Determining the Neutrino Flux from Accelerator Neutrino Beams

NEUTRINO 2010, June 13-19, Athens, Greece

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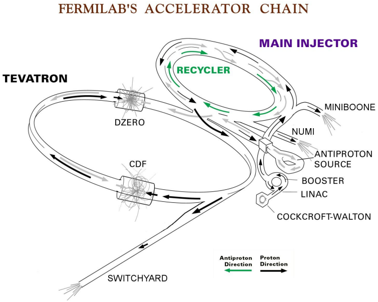
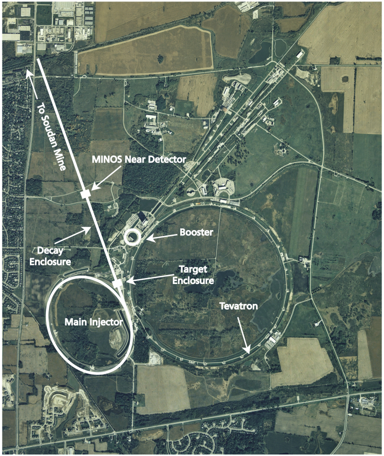
Brookhaven National Laboratory

June 15, 2010

The Fermilab Accelerator Complex



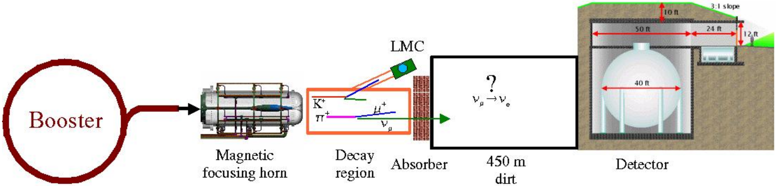


FERMILAB #98-765D

The Neutrino Beamlines at Fermilab

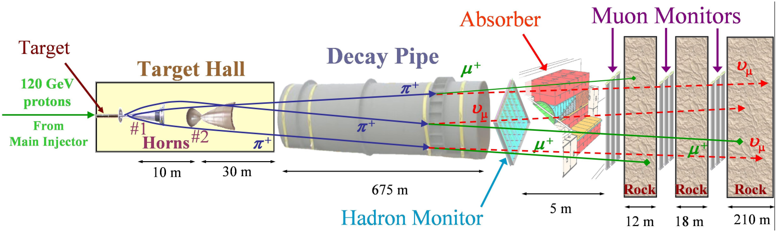
Booster Neutrino Beam (BNB)

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



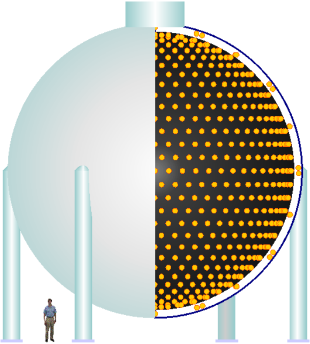
Neutrinos at the Main Injector (NuMI)

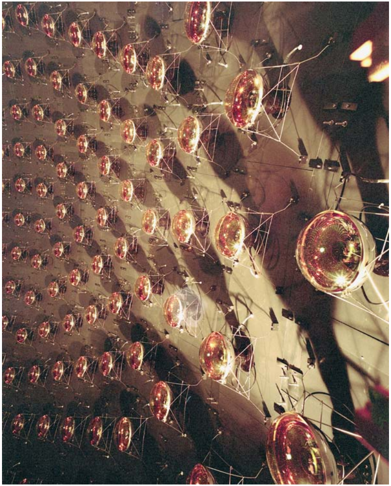
120 GeV proton beam, graphite target l=95cm, 185 kA pulsed horns (2)



The MiniBooNE Detector

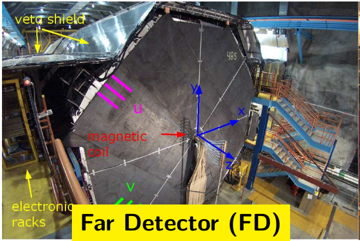
Cerenkov detector: 800T mineral oil, 1280 inner PMTs and 240 Veto PMTs. $\sim$ 10% energy resolution





The MINOS Detectors

Magnetized iron calorimeters with 2.54 cm thick Fe plates sandwiched with scintillator strips (1 cm thick, 4.1 cm wide) readout by WLS fiber.



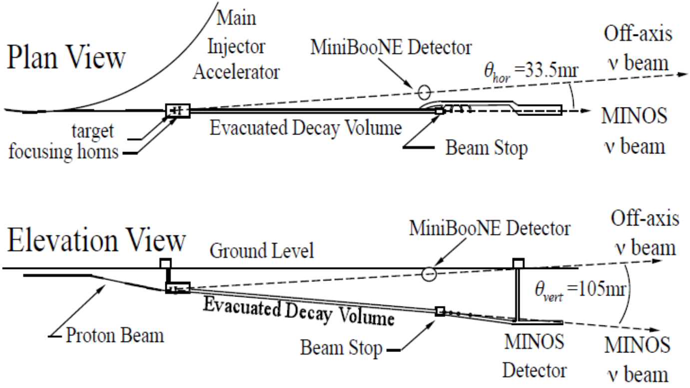
Far Detector (FD)

Near Detector (ND)

- **484 octogonal steel and scintillator plates 8m wide, ⇒ 5.4kTon and 30 m in length.**
- **Toroidal B-field, 1.3 T at r = 2m**
- **Cosmic μ veto shield**

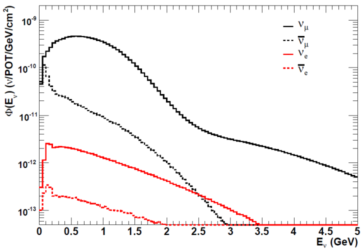
- **282 “squashed” octagonal steel plates, 153 scintillator planes. ⇒ 1kTon and 16 m in length.**
- **Toroidal B-field, 1.3 T at r = 2m**

NuMI Beam in MiniBooNE and MINOS

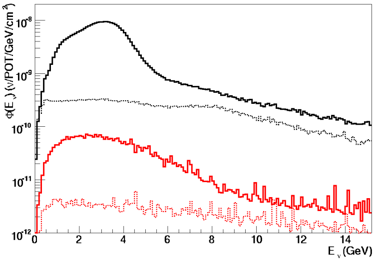


MiniBoone/MINOS Neutrino Fluxes

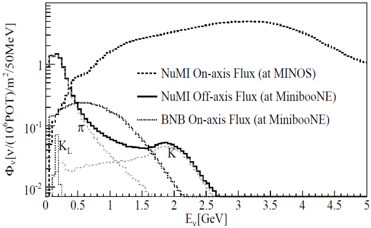
MiniBooNE



MINOS ND

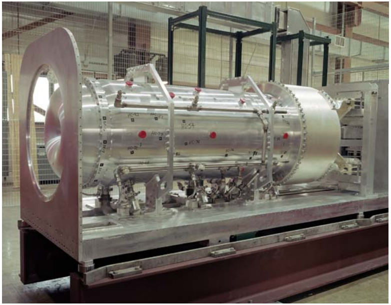


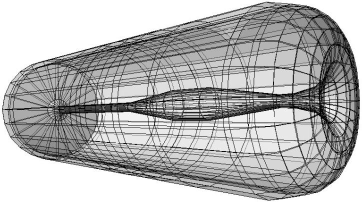
NuMI beam in MiniBooNE



Simulation of the BNB

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

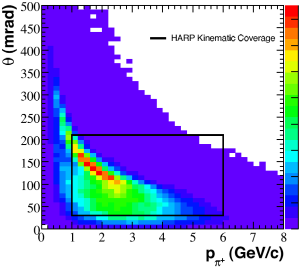


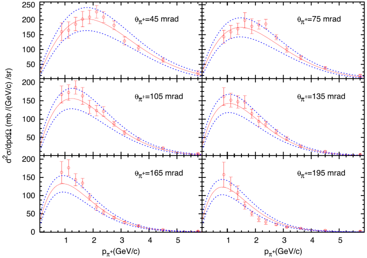


- **GEANT4 simulation of beamline geometry. Generation of the primary protons according to expected beam optics.**
- **Simulation of primary p-Be interactions using custom tables for production of p,n,$\pi^{\pm}$, $K^{\pm}$ and K^{0} based on external hadro-production data.**
- **GEANT4 propagates particles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

MiniBooNE p-Be Hadronic Interaction Models

	p-(Be/Al)	n-(Be/Al)	$\pi^{\pm}$-(Be/Al)
σ_{TOT}	Glauber	Glauber	Data ($p < 0.6/0.8\,\mathrm{GeV}/c$)
		(checked with data)	Glauber ($p > 0.6/0.8\,\mathrm{GeV}/c$)
σ_{INE}	Data	(same as p-Be/Al)	Data
σ_{QEL}	Shadow	Shadow	Data ($p < 0.5\,\mathrm{GeV}/c$)
			Shadow ($p > 0.5\,\mathrm{GeV}/c$)

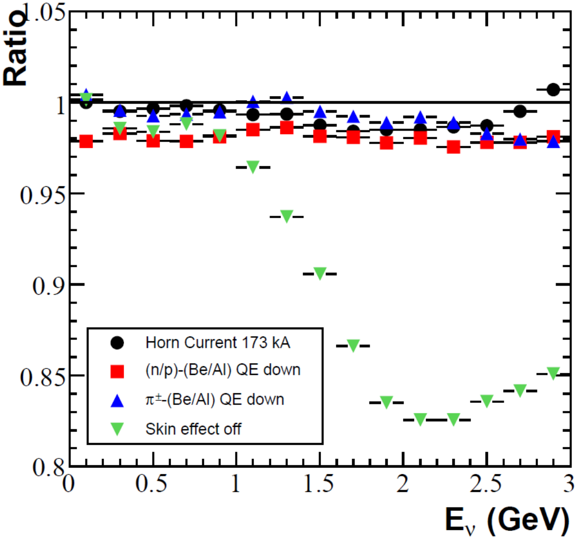




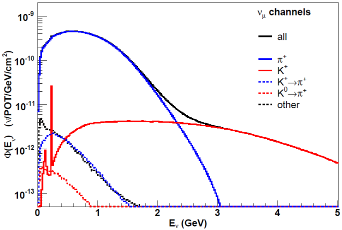
<u>Data</u>: Use HARP 8.89 GeV/c p-Be and BNL E910 6.4 GeV/c p-Be interactions with best fit to Sanford-Wang model.

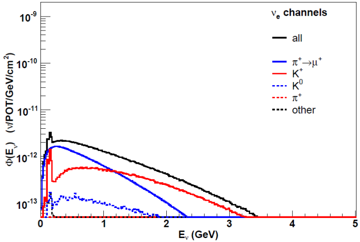
BNB Simulation Uncertainties

Ratio to nominal ν_μ flux



Measurements of ν_μ Flux from MiniBoone

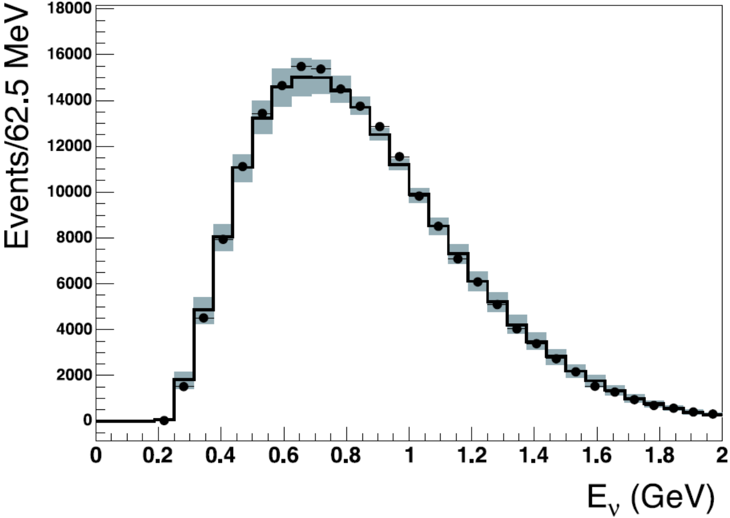




Source of Uncertainty	ν_μ	$\overline{\nu}_\mu$	ν_e	$\overline{\nu}_e$
Proton delivery	2.0%	2.0%	2.0%	2.0%
Proton optics	1.0%	1.0%	1.0%	1.0%
π^+ production	14.7%	1.0%	9.3%	0.9%
π^- production	0.0%	16.5%	0.0%	3.5%
K^+ production	0.9%	0.2%	11.5%	0.3%
K^0 production	0.0%	0.2%	2.1%	17.6%
Horn field	2.2%	3.3%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

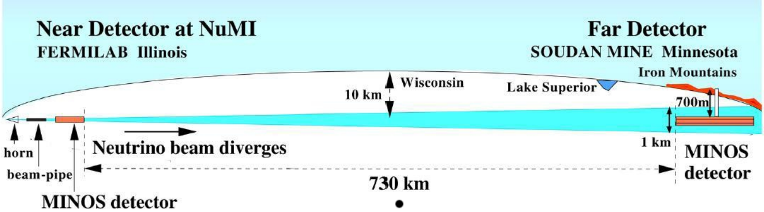
Hadron production uncertainties dominate: 15-18%

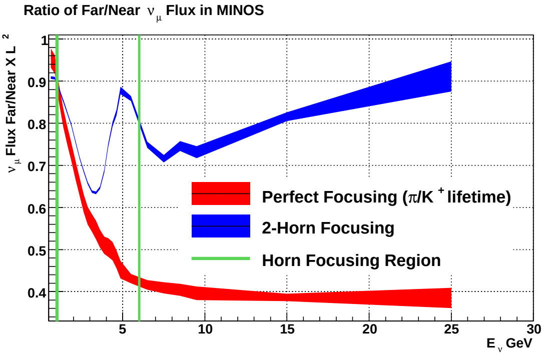
Measurement of the ν_μ Interaction Rate in MiniBooNE



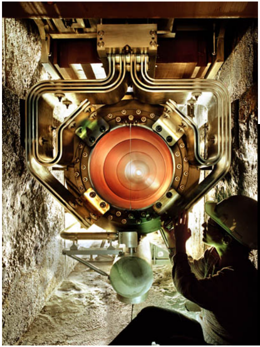
To match data, flux had to be scaled by 1.21

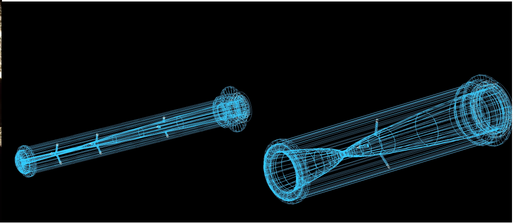
The NuMI Near and Far Detector Flux





Simulation of the NuMI Beamline



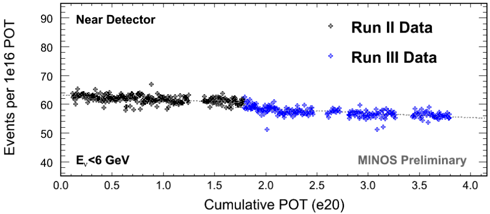


- **GEANT4 is used to define the detailed NuMI beamline geometry**
- **GEANT4 geometry interfaces to FLUKA08. FLUKA08 is used to generate proton beam and model all primary and secondary particle interaction.**

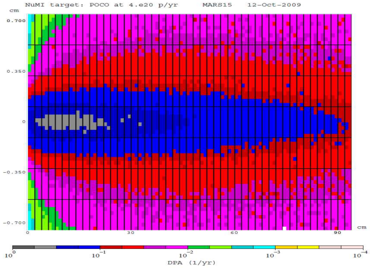
Simulating NuMI Target Degradation

Poster by N. Simos, N. Mokhov, M. Bishai

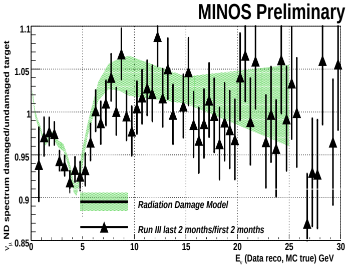
Observe a reduction in the ν event rate < 6 GeV in NuMI target 2:



MARS simulation of target damage



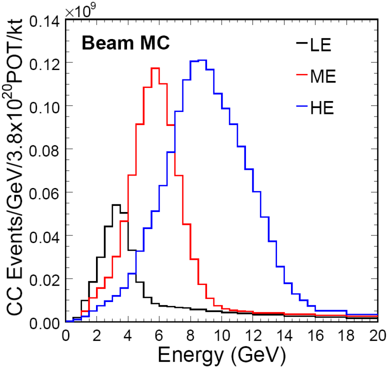
Target damage model in FLUKA08



Using the MINOS ND to constrain NuMI Simulation

Technique developed by Sacha Kopp and Zarko Pavlovich

The NuMI flux can be changed by moving the target w.r.t horns. LE: target 35cm into horn 1, ME: target -1m from LE position
HE: target -2.5m from LE position



A simultaneous fit to the ν_μ and $\bar{\nu}_\mu$ ND event rates produced in different beam tunes and with different horn currents is performed.

Using the MINOS ND to constrain NuMI Simulation

Technique developed by Sacha Kopp and Zarko Pavlovich

- Target yields of secondaries have been parameterized according to:

$$\boxed{\frac{d^2N}{dx_F dp_T} = [A + Bp_T] * \exp\left(-Cp_T^{3/2}\right)}$$

where A, B and C are functions of x_F.

determines low p_T yields

determines how fast distribution rises

determines high p_T fall-off

- Consider linear warpings of A, B and C as $f(x_F)$:

$$A' = ([0]+[1]*x_F) * A$$

$$B' = ...$$

- Need 6 parameters for positives to construct:

$$\boxed{W(ptype, p_T, x_F) = \frac{[A' + B'p_T] * \exp\left(-C'p_T^{3/2}\right)}{[A + Bp_T] * \exp\left(-Cp_T^{3/2}\right)}}$$

- Need 2 parameters for negatives to construct:

$$\boxed{W^- = ([0]+[1]*x_F) * W^+}$$

6 pi+, 6 K+, 2 pi- and 2 K- parameters.

Hadron production ratios as $f(p_z)$ are penalized in penalty term.

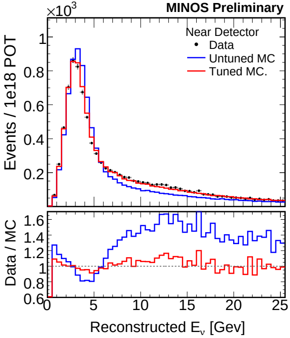
Beam fits to MINOS ND Data, 2010

Non-target production effects included in fit: Horn current, horn current distributions, target position, E_ν scale and offset, target damage effects.

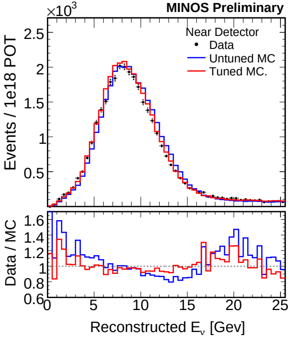
NA49 constrains π^+/π^-.

K^+/K^- and K^+/π^+ constrained to FLUKA 08

NuMI low-energy beam tune

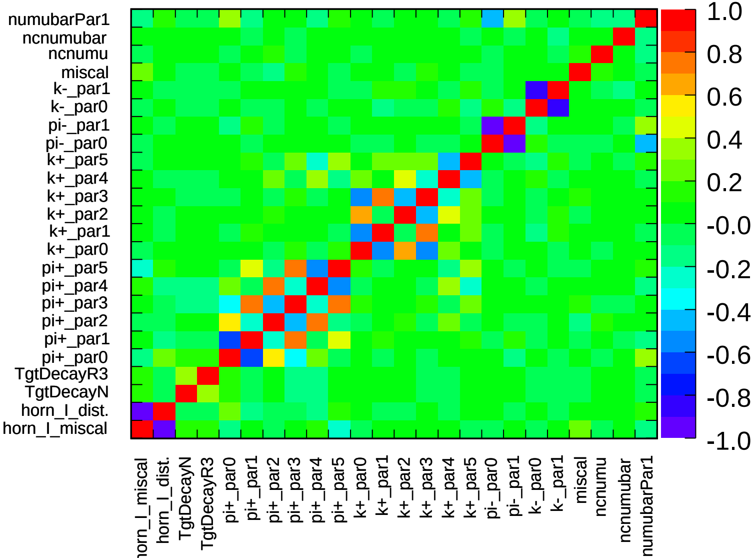


NuMI high-energy beam tune

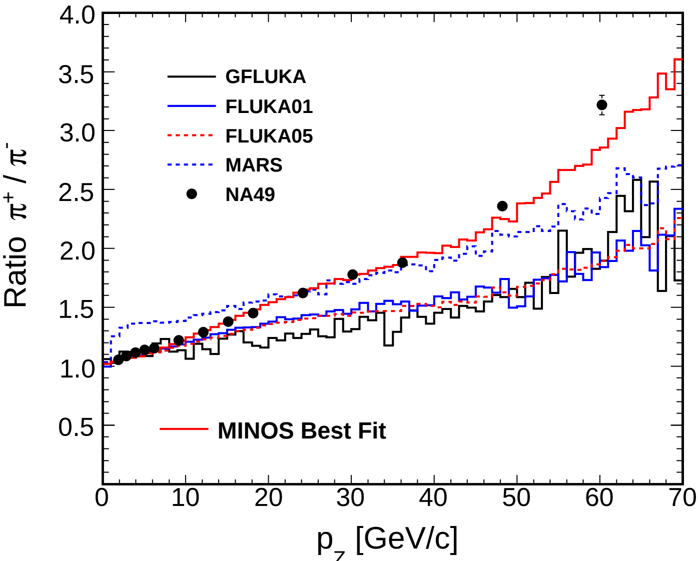


Beam Fit Parameter Correlations

Correlation Matrix



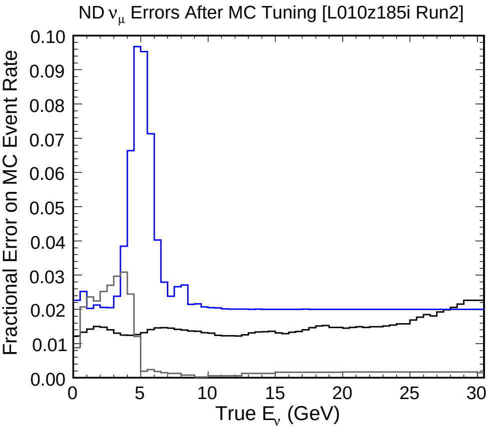
MINOS ND Data Beam Fits vs p-C NA49



Uncertainties in NuMI Flux Simulation (2010)

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

ND Event Rate



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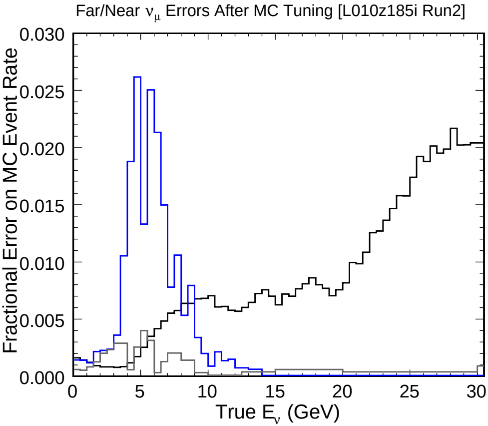
Far/Near Extrapolation



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
$\pi \rightarrow \mu$ propagation	-	-	20%

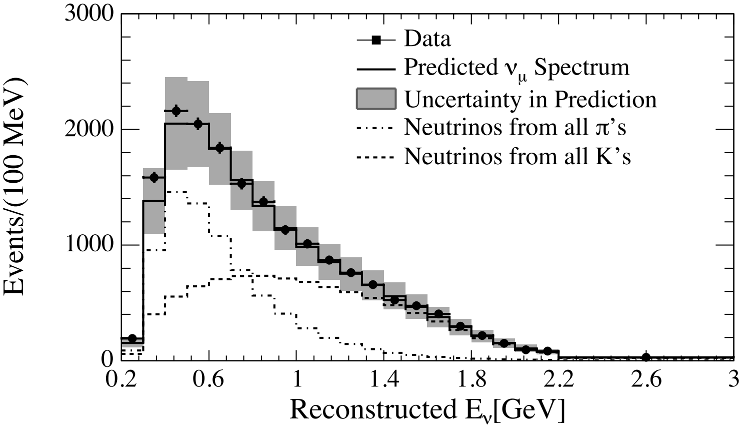
Uncertainties on flux from target hadro-production is smaller after fit to ND rate

The overall uncertainty on ν_e is LARGE

MiniBooNE ν Interactions from NuMI Beamline - 2010

Poster by Zelimir Djurcic

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



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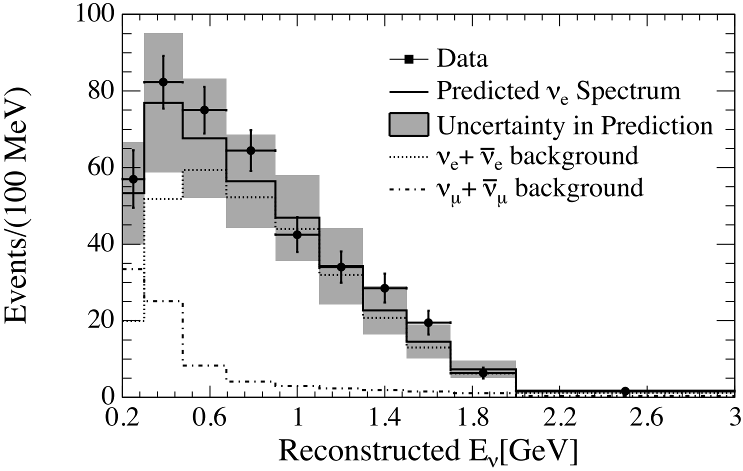

Summary and Conclusions

- **The MiniBooNE and MINOS experiments have developed detailed simulations of the neutrino beamlines.**
- **MiniBooNE uses p-Be hadron production data from other experiments (HARP, BNL E910) to predict the ν_μ rate in the detector. The predicted flux uncertainty is large $\sim$ 20% dominated by target hadro-production.**
- **MINOS uses the near detector data in addition to data from other experiments to constrain target hadro-production. The flux uncertainty using a near detector constraint is $<$ 10% and is dominated by focusing uncertainties.**
- **Most, BUT NOT ALL, neutrino flux uncertainties cancel when using a near detector to extrapolate to a far detector. In MINOS, cancellation is good to 3%.**
- **Due to large modeling uncertainties in the propagation of $\pi \longrightarrow \mu$, MINOS is unable to use ν_μ to constrain beam ν_e.**
- **The event rate of ν_μ interactions in MiniBooNE from the NuMI beamline has been successfully predicted using the on-axis MINOS ND to constrain the beamline simulation.**