Brookhaven National Laboratory

Neutrino Oscillations and Neutrino Beams

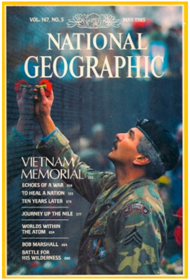
NuSTEAM/NuPUMAS, July 7-18, 2025
Brookhaven National Lab

Mary Bishai
Brookhaven National Laboratory

July 14^{th}, 2025

About Me https://www.bnl.gov/staff/mbishai

- **Born in Egypt, grew up Egypt/Nigeria**
- **1987-1989: Undergraduate at the American University in Cairo.**
- **1989-1991: B.A in Physics University of Colorado, Boulder**
- **1991-1998: Ph.D. in Experimental Particle Physics, Purdue University, Indiana, USA.**
- **1998-2004: Postdoc on the Collider Detector at Fermilab (CDF) experiment. Worked on silicon strip detectors, measurements of b-quark production (1000+ citations).**



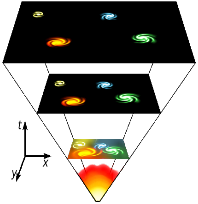
May 1985: inspired by "Worlds Within the Atom" National Geographic

- **2004-now: Staff scientist at BNL working on neutrino projects: MINOS, LBNE (Project Scientist), MicroBooNE, Daya Bay, DUNE**
- **2014: Elected Fellow of the American Physical Society**
- **Jan 2023 - April 2025: Elected co-spokesperson of DUNE experiment collaboration (1400 members, 36 countries)**

Introduction

Sources of Neutrinos

Big Bang

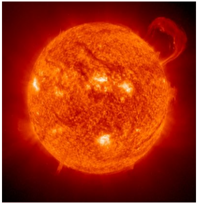


10^{-4} eV
$56/\text{cm}^3$

Reactors

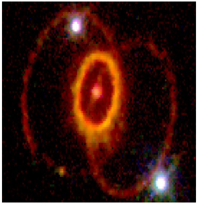
few MeV
$10^{21}/\text{GW}_{th}/\text{s}$

Sun



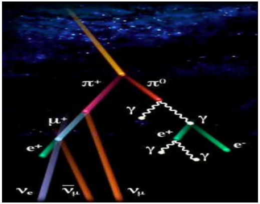
0.1-14 MeV
$10^{10}/\text{cm}^2/\text{s}$

SuperNova



$\sim$ 10 MeV
$10^{9}/\text{cm}^2/\text{s}$

Atmosphere



$\sim$ 1 GeV
$\text{few}/\text{cm}^2/\text{s}$

Accelerators

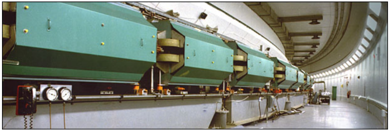
1-20 GeV
$10^{6}/\text{cm}^2/\text{s}/\text{MW}$ (at 1km)

Extragalactic

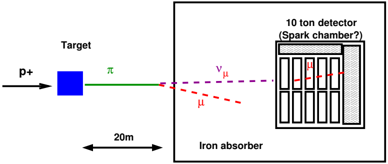
TeV-PeV
varies

Producing Neutrinos from an Accelerator

1962: Leon Lederman, Melvin Schwartz and Jack Steinberger use a proton beam from BNL's Alternating Gradient Synchrotron (AGS) to produce a beam of neutrinos using the decay $\pi \to \mu\nu_x$

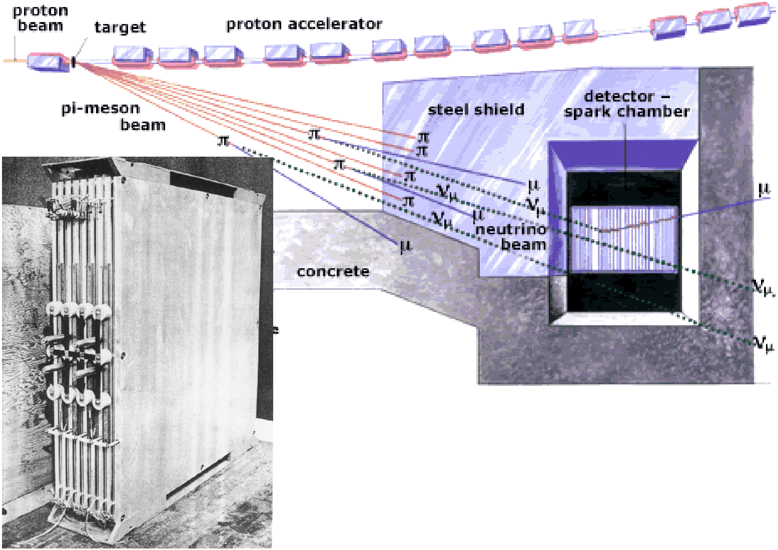


The AGS

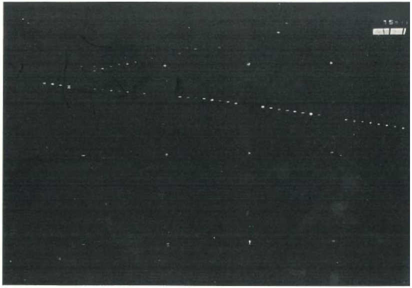


Making ν's

The Two-Neutrino Experiment

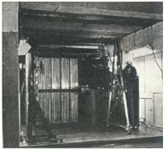


The Two-Neutrino Experiment



Neutrino Event

Columbia (Nevis)



BNL

Classification of "Events"

Single Tracks

p_μ < 300 MeV/c[a]	49
p_μ > 300	34
> 400	19
> 500	8
> 600	3
> 700	2
Total "single Muon Events"	34

Vertex Events

Visible Energy Released < 1 BeV	15
Visible Energy Released > 1 BeV	7
Total vertex events	22

"Shower" Events

Energy of "electron" = 200 ± 100 MeV	3
220	1
240	1
280	1
Total "shower events"[b]	6

a These are not included in the "event" count.

b The two shower events which are so located that their potential energy release in the chamber corresponds to muons of less than 300 MeV/c are not included here.

The first event!

The Two-Neutrino Experiment

Result: **40 neutrino interactions recorded in the detector, 6 of the resultant particles where identified as background and 34 identified as** $\mu \Rightarrow \nu_x = \nu_\mu$

The first successful accelerator neutrino experiment was at Brookhaven Lab.

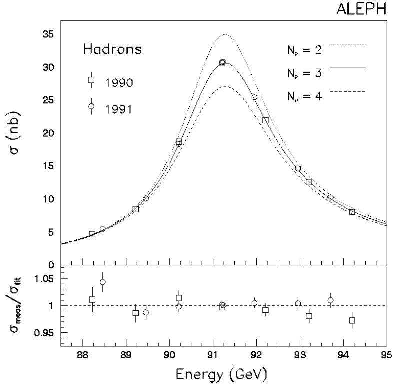
1988 NOBEL PRIZE

Number of Neutrino Flavors: Particle Colliders

1980's - 90's: The number of neutrino types is precisely determined from studies of Z^0 boson properties produced in e^+e^- colliders.

The LEP e^+e^- collider at CERN, Switzerland

The 27km LEP ring was reused to build the Large Hadron Collider



$N_\nu = 2.984 \pm 0.008$

Neutrino Mixing ⇒ Oscillations

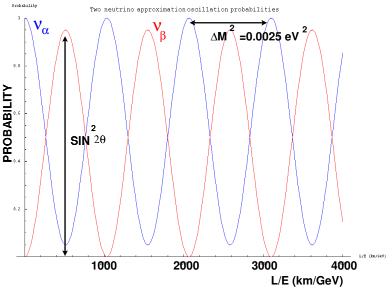
$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \to \nu_b) &= |<\nu_b|\nu_a(t)>|^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2 t} - e^{-iE_1 t}|^2 \end{aligned}$$

$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27\Delta m^2_{21} L}{E}$$

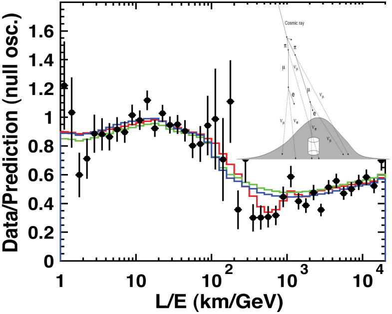
where $\Delta m^2_{21} = (m^2_2 - m^2_1)$ in eV^2, L (km) and E (GeV).

Observation of oscillations implies non-zero mass eigenstates



Two Different Mass Scales! $\Delta m^2(\mathrm{eV}^2) = \frac{1}{1.27}\frac{\pi}{2}\frac{E(\mathrm{GeV})}{L(\mathrm{km})}$

SuperKamkiokande (Japan), atmospheric ν_μ disappearance



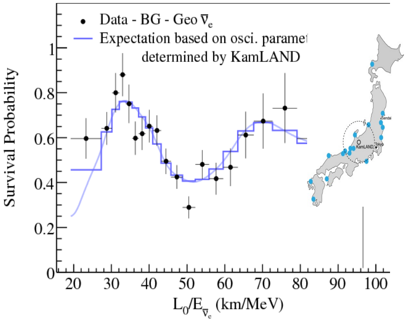
Global fit 2024:

$\Delta m^2_{\mathrm{atm}} =$

$\sin^2 2\theta_{\mathrm{atm}} = 0.986^{+0.047}_{-0.059}$

Atmospheric L/E $\sim$ 500 km/GeV

KamLAND (Japan), reactor $\bar{\nu}_e$ disappearance



Global fit 2024:

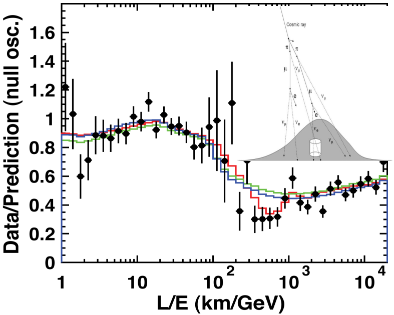
$\Delta m^2_{\mathrm{solar}} =$

$\sin^2 2\theta_{\mathrm{solar}} = 0.853^{+0.047}_{-0.044}$

Solar L/E $\sim$ 15,000 km/GeV

Two Different Mass Scales! $\Delta m^2(\mathrm{eV}^2) = \frac{1}{1.27}\frac{\pi}{2}\frac{E(\mathrm{GeV})}{L(\mathrm{km})}$

SuperKamkiokande (Japan), atmospheric ν_μ disappearance



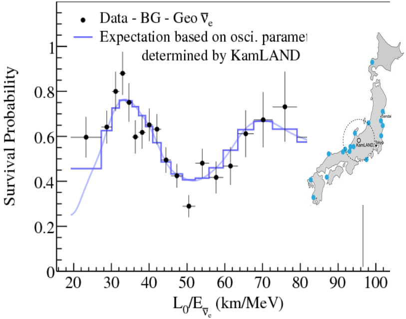
Global fit 2024:

$\Delta m^2_{\mathrm{atm}} = 2.534^{+0.025}_{-0.023} \times 10^{-3}\ \mathrm{eV}^2$

$\sin^2 2\theta_{\mathrm{atm}} = 0.986^{+0.047}_{-0.059}$

Atmospheric L/E ∼ 500 km/GeV

KamLAND (Japan), reactor $\bar{\nu}_e$ disappearance



Global fit 2024:

$\Delta m^2_{\mathrm{solar}} = 7.49^{+0.19}_{-0.19} \times 10^{-5}\ \mathrm{eV}^2$

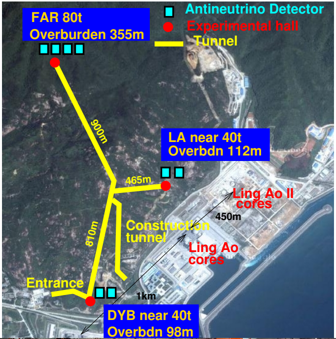
$\sin^2 2\theta_{\mathrm{solar}} = 0.853^{+0.047}_{-0.044}$

Solar L/E ∼ 15,000 km/GeV

Different oscillation scales ⇒ 3 ν masses

Daya Bay Reactor $\bar{\nu}_e$ Disappearance Experiment Fun

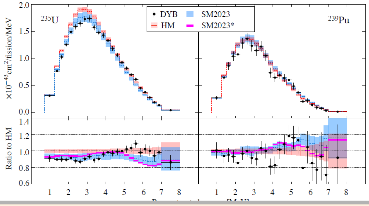
Fact: $\sim$ 5% of the energy emitted from a nuclear reactor is $\bar{\nu}_e$



Daya Bay reactors, China: 17.4 GW$_{th}$

231 collaborators from 6 countries

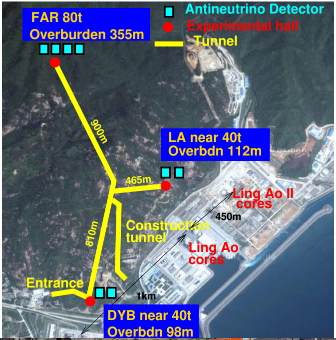
41 instutions (17 US)

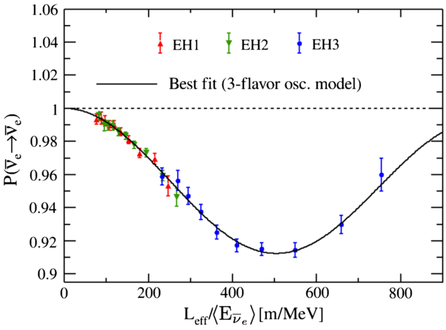


Jan 1, 2025: **Using $\sim$ 5 million neutrino interactions in the near detectors, precise measurement of reactor antineutrino spectrum with (1.3%,3%,8%) uncertainties from (all,^{235}U,^{239}P) fissile isotopes** *thus reaching the best precision in the world. (see Chao Zhang's talk!)*

Daya Bay Reactor $\bar{\nu}_e$ Disappearance Experiment

Fact: $\sim$ 5% of the energy emitted from a nuclear reactor is $\bar{\nu}_e$

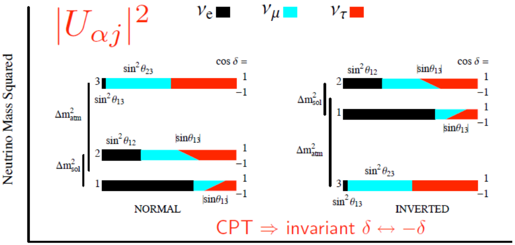




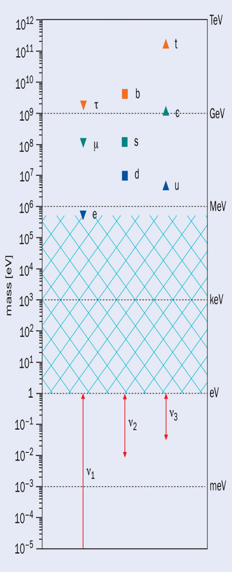
Measurement of the 3rd and smallest mixing amplitude: latest most precise result (2020):

$$\sin^2 2\theta_{13} = 0.0856 \pm 0.003$$

Neutrino Mixing: 3 flavors, 3 amplitudes, 2 mass scales



Fractional Flavor Content varying cos δ



3 quantum states interfering ⇒ phase δ (unknown)

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Neutrino Oscillation Scales

The mass-squared differences Δm^2_{21} (solar), Δm^2_{32} (atmospheric) and $\Delta m^2_{sterile} = 1 eV^2$ (LSND?) drive very different experimental scales. The location of the oscillation maxima occur at

$$
\begin{aligned}
L/E^{\nu}_n &= (2n-1)\frac{\pi}{2}\frac{1}{(1.267 \times \Delta m^2\ (\mathrm{eV}^2))} \\
&\approx (2n-1) \times 1\ \mathrm{km/GeV(m/MeV)\ for}\ \Delta m^2_{43}\ \mathrm{(LSND)} \\
&\approx (2n-1) \times 500\ \mathrm{km/GeV(m/MeV)\ for}\ \Delta m^2_{32}\ \mathrm{(atmos.)} \\
&\approx (2n-1) \times 15,000\ \mathrm{km/GeV(m/MeV)\ for}\ \Delta m^2_{21}\ \mathrm{(solar)}
\end{aligned}
$$

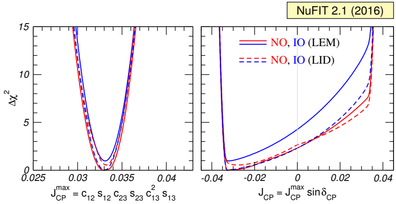
where E^{ν}_n is the neutrino energy at the maximum of oscillation node n.

Oscillations of GeV (MeV) scale neutrinos over distances from 1 - 15,000 km (m) probe 3x3 PMNS parameters and beyond. High energy particle accelerators operate at the GeV scale while reactors generate neutrinos at the MeV scale.

CP Violation in PMNS (leptons) and CKM (quarks)

In 3-flavor mixing the degree of CP violation is determined by the Jarlskog invariant:

$$J_{CP}^{\rm PMNS} \equiv \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos \theta_{13} \sin \delta_{\rm CP}.$$



(JHEP 11 (2014) 052, arXiv:1409.5439)

Given the current best-fit values of the ν mixing angles :

$$J_{CP}^{\rm PMNS} \approx 3 \times 10^{-2} \sin \delta_{\rm CP}.$$

For CKM (mixing among the 3 quark generations):

$$J_{CP}^{\rm CKM} \approx 3 \times 10^{-5},$$

despite the large value of $\delta_{CP}^{\rm CKM} \approx 70°$.

$\nu_\mu \rightarrow \nu_e$ Oscillations in the 3-flavor ν SM

In the ν 3-flavor model matter/anti-matter asymmetries in neutrinos are best probed using $\nu_\mu/\bar{\nu}_\mu \rightarrow \nu_e/\bar{\nu}_e$ oscillations (or vice versa). With terms up to second order in $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31} = 0.03$ and $\sin^2\theta_{13} = 0.02$, (M. Freund. Phys. Rev. D 64, 053003):

$$P(\nu_\mu \rightarrow \nu_e) \cong P(\nu_e \rightarrow \nu_\mu) \cong \underbrace{P_0}_{\theta_{13}} + \underbrace{P_{\sin\delta}}_{\text{CP violating}} + \underbrace{P_{\cos\delta}}_{\text{CP conserving}} + \underbrace{P_3}_{\text{solar oscillation}}$$

where **for oscillations in vacuum:**

$$P_0 = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(\Delta),$$

$$P_{\sin\delta} = \alpha\, 8J_{cp}\sin^3(\Delta),$$

$$P_{\cos\delta} = \alpha\, 8J_{cp}\cot\delta_{\mathrm{CP}}\cos\Delta\sin^2(\Delta),$$

$$P_3 = \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2(\Delta),$$

where $\Delta = 1.27\Delta m^2_{31}(eV^2)L(km)/E(GeV)$

For $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, $\underbrace{P_{\sin\delta} \rightarrow -P_{\sin\delta}}_{\text{CP asymmetry}}$,

$\nu_\mu \to \nu_e$ Oscillations in the 3-flavor ν SM

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where **for oscillations in matter with constant density:**

$$P_0 = \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(A-1)^2}\sin^2[(A-1)\Delta],$$

$$P_{\sin\delta} = \alpha\frac{8J_{cp}}{A(1-A)}\sin\Delta\sin(A\Delta)\sin[(1-A)\Delta],$$

$$P_{\cos\delta} = \alpha\frac{8J_{cp}\cot\delta_{CP}}{A(1-A)}\cos\Delta\sin(A\Delta)\sin[(1-A)\Delta],$$

$$P_3 = \alpha^2\cos^2\theta_{23}\frac{\sin^2 2\theta_{12}}{A^2}\sin^2(A\Delta),$$

where $\Delta = 1.27\Delta m^2_{31}(eV^2)L(km)/E(GeV)$ and $A = \sqrt{2}G_F N_e 2E/\Delta m^2_{31}$.

$$\text{For } \bar{\nu}_\mu \to \bar{\nu}_e, \underbrace{P_{\sin\delta} \to -P_{\sin\delta}}_{\text{CP asymmetry}}, \quad \underbrace{A \to -A}_{\text{matter asymmetry}}$$

Expected Appearance Signal Event Rates

ν Exercise: The total number of electron neutrino appearance events expected for a given exposure from a muon neutrino source as a function of baseline is given as

$$N^{\text{appear}}_{\nu_e}(L) = \int \Phi^{\nu_\mu}(E_\nu, L) \times P^{\nu_\mu \to \nu_e}(E_\nu, L) \times \sigma^{\nu_e}(E_\nu) dE_\nu$$

Assume the neutrino source produces a flux that is constant in energy and using only the dominant term in the probability(no matter effect)

$$\begin{aligned} \Phi^{\nu_\mu}(E_\nu, L) &\approx \frac{C}{L^2}, \quad C = \text{number of } \nu_\mu/\text{m}^2/\text{GeV}/\text{sec at 1 km} \\ P^{\nu_\mu \to \nu_e}(E_\nu, L) &\approx \underbrace{\sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(1.27\Delta m^2_{31} L/E_\nu)}_{P_0} \\ \sigma^{\nu_e}(E_\nu) &= 0.7 \times 10^{-42}(\text{m}^2/\text{GeV}/N) \times E_\nu, \quad E_\nu > 1 \text{ GeV} \end{aligned}$$

Prove that the rate of ν_e appearing integrated over a constant range of L/E is independent of baseline for $L > 500$ km!

Expected Appearance Signal Event Rates

$$N^{\text{appear}}_{\nu_e}(L) \propto \text{constant term} \times \int \frac{\sin^2(ax)}{x^3}dx,$$

$$x \equiv L/E_\nu, \;\; a \equiv 1.27\Delta m^2_{31} \text{ GeV}/(\text{eV}^2.\text{km})$$

ν Exercise:

$C \approx 1 \times 10^{17}\ \nu_\mu/\text{m}^2/\text{GeV}/\text{yr}$ at 1 km (from 1MW accelerator)
$\sin^2 2\theta_{13} = 0.084$, $\sin^2\theta_{23} = 0.5$, $\Delta m^2_{31} = 2.4 \times 10^{-3}\text{eV}^2$

Calculate the rate of ν_e events observed per kton of detector integrating over the region $x = 100$ km/GeV to 2000 km/GeV. Use your favorite program to do the integral!

Expected Appearance Signal Event Rates

$$N_{\nu_e}^{\mathrm{appear}}(L) \propto \text{constant term} \times \int \frac{\sin^2(ax)}{x^3} dx,$$

$$x \equiv L/E_\nu, \;\; a \equiv 1.27 \Delta m^2_{31} \; \mathrm{GeV/(eV^2.km)}$$

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Calculate the rate of ν_e events observed per kton of detector integrating over the region $x = 100$ km/GeV to 2000 km/GeV. Use your favorite program to do the integral!

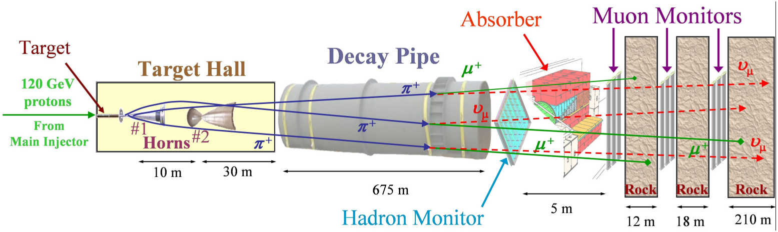
$$N_{\nu_e}^{\mathrm{appear}}(L) \approx (2 \times 10^6 \mathrm{events/kton/yr}) \cdot (\mathrm{km/GeV})^2 \int_{x_0}^{x_1} \frac{\sin^2(ax)}{x^3} dx,$$

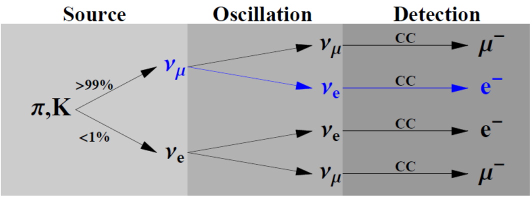
$$N_{\nu_e}^{\mathrm{appear}}(L) \sim \mathcal{O}(20 - 30) \; \mathrm{events/kton/yr}$$

Neutrinos from Accelerators: Decay-in-flight

Conventional Muon Neutrino Beams

High power conventional neutrino beams (NuMI):





Neutrinos from Accelerators

To produce neutrinos from accelerators

$p^+ + A \rightarrow \pi^\pm + X, \quad \pi^\pm \rightarrow \mu^\pm + \nu_\mu/\bar{\nu}_\mu$

where A = Carbon (Graphite), Berillyium, Tungsten, X is other particles

ν Exercise: The Main Injector accelerator at Fermilab produces 4.86×10^{13} 120 GeV protons in a 10 microsecond pulse every 1.33 seconds to the NuMI beamline. What is the average power of the proton beam delivered in megawatts?

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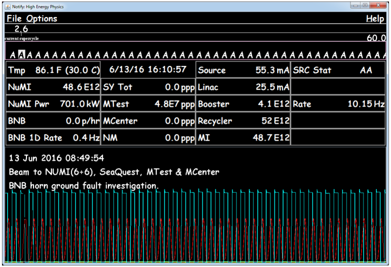
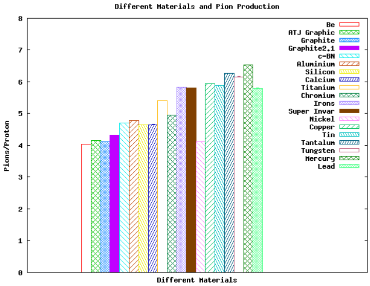
ν **Exercise:** The Main Injector accelerator at Fermilab produces 4.86×10^{13} 120 GeV protons in a 10 microsecond pulse every 1.33 seconds to the NuMI beamline. What is the average power of the proton beam delivered in megawatts?

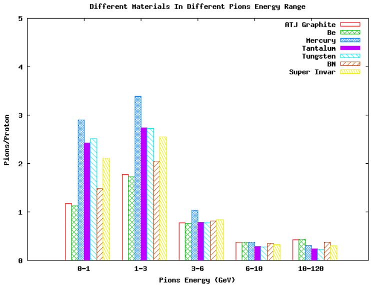
Power = 120 GeV $\times$ 4.86 10^{13} protons $\times$ 1.6 10^{-10} Joules/GeV $\times$ 1/1.33s = 702 kW



Decay-in-flight beams: Fundamentals

The result of a FLUKA (http://www.fluka.org/fluka.php) simulation of pion production from 120 GeV protons is shown below





ν **Exercise:** **What fraction of 6 GeV pions on average will decay before reaching the end of an evacuated pipe 200m (675m) long? The π^+ rest mass and lifetime are 140 MeV and 26 ns**

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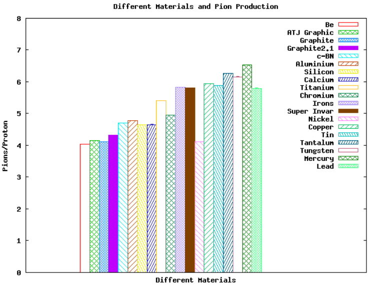
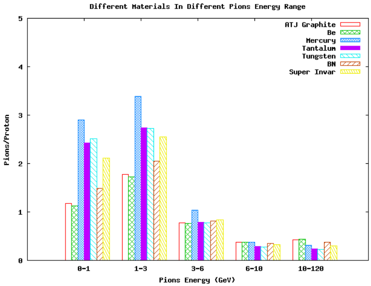


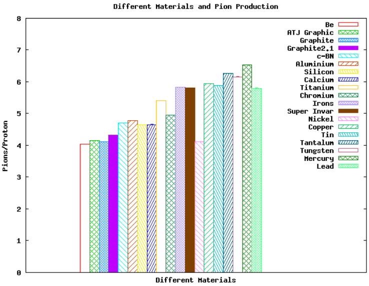


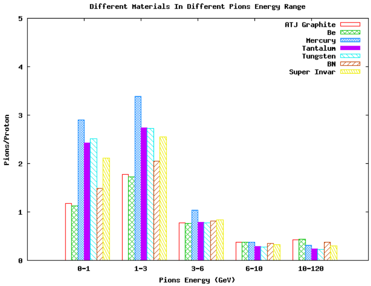
ν Exercise: What fraction of 6 GeV pions on average will decay before reaching the end of an evacuated pipe 200m (675m) long? The π^+ rest mass and lifetime are 140 MeV and 26 ns

6 GeV π^+ lifetime: $\tau = \gamma\tau_0 = \frac{E}{m_0 c^2} \times 26\text{ns} = 1.1\mu\text{s}$, $c\tau = 334$ m

Decay-in-flight beams: Fundamentals

The result of a FLUKA (`http://www.fluka.org/fluka.php`) simulation of pion production from 120 GeV protons is shown below



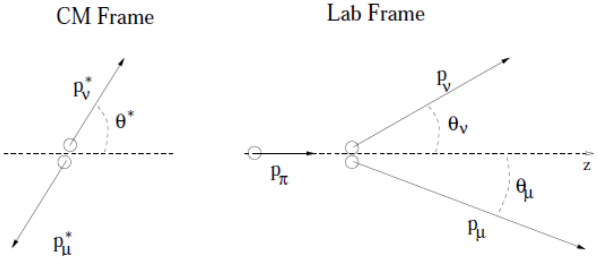


ν **Exercise: What fraction of 6 GeV pions on average will decay before reaching the end of an evacuated pipe 200m (675m) long? The π^+ rest mass and lifetime are 140 MeV and 26 ns**

6 GeV π^+ lifetime: $\tau = \gamma\tau_0 = \frac{E}{m_0 c^2} \times 26\text{ns} = 1.1\mu\text{s}$, $c\tau = 334$ m

$$F_{decays} = (1 - \exp^{-l/c\tau}) = 0.45(0.87)$$

Pion Decay-in-Flight (DIF) beams: kinematics



ν Exercise: **Solve the $\pi/K \rightarrow \mu\nu$ two body decay for high energy pions and Kaons ($E_{\pi,K} >> m_{\pi,K}$) and show that the energy of the neutrino E_ν and the probability that a neutrino is emited withn a solid angle $dP/d\Omega$ can be approximated as follows:**

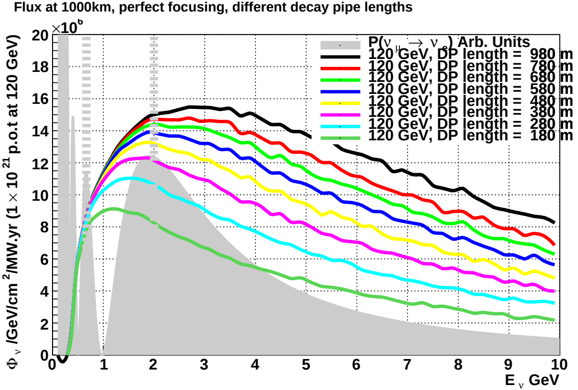
$$E_\nu = \frac{\left(1 - \frac{m_\mu^2}{m_{\pi,K}^2}\right) E_{\pi,K}}{1 + \gamma^2\theta_\nu^2}, \quad \frac{dP}{d\Omega} \sim \frac{1}{4\pi}\left(\frac{2\gamma}{1+\gamma^2\theta_\nu^2}\right)^2$$

Assume $\theta_\nu << 1$

Neutrino fluxes with perfect focusing

ν_μ fluxes from pion decay-in-flight (DIF) beams assuming perfect focusing and charge selection:

120 GeV, decay channel lengths from 200m to 1km

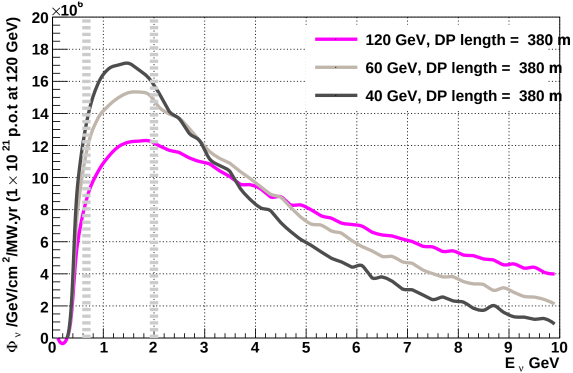


Gain with longer decay channels, BUT excavation is challenging/expensive

Neutrino fluxes with perfect focusing

ν_μ fluxes from pion decay-in-flight (DIF) beams assuming perfect focusing and charge selection:

40 to 120 GeV, decay channel length = 400m

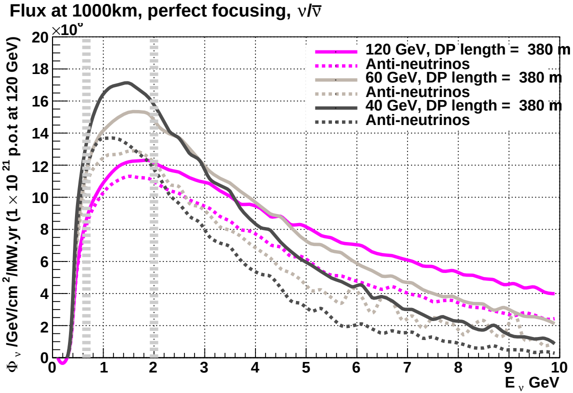


Lower energy flux benefits at lower P beam energy BUT only at constant power = more protons.

Neutrino fluxes with perfect focusing

ν_μ fluxes from pion decay-in-flight (DIF) beams assuming perfect focusing and charge selection:

Neutrino vs anti-neutrino fluxes

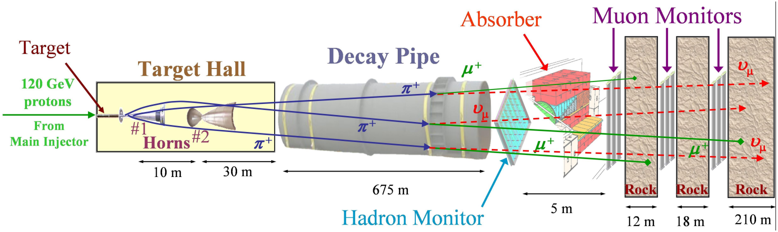


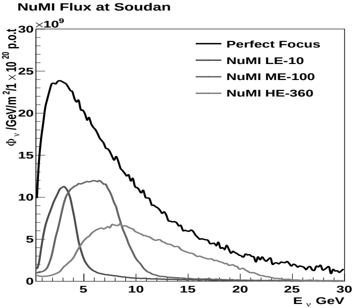
$\bar{\nu}/\nu$ fluxes are more favorable at higher proton beam energies.

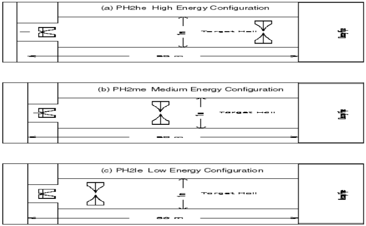
Examples of Neutrino decay-in-flight Beamlines

Examples of Conventional Neutrino Beams

Multi-GeV, on-axis, tunble beams: NuMI





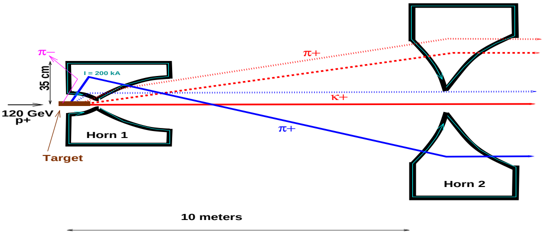


H1-H2: LE=10m, ME=23m, HE=40m

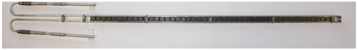
Target z_0 = -35cm from H1

Examples of Conventional Neutrino Beams

NuMI Focusing System Details



NuMI Target



6.4 x 15 mm^2 graphite segments. 1m long = 1.9 interaction lengths. $\mathcal{O}$(10) KW beam power at 1 mm beam width. Water cooled.

Horn 1

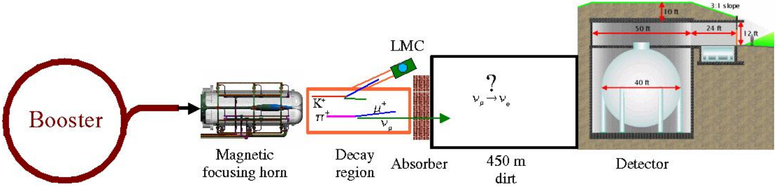
Horn 2

Parabolic magnetic lens. 3T at 200 kA

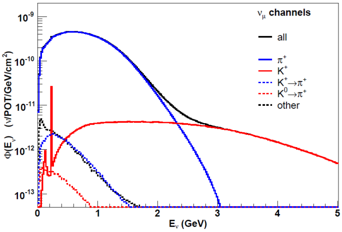
Examples of Conventional Neutrino Beams

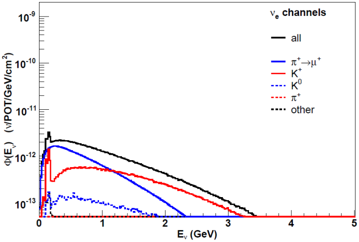
sub-GeV on-axis Beams: Booster Neutrino Beam

8 GeV proton, Be target l=71cm, 174 kA pulsed horn (1).



ν_μ Flux	ν_e Flux

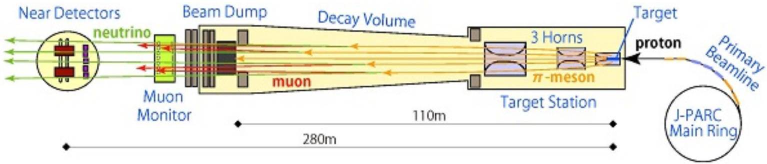




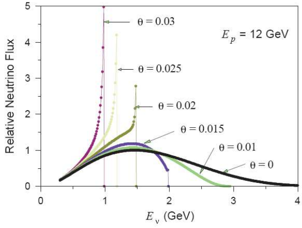
Examples of Conventional Neutrino Beams

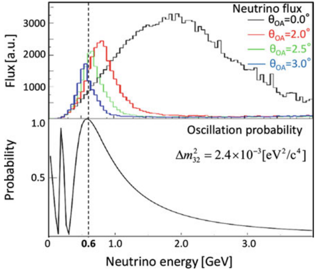
Off-axis beams: JPARC Neutrino Beam

30 GeV proton, C target l=90cm, 250-320 kA pulsed horns (3)

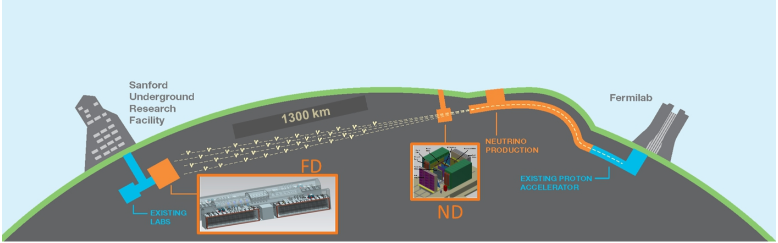


First proposed for BNL E-889 (1995): A narrow beam of ν_μ can be achieved by going off-axis to the π beam. More flux at sub-GeV.



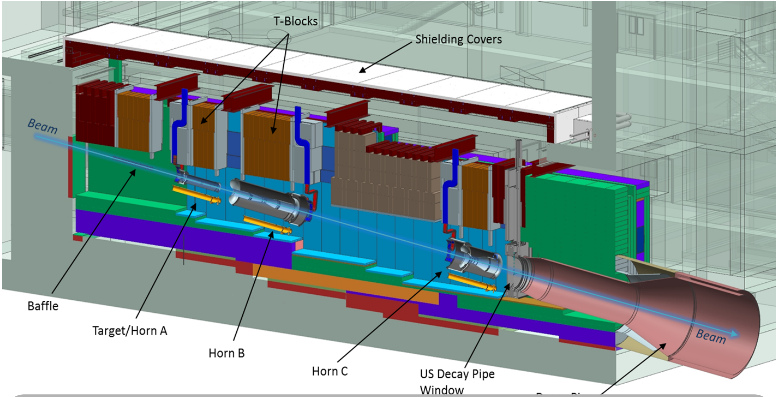


The Deep Underground Neutrino Experiment



- **A very long baseline experiment: 1300km from Fermilab in Batavia, IL to the Sanford Underground Research Facility (former Homestake Mine) in Lead, SD.**
- **A highly capable near detector at Fermilab.**
- **A very deep (1 mile underground) far detector: massive 40-kton Liquid Argon Time-Projection-Chamber with state-of-the-art instrumentation.**
- **High intensity *tunable* wide-band neutrino beam from LBNF produced from upgraded MW-class proton accelerator at Fermilab.**

LBNF/DUNE Beamline Target Hall Design



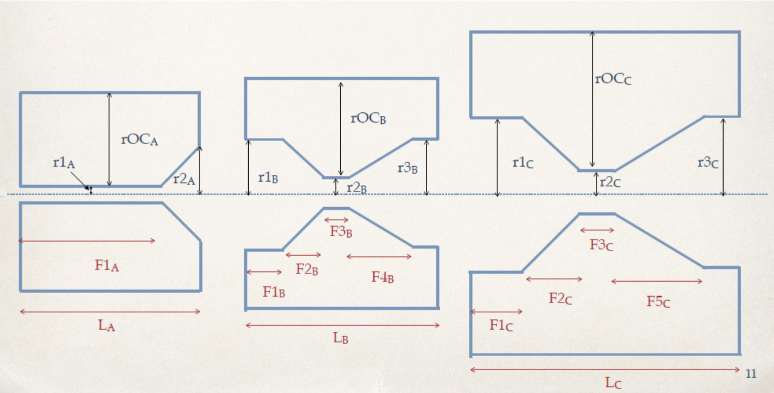
A Genetic Algorithim was used to optimized the target and focusing system design to maximize CP violation sensitivity. The focusing system is 3 horns operated at $\sim$ 300 kA with a 2.3m long graphite target inserted into the first horn. $\approx$ 40% of beam power is deposited in target hall shielding!

Optimization of beamline designs: DUNE/LBNF beam

- **The 2015 reference design for LBNF/DUNE was a NuMI-like movable target (segmented rectangular graphite fins with water cooling $\approx$ 1m long) and 2 modified NuMI horns 6.6m apart**
- **In Sep 2017 LBNF adopted a focusing design with 3 horns optimized using a *genetic algorithim* with the physics parameter to be measured (CPV sensitivity) used to gauge fitness.**
- **Target geometry is optimized at the same time, as well as proton beam energy with realistic Main Injector power profile (1.03 MW at 60 GeV to 1.2 MW at 120 GeV).**
- **Limits on horn current, diameter and length are imposed based on experience with T2K and NuMI horn manufacturing**
- **Limits on horn separation imposed based on size of target chase.**

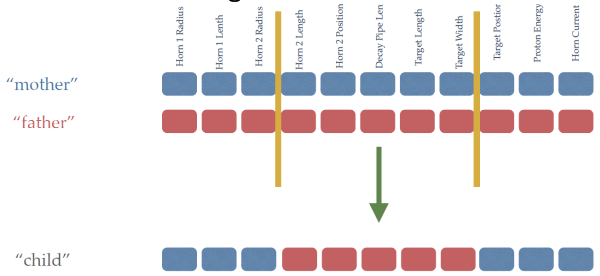
Optimization of beamline designs: DUNE/LBNF beam

Horn parameters used in GEANT4 simulation for GA optimization:



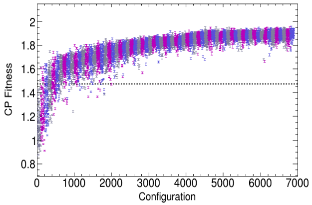
Optimization of beamline designs: DUNE/LBNF beam

Schematic of the Genetic Algorithim:



CP Fitness = minimum significance with which 75% of δ_{cp} can be determined $\neq 0$ or π for a given exposure

Fast CP Fitness estimator was determined by calculating the change in CP sensitivity given some fixed change in a single energy bin.



CP Fitness vs configuration

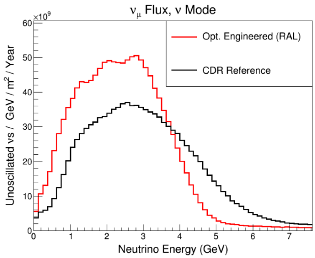
Optimization of beamline designs: DUNE/LBNF beam

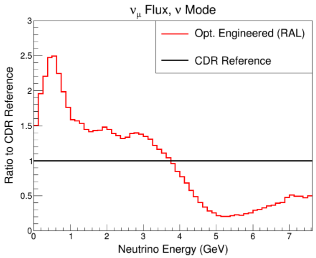
Optimized horn design with 297kA current :

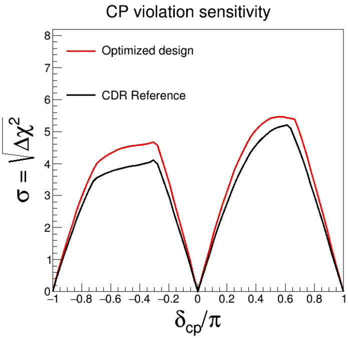
Parameter	Value		Parameter	Value
Horn A Length (mm)	2218		Horn A F1 (% of length)	53
Horn A R1 (mm)	43		Horn A OC Radius (mm)	369
Horn A R2 (mm)	33			
Horn B Length (mm)	3932		Horn C Length (mm)	2184
Horn B R1 (mm)	159		Horn C R1 (mm)	284
Horn B R2 (mm)	81		Horn C R2 (mm)	131
Horn B R3 (mm)	225		Horn C R3 (mm)	362
Horn B F1 (% of length)	31		Horn C F1 (% of length)	20
Horn B F2 (% of length)	22		Horn C F2 (% of length)	9
Horn B F3 (% of length)	2		Horn C F3 (% of length)	7
Horn B F4 (% of length)	16		Horn C F4 (% of length)	35
Horn B OC Radius (mm)	634		Horn C OC Radius (mm)	634
Horn B Position (mm)	2956		Horn C Position (mm)	17806

Optimized target is 4λ (2m C) with $\sigma_{\text{beam}} = 2.7$mm, $E_p \sim 110$ GeV

Optimization of beamline designs: DUNE/LBNF beam





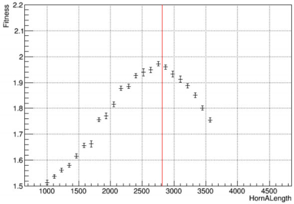


Computationally advanced optimization techniques = significant gain in flux and CPV sensitivity from *many* small changes

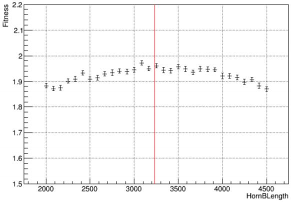
> **Gain in sensitivity ≡ 70% increase in FD mass**

Optimization of beamline designs: DUNE/LBNF beam

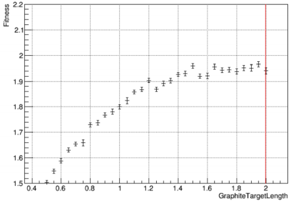
Scan over some sample optimization parameters:



Horn A length



Horn B length

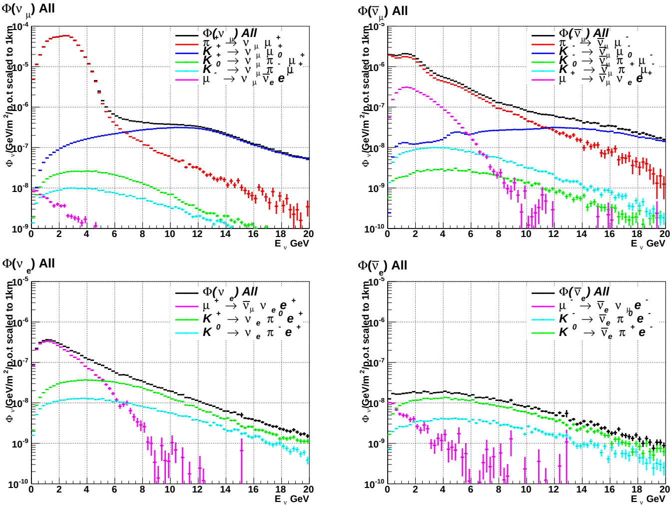


Target length

DIF Flux Estimation and Uncertainties in Long-Baseline Experiments

LBNF/DUNE Flux components at near and far

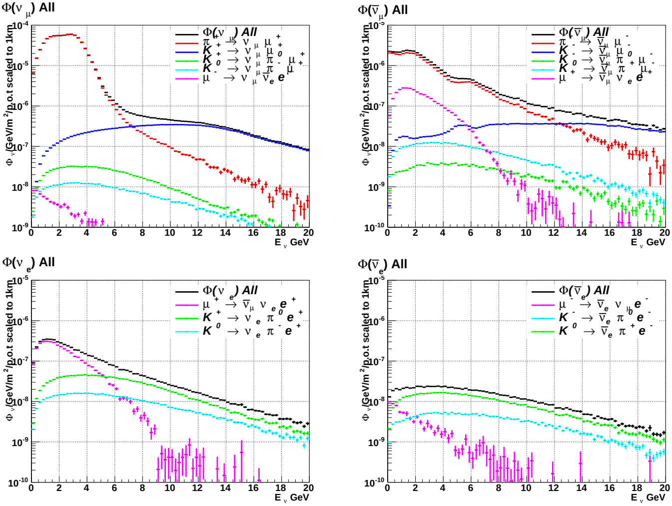
ND 570



Baseline scaled to 1km from middle of decay channel

LBNF/DUNE Flux components at near and far

FD 1300km



Baseline scaled to 1km from middle of decay channel

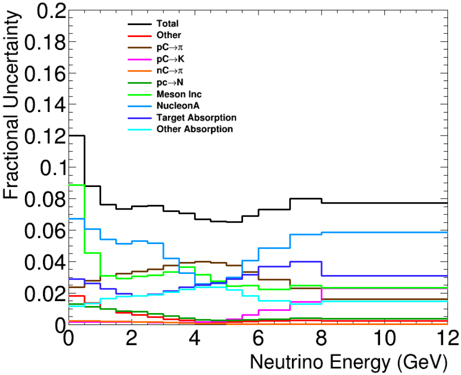
Flux Modeling Uncertainties at ND

The main sources of flux modeling uncertainties are:

- **Hadron production uncertainties: driven by uncertainities in the hadron interaction models used to estimate hadron distributions exiting the target (prior to focusing) as well as secondary and tertiary interactions of hadrons with beamline material. Fully evaluated for LBNF/DUNE using the ppfx package developed for MINERνA.**
- **Focusing uncertainties: Dominated by horn material, geometry and magentic field modeling as well as target geometry and density. Alignment of the neutrino beamline elements can also have large impact on ν flux. Includes proton counting uncertainities. These uncertainties are assessed by simulating individual effects in Geant 4 and combining.**
- **Other beamline uncertainties: Primarily uncertainties on the distribution of passive material in the beamline: for e.g. impact of Nitrogen in the target chase, decay pipe window thickness...etc. Experience with NuMI indicates these are subdominant**

Flux Modeling Uncertainties at ND

L. Fields and A. Bashyal

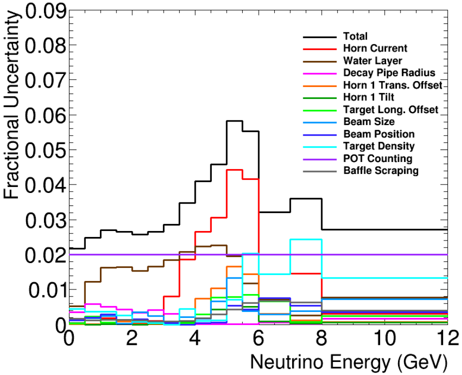


Hadron Prod. Uncertainties

NA49/MIPP/older datasets used to constrain $pC \rightarrow \pi^{\pm}, K^{\pm}, n(p)X$

Pion production by neutrons from data (assuming isospin symmetry)

Nucleon incident interactions not covered by data

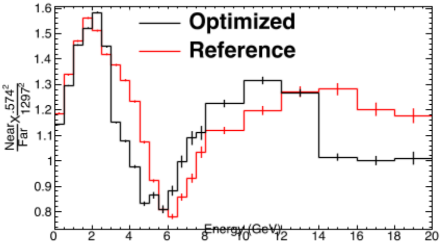


Focusing Uncertainties

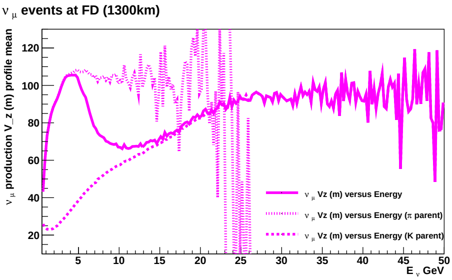
Detailed focusing uncertainties based on the NuMI experience in MINERνA. Detailed estimates for both 2015 NuMI-like design and CPV optimized design with simplified 2 horns.

Near to Far Extrapolation

Simple ratio of near spectrum/far spectrum:



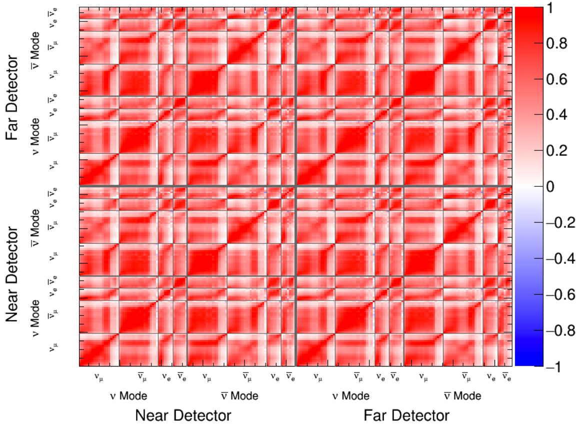
Neutrino parent decay location in decay pipe:



π/K decay kinematics and decay channel geometry are primary reason for strange shape of N/F ratio

Near to Far Extrapolation

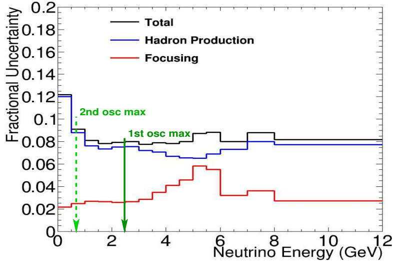
To correctly relate near to far fluxes - need to use a correlation matrix:



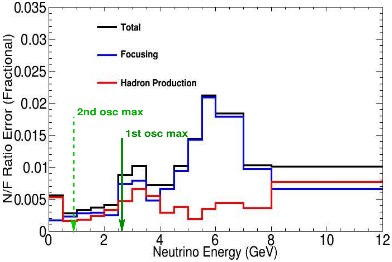
Flux correlation matrix comes from simulation and is highly correlated

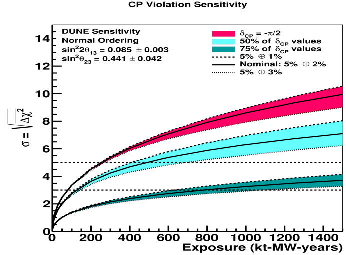
FD Flux Determination Uncertainities

Uncertainty on FD flux prediction



Residual uncertainty on flux at FD



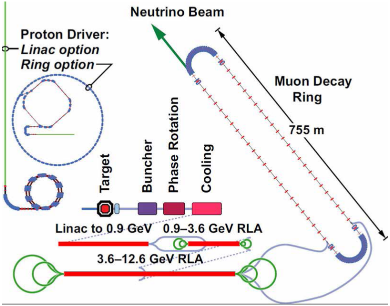


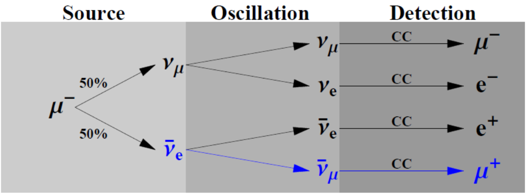
How well do we actually trust the simulation to correctly estimate the uncertainties on near → far extrapolation?

Muon decay-in-flight Beams and Neutrino Factories

Neutrino Factories/Muon Storage Rings

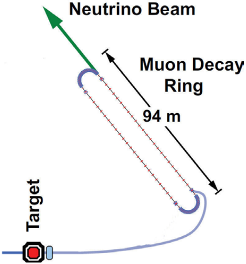
Long baseline experiments



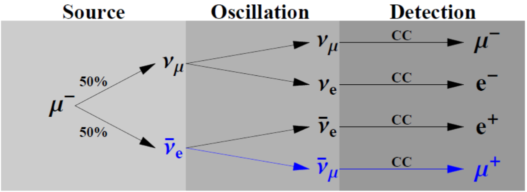


Neutrino Factories/Muon Storage Rings

Short baseline experiments



Neutrinos from STOred Muons (NuSTORM) @ CERN proposal:
https://cds.cern.ch/record/2654649?ln=en



Conventional Beams vs Neutrino Factories

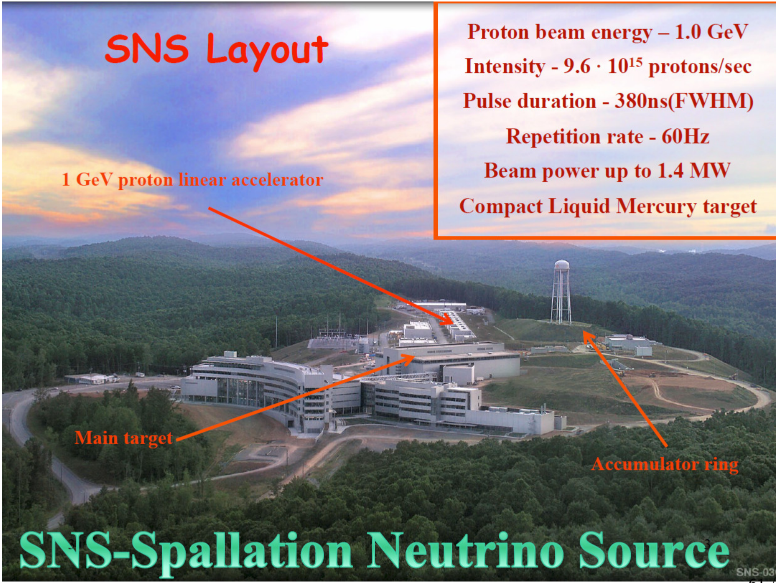
From A. Blondel et. al. NIM A 451 (2000) 102-122

	Conventional	Neutrino factory
Parents	π^+, K^+ or π^-, K^-	μ^- or μ^+
ν_μ beam	ν_μ	$\nu_\mu : \bar{\nu}_e = 1{:}1$
Background	$\sim 2\%$ of $\bar{\nu}_\mu$, $\sim 1\%$ of ν_e	none
$\bar{\nu}_\mu$ beam	$\bar{\nu}_\mu$	$\bar{\nu}_\mu : \nu_e = 1{:}1$
Background	$\sim 6\%$ of ν_μ, $\sim 0.5\%$ of $\bar{\nu}_e$	none
$\Delta E/E$ of neutrino energy	$\pm 10\%$	$< 1\%$
$\Delta R/R$ of neutrino radius	$\pm 10\%$	$< 1\%$
Neutrino flux uncertainty	$\pm 10\%$	$< 1\%$
ν_μ/cm^2 per year at 732 km	3×10^7 for 4.5×10^{19} 400 GeV/c p.o.t.	3×10^9 for 10^{21} injected 50 GeV/c μ

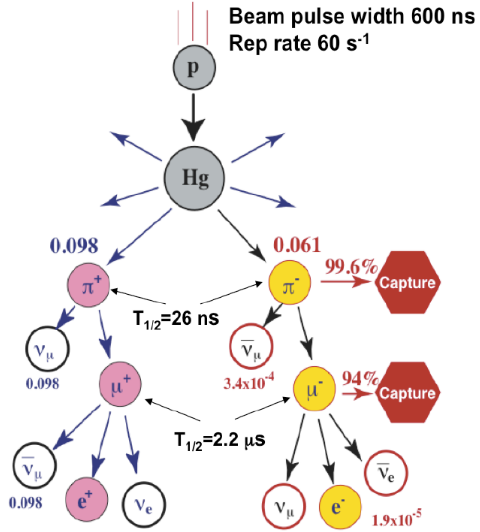
Neutrino factories technologically challenging - but best chance for probing $\nu_e \rightarrow \nu_\mu$ appearance Muon storage rings currently only viable for short baseline.

Neutrinos from Accelerators: Decay-at-rest

Spallation Neutron Source Pion decay-at-rest beams



Spallation Neutron Source Pion decay-at-rest beams

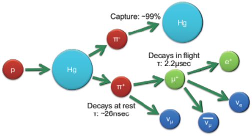


Decay-at-rest Kinematics

ν Exercise: At the SNS a π^+ will decay at rest to a μ^+ and a ν_μ. This is a two body decay which leads to a monochromatic beam of ν_μ. What is the energy of the ν_μ? Derive the two body formula for mass M decaying to $m_1 + m_2$ in the rest frame of M:

$$E_2 = \frac{M^2 + m_2^2 - m_1^2}{2M} \tag{1}$$

Decay-at-rest Kinematics



$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$ 2-body decay: monochromatic 29.9 MeV ν_μ PROMPT

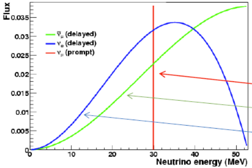
$$\downarrow$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$ 3-body decay: range of energies between 0 and $m_\mu/2$ DELAYED (2.2 μs)

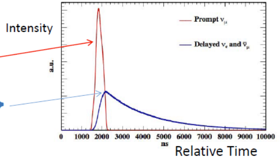
1 MW power for high ν flux

60 Hz timing protons on target (POT)

Produces sharply pulsed time structure for background rejection factor ~ 10^{-4}



Prompt ν_μ
delayed ν_μ–bar
delayed ν_e

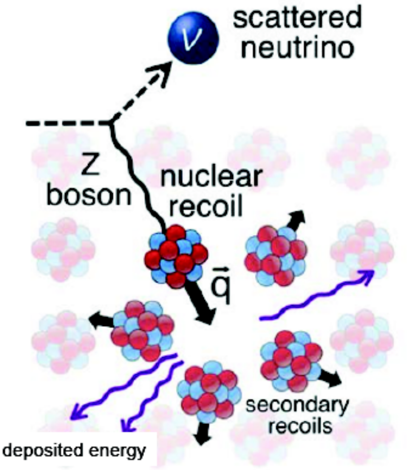


5

Measurement of Coherent ν-Nucleus Scattering

The only experimental signature:

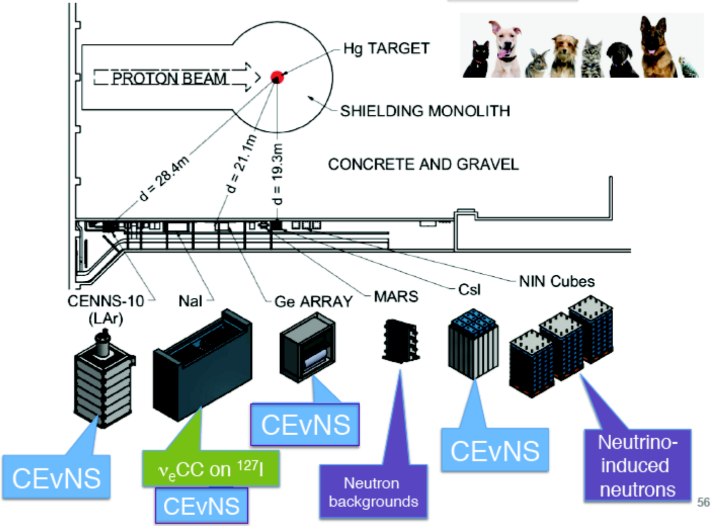
tiny energy deposited by nuclear recoils in the target material



The COHERENT Experiment and Proposed Upgrades

slides from K. Scholberg

Neutrino Alley Deployments: current & near future



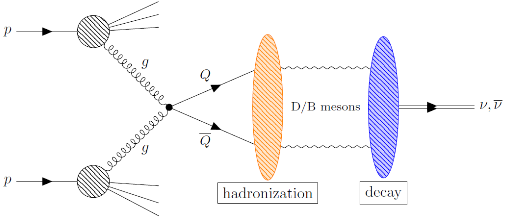
Neutrinos from colliding beams

Prompt neutrinos

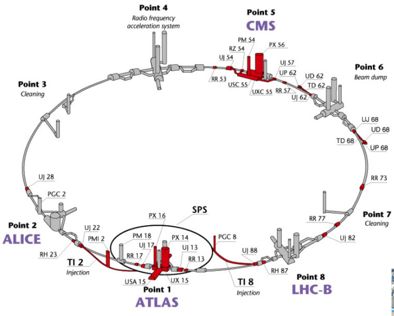
- In pp collision at the LHC, various hadrons are produced.
- A number of neutrinos are produced from subsequent decay of the secondary hadrons.

  e.g.) $\pi, K, D, B \ldots \rightarrow \nu + X$

- Neutrinos generated from the decay of charmed/bottom hadrons are called prompt neutrinos.

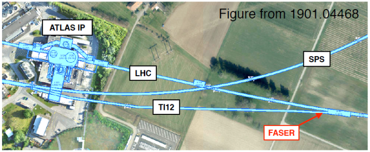


Possible sites for detection



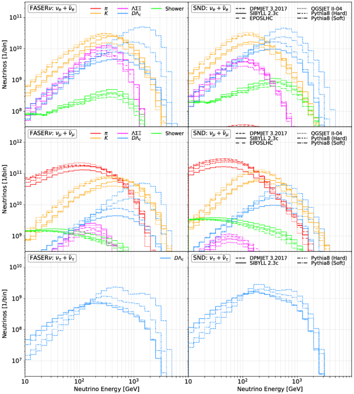
- Near CMS interaction point (IP)
  - 25 m from IP (quadruplet region)
  - 90 &120 m from IP (UJ53 & UJ57)
  - 240 m from IP (PR53 and PR57)
- Near ATLAS IP
  - 480 m from IP (TI18 and TI12)

Ref:1903.06564 (CMS note)
1901.04468 (FASER)



Forward Neutrinos from the LHC

The ForwArd Search ExpeRiment (FASERν) is an emulsion detector added to FASER an approved experiment dedicated to searching for light, extremely weakly interacting particles at the LHC located 480 m from the ATLAS interaction point. Calculations of forward neutrino fluxes at the LHC from arXiv 2105.08270:



Summary and Conclusions

Summary and Conclusions

- **High energy and high power proton accelerators can be used to generate neutrino beams of all 3 flavors ν_e, ν_μ, ν_τ with energies from 10's of MeV to multi-TeV**
- **High purity ν_μ GeV-scale neutrino beams from pion decay-in-flight are used by short and long-baseline experiments to study $\nu_\mu \to \nu_e$ oscillations**
- **Neutrino beams from pion decay-at-rest with energies of 10's MeV are used for measurements of coherent neutrino-nucleus scattering as well as searches for non-standard oscillations**
- **Neutirno beams from muon decay-in-flight produce equal numbers of ν_μ and ν_e and can be used to study $\nu_e \to \nu_\mu$ oscillations**
- **Far forward experiments at the LHC can study multi-TeV neutrino interactions and produce ν_τ beams**