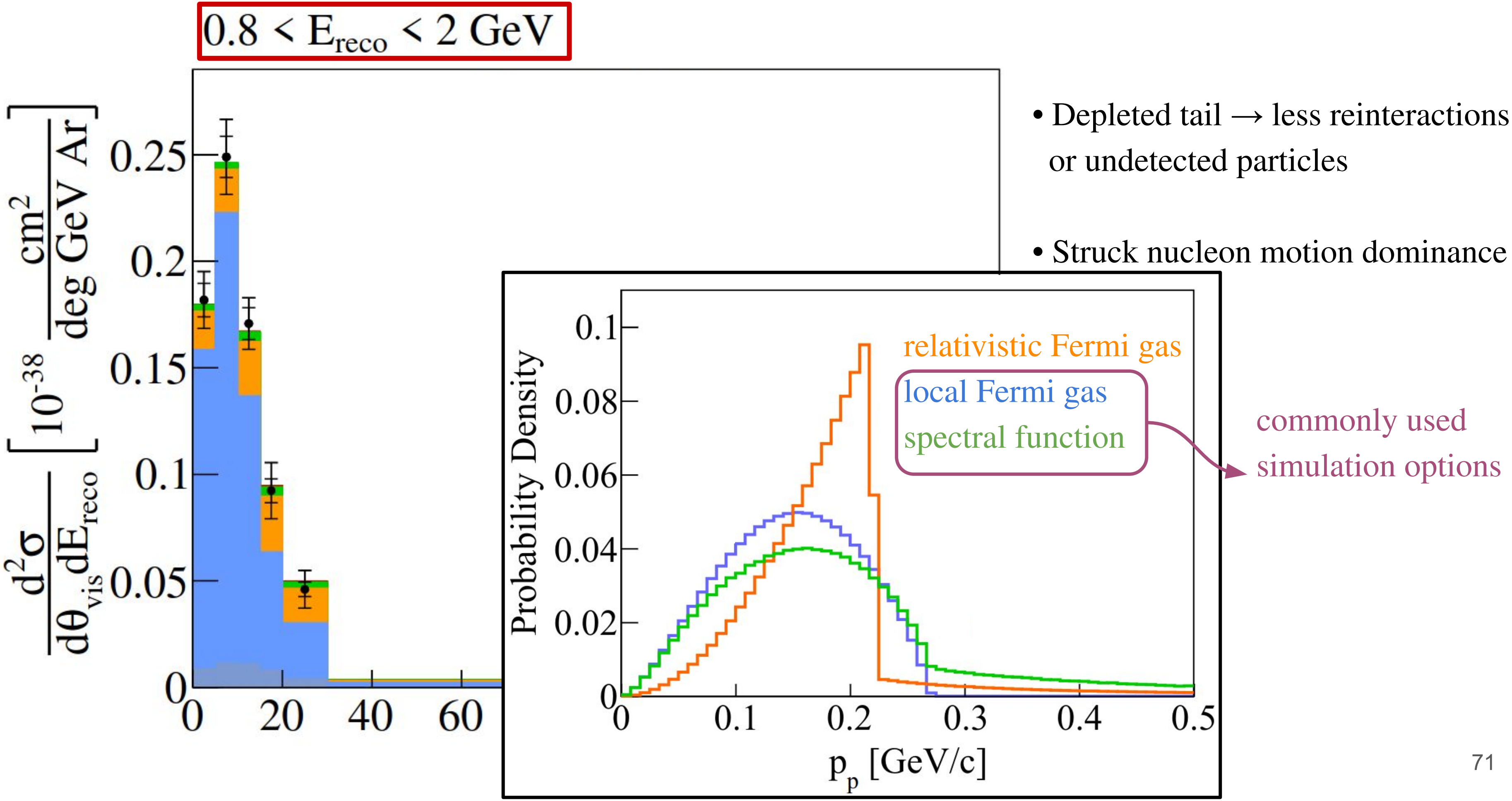
$$E_{\text{reco}} = E_\mu + K_p + B$$



- Depleted tail → less reinteractions or undetected particles
- Struck nucleon motion dominance

Cross section measurements

$$E_{\mathrm{reco}} = E_\mu + K_p + B$$

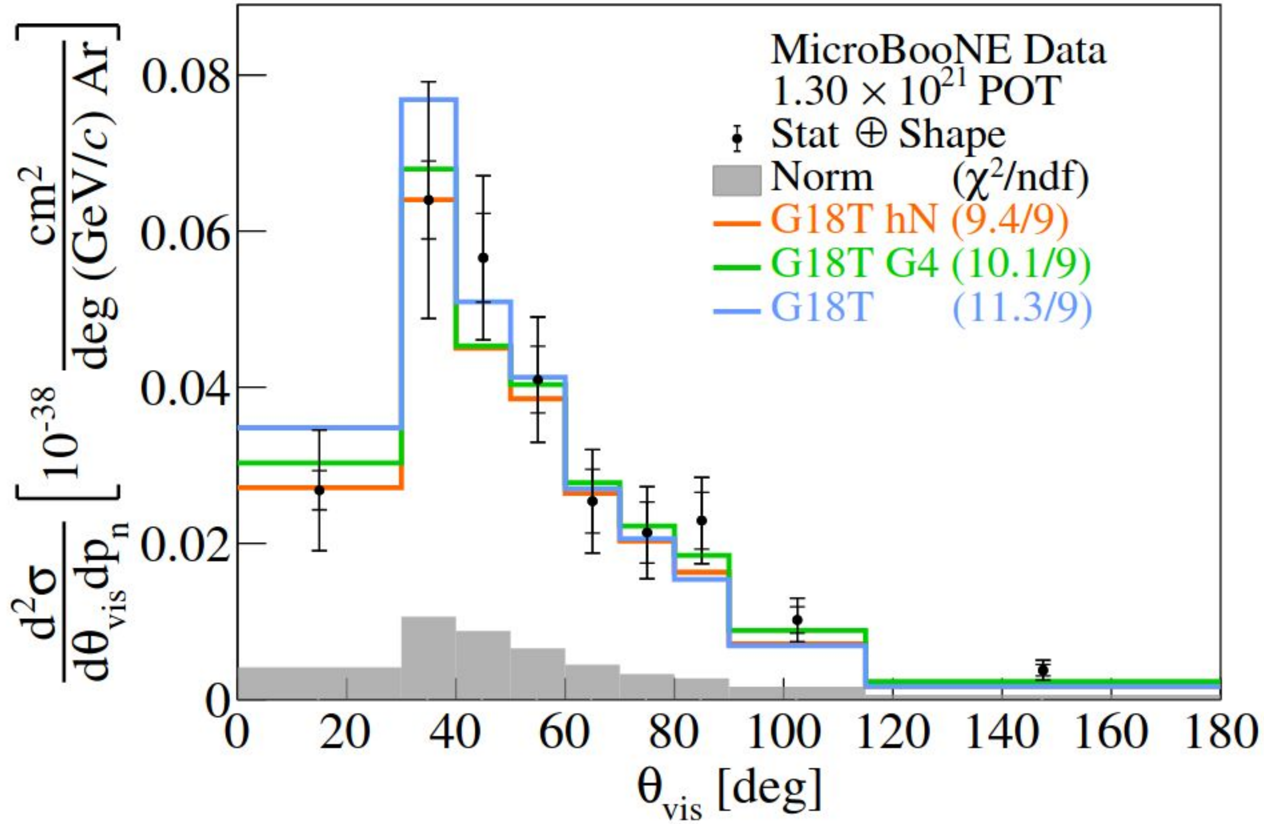


- Depleted tail → less reinteractions or undetected particles
- Struck nucleon motion dominance

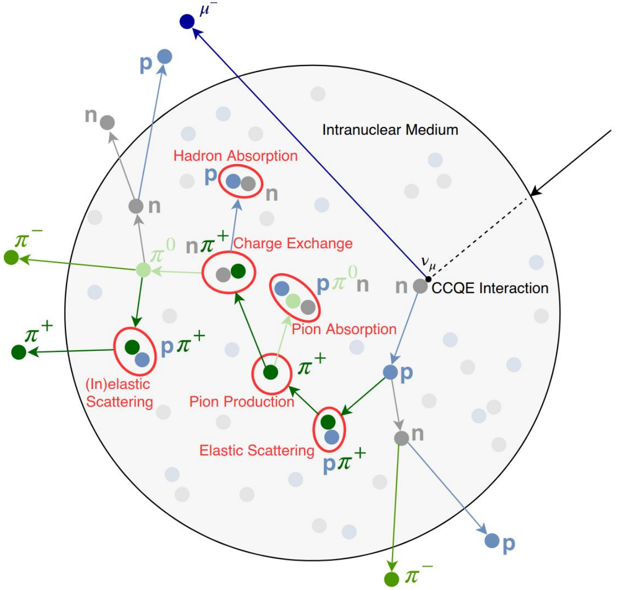
Hadron reinteractions

$$p_n = |\vec{p}_n| = \sqrt{p_L^2 + \delta p_T^2}$$

$0.4 < p_n < 1$ GeV/c



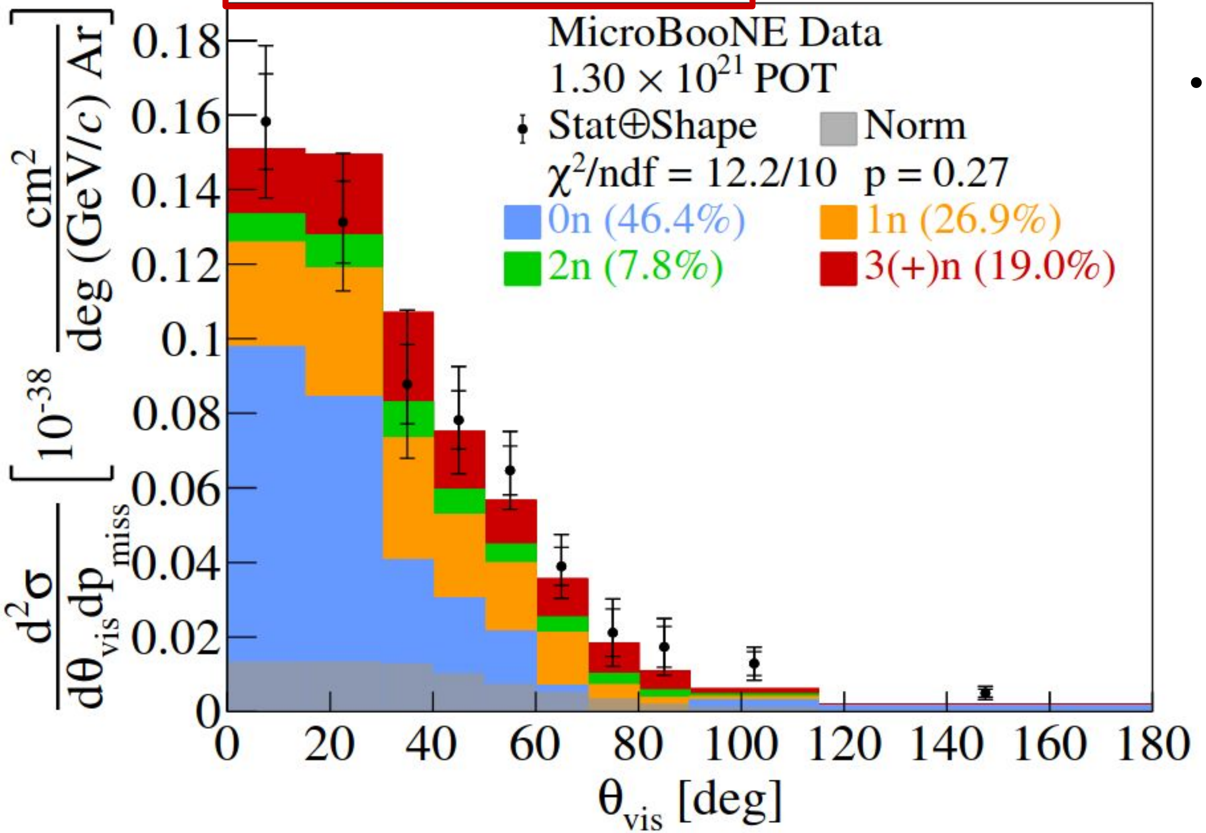
- Long tail → more reinteractions
- Reinteraction models investigated



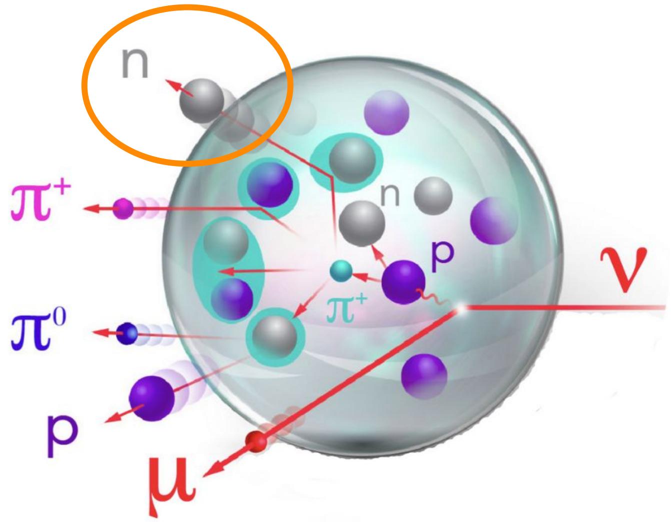
Neutrons

$$\vec{b} = \vec{p}_\mu + \vec{p}_p$$
$$p_{\text{miss}} = E_{\text{reco}} - b$$

$0.2 < |p_{miss}| < 0.5$ GeV/c

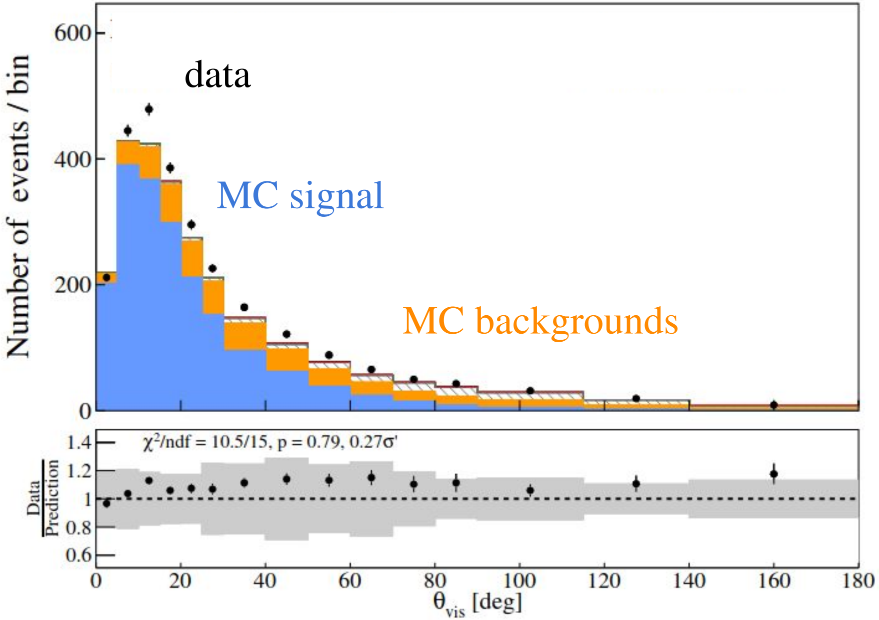


- Long tail → more undetected particles



Summary

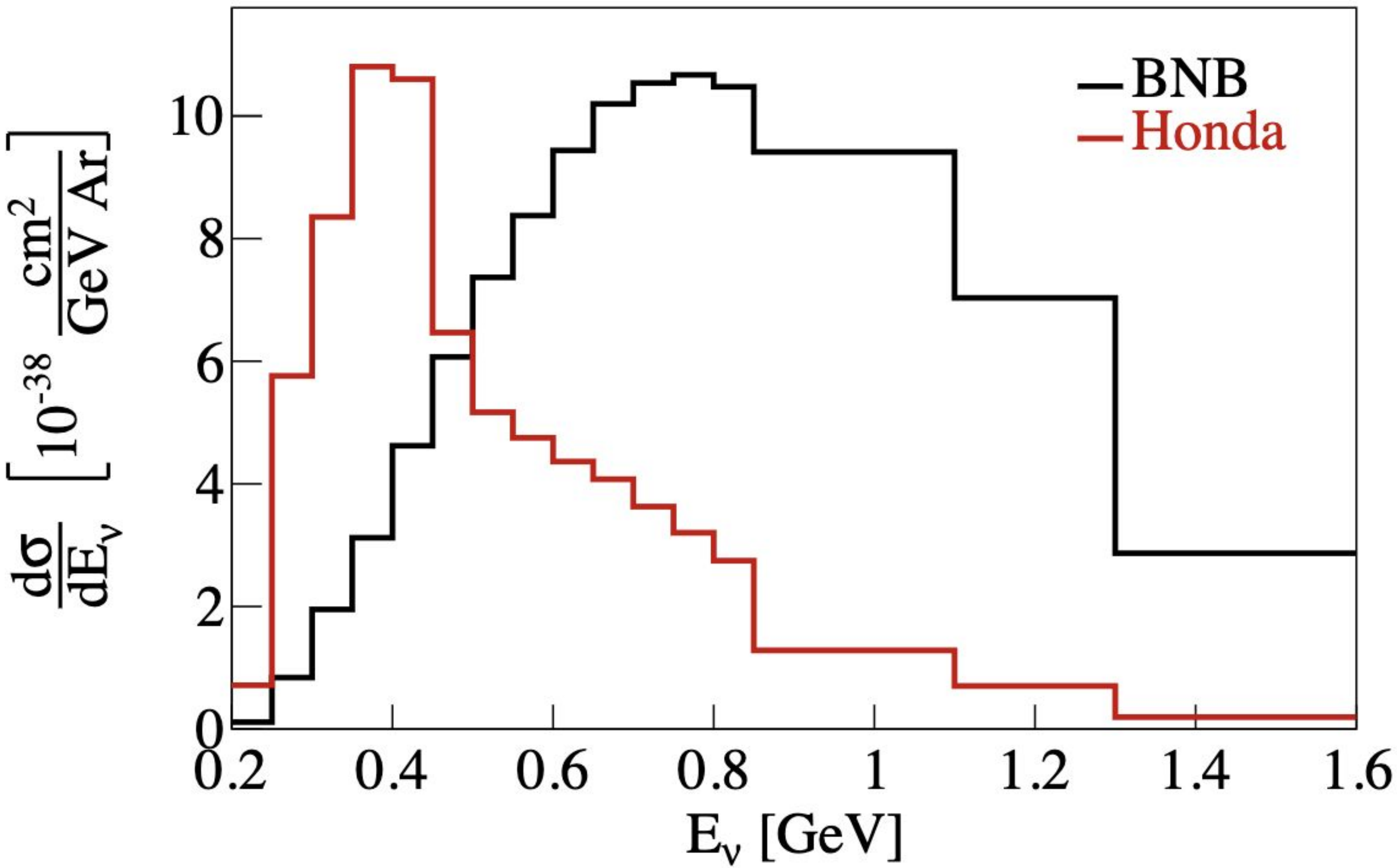
- First-ever neutrino angle reconstruction data-driven study with the MicroBooNE LArTPC
- Quantified angular reconstruction performance in specific phase-space regions
- Path forward towards atmospheric oscillation analyses

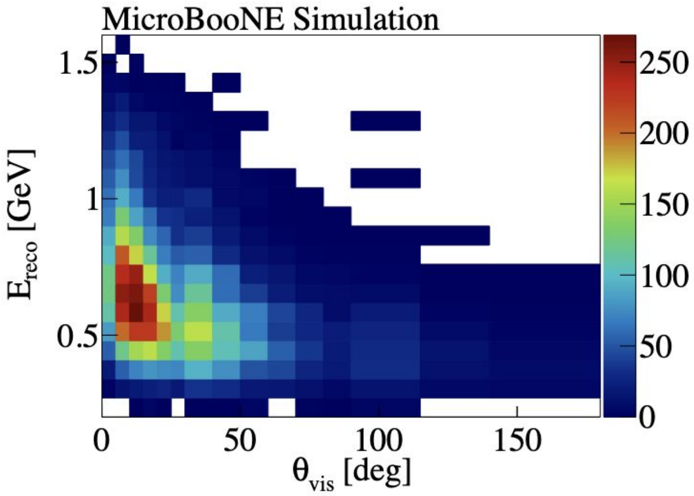


Thank you!

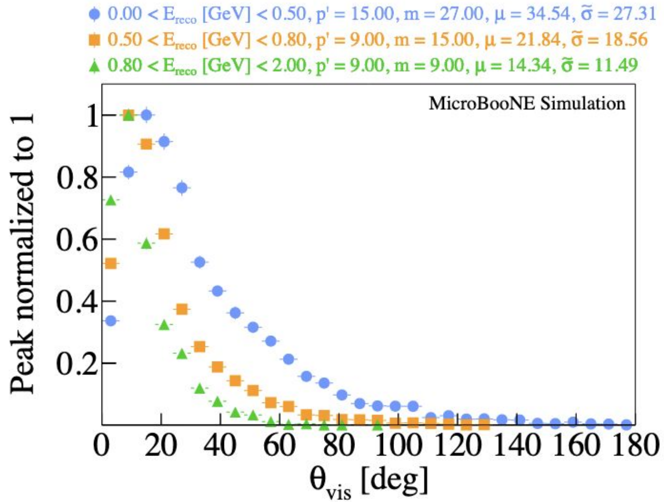
Backup Slides

Flux-averaged cross section




MicroBooNE Simulation
E_{reco} [GeV]
θ_{vis} [deg]

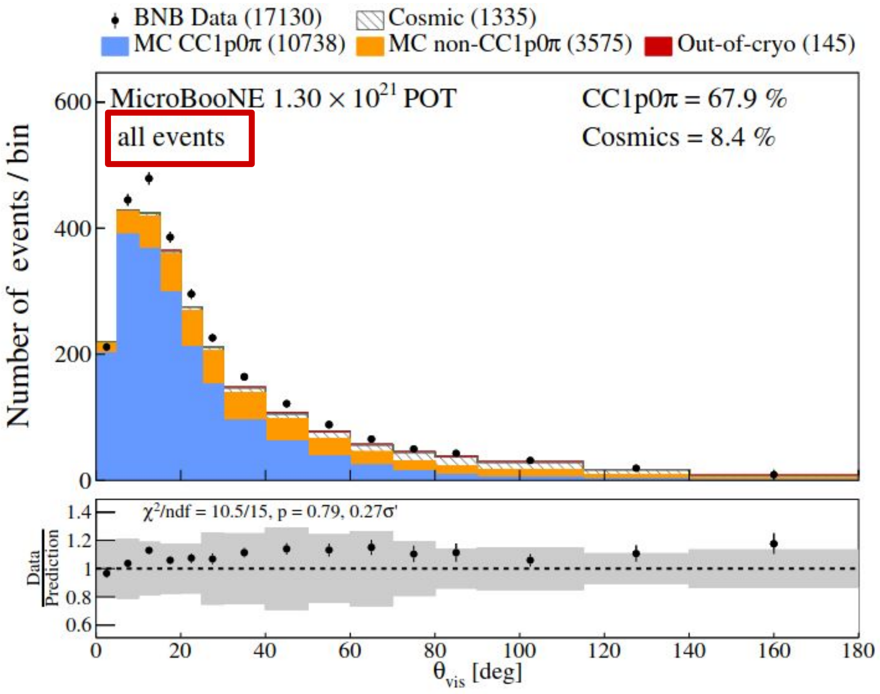
(a)


0.00 < E_{reco} [GeV] < 0.50, p' = 15.00, m = 27.00, μ = 34.54, σ̃ = 27.31
0.50 < E_{reco} [GeV] < 0.80, p' = 9.00, m = 15.00, μ = 21.84, σ̃ = 18.56
0.80 < E_{reco} [GeV] < 2.00, p' = 9.00, m = 9.00, μ = 14.34, σ̃ = 11.49
MicroBooNE Simulation
Peak normalized to 1
θ_{vis} [deg]

θ_{vis} evolution

μ = mean, σ = standard deviation, m = median

Region	μ [deg]	$\tilde{\sigma}$ [deg]	m [deg]
All events	23.2	21.1	16.5
$E_{\text{reco}} < 0.5\,\text{GeV}$	34.5	27.3	26.5
$0.5 < E_{\text{reco}} < 0.8\,\text{GeV}$	21.8	18.6	16.5
$0.8 < E_{\text{reco}} < 2\,\text{GeV}$	14.3	11.5	10.5
$p_n < 0.2\,\text{GeV}/c$	10.0	5.8	9.5
$0.2 < p_n < 0.4\,\text{GeV}/c$	21.8	11.4	19.5
$0.4 < p_n < 1\,\text{GeV}/c$	49.3	26.3	44.5
$\lvert p_{\text{miss}} \rvert < 0.1\,\text{GeV}/c$	20.7	19.4	15.5
$0.1 < \lvert p_{\text{miss}} \rvert < 0.2\,\text{GeV}/c$	23.6	21.3	16.5
$0.2 < \lvert p_{\text{miss}} \rvert < 0.5\,\text{GeV}/c$	29.8	23.6	23.5

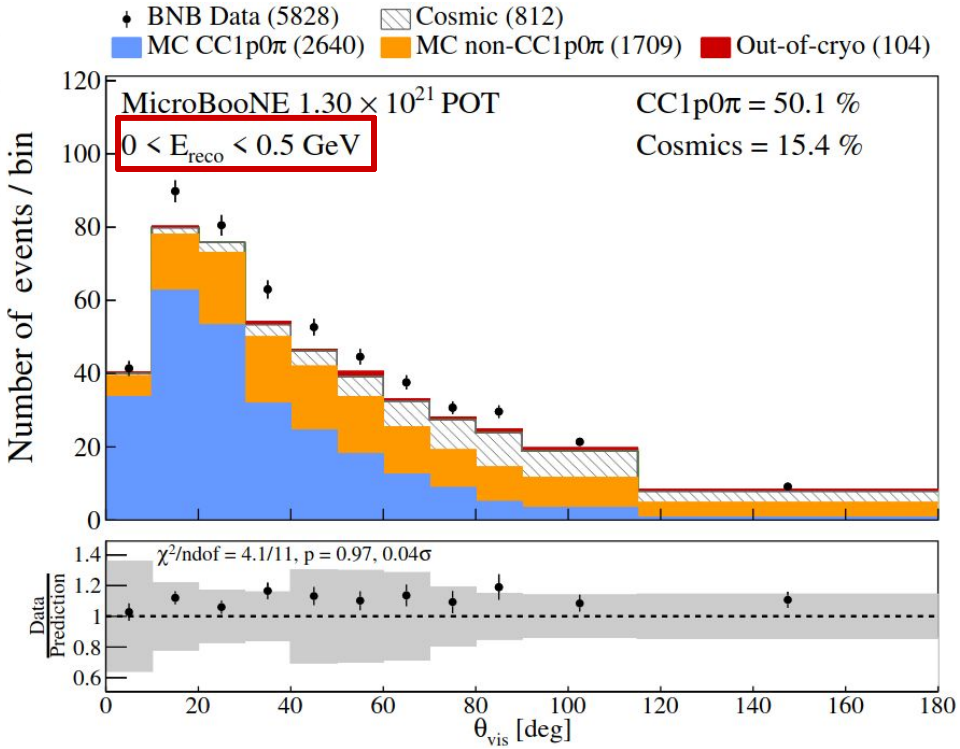


θ_{vis} evolution

μ = mean, σ = standard deviation, m = median

Region	μ [deg]	$\tilde{\sigma}$ [deg]	m [deg]
All events	23.2	21.1	16.5
$E_{\mathrm{reco}} < 0.5\,\mathrm{GeV}$	34.5	27.3	26.5

Broad tail

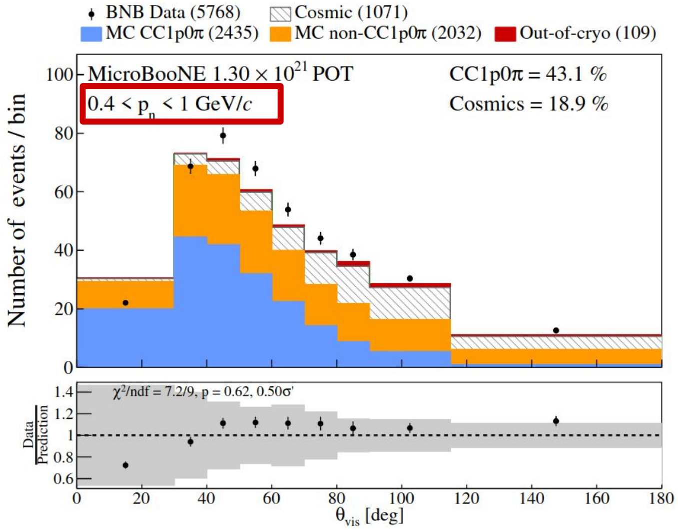


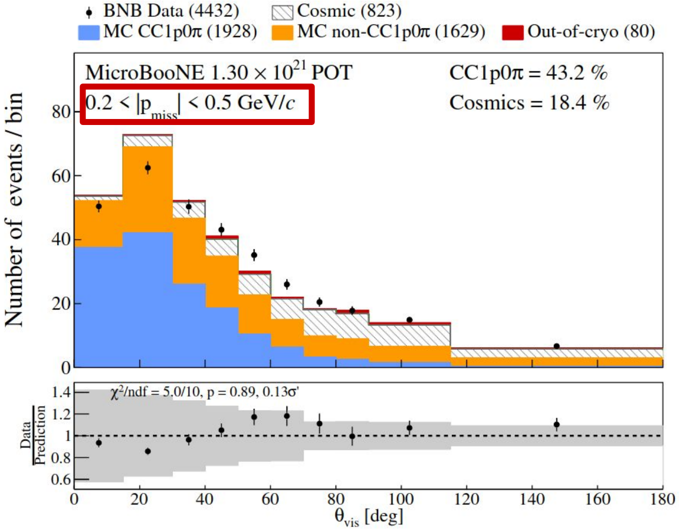
θ_{vis} evolution

μ = mean, σ = standard deviation, m = median

Region	μ [deg]	$\tilde{\sigma}$ [deg]	m [deg]
All events	23.2	21.1	16.5
$0.4 < p_n < 1\,\mathrm{GeV}/c$	49.3	26.3	44.5
$0.2 < \lvert p_{\mathrm{miss}} \rvert < 0.5\,\mathrm{GeV}/c$	29.8	23.6	23.5

Broad tail

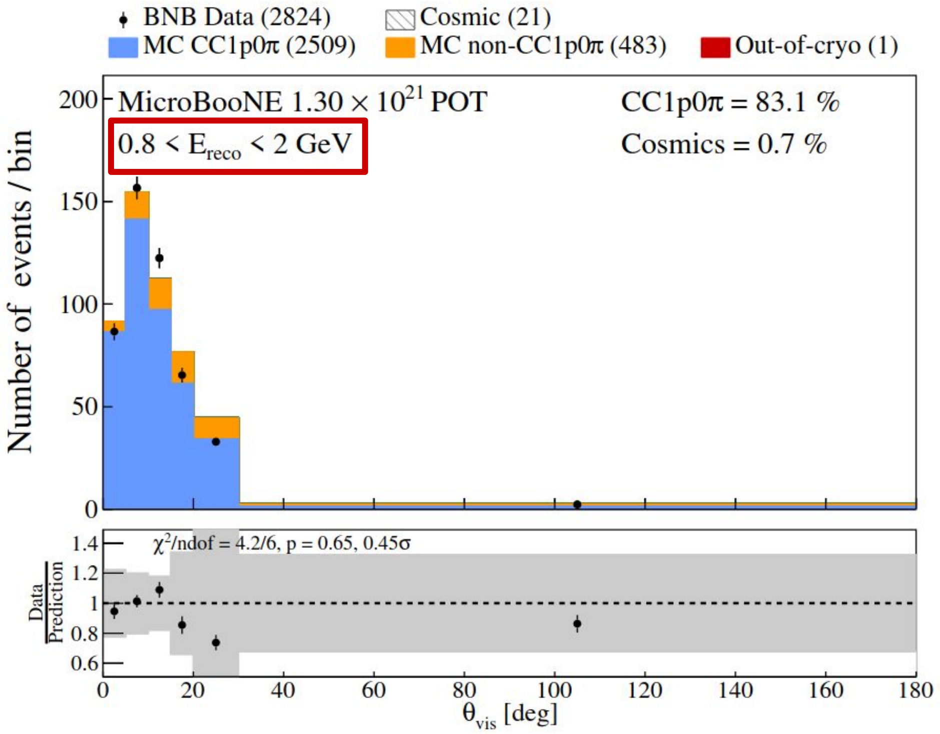




θ_{vis} evolution

μ = mean, σ = standard deviation, m = median

Region	μ [deg]	$\tilde{\sigma}$ [deg]	m [deg]
All events	23.2	21.1	16.5
$0.8 < E_{reco} < 2\,\text{GeV}$	14.3	11.5	10.5

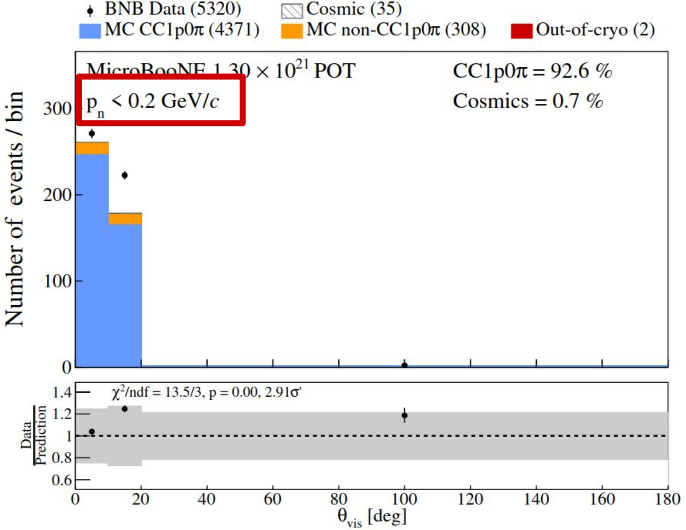


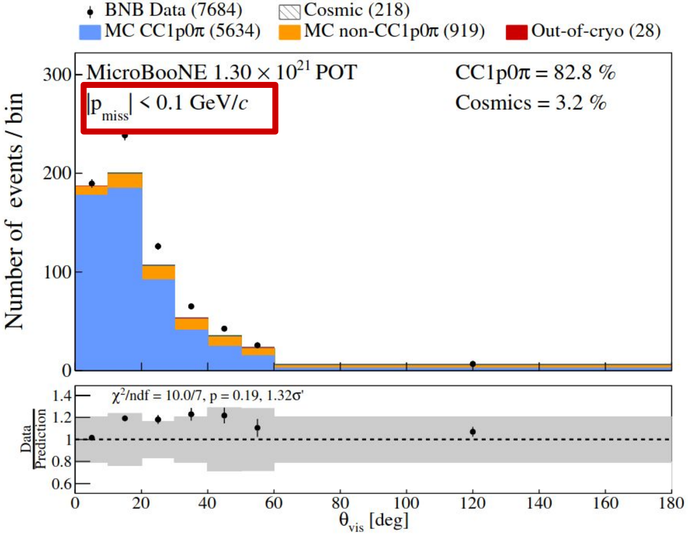
Less broad distribution

θ_{vis} evolution

μ = mean, σ = standard deviation, m = median

Region	μ [deg]	$\tilde{\sigma}$ [deg]	m [deg]
All events	23.2	21.1	16.5
$p_n < 0.2\,\mathrm{GeV}/c$	10.0	5.8	9.5
$\lvert p_{\mathrm{miss}} \rvert < 0.1\,\mathrm{GeV}/c$	20.7	19.4	15.5





Less broad distribution

Comparison to DUNE model

MicroBooNE uses a different default model (G18T) compared to DUNE's (AR23_20i_00_000 or AR23)

Main difference	G18T	AR23
QE/MEC tune	Tuned to T2K data	No tune

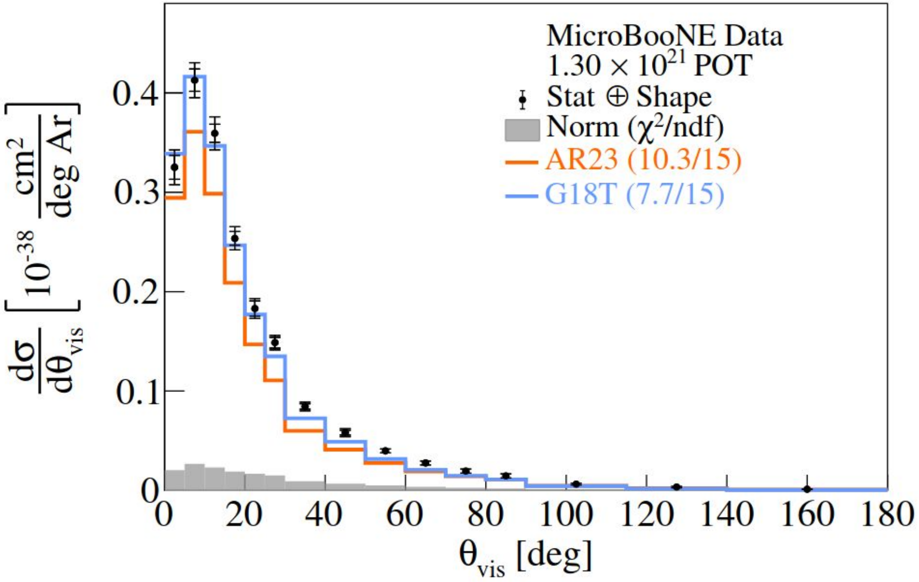
Most other models, eg resonance production, deep inelastic scattering, final state interactions, are ~the same

Comparison to DUNE model

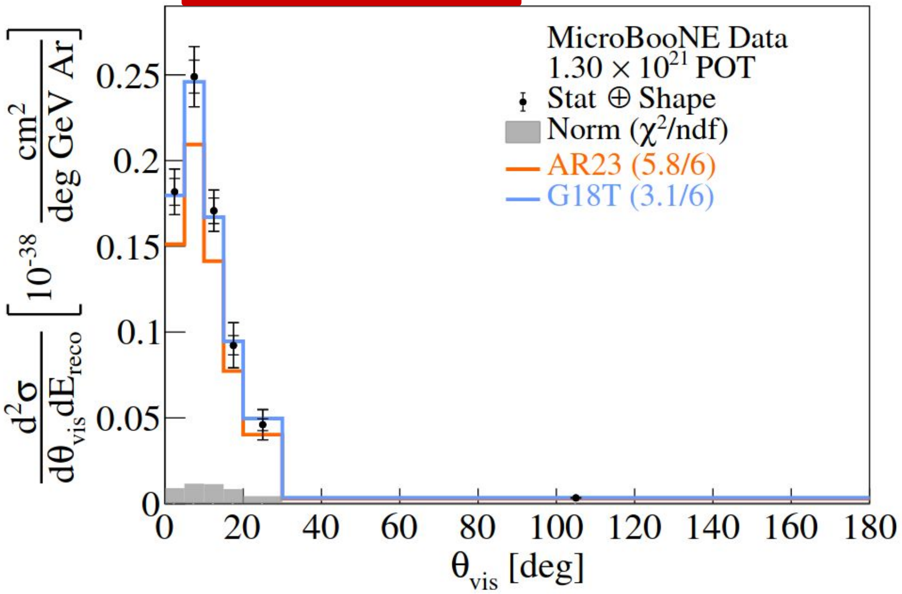
AR23 yields a systematically lower prediction across

However, no QE tune is included in the AR23 prediction (~20% effect)

all events

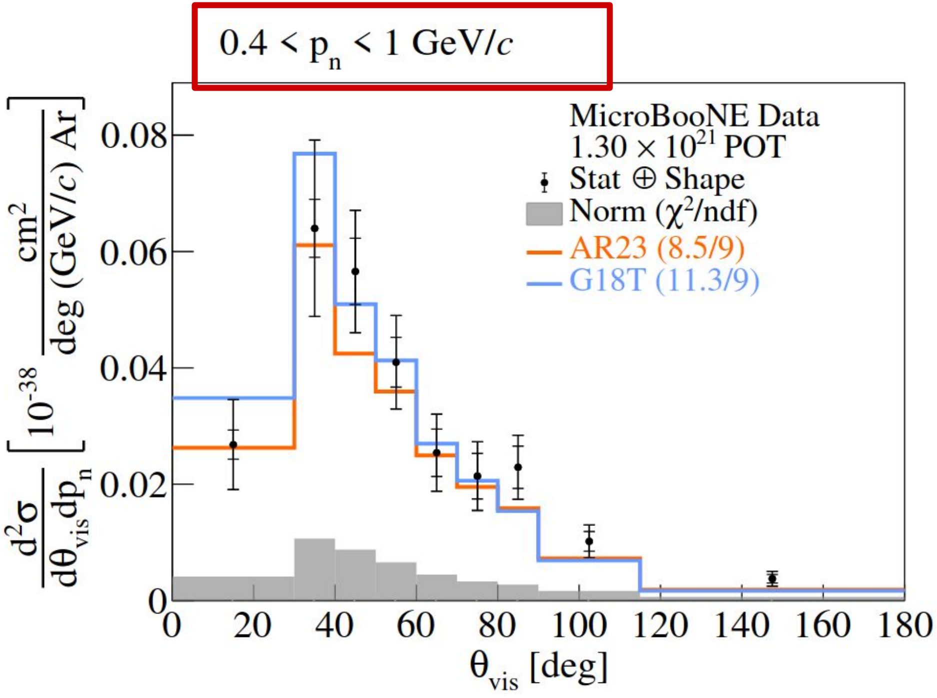


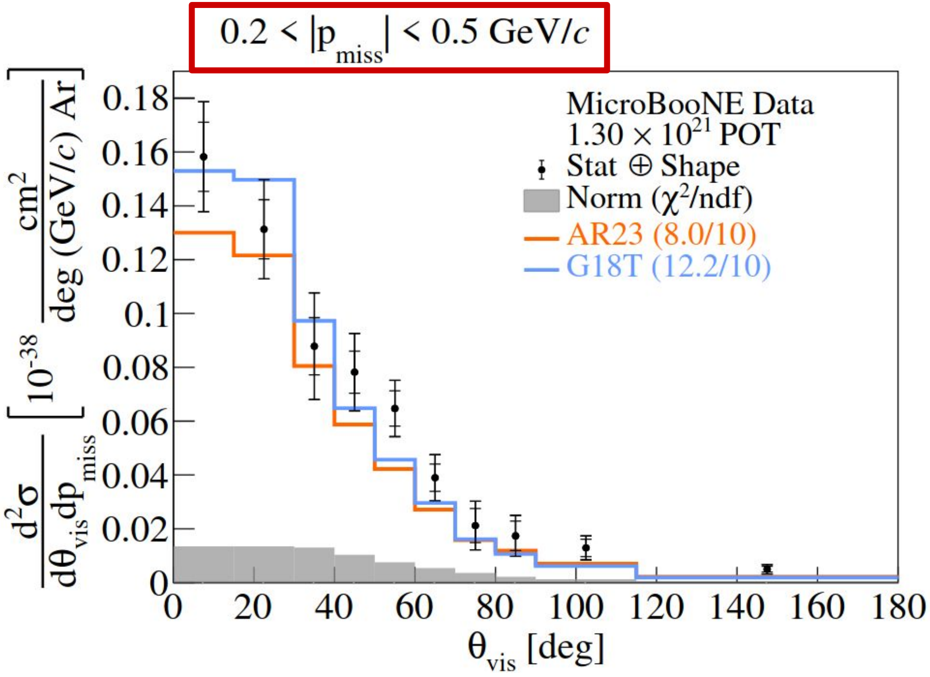
$0.8 < E_{reco} < 2$ GeV



Comparison to DUNE model

AR23 yields a slightly lower prediction but within uncertainties



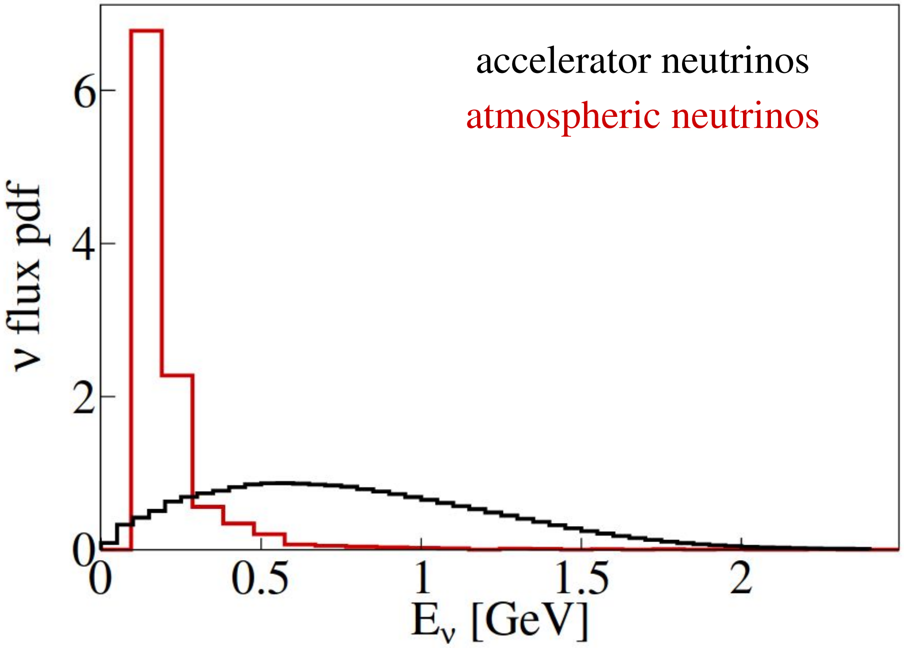


DUNE projection

What should we expect?

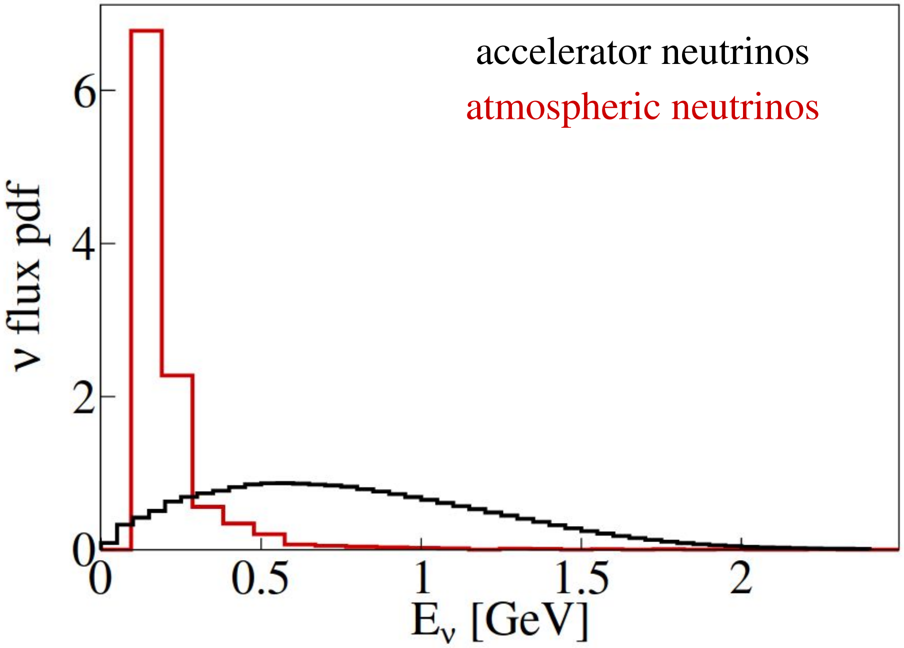
DUNE projection

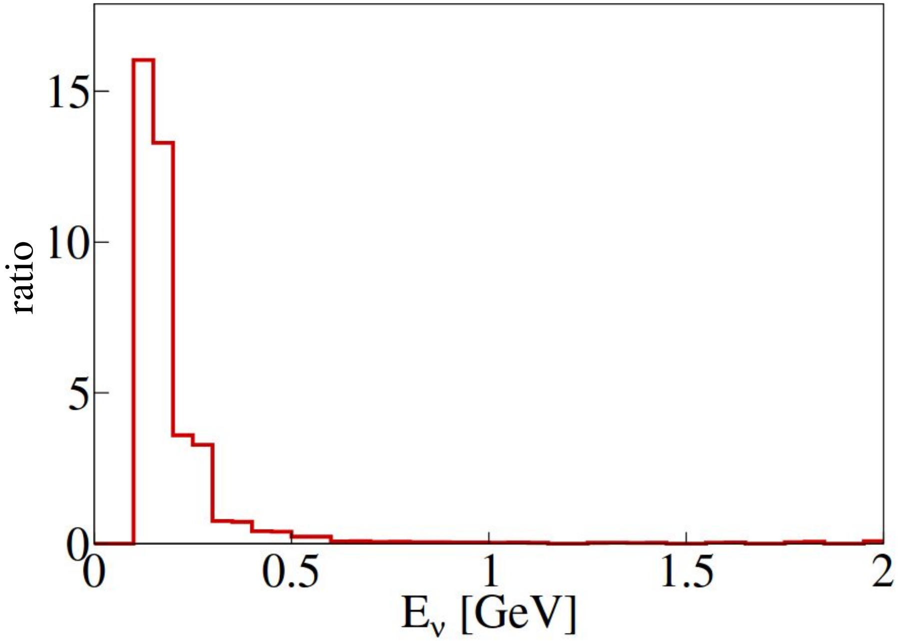
Using flux probability distribution functions (pdf) ratio to obtain a reweighting function



DUNE projection

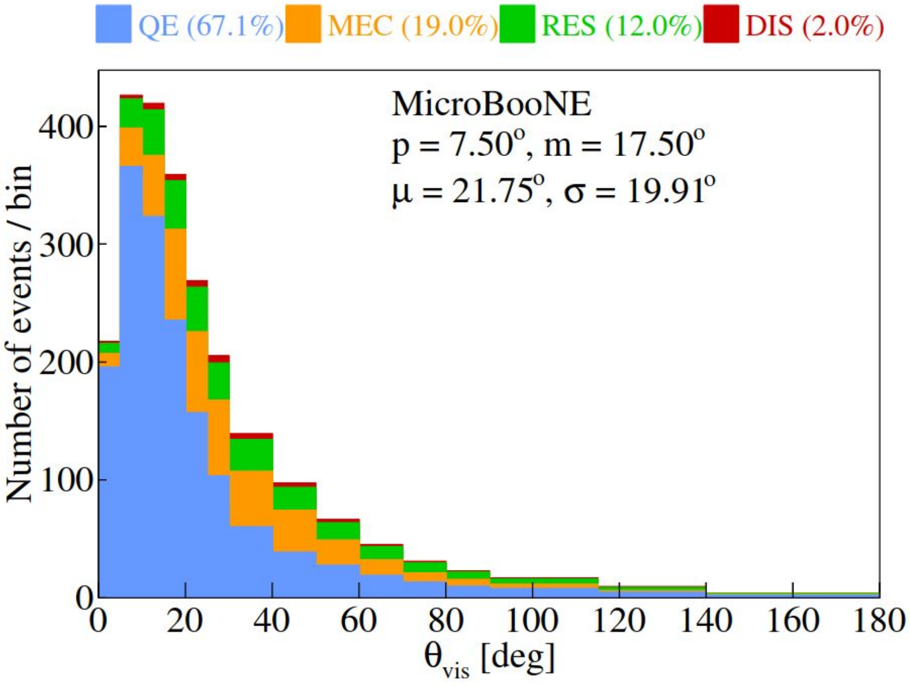
Using flux probability distribution functions (pdf) ratio to obtain a reweighting function





DUNE projection

Using the reweighting function on the previous slide to reweight events on an event-by-event basis as a function of the neutrino energy, we make a projection for DUNE



DUNE projection

Using the reweighting function on the previous slide to reweight events on an event-by-event basis as a function of the neutrino energy, we make a projection for DUNE