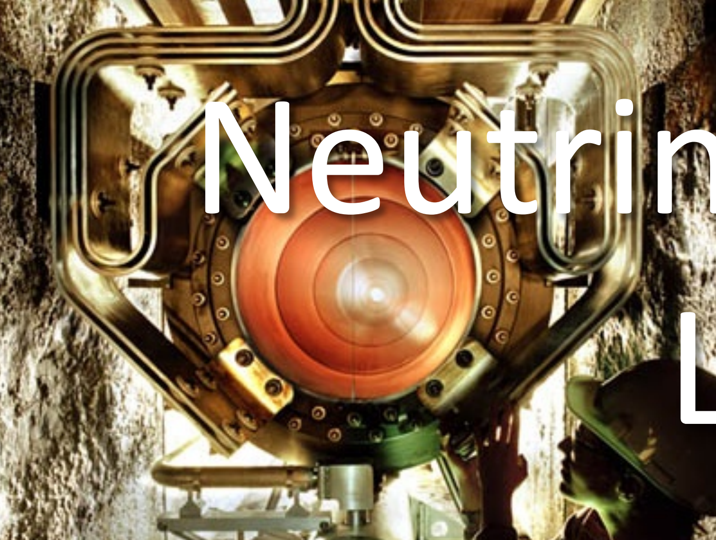
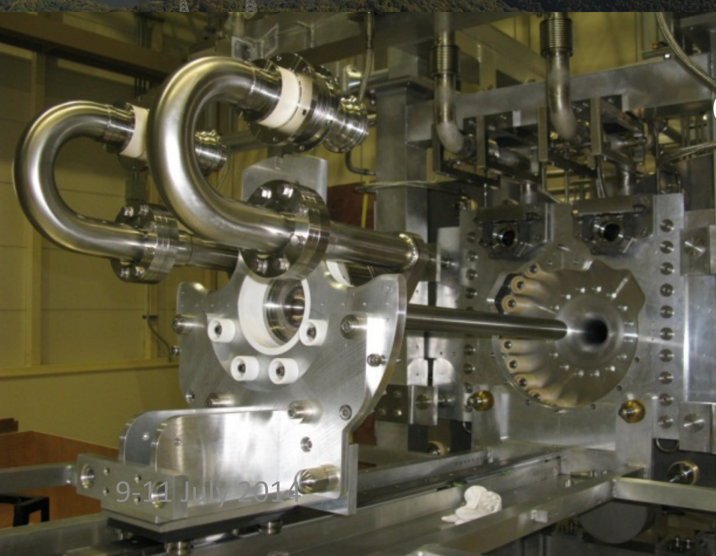
Neutrino Experiments Lecture I








Deborah Harris
Fermilab

July 9-11, 2014

Invisibles School 2014

Gif-sur-Yvette, FRANCE

Goals of this Course

- 1st Goal: give you an understanding of how to make measurements of a particle that is
  - Neutral
  - Almost never interacts
- Physics requires these measurements to be:
  - Over many orders of magnitude of energy
  - Over many orders of magnitude of distance distance
- Many experiments out there to describe
  - Solar, Reactor, Atmospheric, Accelerator-based
  - Absolute and Majorana Mass

Schedule

- Lecture 1 (9 July)
  - What do we know how to measure right now?
  - What neutrino sources are available?
  - How do neutrinos interact in matter?
- Lecture 2 (10 July)
  - How do non-neutrino particles interact in matter?
  - What neutrino detectors are out there?
- Lecture 3 (11 July)
  - Oscillation Measurements
- Lecture 4 (12 July)
  - Absolute Mass and Majorana Mass Measurements

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?

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   A. *Absolute*
   B. Relative

To be covered Friday

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   B. Relative

To be covered today and tomorrow

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?

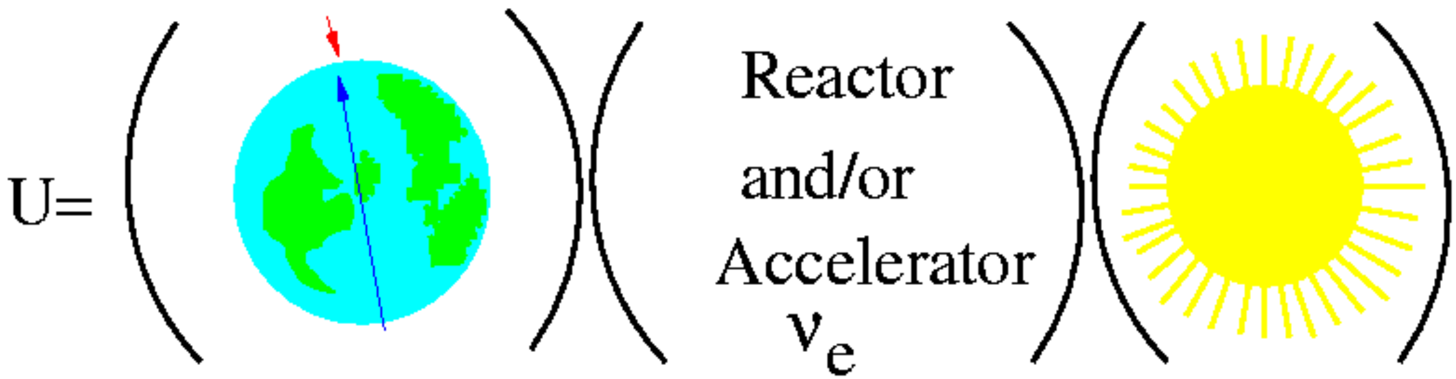
Do we really understand flavor?

- Simplistic way of describing mixing matrix

Lesson Learned from CKM: 3 mixing angles and a phase

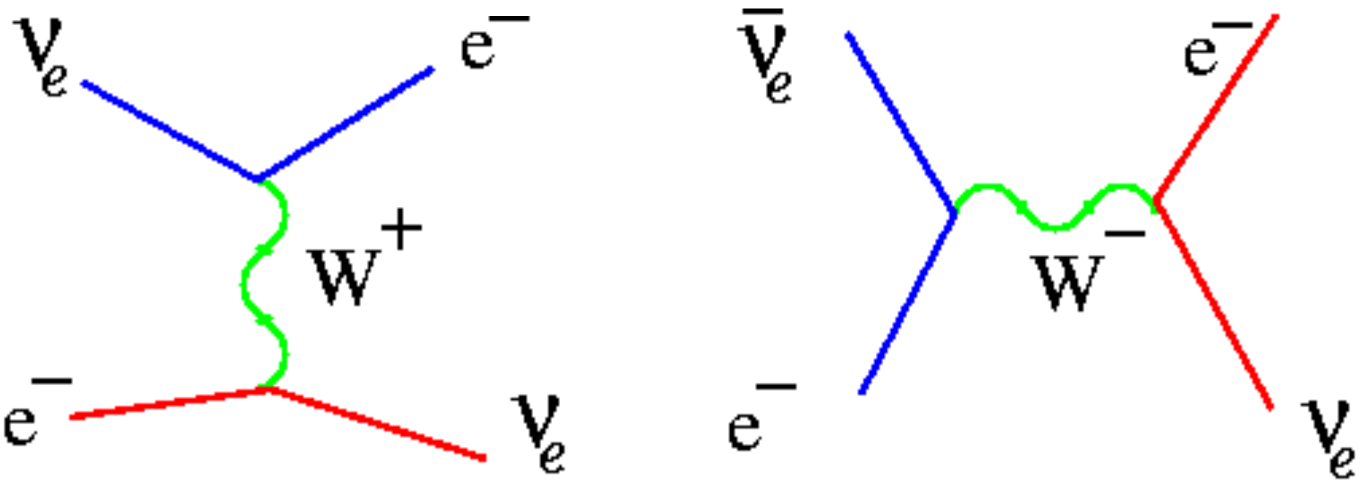
Call them $\theta_{12}, \theta_{23}, \theta_{13}, \delta$ if $s_{ij} = \sin\theta_{ij}, c_{ij} = \cos\theta_{ij}$, then

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



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

ν Oscillation Probabilities

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

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

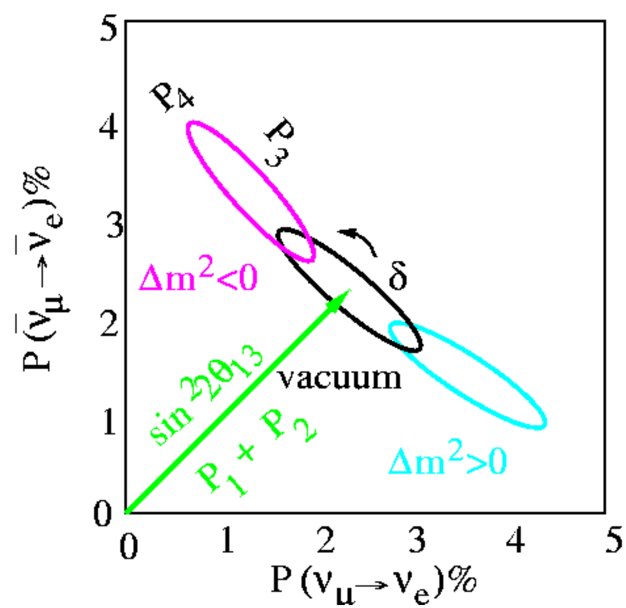
- ν_e appearance in a ν_μ beam: even more complicated…
- $P(\nu_\mu\to\nu_e)=P_1+P_2+P_3+P_4$

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

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

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

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



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:

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

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

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

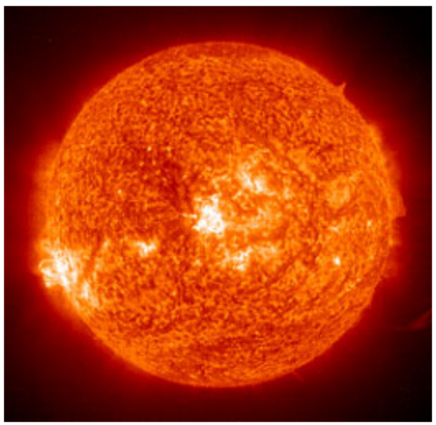
Neutrino Sources

- 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

How does the Sun Shine?

A Helium nucleus is produced by the fusion of 4 Hydrogen nuclei;

$$4p \rightarrow He + 2e^{+} + 2\nu_e$$



This reaction produces about 27 MeV energy.
Then, the total neutrino flux on the Earth is;

$$flux = \frac{1}{4\pi R^2} \times \frac{L_{sun}}{27\,MeV} \times 2\nu_e$$

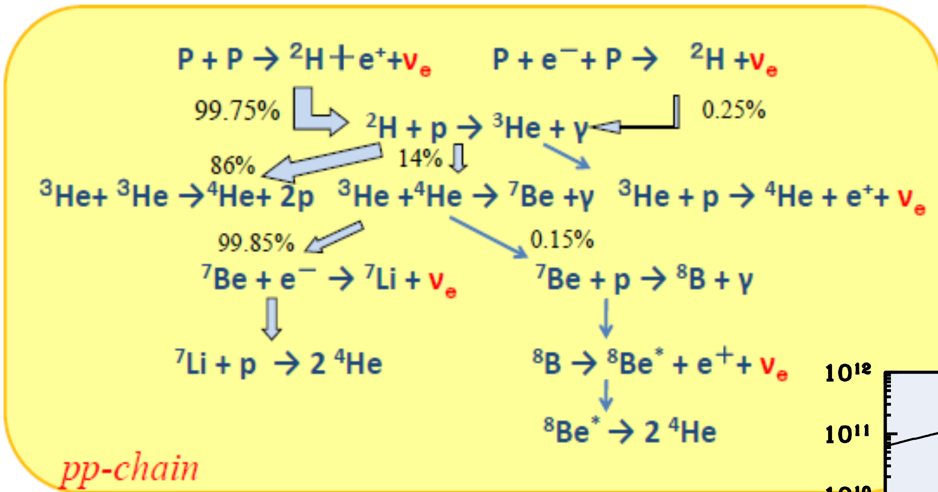
$$(L_{sun} = 3.86 \times 10^{33}\, erg/\sec)$$

$$= 6 \times 10^{10}\, \nu_e / cm^2 / \sec$$

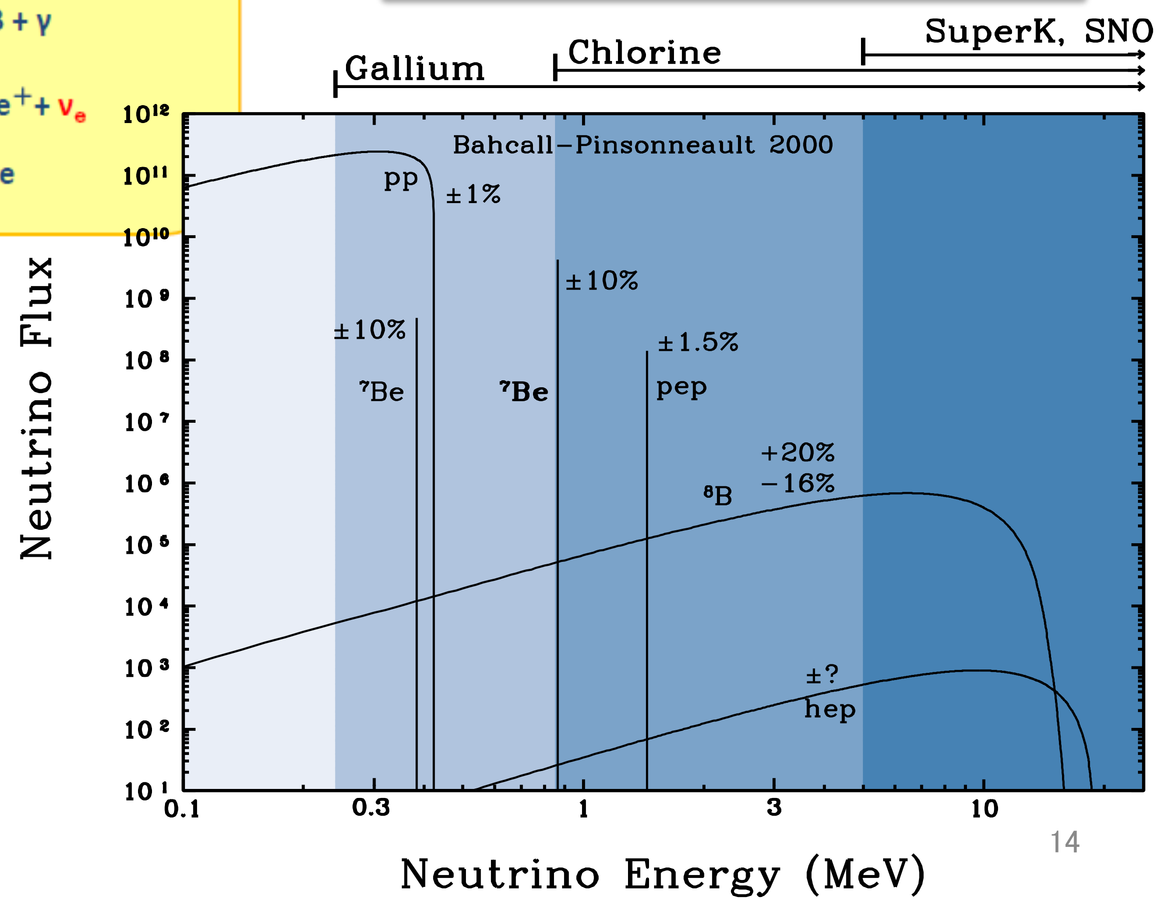
Observing neutrinos from the sun is direct proof that the generation of the energy in the Sun is due to nuclear fusion.

T. Kajita, INSS 2013

Solar Neutrino Energy Spectrum



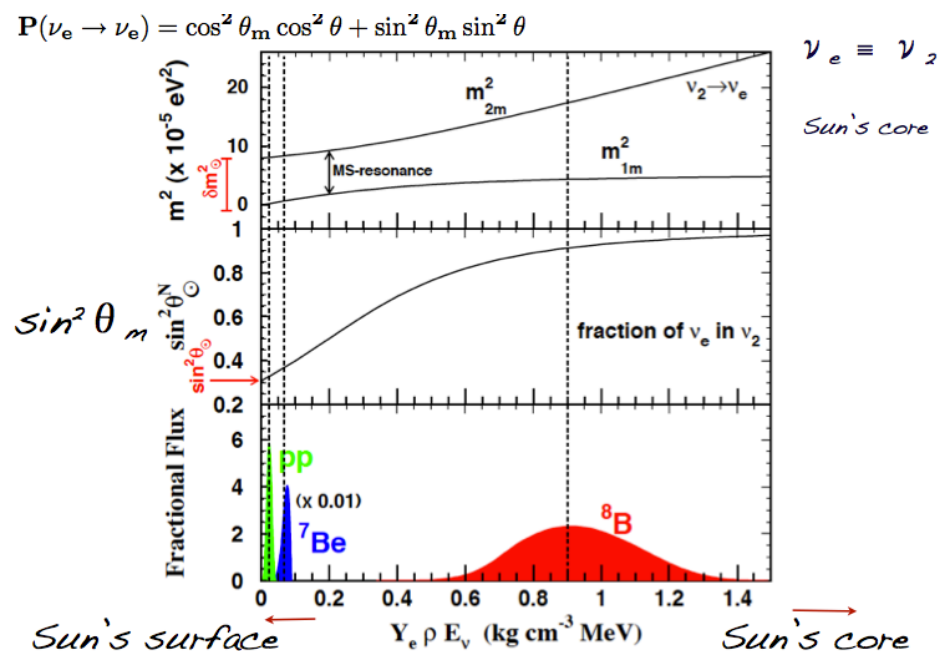
However, in reality, 4 protons cannot make a Helium nucleus at a time…



T. Kajita, INSS 2013

Other Beam Parameters

- Baselines Available: all close to 10^8km
  - Distance to sun changes based on the season
  - Day/night asymmetry changes whether or not ν's went through the earth before detection
- Beam Composition ν_e
- Matter effects
  - See Renata's lecture from yesterday
  - ^{8}B ν's feel matter effects from sun



Experimental Challenges with Solar Neutrino Measurements

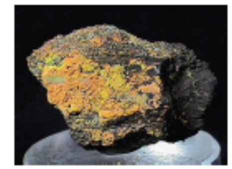
- Neutrinos are very low in energy
  - Very few interactions are accessible
  - Cannot make final state muons or taus, so only neutral current or ν_e charged current interactions are available
  - Different detectors have different energy thresholds, most neutrinos from sun not visible by most techniques
  - Cannot turn off the sun to measure backgrounds in the detector
  - "Standard Solar Model" had many tunable parameters…flux predictions were suspect for a long time.

Neutrinos from a Reactor

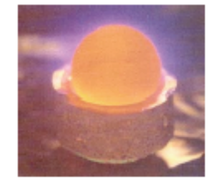
- Like the sun, but fission instead of fusion

$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n \rightarrow$$
$$\ldots ^{94}_{40}Zr + ^{140}_{58}Ce$$

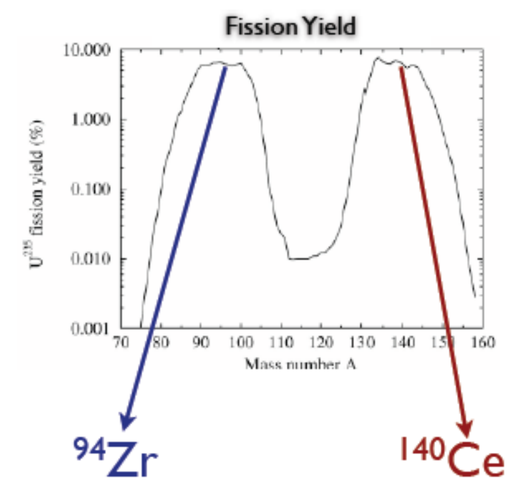
Sample Fission: ^{235}U



^{235}U

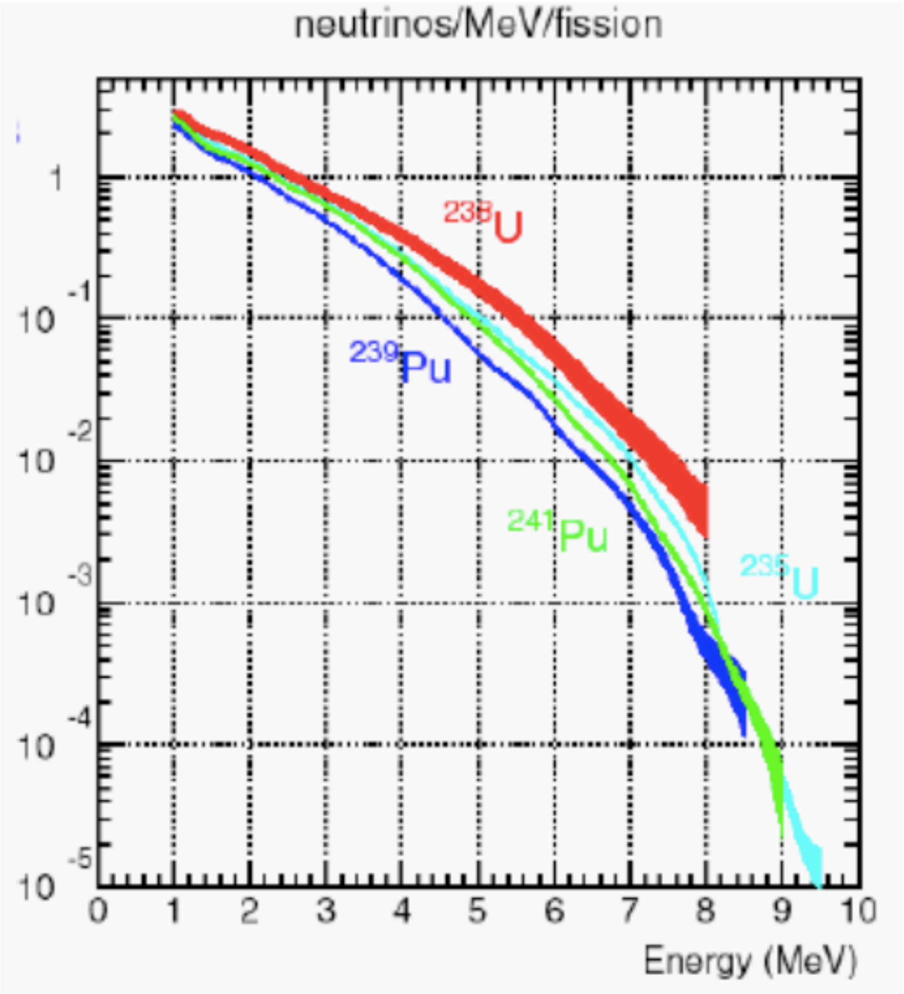


^{239}Pu



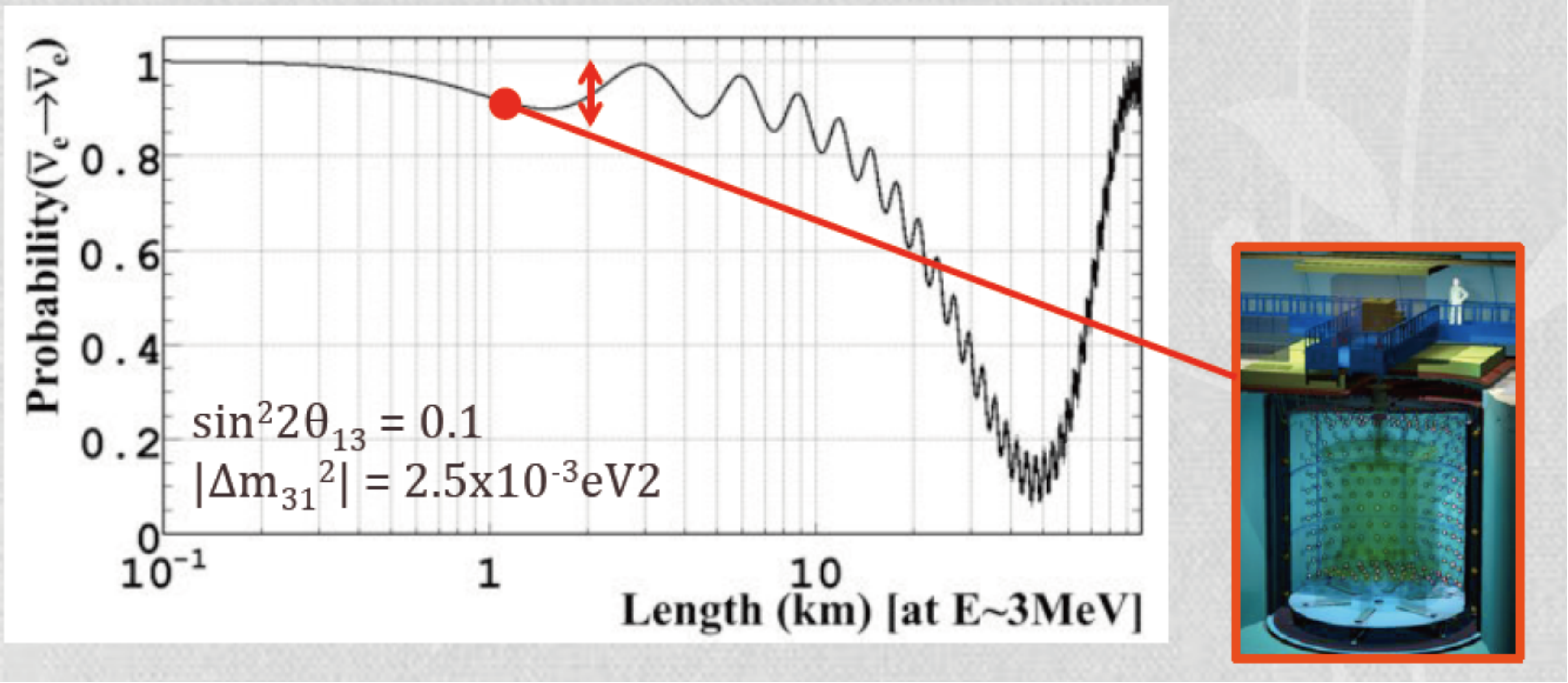
Energy Spectrum from Reactors

- Several processes occurring during the fuel cycle of a reactor, with different yields and energy spectra



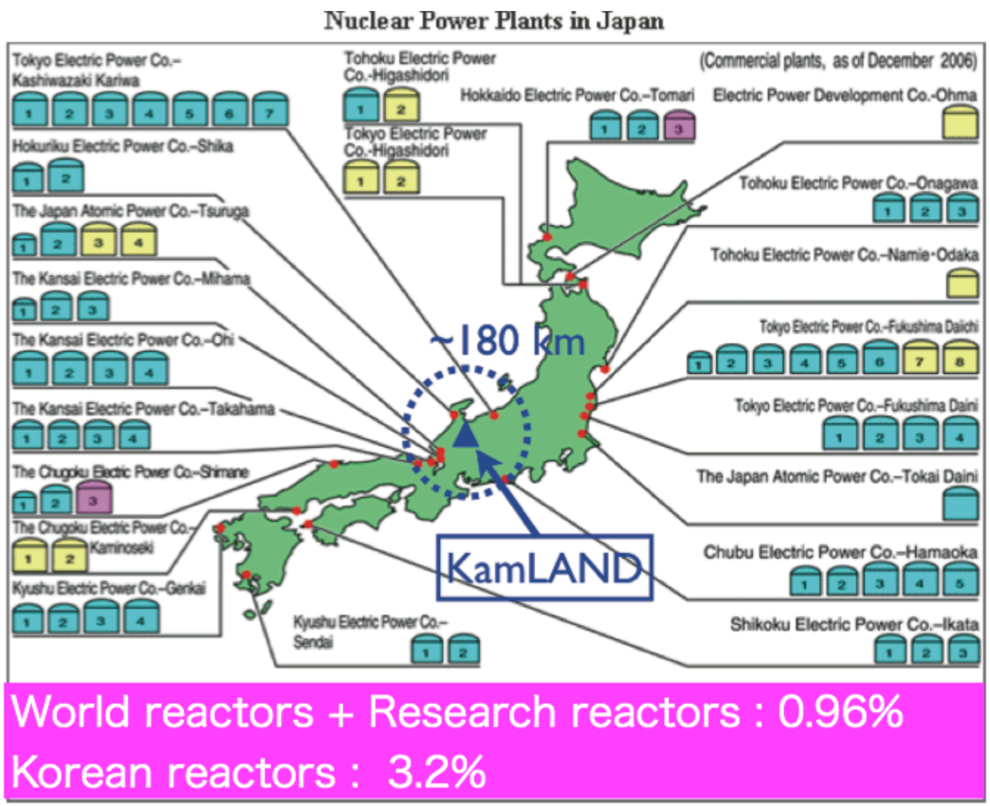
Baselines available

- Reactors send out neutrinos in all directions, so you could put detectors at any baseline you chose
- Different physics can be reached at different baselines

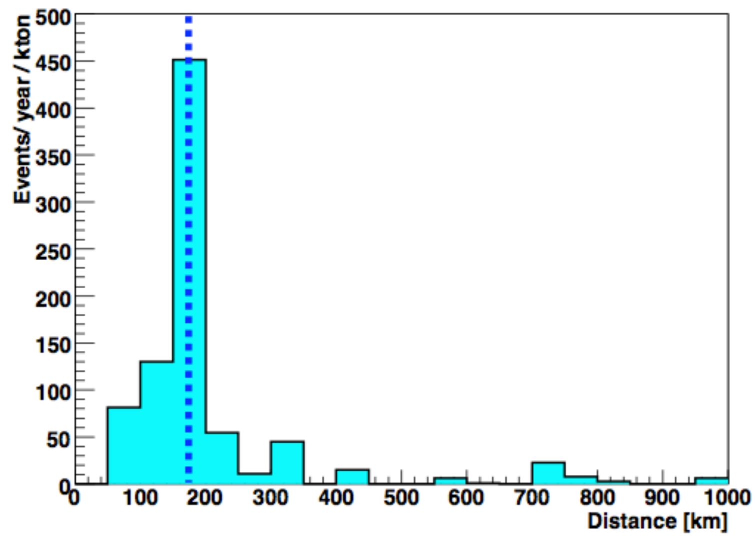


Extreme Example of Long baseline

- Kamland experiment: sees neutrinos from large array of reactors in Japan

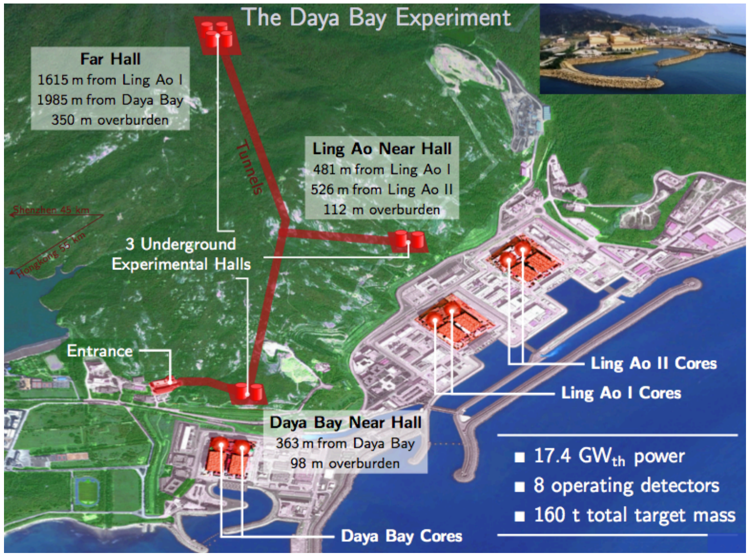


Effective baseline ~180 km



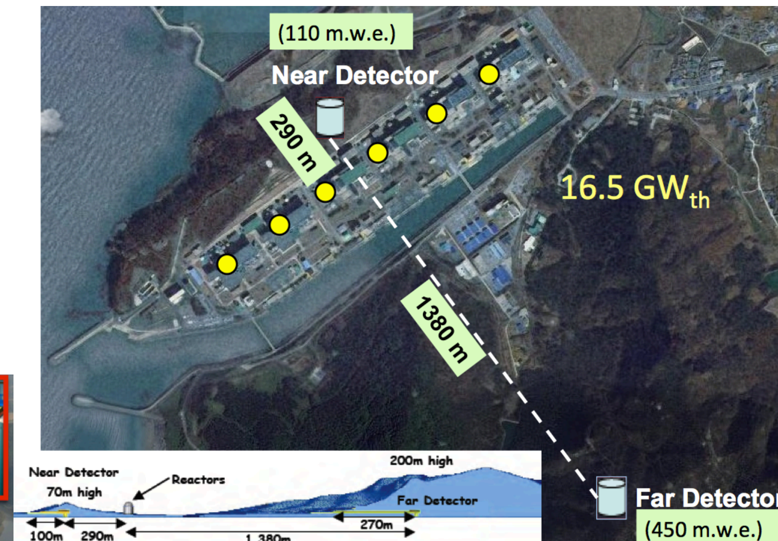
Ichimura, ν2008

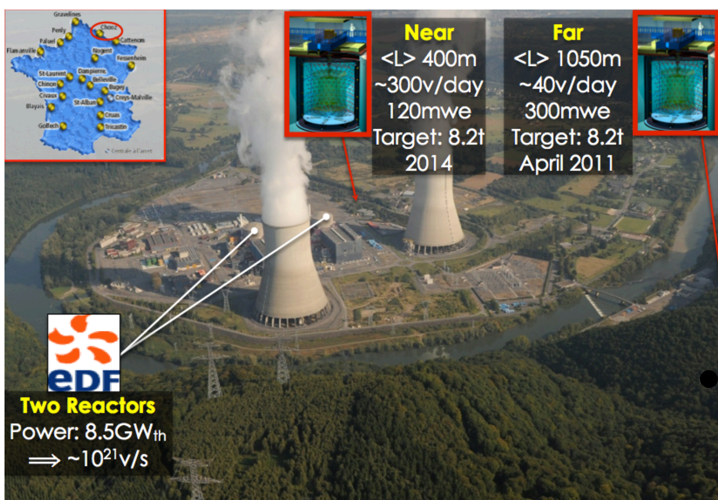
Shorter Baselines used



Daya Bay: 3 cores, 3 halls, baselines of 1.6-2.0km

Reno: 6 reactor cores, 2 halls, baseline(s) ~1.3km

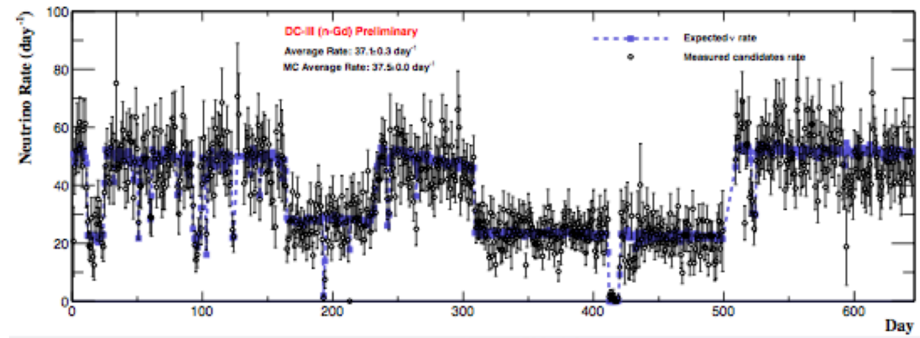




- Double Chooz: 2 cores, 2 halls at 0.4 and 1.0km

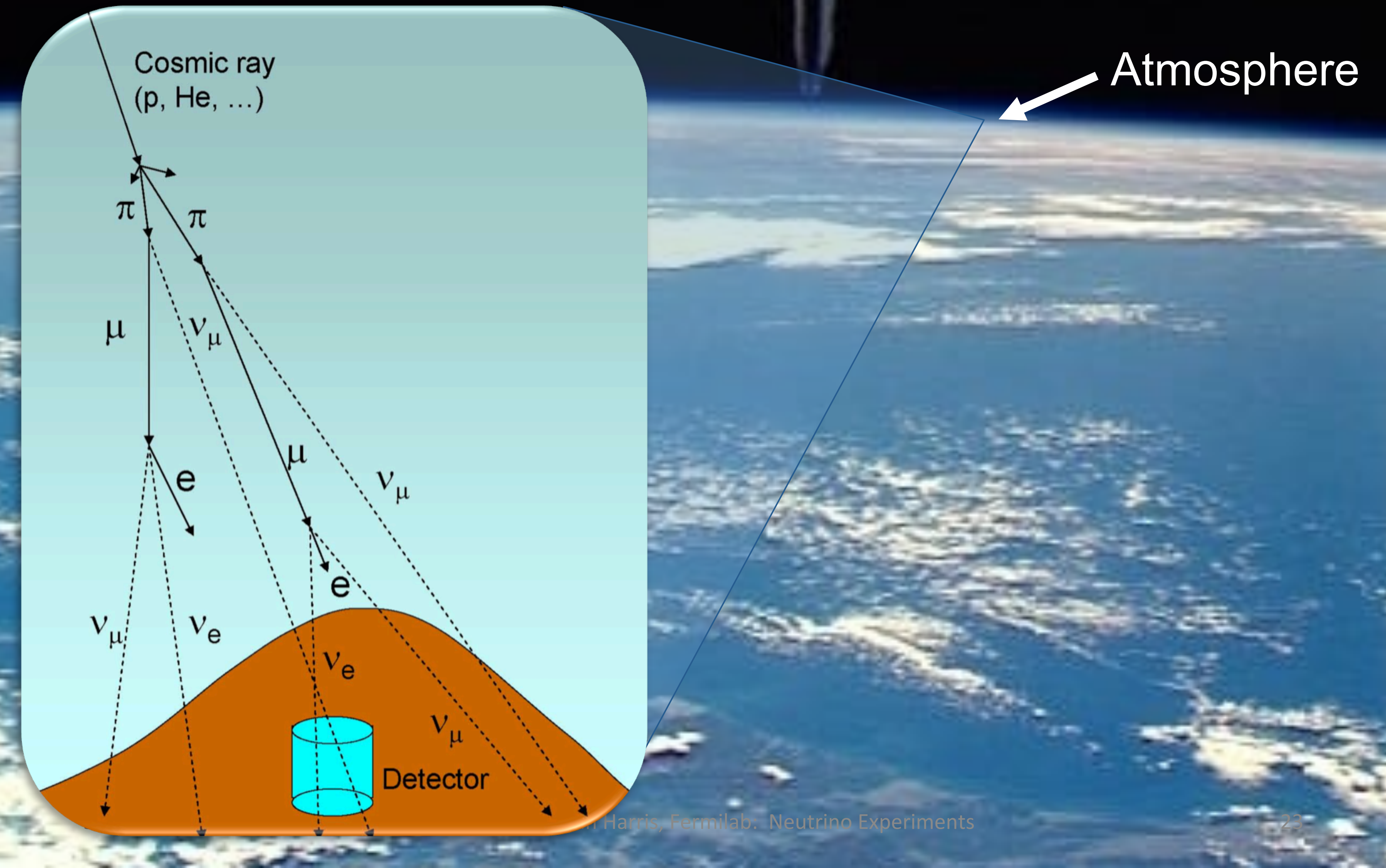
Experimental Challenges with Reactor Fluxes

- Flux changes over time because of fuel cycle
  - Double Chooz(ν2014) at right

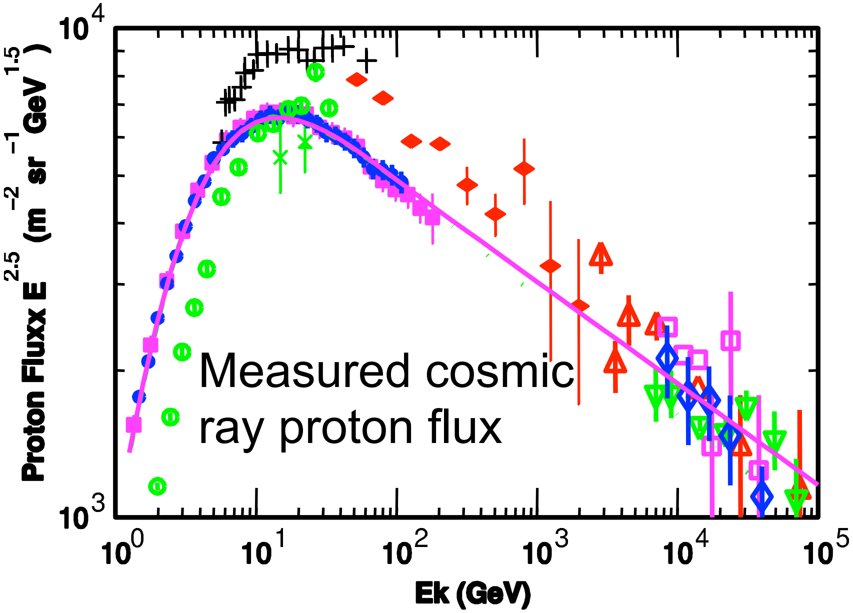


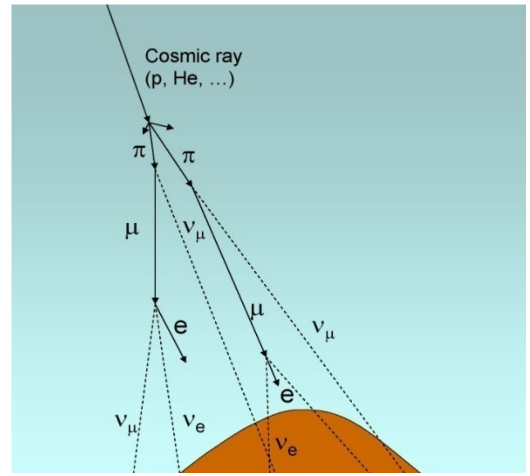
- Have several cores, not all at the same distance from the detector
- Energy deposited in detector is so low you can't possibly figure out original direction of neutrino
- Hard to determine backgrounds since reactors are always on (usually), signal rates very different between near and far detectors

Atmospheric Neutrinos



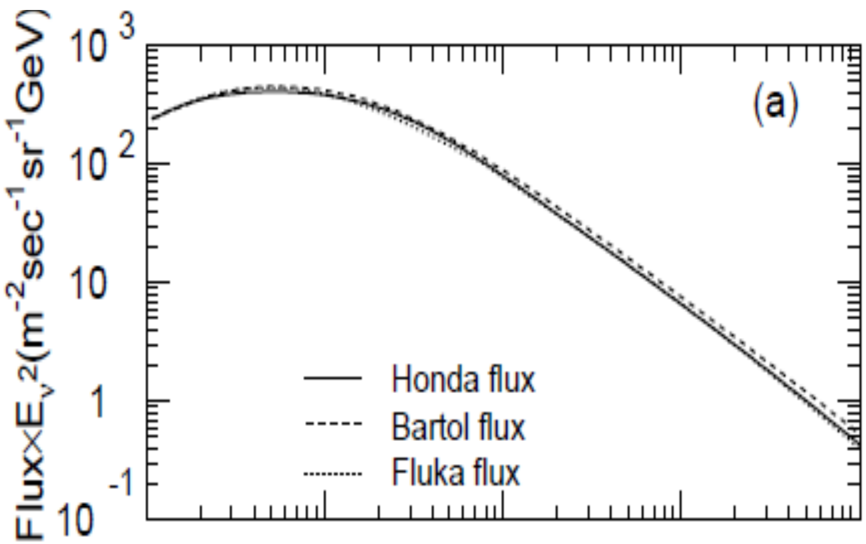
From Cosmic Rays to Neutrinos





Carrying out the calculation all over the Earth

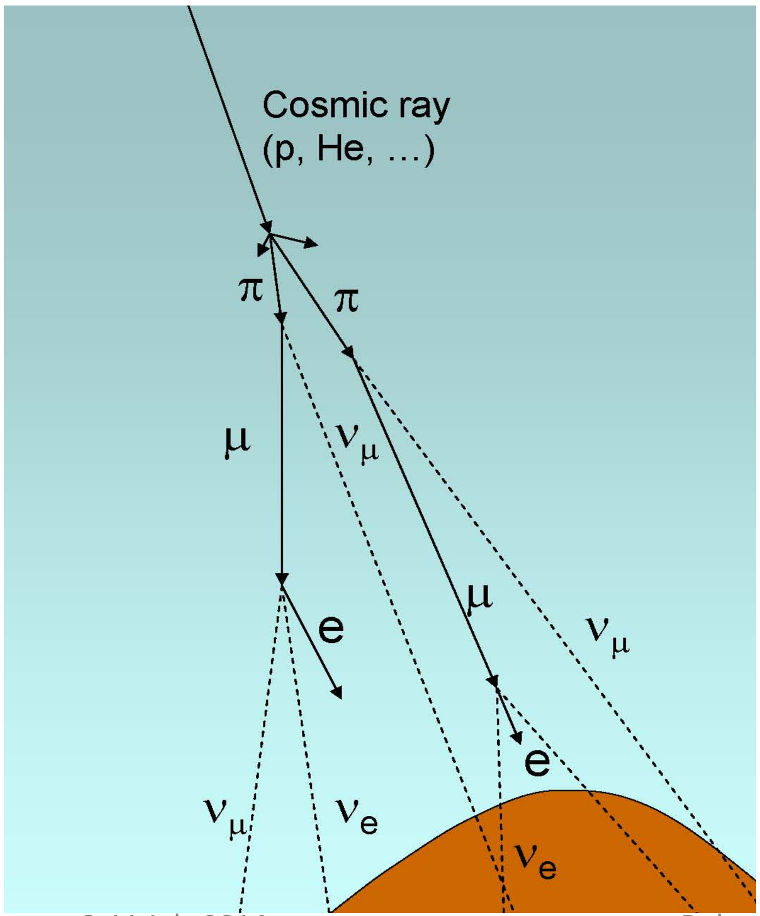
+ solar activity
+ geomagnetic field
+ (p+Nucleon) int.
+ decay of π or K

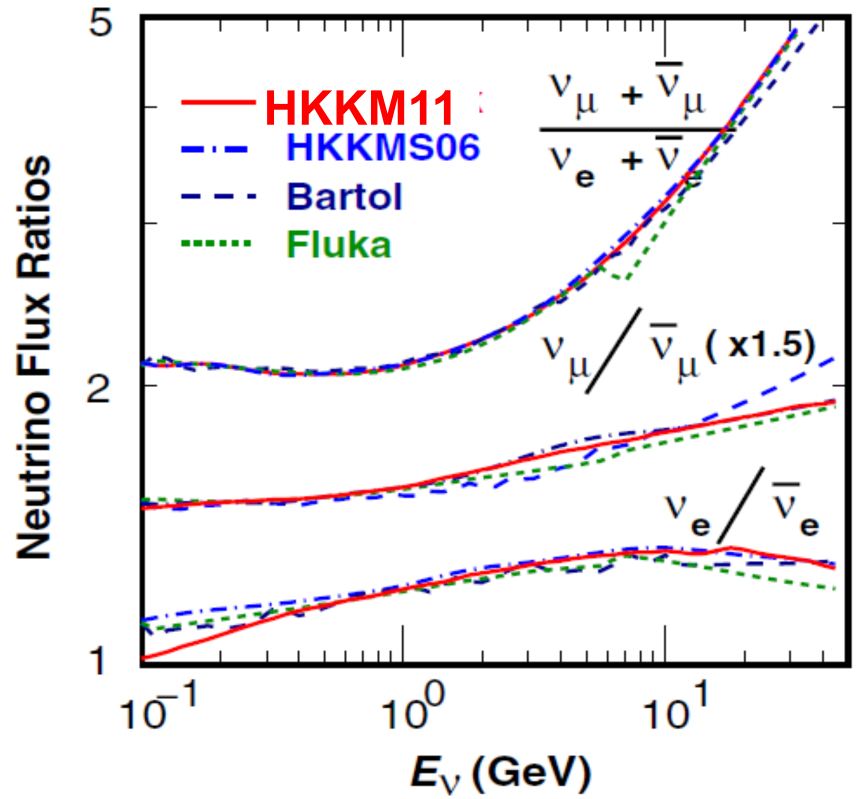


T.Kajita, INSS 2013

What is known well

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





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

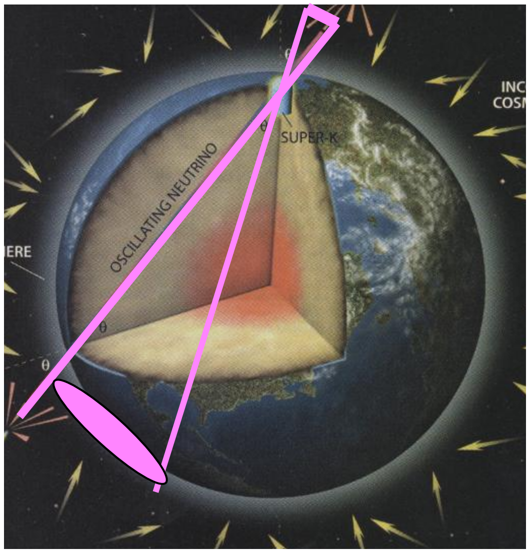
✓ ν_μ/ν_e ratio is calculated to an accuracy of about 2% below ~5GeV.

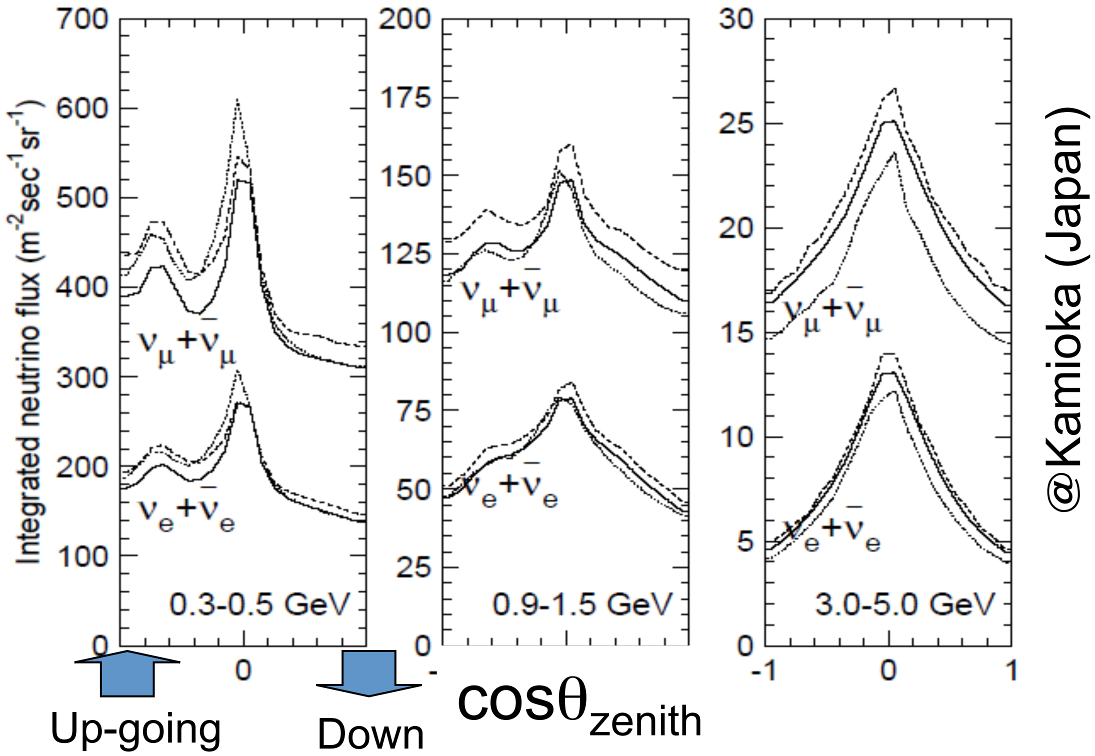
✓ν and anti−ν ratios also accurately calculated.

T.Kajita, INSS 2013

What else is known well: up/down

Zenith angle





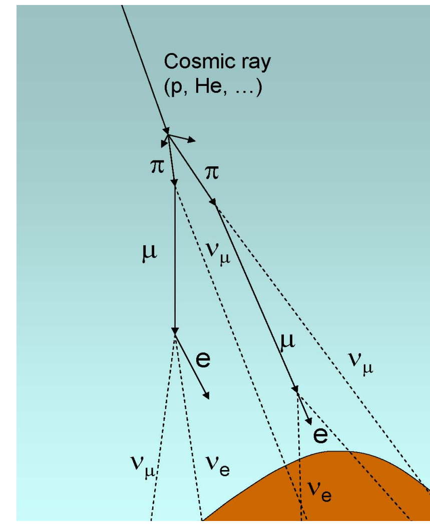
Up/down ratio very close to 1.0 and accurately calculated (1% or better) above a few GeV.

Experimental Challenges with Atmospheric Fluxes

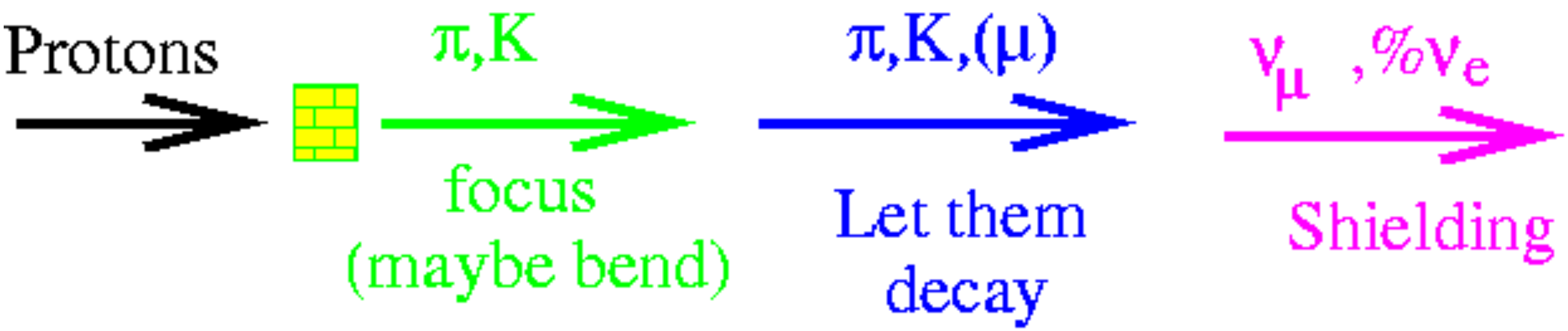
- Absolute rates are hard to predict
- Overall rates are low and steeply falling in energy
- Near equal mix of neutrino and antineutrino means CP violation measurement is near impossible
- *Homework question: how might you be able to see matter effects using atmospheric neutrinos? Do you NEED a magnetic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

Neutrinos from Accelerators

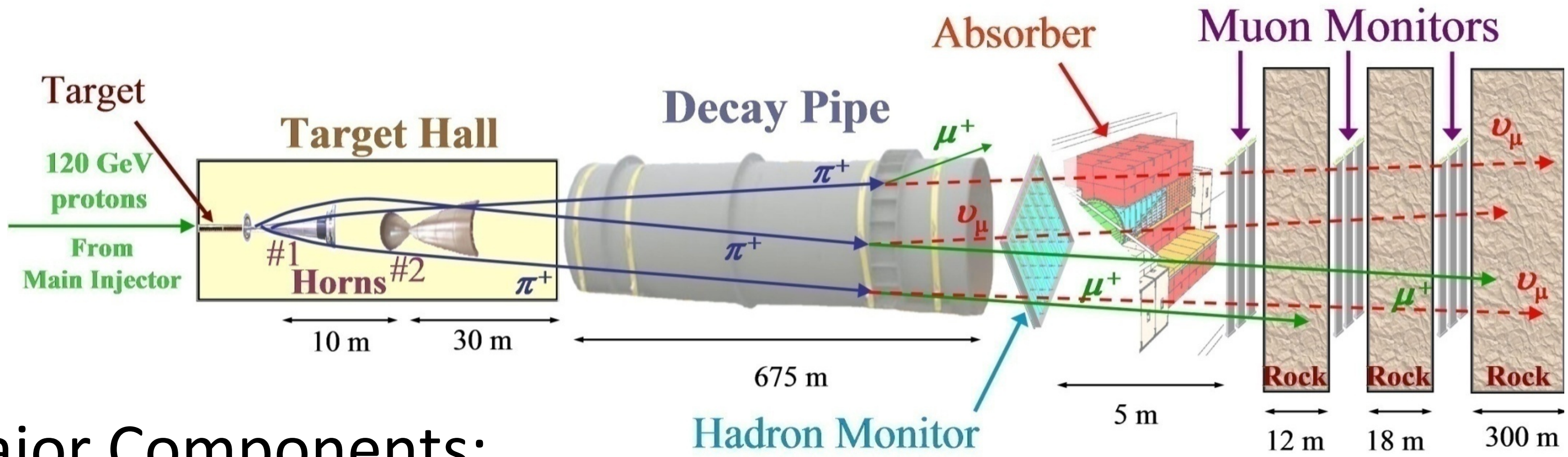
- Atmospheric Neutrino Beam:
  - High energy protons strike atmosphere
  - Pions and kaons are produced
  - Pions decay before they interact
  - Muons also decay



- 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:

$\pi^+ \to \mu^+ \nu_\mu$

$K^+ \to \mu^+ \nu_\mu$

Most ν_e's from 3-body decays:

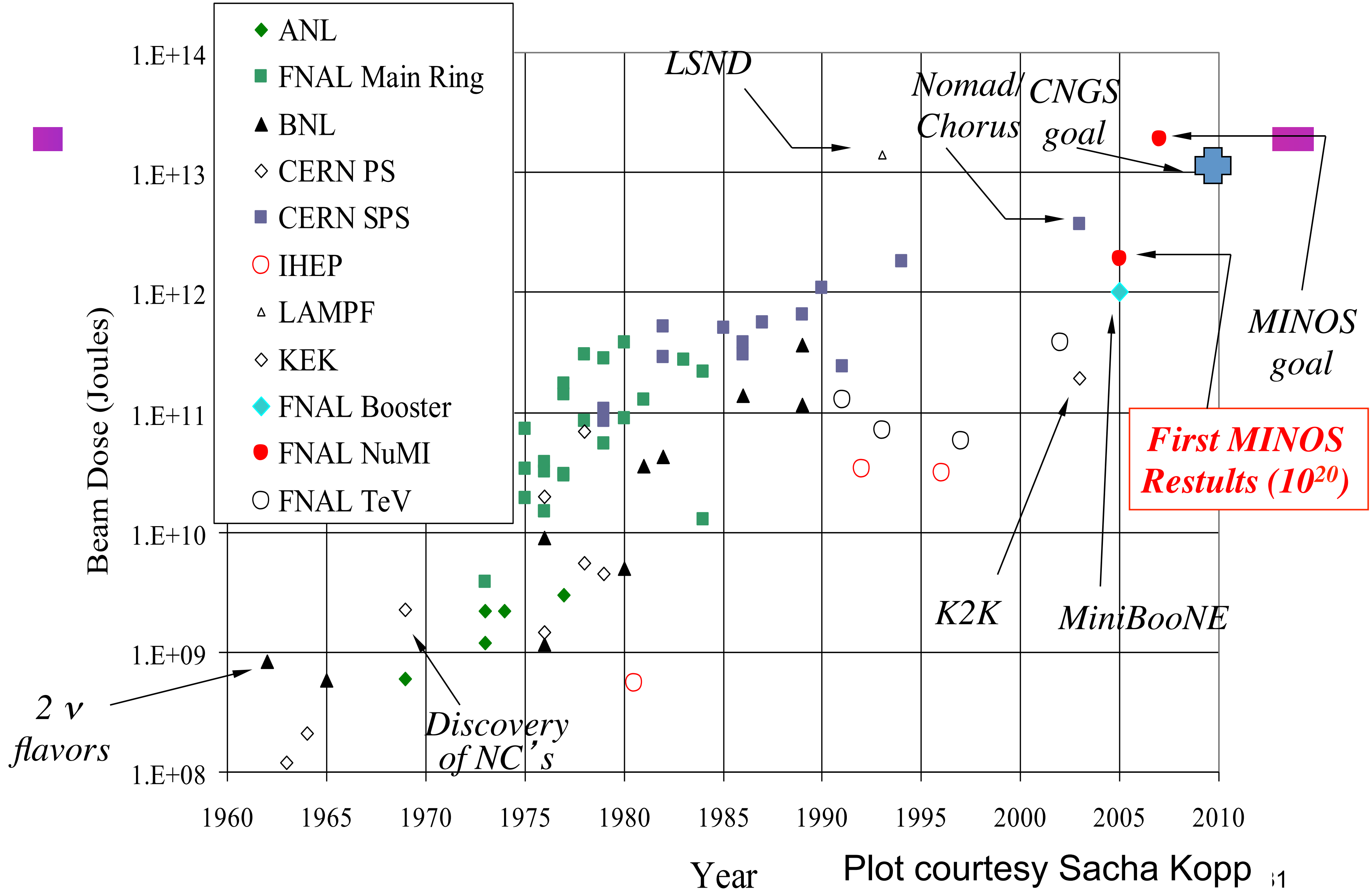
$\mu^+ \to e^+ \nu_e \nu_\mu$

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

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

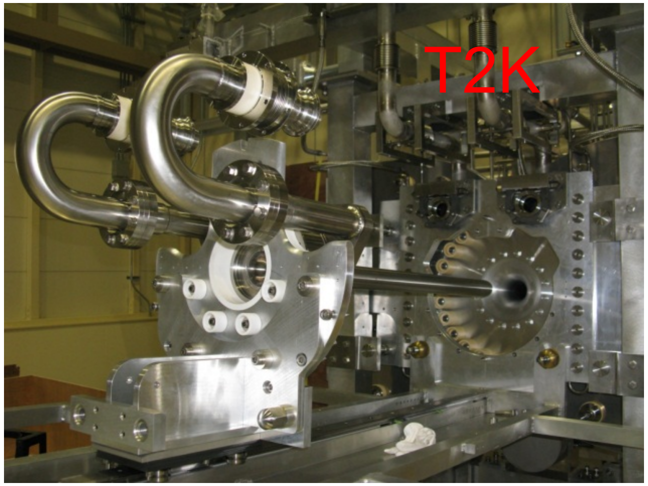
Proton Source	Experiment	Proton Energy (GeV)	p/yr	Power (MW)	Neutrino Energy (GeV)
KEK	K2K	12	$1\times10^{20}/4$	0.0052	1.4
FNAL Booster	MiniBooNE	8	5×10^{20}	0.05	1
FNAL Main Injector	MINOS and NOvA	120	$3\text{-}6\times10^{20}$	0.3 to 0.7	3-17
CNGS	OPERA	400	0.45×10^{20}	**0.48**	25
J-PARC	T2K	40-50	11×10^{20}	0.25 to 0.75	0.77

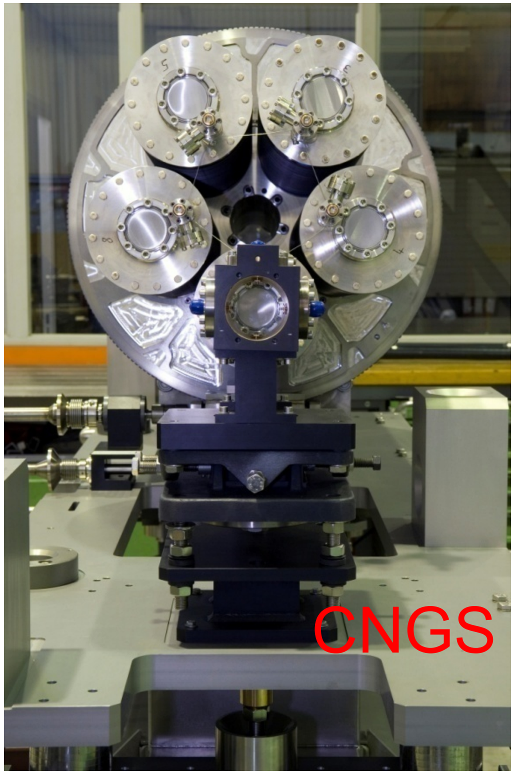


Plot courtesy Sacha Kopp

Neutrino Production Targets

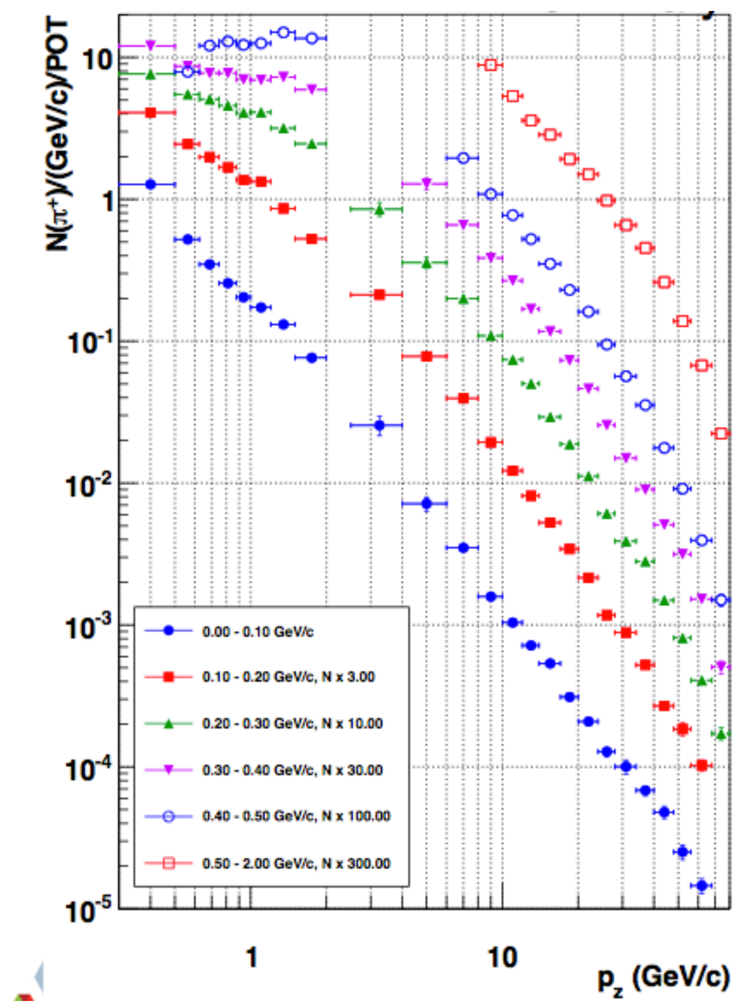
- Have to balance many competing needs:
  - The longer the target, the higher the probability the protons will interact
  - The longer the target, the more the produced particles will scatter
  - The more the protons interact, the hotter the target will get—targeting above ~1MW not easy!
  - Rule of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





Hadron Production

- This is tricky stuff, hard to predict with theory alone
- Copious thin target measurements available, but neutrino targets are usually long
- NA61 data from CERN: thin and thick target data used for T2K analysis
- New this year: MIPP hadron production results (Fermilab), using same target as used for MINOS, and 120GeV protons (at right)



Ref: J.M.Paley, M.D.Messier, R.Raja et al, arXiv: 1404.5882

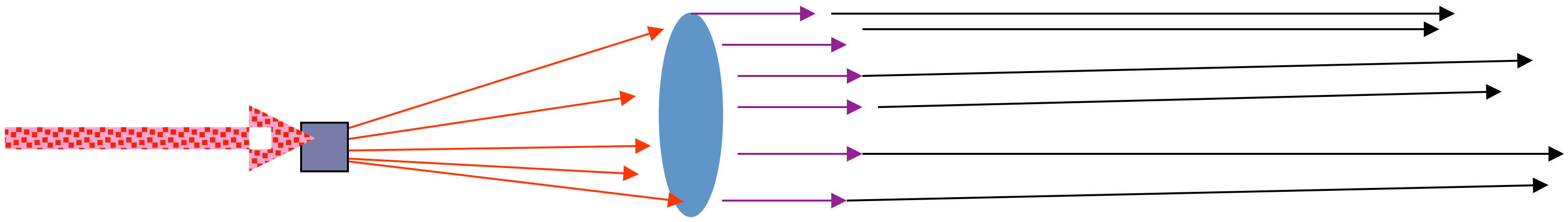
Focusing Systems

- 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?

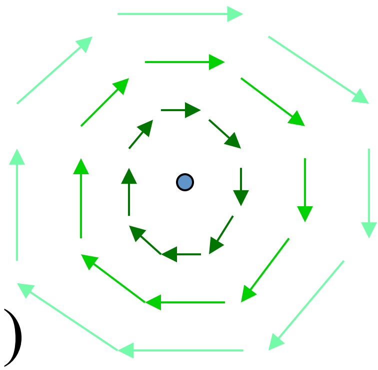
- Imagine particles flying out from a target:
  - When particle gets to front face of horn, it has transverse momentum proportional to radius at which it gets to horn



B Field from line source of current is

in the Φ direction

but has a size proportional to 1/r



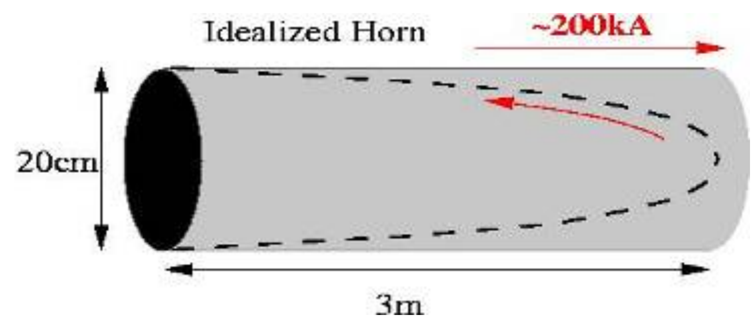
How do you get around this? (hint: $\partial pt \propto B \times \partial l$)

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∝1/r, but make dl ∝ 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

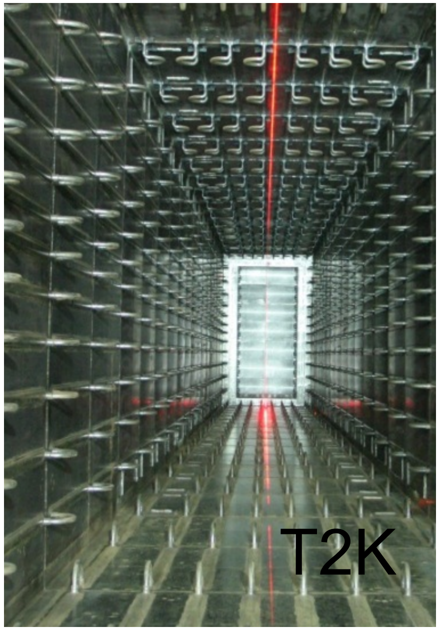
	Length (m)	Diameter (m)	# in beam
K2K	2.4,2.7	0.6,1.5	2
MBooNE	~1.7	~0.5	1
NuMI	3,3	0.3,0.7	2
CNGS	6.5m	0.7	2
T2K	1.4,2,2.5	.47,.9,1.4	3

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…

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

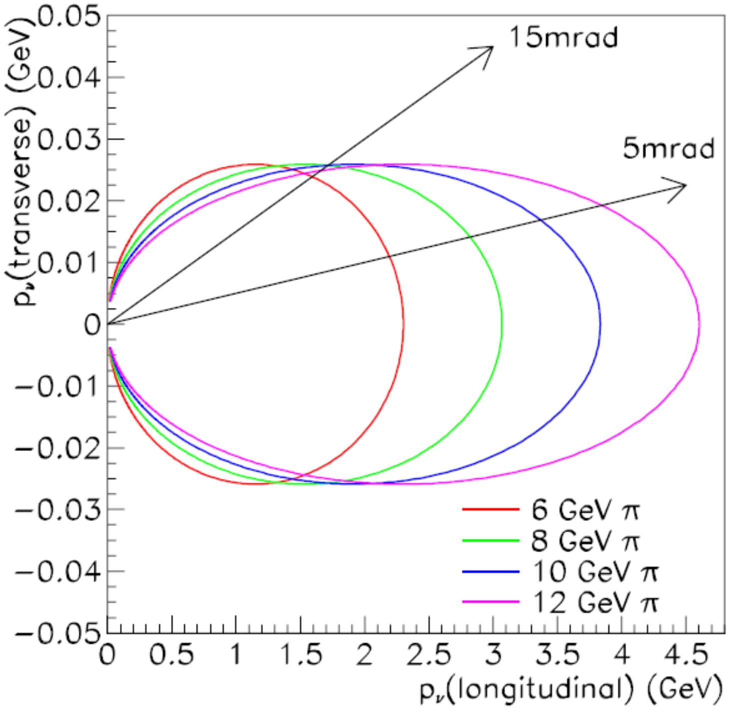
y_π=the number of pion lifetimes in one decay pipe…

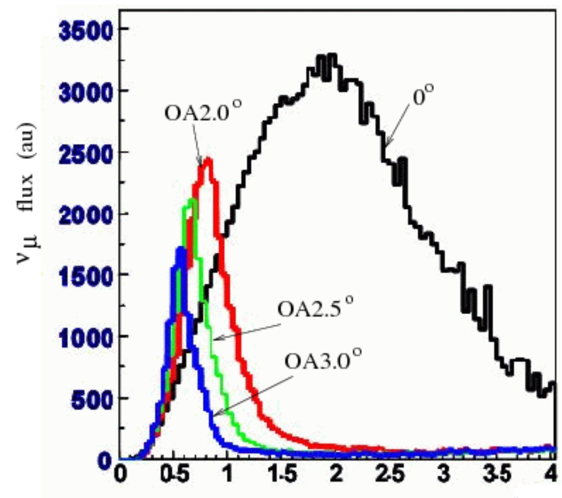
$$y_\pi = \frac{Lm_\pi c^2}{E_\pi c \tau_\pi}$$

	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%

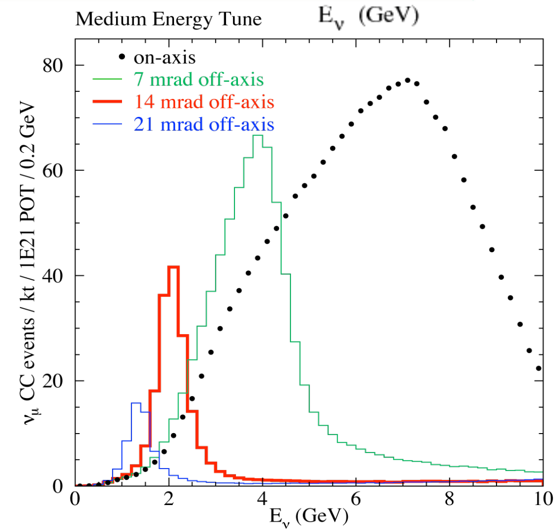
Off-Axis Technique

- 1-1 relationship between neutrino energy and pion energy+angle between neutrino and pion *(derive)*
- 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
- *Question: what are the advantages of a neutrino beam made of muon decays?*

Neutrino Source Summary

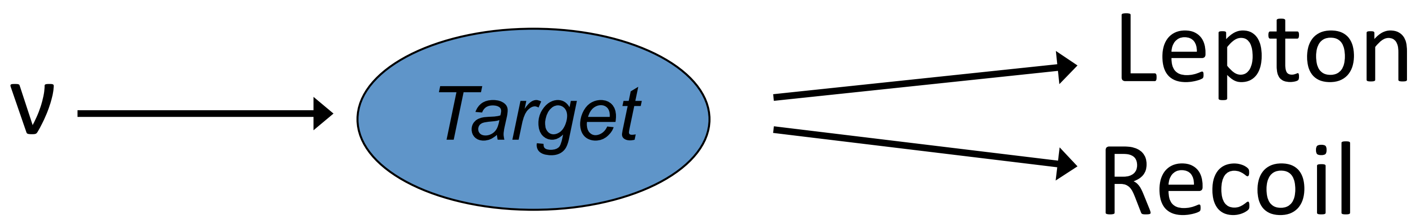
Source	Flux	ν Energy	Composition	Baseline	Matter Effects?
Sun	6×10^{10} ν/cm^2/sec	0.1-10MeV	ν_e (ν_2)	10^8km	yes
Reactor	10^{20} ν/sec/GW	1-10MeV	Anti-ν_e	1-180km	Not yet…
Atmosphere	1 ν/cm^2/sec	0.1-10^4GeV	ν_e+ν_μ and anti-	80-10^4km	yes
Accelerator	6×10^5 ν/cm^2/sec @1km*	0.1-100GeV	ν_μ+%ν_e or anti-ν_μ+%ν_e	1-1000km	yes

* NuMI beamline “low energy tune”, on axis, currently x3 higher!

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

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Thresholds and Processes

Process	Considerations	Threshold (typical)
$\nu N \rightarrow \nu N$ (elastic)	Target nucleus is often free (recoil is very small)	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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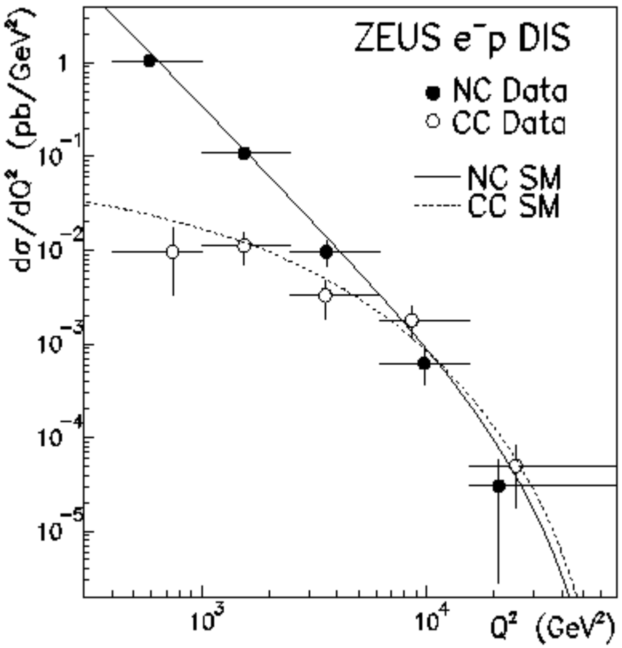
Why is the interaction so weak?

- Weak interactions are weak because of the massive W and Z bosons exchange

$$\frac{d\sigma}{dq^2} \propto \frac{1}{(q^2 - M^2)^2}$$

q is 4-momentum carried by exchange particle
M is mass of exchange particle

At HERA see W and Z propagator effects
- Also weak ~ EM strength



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- Explains dimensions of Fermi "constant"

$$G_F = \frac{\sqrt{2}}{8}\left(\frac{g_W}{M_W}\right)^2$$
$$= 1.166\times10^{-5}/GeV^2 \quad (g_W \approx 0.7)$$

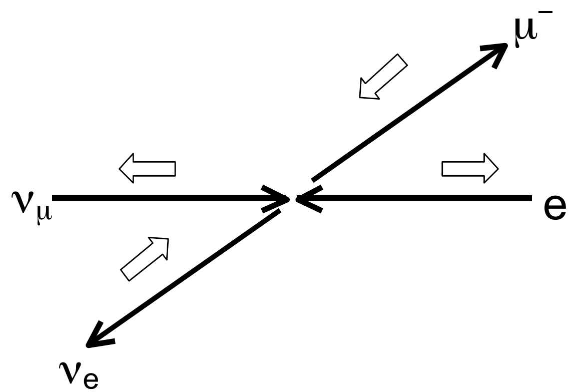
Neutrino-Electron Scattering

- Inverse μ−decay:

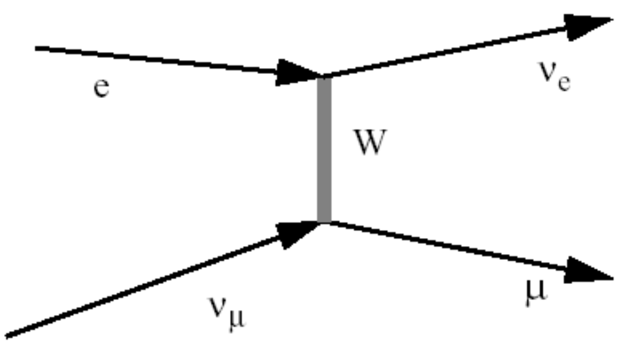
$$\nu_\mu + e^- \rightarrow \mu^- + \nu_e$$

  - Total spin J=0

    (*Assuming massless muon,* helicity=chirality)



$$Q^2 \equiv -\left(\underline{e} - \underline{\nu}_e\right)^2$$



$$\sigma_{TOT} \propto \int_0^{Q^2_{max}} dQ^2 \frac{1}{(Q^2 + M_W{}^2)^2}$$

$$\approx \frac{Q^2_{max}}{M_W{}^4}$$

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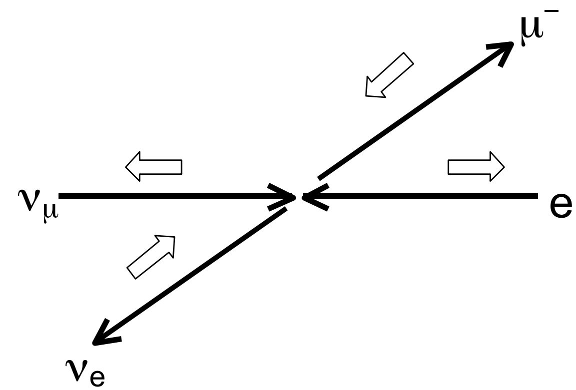
Neutrino-Electron Scattering

$$\sigma_{TOT} \propto Q^2_{\max} = s$$

$$\sigma_{TOT} = \frac{G_F^2 s}{\pi}$$
$$= 17.2\times 10^{-42} cm^2 / GeV \cdot E_\nu (GeV)$$



- Why is it proportional to beam energy?

$$s = (\underline{p}_{\nu_\mu} + \underline{p}_e)^2 = m_e^2 + 2m_e E_\nu \text{ (e}^- \text{ rest frame)}$$

- Proportionality to energy is a generic feature of point-like scattering!
  - because $d\sigma/dQ^2$ is constant (at these energies)

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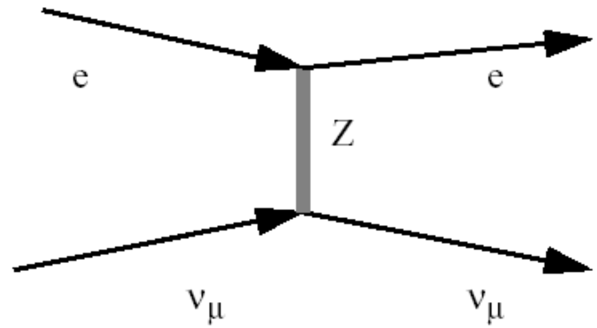
Neutrino Electron Elastic Scattering

- 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: $-1/2 + \sin^2\theta_W$

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

  - Right-handed: $\sin^2\theta_W$

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

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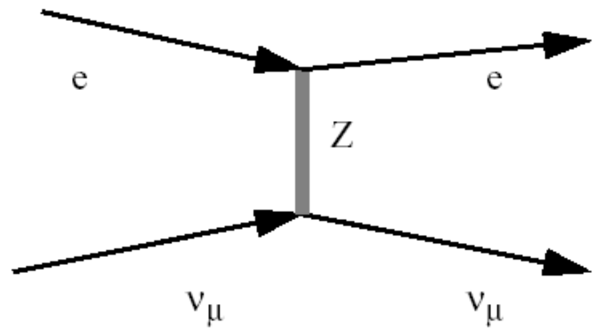
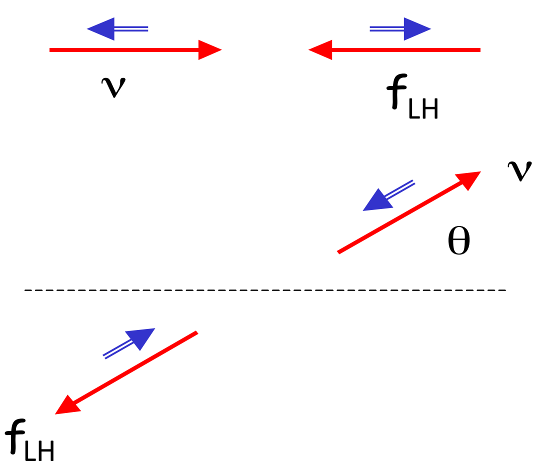
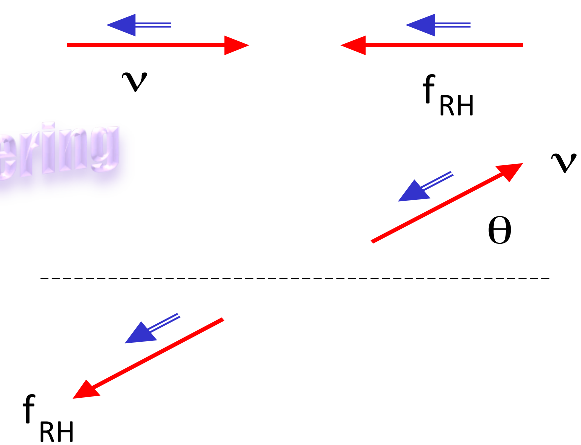
Neutrino Electron Scattering, cont'd

- 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?

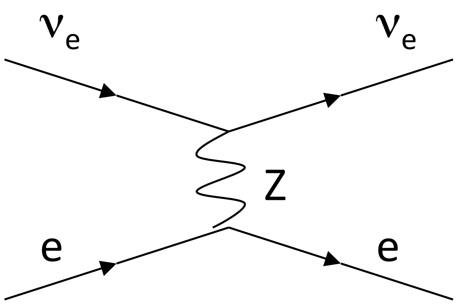
The rection

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

has a much smaller cross-section than

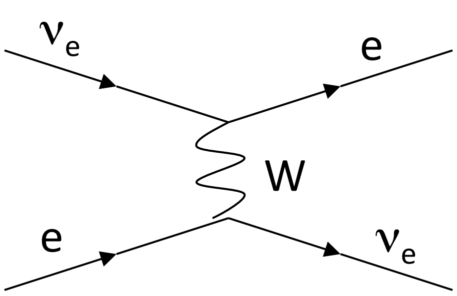
$$\nu_e + e^- \rightarrow \nu_e + e^-$$

Why?



$$\nu_e + e^- \rightarrow \nu_e + e^-$$

has a second contributing reaction, charged current



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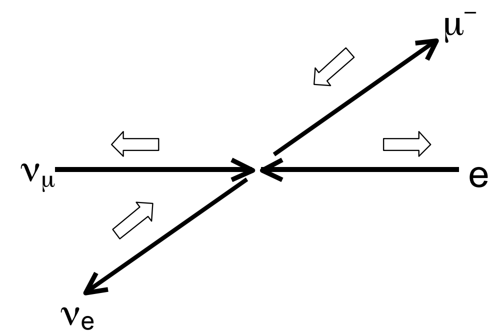
Muon Neutrino thresholds:

- Inverse muon decay:
  - Need enough energy to create a final state muon
  - *Question: how much energy do you need for this process?*



What about other targets?

- 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

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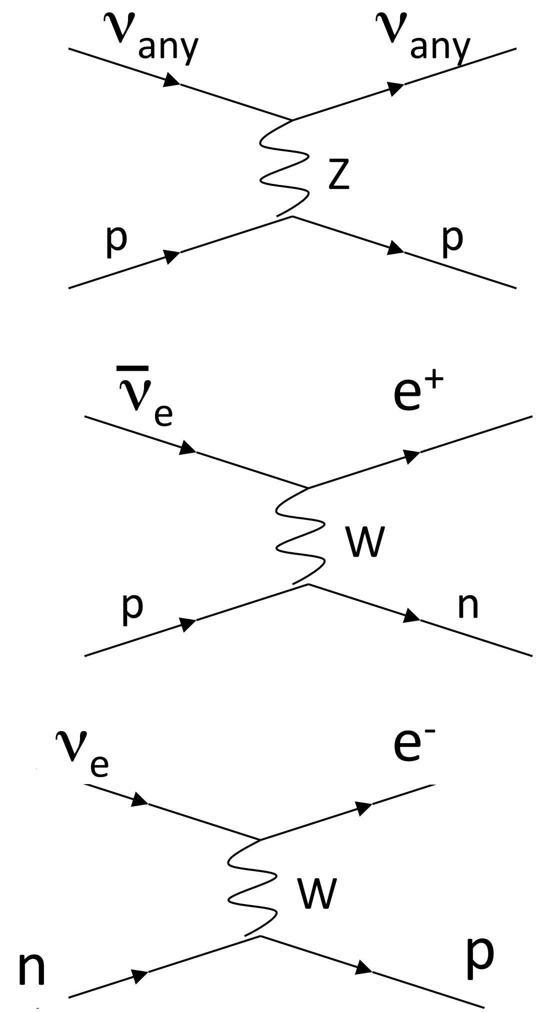
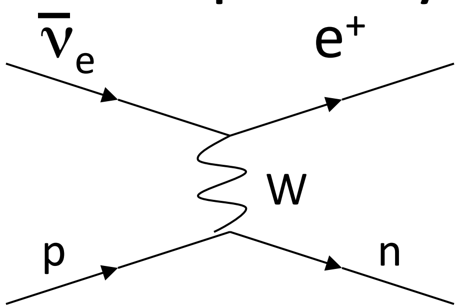


Final State Mass Effects

- In IBD, $\nu_e + p \rightarrow e^+ + n$, have to pay a mass penalty *twice*
  - *M_n-M_p≈1.3 MeV, M_e≈0.5 MeV*



- What is the threshold?
  - kinematics are simple, at least to zeroth order in M_e/M_n → heavy nucleon kinetic energy is zero

$$s_{\text{initial}} = (\underline{p}_\nu + \underline{p}_p)^2 = M_p^2 + 2M_p E_\nu \text{ (proton rest frame)}$$

$$s_{\text{final}} = (\underline{p}_e + \underline{p}_n)^2 \approx M_n^2 + m_e^2 + 2M_n\left(E_\nu - \left(M_n - M_p\right)\right)$$

- Solving…

$$E_\nu^{\min} \approx \frac{\left(M_n + m_e\right)^2 - M_p^{\ 2}}{2M_p} \approx 1.806 \text{ MeV}$$

- *What is threshold for neutrino analog?*

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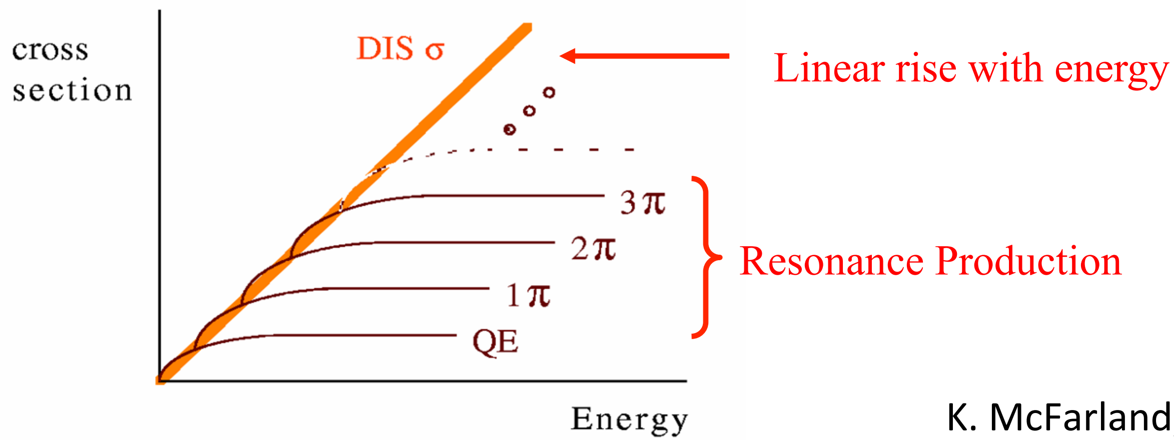
Neutrino-Nucleon Scattering

- 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)
    ν_μ + quark $\rightarrow \mu^-$ + quark'

- Neutral - Current: Z^0 exchange
  - Elastic Scattering:
    (Target unchanged)
    $\nu_\mu + N \rightarrow \nu_\mu + N$
  - Nuclear Resonance Production:
    (Target goes to excited state)
    $\nu_\mu + N \rightarrow \nu_\mu + N + \pi$ (N^* or Δ)
  - Deep-Inelastic Scattering
    (Nucleon broken up)
    ν_μ + quark $\rightarrow \nu_\mu$ + quark



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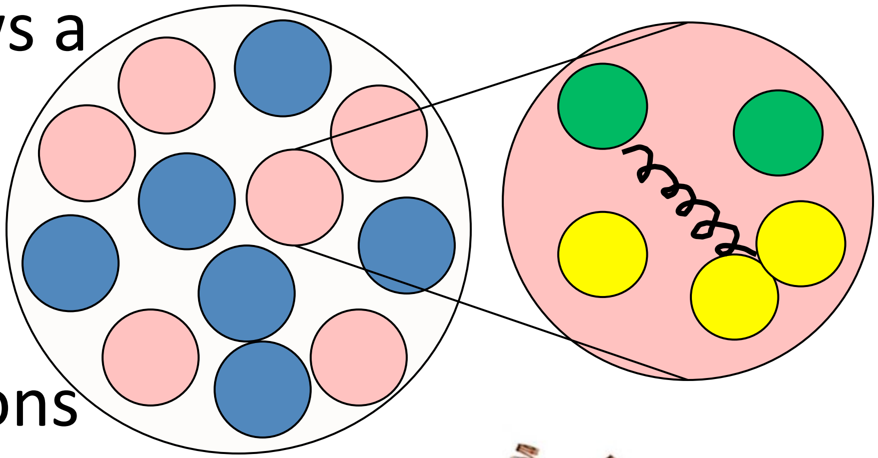
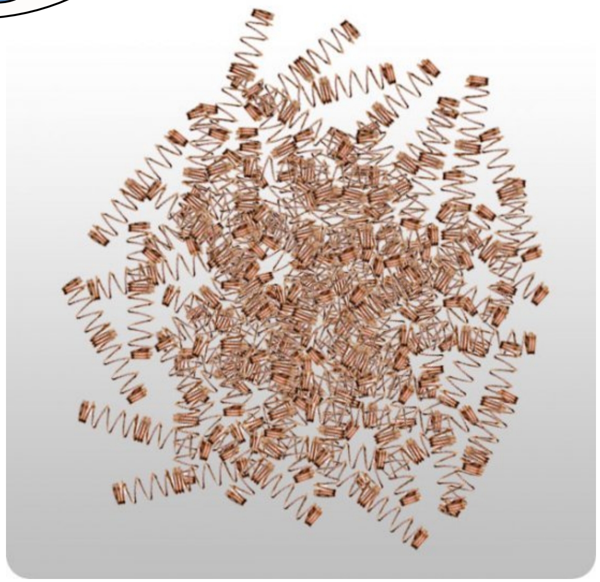
Scattering off Nuclei

- 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.





To be discussed in 3rd lecture…

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
  - Those particles can produce backgrounds to your oscillation analysis!

Source	ν Energy	Composition	Reactions
Sun	0.1-10MeV	ν_e (ν_2)	ν-e or CCQE
Reactor	0.1-10MeV	Anti-ν_e	CCQE
Atmosphere	0.1-1000GeV	$\nu_e+\nu_\mu$	CCQE+RES +DIS
Accelerator	0.1-100GeV	ν_μ+%ν_e or anti-ν_μ+%ν_e	CCQE+RES +DIS

Questions from Lecture

- Given the luminosity of the sun, how long would the sun last if it was simply burning chemical energy instead of nuclear energy? (assume sun is 2×10^{30}kg)
- How might you be able to see matter effects using atmospheric neutrinos? Do you NEED a magnetic field in your detector? (students on INO or PINGU should answer a different question…)
- What is better: air, vacuum window, or He-filled decay pipe? Does it depend on pion energy? (recall multiple scattering formula)
- Derive the relationship between the neutrino energy and the pion energy and angle between neutrino and pion
- What is threshold for $\nu_e + n \rightarrow e^- + p$?
  - Hint: where do you find neutrons?
  - What about for ν_μ?
  - What about for ν_τ?