Long Baseline Oscillations Part 1

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TRISEP School

Goals of these Lectures

- 1st Goal: give you an understanding of how to make LONG BASELINE measurements of a particle that is
  - Neutral
  - Almost never interacts
- "Long Baseline" is in the eye of the beholder
  - Solar
  - Reactor
  - Atmospheric
  - Accelerator-based

Schedule

- First Lecture
  - Reminders from Monday's lectures:
    - What do we want to measure with neutrinos, again?
  - What does "long baseline" mean?
  - What neutrino sources are available?
  - How do neutrinos interact?

  (at "long baseline" energies)?
- Second Lecture
  - What can neutrino detectors measure?
  - Putting it all together—the 2-detector experiment
  - Where are we now? (T2K and NOvA)
  - Next Steps for long baseline oscillations: (DUNE and HyperK)

What are the parameters we want to measure?

1. Neutrino Masses
   A. Absolute
   B. Relative
2. Nature of Neutrinos: Majorana or Dirac?
3. Neutrino Mixing Matrix
   1. 3 rotation angles and 1 CP-violating phase
   2. Is the matrix unitary?
   3. Is this a 3x3 matrix, or are there other generations out there?

What are the parameters that we want to measure?

1. Neutrino Masses
   A. *Absolute*
   B. Relative

   Already covered by Michelle and Steve

2. *Nature of Neutrinos: Majorana or Dirac?*
3. Neutrino Mixing Matrix
   1. 3 rotation angles and 1 CP-violating phase
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1. Neutrino Masses
   A. *Absolute*
   B. Relative

To be covered today

2. *Nature of Neutrinos: Majorana or Dirac?*
3. Neutrino Mixing Matrix
   1. 3 rotation angles and 1 CP-violating phase
   2. Is the matrix unitary?
   3. Is this a 3x3 matrix, or are there other generations out there?

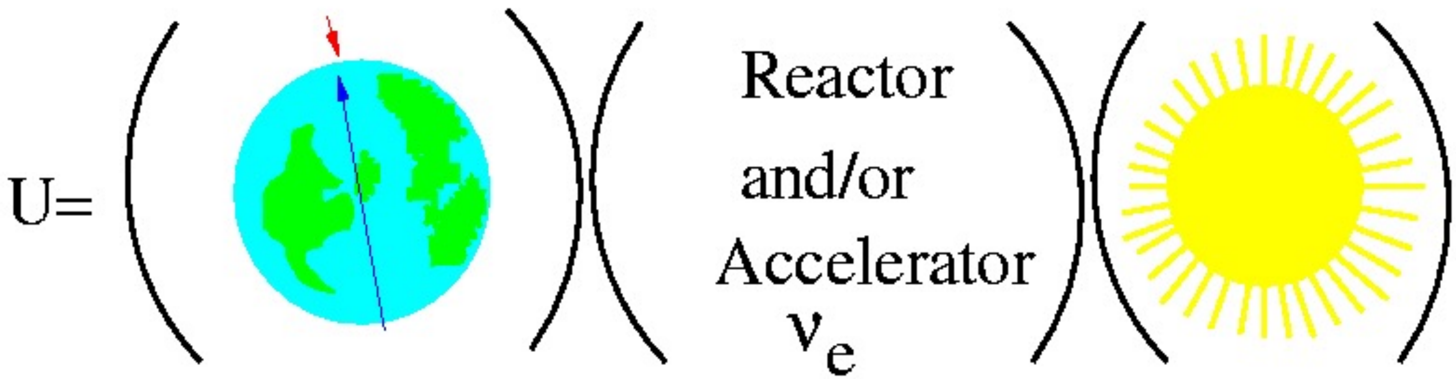
Do we really understand flavor?

- Simplistic way of describing mixing matrix

Lesson Learned from CKM: 3 mixing angles and a phase

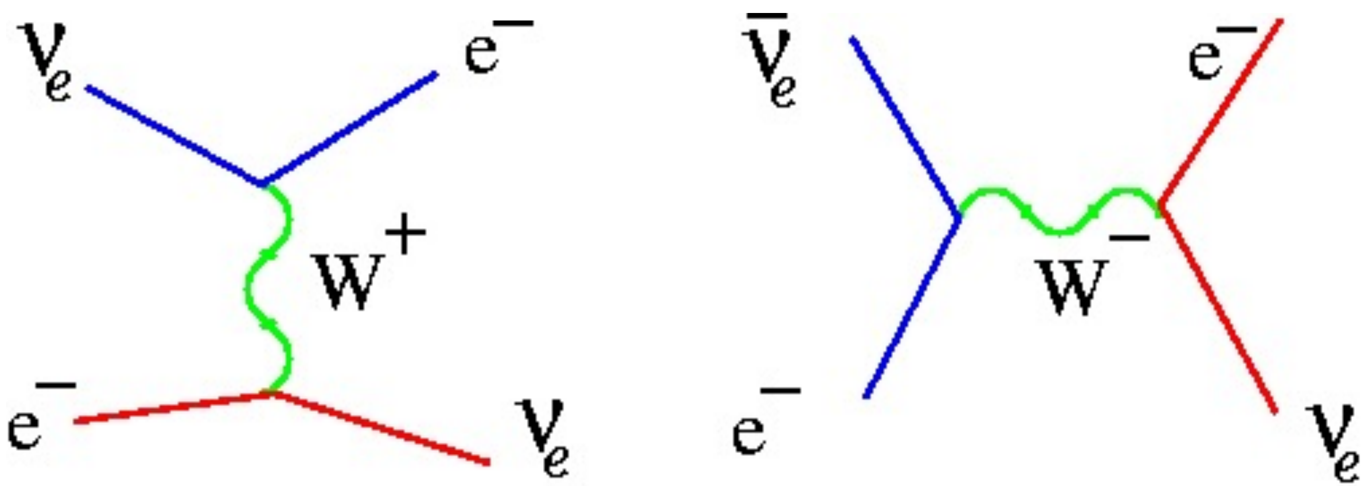
Call them $\theta_{12}, \theta_{23}, \theta_{13}, \delta$ if $s_{ij} = \sin\theta_{ij}, c_{ij} = \cos\theta_{ij}$, then

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



Additional Complication: Matter Effects

- The oscillation probability changes differently for electron neutrinos vs antineutrinos when they propagate through matter in a straightforward way



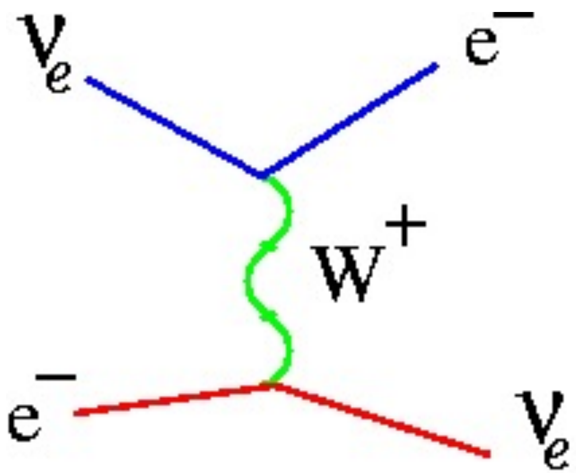
Wolfenstein, PRD (1978)

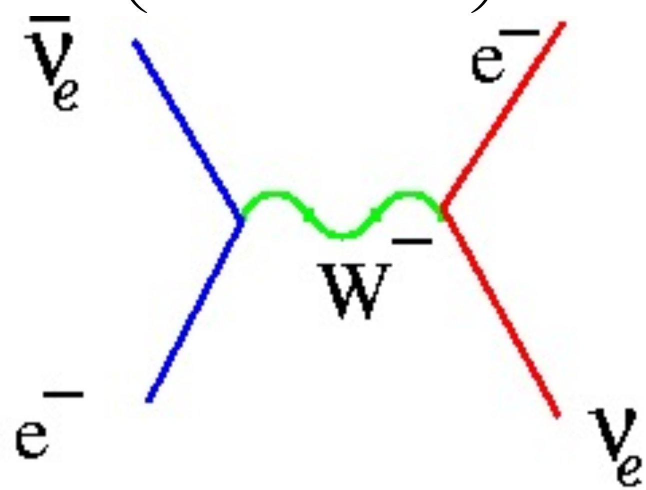
- Can't treat neutrinos propagating through earth simply as mass eigenstates, have to take into account electron flavor
- This would give an apparent CP violation just because the earth is not CP-symmetric

Additional Complication: Matter Effects, with math…

- Remember the 2-generation formula?

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \sin^2\left(\frac{(m_2^2 - m_1^2)L}{4E}\right)$$





Wolfenstein, PRD (1978)

$$x = \frac{2\sqrt{2} G_F n_e E_\upsilon}{\Delta m^2}$$

$n =$ e⁻ density

$$\sin^2 2\Theta_M = \frac{\sin^2 2\Theta}{\sin^2 2\Theta + (\pm x - \cos 2\Theta)^2} \qquad L_M = L \times \sqrt{\sin^2 2\Theta + (\pm x - \cos 2\Theta)^2}$$

ν Oscillation Probabilities

- ν_μ Disappearance: $1-\sin^2 2\theta_{23}\sin^2(\Delta m^2_{32}L/4E)$
- ν_e Disappearance:

$$P_{\bar{\nu}_e\to\bar{\nu}_e} \approx 1-\sin^2 2\theta_{13}\sin^2\left(\Delta m^2_{31}L/4E\right)-\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\Delta m^2_{21}L/4E\right)$$

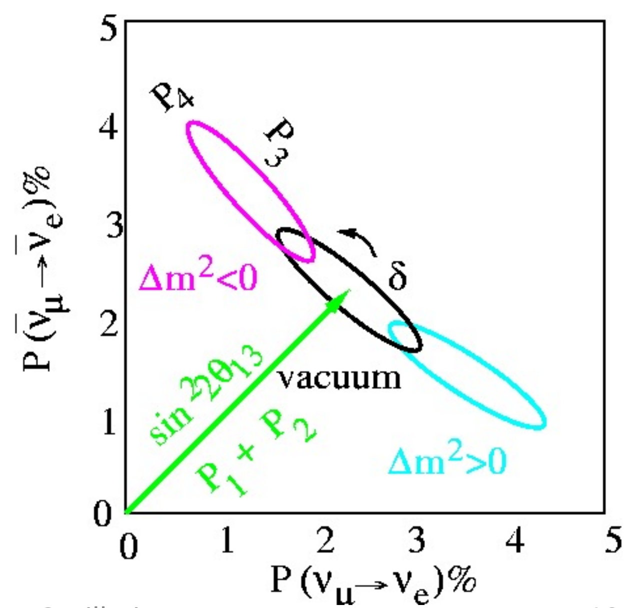
- ν_e appearance in a ν_μ beam: even more complicated…
- $P(\nu_\mu\to\nu_e)=P_1+P_2+P_3+P_4$

$$P_1 = \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2\sin^2\frac{B_\pm L}{2}$$

$$P_2 = \cos^2\theta_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2\sin^2\frac{AL}{2}$$

$$P_3 = J\cos\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\cos\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

$$P_4 = \mp J\sin\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\sin\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$



Minakata & Nunokawa JHEP 2001

To measure probabilities, need…

- Neutrino Flavor
- Distance between creation and detection
- Neutrino Energy
  - No source we can use today is monochromatic!
  - Initial state: neutrino plus nucleon or electron
  - Final state: a bunch of stuff you only measure so well, sometimes you only measure the charged lepton
- Neutrino or Antineutrino?
  - Accelerator-based beams are always a mixture of both
  - Atmospheric neutrinos are also a mixture
  - Reactors and the sun are only one or the other

Measuring Oscillation Probabilities

For a given number of signal ν_x events in a detector,
Assuming you are starting with a source of ν_y:

$$N = \varphi_{\nu_y} \sigma_{\nu_x} P(\nu_y \to \nu_x) \varepsilon_x M$$

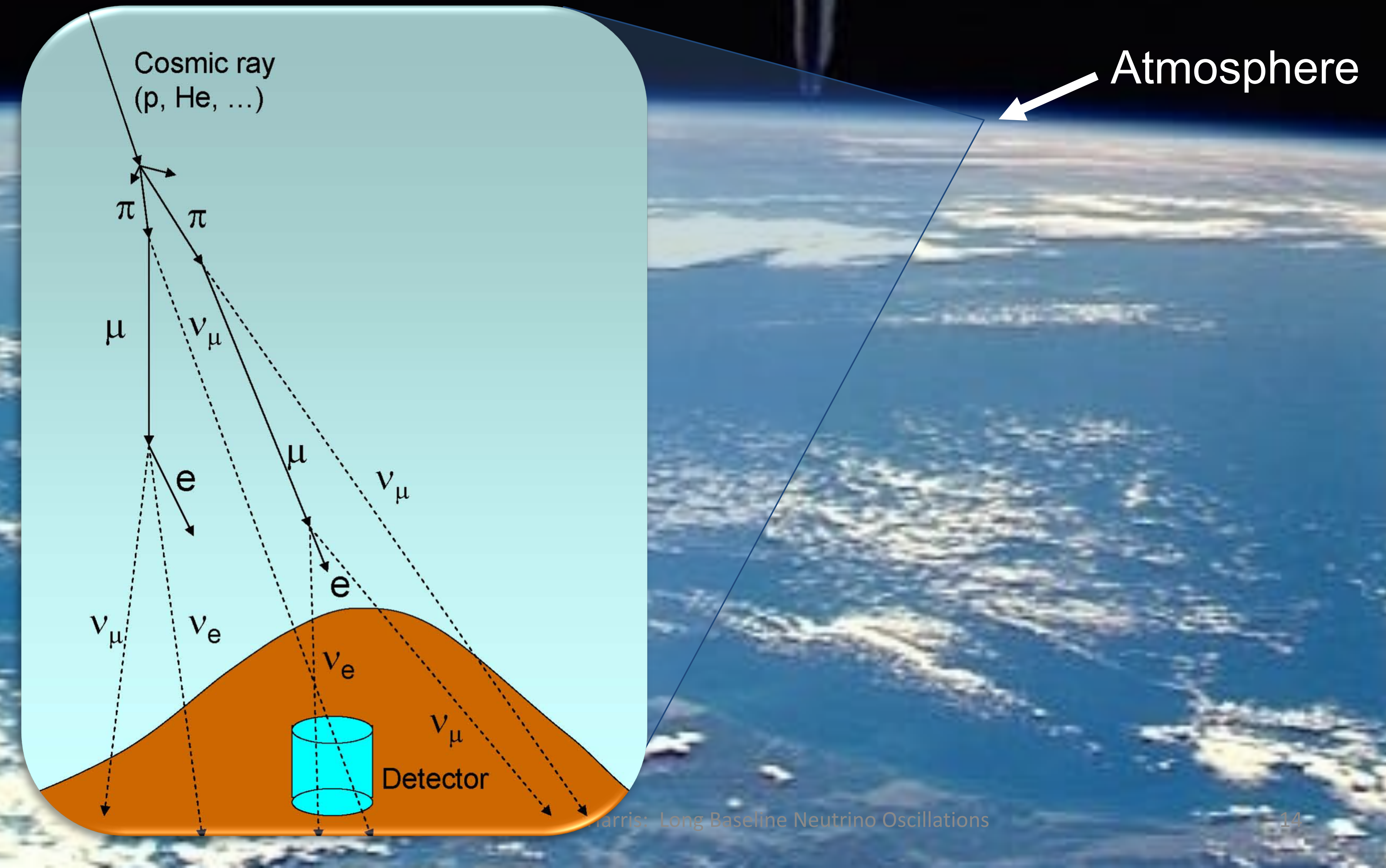
ϕ=flux, σ= cross section ε=efficiency M=detector mass

$$P(\nu_\mu \to \nu_x) = \frac{N}{\varphi_{\nu_\mu} \sigma_{\nu_x} \varepsilon_x M}$$

Neutrino Sources

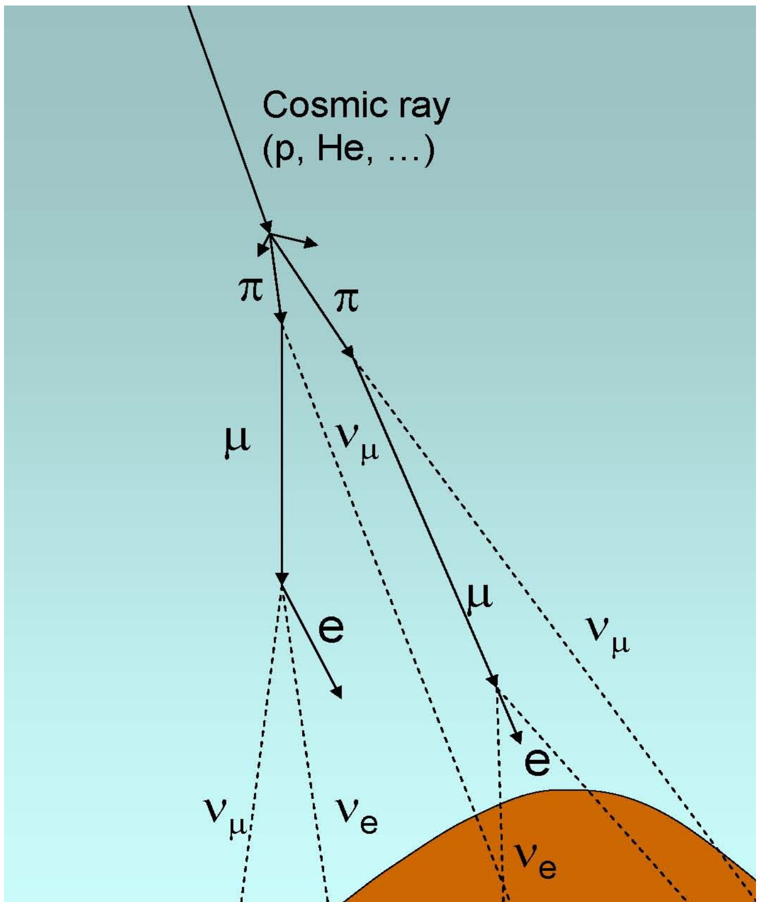
- Key Parameters:
  - Flux
  - Energy
  - Baseline(s) available
  - Neutrino Beam Flavor and Helicity Composition
  - Sensitive to Matter Effects?
    - What do the neutrinos travel through between production and detection

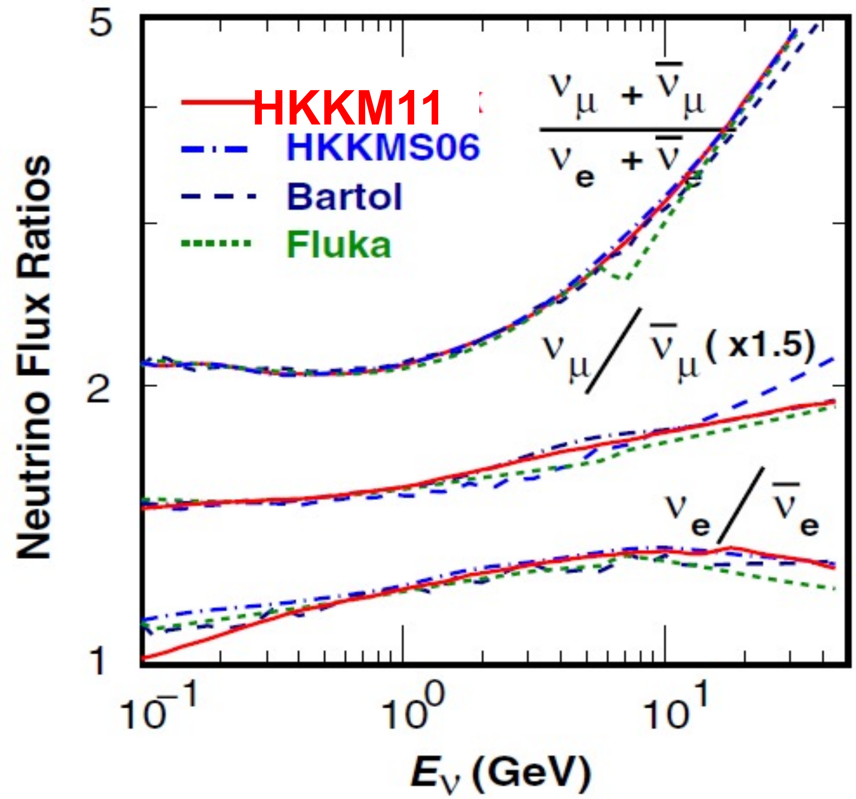
Atmospheric Neutrinos



What is known well

$(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$





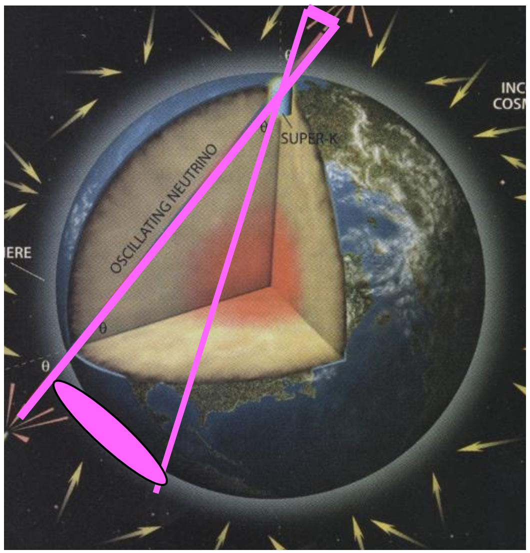
M. Honda et al., PRD 83, 123001 (2011)

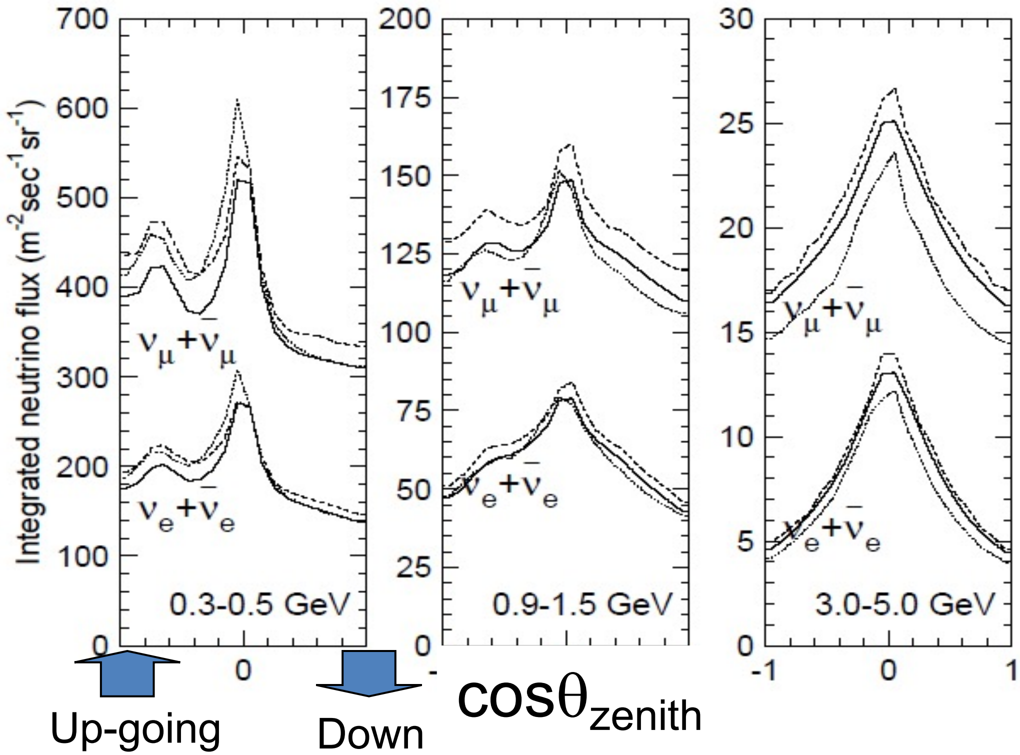
- ✓ ν_μ/ν_e ratio is calculated to an accuracy of about 2% below ~5GeV.
- ✓ ν and anti–ν ratios also accurately calculated.

T.Kajita, INSS 2013

What else is known well: up/down

Zenith angle





@Kamioka (Japan)

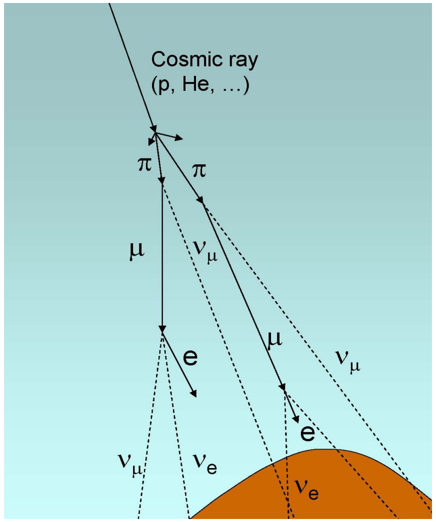
Up/down ratio very close to 1.0 and accurately calculated (1% or better) above a few GeV.

Experimental Challenges with Atmospheric Fluxes

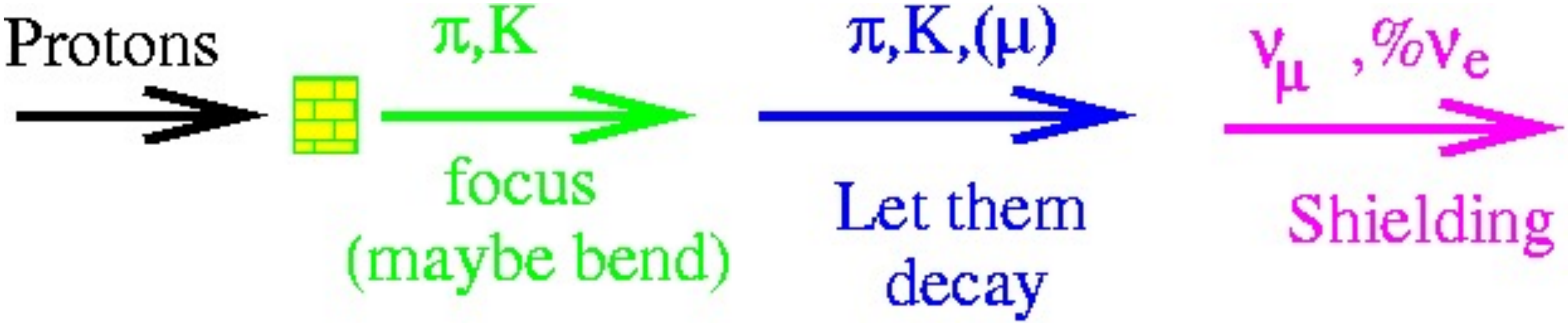
- Absolute rates are hard to predict
- Overall rates are low and steeply falling in energy
- Near equal mix of neutrino and antineutrino means CP violation measurement is near impossible
- *Thought question: how might you be able to see matter effects using atmospheric neutrinos? Do you NEED a magnetic field in your detector?*

Neutrinos from Accelerators

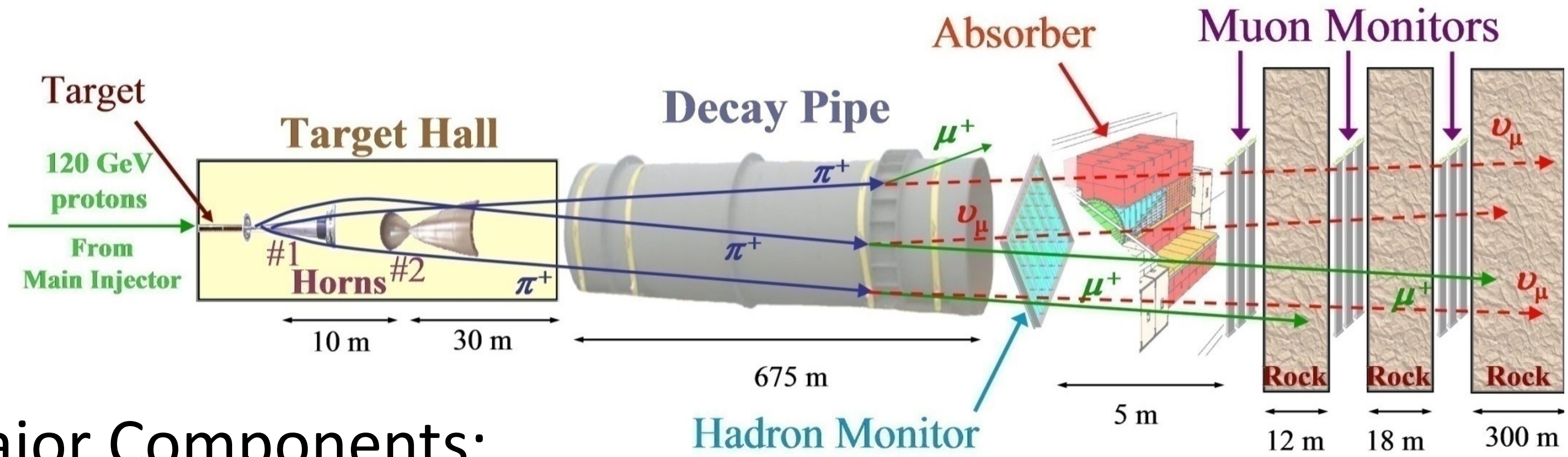
- Atmospheric Neutrino Beam:
  - High energy protons strike atmosphere
  - Pions and kaons are produced
  - Pions decay before they interact
  - Muons also decay



- Conventional Neutrino Beam: very similar!



Example: NuMI beamline at Fermilab



Major Components:

- Proton Beam
- Pion Production Target
- Focusing System
- Decay Region
- Absorber
- Shielding…

Most ν_μ' s from 2-body decays:

$\pi^+ \rightarrow \mu^+ \nu_\mu$

$K^+ \rightarrow \mu^+ \nu_\mu$

Most ν_e' s from 3-body decays:

$\mu^+ \rightarrow e^+ \nu_e \nu_\mu$

$K^+ \rightarrow \pi^0 e^+ \nu_e$

Proton beam Basics

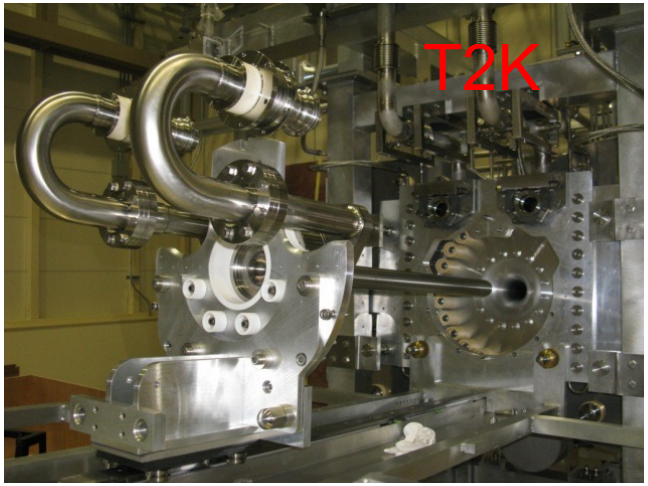
- Rules of Thumb
  - number of pions produced is roughly a function of "proton power" (or total number of protons on target x proton energy)
  - The higher energy ν beam you want, the higher energy p you need

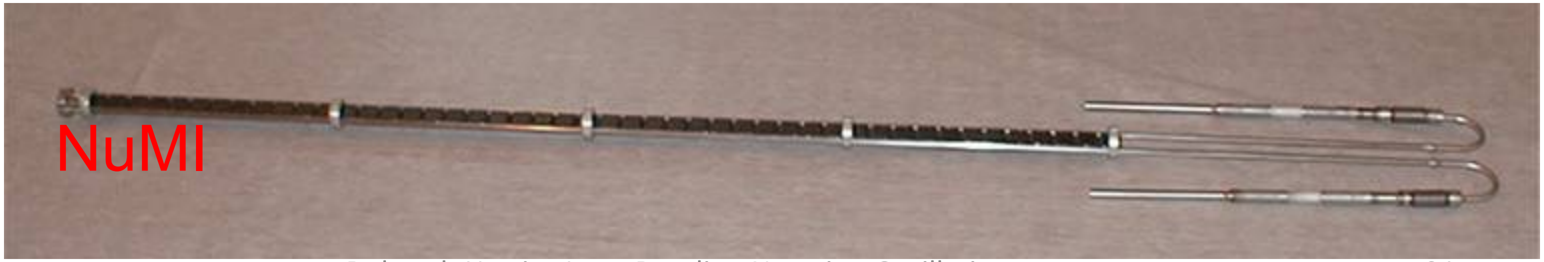
Proton Source	Experiment	Proton Energy (GeV)	p/yr	Power (MW)	Neutrino Energy (GeV)
KEK	K2K	12	$1\times10^{20}/4$	0.0052	1.4
FNAL Booster	SBN	8	5×10^{20}	0.05	1
FNAL Main Injector	MINOS and NOvA	120	$3\text{-}6\times10^{20}$	**0.835!!**	3-17
CNGS	OPERA	400	0.45×10^{20}	0.48	25
J-PARC	T2K	30	11×10^{20}	0.522	0.77

Late-breaking News: June 14: NuMI achieved new power record: 835kW for 1 hour

Neutrino Production Targets

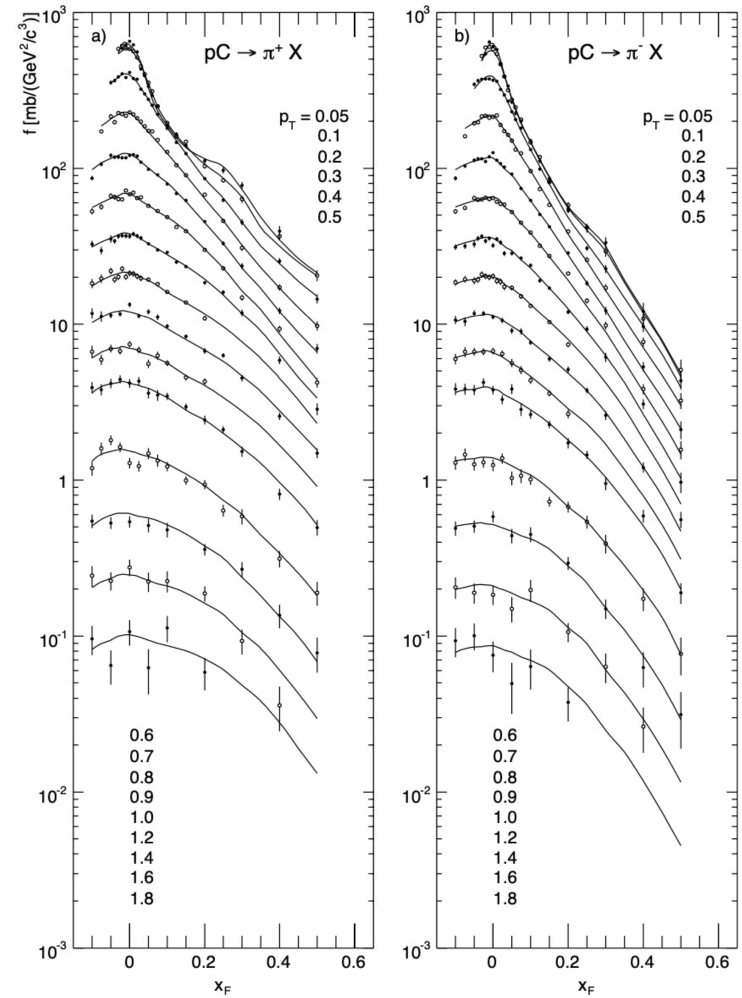
- Have to balance many competing needs:
  - The longer the target, the higher the probability the protons will interact
  - The longer the target, the more the produced particles will scatter
  - The more the protons interact, the hotter the target will get—targeting above ~1MW not easy!
  - Rule of thumb: want target to be 3 times wider than +- 1 sigma of proton beam size





Making pions from a beam of protons

- This is tricky stuff, hard to predict with theory alone
- Copious thin target measurements available, but neutrino targets are usually long
- NA61/SHINE data from CERN: thin and thick target data used for T2K, NuMI, DUNE analysis
  - Starting to publish now, more data expected
- At right: NA49 data from CERN, 158GeV
- EMPHATIC experiment at Fermilab: thin target measurements, to be used by HyperK and DUNE



x_f=π momentum/p momentum

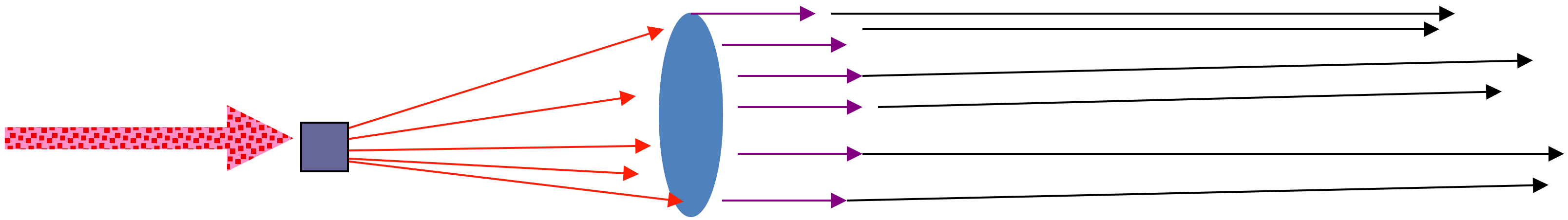
Ref: C. Alt et al., Eur.Phys.J. C49 (2007) 897-917

Focusing Systems

- Want to focus as many particles as possible for highest neutrino flux
- Typical transverse momentum of secondaries: approximately Λ_{QCD}, or about 200MeV
- Minimize material in the way of the pions you've just produced
- What kinds of magnets are there?
  - Dipoles—no, they won't focus
  - Quadrupoles
    - done with High Energy neutrino beams
    - focus in vertical or horizontal, need pairs of them
    - they will focus negative and positive pions simultaneously

What focusing works best?

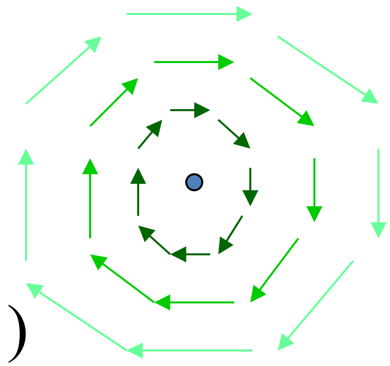
- Imagine particles flying out from a target:
  - When particle gets to front face of horn, it has transverse momentum proportional to radius at which it gets to horn



B Field from line source of current is

in the Φ direction

but has a size proportional to 1/r



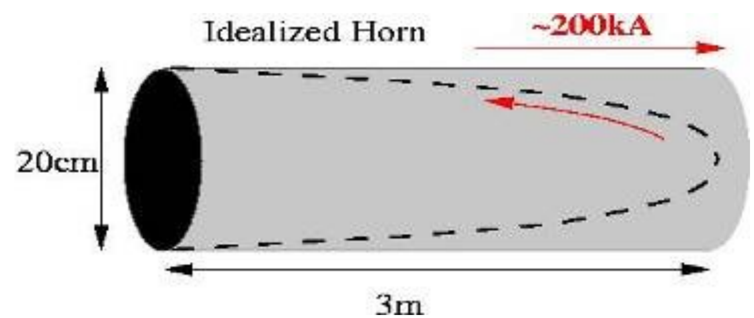
How do you get around this? (hint: $\partial pt \propto B \times \partial l$)

What should the B field be?

FROM  TO 

- Make the particles at high radius go through a field for longer than the particles at low radius. ($B \propto 1/r$, but make $dl \propto r^2$)
- Horn: a 2-layered sheet conductor
- No current inside inner conductor, no current outside outer conductor
- Between conductors, toroidal field proportional to 1/r

$$\delta p_t \approx \frac{e\mu_0 I}{2\pi c r} \times \frac{r^2 l}{r_{outer}^2} \approx p_{tune}\theta$$



Horn Photo Album

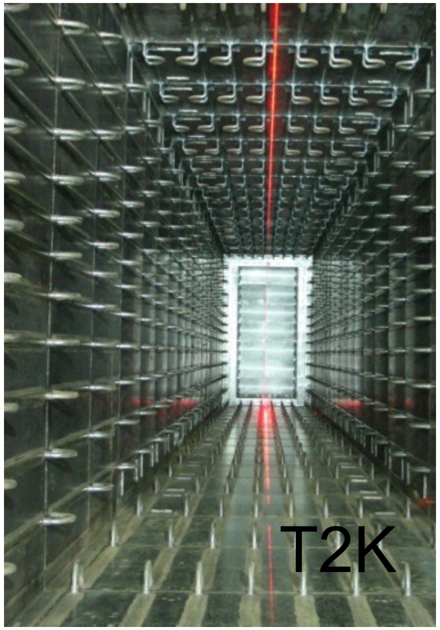
	Length (m)	Diameter (m)	# in beam
K2K	2.4,2.7	0.6,1.5	2
MBooNE	~1.7	~0.5	1
NuMI	3,3	0.3,0.7	2
CNGS	6.5m	0.7	2
T2K	1.4,2,2.5	.47,.9,1.4	3

Designing what provides the 180kA is almost as important as designing the horn itself!

Decay Regions

- How long a decay region you need (and how wide) depends on what the energy of the pions you're trying to focus.
- The longer the decay region, the more muon decays you'll get (per pion decay) and the larger ν_e contamination you'll have
- *What is better: air, vacuum window, or He-filled decay pipe? Does it depend on energy?*

	Length	Diameter
BNB	50m	1.8m
NuMI	675m	2m
CNGS	1000m	2.45m
T2K	130m	Up to 5.4m



Beamline Decay Pipe Comparison

Can show that neglecting things hitting the side of the decay pipe…

$$\frac{\Phi(\nu_e)}{\Phi(\nu_\mu)} = \frac{Lm_\mu c}{E_\pi \tau_\mu}\left(\frac{1}{e^{y_\pi}-1} + 1 - \frac{1}{y_\pi}\right)$$

y_π=the number of pion lifetimes in one decay pipe…

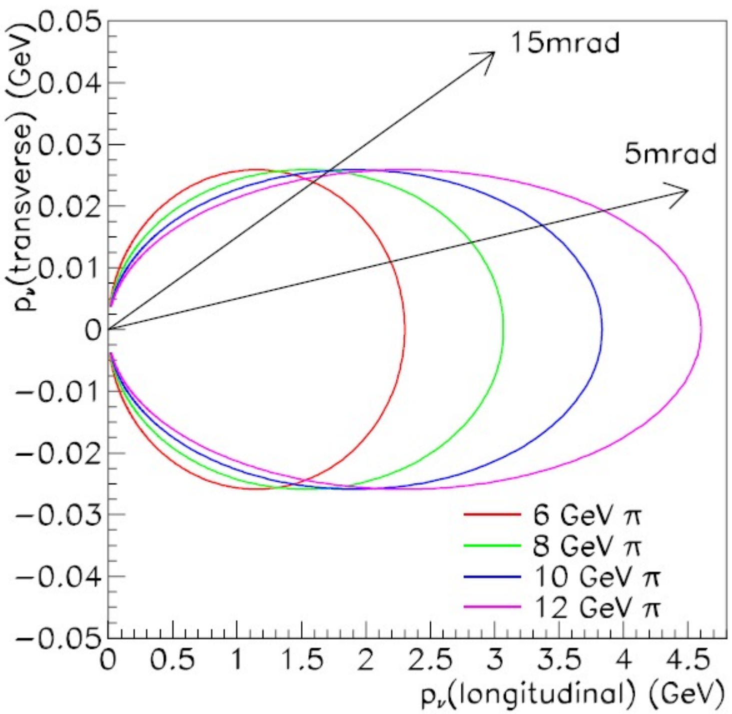
$$y_\pi = \frac{Lm_\pi c^2}{E_\pi c \tau_\pi}$$

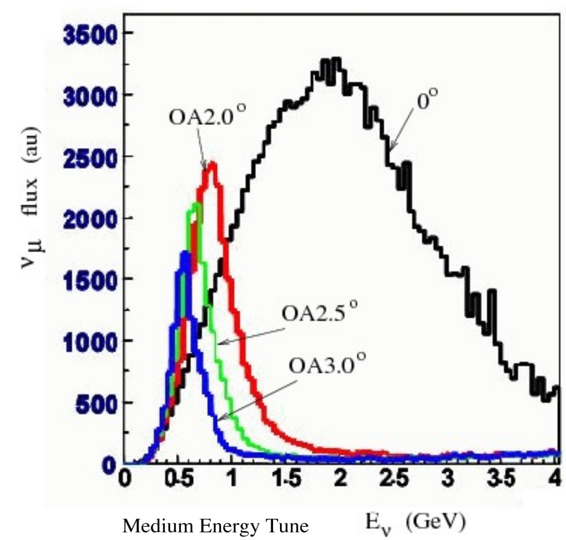
	Length	E_π (GeV)	y_π	y_μ	$\Phi(\nu_e)/\Phi(\nu_\mu)$ (theoretical)
BNB	50m	2.5	0.36	0.3%	0.15%
MINOS	675m	9	1.3	1.2%	0.8%
CNGS	1000m	50	0.36	0.3%	0.15%
T2K	130m	9	0.47	0.2%	0.10%

Off-Axis Technique

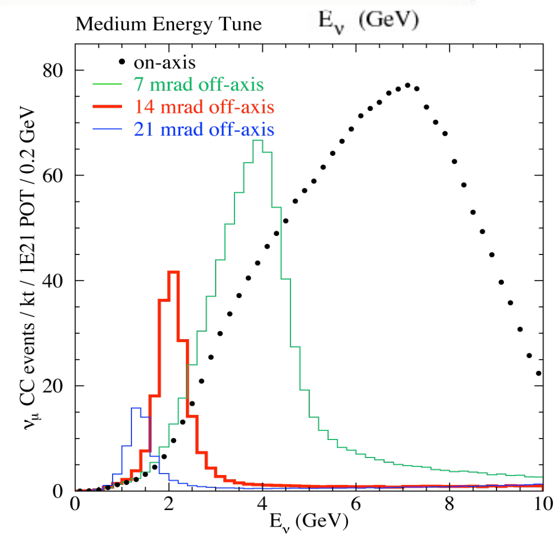
Ref: D. Beavis et al, BNL No. 52459, 4/95

- 1-1 relationship between neutrino energy and pion energy+angle between neutrino and pion
- Off axis neutrino beams: aim pions and kaons AWAY from detector





T2K



NOvA

Experimental Challenges with Accelerator-based Neutrinos

- Operations
  - Target and horns must be robust
  - Still working on a target that can survive 1MW beam power
- Composition
  - Can never make pure beam, always some contamination of anti-neutrinos or ν_e's in what you designed as ν_μ beam
- Flux Predictions
  - Hadron production uncertainties still at the 5% level even with new data
  - Using different hadron shower models to predict flux gives even higher differences
  - Beamline optics can also introduce uncertainties

Neutrino Source Summary

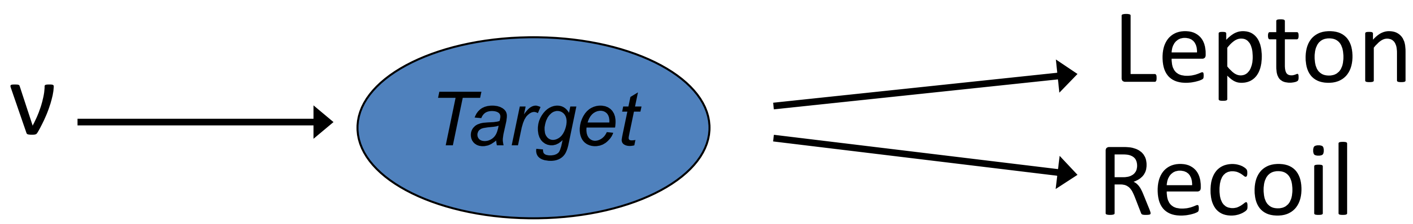
Source	Flux	ν Energy	Composition	Baseline	Matter Effects?
Sun	6×10^{10} $\nu/cm^2/sec$	0.1-10MeV	ν_e (ν_2)	10^8km	yes
Reactor	10^{20} $\nu/sec/GW$	1-10MeV	Anti-ν_e	1-180km	No but…
Atmosphere	1 $\nu/cm^2/sec$	0.1-10^4GeV	ν_e+ν_μ and anti-	80-10^4km	yes
Accelerator	2×10^6 $\nu/cm^2/sec$ @1km*	0.1-100GeV	ν_μ+%ν_e or anti-ν_μ+%ν_e	1-1000km	yes

* NuMI beamline Medium Energy tune on axis, currently x3 higher!

OKAY, WE HAVE A BEAM OF NEUTRINOS, NOW WHAT?

NEUTRINO INTERACTIONS

Thresholds and Processes

- We detect neutrino interactions only in the final state, and often with poor knowledge of the incoming neutrinos
- Creation of that final state may require energy to be transferred from the neutrino
- 

  - In charged-current reactions, where the final state lepton is charged, this lepton has mass
  - The recoil may be a higher mass object than the initial state, or it may be in an excited state

K. McFarland, INSS 2013

Thresholds and Processes

Process	Considerations	Threshold (typical)
$\nu N \rightarrow \nu N$ (elastic)	Target nucleus is often free (recoil is very small) CEνNS!	none
$\nu_e n \rightarrow e^- p$	In some nuclei (mostly metastable ones), this reaction is exothermic if proton not ejected	None for free neutron some others.
$\nu e \rightarrow \nu e$ (elastic)	Most targets have atomic electrons	~ 10eV – 100 keV
anti-$\nu_e p \rightarrow e^- n$	$m_n > m_p$ & m_e. Typically more to make recoil from stable nucleus.	1.8 MeV (free p). More for nuclei.
$\nu_\ell n \rightarrow \ell^- p$ (quasielastic)	Final state nucleon is ejected from nucleus. Massive lepton	~ 10s MeV for ν_e +~100 MeV for ν_μ
$\nu_\ell N \rightarrow \ell^- X$ (inelastic)	Must create additional hadrons. Massive lepton.	~ 200 MeV for ν_e +~100 MeV for ν_μ

- Energy of neutrinos determines available reactions, and therefore experimental technique

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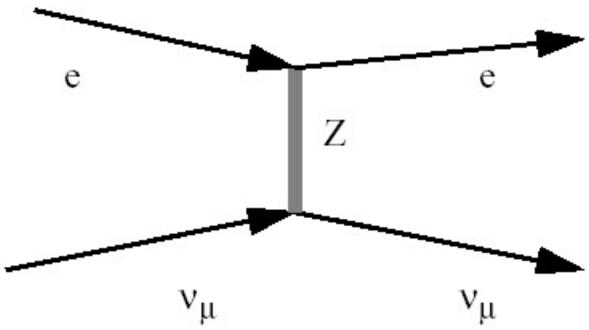
Neutrino Electron Elastic Scattering

- Elastic scattering:

$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$

  - Recall, EW theory has coupling to left *or* right-handed electron
  - Total spin, J=0,1



Z Couplings	g_L	g_R
ν_e , ν_μ , ν_τ	1/2	0
e , μ , τ	$-1/2 + \sin^2\theta_W$	$\sin^2\theta_W$
u , *c* , *t*	$1/2 - 2/3\ \sin^2\theta_W$	$-2/3\ \sin^2\theta_W$
d , *s* , *b*	$-1/2 + 1/3\ \sin^2\theta_W$	$1/3\ \sin^2\theta_W$

- Electron-Z^0 coupling
  - Left-handed: $-1/2 + \sin^2\theta_W$
  - Right-handed: $\sin^2\theta_W$

$$\sigma \propto \frac{G_F^2 s}{\pi}\left(\frac{1}{4} - \sin^2\theta_W + \sin^4\theta_W\right)$$

$$\sigma \propto \frac{G_F^2 s}{\pi}\left(\sin^4\theta_W\right)$$

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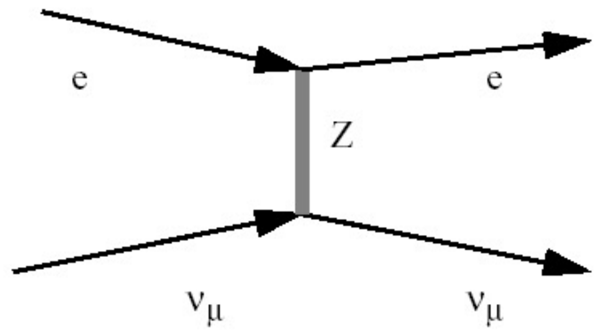
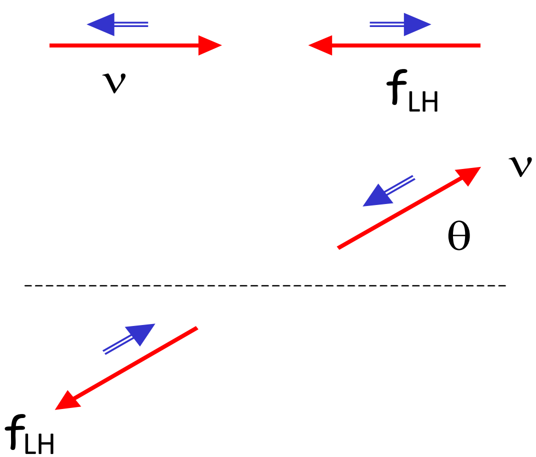
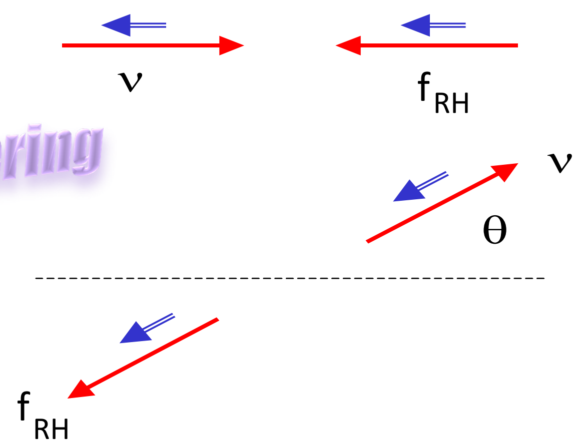
Neutrino Electron Scattering, cont'd

- What are relative contributions of scattering from left *and* right-handed electrons?





Backwards scattering is disfavored



$$\frac{d\sigma}{d\cos\theta} = \text{const}$$

$$\frac{d\sigma}{d\cos\theta} = \text{const} \times \left(\frac{1+\cos\theta}{2}\right)^2$$

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What about ν_e scattering off e's?

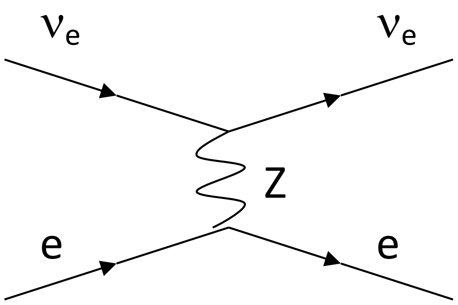
The reaction

$$\nu_\mu + e^- \to \nu_\mu + e^-$$

has a much smaller cross-section than

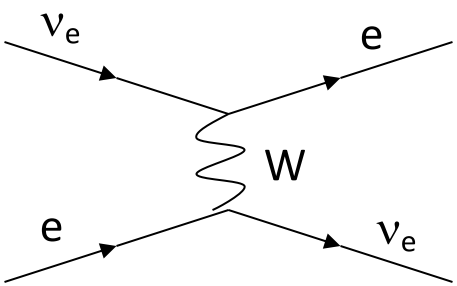
$$\nu_e + e^- \to \nu_e + e^-$$

Why?



$$\nu_e + e^- \to \nu_e + e^-$$

has a second contributing reaction, charged current



Although rate is higher for ν_e, compared to ν_μ or ν_τ hasn't been used for oscillations at accelerator-based long baseline experiments: why?

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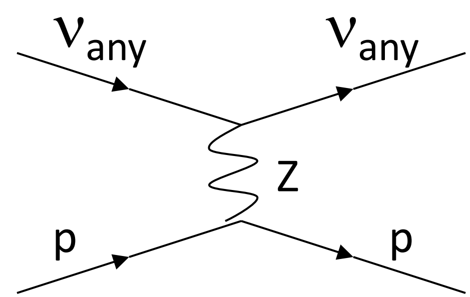
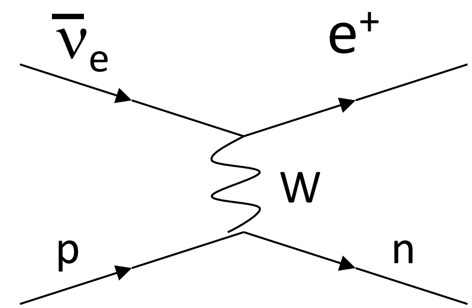
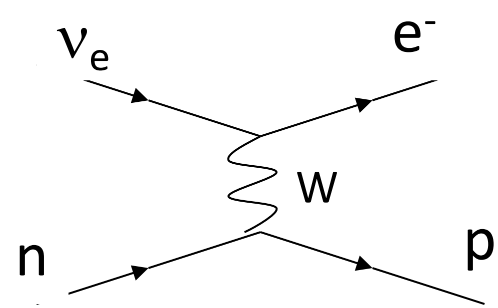
What about protons and neutrons?

- Imagine now a proton target
  - Neutrino-proton elastic scattering:
    $$\nu_e + p \rightarrow \nu_e + p$$
  - "Inverse beta-decay" (IBD):
    $$\text{anti-}\nu_e + p \rightarrow e^+ + n$$
  - and "stimulated" beta decay:
    $$\nu_e + n \rightarrow e^- + p$$
  - IBD was the Reines and Cowan discovery signal
- Cross section much higher
  - Think of what *s* is here ($2*m_{target}*E_\nu$)

$$\sigma \propto \frac{G_F^2 s}{\pi}$$







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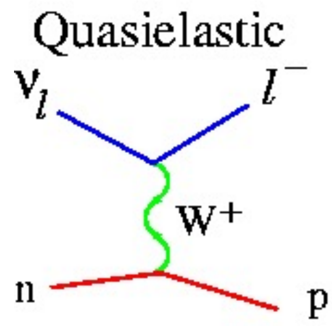
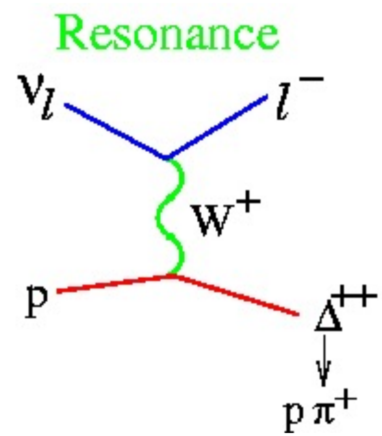
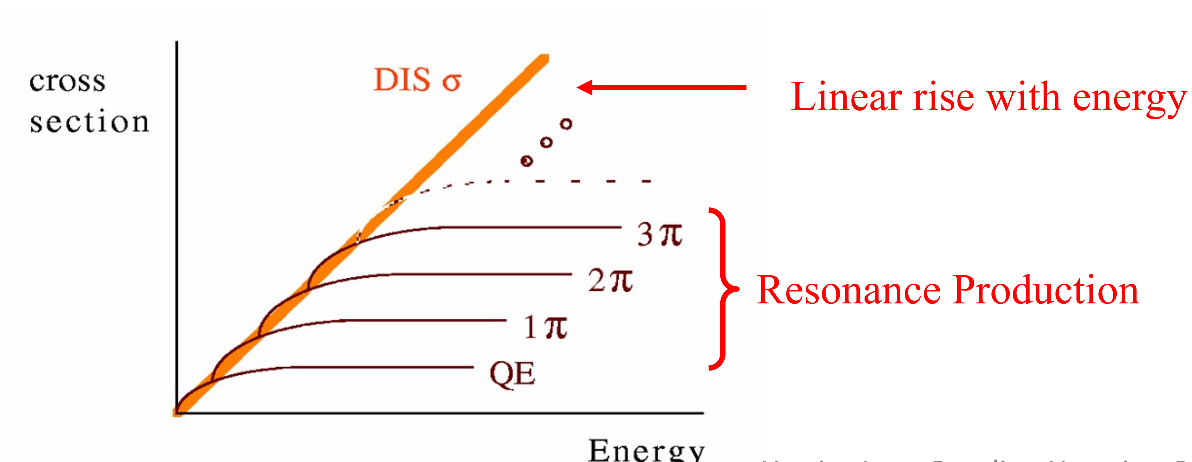
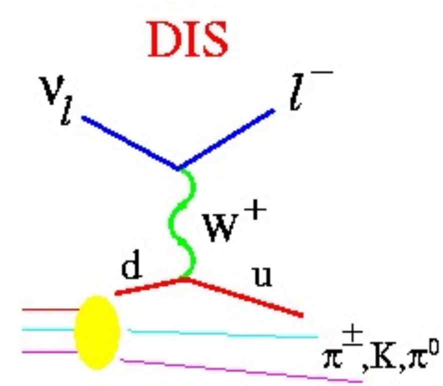
Neutrino-Nucleon Scattering

- Charged - Current: $W^{\pm}$ exchange
  - Quasi-elastic Scattering:
    (Target changes but no break up)
    $\nu_\mu + n \rightarrow \mu^- + p$
  - Nuclear Resonance Production:
    (Target goes to excited state)
    $\nu_\mu + n \rightarrow \mu^- + p + \pi^0$ (N^* or Δ)
    $n + \pi^+$
  - Deep-Inelastic Scattering:
    (Nucleon broken up)
    $\nu_\mu + \text{quark} \rightarrow \mu^- + \text{quark}'$









Harris: Long Baseline Neutrino Oscillations

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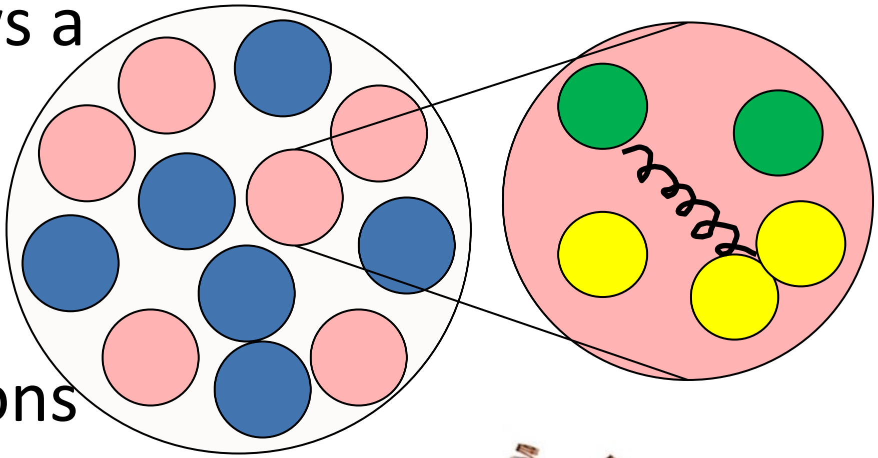
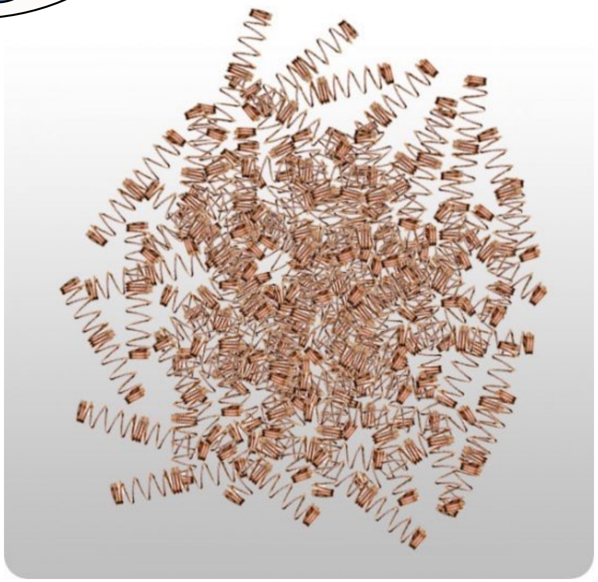
Scattering off Nuclei

- The fundamental theory allows a complete calculation of neutrino scattering from quarks
- But those quarks are in nucleons (PDFs), and those nucleons are in a strongly interacting tangle
- Imagine calculating the excitations of a pile of coupled springs. Very hard in general.





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Summary for Neutrino Interactions

- Total cross section proportional to neutrino energy
- Angular dependence because of ν helicity and conservation of spin
  - Consequence: Neutrinos have higher cross section than anti-neutrinos
- ν-e scattering is the ONLY perfectly known cross section
  - Everything else is more complicated: **NEED BETTER THEORY PREDICTIONS!**
- The higher the ν energy, the more final state particles produced
  - Need to understand how ν energy shows up in detector, AND backgrounds