Neutrinos

Leonidas Aliaga

The 2019 Undergraduate Lecture Series

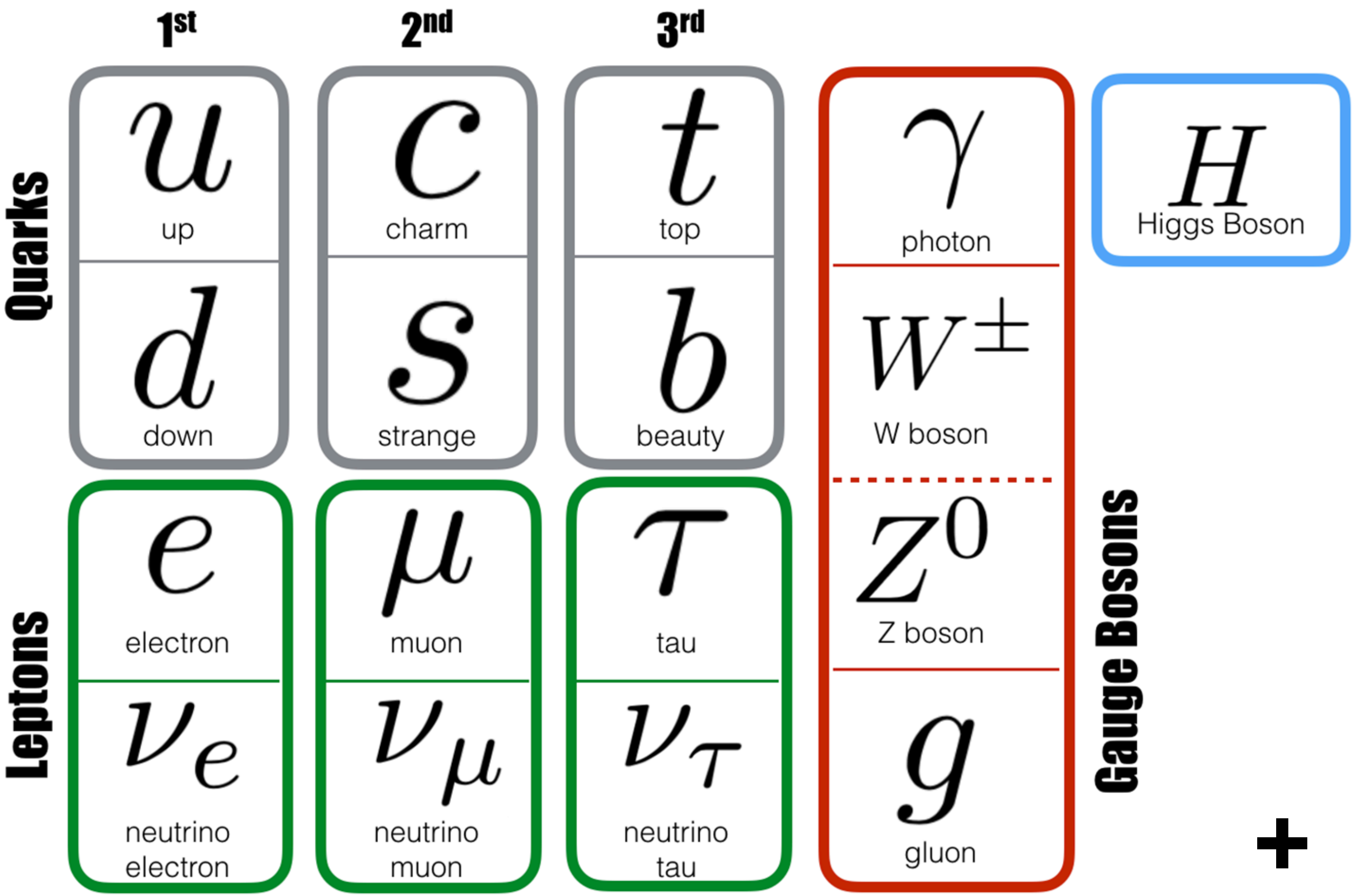
July 9, 2019

Outline

- Introduction
- How the neutrinos were discovered?
- What is really the identity of neutrinos?
- How do we study neutrinos at Fermilab?

Introduction

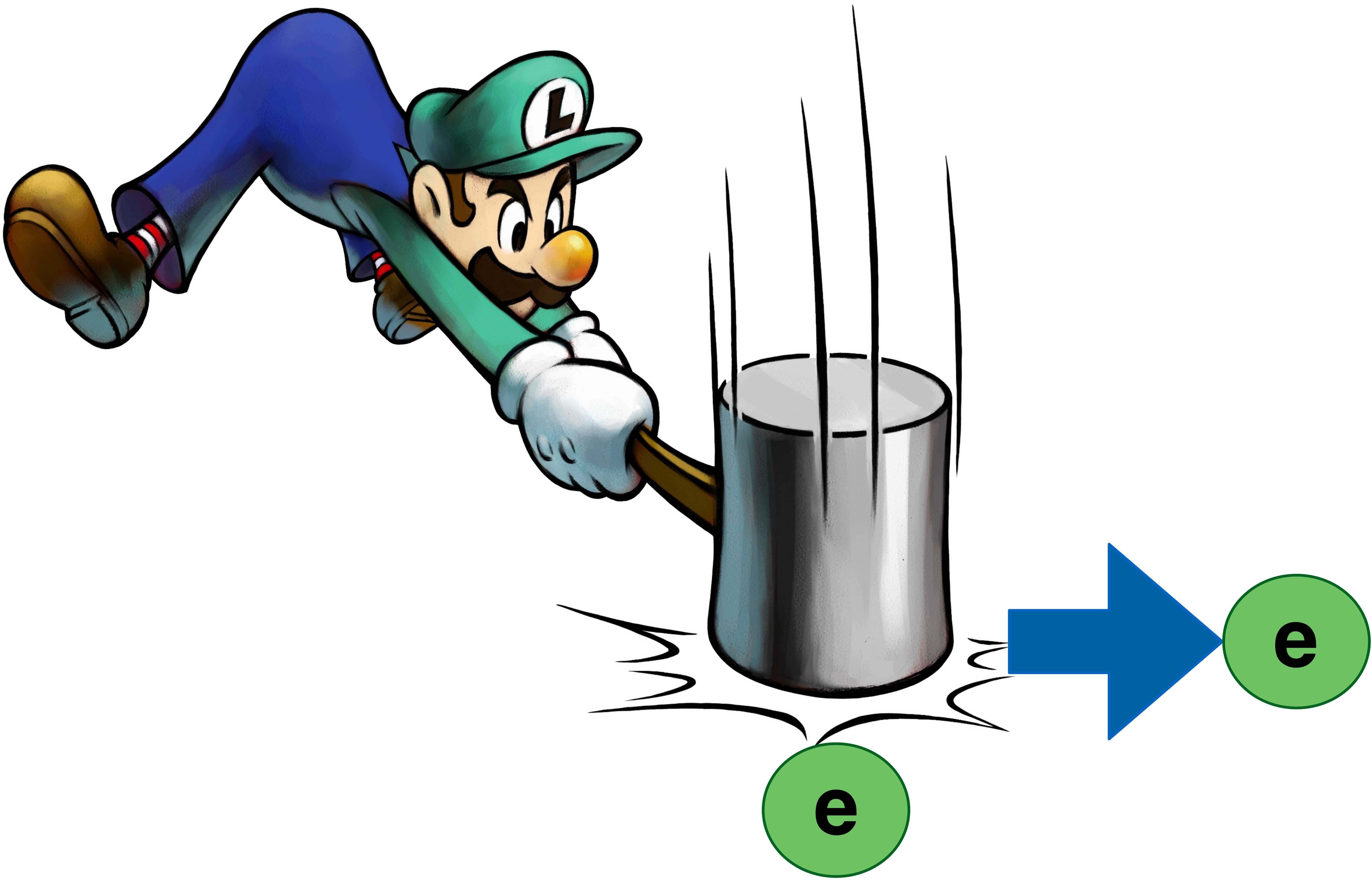
Standard Model of Elementary Particles



https://www.physik.uzh.ch

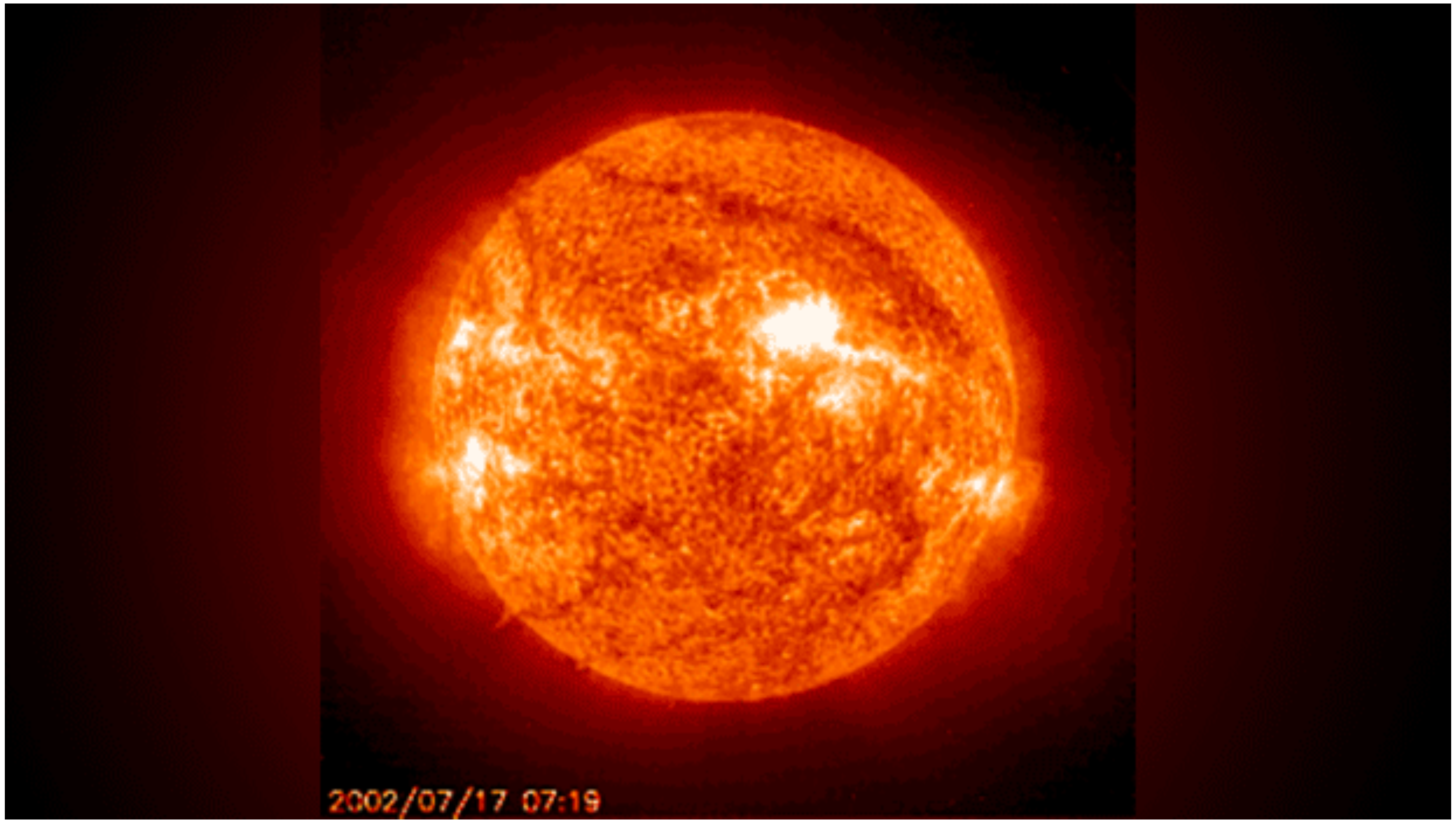
+ antiparticles

What does elementary particle mean?



What do we know about neutrinos

They are abundant: emitted from the sun, other stars, and including the Big Bang are traveling through out space



Millions and millions and millions of neutrinos are also passing through YOU at this very MOMENT!

65 billion of neutrinos / cm2 / sec from the Sun.

What do we know about neutrinos

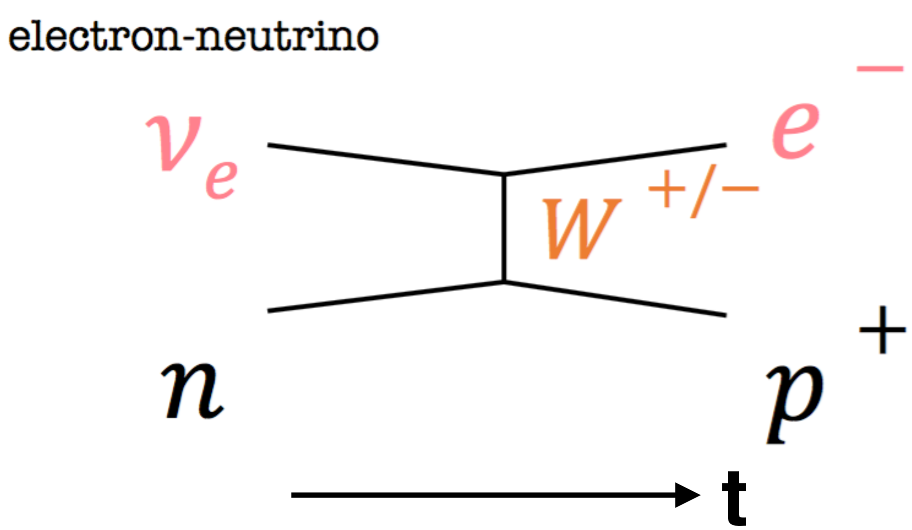
Neutrino interactions are extremely rare!

The probability of their interactions is very small

(neutrinos at Fermilab can travel up to 200 Earths before interacting)

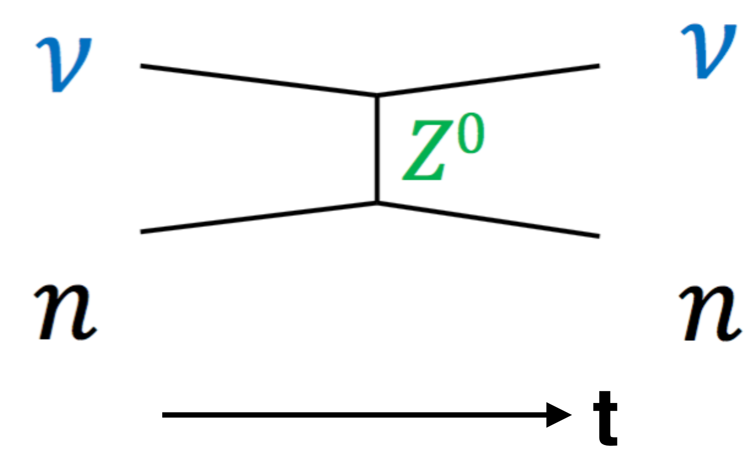
Neutrino and weak interactions

charged-current



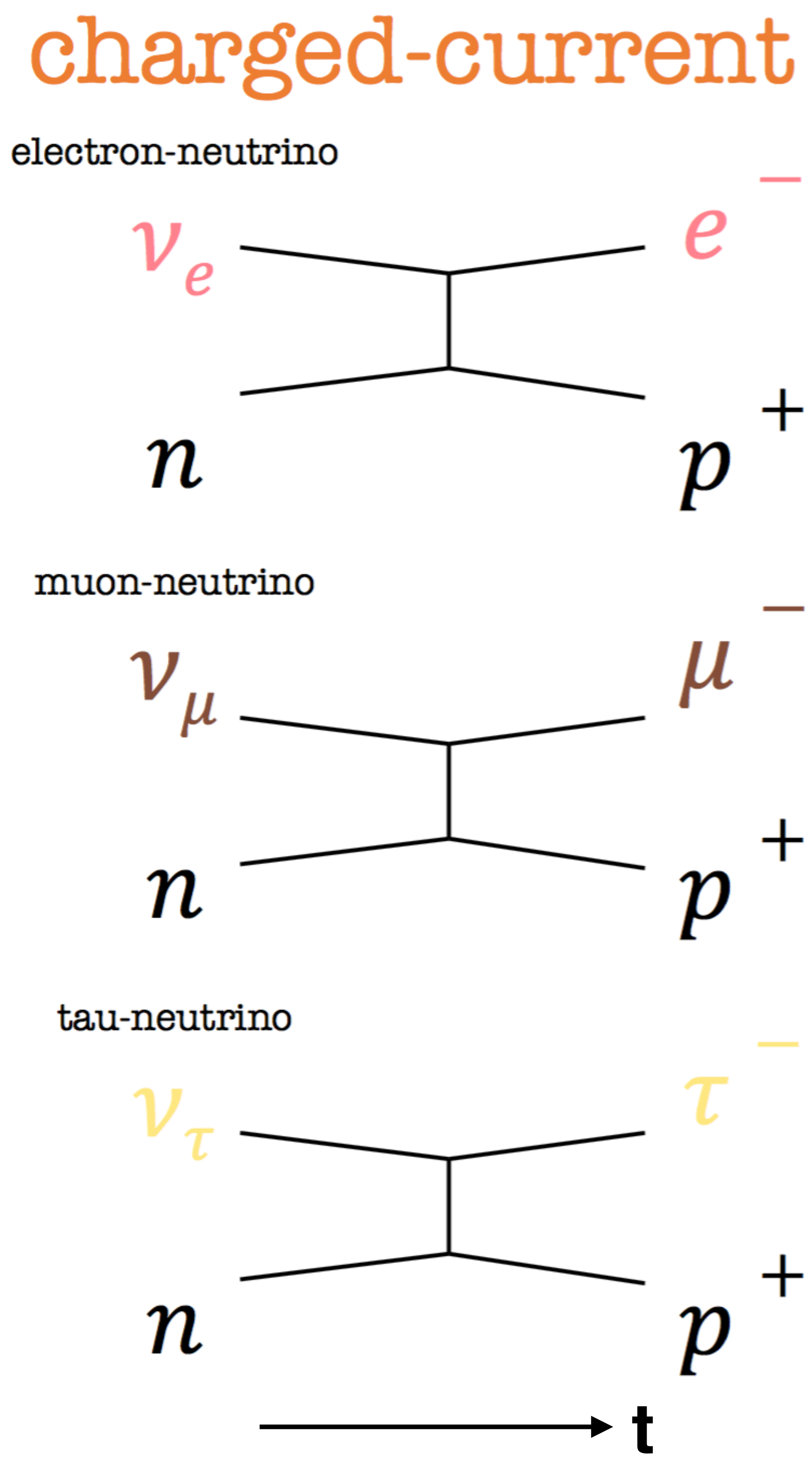
$W^{+/-}$ = charged boson

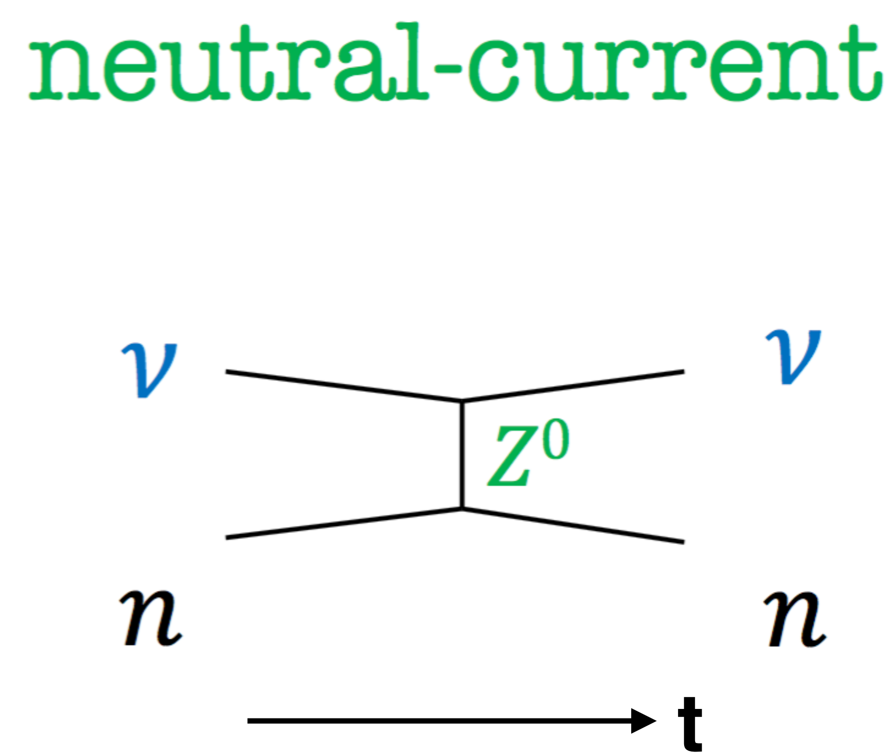
neutral-current



Z^0 = neutral boson

Neutrino and weak interactions

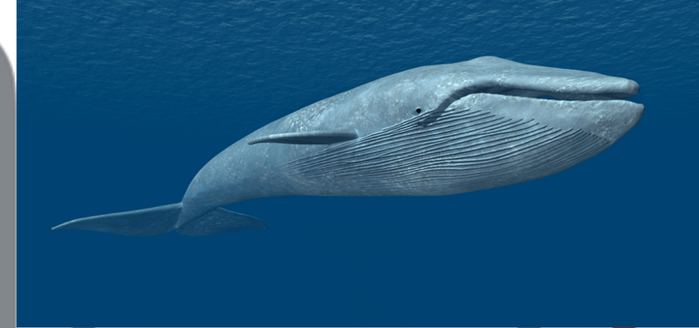




Z^0 = neutral boson

u up

c charm



top

γ photon

H Higgs Boson

d

s strange

beauty

$W^{\pm}$ W boson

electron

muon

τ tau

Z^0 Z boson

ν_e neutrino electron

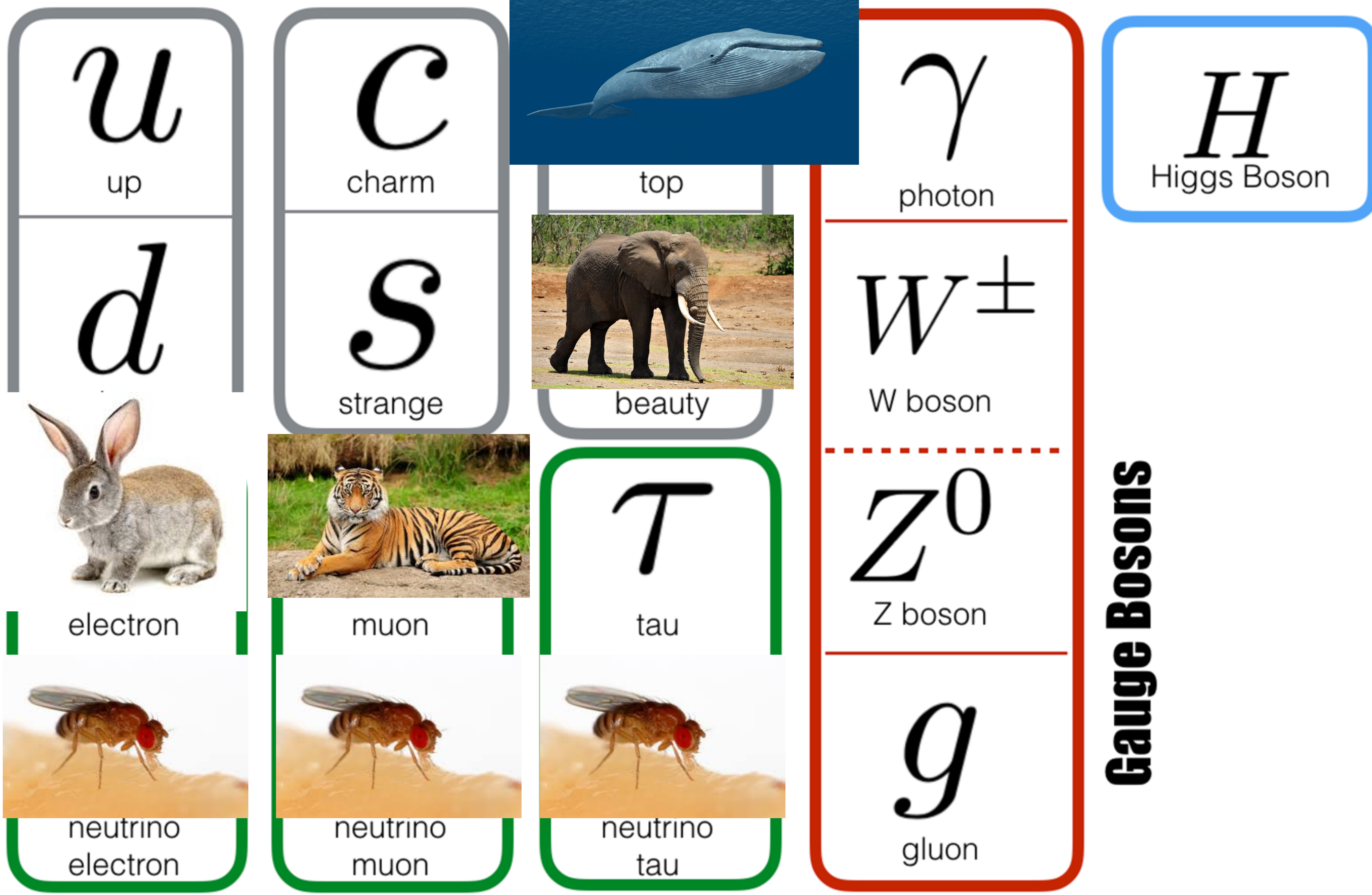
ν_μ neutrino muon

ν_τ neutrino tau

g gluon

Gauge Bosons

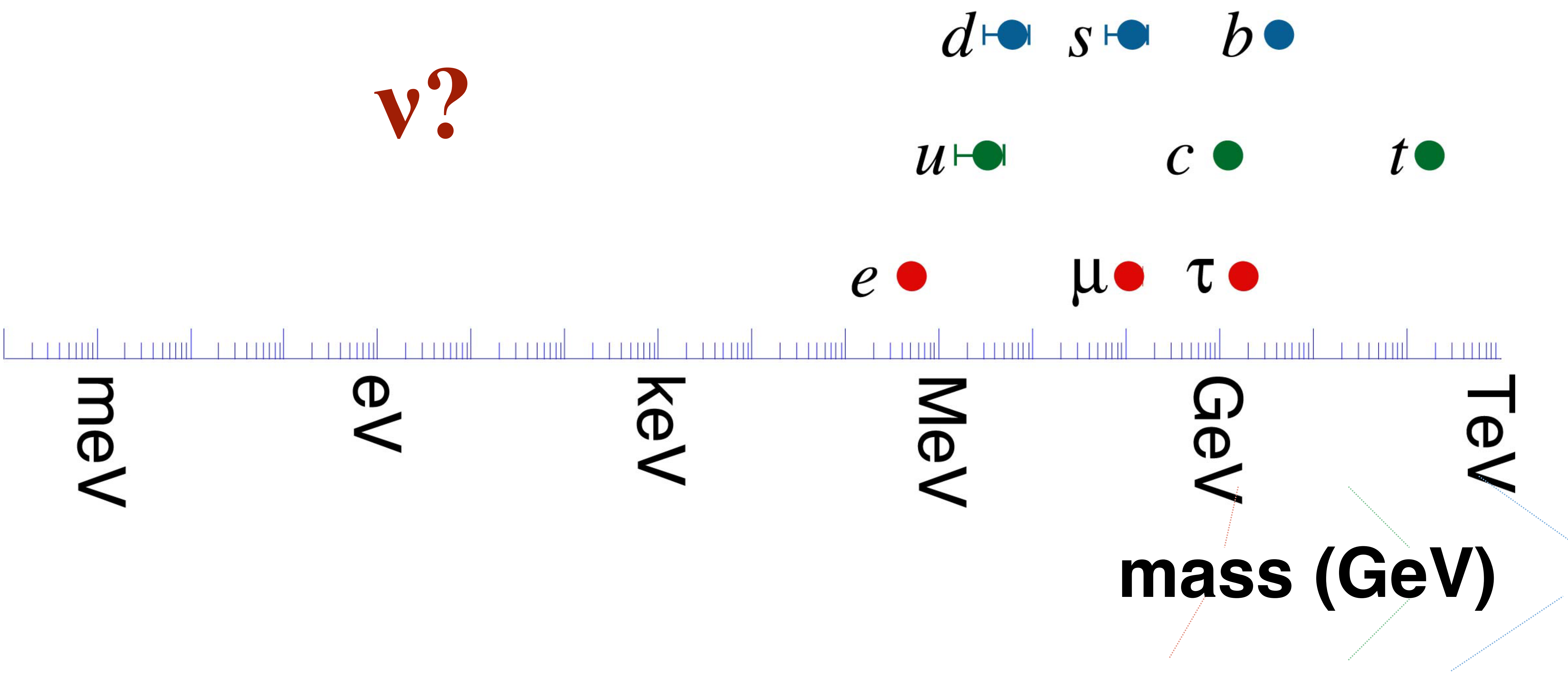
Andre De Gouvea: https://www.youtube.com/watch?v=UY1QQr-PZOg



Andre De Gouvea: https://www.youtube.com/watch?v=UY1QQr-PZOg

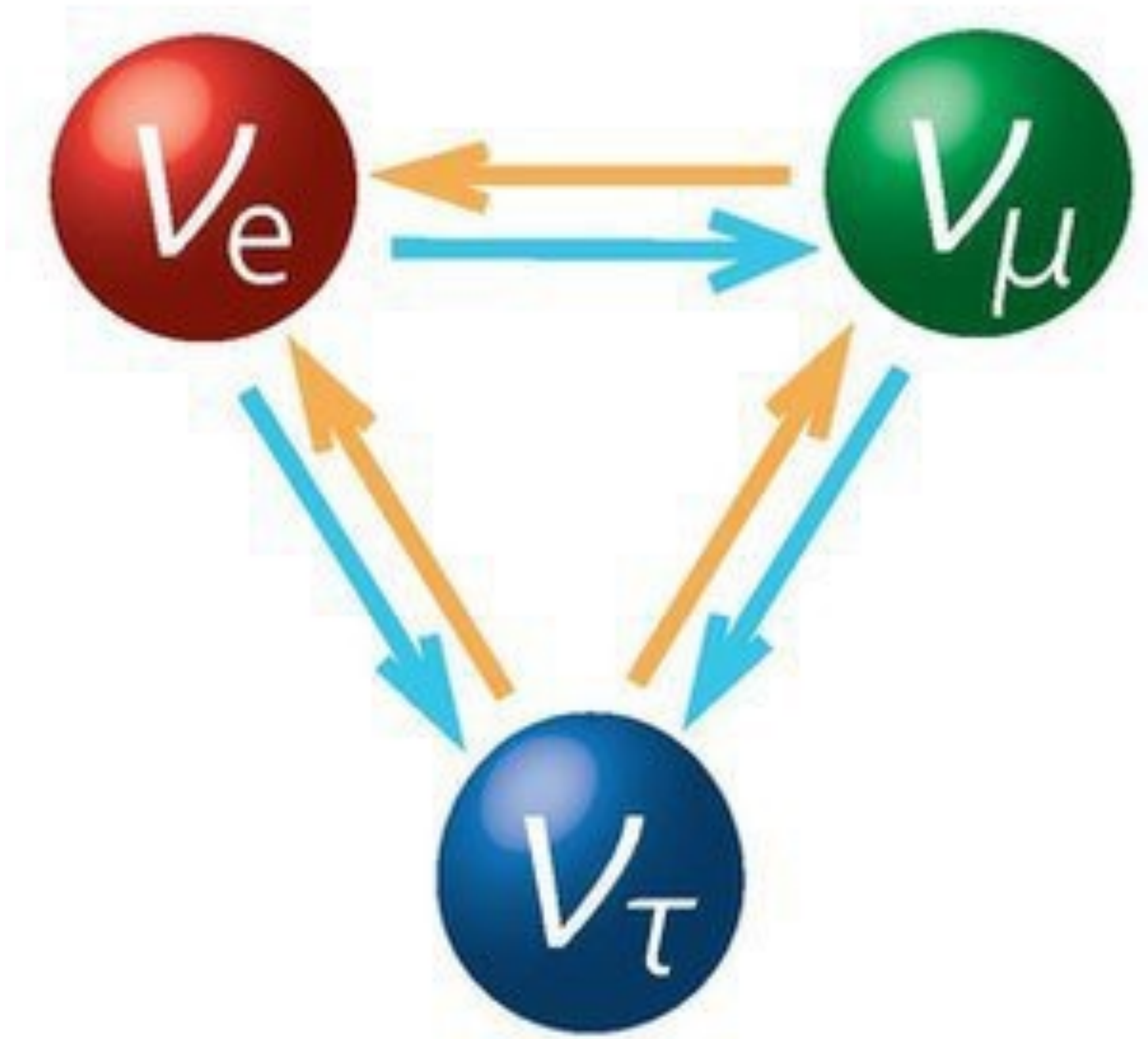
Masses

The difference between the generations is the mass.



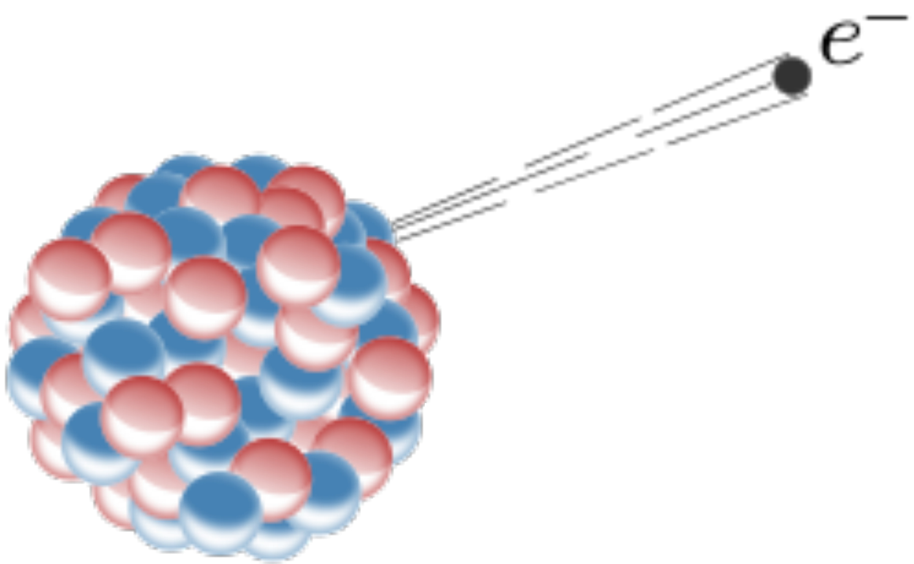
What do we know about neutrinos

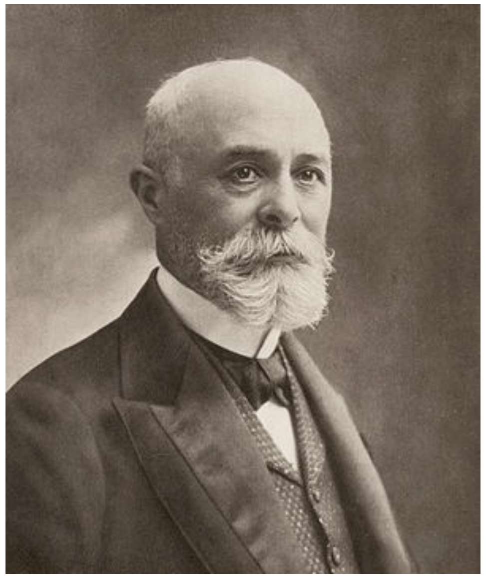
They have very small masses and they change identity



How the neutrinos were discovered?

Beta decay problem <= 1930's




Henri Becquerel


Marie Curie


Pierre Curie

Unstable nucleus loses energy by emitting an electron transforms an atom into different type of atom

For instance:

$^{14}_{6}C \rightarrow ^{14}_{7}N + e^-$

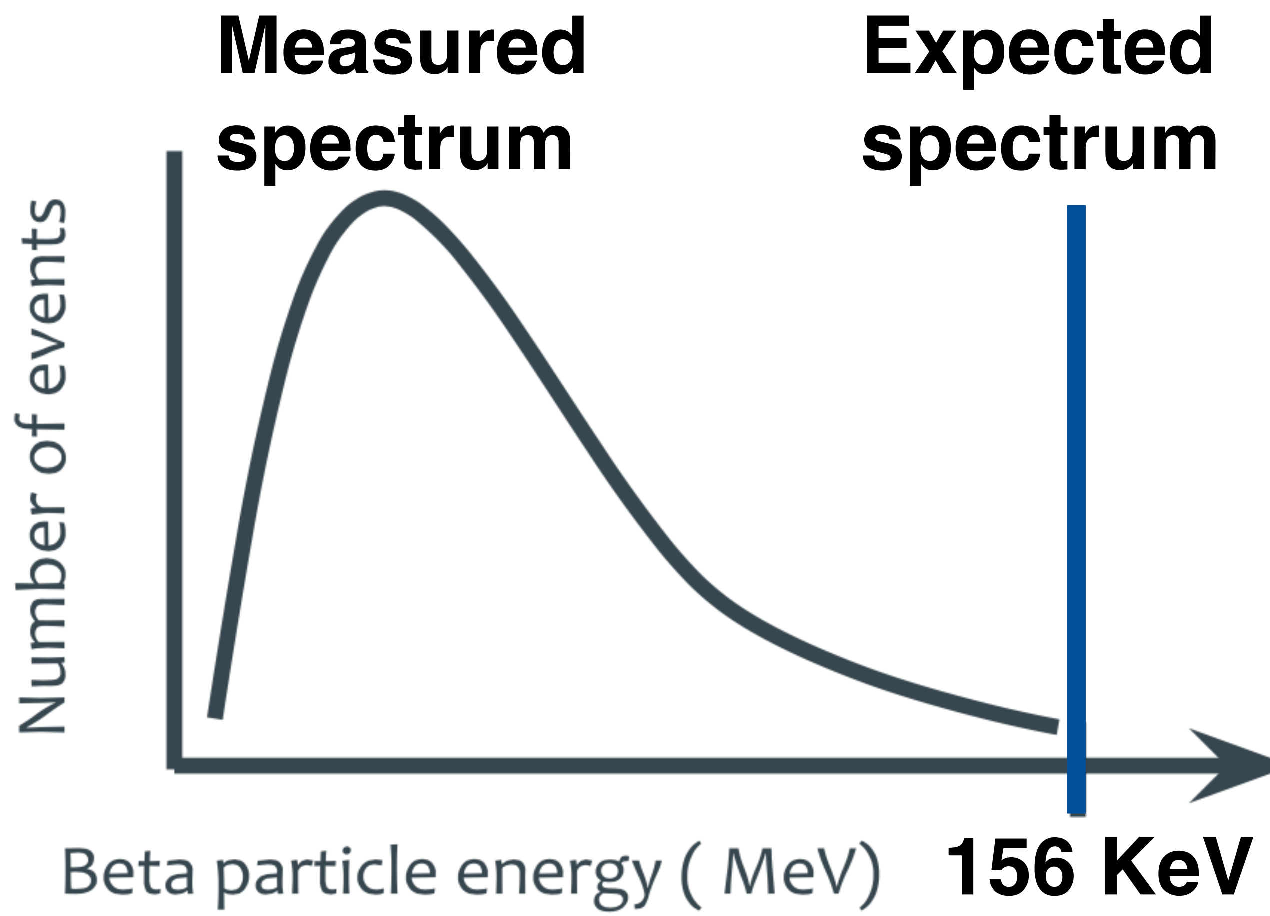
13 043.94 MeV/c² **13 043.27 MeV/c²** **0.511 MeV/c²**

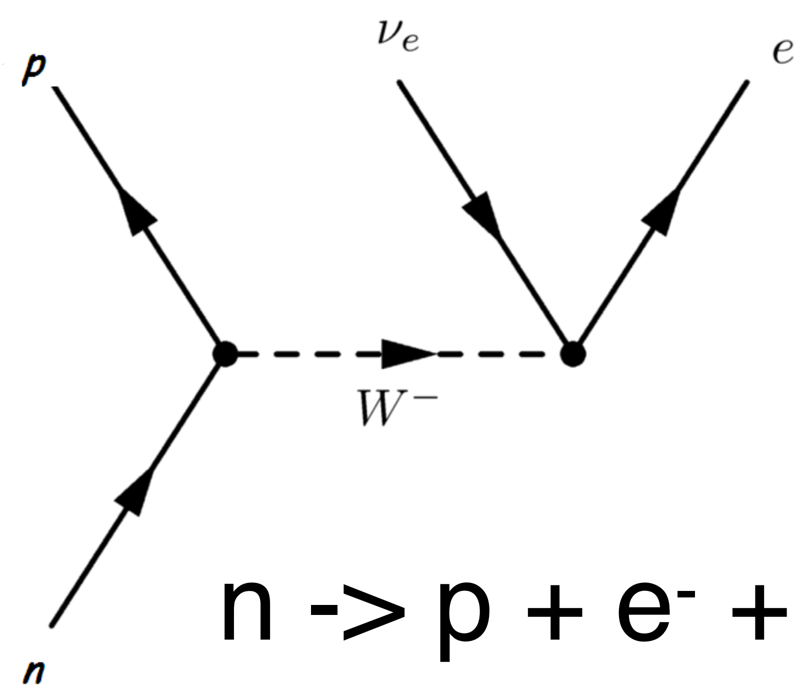
Beta decay problem > 1930's

(1930) Pauli postulated an additional particle (neutral and very small) in beta decays.

(1933) Fermi formulated the theory the weak force to explain the process.

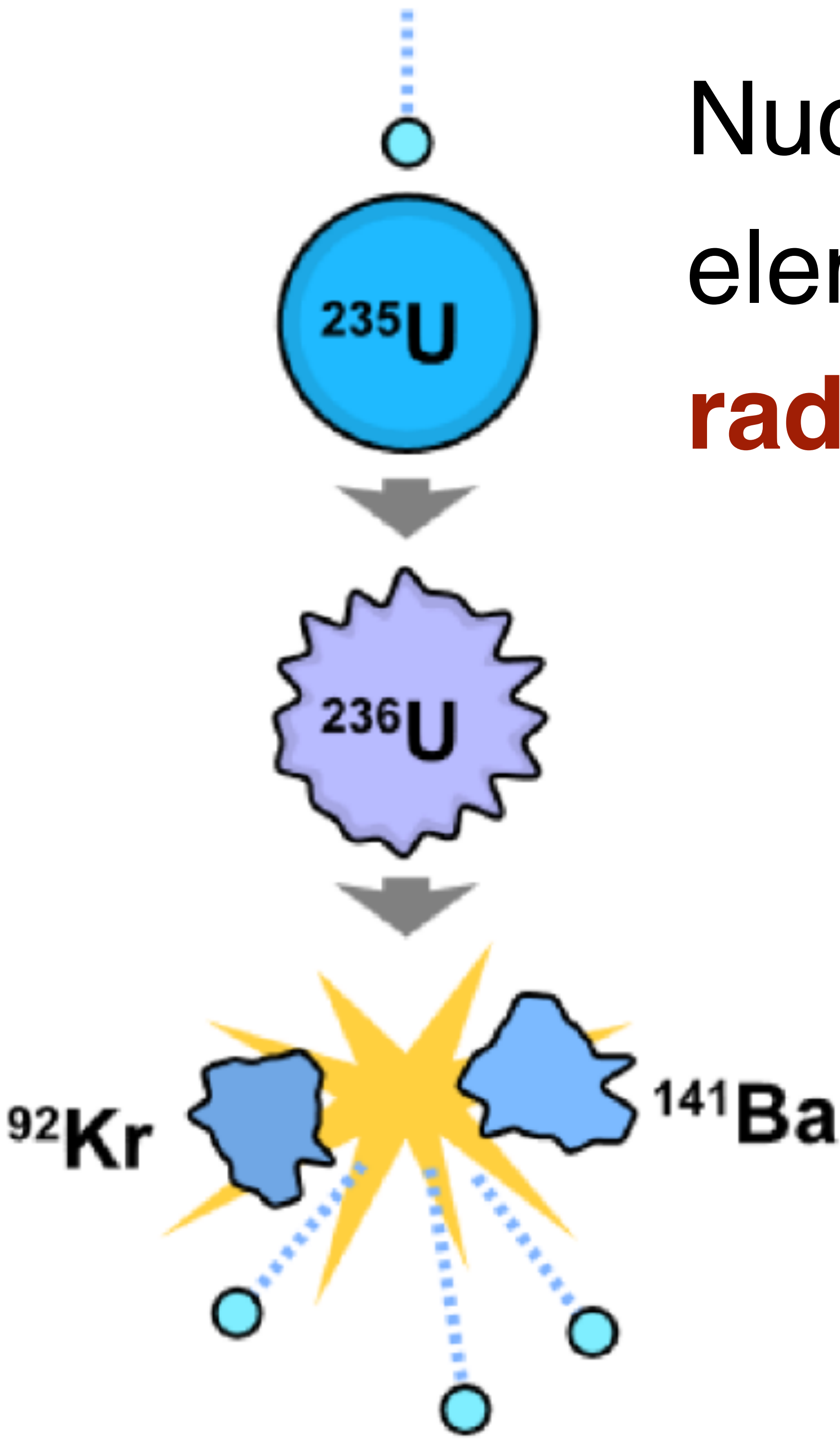
(1936) Yukawa proposed W boson as a carrier of the weak force.





$$n \rightarrow p + e^- + \bar{\nu}_e$$

Detect Neutrinos from Reactors



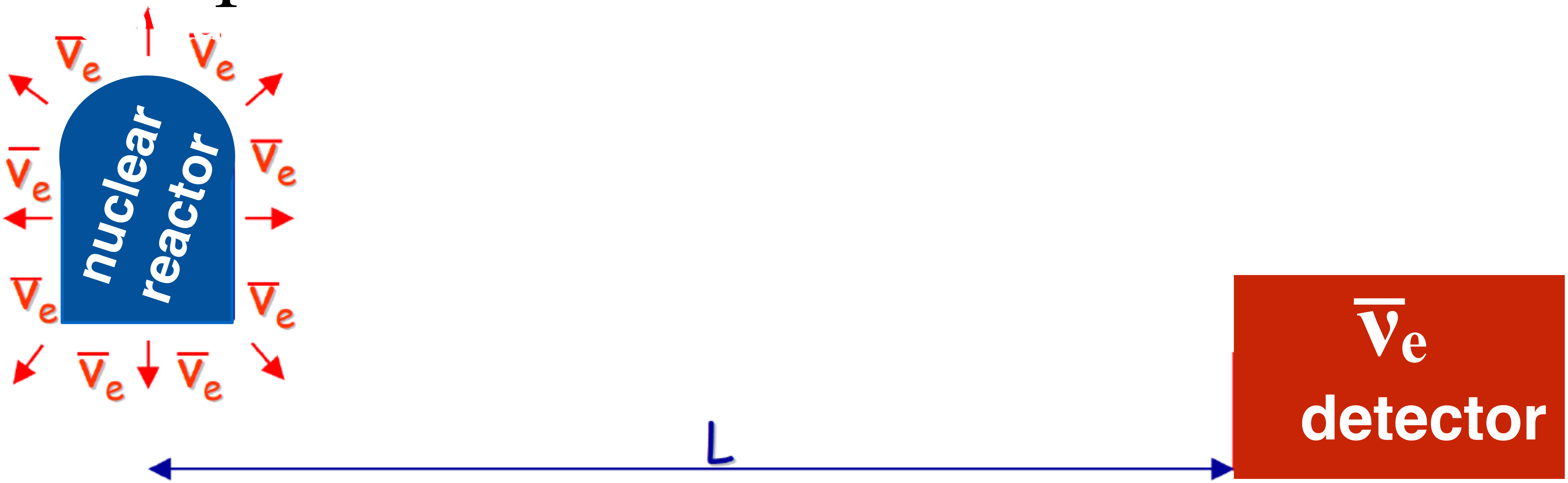
Nuclear fission: bombarding heavy elements with slow neutrons: **artificial radioactivity**

Neutrons are unstable:

$$n \longrightarrow p + e^- + \overline{\nu}_e$$

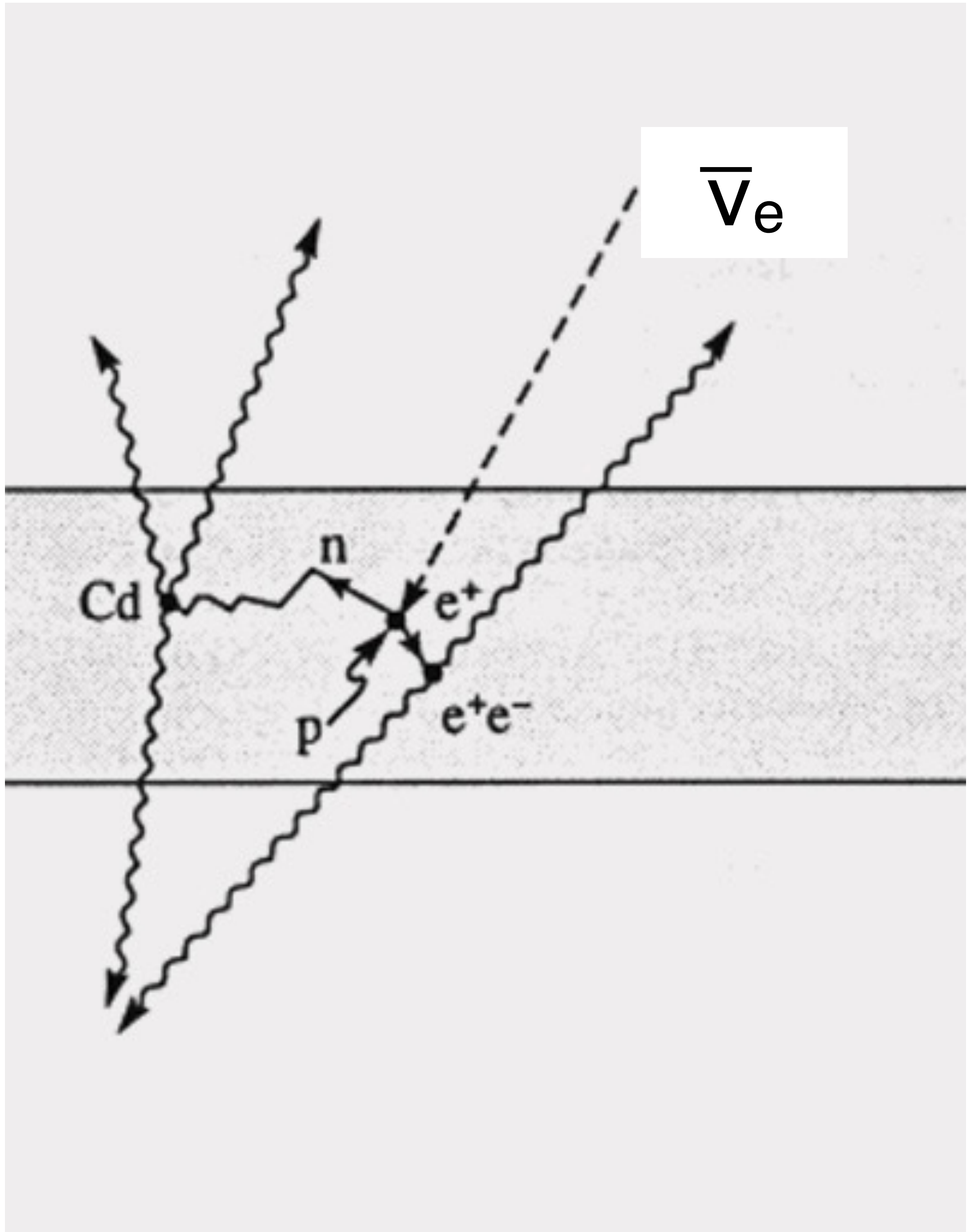
Neutrinos from Reactors

$$n \longrightarrow p + e^- + \bar{\nu}_e$$



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

Poltergeist project



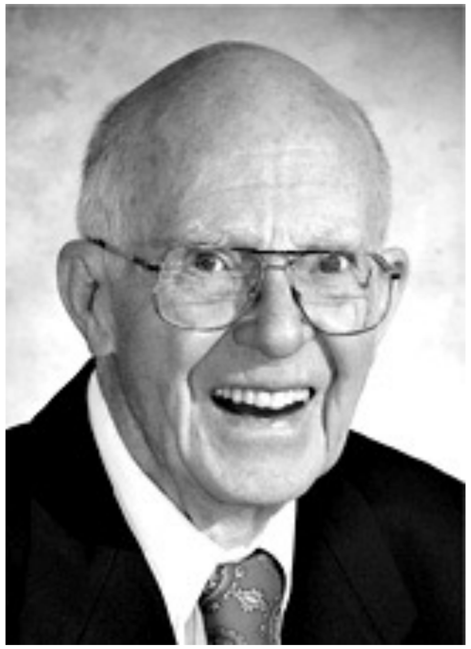
- (1956) A team lead by Clyde Cowan and Frederick Reines designed an experiment to detect neutrinos from a reactor.
- ***Observed 0.56 counts per hour.***

https://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-97-2534-02

Homestake experiment

- (1961) Ray Davis confirmed the detection of solar neutrinos.
- Neutrino interactions convert Cl-37 into radioactive Ar-37.

It was expected 1 neutrino per day.



Ray Davis

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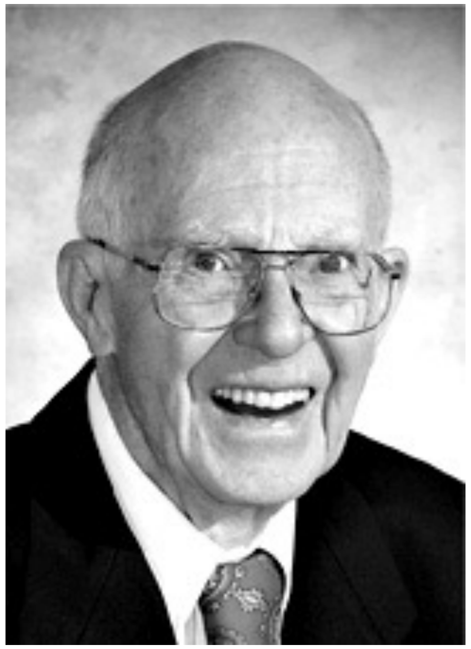
It was expected 1 neutrino per day. However, they only saw 1 neutrino every fourth days.



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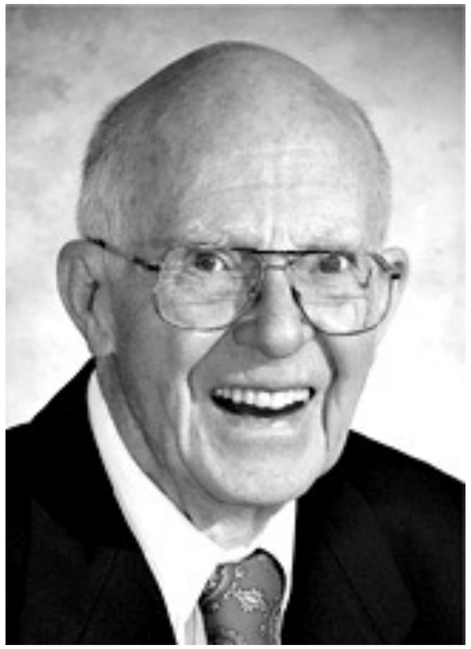

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Our understanding of how our detector behaves is wrong

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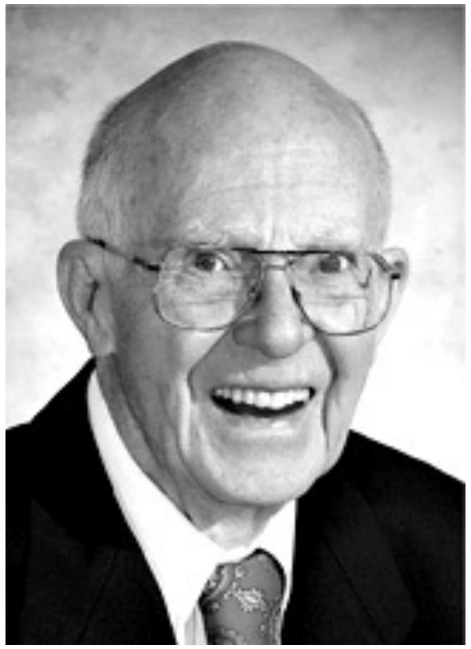

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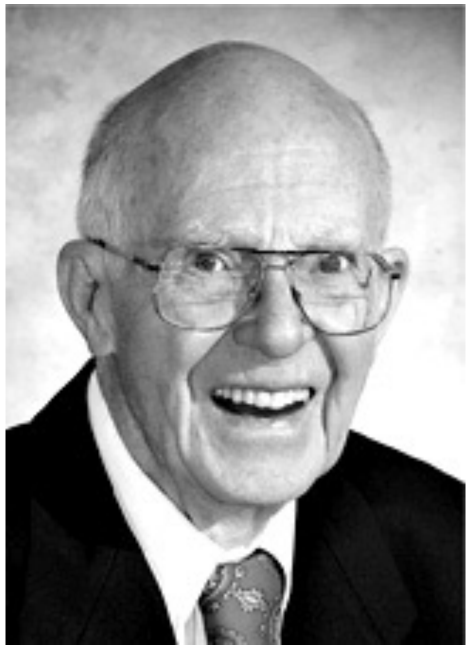
Our understanding of how our detector behaves is wrong

Is the Solar model wrong?

Homestake experiment



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Our understanding of how our detector behaves is wrong

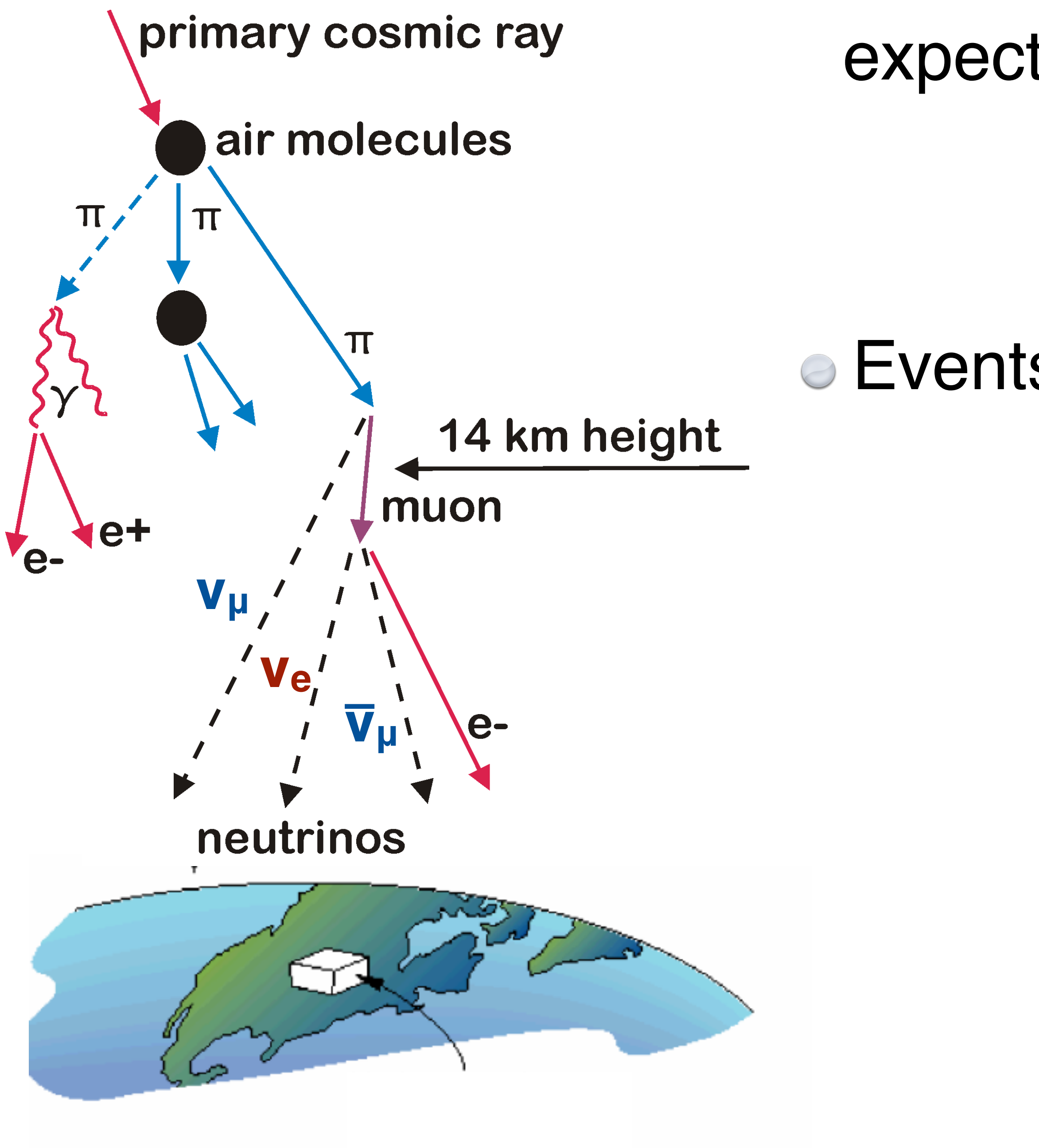
Is the Solar model wrong?

Our understanding on how neutrinos behave is wrong?

https://cdn.journals.aps.org/files/RevModPhys.75.985.pdf

Atmospheric neutrinos

- Cosmic rays (mostly) interact in the upper atmosphere creating a hadronic showers (mostly pions).

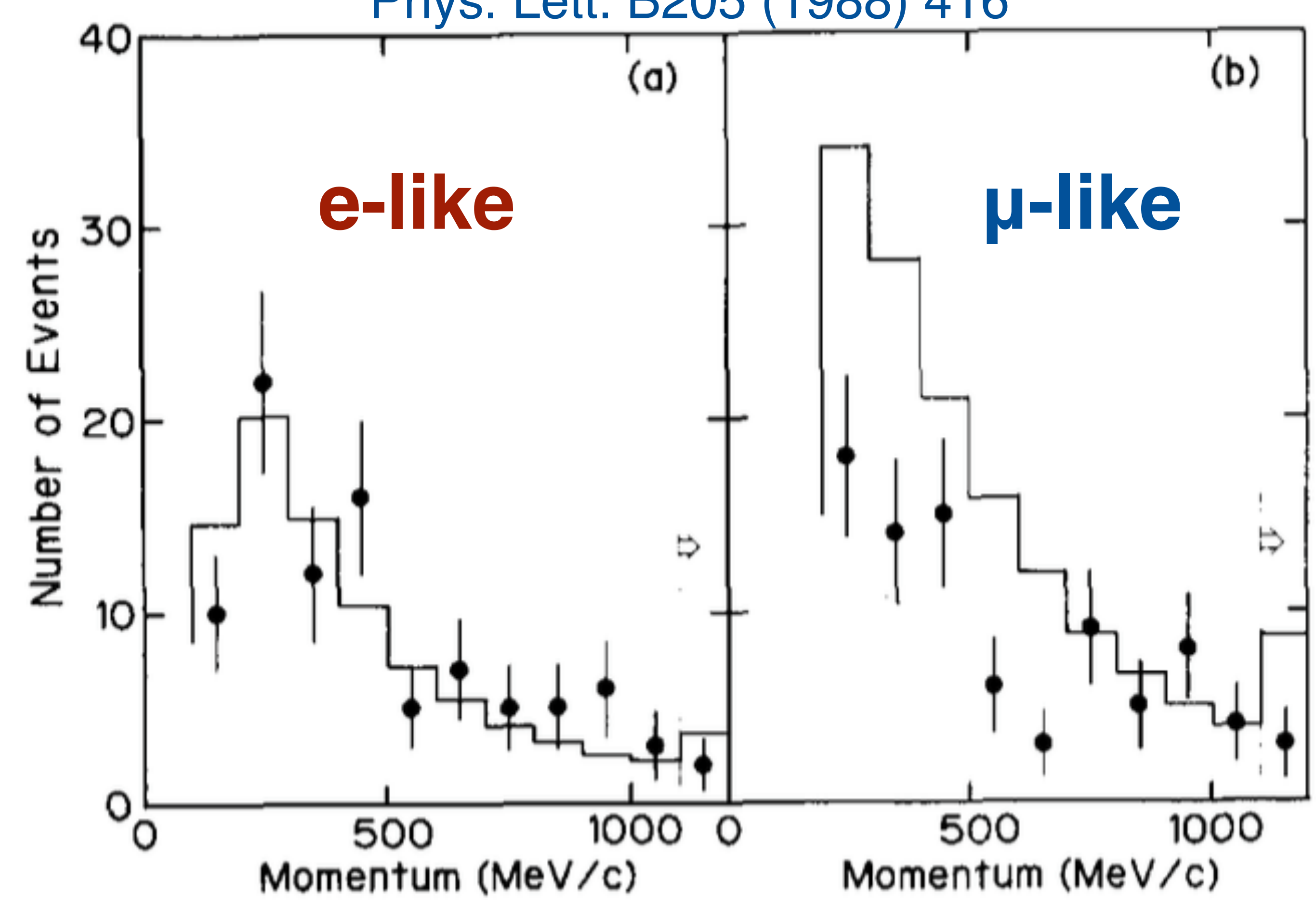


- Roughly 2:1 muon neutrinos to electron neutrinos expected:

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

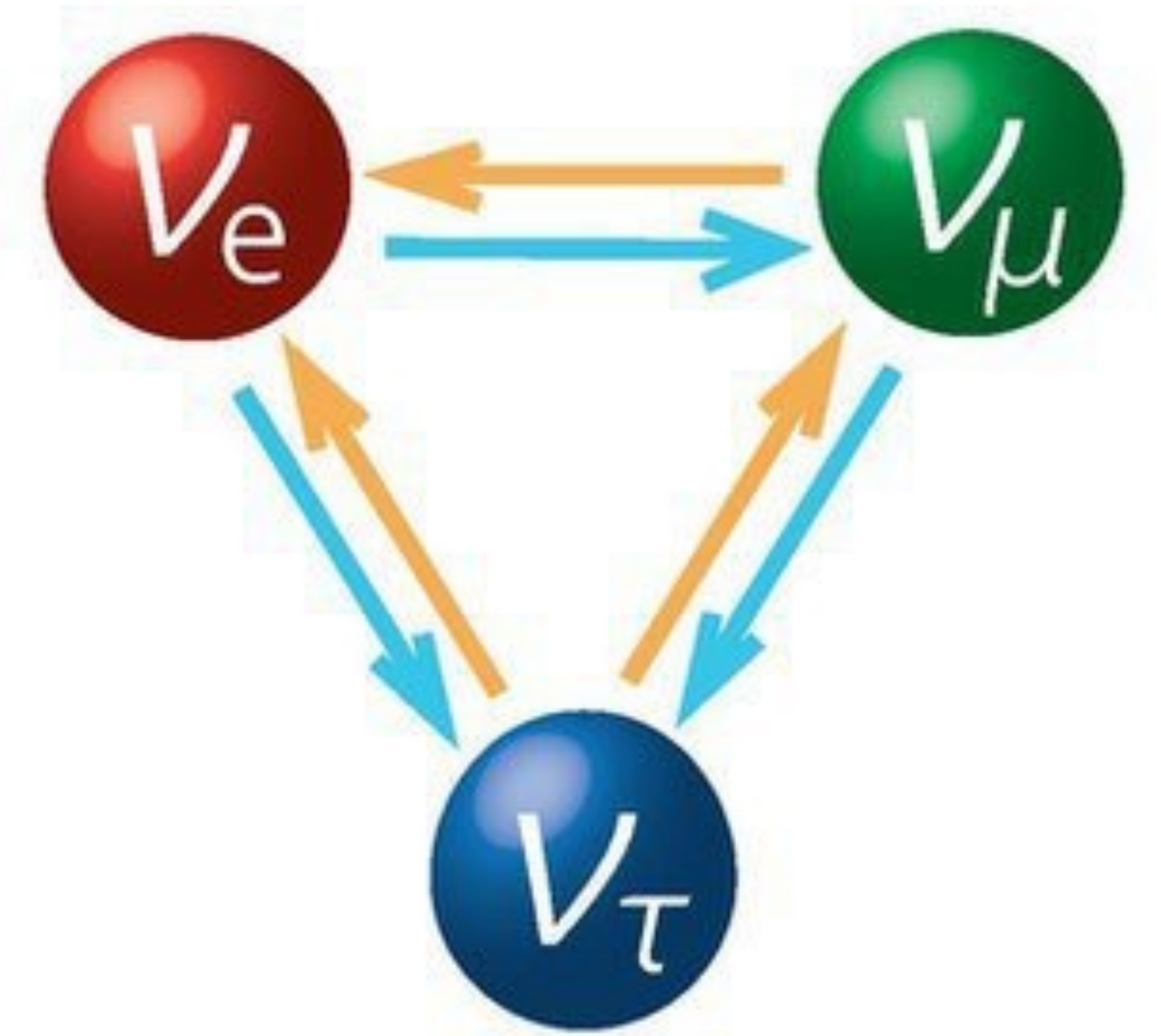
- Events found in Kamiokande (~3kton WC) 1988

Phys. Lett. B205 (1988) 416



What is really the identity of neutrinos?

Neutrinos Oscillation



Create in one flavor, but detect in another flavor

Create in one flavor, but detect in another flavor

Created or detected

States associated to the corresponding lepton

ν_e

ν_μ

ν_τ

Create in one flavor, but detect in another flavor

Created or detected

Traveling

States associated to the corresponding lepton

ν_e

ν_μ

ν_τ

ν_1

ν_2

ν_3

States with well determined mass

Create in one flavor, but detect in another flavor

Created or detected ***Traveling***

States associated to the corresponding lepton

ν_e ν_1

ν_μ ν_2

ν_τ ν_3

States with well determined mass

They do not match

Create in one flavor, but detect in another flavor

$$\nu_e = \nu_1 + \nu_2 + \nu_3$$

$$\nu_\mu = \nu_1 + \nu_2 + \nu_3$$

$$\nu_\tau = \nu_1 + \nu_2 + \nu_3$$

Create in one flavor, but detect in another flavor

distance

$$\nu_e = \nu_1 + \nu_2 + \nu_3$$

$$\nu_\mu = \nu_1 + \nu_2 + \nu_3$$

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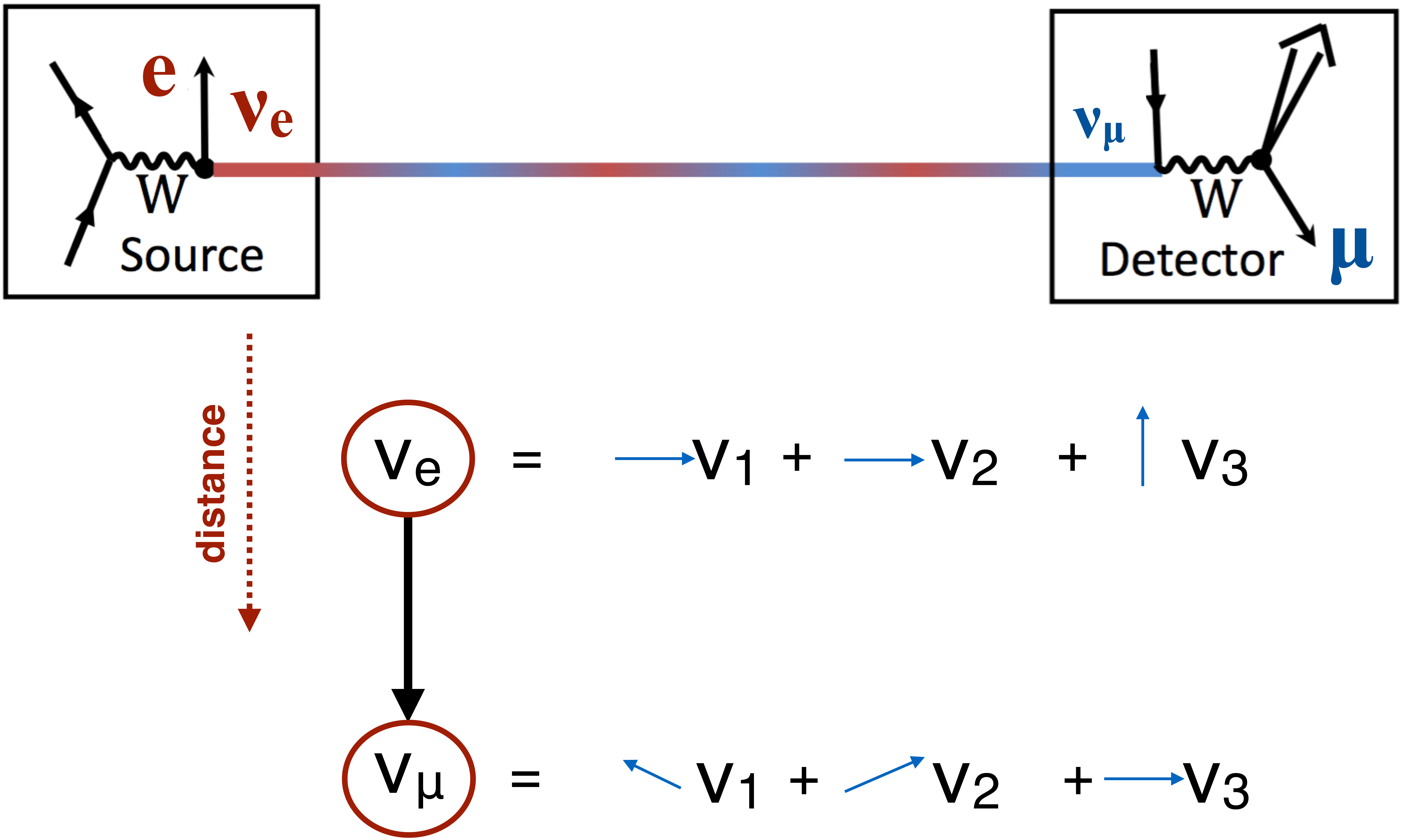

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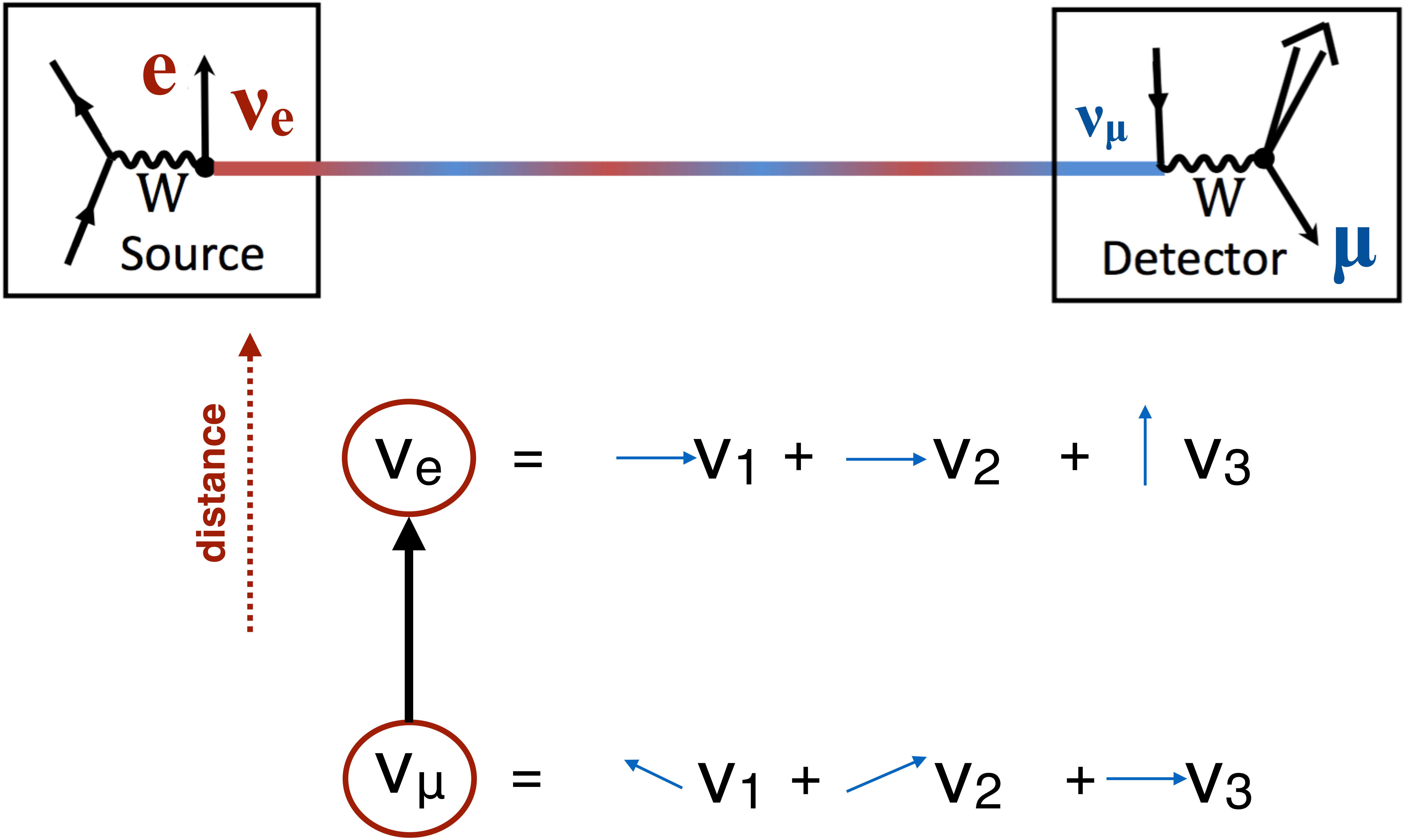
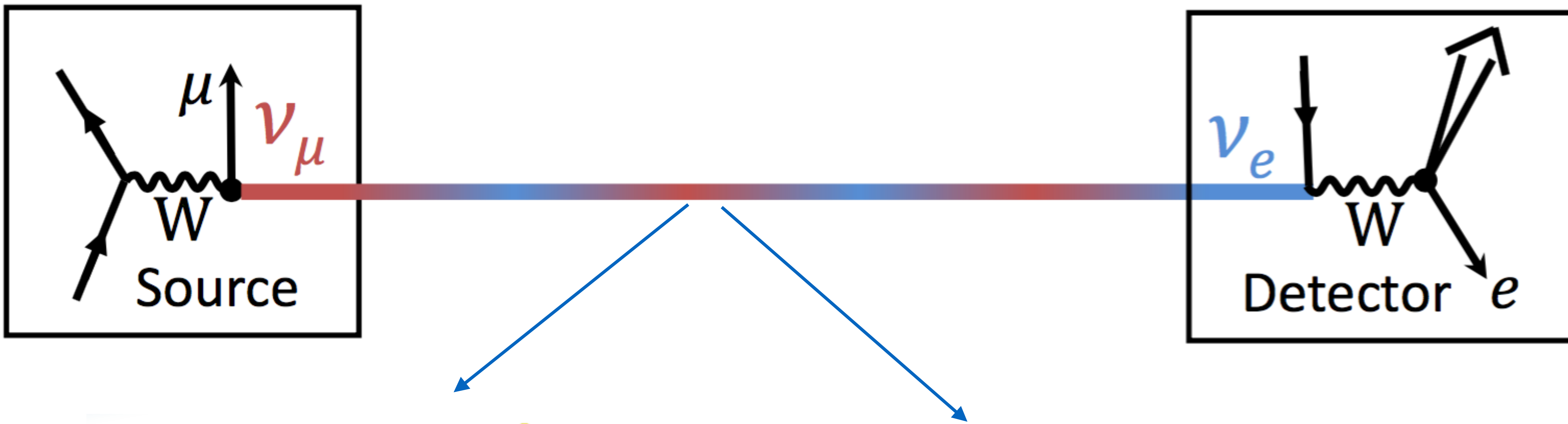
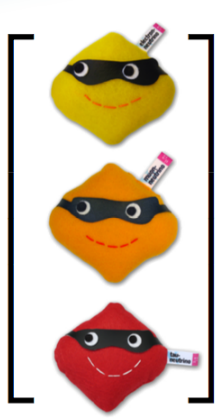
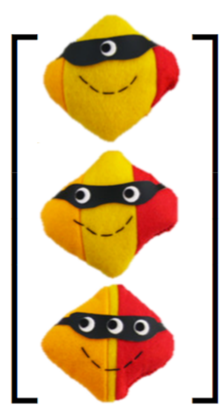


Create in one flavor, but detect in another flavor

https://www.youtube.com/watch?v=7fgKBJDMO54

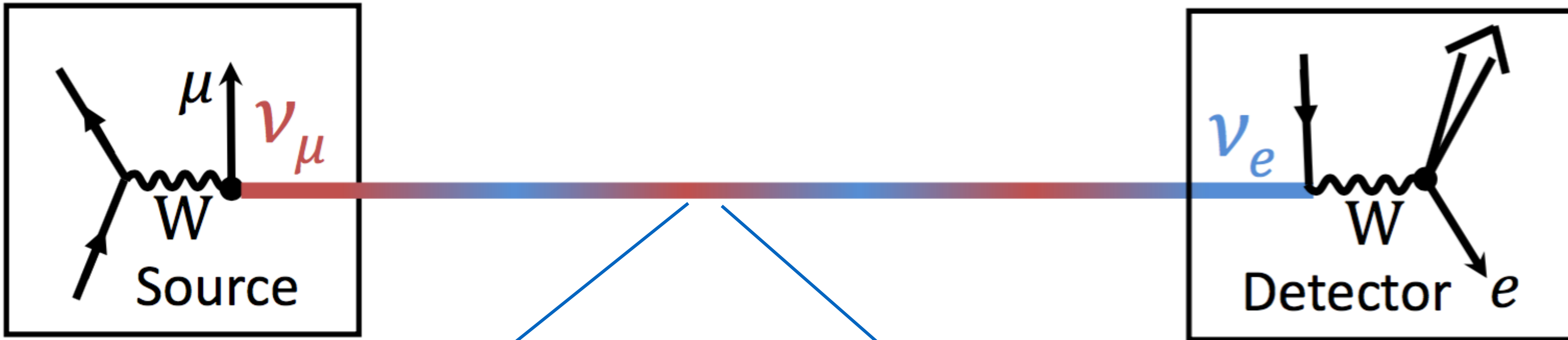
Create in one flavor, but detect in another flavor

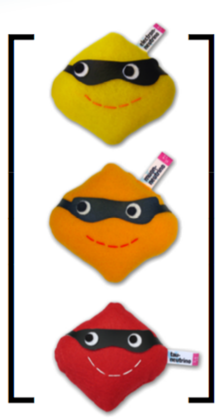
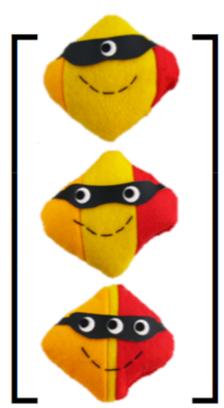


 $= U_{\text{PMNS}}$ 

$\phi(p,E,r,t)$

Create in one flavor, but detect in another flavor



 $= U_{\text{PMNS}}$ 

$\phi(p,E,r,t)$

$$\boxed{P_{\alpha\to\beta} = \left|\langle \nu_\beta(t) | \nu_\alpha \rangle\right|^2}$$

α, β: e, μ, τ

If we have only 2 neutrinos…

Each flavor is a superposition of different masses:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

"Mixing Matrix"

$$\boxed{P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)}$$

α, β: e, μ, τ

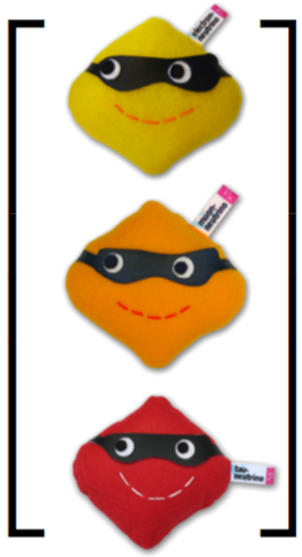
$\Delta m^2 = m_i^2 - m_j^2$

The complete view with 3 flavor oscillation

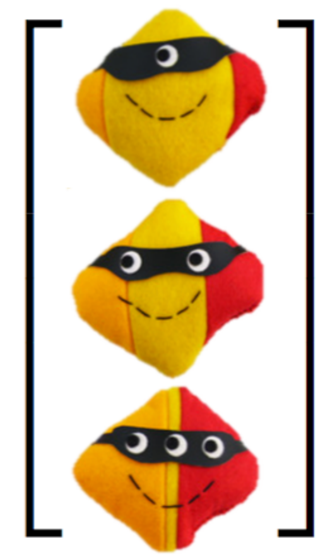
PMNS

$$
= \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}
$$

The complete view with 3 flavor oscillation



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



The complete view with 3 flavor oscillation

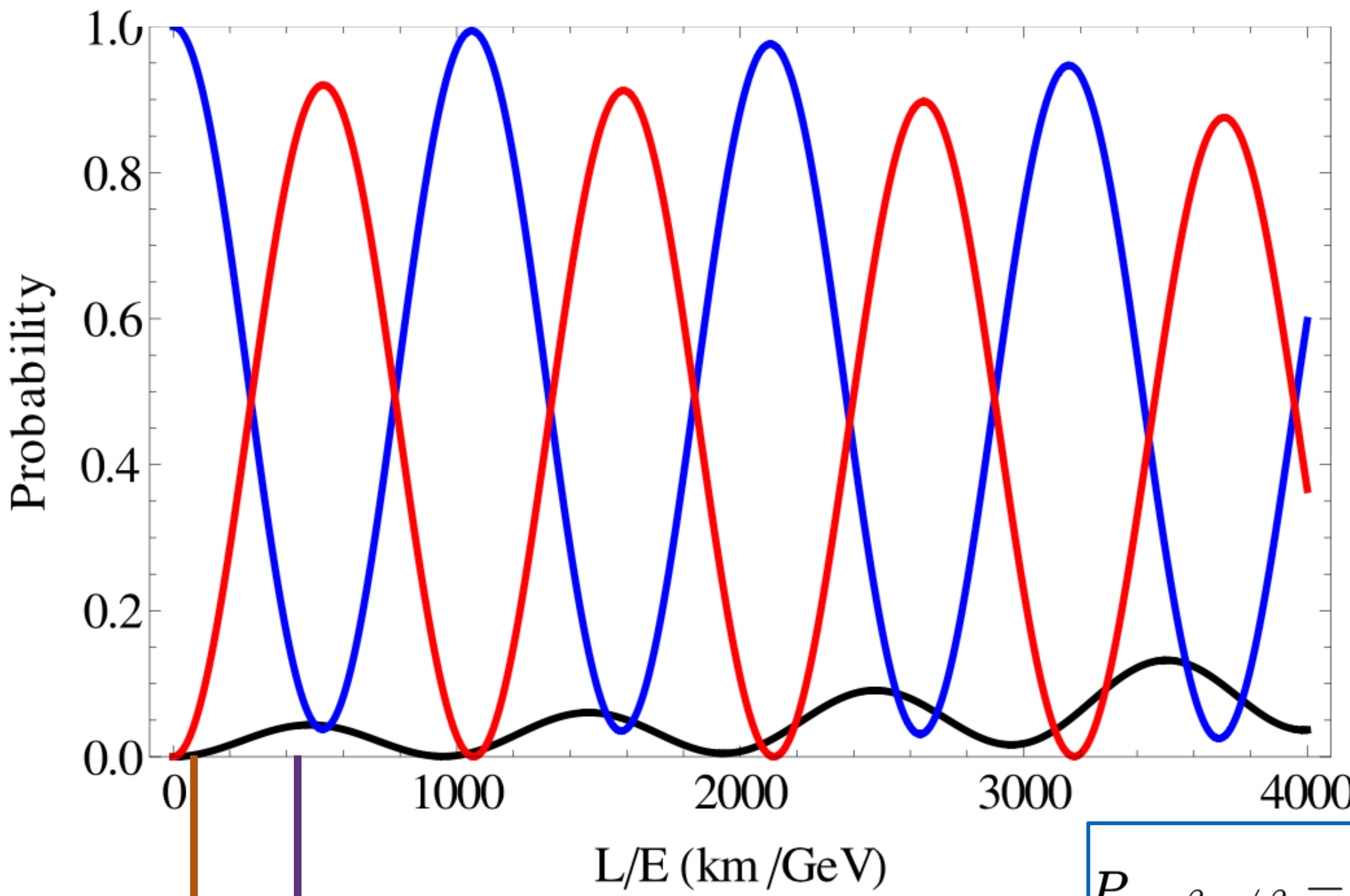
$$= R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12})$$

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

$c_{23} = \cos\theta_{23}$, …

$s_{23} = \sin\theta_{23}$, …

Oscillation probability for an initial ν_μ



Blue: ν_μ

Black: ν_τ

Red : ν_e

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

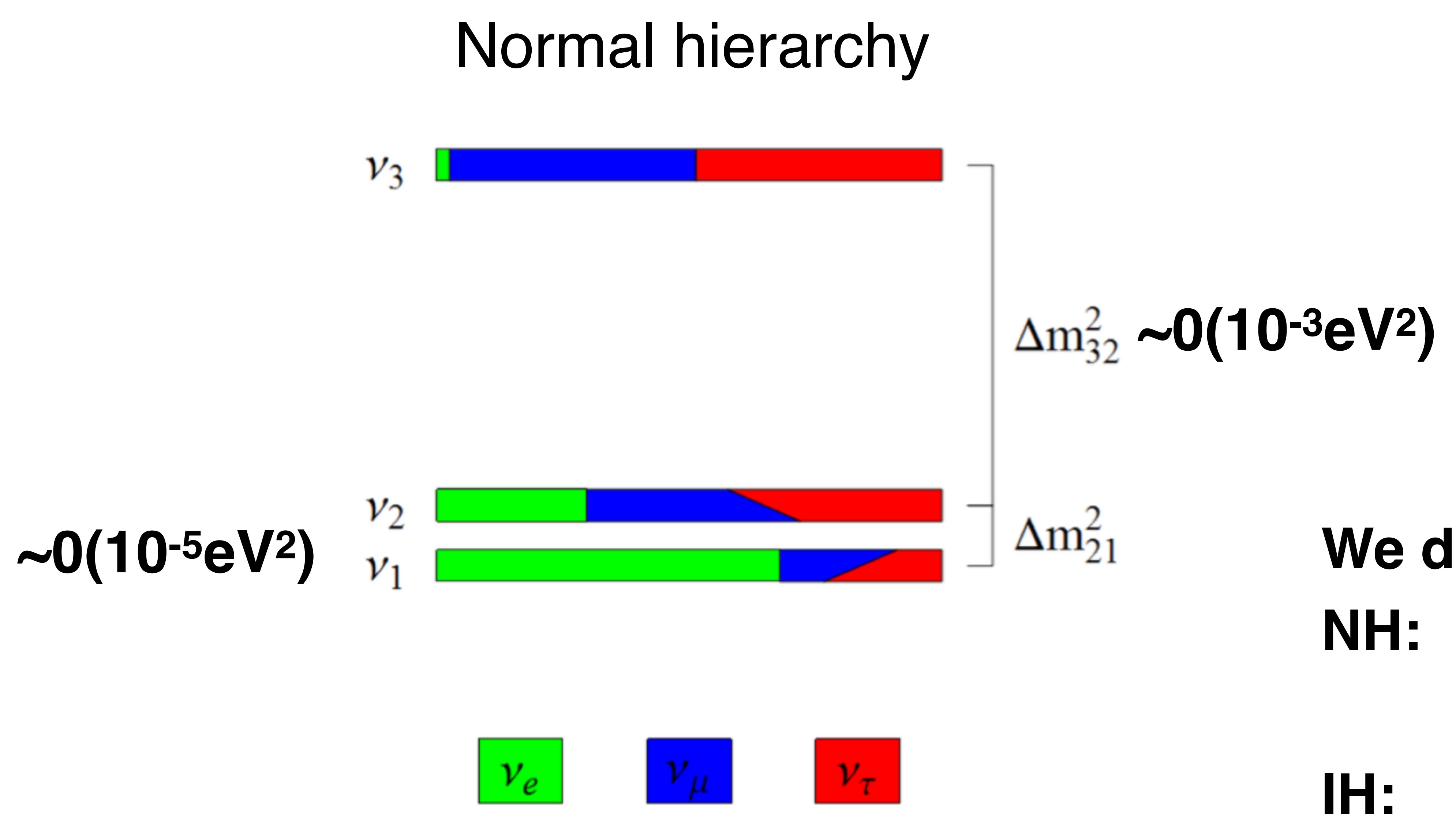
For NOvA FD, L = 810 km and E ~ 2GeV, **L/E ~ 405 km/GeV**

For NOvA ND, L = 1 km and E ~ 2GeV, L/E ~ 0.5 km/GeV

https://en.wikipedia.org/wiki/Neutrino_oscillation

Current knowledge of the oscillation parameters

Measured from Sun, atmosphere, reactor and accelerators"



We do not know if

NH: $m_3 > m_1, m_2$ ….

or

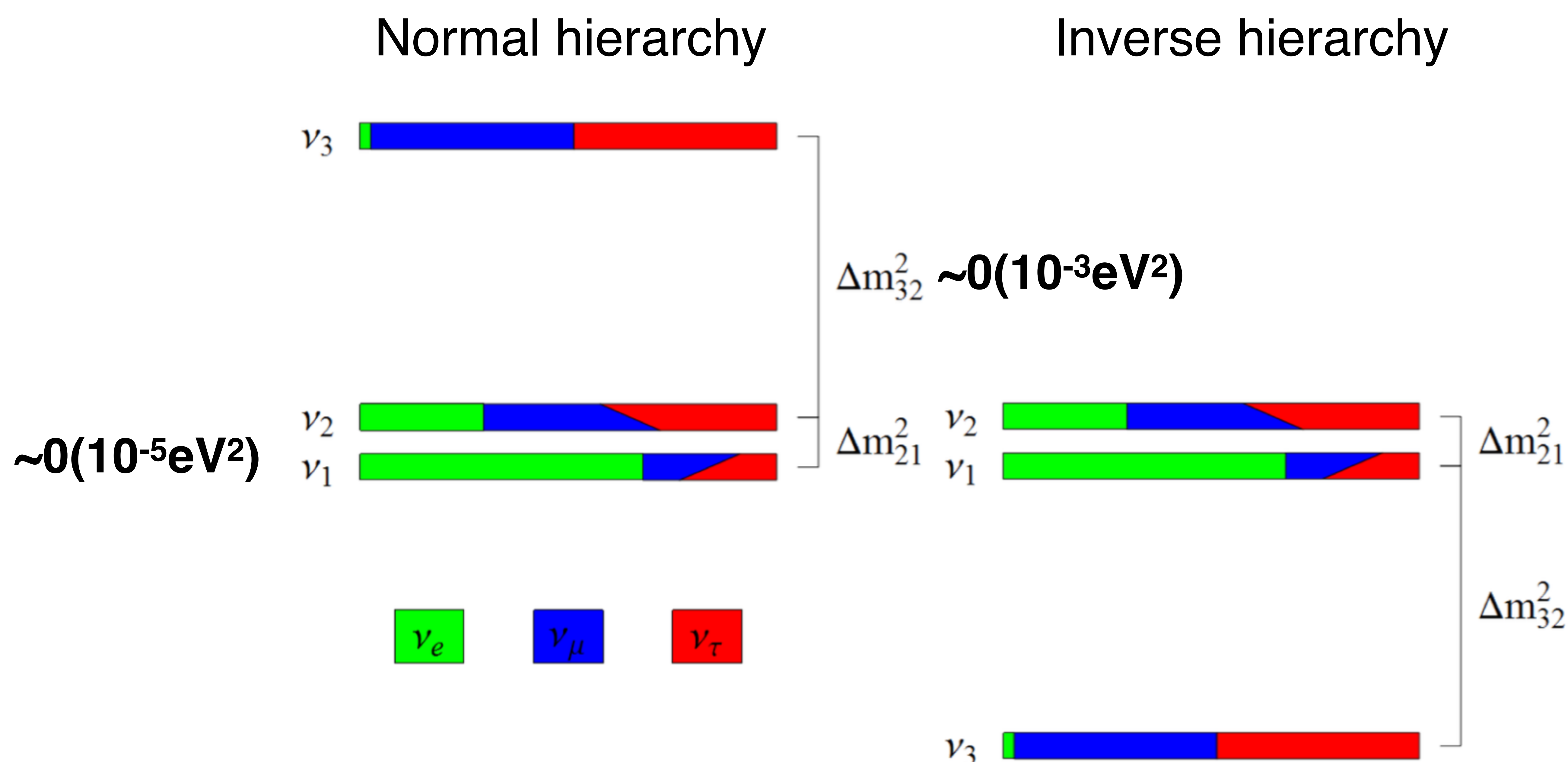
IH: $m_3 < m_1, m_2$

We know that $m_2 > m_1$, see:

https://en.wikipedia.org/wiki/Mikheyev–Smirnov–Wolfenstein_effect

Current knowledge of the oscillation parameters

Measured from Sun, atmosphere, reactor and accelerators



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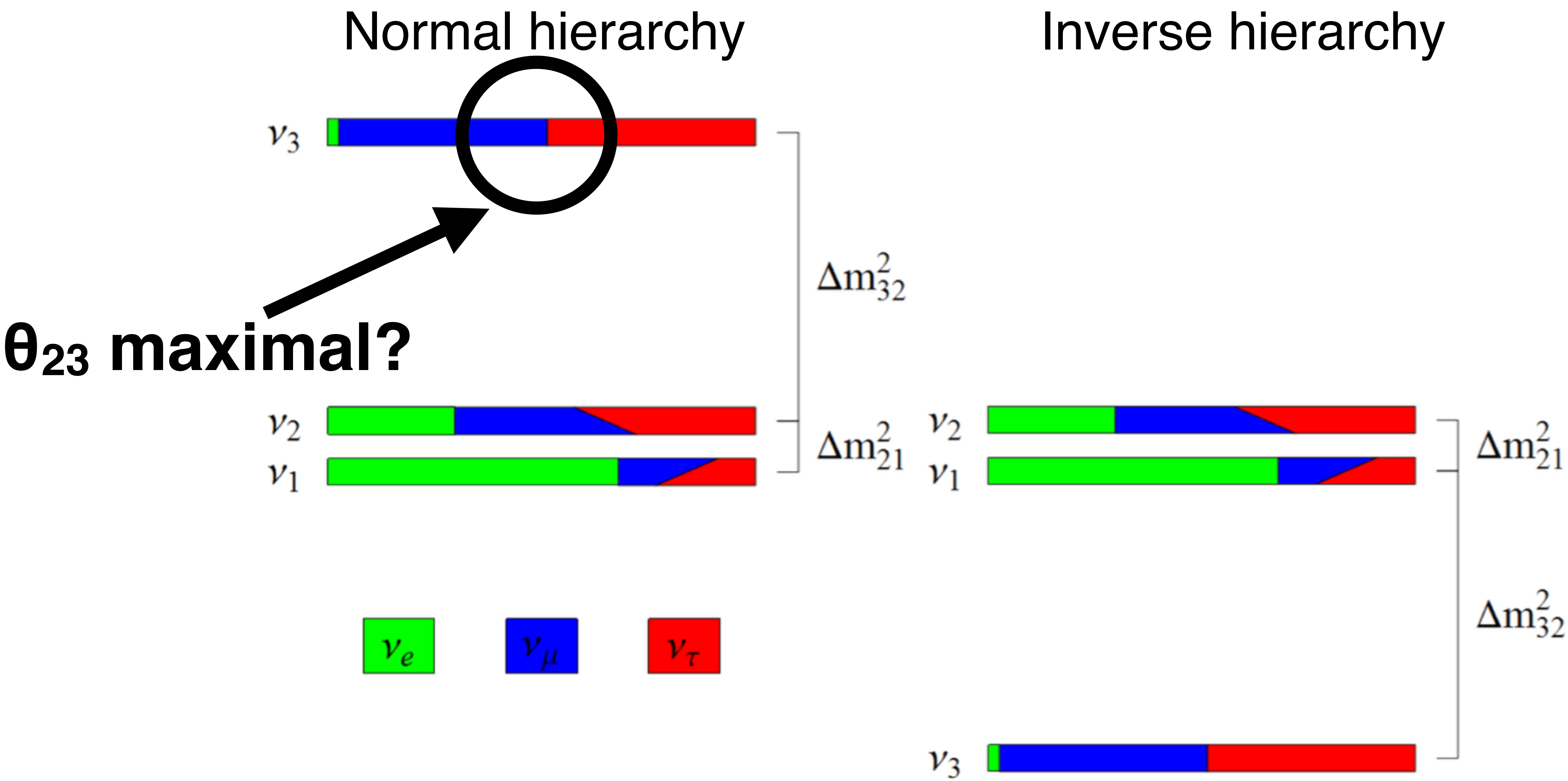


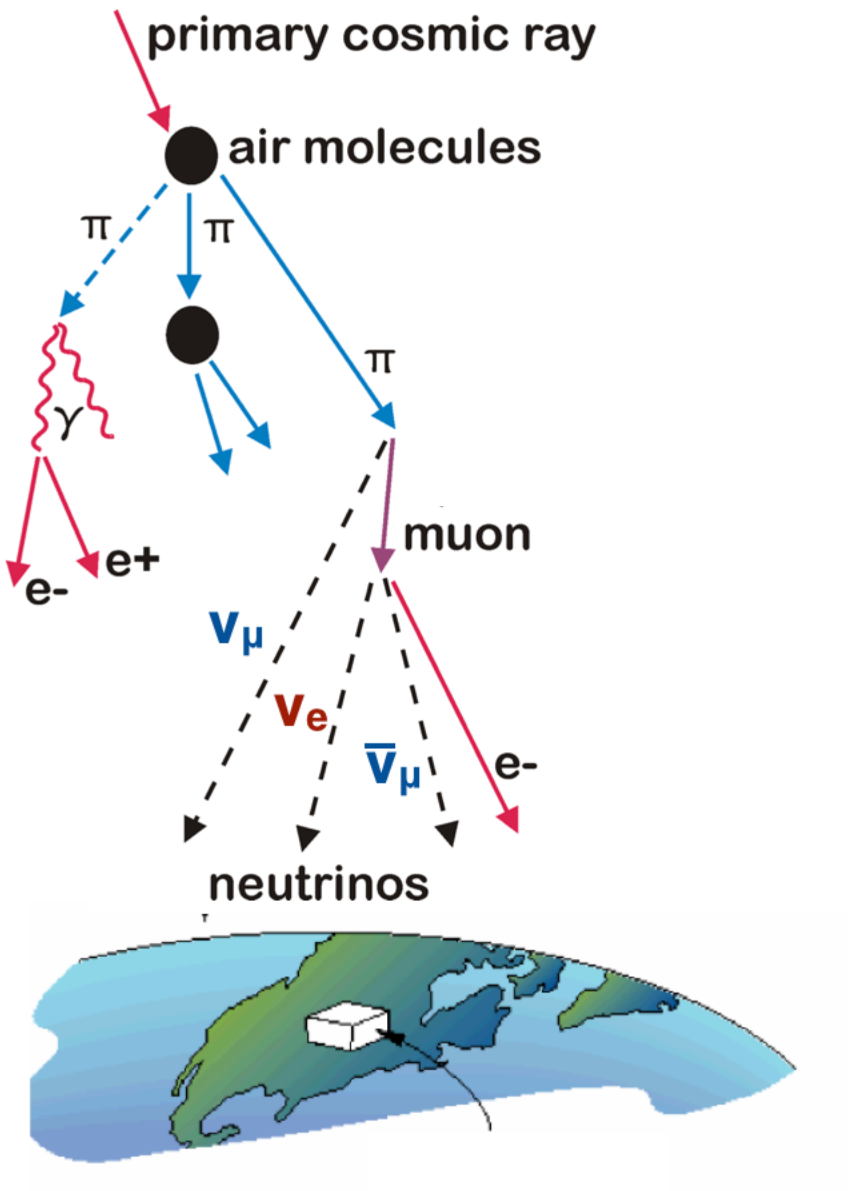
Neutrinos at Fermilab


NEUTRINO EXPERIMENTS

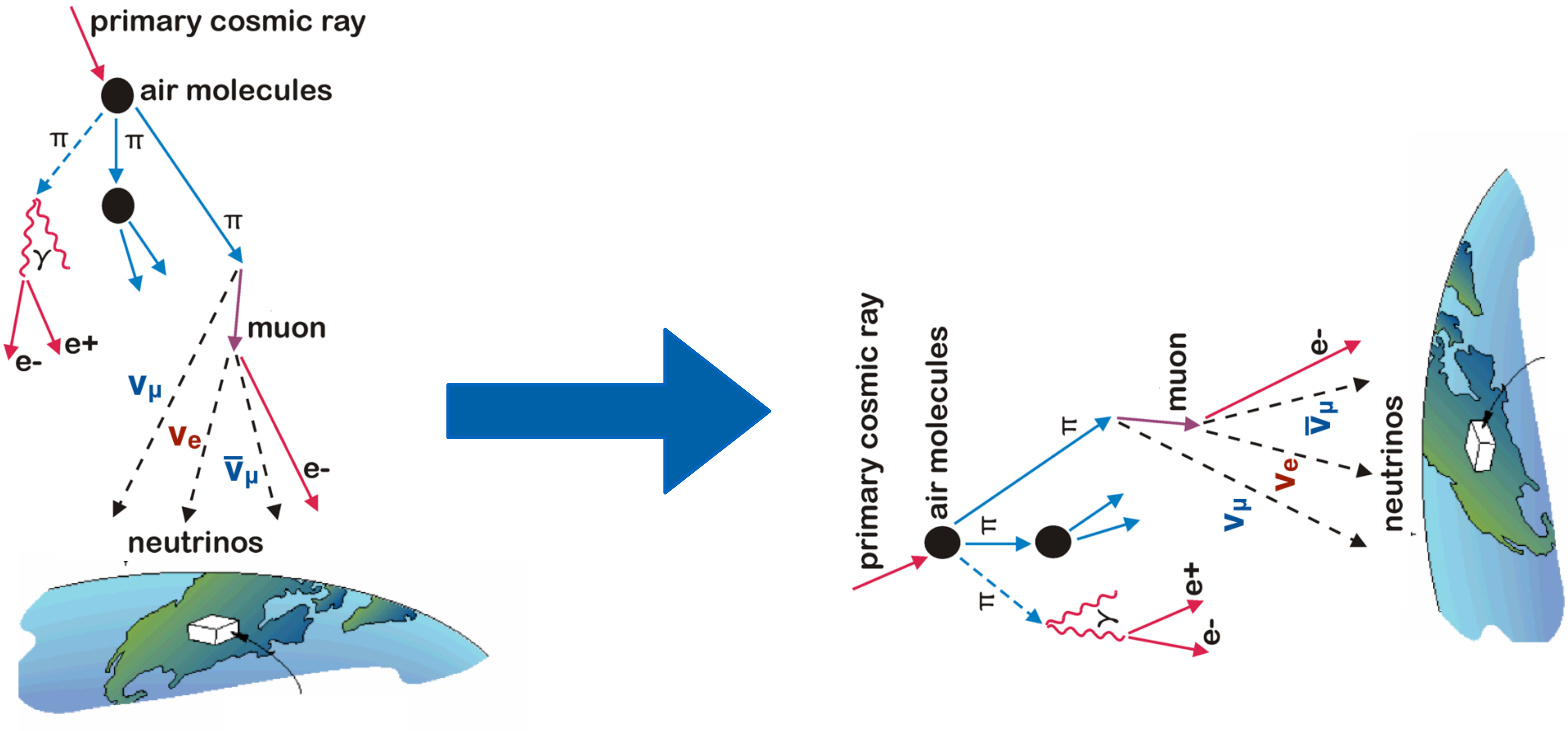

NEUTRINO THEORIES

https://www.smbc-comics.com/comic/2010-08-29

Accelerator Neutrino Beam



Accelerator Neutrino Beam: same concept as the atmospheric neutrino



- The concept of the **neutrino beam from accelerators** was proposed independently by Pontecorvo and Schwartz (1959 - 1960).

By 1960s….

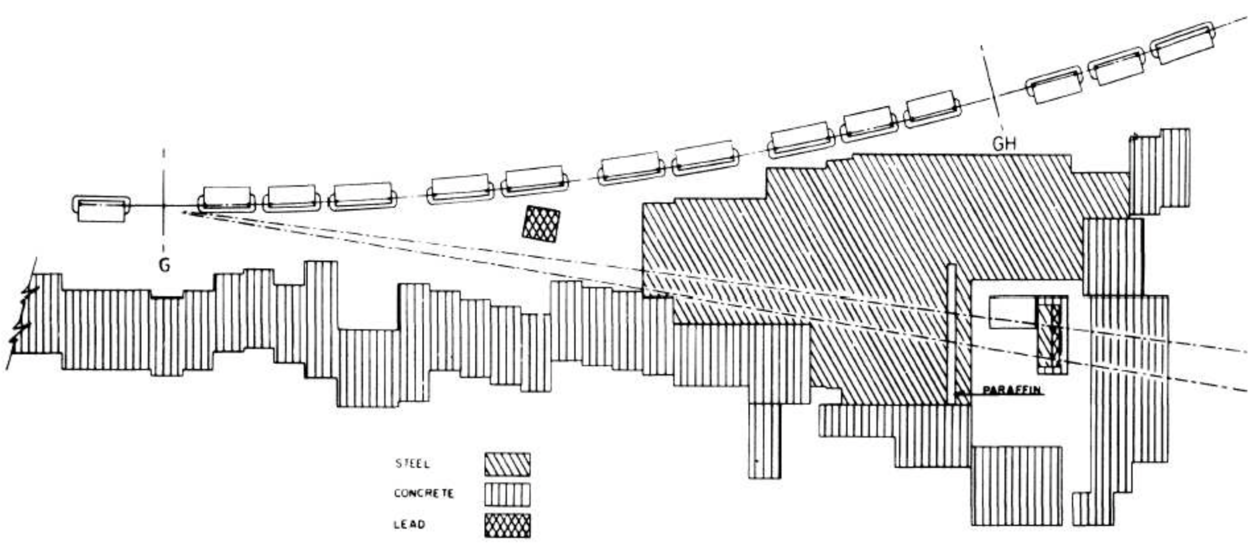
- The Standard Model was under construction… many remaining unsolved problems in the electroweak sector….

For instance, ***are ν*** *(emitted in β decays)* ***and ν*** *(emitted in π -> μ)* ***identical particles?***

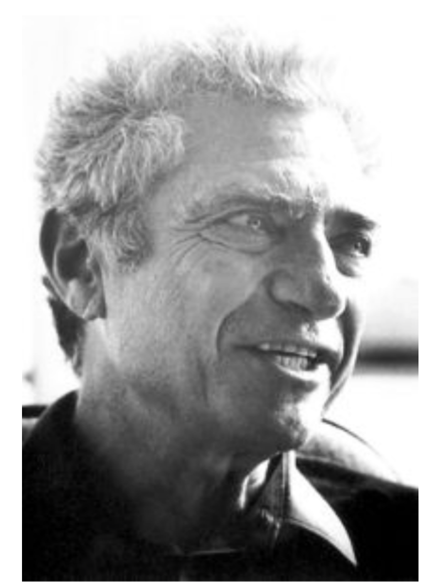
Is it possible to use high energy ν's to study weak interactions?

- The concept of the **neutrino beam from accelerators** was proposed independently by Pontecorvo and Schwartz to answer the question…

Yes! we get 1 ν per hour.

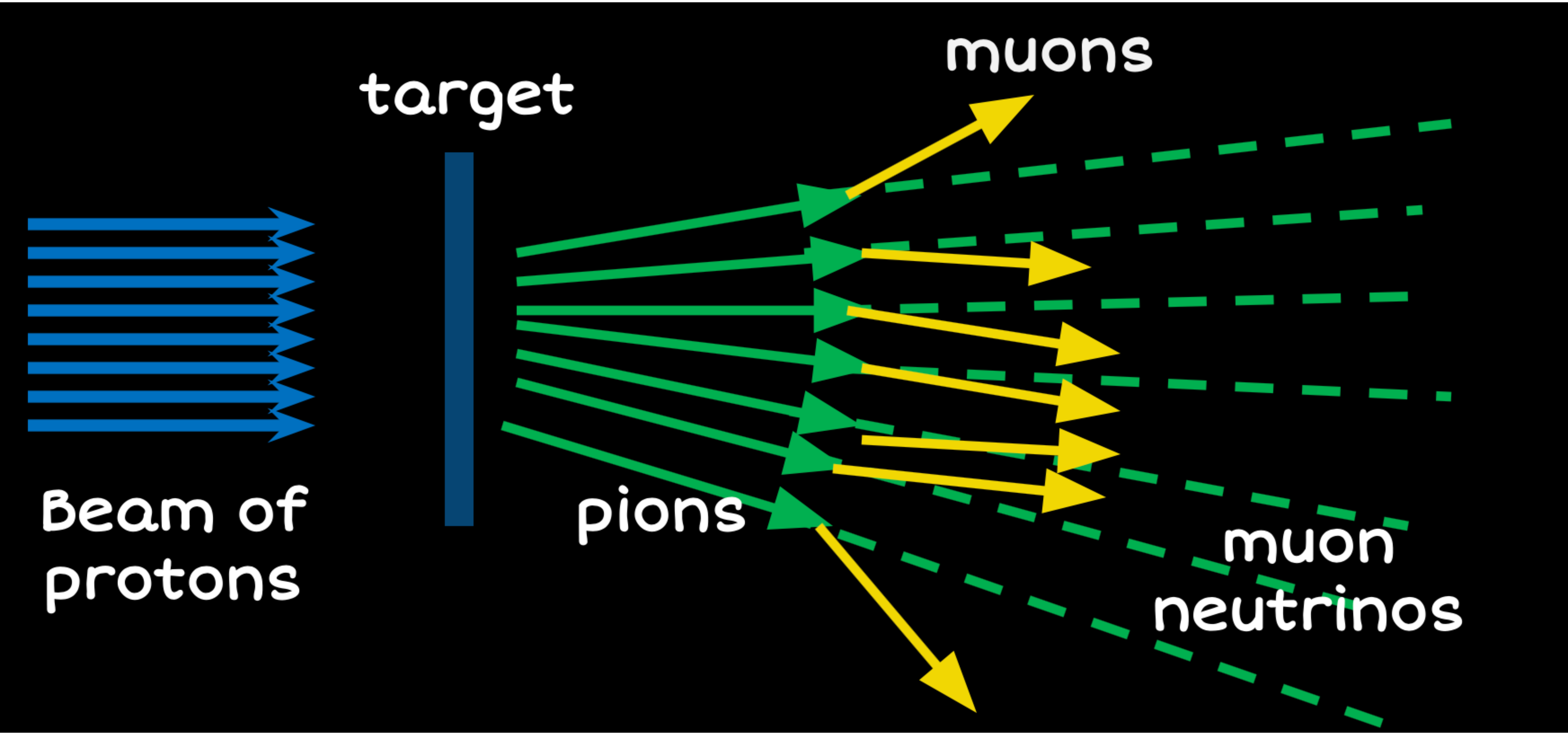


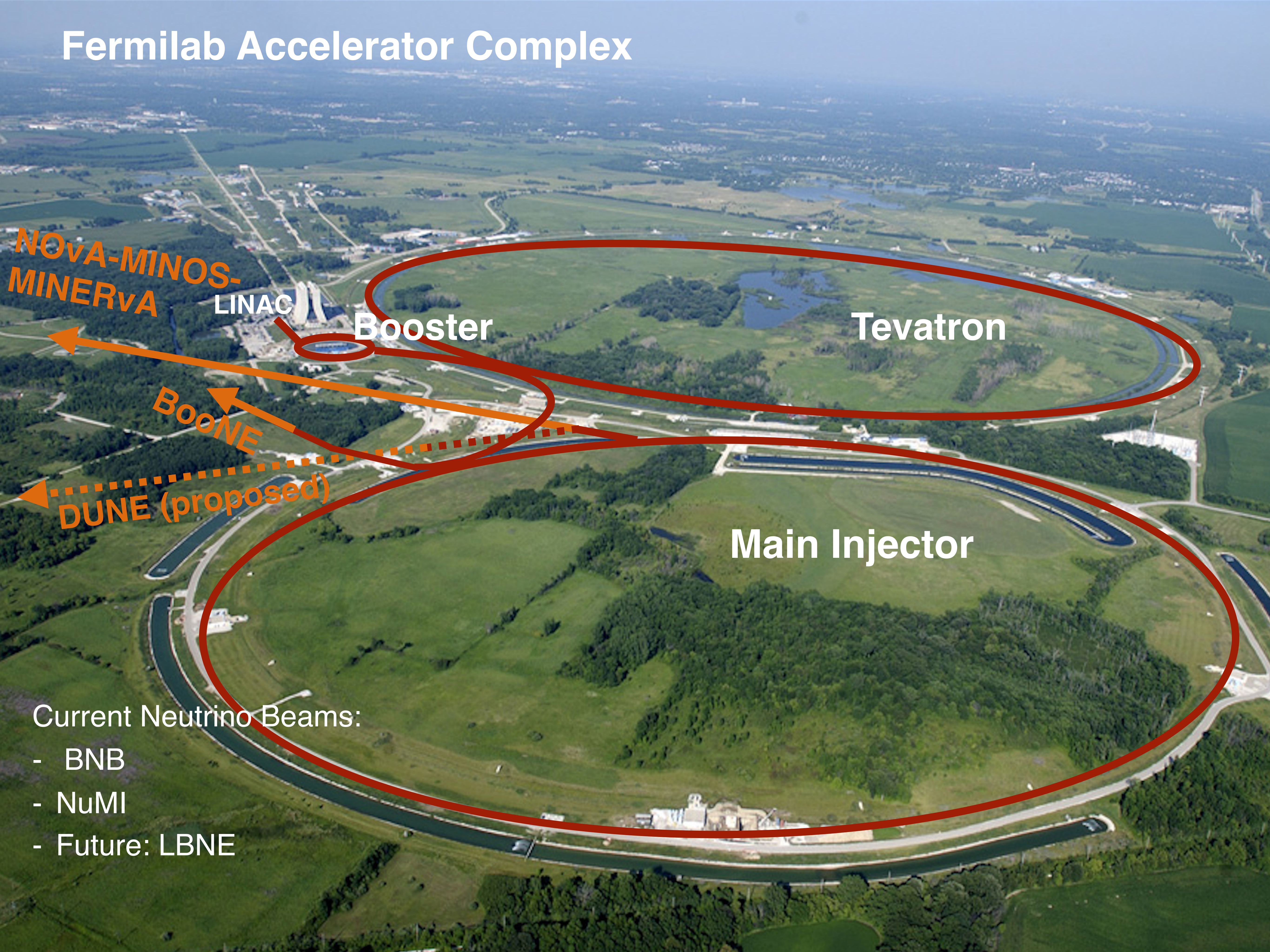




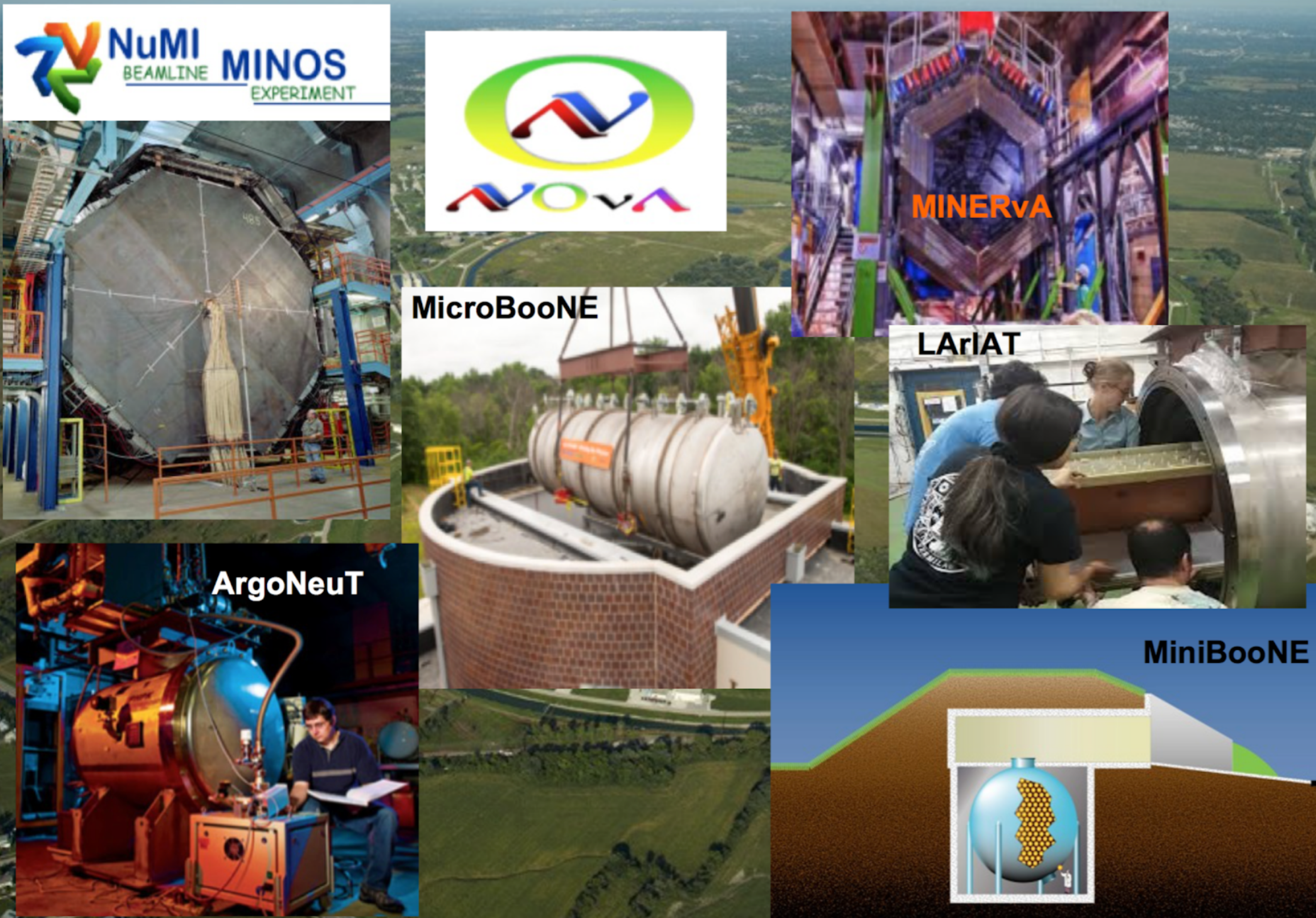
LEDERMAN SCHWARTZ STEINBERGER

How to make a neutrino beam



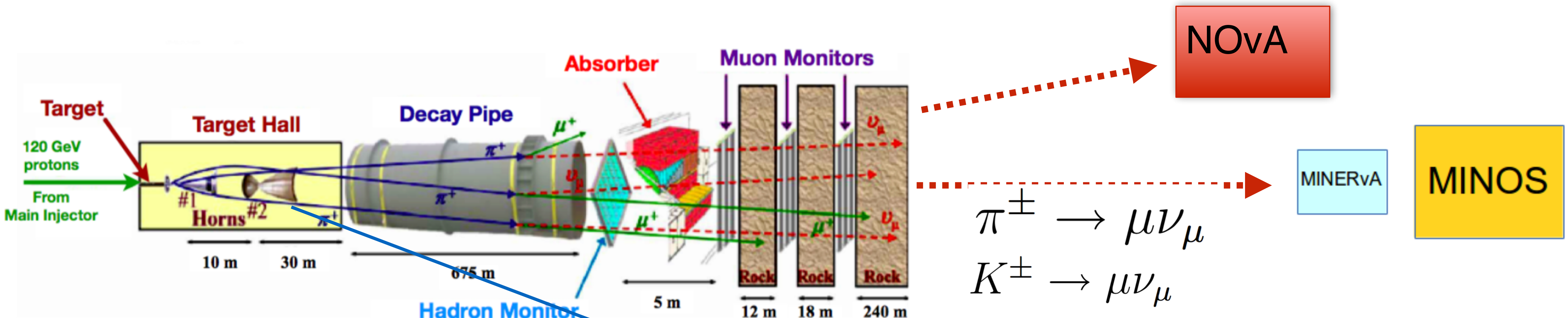

Fermilab Accelerator Complex
NOvA-MINOS-MINERvA
LINAC
Booster
Tevatron
BooNE
DUNE (proposed)
Main Injector
Current Neutrino Beams:
- BNB
- NuMI
- Future: LBNE

Several Neutrino experiments at Fermilab...



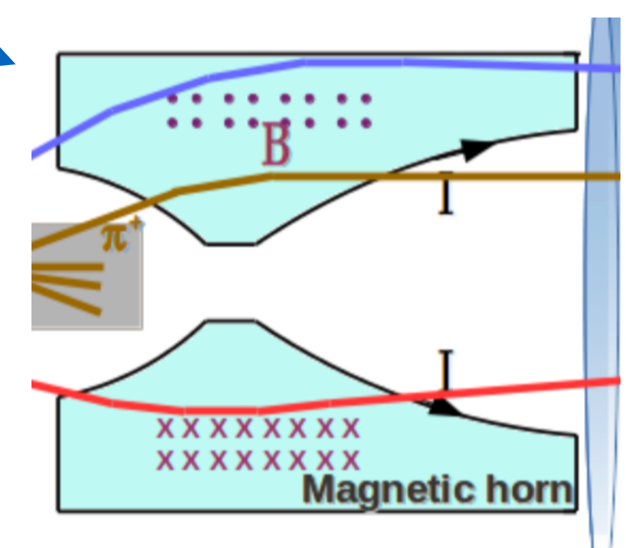
NuMI (Neutrinos at the Main Injector)

120 GeV protons strike a graphite target and hadronic cascade is created.

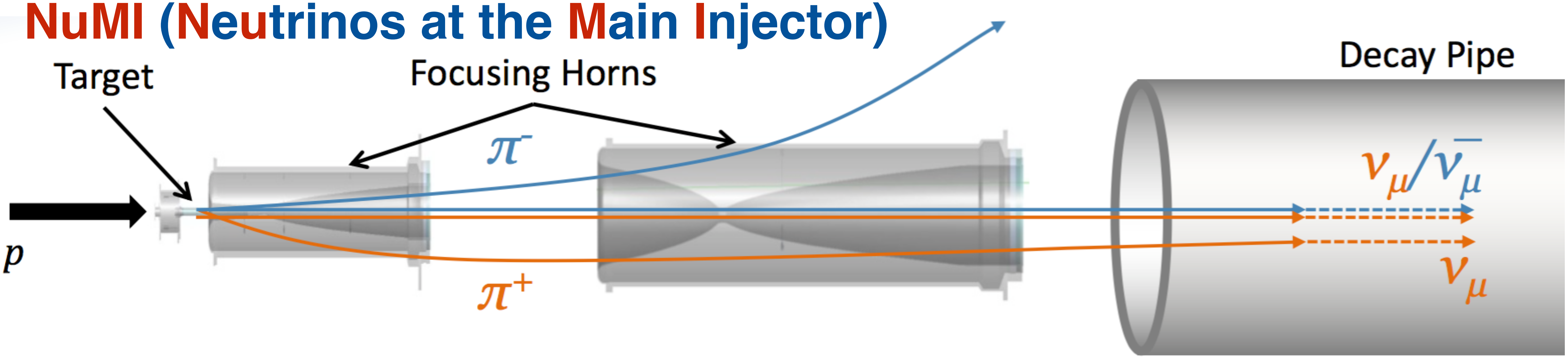


$$\pi^{\pm} \longrightarrow \mu\nu_{\mu}$$
$$K^{\pm} \longrightarrow \mu\nu_{\mu}$$

Pions and kaons are focused by 2 magnetic horns.

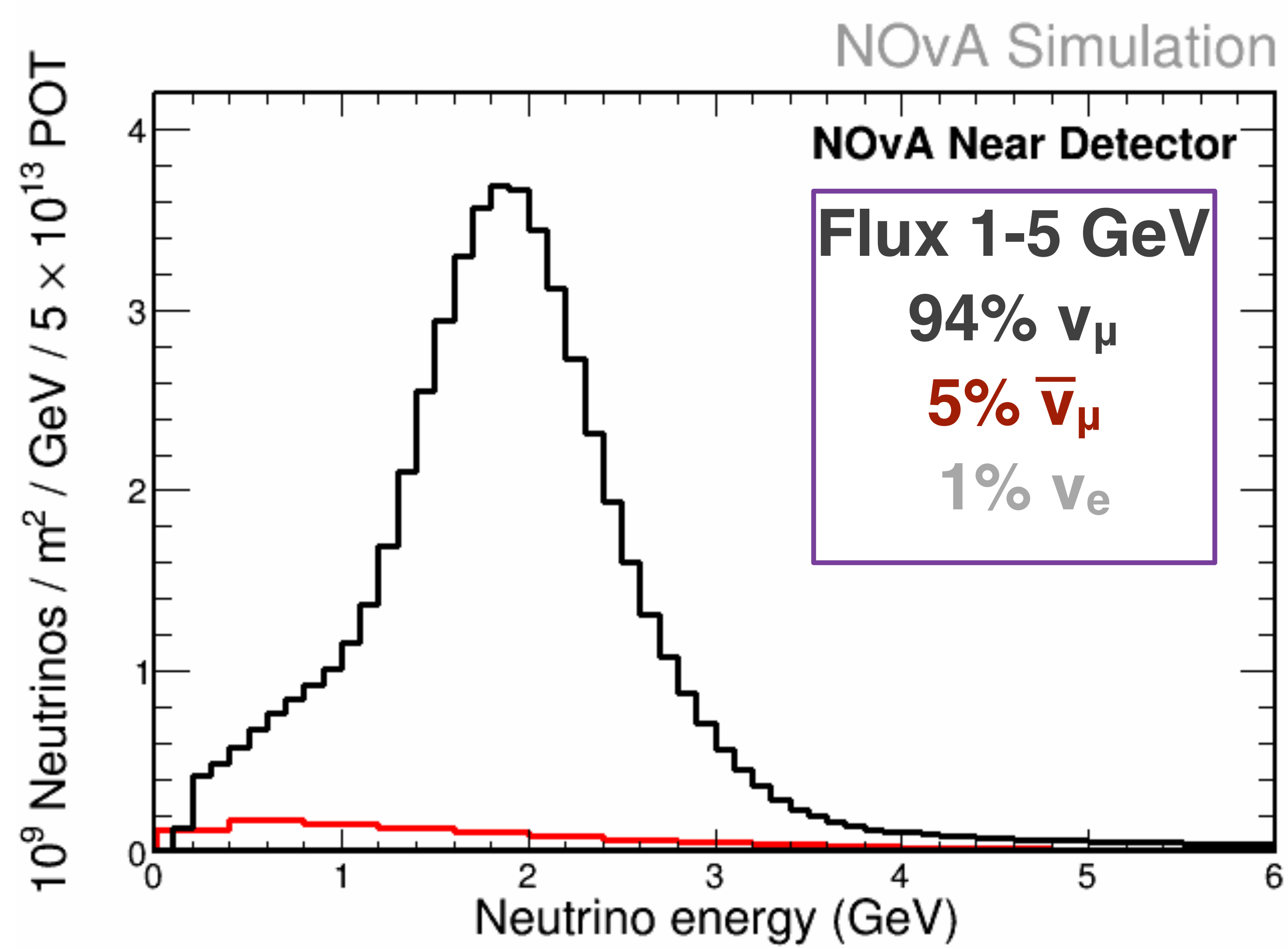


NuMI (Neutrinos at the Main Injector)

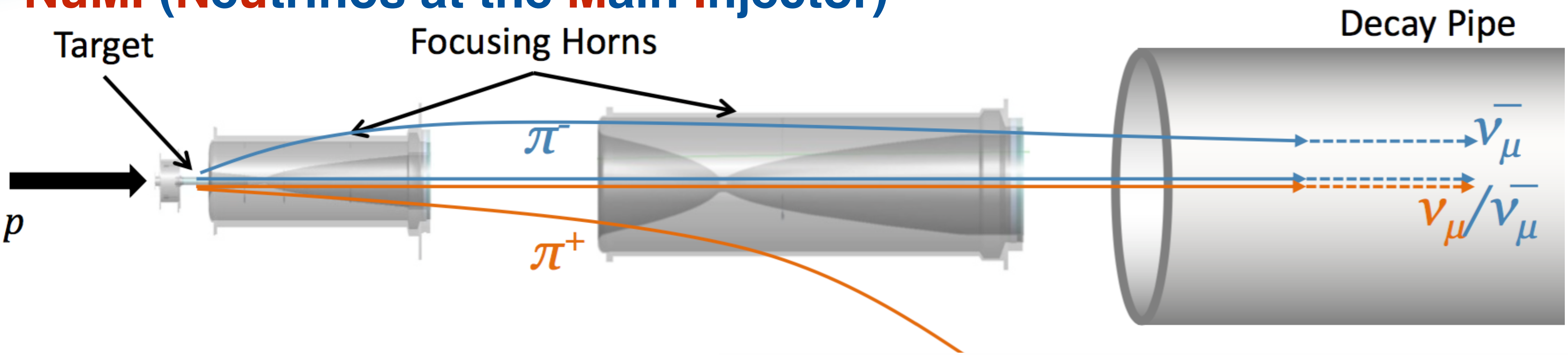


Neutrinos mostly coming from:

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

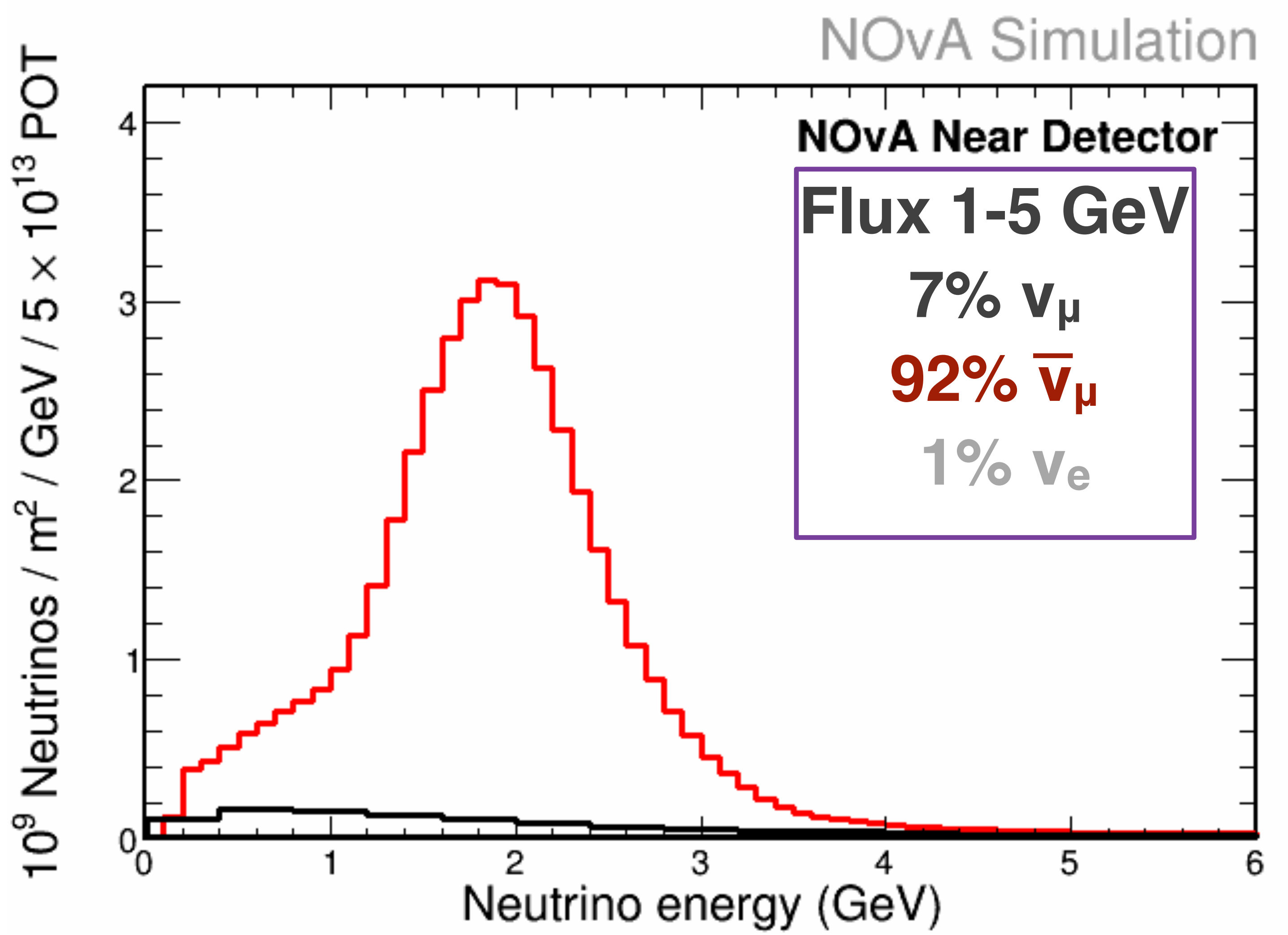


NuMI (Neutrinos at the Main Injector)



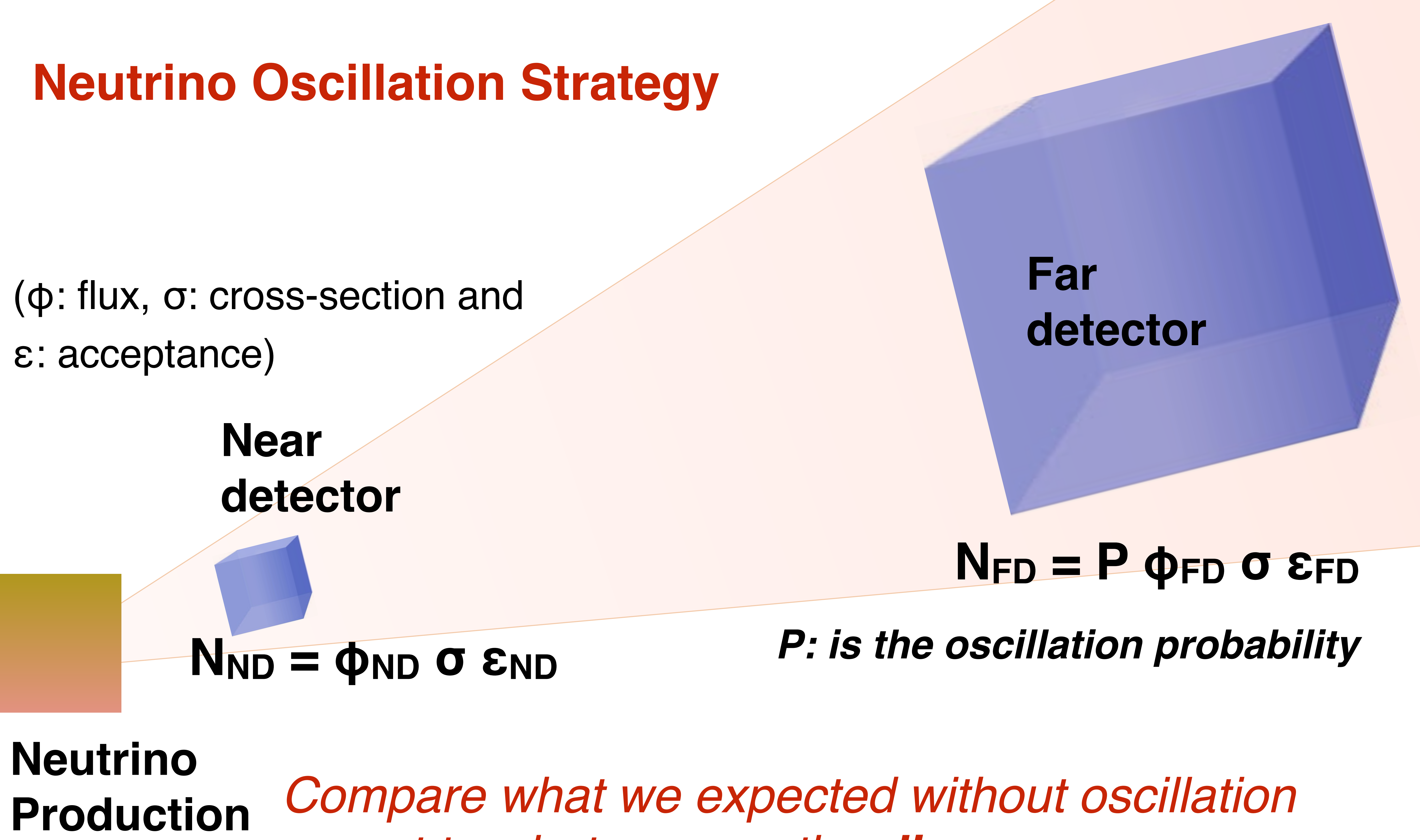
Antineutrinos mostly coming from:

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$



Neutrino Oscillation Strategy

(ϕ: flux, σ: cross-section and
ε: acceptance)



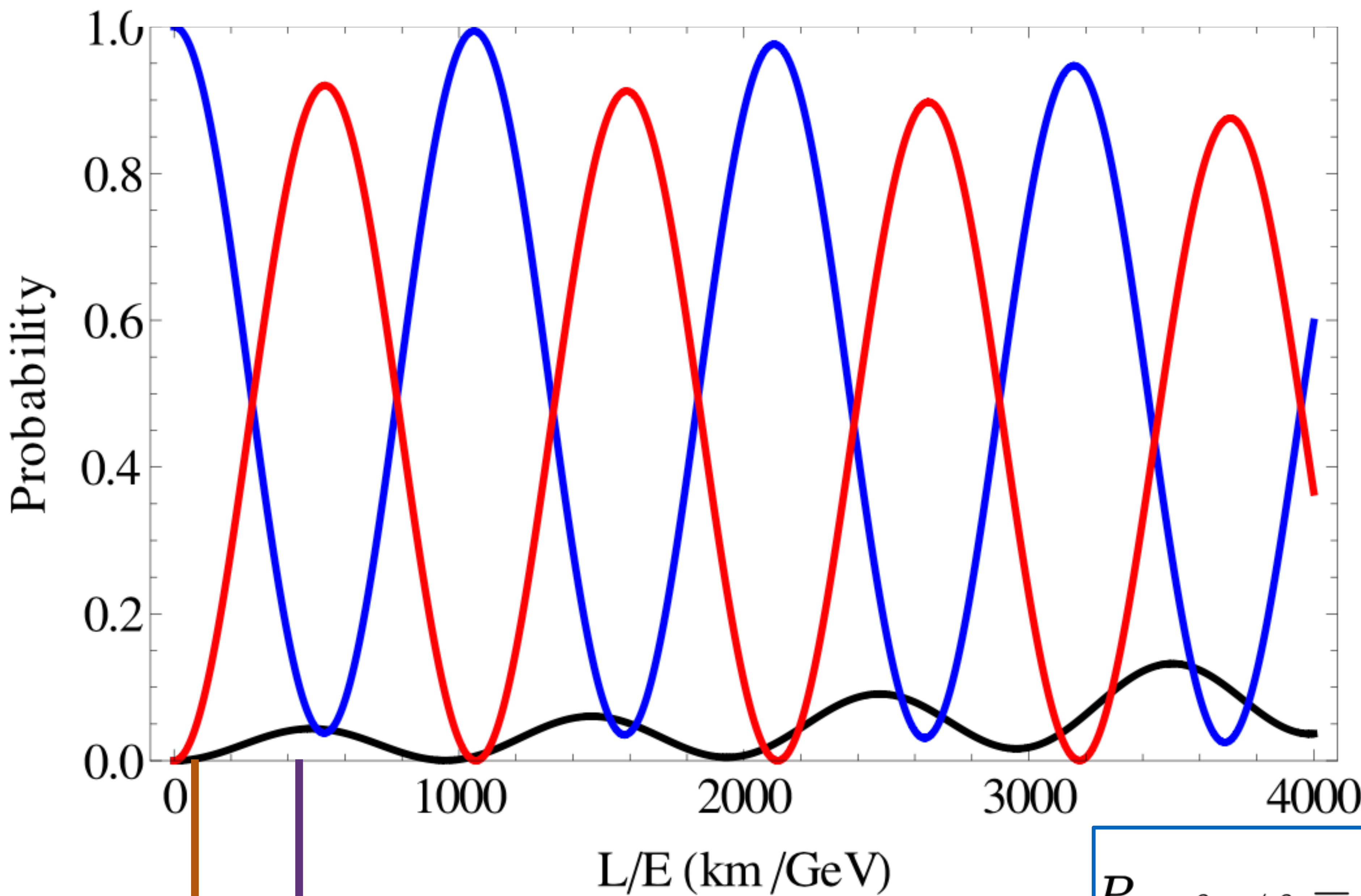
$$N_{FD} = P\ \phi_{FD}\ \sigma\ \varepsilon_{FD}$$

P: is the oscillation probability

$$N_{ND} = \phi_{ND}\ \sigma\ \varepsilon_{ND}$$

*Compare what we expected without oscillation repeat to what we see: the **discrepancy comes from the neutrino oscillation***

Oscillation probability for an initial ν_μ



Blue: ν_μ

Black: ν_τ

Red : ν_e

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

For NOvA FD, L = 810 km and E ~ 2GeV, **L/E ~ 405 km/GeV**

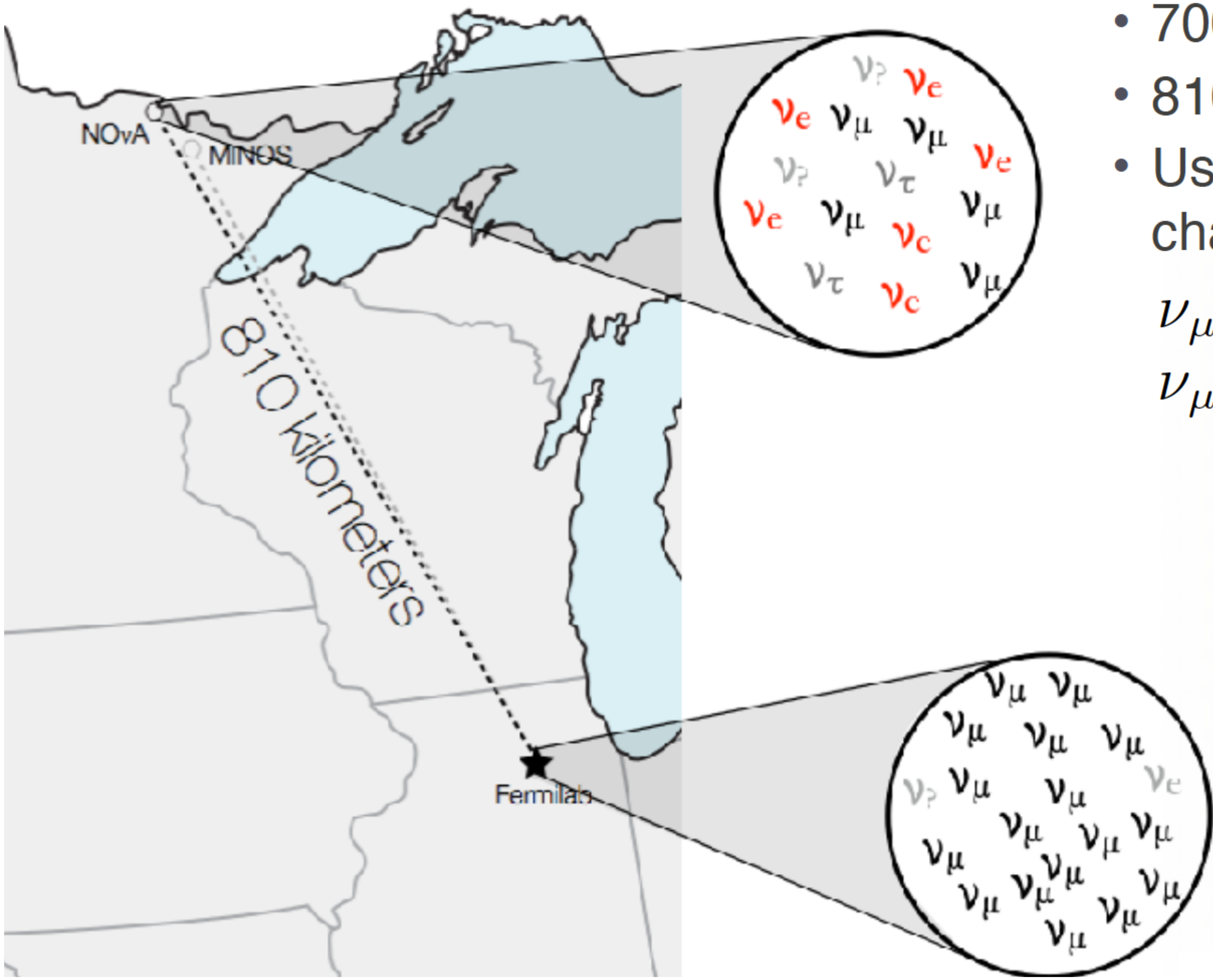
For NOvA ND, L = 1 km and E ~ 2GeV, L/E ~ 0.5 km/GeV

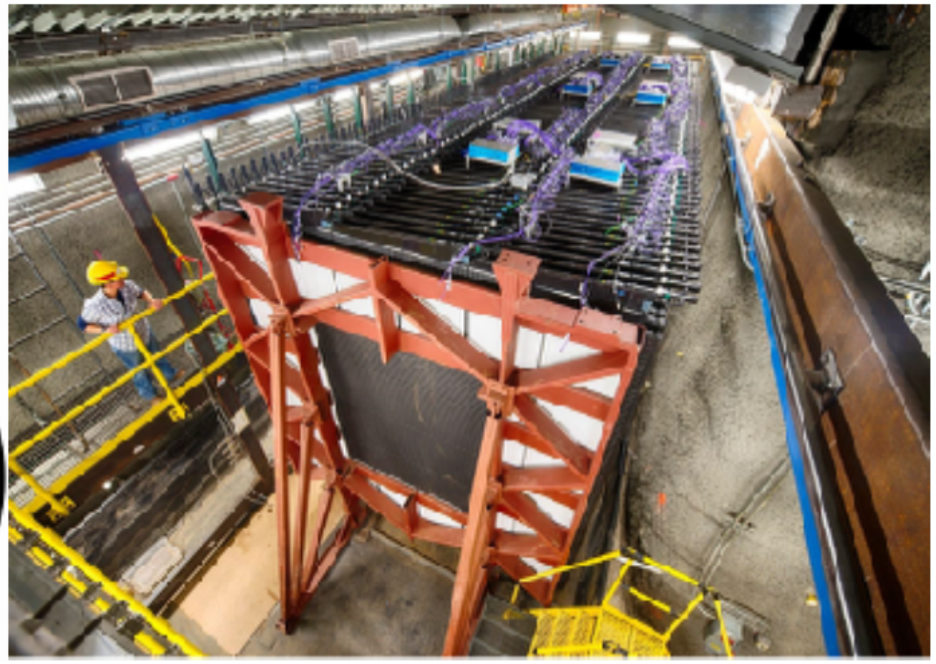
https://en.wikipedia.org/wiki/Neutrino_oscillation

The NOvA Experiment

- Observe neutrinos from NuMI neutrino beam line at Fermilab
- Two functionally identical detectors, 14 milliradians off-axis from beam center
- 700 kW beam
- 810 km baseline
- Uses four primary oscillation channels:

$$\nu_\mu \to \nu_\mu \qquad \overline{\nu}_\mu \to \overline{\nu}_\mu$$
$$\nu_\mu \to \nu_e \qquad \overline{\nu}_\mu \to \overline{\nu}_e$$

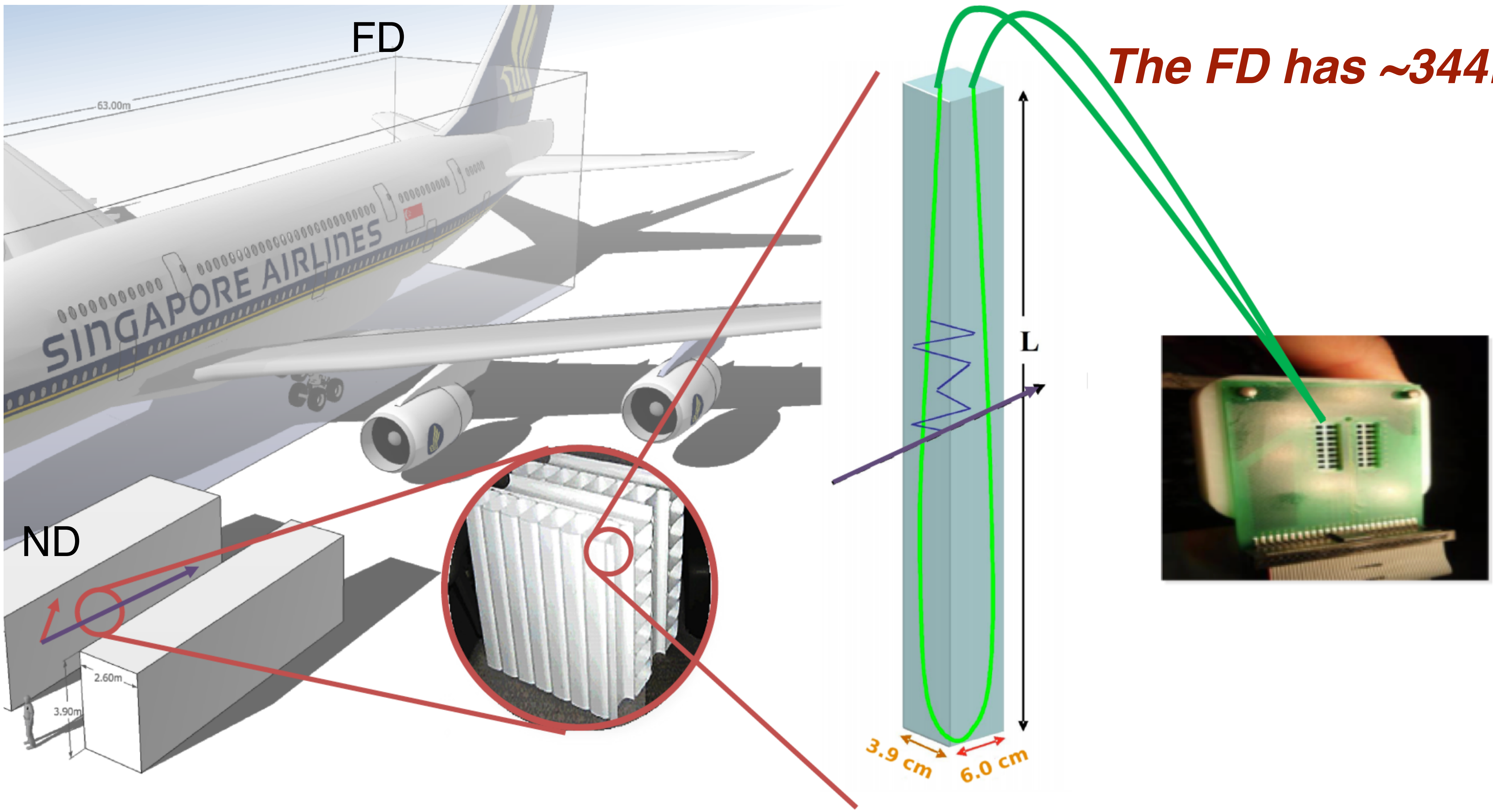




- The NOvA detectors are:
  - Large, 14 kTon at the Far Detector
  - Consist of plastic cells filled with liquid scintillator
  - Arranged in alternating directions for 3D reconstruction
- The far detector is on the surface while the near detector is 300 ft underground.

The ND has ~20K channels

The FD has ~344K channels



- Light is produced when charged particles pass through the cells.
- The light is picked up by a wavelength shifting fiber.
- It is then transported to an **A**valanche **P**hoto**D**iode where the light is collected and amplified.

Nobel Prize in 2015 for Discovering Neutrino Oscillations

Takaaki Kajita

Super - Kamiokande

Arthur B. McDonald

SNO

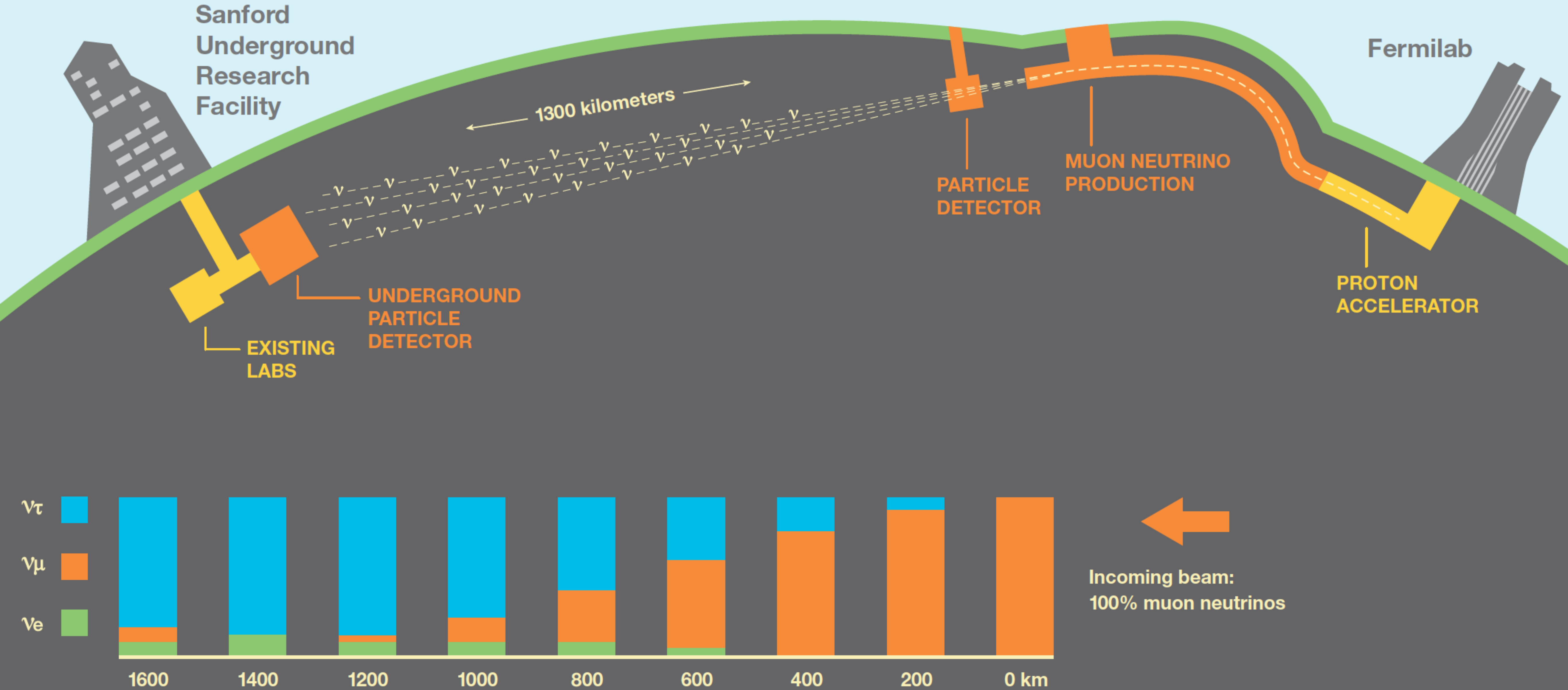
Do we have everything?

Not yet!

	What is the absolute neutrino mass?	Are neutrinos Dirac or Majorana particles?	What is the neutrino mass ordering?	Is there CP violation in the neutrino sector?	Are there more than 3 neutrino flavors?	Is our picture of neutrinos correct?
β decay	✓					✓
$0\nu\beta\beta$ decay	✓	✓				✓
astrophysics and cosmology	✓		(✓)		✓	✓
Atmospheric oscillations			(✓)	(✓)	✓	✓
Reactor oscillations			(✓)		✓	✓
Accelerator oscillations			✓	✓	✓	✓

(credit: S. Zeller)

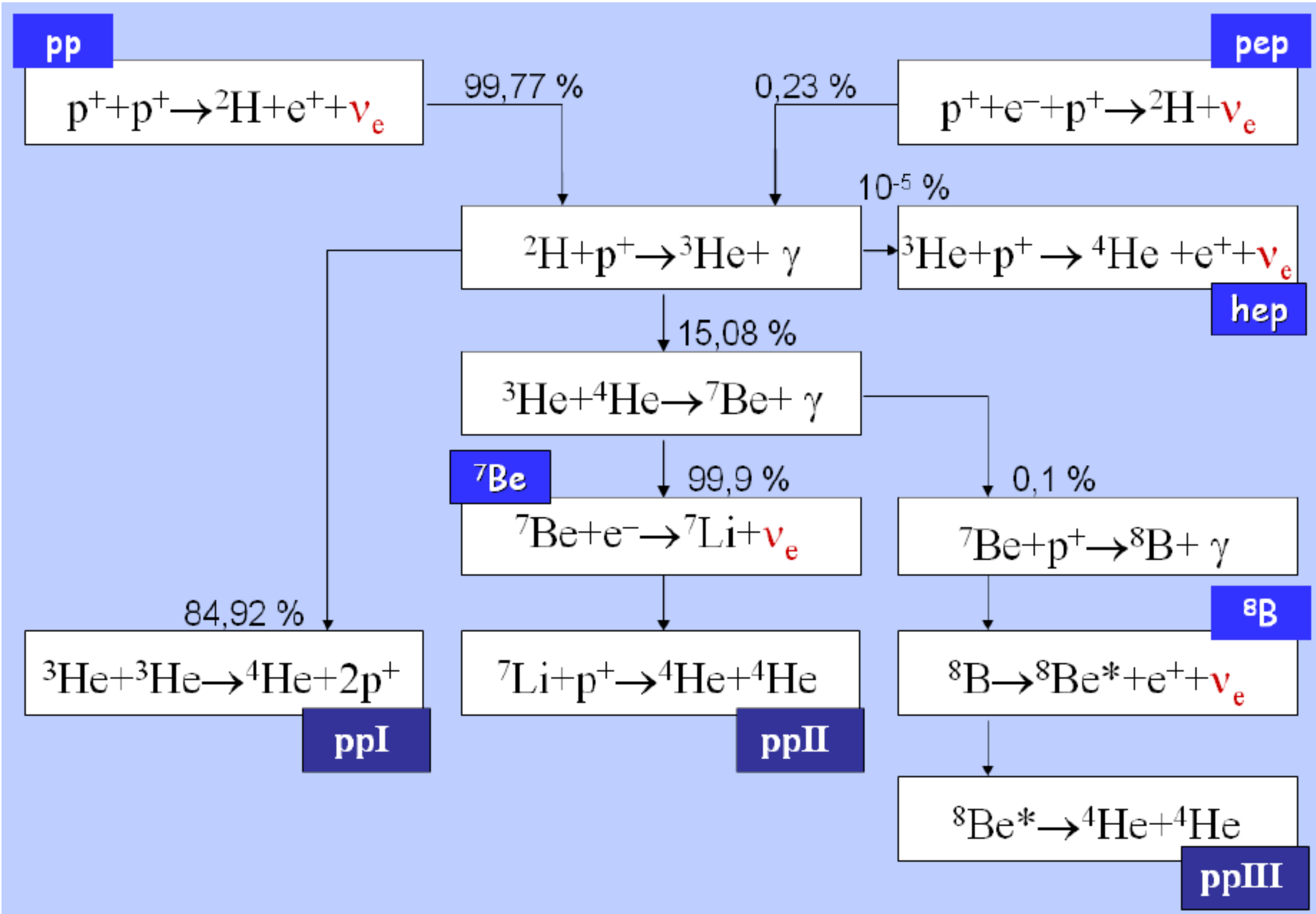
Deep Underground Neutrino Experiment



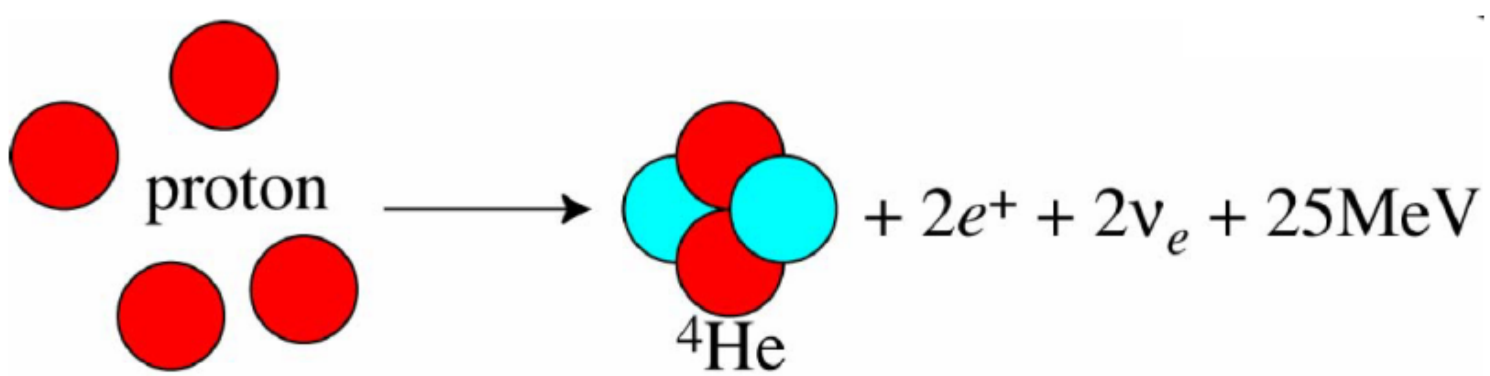
Probability of detecting electron, muon and tau neutrinos

Backup

Neutrinos from the Sun



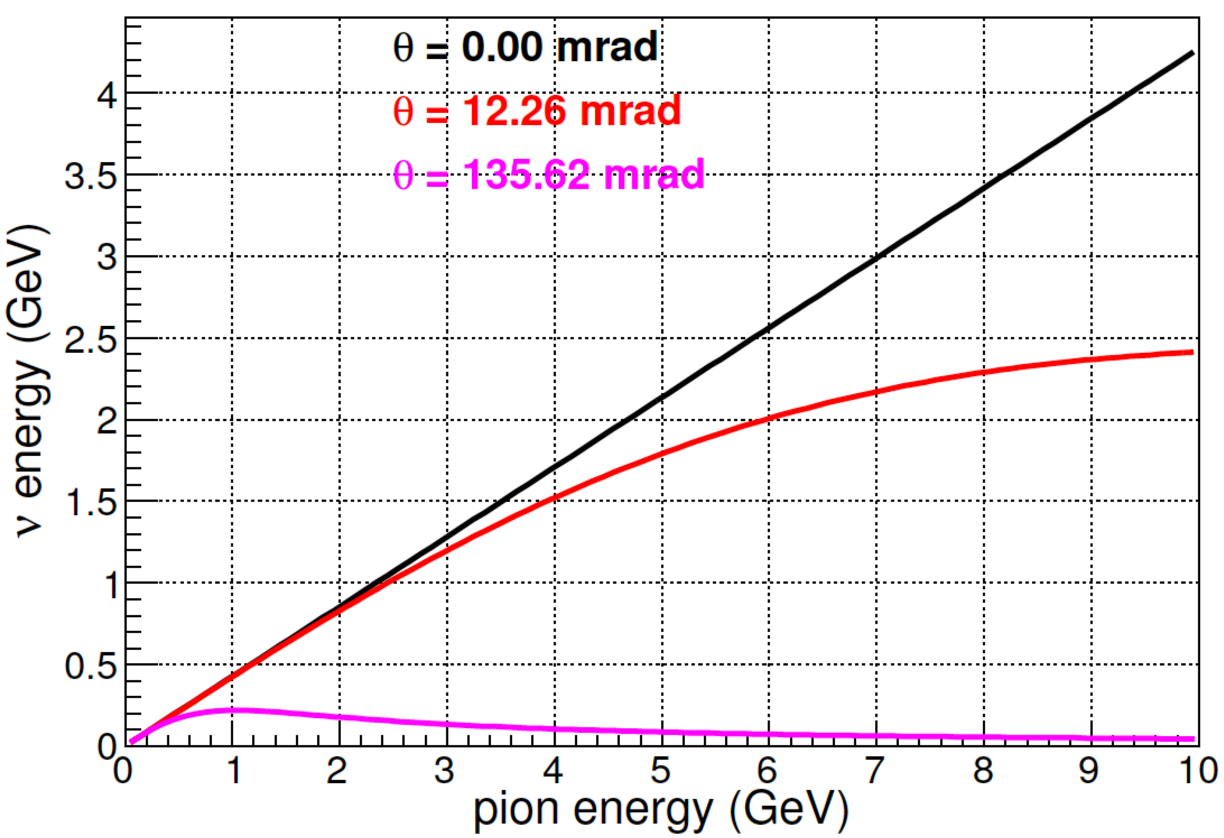
- For instance:



How to Make a Conventional Neutrino Beam

Neutrino decay:

- Main decay to neutrino mode for neutrino beam:



Decay	Chanel	Branching ratio (%)
1	$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$	99.9877
2	$\pi^{\pm} \rightarrow e^{\pm} + \nu_{e}(\bar{\nu}_{e})$	0.0123
3	$K^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$	63.55
4	$K^{\pm} \rightarrow \pi^{0} + e^{\pm} + \nu_{e}(\bar{\nu}_{e})$	5.07
5	$K^{\pm} \rightarrow \pi^{0} + \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$	3.353
6	$K^{0}_{L} \rightarrow \pi^{\pm} + e^{\mp} + \nu_{e}$	40.55
7	$K^{0}_{L} \rightarrow \pi^{\pm} + \mu^{\mp} + \nu_{\mu}$	27.04
8	$\mu^{\pm} \rightarrow e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \bar{\nu}_{\mu}(\nu_{\mu})$	100.0

- From 2 pion body decay:

$$\boxed{E_{\nu} \approx \frac{(1 - \frac{m_{\mu}^{2}}{M^{2}})E_{\pi(K)}}{1 + \gamma^{2}\tan^{2}\theta_{\nu}}}$$

- dP/dΩ ??

How to study oscillation

$$P\left(\nu_\mu \rightarrow \nu_e\right) \approx \left|\sqrt{P_{\text{atm}}}e^{-e(\Delta_{32}+\delta_{CP})} + \sqrt{P_{\text{sol}}}\right|^2$$

$$\approx P_{\text{atm}} + P_{\text{sol}} + 2\sqrt{P_{\text{atm}}P_{\text{sol}}}\left(\cos\Delta_{32}\cos\delta_{CP} \mp \sin\Delta_{32}\sin\delta_{CP}\right)$$

$$\sqrt{P_{\text{atm}}} = \sin(\theta_{23})\sin(2\theta_{13})\frac{\sin(\Delta_{31} - aL)}{\Delta_{31} - aL}\Delta_{31}$$

$\nu_\mu \rightarrow \nu_e$ depends on:

- CP phase: δ_{CP}
- Mass hierarchy and matter effects
- Atmospheric parameters: $\sin^2(\theta_{23})$, Δm^2_{32}
- The smallest mixing angle: θ_{13}
- Solar parameters: $\sin^2(\theta_{12})$, Δm^2_{12}

Open Questions

Disappearance Constraints

NOvA: $\nu_\mu \rightarrow \nu_\mu$

Reactor: $\nu_e \rightarrow \nu_e$

Solar: $\nu_e \rightarrow \nu_e$