VIETNAM SCHOOL ON NEUTRINOS (VSON 6)
July 10 – July 22, 2022

Introduction to Neutrino Interactions

Nguyen Thi Hong Van
Institute of Physics
Vietnam Academy of Science and Technology

References

- K Zuber, "*Neutrino Physics*", Institute of Physics Publishing, 2004.
- C. Giunti and C.W.Kim, "*Fundamentals of Neutrino Physics and Astrophysics*", Oxford University Press, 2007.
- Ulrich Mosel, "*Neutrino Interactions with Nucleons and Nuclei: Importance for Long-Baseline Experiments*", arXiv:1602.00696v3
- Kevin McFarland, "*Neutrino Interactions*", arXiv:0804.3899v1
- Kevin McFarland, "Interactions of Neutrinos", lectures at INWS 2015, Brasil, August 2015.
- Steve Boyd, Lecture of "*Neutrino Physics*"
- Neutrino Interactions - Thesis - Daniel I. Scully

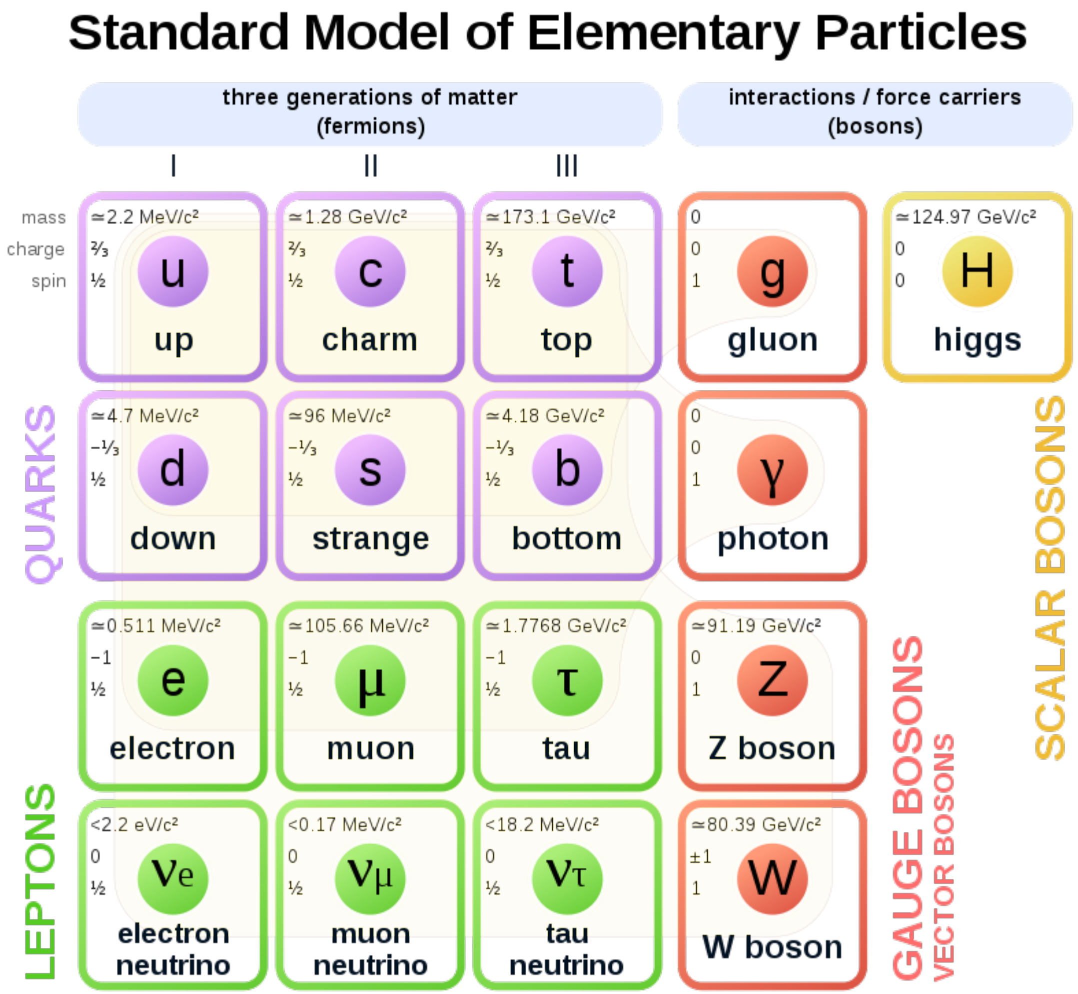
Contents

- Introduction to neutrinos and neutrino interactions
- Weak interaction in Standard Model
- Weak interaction for neutrinos
- Neutrino – Electron scattering
- Neutrino – Nucleons scattering
- Neutrino – Nucleus scattering

Introduction to neutrinos

Neutrinos

- No electric charge
- No color
- Participate in weak interaction
- Cannot be observed Directly in detector



Why study neutrino interactions?

- Neutrino interaction is a signature of neutrino existence
- Study neutrino interactions to understand the weak interaction and electroweak unification theories.
- Neutrino interactions give information for neutrino mass and neutrino mixing,…
- In experiments: better understanding of neutrino interactions → more precise measuring neutrino oscillations.

Weak Interactions of SM

$$L_{\text{int}} = i\frac{g}{\sqrt{2}}\left[j_\mu^{(+)}W^\mu + j_\mu^{(-)}W^{\mu+}\right] + i\frac{g}{2\cos\theta_W}\,j_\mu^{(Z)}Z^\mu$$

Coupling strength

$$j_\mu^{\pm} = \bar{u}\frac{-ig_W}{2\sqrt{2}}\gamma^\mu\left(1 \pm \gamma^5\right)u$$

Dirac spinors

- Charged Current (CC) interactions:

  (*mediated by W bosons*)

$$j_\mu^{0} = \bar{u}\frac{-ig_Z}{2}\left(g_V\gamma^\mu - g_A\gamma^\mu\gamma^5\right)u$$

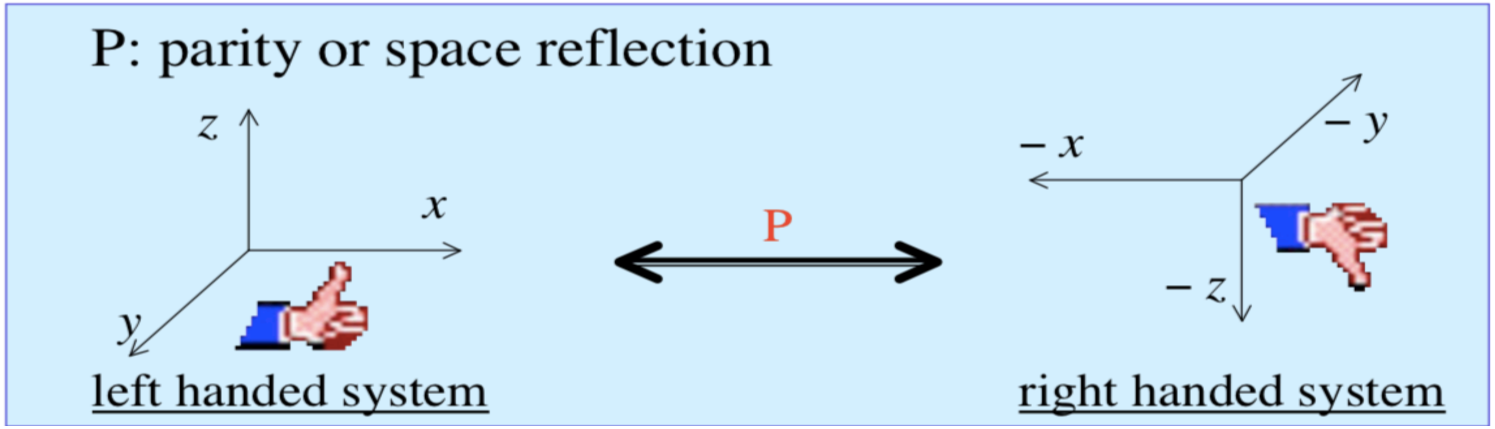
- Neutral Current (NC) interaction:

  (*mediated by Z boson*)

Particles	g_V	g_A
Neutrinos	½	½
Charged Leptons	$\frac{1}{2} + 2\sin^2\theta_W$	-½
Up-type Quarks	$\frac{1}{2} - \frac{4}{3}\sin^2\theta_W$	½
Down-type Quarks	$-\frac{1}{2} + \frac{2}{3}\sin^2\theta_W$	-½

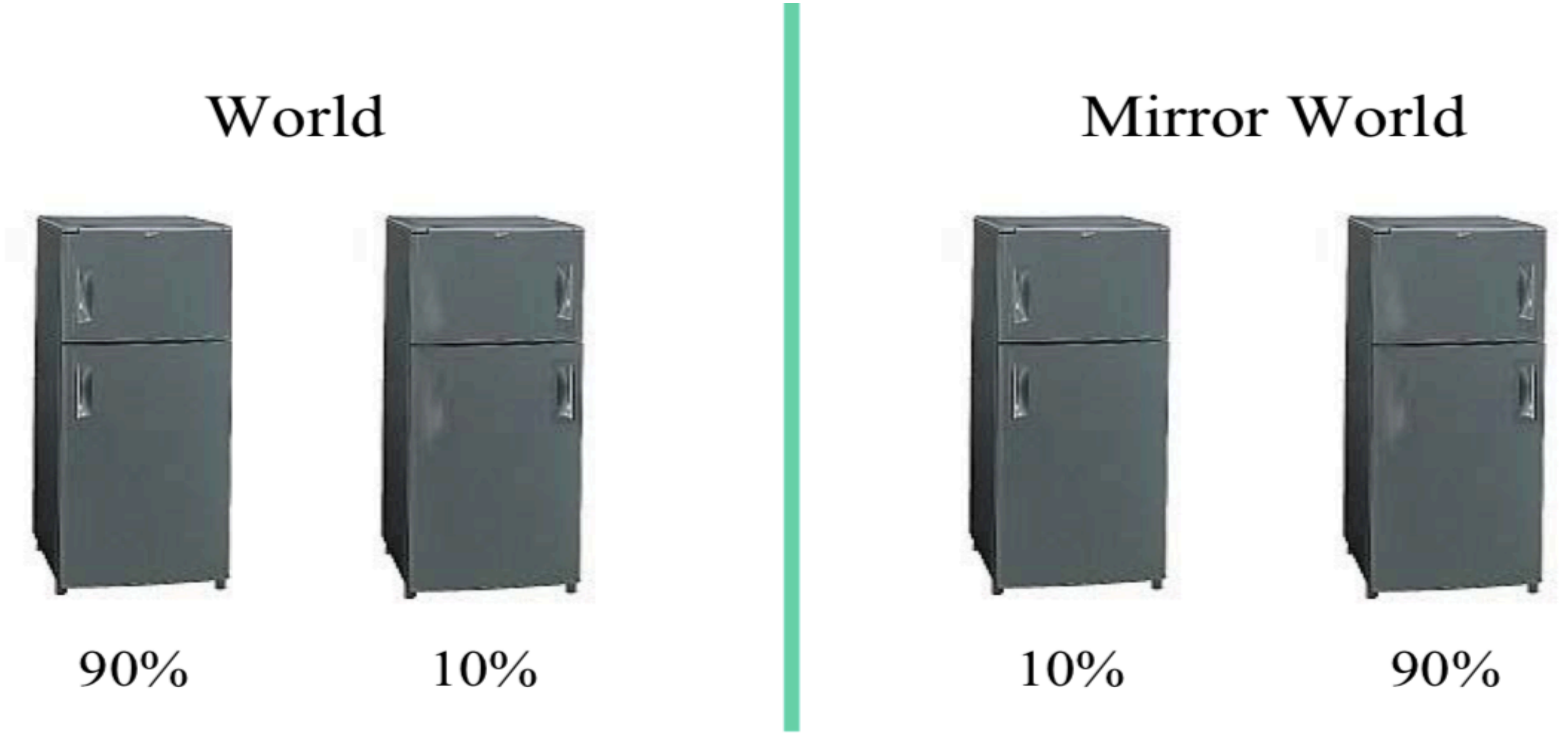
- Weak mixing angle: $\frac{g_W}{g_Z} = \cos\theta_W$

Parity symmetry



$$\vec{E}(\vec{x},t) \xrightarrow{P} -\vec{E}(-\vec{x},t)$$
$$\vec{B}(\vec{x},t) \xrightarrow{P} \vec{B}(-\vec{x},t)$$
$$\vec{j}(\vec{x},t) \xrightarrow{P} -\vec{j}(-\vec{x},t)$$
$$\nabla \xrightarrow{P} -\nabla$$

Example of Parity symmetry violation



World ≠ Mirror World
(parity violation)

Lecture for CERN summer student
Given by Tatsuya Nakada

Parity violation by weak interaction

- Vector current (*odd parity*): $\hat{P}\left(\bar{\psi}\gamma^{\mu}\psi\right) = -\left(\bar{\psi}\gamma^{\mu}\psi\right)$
- Axial-vector current (*even parity*): $\hat{P}\left(\bar{\psi}\gamma^{\mu}\gamma^{5}\psi\right) = \bar{\psi}\gamma^{\mu}\gamma^{5}\psi$
- Weak current is a mixture of vector and axial vector currents:

$$j_{\mu}^{\pm} = \bar{u}\frac{-ig_{W}}{2\sqrt{2}}\gamma^{\mu}\left(1 \pm \gamma^{5}\right)u$$

- → Parity of a system is violated by weak force! (first postulated by Lee & Yang in 1950)

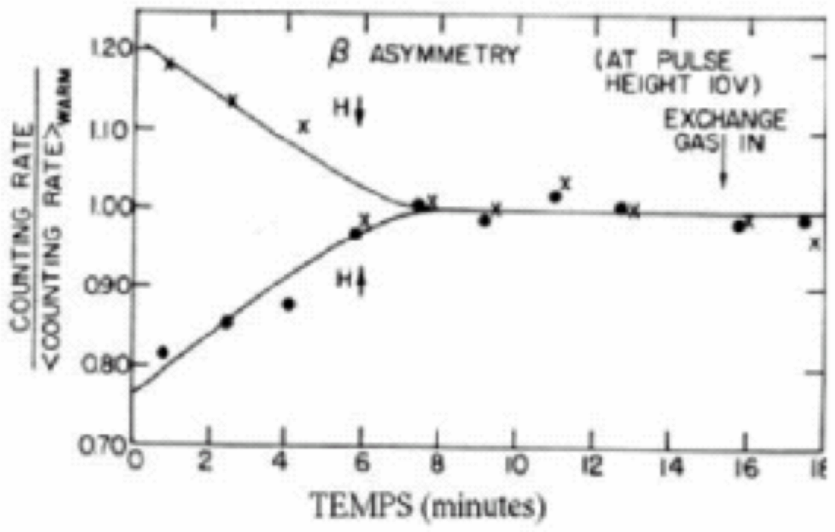
Parity violation confirmed by experiment

- Helicity operator: projection of spin on the momentum direction.

$$H = \frac{\vec{\sigma}\cdot\vec{p}}{|\vec{p}|} \xrightarrow{P} \frac{\vec{\sigma}\cdot(-\vec{p})}{|\vec{p}|} = -H$$

- Parity violation appeared in the the asymmetry of polarized ^{60}Co (by Wu in 1957):

$$^{60}Co \rightarrow {}^{60}Ni^* + e^- + \bar{\nu}_e$$



More electrons emitted in direction opposite to ^{60}Co spin → parity violation!

Weak interaction and chirality

- CC weak interaction: $$j_\mu^{\pm} = \bar{u}\frac{-ig_W}{2\sqrt{2}}\gamma^\mu\left(1 \pm \gamma^5\right)u$$

- Chirality:

Lorentz invariant

but not directly measurable!:

$$u = u_L + u_R$$

$$u_L = ½\left(1 - \gamma^5\right)u$$

$$u_R = ½\left(1 + \gamma^5\right)u$$

Chiral projection

$$j_\mu^{-} = \frac{-ig_W}{2\sqrt{2}}\bar{u}\left(1 + \gamma^5\right)\gamma^\mu\left(1 - \gamma^5\right)u = \frac{-ig_W}{2\sqrt{2}}\bar{u}_L\gamma^\mu u_L$$

Vector current interacting only with the left-handed particle, or right-handed anti-particle

Weak interaction for neutrinos

- In case of neutrinos, both CC and NC interactions can be viewed as a vector current interacting only with the left-handed particle, or right-handed anti-particle
- Neutrinos only participate in weak interaction, they are produced in a left-handed eigen-state (chiral).
- If neutrinos are consider as no mass:
  - Chirality and helicity are the same
  - Neutrinos are always in left-handed state and no right-handed neutrinos exist!
- In fact neutrinos are massive, right-handed neutrino exists, e.g. as sterile neutrinos.

Details of
Neutrino Interactions

Convenient variables used

- 4-momentum transfer:

  $Q^2 = -q^2$

- Inelasticity: $y = \frac{q \cdot P_{\text{target}}}{P_\nu \cdot P_{\text{target}}}$

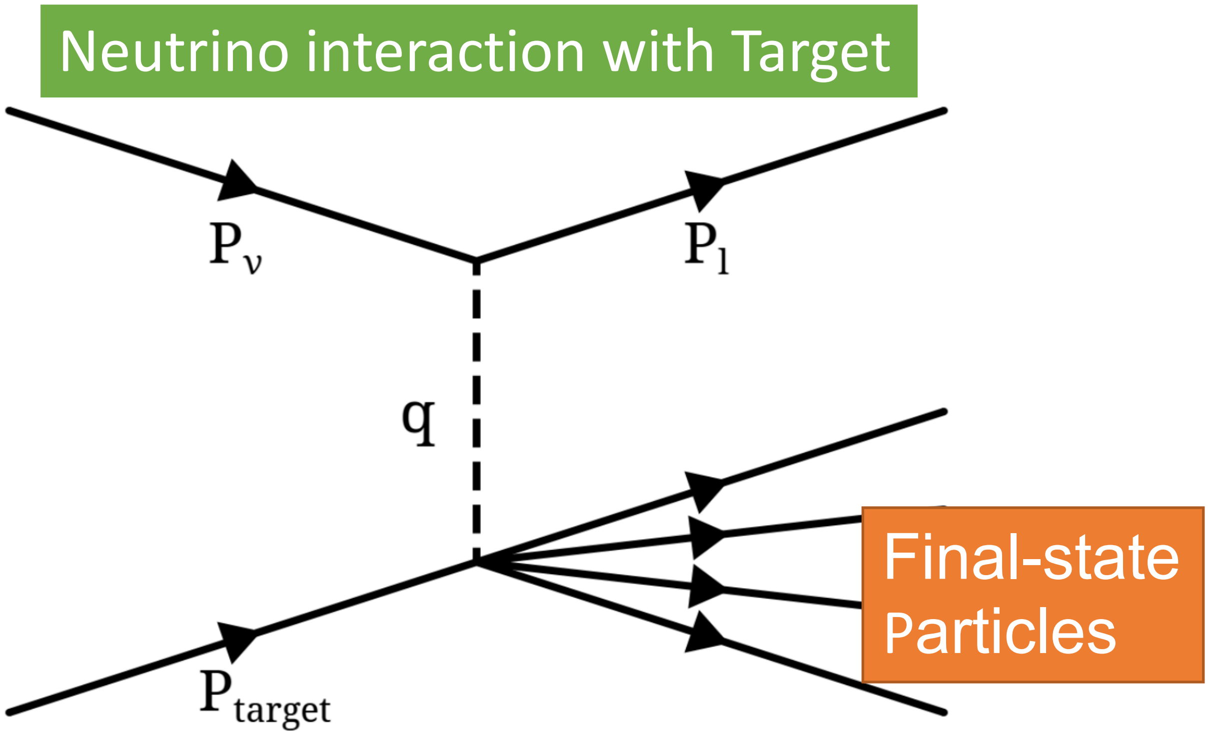
  In the target's rest frame:

  $$y = \frac{q_0}{E_\nu} = \frac{E_\nu - E_l}{E_\nu}$$

- Bjorken scaling variable:

  $$x = \frac{-q^2}{2P_{\text{target}} \cdot q}$$

- Invariant hadronic mass: $W = \sqrt{(q + P_{\text{target}})^2}$

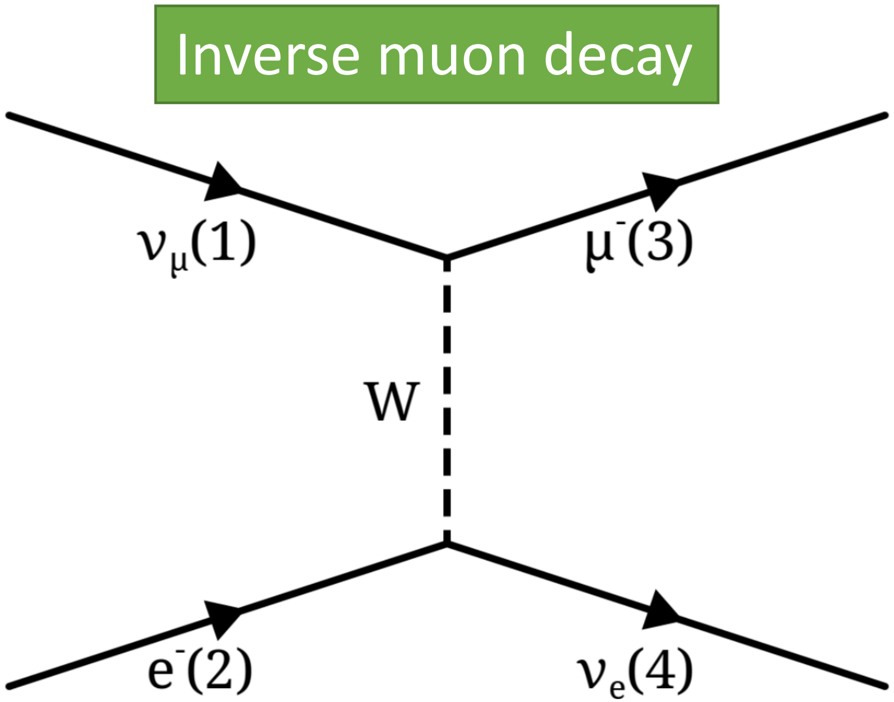


Neutrino – Electron Interactions

Neutrino – Electron interactions: CC

Threshold neutrino energy required:

$$E_\nu \geq m_l - m_e$$



Total cross-section in the center of mass frame (neglecting mass of electron and neutrino):

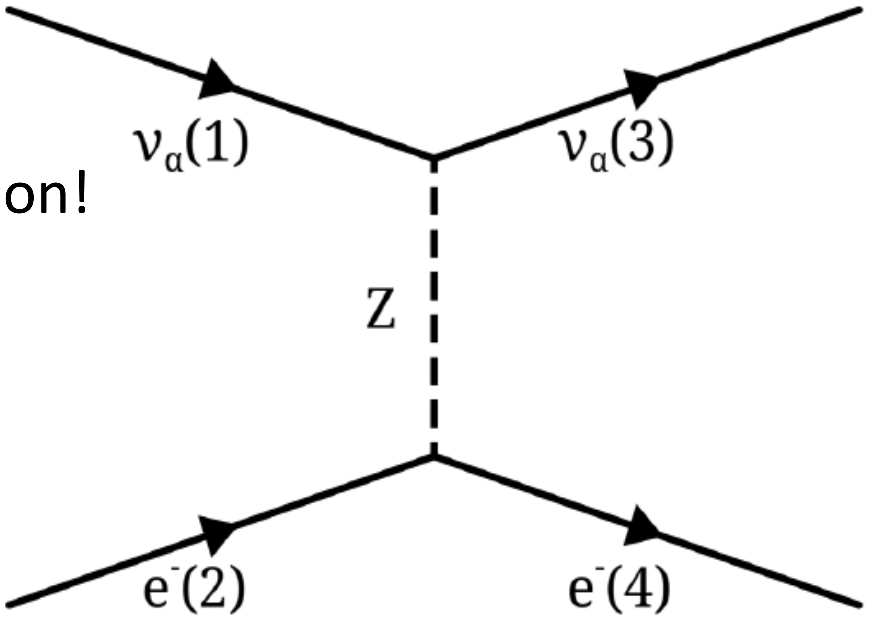
$$\sigma = \frac{1}{8\pi} \frac{{g_W}^4 {E_\nu}^2}{{M_W}^4} \left(1 - \frac{{m_\mu}^2}{4{E_\nu}^2}\right)^2$$

Fermi's coupling: $\frac{G_F}{\sqrt{2}} = \frac{{g_W}^2}{8{M_W}^2}$

Measurement in Charm II: $\sigma(\nu_\mu e^-) = (1.651 \pm 0.093) \times 10^{-41} \left(\frac{E}{1\,GeV}\right) cm^2$

Neutrino – electron interactions: NC

NC electron elastic scattering



- Incoming neutrinos can be: ν_e , ν_μ and ν_τ
- There is no change in mass → threshold-less interaction!
- Total cross-section (*9% of the inverse muon decay*):

$$\sin^2\theta_W = 0.2324 \pm 0.0058 \pm 0.0059$$

$$\sigma_{TOT} = \frac{G_F^2 s}{\pi}\left(\frac{1}{4} - \sin^2\theta_W + \frac{4}{3}\sin^4\theta_W\right) = 1.4\times10^{-42} cm^2/GeV \cdot E_\nu(GeV)$$

Neutrino – electron interactions: CC & NC

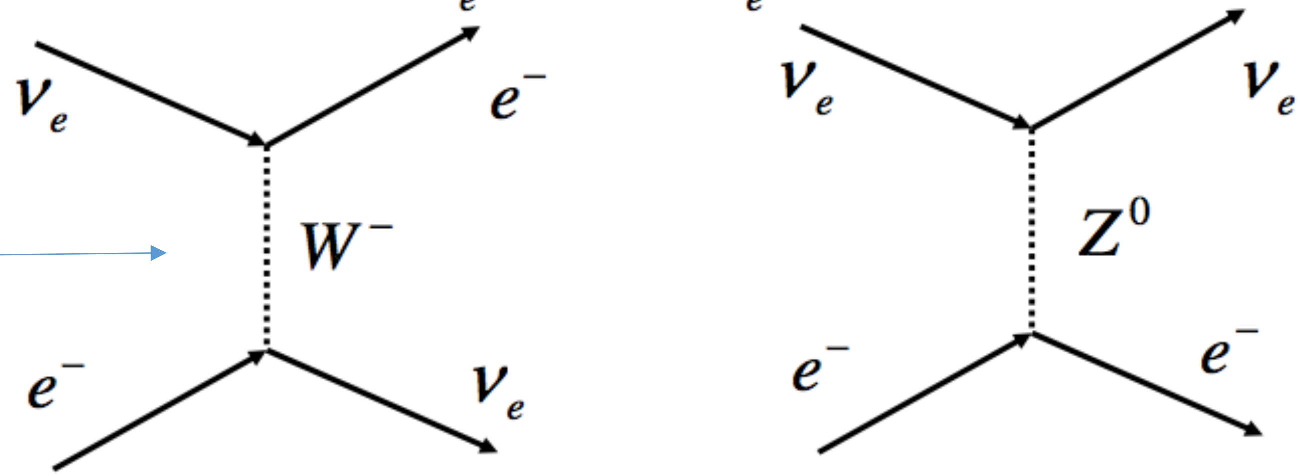
$$\nu_e + e^- \rightarrow \nu_e + e^-$$

- In case of incoming neutrino ν_e

→In addition to NC, there is the second contributing, CC scattering.

→The cross section is much bigger than the case of

ν_μ and ν_τ

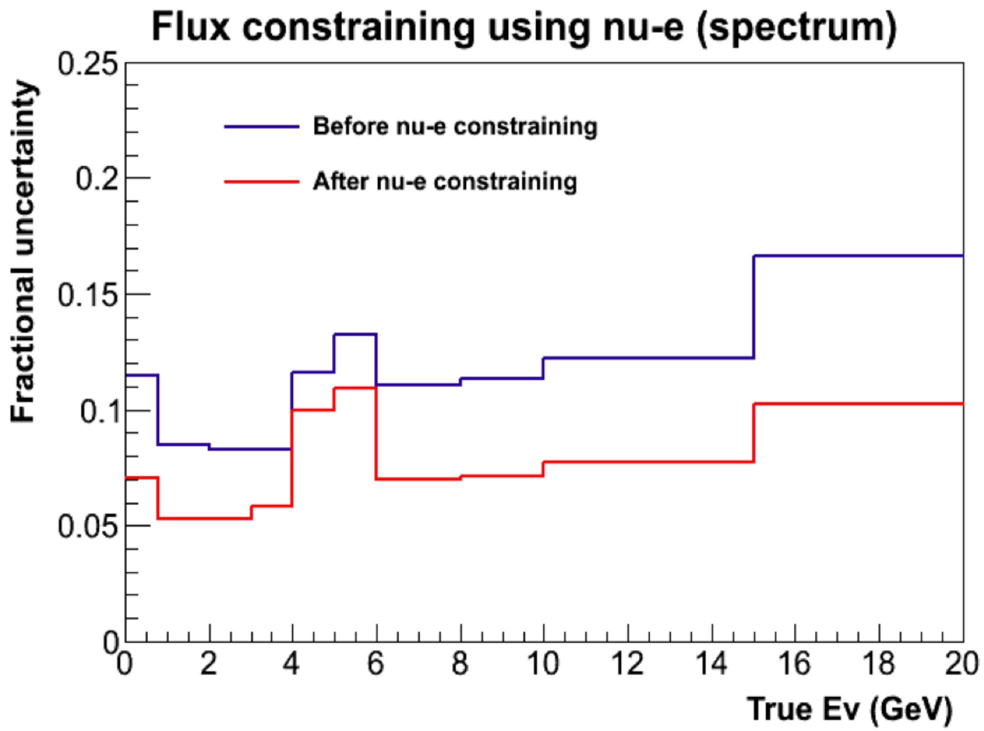


From

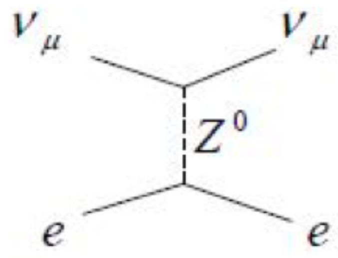
$$\sigma(\nu_e e^-) = \frac{G_F{}^2 s}{\pi}\left[\left(\frac{1}{2}+\sin^2\theta_W\right)^2 + \frac{1}{3}\sin^4\theta_W\right] = 0.96\times10^{-41}\left(\frac{E_\nu}{1\,GeV}\right) cm^2$$

Neutrino – electron interactions: Application

- To constraint neutrino flux
using the uncertainty of cross-section



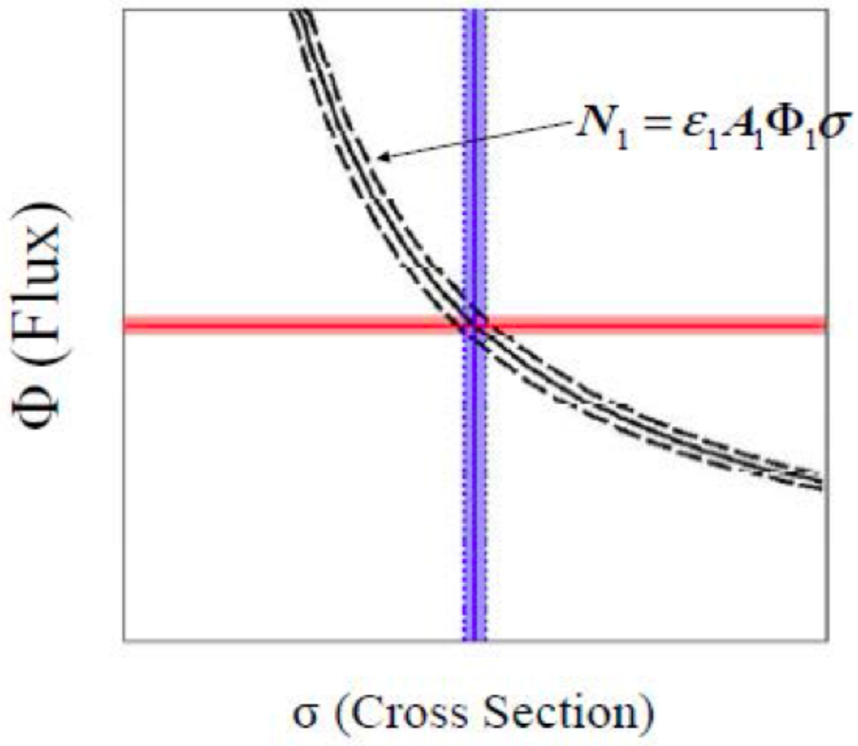
Known Interaction (Standard Candle)



Flux constraint using ND

$$\Phi = \frac{N}{\varepsilon A \sigma}$$

Cross-section uncertainty goes into flux uncertainty



- ν-e scattering is well known interaction we can use to constrain the neutrino flux

ν-e Scattering

20 December 2013 Jaewon Park, U. of Rochester FNAL JETP

Neutrino – Nucleons Interactions

Neutrino – Nucleons interactions

1. Charged current quasi-elastic scattering: $\nu_\mu + n \rightarrow \mu^- + p$
2. Neutral current elastic scattering: $\nu_\mu + N \rightarrow \nu_\mu + N$
3. Single π,η,K resonance productions: $\nu_\mu + N \rightarrow l + N' + \pi\ (\eta, K)$
4. Coherent pion productions: $\nu_\mu + X \rightarrow \nu_\mu + X + \pi_0$
5. Deep inelastic scattering : $\nu_\mu + N \rightarrow l + N' + m\pi(\eta, K)$

l: lepton; N, N': nuclons; m: integer

Pion (π)
$\pi^+(u\bar{d})$; $\pi^-(d\bar{u})$
$\pi^0\ (u\bar{u}\ /d\bar{d})$
$M_\pi \sim 140$ MeV

Eta (η)
$\eta = \frac{u\bar{u} + d\bar{d} - 2\,s\bar{s}}{\sqrt{6}}$
$M_\eta \sim 548$ MeV

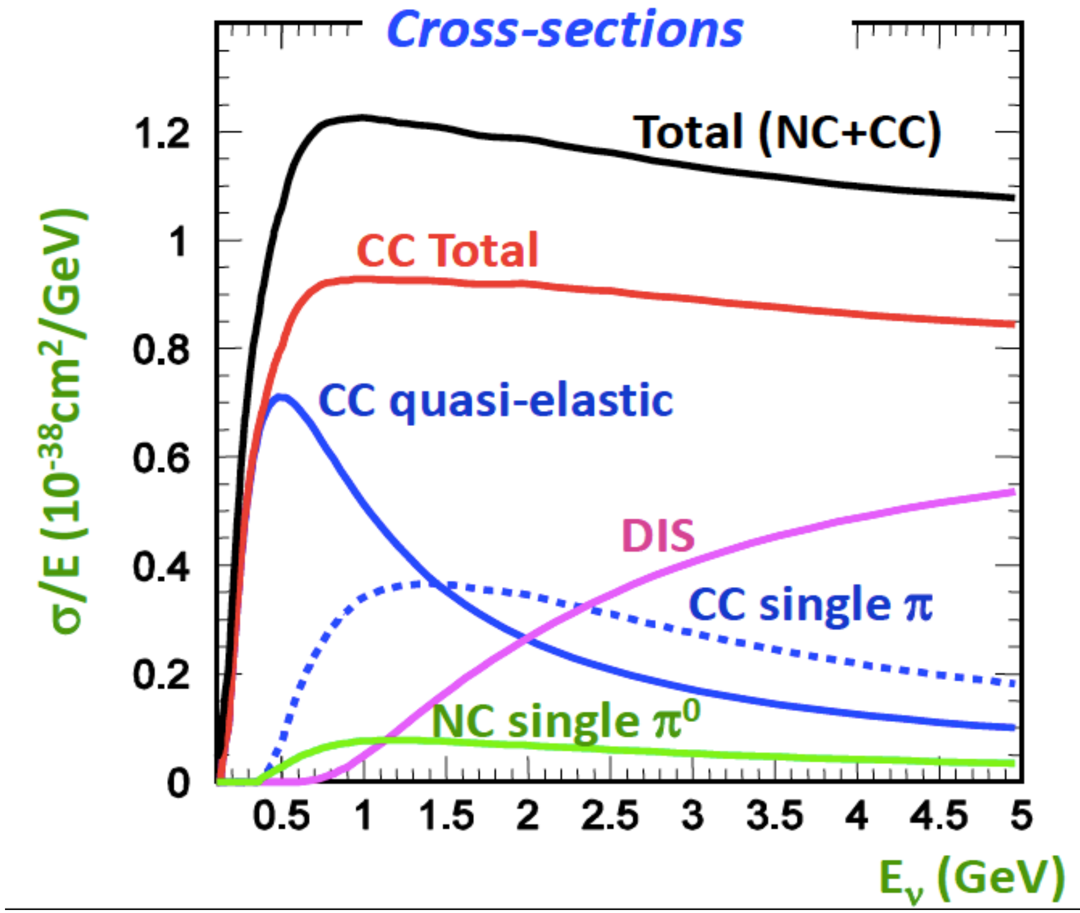
Kaon (K)
$K^+ = u\bar{s}$; $K^- = s\bar{u}$
$K^0 = d\bar{s}/s\bar{d}$
$m_K \sim 495$ MeV

Proton (p)
p = uud
$m_p \sim 940$ MeV

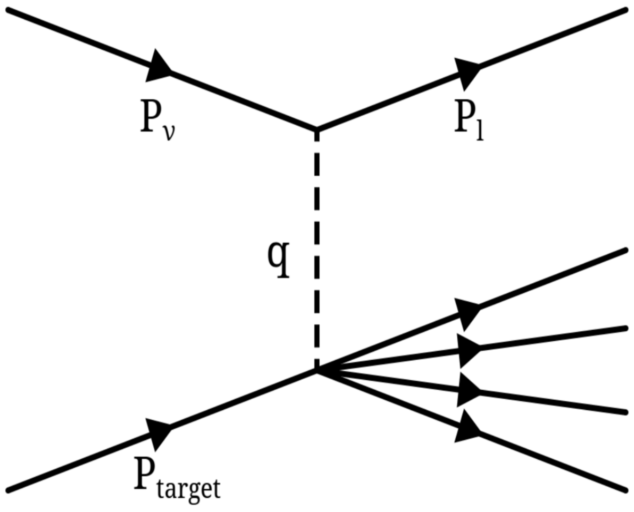
Neutron (n)
n = udd
$m_n \sim 940$ MeV

Neutrino – Nucleons interactions

- Nucleon target gives much more cross-section than electron target.
- Elastic interactions:
  - Dominate at small Q^2
  - Nucleon recoil intact
  - CC interactions are referred to as "*quasi - elastic*" (change of charge and the mass transfer to the lepton in the final state).
- Inelastic scattering:
  - At low Q^2, resonance production is dominated.
  - At high Q^2, DIS production is dominated



Neutrino – Nucleons interactions



CC – $W^\pm$ exchange

- Quasi-elastic Scattering
  Target changes but no breakup
  $\nu_\mu + n \rightarrow \mu^- + p$
- Coherent/Diffractive production
  Target unchanged
  $\nu_\mu + n \rightarrow \mu^- + n + \pi^+$
- Nuclear resonance production
  Target goes to excited state and decays
  $\nu_\mu + n \rightarrow \mu^- + p + \pi^0$ (N* or Δ)
  $n + \pi^+$
- Deep Inelastic Scattering
  Target breaks up
  ν_μ + quark $\rightarrow \mu^-$ + quark'

q^2

NC – Z^0 exchange

- Elastic Scattering
  Target unchanged
  $\nu_\mu + n \rightarrow \nu_\mu + n$
- Coherent/Diffractive production
  Target unchanged
  $\nu_\mu + N \rightarrow \nu_\mu + N + \pi^0$
- Nuclear resonance production
  Target goes to excited state and decays
  $\nu_\mu + N \rightarrow \nu_\mu + N + \pi$ (N* or Δ)
- Deep Inelastic Scattering
  Target breaks up
  ν_μ + quark $\rightarrow \nu_\mu$ + quark

NC Elastic and CC QE interactions

- In these processes of neutrino-nucleon interaction, a single lepton and a single nucleon are produced in which the nucleon recoils intact.
- In case of NC, for all flavours of neutrinos and anti-neutrinos, we have "*NC elastic*" scattering:

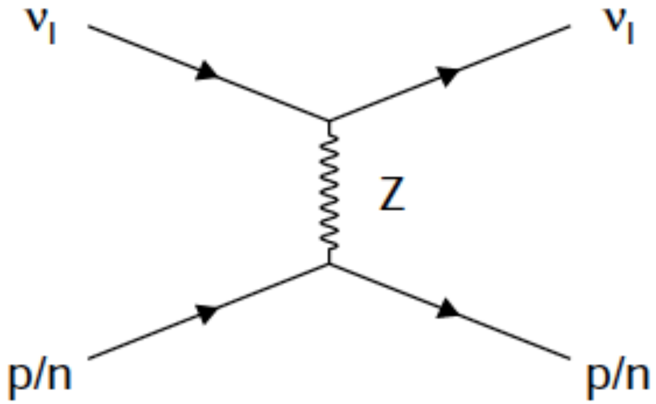
$$\boldsymbol{\nu + N \rightarrow \nu + N}$$

- In case of CC interaction, when neutrinos acquire sufficient energy:

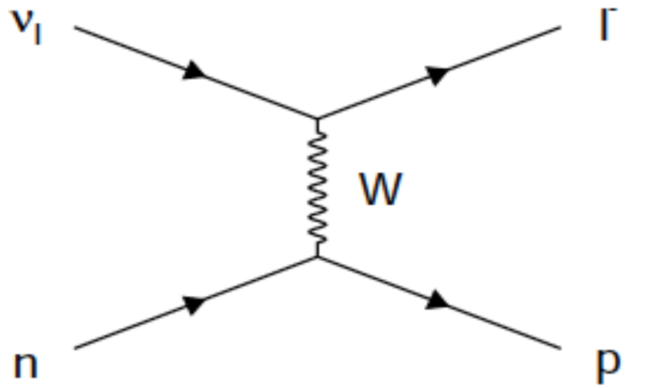
$$\boldsymbol{\nu_l + n \rightarrow p + l^-}$$

  → Need energy to create the lepton's mass → this is referred to as "*CC Quasi-elastic*" (CC QE) scattering.

NC Elastic

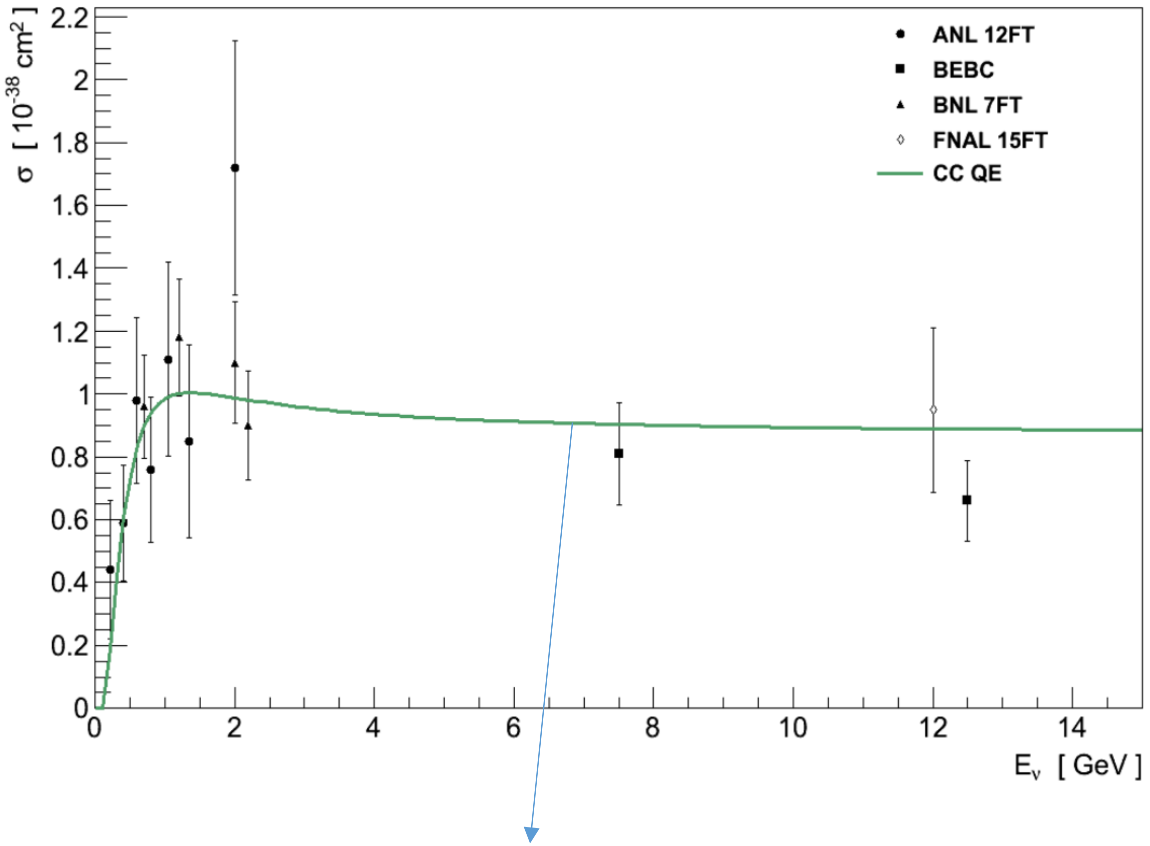


CC QE



CC QE interactions

- CC QE interactions is an important channel for ν oscillation experiments:
  - QE gives largest contribution to the cross-section of neutrino-nucleon interaction in a low region energy of neutrino (< 1 GeV).
  - QE is two body reaction → the incident neutrino energy can be reconstructed from kinematics of the charged lepton → for measuring oscillation parameters.



This implies that it is difficult to keep for the nucleon to remain intact at higher q^2

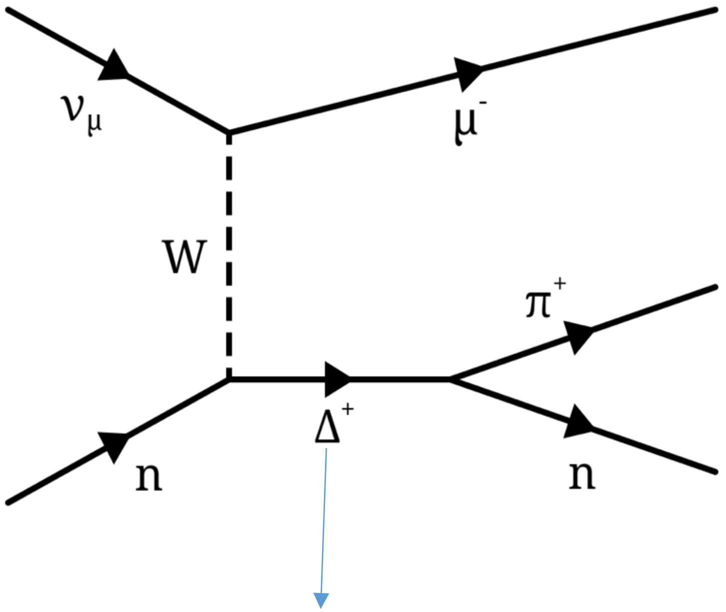
Resonance production

- This production obtained with higher Q^2 transfer (or neutrino's energy,

$0.5\ \text{GeV} < E < 10\ \text{GeV}$)

→ inelastic scattering!

- The lepton part is alsmost the same as in the case of elastic scattering.
- In the hadronic part, the target nucleon is knocked into a baryon resonance →then decay into a nucleon + a single pion (mostly) or multi pions or Kaons or a radiative photon.



The available resonance depending on neutrino's energy

Single pion production

Excitation of baryon resonance

$\nu + N \rightarrow \ell(\nu) + N^*$

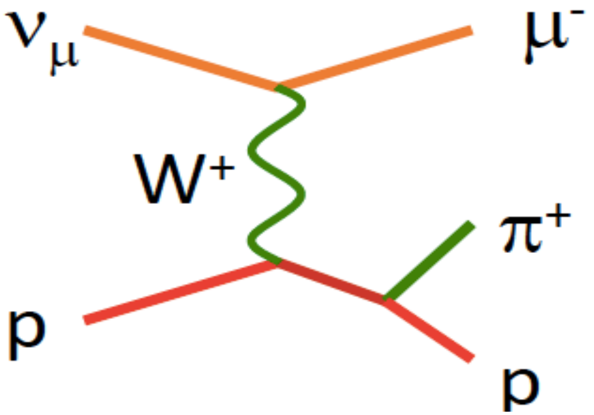
$\hookrightarrow \pi(\gamma) + N'$

Decay of baryon resonance

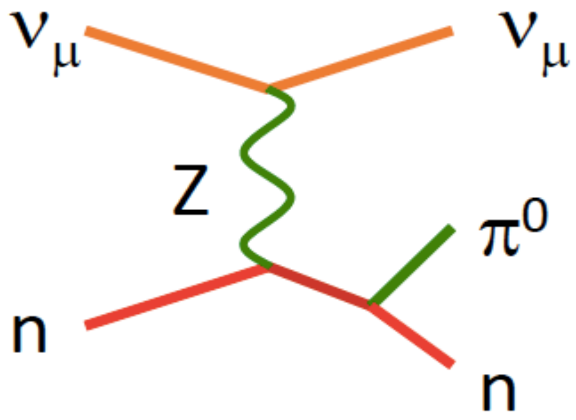
$$\begin{aligned} \nu_l + p &\rightarrow l^- + \pi^+ + p \\ \nu_l + n &\rightarrow l^- + \pi^+ + n \\ \nu_l + n &\rightarrow l^- + \pi^0 + p \end{aligned}$$

$$\begin{aligned} \nu_l + p &\rightarrow \nu_l + \pi^+ + n \\ \nu_l + p &\rightarrow \nu_l + \pi^0 + p \\ \nu_l + n &\rightarrow \nu_l + \pi^0 + n \\ \nu_l + n &\rightarrow \nu_l + \pi^- + p \end{aligned}$$

Charged Current



Neutral Current



Single pion production

$\nu + N \rightarrow \ell(\nu) + N^{*}$

$\quad\quad\quad\quad\quad\quad\quad \hookrightarrow \pi(\gamma) + N'$

Main background of the nucleon decay:

Particles in the final state are the same as the ones from nucleon decay

Main background for the search of $\nu_\mu \rightarrow \nu_e$ at T2K

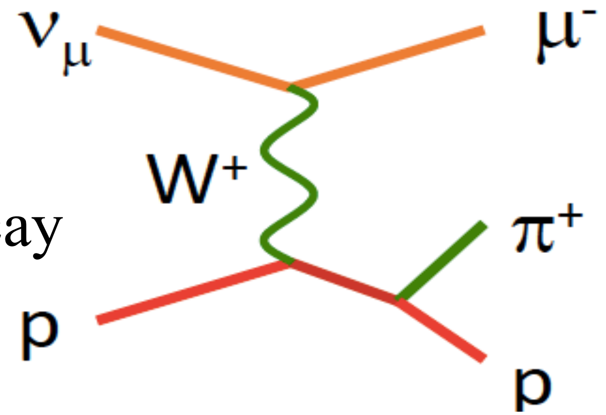
In the NC scattering, π^0 and γ production can mimic ν_e

Major contamination to the energy spectrum measurement

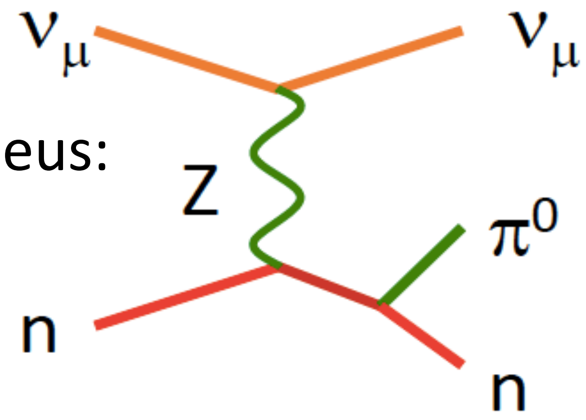
In the CC scattering, π production can be absorbed in the nucleus:

- π can be considered as missing energy,
  $\rightarrow$ background in searching for $\nu_\mu \rightarrow \nu_\mu$ disappearance
- CC1pi can be mimicked as CCQE.

Charged Current



Neutral Current



Single meson and photon production

Delta (Δ)

Δ^{++} = uuu; Δ^{+} = uud

Δ^{0} = udd; Δ^{-} = ddd

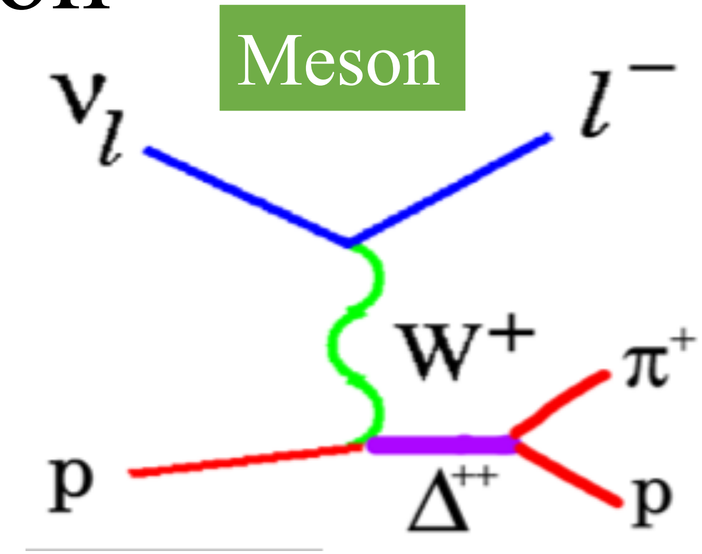
m_{Δ} = 1232 MeV

$\nu + N \rightarrow \ell + \Delta(N^*)$

$\quad \hookrightarrow N' + \pi(K, \eta)$

$\nu + N \rightarrow \ell + \Delta(N^*)$

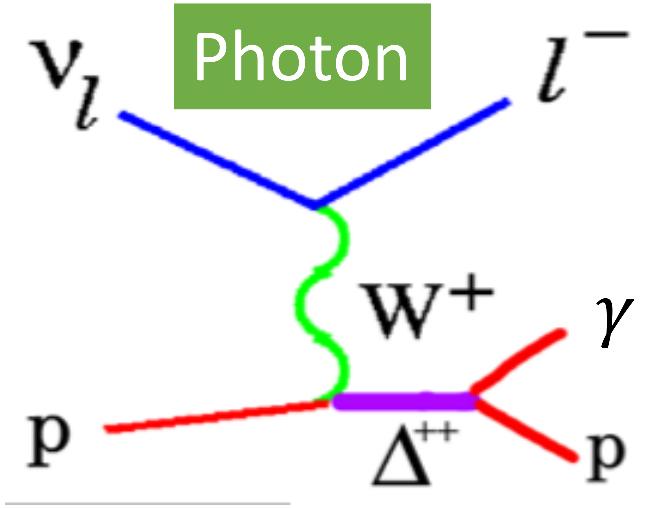
$\quad \hookrightarrow K + \Lambda$



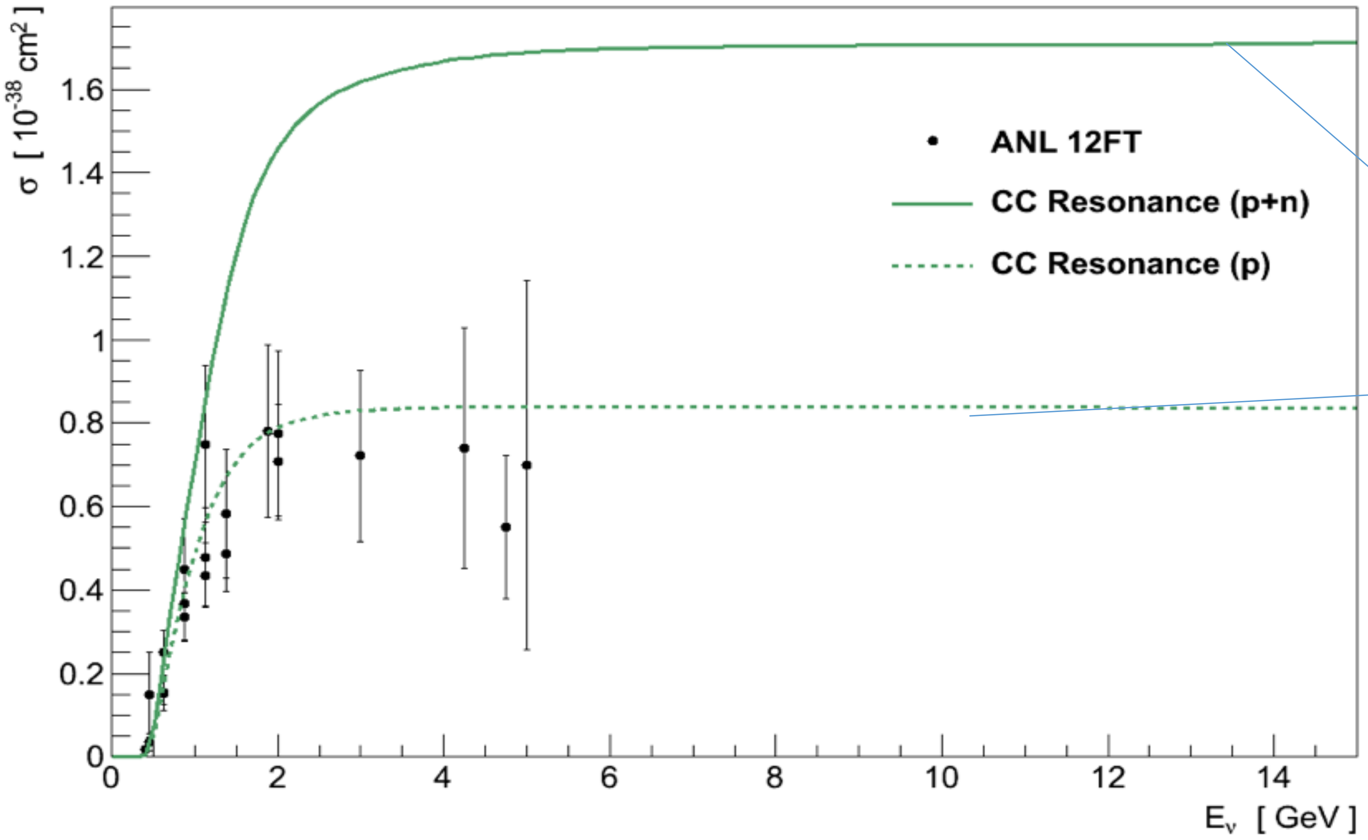
$\nu + N \rightarrow \ell + \Delta(N^*)$

$\quad \hookrightarrow N' + \gamma$

Can be background of the $\nu_\mu \rightarrow \nu_e$ appearance !



Single pion production cross-section



- **Data points**: total inclusive ν_μ CC interaction $\nu_\mu p \rightarrow \mu^- p \pi^+$

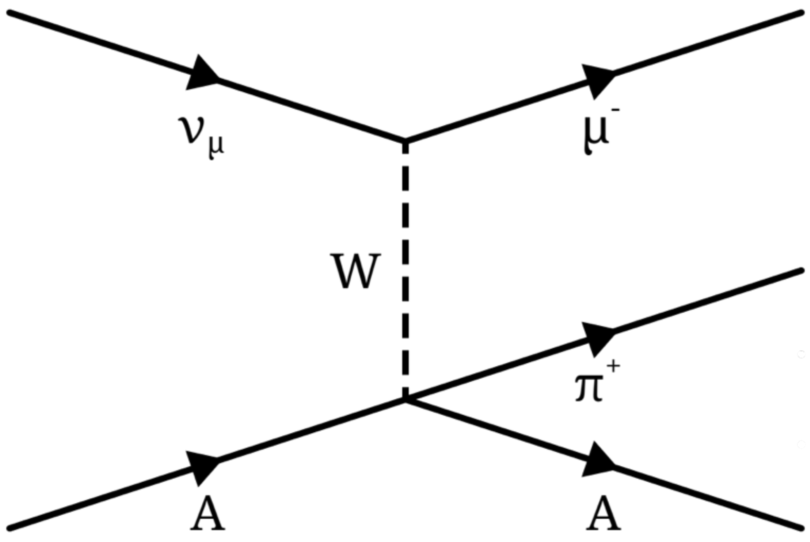
ν_μ CC 1pi cross-section on deuterium

This process is dominated in the range 0.5 GeV < E < 10 GeV

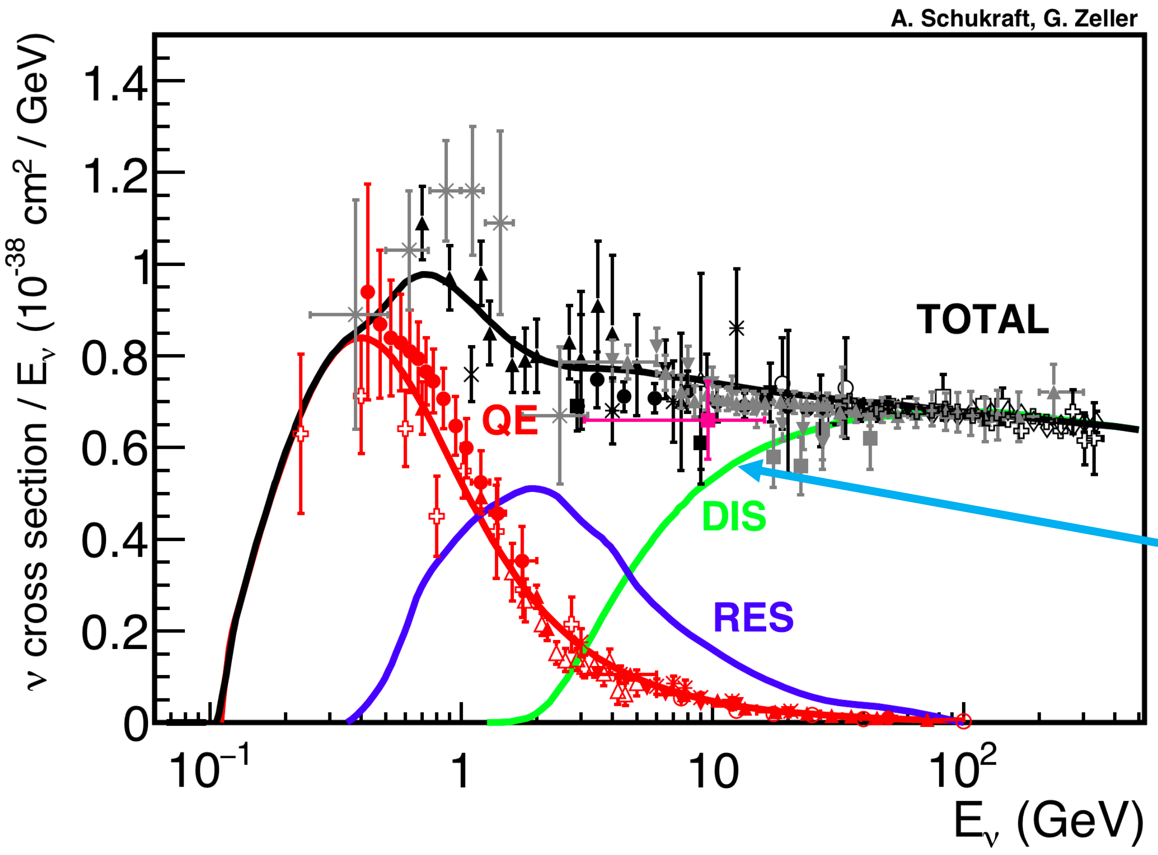
Coherent Interactions (nuclear target)

- Pion production without breaking the target nucleus.
- Cross-section is smaller than the resonance-mediated production.
- At low range of E_ν : NC scattering:

  $\nu + X \rightarrow \nu + X + \pi_0$
- Recently, cross-section of **charged current** coherent pion production ($\nu + {}^{12}C \rightarrow l^{\pm} + {}^{12}C + \pi^0$) was found to be very small in ~ < GeV region.
- CC experimently observed in higher E_ν

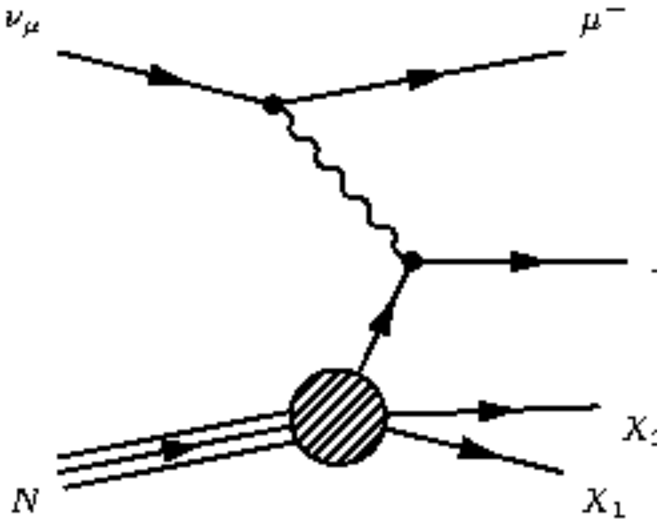


Deep Inelastic Scattering



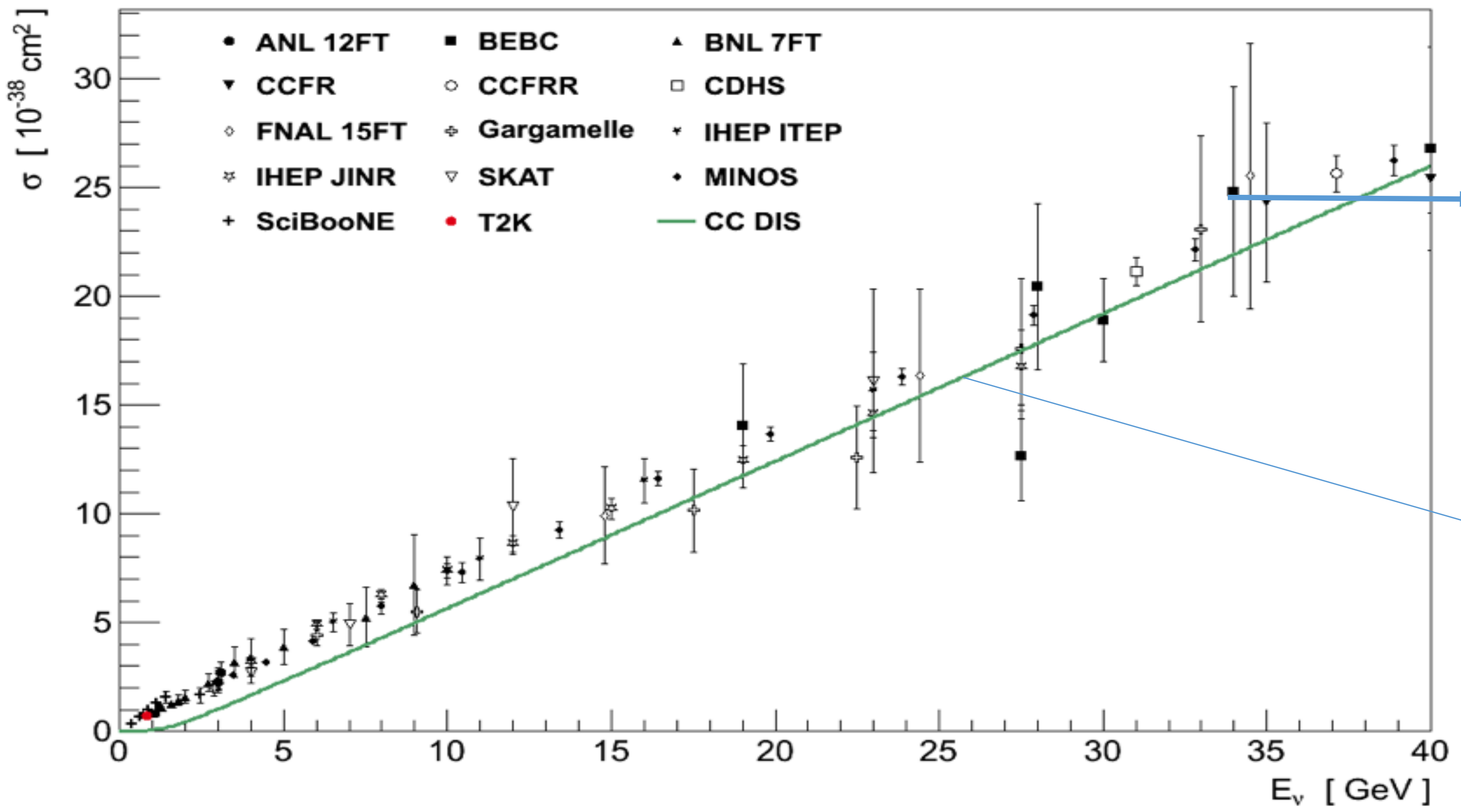
- DIS process appears from E > few GeV
- Nucleons are made of quarks.
- Understood as neutrino – quark interaction.
- E_ν is calculated as energy of lepton + energy of hadrons.

$\nu + N \rightarrow l + \text{hadrons}$



Hadrons

Deep Inelastic Scattering



- **Data points**: total inclusive ν_μ CC interaction measured on different targets.

ν_μ CC DIS cross-section on deuterium

DIS process dominates for $E_\nu > 10$ GeV and increases linearly with E_ν until W, Z mass!

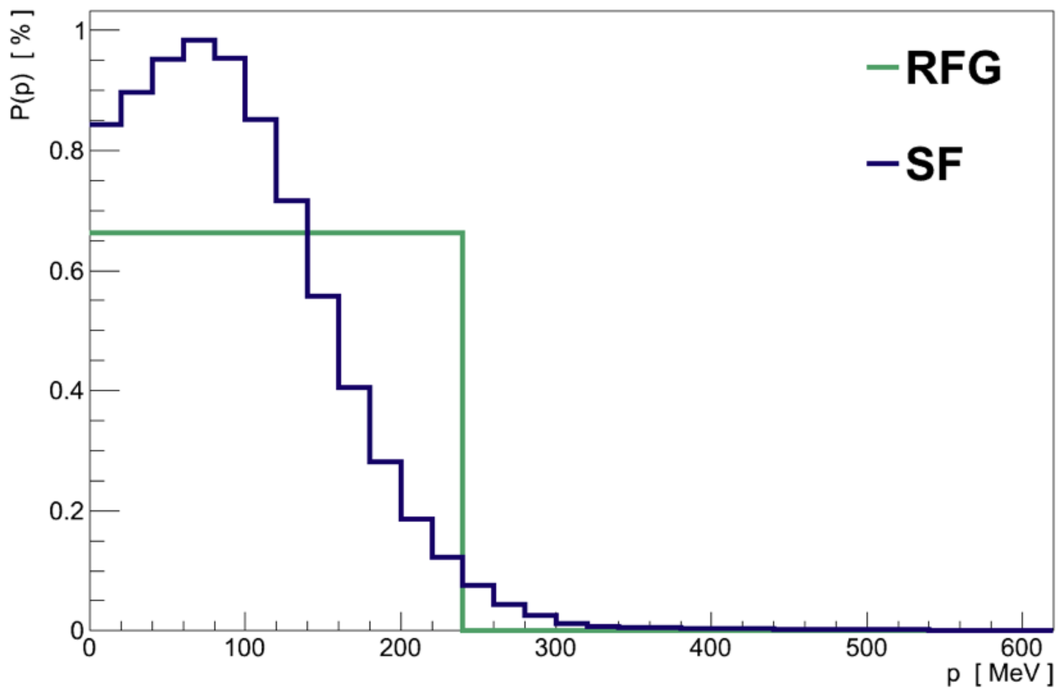
Neutrino – Nucleus Interactions

Neutrino – nucleus interactions: motivation

- Limitation of neutrino – electron interaction:
    - Well-understood but cross-section is much smaller than neutrino – nucleon interactions
    - Impossible to create a target made of only free electrons in the reality.
- Experiments think of neutrino – nucleons interaction:
    - Impossible to construct a target made of pure neutrons
    - Hydrogen target containing only proton → CC QE interaction is only for anti-neutrinos with lower cross-section.
    - Deuterium made of proton and neutron is a good target but it is light →low interaction rate.
- Neutrino-nucleus interactions:
    - Give higher interaction rate
    - In experiments, detectors are build using heavier nuclei such as carbon, oxygen or iron
    - Nuclear effects are present making complication in understanding interactions observed in detectors!

Neutrino-nucleus interactions: nuclear effects

- Initial state of the nucleons:
  - Nucleons in a nucleus move around inside the nuclear potential, changing their momentum and direction.
  - The direction and momentum of the nucleon affects the kinematics of any interaction
  - The initial momentum spectra of nucleons is not well known.
  - → Need models to describe this.
- Final State Interaction (FSI)
- Nuclear effects become more important at low energy region.
- Nuclear effects are simulated by MC generators.



The nucleon momentum distributions from a RFG and a SF (both for Carbon)