Making Neutrino Beams - II

Neutrino Beam Flux Determination

International Neutrino Summer School 2021, Aug 2-13, CERN

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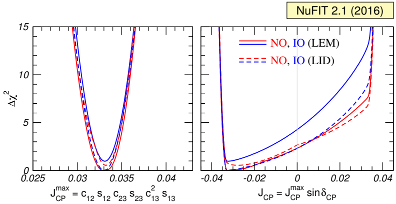
Neutrino Beams Contd: Long-Baseline Neutrino Experiment Fluxes and Event Rates

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

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

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



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

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

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

For CKM (mixing among the 3 quark generations):

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

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

$\nu_\mu \rightarrow \nu_e$ 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:**

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

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

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

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

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

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

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

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)

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

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

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

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

ν Exercise:

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

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 ROOT to do the integral!

Expected Appearance Signal Event Rates

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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 ROOT to do the integral!

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

$$N^{\mathbf{appear}}_{\nu_e}(L) \sim \mathcal{O}(20 - 30)\ \mathbf{events/kton/yr}$$

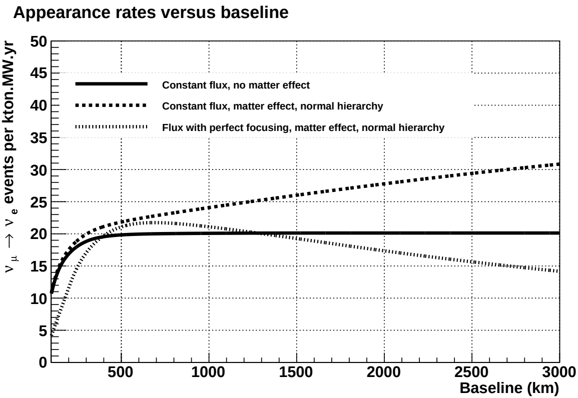
Event Rates vs. Baseline Perfect Focusing

$$\mathcal{R} = \int \Phi^{\nu_\mu}_{\text{perfect}}(E_\nu) \times \sigma(E_\nu) \times P(\nu_\mu \to \nu_e)\, dE_\nu$$

$(\sin^2 2\theta_{13} = 0.09, \sin^2 \theta_{23} = 0.5, \delta_{cp} = 0, |\Delta m^2_{31}| = 2.4 \times 10^{-3})$

Flux: 120 GeV, perfect focusing, ~ 400m decay channel, on-axis

Normal Hierarchy



How well can we focus/collect the pions?

Neutrino Event Rates - Superbeams vs νFactories

From arXiv:1307.7335, for 50 kton.years* of exposure:

		Super Beams		
Experiment	**Baseline**	$\nu_\mu \to \nu_\mu$	$\nu_\mu \to \nu_\tau$	$\nu_\mu \to \nu_e$
T2K **30 GeV, 750 kW** 9×10^{20} **POT/year**	**295km (off-axis)**	**900**	< 1	**40 - 70**
MINOS LE **120 GeV, 700 kW** 6×10^{20} **POT/year**	**735km**	**11,000**	**115**	**230-340**
NOνA **120 GeV, 700 kW** 6×10^{20} **POT/year**	**810km (off-axis)**	**1500**	**10**	**120 - 200**
LBNE (LBNF) LE **80 GeV, 1.2MW** 1.5×10^{21} **POT/year**	**1,300km**	**4300**	**160**	**350 - 600**
LBNE (LBNF) ME **80 GeV, 1.2MW** 1.5×10^{21} **POT/year**	**1,300km**	**12,000**	**690**	**290 - 430**

		ν Factory at Fermilab		
Experiment	**Baseline**	$\nu_\mu \to \nu_\mu$	$\nu_\mu \to \nu_\tau$	$\nu_e \to \nu_\mu$
NuMAX I **3 GeV, 1MW** 0.94×10^{20} μ/year **(no μ cooling)**	**1,300km**	**340**	**30**	**70 - 120**
NuMAX II **3 GeV, 3MW** 5.6×10^{20} μ/year	**1,300km**	**2000**	**300**	**420 - 700**

* **Facility duty factor taken into consideration**

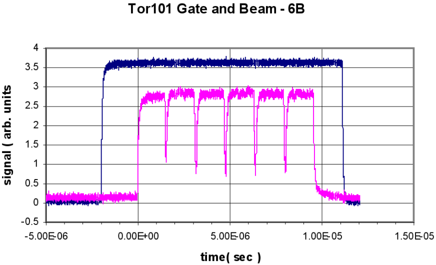
Measurements for DIF Flux Estimation and Uncertainties

Measuring the Beam Current and Position

In-situ measurements of proton intensity with high accuracy

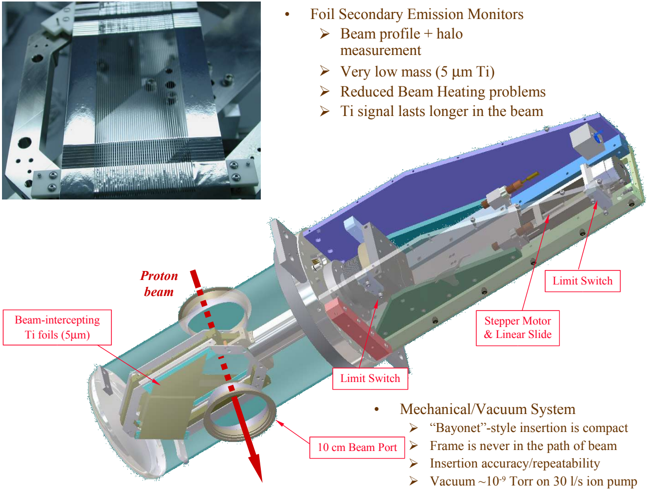
Characteristics of NuMI Beam P sition Monitors:

- **Software algorithm to searc 400 μsec to find the beam.**
- **NuMI bunches come in 6 batches from booster. Position is measured batch by batch.**
- **Linear over 15-20 mm. 50 μm accuracy in pretarget.**
- **11 vertical and 13 horizontal measurements over 360m.**



Feedback from BPMs used to auto-steer the beam to target center

Measuring the Beam Profile: NuMI



- Foil Secondary Emission Monitors
  - Beam profile + halo measurement
  - Very low mass (5 µm Ti)
  - Reduced Beam Heating problems
  - Ti signal lasts longer in the beam

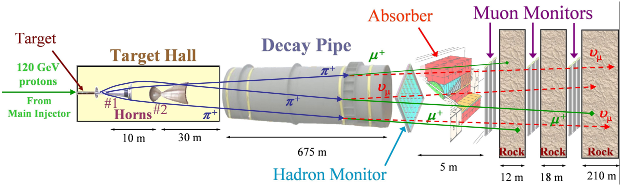
- Mechanical/Vacuum System
  - “Bayonet”-style insertion is compact
  - Frame is never in the path of beam
  - Insertion accuracy/repeatability
  - Vacuum ~10^{-9} Torr on 30 l/s ion pump

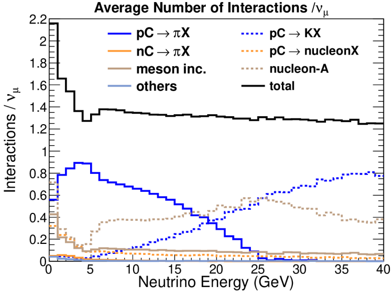
Beam profile at target needs to be measured

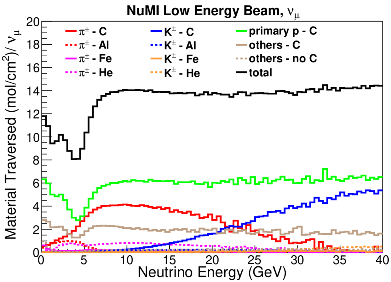
Hadron production in beamlines

The NuMI beam measured by MINERνA

120 GeV proton beam, graphite target l=95cm, 185 kA pulsed horns (2)



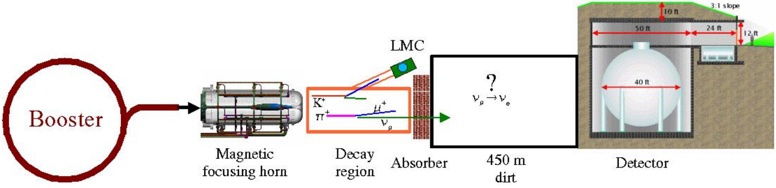




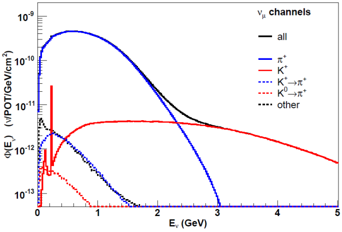
Hadron production in beamlines

Short baseline beams - sub-GeV: Booster Neutrino Beam

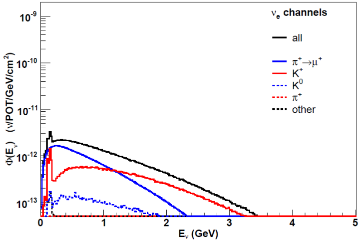
8 GeV proton, Be target l=71cm, 174 kA pulsed horn.



ν_μ Flux

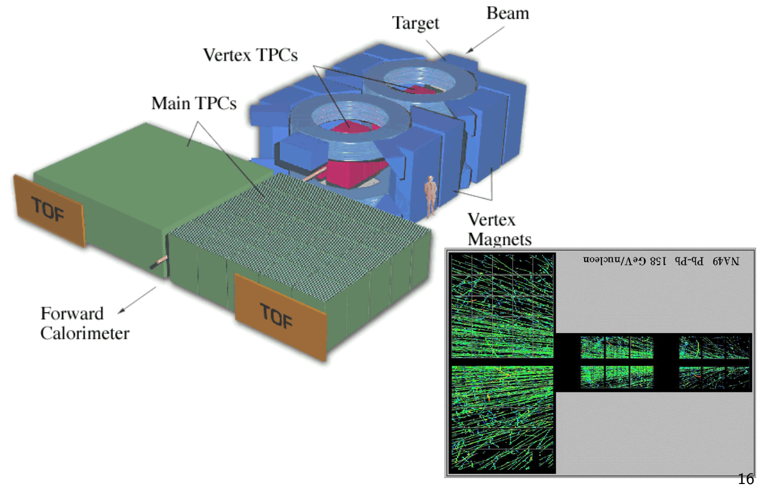


ν_e Flux

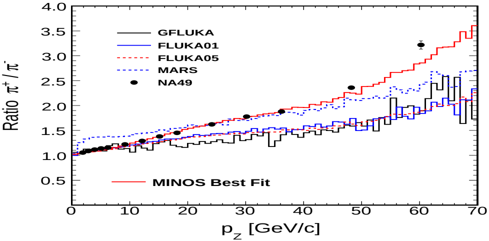


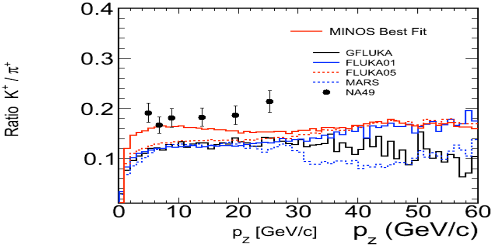
Hadron Production Experiments

Dedicated large acceptance hadron spectrometers are used to measure hadrons produced in p-p and p-A collisions on thin/thick targets. For example the NA49 experiment at CERN:



NuMI Beam Simulation and 158 GeV p-C NA49 Data

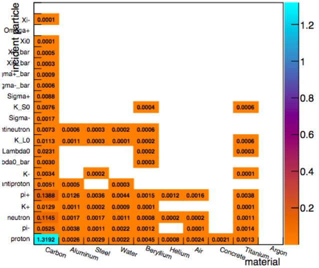




MC target hadron production must be constrained by external data.

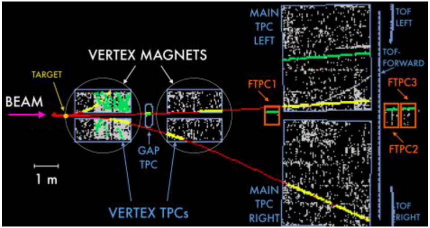
Ongoing program with NA61/SHINE

Measuring target hadron production for DUNE/T2K



incident particle	Carbon	Aluminum	Steel	Water	Beryllium	Helium	Air	Concrete	Titanium	Argon
Xi-	0.0001									
Omega+										
Xi0	0.0001									
Xi-_bar	0.0005									
Xi0_bar	0.0003									
ıma+_bar	0.0009									
gma-_bar	0.0006									
Sigma+	0.0088									
K_S0	0.0076				0.0004				0.0006	
Sigma-	0.0017									
ıtineutron	0.0073	0.0006	0.0003	0.0002	0.0006					
K_L0	0.0113	0.0011	0.0003	0.0001	0.0002				0.0006	
Lambda0	0.0231				0.0002				0.0003	
bda0_bar	0.0030				0.0003					
K-	0.0034		0.0002						0.0001	
ıntiproton	0.0051	0.0005		0.0003						
pi+	0.1388	0.0126	0.0036	0.0044	0.0015	0.0012	0.0016		0.0038	
K+	0.0129	0.0011	0.0002	0.0009	0.0001				0.0001	
neutron	0.1145	0.0017	0.0017	0.0011	0.0008	0.0002	0.0002		0.0011	
pi-	0.0525	0.0038	0.0011	0.0022	0.0012		0.0001		0.0014	
proton	1.3192	0.0026	0.0029	0.0022	0.0045	0.0008	0.0024	0.0021	0.0013	

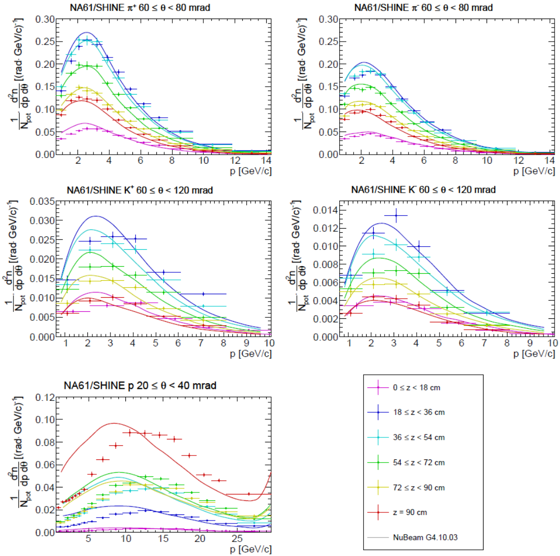
Beamline interactions per ν in DUNE ND



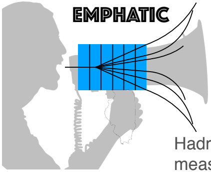
Event display from NA61

- **2016 dataset:** π^+ C/Be at 60 GeV, p^+ C,Be at 120 GeV, p^+ C,Al,Be at 60 GeV. Currently under analysis.
- **2017 dataset:** π^+ Al at 60 GeV,π^+ Al at 60 GeV,π^- C at 60 GeV, p^+ C,Be at 120 GeV, p^+ C at 90 GeV.

Double differential cross-sections on T2K replica target - 2018

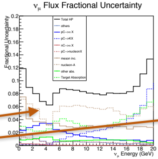


EMPHATIC at Fermilab



A new hadron production experiment for improved neutrino flux predictions

Hadron production measurements to reduce flux uncertainties from secondary and tertiary interactions in the neutrino production target



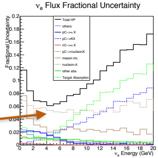
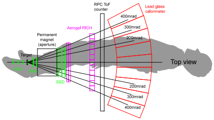
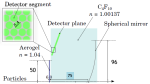
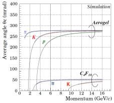
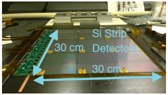


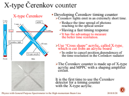
Table-top-sized experiment









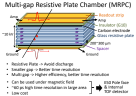


X-type Čerenkov counter

- Developing Čerenkov timing counter
  - Čerenkov lights emit in an extremely short time.
    - ✓Reduce the time spread of photons reaching to the optical sensor
    - ✓Having a fast timing response
    - ✓It has the advantage to measure the better time resolution.
  - Use "Cross shape" acrylic, called X-type, which is cut from an acrylic board
    - ✓In order to cancel position dependences of the time resolution in the Čerenkov radiator
  - The Čerenkov counter is made up of X-type acrylic and MPPC with a shaping amplifier circuit.

It is the first time to use the Čerenkov detector for a timing counter with the X-type acrylic.

Physics with General Purpose Spectrometer in the High-momentum Beam Line 2018/8/28 ④



Multi-gap Resistive Plate Chamber (MRPC)

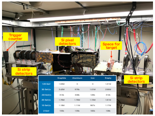
- Resistive Plate -> Avoid discharge
- Smaller gap -> Better time resolution
- Multi gap -> Higher efficiency, better time resolution

- Can be used under magnetic field
- ~60 ps high time resolution in large area
- Low cost

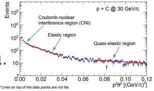
} → E50 Pole face & Internal TOF detector

2 week-long test run this past January already collected useful data.

MT6.1-A



4-momentum transfer (raw data)

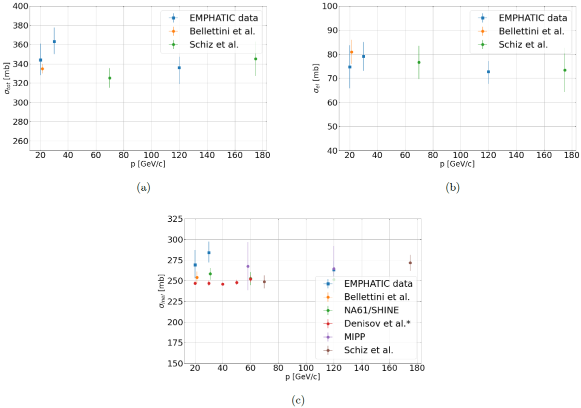


*Lines on top of the data points are not fits

See posters by J. Paley, M. Pavin & T. Vladisavljevic, and T. Sugimoto!

Recent EMPHATIC Measurements - 2020

Proof of principal measurements of proton elastic and inelastic scattering cross-sections:



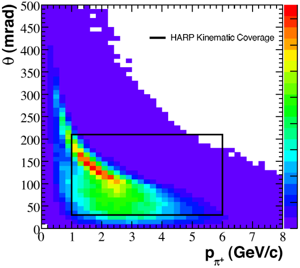
(a)

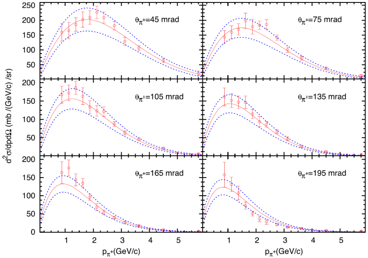
(b)

(c)

FIG. 16: Comparisons of the total (a), elastic (b), and inelastic cross-section (c) obtained from the fits with older data.

MiniBooNE 8 GeV p-Be Hadronic Interaction Models

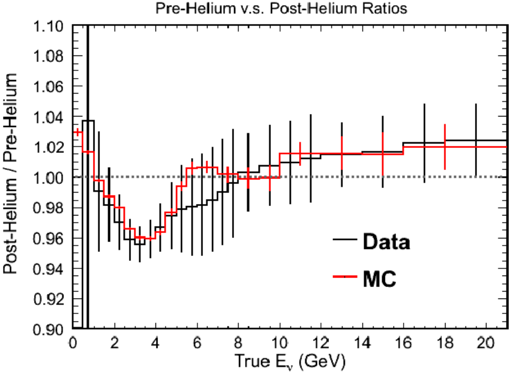




<u>Data</u>: Use HARP 8.89 GeV/c p-Be and BNL E910 6.4 GeV/c p-Be interactions with best fit to parameteric model.

Interactions with other beamline materials

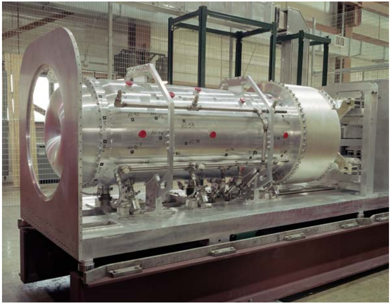
Helium in the NuMI decay pipe: data and simulations

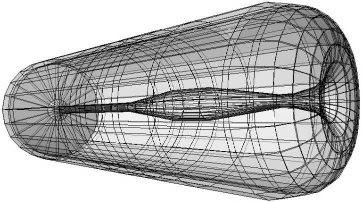


Hadron interactions in ALL beamline materials must be considered

Transporting Hadrons: BNB Simulation

Phys. Rev. D. 79, 072002 (2009)

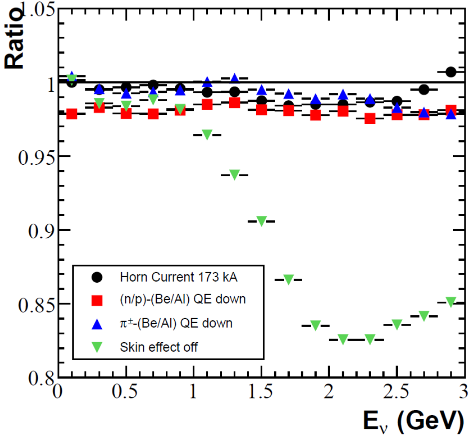




- **GEANT4 simulation of beamline geometry. Generation of the primary protons according to expected beam optics.**
- **Simulation of primary p-Be interactions using custom tables for production of p,n,$\pi^{\pm}$, $K^{\pm}$ and K^0 based on external hadro-production data.**
- **GEANT4 propagates particles generated in p-Be, including secondary interactions in the beamline materials.**

BNB Simulation Uncertainties

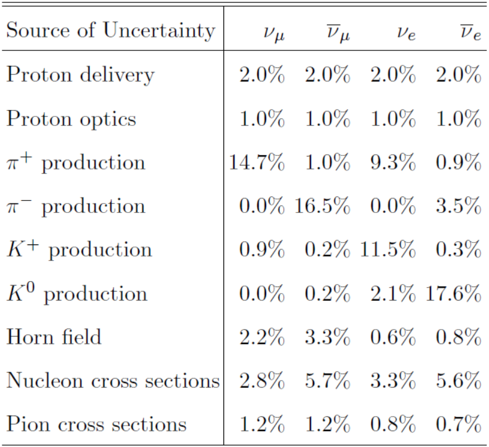
Ratio to nominal ν_μ flux



Horn focusing simulation large source of absolute flux uncert.

How do we obtain data to constrain this?

Uncertainties on MiniBooNE ν_μ Flux Determination



Source of Uncertainty	ν_μ	$\overline{\nu}_\mu$	ν_e	$\overline{\nu}_e$
Proton delivery	2.0%	2.0%	2.0%	2.0%
Proton optics	1.0%	1.0%	1.0%	1.0%
π^+ production	14.7%	1.0%	9.3%	0.9%
π^- production	0.0%	16.5%	0.0%	3.5%
K^+ production	0.9%	0.2%	11.5%	0.3%
K^0 production	0.0%	0.2%	2.1%	17.6%
Horn field	2.2%	3.3%	0.6%	0.8%
Nucleon cross sections	2.8%	5.7%	3.3%	5.6%
Pion cross sections	1.2%	1.2%	0.8%	0.7%

Hadron production uncertainties dominate: 15-18%

A Spectrometer for Focused Hadron Flux Measurements for LBNF?

Proposal by Laura Fields:

The **LBNF Spectrometer** is a concept for a thick-target hadron production **measurement after the focusing horns**. It would involve a **replica of the LBNF** target and horns in an external beamline at Fermilab. In addition to hadron production in the target, the spectrometer would also **measure hadron production and absorption in the horns and the effects of the magnetic fields** in the horns.

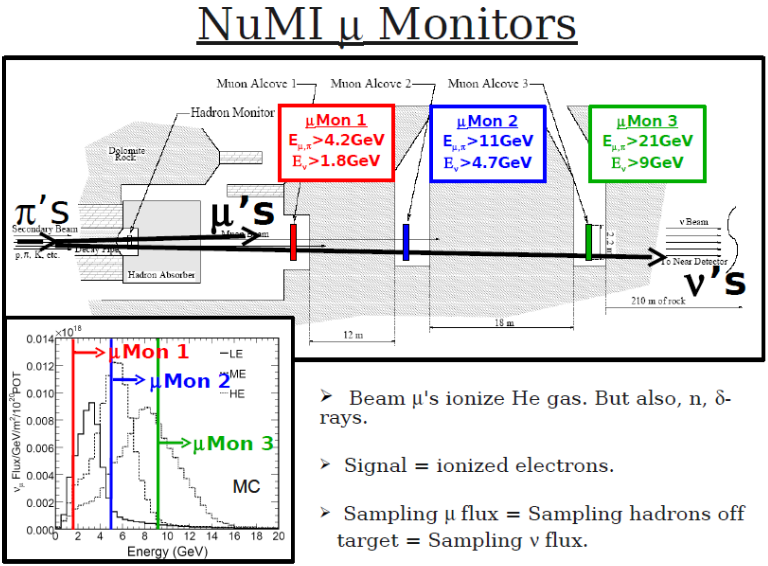
Detector technology is always challenging

Need to get more people interested and involved to succeed

In-situ flux measurements

Muon flux measurements

Muon Flux Monitors in NuMI

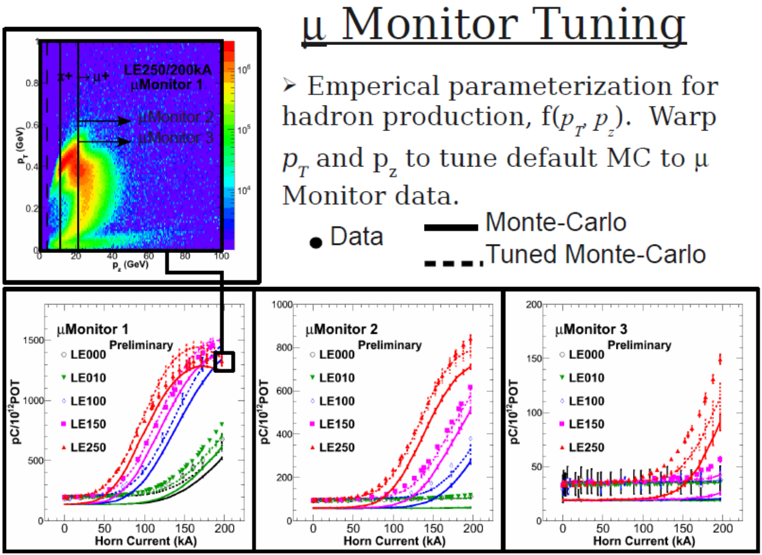


NuMI μ Monitors

- Beam μ's ionize He gas. But also, n, δ-rays.
- Signal = ionized electrons.
- Sampling μ flux = Sampling hadrons off target = Sampling ν flux.

From Laura Loiacono

Tuning MC Using μ Flux Measurements



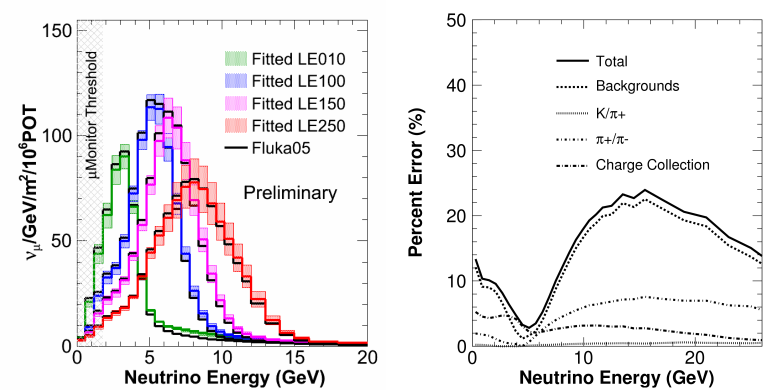
μ Monitor Tuning

- Emperical parameterization for hadron production, f(p_T, p_z). Warp p_T and p_z to tune default MC to μ Monitor data.

● Data
Monte-Carlo
Tuned Monte-Carlo

From Laura Loiacono

NuMI Flux from Muon Monitors

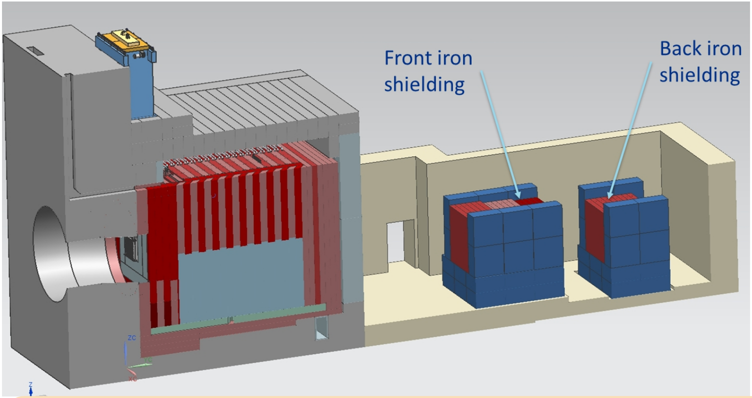


Accurate ν flux measurements from μ monitors DIFFICULT

From Laura Loiacono

Muon Beam Monitors in LBNF/DUNE

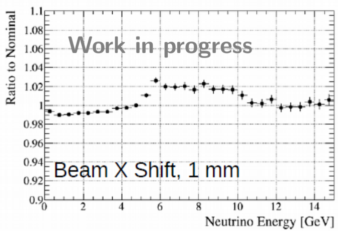
Layout of Muon Alcove and Shielding in LBNF

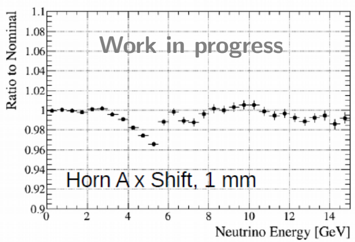


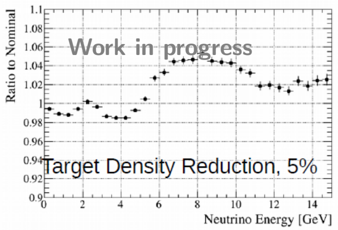
High intensity makes it difficult to measure μ spectrum accurately. With a 2.4 MW beam, the absorber thickness is too large to sample the lower energy muons. But these systems play an essential role in monitoring *flux stability*

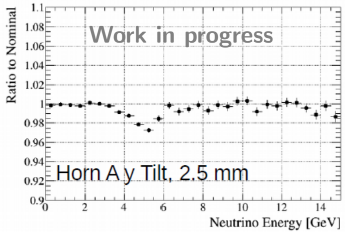
Correlation between neutrino and muon spectrum

ν Spectrum Changes



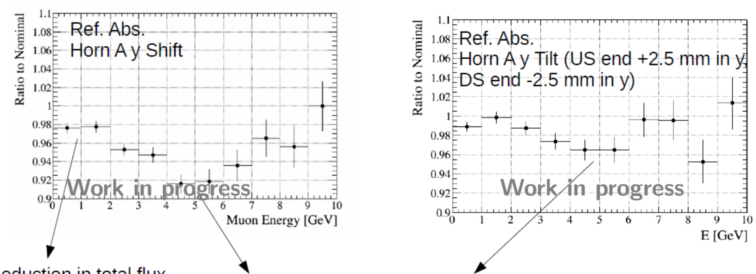






Correlation between neutrino and muon spectrum

μ Spectrum Changes



Reduction in total flux

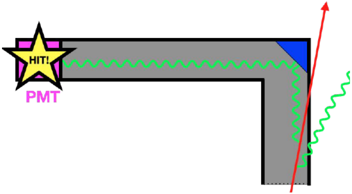
Shape changes at max near 5 GeV

Changes are v. small - need novel detector concepts

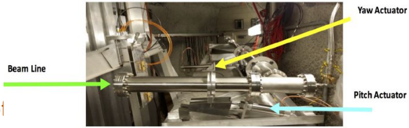
Muon Monitor Technologies under R&D

- **Array of ionization detectors: Measures muon beam center and intensity. Spill by spill monitoring of beam stability. Both diamond and silicon under study**
- **Threshold gas Cherenkov detector (R&D): Uses signal intensity at different gas pressure and angles to extract rough muon spectrum.**
- **Stopped muon counters (R&D): separate stations with steel shielding in between could measure muon flux at several energies. Better measurement of beam flux spectrum and composition.**

Gas Cherenkov counter concept:

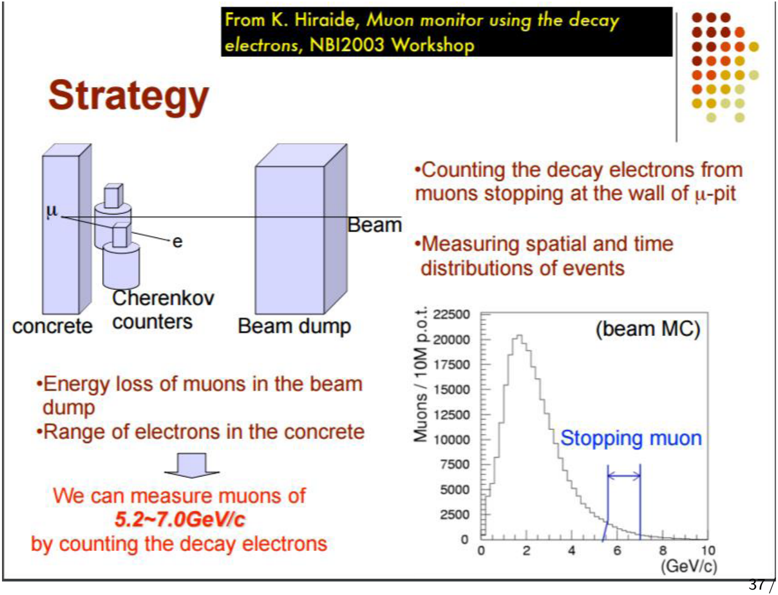


Prototype in NuMI beamline:



Currently only ionization detectors included in the beam design.

Stopped Muon Concept



From K. Hiraide, *Muon monitor using the decay electrons*, NBI2003 Workshop

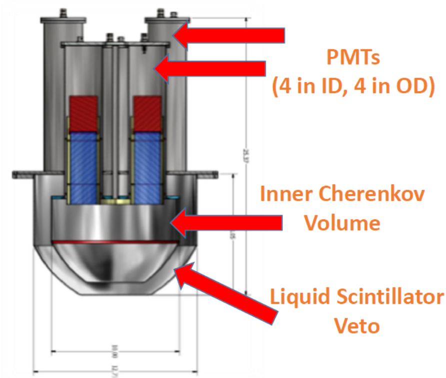
Strategy

- Counting the decay electrons from muons stopping at the wall of μ-pit
- Measuring spatial and time distributions of events

- Energy loss of muons in the beam dump
- Range of electrons in the concrete

We can measure muons of
5.2~7.0GeV/c
by counting the decay electrons

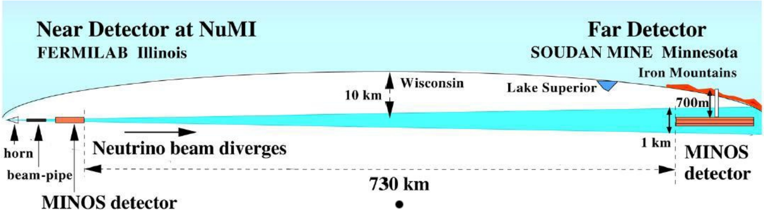
Stopped Muon Prototype

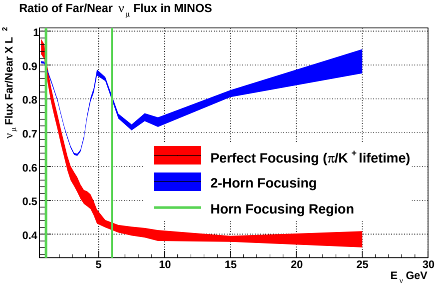


Prototypes tested in NuMI beam

Neutrino flux measurements in NDs

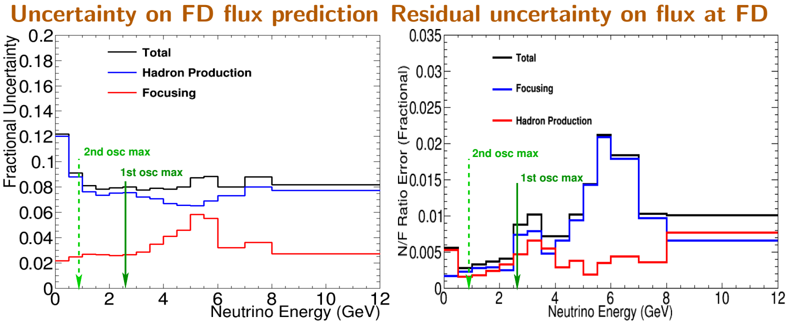
Long Baseline: Near and Far ν Detectors





Near detector neutrino flux not identical to far!

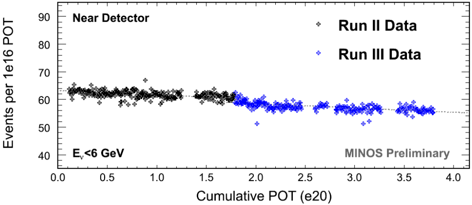
Why a Near Detector? (LBNF example)


Uncertainty on FD flux prediction **Residual uncertainty on flux at FD**

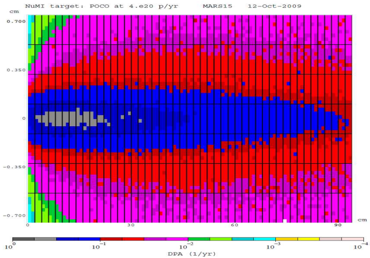
Flux uncertainties partially cancel with near/far

Flux Stability with High Precision Near Detector

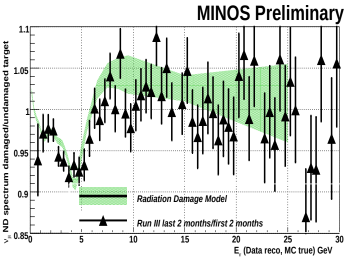
Observe a reduction in the ν event rate < 6 GeV in NuMI target 2:



MARS simulation of target damage

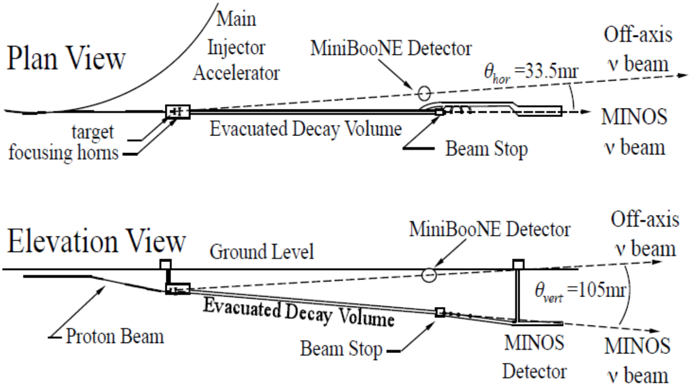


Target damage model in FLUKA08

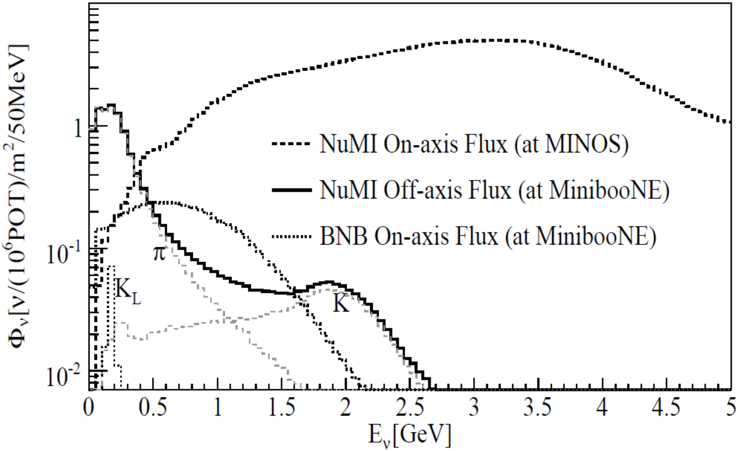


On and off-axis ν flux measurements

NuMI in MiniBooNE

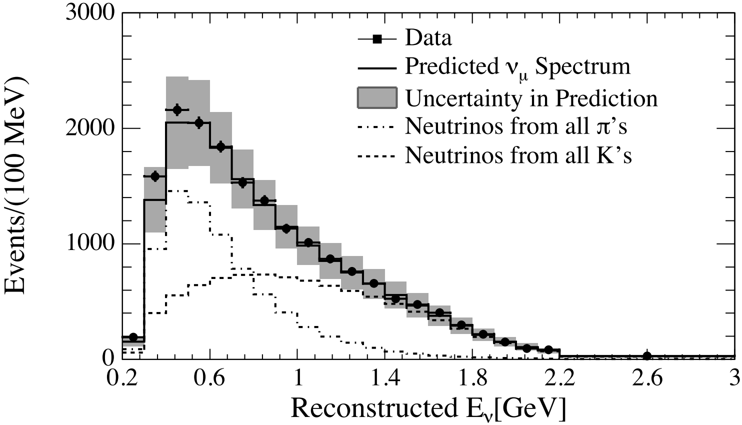


NuMI in MiniBooNE



MiniBooNE ν Interactions from NuMI Beamline - 2010

The NuMI simulation tuned to match the MINOS ND event rate was used to predict the ν rate in the MiniBooNE detector:



Off-axis ν measurements can constrain π/K production

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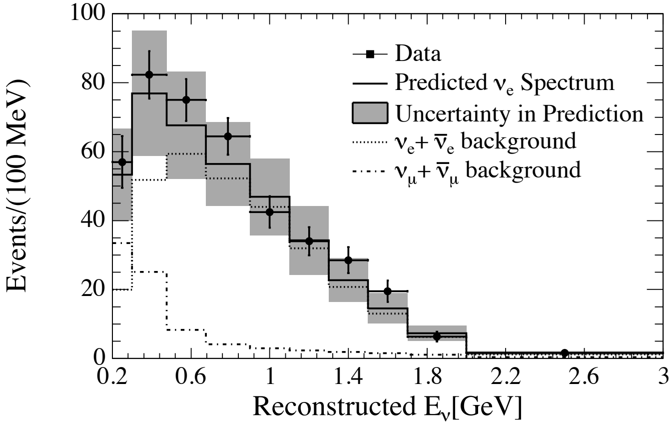

Off-axis ν measurements can constrain π/K production

Summary and Conclusions

Summary

Intensity frontier = precision frontier in neutrino physics. Measurements of KNOWN parameters with accuracies $\sim 1\%$

New physics could be ANYWHERE $\mathrm{L/E}_\nu$ = 1 - 1000km/GeV

A full scale assault on flux measurements is needed from many different directions:

- **High precision control of proton beams**
- **External target hadron production data**
- **Benchtop measurements of skin depth effect, horn magentic field?**
- **Simulate every gram of material in the beamline**
- **Measurements of muon flux to better than 5%**
- **REDUCING DETECTOR/CROSS-SECTION SYSTEMATICS in near neutrino measurements.**

$\bar{\nu} \longrightarrow$

LET THE GAMES BEGIN!

Thank you