Neutrino beams and sources

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Outline

- Brief history of neutrinos
- Neutrino sources
- Accelerator neutrino beams and neutrino beams at Fermilab
- Precisely predicting accelerator neutrino fluxes

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

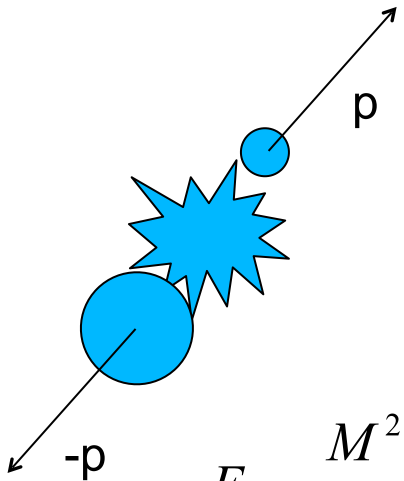
Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}\ \mathrm{cm})$.

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

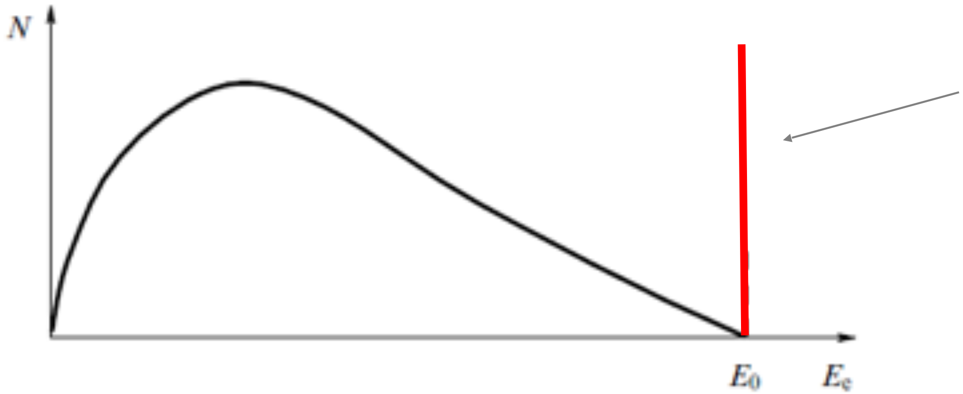
Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir mündlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht

Brief history

- 1930 Pauli introduces neutrino
- Explains continuous beta spectrum



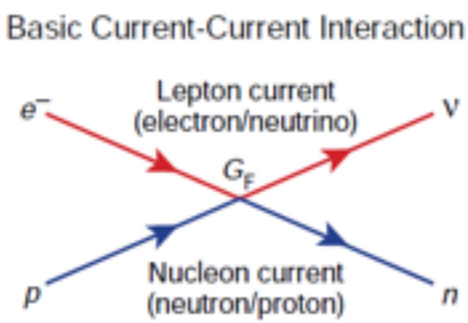
$$E_0 = \frac{M^2 - m_1^2 + m_2^2}{2M}$$



- Expected discreet spectrum for two body decay
- Observed continuous beta spectrum

Weak interactions

- 1934 Fermi develops Theory of Beta Decay



- Bethe-Peierls calculate the cross section for neutrino interaction $\sigma_{\nu p}$~$5x10^{-44}cm^2$
- Need light years of steel to stop neutrino

The "Neutrino"

THE view has recently been put forward[1] that a neutral particle of about electronic mass, and spin $\frac{1}{2}\hbar$ (where $\hbar = h/2\pi$) exists, and that this 'neutrino' is emitted together with an electron in β-decay. This assumption allows the conservation laws for energy and angular momentum to hold in nuclear physics[2]. Both the emitted electron and neutrino could be described either (a) as having existed before in the nucleus or (b) as being created at the time of emission. In a recent paper[3] Fermi has proposed a model of β-disintegration using (b) which seems to be confirmed by experiment.

According to (a), one should picture the neutron (b) as being created at the time of emission. In a recent paper[3] Fermi has proposed a model of β-disintegration using (b) which seems to be confirmed by experiment.

According to (a), one should picture the neutron as being built up of a proton, an electron and a neutrino, while if one accepts (b), the rôles of neutron and proton would be symmetrical[4] and one would expect that positive electrons could also sometimes be created together with a neutrino in nuclear transformations. Therefore the experiments of Curie and Joliot[5] on an artificial positive β-decay give strong support to method (b), as one can scarcely assume the existence of positive electrons in the nucleus.

Why, then, have positive electrons never been found in the natural β-decay? This can be explained by the fact that radioactivity usually starts with α-emission and therefore leads to nuclei the charge of which is too small compared with their weight. The artificial β-emission was found for two unstable nuclei (most probably N^{13} and P^{30}) formed by capture of an α-particle and emission of a neutron, and therefore having too high a charge for their mass.

A consequence of assumption (b) is that two isobares differing by 1 in atomic number can only be stable if the difference of their masses is less than the mass of electron and neutrino together. For otherwise the heavier of the two elements would disintegrate with emission of a neutrino and either a positive or negative electron. There will be only a limited region on the mass defect curve, probably at medium atomic weight, where such small differences are possible. In fact, neighbouring isobares have only been found with the mass numbers 87, 115, 121, 123, (187), (203), while isobares with atomic numbers differing by 2 are very frequent. In the first case, one of the two nuclei (Rb) is known to emit β-rays. In each of the last two cases one of the two isobares is stated to be exceedingly rare and its identification might be due to experimental error. The other three cases actually lie close together and have medium weight. A particular case of isobares are proton and neutron. Since all experimentally deduced values of the neutron mass lie between 1·0068 and 1·0078, they are certainly both stable even if the mass of the neutrino should be zero.

The possibility of creating neutrinos necessarily implies the existence of annihilation processes. The most interesting amongst them would be the following: a neutrino hits a nucleus and a positive or negative electron is created while the neutrino disappears and the charge of the nucleus changes by 1.

The cross section σ for such processes for a neutrino of given energy may be estimated from the lifetime t of β-radiating nuclei giving neutrinos of the same energy. (This estimate is in accord with Fermi's model but is more general.) Dimensionally, the connexion will be

$$\sigma = At$$

where A has the dimension cm.[4] sec. The longest length and time which can possibly be involved are $\hbar/mc$ and $\hbar/mc^2$. Therefore

$$\sigma < \frac{\hbar^3}{m^3c^4t}$$

For an energy of $2 \cdot 3 \times 10^6$ volts, t is 3 minutes and therefore $\sigma < 10^{-44}$ cm.[2] (corresponding to a penetrating power of 10^{16} km. in solid matter). It is therefore absolutely impossible to observe processes of this kind with the neutrinos created in nuclear transformations.

With increasing energy, σ increases (in Fermi's model[3] for large energies as $(E/mc^2)^2$) but even if one assumes a very steep increase, it seems highly of this kind with the neutrinos created in nuclear transformations.

With increasing energy, σ increases (in Fermi's model[3] for large energies as $(E/mc^2)^2$) but even if one assumes a very steep increase, it seems highly improbable that, even for cosmic ray energies, σ becomes large enough to allow the process to be observed.

If, therefore, the neutrino has no interaction with other particles besides the processes of creation and annihilation mentioned—and it is not necessary to assume interaction in order to explain the function of the neutrino in nuclear transformations—one can conclude that there is no practically possible way of observing the neutrino.

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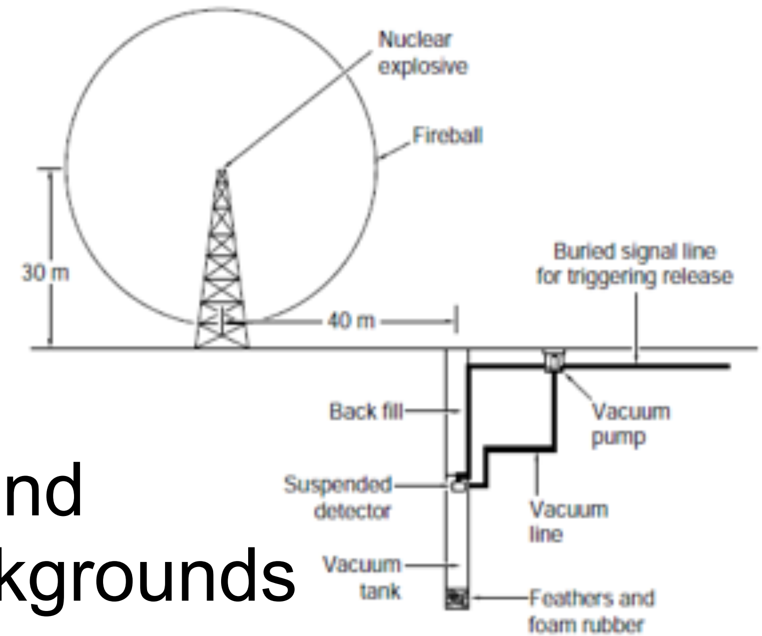
University,
Manchester.
Feb. 20.

[1] W. Pauli, quoted repeatedly since 1931, to be published shortly in "Rapports du Septième Conseil Solvay, Brussels", 1933.
[2] C. D. Ellis and N. F. Mott, Proc. Roy. Soc., A, 141, 502; 1933.
[3] E. Fermi, La Ricerca Scientifica, 2, No. 12; 1933.
[4] This point of view was first put forward by I. Curie and F. Joliot at the Conseil Solvay, 1933.
[5] I. Curie and F. Joliot, NATURE, 133, 201, Feb. 10, 1934.

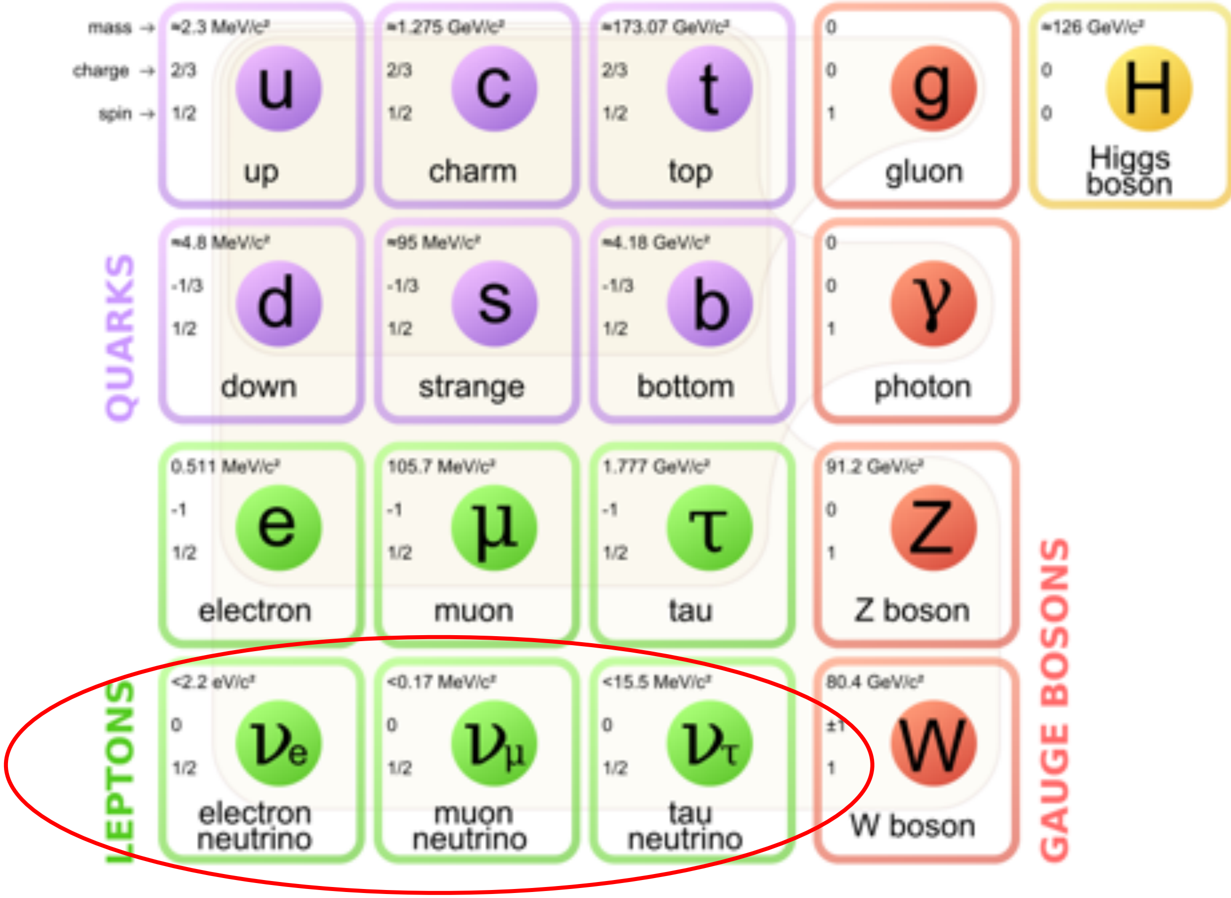
First neutrino detection

- Need intense source of neutrinos
- Nuclear bomb
  - Almost went with it, but found a better way to handle backgrounds
- Nuclear reactor
  - Source of electron anti neutrinos
  - 1956 Cowan & Reines detect first neutrinos



$$\overline{\nu} + p \rightarrow n + e^{+}$$

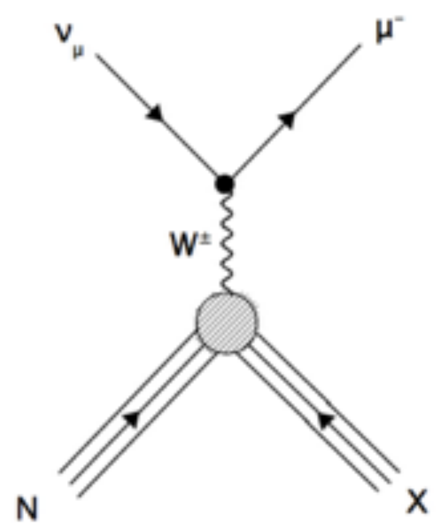
Standard Model



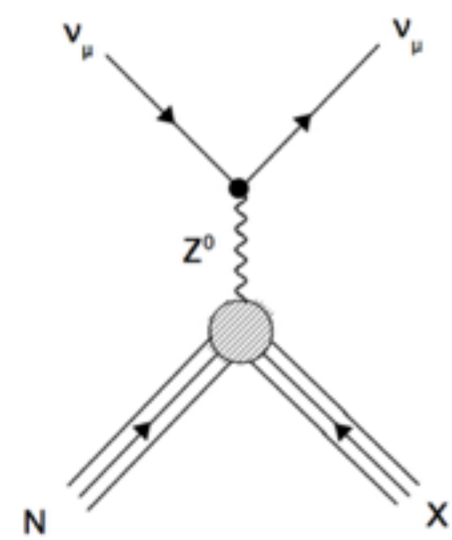
Neutrino detection

- We detect outgoing particles created when neutrino interacts
- Two types of interactions:

Charged current
-Possible to determine incoming neutrino type and energy



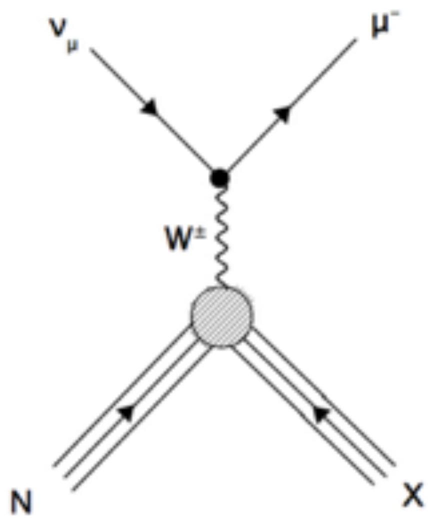
Neutral current
-No information about incoming neutrino flavor or energy

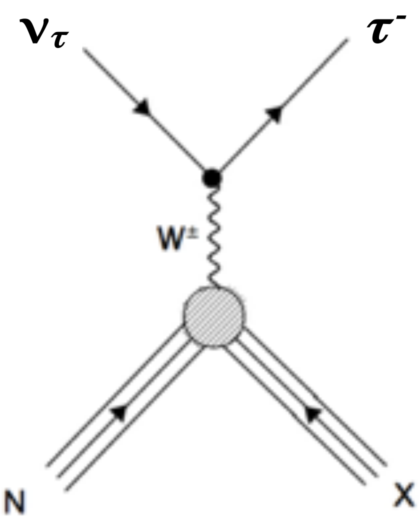


Cross sections

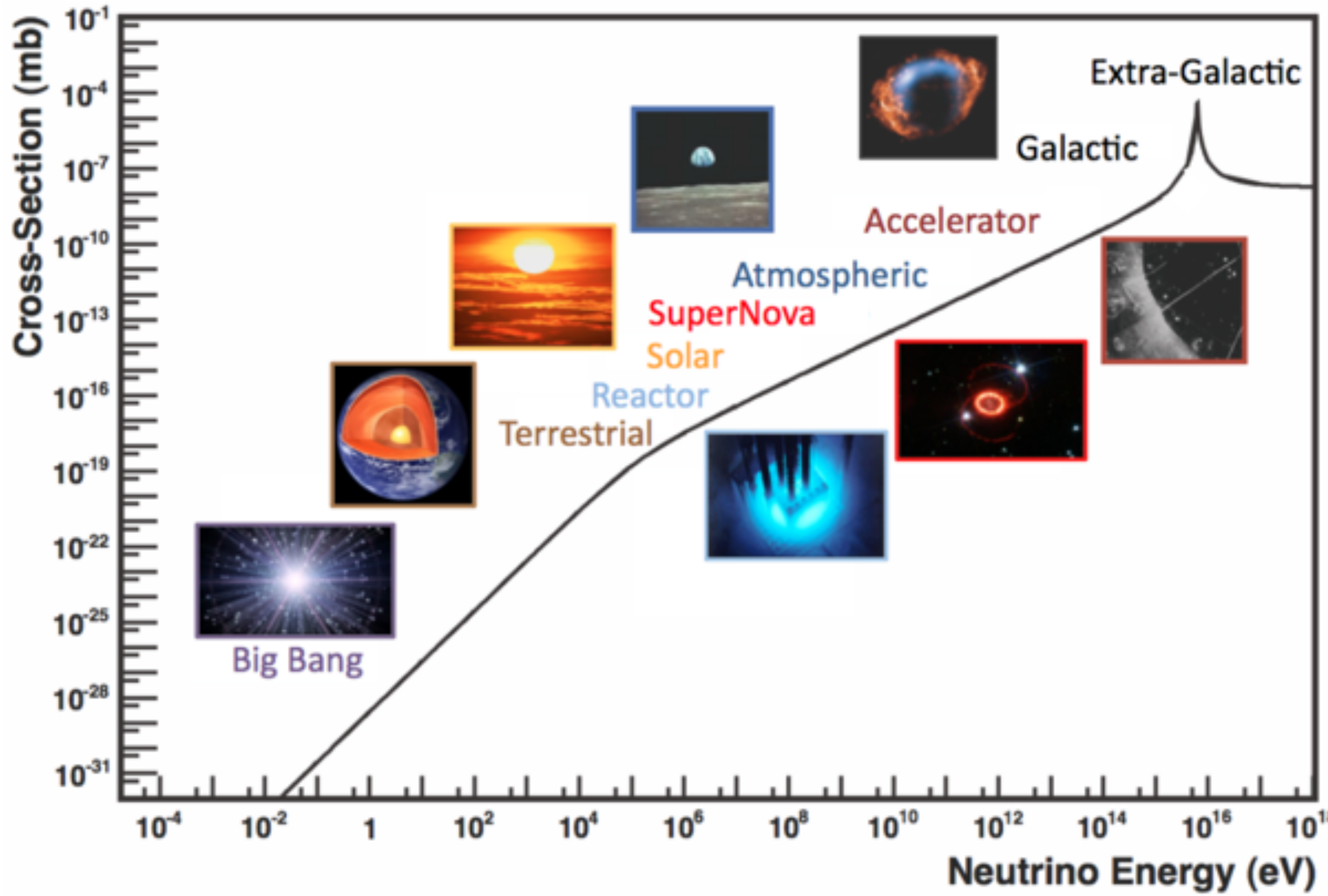
- Thresholds for CC interactions
  - neutrino needs to have enough energy to produce the outgoing lepton

$$E_{\nu_\mu} > 110\,\mathrm{MeV} \qquad\qquad E_{\nu_\tau} > 3.5\,\mathrm{GeV}$$





Neutrino sources



J.A. Formaggio, G.P. Zeller Rev.Mod.Phys. 84 (2012) 1307

Neutrino sources

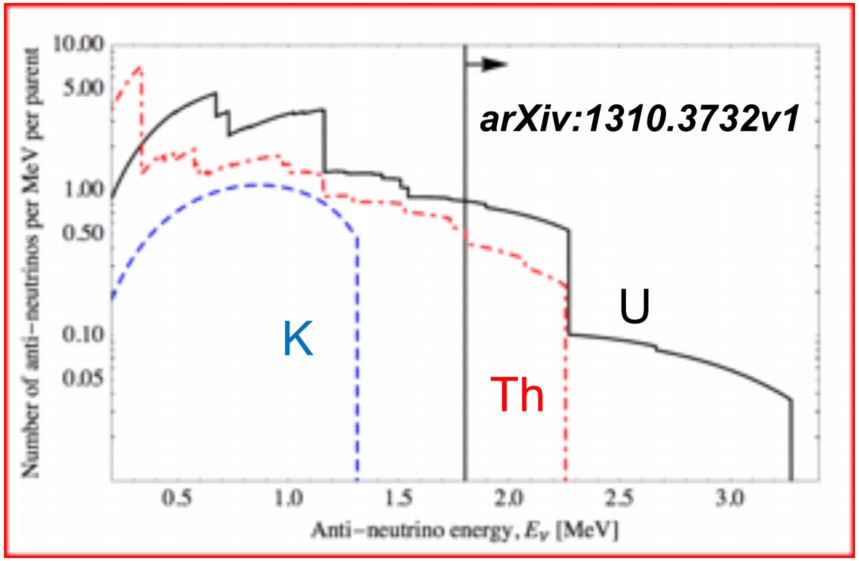
- Geoneutrinos
- Solar
- Atmospheric
- Supernova
- Radioactive sources
- Reactor
- Accelerator

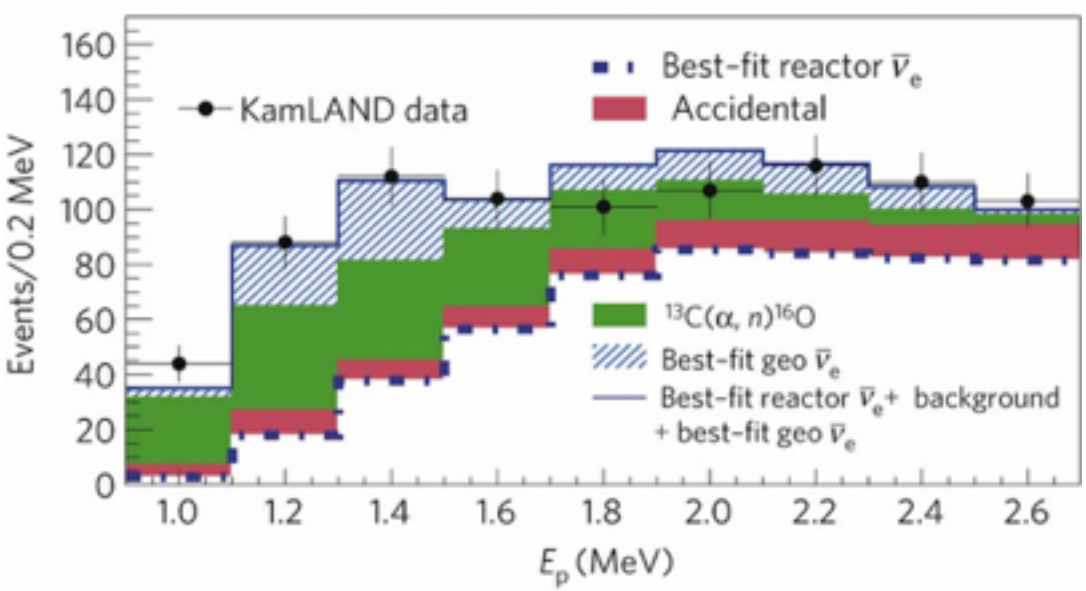
No control over source

Controlled sources

Radioactive sources

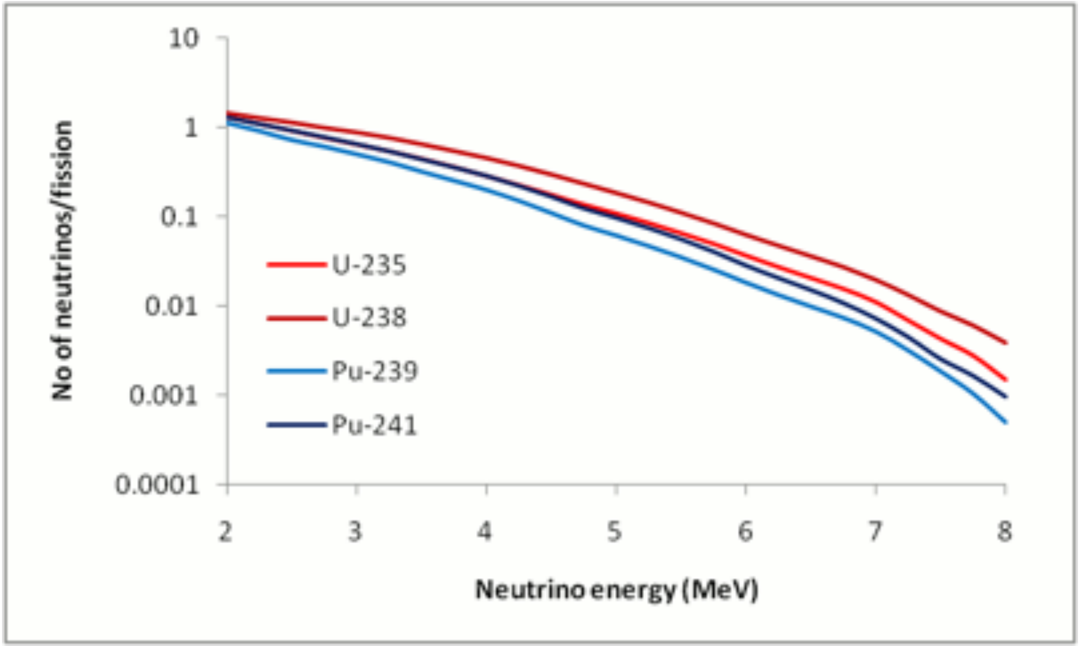
- Radioactive source
  - ~MCi sources
  - Pointlike
  - 10^{12}-10^{16} ν/kg/s
- Geoneutrinos
  - Decays of Uranium, Thorium, Potassium within Earth
  - ~10^{6} ν /cm^{2}/s



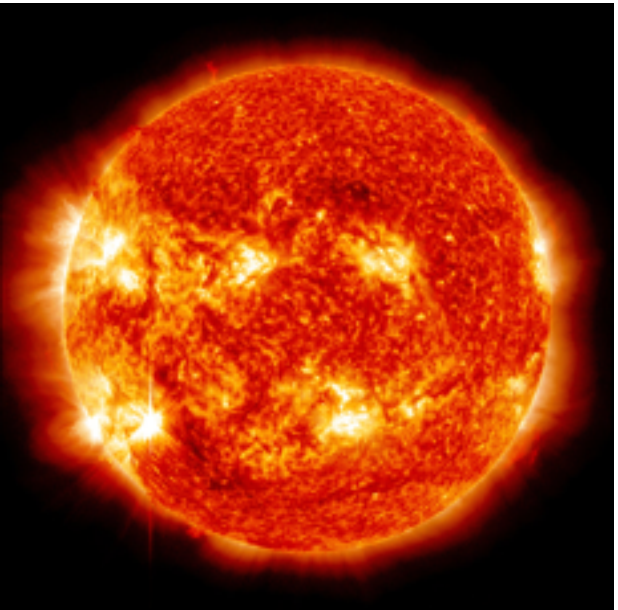


Reactor neutrinos

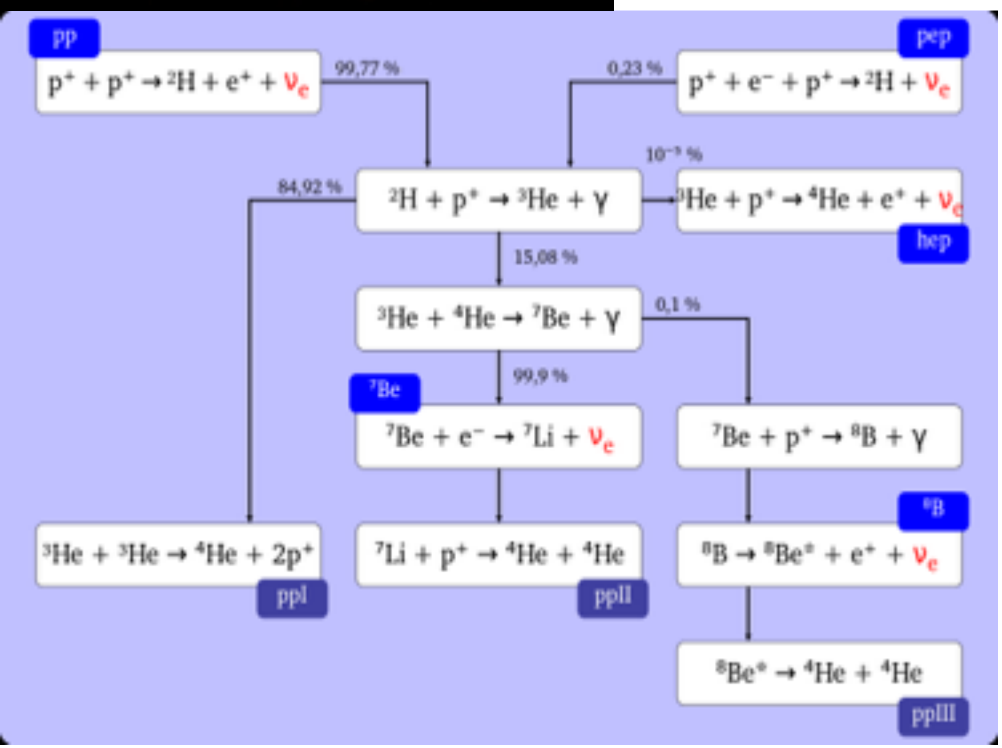
- Powerful source of $\bar{\nu}_e$
- Neutrinos from beta decays of fission products
- Average reactor core produces ~10^{20} $\bar{\nu}_e$/s

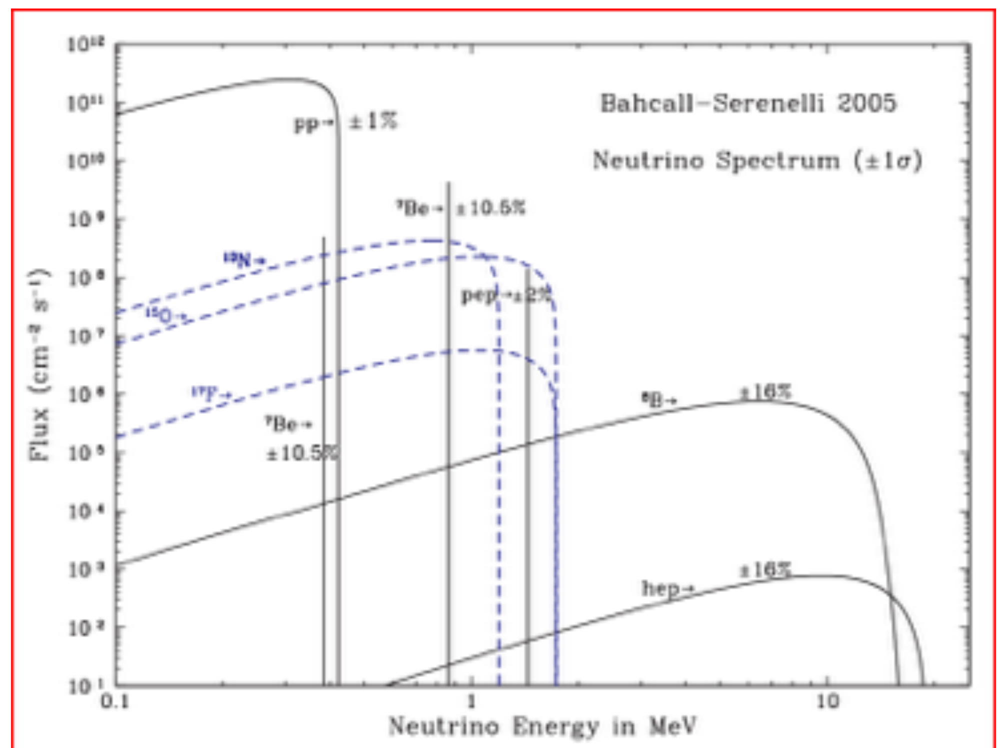


Solar neutrinos

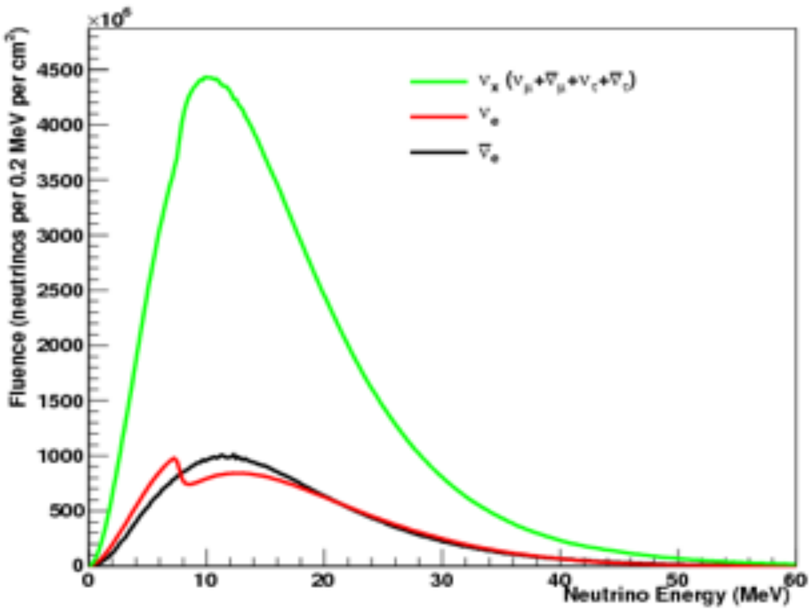


- Standard solar model
- Flux at Earth ~$10^{11}/cm^2/s$





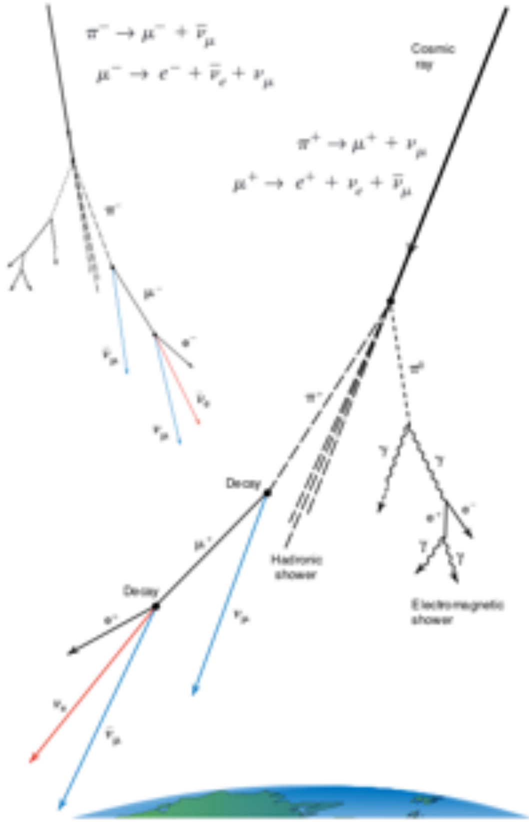
Supernova neutrinos

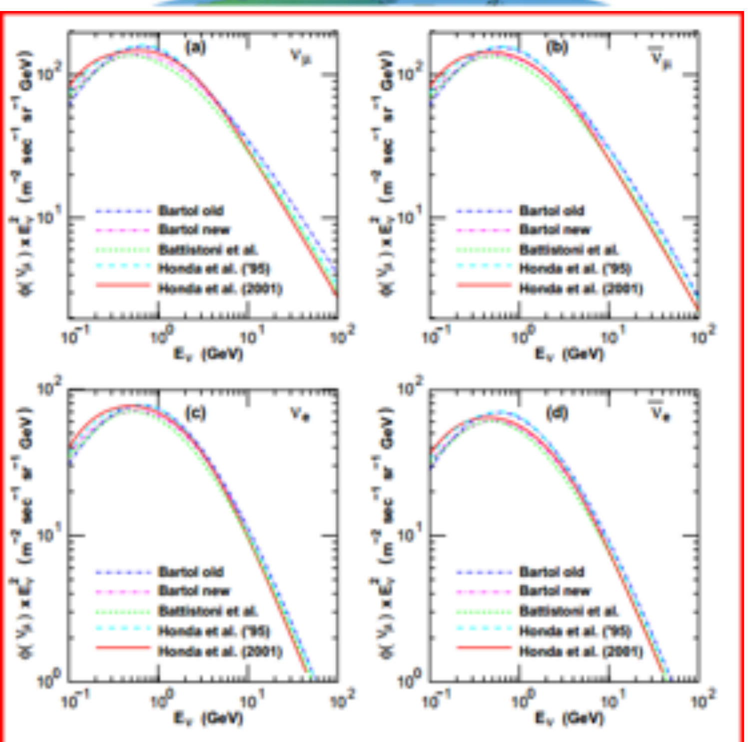


Integrated flux over 10s

- Core collapse supernova produces a large burst of neutrinos (~10^{58})
- Almost all gravitational energy released through neutrinos
- Carry information about supernova mechanism
- Help us understand physics of neutrinos

Scholberg, Kate Ann.Rev.Nucl.Part.Sci. 62 (2012) 81-103 arXiv:1205.6003 [astro-ph]





Atmospheric neutrinos

- Cosmic rays (mostly protons) interact in upper atmosphere creating hadronic showers (mostly pions)
- Roughly 2:1 muon neutrinos to electron neutrinos
- Total fluxes known to ~20%, however ratios at few % level

Accelerator neutrinos

- Intense source
- Well controlled
  - Energy
  - Timing

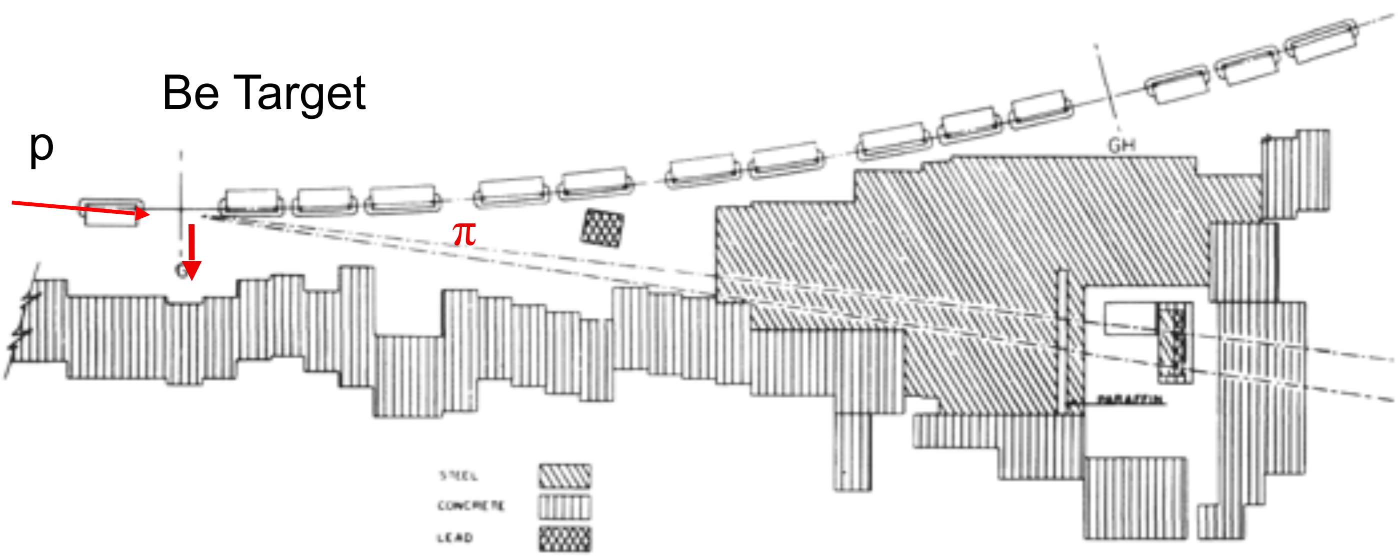
- I'll focus on conventional neutrino beams (not going to talk about stopped pion sources, beta beams, neutrino factory)
- Neutrinos produced in $\pi/K/\mu$ decays

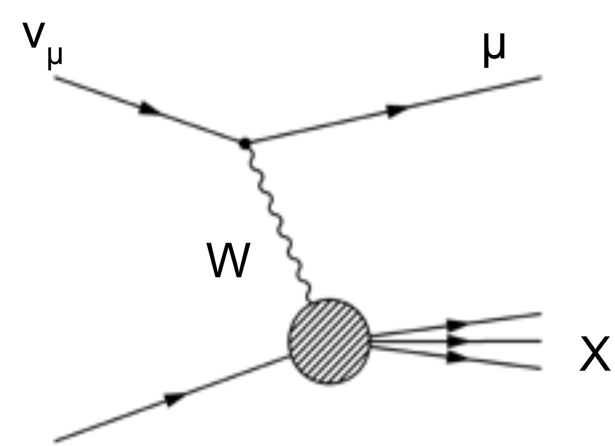
First accelerator experiment

- Idea independently proposed by Pontecorvo and Schwartz
- 1962 Lederman, Schwartz & Steinberger using AGS at BNL

$$p+Be \rightarrow \pi^{+} + X$$
$$\hookrightarrow \mu^{+} + \nu_{\mu}$$

- Detected muon neutrino → existence of two kinds of neutrinos





Phys.Rev.Lett. 9, 36 (1962)

Neutrinos in the beam

- Dominant source is pion decay $\pi \to \mu + \nu_\mu$ (BR≈100%)
  - Simple 2 body decay in CM system
  - Neutrino energy:

$$E_\nu \approx \frac{0.43 E_\pi}{1+\gamma^2\theta^2}$$

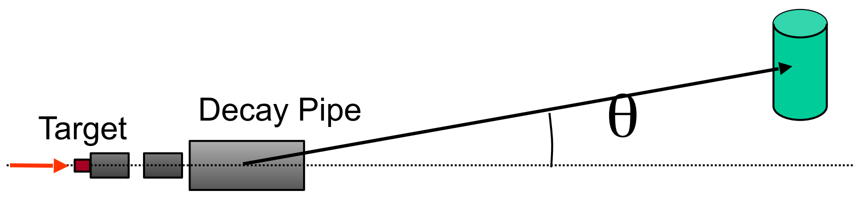
- Neutrinos boosted in the direction of the proton beam

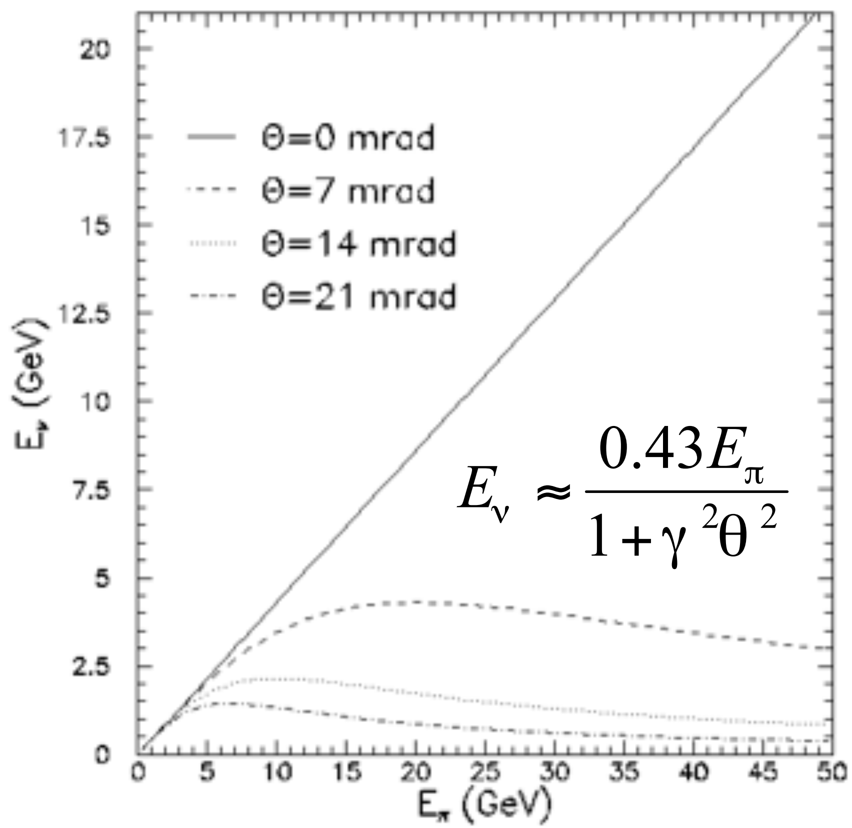
$$\frac{dN}{d\Omega} \approx \frac{1}{4\pi}\left(\frac{2\gamma}{1+\gamma^2\theta^2}\right)^2$$

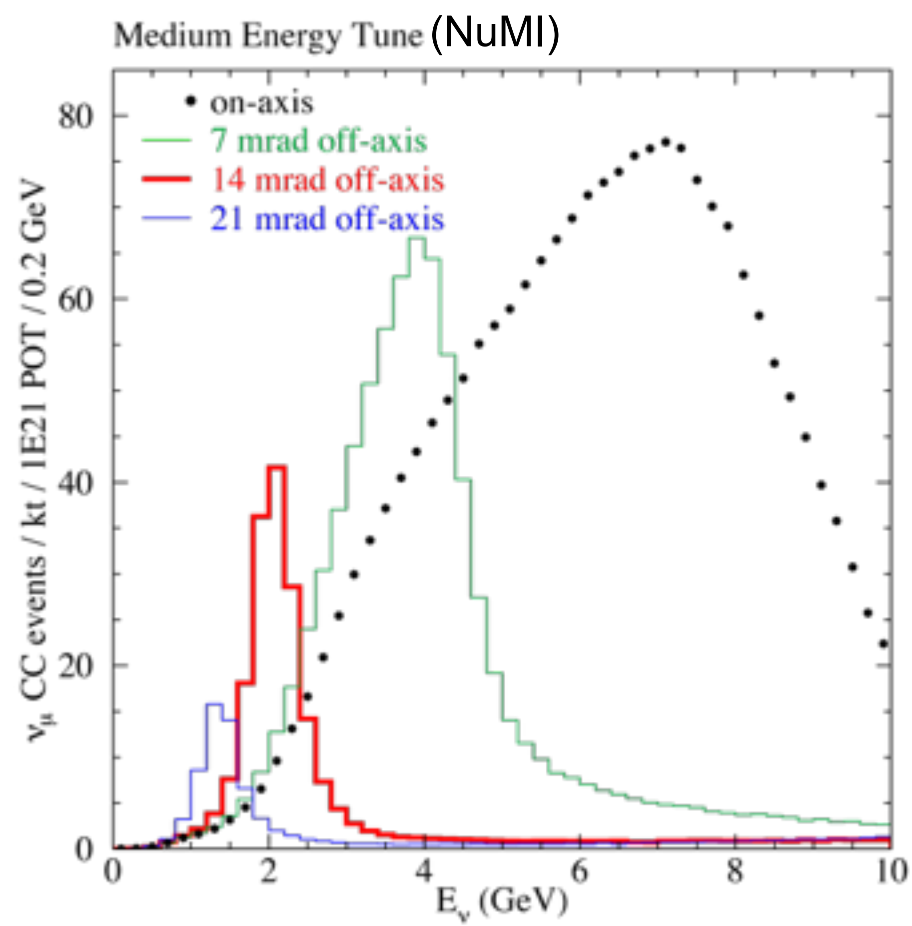
- Fraction of events from kaon and muon decays – add electron neutrino component

Off-axis flux

- On-axis neutrino energy tightly related to hadron energy
- Off-axis, neutrino spectrum is narrow-band and softened
- Concept used by NOvA and T2K







Focusing the beam

- Angle of neutrinos from pion decays with respect to pion momentum ~1/ γ
- Pions emerge from target with angle ~2/γ
- Removing pion divergence would increase flux by ~25x
- Simon van der Meer developed magnetic device to focus secondaries emerging from the target

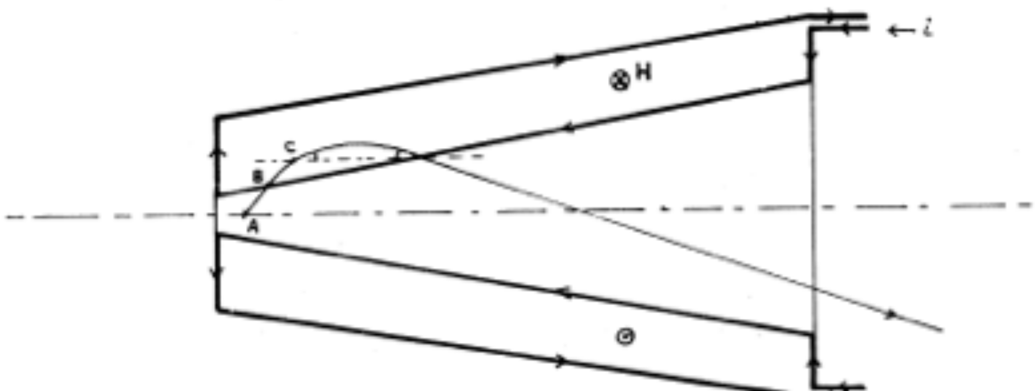
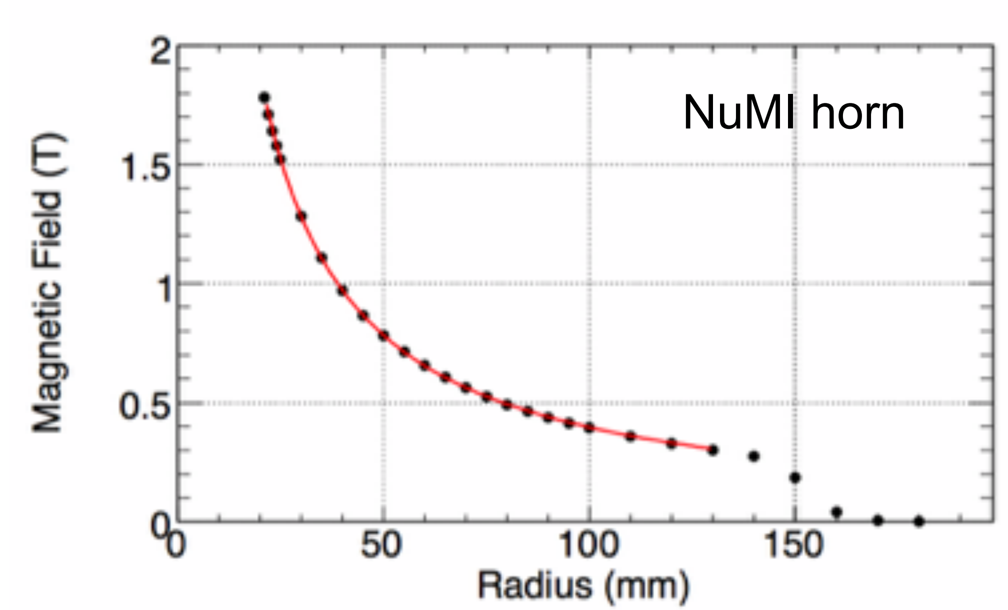


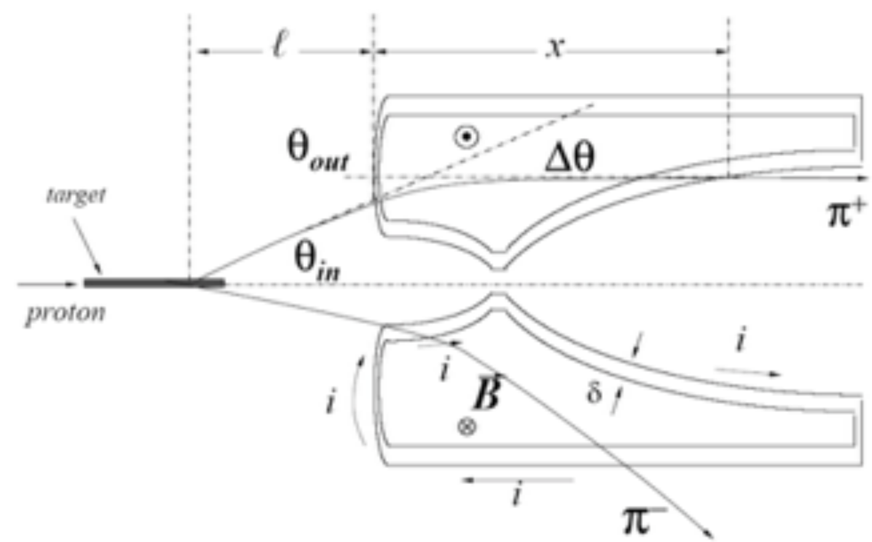
Fig.2

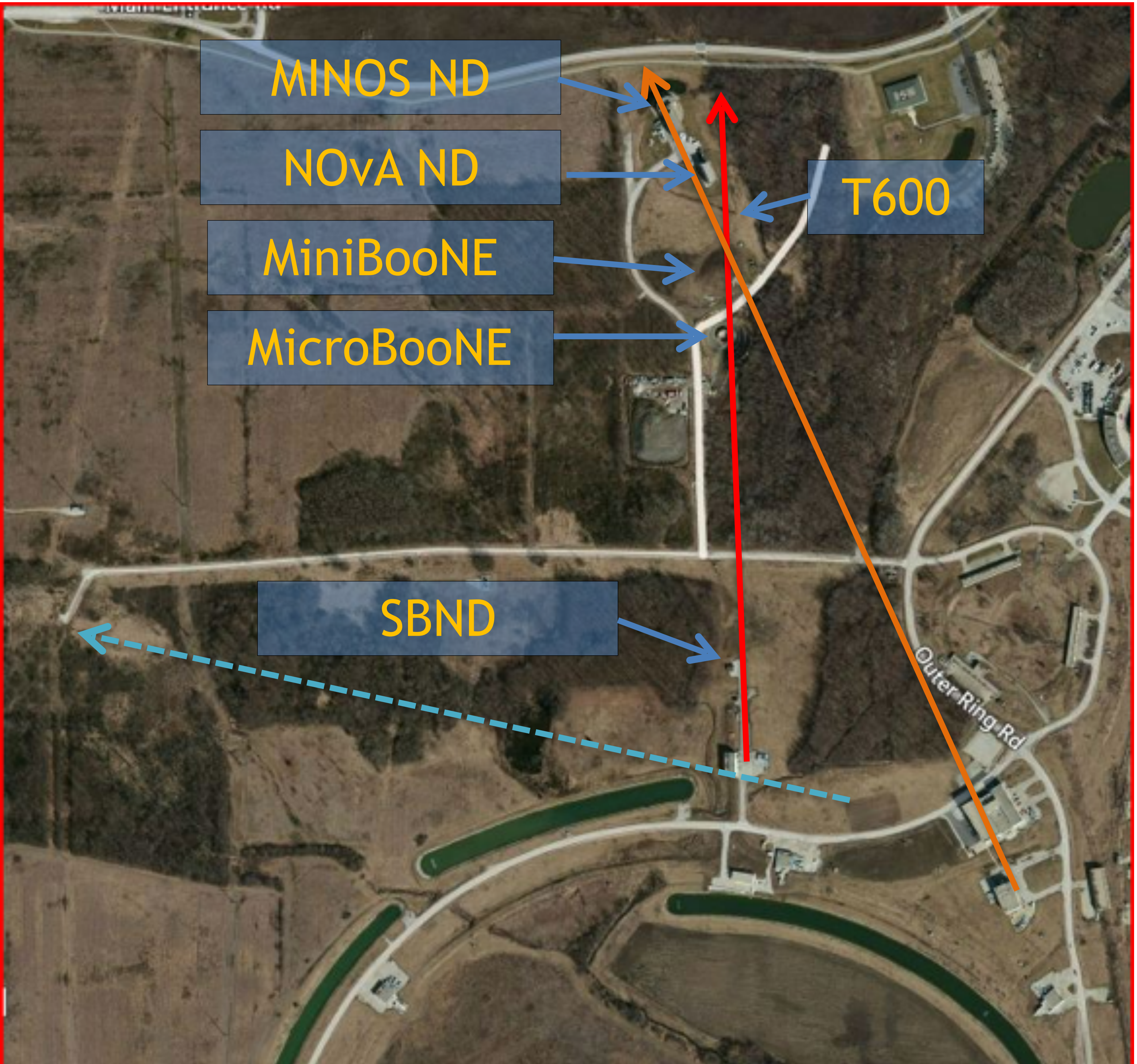
Focusing the beam (cont'd)

- Field inside the horn drops with 1/r
- Inner conductor shaped such that pions at wider angle get more kick (∫Bdl)



NuMI horn 2

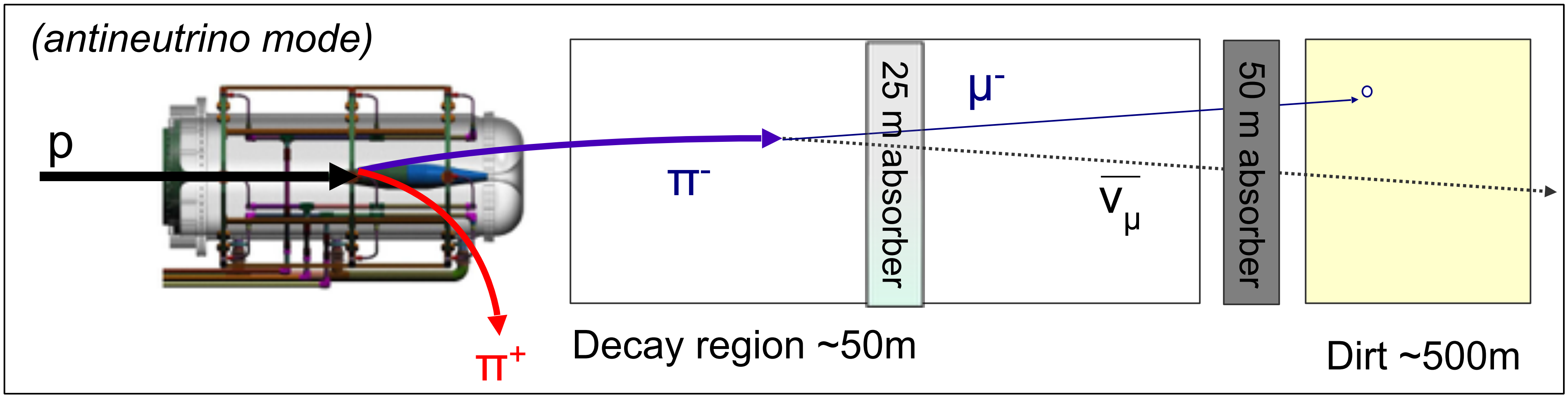




Fermilab neutrino beamlines

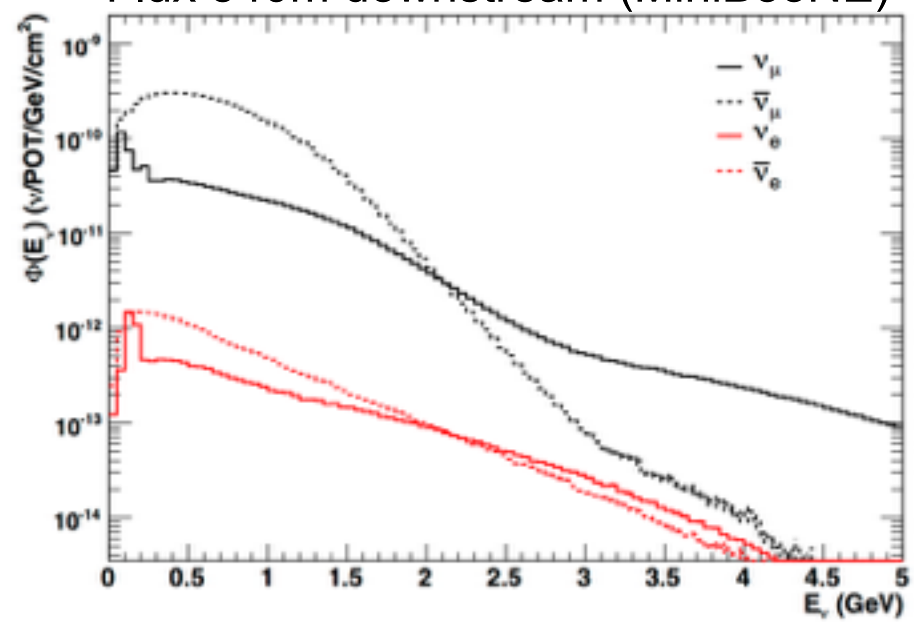
- BNB
- NuMI
- LBNF

Fermilab neutrino beams - BNB

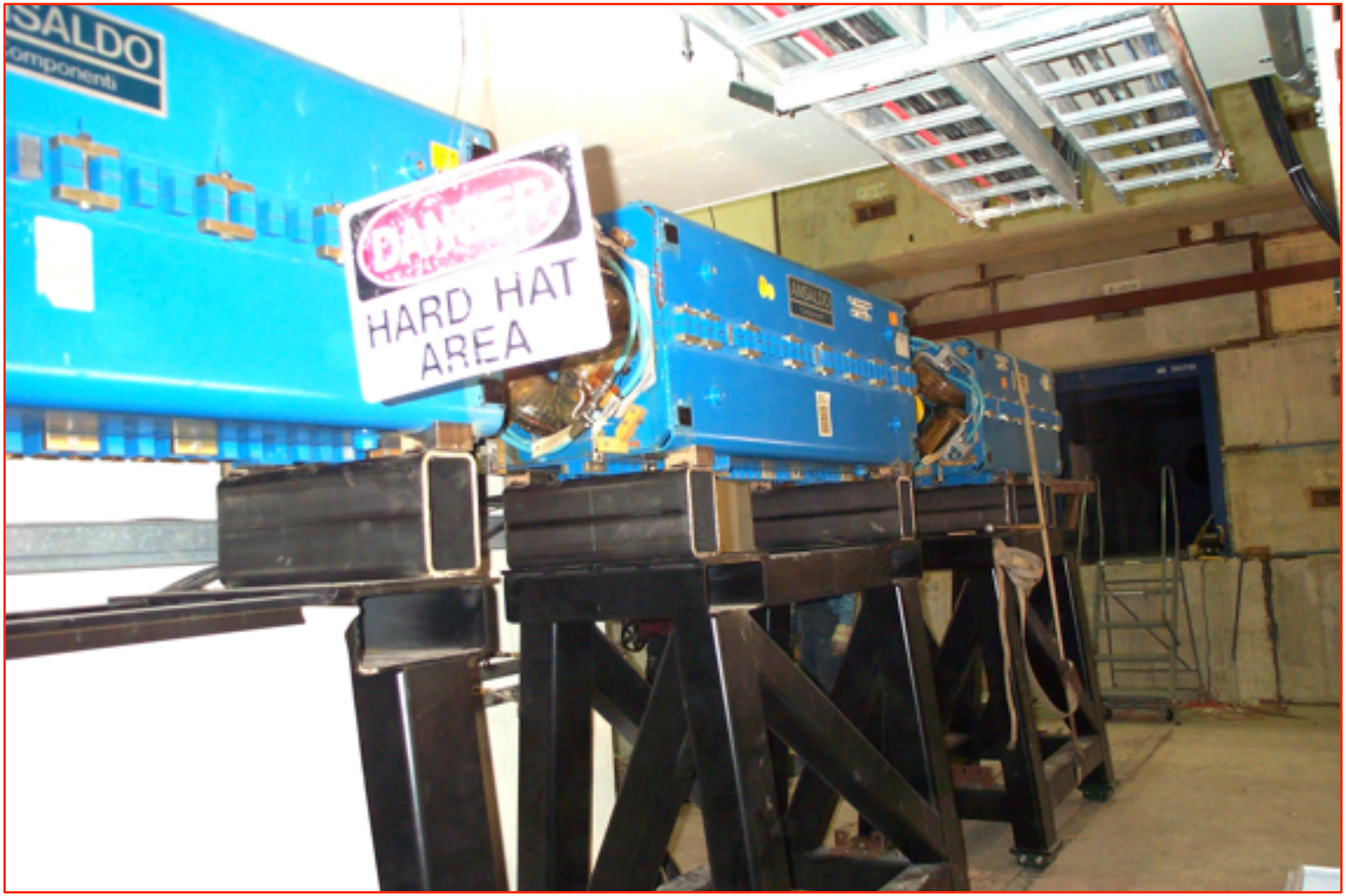


- 8GeV protons from Booster
- Beryllium target
- Focusing horn pulsed with 174kA
- 50m long decay pipe (deployable 25m absorber)

Flux 540m downstream (MiniBooNE)

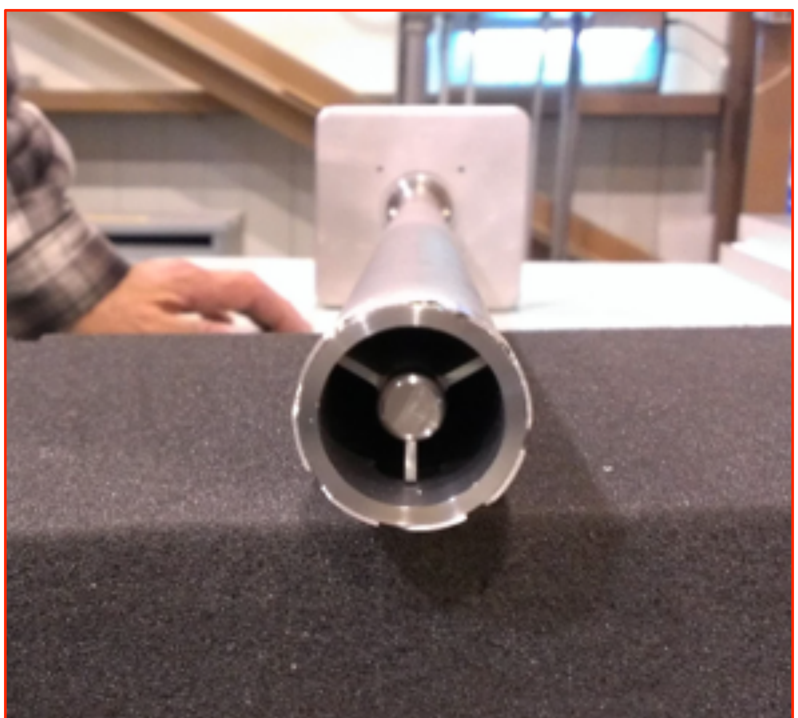


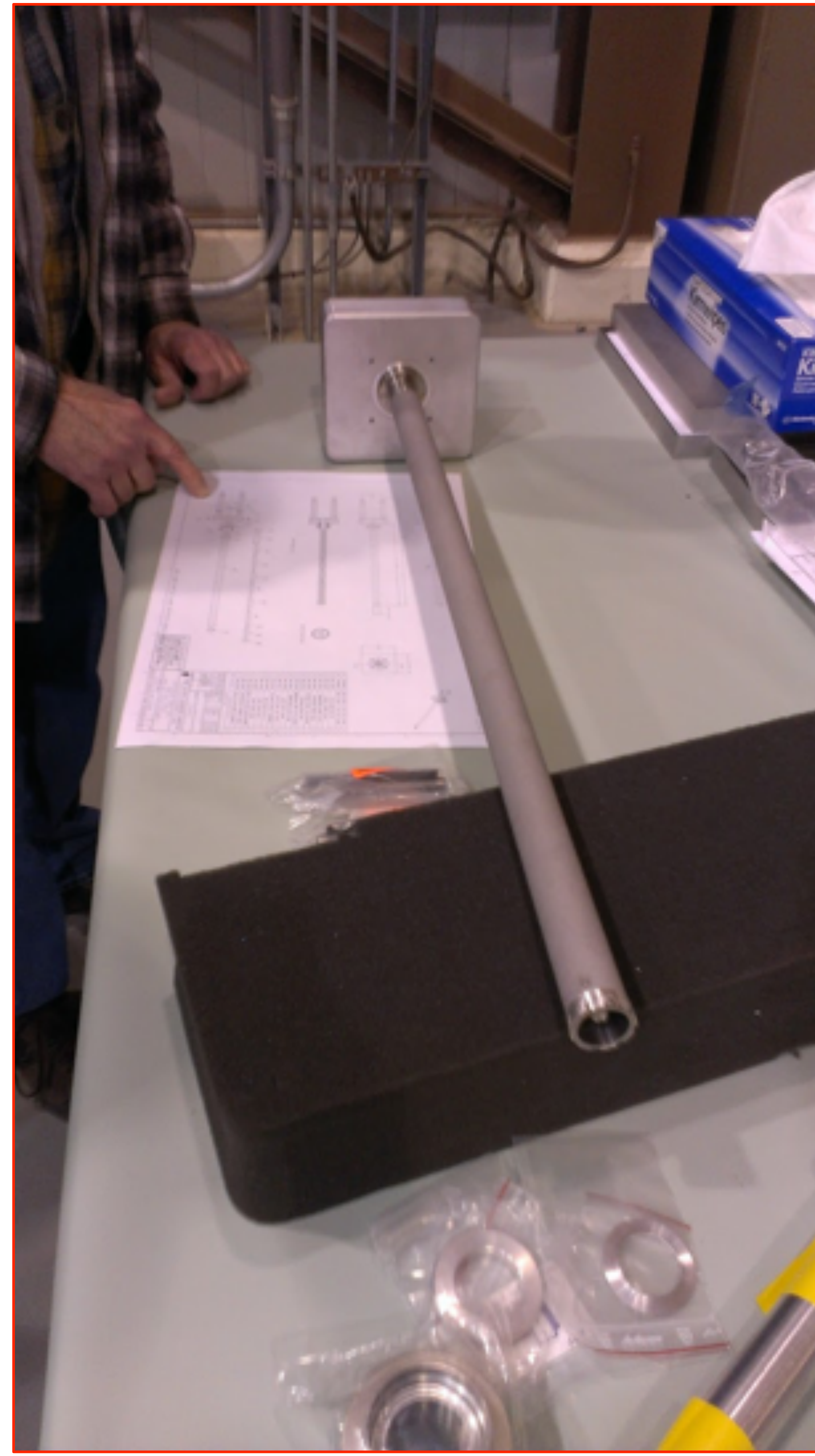
BNB - Primary beamline



BNB - Target

- 70 cm long Be target
- Seven slugs, each 10cm long and 1cm diameter
- Encased in outer Be tube
- Air cooled

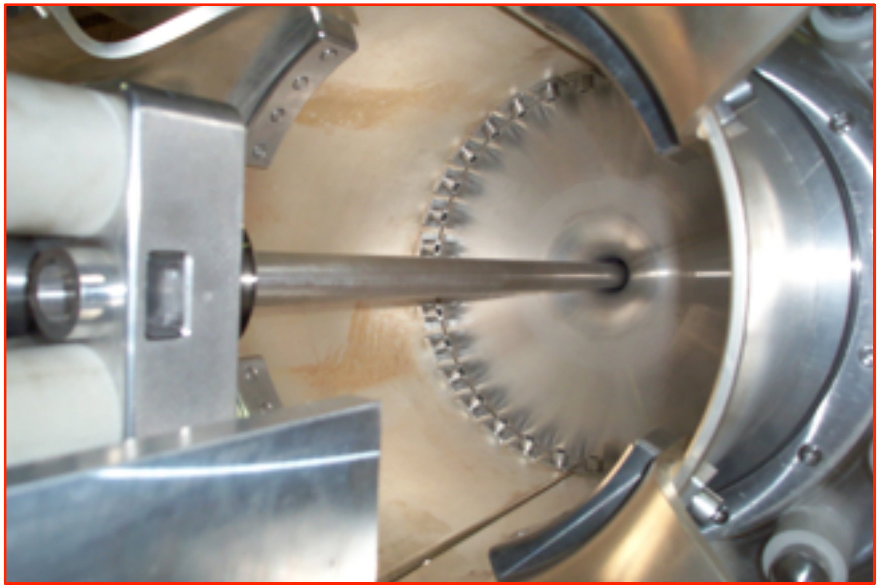




BNB - Horn

- 1.8m long
- Pulsed with 174kA (positive or negative)
- Replaced 2 horn/target assemblies since start of running

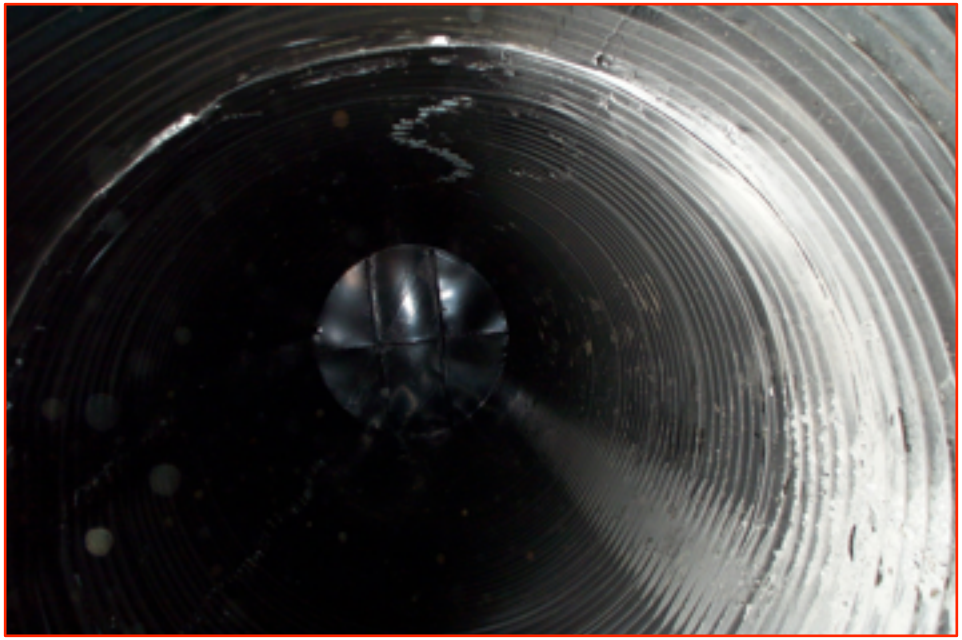
Horn	Pulses	POT
1	97M	3.7E+20
2	375M	1.6E+21
3	80M	3.5E+20



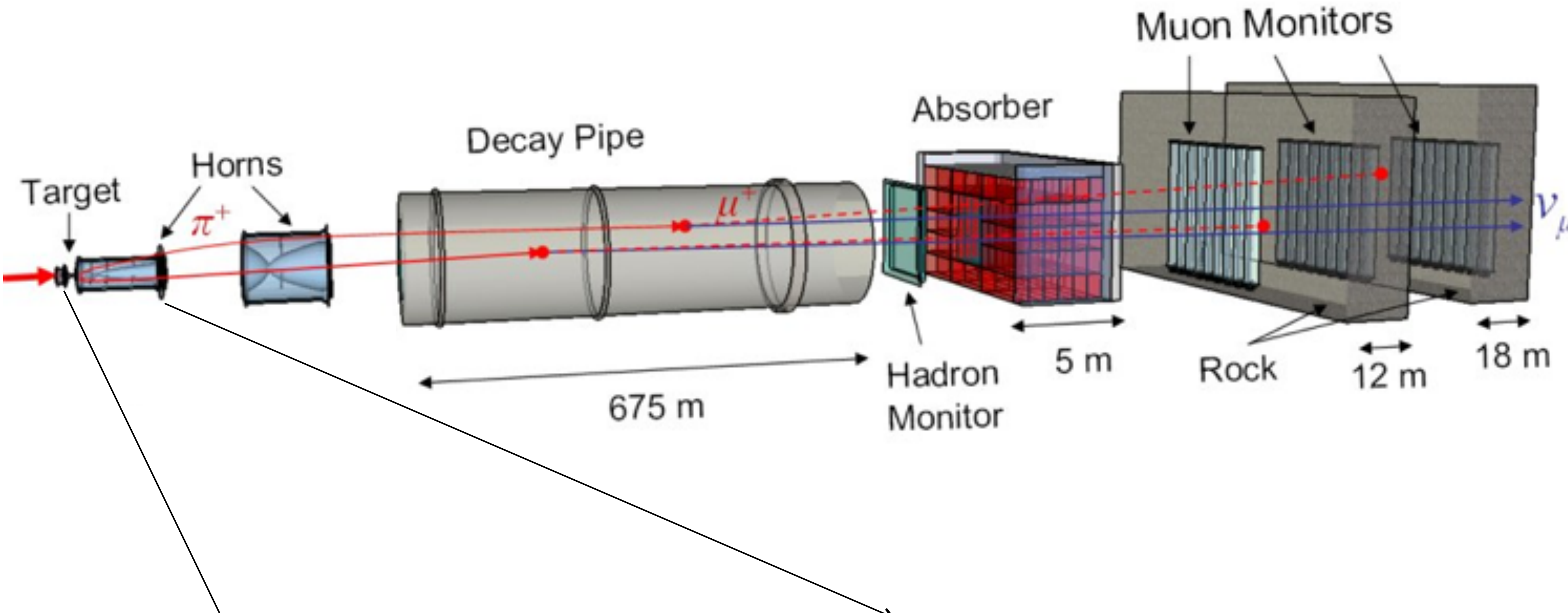
BNB - target hall

BNB - Decay pipe

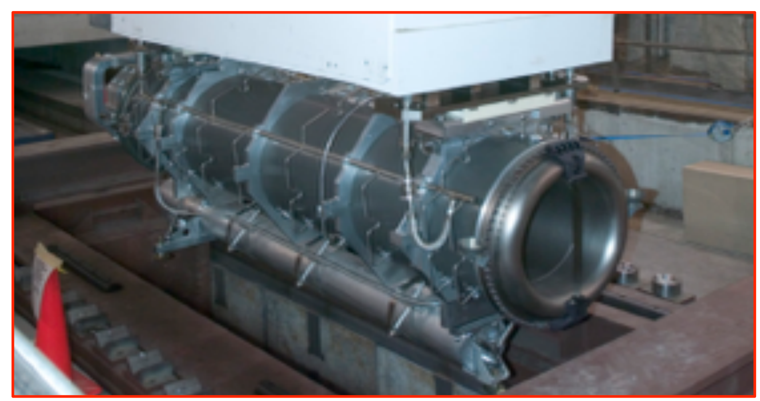
- 50m long decay pipe
- 1m radius steel pipe covered with dolomite
- deployable absorber at 25m



Fermilab neutrino beams - NuMI

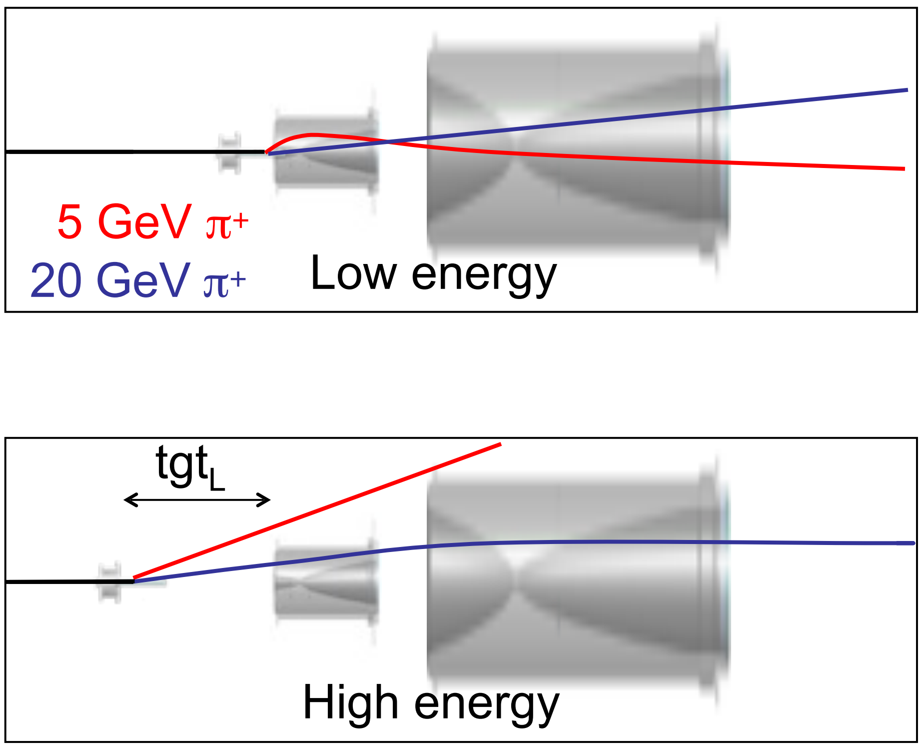


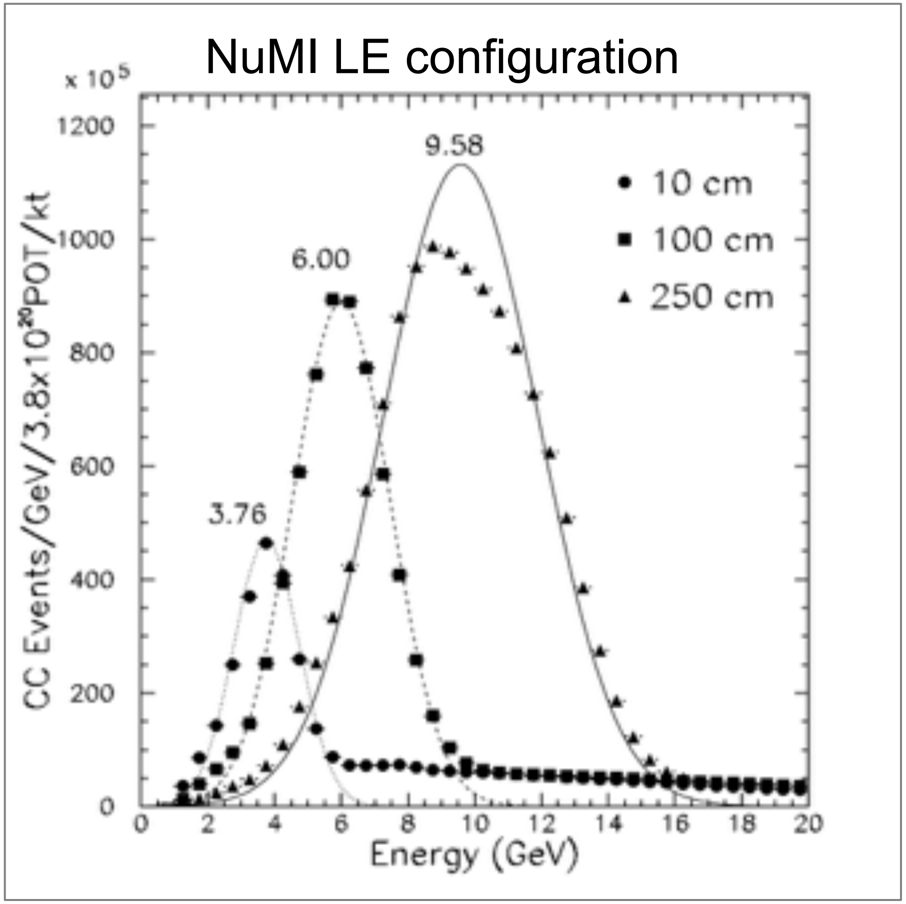
Low energy target



Tune neutrino energy

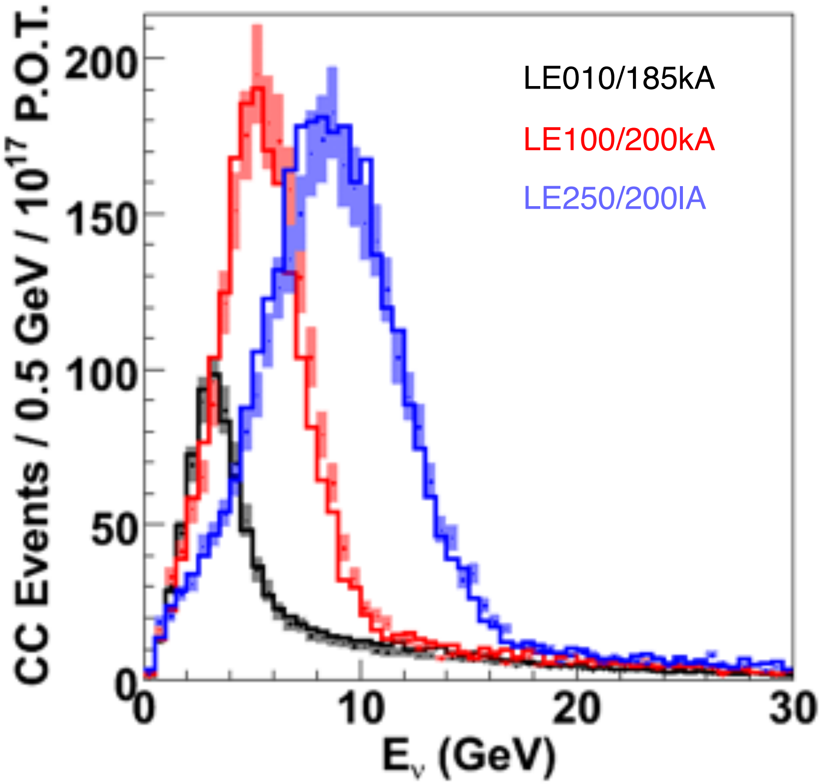
- Neutrino spectrum depends on target position with respect to horn
- NuMI had capability to tune the neutrino energy

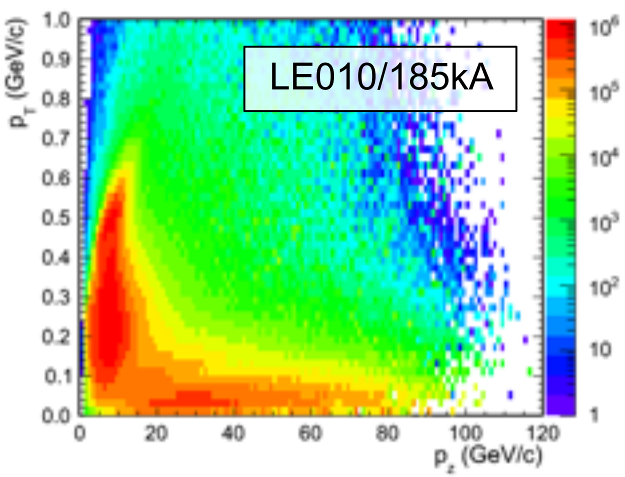


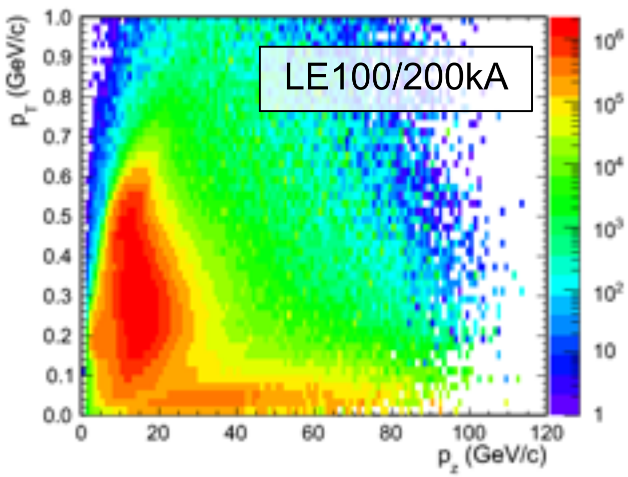


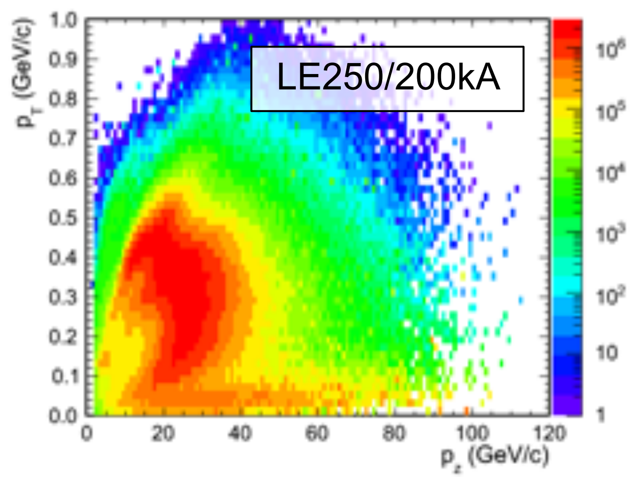
NuMI energy tuning

- Different beam tunes probe different regions of π (x_F,p_T)
- In MINOS era target was installed on a carrier which allowed it to be moved upstream by up to 250cm
- For NOvA running target and horns were repositioned to produce more optimized medium energy spectrum



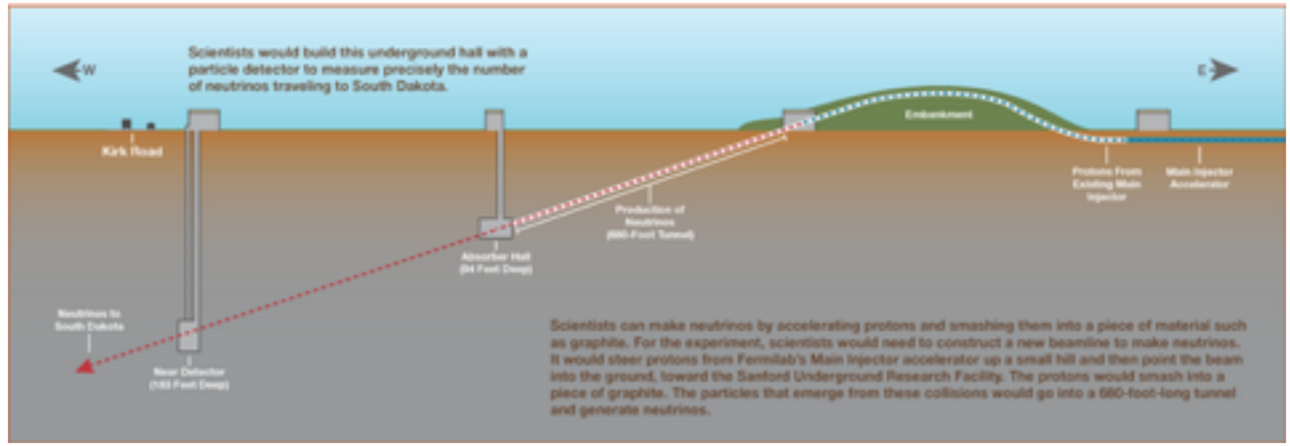


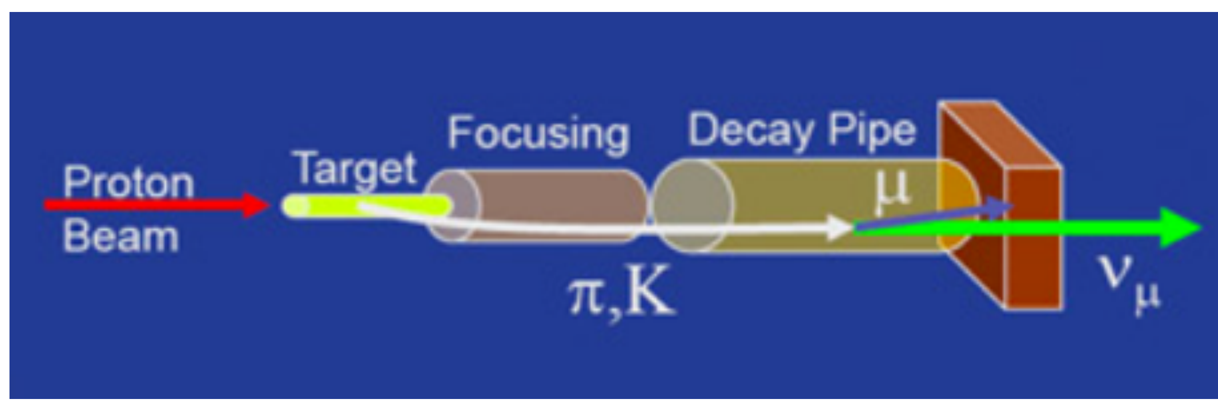




Fermilab neutrino beams
Long Baseline Neutrino Facility

- Beamline being designed for future long baseline experiment – DUNE
- Beam to the Sanford Underground Research Facility (SURF) in Lead, SD – 1300km away



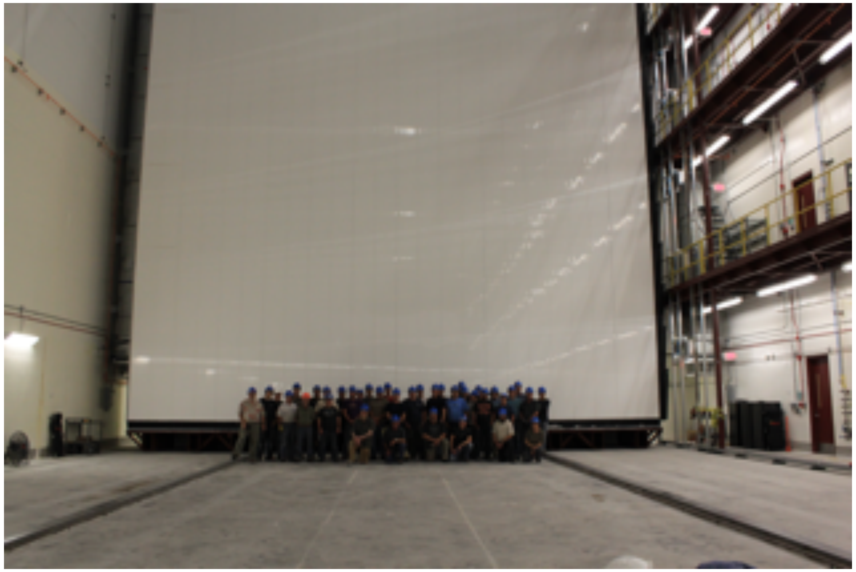


Fermilab neutrino beams

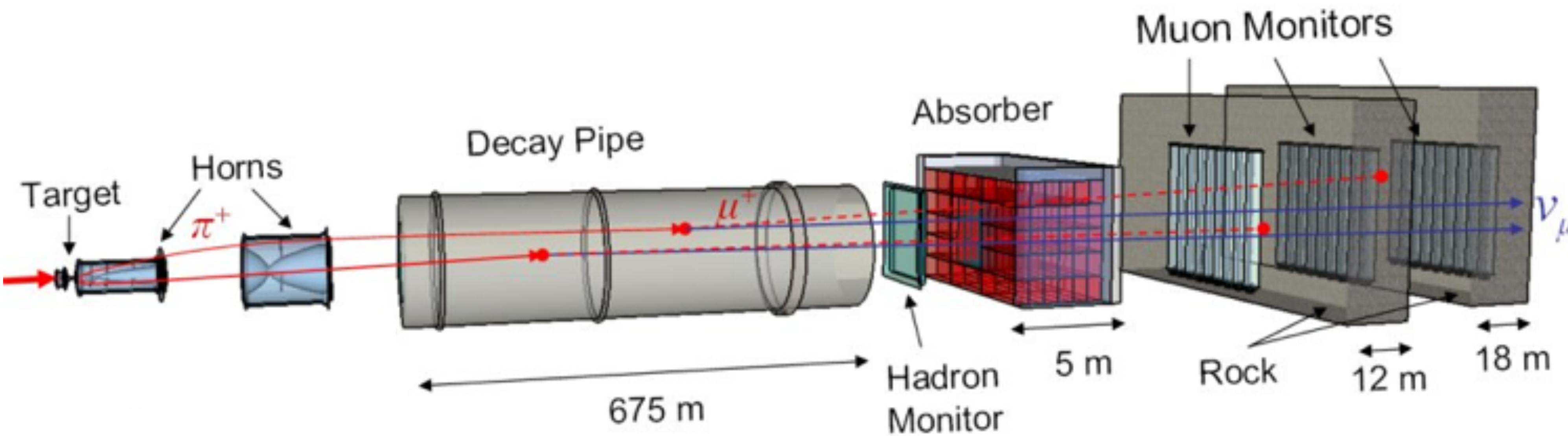
	BNB	NuMI
Primary proton beam	8 GeV from Booster	120 GeV from Main Injector
Spill length	1.6us	10us
Protons/spill	5e12	5e13
Rate	5Hz	0.75Hz
Power	30kW	700kW
Target	Beryllium	Carbon
Focusing	1 horn	2 horns
Decay pipe length	50m (deployable absorber @25m)	730m

The experiments

- BNB
  - MiniBooNE
  - SciBooNE
  - MicroBooNE
  - *SBND, ICARUS*
- NuMI
  - MINOS, MINOS+
  - ArgoNeut
  - Minerva
  - NOvA



Flux predictions



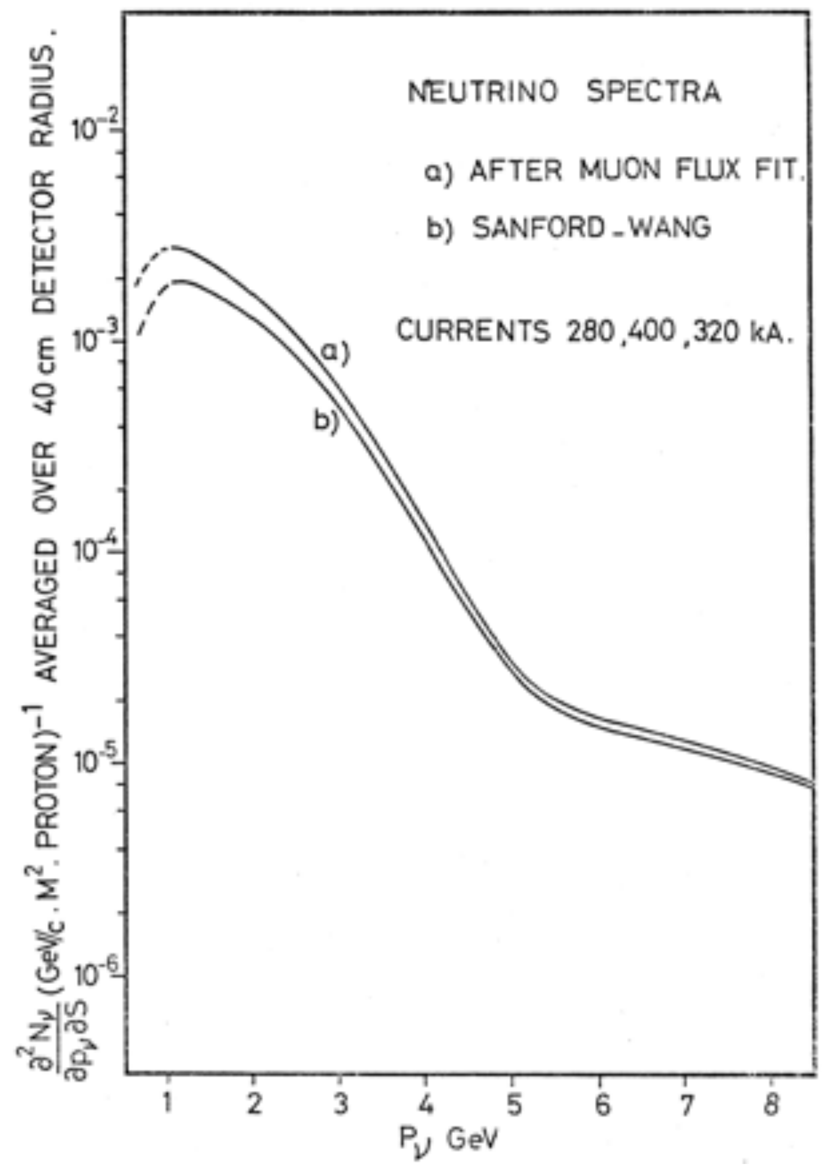
- Use MC to:
  - Predict hadron production in p+Target interactions
  - Simulate particle reinteractions in target and downstream material
  - Track charged particles through magnetic field and down to their decay point

Systematic errors

- Hadron production
  - Dominant source
- Non-hadron production
  - Proton beam
  - Focusing of secondaries
  - MC geometry

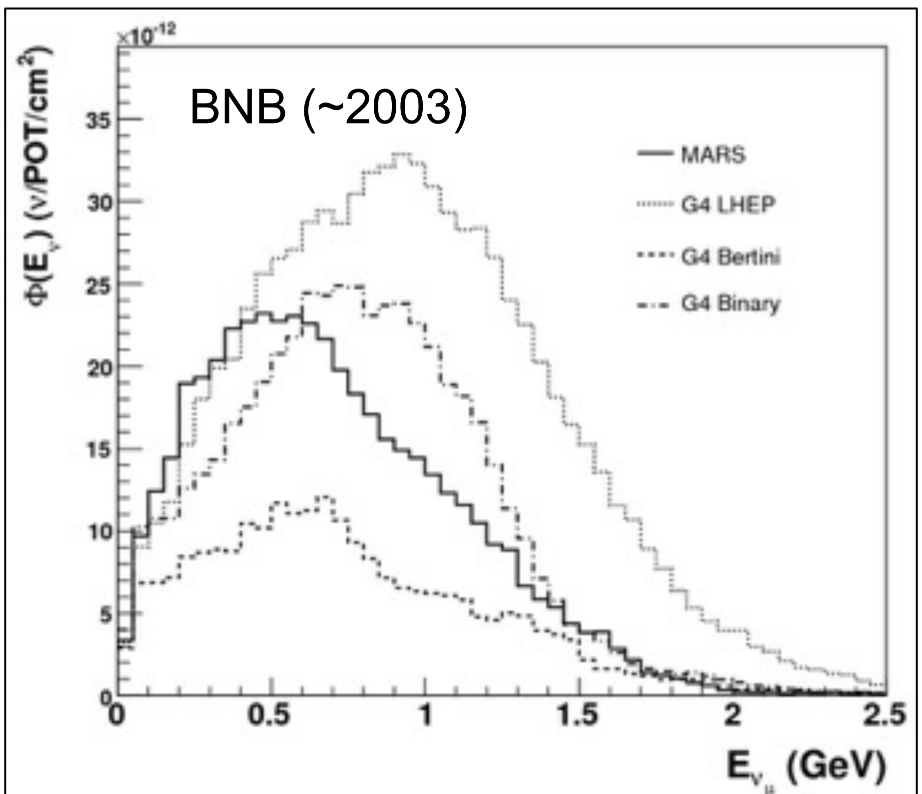
Calculating flux is hard

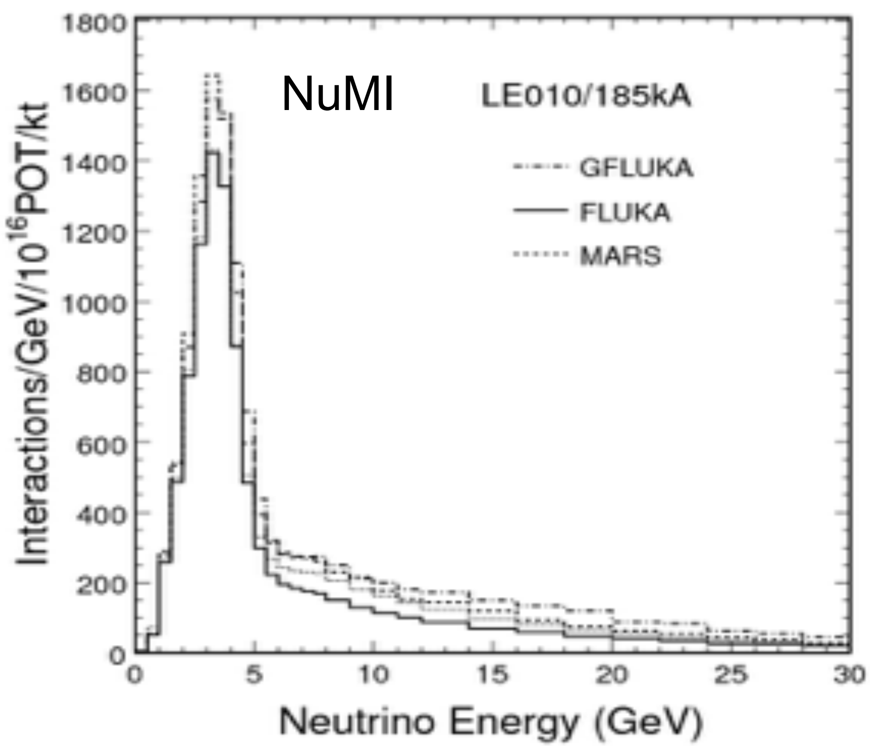
- Past neutrino experiments had to apply corrections
- More often than not flux prediction didn't match data
  - Using some process with known cross section
- Flux uncertainty large 10-30%



Hadron production

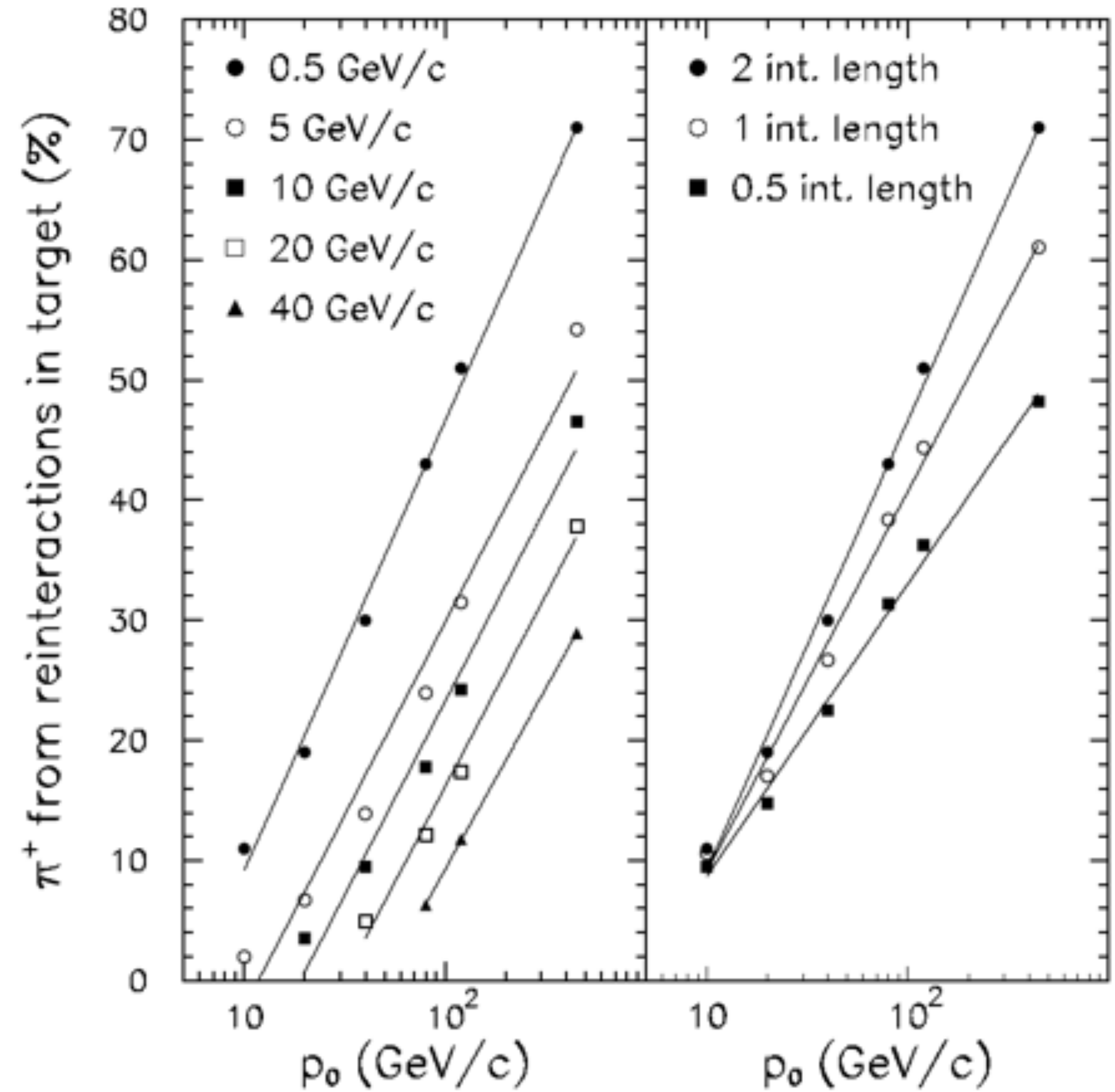
- Models give range of predictions
  - Scaling to primary proton momentum, target material
- Large initial flux uncertainty





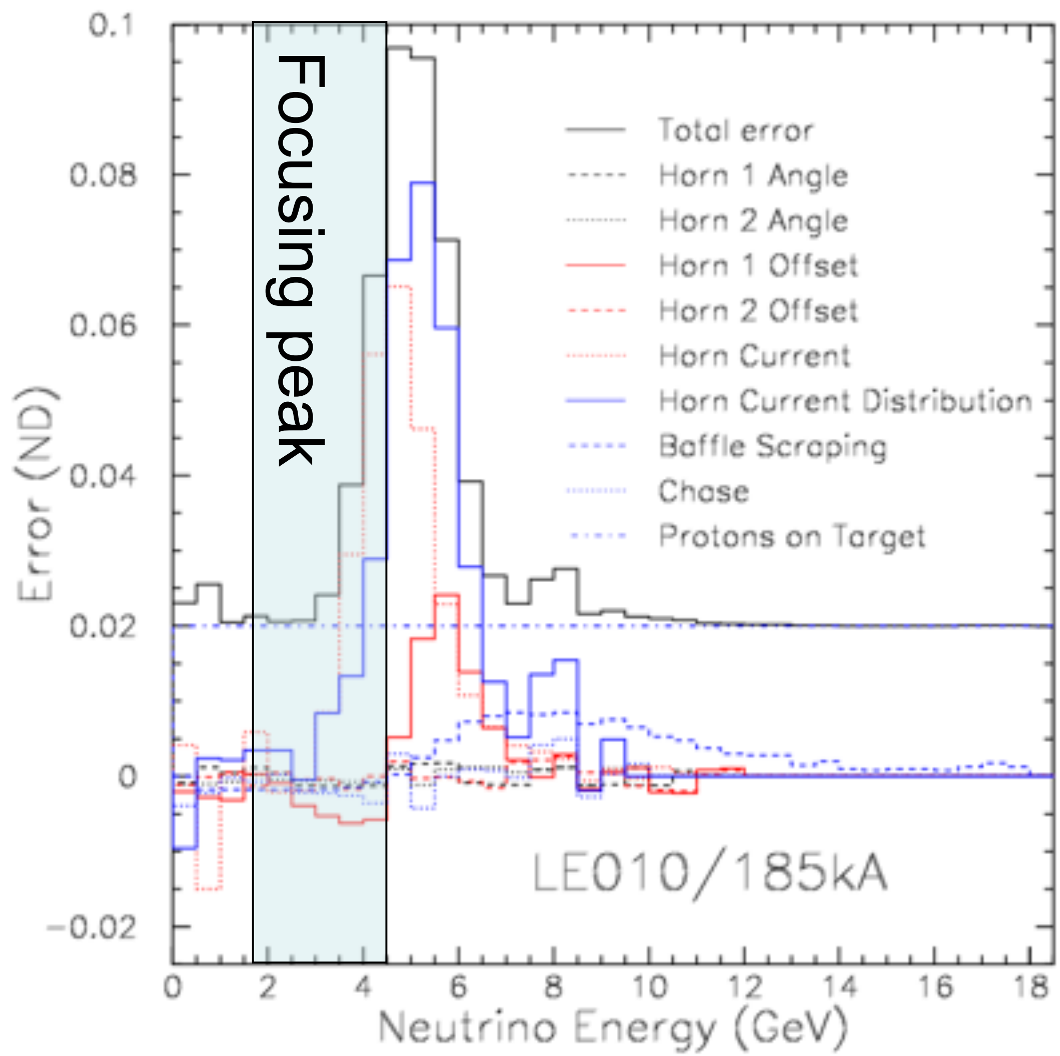
Thick-target effects

- Hadron production data largely from thin target experiments
- Neutrino production targets ~2 interaction lengths
- Large fraction of particles created by reinteractions in the target
- Hadron production experiments with replica targets (HARP thick target, MIPP)



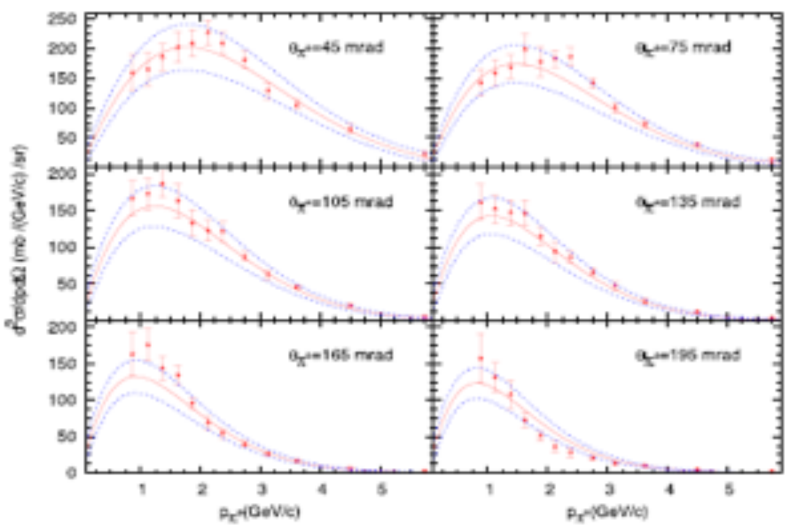
Non-hadron production errors

- NuMI example
- Errors biggest at the falling edge of the peak
- Use data to constrain errors
  - Calibration
  - Optical survey
  - Beamline instrumentation



Single detector experiments (for example MiniBooNE)

- Use pi+/pi- production from HARP (p+Be at 8GeV)



- Global fits to K production data
- With propagated uncertainties BNB flux known at the ~10% level

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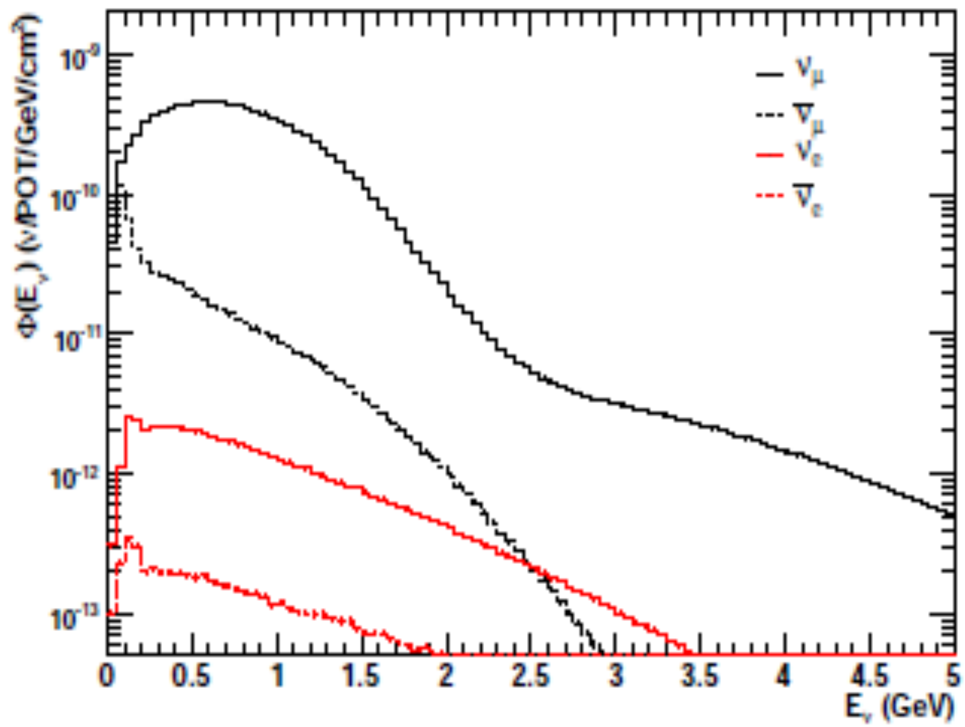
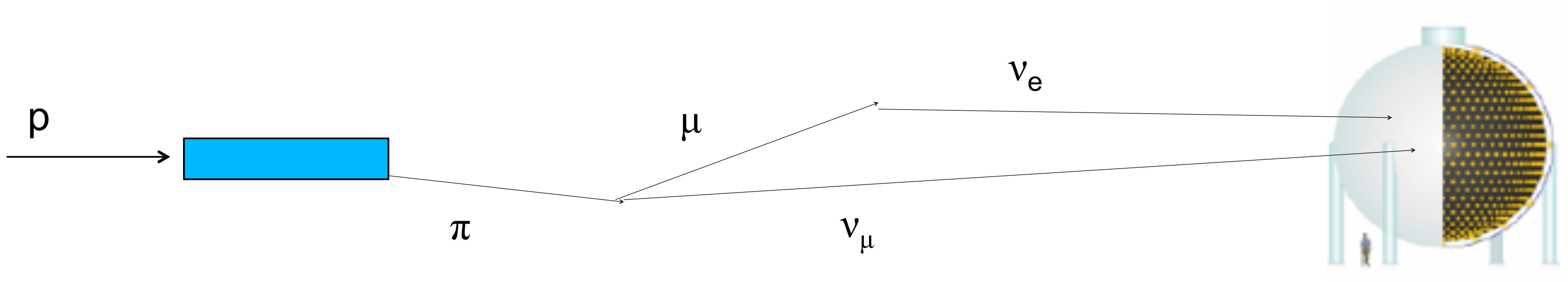


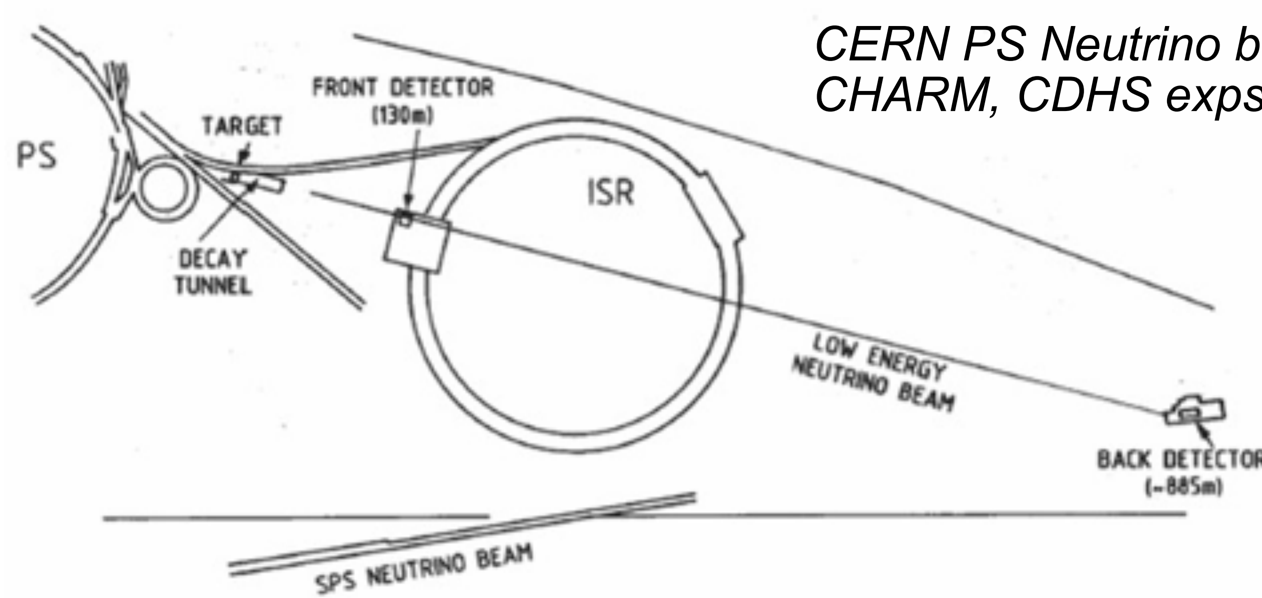
Single detector experiment (cont'd)

- MiniBooNE appearance analysis uses correlation between ν_μ and ν_e events (similar to ν_e/ν_μ ratio) to constrain ν_e backgrounds further
- Use high statistics ν_μ event sample to constrain ν_e that share same π/K parentage



Two detector experiments

- Reducing neutrino flux uncertainties
- Measure neutrino flux in near detector to infer flux at far
- Same detector technology near and far to cancel other systematics
- Need to calculate corrections on top of R^{-2}
  - For MINOS 20-30%



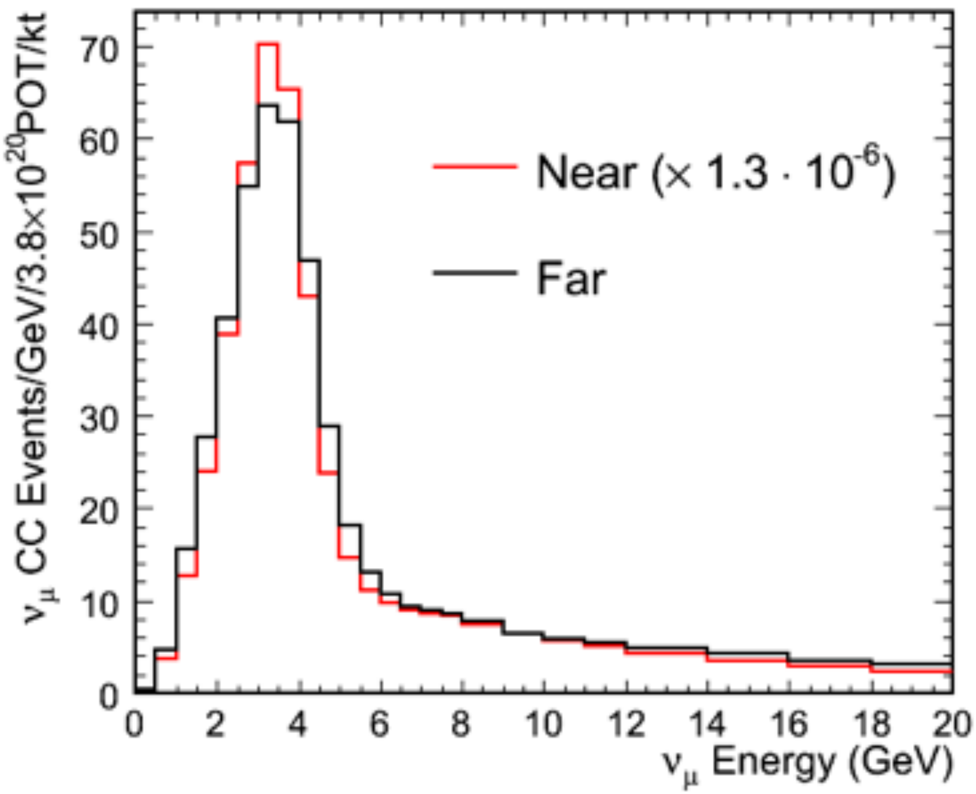
CERN PS Neutrino beam – CHARM, CDHS exps.

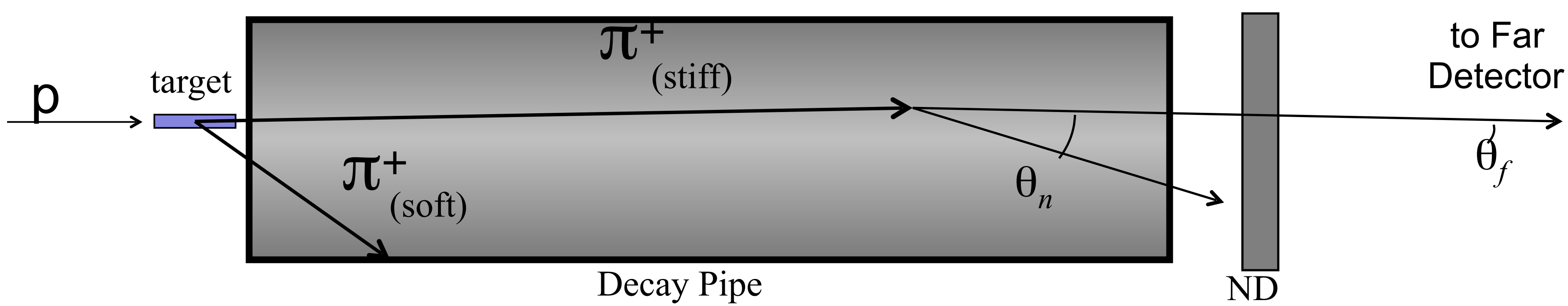
Near and Far spectra

- Flux not the same
- Recall E_ν dependence on parent momentum

$$E_\nu \approx \frac{0.43 E_\pi}{1+\gamma^2\theta^2}$$

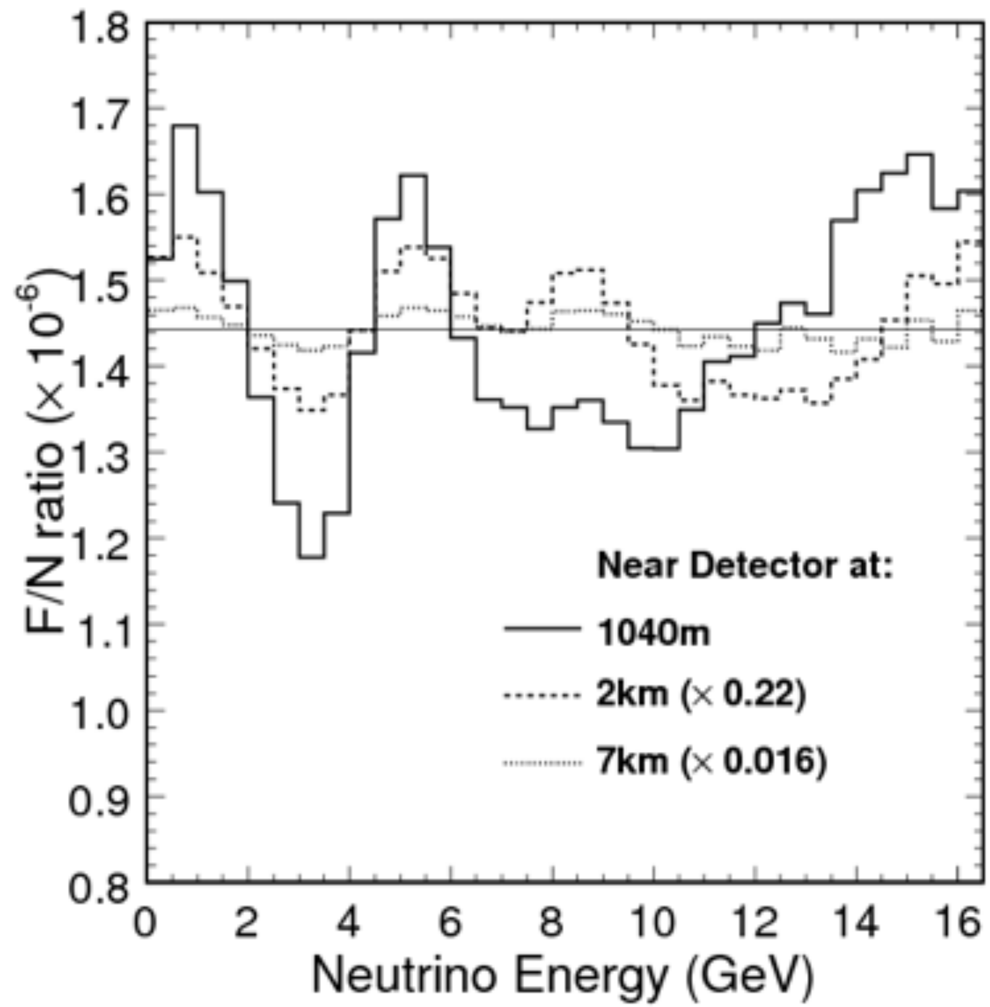
- Flux ~$1/L^2$





Far over Near ratio

- 20-30% correction on top of R^{-2} with Near Detector at 1km
- To reduce these corrections to 2% level would have to put ND at 7km

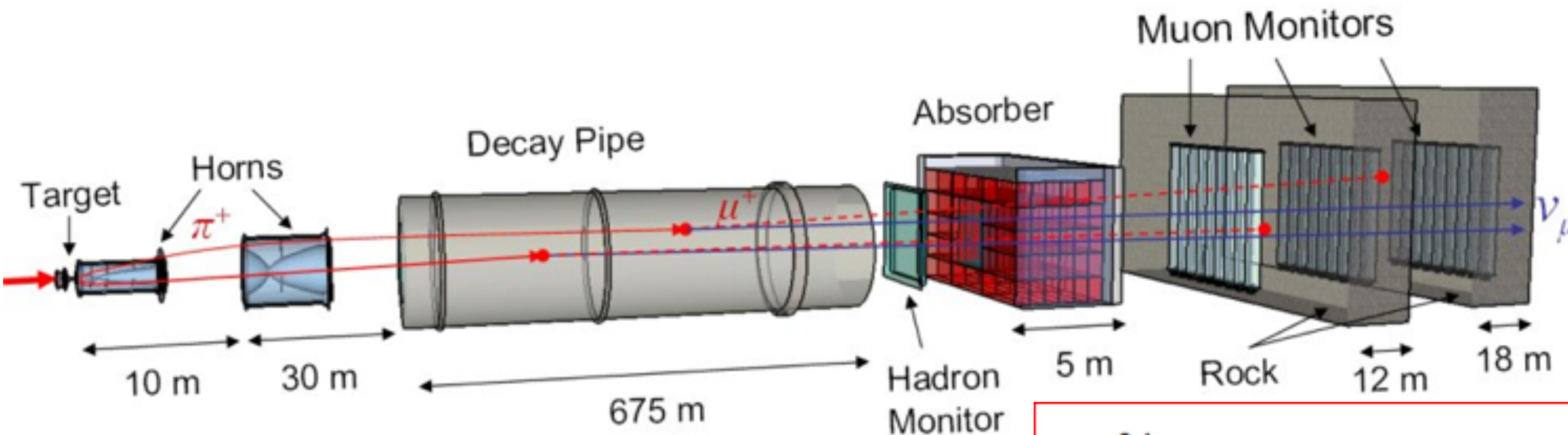


Conclusion

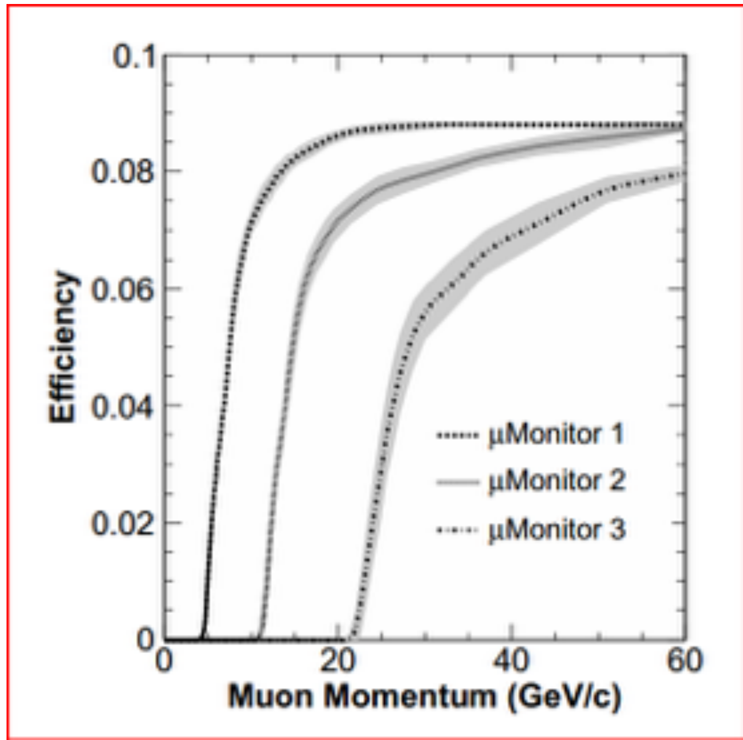
- Neutrino experiments getting more and more precise
- Need well understood flux
- Two running neutrino beams at Fermilab
  - 8 GeV Booster Neutrino Beamline (BNB)
  - 120 GeV Neutrinos at Main Injector (NuMI)
- Flux predictions based on dedicated hadron production experiments (5-10% precision)
- For oscillation experiments need more precision
  - Reduce error with multi detector setups

Backup

Muon monitors (NuMI)



- Tune p+C hadron production to match the muon fluxes in muon monitors
- 3 monitors at various rock depth along the beam



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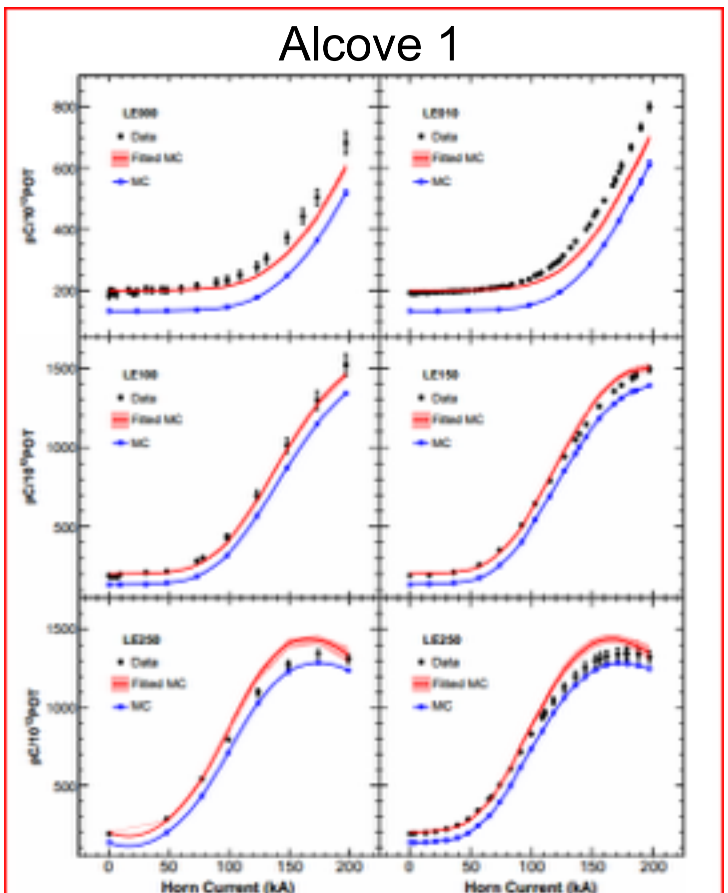
Muon monitors (NuMI)

- 3 muon monitor alcoves, each with a different threshold



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