

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

Neutrino Physics

Minerba Betancourt, Fermilab 01 August 2024

Is the standard model complete?

- Why is there such large gap between neutrino masses and quark masses?
- $\frac{1}{2}$ a $\frac{2}{3}$ a $\frac{4}{3}$ Why do quarks and leptons exhibit different behavior?
	- What is the absolute mass of neutrino?

Where do neutrinos come from?

- Neutrinos are the most common matter particles in the universe 10^{-7} $\overline{v}_e e^-$ in mb) 10^{-4} **SuperNova** 10^{-7} Reactor 个 10^{-10} C_{D} o $\frac{1}{2}$ o $\frac{1$ Accelerator Terrestrial Cosmic Atmospheric Solar 10^{-19} 10^{-22} 10^{-25} **Big Bang** 10^{-28} 10^{-31} 10^8 10^{10} 10^{14} 10^{16} $10²$ $10⁴$ $10⁶$ 10^{12} 10^{-4} 10^{-2} 10^{18} \blacktriangleleft **Neutrino Energy (eV)**
- Reviewing the neutrino interactions relevant to neutrino oscillation at the few GeV region <u> 춘 Fermilab</u>

Neutrinos Oscillate!

<u>as particular type as it to a particular type as it is the set of a particular type and the set of a particular type and the set of a particular term of a particular term of a particular term of a </u> • The oscillation affects the *probability* that a neutrino is **This oscillation affects the probability that a neutrino is**

• Neutrinos have mass and weak flavor states Thos have mass and weak flavor states
(i) $\left(\cos \theta - \sin \theta \sin \theta \right)$ ($\cos \theta - \sin \theta \left(y\right)$) \int_0^t ⎞ $\sqrt{}$ $\sqrt{}$ \overline{a} $\sqrt{}$ ⎞ $\rm\,M$ $\binom{1}{l}$

• The path length and energy are experimental parameters.

$$
\begin{bmatrix} v_{\mu} \\ v_{\tau} \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} w_{\mu} \\ w_{\tau} \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} v_{2} \\ v_{3} \end{bmatrix}
$$

• There is a non-zero probability of detecting a different neutrino flavor than that produced at the source produced at the source There is a non-zero probability of detecting a different neutrino flavor than that

$$
P(V_{\mu} \to V_{\tau}) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m_{23}^2 L}{E_v}\right)^2(2\theta)\sin^2\left(\frac{1.27\Delta m_{23}^2 L}{E_v}\right)
$$

• The physics parameters are: the mixing angle and one mass squared difference $\overline{\mathbf{u}}$ physics parameters are: \overline{a}

What do we know?

Minerba Betancourt • The probability of a neutrino v_{μ} transforming into a v_{e} • where the mixing matrix has 3 mixing angles and one phase 5 $\begin{array}{ccc} \hline \end{array}$ $\begin{array$ $\frac{1}{2}$ mixing angles $\left(0 - \sin\theta_{23} \cos\theta_{23}\right)$ Considering three generations of neutrinos, in the neutrino oscillations formulation with mass eigenstates through the PMNS matrix. Writing the equation (1) for the $U=% {\textstyle\sum\nolimits_{j\in N(i)}} e_{ij}e_{ij}^{\dag}e_{ij}^{\dag}e_{ij}^{\dag}$ $^{\prime}/$ \overline{a} \mathfrak{P} 0 $\overline{\text{are}}$ de $0 \ \ cos\theta_{23}$ al $\dot{\bm{so}}$ r θ_{23} 0.92^{2}_{32} $+$ $\tfrac{1}{2}$ $^{2}_{7}$ 0.02^{2}_{7} $^{2}_{7}$ $^{2}_{8}$ $^{2}_{9}$ $^{2}_{10}$ $\sum_{i=1}^{n}$ vji $\sum_{i=1}^{n}$ $\mathrm{t}\mathrm{f}\mathrm{c}$ $\cos\theta_{13}$ and Δm_1^2 *in* θ_{13} and θ θ he multiplication $-si\gamma\theta_{13}e^{i\delta}_{11} \simeq \Omega_{\Omega_2}e^{i\gamma\theta_{13}}$ $\sum_{\mathbf{h}\mathbf{h}}$ e **j**t \int_{0}^{1} qr **ce** *fi***nging search** de ee sinaU<u>ft</u>ce*l cost*}{1/9 $0_{\sim 0}$ $\sim 18^{-5}$ $\frac{1}{2}$ $\sum_{i=1}^{n}$ \int where $c_{jk} = cos\theta_{jk}$ and $s_{jk} = sin\theta_{jk}$. The parameters of the matrix can be classified in $\sum_{k=1}^{\infty}$ (and $\sum_{k=1}^{\infty}$ different neutrino oscillations. This is the probability that a neutrino that starts as ν_e $|\nu_{\mu}| = U^{\uparrow} |\nu_2|$ We can see from the probability equation (7) if the neutrino masses are equal to zero oscillations do not occur. A. Three neutrino mixing Considering three generations of neutrinos, in the neutrino oscillations formulation with mass eigenstates through the PMNS matrix $\mathcal{P}(\nu_{\alpha}^{\text{Vriting}} \rightarrow \nu_{\beta}) \stackrel{\text{equation}}{=} \sum_{\alpha}$.
วว $\overline{23}$ νe $\sqrt{ }$ ντ $\overline{}$ $\sqrt{ }$ 1 $\mathcal{L}_{1,2} e^{i\delta}$ 13^C ϵ 13 \int $\sqrt{2}$ c13c¹² c13s¹² s13e[−]i^δ $\begin{array}{c|c|c|c}\n & 12 & 12 \\
 & 1 & 12 & 2 & 3\n\end{array}$ ^s23s¹² [−] ^s13c23c12eⁱ^δ [−]s23c¹² [−] ^s13c13s12eⁱ^δ ^c13c²³ Π he atmospheri Π neutrino 2 η llations are determined by the θ_{23} and Δm^2_{23} paramete are determined $\cos\theta$ and Δm_1^2 $n\theta$ is θ the gross \mathcal{H}_2 in \mathcal{G}_2 and θ_1 and Δm_1^2 is θ_2 and θ_3 is a set of θ_1 and θ_2 is a set of θ_3 and θ_4 is a set of θ_2 and θ_3 an also the written as the multiplication of the three simulatives $U =$ ₹Ğ $\overline{ }$ $1 \simeq \Delta m_{32}$ 0 $0 \quad cos\theta_{23} \quad sin\theta_{23}$ $\lim_{n \to \infty} \frac{1}{n}$ cos θ_{23} 的 $\overline{ }$ $\cancel{\gamma}$ $\overline{1}$ $c\widetilde{o}$ s $\theta_3^2\times 10^{-5}e^{-\widetilde{o}\sqrt[3]{m}\theta_{13}}$ $0 \qquad 1 \qquad 0$ $-e^{-i\delta}sin\theta_{13}$ 0 $cos\theta_{13}$ \setminus $\overline{ }$ $\sqrt{ }$ $\overline{ }$ $cos\theta$ $-sin$ $\overline{0}$ The parameters θ_{13} and δ still unknown. Using this matrix and the probability from equation (7) , μ is possible to construct the probability of vertex μ oscillations in vacuum. The complete expression for the probability is $\sim 2 \times 10^{-3}$ eV^2 $V = \begin{bmatrix} 0 & 0.8\theta_{22} & \sin\theta_{22} \\ 0 & cos\theta_{22} & sin\theta_{22} \end{bmatrix}$ $\begin{bmatrix} 0 & 1 & 0 \\ 0 & 1 & 0 \end{bmatrix}$ $P(V_{\alpha} \leftrightarrow V_{\beta}) =$ **The** *j* $v^{\text{poton}}_{\beta j}$ $\lim_{\Delta m} \frac{2L}{L}$ $\frac{2}{E}$ ^{*d*} $\left| \begin{matrix} 1 & 0 \\ 0 & 1 \end{matrix} \right|$ $in\theta_{jk}$. The parameters of \sharp $\mathbb F$
A ions are delermined by \sharp $\sqrt{2}$ 4 ν_e ν_μ ν_{τ} $\overline{1}$ $\Big|$ = U^* $\sqrt{2}$ 4 ν_1 ν_2 ν_3 $\overline{1}$ $\mathbf{1}$ *i*=1 *j*=1 through the PMNS matrix $\left(\nu_{\alpha}^{Writing} \downarrow_{\beta}^{the} \underset{=} {\text{equation}} \right) \stackrel{\text{for the}}{\longrightarrow} \mathcal{U}_{\alpha i}^{th}$ $\begin{array}{|c|c|c|c|c|c|c|c|} \hline & -s_{12} & c_{12} & & \downarrow & \nu_2 & & \end{array}$ Δm2 ij=mi 2-mj 2 difference in the squared masses, Uαj mixing amplitudes * $P_{\text{TE}}(\text{exp}(t) = 1)$
 $P_{\text{TE}}(\text{exp}(t) = 1)$ $\text{sin}^2 2\theta \text{ s}$ $\overline{}$ $\begin{array}{c} \hline \end{array}$ $\begin{array}{c} \hline \end{array}$ $\begin{array}{c} \hline \end{array}$ $\begin{array}{c} \end{array}$ ν_e ν_μ ν_τ ⇥ = $\sqrt{ }$ ⇧ 1 *c*²³ *s*²³ *s*²³ *c*²³ $\sum_{i=1}^{n}$ $\overline{ }$ $\sqrt{ }$ ⇧ c_{13} $s_{13}e^{-i\delta}$ 1 $-s_{13}e^{i\delta}$ *c*₁₃ $\sum_{i=1}^{n}$ $\overline{ }$ $\sqrt{ }$ ⇧ *c*¹² *s*¹² *s*¹² *c*¹² 1 $\sum_{i=1}^{n}$ $\overline{ }$ $\begin{array}{c} \hline \end{array}$ $\begin{array}{c} \end{array}$ ν_1 ν_2 ν_3 ⇥ $P_{\alpha\beta} = \sin^{\frac{\text{wper}}{\text{exp}}\left(\frac{C}{\text{s}}\right)} \sin^{\frac{\text{cos}}{\text{s}}\text{exp}}$ \mathbf{u} \mathbf{d} $s_{jk} = sin\theta_{jk}$. The parameter of $\begin{bmatrix} \mathbf{d} & \mathbf{d} & \mathbf{d} \\ \mathbf{d} & \mathbf{d} & \mathbf{d} & \mathbf{d} \end{bmatrix}$ $\mathbf{d} \mathbf{d}$ \math $\nu_\mu \rightarrow \nu_\mu$ $\nu_{\mu} \rightarrow$ The parameters θ_{13} and <u> δ </u> still μ ^r Using this matrix and the proba $\bar{\nu}_e^e \stackrel{\text{\tiny def}}{\rightarrow} \bar{\nu}_e^e$ $U_{\text{quation}} \rightarrow V_{\text{y}}$ is post $\nu_e \rightarrow \nu_e$
and δ still up $\frac{1}{\Delta} \left(\frac{1}{2} + \frac{1}{2} \pi \sqrt{3} \pi \frac{1}{2} \pi \sqrt{3} \pi \$ \simeq $\simeq 2\times 10^{-3} \ {\rm eV}^2$ $\mathcal{V}_{\alpha} \to \mathcal{V}_{\beta}$ \equiv $\sum_{i}^{\text{new}} \mathcal{U}_{\beta j}^{\text{new}} e^{\frac{i}{2E} \mathcal{U}_{\alpha j}}$ $\mathcal{U}_{\alpha j}^{\text{new}}$ () if the atmospheric and some settled in the settle ν_1 has 3 mixing angles and one phanels and one has β

What do we know? W? Neutrino oscillations

• The probability of a neutrino v_{μ} transforming into a v_{e}

$$
P(\nu_{\alpha} \to \nu_{\beta}) = |\sum_{j}^{l} U_{\beta j}^{2} e^{-i \frac{\Delta m_{j}^{2} L}{2E}} U_{\alpha j}^{l} |_{\beta}^{2}
$$
\n
$$
\begin{bmatrix} \nu_{\mu} \\ \nu_{\tau} \end{bmatrix} = U^{*} \begin{bmatrix} \nu_{2} \\ \nu_{3} \end{bmatrix}
$$

$$
\begin{aligned}\n\oint_{\nu_{\tau}}^{\nu_{e}} \psi_{\mu}^{\text{he}} \text{else} \pm \text{he} \text{mixing} \text{angles} \text{and} \text{or} \text{else} \\
\downarrow_{\nu_{\tau}}^{\nu_{\tau}} \left\{\n\begin{array}{l}\n\text{mixing angles and one} \\
-\text{s}_{13}e^{i\delta} \\
\text{s}_{13}e^{-i\delta} \\
\text{else and one} \\
\text{else}\n\end{array}\n\right\} \\
\text{where} \text{size}\n\end{aligned}
$$
\n
$$
\begin{aligned}\nP_{\alpha\beta} = \sin^{2}(2\theta) \sin^{2}\left(1.27\Delta m^{2} \left[\text{eV}^{2}\right] \frac{L \left[\text{km}\right]}{E \left[\text{GeV}\right]}\n\right) \\
\downarrow_{\nu_{\alpha}}^{\nu_{\alpha}} \left\{\n\begin{array}{l}\n\text{min} \\
\text{max} \\
\text{min}\n\end{array}\n\right\} \\
\text{where} \text{size}\n\end{aligned}
$$
\n
$$
\begin{aligned}\n\text{max}_{\alpha_{1}}^{2} = \sin^{2}(2\theta) \sin^{2}\left(1.27\Delta m^{2} \left[\text{eV}^{2}\right] \frac{L \left[\text{km}\right]}{E \left[\text{GeV}\right]}\n\right) \\
\downarrow_{\nu_{\alpha}}^{\nu_{\alpha}} \left\{\n\begin{array}{l}\n\text{min} \\
\text{min} \\
\text{min}\n\end{array}\n\right\} \\
\text{where} \text{size}\n\end{aligned}
$$
\n
$$
\begin{aligned}\n\text{max}_{\alpha_{2}}^{2} = \sin^{2}(2\theta) \sin^{2}\left(1.27\Delta m^{2} \left[\text{eV}^{2}\right] \frac{L \left[\text{km}\right]}{E \left[\text{GeV}\right]}\n\right) \\
\downarrow_{\nu_{\alpha}}^{\nu_{\alpha}} \left\{\n\begin{array}{l}\n\text{min} \\
\text{min} \\
\text{min}\n\end{array}\n\right\} \\
\text{where} \text{size}\n\end{aligned}
$$

atmospheric and long baseline

 $\nu_{\mu} \rightarrow \nu_{\tau}$ $\nu_{\mu} \rightarrow \nu_{e}$ reactor and long baseline

 $\frac{\nu_e}{\nu_u} + \nu_\tau$ = sin² 2*0* sin $\nu_e \rightarrow \nu_\mu + \nu_\tau$

solar and reactor

 $\lceil \nu_e \rceil$ $\lceil \nu_1 \rceil$

Neutrino Oscillation at Long Baseline <u>New Soundhon at Long Baseline</u>

Following presentation by Nunokawa, Parke, Valle, in "CP Violation and Neutrino Oscillations", Prog.Part.Nucl.Phys. 60 (2008) 338-402. arXiv:0710.0554 [hep-ph]

$$
P(\nu_{\mu} \to \nu_{\mu}) \simeq 1 - 4 \cos^2 \theta_{13} \sin^2 \theta_{23} \left[1 - \cos^2 \theta_{13} \sin^2 \theta_{23} \right] \sin^2 \Delta_{3i}
$$

\n
$$
\simeq 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{3i}
$$

\n
$$
P(\nu_{\mu} \to \nu_e) \simeq |\sqrt{P_{\text{atm}}} e^{-i(\Delta_{32} + \delta)} + \sqrt{P_{\text{sol}}}|^2
$$

\n
$$
= P_{\text{atm}} + P_{\text{sol}} + 2\sqrt{P_{\text{atm}} P_{\text{sol}}} \left(\cos \Delta_{32} \cos \delta \mp \sin \Delta_{32} \sin \delta \right)
$$

$$
\sqrt{P_{\text{atm}}} = \sin \theta_{23} \sin 2\theta_{13} \frac{\sin (\Delta_{31} \mp aL)}{\Delta_{31} \mp aL} \Delta_{31}
$$
\n
$$
a = G_F N_e / \sqrt{2} \simeq \frac{1}{3500 \text{ km}} \frac{aL = 0.08 \text{ for } L = 295 \text{ km}}{aL = 0.23 \text{ for } L = 810 \text{ km}}
$$
\n
$$
\sqrt{P_{\text{sol}}} = \cos \theta_{23} \sin 2\theta_{12} \frac{\sin (aL)}{aL} \Delta_{21}
$$
\n
$$
a = \frac{G_F N_e}{\sqrt{2}} \simeq \frac{1}{3500 \text{ km}} \frac{aL = 0.23 \text{ for } L = 810 \text{ km}}{aL = 0.37 \text{ for } L = 1300 \text{ km}}
$$

Mark Messier, Neutrino 2023 summer school

춘 Fermilab

The Atmospheric Neutrino Anomaly

- Cosmic rays hit the earth isotropically
- People expected:

 $\frac{(-\nu_{\mu}\sqrt{2\cdot p^2})}{\Phi_{\nu_{\mu}}(Down)}=1$

• However, Super-Kamiokande found

 $\Phi_{\nu_{\mu}}(Up)$ $\frac{1 - \nu_{\mu} (1 - \nu_{\mu})}{\Phi_{\nu_{\mu}}(Down)} = 0.54 \pm 0.04$

neutrino oscillation

ATMOSPHERIC NEUTRINOS

Priman

primary cosmic ray

Field moves quickly Exercise 2018

- Around 2003 neutrino physicists searched for the parameter sin² θ_{13} \cdot the parameter sin² θ_{13}
- The parameter sin²θ₁₃ has now been measured a clear the set of the s $\frac{1}{2\pi}$ (sin $\frac{1}{2\pi}$)
- In 2012 Daya Bay measured sin²θ₁₃ for the $first time$ \qquad 012 Daya Bay measured sin² θ_{13} for th - **Statistics**:
- Today is best known angle! powerful reactors (17.6 GWh) \mathbf{R}

 $\overline{}$ of the 3 neutrino mixing framework. $Reach. \rightarrow \sin^2 \theta_{13}(4.7\%)$ - **Reactor-related uncertainty**:

Results from Neutrino 2014

- **Detector-related uncertainty**:

• Other reactor and accelerator experiments

- **Background**:

 $2^{\circ} < \theta_{13} < 9.0^{\circ}$

Remaining Questions neutrino masses-squared, as follows: *m*² 8 **Remathing Q.0 estions**

- Is there CP violation in the Lepton sector? ³ *> m*² ² *> m*² ¹, termed the normal mass-ordering (NMO), or *m*² 40 ^p vietatio_n in the Iepton sector?
	- May explain matter-antimatier asymmetry plain matter_zantimatter asyr
	- What is the mass hierarchy? (sign of Λ_{m^2}) $T^{\prime\prime}$ \mathbb{R} \overline{p} or tan the able to understand the reach of experiments that study whether 8.2 ⁸ $\frac{1}{2}$ are their own antiparticle or not $\Delta m^2_{\rm B2}$ $\frac{1}{2}$ are negative. The two mass orderings are depicted in Figure 1. The mass of mass order in Figure 1. The mass of mass of $\frac{1}{2}$ $\sim 10^{-9}$ eV² ($\pm 10^2$ ₉) χ 10 $^{\circ}$ eV² (\pm 1.1%) $\Delta m_{\rm P2}^2 = (2.510 \pm 0.027) \times 10^{-3}$ eV² ($\pm m_{\rm P2}^2$) $\Delta m_{23}^{\text{HPI} \text{DOT}}$ (2.510 \pm 0.027) \times 10³ eV₂ (\pm 1.1%)

How to make a neutrino beam

Neutrinos From Accelerators

• A beam of protons interact with a target and produce pions and kaons

scattering are possible.

- Focusing system (2 horns, with current, emitting B field)
- Decay region (large pipe, filled with helium) \mathcal{P} Protons collide with a 2 \mathcal{P} and 2 \mathcal{P} and 2 \mathcal{P} arguments to \mathcal{P} and 2 \mathcal{P} a
- Monitors and absorbers
- Neutrino beam produces mainly v_{μ} and small component of v_{e} v_{μ} and small component of $v_{\rm e}$

Neutrino Energy Spectrum

- The target and second magnetic horn can be moved relative to the first horn to produce different energy spectra
- This allows a study of neutrino interaction physics across a broad neutrino energy range
- Neutrino oscillation experiments use interactions in the near and far detectors to study oscillation physics • Neutrino oscilla

Study oscillation

Neutrino Oscillation Program at Fermilab

Long-baseline Experiments: What can we learn? Daseline experiments: what can we learn?
————————————————————

- Use a high intensity beam of neutrinos from Fermilab
- Construct detectors at far locations: MINOS+ at 735 km (ended data-taking), NOvA at 810 km (taking data) and DUNE at 1300 km (in design)

$P[\nu_{\mu} \rightarrow \nu_{e}] \neq P[\overline{\nu}_{\mu} \rightarrow \overline{\nu}_{e}]$?	also, T2K in Asia
Termilab Long-baseline experiments	Nova
DUNE	Ashriver
DUNE	Ashriver
Home State	Nontrich Dakota
Manmesous	Manmesous
Manmesous	Manmesous
Manus and P	Minvarace
Nebraska	lowa

Short-baseline Experiments

 10^{-10}

[−]**⁹ 10**

 10^{-8}

[−]**⁷ 10**

 10^{-6}

 10^{-5}

 -1 POT -1 GeV

-2 [m ν **#**

−**4]10**

- Three argon Time Projection Chambers (TPC) detectors at different baselines from Booster neutrino beam searching for sterile neutrino oscillations
	- Measuring both appearance and disappearance channels

Calorimeter Modul The NOMAD detector [29] consisted of an active target of 44 drift chambers with a total fiducial mass of 2.7 tons, **V8** of 44 drift chambers with a total fiducial mass of 2.7 tons,
located in a 0.4 Tesla dipole magnetic field as shown in of 44 drift chambers with a total fiducial mass of 2.7 tons, **V8** located in a 0.4 Tesla dipole magnetic field as shown in **Neutrino Neutrino** Fig. 1. The $X \times Y \times Z$ total volume of the drift chambers **beam**^{Fig. 1} The $X \times Y$ **Fig.** 1 $\operatorname{Fig. 1}$ The $X \rtimes Y$ \times Z to tal wolume of the different chambers **Beam** Fig. 1. The $X \times Y \times Z$ to
 A II A consumer to the section measurements about $300 \times 300 \times 400$ **Beam** is abo<mark>ut 300 × 400 cm³.</mark> is about $300 \times 300 \times 400$ cm³. All Accelerator-Base Oprinchange of a nearly isoscalar target⁻ for neutrino D**rift chambers [37], made of low Z material serve**d $\frac{1}{2}$ $Drift$ chambers -37 , made of low Z material served \mathbf{u} and \mathbf{u} and \mathbf{u} and \mathbf{u} the dual role of a nearly isoscalar target¹ for neutrino inthe qual role of a nearly isoscalar target- for neutrino
teractions and of tracking medium. The average densi-• We are using heavy targets for those it in the second experiment of the discrete states. The MINERVA Experiment hm**experim erres.** F The MINERvA Experiment bers provided an overall efficiency for charged track **Hadronic MINERVA Experiments** Fig. 1. A side-view of the NOMAD detector. \hbox{han} 95% and a momentu **Electromagnetic** • Using heavy targets involves model than 95% and a momentum resolution of better than 95% and a momentum resolution of better than 95% and a momentum resolution of better than 95% and a momentum resolution of the Charles \mathbb{Z}_p^{\bullet} and $\mathbb{$ **ES LIAO GE HADE approximate by the TCHOWES** form $\frac{\sigma_p}{p} \approx \frac{0.05}{\sqrt{L}} \oplus \frac{0.000p}{\sqrt{L^5}}$, where the momentum p is in GeV . Fin with momentum well below 1 GeV/c and with emission μ Fine-grained scintillator tracker surrou required adoptive 60 degrees. • Fine-grained scintillator tracker surrounded by calori tify yranica sofitunator traonor e • We need to model nuclear effect $\mathbf{F}_{\text{seed}}^{\text{max}}$ range $\mathbf{F}_{\text{code}}^{\text{max}}$ of the active target was used for particle identification. Liquid Argon \blacksquare U-turn due to the magnetic field. There were no special to the magnetic field. There were no special to the magnetic field. The magnetic field of the magnetic field of the magnetic field. The magnetic field of the used to determine the event topology (the assignment cial efforts invested into tuning the NOMAD reconstruc- \mathbb{Z} scintillation counter trigger planes \mathbb{Z} $H = \sqrt{\frac{1}{2} \sqrt{1 - \frac{1}{2} \sqrt{1$ tracks to vertices), to reconstruct the vertex position a S iew \overline{S} and \overline{S} is the NOMAD active target target target target. \mathcal{A} and \mathcal{A} and \mathcal{A} are defined by \mathcal{A} \blacksquare (which is rather different that the fact that the track parameters and vertex and, finally, to ide

tify the vertex type (primary, secondary, etc.). A tran angle above 60 degrees. For positive particles in the up-transition \mathcal{L} the track parameters \mathbf{a} parameters and, finally, to identical are in the 1/8 region of ionization in the 1/8 region of ionization losses, traversion in the 1/8 region of the 1/ **Carbon** $\frac{d}{d\theta}$ and the tracking region provided an energy region provided an energy region provided an energy region provided and θ $\frac{1}{\sqrt{2}}$ we have the NOMAD detector such conditions of the NOMAD 5 larger amount of material, crossing drift cells at very large **। हिंदीन का** $\mathcal{L}_{\text{scat}}$ tion radiation detector (TRD) [38,39] placed at the e $\overline{}$ where the spacial resolution of the drift chambers is the drift chambers is the drift chambers is the drift chambers is the drift chambers in the drift chambers is the drift chambers in the drift chambers is t $\frac{1}{\sqrt{2}}$ important that the $\frac{1}{\sqrt{2}}$ is the area of $\frac{1}{\sqrt{2}}$ in $\begin{bmatrix} 1 & 0 & 0 \ 0 & 0 & 0 \end{bmatrix}$ NOMAD $\begin{array}{c|c|c|c|c|c|c|c|c} \hline \text{non random detector (1 AU) [38, 39] placed at the e} & & \text{non random detection (1 AU) [38, 39] placed at the e} & \text{non standard deviation (1 AU) [38, 39] red.} & \text{non standard deviation (1 AU) [38, 39] red.} & \text{non standard deviation (1 AU) [38, 39] red.} & \text{non standard deviation (1 AU) [38, 39] red.} & \text{non standard deviation (1 AU) [38, 39] red.} & \text{non standard deviation (1 AU) [38, 39] red.} & \text{non standard deviation (1 AU) [38$ $\mathbf{\mathbb{R}}$ ooNE **Muon** $||$ neutrino interactions. In addition, and in addition, and in addition, and in addition, and in a interactions. In addition, $||$ a U-turn due to the magnetic field. The magnetic field $\frac{1}{2}$ is a specified vertex $\frac{1}{2}$ in the magnetic field $\frac{1}{2}$ **Chambers** $h = \frac{1}{\omega}$. Some of the these effects are different are difficult at ω **Dipole Magnet** a set of muon chambers located after the electromagnetic state $\mathbb{E}[\mathbf{z}]\mathbf{z}$ **Front** ⊗ **B = 0.4 T TRD** lanes [40] were used ICARUS $\sum_{i=1}^n \Delta_i$ in the district of the NOMAD reconstruction tuning the NOMAD reconstruction of Δ \overline{r} $\begin{bmatrix} \mathbf{r} & \mathbf{r} & \mathbf{r} \end{bmatrix}$ in the muon identification is much in the muon in the muon in the muon in the muon is provided to \mathbf{r} *MINOS ND magnetized* **Calorimeter Modules Preshower** t response in the MC simulation problem problem t \mathbf{C} and \mathbf{C} and \mathbf{C} are momenta greater for \mathbf{C} **V8** Front View $\sum_{n=1}^{\infty}$ NOMAD active target t time program to t , we can find the reconstruction of t r reconstruction efficiencies for this particular confidult for the r \mathbf{t} **Neutrino** (which is rather difficult due to the fact that the f \cdot imeter [41, of outgoing protons could be different for the simulated be differ The NOMAD neutrino beam consisted mainly of variable mainly of variable mainly of variable mainly of variable **14Kton Beam** events and real data. \mathbb{R} region of ionization of ionization loss set ionization loss set ionization ionization loss set ionization ionization ionization losses, the set of \mathbb{R} with an about 7% and less than 1% of \mathcal{A} <u>III Diiih n</u> provided an $\sum_{i=1}^{\infty}$ νε από το προσωπικό του απ \mathbf{u} larger amount of material, crossing drift cells at very larger at very larger \mathbf{v} $electromag$ \blacksquare we observe the \blacksquare and \blacksquare and \blacksquare and \blacksquare and \blacksquare and \blacksquare \mathcal{L} $\mathcal{$ **is stude** MC. T main goal of the NOMAD experiment was the angles where the spacial resolution of the spacial resolution of the drift chambers is a spacial resolution of e total ene In the current analysis in $\overline{}$ search for neutrino oscillations in a wide band neutrino \mathcal{L} $\mathcal{$ considerably worse and where a large and where a large and where a large and where \mathcal{C} an iron ab \mathbf{u} reconstruction effects discussed above from \mathbf{v} beam from the CERN SPS \mathbb{R} \mathbf{t} of event reconstruction similar to that of bubble chamber his produced, etc.). Some of the some of a set of muon chambers located after the electromagnetic set of \mathbf{r} change the proton kinematics and thus introduce drastic $e^{\frac{1}{2} \left(\frac{1}{2} \right)}$ nt to parametrize and to simulate at the level of the deteclentification changes in the final results due to the efficiency mismatch $\frac{167}{167}$ mm **16.7 mm** Fig. 1. A side-view of the MiniBooNE between simulated and real data). In order to get rid of an $\frac{1}{\sqrt{1-\frac{1}{\sqrt{1+\frac{1$ of neutrino interactions. δ for mome interplay between these two effects is was considered to choose two effects in \mathcal{C} Minerba Betancourt I The MINERVA Experiment of the Contract of the Contract of the MINERVA Experiment of the Contract of the C **17 mm** reconstruction effects for this particular configuration \sim 3 dif than \mathbb{R} GeV/c. \mathbb{R} the region in the detector \mathcal{A} and \mathcal{B} and \mathcal{B} 2 \blacksquare \overline{z} $\overline{$ \sim of \sim of \sim of \sim of \sim $\sum_{i=1}^n a_i$ reso The North Constantino beam consisted mainly of your consisted mainly of the second mainly of the r_0 updod by r_0 rounded by calorimeters such conditions and the NOMAD detector surrounded by calorimeters surrounded by calori \mathbb{Z}/\mathbb{Z} are emitted in the lower hemisphere of \angle events and real data. u and less than 1% \mathcal{L} mean that the second control these particles are almost immediately making into the second control to the second Design, calibration, and performance of the MINERvA dete ιm composition can a U-turn due to the magnetic field. The magnetic field. There were no special to the magnetic field. There were Design, Calibration, and penormance of the
Nuclear Inst. and Methods in Physics Rese *MINOS ND magnetized* cial efforts in the NOMAD reconstruction found in [30]. The most upsteam drift chamber was used as an additional change of the most upsteam of the chamber was used as a
District chamber was used as an additional change as an additional change of the change of the change of the Nuclear **Inst. and Methods in Physics Research**, A, Volume

Minerba Betancourt/Mond 2017, Pages 130-159 tion program to reconstruct this particular configuration The main goal of the main grade of the SBND experiment was the SBND t ional veto to research, A , volume $\sum_{i=1}^n \sum_{i=1}^n \sum_{i$ $\mathsf{Side}\ \mathsf{HC}$ \ldots . \ldots is the NOMAD active target the NOMAD active target \ldots rent Queen and muon track is in general extensive in the muon track is in general extensive in the muon track is in $\frac{1}{2}$ Minerba Betancourt/Morton of the current analysis in the current service of the current to discrete the current to discrete the current to discrete the current to discrete the current of the current of the current of the c is crucial for the study of single track events. *Minerba Betancourt/Moriond QCD 2014* $rac{1}{2}$ region of $rac{1}{2}$ reg search for neutrino oscillations in reconstructed. However, when we study protons emitted larger amount of material, crossing drift cells at very large the reconstouction efficiency effects discussed above from beam from the CERN SPS [43,44]. A very good quality in the visible the visible of the visible candidate with protons with ρ **MINOS Near Detecto
(Muon Spectrometer** and an angles where the space of the space of the space of the drift chambers is a space of the drift chambers is \mathbb{R} Carbon, *ciron*, *deadillar* to tha 100 kV $\frac{1}{\text{MUCed}} \text{by} \text{g} \text{int} \text{tr}$ \mathcal{A} σ are σ and σ and σ and σ bubble changes changes of σ considerably worse and where a large amount of multiple change the proton kinematic drastic and thus interview of the proton kinematic drastic $h = \frac{1}{2}$ 49%) and consists mainly of Carbon; a detailed de- $\text{experiments and a large data sample of }$ **helium,** *w***ater** \blacksquare see drift chamber composition can be found in $[37]$ $\frac{1}{\sin \theta}$ and the detector $\frac{1}{\sin \theta}$ $\frac{1}{\sin \theta}$ $\frac{1}{\sin \theta}$ $\frac{1}{\sin \theta}$ $\frac{1}{\sin \theta}$ $\frac{1}{\sin \theta}$ anges in the final results due to the effect of the ef years bruard, tam all et 095-1998 allow for detailed studies tor response in the MC simulation program. Thus, the MC simulation program. Thus, the MC simulation program. T $\begin{picture}(180,10) \put(0,0){\line(1,0){10}} \put(1,0){\line(1,0){10}} \put(1$ of neutrino interactions. reconstruction efficiencies for this particular configuration $\frac{1}{15}$ for $\frac{1}{20}$ \blacksquare interplay between these two \blacksquare events and real data. a different rotated plane views to the contract of the contrac **17 mm** 4 m $\sum_{i=1}^n\|f_i\|_2^2=\max_{i=1}^n\|f_i\|_2^2$ <u>Let us stress, however, that for protons emitted down-</u> 1 Mineral Mineral Mineral \mathbb{R}^n , the \mathcal{L} in \mathcal{L} is \mathcal{L} in \mathcal{L} and \mathcal{L} and \mathcal{L} and \mathcal{L} is a set of \mathcal{L} is a set of wards we observed a good agreement between data and the served and the served agreement between data and the served and the served and the served agreement between data and the served agreement of the served and the served \mathcal{L} and \mathcal{L} and \mathcal{L} and \mathcal{L} and \mathcal{L} are achieved by selecting \mathcal{L} 3.1 Reconstruction of QEL resolve high multiplicity and the solve of the solve MC. *E* detector \mathcal{L} where \mathcal{L} are emitted in the lower hemisphere of the lower hemi $\overline{}$ 5 m $\overline{}$ 5 m $\overline{}$ $\overline{}$ $\overline{}$ 2 m *E* ector. This ap leters for description A detailed information about the construction and performance change the proton kinematics and thus introduce drastic mance of the NOMAD drift chambers \blacksquare $\overline{}$ i i **TENIS** $\sqrt{2}$ \overline{z} changes in the final results due to the efficiency mismatch between simulated and real data). In order to get rid of and real data \mathcal{L} upsteam drift chamber was used as an addideveloped reconstruction algorithms $\frac{3 \text{ different}}{\text{resolve}}$ interpretation the compact two effects is well as compact to choose two effects in \mathcal{L} 5_w tion of the research of $\mathcal{L}_{\text{MIGS}}$ is and Methods in Physics Research, A, Volume 743, 11 Apple 743, 11 Ap Let us briefly describe some features r_{chulated} Let us brienly describe some reachlisterhode 4 Peral easily

> reconstructed. However, when we study protons emitted in the ν_{μ} QEL two-track candidates we deal with protons

with two 12a6 driftSregions

interactions upstream of the NOMAD active target. This

is crucial for the study of single track events.

TRD

⊗ **B = 0.4 T**

Front

¹ the NOMAD active target is nearly isoscalar $(n_n : n_p =$ 47.56% : 52.43%) and consists mainly of Carbon; a detailed description of the drift chamber composition can be found in [37]

 Tr International Tr Tr active target

3 different rotated plane views to ciency. This could be achieved by search by selecting the action of the action of the action of the selection of the sel resolve high multiplicity events

5

 \cos Hesearch, A, volume 745, TT April 2014, F ormance of the MINERvA detector The most upsteam drift chamber was used as an additional as an additional chamber of the most upstead as an addi-1 Physics Research, A, Volume 743, 11 April 2014, Pages 130-159

t/Moriond QCD 2014
Crucial for the study of single track events.

 \overline{N}

6 • QE-like: any number of nucleons, but no pions • QE-like: any number of nucleons, but no pions

In More Detail

- Oscillation probability depends on neutrino energy E_v
- We need to reconstruct the neutrino energy precisely

$$
P(\nu_{\alpha} \to \nu_{\beta}) \approx 1 - \sin^2 2\theta \sin^2(\frac{\Delta m^2 L}{E_{\nu}})
$$

- Neutrino energy reconstruction is obtained using the final state particles of neutrino-nucleus interaction
	- Fully active experiments reconstruct the energy using: $E_v=E_{\text{lepton}}+hadron$

• Nuclear effects modify the kinematics of the particles and the reconstruction of the neutrino energy

 $\mathbb{P}^{\mathcal{L}}$ and $\mathbb{P}^{\mathcal{L}}$

e of Nuclear Effects (Final State Interaction)
ate interaction (FSI): **Example of Nuclear Effects (Final State Interaction)**

• Final state interaction (FSI):

20

- Due to final state interactions, particles can interact with nucleons and pions can be absorbed before exiting the nucleus and other nucleons get knocked out

Example of Nuclear Effects (multi-nucleon interaction)

• Nuclear effects modify the neutrino energy, for example multi-nucleon interactions

nucleons

- The resulting di-nucleon pair undergo final state interaction and produce low energy proton and neutrons which we do not detect well
- Multi-nucleon processes smear the reconstructed neutrino energy
- The nuclear effects are big (>20%)

Example of Nuclear Effects (Final State Interactions)

 \sum ier examples of final state interactions: **EXAMPLES OF ITHAL STATE INTERACTE**

Studying Nuclear Effects in MINERvA

- Fine-grained scintillator tracker surrounded by calorimeters
- e
INIERvA has different purlear targets iron load carbon belium a • MINERvA has different nuclear targets iron, lead, carbon, helium, and water

Design, calibration, and performance of the MINERvA detector Nuclear Inst. and Methods in Physics Research, A, Volume 743, 11 April 2014, Pages 130-159

Cross Section Measurements

• Cross section is extracted using: • Event selection: bss section is extracted using:

Background Constraint Procedure for Non-CCQE like

- Using the unattached visible energy for the events passing the proton pID for two different bins of $Q²$ in the tracker
- Using the background dominated region in the unattached visible energy distribution
- Let the background float in the fit while keeping the signal constant until the total matches the data distributions

Comparing with Generators (GENIE vs NuWro)

Data prefers the simulation with final state interactions

E Fermilab

• The A dependence in NuWro seems to be more favored by the data

MINERvA Results

Addressing these Remaining Questions CP Violaton? Neutino vs Ant-neutino oscilatons

- Is there CP violation in the lepton sector
- What is the mass hierarchy? (sign of Δm^2_{32})

 $P[\nu_{\mu} \to \nu_{e}] \neq P[\overline{\nu}_{\mu} \to \overline{\nu}_{e}]$?

- Use simulations to extrapolate from near detector to far detector $\sigma_{\nu\mu}{\longrightarrow}\sigma_{\nu e}$
- We definitely need a nuclear model to convert from produced to detected energy spectra and topologies in the near and the far detectors cross convert is only produced to detected effer ζ
- This illustrates the significance of precise knowledge of neutrino interactions physics needed for oscillation studies

● Neutinos mass hierarchy?

Where is the Far and Near Detector?

 \mathcal{L} is a set of \mathcal{L} , and $\mathcal{L}_\mathcal{L}$ is a set of $\mathcal{L}_\mathcal{L}$ in the $\mathcal{L}_\mathcal{L}$

Where are all those neutrinos headed? **Neutrinos make the journey from Fermilab to northern Minnesota**

t in t is t Fermilab to the second stress of the second stress of the second stress in the second stress in the second str
The second stress in the s w iscon Minnesota in **Minnesota Illinois Wisconsin**

Ely Min Contract Contrac

Wisconsin

 $\sum_{i=1}^n \frac{1}{i}$

Minerba Betancourt

29

A Neutrino Interaction from the NOvA Experiment A MUON NEUTRINO A MUON NEUTRINO A GERMANIA E DE L'ANGUERRO DE L'ANGUERRO DE L'ANGUERRO DE L'ANGUERRO DE L'ANGU
A MUON NEUTRINO A MUON NEUTRIN

Neutrino Oscillations at Long Baseline .
. . ।
।
। <u>I LO</u> at Long !!!

Phys.Rev.Lett. 106 (2011) 181801

NOvA Experiment

measurements

and **and in Erika Catano**, Fermilab JETP, June 2 Erika Catano, Fermilab JETP, June 2024

m232 is now the most precisely known PMNS parameter

Am-₃₂ is now the most precisely known PMNS parameter.
NOvA's new result achieves a precision of 1.5% **Δm2 ³² is now the most precisely known PMNS parameter. NOvA's new result achieves a precision of 1.5%**

Erika Catano, Fermilab JETP, June 2024

Next Long-baseline neutrino experiment

- Long-baseline neutrino oscillations, including discovery sensitivity to CP violation and neutrino mass ordering
- MeV-scale neutrino physics, including supernova burst astrophysics and solar neutrinos baryon number violation proportions, non-standard output moved
- Broad program of physics searches beyond the Standard Model

Neutrino Beam and Underground Facilities

- Most intense neutrino beam in the word will provide up to 1.3 MW intensity, designed to allow for future upgrade to 2.4 MW **Prost intense neutrino beam in the word will provide up to 1.3 PTVV intensity,**
- Deep underground cavern at SURF to accommodate four 17-kiloton argon Far Detector modules and underground near site oughed to allow for future upgrade to 2.4 MW
Leep underground cavern at SLIRE to accommodate four 17-kiloton argon Far

7 2022 Fermilab Users' Meeting

Near Detector at Fermilab

- Near Detector Complex houses a set of detectors to predict the far detector spectrum and monitor the beam stability
- A liquid argon TPC (ND-LAr) plus a Muon Spectrometer (TMS), these can move off -axis (PRISM system)
- An on-axis detector (SAND) **The DUNE ND Complex - Phase I**

Two LArTPC designs for Far Detector

- First detector to be installed in NE cavern has horizontal drift technology like - 1st detector to be installed in NE cavern has horizontal drift (like ICARUS and **ICARUS**
- Second detector will go into SE cavern and has vertical drift technology

and recording tracks

Far and Near Detector Prototyping

- Large-scale DUNE prototypes operated at CERN Neutrino Platform with low noise, stable high voltage and high purity
- Stable operation of ProtoDUNE shows that the technology will work and is scalable to full DUNE
- Several publications from the successful operation between 2018 and 2020 **DUNE prototype in CERN**

• Near Detector LAr 2x2 prototype Module-1 operated successfully at Bern, aled Successiuny at Deni, preparation for neutrino beam test at Fermilab underway <u> 춘 Fermilab</u>

Starila Nautrino Physics **Sterile Neutrino Physics**

 w Sterile neutrino scenario is far from understood:

- disappearance experiments (IceCube, NOvA, MINOS/MINOS+) Alternative (Beyond Standard Model) explanations (and LSND) in the MiniBoone explain that MiniBoone and LSND. - No evidence in ν_μ disappearance experiments (IceCube, NOvA, MINOS/MINOS+)
	- No precise indication from recent \bar{v} flux measurement at reactors
	- "#\$%&&'&&()*+,-./&012&&'&&3.45.*6&!78&9:9; **23** the best fit to the best fit to the new the model of the set of the - Planck data/Big Bang cosmology: at most one further flavor with m_{new}<0.24 eV

Short Baseline Program (SBN)

- Three LArTPC detectors at different baselines from Booster neutrino beam searching for sterile neutrino oscillations
	- Measuring both appearance and disappearance channels
- Measure neutrino cross sections on liquid argon
- Same detector technology and neutrino beamline: reducing systematic uncertainties to the % level $\frac{1}{2}$
- A detection technique providing an excellent neutrino identification to reduce the backgrounds $\frac{1}{2}$ the well community of the well beam $\frac{1}{2}$

Liquid Argon TPC Detection Technique

- Tracking device: precise 3D event topology with \sim mm³ resolution for ionizing particle
- Scintillation light detected by PMTs to provide event time and trigger
- Charged particles from neutrino interactions ionize the LAr, production ionization electrons drifting in 1 ms toward readout sense wires

- Powerful particle identification by dE/dx vs range
- Remarkable e/ γ separation: calorimetric capabilities can distinguish e from γ at the shower start

First Low-Energy Excess Search with MicroBooNE

• No evidence for an enhanced rate of single photons from NC Δ ->N γ decay above nominal MC predictions

- Observe v_e candidate events in agreement, or below, the predicted rates
- Reject the hypothesis that v_e CC interactions are fully responsible for the MiniBooNE excess at > 97% C. L. in all analyses

https://arxiv.org/abs/2110.14054

First Low-Energy Excess Search with MicroBooNE

• The MicroBooNE experiment presented the results of the first analyses searching for an excess of low-energy electromagnetic events

an excess of low-energy electromagnetic electromagnetic electromagnetic electromagnetic electromagnetic electr
In the control of low-energy electromagnetic electromagnetic electromagnetic electromagnetic electromagnetic e

• No hints of an electromagnetic events excess, but results do not rule out existence of sterile neutrinos

 $\frac{3}{26}$ Fermilab

Sensitivity of SBN program

• Searches for both v_e disappearance and v_μ appearance

νe appearance νμ disappearance

• SBN cover much of the parameters allowed by past anomalies at >5σ significance

ICARUS (Imaging Cosmic And Rare Underground Signals)

- Liquid Argon technology for v physics was proposed in 1977 by C. Rubbia
- Many years of R&D at INFN/CERN culminated in first large-scale experiment at LNGS underground labs
- 2 TPCs per module with central cathode, 1.5 m drift, $E_D = 0.5$ kV/cm, Δt ~1 ms
- 3 readout wire planes (2 induction+collection) per TPC, ~54000 wires at 0, 60 degrees, 3 mm. ... neutring pitch: a continuous read-out
- 360 $(8"$ PMTs $)$

ICARUS at FNAL

- Several technology improvements were introduced, aiming to further improve the achieved performance ICARUS previous runs: new cold vessels, improvement of the cathode planarity, higher system ovements were introduced, aiming to further im d uparado of the DMT apgrade or d $\mathbf{r} = \mathbf{r} \cdot \mathbf{r}$ modules were assembled at LNF (Italy) and $\mathbf{r} = \mathbf{r} \cdot \mathbf{r}$
- ICARUS began commissi

rino data in June 2021

coordinates of the track crossing point. **side CRT**

 $\mathcal{F}(\mathcal{F})=\mathcal{F}(\mathcal{F})$ and times spatial ($\mathcal{F}(\mathcal{F})$ and times $\mathcal{F}(\mathcal{F})$

Top CRT

600 500

400 300 200

Neutrino Oscillation Analysis

CARUS is pursing single-detector neutrino oscillation measurement

reconstruction (Pandora) and machine learning based reconstruction

CC 0π Event Selection for fully contained Events where m^N is the mass of N, and the last line follows from α is a first operator of α = \mathbf{I} II. Single-Transverse Kinematic Single-Transv CC O π Event Select 0 - Eught Cologian for fully contained Event

- First cross section measurement: $1\mu + N$ proton+0 π • First cross section measurement: l*μ*+Nproton+0π \vec{p}_ℓ
- Observables δP_T and $\delta \alpha_T$ sensitive to initial and final state effects \overline{C} to muttal and mial state \overline{C} $\sum_{N=0}^{\infty}$ • Observables δP_T and $\delta \alpha_T$ sensitive to initial and final state effects $\sum_{\vec{r} \in \mathbb{N}^N} \left| \sum_{\vec{r} \in \mathcal{F}^N_T} \alpha_{\vec{r}} \right| \geq \epsilon$ $\overline{}$ unknown initial nucleon momentum and the initial nucleon momentum and the initial nucleon momentum and the initial nucleon $\overline{}$ • Observables δP_T and δa_T sensitive to initial and final state effects
	- Events with contained muons and protons • Events with contained muons and protons
• Main background is events with pions
- Main background is events with pions • Main background is events with pions the charged lepton retains most of the increase of the

order approximation because the polarization because the polarization term ∼extensive the polarization term ∼e
Internacional control term ∝extensive the polarization term ∝extensive the polarization term ∝extensive the po

 $\delta \alpha_{\rm m} = \arccos \frac{-p_{\rm T} \cdot op_T}{\sigma}$ $\delta \alpha_{\rm T} \equiv \arccos \frac{-\vec{p}_{\rm T}^{\ell'} \cdot \delta \vec{p}_{\rm T}}{p_{\rm T}^{\ell'} \delta p_{\rm T}},$

 $p_{\rm T}^{\ell'}$ $^{\ell'}_{\rm T}\delta p_{\rm T}$

 $\frac{\partial \ell'}{\Gamma} \cdot \delta \vec p_\text{T}$

 T , T , T

 $,$

IMBALANCE

To make a neutrino energy-independent measurement of nuclear effects, the in-medium energy-momentum energy-mome

 $x = \sqrt{\frac{P_{\perp}}{A}} \sqrt{\dot{q}} = -\vec{p}_{\perp}^{\ell}$ $\vec{p}_{N'}$ \vec{p}_{max}

 $\delta \vec{p}_{\rm T} \equiv \vec{p}_{\rm T}^{\ell'} + \vec{p}_{\rm T}^{\rm N'}$

 \mathbf{L}

BSM Searches with NuMI Higgs Portal Scalar at ICARUS

52

• Certain BSM searches benefit from sitting off-axis such as kaon coupled Higgs portal scalars • **Heavy QCD Axion** or **Axion-Like Particle (ALP)**: Pseudoscalar

EXAM MODELS CONSIDERATION involving kaon decay and contained dimuon final **new physics and Heavy Axion and Heavy QCD Axion** $\overline{\text{Nep}}$ involving kaon decay and contained dimuo

Fate State Presonance t specific value

SBND Experiment

- The SBND detector contains three systems, a TPC system, a photon detector system (PDS) with 120 PMTs and 192 X-Arapucas and a Cosmic Ray Tagger (CRT)
- SBND is located on the surface

SBND Detector Installation

Neutrino Interactions at SBND SBND data will enable a generational advance in the study of neutrino-argon interactions in the GeV energy range, with low thresholds for particle tracking and calorimetry and enormous statistics. Sboutrino-bataractional at GEND with low thresholds for particle tracking and calorimetry and calorimetry and calorimetry and enormous statistics

cross-section measurements of the cross-section measurements of the cross-section measurements of the cross-section
The cross-section measurements of the cross-section measurement of the cross-section measurements of the c • New data sets will reach the order of millions of neutrino interactions for single cross-section measurements of the contract of channels

BSM Searches with Booster

• Rich BSM searches: Neutrino tridents, dark matter, Higgs portal, heavy neutral lepton, millicharged particles… $\sum_{i=1}^{\infty}$ particles...

Detector Commissioning Journey to Data Taking: Successful Commissioning

- Starting to commission the different systems TPC, PMT and CRT \mathcal{N} Successful demonstration of SBND commissioning using \mathcal{N} and \mathcal{N} \sim 1.600 commission and direction of the duration of the BNB spilling the BNB spilling spilling spilling \sim
	- \cdot 1.6 μ wide per reflecting the duration of the BNB spill

First neutrino interactions

Summary

- Neutrinos are great probes to answer fundamental questions about the nature of matter and the evolution of the universe
- Several discoveries since the first experimental evidence of neutrinos
- Fermilab has excellent program looking to answer the remaining questions in neutrino oscillations
- Long baseline program: measuring the three mixing angles, mass hierarchy and searching for CP violation
	- DUNE is making excellent progress with the detector prototypes and design
- The SBN detectors will perform a world-leading search for eV-scale sterile neutrino by looking at both appearance and disappearance channels
	- Rich physics program of neutrino-argon scattering measurements and BSM physics
	- SBND completed the construction of the detector and starting the commissioning
	- ICARUS is collecting physics quality data with Fermilab neutrino beams and making the first measurements

Neutrino Interactions from NuMI off axis at ICARUS

• Excellent statistics to make cross section measurements for quasi-elastic and pion production scattering, for both electron and muon neutrinos

Expected event rates for 1 year POINT RES and DIS are the dominant processes for DUNE.

SBND Detector

