Neutrino physics

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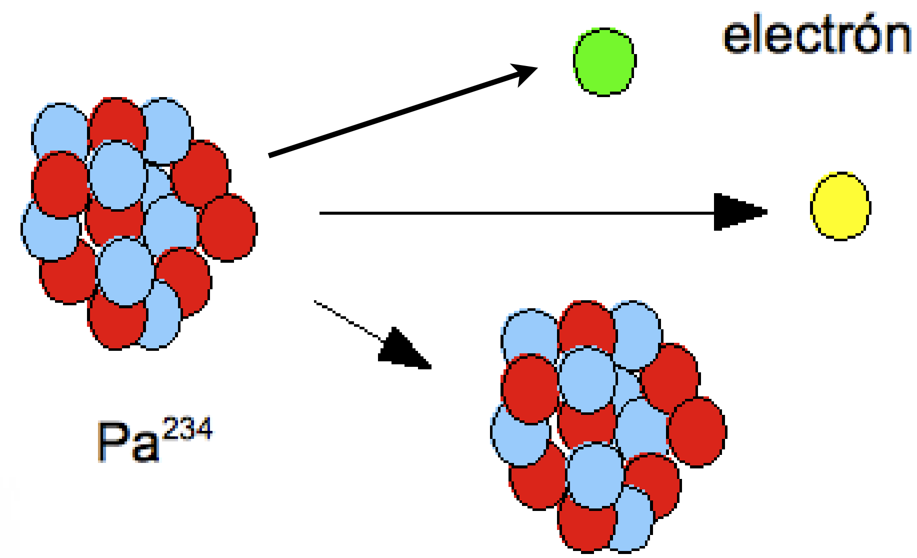
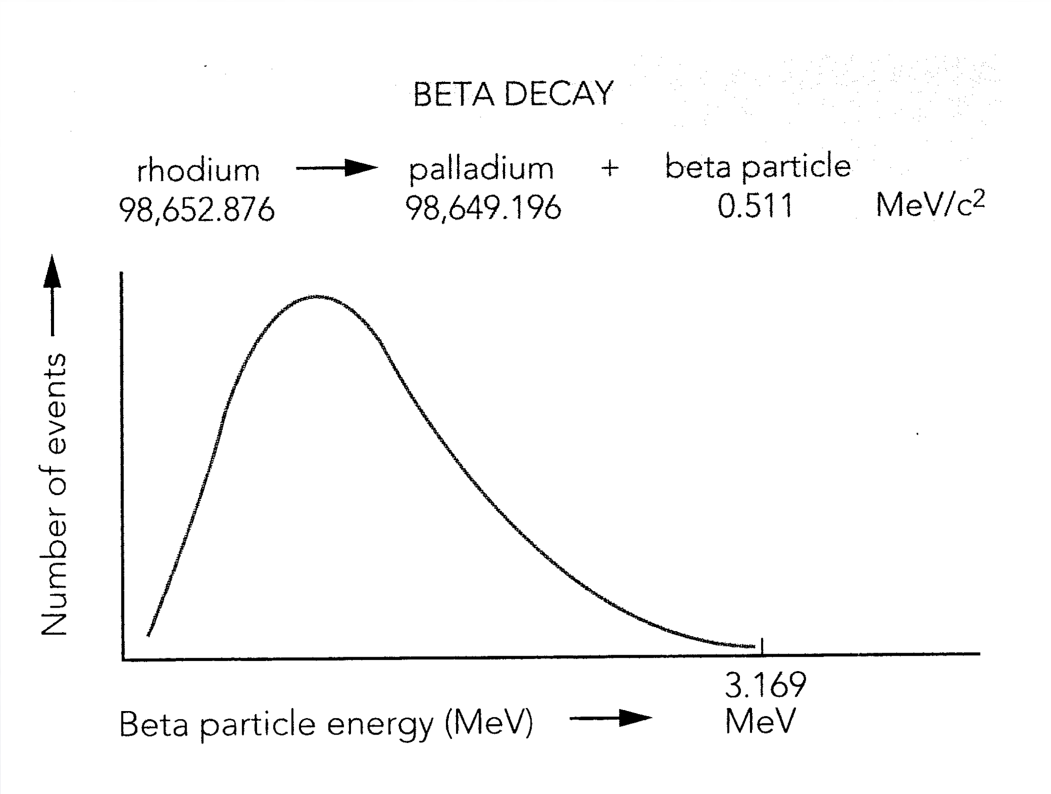
Outlook

- Neutrinos: discovery and early ideas.
- What are neutrinos.
- Neutrino interactions.
- Oscillation phenomenology:
    - Solar neutrinos
    - Atmospheric neutrinos + Long Base line experiments.
    - θ_{13} & CP violation.
- Majorana mass & $0\nu2\beta$
- Closing remarks

Neutrinos

- Neutrinos were proposed in 1931 by Pauli in a desperate attempt to understand the beta spectrum.
- He proposed the existence of an almost massless particle of spin 1/2 that is invisible:
  - no charge
  - weakly interacting.





Neutrinos

We know now that Pauli was basically right

- Neutrinos are fermions of spin 1/2
- No electric charge and no QCD color (no electromagnetic or strong interactions).
- They interact only through weak and gravitation interactions (feeble).
- Very low mass: $< 10^{-6}$ times the electron mass.
- After discovery of the parity violation in β-decays, the two-component neutrino theory (Landau , Lee and Yang and Salam, 1957) was the first theoretical idea about neutrino masses.
  - *Two* neutrinos (Left-Right), one of them is "sterile" (do not interact) so it is not "needed".

- There are 4 independent solutions to the Dirac Equation:

$$i\gamma^\alpha \partial_\alpha \nu_L(x) - m_\nu \nu_R(x) = 0$$
$$i\gamma^\alpha \partial_\alpha \nu_R(x) - m_\nu \nu_L(x) = 0$$

Relativistic spin 1/2 plane wave equation

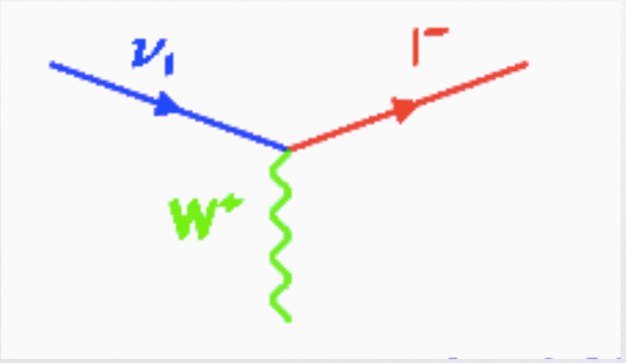
- The 4 solutions (2 particle and 2 antiparticles) can be represented as eigenstates of the (chirality) projector:

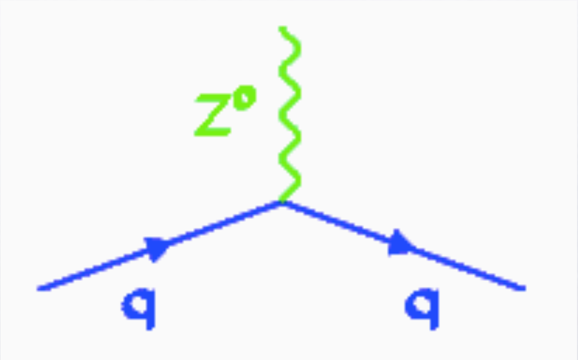
$$P^{R,L} = \frac{1}{2}(1 \pm \gamma^5)$$

Chirality is a Lorentz invariant

- It turns out that nature relates chirality to the weak interactions.

$$-i\frac{g}{\sqrt{2}}\gamma^\mu \frac{1}{2}(1-\gamma^5) \qquad -i\frac{g}{\cos\theta_W}\gamma^\mu \frac{1}{2}(g_V - g_A\gamma^5)$$





$g_V = g_A = 1$ for neutrinos

Chirality & interactions

- Only Left handed neutrinos and right handed neutrinos interact as a consequence of the weak interaction.
  - It is not true for charged leptons where right handed partners interact through neutral currents.

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

- A "traditional" mass term requires the existence of Right handed partners:

Dirac $$\mathcal{L}_D = -m_D\bar{\nu}_L\nu_R + h.c.$$

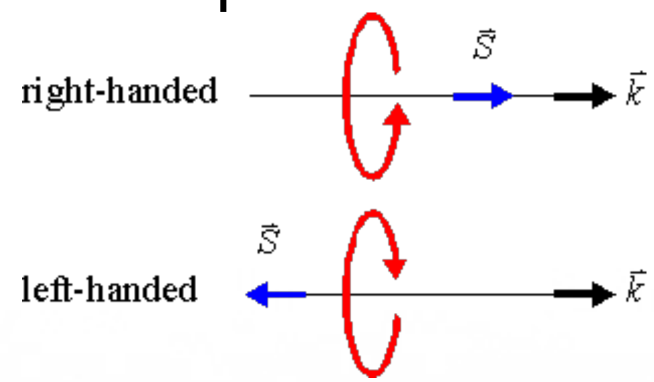
- But, those partners are sterile (do not interact) in the Standard Model.

If they do not interact, they are not needed, so theoretically

m_ν= 0 is (was) the preferred solution.

Helicity

- Helicity is related to the projection of spin in the direction of movement:



Helicity is **not** a Lorentz invariant

Lorentz boost will change particle direction but not the spin rotation sense.

- The helicity projector is

$$P^{L,R} = \frac{1}{2}\left(1 \pm \frac{\vec{\sigma}\cdot\vec{p}}{|p|}\right)$$

- The limit for ultra relativistic particles (or massless) is chirality projector:

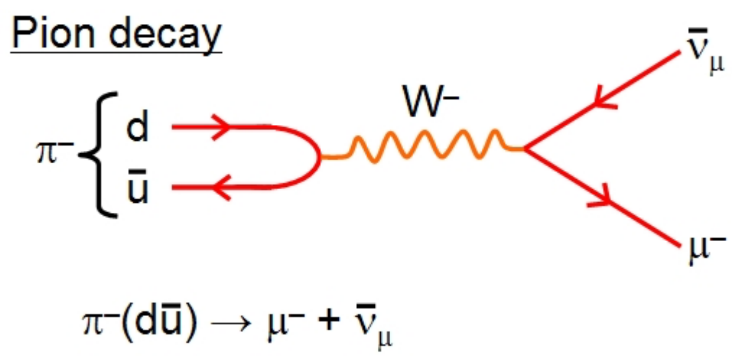
$$\lim_{v\to c} P^{L,R} = \lim_{v\to c}\frac{1}{2}\left(1 \pm \frac{\vec{\sigma}\cdot\vec{p}}{|p|}\right) = \frac{1}{2}(1 \pm \gamma^5)$$

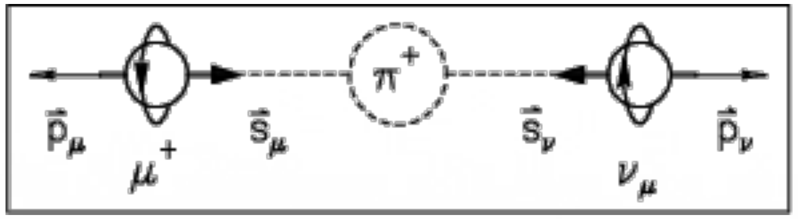
- This is the origen of confusion between the two terms.

For massive particles we can produce left handed chiral and right handed helicity states.

Helicity vs Chirality

- This is important to understand charged pion decay.
- Charged pion is spin 0 particle decaying to neutrino and charged lepton.





- Spin = 0 forces the final state leptons to have opposite spin and helicity.
- But, weak interactions requires both to be left handed chiral.
- The chiral state has always small component of "wrong helicity" proportional to the lepton mass.
  - Decay to muon is more probable than to electron even if it is not favoured by the available phase space.

This is a consequence of $(1-\gamma^5)$

What is weak ?

- Neutrinos interact solely through weak interactions.
  - Charged and neutral currents.
- These forces are mediated by massive W and Z bosons.

$$\frac{d\sigma}{dq^2} \propto \frac{\sqrt{2}g_w^2}{8(q^2 - M^2)} \rightarrow \frac{\sqrt{2}g_w^2}{8M^2} = 1.17 \times 10^{-5}/GeV^2$$

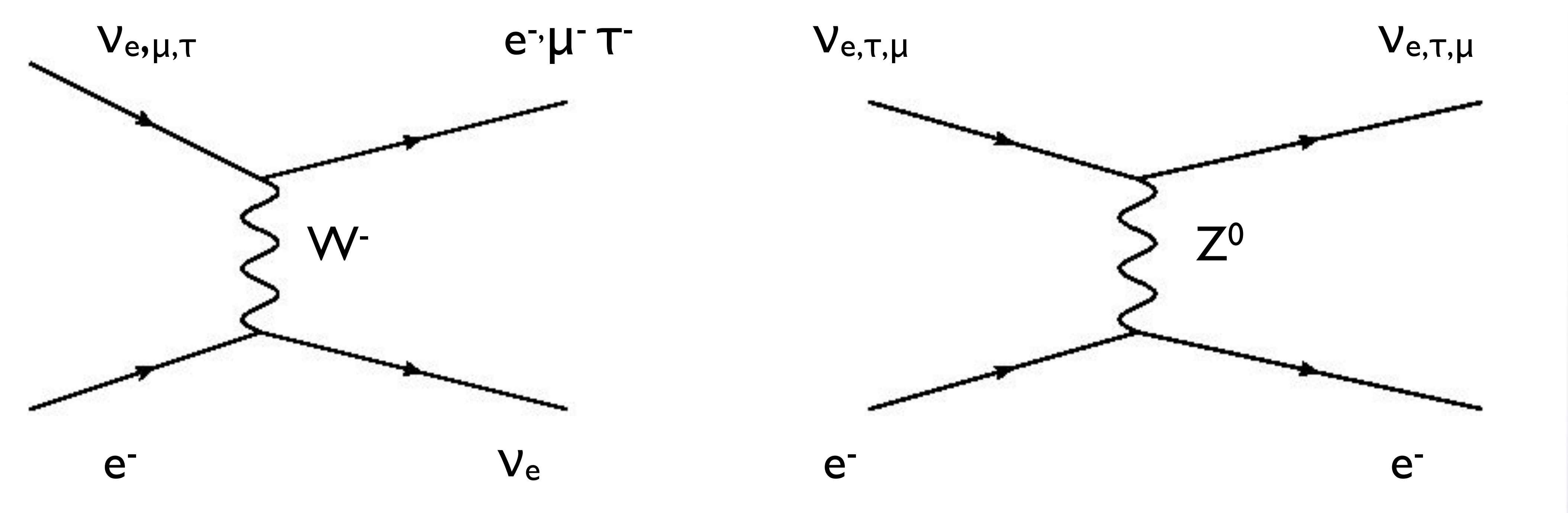
  - M_W ~ 80 GeV and g_w ~ 0.7
- This is between 10^4 and 10^7 weaker (depending of q^2) than the electromagnetic.

Neutrino interactions

- Being so weak, the detection of neutrinos needs very massive targets: matter!.
  - Avogadro's number help!
- In matter, the neutrino will find:
  - electrons
  - protons/neutrons
  - nuclei.
- Significant differences between antineutrinos, neutrinos and neutrino flavours.

Neutrino-electron

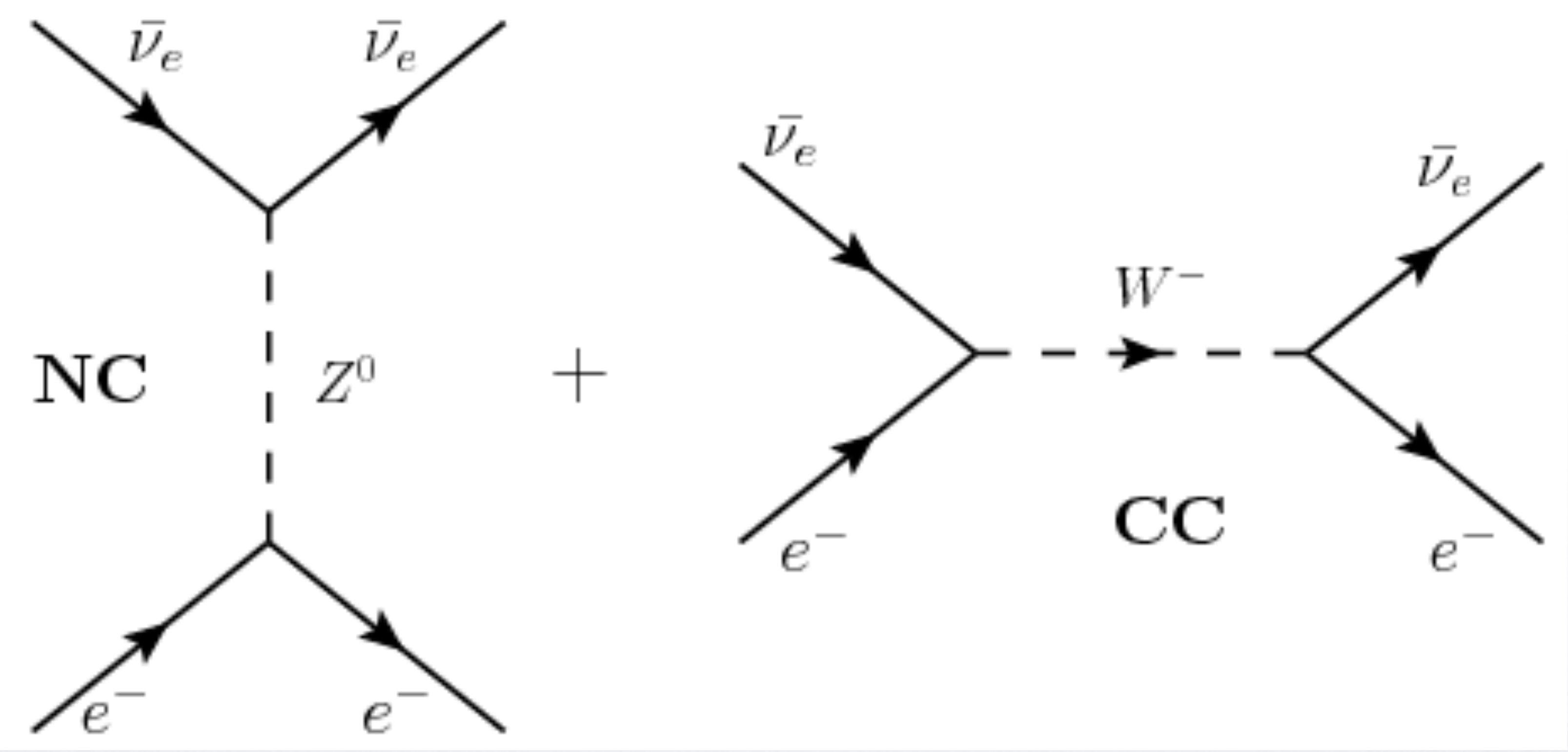
- All neutrinos interact through neutral current with electrons.
- Only electron neutrinos has charged current interactions unless the energy of the neutrino is larger than the lepton mass.



$$E_{\nu_{\mu,\tau}} > m_{\mu,\tau}$$

Antineutrino-electron

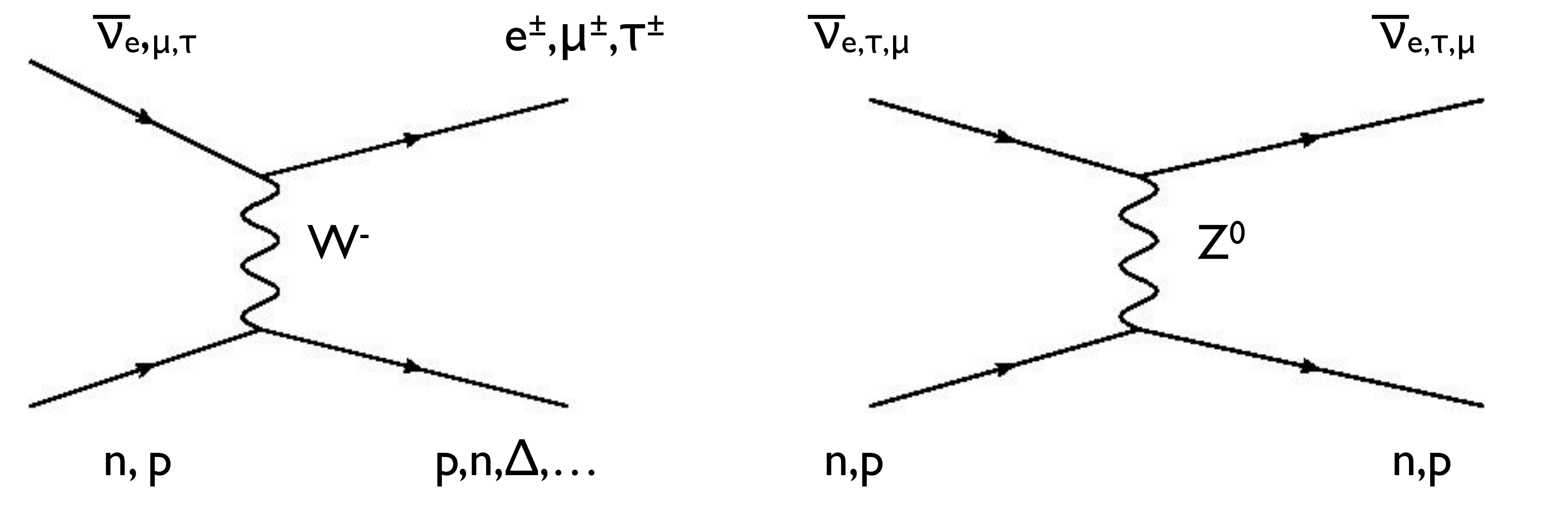
- All anti-neutrinos interact through neutral current with electrons.
- Only electron anti-neutrinos suffer charged current interactions



If $E_{\bar{\nu}_e} > m_{\mu,\tau}$ muon and tau neutrinos possible in final state.

Neutrino-nucleon

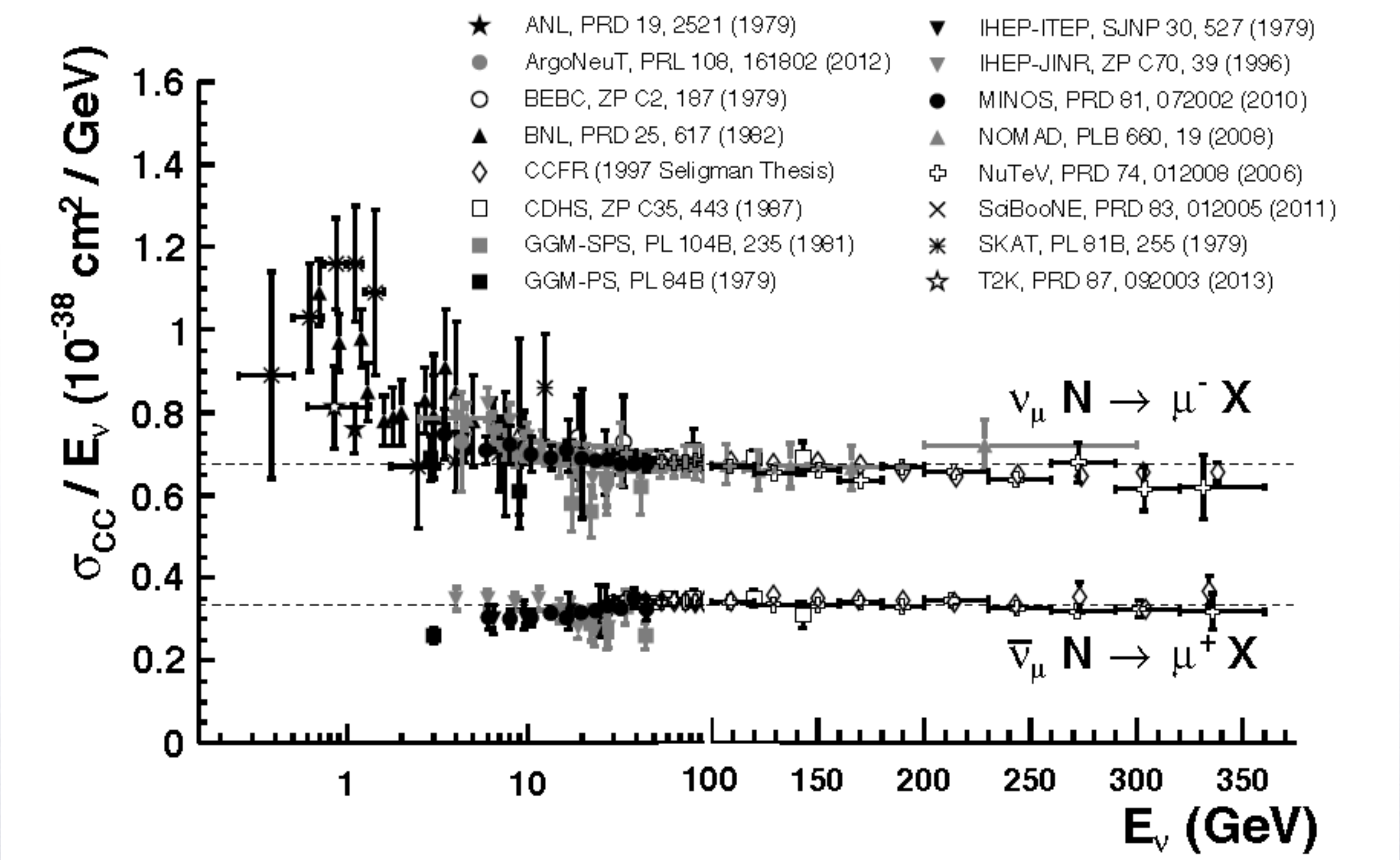
- Both neutrino and antineutrinos have charged and neutral current interactions with nucleons.



- But with different strength.

$$\sigma_{\nu,CC} \approx 2\sigma_{\bar{\nu},CC}$$

Neutrino-nucleon



Neutrino-nucleon

- Several interaction channels depending on the hadronic final states. (Similar for neutral currents)

CCQE

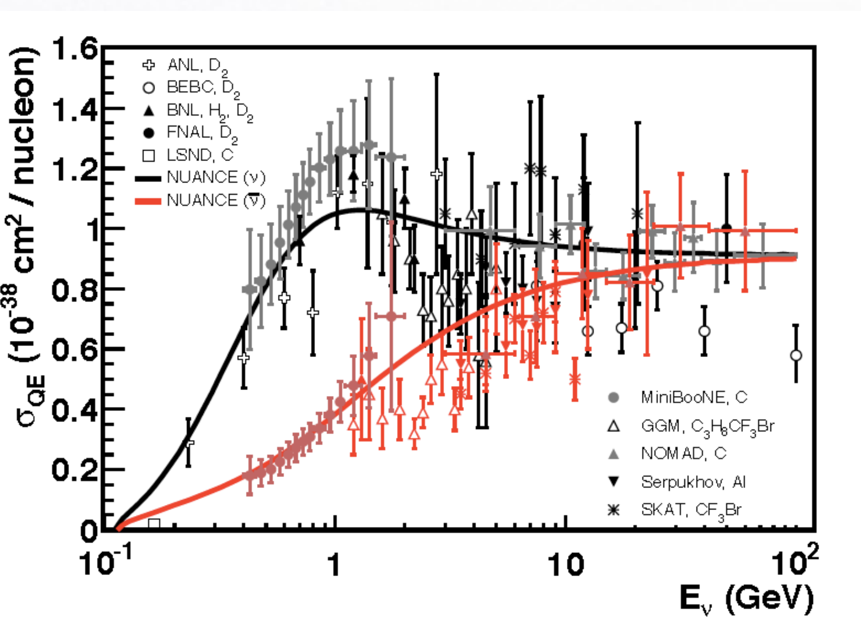
$$\nu_\mu n \rightarrow \mu^- p$$
$$\bar{\nu}_\mu p \rightarrow \mu^+ n$$

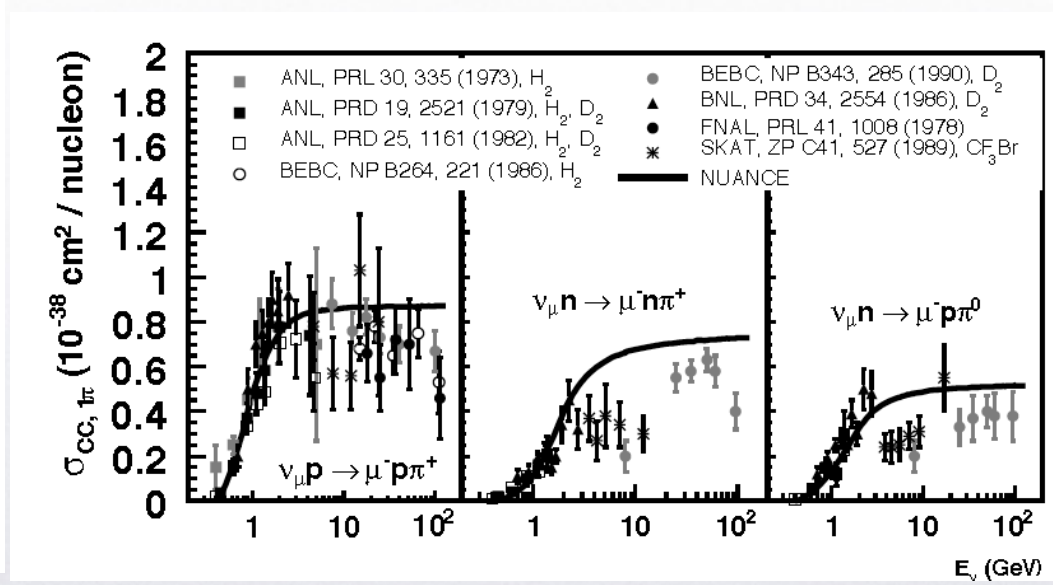
CCRes

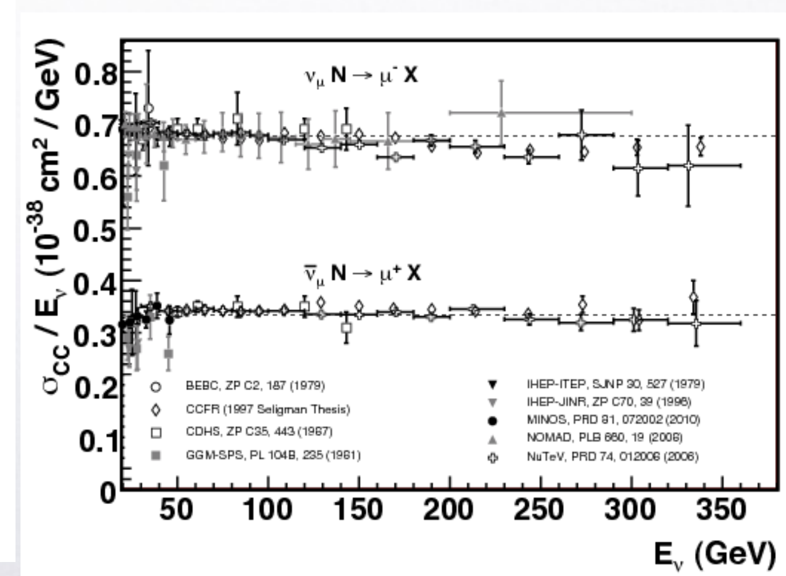
$$\bar{\nu}_\mu p \rightarrow \mu^+ \Delta^0$$
$$\bar{\nu}_\mu n \rightarrow \mu^+ \Delta^-$$
$$\nu_\mu p \rightarrow \mu^- \Delta^{++}$$
$$\nu_\mu n \rightarrow \mu^- \Delta^+$$

CCDIS

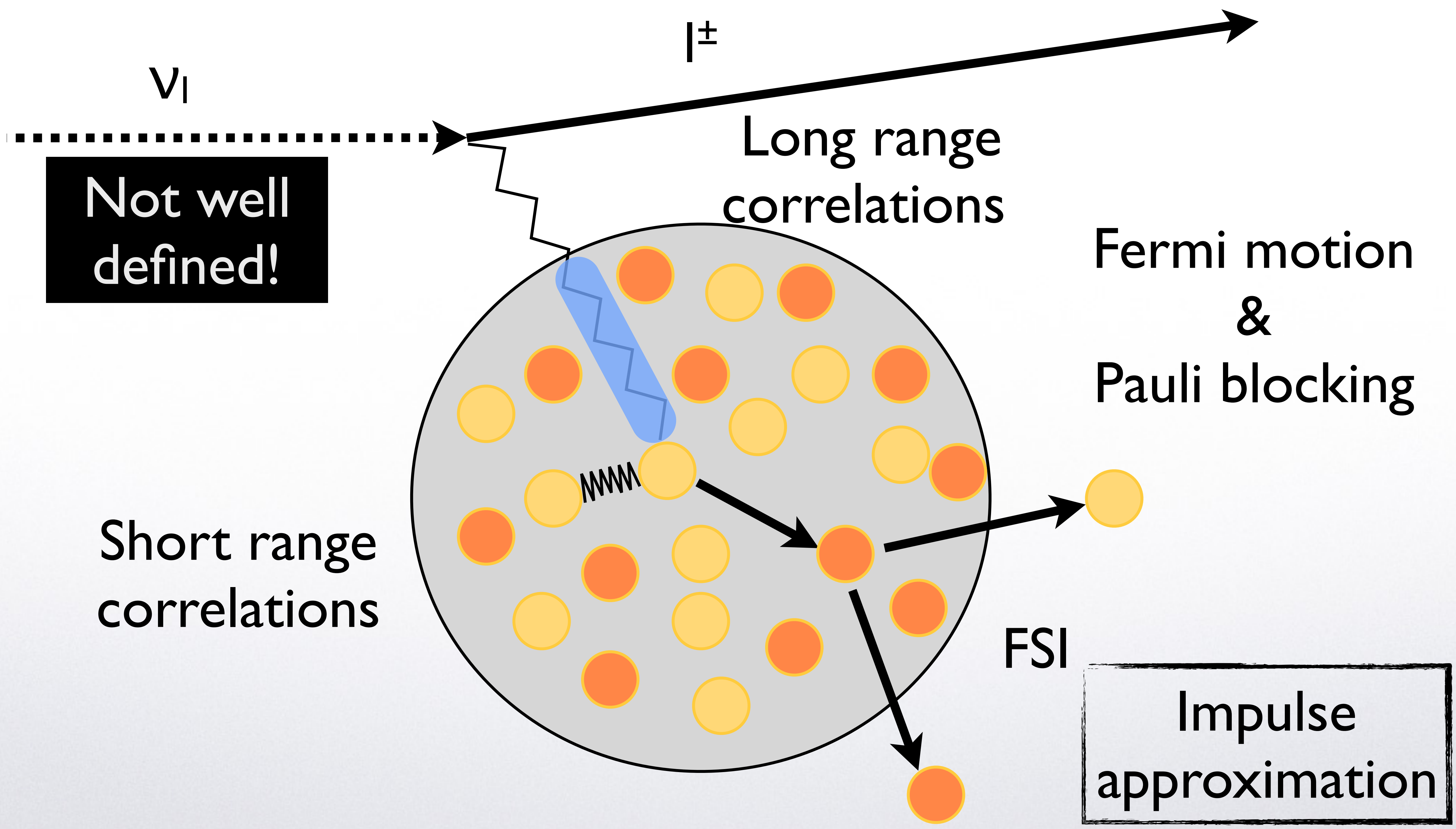
$$\bar{\nu}_\mu N \rightarrow \mu^+ X$$
$$\nu_\mu N \rightarrow \mu^- X$$



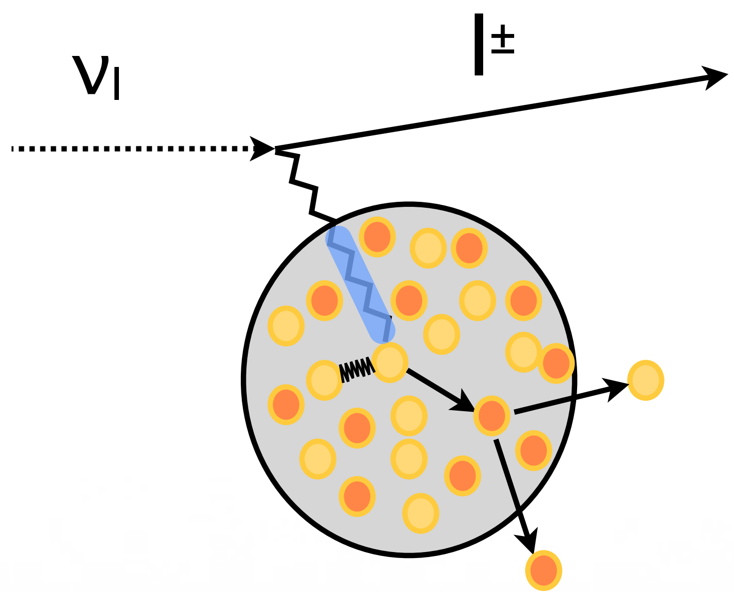




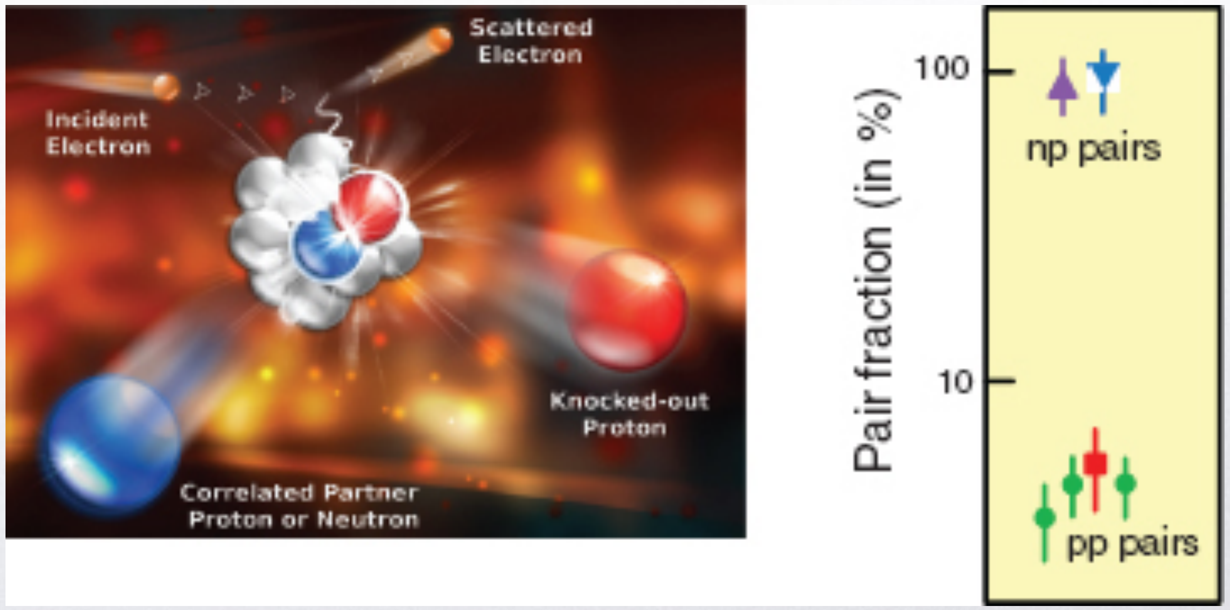
Neutrino interactions



Modelling interactions

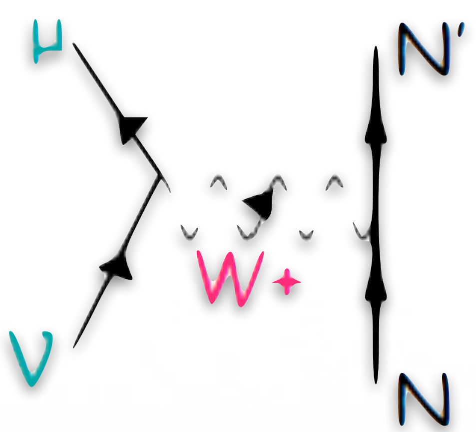


- Normally considered the "impulse approximation" or factorisation:
  - nucleon **assumed** free in nuclear media !
  - nucleon free in nuclear potential: no nucleon correlations!.
- Nuclear effects added on the top:
  - Fermi momentum.
  - Pauli blocking.
  - Short and long range nuclear correlations.

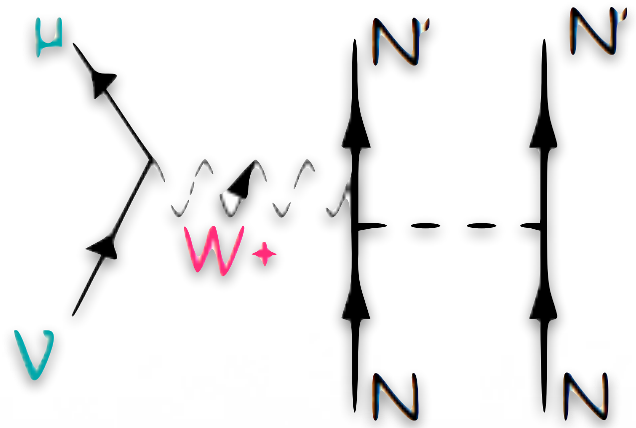


Modelling interactions

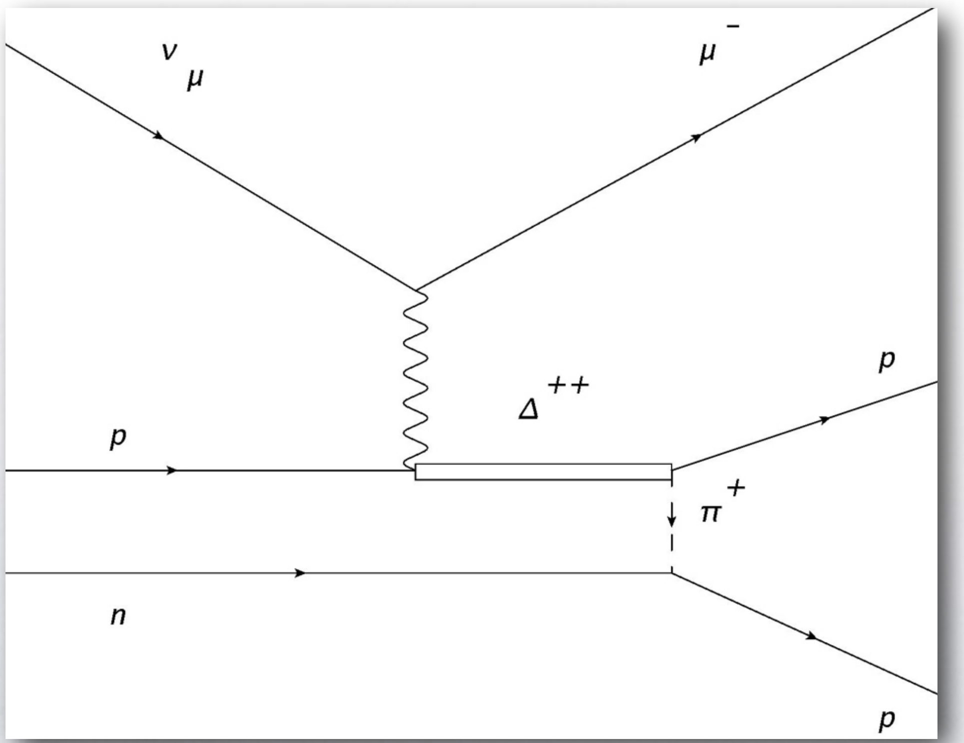
CCQE

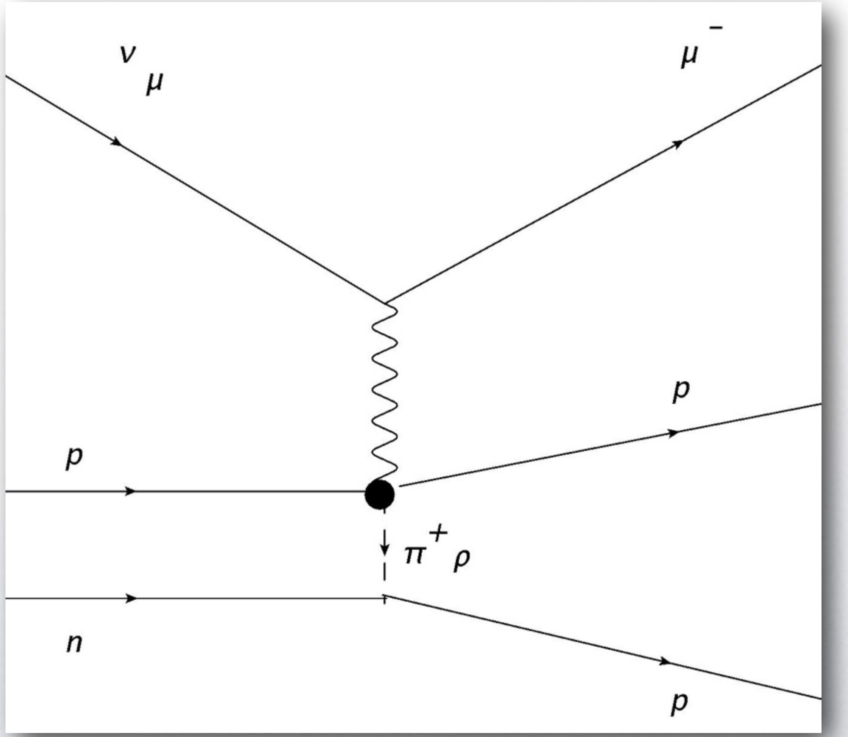


CC-2p2h



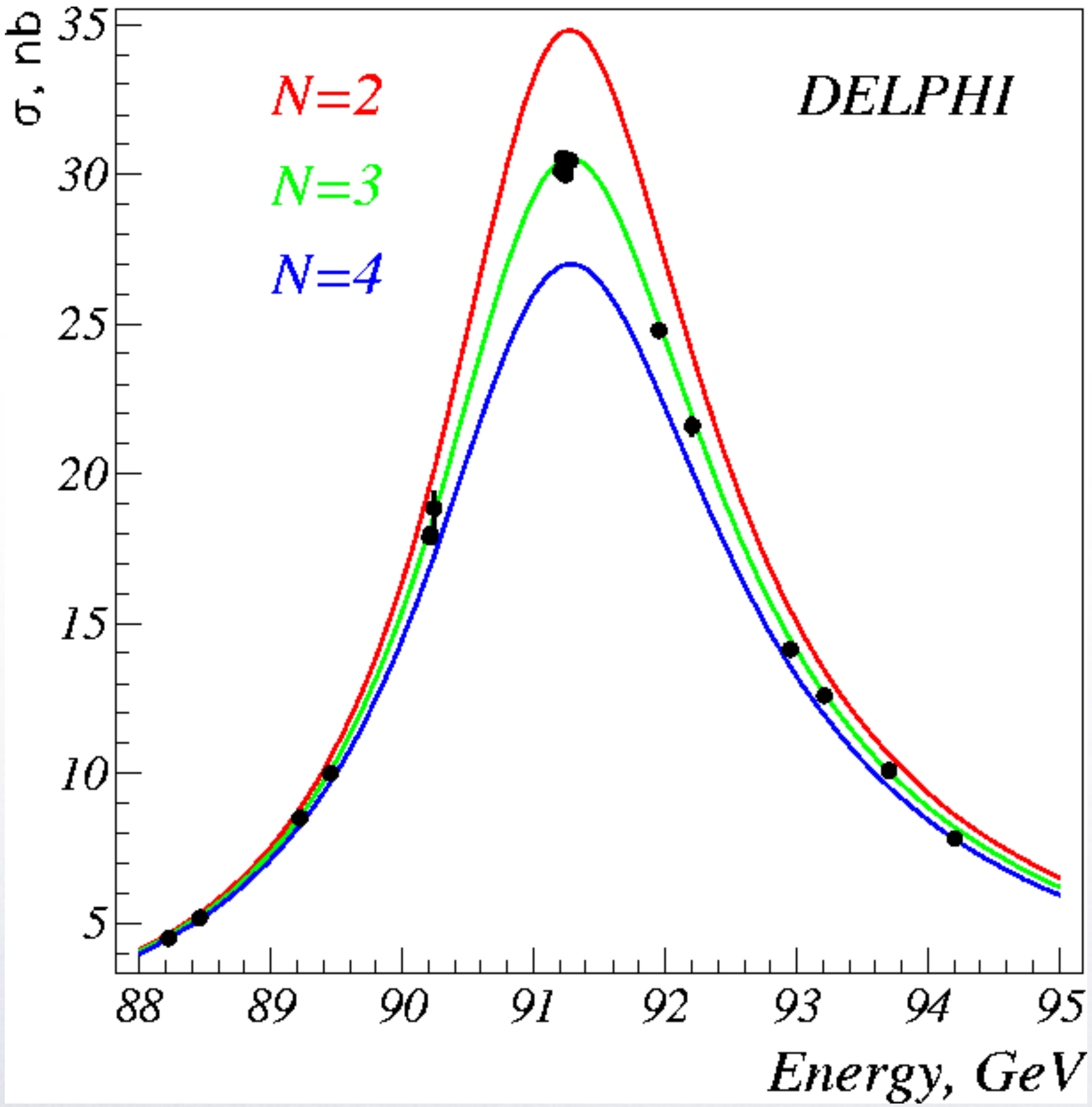
- Charge current without pions are made of several interactions
- 2p2h is basically the exchange of a meson between two close by nucleons in the nucleons with the emission of 2 nucleons.





- The pion can be produced in a contact point or virtual Δ^{++}.

Number of neutrinos



- Measure as the width of the Z boson scanning the production as function of the center of mass energy

$$e^+e^- \rightarrow Z^0 \rightarrow visible$$

- The width is the sum of the width to all possible disintegration channels

$$\Gamma = \sum_{\nu}\Gamma_{\nu} + \sum_{q\bar{q}}\Gamma_{q\bar{q}} + \sum_{l^+l^-}\Gamma_{l^+l^-}$$

Neutrino and mass

Neutrino oscillation

Early ideas

- Pontecorvo proposed, back in 1957, that the lepton sector might show oscillation phenomena similar to that of the K^0 meson. Neutrinos were neutral particles, and the lepton-hadron analogy was assumed.
- At that time Davis was doing experiments with anti-neutrinos from a reactor looking for the reaction:

$$\bar{\nu}_e \ {}^{37}Cl \rightarrow e^- \ {}^{37}Ar$$

  - And observed some events.

As many other times there were hints that finally vanished.

- At that time only one neutrino especie was known and then the only option was to have oscillations (also similar to K^0 system) was:

$$\nu \rightleftharpoons \bar{\nu}$$

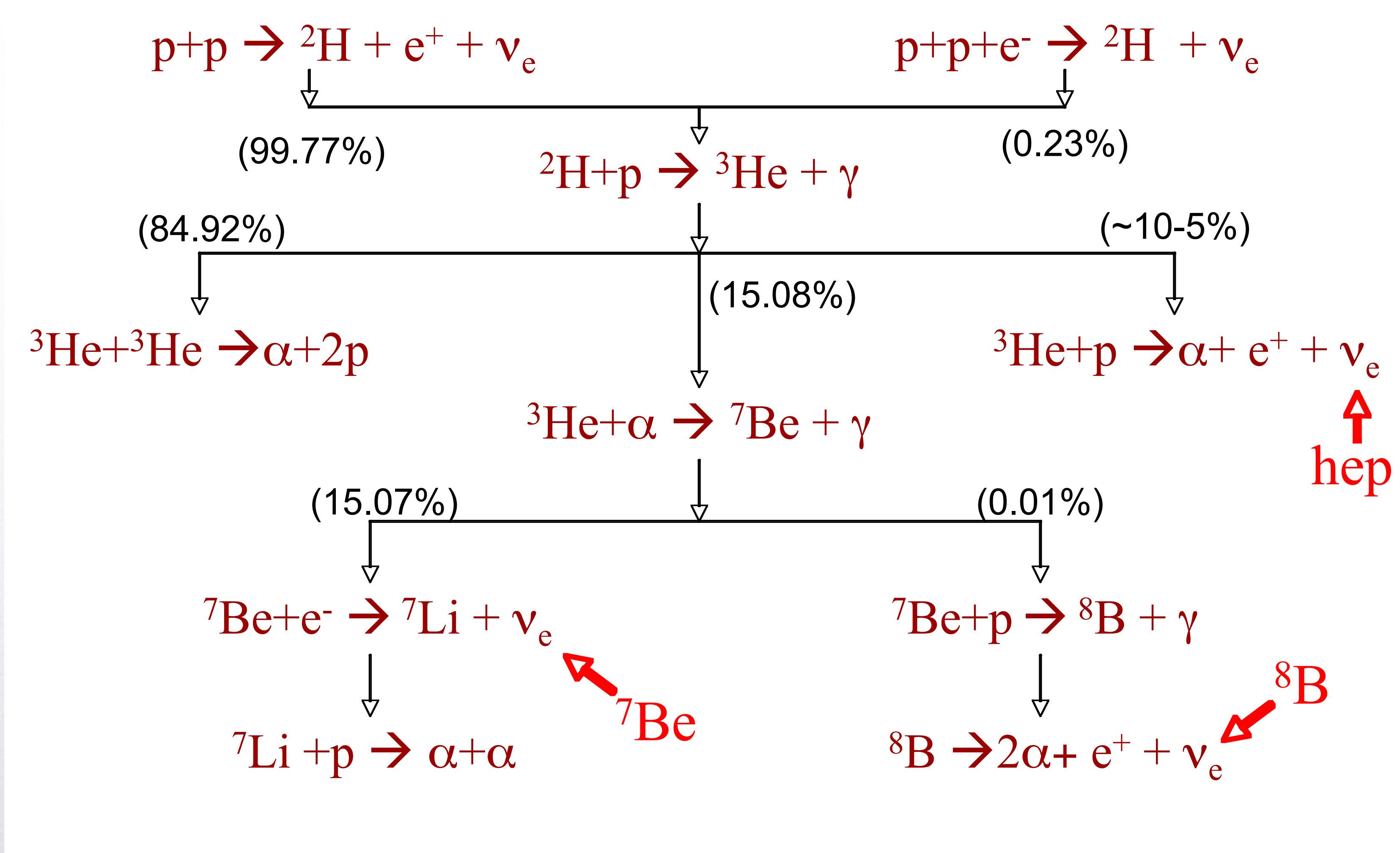
- In his model, he was already proposing that ν were a mixed system of two "Majorana particles" with different mass (ν_1,ν_2). (We will come back to this!)

Neutrino oscillation

- The ν_μ was discovered at Brookhaven in 1962 by Lederman, chwartz and Steinberger.
- At this time, Pontecorvo proposed the alternative model based on $\nu_\mu \leftrightharpoons \nu_e$ oscillations. The model "only" required that neutrinos were massive.
- Around same time the first experiments to detect Solar neutrinos were proposed by Davis & Bahcall. Pontecorvo suggested that if neutrinos oscillate, the experiments will see fraction of the predicted neutrinos from the sun …
    - $\nu_e \rightarrow \nu_\mu$
    - *+ not enough energy to produce a muon, so* ν_μ *is invisible.*

Solar neutrinos

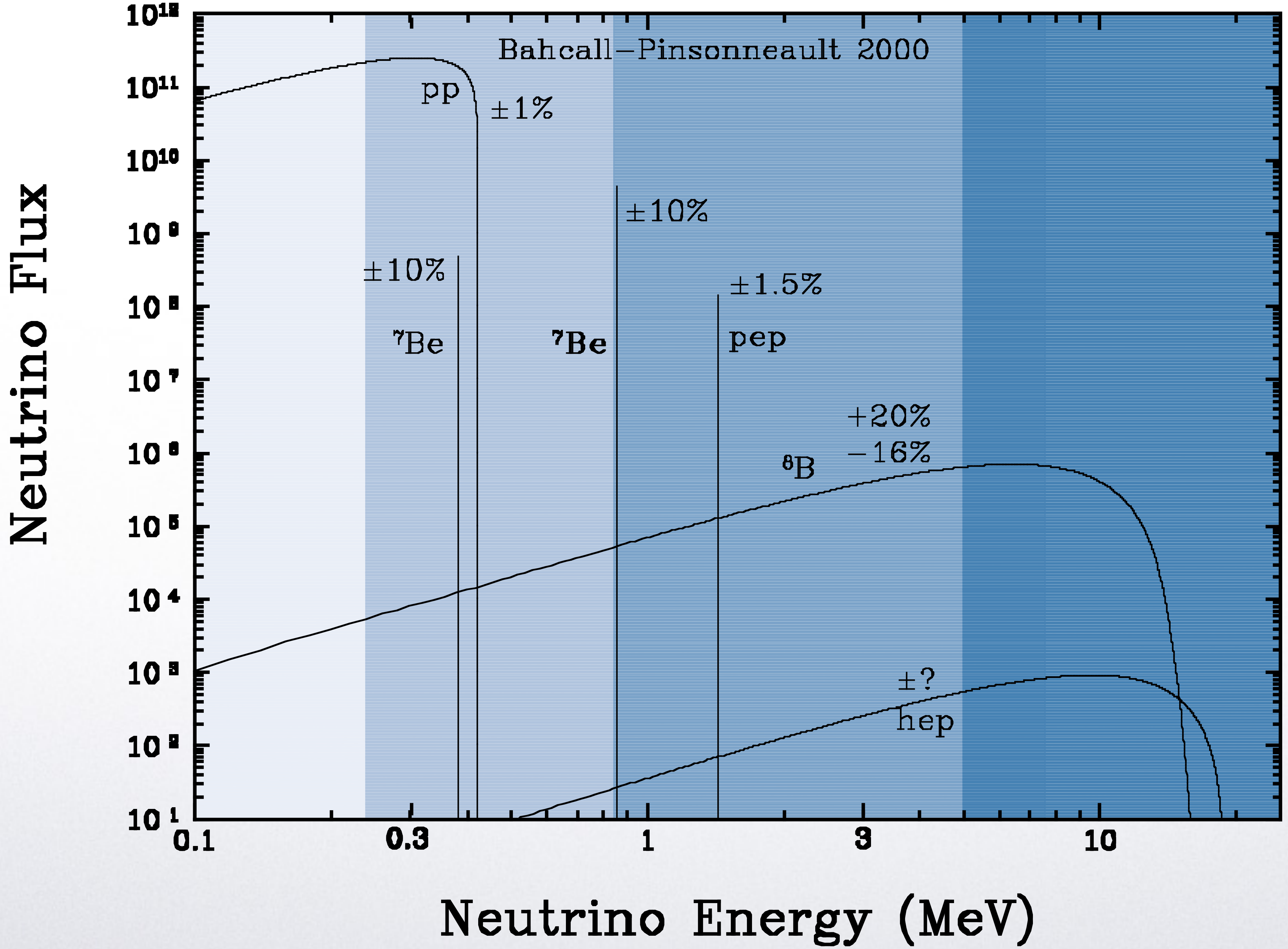
- The sun is a thermal fusion nuclear reactor.
- The sequence of reactions is known to a good level.
- This allows to predict a relation between the neutrinos and the sun luminosity.



Solar neutrinos

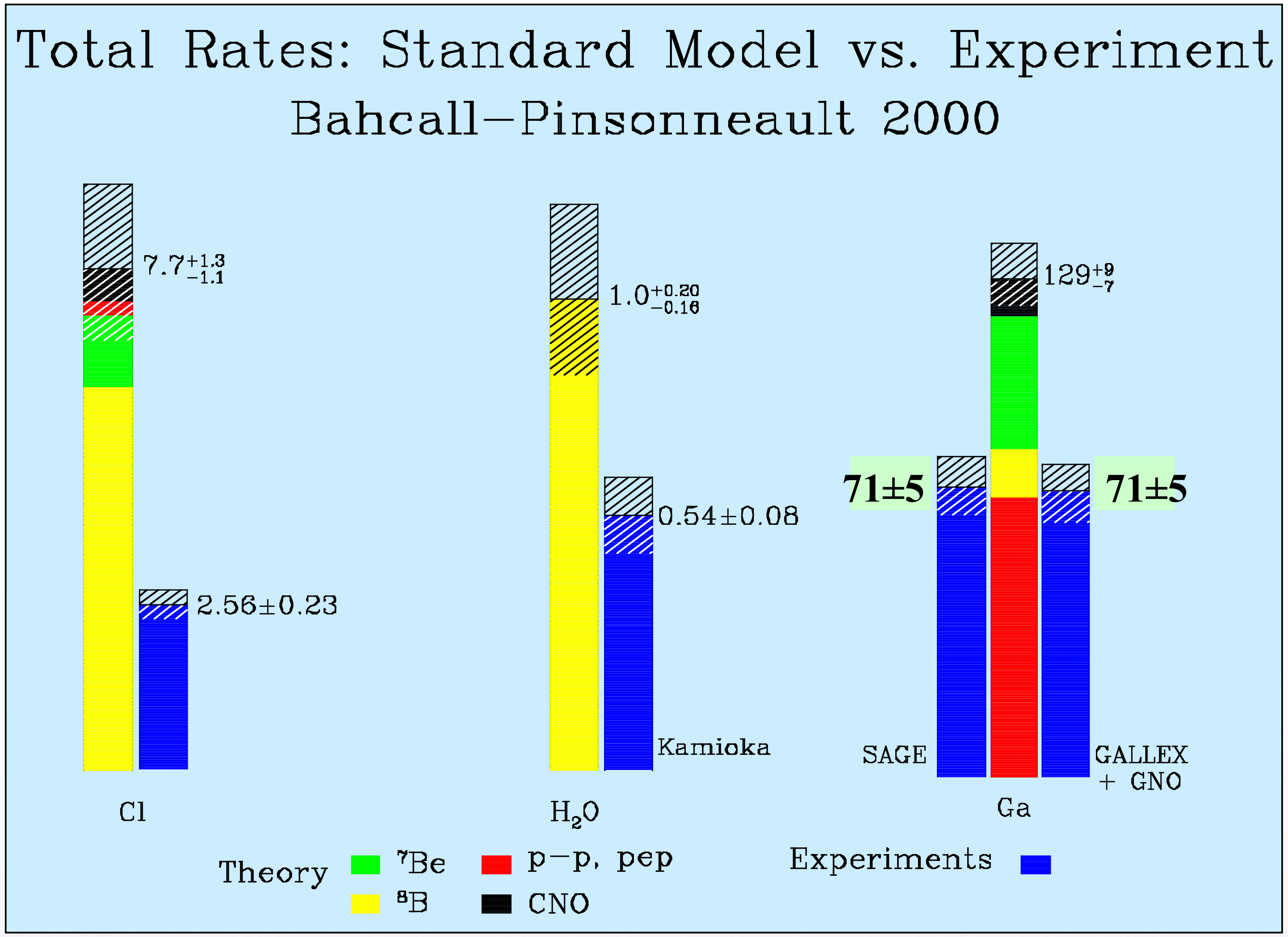
- Solar net reaction is $4p \to {}^4He\ \ 2e^+\ \ 2\,\nu_e$
- The sun releases 25.7MeV/c^2, or 4.12x10^{-12} Jules per Helium nucleus produced (or ½ of that per neutrino).
  - The solar constant is 1370Watts/m^2 at Earth's orbit.
  - The neutrino flux should be then 1370/(2.06x10^{-12})/m^2/sec or
    - **6.65x10^{10}/cm^2/sec.**
- This number is known to ~10% level.

Solar neutrinos



- The first experiments were based on radiochemical detection:
  - Chlorine: $\nu_e {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar}\, e^-$ ($E_\nu > 0.8$ MeV)
  - SAGE/Gallex/GNO: $\nu_e {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge}\, e^-$ ($E_\nu > 0.2$ MeV)
- Later the water Cherenkov detector Kamiokande was added to the list with a threshold of ~6 MeV.
  - Water Cherenkov added the possibility of online event recording and the determination of neutrino direction:
    - Reduced background, Day/Night and seasonal effects...

The experiments



- All of them detected neutrinos, but at a different rate than expected: solar model?, detector efficiencies?, neutrino deficit through oscillations?,…
- This disagreement was called for years "the solar neutrino problem".

Solar neutrino problem

The strength of paradigm

- Pontecorvo: "Unfortunately, the weight of the various thermonuclear reactions in the sun, and the central temperature of the sun are insufficiently well known in order to allow a useful comparison of expected and observed solar neutrinos..."
- Georgi & Luke: "Most likely, the solar neutrino problem has nothing to do with particle physics. It is a great triumph that astrophysicists are able to predict the number of ^{8}B neutrinos to within a factor of 2 or 3..."
- Yang: "I did not believe in neutrino oscillations even after Davis' painstaking work and Bahcall's careful analysis. The oscillations were, I believed, uncalled for."
- Drell: "… the success of the Standard Model was too dear to give up."

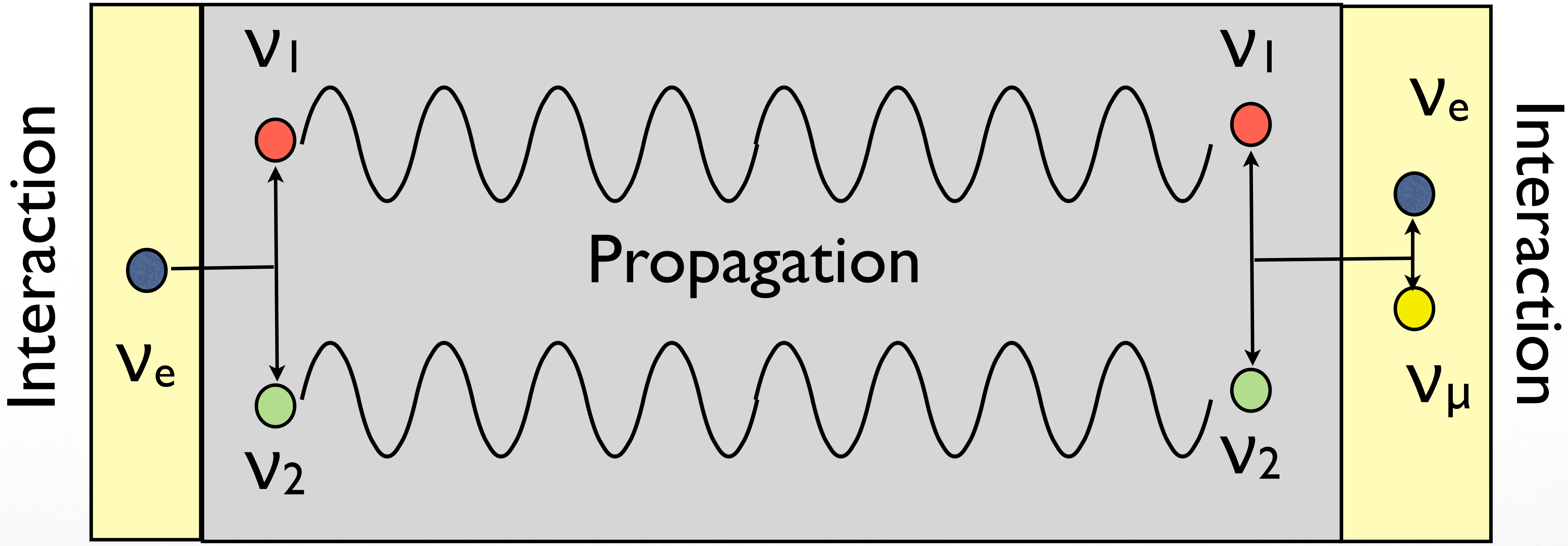
Neutrino oscillation

The theory

- The first phenomenological neutrino oscillation model was elaborated by Gribov and Pontecorvo in 1969.
- The model assumed that:
  - neutrinos have mass, albeit a very small one.
  - neutrinos interacts as ν_e or ν_μ (neutrino flavour).
  - the eigenstates of flavour and mass(Lorentz) are not the same. They can be related via a linear combination or rotation between the two bases.

$$
\begin{aligned}
|\nu_e> &= \cos\theta|\nu_1> + \sin\theta|\nu_2> \\
|\nu_\mu> &= -\sin\theta|\nu_1> + \cos\theta|\nu_2>
\end{aligned}
$$

Neutrino oscillation



- If neutrinos 1 & 2 propagate at different speeds (mass) and they keep the coherence at the interaction point the proportions are changed and it might appear other neutrino flavour.

The theory

- Neutrinos are transported in vacuum following the Schrödinger equation in vacuum:

$$|\nu_e> \quad = \quad \cos\theta|\nu_1> + \sin\theta|\nu_2>$$

- When we produce electron neutrino:

$$i\hbar\frac{\partial\nu}{\partial t} = H\,\nu = E\,\nu = \sqrt{m_\nu^2 + p^2}\,\nu$$

- $m_\nu << p$:

$$i\hbar\frac{\partial\nu}{\partial t} = (p + \frac{m_\nu^2}{2p})\nu$$

$$\nu(t) = e^{i(p+\frac{m_\nu^2}{2p\hbar})t}\nu(0)$$

The theory

- If we produce a ν_e, after some time the state is:

$$|\nu_e;t>=\cos\theta e^{i(p+\frac{m_1^2}{2p})\frac{t}{\hbar}}|\nu_1;0> +\sin\theta e^{i(p+\frac{m_2^2}{2p})\frac{t}{\hbar}}|\nu_2;0>= e^{i(p+\frac{m_1^2}{2p})}(\cos\theta|\nu_1;0> +\sin\theta e^{i\frac{m_2^2-m_1^2}{2p}\frac{t}{\hbar}}|\nu_2;0>)$$

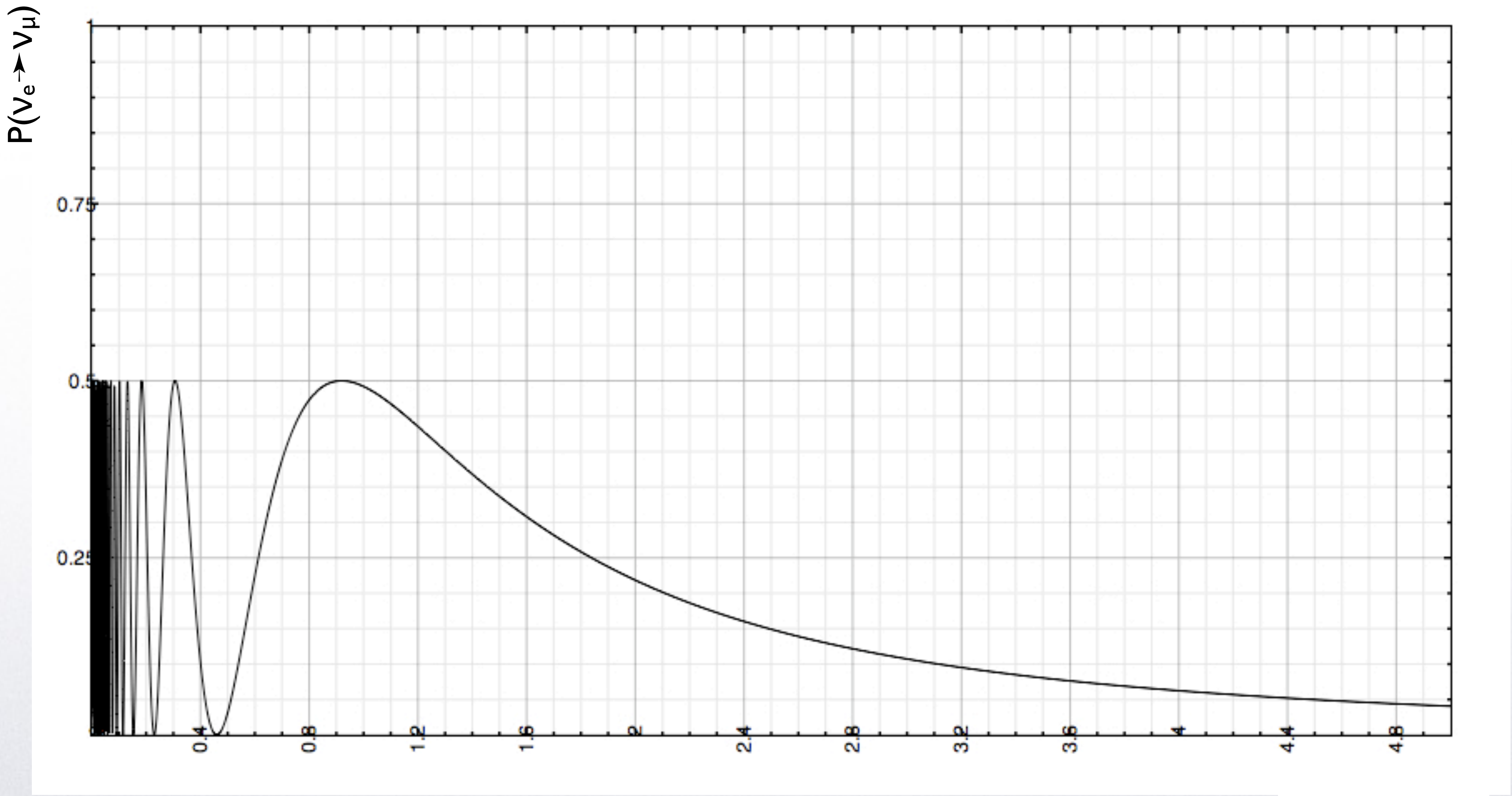
- The probability of getting a ν_μ at the interaction is then:

$$\begin{aligned} |<\nu_\mu|\nu_e;t>|^2 &= |-\cos\theta\sin\theta<\nu_1|\nu_1;0> +\sin\theta\cos\theta e^{i\frac{m_2^2-m_1^2}{2p}\frac{t}{\hbar}}<\nu_2|\nu_2;0>|^2 \\ &= \sin^2\frac{\theta}{2}\sin^2\frac{m_2^2-m_1^2}{4p}\frac{t}{\hbar}=\sin^2\frac{\theta}{2}\sin^2 1.267\frac{\Delta m^2 L}{E}\frac{GeV}{eV^2 km}\end{aligned}$$

- Flavour-lepton number is not conserved!. Opens the possibility for flavour violation in lepton decay & production.

Neutrino Oscillation

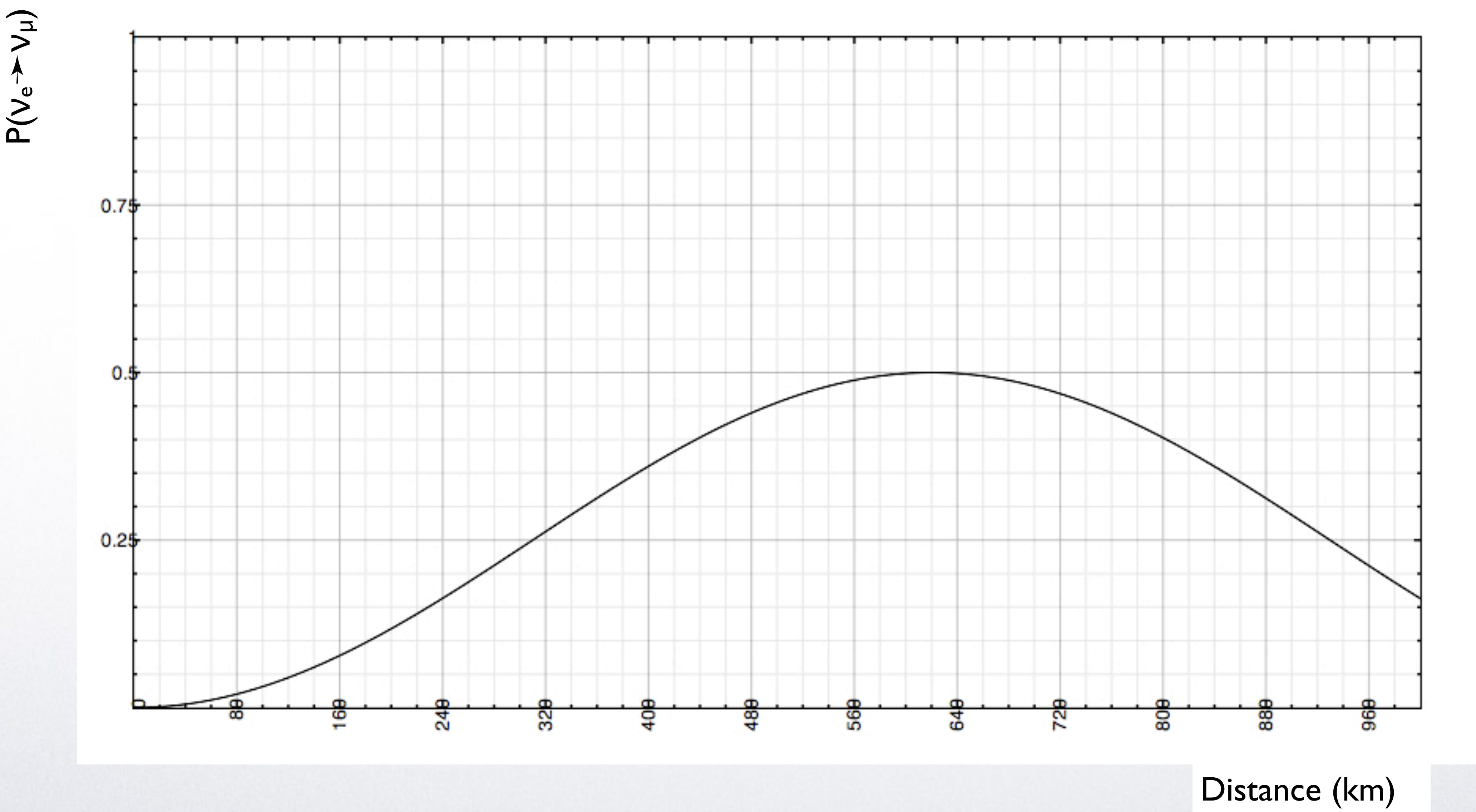
$\theta = 3.141592/2.$ $\Delta m^2 = 2.\mathrm{x}10^{-3}\ \mathrm{eV}^2$



Energy (GeV)

Neutrino Oscillation

$\theta = 3.141592/2. \quad \Delta m^2 = 2.\mathrm{x}10^{-3}\ eV^2$



Quantum coherence

- In quantum mechanics the coherence of two states is essentially their ability to interfere. Fully coherent states can be described by a superposition of the states, and interference may take place. If the states are, instead, fully incoherent, there will be no interference.
- Neutrino oscillation happen only in the coherent period.
- Neutrino wave packages need to overlap in space to ensure the coherence.
- When the 3 mass state neutrinos wave packages are separated (L >> L^{coh}) the oscillation stops.

$$L_{ij}^{coh} = (p/\sigma_p)(2p/\Delta m_{ij}^2)$$

- We get then 3 mass states, none of them with a well defined flavour.

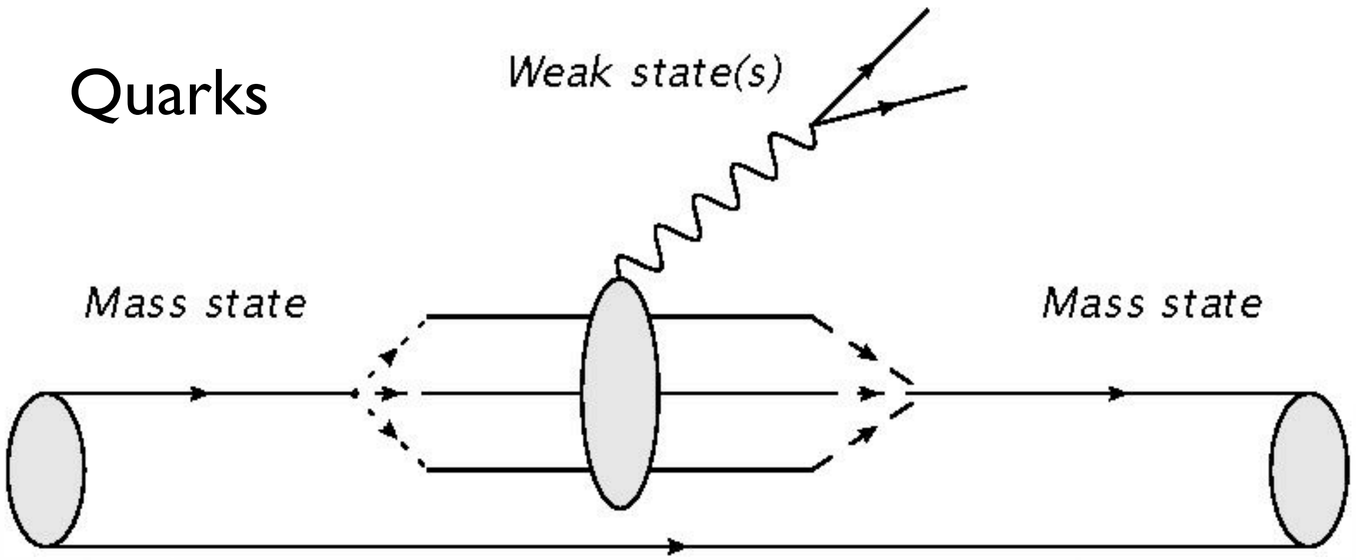
The theory

$$U_{PNMS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

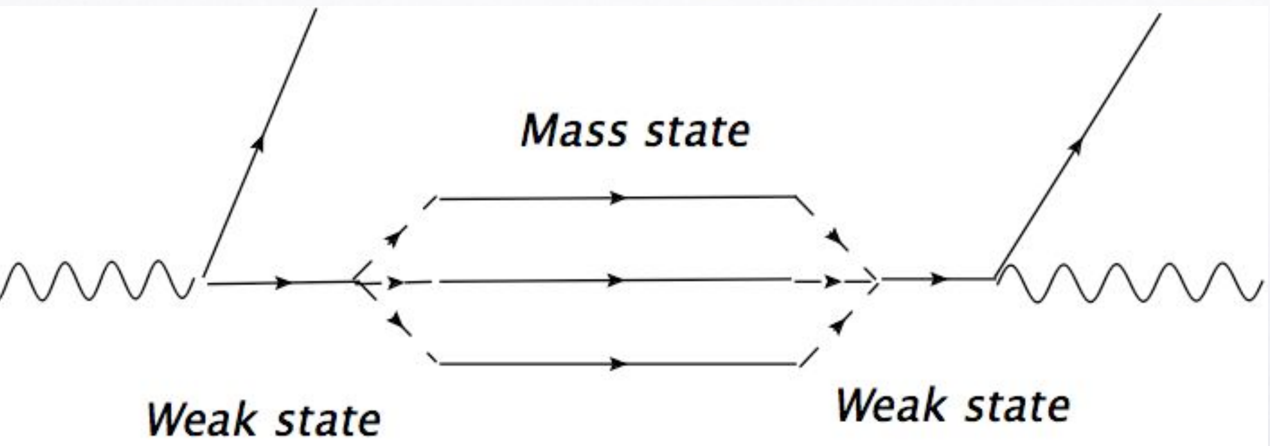
$$\begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \end{pmatrix} = U_{PNMS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- With 3ν, there are 3 angles and 1 imaginary phase:
- The phase allows for CP violation similar to the quark sector.
- There are also 2 values of Δm^2, traditionally Δm^2_{12} &Δm^2_{31}.

Quarks



ν´s



- Quarks & neutrinos exists in matter and vacuum as mass states.
- In quark mixing, the quark is at the mass state at the initial and final state.
- In neutrino oscillations, the mass state are intermediate states, initial and final are flavour states.
- There are cases where the neutrino behaves “as the quarks do”: i.e. lepton flavor violation in decays.

Neutrinos in matter

The theory

- Neutrinos can have two types of interaction with matter:
  - Incoherent inelastic:
    - $\sigma \sim 10^{-43}\,(E/\mathrm{MeV})^2\,\mathrm{cm}^2$
  - Coherent:
    - The medium is unchanged and the scattered and un-scattered waves interfere enhancing the effect.
    - Coherent interactions introduces a phase in the propagation, that can be invisible…

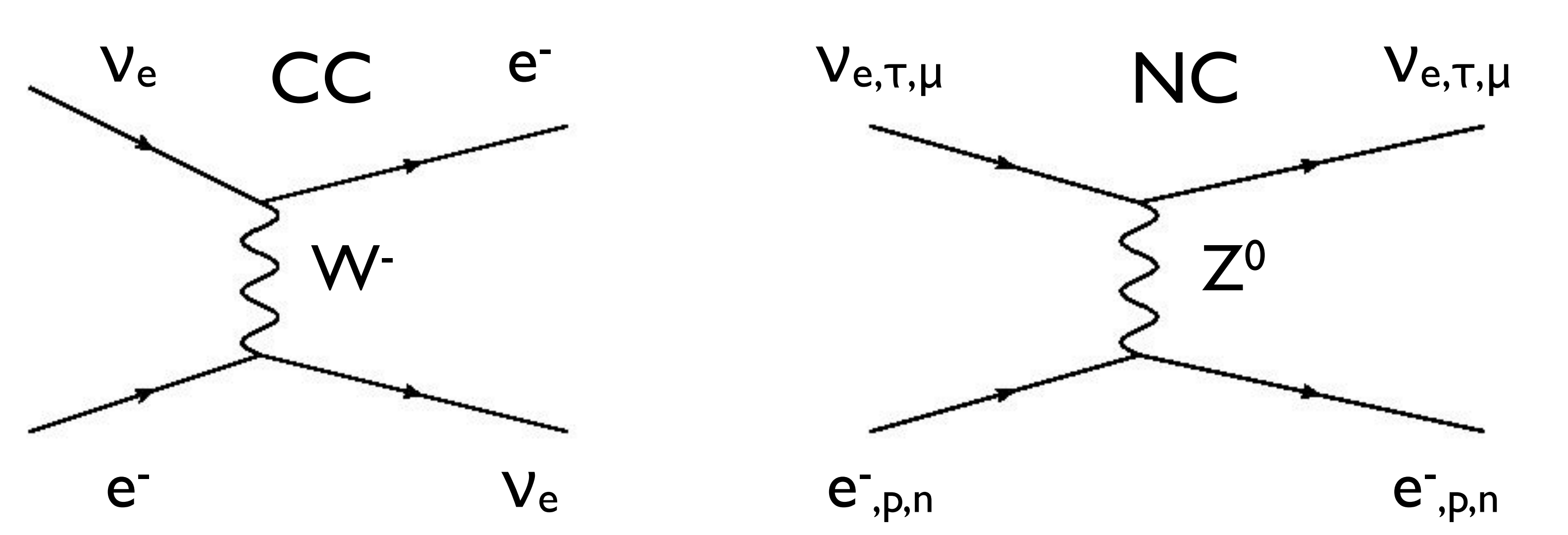
Except for the fact that matter has electrons but no muons or taus!

Neutrinos in matter

The theory

- The coherent interaction potential (real V_C) introduces a phase that depends on the neutrinos flavour.
- The Schrödinger equation of ν in matter

$$i\hbar\frac{\partial \nu_i}{\partial t} = (\frac{m_i^2}{2E} + V_C^i)\nu_i$$



Neutrinos in matter

The theory

- During the evolution of the neutrino in matter, it will be a linear combination of the three neutrino flavour.
  - Each one with a different phase.
- The NC phase is common and factorises. The CC remains and it applies to electron neutrinos only:

$$V_c = diag(\pm\sqrt{2}G_F n_e + V_\beta, V_\beta, V_\beta) \equiv diag(\pm\sqrt{2}G_F n_e, 0, 0)$$

- This is like adding an index of refraction to the electron neutrino.
  - mass eigenstates and eigenvalues are changed:

Matter introduces an effective mass splitting and mixing angle.

Neutrinos in matter

The theory

- The new mass levels and mixing angles can be computed (for 2 neutrinos) to be:

$$\mu^2_{1,2}(x) = \frac{m_1^2 + m_2^2}{2} + E_\nu(V_\alpha + V_\beta) \mp \frac{1}{2}\sqrt{[\Delta m^2 \cos 2\theta - A]^2 + [\Delta m^2 \sin 2\theta]^2}$$

$$\tan 2\theta_m = \frac{\Delta m^2 \sin 2\theta}{\Delta m^2 \cos 2\theta - A}$$

$$A = 2E_\nu(V_\alpha - V_\beta)$$

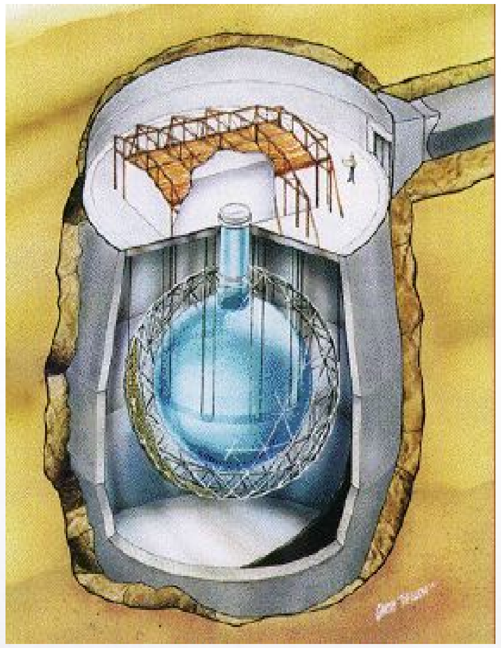
- Taking $V_\alpha = \pm\sqrt{2}\, G_F\, n_e$, $V_\beta = 0$
- When crossing $A \sim \Delta m^2 \cos(2\theta)$, $\tan(2\theta_m)$ changes sign:
  - The proportions of 1&2 invert for α & β states ("level crossing").

A depends on neutrino energy and electron density:

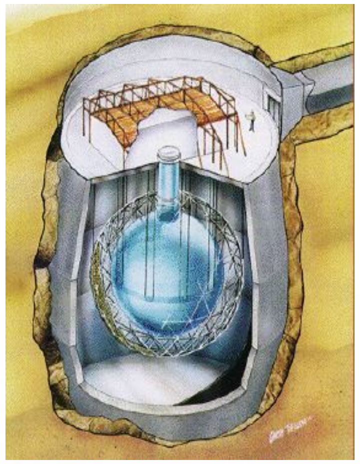
A matter effect is smaller for smaller E_ν & electron density n_e

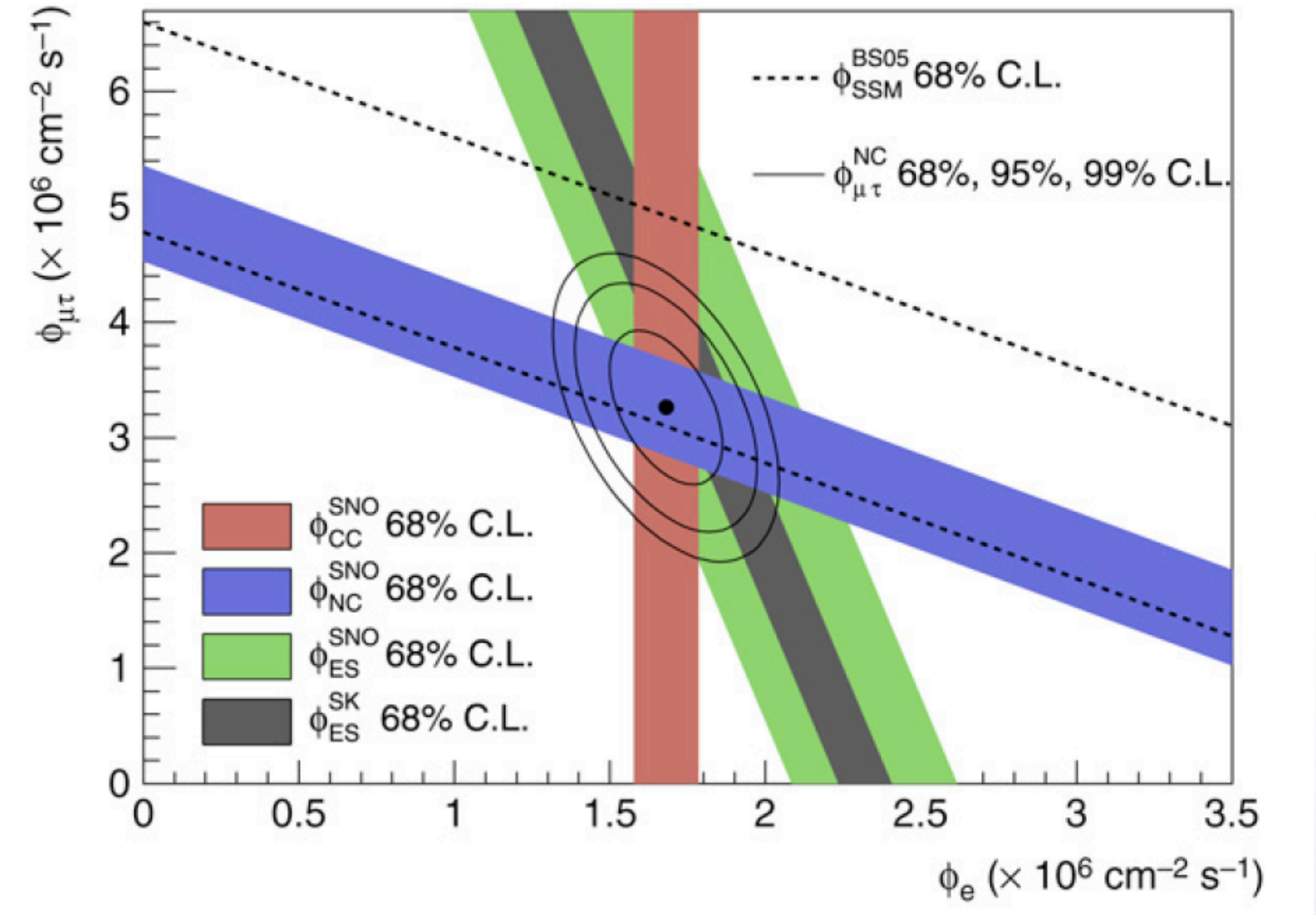
Matter effects are more or less relevant depending on mixing angle and Δm^2

Solving the solar neutrino problem



- SNO experiment was proposed to measure the total solar neutrino flux and the electron component.
  - Elastic scattering: ν_x e$^-$ → ν_x e$^-$
    - ν_e is 7 times larger than $\nu_{\mu,\tau}$
  - Charged current: ν_e d → p p e$^-$
    - direction and spectrum
  - Neutral current: ν_x d → ν_x n p
    - unbiassed total neutrino flux.





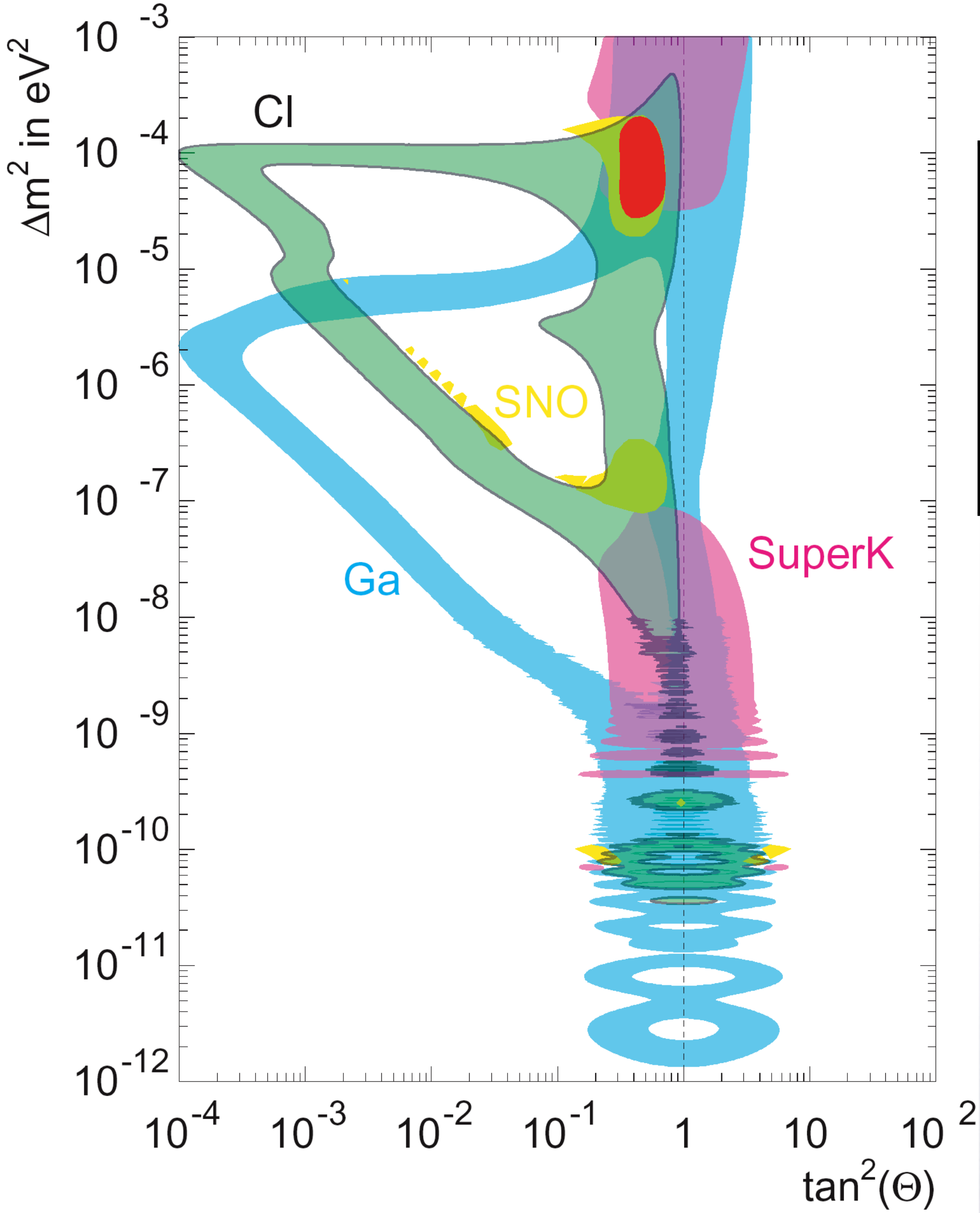
$$\Phi_{SNO}^{CC} = \left(1.68^{+0.06}_{-0.06}{}^{+0.08}_{-0.09}\right) \times 10^6 \text{ cm}^{-2}\text{ s}^{-1} \Rightarrow \frac{\Phi_{SNO}^{CC}}{\Phi_{SSM}} = 0.29 \pm 0.02,$$

$$\Phi_{SNO}^{ES} = (2.35 \pm 0.22 \pm 0.15) \times 10^6 \text{ cm}^{-2}\text{ s}^{-1} \Rightarrow \frac{\Phi_{SNO}^{ES}}{\Phi_{SSM}} = 0.41 \pm 0.05,$$

$$\Phi_{SNO}^{NC} = (4.94 \pm 0.21^{+0.38}_{-0.34}) \times 10^6 \text{ cm}^{-2}\text{ s}^{-1} \Rightarrow \frac{\Phi_{SNO}^{NC}}{\Phi_{SSM}} = 0.87 \pm 0.08.$$

Oscillation from sun

Status after first SNO data



Solar matter oscillations

Oscillations inside the sun

Vacuum oscillations

Oscillations between sun & earth

Remember

Matter effects are more or less relevant depending on mixing angle and Δm^2

Solar neutrinos

Mikeev, Smirnov, Wolfenstein (MSW) effect

The theory

- The sun produces ν_e. The neutrino propagates in a high density matter with a radial dependency.
- In the sun, the matter hamiltonian dominates the vacuum hamiltonian. ($A \gg \Delta m^2 \cos(2\theta)$).
- Matter hamiltonian is diagonal in flavour. The sun produces an electron neutrino that is also eigenstate of the Hamiltonian, with the highest effective mass (V>0).

$$\mu_1^2 = \frac{m_1^2 + m_2^2}{2}$$

$$\mu_2^2 = \frac{m_1^2 + m_2^2}{2} + 2E_\nu V_{\nu_e}$$

Solar neutrinos

The theory

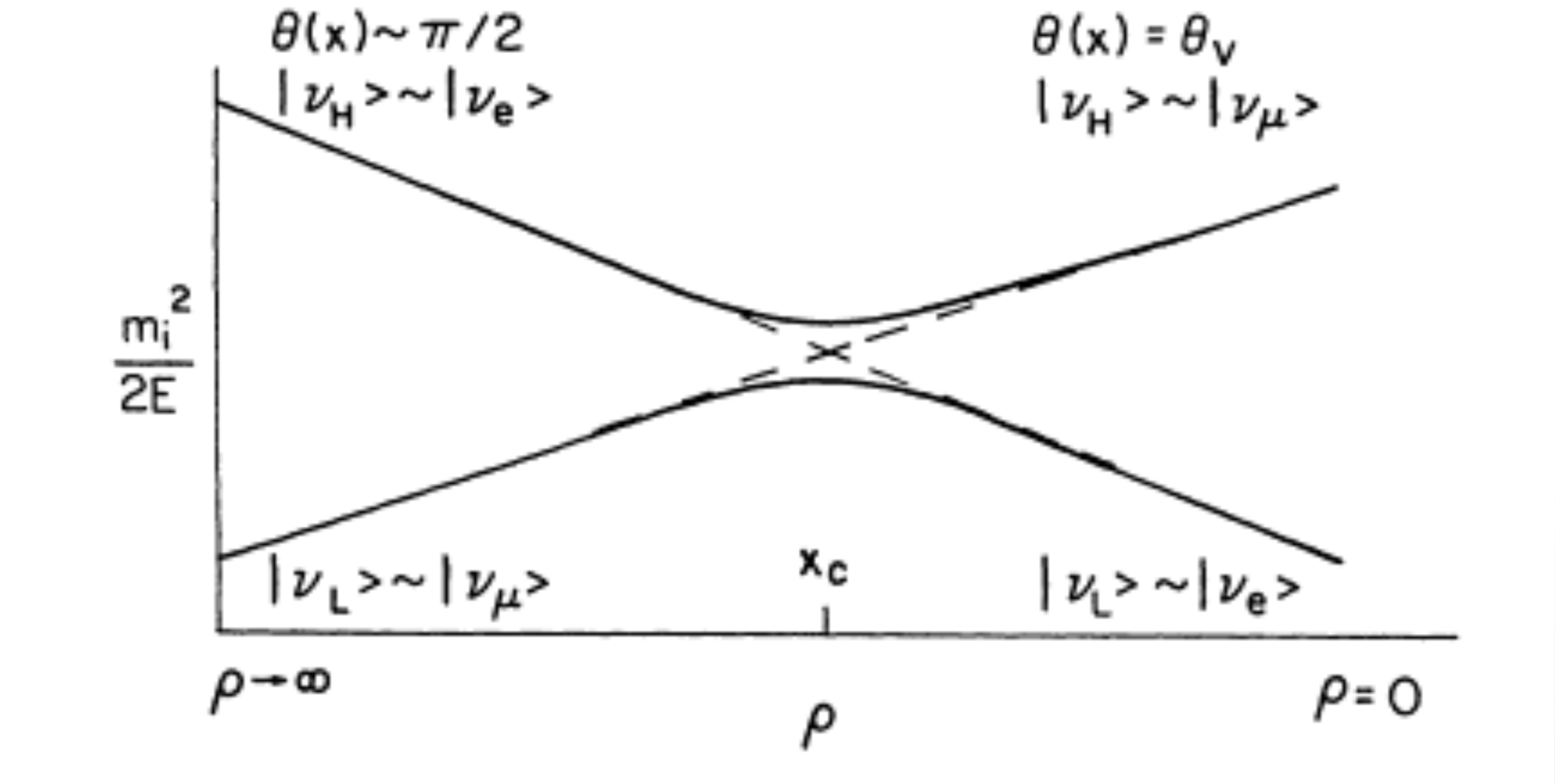
Mikeev, Smirnov, Wolfenstein (MSW) effect

- The electron density varies adiabatically (slowly)… so the solution of the Shrödinger can be obtained without time dependency. The neutrino is always an eigenstate of the Hamiltonian.
- When the neutrino leaves the sun, it is still in eigenstate of the propagation, but this time "in vacuum" (ν_2)

$$\mu_2^2 = m_2^2$$

- The vacuum state ν_2, propagates without interference to the Earth ⇒ no seasonal dependency.
- This effect occurs because locally the off-diagonal terms of the Hamiltonian are negligible with respect to the diagonal.

The theory

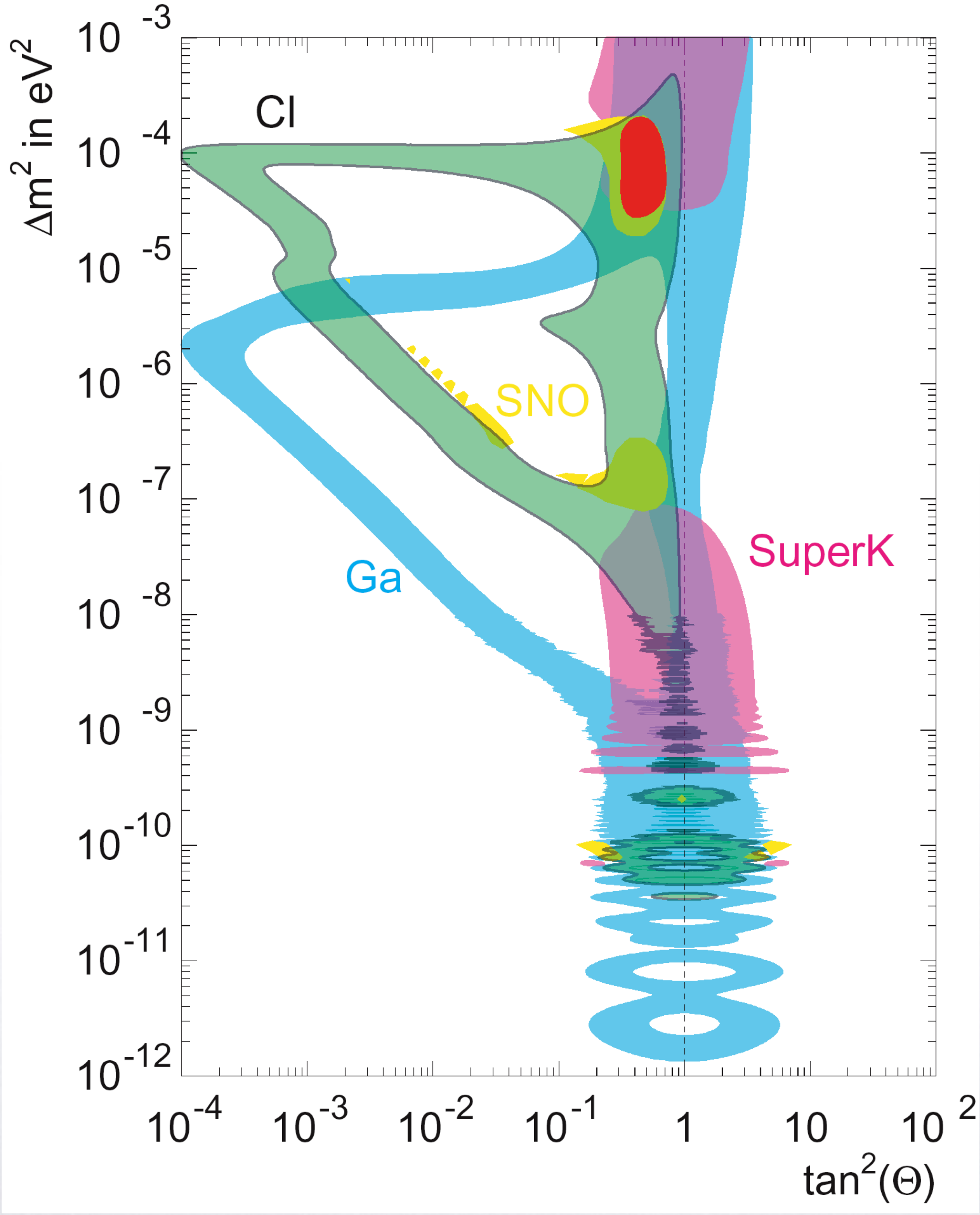


- Because, there is "level crossing", the main state in matter is the opposite to the most probable mass state from ν_e in vacuum.

Oscillation from sun

The experiments

Status after first SNO data

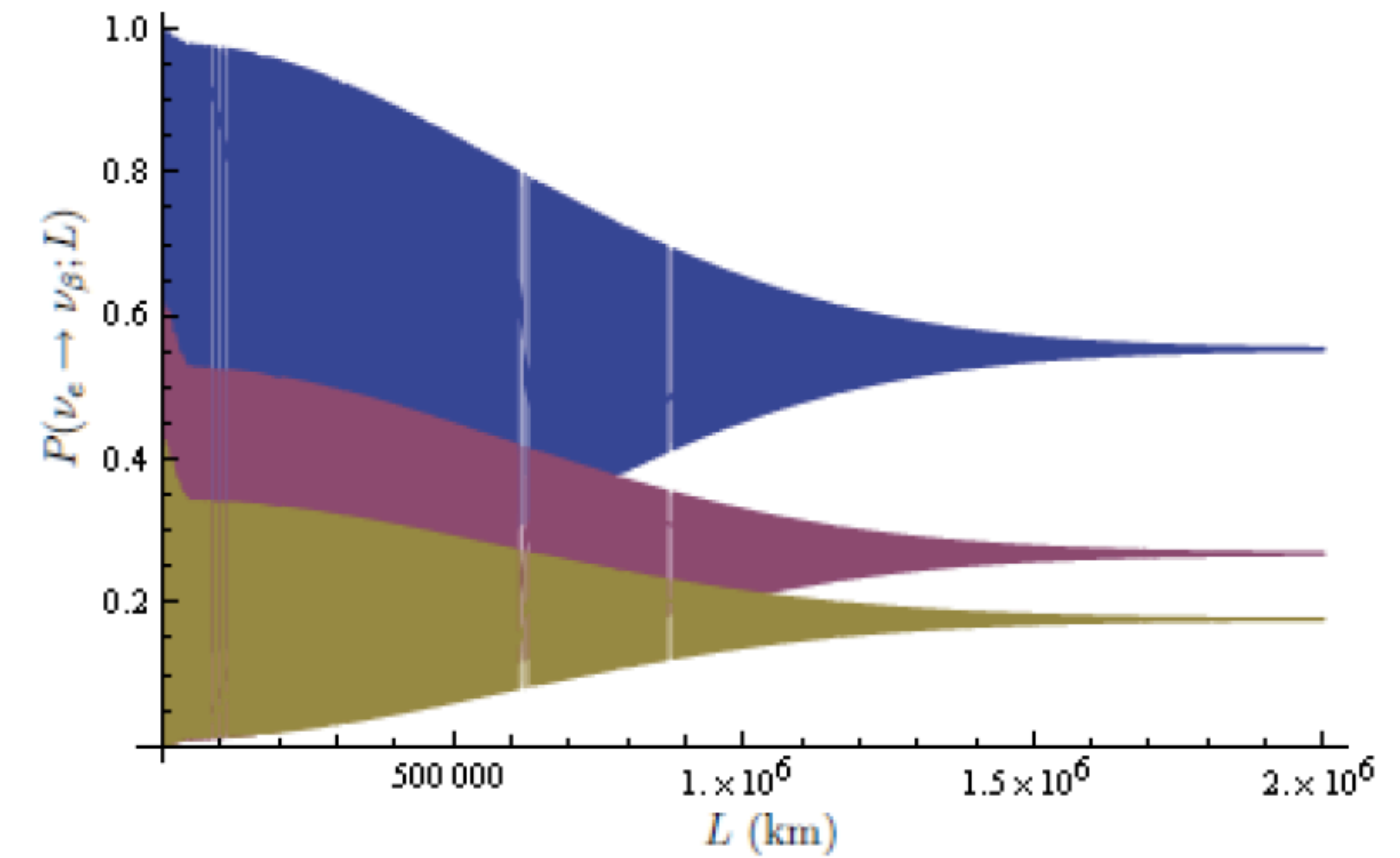


Solar matter oscillations

Vacuum oscillations

Need good Δm^2, $\tan(\theta)$, day-night or seasonal effect determination.

Support slide


1.0
0.8
0.6
0.4
0.2
$P(\nu_e \to \nu_\beta; L)$
500 000
$1.\times10^6$
1.5×10^6
$2.\times10^6$
L (km)