Big World of Small Neutrinos

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Neutrino of Love

I go undetected
In all my interactions
I cannot be seen
From any point of view
You won't know if I'm here
Except when I'm gone
I'm the neutrino of love
And I'm coming over you

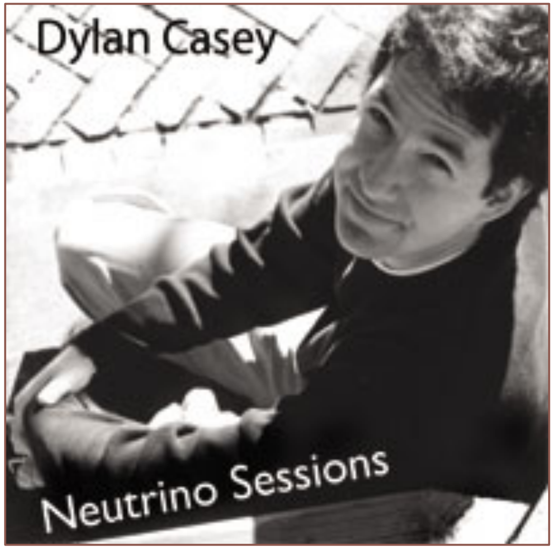
You cannot keep me in a cage
No matter how thick the walls
I will escape
You cannot hold me in a box
Cannot bind me with a lock
Cannot keep me anyway
I'm not afraid of the dark
I'm the neutrino
Neutrino of love
I'm the neutrino
Neutrino of love

I'm the neutrino baby
Neutrino of love

Cannot prevent my infiltration
Neutrino

Cannot prevent my penetration
Neutrino

I am the neutrino



Dylan Casey: guitar and vocals, 2001

Neutrino of Love

The musical description of neutrinos by Dylan Casey in his song “Neutrino of Love” is really fantastic

Yes indeed, neutrinos are elusive, mysterious, yet abundant

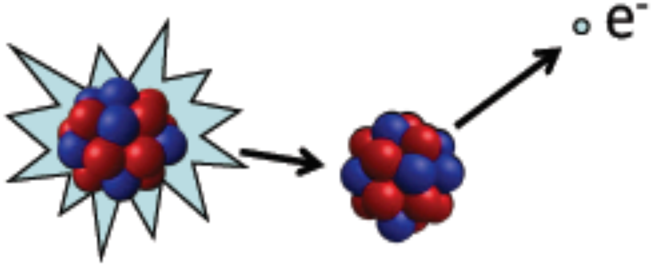
Despite that (or because of that!), even after sixty years of it’s discovery, it still poses many mysteries and creates challenges to the physicists who want to detect it

Like electrons, they are elementary particles

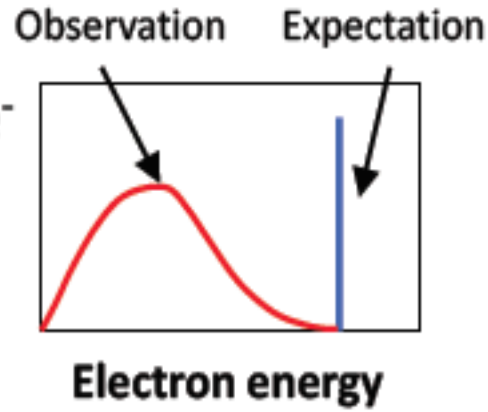
F. Reines would narrate neutrino as, it is “...the most tiny quantity of reality ever imagined by a human being”

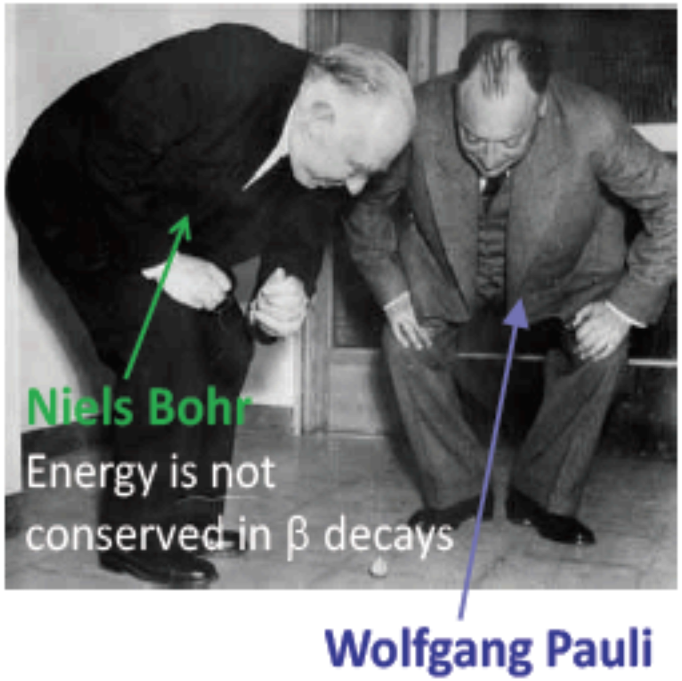
Mission Impossible: Detect Neutrinos

The problem (1914)

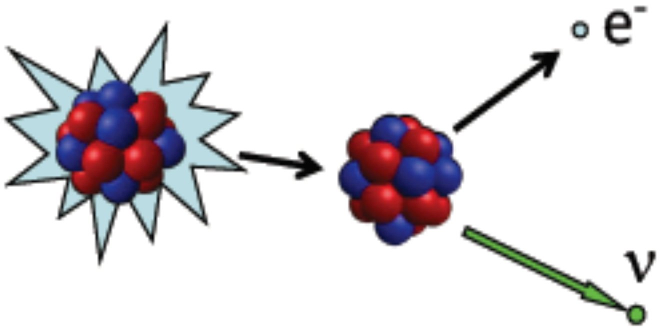


$n \rightarrow p + e^-$





The desperate remedy (1930)



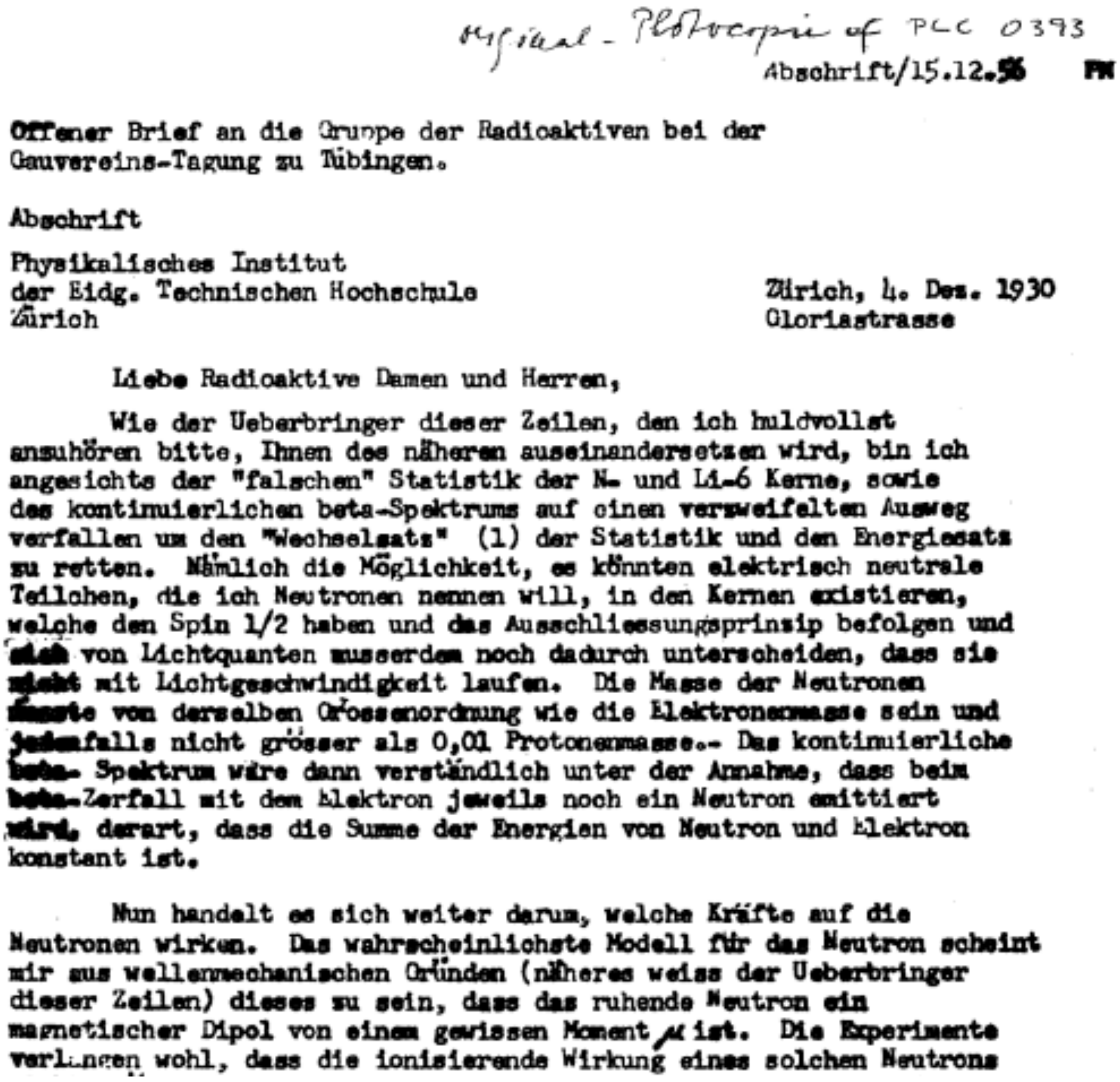
$n \rightarrow p + e^- + \nu$

There is a neutral particle able to cross all detectors without leaving any trace and carrying all the missing energy

> *«I have done a terrible thing. I have postulated a particle that cannot be detected.» (1930)*

Fortunately Pauli was wrong and neutrinos have been detected successfully

Postulate of the Neutrino



Original - Photocopie of PLC 0393

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

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

Wolfgang Pauli, 1930

Pauli proposed that an undetectable particle shared the energy with the emitted electron in beta-decay

1934: Fermi named the new particle ‘neutrino’

Neutrinos are Everywhere

Detected (1950s)

✓ **Nuclear Reactors**

Detected (1960s)

Sun ✓

Created & Detected (1960s)

✓ **Particle Accelerators**

Detected (1980s)

Supernovae
(Stellar Collapse)
SN 1987A ✓

Detected (1960s)

✓ **Earth Atmosphere**
(Cosmic Rays)

IceCube reports the detection of 82 extremely HE events > 30 TeV energy

Astrophysical
Accelerators **Soon ?**

Detected (2000s)

✓ **Earth Crust**
(Natural
Radioactivity)

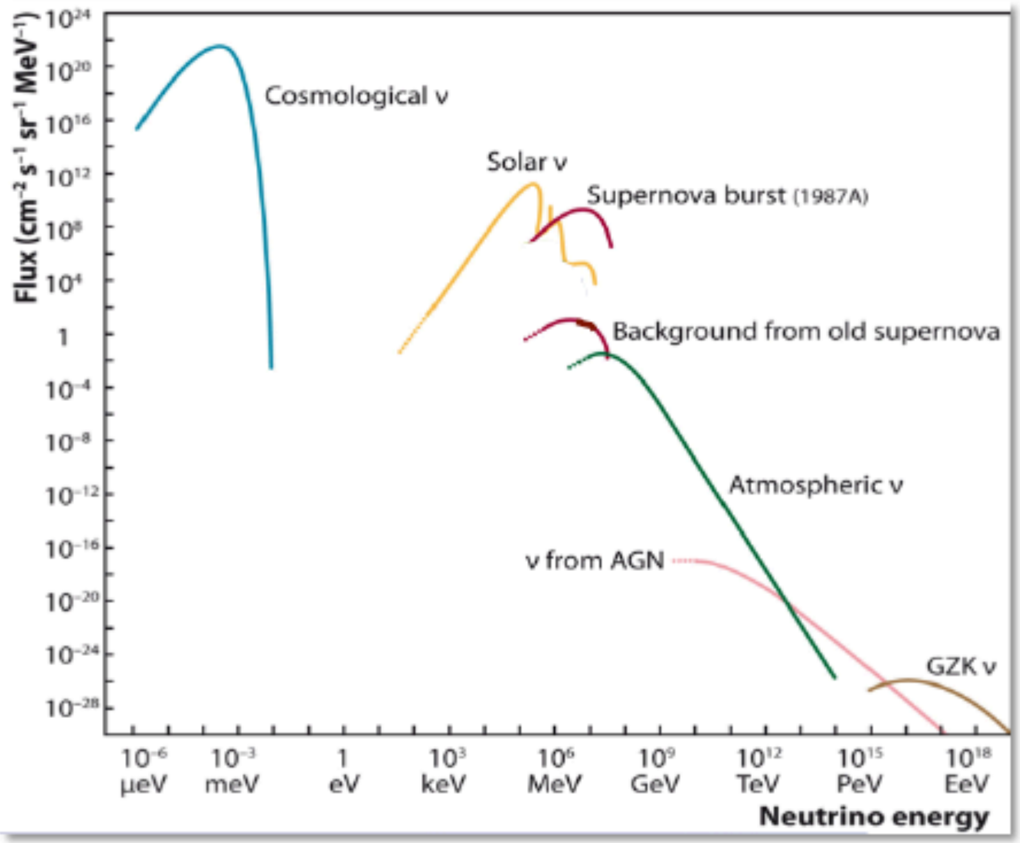
Not even close

Cosmic Big Bang
(Today 330 ν/cm^3)
Indirect Evidence

Extremely rich and diverse neutrino physics program

Neutrinos From the Heavens

- neutrinos are unique messengers …



- they are not deflected by interstellar magnetic fields

  → *point back to their source*

- they rarely interact with matter

  → *arrive directly from regions where light cannot come*

- ν's carry information about the workings of the highest energy and most distant phenomenon in the univere

- "neutrino astronomy"

neutrinos from stars

$\underbrace{\textit{supernova, solar}}$*, atmospheric, and cosmic neutrinos*

The Greisen-Zatsepin-Kuzmin (GZK) limit: theoretical upper limit on the energy of protons traveling from other galaxies through the intergalactic medium to our galaxy

Few Unique Features of Neutrinos

- **After photon, neutrino is the second-most abundant particles in the universe**

Cosmic microwave background: 400 photons / cm^3 (Temperature: ~ 2.7 K)

mean energy $E_\gamma = k_B T = 2.3\times10^{-4}$ eV

Cosmic neutrino background: 330 neutrinos / cm^3 (Temperature: ~ 1.95 K)

(These are known as relic neutrinos: very low in energy: ~ 0.0002 eV)

(Even empty space between galaxies is full of neutrinos)

About 100 trillion neutrinos pass through our body every second

Hundred trillion = 100 000 000 000 000

- **The Sun produces ~ 10^{38} neutrinos per second**

But most of the neutrinos are relics of the Big Bang (~ 10^{10} years old)

Few Unique Features of Neutrinos

- **Nature’s most elusive messenger, interacts very rarely, very hard to detect**

Invisible: do not interact with light

100 billion neutrinos + the whole Earth = only one interaction

Stopping radiation with lead shielding: 50 cm for α, β, γ

Stopping neutrinos from the Sun: light years of lead

- **Arrives ‘unscathed’ from the farthest reaches of the Universe**

Brings information from deep within the stars (Not possible with light)

- **The lightest massive particles**

A million times lighter than the electron

No direct mass measurement yet

Close Encounter with Neutrinos

- ⊙ **When we take our morning walk on the green Nature, our body receives**

  400000 billion neutrinos from the Sun

  50 billion neutrinos from the natural radioactivity of the Earth

  10 – 100 billion neutrinos from the nuclear power plants all over the world

- ⊙ **We can still enjoy our walk. Typically a neutrino has to zip through**

  10,000,000,000,000,000,000 people before doing anything

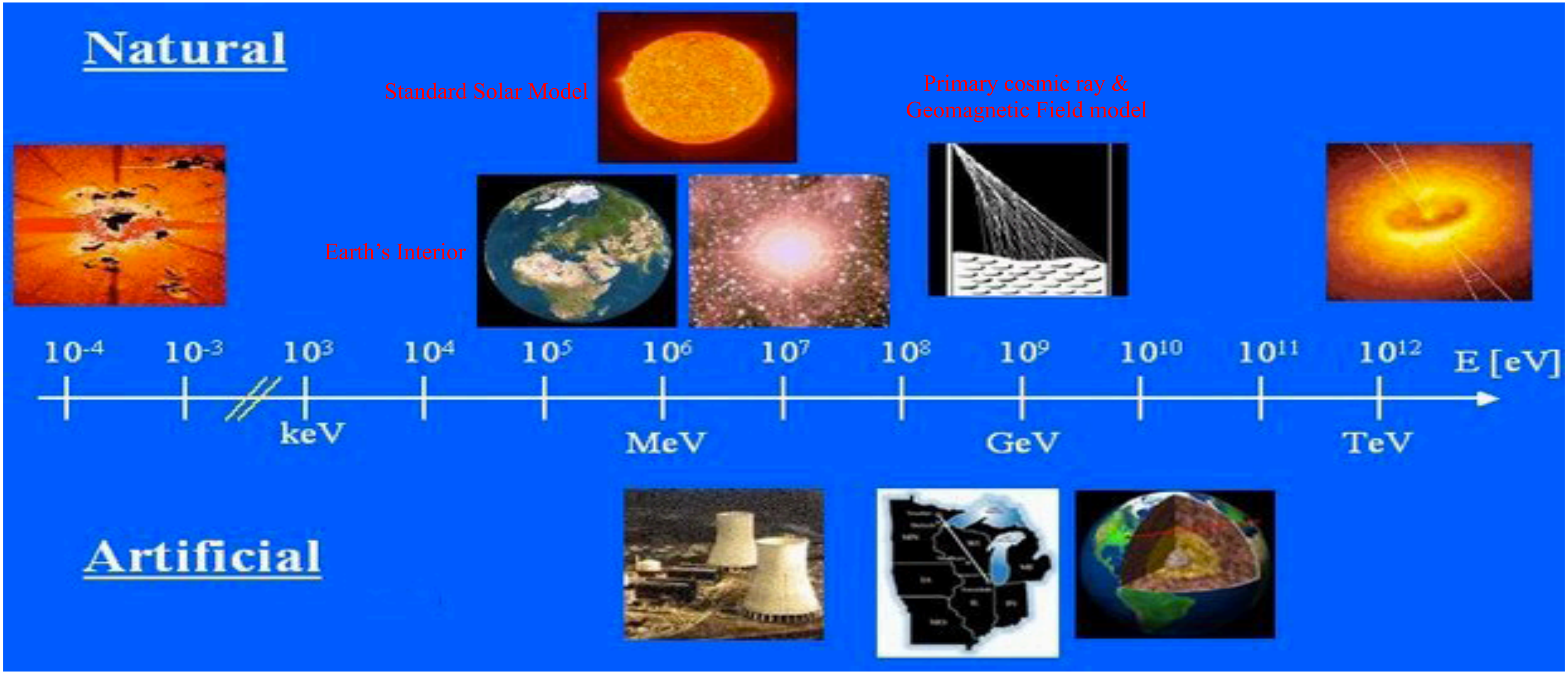
- ⊙ **Our body contains about 20 milligrams of ^{40}K which is beta-radioactive**

  We emit about 340 million neutrinos per day, which run from our body

  at the speed of light until the end of the Universe

Neutrinos: Exceptional Probe for Environments

Neutrino Observation: Go Beyond optical and radio observation



Detect neutrinos from the Sun, Supernovae, AGN, GRBs: Era of Neutrino Astronomy

v detection involves several methods on surface, underground, under the sea, or in the ice

v detector masses range from few kgs to megatons, with volumes from few m^3 to km^3

Neutrino Interaction Cross Section

Elastic scattering: $\bar{\nu} e^- \rightarrow \bar{\nu} e^-$

Dimensional estimate assuming $E_{\mathrm{CM}} \gg m_e$: $\boxed{\sigma \sim G_F^2 E_{\mathrm{CM}}^x}$

(E$_{\mathrm{CM}}$ is the only available Lorentz-invariant scale parameter)

Dimensional analysis:

$$[\mathrm{GeV}^{-2}] = [\mathrm{GeV}^{-4}][\mathrm{GeV}^{x}] \quad \Rightarrow \quad x = 2$$

$$\boxed{\sigma \sim G_F^2 E_{\mathrm{CM}}^2}$$

Energies in the CM frame (E$_{\mathrm{CM}}$) and the lab frame (E$_\nu$)

$$E_{\mathrm{CM}}^2 = (E_{\bar{\nu}} + m_e)^2 - p_{\bar{\nu}}^2 \approx 2 m_e E_{\bar{\nu}}$$

Therefore, $\sigma \sim 2 m_e G_F^2 E_{\bar{\nu}}$

Neutrino Interaction Cross Section

Natural units: $\sigma \sim 2 m_e G_F^2 E_{\bar{\nu}}$ [unit: GeV^{-2}]

Practical units: $\sigma \sim 2(\hbar c)^2 m_e G_F^2 E_{\bar{\nu}}$

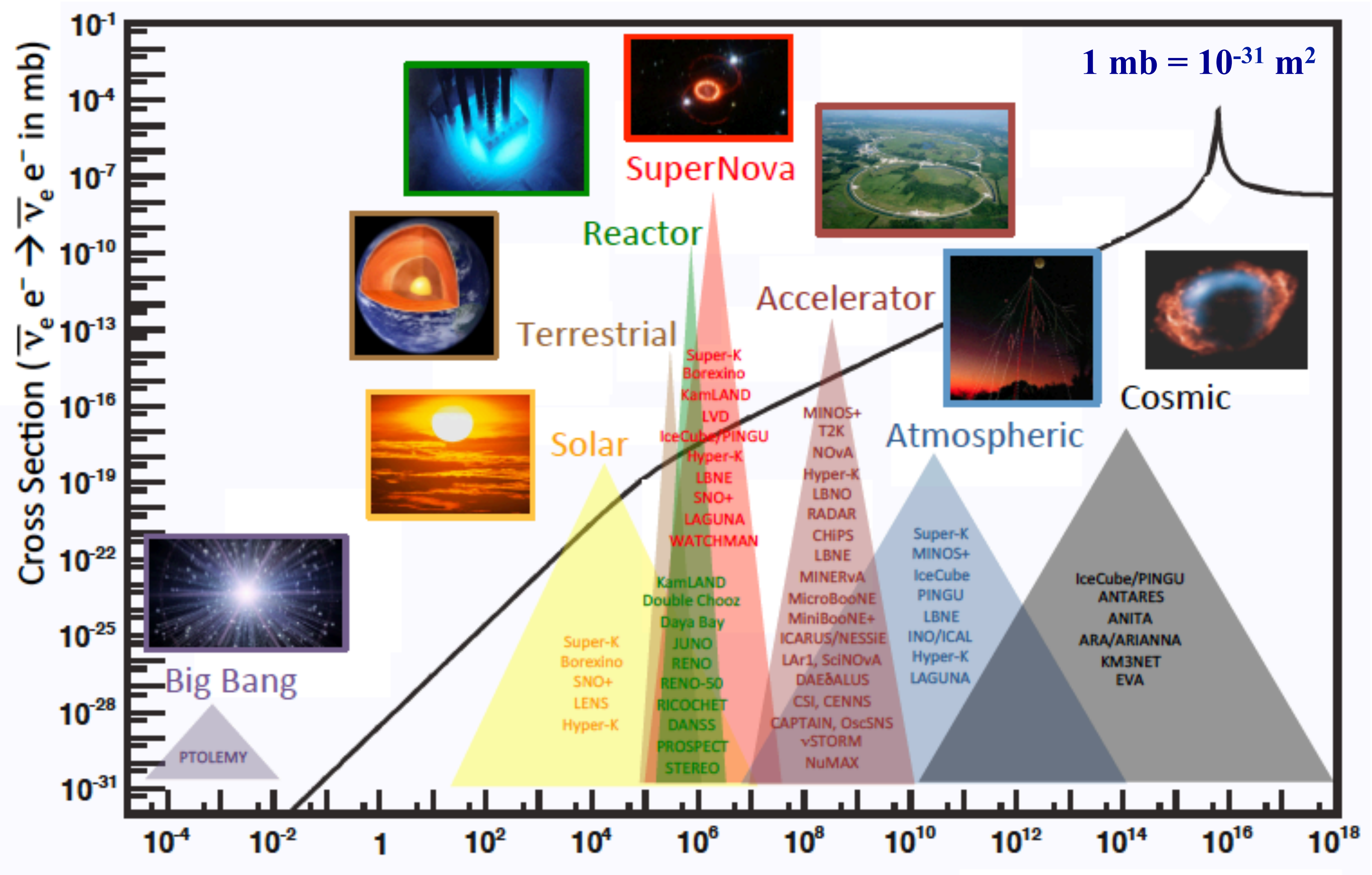
[Unit: GeV^{-2} × (GeV×cm)^2 = cm^2]

The cross-section has a linear energy-dependence

Numerically,

$$
\begin{aligned}
\sigma \sim & \; 2 m_e G_F^2 E_{\bar{\nu}} (\hbar c)^2 = \\
= & \; 2 \cdot 0.5 \text{ MeV} \cdot (1.166 \times 10^{-5} \text{ GeV}^{-2})^2 E_{\bar{\nu}} (0.2 \text{ GeV fm})^2 \sim \\
\sim & \; 10^{-43} \left(\frac{E_{\bar{\nu}}}{\text{MeV}} \right) \text{cm}^2
\end{aligned}
$$

Neutrinos are omnipresent: Friends across 23 orders of magnitude



$$\sigma \sim 2m_e G_F^2 E_{\bar{\nu}} (\hbar c)^2$$

$$\sim 10^{-43} \left(\frac{E_{\bar{\nu}}}{\mathrm{MeV}}\right) \mathrm{cm}^2$$

σ(1 MeV) ~ 10^{-43} cm^2, σ(1 GeV) ~ 10^{-40} cm^2

J. L. Hewett et al., arXiv:1310.4340v1, Snowmass 2013 Neutrino Working Group

S. K. Agarwalla, EHEP 2019, TIFR, Mumbai, India, 24th to 26th January, 2019

Neutrino Mean Free Path

Mean free path of a typical reactor/solar (~1 MeV) (anti)neutrino in rock:

$$\lambda = (n\sigma)^{-1} \approx \left(\frac{\rho}{2m_p}\sigma\right)^{-1} \approx \frac{2 \times 1.67 \times 10^{-24}\ \mathrm{g}}{3\ \mathrm{g/cm^3} \times 10^{-43}\ \mathrm{cm^2}} \approx$$

$$\approx \quad 10^{17}\ \mathrm{m} \approx 10\ \text{light years}$$

n: density of protons [cm^{-3}].
ρ: density of matter [g cm^{-3}].
About half of the nucleons are protons.

(~ distance to α Canis Minoris)

Consider a ~1 MeV neutrino produced in the Solar core.
Probability of interaction before leaving Sun:

$$P = 1 - e^{-R_\odot/\lambda} \approx R_\odot/\lambda \sim \frac{7 \times 10^8\ \mathrm{m}}{10^{17}\ \mathrm{m}} \sim 10^{-8}$$

(average Solar density = 1.4 g/cm^3)

Take Home Message →

Low energy neutrinos are direct probes into the Sun’s (and Earth’s) interior
(but not into neutron stars having densities around 10^{14} g/cm^3)

Neutrino Detection

Starting point: imagine you want to build a neutrino detector

→ to measure neutrino oscillation parameters
→ or to peer deep into the Universe
→ or to look for some other exciting new physics related to neutrinos

Things to keep in mind:

a) what type of neutrino do you want to detect? ν_e , ν_μ , ν_τ or $\overline{\nu}_e$, $\overline{\nu}_\mu$, $\overline{\nu}_\tau$

b) what is the source of neutrinos? influences the energy of ν and interaction type(s)

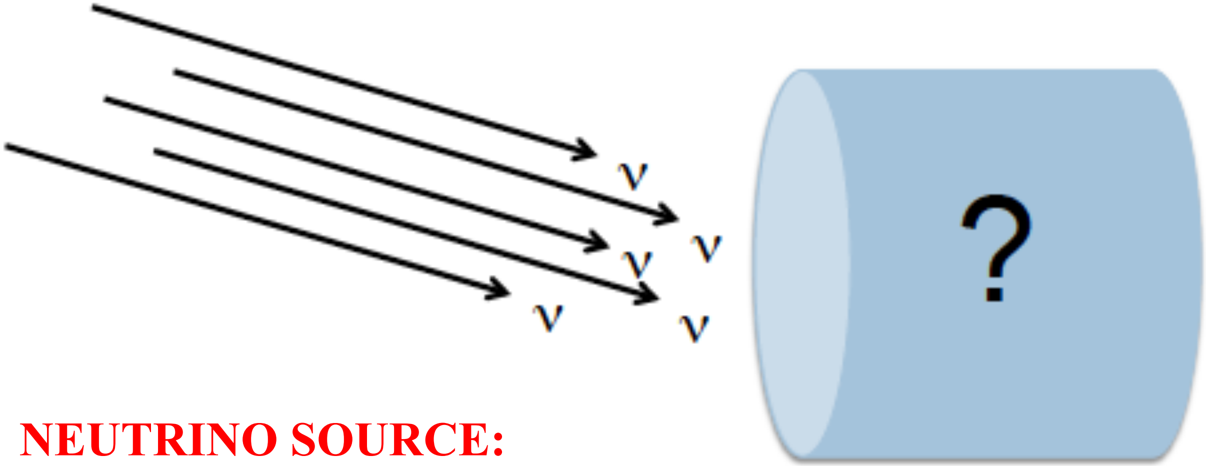
c) what do you want to measure?
– final state particles? – directional information? – energy information?

d) how many events do you need to achieve the required sensitivity?
– determines the size of the detector and what you put in

e) how much money do you have? **(most important!)**

Neutrino Detection

Lets start the game…..



NEUTRINO SOURCE:

Supernova, Sun, Atmosphere, Cosmic, Geo-neutrinos

Accelerator, Reactor, Radioactive Decays

NEUTRINO DETECTOR

QUESTIONS?

- **How many neutrino interactions should I expect to see?**
- **How will they look like?**

Neutrino Economics

$$N_\nu(E) \sim \Phi_\nu(E) \times \sigma_\nu(E) \times \text{target}$$

ν flux

(# neutrinos)

depends on your ν source

at 1 GeV $\sigma(\nu p) \sim 10^{-38}$ cm^2

compare to $\sigma(pp) \sim 10^{-26}$ cm^2

→ *ν physics is a very patient business*

ν cross section

tiny ($\sim 10^{-38}$ cm^2)

$\sigma_\nu^{tot} \sim E_\nu$

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

tells you the probability for a ν to interact with another particle

H. Bethe and R. Peirels:

- "there is no practically possible way of observing the neutrino"

Neutrino Economics

$$N_\nu(E) \sim \Phi_\nu(E) \times \sigma_\nu(E) \times \text{target}$$

ν flux

(# neutrinos)

depends on your ν source

make this large!

ν cross section

tiny ($\sim 10^{-38}$ cm^2)

$\sigma_\nu^{tot} \sim E_\nu$

can't do much about this unless you can increase the energy of your neutrinos

detector

(# targets, detection ε)

make this large!

Designing a Neutrino Detector

Reactor antineutrino production rate per unit of thermal power:

$F_\nu / P_{th} \sim 10^{20}\ s^{-1} GW^{-1}$.

Power output of a typical reactor: $P_{th} \sim 1$ GW, therefore $F_\nu \sim 10^{20}\ s^{-1}$.

Let's place a detector at a distance $L = 10m$ from the reactor core.
Antineutrino flux at the detector: $d\Phi/dt = F_\nu / (4\pi L^2) \sim 10^{13}\ cm^{-2}\ s^{-1}$.

Detector active mass: $m_{det} = 100$ kg.

Rate of IBD interactions in the detector:

$F_{int} \approx (m_{det}/(2m_p))\sigma(d\Phi/dt) \approx 0.3\times10^{29}\times10^{-43}\ cm^2\times10^{13}\ cm^{-2}s^{-1} = 0.03\ s^{-1}$.

~2 interactions / minute

Most reactor antineutrinos are below IBD threshold.
Also, some protons are bound in nuclei (80% for H_2O).
The detector is not 100% efficient. Rate of detected interactions:

~ few interactions / hour

IBD Detection Principle

Inverse beta decay signature:

prompt signal from the positron annihilation +
delayed signal from the neutron capture

$$\boxed{\bar{\nu}_e + p \to e^+ + n}$$

$E_{threshold}$ = 1.8 MeV

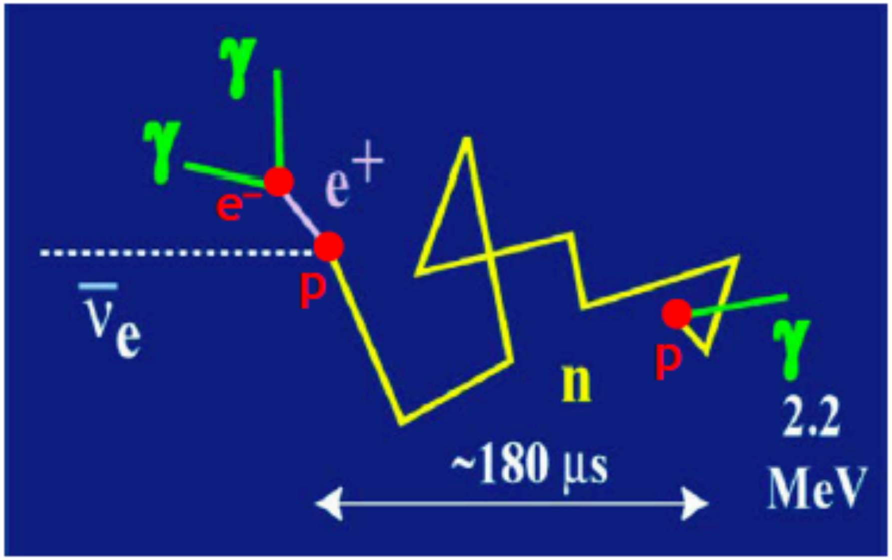
Positron detection: via annihilation

$$\boxed{e^+ + e^- \to \gamma + \gamma}$$

Neutron detection:
via thermalization & capture, e.g.

$$\boxed{n + p \to d + \gamma\ (2.2\ \mathrm{MeV})}$$

(typical capture time τ~200 μs)
(τ~10μs for Cd, Gd-doped targets)



A possible detector type: scintillation detector

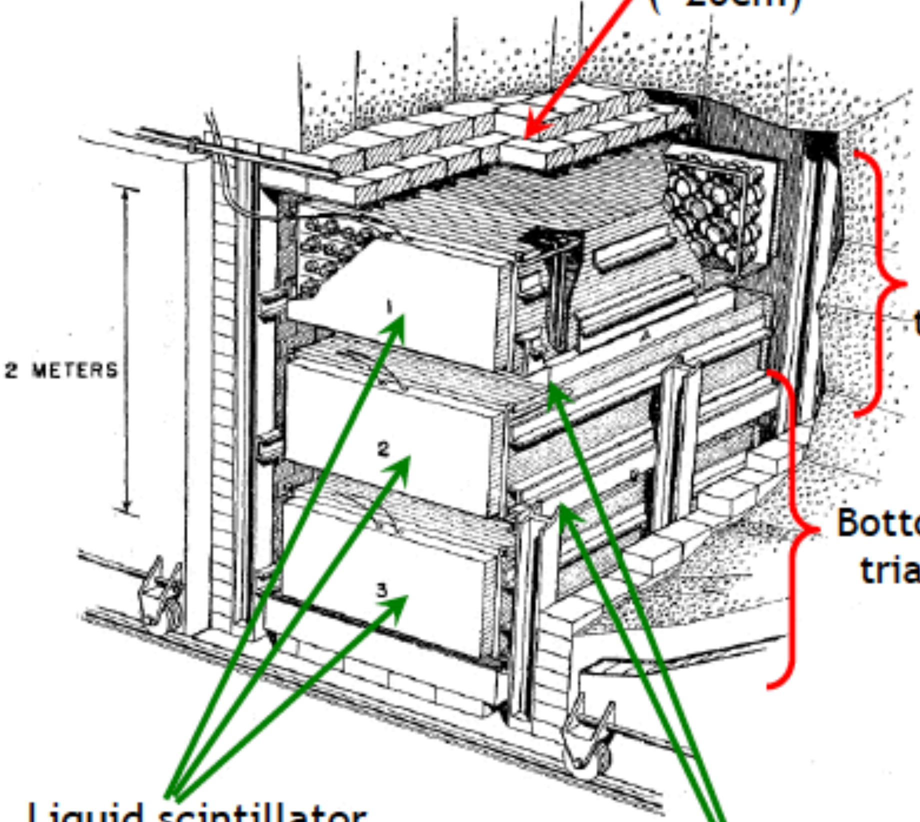
Scintillation: fast (~1ns) isotropic luminescence produced by absorption of ionising radiation

→ A real-time experiment

Cowan-Reines Experiment

(Savannah River nuclear power plant, South Carolina, US, 1955–56)

Experimental setup



Pb shielding (~20cm)

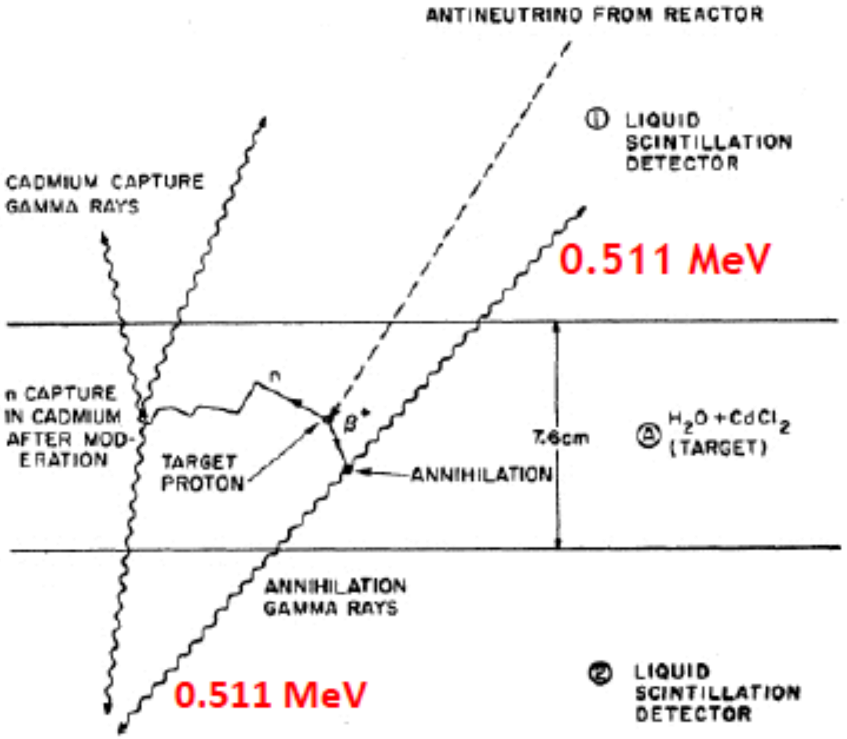
Top triad

Bottom triad

Liquid scintillator detectors (each equipped with 110 photomutipliers)

Thin $H_2O+CdCl_2$ target tanks ($0.2m^3$ each). Cd/H atomic ratio = 1%.

Antineutrino interaction event



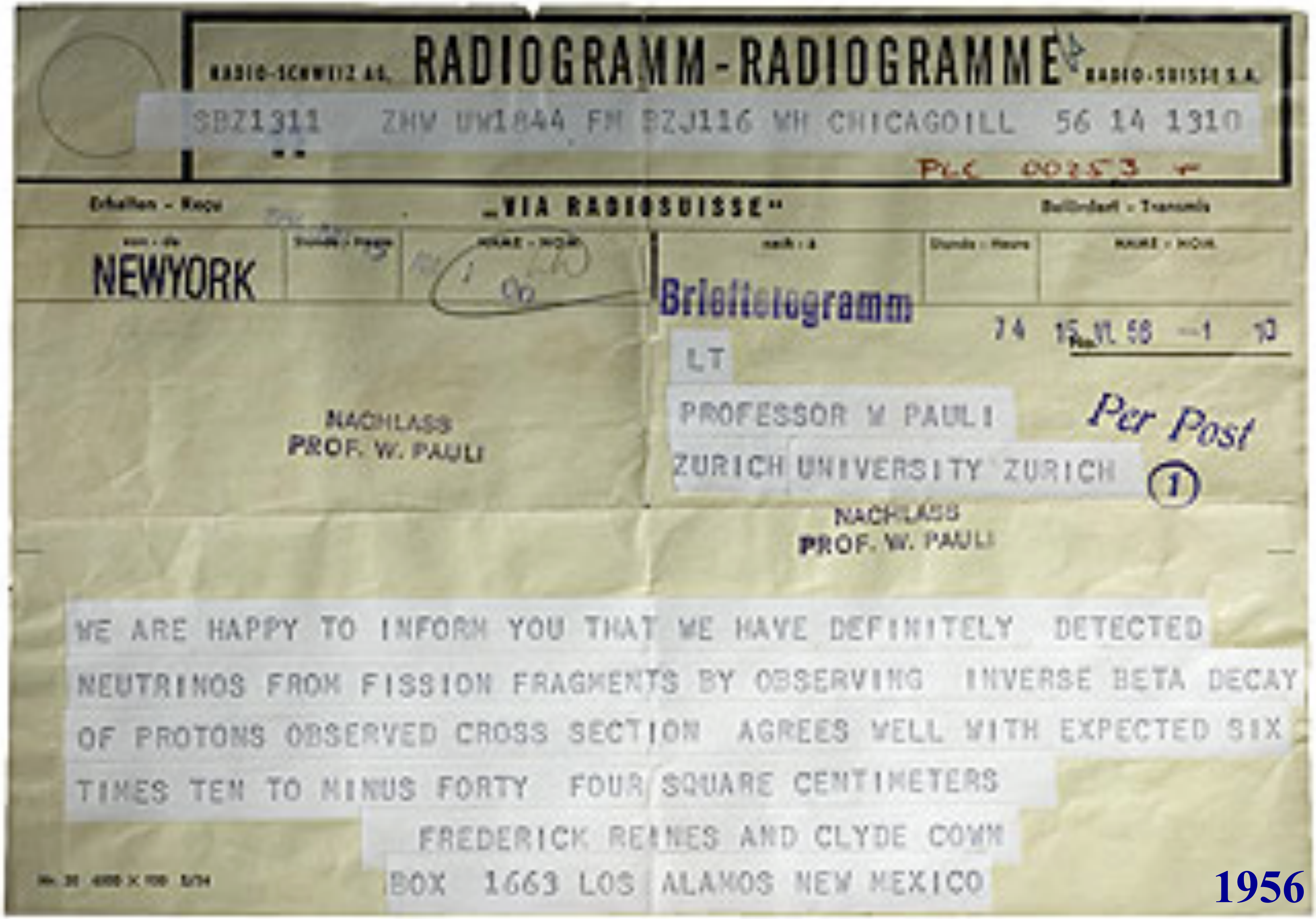
0.511 MeV

0.511 MeV

Prompt signal: 2×0.511 MeV photons.
Delayed signal: n capture on Cd, ~8 MeV.
Both signals: coincidence in two detectors.

Reines et al., Phys. Rev. 117 (1960) 159

Reines-Cowan Announcement



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Per Post

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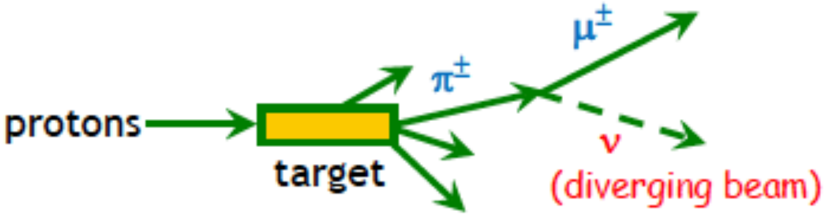
WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN
BOX 1663 LOS ALAMOS NEW MEXICO

1956

The neutrino was discovered in 1956.
Nobel Prize awarded in 1995.

First Accelerator Neutrinos



Are the ν produced together with muons identical to the ν produced together with electrons (e.g. in a reactor)?

Neutrino interaction (IBD) cross-section:

$$\sigma(1\ \mathrm{MeV}) \sim 10^{-43}\ \mathrm{cm}^2; \quad \sigma(1\ \mathrm{GeV}) \sim 10^{-38}\ \mathrm{cm}^2$$

Accelerator-produced (GeV) ν's are
~10^5 times more likely to interact than reactor ones

Interaction probability in 2.25m thick Al block (used as the first detector):

$$P \approx \frac{\rho}{\underbrace{2m_p}_{\text{density of relevant nucleons}}}\sigma L \approx \frac{2.7\ \mathrm{g/cm^3}/2}{1.66 \times 10^{-24}\ \mathrm{g}} \cdot 10^{-38}\ \mathrm{cm}^2 \cdot 2.25\ \mathrm{m} \approx 2 \times 10^{-12}$$

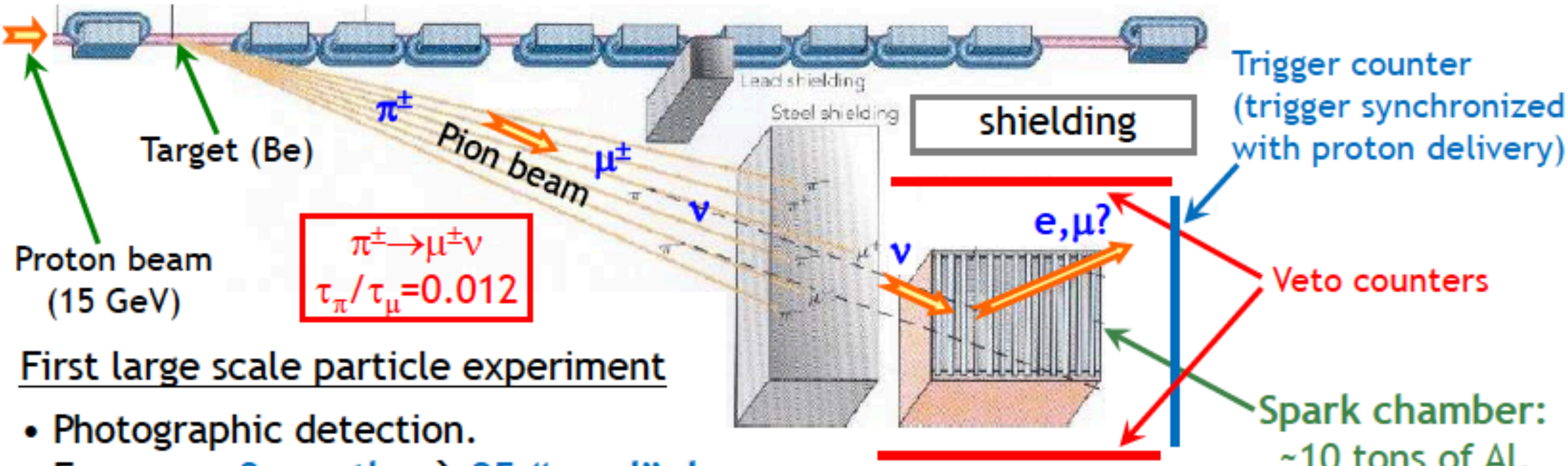
Production rates required for an experiment:

$$\nu\ \mathbf{beam} \sim 10^{12}/\mathbf{hour} \quad \Rightarrow \quad p\ \mathbf{beam} \sim 10^{13}/\mathrm{s}$$ (high intensity)

The first accelerator proton beam of such intensity became available in the Brookhaven lab (US) in the early 1960s

The Discovery of Muon Neutrino

Lederman–Schwartz–Steinberger experiment, Brookhaven, 1962



$\pi^\pm \rightarrow \mu^\pm \nu$
$\tau_\pi / \tau_\mu = 0.012$

First large scale particle experiment

- Photographic detection.
- Exposure: 8 months → 25 "good" days.
- Detector "ON" for a total of 5.5 s.
- ~10^{14} neutrinos through the detector.
- ~5000 spark chamber photographs taken.

Method:

- Detect inverse beta decay in the spark chamber: e.g. $\nu n \rightarrow \ell^- p$
- Identify the lepton type (e or μ).

Results:

❖ 29 muon tracks identified:

$$\nu n \rightarrow \mu^- p$$

❖ No electron tracks identified: the reaction $\nu n \rightarrow e^- p$ WAS NOT OBSERVED

ν_e and ν_μ demonstrated to be different particles: Nobel Prize 1988

The Discovery of Tau Neutrino

Secondary beam production:

$$p(800\ \mathrm{GeV}) + W \rightarrow \ldots$$

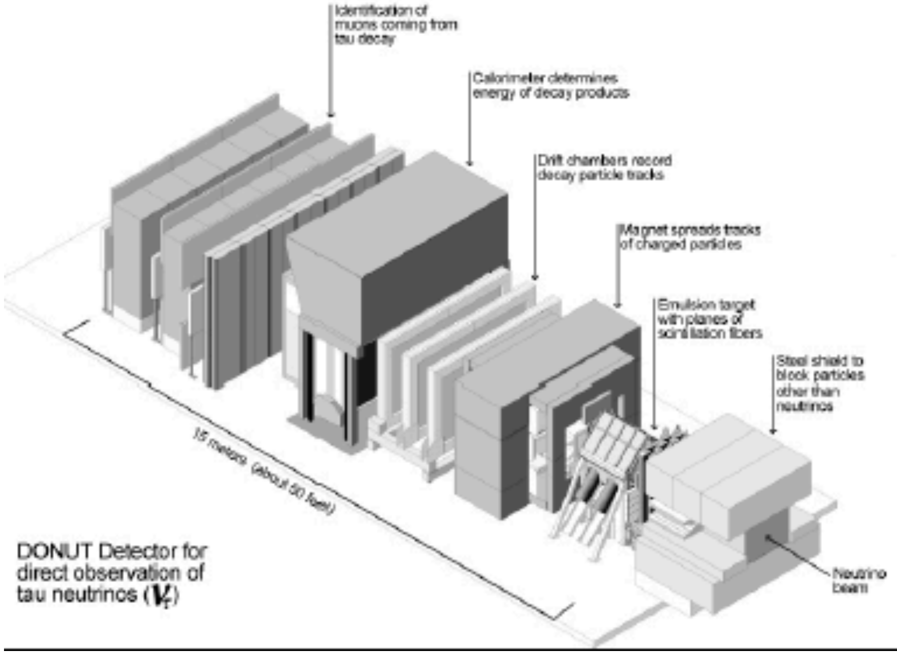
(tungsten)

Primary tau-neutrino source:

$$D_S^+(c\bar{s}) \rightarrow \tau^+\nu_\tau$$ [BR=5.6%]

(~5% of all ν's are expected to be ν_τ)

Detector type:
Pb/emulsion sandwich + spectrometer

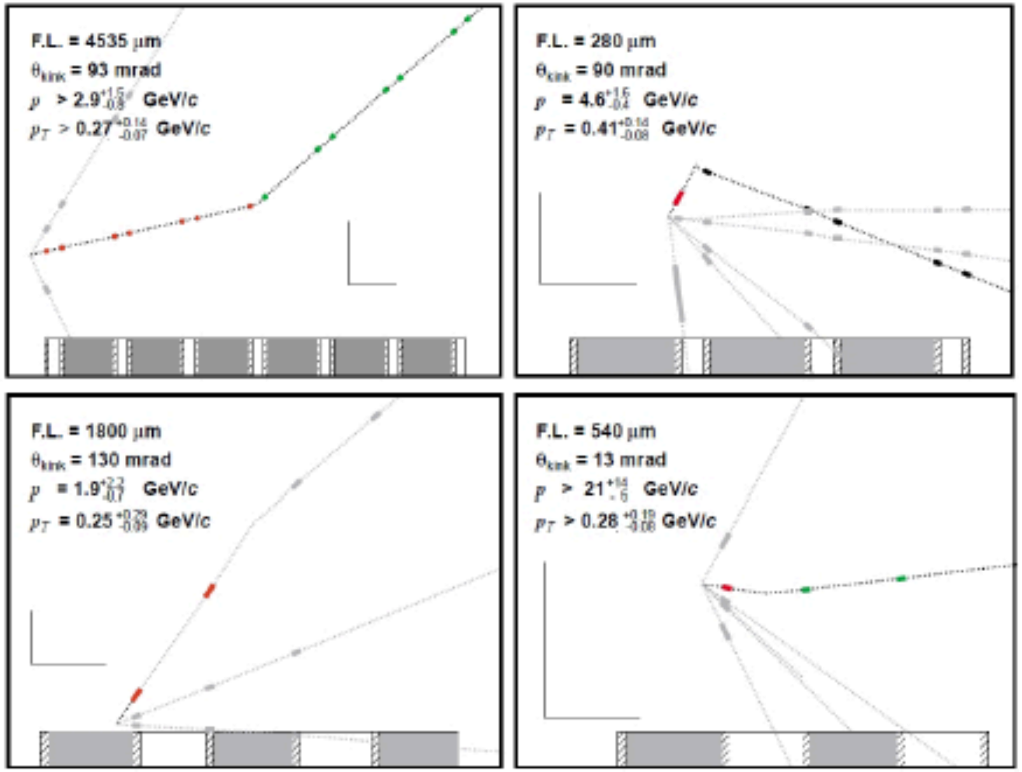


DONUT Detector for direct observation of tau neutrinos (ν_τ)

ν_τ postulated following τ discovery in 1975; directly observed by the FNAL E872 (DONUT) experiment in 2000.

$$\nu_\tau n \rightarrow \tau^- p; \quad \tau^- \rightarrow \mu^- \nu_\tau \bar{\nu}_\mu$$

Mean τ free path: $\gamma c\tau$=2mm; decay into a single charged track: "track with a kink"



Discovery of Invisible Neutrinos

- **Electron neutrino ν_e : 1956**

Reactor anti-neutrinos: $\bar{\nu}_e + p \to n + e^+$

Nobel Prize to Frederick Reines in 1995

Clyde Cowan

Frederick Reines

- **Muon neutrino ν_μ : 1962**

Neutrinos from pion decay:

$$\pi^- \to \mu^- + \nu_{(\mu)}$$

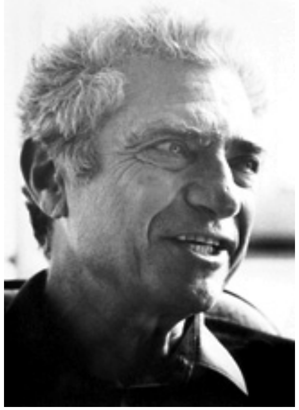
$$\nu_{(\mu)} + N \to N' + \mu^-$$

Always a muon, never an e^-/e^+

Nobel Prize in 1988

Leon M. Lederman

Melvin Schwartz

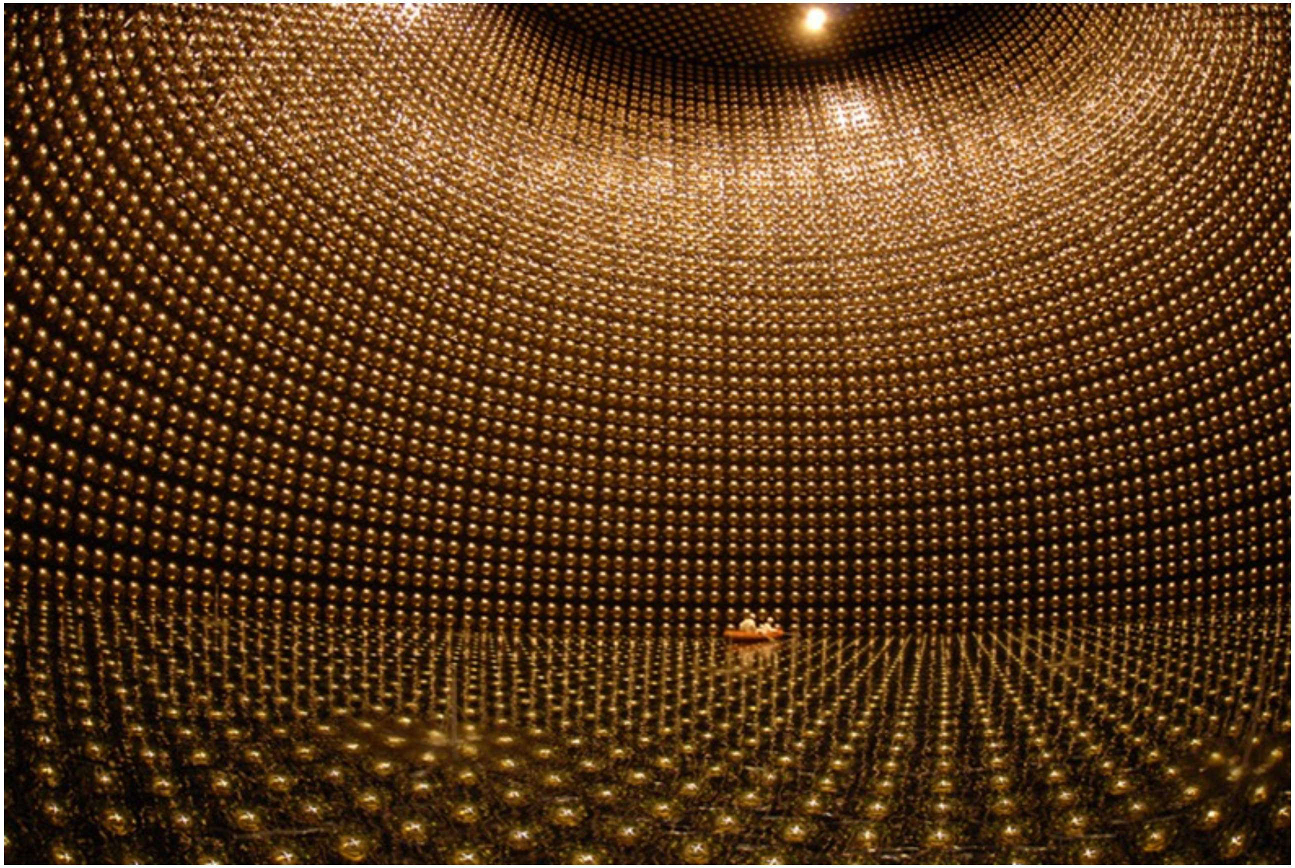


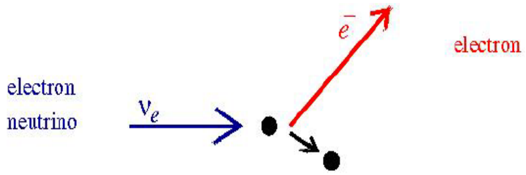
Jack Steinberger

- **Tau neutrino ν_τ : 2000**

DONUT experiment at Fermilab: $\nu_\tau + N \to \tau + N'$

Neutrino Detection in Super-Kamiokande





Around 11,146 Photomultiplier tubes (PMT)

Observes about 5 -10 neutrinos per day (out of ≥ 10^{25} neutrinos passing through)

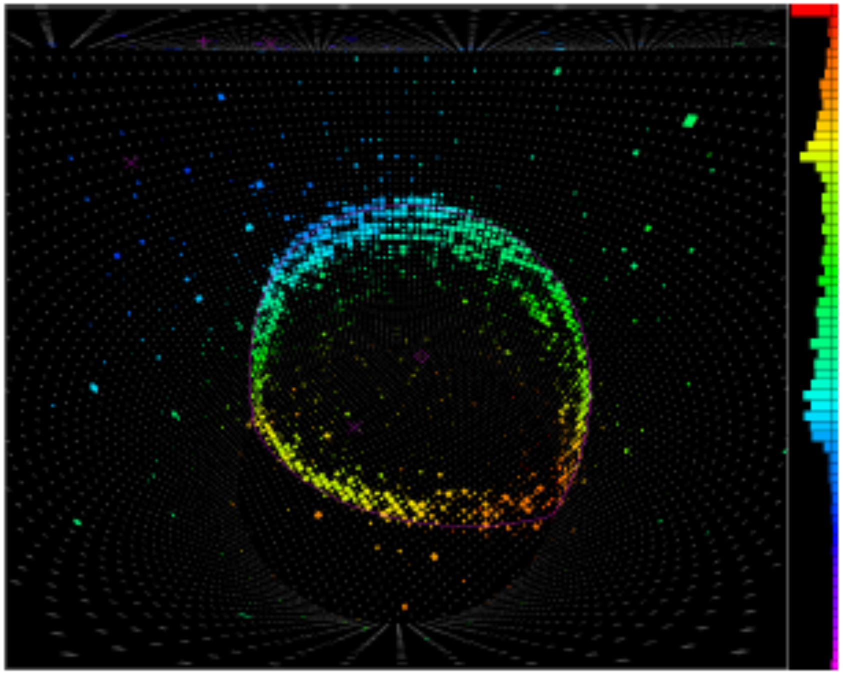
Super-Kamiokande detector in Japan is located 1,000 m (3,300 ft) underground in the Mozumi mine. It consists of a cylindrical stainless steel tank (41.4 m tall and 39.3 m in diameter) holding 50,000,000 litres of ultra-pure water

Important message: Build very large detectors & wait for a very long time

Super-Kamiokande

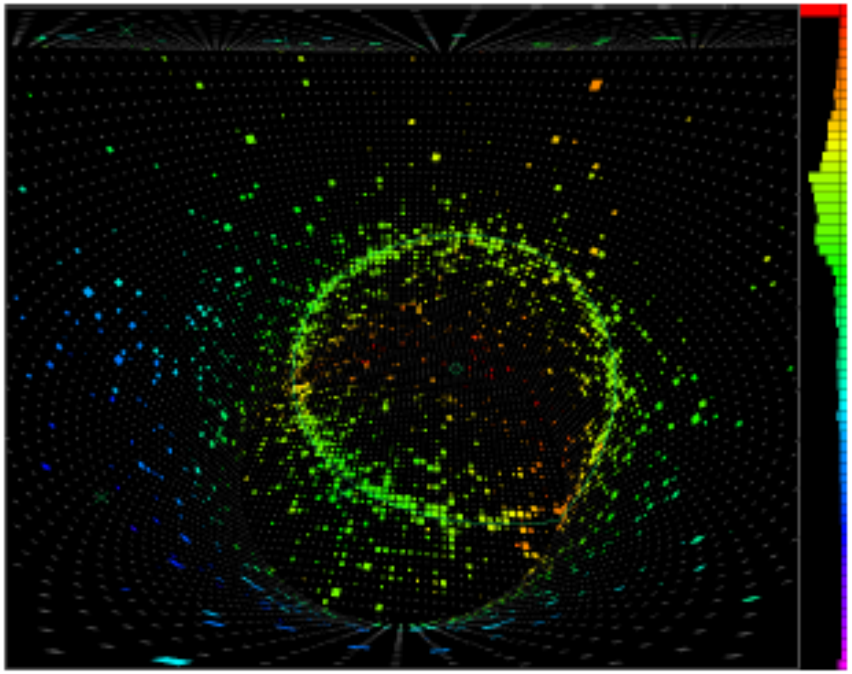
muon from ν_μ

(sharp outer edge)



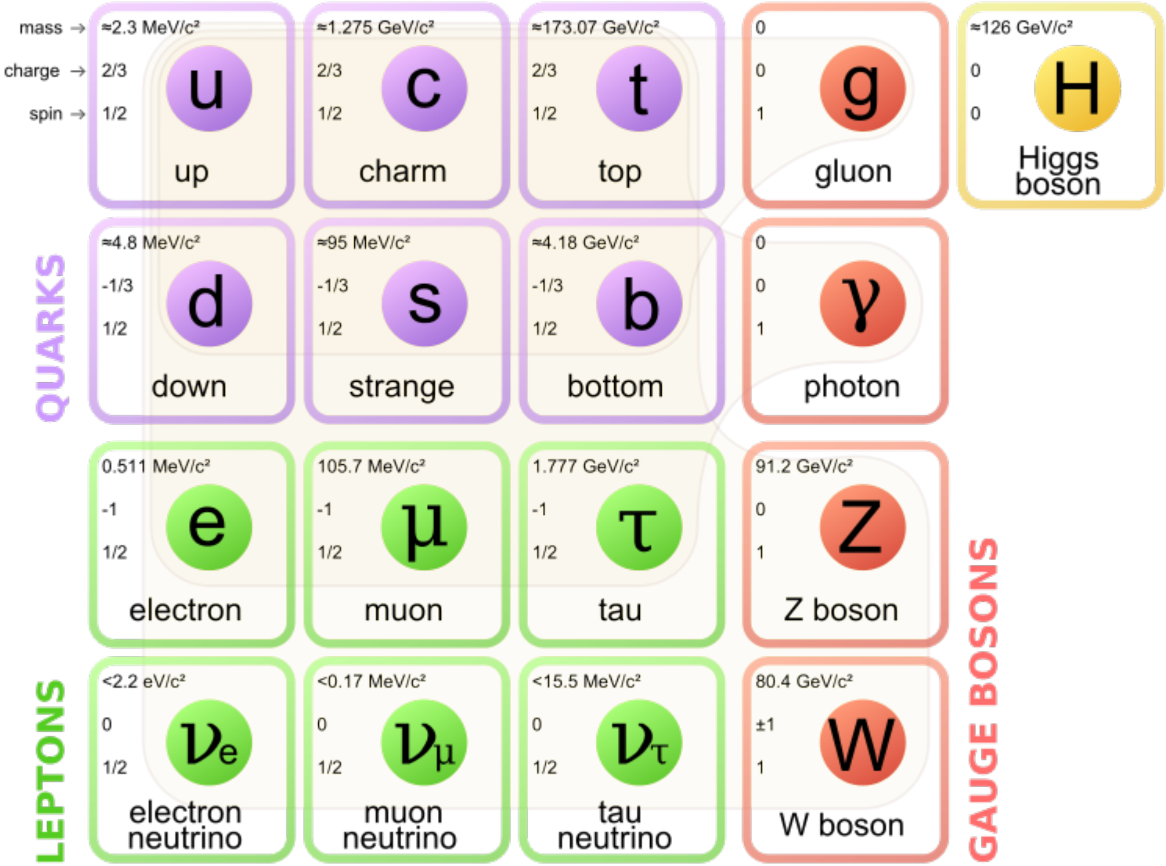
electron from ν_e

(fuzzy ring)



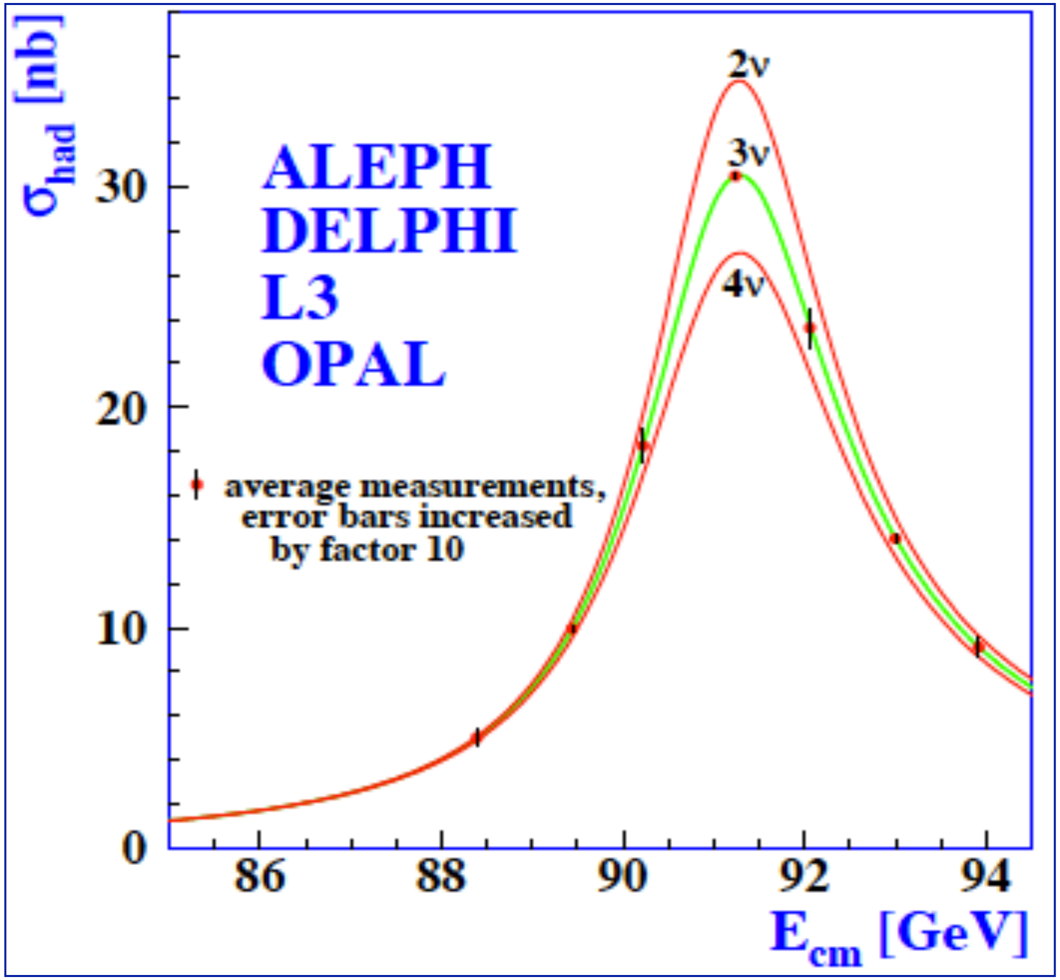
- detector responsible for discovery of atmospheric ν oscillations (1998), being used for T2K to measure $\nu_\mu \rightarrow \nu_e$ oscillations with accelerator ν's

The Standard Model of Particle Physics



- 3 *active* neutrinos:
  ν_e , ν_μ , ν_τ
- zero charge (neutral)
- spin 1/2
- almost massless:
  at least a million times
  lighter than electron

Three Light Active Neutrinos



Precision data of the Z-decay width at the e^+e^- collider at LEP

$$e^+e^- \to Z \xrightarrow{\text{invisible}} \sum_{a=\text{active}} \nu_a\bar{\nu}_a$$

$$N_{\nu_{\text{active}}} = 2.9840 \pm 0.0082$$

[LEP, Phys. Rept. 427 (2006) 257, hep-ex/0509008]

3 light active flavor neutrinos

$\nu_e \;\; \nu_\mu \;\; \nu_\tau$

http://pdg.lbl.gov/2016/reviews/rpp2016-rev-light-neutrino-types.pdf

Neutrinos are Left Handed

- Helicity is projection of spin along the particles direction
  - Frame dependent (if massive)

The operator: $\sigma \cdot \mathbf{p}$

- Neutrinos only interact weakly with a (V-A) interaction
  - All **neutrinos** are **left-handed**
  - All **antineutrinos** are **right-handed**

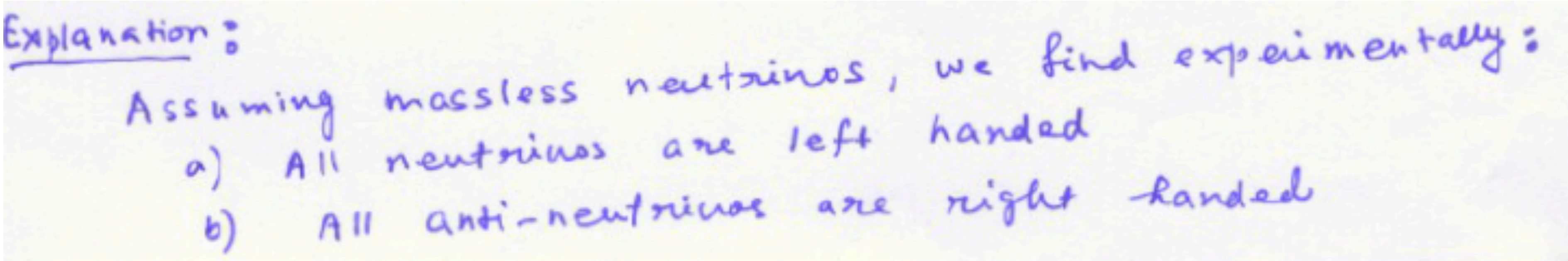
- If neutrinos have mass then left-handed neutrino is:
  - Mainly left-helicity
  - But also small right-helicity component $\propto m/E$

- Handedness (or chirality) is Lorentz-invariant
  - Only same as helicity for massless particles.

- Only left-handed charged-leptons (e^-,μ^-,τ^-) interact weakly but mass brings in right-helicity:

$$\begin{aligned} R_{theory} &= \frac{\Gamma(\pi^\pm \to e^\pm \nu_e)}{\Gamma(\pi^\pm \to \mu^\pm \nu_\mu)} \\ &= \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{m_\pi{}^2 - m_e{}^2}{m_\pi{}^2 - m_\mu{}^2}\right)^2 \\ &= 1.23 \times 10^{-4} \end{aligned}$$

Neutrinos are Left Handed

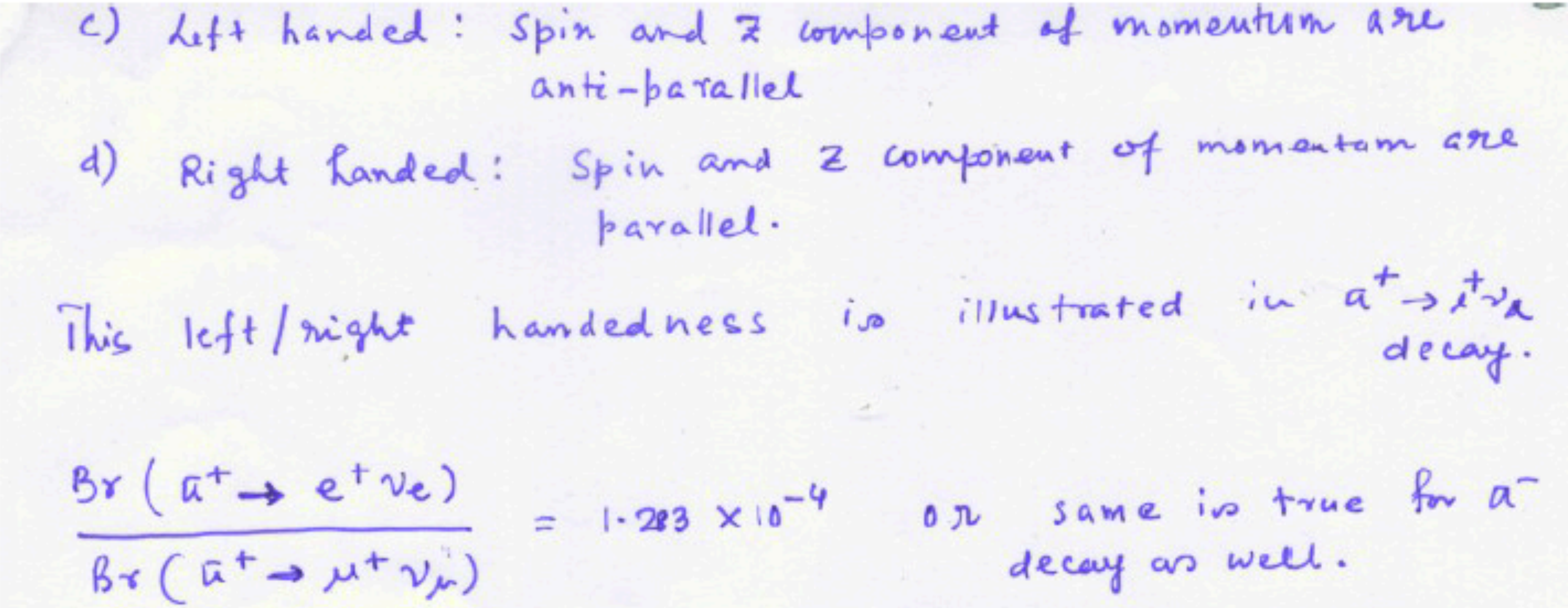


Explanation:

Assuming massless neutrinos, we find expeimentally:

a) All neutrinos are left handed

b) All anti-neutrinos are right handed



c) Left handed: Spin and Z component of momentum are anti-parallel

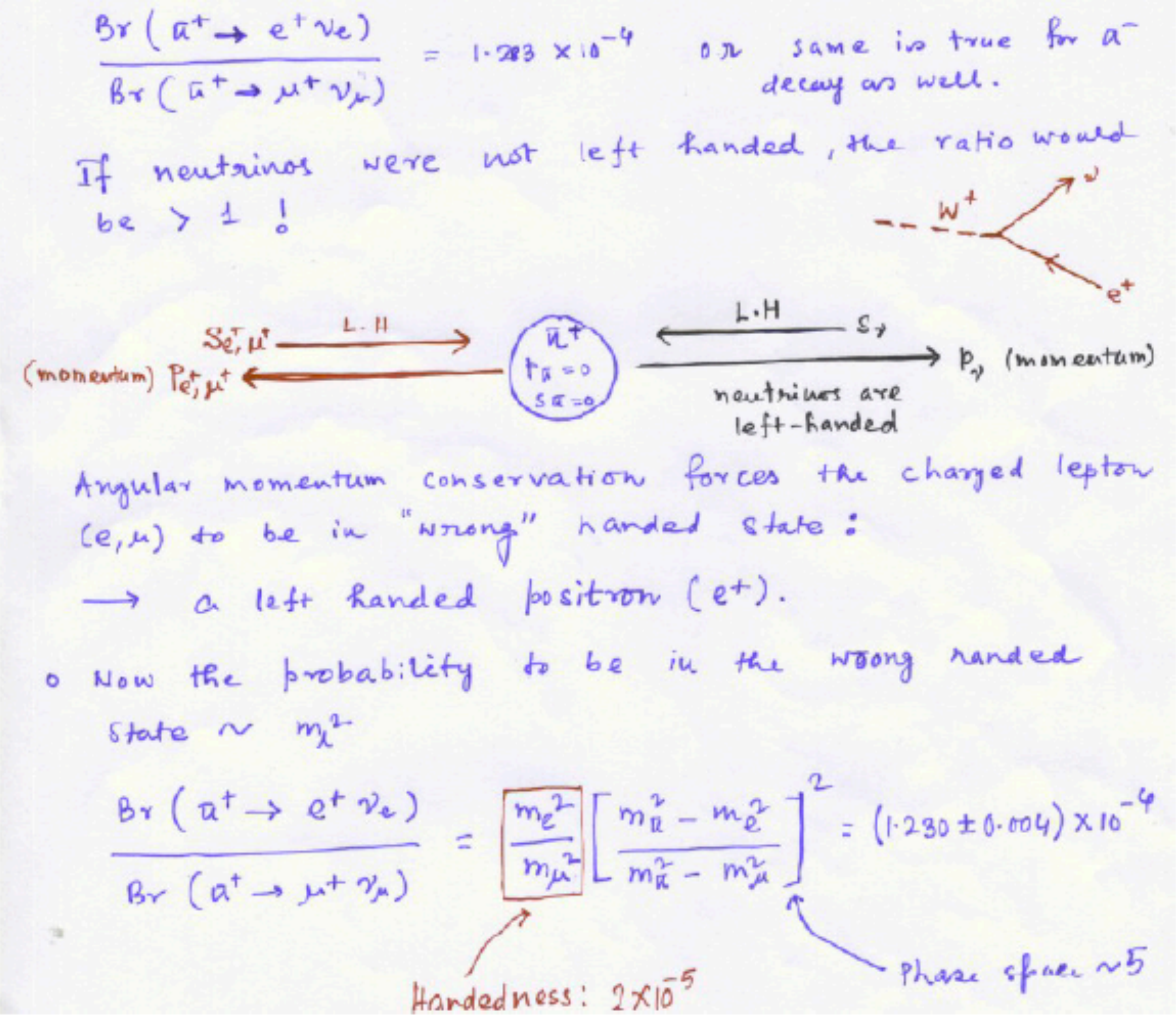
d) Right handed: Spin and Z component of momentum are parallel.

This left/right handedness is illustrated in $\pi^+ \to \ell^+ \nu_\ell$ decay.

$$\frac{Br(\pi^+ \to e^+ \nu_e)}{Br(\pi^+ \to \mu^+ \nu_\mu)} = 1.283 \times 10^{-4}$$

or same is true for π^- decay as well.

Neutrinos are Left Handed



$$\frac{Br(\pi^+ \to e^+ \nu_e)}{Br(\pi^+ \to \mu^+ \nu_\mu)} = 1.283 \times 10^{-4}$$

or same is true for π^- decay as well.

If neutrinos were not left handed, the ratio would be > 1 !

Angular momentum conservation forces the charged lepton (e, μ) to be in "wrong" handed state:

→ a left handed positron (e^+).

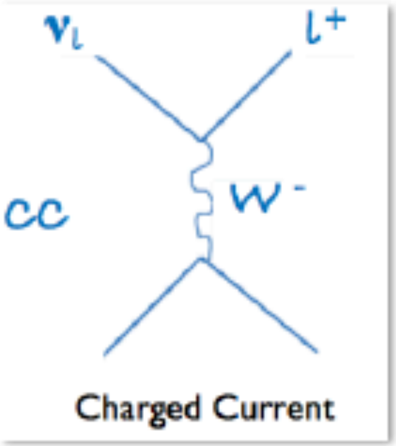
- Now the probability to be in the wrong handed state ~ m_ℓ^2

$$\frac{Br(\pi^+ \to e^+ \nu_e)}{Br(\pi^+ \to \mu^+ \nu_\mu)} = \boxed{\frac{m_e^2}{m_\mu^2}} \left[\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right]^2 = (1.230 \pm 0.004) \times 10^{-4}$$

Handedness: 2×10^{-5}

Phase space ~5

Two Basic Interactions



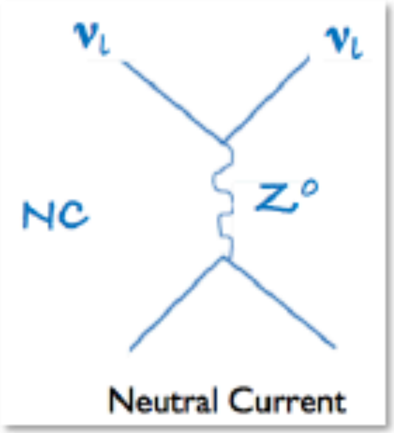
Charged Current (CC)

- neutrino in
- charged lepton out

this is how we detected neutrinos in the first place

$\nu_e \to e^-$ $\quad \overline{\nu}_e \to e^+$
$\nu_\mu \to \mu^-$ $\quad \overline{\nu}_\mu \to \mu^+$
$\nu_\tau \to \tau^-$ $\quad \overline{\nu}_\tau \to \tau^+$

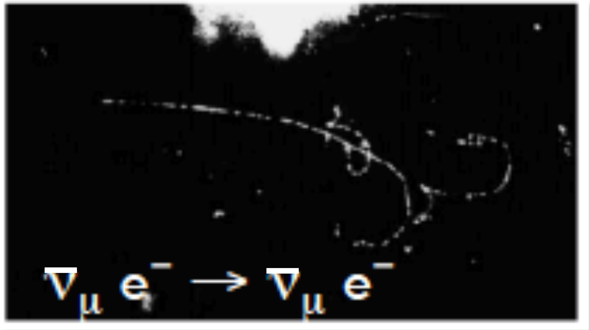
- flavor of outgoing lepton "tags" flavor of incoming neutrino
- charge of outgoing lepton determines whether ν or anti-ν



Neutral Current (NC)

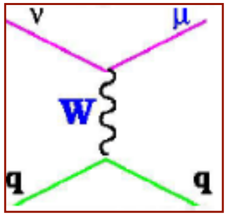
- neutrino in
- neutrino out

1st observed in 1972

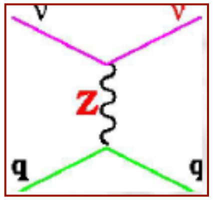


- all ν reactions involve some version of these two exchanges

W-q coupling is I_3

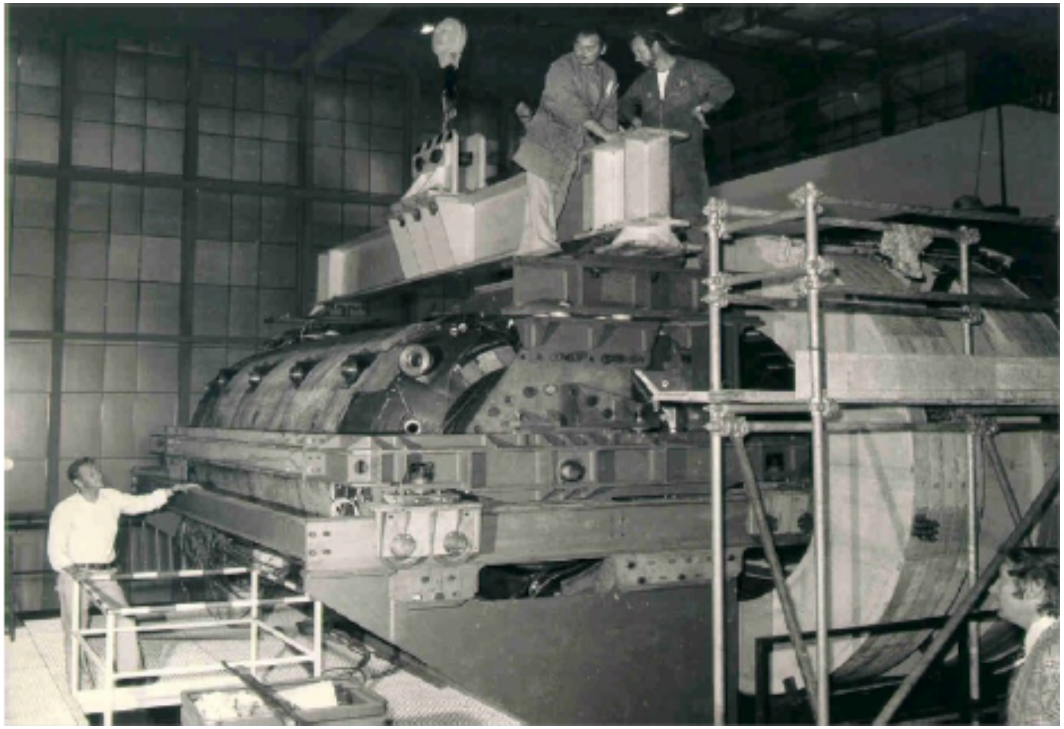


$$R_\nu = \frac{\sigma_{NC}(\nu N \to \nu X)}{\sigma_{CC}(\nu N \to \mu X)} = 0.307 \pm 0.008$$



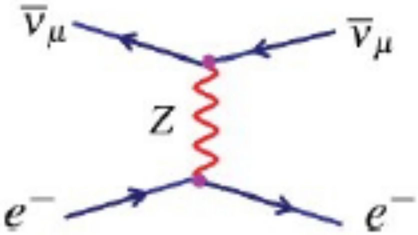
Z-q coupling is I_3-$Q\sin^2\theta_W$

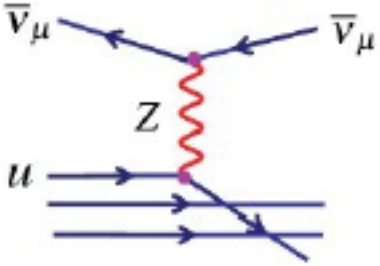
Gargamelle – Discovery of Weak Neutral Current



Gargamelle:
First Large Bubble Chamber

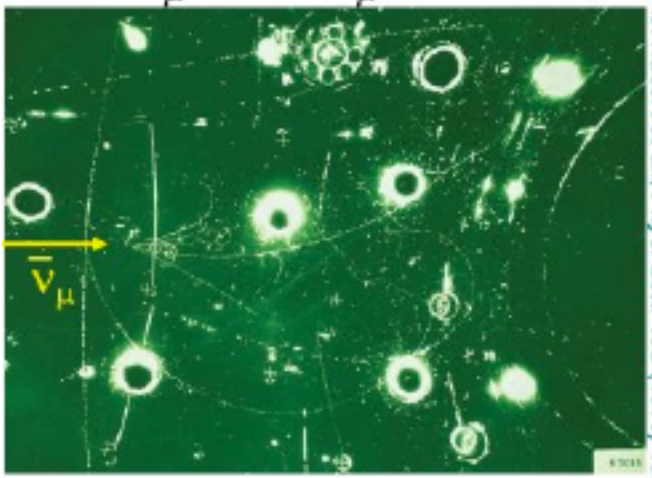
Discovery of Weak Neutral Current in 1973





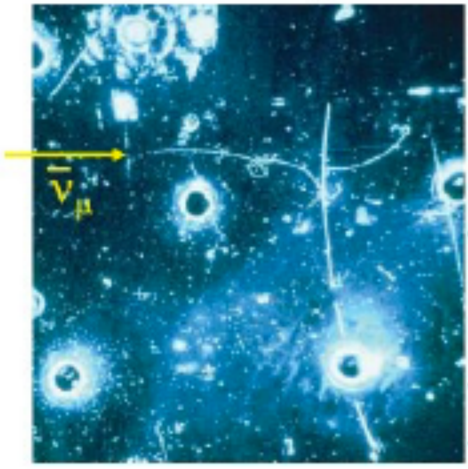
Cannot be due to W exchange
-- First evidence for Z boson

$\overline{\nu}_\mu + N \rightarrow \overline{\nu}_\mu +$ hadrons



F.J. Hasert et al., Phys. Lett. 46B (1973) 138

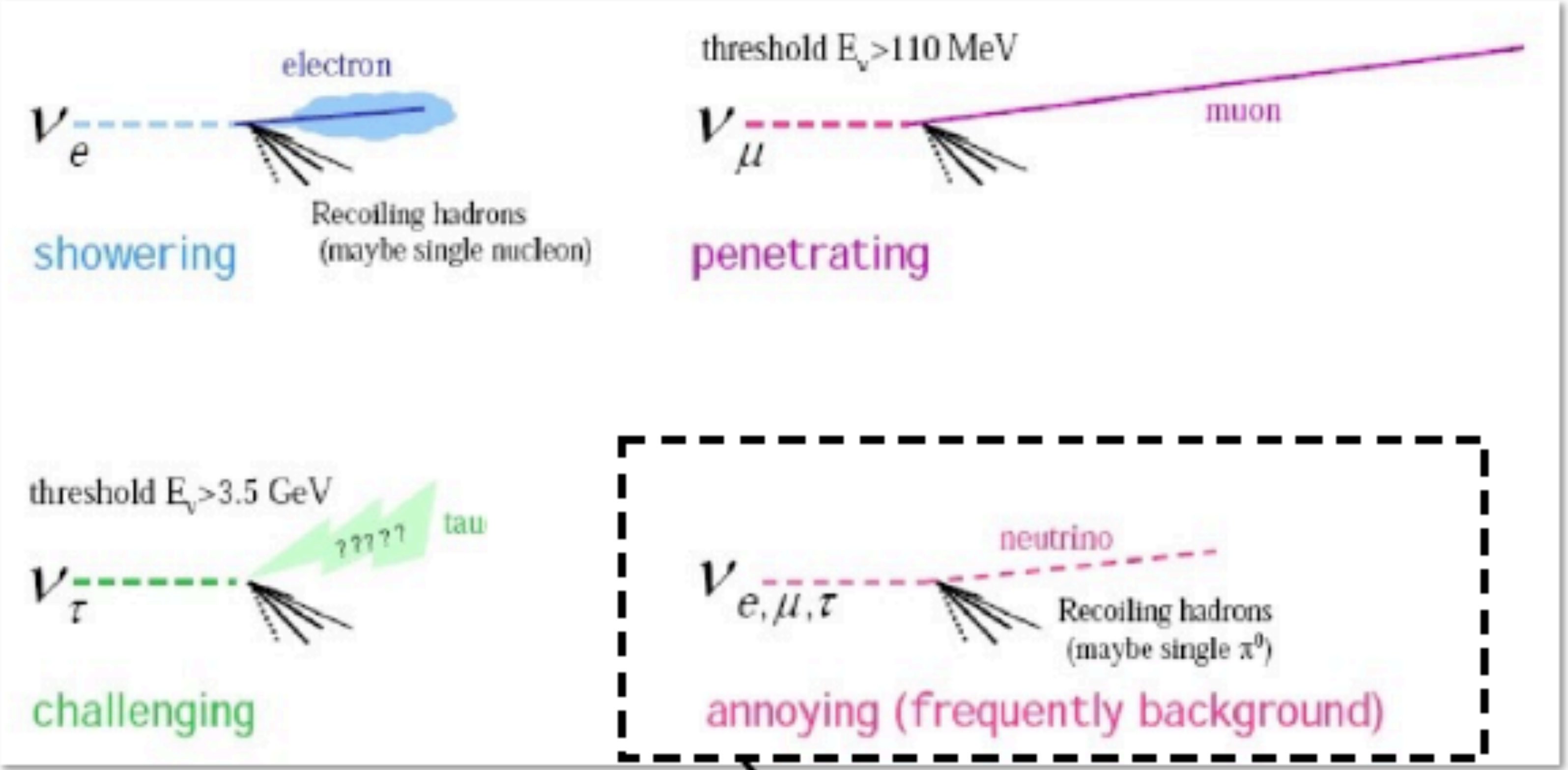
$\overline{\nu}_\mu + e^- \rightarrow \overline{\nu}_\mu + e^-$



F.J. Hasert et al., Phys. Lett. 46B (1973) 121

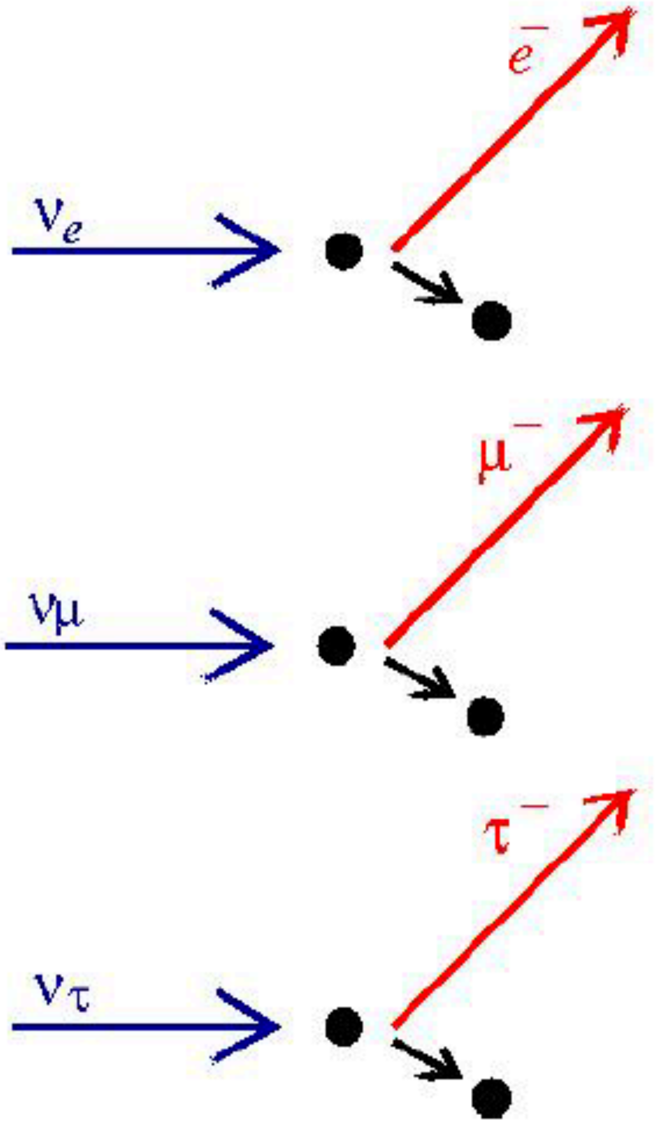
Neutrino Flavor Identification

- each ν leaves its own recognizable pattern that you can then see



NC interaction looks the same for all flavors

Three kinds (flavors) of neutrinos: ν_e ν_μ ν_τ



electron
neutrino

electron

$m_e = 0.511$ MeV $P_{\text{thresh}} = 0.511$ MeV

muon
neutrino

muon
200 times heavier than electron

$m_\mu = 106$ MeV $P_{\text{thresh}} = 112$ MeV

tau
neutrino

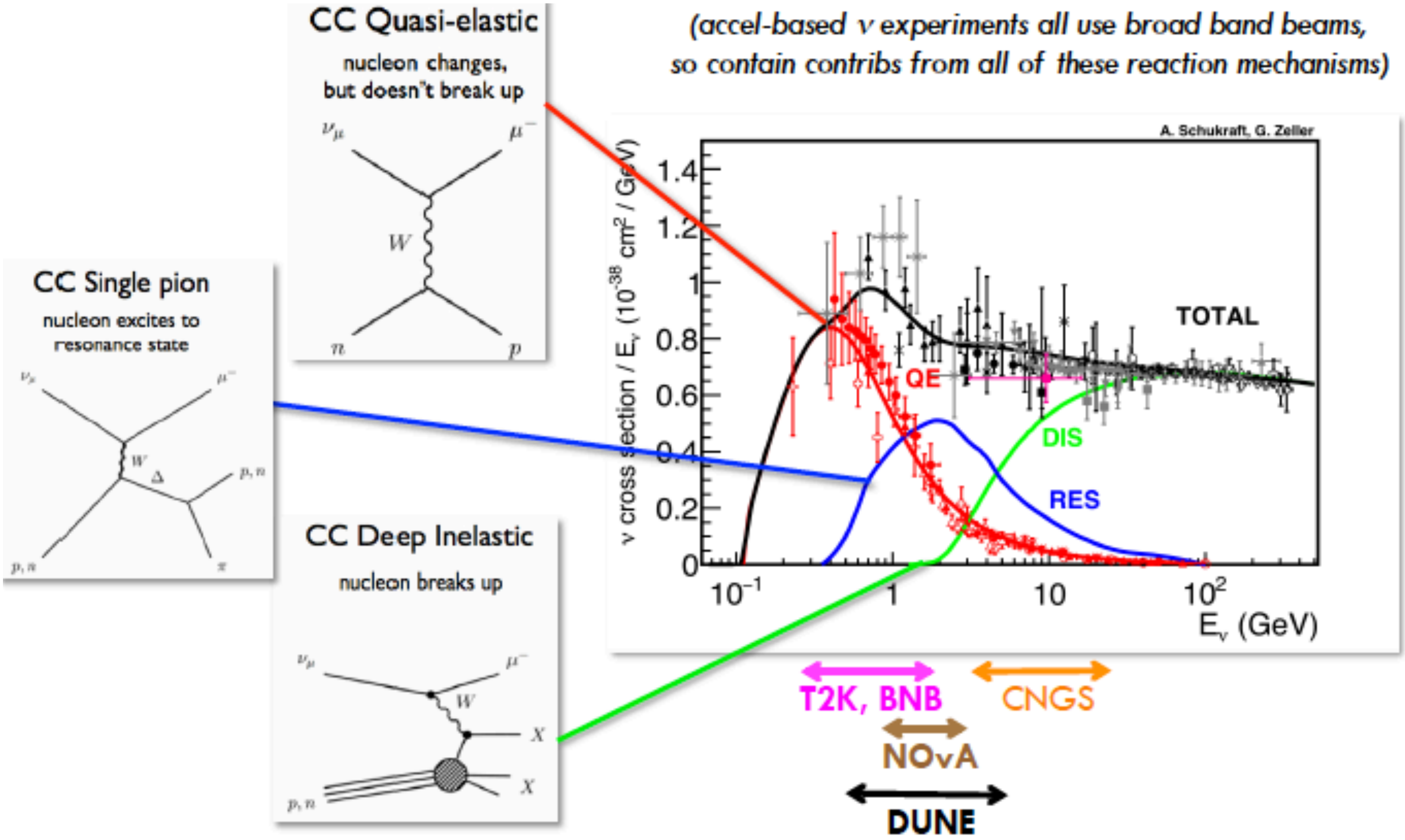
tau
3500 times heavier than electron

$m_\tau = 1.78$ GeV $P_{\text{thresh}} = 3.47$ GeV

$$\boxed{E_\nu > \frac{m_\tau^2 + 2m_\tau m_{\text{nucleon}}}{2m_{\text{nucleon}}} \approx 3.5\ \text{GeV}}$$

Antineutrinos $\overline{\nu}_e, \overline{\nu}_\mu, \overline{\nu}_\tau$ produce positively charged particles

Neutrino Interactions



CC Quasi-elastic

nucleon changes,
but doesn't break up

CC Single pion

nucleon excites to
resonance state

CC Deep Inelastic

nucleon breaks up

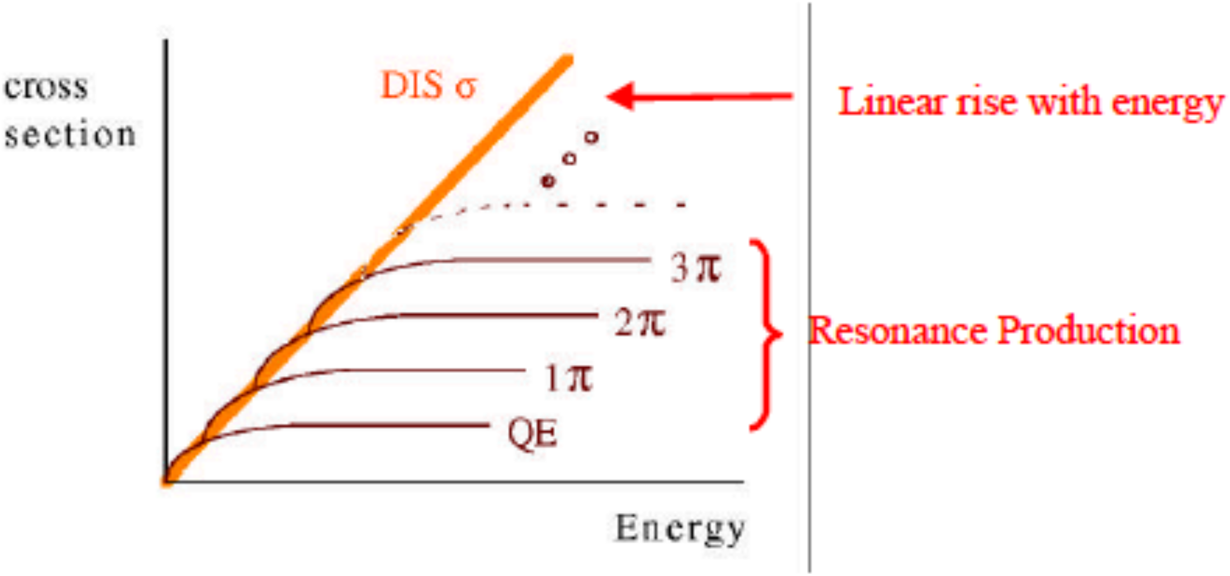
*(accel-based ν experiments all use broad band beams,
so contain contribs from all of these reaction mechanisms)*

Reference: J. Formaggio, G. Zeller, Rev. Mod. Phys. 84, 1307 (2012)

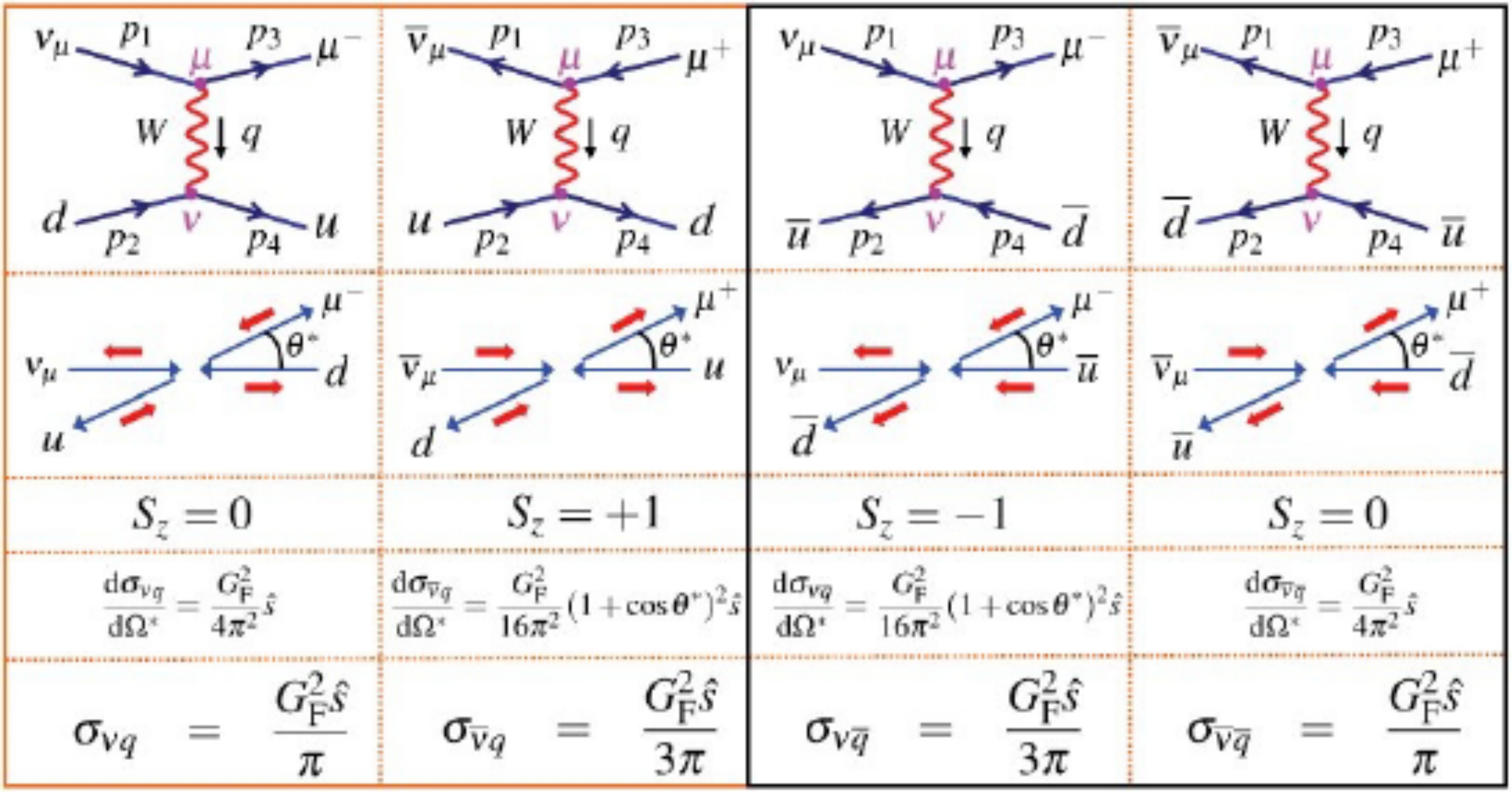
Neutrino Interactions

- 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)
    $\nu_\mu + n \rightarrow \mu^- + p + \pi^0 \quad (N^* \text{ or } \Delta)$
    $\qquad\qquad\qquad\quad n + \pi^+$
  - Deep-Inelastic Scattering:
    (Nucleon broken up)
    $\nu_\mu + \text{quark} \rightarrow \mu^- + \text{quark}'$

- Neutral - Current: Z^0 exchange
  - Elastic Scattering:
    (Target doesn't break up or change)
    $\nu_\mu + N \rightarrow \nu_\mu + N$
  - Nuclear Resonance Production:
    (Target goes to excited state)
    $\nu_\mu + N \rightarrow \nu_\mu + N + \pi \quad (N^* \text{ or } \Delta)$
  - Deep-Inelastic Scattering
    (Nucleon broken up)
    $\nu_\mu + \text{quark} \rightarrow \nu_\mu + \text{quark}$



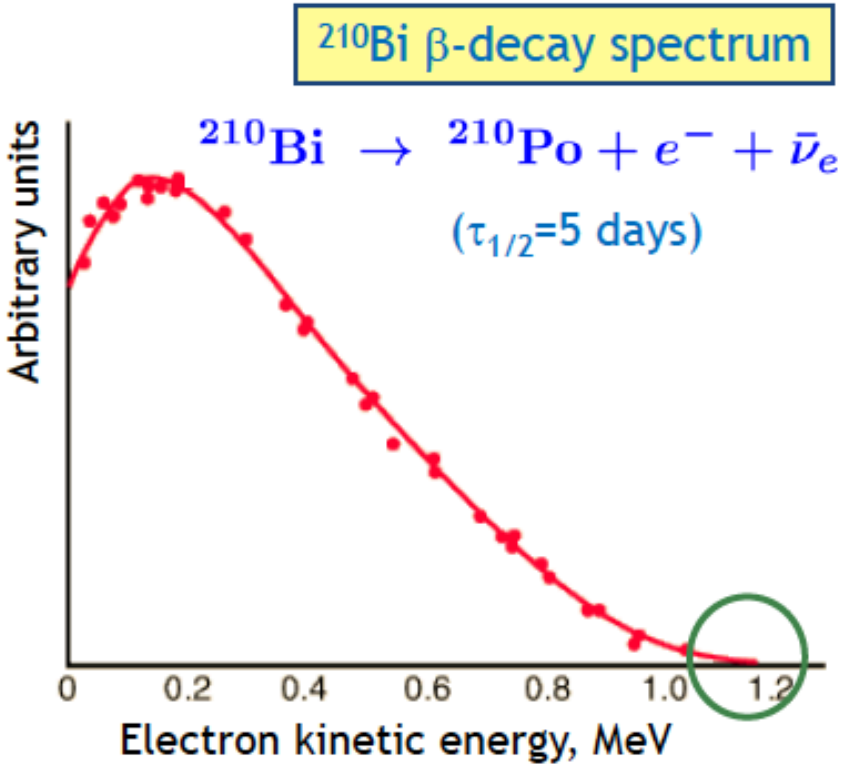
Neutrino – Quark Scattering



$S_z = 0$	$S_z = +1$	$S_z = -1$	$S_z = 0$
$\frac{d\sigma_{\nu q}}{d\Omega^*} = \frac{G_F^2}{4\pi^2}\hat{s}$	$\frac{d\sigma_{\overline{\nu} q}}{d\Omega^*} = \frac{G_F^2}{16\pi^2}(1+\cos\theta^*)^2\hat{s}$	$\frac{d\sigma_{\nu \overline{q}}}{d\Omega^*} = \frac{G_F^2}{16\pi^2}(1+\cos\theta^*)^2\hat{s}$	$\frac{d\sigma_{\overline{\nu}\overline{q}}}{d\Omega^*} = \frac{G_F^2}{4\pi^2}\hat{s}$
$\sigma_{\nu q} = \frac{G_F^2\hat{s}}{\pi}$	$\sigma_{\overline{\nu} q} = \frac{G_F^2\hat{s}}{3\pi}$	$\sigma_{\nu\overline{q}} = \frac{G_F^2\hat{s}}{3\pi}$	$\sigma_{\overline{\nu}\overline{q}} = \frac{G_F^2\hat{s}}{\pi}$

Differences in neutrino-quark and neutrino-antiquark scattering, direct consequence of V-A structure!

Neutrino Mass Measurements: Beta Decays


^{210}Bi β-decay spectrum

$$^{210}\mathrm{Bi} \rightarrow {}^{210}\mathrm{Po} + e^- + \bar{\nu}_e$$

($\tau_{1/2}$=5 days)

Q: What is the smallest possible energy E_{min} of a neutrino with a mass m_ν?

A: $E^2 = p^2+m^2$, therefore $E_{min} = m_\nu$

Q: What part of the e^- energy spectrum is most sensitive to the neutrino mass?

A: The "endpoint" at highest E_e (massive ν takes more energy; less energy available for the electron)

$$A \rightarrow B + e^- + \bar{\nu}_e$$

$$E_e^{\max} = \frac{m_A^2 + m_e^2 - (m_B + m_{\bar{\nu}})^2}{2m_A}$$

Q: Which β-source is most suitable for E_{max} measurement? High or low released energy E_{max}? Long or short mean lifetime?

A: Low released energy E_{max}: more electrons are close to E_{max}. Short lifetime: high specific activity; smaller and thinner samples.

Endpoint vs. Neutrino Mass

Beta-decay: $A \longrightarrow B + e^- + \bar{\nu}_e$

Electron energy endpoint (derived in lecture 2):

$$E_e^{\max} = \frac{m_A^2 + m_e^2 - (m_B + m_{\bar{\nu}})^2}{2m_A}$$

Dependence of the energy endpoint on the neutrino mass:

$$E_e^{\max}(m_\nu) - E_e^{\max}(0) = -\frac{(m_B + m_\nu)^2}{2m_A} + \frac{m_B^2}{2m_A} \approx$$

$$\approx -\frac{2m_B m_\nu}{2m_A} = -\frac{m_B}{m_A} m_\nu \approx -m_\nu$$

A very simple linear dependence: $\boxed{\Delta E_e^{\max} \approx -m_\nu}$

Tritium Beta Decay and the Neutrino Mass

$$\boxed{{}^3\mathrm{H} \longrightarrow {}^3\mathrm{He} + e^- + \bar{\nu}_e}$$

(pnn) (ppn)

$$\Delta E_e^{\mathrm{kin\ max}} = E_e^{\mathrm{max}} - m_e \approx 18.6\ \mathrm{keV} - m_\nu$$

(m_e = 511 keV ≫ 18.6 keV: non-relativistic electrons)

In practice, this decay is sensitive to an effective "electron neutrino mass":

$$m_{\nu_e}^2 \equiv \sum_i |U_{ei}|^2 m_i^2$$

Few advantages of tritium source:

a) Low endpoint energy: $E^{\mathrm{kin\ max}}$ = 18.6 keV, ~ 60 times lower than ^{210}Bi

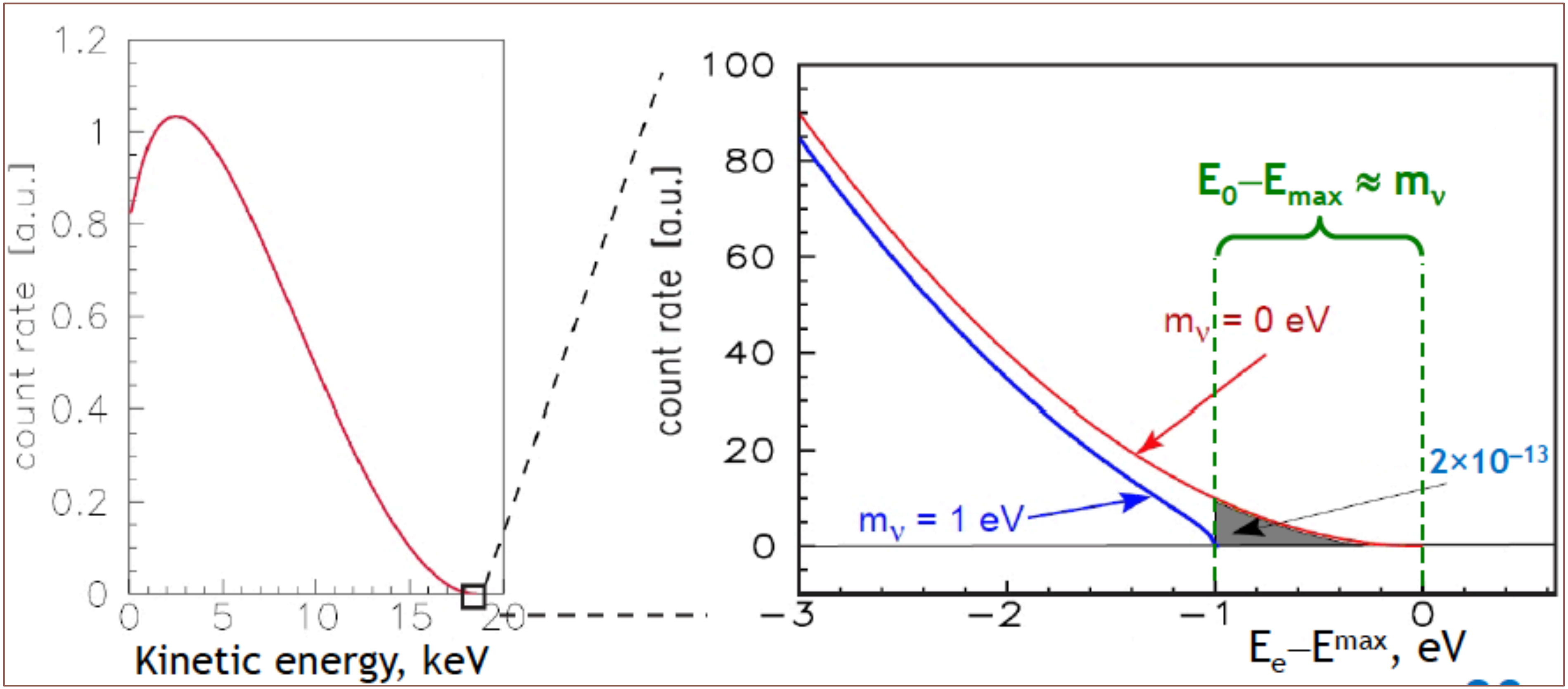
b) Relatively short lifetime ($\tau_{1/2} \approx$ 12 years) and low atomic mass

c) High specific activity (4×10^{14} Bq/g) [Radioactive content of any material]

d) Small amount of ^{3}H required → reduces scattering of electrons in target

e) Simple electronic shell configuration → precise calculations of the final state spectrum

Tritium Beta Decay and the Neutrino Mass



Experiment measures the shape of the endpoint of the spectrum, not the value of the endpoint. This is done by counting events as a function of a low-energy cut-off.

To perform this experiment, lots of statistics needed. Only 2×10^{-13} of all decays in last 1 eV

No evidence for non-zero neutrino mass: experimental limit: **$m(\nu_e) < 2.3$ eV @ 95% C.L.**

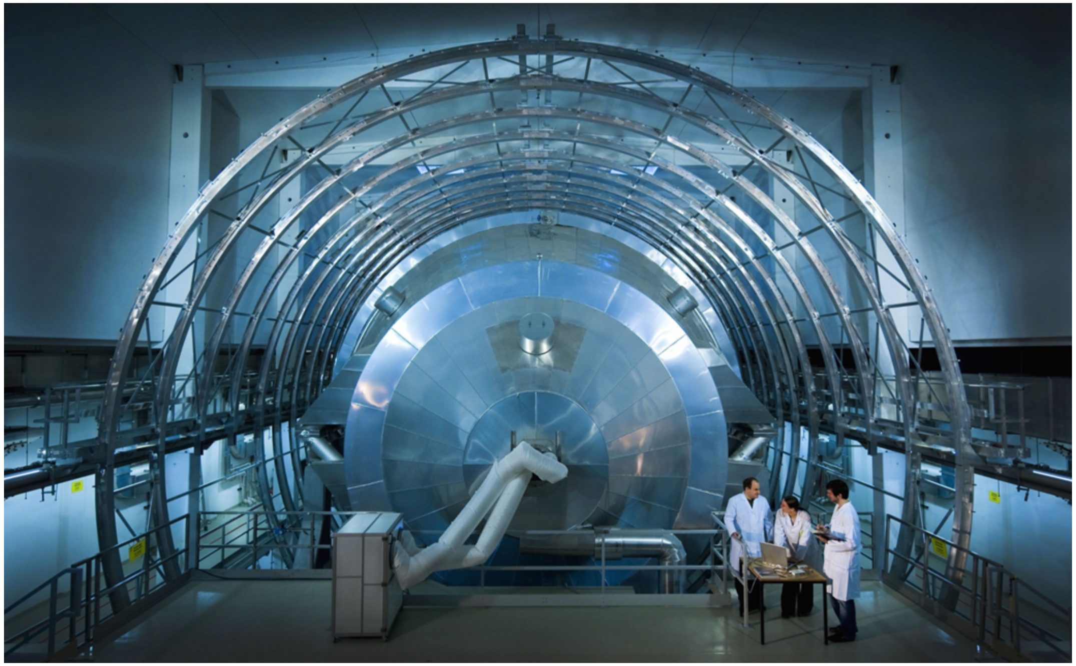
Reference: The Mainz β-decay experiment, Kraus et al., EPJC 40 (2005) 447 (hep-ex/0412056v2)

Troitsk: **$m(\nu_e) < 2.05$ eV @ 95% C.L.** [Aseev et al., PRD 84 (2011) 112003, arXiv:1108.5034 [hep-ex]]

Future: The Karlsruhe Tritium Neutrino (KATRIN) Experiment

Vessel delivery to Karlsruhe Institute of Technology (Germany)

Future: The Karlsruhe Tritium Neutrino (KATRIN) Experiment



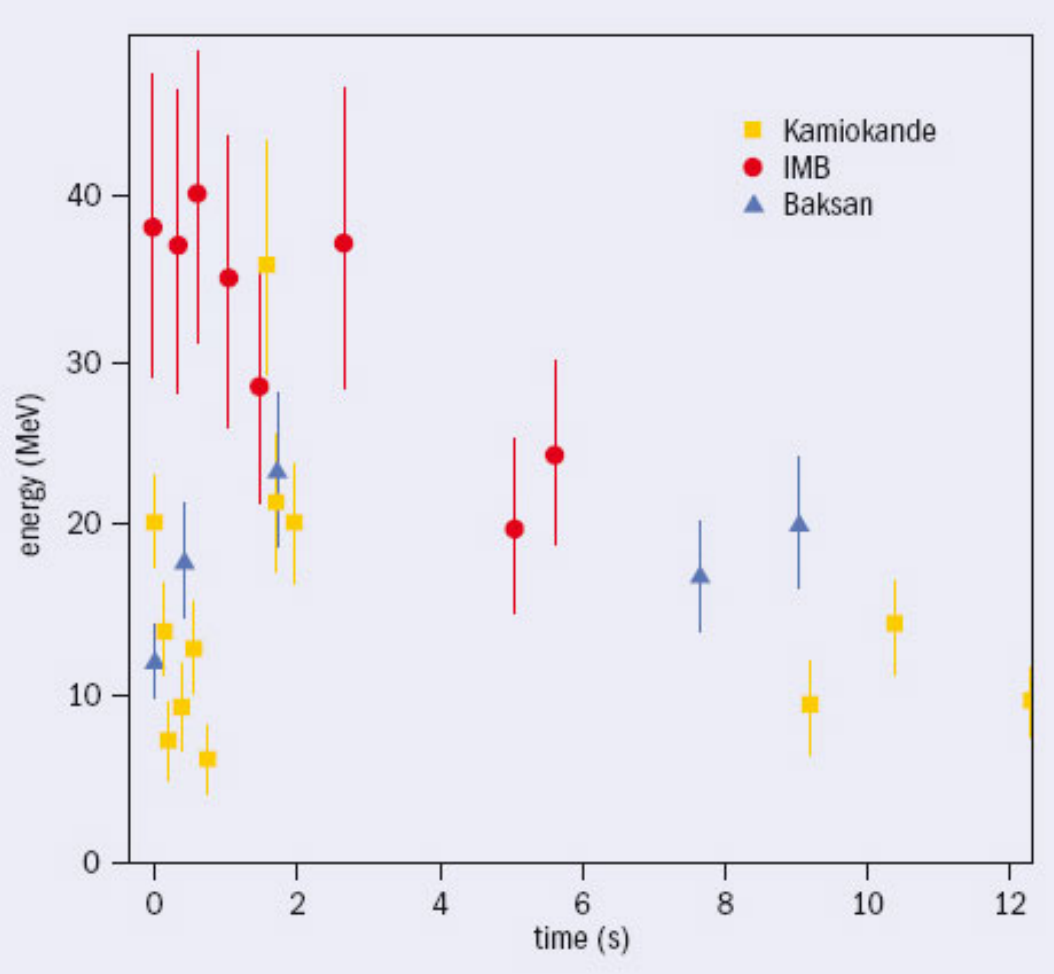
Installation work

- **Vessel length: L = 24 m**
- **Volume: 1400 m^3**
- **High vacuum (~ 10^{-11} mbar)**
- **Low radioactivity**
  (low cobalt content in steel)

- **Expected resolution on neutrino mass: 0.2 eV**
- **A factor of 10 improvement as compared to Mainz and Troitsk limits**
- **Expect m$_{\nu,\mathrm{eff}}$ data in early 2019**

Supernova 1987A

Approximately 2 to 3 hours before the visible light from SN 1987A in Large Magellanic Cloud (a satellite galaxy of the Milky Way at a distance about 50 kiloparsecs ≈ 163,000 light-years) reached Earth, a burst of neutrinos was observed at 3 neutrino observatories. This was likely due to neutrino emission, which occurs simultaneously with core collapse, but before visible light was emitted. Visible light is transmitted only after the shock wave reaches the stellar surface



At 07:35 UT, Kamiokande II detected 12 antineutrinos; IMB, 8 antineutrinos; and Baksan, 5 antineutrinos; in a burst lasting less than 13 seconds

Minimum energy of these neutrinos was around 10 MeV and the maximum energy was around 40 MeV

Would you like to try this?

Question: Can we use the information given in previous slide to estimate the mass of neutrino? Assume that two neutrinos leave the supernova at the same time and arrive on Earth ten seconds apart. Kinetic energy of first neutrino is 20 MeV and that of the second is 10 MeV? Estimate the rest mass of neutrino.

Answer: ≈ 21.7 eV

[Hint: The distance of the supernova from the Earth is around 1.7×10^5 light-years]

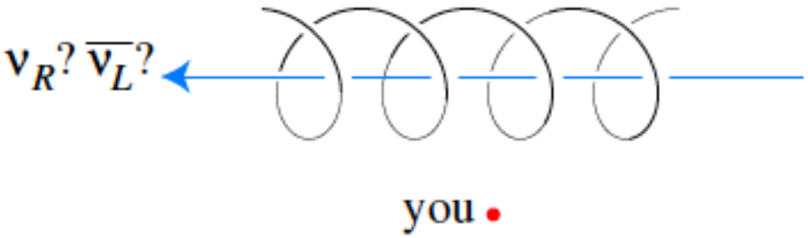
- ☐ Limit on neutrino mass $m_\nu < 11$ eV *Bahcall and Glashow (1987)*
- ☐ Recent analysis $m_\nu < 5.7$ eV *Loredo and Lamb (2002)*
- ☐ JUNO may place limit $m_\nu < 1$ eV if another SN will happen soon

Neutrinos: Dirac or Majorana

☞ **Dirac neutrino needs a global symmetry !**

- For a fermion field, Lorentz invariance allows two kinds of mass terms: $\bar{\psi}\psi$ and $\psi^T C^{-1}\psi$.
- Under $\psi \rightarrow e^{i\alpha}\psi$ transformation ($U(1)$ symmetry), the first is invariant whereas the second is not. the first mass term is Dirac mass and second is Majorana.
- e, μ, q.. must be Dirac fermions because they have $Q_e \neq 0$ (the $U(1)$ symmetry is $U(1)_{em}$).
- since $Q(\nu) = 0$, $U(1)_{em}$ symmetry does not force ν to be Dirac. So it can be Dirac type i.e. $\nu \neq \bar{\nu}$ if there is exact lepton number sym. Otherwise Majorana i.e. $\nu = \bar{\nu}$.
- Important point: 3 Majorana ν's imply 3 ν degrees of freedom; whereas 3 Dirac ν's imply six i.e. 3 active plus 3 sterile.

Neutrinos: Dirac or Majorana



A massive charged fermion (s=1/2) is described by 4 degrees of freedom:

$$(e^-_L \leftarrow \mathrm{CPT} \rightarrow e^+_R)$$

$$\updownarrow \text{Lorentz}$$

$$(e^-_R \leftarrow \mathrm{CPT} \rightarrow e^+_L)$$

A massive neutral fermion (s=1/2) is described by 4 or 2 degrees of freedom:

$$(\nu_L \leftarrow \mathrm{CPT} \rightarrow \bar{\nu}_R)$$

$$\updownarrow \text{Lorentz}$$

“DIRAC”

$$(\nu_R \leftarrow \mathrm{CPT} \rightarrow \bar{\nu}_L)$$

$$(\nu_L \leftarrow \mathrm{CPT} \rightarrow \bar{\nu}_R)$$

“MAJORANA”

$$\updownarrow \text{Lorentz}$$

$$(\bar{\nu}_R \leftarrow \mathrm{CPT} \rightarrow \nu_L)$$

How many degrees of freedom are required to describe massive neutrinos?

Neutrinos: Dirac or Majorana

If neutrino masses were indeed zero, this is a nonquestion: there is no distinction between a massless Dirac and Majorana fermion.

Processes that are proportional to the Majorana nature of the neutrino vanish in the limit $m_\nu \to 0$. Since neutrinos masses are very small, the probability for these to happen is very, very small: $A \propto m_\nu / E$.

The "smoking gun" signature is the observation of LEPTON NUMBER violation. This is easy to understand: Majorana neutrinos are their own antiparticles and, therefore, cannot carry any quantum numbers — including lepton number.

The deepest probes are searches for Neutrinoless Double-Beta Decay.

Neutrinos and antineutrinos are possibly distinguished by a unique charge, the lepton number

If lepton number is not conserved nothing distinguishes neutrino from antineutrino

Neutrino may be its own antiparticle

Neutrinos: Dirac or Majorana

Weak Interactions are Purely Left-Handed (Chirality):

For example, in the scattering process $e^- + X \to \nu_e + X^{'}$, the electron neutrino is, in a reference frame where $m \ll E$,

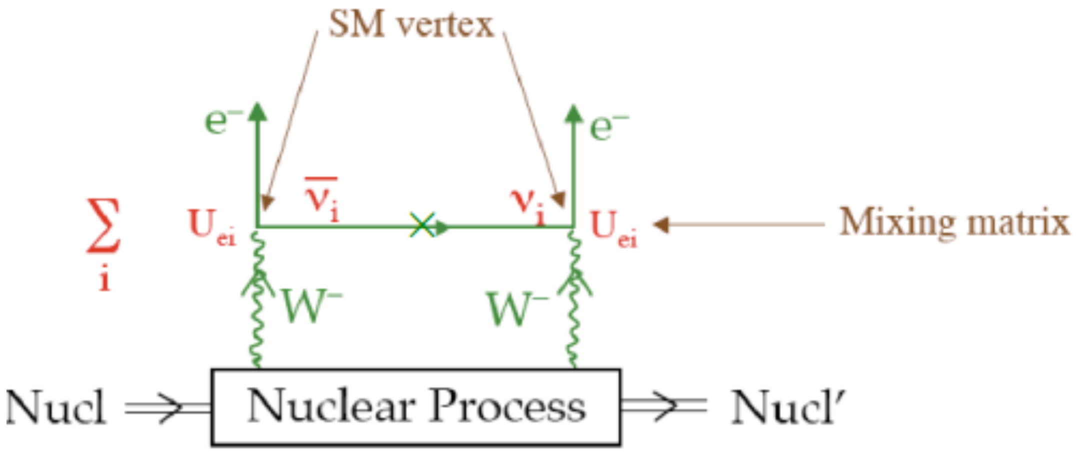
$$|\nu_e\rangle \sim |L\rangle + \left(\frac{m}{E}\right)|R\rangle.$$

If the neutrino is a Majorana fermion, $|R\rangle$ behaves mostly like a "$\bar{\nu}_e$," (and $|L\rangle$ mostly like a "ν_e,") such that the following process could happen:

$$e^- + X \to \nu_e + X, \quad \text{followed by} \quad \nu_e + X \to e^+ + X^{'}, \qquad P \simeq \left(\frac{m}{E}\right)^2$$

Lepton number can be violated by 2 units with small probability. Typical numbers: $P \simeq (0.1\text{ eV}/100\text{ MeV})^2 = 10^{-18}$. VERY Challenging!

Neutrinos: Dirac or Majorana



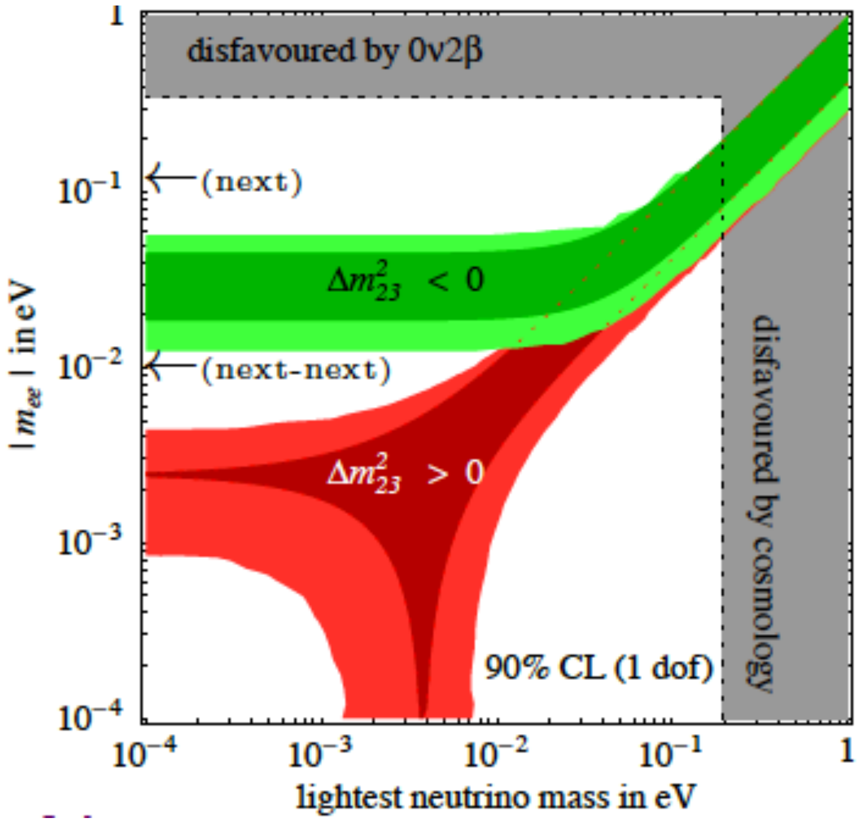
Best Bet: search for

Neutrinoless Double-Beta

Decay: $\boxed{Z \to (Z+2)e^- e^-}$

Helicity Suppressed Amplitude $\propto \frac{m_{ee}}{E}$

Observable: $m_{ee} \equiv \sum_i U_{ei}^2 m_i$



The Standard Model: Massless Neutrinos

The Standard Model is a gauge theory & it unifies strong, weak & electromagnetic forces!

$$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$$

$(1,2)_{-\frac{1}{2}}$	$(3,2)_{\frac{1}{6}}$	$(1,1)_{-1}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	e_R	u^i_R	d^i_R
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$	μ_R	c^i_R	s^i_R
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$	τ_R	t^i_R	b^i_R

3-fold repetition of the same representation!

- 3 *active* neutrinos: ν_e , ν_μ , ν_τ
- Neutral elementary particles of Spin ½
- Only couple to *weak force* (& gravity)
- Only *left handed* neutrinos
- There are no right-handed neutrinos
- *No* Dirac Mass term: $m(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L)$

Neutrinos are massless in the Basic SM

❑ Over the past decade, marvelous data from world class neutrino experiments firmly established that they change flavor after propagating a finite distance

❑ Neutrino flavor change (oscillation) demands non-zero mass and mixing

Non-zero ν mass: first experimental proof for physics beyond the Standard Model

!! An extension of the Standard Model is necessary !!

Neutrino Physics: An Exercise in Patience

Three most fundamental questions were being asked in the past century…

1. How tiny is the neutrino mass? (Pauli, Fermi, ’30s)

Planck + BAO + WMAP polarization data: upper limit of 0.23 eV for the sum of ν masses

Planck Collaboration, arXiv:1303.5076 [astro-ph.CO]

2. Can a neutrino turn into its own antiparticle? (Majorana, ’30s)

Hunt for ν-less Double-β decay (Z,A → Z+2, A) is still on, demands lepton number violation

Nice Review by Avignone, Elliott, Engel, Rev.Mod.Phys. 80 (2008) 481-516

3. Do different ν flavors ‘oscillate’ into one another? (Pontecorvo, Maki-Nakagawa-Sakata, ’60s)

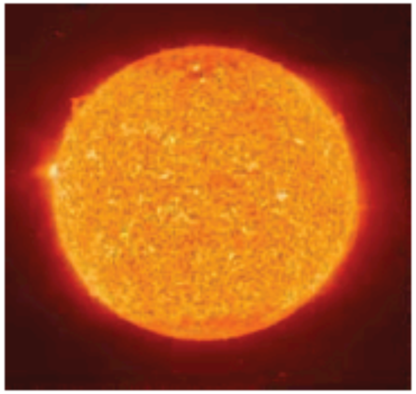
B. Pontecorvo, Sov. Phys. JETP 26, 984 (1968) [Zh. Eksp. Teor. Fiz. 53, 1717 (1967)]

Last question positively answered only in recent years. Now an established fact that **neutrinos are massive** and leptonic flavors are not **symmetries of Nature**

After the measurement of $\boldsymbol{\theta_{13}}$, a clear first order picture of the three-flavor lepton mixing matrix has emerged, signifies a major breakthrough in ν physics

Golden Age of Neutrino Physics (1998 – 2018 & Beyond)

sun

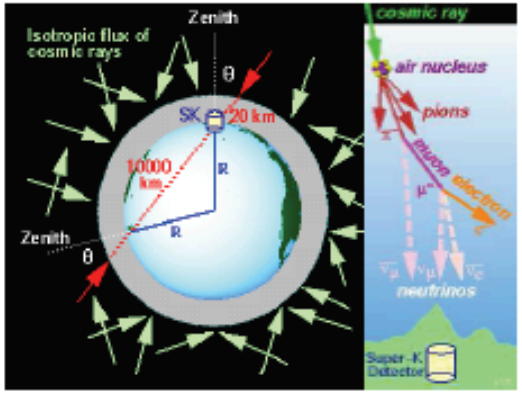


Homestake, SAGE, GALLEX
SuperK, SNO, Borexino

reactors

KamLAND, CHOOZ
Double Chooz, Daya Bay, RENO

atmosphere



SuperKamiokande
IceCube, DeepCore

accelerators

K2K, MINOS, T2K
NOvA

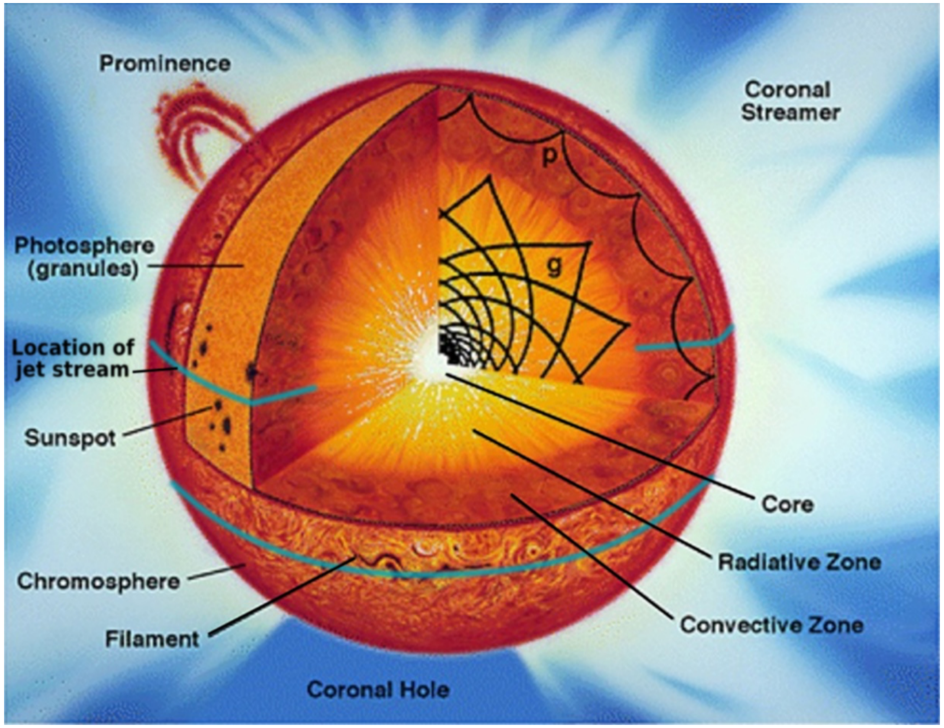
Over the last two decades or so, precious data from world-class experiments

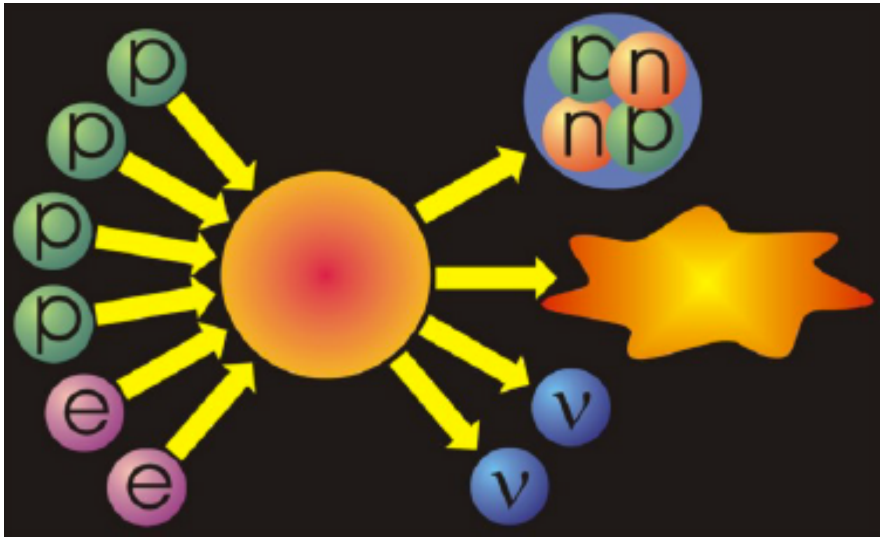
- Solar neutrinos (ν_e)
- Atmospheric neutrinos $(\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e)$
- Reactor anti-neutrinos $(\bar{\nu}_e)$
- Accelerator neutrinos $(\nu_\mu, \bar{\nu}_\mu)$

Data from various neutrino sources and vastly different energy and distance scales

We have just started our journey in the mysterious world of neutrinos

How does the Sun shine?





- Nuclear fusion reactions: mainly

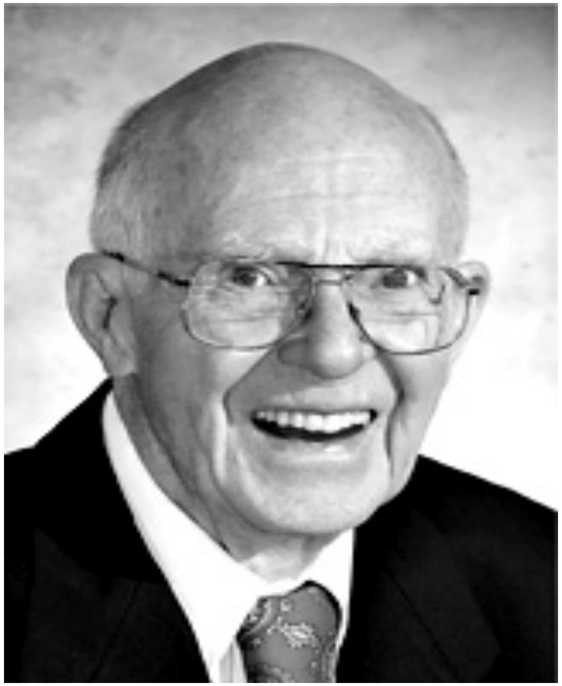
$$4\,{}^1_1\mathrm{H} + 2e^- \rightarrow {}^4_2\,\mathrm{He} + \mathrm{light} + 2\nu_e$$

- Neutrinos needed to conserve energy, momentum, angular momentum

Neutrinos are essential for the Sun to shine

Detection of Cosmic Neutrinos

The Nobel Prize in Physics 2002



Raymod Davis Jr.

Detected Solar Neutrinos

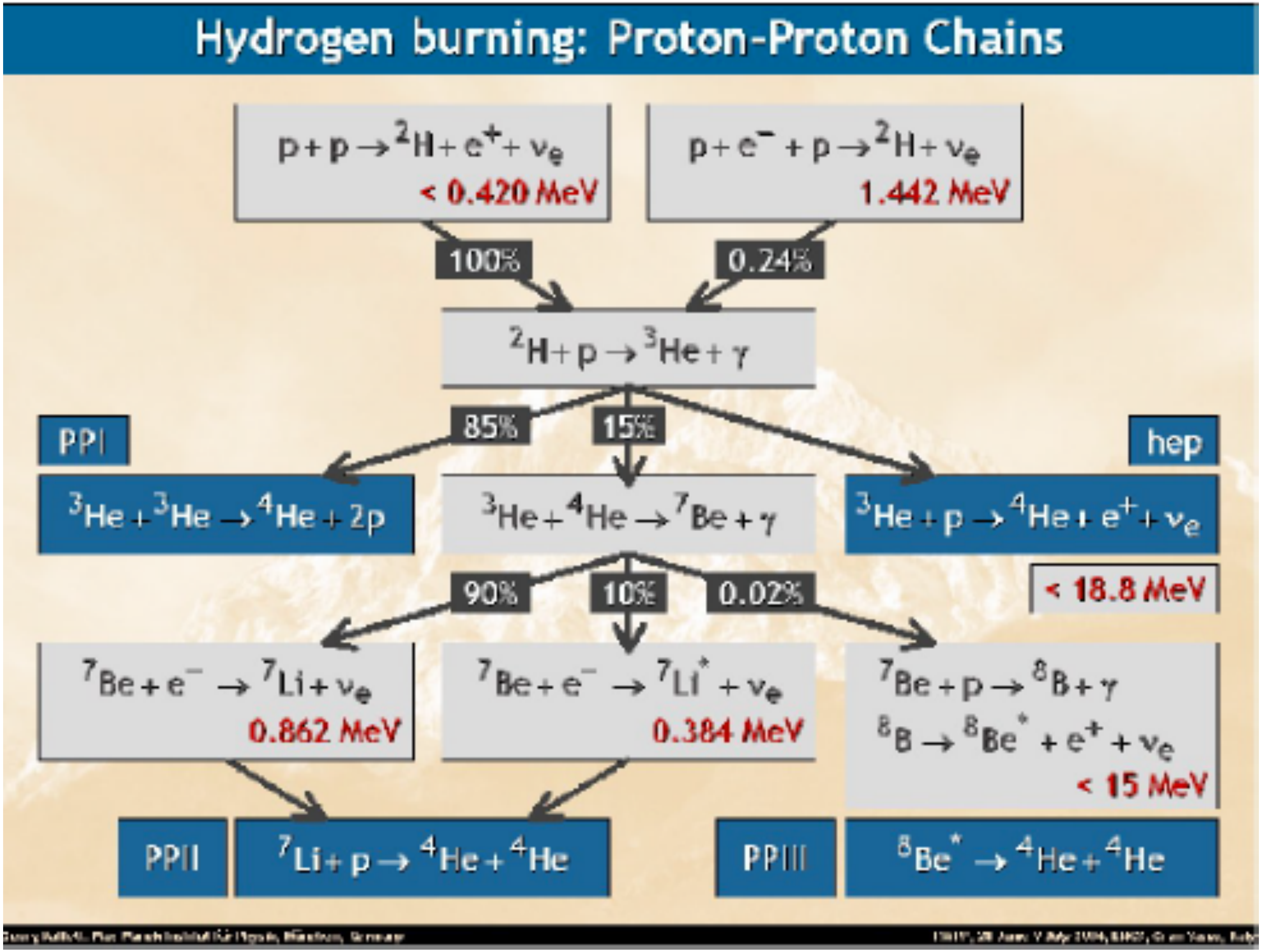
Masatoshi Koshiba

Detected Supernova Neutrinos

Detection of Cosmic Neutrinos ➔ A New Window on the Universe

Era of Neutrino Astronomy began

Neutrinos from the Sun



Hydrogen burning: Proton-Proton Chains

$p + p \rightarrow {}^2H + e^+ + \nu_e$

< 0.420 MeV

$p + e^- + p \rightarrow {}^2H + \nu_e$

1.442 MeV

100%

0.24%

${}^2H + p \rightarrow {}^3He + \gamma$

85%

15%

PPI

${}^3He + {}^3He \rightarrow {}^4He + 2p$

${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

hep

${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$

< 18.8 MeV

90%

10%

0.02%

${}^7Be + e^- \rightarrow {}^7Li + \nu_e$

0.862 MeV

${}^7Be + e^- \rightarrow {}^7Li^* + \nu_e$

0.384 MeV

${}^7Be + p \rightarrow {}^8B + \gamma$

${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

< 15 MeV

PPII

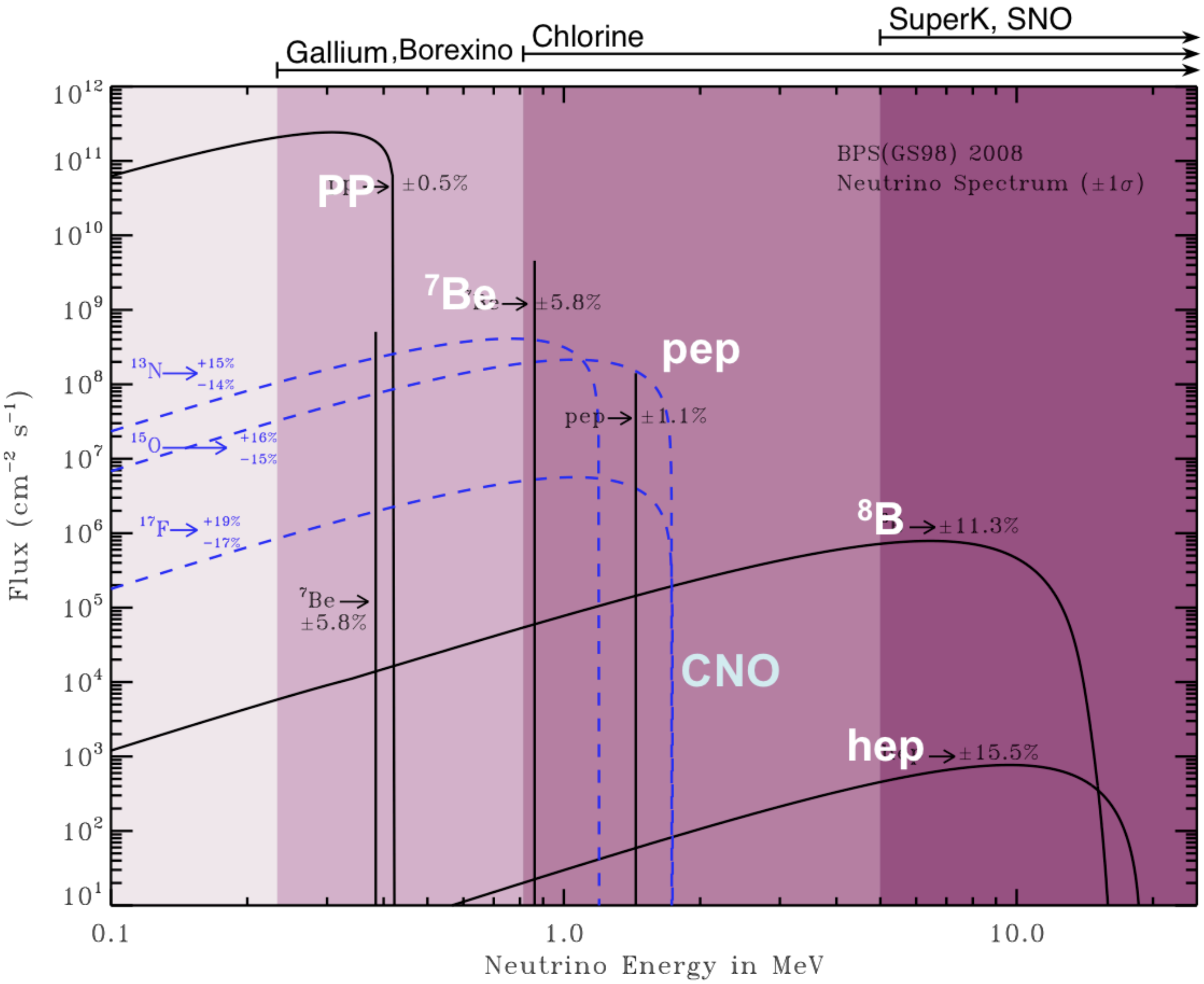
${}^7Li + p \rightarrow {}^4He + {}^4He$

PPIII

${}^8Be^* \rightarrow {}^4He + {}^4He$

S. K. Agarwalla, EHEP 2019, TIFR, Mumbai, India, 24th to 26th January, 2019

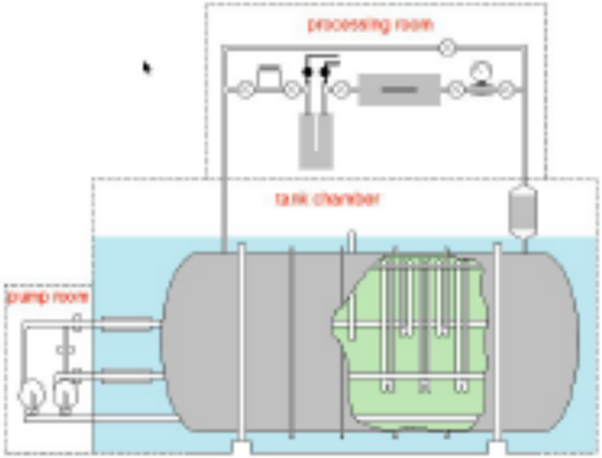
The Solar Neutrino Spectra



- Magnitudes of fluxes depend on details of solar interior
- Spectral shapes robustly known

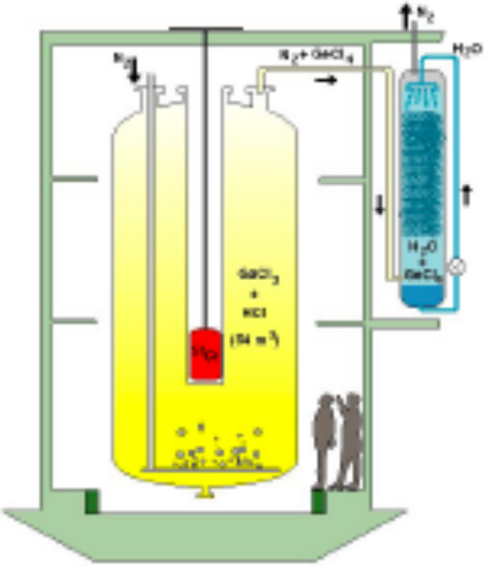
Detecting Neutrinos from the Sun

- The Sun produces ν_e
- These ν_e can be detected at Earth: difficult, but possible



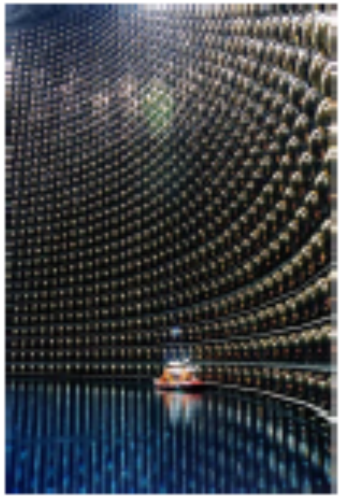
$\nu_e + \mathrm{Cl} \rightarrow \mathrm{Ar} + e^-$

Homestake



$\nu_e + \mathrm{Ga} \rightarrow \mathrm{Ge} + e^-$

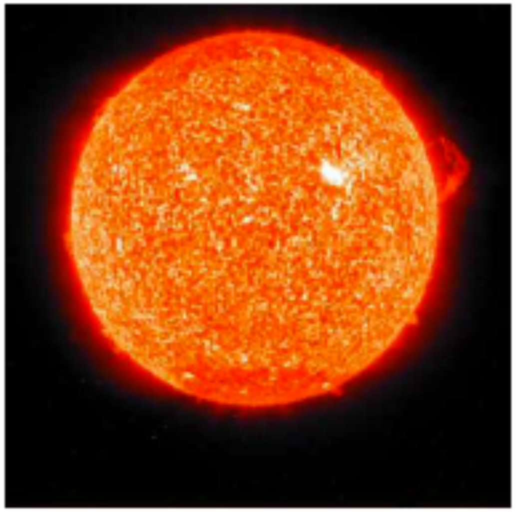
Gallex



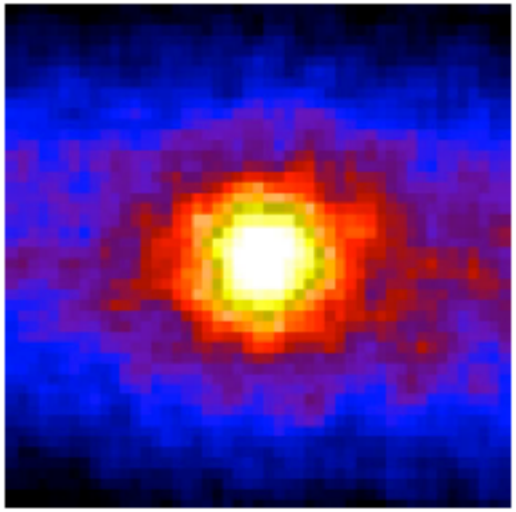
$\nu_e + e^- \rightarrow \nu_e + e^-$

SuperKamiokande

Seeing the Sun with Neutrinos

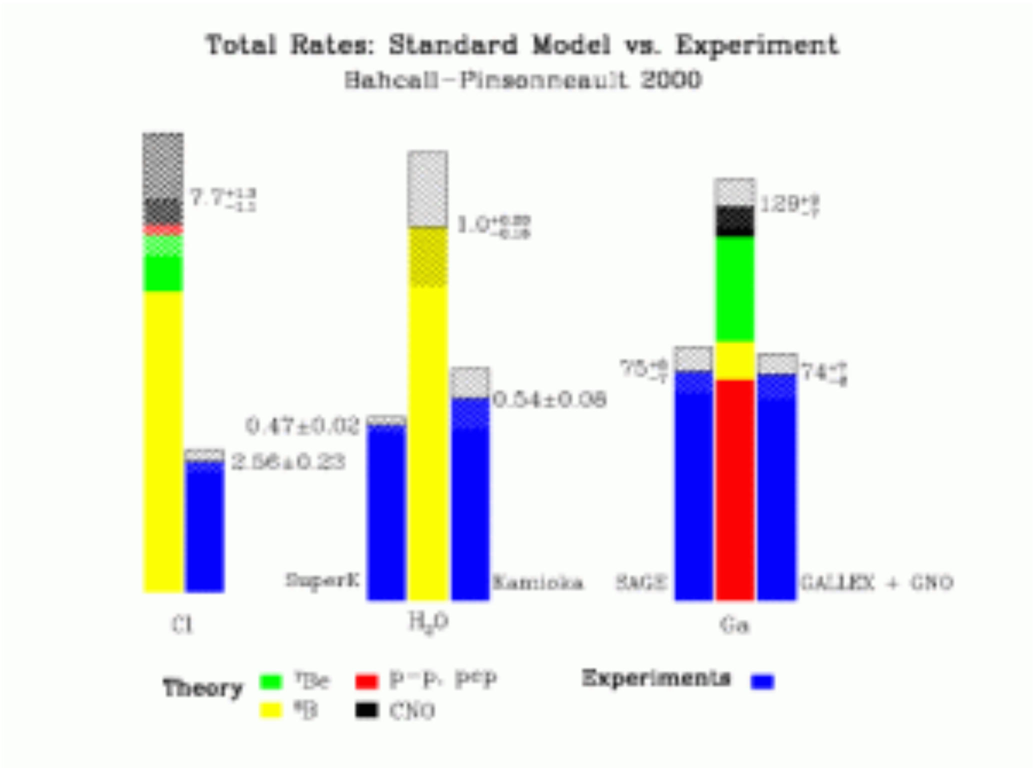


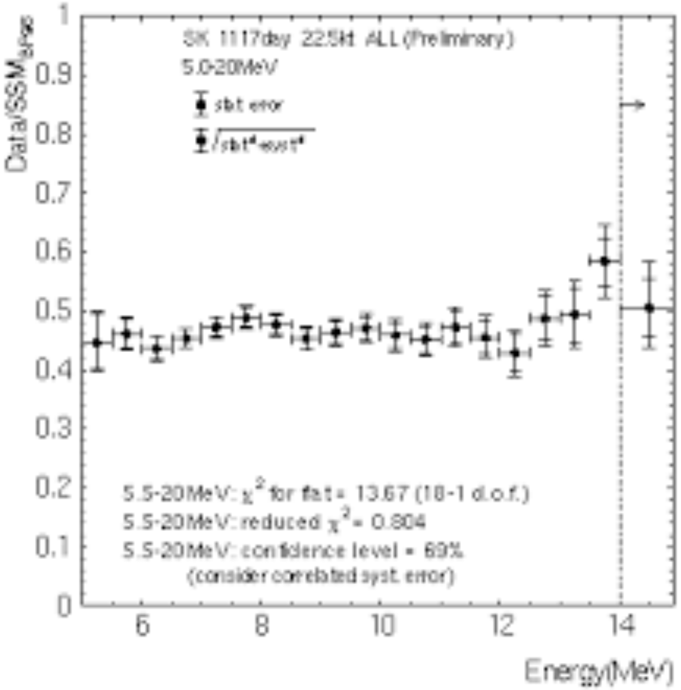
- Light from the Sun's surface:
  due to nuclear reactions
  millions of years ago
- Neutrinos from the Sun's core:
  due to nuclear reactions
  8 minutes ago



- We know how much light we get from the Sun...
- So we know how many neutrinos should arrive.

Do we really understand how the Sun shines?





The Solar Neutrino Anomaly

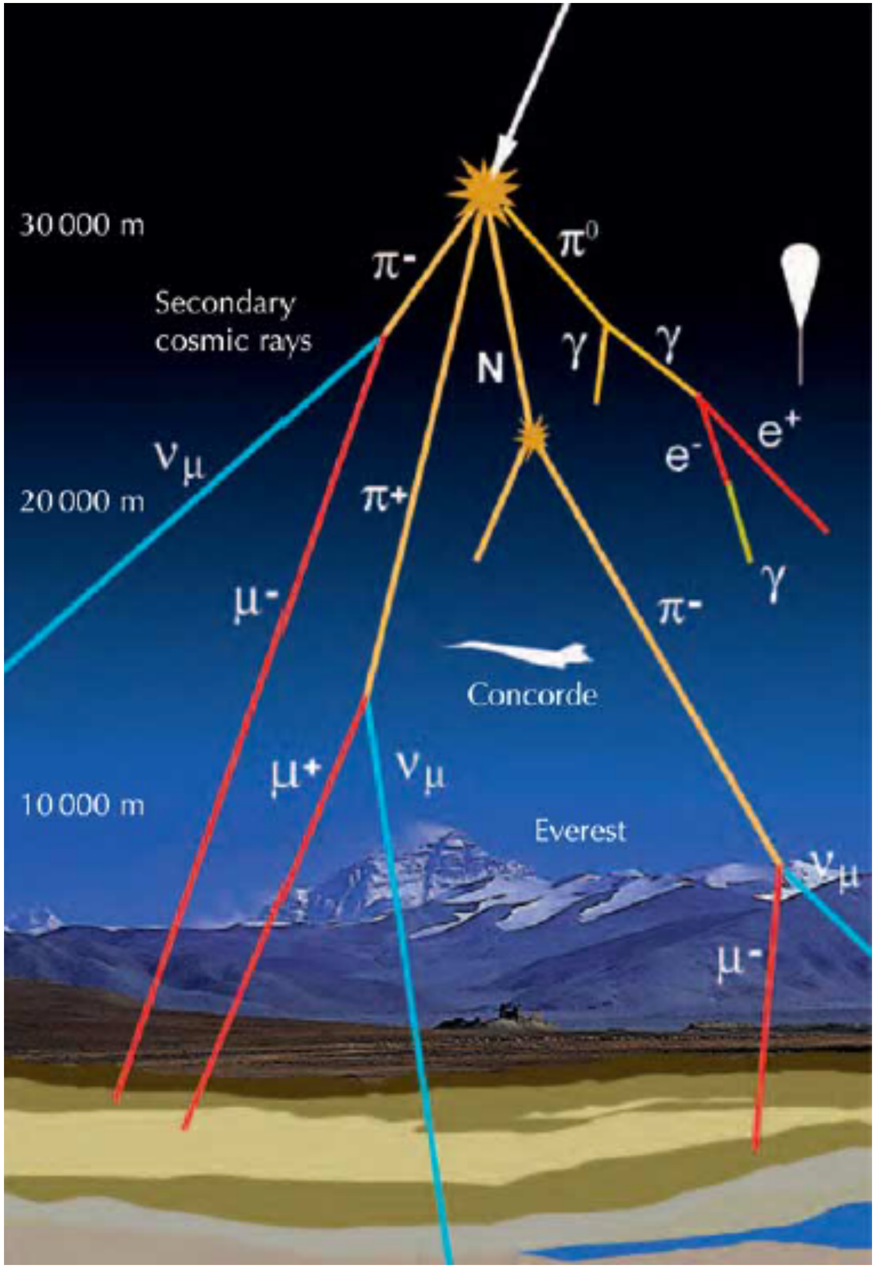
Puzzle:

- Only about 30%–50% of neutrinos from the Sun found
- Different experiments give different neutrino loss...
  (They look at different energy ranges, of course..)
- SuperKamiokande shows similar neutrino loss at all energies

Possible Reasons:

- The astrophysicists cannot calculate accurately
- The experimentalists cannot measure accurately
- Neutrinos behave differently from what everyone thought

Atmospheric Neutrinos: Neutrinos from Cosmic Rays

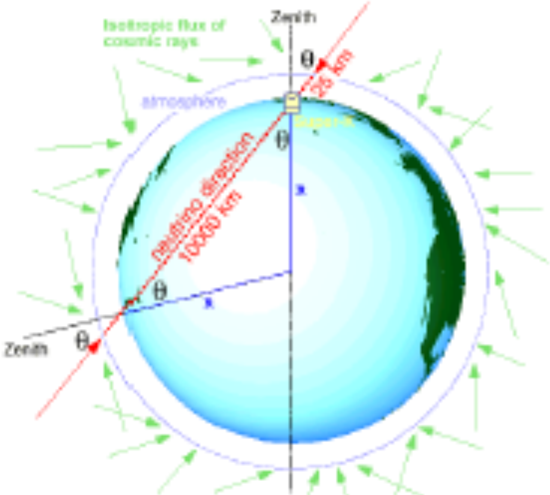


$$\pi^+ \to \mu^+ + \nu_\mu$$

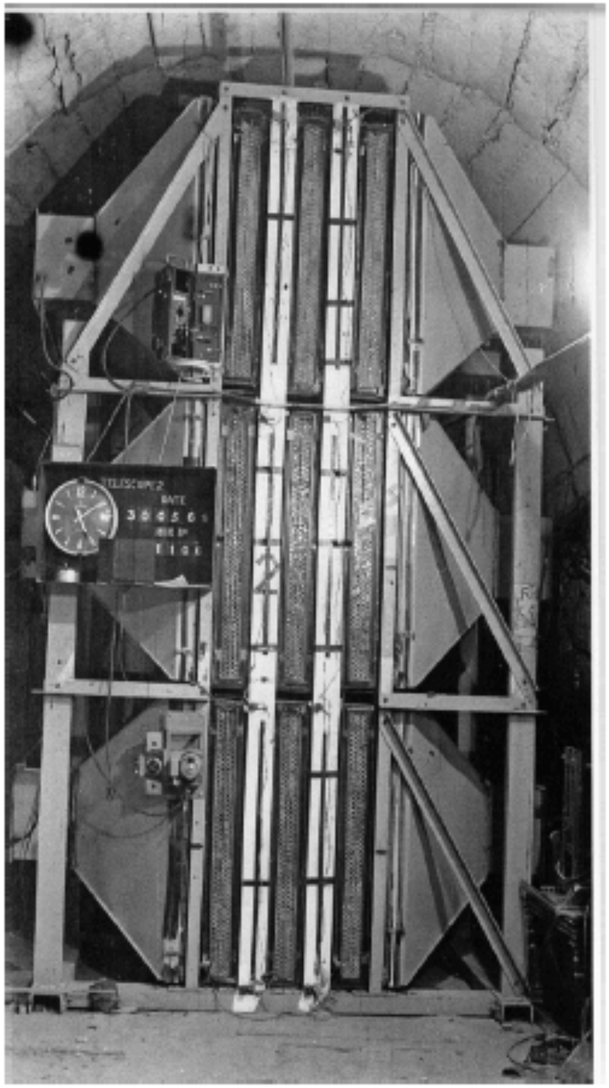
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

"ν_μ" flux $= 2\times$ "ν_e" flux

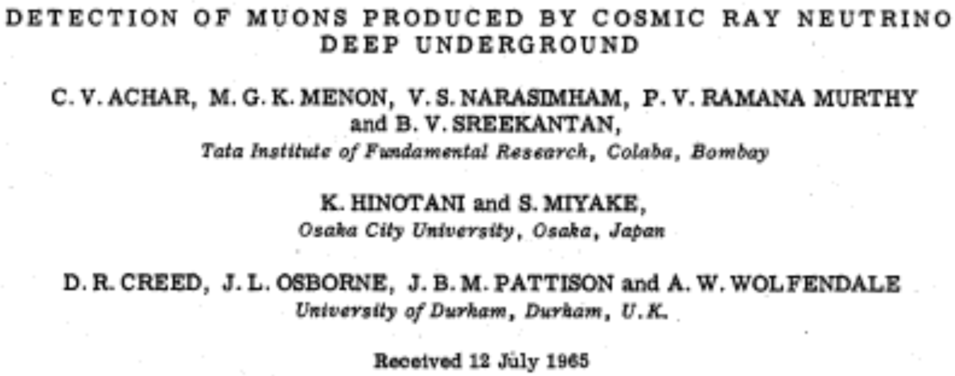
"Down" flux = "Up" flux



The first atmospheric neutrinos detected in India



Detector in
Kolar Gold Fields



DETECTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINO DEEP UNDERGROUND

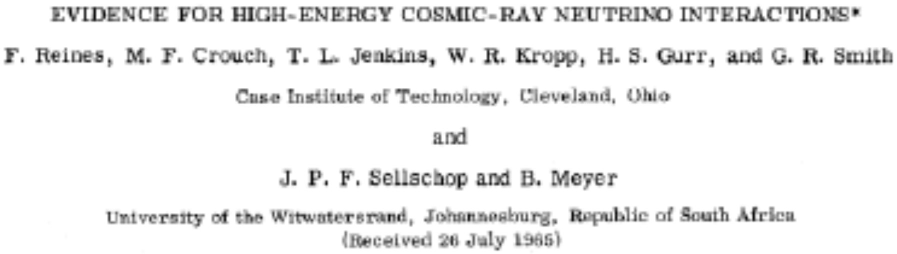
C. V. ACHAR, M. G. K. MENON, V. S. NARASIMHAM, P. V. RAMANA MURTHY
and B. V. SREEKANTAN,
Tata Institute of Fundamental Research, Colaba, Bombay

K. HINOTANI and S. MIYAKE,
Osaka City University, Osaka, Japan

D. R. CREED, J. L. OSBORNE, J. B. M. PATTISON and A. W. WOLFENDALE
University of Durham, Durham, U.K.

Received 12 July 1965

Physics Letters 18, (1965) 196
(15th Aug 1965)



EVIDENCE FOR HIGH-ENERGY COSMIC-RAY NEUTRINO INTERACTIONS*

F. Reines, M. F. Crouch, T. L. Jenkins, W. R. Kropp, H. S. Gurr, and G. R. Smith
Case Institute of Technology, Cleveland, Ohio
and
J. P. F. Sellschop and B. Meyer
University of the Witwatersrand, Johannesburg, Republic of South Africa

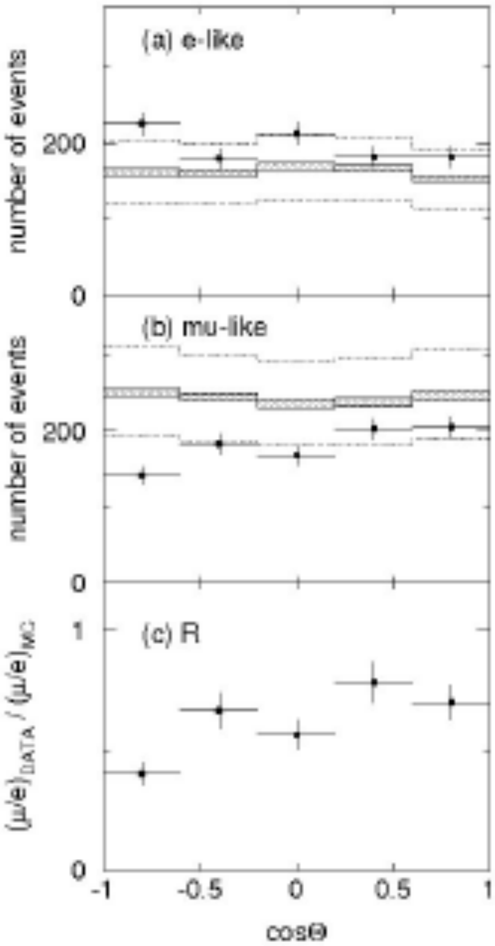
(Received 26 July 1965)

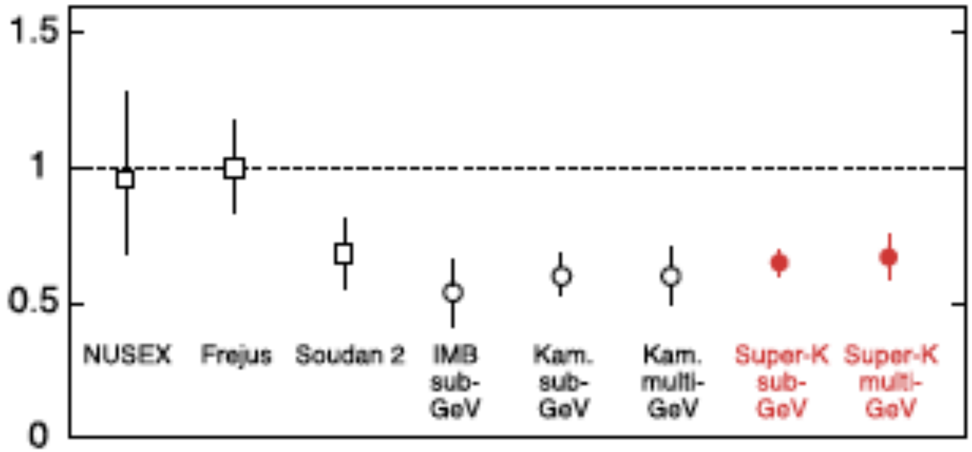
PRL 15, (1965) 429
(30th Aug 1965)

Atmospheric Neutrino Anomaly

Super-Kamiokande

Double ratio:





$$R = \frac{(N_\mu/N_e)_{data}}{(N_\mu/N_e)_{MC}}$$

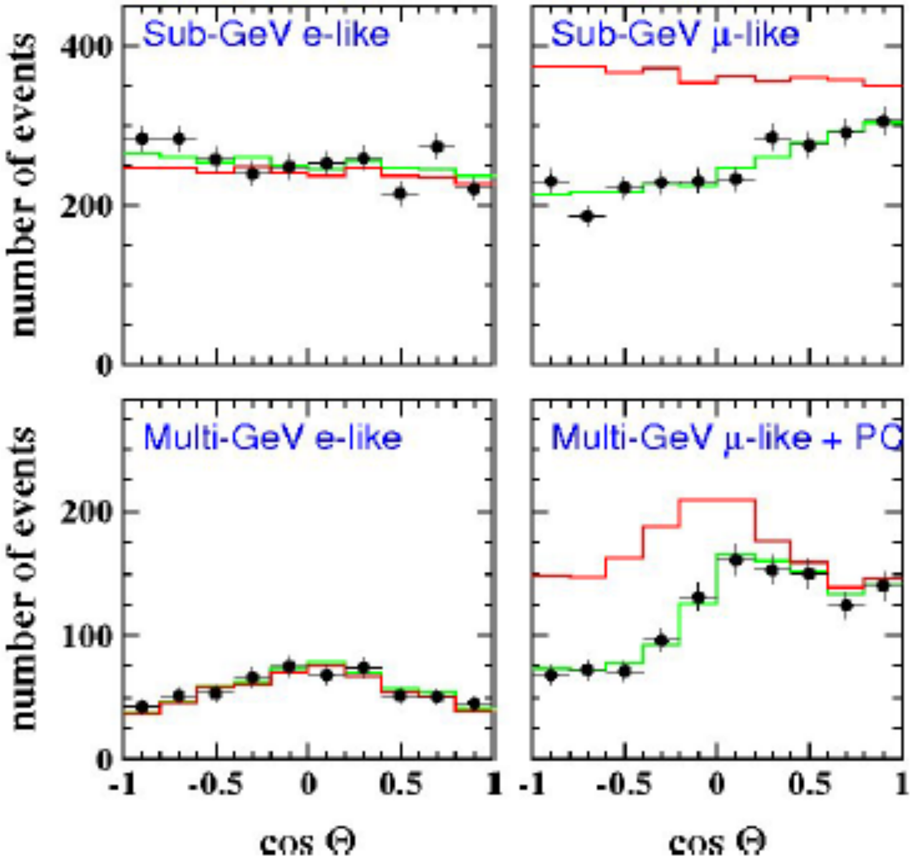
- Expected $R = 1$
- Observed $R < 1$

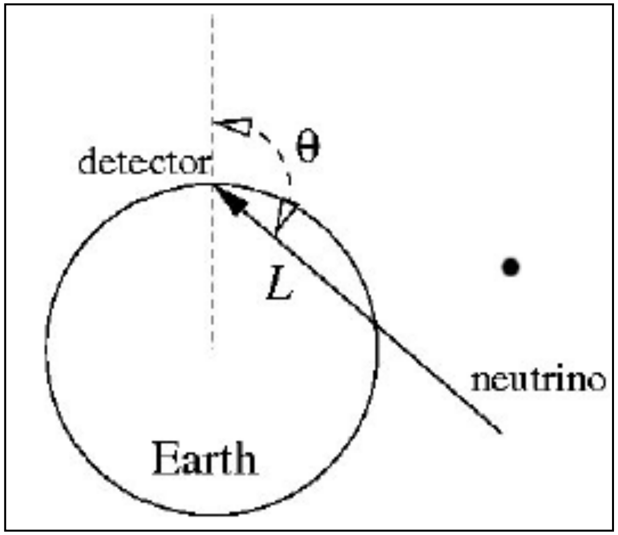
Year 1988:
First results from Kamiokande
on atmospheric neutrino anomaly

K.S. Hirata, et al., Experimental study of the atmospheric neutrino flux, Phys. Lett. B 205 (1988) 416.

Atmospheric Neutrino Anomaly

Superkamiokande:





Zenith angle dependence

Crucial observations from zenith angle data

- Electron neutrinos match predictions
- High energy ν_μ from above: match predictions
- High energy ν_μ through the earth: partially lost
- Low energy ν_μ: lost even when coming from above, loss while passing through the Earth even greater

The Breakthrough Idea

Бруно Понтекорво

Bruno Pontecorvo
(original idea suggested for solar neutrinos, with neutrino-antineutrino mixing.)

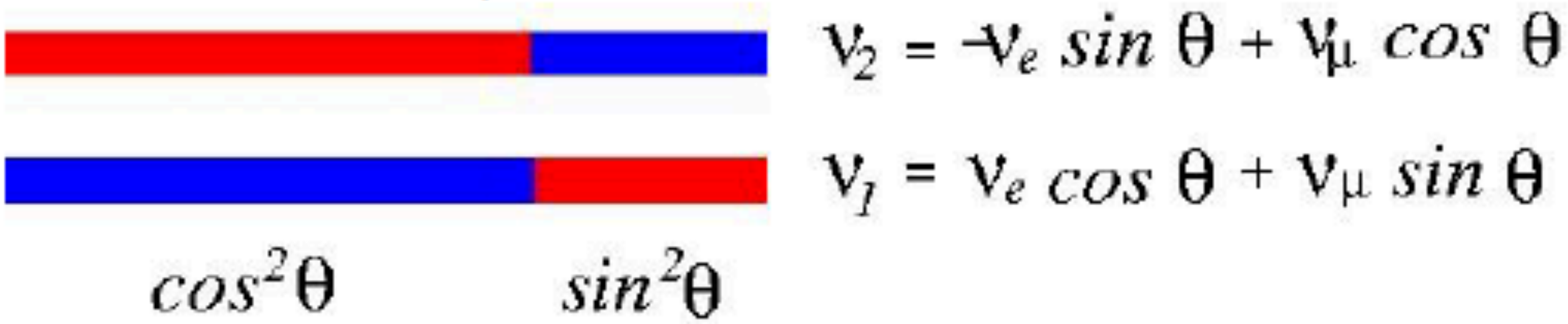
Maybe the neutrino flavours change !

- All the experiments are looking for ν_e and ν_μ
- What if ν_e / ν_μ are getting converted to ν_τ ?
- This is possible, but only if the neutrinos have different masses and they mix !

Neutrino Mixing

Neutrino flavours ν_e, ν_μ, ν_τ do not have fixed masses !!

For example, ν_e–ν_μ mixing:



$$\nu_2 = -\nu_e \sin\theta + \nu_\mu \cos\theta$$

$$\nu_1 = \nu_e \cos\theta + \nu_\mu \sin\theta$$

$\cos^2\theta$ $\sin^2\theta$

- Only ν_1 and ν_2 have fixed masses
  (*They are eigenstates of energy / eigenstates of evolution*)
- Then, if you produce ν_e, it may be observed as ν_μ !

Effective Hamiltonian for a Single Neutrino

$$H = \sqrt{p^2 + m^2} \approx p + \frac{m^2}{2p} \approx p + \frac{m^2}{2E}$$

Schrödinger's equation:

$$i\frac{d}{dt}|\nu(t)\rangle = H|\nu(t)\rangle$$

Time evolution:

$$\begin{aligned} |\nu(t)\rangle &= |\nu(0)\rangle e^{-iHt} \\ &= |\nu(0)\rangle e^{-ipt} e^{-i\frac{m^2}{2E}t} \end{aligned}$$

- Simple for a mass eigenstate with fixed momentum !

Time Evolution for a Flavor Eigenstate

- Initial flavour state $|\nu_\alpha\rangle$:

$$|\nu_\alpha\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

- State after time t:

$$|\nu_\alpha(t)\rangle = \cos\theta|\nu_1\rangle e^{-ipt}e^{-i\frac{m_1^2}{2E}t} + \sin\theta|\nu_2\rangle e^{-ipt}e^{-i\frac{m_2^2}{2E}t}$$

- "Survival" probability of finding the flavour $|\nu_\alpha\rangle$ at time t:

$$P(\nu_\alpha \to \nu_\alpha) = |\langle\nu_\alpha|\nu_\alpha(t)\rangle|^2$$

Vacuum oscillations:

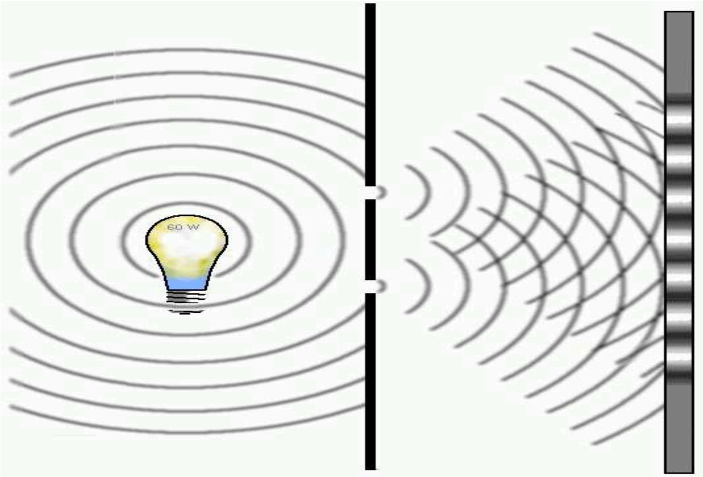
$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

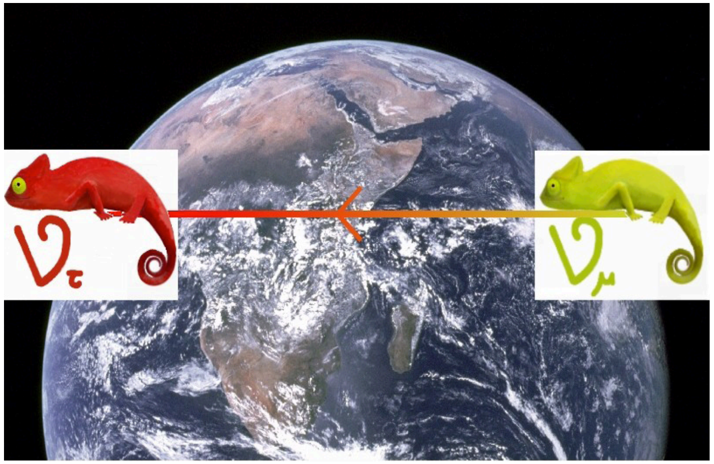
$$\Delta m^2 \equiv m_2^2 - m_1^2$$

(In Natural units, where $c = 1 = \hbar$)

Neutrino Flavor Oscillations

1957: Bruno Pontecorvo proposed Neutrino Oscillations in analogy with $K^0 \leftrightarrows \bar{K}^0$ oscillations (Gell-Mann and Pais, 1955)





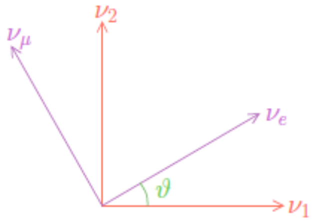
- *Neutrino oscillation: Quantum Mechanical interference phenomenon*
- *Like electrons in the double slit experiment*
- *In Neutrino Oscillation: Neutrino changes flavor as it propagates*
- *It happens if neutrinos have masses (non-degenerate) and there is mixing*

Neutrino Oscillations: 2 Flavors

- **Flavor States :** ν_e **and** ν_μ **(produced in Weak Interactions)**
- **Mass Eigenstates :** ν_1 **and** ν_2 **(propagate from Source to Detector)**

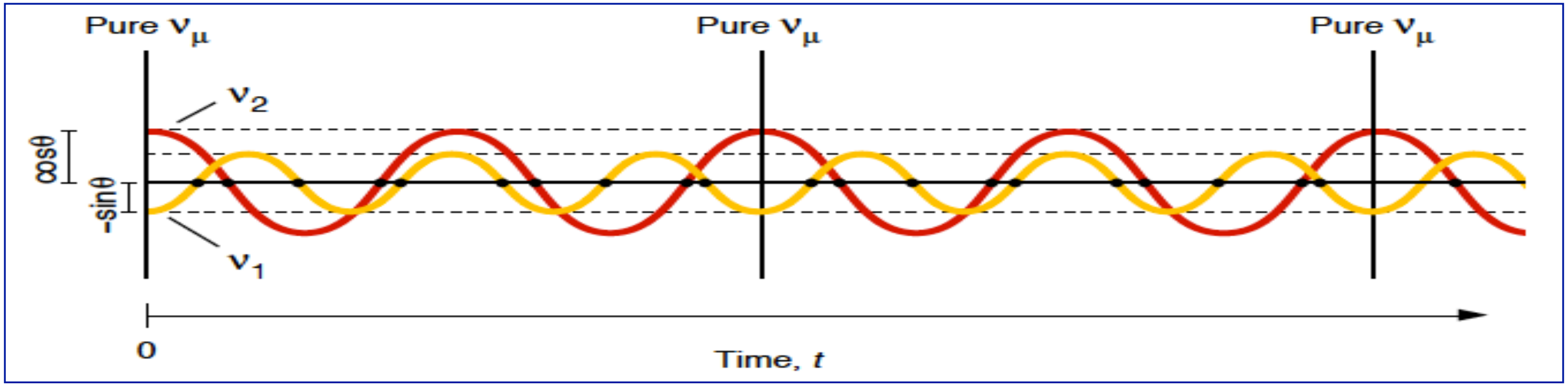
A Flavor State is a linear superposition of Mass Eigenstates

$$|\nu_\alpha\rangle = \sum_{k=1}^{2} U_{\alpha k} \, |\nu_k\rangle \qquad (\alpha = e, \mu)$$



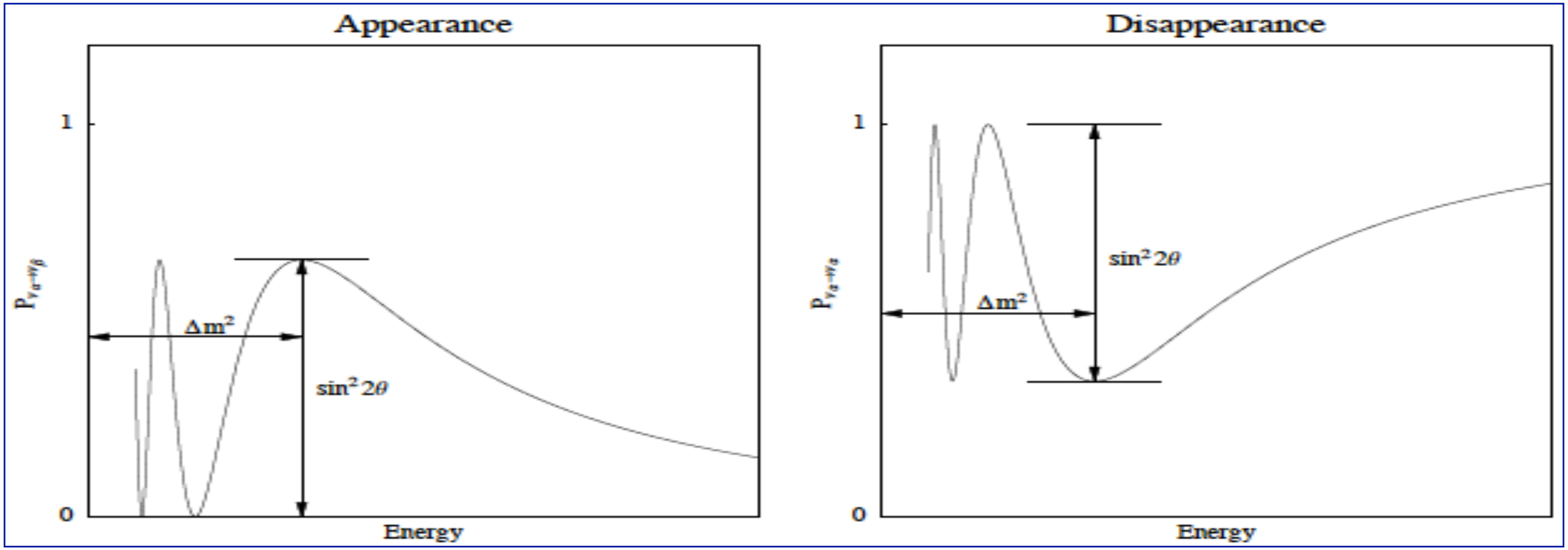
$$U = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix}$$

$$|\nu_e\rangle = \cos\vartheta \, |\nu_1\rangle + \sin\vartheta \, |\nu_2\rangle$$
$$|\nu_\mu\rangle = -\sin\vartheta \, |\nu_1\rangle + \cos\vartheta \, |\nu_2\rangle$$



If the masses of these two states are different then they will take different times to reach the same point and there will be a phase difference and hence interference

Oscillation Probabilities in 2 Flavors



$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta \;\; \sin^2(1.27 \Delta m^2 \frac{L}{E})$$

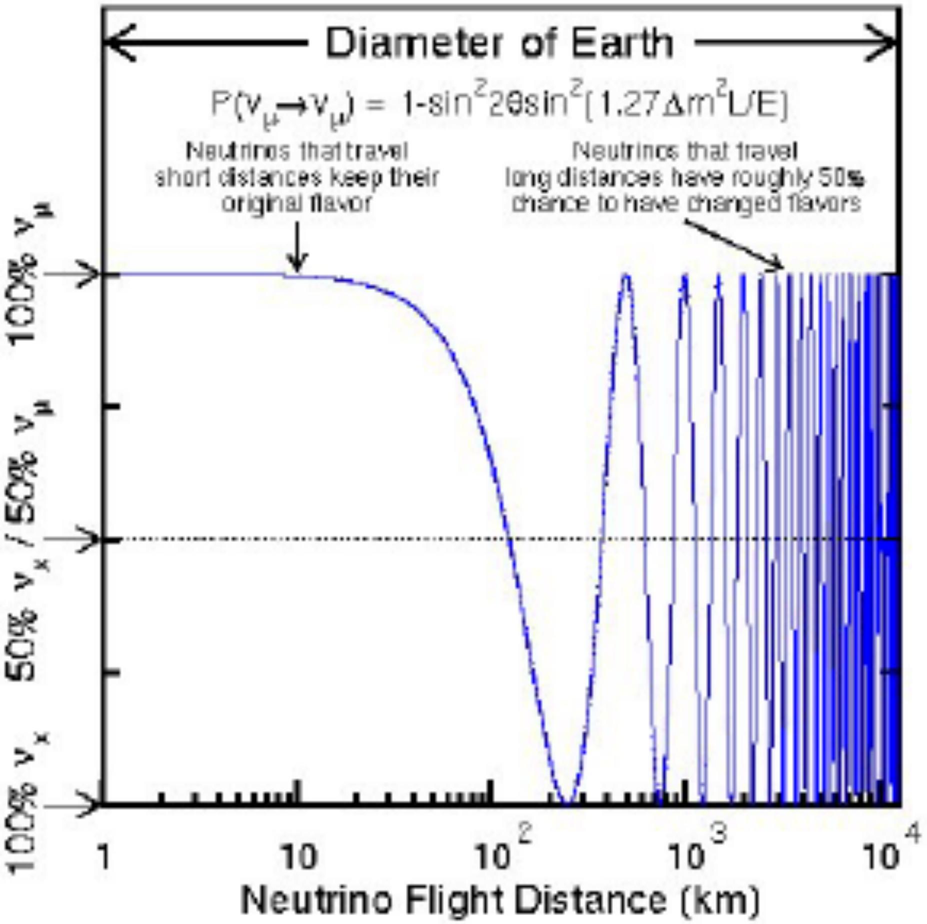
$$P_{\nu_\alpha \to \nu_\alpha} = 1 - \sin^2 2\theta \;\; \sin^2(1.27 \Delta m^2 \frac{L}{E})$$

Δm^2 is in eV^2, L is in m (km) and E in MeV (GeV)

$$\lambda = 2.47\text{km} \left(\frac{E}{\text{GeV}}\right) \left(\frac{\text{eV}^2}{\Delta m^2}\right) \Rightarrow \text{oscillation length}$$

Neutrino Oscillations only sensitive to mass squared difference
but not to the absolute Neutrino mass scale

Neutrino oscillations as a function of distance travelled



- More neutrinos 'lost" when $\cos(\Theta) < 0$

(Θ : angle made with the zenith)

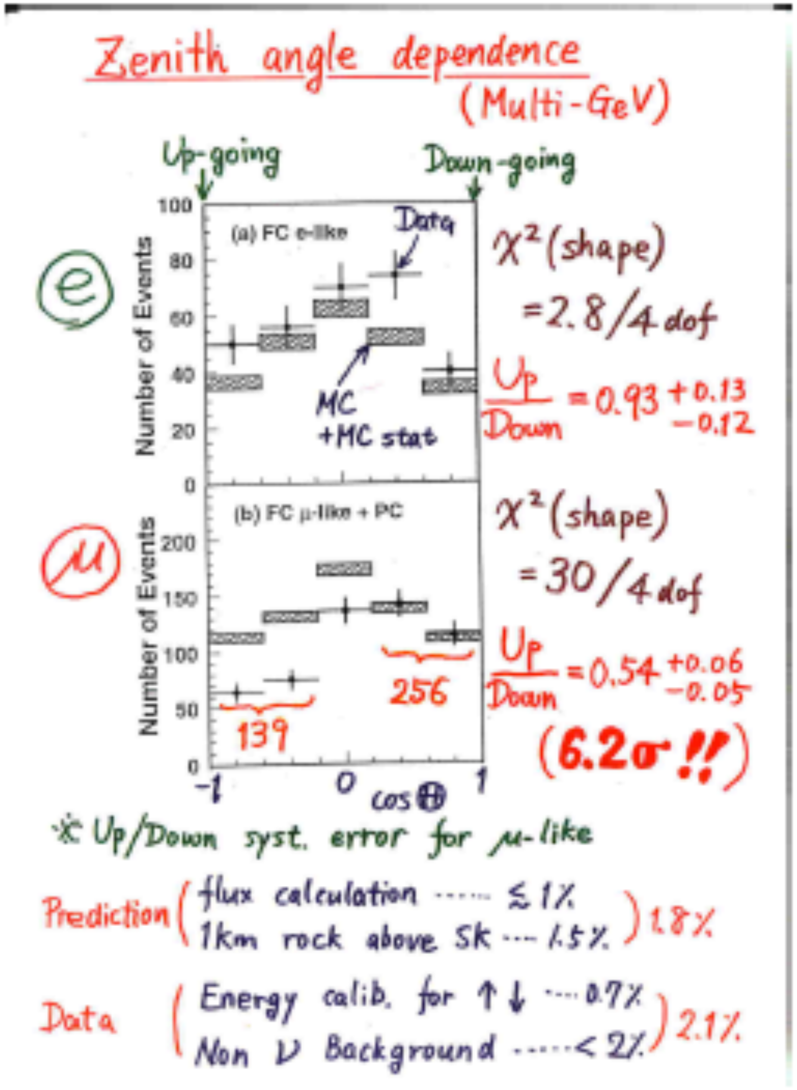
$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2\,(\mathrm{eV}^2)\,L\,(\mathrm{km})}{E\,(\mathrm{GeV})}\right)$$

Broad features of atmospheric neutrino data explained

- Electron neutrinos match predictions
- High energy ν_μ from above: match predictions
- High energy ν_μ through the earth: partially lost
- Low energy ν_μ: lost even when coming from above, loss while passing through the Earth even greater

Solution to the Atmospheric Neutrino Anomaly

- Indeed more ν_μ travelling through the Earth are lost
- The zenith angle dependence fits the form of the probability expressions exactly
- Neutrino oscillation hypothesis proved !



Zenith angle dependence (Multi-GeV)

χ^2(shape) $= 2.8/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.93^{+0.13}_{-0.12}$

χ^2(shape) $= 30/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.54^{+0.06}_{-0.05}$

(6.2σ !!)

※ Up/Down syst. error for μ-like

Prediction (flux calculation ······ ≲ 1% ; 1km rock above SK ··· 1.5%) 1.8%

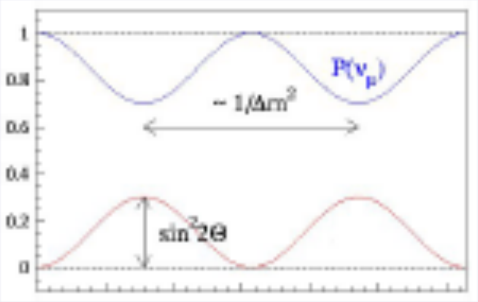
Data (Energy calib. for ↑↓ ···· 0.7% ; Non ν Background ····· < 2%) 2.1%

Solution to the Atmospheric Neutrino Anomaly

Prerequisites

- Neutrino flavours mix with each other
- Neutrinos have different masses
- ν_e do not participate in the oscillations

Neutrino oscillations: ν_μ oscillate into ν_τ



$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$\Delta m^2 \equiv m_2^2 - m_1^2$$

- Measurements can determine $\sin 2\theta_{\rm atm}$ and $\Delta m^2_{\rm atm}$.

The Breakthrough Idea

Бруно Понтекорво

Bruno Pontecorvo

Original idea with $\nu - \bar{\nu}$ mixing

Maybe the neutrino flavours change !

- All the experiments are looking for ν_e
- What if ν_e are getting converted to other flavours of neutrinos (ν_μ or ν_τ) ?
- This is possible, but only if the neutrinos have different masses and they mix !

Neutrino Flavor Changes Inside the Sun

John Bahcall

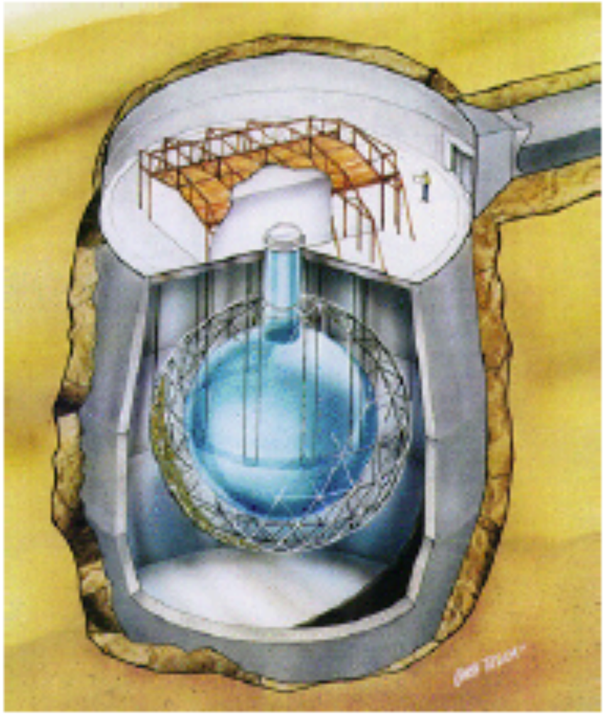
Lincoln Wolfenstein

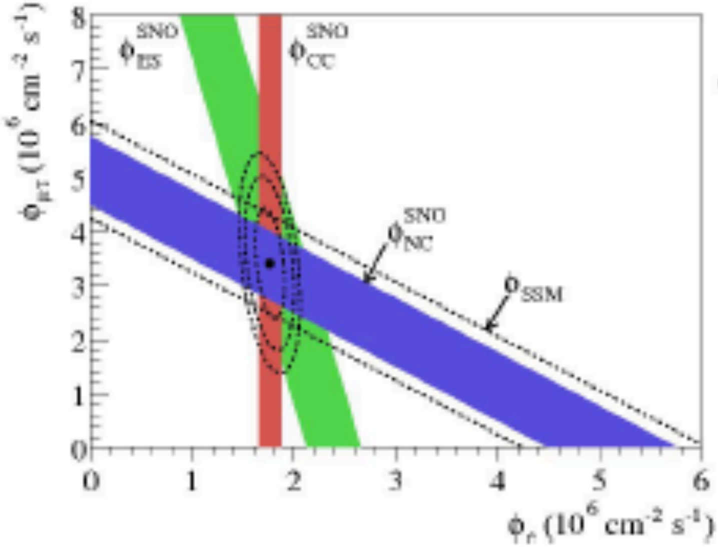
Stanislav Mikheyev

Alexei Smirnov

- **Bahcall:** Calculated the neutrino production inside the Sun in detail
- **Wolfenstein:** Showed that the neutrino mixing gets affected by the matter inside the Sun
- **Mikheyev – Smirnov:** Showed how these matter effects affect the neutrino flavour changes

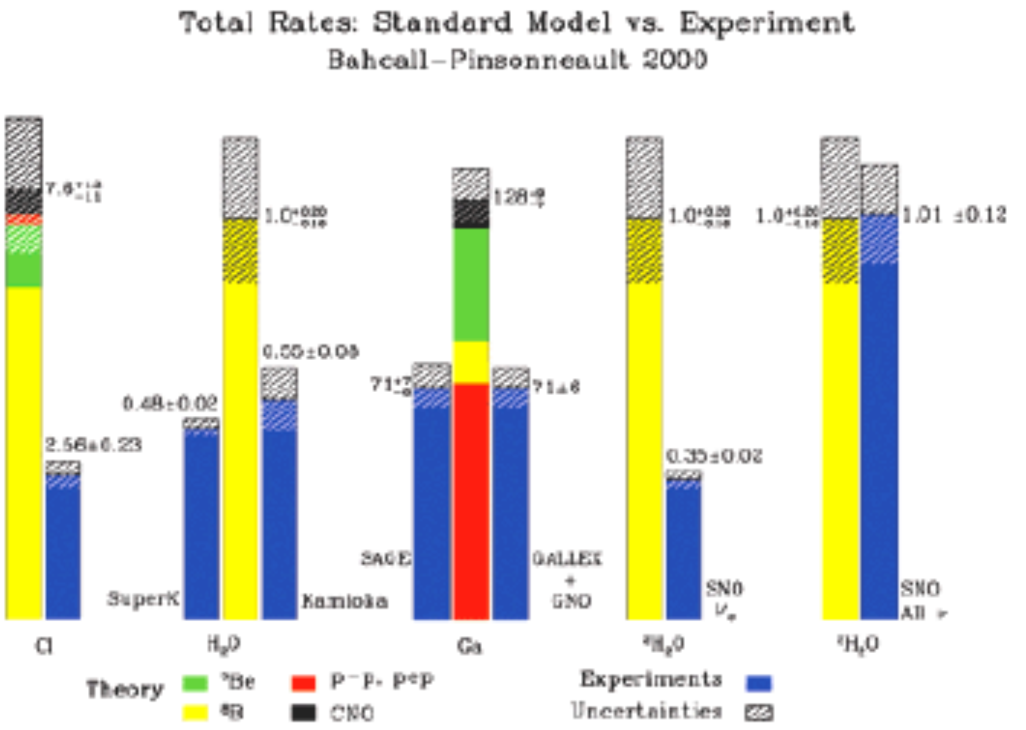
Heavy water Cherenkov experiment: SNO





- **Heavy water Cherenkov**
- $\nu_e \, D \to p \, p \, e^-$
  sensitive to Φ_e
- $\nu_{e,\mu,\tau} \, e^- \to \nu_{e,\mu,\tau} \, e^-$
  Sensitive to $\Phi_e + \Phi_{\mu\tau}/6$
- $\nu_{e,\mu,\tau} \, D \to n \, p \, \nu_{e,\mu,\tau}$
  sensitive to $\Phi_e + \Phi_{\mu\tau}$
- Neutral current: no effect of oscillations

Solar neutrino problem solved (2002)



- All neutrinos from the Sun are now accounted for !
- Our understanding of the Sun is vindicated...

Solution of solar neutrino problem

- ν_e mixes with ν_μ/ν_τ
- Survival probability is almost flat:
  no oscillations observable but “flavour conversions”
- The measurements can determine $\sin^2\theta_\odot$
- To determine $\Delta m^2_\odot$ accurately, have to conduct terrestrial experiments (using reactors)

Solar Neutrino Solution (MeV): Current Status

- Solution through “neutrino oscillations in matter”:
  - Neutrinos have different masses, ν_e mixes with others
  - The matter inside the Sun plays a major role in determining how many ν_e survive.

- Survival probability of electron neutrinos:

$$\boxed{P(\nu_e \to \nu_e) \approx P_f \cos^2\theta_\odot + (1 - P_f)\sin^2\theta_\odot}$$

P_f: “flip probability” at level crossing (Landau-Zener)

- Can measure $\Delta m^2_\odot$ and $\theta_\odot$:
  - Observed: $\Delta m^2_\odot \approx 8 \times 10^{-5}\,\mathrm{eV}^2$, $\theta_\odot \approx 30^\circ$
  - Parameters confirmed by reactor neutrino experiments (KamLand)

Atmospheric Neutrino Solution (GeV): Current Status

- Solution through (mainly) vacuum oscillations:
  - ν_μ convert predominantly to ν_τ
  - More accurate experiments needed to detect Earth matter effects
- Survival probability of ν_μ :

$$\boxed{P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E}\right)}$$

- Can measure $\Delta m^2_{\rm atm}$ and $\theta_{\rm atm}$:
  - $\Delta m^2_{\rm atm} \approx 2.4 \times 10^{-3}$ eV^2, Mixing angle $\theta_{\rm atm} \approx 45^\circ$
  - Confirmed by "short baseline" experiments (K2K, MINOS, T2K)

Neutrino Oscillations in 3 Flavors

$c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

θ_{23} : $P(\nu_\mu \rightarrow \nu_\mu)$ by
Atoms. ν and ν beam

θ_{13}: $P(\nu_e \rightarrow \nu_e)$ by Reactor ν
θ_{13} & δ: $P(\nu_\mu \rightarrow \nu_e)$ by ν beam

θ_{12} : $P(\nu_e \rightarrow \nu_e)$ by
Reactor and solar ν

Three mixing angles: θ_{23} , θ_{13} , θ_{12} and one CP violating (Dirac) phase δ_{CP}

$$\tan^2\theta_{12} \equiv \frac{|U_{e2}|^2}{|U_{e1}|^2}; \qquad \tan^2\theta_{23} \equiv \frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2}; \qquad U_{e3} \equiv \sin\theta_{13}e^{-i\delta}$$

3 mixing angles simply related to flavor components of 3 mass eigenstates

Over a distance L, changes in the relative phases of the mass states may induce flavor change

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}[U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}]\sin^2\Delta_{ij} - 2\sum_{i>j} \mathrm{Im}[U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}]\sin 2\Delta_{ij}$$

$$\Delta_{ij} = \Delta m^2_{ij}L/4E_\nu$$

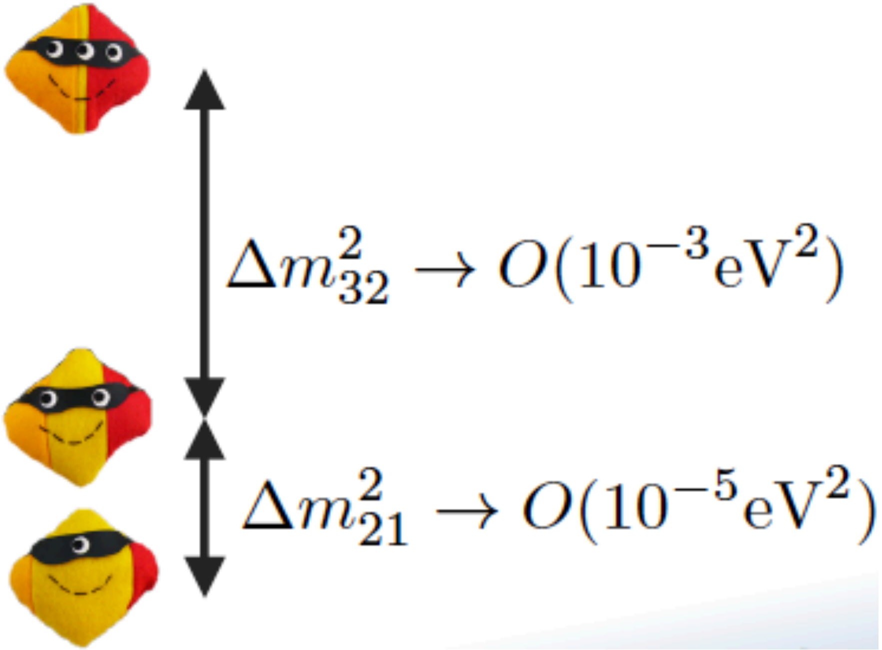
$$\Delta m^2_{ij} = m^2_i - m^2_j$$

2 independent mass splittings Δm^2_{21} and Δm^2_{32}, for anti-neutrinos replace δ_{CP} by -δ_{CP}

Three-Flavor Neutrino Oscillations

$$= R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12})$$

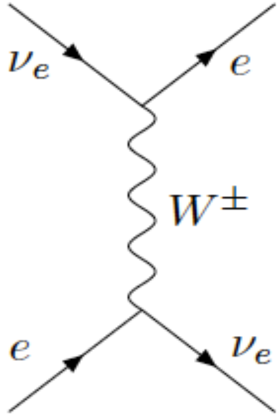
- Oscillations among the three neutrino flavors depend on:
  - The mixing matrix
    - $\theta_{23}, \theta_{13}, \delta_{CP}, \theta_{12}$
  - The mass differences
    - $\Delta m^2{}_{32}, \Delta m^2{}_{21}$



$\Delta m^2_{32} \to O(10^{-3}\mathrm{eV}^2)$

$\Delta m^2_{21} \to O(10^{-5}\mathrm{eV}^2)$

Neutrino Oscillations in Matter



Neutrino propagation through matter modify the oscillations significantly

Coherent forward elastic scattering of neutrinos with matter particles

Charged current interaction of ν_e with electrons creates an extra potential for ν_e

MSW matter term: $\boxed{A = \pm 2\sqrt{2} G_F N_e E}$ or $\boxed{A(\mathrm{eV}^2) = 0.76 \times 10^{-4} \rho\ (\mathrm{g/cc}) E(\mathrm{GeV})}$

N_e = electron number density , + (-) for neutrinos (anti-neutrinos) , ρ = matter density in Earth

Matter term changes sign when we switch from neutrino mode to anti-neutrino mode

$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq 0$ → ***even if $\delta_{CP} = 0$, causes fake CP asymmetry***

Matter term modifies oscillation probability differently depending on the sign of Δm^2

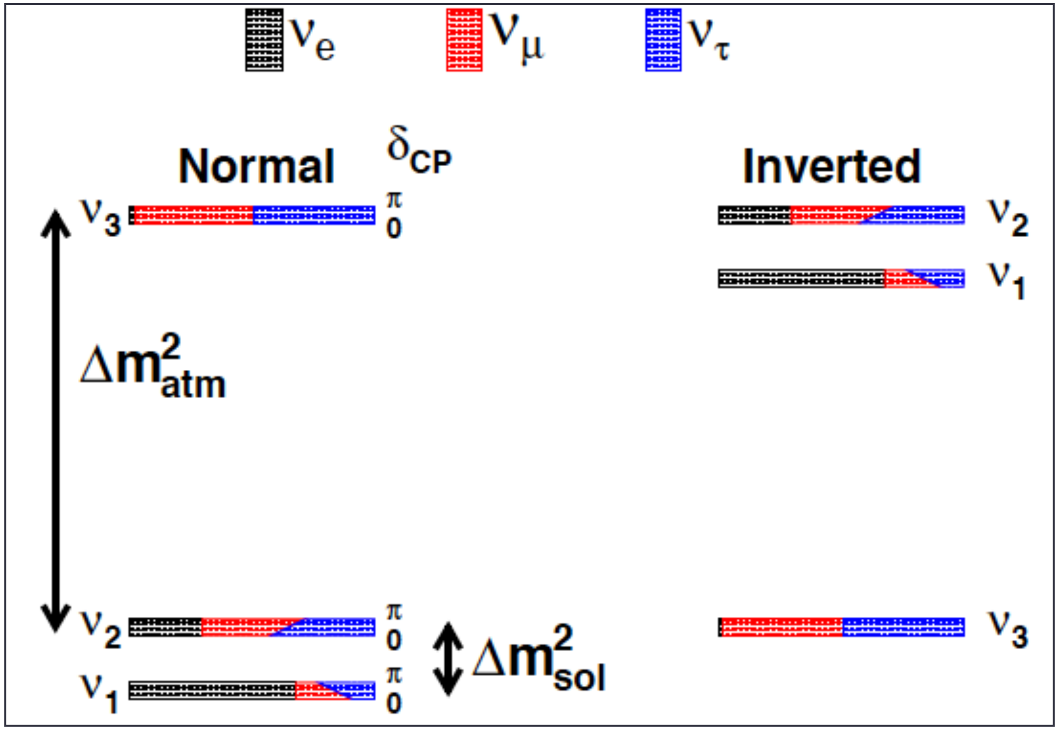
$\Delta m^2 \simeq A \quad \Leftrightarrow \quad E_{\mathrm{res}}^{\mathrm{Earth}} = 6 - 8\,\mathrm{GeV}$ → ***Resonant conversion – Matter effect***

	ν	$\bar{\nu}$
$\Delta m^2 > 0$	MSW	-
$\Delta m^2 < 0$	-	MSW

→ ***Resonance occurs for neutrinos (anti-neutrinos) if Δm^2 is positive (negative)***

Neutrino Mass Hierarchy: Important Open Question

- The sign of Δm^2_{31} $(m^2_3 - m^2_1)$ is not known



$$\boxed{|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2}$$

ν_e component of ν_1 > ν_e component of ν_2 > ν_e component of ν_3

Neutrino mass spectrum can be normal or inverted hierarchical

We only have a lower bound on the mass of the heaviest neutrino

$$\boxed{\sqrt{2.5 \cdot 10^{-3}\text{eV}^2} \sim 0.05 \text{ eV}}$$

We currently do not know which neutrino is the heaviest

Mass Hierarchy Discrimination : A Binary yes-or-no type question

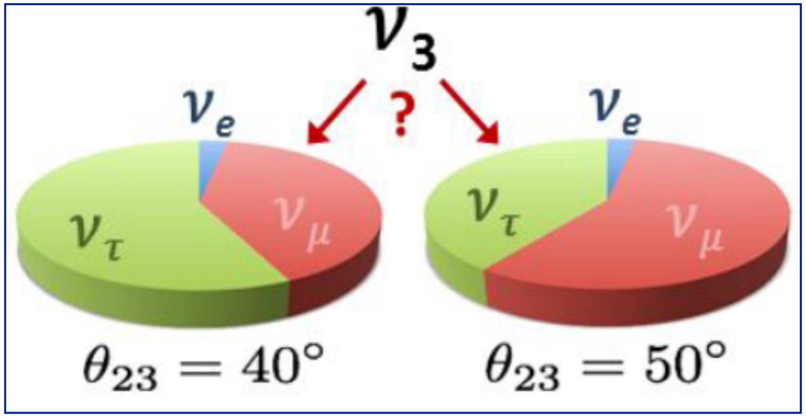
Octant of 2-3 Mixing Angle: Important Open Question

→ *In ν_μ survival probability, the dominant term is mainly sensitive to $\sin^2 2\theta_{23}$*

→ *If $\sin^2 2\theta_{23}$ differs from 1 (recent hints), we get two solutions for θ_{23}*

→ *One in lower octant (LO: $\theta_{23} < 45$ degree)*

→ *Other in higher octant (HO: $\theta_{23} > 45$ degree)*



Octant ambiguity of θ_{23}

Fogli and Lisi, hep-ph/9604415

ν_μ to ν_e oscillation channel can break this degeneracy
preferred value would depend on the choice of neutrino mass hierarchy

Leptonic CP-violation: Important Open Question

Is CP violated in the neutrino sector, as in the quark sector?

Mixing can cause CPV in ν sector, provided $\delta_{CP} \neq 0°$ *and* $180°$

Need to measure the CP-odd asymmetries:

$$\Delta P_{\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta;\, L) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta;\, L) \quad (\alpha \neq \beta)$$

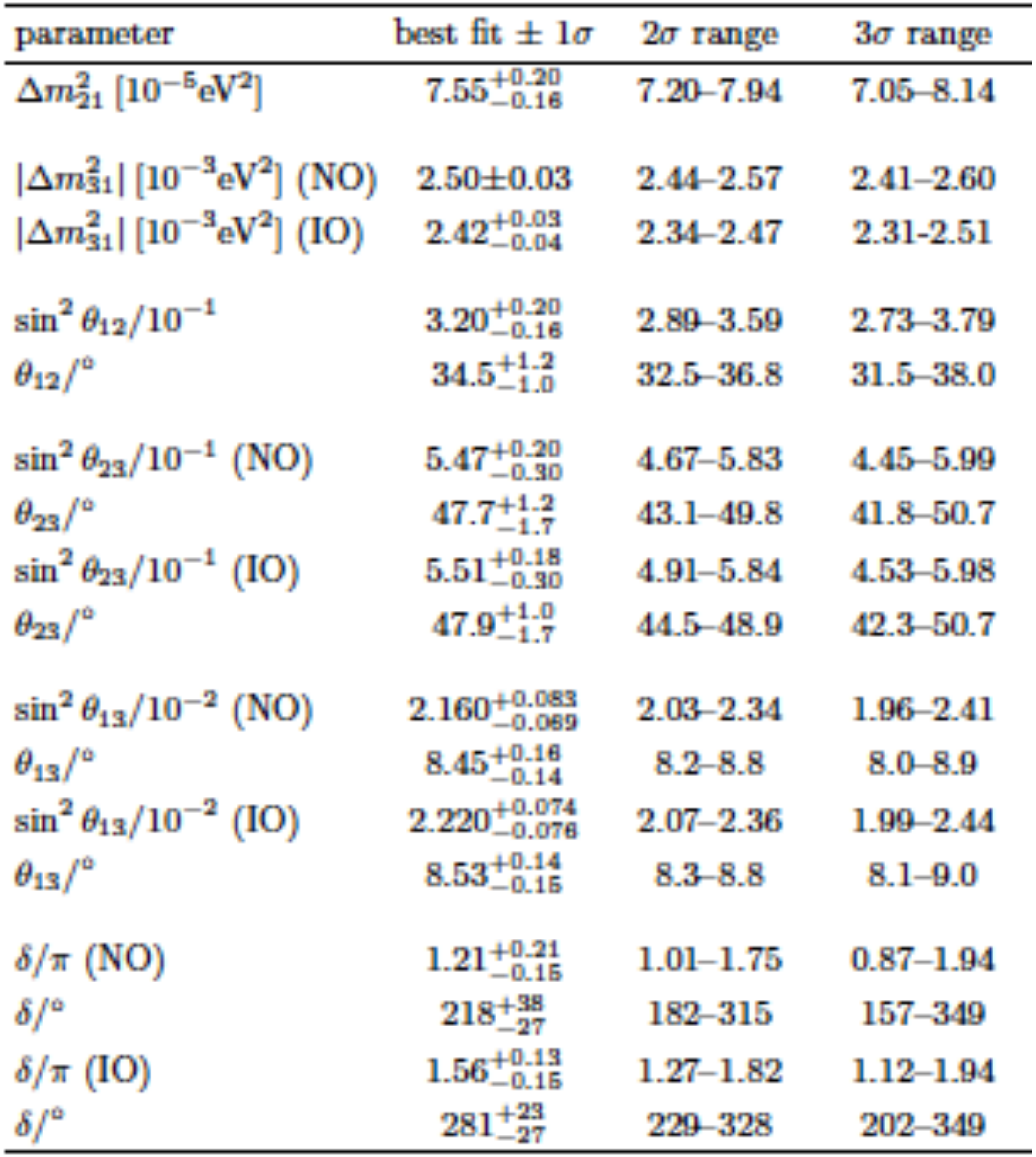
$$\Delta P_{e\mu} = \Delta P_{\mu\tau} = \Delta P_{\tau e} = 4J_{CP} \times \left[\sin\left(\frac{\Delta m^2_{21}}{2E}L\right) + \sin\left(\frac{\Delta m^2_{32}}{2E}L\right) + \sin\left(\frac{\Delta m^2_{13}}{2E}L\right)\right]$$

Jarlskog CP-odd Invariant → $J_{CP} = \frac{1}{8}\cos\theta_{13}\,\sin 2\theta_{13}\,\sin 2\theta_{23}\,\sin 2\theta_{12}\,\sin\delta_{CP}$

Three-flavor effects are key for CPV, need to observe interference

Conditions for observing CPV: *1) Non-degenerate masses* ✔
2) Mixing angles $\neq 0°$ *and* $90°$ ✔
3) $\delta_{CP} \neq 0°$ *and* $180°$ *(Hints)*

Present Status of Oscillation Parameters



parameter	best fit ± 1σ	2σ range	3σ range
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.55^{+0.20}_{-0.16}$	7.20–7.94	7.05–8.14
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (NO)	2.50 ± 0.03	2.44–2.57	2.41–2.60
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (IO)	$2.42^{+0.03}_{-0.04}$	2.34–2.47	2.31-2.51
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.89–3.59	2.73–3.79
$\theta_{12}/^\circ$	$34.5^{+1.2}_{-1.0}$	32.5–36.8	31.5–38.0
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.67–5.83	4.45–5.99
$\theta_{23}/^\circ$	$47.7^{+1.2}_{-1.7}$	43.1–49.8	41.8–50.7
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.91–5.84	4.53–5.98
$\theta_{23}/^\circ$	$47.9^{+1.0}_{-1.7}$	44.5–48.9	42.3–50.7
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	2.03–2.34	1.96–2.41
$\theta_{13}/^\circ$	$8.45^{+0.16}_{-0.14}$	8.2–8.8	8.0–8.9
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	2.07–2.36	1.99–2.44
$\theta_{13}/^\circ$	$8.53^{+0.14}_{-0.15}$	8.3–8.8	8.1–9.0
δ/π (NO)	$1.21^{+0.21}_{-0.15}$	1.01–1.75	0.87–1.94
$\delta/^\circ$	218^{+38}_{-27}	182–315	157–349
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.27–1.82	1.12–1.94
$\delta/^\circ$	281^{+23}_{-27}	229–328	202–349

Salas, Forero, Ternes, Tortola, Valle, arXiv:1708.01186v2 [hep-ph]

Relative 1σ Precision

2.4%

1.4%

5.5%

4.7%

4.4%

3.5%

--

Note: IO ranges: calculated w.r.t. local minimum

Quark Mixing vs. Neutrino Mixing

$$V_{\rm CKM} = \begin{pmatrix} 0.97434^{+0.00011}_{-0.00012} & 0.22506 \pm 0.00050 & 0.00357 \pm 0.00015 \\ 0.22492 \pm 0.00050 & 0.97351 \pm 0.00013 & 0.0411 \pm 0.0013 \\ 0.00875^{+0.00032}_{-0.00033} & 0.0403 \pm 0.0013 & 0.99915 \pm 0.00005 \end{pmatrix}$$

PDG 2016

$$|U|_{3\sigma} = \begin{pmatrix} 0.799 \to 0.844 & 0.516 \to 0.582 & 0.140 \to 0.156 \\ 0.234 \to 0.502 & 0.452 \to 0.688 & 0.626 \to 0.784 \\ 0.273 \to 0.527 & 0.476 \to 0.705 & 0.604 \to 0.765 \end{pmatrix}$$

(PMNS)

NuFIT 3.1 (2017)

The goal is to achieve the CKM level precision for the PMNS
A Long Journey Ahead! But, the precision is improving rapidly for PMNS

Good News: There may be large CPV in neutrino sector than quark sector

$$J_{CP} = \frac{1}{8} \cos\theta_{13}\, \sin 2\theta_{13}\, \sin 2\theta_{23}\, \sin 2\theta_{12}\, \sin\delta_{CP}$$

$J_{\rm CKM} \sim 3 \times 10^{-5}$, whereas $J_{\rm PMNS}$ can be as large as 3×10^{-2}

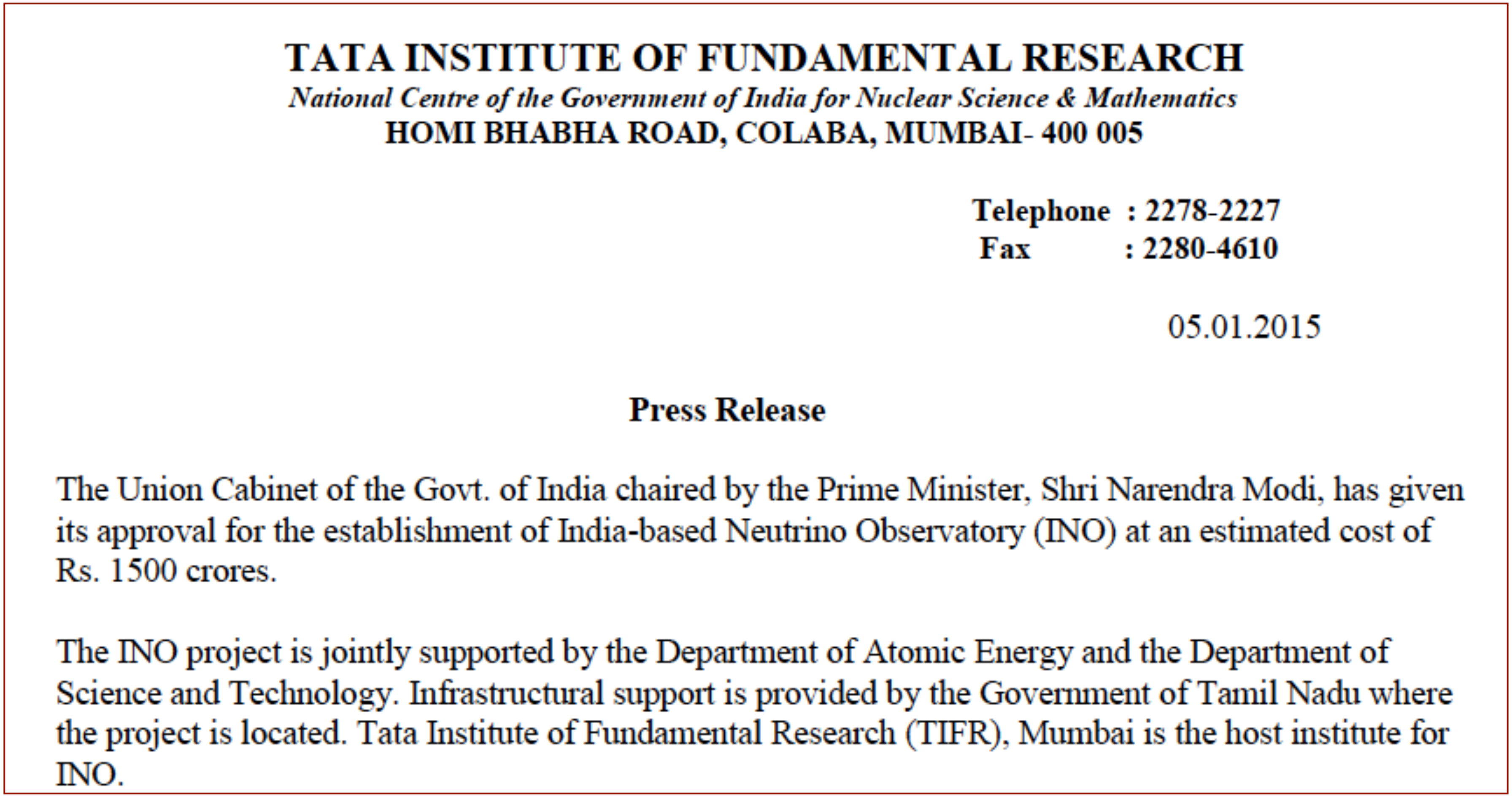
An Indian Initiative to build a world-class underground laboratory to pursue non-accelerator based high energy and nuclear physics research

The initial goal of INO is to study fundamental properties of neutrinos

For more updates visit: http://www.ino.tifr.res.in/ino/

You can join us at: https://www.facebook.com/ino.neutrino

Press Release on INO



TATA INSTITUTE OF FUNDAMENTAL RESEARCH
National Centre of the Government of India for Nuclear Science & Mathematics
HOMI BHABHA ROAD, COLABA, MUMBAI- 400 005

Telephone : 2278-2227
Fax : 2280-4610

05.01.2015

Press Release

The Union Cabinet of the Govt. of India chaired by the Prime Minister, Shri Narendra Modi, has given its approval for the establishment of India-based Neutrino Observatory (INO) at an estimated cost of Rs. 1500 crores.

The INO project is jointly supported by the Department of Atomic Energy and the Department of Science and Technology. Infrastructural support is provided by the Government of Tamil Nadu where the project is located. Tata Institute of Fundamental Research (TIFR), Mumbai is the host institute for INO.

Finally the wait of 15 years is over! But, we have miles to go…

Introducing INO Collaboration

The INO Collaboration

- **INO Collaborating Institutions**

Collaborating Institutions:

- AMU
- BARC
- BHU
- CU
- DU
- HNBGU
- HPU
- HRI
- IGCAR
- IITB
- IITG
- IITM
- IMSc
- IOP
- JU
- KU
- MU
- NBU
- PRL
- PU
- SINP
- SMIT
- SU
- TIFR
- UoH
- VECC

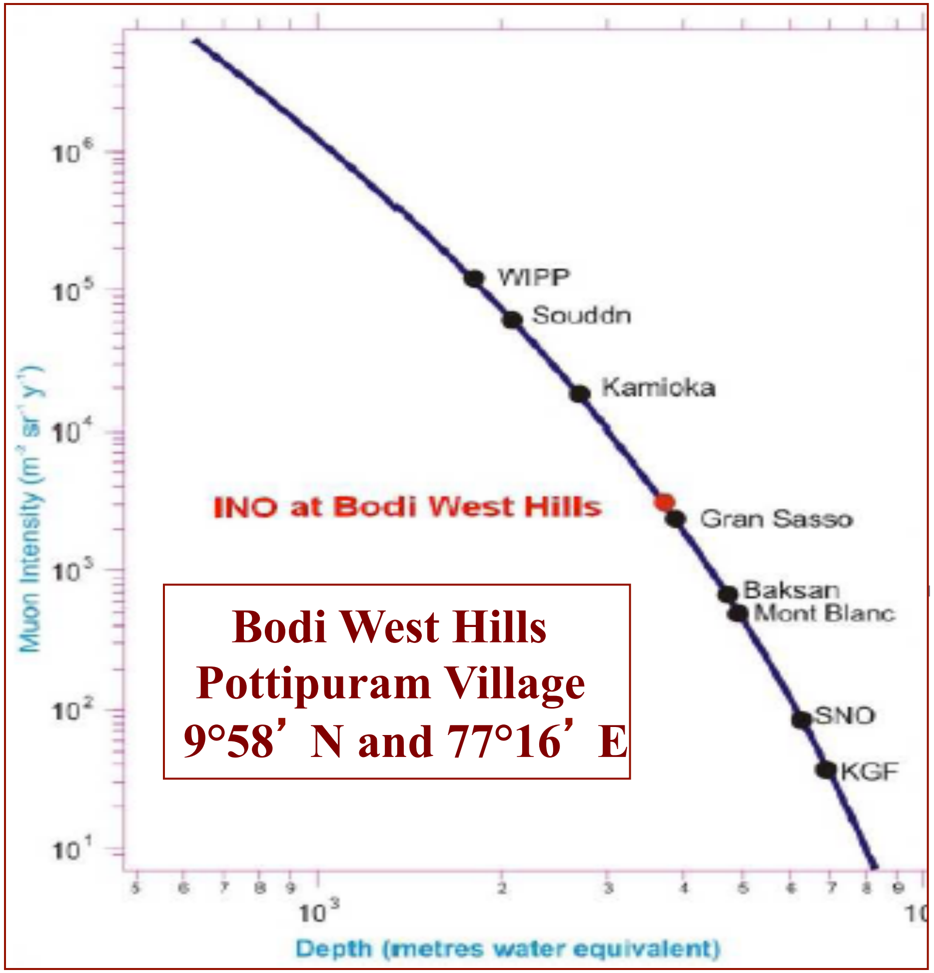
+IISER (Mohali), American College ,
Tezpur Univ, CKU (Gulbarga)

Participants of the INO Collaboration meeting at Madurai Kamaraj University (22-23 March 2018)

~28 institutions (national labs, Universities, IITs) participating

Nearly 100 scientists from 28 research institutes & universities all over India
One of the largest basic science projects in India in terms of man power & cost as well
We are growing day by day!

Coordinates of INO



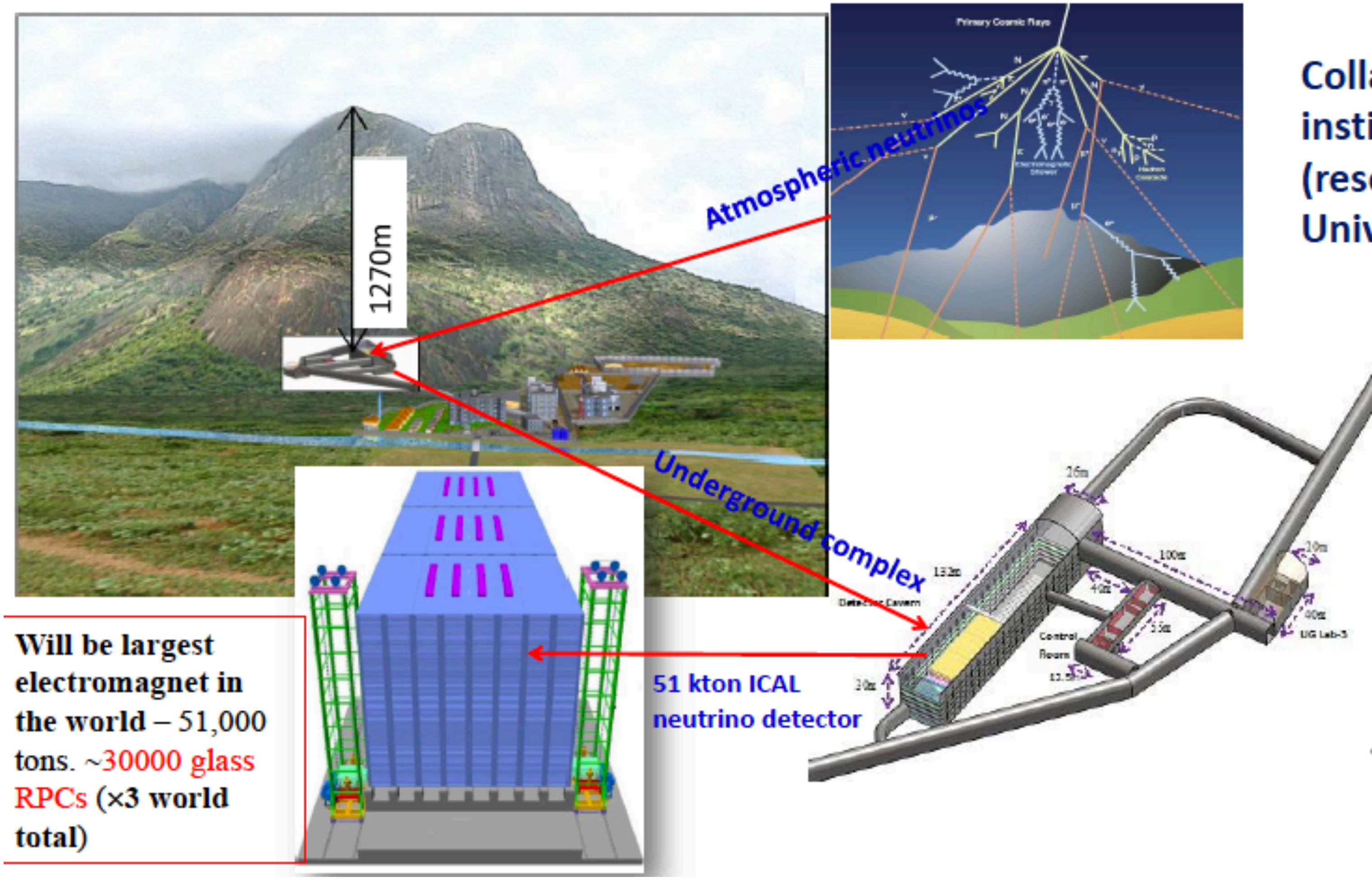
Bodi West Hills
Pottipuram Village
9°58' N and 77°16' E

Located 115 km west of the Madurai city in the Theni district of Tamil Nadu

Madurai has an International Airport

India-based Neutrino Observatory

India based Neutrino Observatory at Pottipuram (Theni)

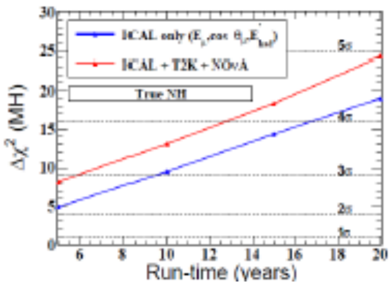


Collaboration of ~28 institutions (research centres, Universities, IITs)

Will be largest electromagnet in the world – 51,000 tons. ~30000 glass RPCs (×3 world total)

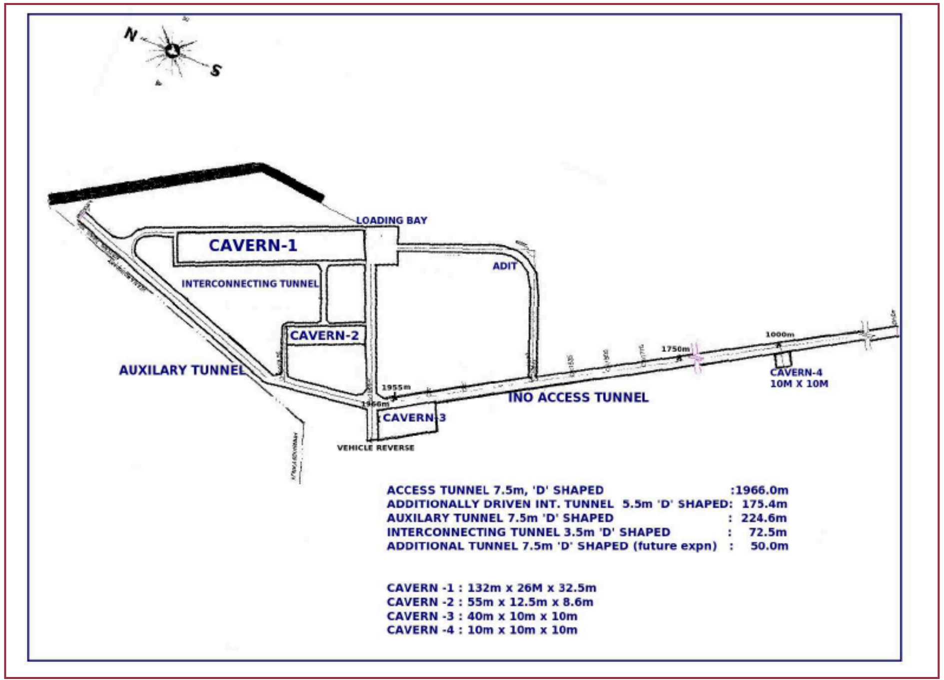
51 kton ICAL neutrino detector

Mass ordering of ν



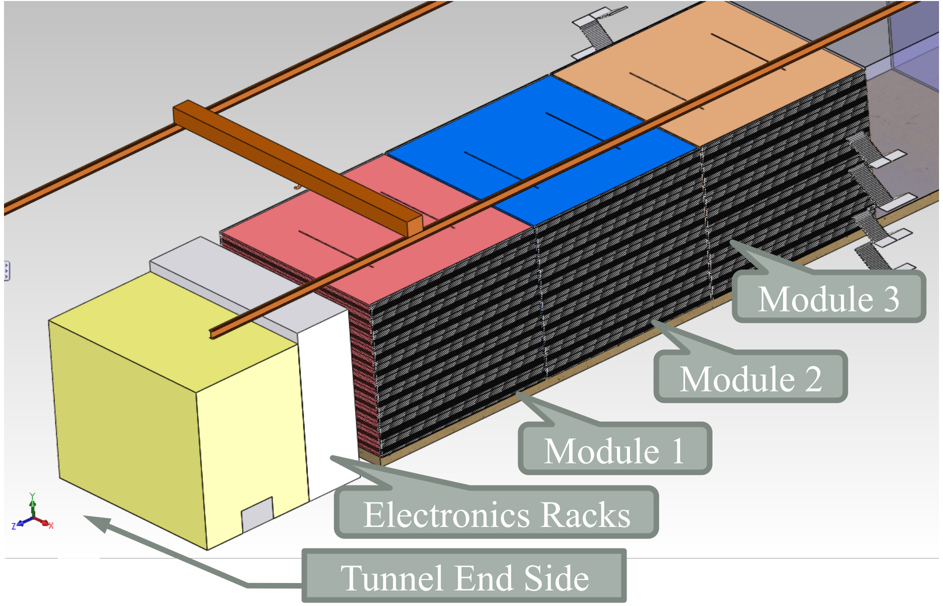
Approved projects under INO

- *Come up with an underground lab & surface facilities near Pottipuram village in Theni district of Tamil Nadu*
- *Build massive 50 kt magnetized Iron calorimeter (ICAL) detector to study properties of neutrinos*
- *Construction of INO centre at Madurai: Inter-Institutional Centre for High Energy Physics (IICHEP)*
- *Human Resource Development (INO Graduate Training Program)*
- *Completely in-house Detector R&D with substantial INO-Industry interface*
- *Time Frame for 1st module: 2022*



ACCESS TUNNEL 7.5m, 'D' SHAPED	:1966.0m
ADDITIONALLY DRIVEN INT. TUNNEL 5.5m 'D' SHAPED:	175.4m
AUXILARY TUNNEL 7.5m 'D' SHAPED	: 224.6m
INTERCONNECTING TUNNEL 3.5m 'D' SHAPED	: 72.5m
ADDITIONAL TUNNEL 7.5m 'D' SHAPED (future expn)	: 50.0m

CAVERN -1 : 132m x 26M x 32.5m
CAVERN -2 : 55m x 12.5m x 8.6m
CAVERN -3 : 40m x 10m x 10m
CAVERN -4 : 10m x 10m x 10m

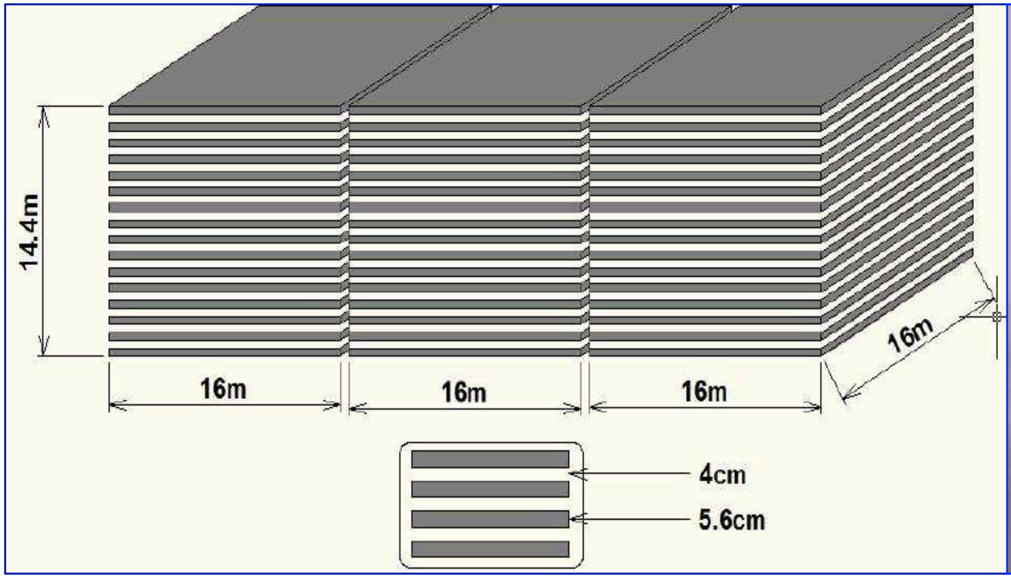


Detector Characteristics

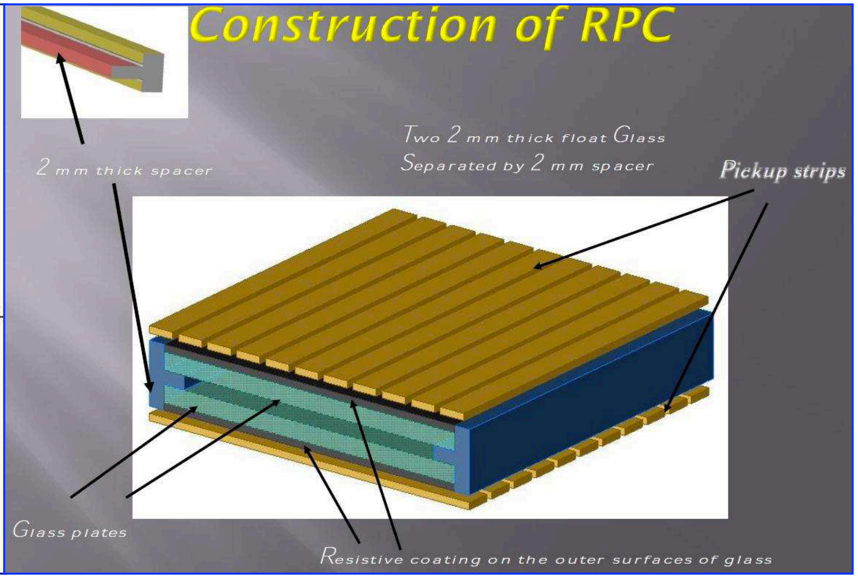
- *Should have large target mass (50 – 100 kt)*
- *Good tracking and Energy resolution (tracking calorimeter)*
- *Good directionality for up/down discrimination (nano-second time resolution)*
- *Charge identification (need to have uniform, homogeneous magnetic field)*
- *Ease of construction & Modularity*
- *Complementary to the other existing and proposed detectors*

Our choice

Magnetized iron (target mass): ICAL



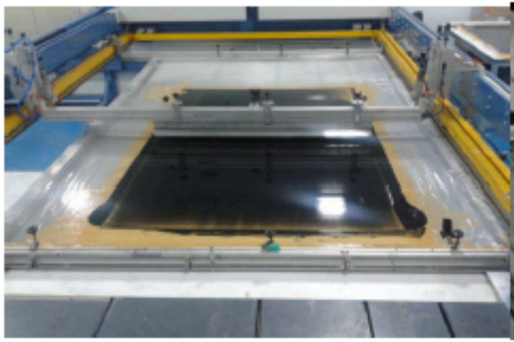
RPC (active detector element)



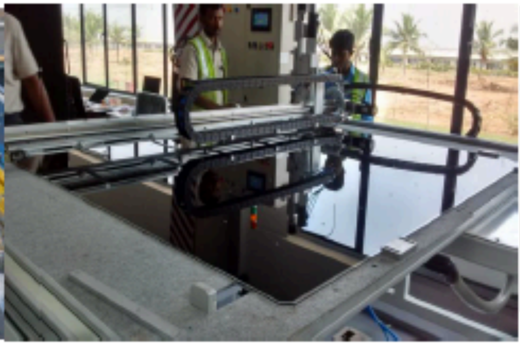
Specifications of the ICAL Detector

No of modules	3
Module dimension	16 m X 16 m X 14.4m
Detector dimension	48.4 m X 16 m X 14.4m
No of layers	150
Iron plate thickness	5.6cm
Gap for RPC trays	4 cm
Magnetic field	1.4 Tesla
RPC unit dimension	195 cm x 184 cm x 2.4 cm
Readout strip width	3 cm
No. of RPCs/Road/Layer	8
No. of Roads/Layer/Module	8
No. of RPC units/Layer	192
Total no of RPC units	28800
No of Electronic channels	$3.7 X 10^6$

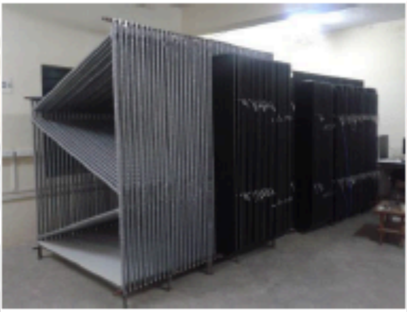
Activities



Screen printing for graphite coating @ St. Gobain, Sriperumbudur)



Gluing spacer buttons with SPM (St. Gobain)



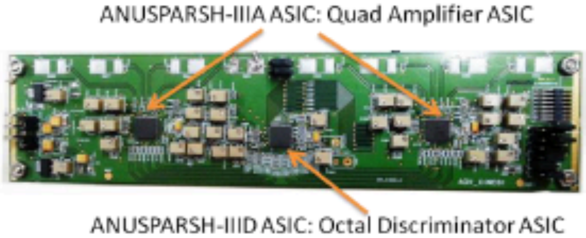
Stand for storing RPCs (IICHEP)

Closed loop gas system

RPC trolley (PCMT, Vellore)

4m×2m steel plates (Essar, Hazira to IICHEP, Madurai) on truck

Inspection of machined steel plate at Essar



Front End RPC, DAQ boards

DC-DC HV supply

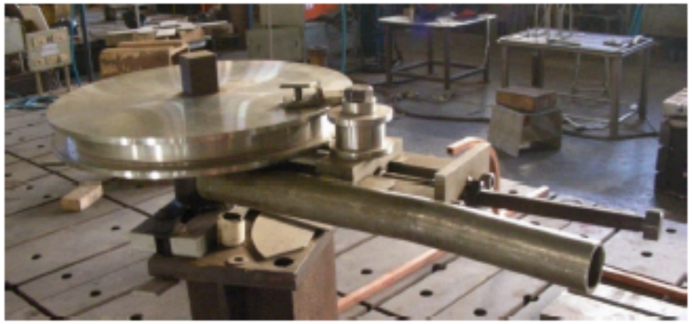
Activities


Plate machining Job


Spacers and Pins


Copper Conductor Spool

Magnet Components (Core & Coil)


Conductor bending machine


Conductor straightening machine


Coil fabrication

Activities

More pictures of mini-ICAL assembly .....

Activities

Gantry Crane for plate handling

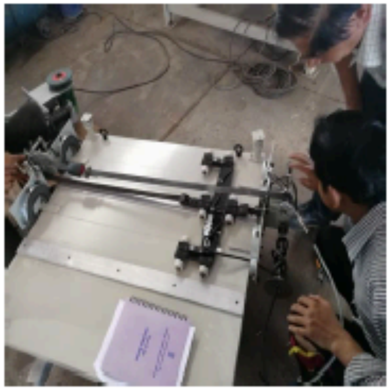
Associated systems

Induction brazing machine

Induction brazing in progress

Brazing joint pressure test

RPC Gap measurement system



Mock-up test set-up

Activities

Magnet assembly in progress

Spacer, Al guide & G-10 bracket

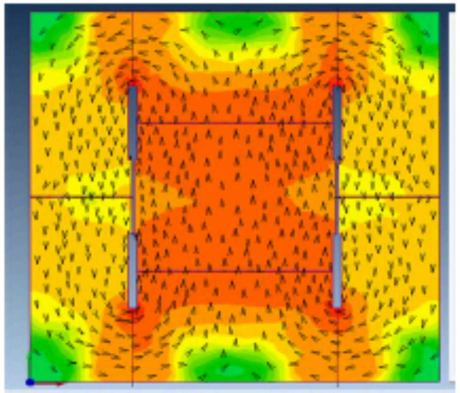
Layers in assembly

Coil Brazing

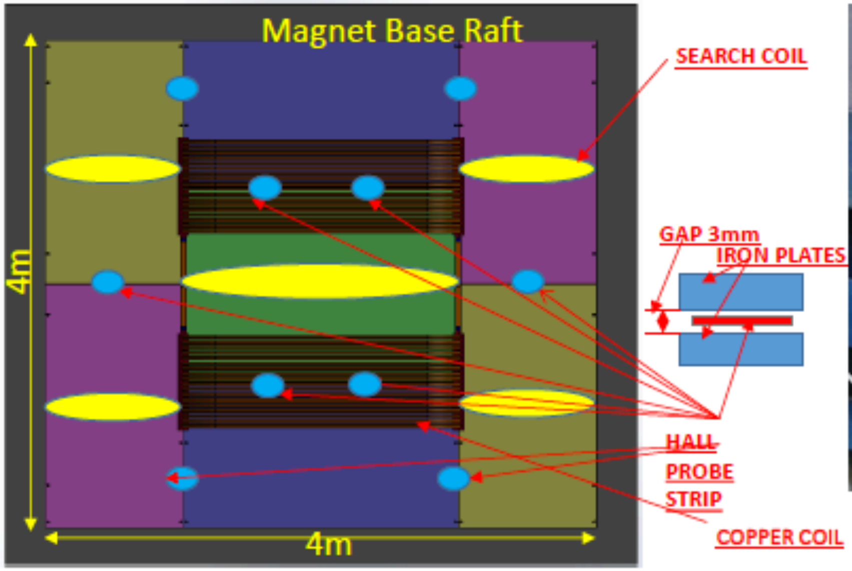
Coil hydrostatic pressure test

Low conductivity water cooling system for magnet & power supply

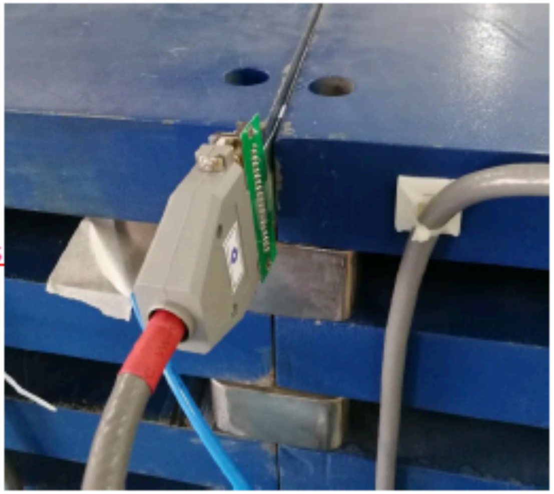
Activities



Field map at 26kAT



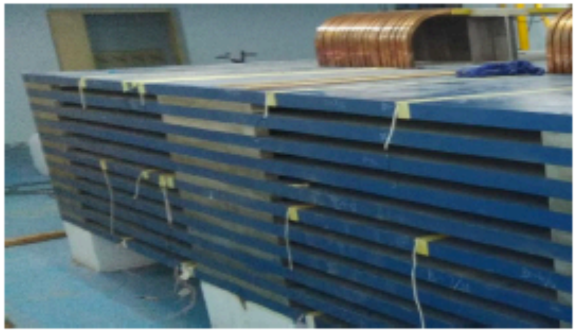
Magnetic measurement system
(1^{st}, 6^{th}, 11^{th} layer)



Hall probe PCB in the gap

Magnet power supply
30V DC, 1200 AMP

Hall probe PCB strip



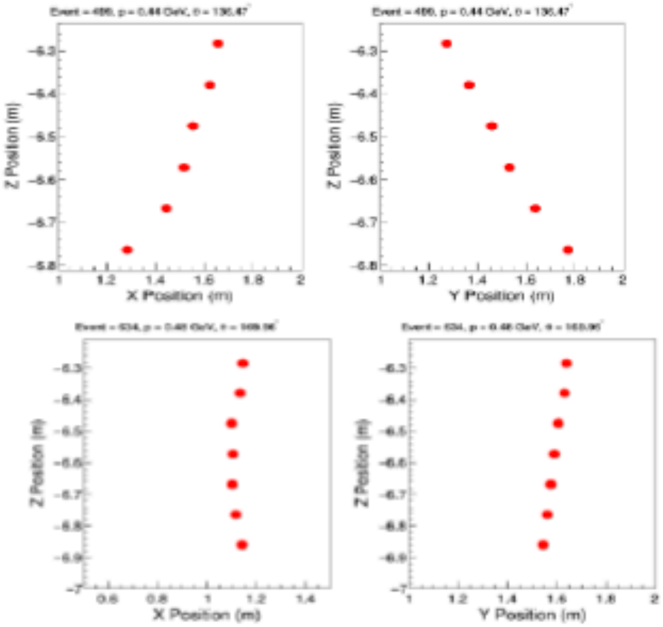
Search coils for flux measurement

Activities

mini-ICAL assembly

Mini-ICAL at IICHEP, Madurai

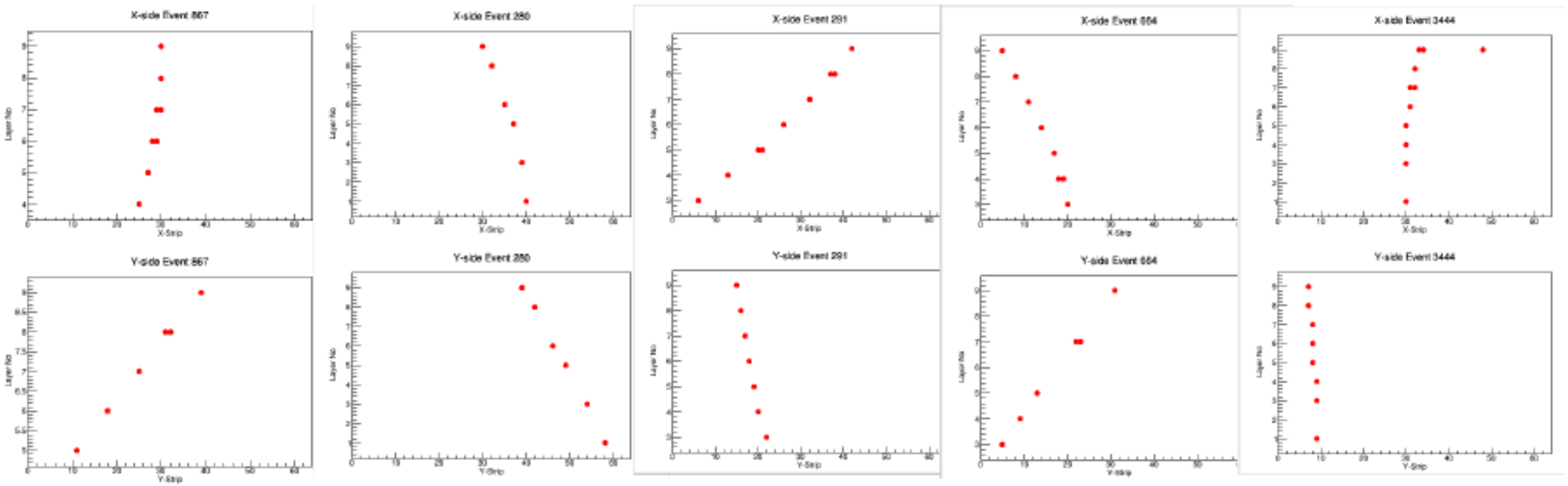
85 ton mini-ICAL detector measuring natural cosmic muons using 10nos. 2m×2m Resistive Plate Chambers with glass gaps made is St. Gobain, Sriperumbudur.



Muon tracks in mini-ICAL detector. Opposite curvatures in bending (X-) plane due to opposite electric charges of down-going muons.

Mini-ICAL at IICHEP, Madurai

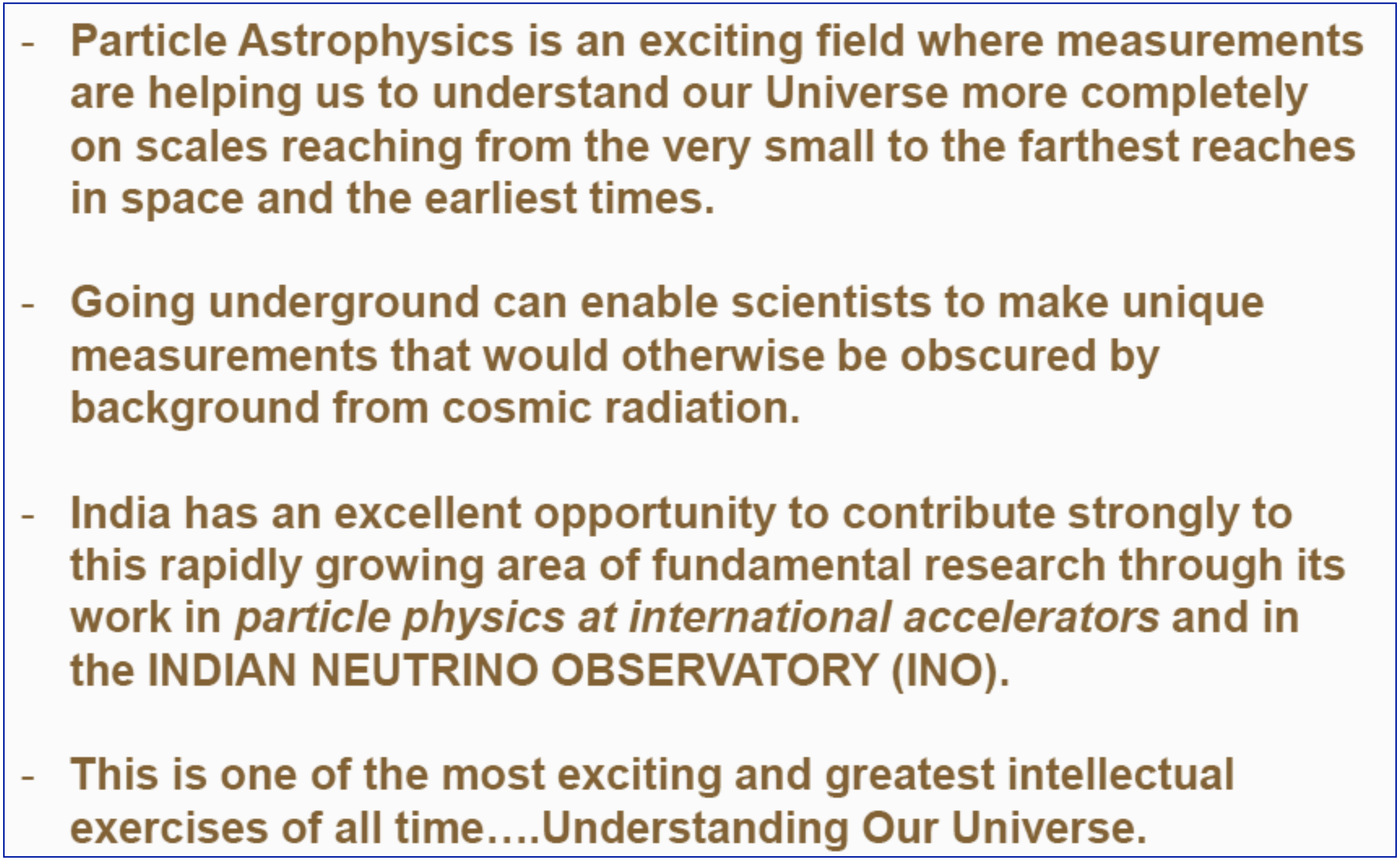
I = 900 A $\Rightarrow$ B ~ 1.4 Tesla



Human Resource Development and Training

- INO Graduate Training Program started in August 2008, students are affiliated to HBNI
- At present students being trained for 1 year at TIFR in both experimental techniques & theory
- After completion of coursework, attached to Ph.D. guides at various collaborating institutions
- Many short/long term visits to RPC labs (Mumbai & Kolkata) of students & faculties from Universities in last several years
- Several students from 1st batch (2008) and 2nd batch (2009) are already working as post-docs at different places
- 39 graduate students have completed their Ph.D. so far under the INO Collaboration

Concluding Remarks from Prof. Art McDonald



- Particle Astrophysics is an exciting field where measurements are helping us to understand our Universe more completely on scales reaching from the very small to the farthest reaches in space and the earliest times.

- Going underground can enable scientists to make unique measurements that would otherwise be obscured by background from cosmic radiation.

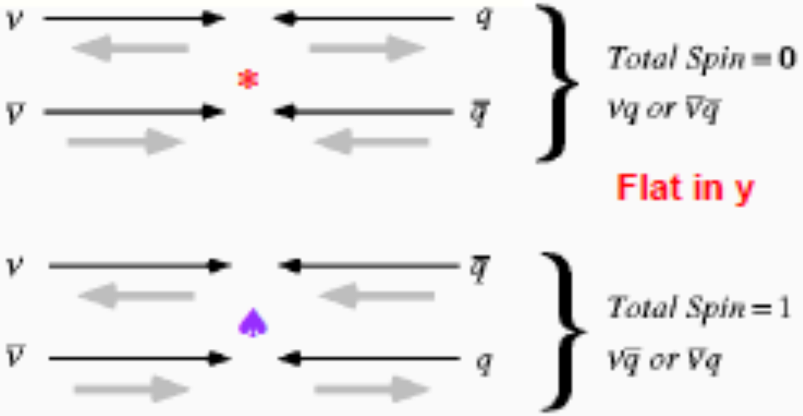
- India has an excellent opportunity to contribute strongly to this rapidly growing area of fundamental research through its work in *particle physics at international accelerators* and in the INDIAN NEUTRINO OBSERVATORY (INO).

- This is one of the most exciting and greatest intellectual exercises of all time….Understanding Our Universe.

Concluding Remarks from Prof. Art McDonald at the 103rd Indian Science Congress meeting, University of Mysore, January 3, 2016

Backup Slides

Chirality, Charge in CC ν-q Scattering



Flat in y

$1/4(1+\cos\theta^*)^2 = (1-y)^2$

$\int(1-y)^2dy=1/3$

- Total spin determines inelasticity distribution
    - Familiar from neutrino-electron scattering

point-like scattering
mplies linear with energy

$$\frac{d\sigma^{\nu p}}{dxdy}=\frac{G_F^2 s}{\pi}\left(x\overset{*}{d}(x)+x\overset{\spadesuit}{\bar{u}}(x)(1-y)^2\right)$$

$$\frac{d\sigma^{\bar{\nu} p}}{dxdy}=\frac{G_F^2 s}{\pi}\left(x\overset{*}{\bar{d}}(x)+x\overset{\spadesuit}{u}(x)(1-y)^2\right)$$

but what is this "q(x)"?

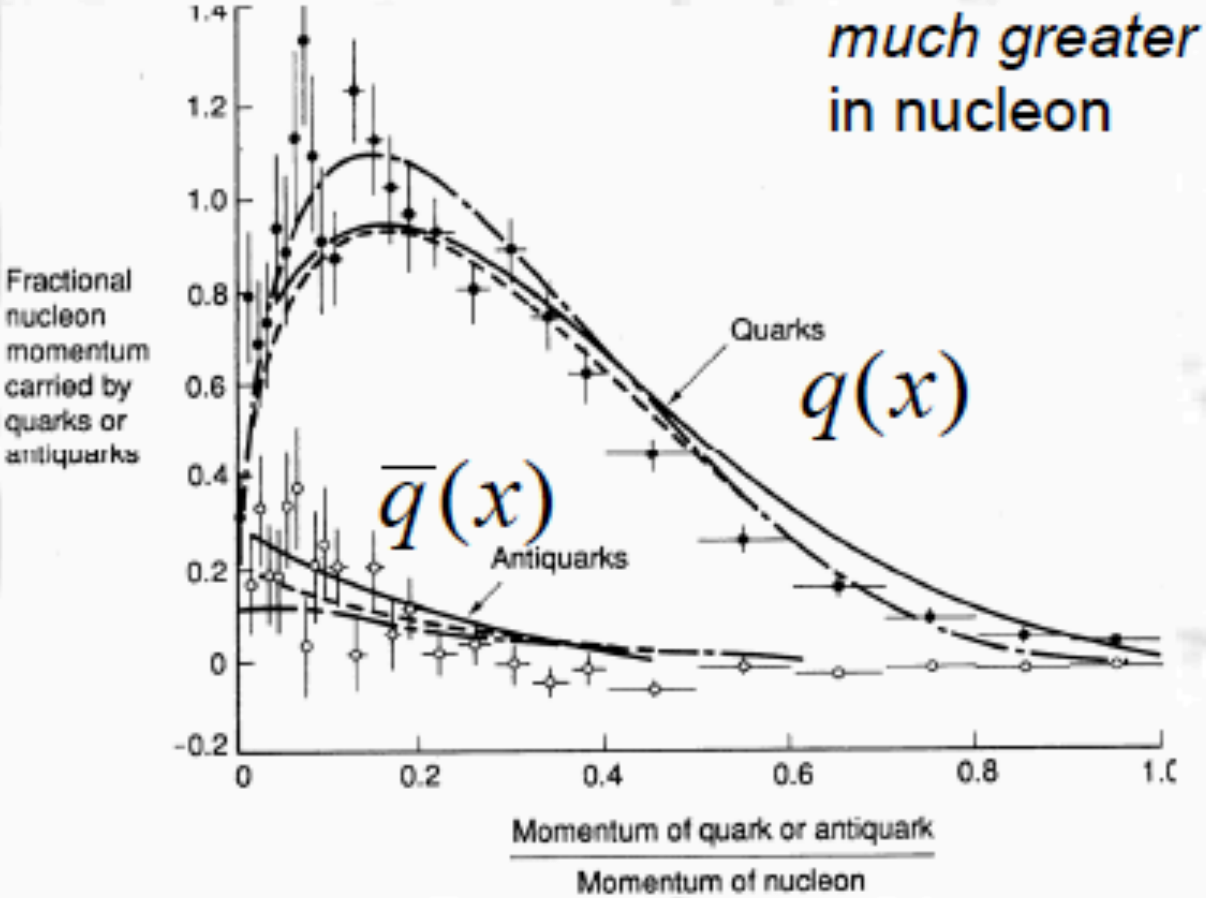
- Neutrino/Anti-neutrino CC each produce particular Δq in scattering

$$\nu d \to \mu^- u$$

$$\bar{\nu} u \to \mu^+ d$$

Momentum of Quarks & Antiquarks

- Momentum carried by quarks *much greater* than anti-quarks in nucleon



y distribution in Neutrino CC DIS

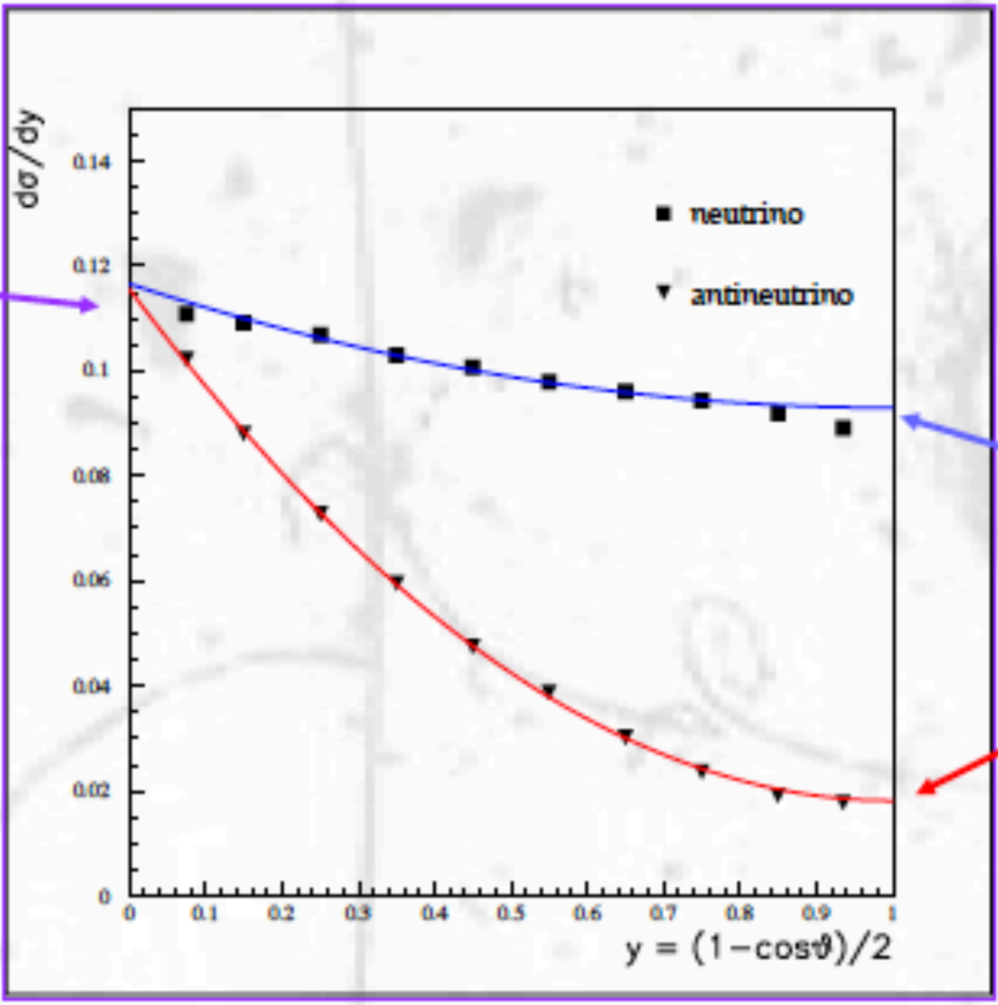
$$\frac{d\sigma(\nu q)}{dxdy} = \frac{d\sigma(\bar{\nu}\bar{q})}{dxdy} \propto 1$$

$$\frac{d\sigma(\nu \bar{q})}{dxdy} = \frac{d\sigma(\bar{\nu} q)}{dxdy} \propto (1-y)^2$$

y=0:

Quarks & anti-quarks

Neutrino and anti-neutrino identical



y=1:

Neutrinos see only quarks.

Anti-neutrinos see only anti-quarks

$$\sigma^{\bar{\nu}} \approx \tfrac{1}{2}\sigma^{\nu}$$

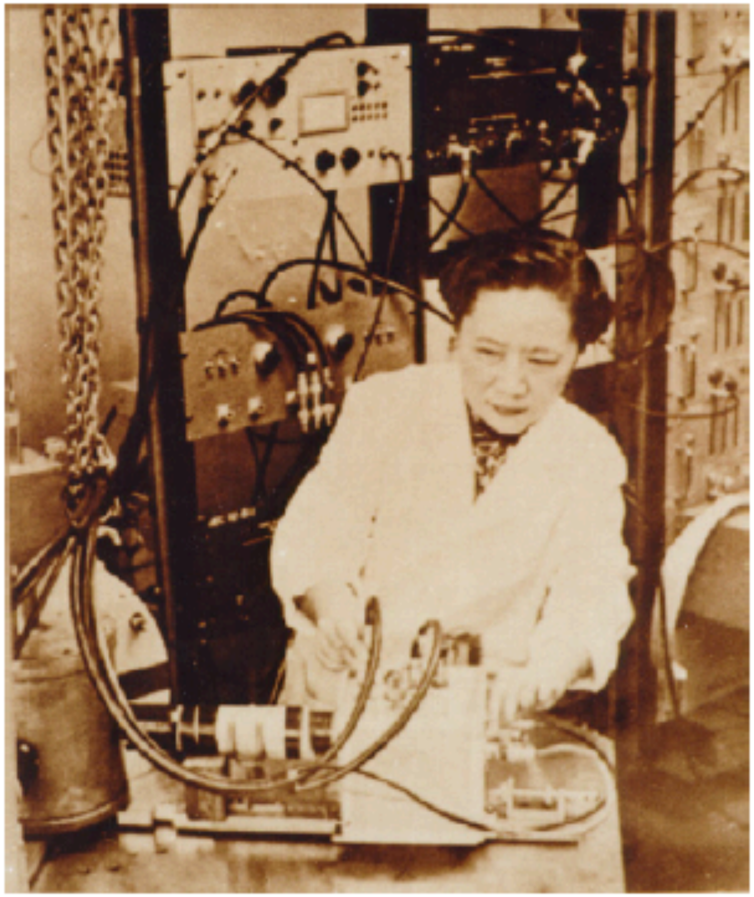
- helicity:
  - projection of particle's spin $\vec{S}$ along direction of motion $\vec{p}$

$$\vec{s} \cdot \vec{p} \quad \Rightarrow \quad \begin{array}{ll} \vec{S} \uparrow\downarrow \vec{p} & \text{negative, left helicity} \\ \vec{S} \uparrow\uparrow \vec{p} & \text{positive, right helicity} \end{array}$$

  - for massive particles: sign of helicity depends on frame
- handedness:
  - Lorentz invariant analogue of helicity
  - two states: left handed (LH) and right handed (RH)
    - massless particles: either pure RH or LH, can appear in either states
    - massive particles: both LH+RH components
      $\Rightarrow$ helicity eigenstate is combination of handedness states
- for $E \to \infty$ can neglect mass $\Rightarrow$ handedness $\equiv$ helicity

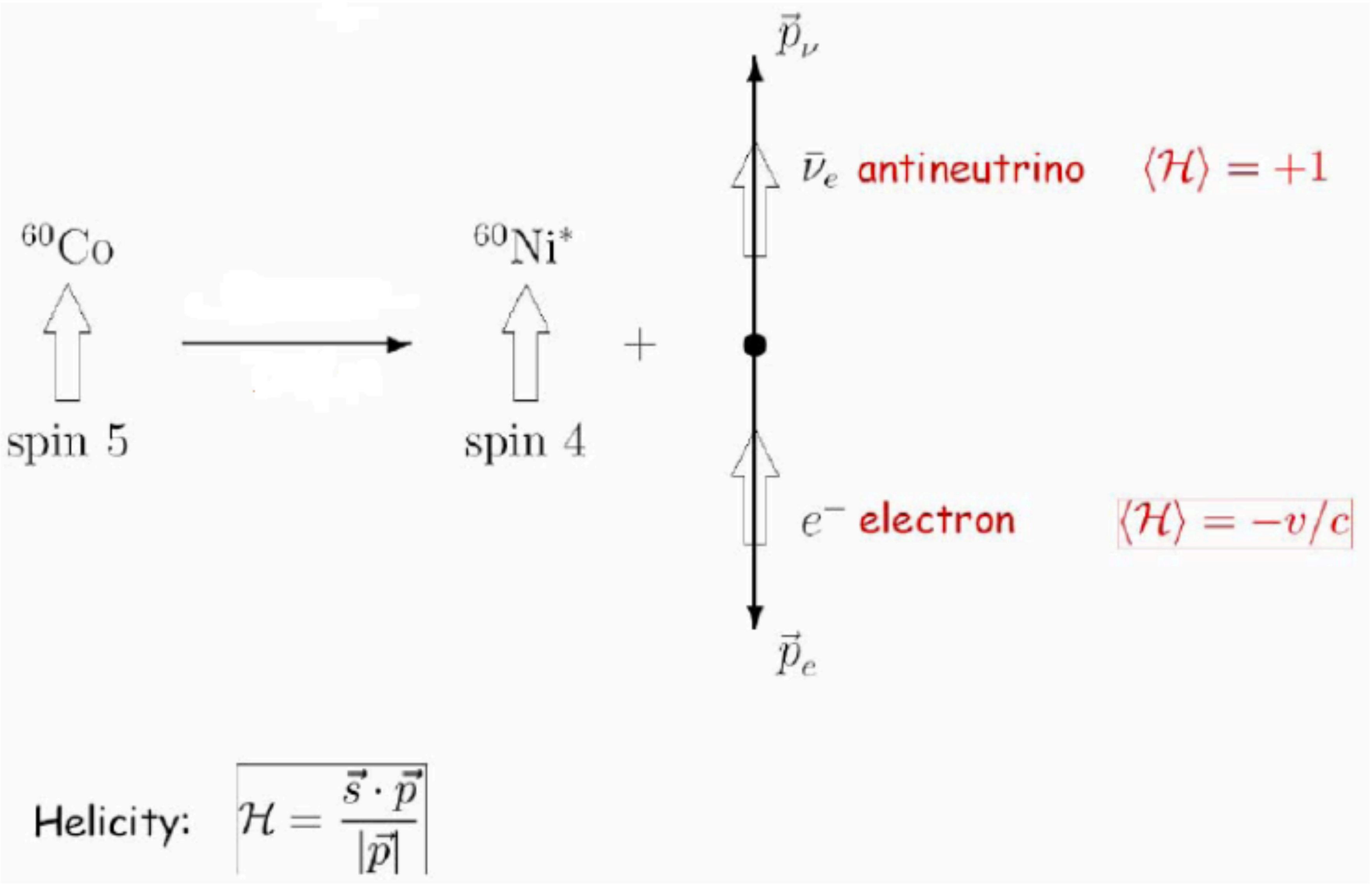
first hint that there are only LH neutrinos and RH antineutrinos

1956: T. D. Lee and C. N. Yang
predict P violation



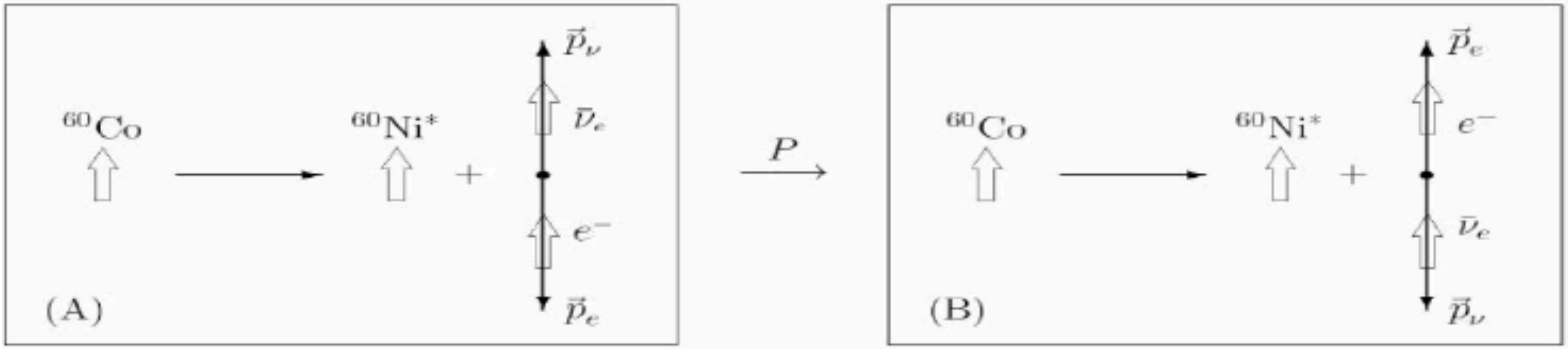
1957: Wu et al. observed
maximum P violation

Parity violation of the weak interaction



Helicity: $\boxed{\mathcal{H} = \frac{\vec{s}\cdot\vec{p}}{|\vec{p}|}}$

Wu-Experiment



parity transformation:

- polar vectors change sign: $\vec{p} \to -\vec{p}$
- axial vectors don't change sign: $\vec{s} \to \vec{s}$

experiment:

- nuclear spins are aligned through magnetic field, measurement of the electrons
- reverse magnetic field for other scenario

result:
beta emisssion is preferentially in the direction opposite to the nuclear spin ⇒ parity is violated

Wu-Experiment

- 1957: experiment to determine the helicity of the neutrino (Goldhaber et al.)
- used electron capture of the nucleus ^{152}Eu:

$$^{152m}Eu + e^- \rightarrow {}^{152}Sm^* + \nu_e \rightarrow {}^{152}Sm + \gamma + \nu_e$$

0	½	1	- ½	0	1	- ½
0	- ½	-1	½	0	-1	½

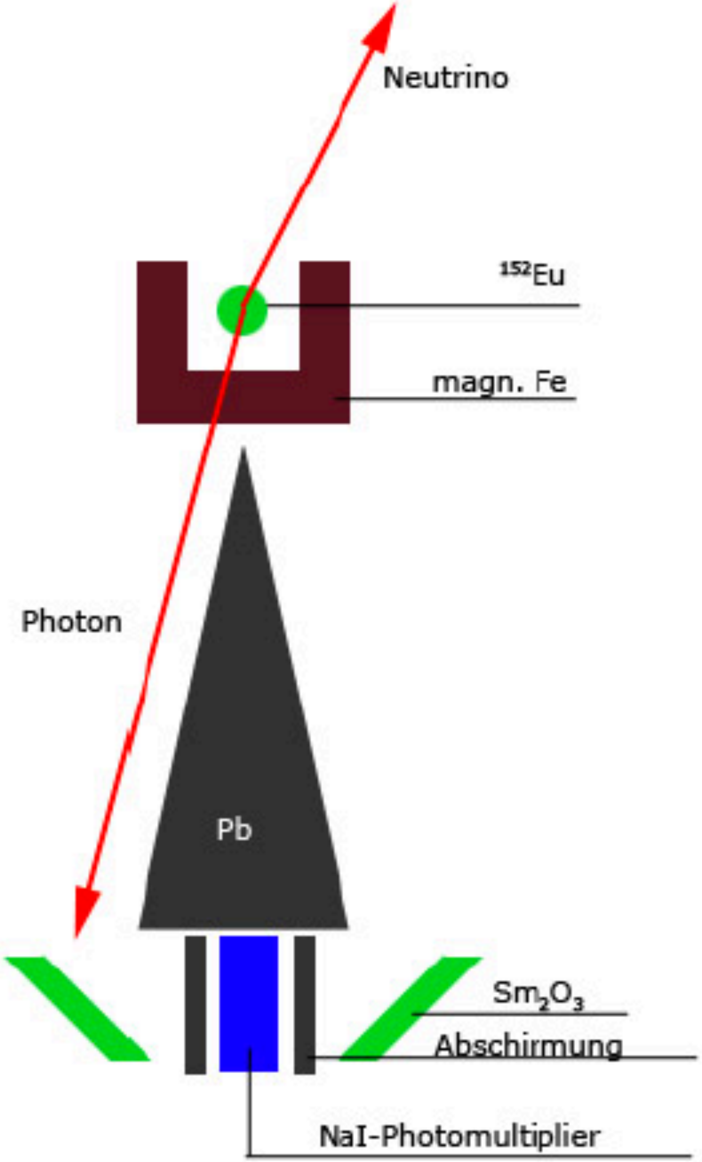
$\Rightarrow \vec{s}(\gamma) \uparrow\downarrow \vec{s}(\nu_e)$

- if neutrino and photon are „back-to-back“

$\Rightarrow H(\nu_e) = H(\gamma)$

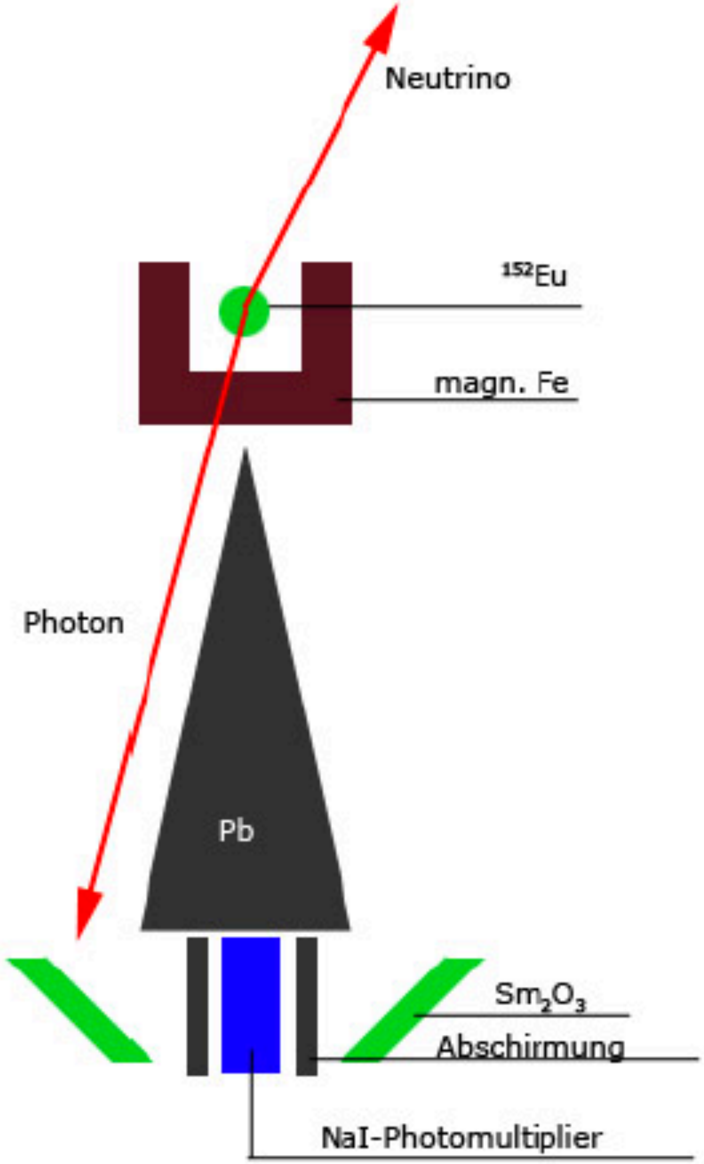
Goldhaber-Experiment

$$Eu + e^- \rightarrow Sm^* + \nu_e \rightarrow Sm + \gamma + \nu_e$$



- energy of Sm^* is distributed on Sm and γ
  $\rightarrow \gamma$ has to less energy to excite another Sm nucleus
- but: Sm^* gets a recoil when the ν_e is emitted $\rightarrow$ doesn't decay in rest
- γ emitted in moving direction of Sm^* nucleus
  $\rightarrow$ gets additional energy
  $\rightarrow$ can be absorbed by another Sm nucleus
  $\Rightarrow$ **resonant absorption possible**

Goldhaber-Experiment



measurement of helicity:

- Eu-source in iron magnet
- photons Compton scattered on electrons of Fe
- $d\sigma/d\Omega(\uparrow\downarrow) > d\sigma/d\Omega(\uparrow\uparrow)$
- reverse magnetic field and count detected photons
  $\Rightarrow$ polarisation of photons
  $\Rightarrow H(\nu) = -1.0 \pm 0.3$

$\Rightarrow$ neutrinos are left handed

Goldhaber-Experiment

Few Unique Features of Neutrinos

- **Known to undergo flavor change**

  (neutrino mass: first clue of physics beyond the Standard Model)

- **Masses are anomalously low**

  (from CMB data $m_\nu < 0.2\ \mathrm{eV}/c^2 = 0.0000004\ m_e$)

- **Only fundamental fermion that can be its own anti-particle**

  (Majorana particle)

- **May open window on the GUT Scale ($\Lambda_{GUT} \sim 10^{16}$ GeV)**

  (via seesaw mechanism)

- **Could explain the matter/anti-matter asymmetry of the Universe**

  (leptogenesis)

The Standard Model: Massless Neutrinos

The Standard Model is a gauge theory & it unifies strong, weak & electromagnetic forces!

$$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$$

$(1,2)_{-\frac{1}{2}}$	$(3,2)_{\frac{1}{6}}$	$(1,1)_{-1}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	e_R	u^i_R	d^i_R
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$	μ_R	c^i_R	s^i_R
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$	τ_R	t^i_R	b^i_R

3-fold repetition of the same representation!

- 3 *active* neutrinos: ν_e , ν_μ , ν_τ
- Neutral elementary particles of Spin ½
- Only couple to *weak force* (& gravity)
- Only *left handed* neutrinos
- There are no right-handed neutrinos
- *No* Dirac Mass term: $m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)$

Neutrinos are massless in the Basic SM

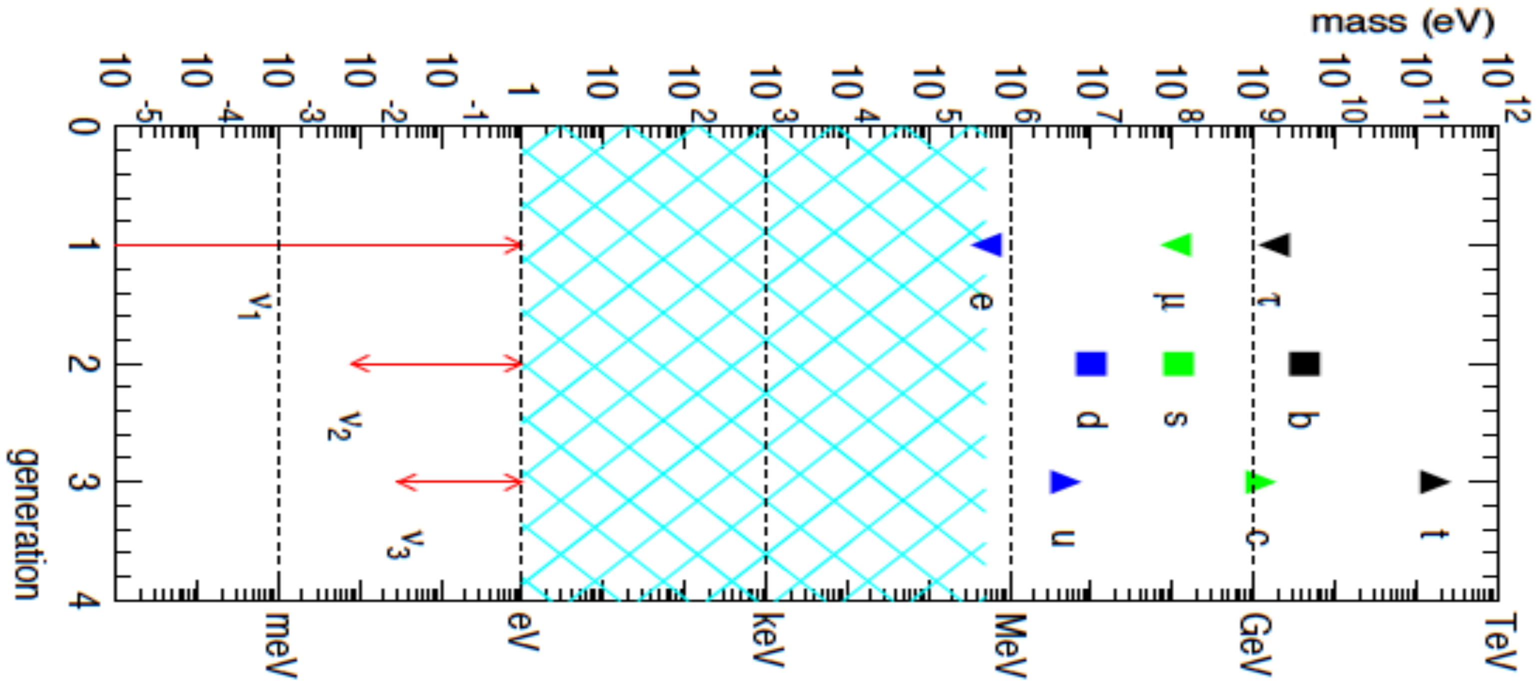
☐ Over the past decade, marvelous data from world class neutrino experiments firmly established that they change flavor after propagating a finite distance

☐ Neutrino flavor change (oscillation) demands non-zero mass and mixing

Non-zero ν mass: first experimental proof for physics beyond the Standard Model

!! An extension of the Standard Model is necessary !!

The Two Fundamental Questions



Why are neutrinos so light? **The origin of Neutrino Mass!**

	Neutrinos (PMNS)	Quarks (CKM)
θ_{12}	35°	13°
θ_{32}	43°	2°
θ_{13}	9°	0.2°
δ	unknown	68°

Why are lepton mixings so different from quark mixings?

The Flavor Puzzle!

Physics Issues with ICAL-INO

Study Atmospheric neutrinos w/ a wide range of Baselines & Energies

Recent discovery of large θ_{13} : A good news for ICAL-INO

What do we want to achieve?

- ***Reconfirm neutrino oscillations using neutrinos and anti-neutrinos separately***
- ***Improved precision of atmospheric oscillation parameters***
- ***Determine neutrino mass hierarchy using matter effects via charge discrimination***
- ***Measure the deviation of 2-3 mixing angle from its maximal value and its octant***
- ***Test bed for various new physics like NSI, CPT violation, long range forces***
- ***Detect Ultra High Energy Neutrinos, Cosmic Muons, Indirect searches of DM***

Current Status of INO

Pre-project activities started with an initial grant of ~ 15 M$

- **Site infrastructure development**

- **Development of INO centre at Madurai city (110 km from underground lab)**
  - Inter-Institutional Centre for High Energy Physics (IICHEP)

- **Construction of an 1/8th size engineering prototype module**

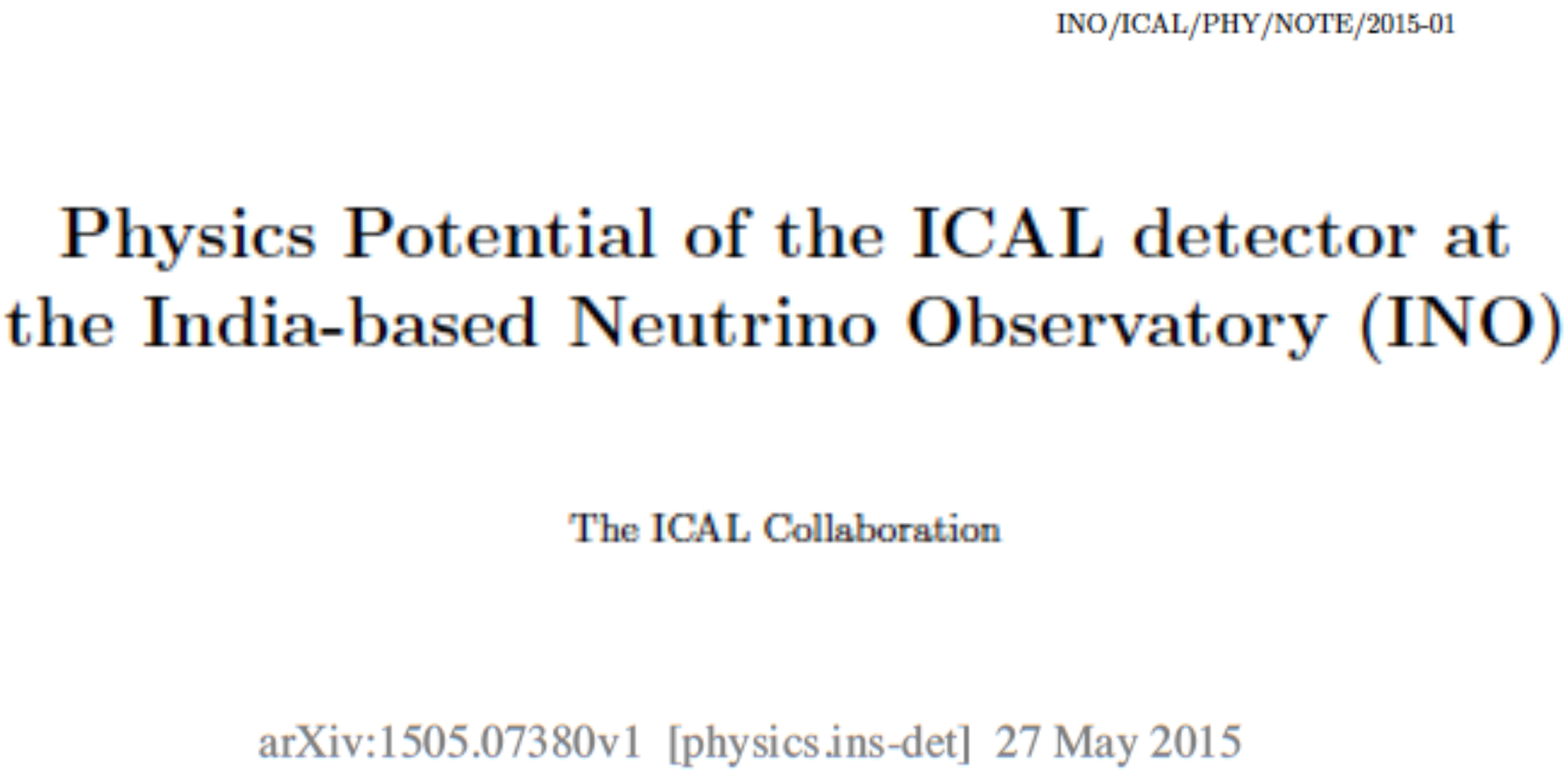
- **Detector R&D is now over**

- **Detailed Project Report for Detector and DAQ system is ready**

- **Soon go for industrial production of RPCs & associated front-end electronics**

- **Full project approved by PM's cabinet committee to start construction**

White Paper on ICAL's Physics Potential



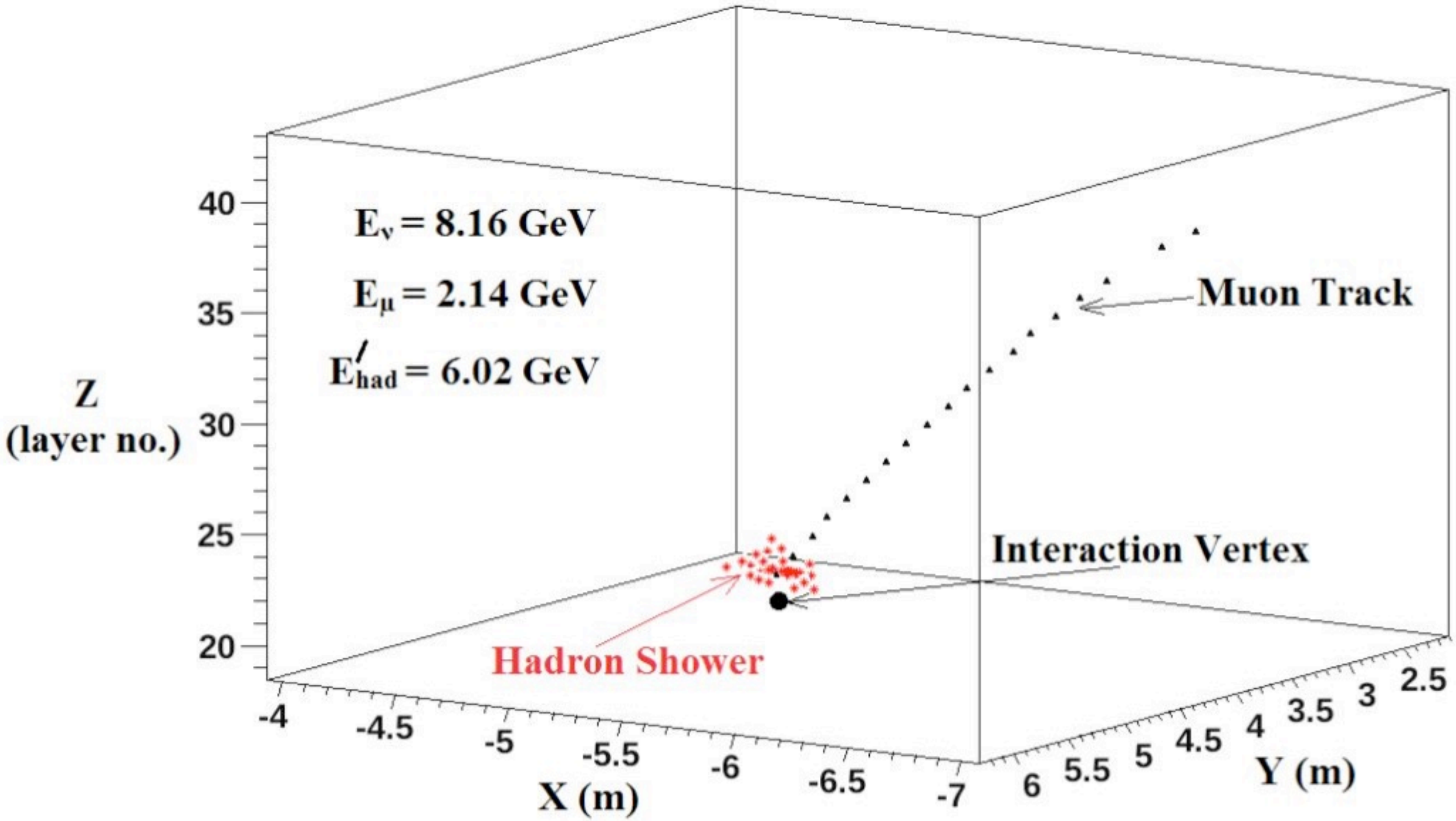
INO/ICAL/PHY/NOTE/2015-01

Physics Potential of the ICAL detector at the India-based Neutrino Observatory (INO)

The ICAL Collaboration

arXiv:1505.07380v1 [physics.ins-det] 27 May 2015

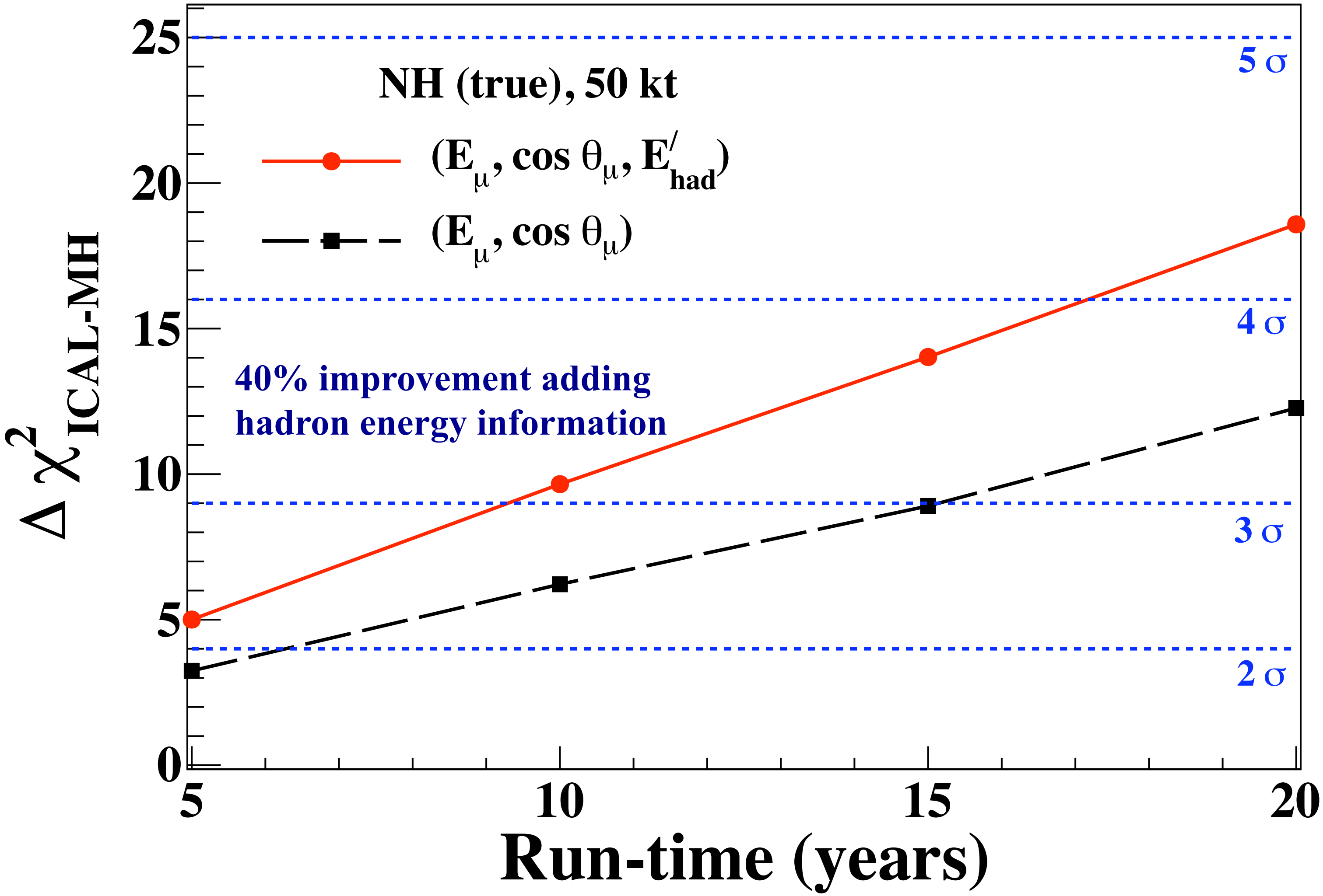
Event Display Inside the ICAL Detector



Using GEANT4 simulation

Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)

Identifying Neutrino Mass Hierarchy with ICAL



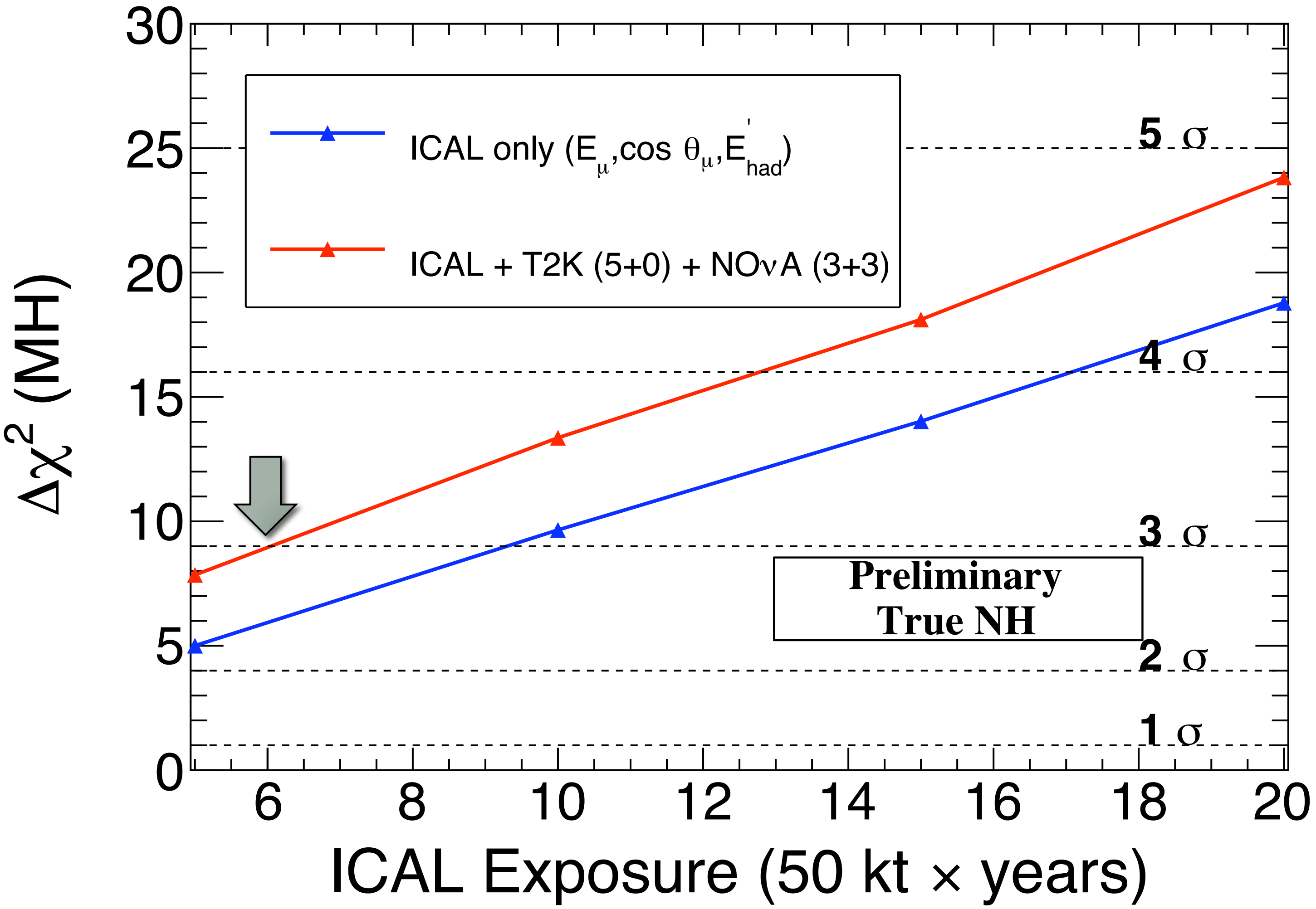
40% improvement adding hadron energy information

Median Sensitivity

Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)

50 kt ICAL can rule out the wrong hierarchy with $\Delta\chi^2 \approx 9.5$ in 10 years

MH Discovery with ICAL+T2K+NOνA



Agarwalla, Chatterjee, Thakore, work in progress (INO Collaboration)

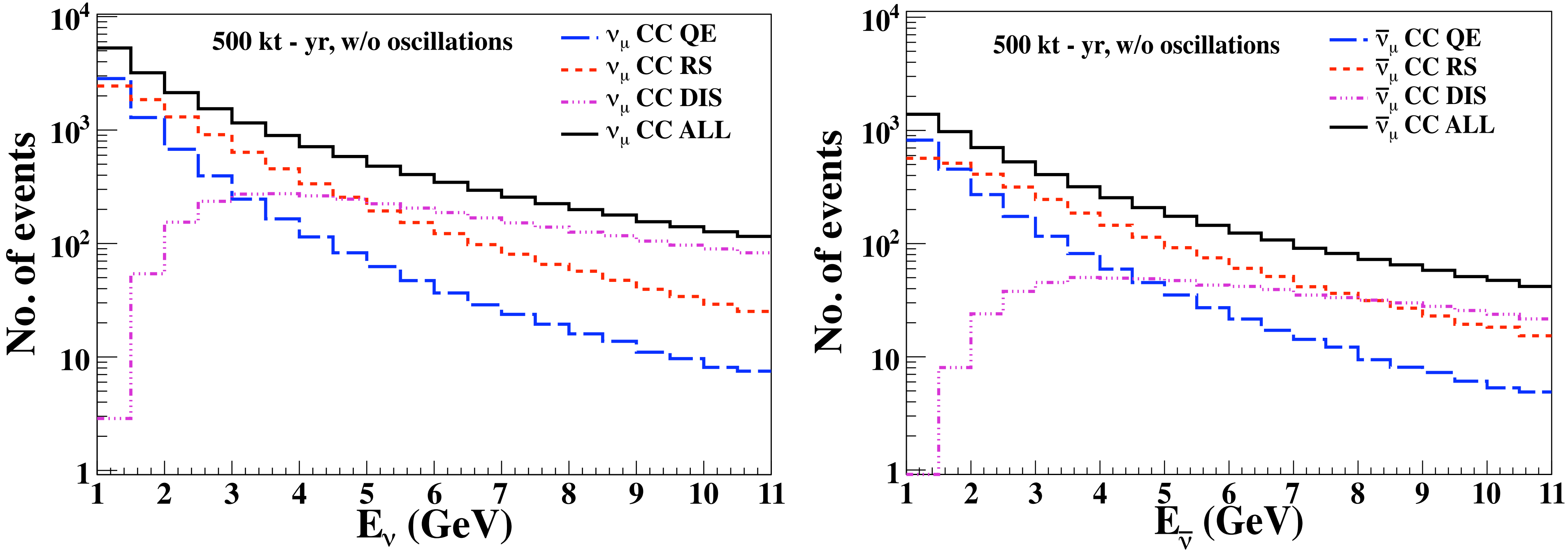
3σ median sensitivity can be achieved in 6 years

Overview of Simulation Framework

NUANCE work in progress to adopt GENIE	**Neutrino Event Generation** $\nu_\ell + N \to \ell + X$. Generates particles that result from a random interaction of a neutrino with matter using theoretical models for both neutrino fluxes and cross-sections.	**Output:** (i) Reaction Channel (ii) Vertex and time information (iii) Energy and momentum of all final state particles
GEANT	**Event Simulation** $\ell + X$ through simulated ICAL Simulates propagation of particles through the ICAL detector with RPCs and magnetic field.	**Output:** (i) x, y, z, t of the particles as they propagate through detector (ii) Energy deposited (iii) Momentum information
DIGITISATION	**Event Digitisation** (X, Y, Z, T) of final states on including noise and detector efficieny Add detector efficiency and noise to the hits.	**Output:** (i) Digitised output of the previous stage
ANALYSIS	**Event Reconstruction** $(E, \vec{p})$ of ℓ, X (total hadrons) Fit the muon tracks using Kalman filter techniques to reconstruct muon energy and momentum; use hits in hadron shower to reconstruct hadron information.	**Output:** (i) Energy and momentum of muons and hadrons, for use in physics analyses.

Simulation work is under progress in full swing!

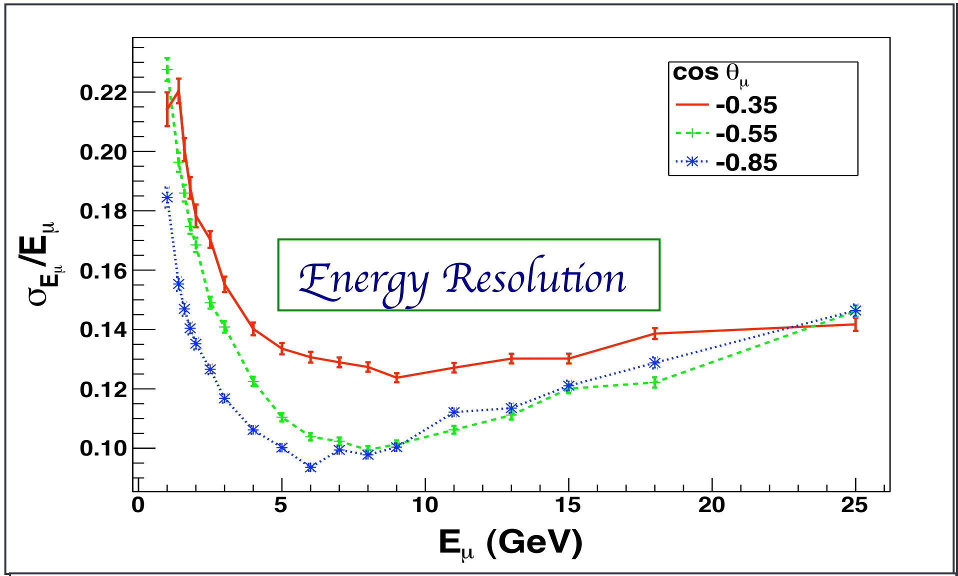
Events in Various Channels

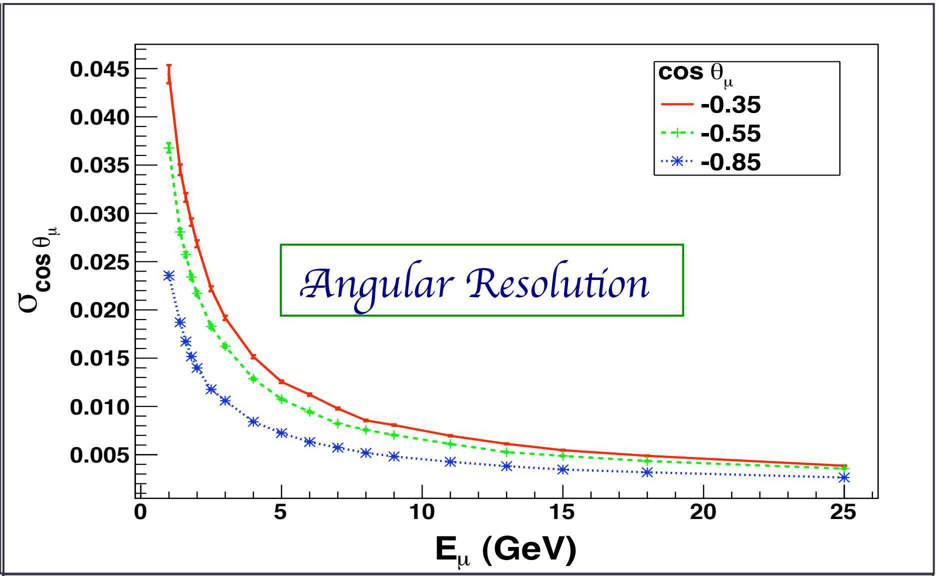


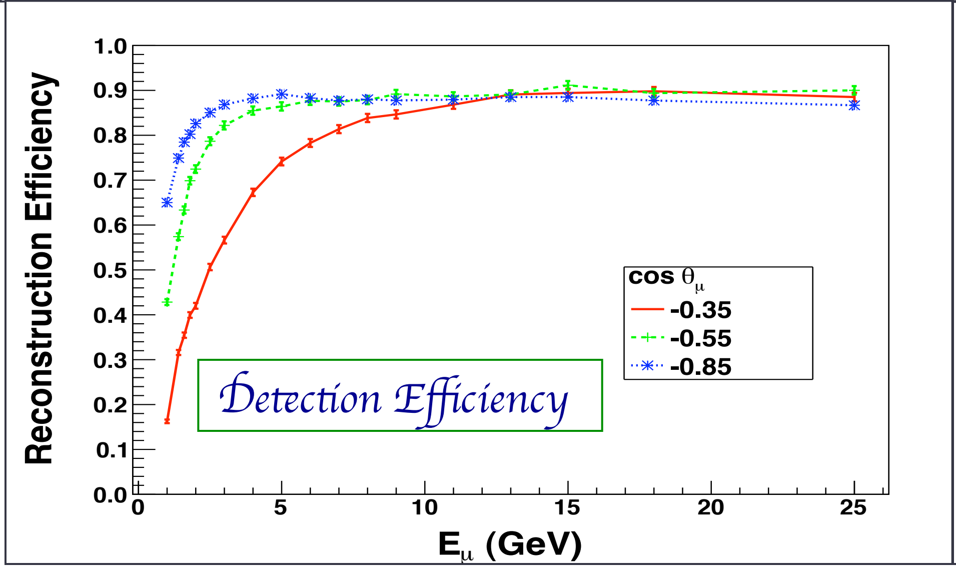
Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)

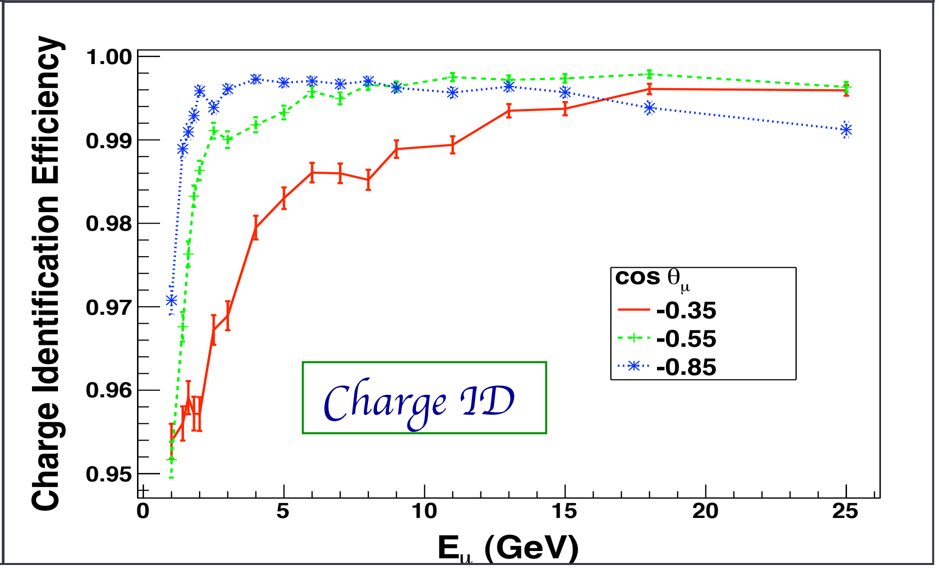
Relative contributions of three cross-section processes to the total events in the absence of oscillation and without detector efficiency and resolutions

Muon Efficiencies and Resolutions



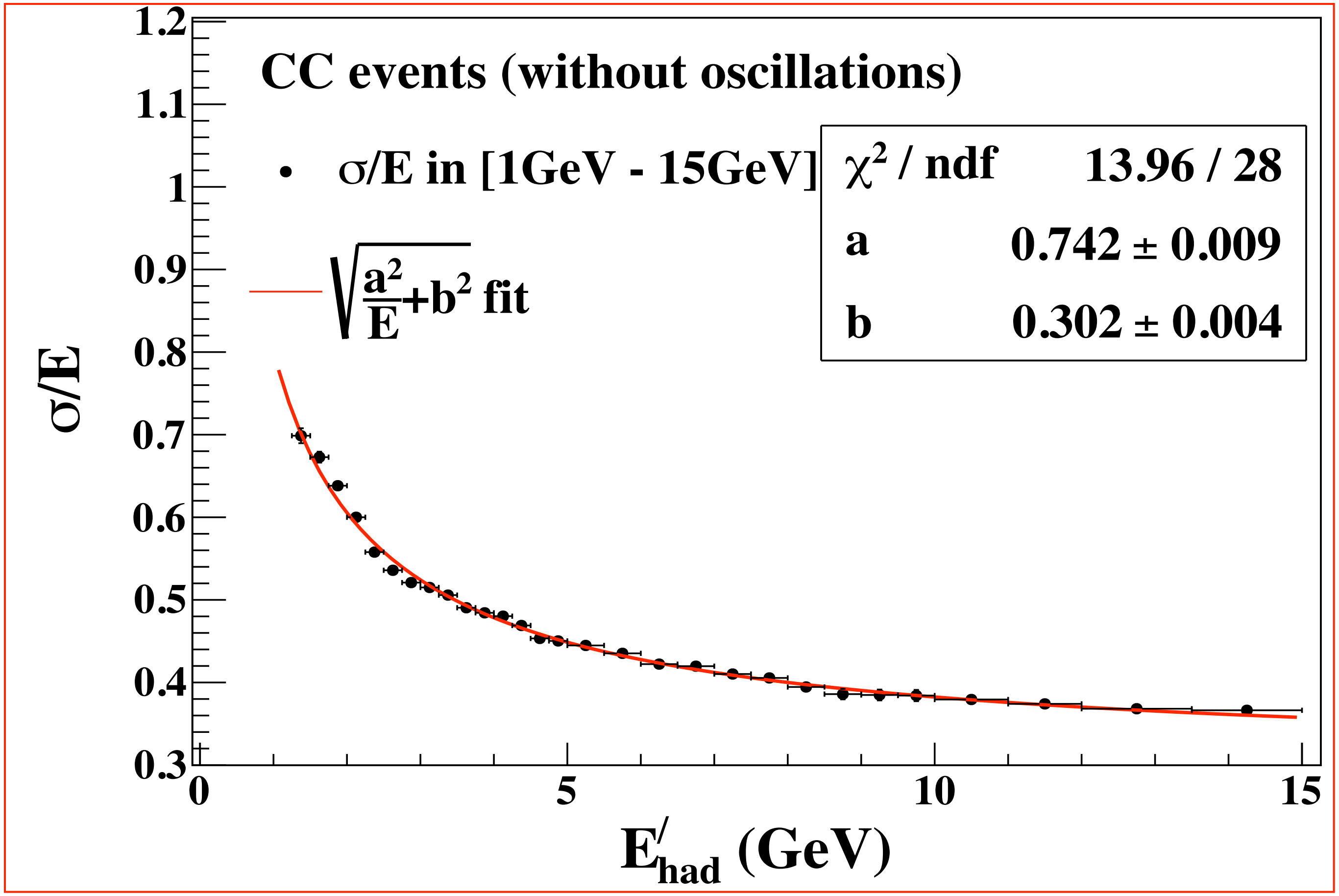






Animesh Chatterjee, Meghna K.K., Kanishka Rawat, Tarak Thakore etal., arXiv:1405.7243 [physics.ins-det]

Hadron Energy Response of ICAL



$E'_h = E_\nu - E_\mu$ (from hadron hit calibration)

Hadron energy resolution: 85% at 1 GeV and 36% at 15 GeV

Moon Moon Devi, Anushree Ghosh, Daljeet Kaur, Lakshmi S. Mohan etal., JINST 8 (2013) P11003

The χ^2 Analysis

We define the Poissonian χ^2_- for μ^- events as :

$$\chi^2_- = \min_{\xi_l} \sum_{i=1}^{N_{E'_{\rm had}}} \sum_{j=1}^{N_{E_\mu}} \sum_{k=1}^{N_{\cos\theta_\mu}} \left[2(N_{ijk}^{\rm theory} - N_{ijk}^{\rm data}) - 2N_{ijk}^{\rm data} \ln\left(\frac{N_{ijk}^{\rm theory}}{N_{ijk}^{\rm data}}\right)\right] + \sum_{l=1}^{5} \xi_l^2 \,,$$

where

$$N_{ijk}^{\rm theory} = N_{ijk}^0 \left(1 + \sum_{l=1}^{5} \pi_{ijk}^l \xi_l\right) .$$

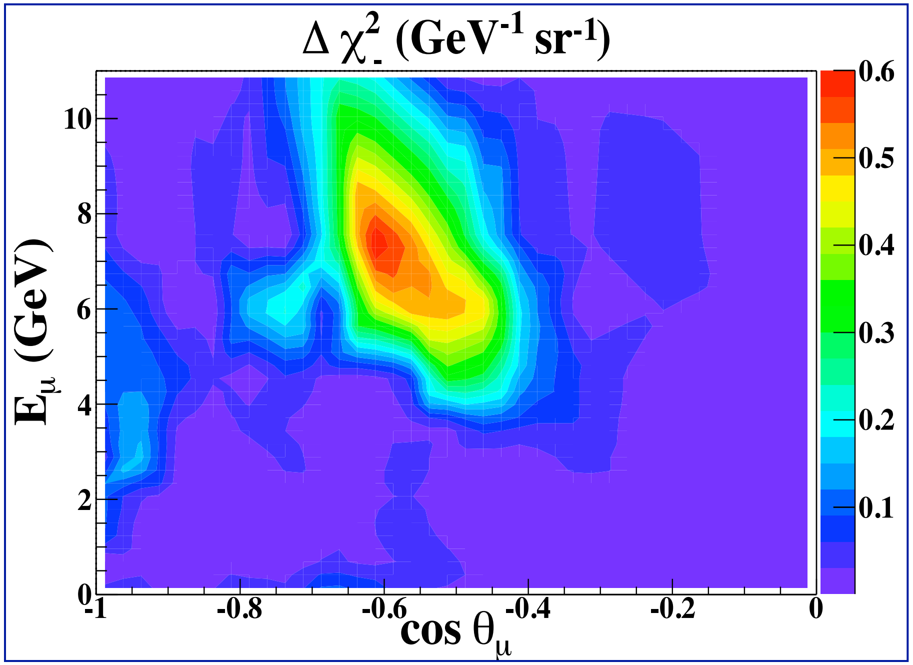
Observable	Range	Bin width	Total bins	
E_μ (GeV)	$[1, 4)$	0.5	6	10
	$[4, 7)$	1	3	
	$[7, 11)$	4	1	
$\cos\theta_\mu$	$[-1.0, -0.4)$	0.05	12	21
	$[-0.4, 0.0)$	0.1	4	
	$[0.0, 1.0]$	0.2	5	
$E'_{\rm had}$ (GeV)	$[0, 2)$	1	2	4
	$[2, 4)$	2	1	
	$[4, 15)$	11	1	

1) Overall 5% systematic uncertainty
2) Overall flux normalization: 20%
3) Overall cross-section normalization: 10%

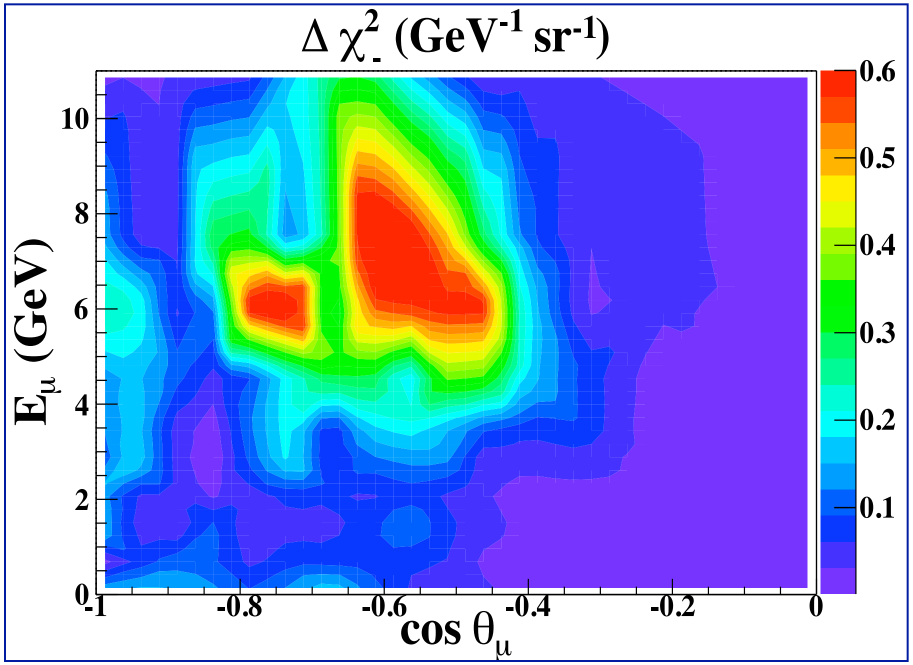
4) 5% uncertainty on the zenith angle dependence of the fluxes
5) Energy dependent tilt factor:
$\Phi_\delta(E) = \Phi_0(E)\,[E/E_0]^\delta \approx \Phi_0(E)\,[1+\delta \ln E/E_0]$
where $E_0 = 2$ GeV and
δ is the 1σ systematic error of 5%

Neutrino Mass Hierarchy Discrimination

Distribution of $\Delta\chi^2$ [χ^2 (IH) - χ^2 (NH)] for mass hierarchy discrimination considering μ^- events



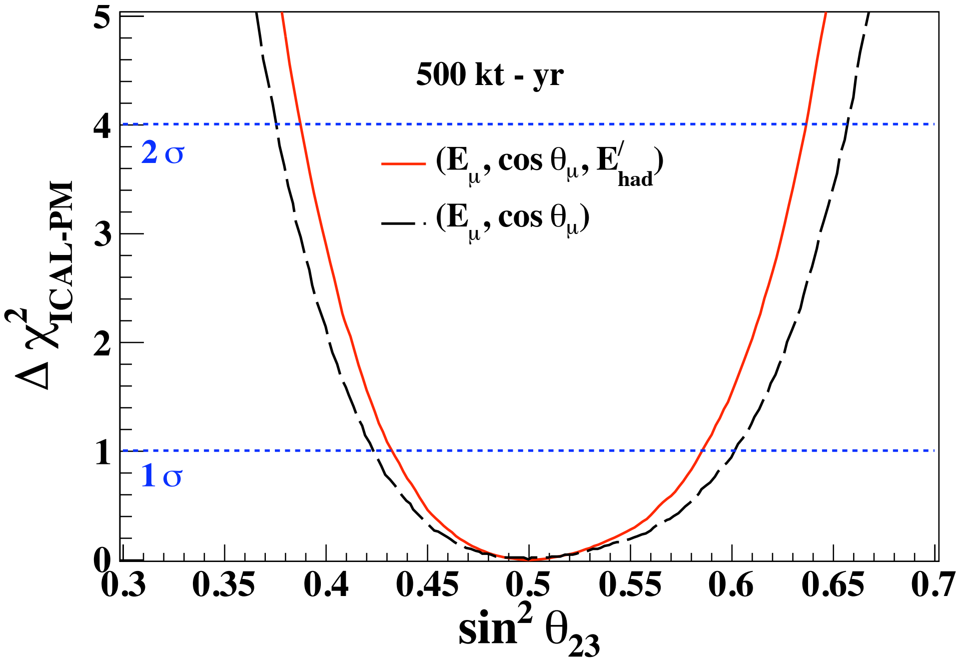
Hadron energy information not used



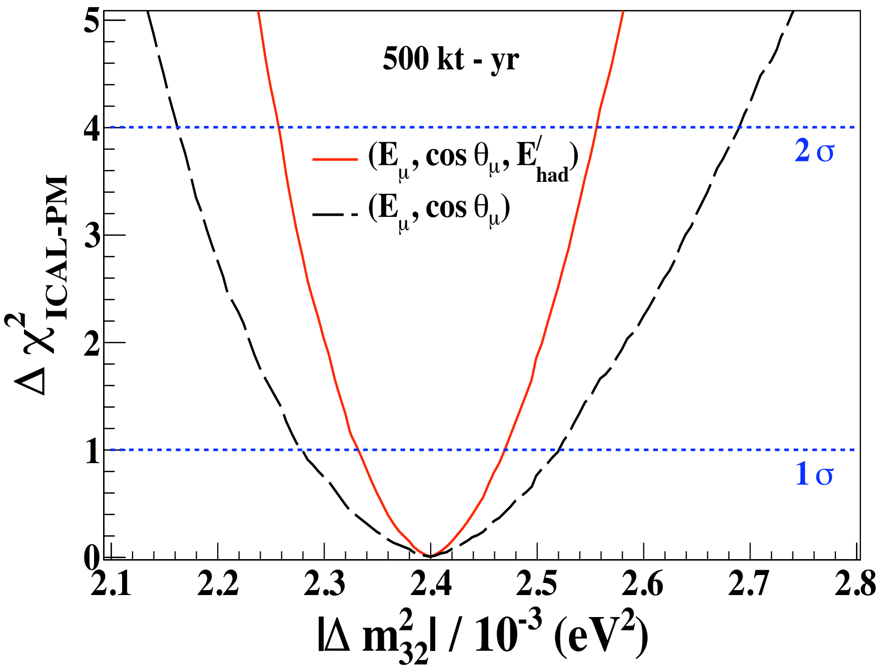
Hadron energy information used

- Further subdivide the events into four hadron energy bins
- Hadron energy carries crucial information
- Correlation between hadron energy and muon momentum is very important

Precision of Atmospheric Oscillation Parameters



Relative 1σ precision: 12%

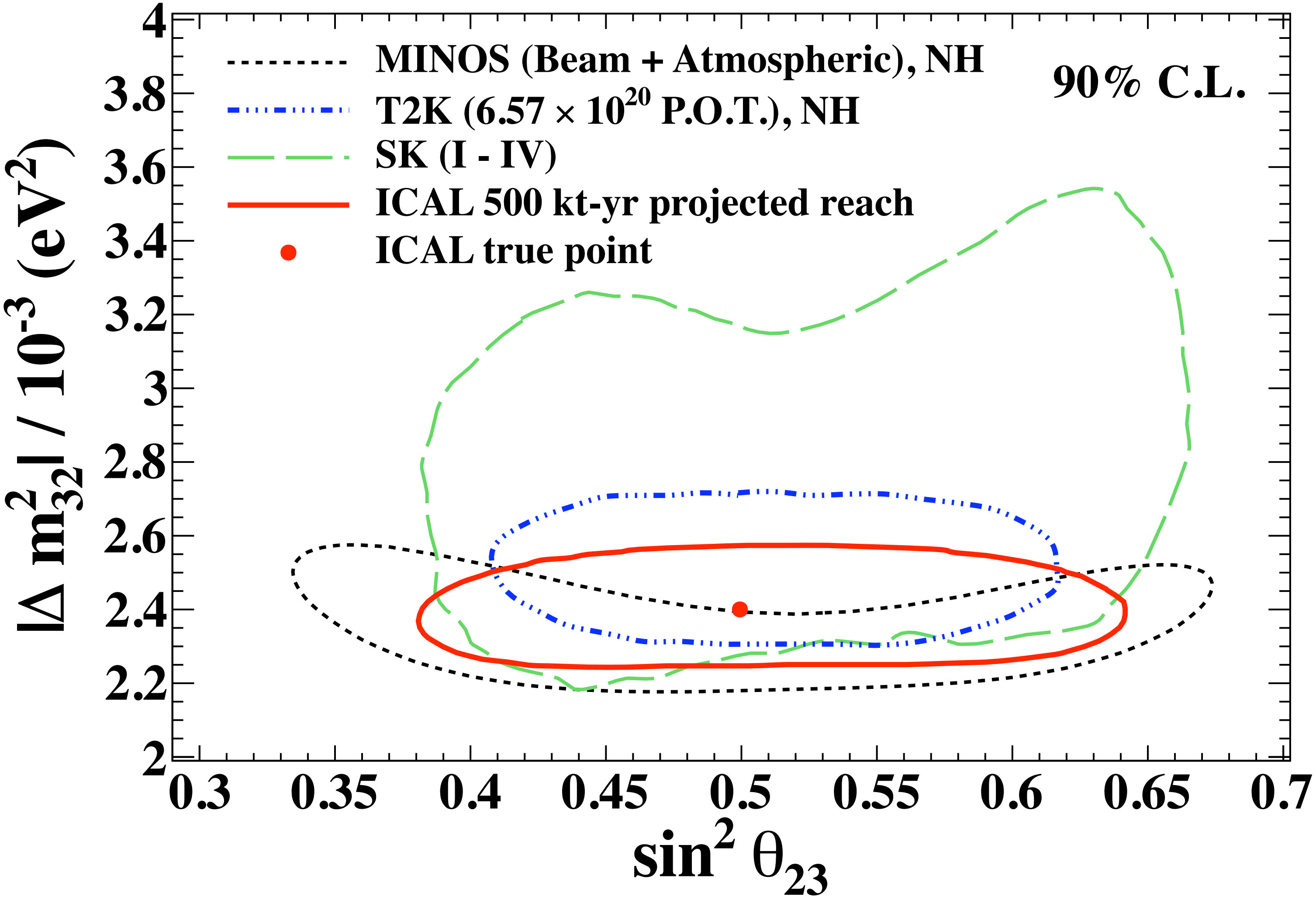


Relative 1σ precision: 2.9%

Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)

Significant improvement in the precision measurement of atmospheric mass splitting by adding hadron energy information with muon momentum

Precision Measurement of Atmospheric Parameters



Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)

ICAL' s expected precision on atmospheric mass splitting is better than SK

Limits on Neutrino Mass

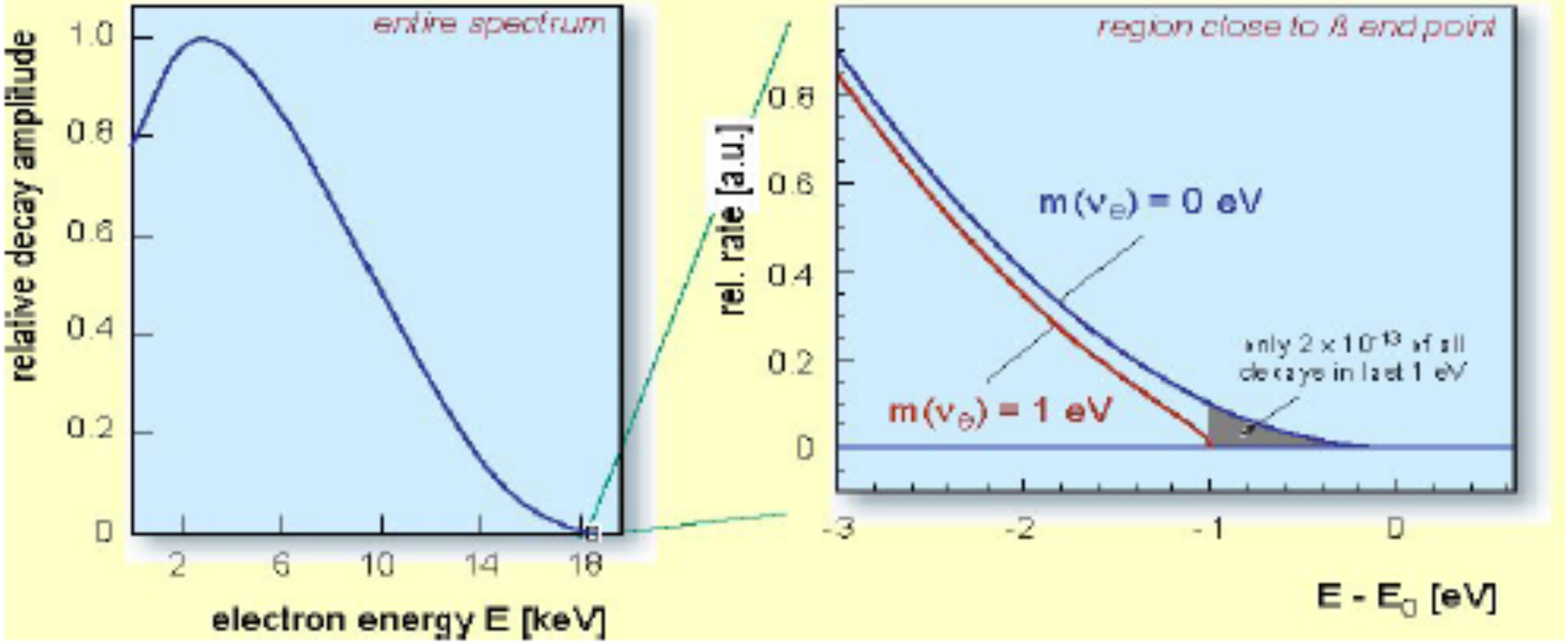
tritium ß-decay and the neutrino rest mass

$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$

superallowed

half life : $t_{1/2} = 12.32$ a

ß end point energy : $E_0 = 18.57$ keV



- Mainz exeriment: $m_{\nu_e} < 2.2$ eV (95% C.L.)
- Troitsk experiment: $m_{\nu_e} < 2.05$ eV (95% C.L.)
- Next generation expt: KATRIN (reach 0.2 eV)