Accelerator Neutrinos at the Intensity Frontier

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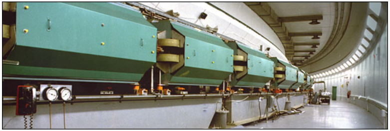
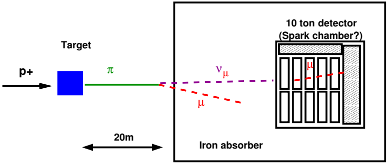
Outline

Accelerator Neutrinos

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



The AGS

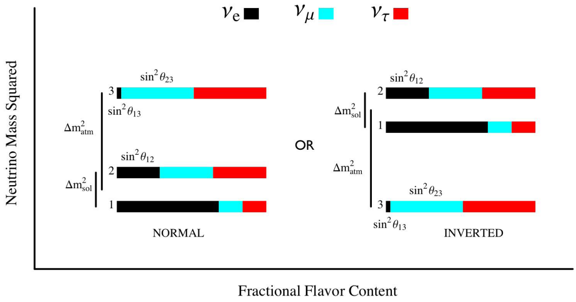


Making ν's

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

Discovery of neutrino flavour

Neutrino Mixing: 3 flavours



Parameter	Value (neutrino PMNS matrix)	Value (quark CKM matrix)
θ_{12}	$34 \pm 1^\circ$	$13.04 \pm 0.05^\circ$
θ_{23}	$38 \pm 1^\circ$	$2.38 \pm 0.06^\circ$
θ_{13}	$8.9 \pm 0.5^\circ$	$0.201 \pm 0.011^\circ$
δm^2	$+(7.54 \pm 0.22) \times 10^{-5}$ eV^2	
$\lvert\Delta m^2\rvert$	$(2.43^{+0.10}_{-0.06}) \times 10^{-3}$ eV^2	$m_3 >> m_2$
δ_{CP}	$-170 \pm 54^\circ$	$67 \pm 5^\circ$

Intensity Frontier: Precision neutrino physics and beyond PMNS

Neutrino Oscillation Scales

The mass-squared differences Δm^2_{21} (solar), Δm^2_{32} (atmospheric) and $\Delta m^2_{sterile} = 1eV^2$ (LSND?) drive very different scales:

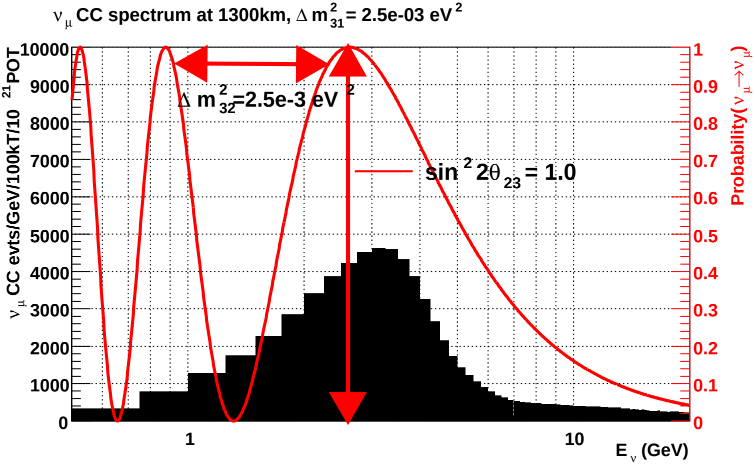
$$\begin{aligned} L/E^{\nu}_{n}\ (\mathrm{km/GeV}) &= (2n-1)\frac{\pi}{2}\frac{1}{(1.267 \times \Delta m^2\ (\mathrm{eV}^2))} \\ &\approx (2n-1) \times 1\ \mathrm{km/GeV\ for}\ \Delta m^2_{sterile}\ (\mathrm{LSND}) \\ &\approx (2n-1) \times 500\ \mathrm{km/GeV\ for}\ \Delta m^2_{32}\ (\mathrm{atmos.})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

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

Oscillations of GeV scale accelerator neutrinos over different baselines probe 3x3 PMNS and beyond

Accelerator Neutrinos and PMNS

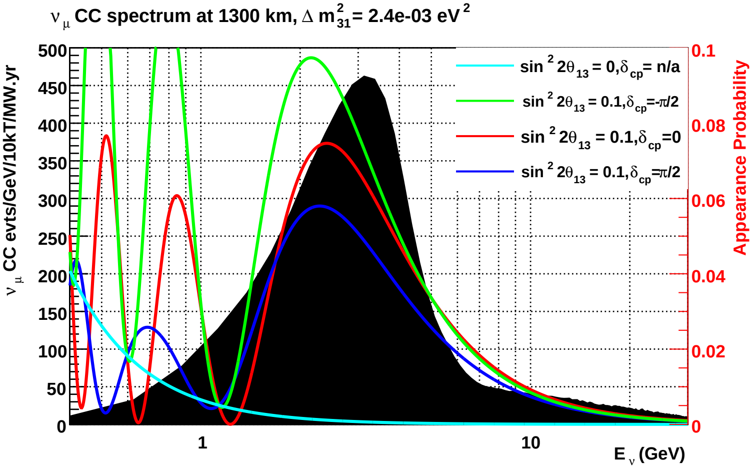
Muon neutrino disappearance



Accelerator Neutrinos and PMNS

$\nu_\mu \longrightarrow \nu_e$ **appearance**

Normal Hierarchy

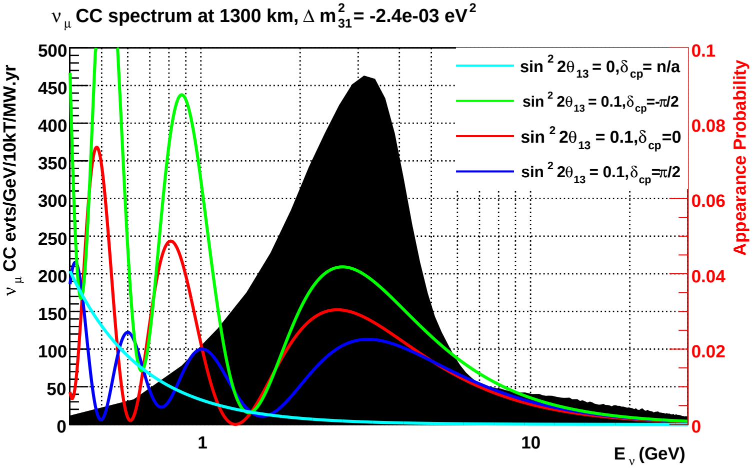


Long baseline accelerator neutrinos probe all 3x3 PMNS matrix elements

Accelerator Neutrinos and PMNS

$\nu_\mu \longrightarrow \nu_e$ appearance

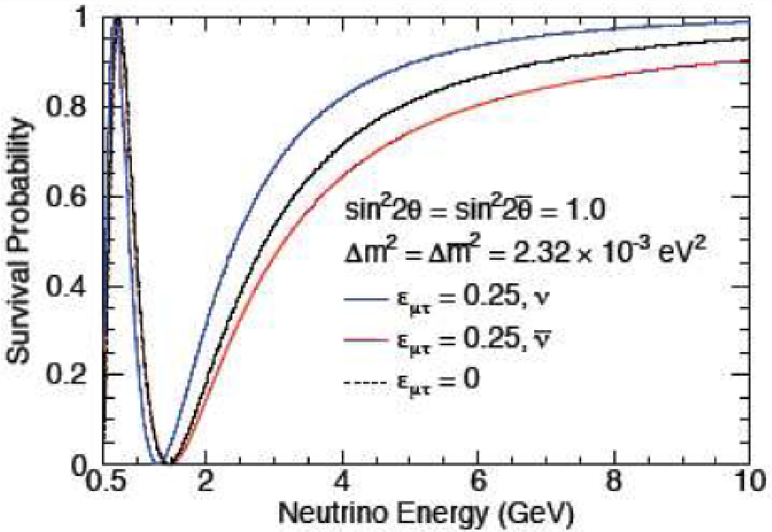
Inverted Hierarchy



And the hierarchy!

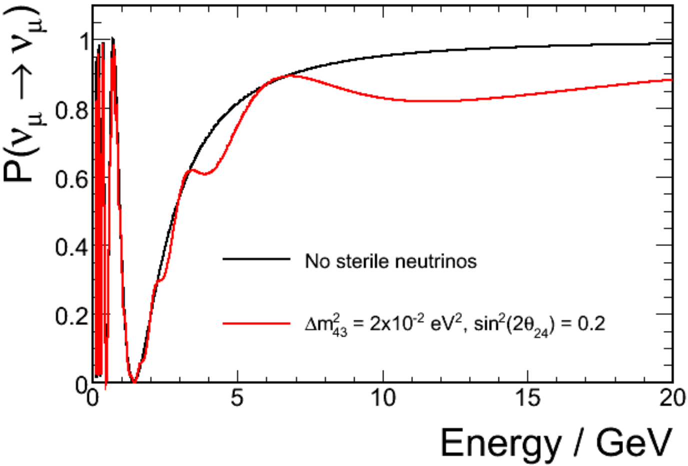
Beyond PMNS

Non-standard interactions at 735km



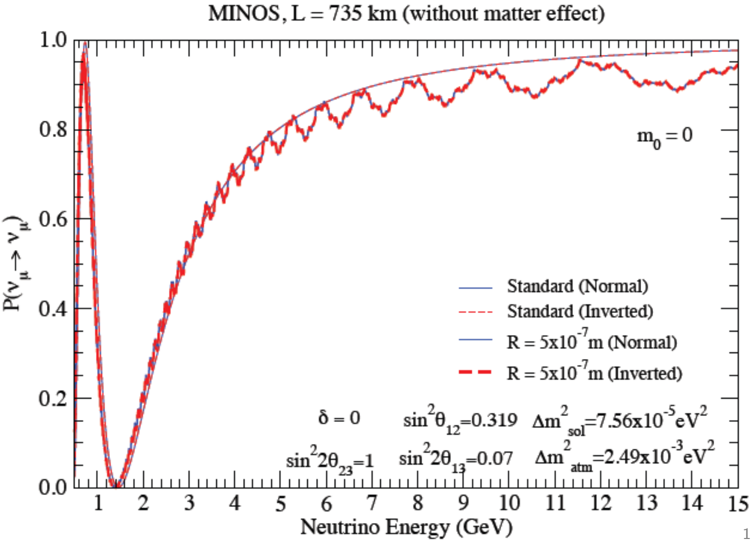
Beyond PMNS

Sterile neutrinos at 735km



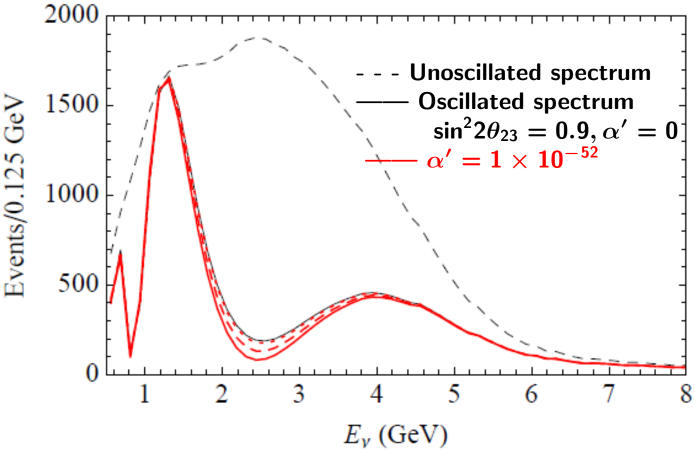
Beyond PMNS

Large extra dimensions at 735km:



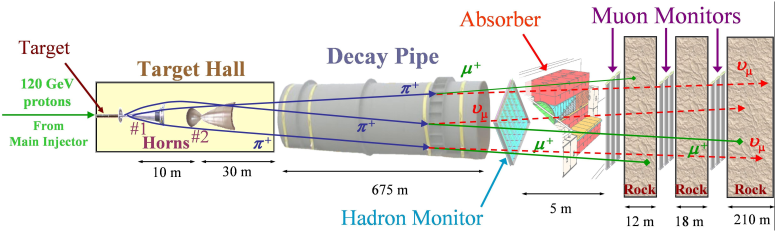
Beyond PMNS

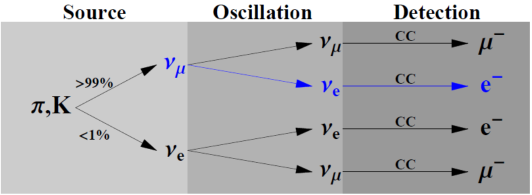
Long range interactions at 1300km



Neutrino beams at the Intensity Frontier (Superbeams)

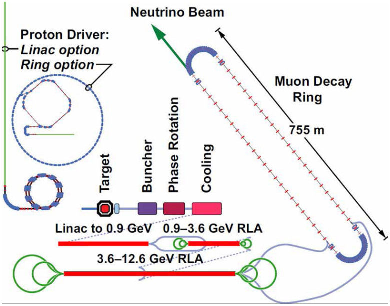
High power conventional neutrino beams (NuMI):

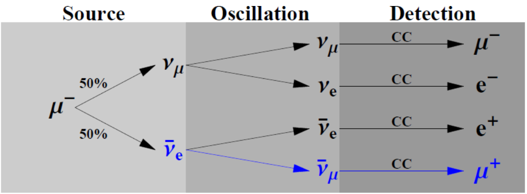




Neutrino Factories/Muon Storage Rings

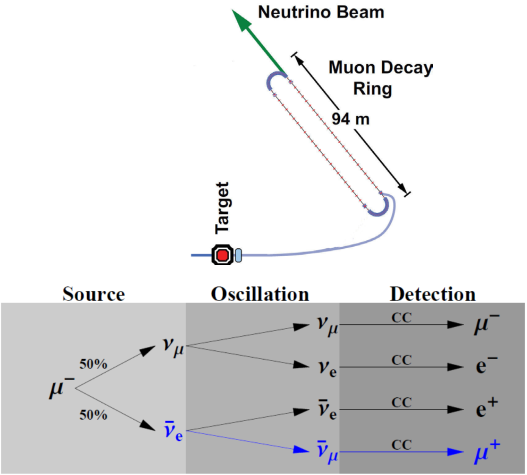
Long baseline experiments





Neutrino Factories/Muon Storage Rings

Short baseline experiments



Superbeams vs Neutrino Factories

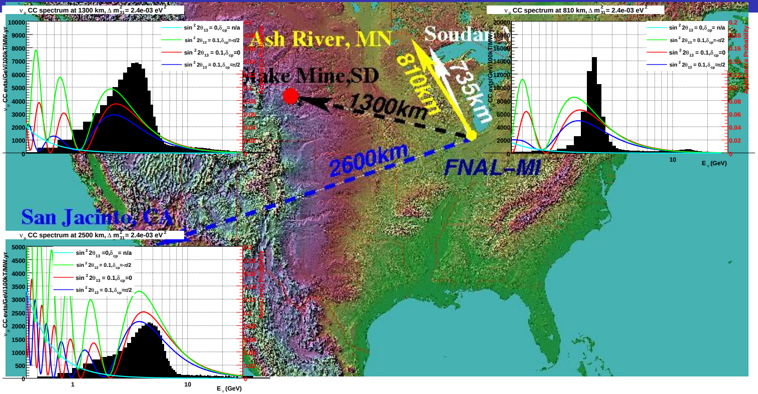
From A. Blondel et. al. NIM A 451 (2000) 102-122

	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.

Muon storage rings only viable for short baseline.

Superbeam Baselines in the U.S.



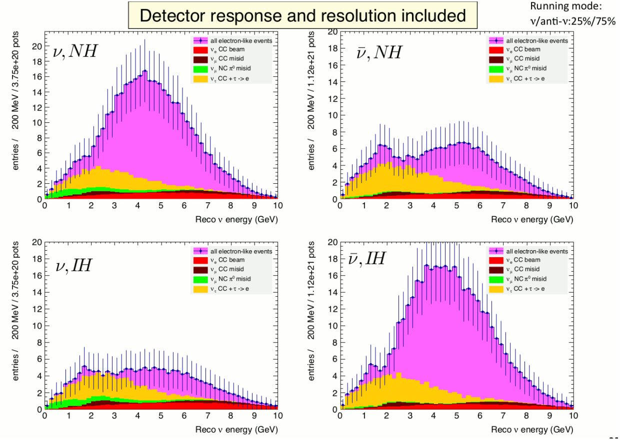
CC event rates per 100kt.MW.yrs (1 MW.yr= 1×10^{21} p.o.t) for $\sin^2 2\theta_{13} = 0.1, \delta_{cp} = 0$, NH:

Expt	ν_μ CC	ν_μ CC osc	ν_μ NC	ν_e beam	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\tau$
Soudan 735km	73K	49K	15K	820	1500	166
Ash River 810km	18K	7.3K	3.6K	330	710	38
Hmstk 1300km	29K	11K	5.0K	280	1300	130
CA 2500km	11K	2.9K	1.6K	85	760	290

Can conventional beam fluxes be constrained to 1% level?

Long Baseline Superbeam Signals/Backgrounds

For the LBNO experiment CERN-Pyhasalmi 2300km:



Beam fluxes outside the signal region produce backgrounds.

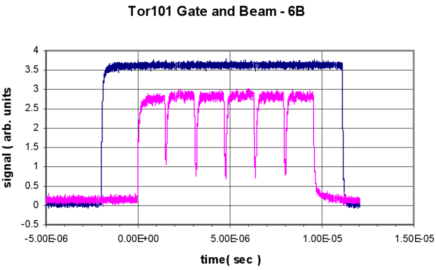
For on-axis long baseline fluxes from 1-100GeV have to be modeled

Measuring the Beam Current and Position

In-situ measurements of proton intensity with high accuracy

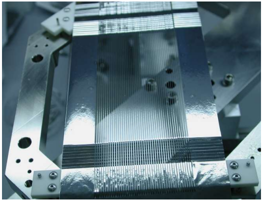
Characteristics of NuMI Beam P sition Monitors:

- **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.**

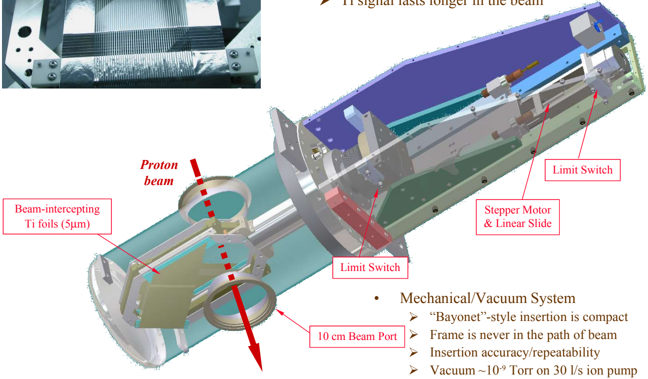


Feedback from BPMs used to auto-steer the beam to target center

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



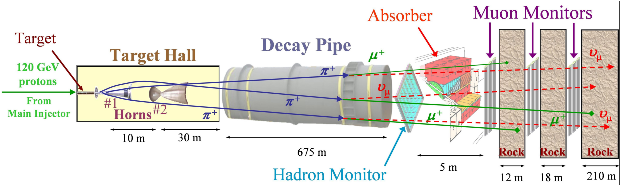
- Mechanical/Vacuum System
  - "Bayonet"-style insertion is compact
  - Frame is never in the path of beam
  - Insertion accuracy/repeatability
  - Vacuum ~10^{-9} Torr on 30 l/s ion pump

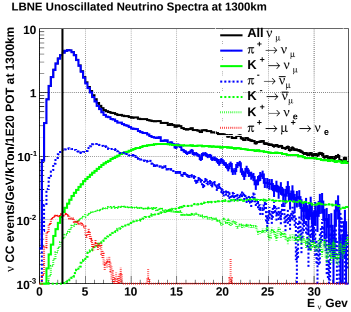
Beam profile at target needs to be measured

Conventional Neutrino Beam Components

Long baseline beams - multi-GeV: NuMI (LBNE)

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

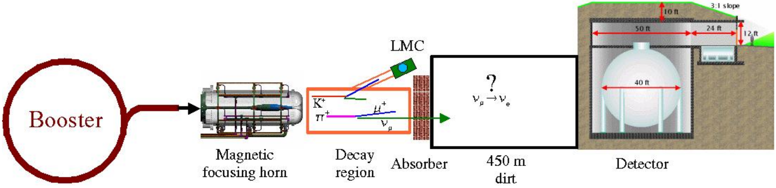




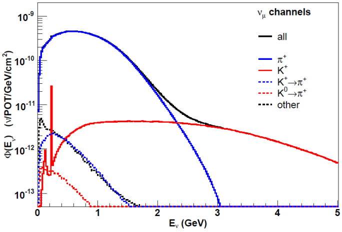
Conventional Neutrino Beam Components

Short baseline beams - sub-GeV: Booster Neutrino Beam

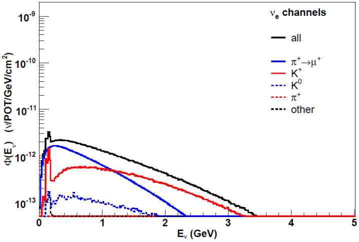
8 GeV proton, Be target l=71cm, 174 kA pulsed horn.



ν_μ Flux

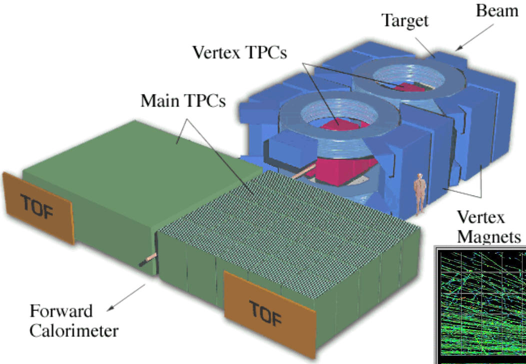


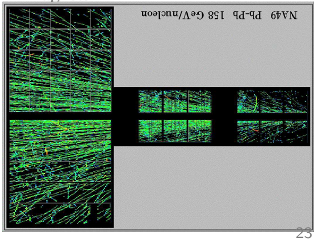
ν_e Flux



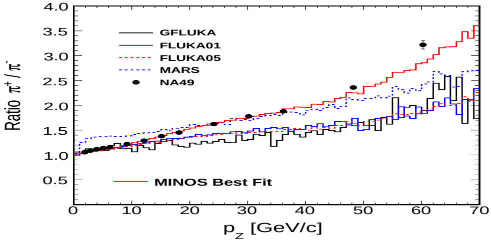
Hadron Production Experiments

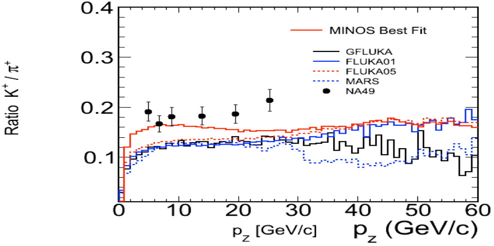
Dedicated large acceptance hadron spectrometers are used to measure hadrons produced in p-p and p-A collisions on thin/thick targets. For example the NA49 experiment at CERN:





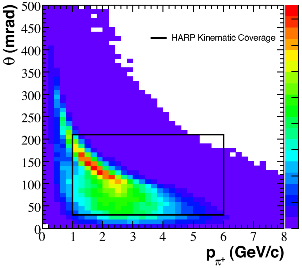
NuMI Beam Simulation and 158 GeV p-C NA49 Data

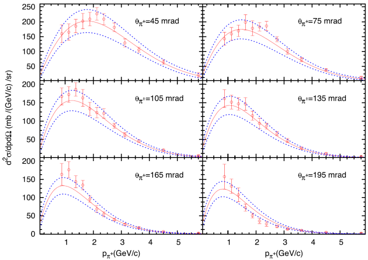




MC target hadron production must be constrained by external data.

MiniBooNE p-Be Hadronic Interaction Models

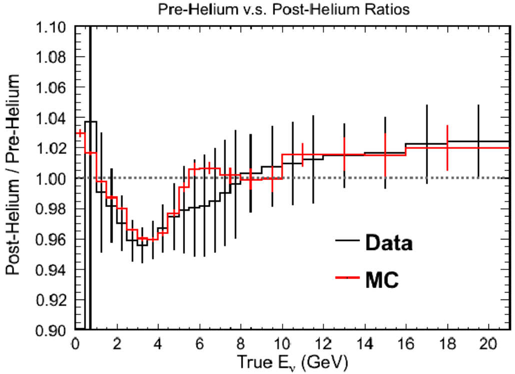




Data: Use HARP 8.89 GeV/c p-Be and BNL E910 6.4 GeV/c p-Be interactions with best fit to parameteric model.

Interactions with other beamline materials

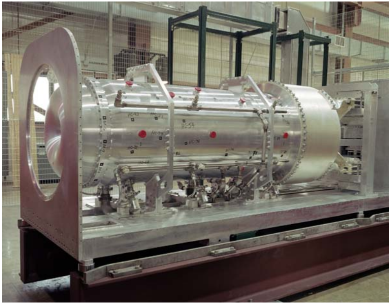
Helium in the NuMI decay pipe: data and simulations

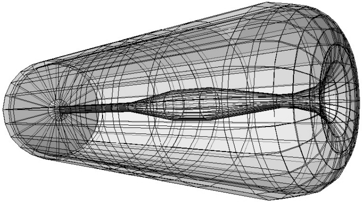


Hadron interactions in ALL beamline materials must be considered

Transporting Hadrons: BNB Simulation

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

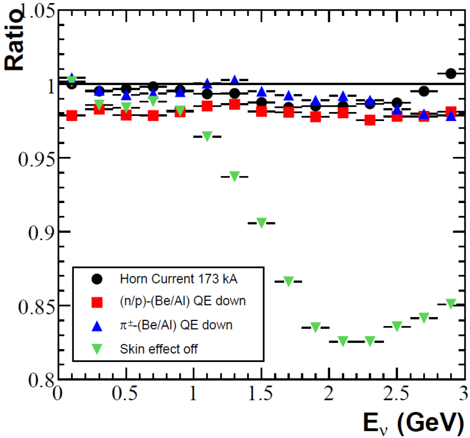




- **GEANT4 simulation of beamline geometry. Generation of the primary protons according to expected beam optics.**
- **Simulation of primary p-Be interactions using custom tables for production of p,n,$\pi^{\pm}$, $K^{\pm}$ and K^0 based on external hadro-production data.**
- **GEANT4 propagates particles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

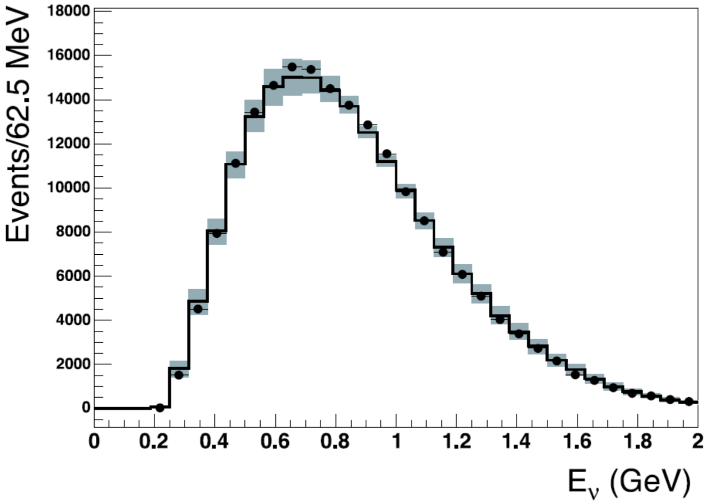
How do we obtain data to constrain this?

Uncertainties on MiniBooNE ν_μ Flux Determination

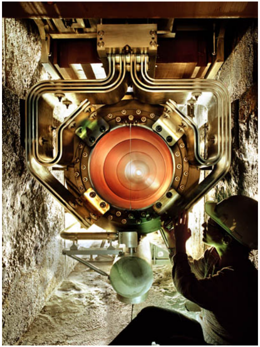
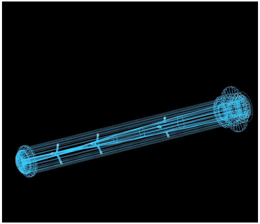
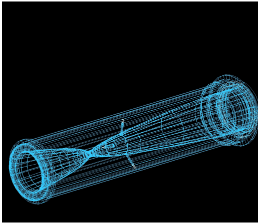
Source of Uncertainty	ν_μ	$\overline{\nu}_\mu$	ν_e	$\overline{\nu}_e$
Proton delivery	2.0%	2.0%	2.0%	2.0%
Proton optics	1.0%	1.0%	1.0%	1.0%
π^+ production	14.7%	1.0%	9.3%	0.9%
π^- production	0.0%	16.5%	0.0%	3.5%
K^+ production	0.9%	0.2%	11.5%	0.3%
K^0 production	0.0%	0.2%	2.1%	17.6%
Horn field	2.2%	3.3%	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%

Measurement of the ν_μ Interaction Rate in MiniBooNE

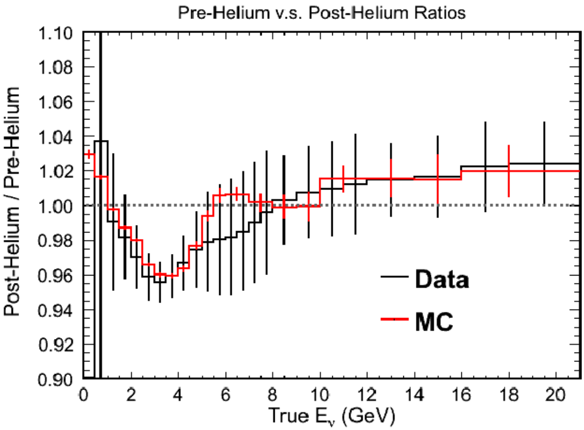


Simulation of the NuMI Beamline

- **GEANT4 is used to define the detailed NuMI beamline geometry**
- **GEANT4 geometry interfaces to FLUKA08. FLUKA08 is used to generate proton beam and model all primary and secondary particle interaction.**

Simulation of the NuMI Decay Pipe Helium

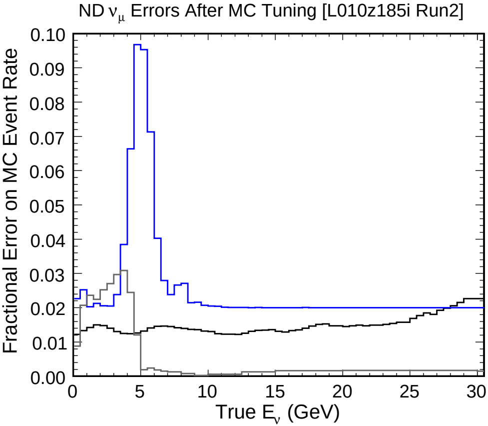


Detailed simulation of all material in beamline needed.

Uncertainties in NuMI Flux Simulation (2010)

— **Beam optics**
— **Target production**
— **Horn material budget**

ND Event Rate



Uncertainties in NuMI Simulation (2010)

ND rate uncertainties (ν-mode) from the NuMI simulation:

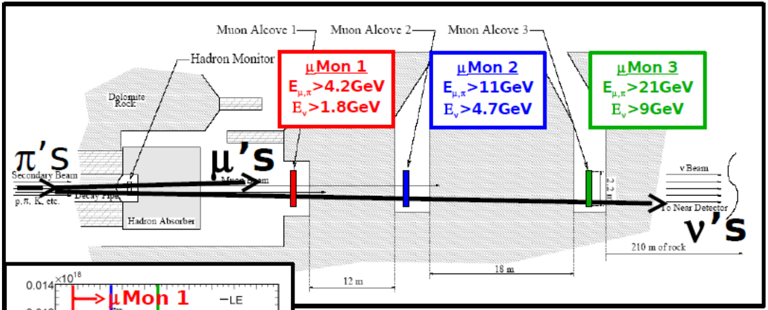
Source of Uncertainty	ν_μ	$\bar{\nu}_\mu$	ν_e
Proton delivery	2%	2%	2%
Focusing	7.5%	small	TBD
Target z position	1%	small	1%
Target hadro-production	1.5%	2.5%	5%
Target degradation	4%	4%	4%
Horn material budget	3%	small	2%
Decay pipe He	small	small	small
$\pi \longrightarrow \mu$ propagation	-	-	20%

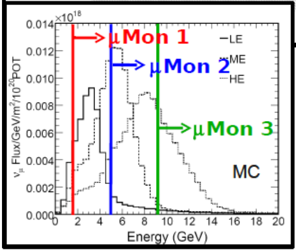
Uncertainties on flux from target hadro-production is smaller after fit to ND rate

The overall uncertainty on ν_e is LARGE

Muon Flux Monitors in NuMI

NuMI μ Monitors





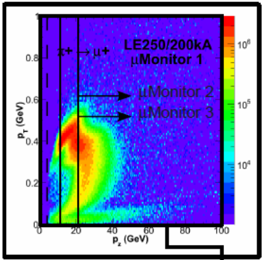
- Beam μ's ionize He gas. But also, n, δ-rays.
- Signal = ionized electrons.
- Sampling μ flux = Sampling hadrons off target = Sampling ν flux.

From Laura Loiacono

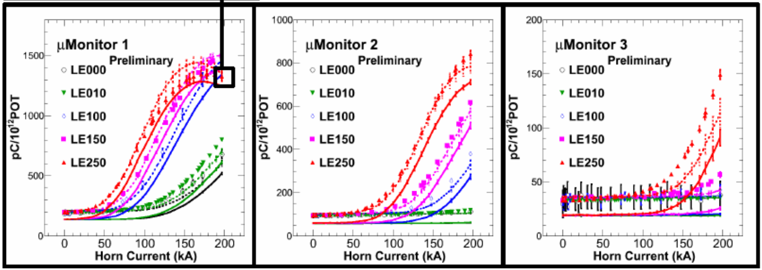
Tuning MC Using μ Flux Measurements

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.

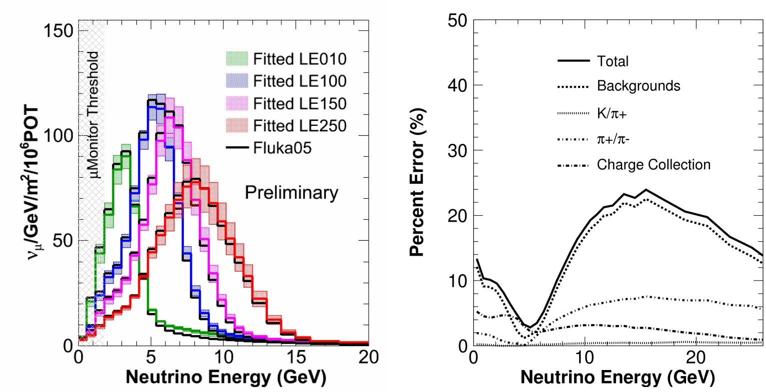


● Data
—— Monte-Carlo
- - - Tuned Monte-Carlo



From Laura Loiacono

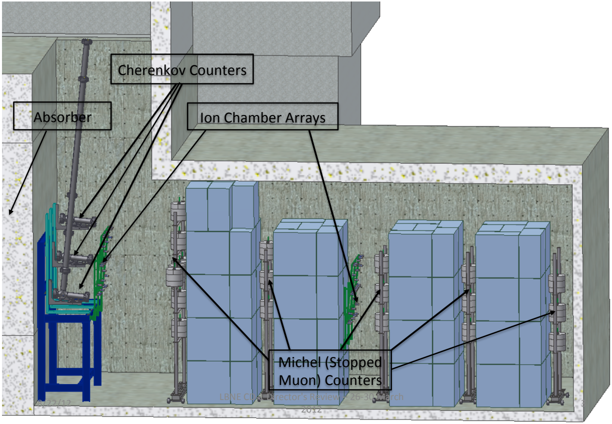
NuMI Flux from Muon Monitors



Accurate ν flux measurements from μ monitors DIFFICULT

From Laura Loiacono

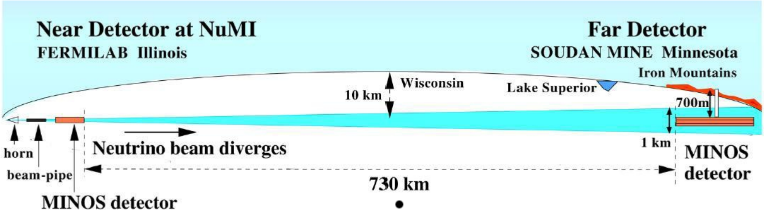
Next Generation Muon Flux Measurements - LBNE

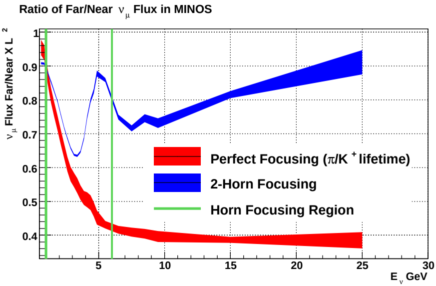


New detector technologies=lower backgrounds/systematics

BUT: flux constraint limited to E$_\nu$ $>$ 2 GeV

Long Baseline: Near and Far ν Detectors



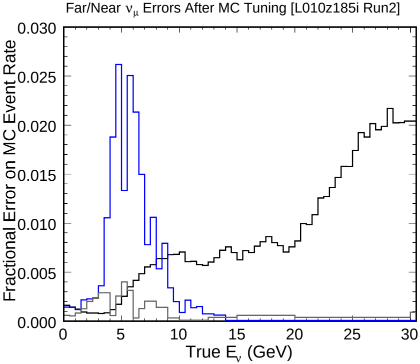


Near detector neutrino flux not identical to far!

Why a Near Detector?

— **Beam optics**
— **Target production**
— **Horn material budget**

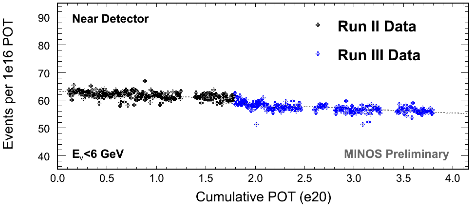
Far/Near Extrapolation



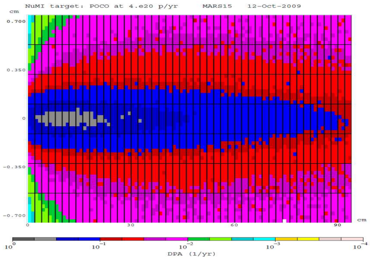
Flux uncertainties partially cancel with near/far

Flux Stability with High Precision Neutrino Measurements

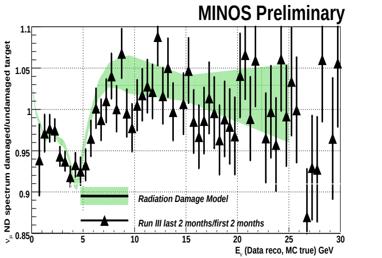
Observe a reduction in the ν event rate < 6 GeV in NuMI target 2:



MARS simulation of target damage

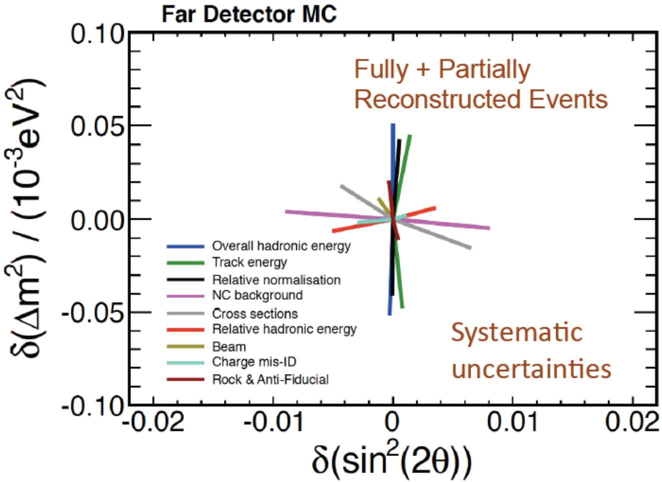


Target damage model in FLUKA08



Challenges of near/far extrapolation

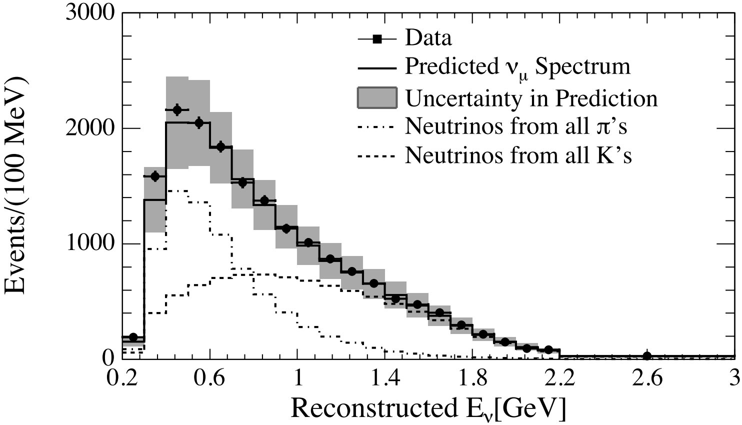
NuMI disappearance measurement (2010)



Detector uncertainties dominate flux uncertainties!

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:



On-axis ν measurements can constrain off-axis and pi/K

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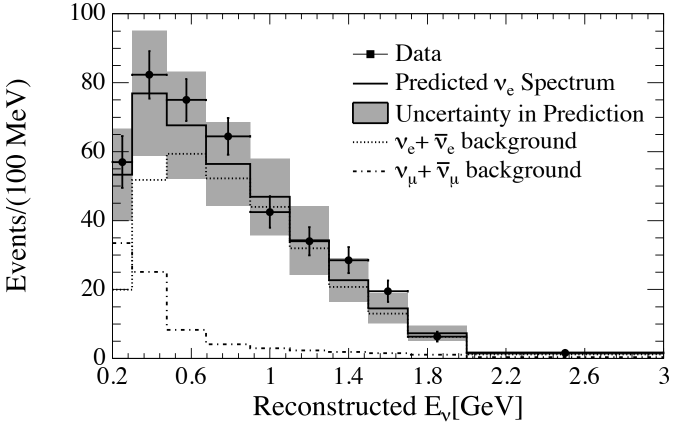

On-axis ν measurements can constrain off-axis and pi/K

Summary

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

New physics could be ANYWHERE 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.**
- **Using far detector data to further constrain systematics (a la MiniBooNE)**

Thank you