Neutrino Interactions and some Implications

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Main Properties

- Neutrinos are important because they have only weak and gravitational interactions: thus they allow precise studies
- They provided first evidence for physics beyond the standard model
- There are expectations that they have important consequences to be investigated

- Neutrinos have small mass differences.

- The small masses suggest a higher mass scale; a popular realization is the see-saw mechanism.
- The structure of the mixing matrix impies a symmetry that is broken

  1) if Global : Goldstone bosons

  2) if Local : additional Higgs particles.

To answer many of these questions we need precise knowledge of their properties that depend on their interactions with other particles: cross sections and decay rates.

IMPLICATIONS for COSMOLOGY

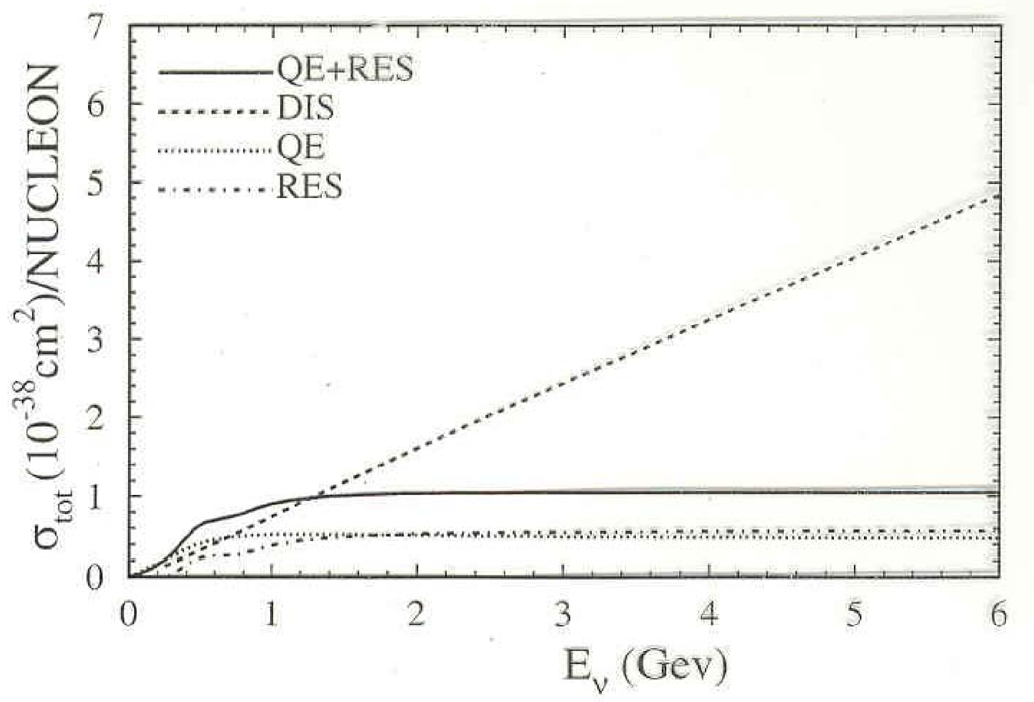
- A very attractive scenario is the generation of the Baryon Asymmetry through a Lepton Asymmetry : LEPTOGENESIS
- I will describe this in several steps.

Anatomy of cross sections

Neutrino Hadron Scattering (asymptotic values) :

- $\sigma(\text{coh},\pi) = (1.0 \text{ to } 3.0)\text{x}10^{-40}$ cm^2
- $\sigma_{\text{quasi elast.}} = 0.50\text{x}10^{-38}$ cm^2
- $\sigma\ (\Delta) = 0.60\ \text{x}10^{-38}$ cm^2
- $\sigma_{\text{dis}} = 0.65\text{x}10^{-38}\ E_\nu$ (Gev) cm^2

  for E_ν= 10 GeV : $6.5\text{x}10^{-38}$ cm^2



Anatomy of Cross Sections

E_ν in GeV

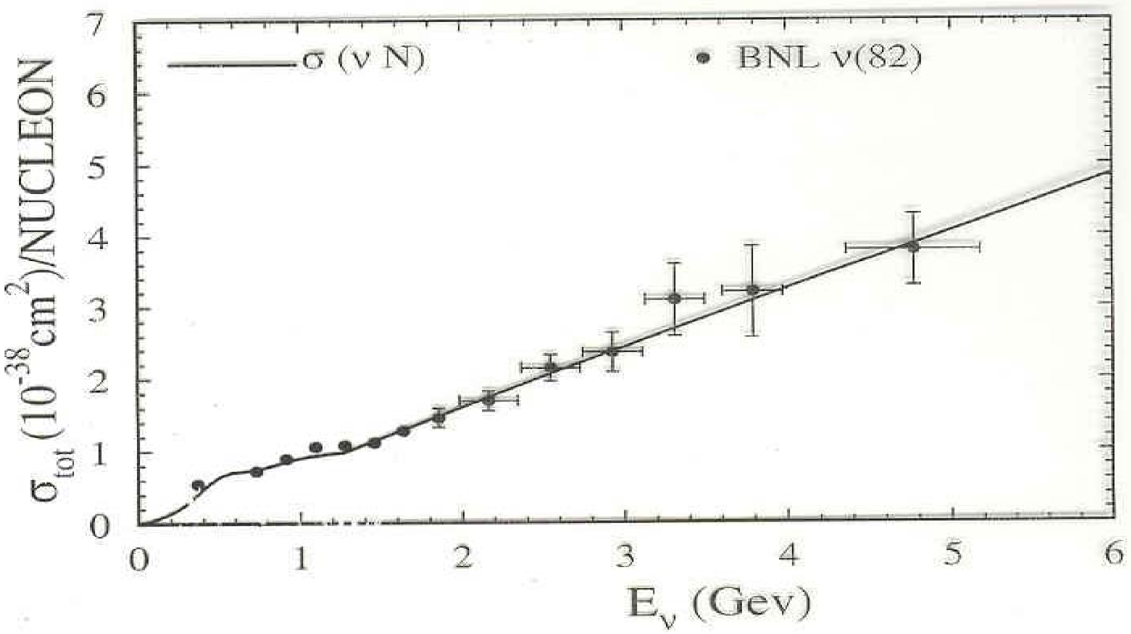
≥ 1.5 $\qquad \sigma_{QE} = 0.50 \times 10^{-38}\ cm^2$

≥ 2.0 $\qquad \sigma_{Res}(\Delta) = 0.60 \times 10^{-38}\ cm^2$; $\sigma_{Res}(p\pi^0) = 0.2 \times 10^{-38}\ cm^2$

≥ 3.0 $\qquad$ DIS: $\sigma = 0.65 \times 10^{-38}\ E_\nu(\text{GeV})\ cm^2$

for $E_\nu = 10$: $6.5 \times 10^{-38}\ cm^2$

$E_\nu = 1$ to 2 GeV $\qquad \sigma_{coh}(\pi^+) \approx 1.0$ to $3.0 \times 10^{-40}\ cm^2$



σ (ν N)
BNL ν(82)
σ_{tot} (10^{-38}cm^2)/NUCLEON
E_ν (Gev)

Doktorarbeit von Dr. Y.-J. Yu

F. Von Holsten hat an das Thema angefangen.

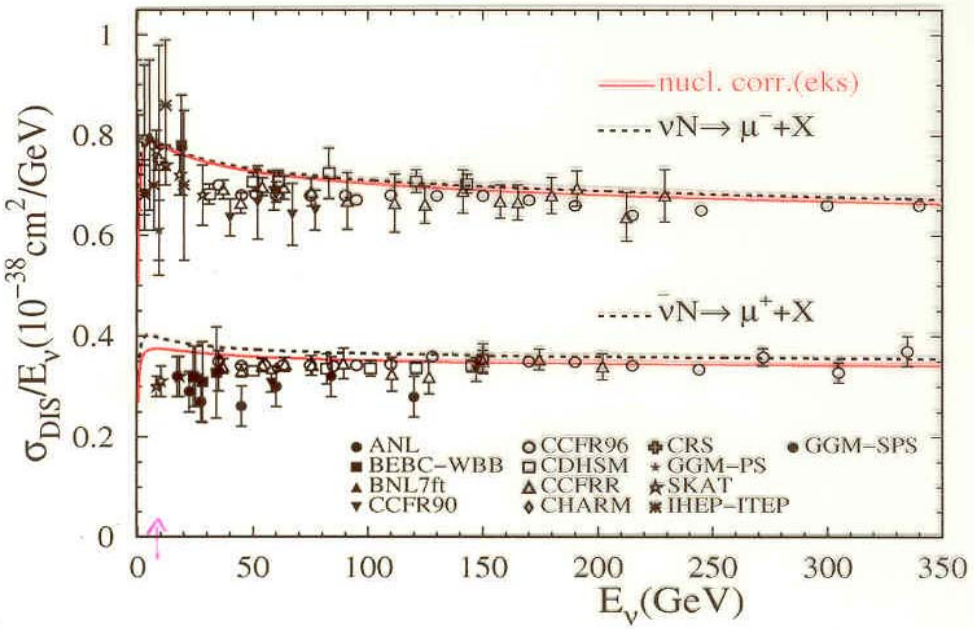


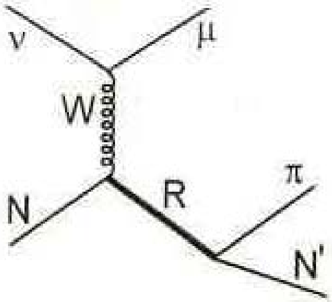
Figure from PDG: Division by E_ν makes errors at high energies look small

Isospin-3/2 and -1/2 resonances in one-pion electro- and neutrinoproduction

O.Lalakulich and E.A. Paschos

Dortmund University, Germany

Theoretical description

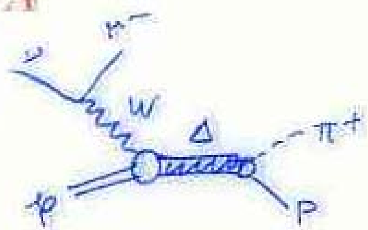


For $E_\nu \sim few\ \mathrm{GeV}$, $2m_N E_\nu << m_W^2$, so the weak vertex is described as Fermi 4-fermion intreraction (current-current interaction)

$$\frac{G_F}{\sqrt{2}} J^{\nu}_{(hadronic)} j_{\nu}^{(leptonic)}, \qquad J^{\nu}_{(hadronic)} = V^{\nu} - A^{\nu}$$

The hadronic current is parametrized in terms of the

nucleon-resonance form factors (vector and axial)

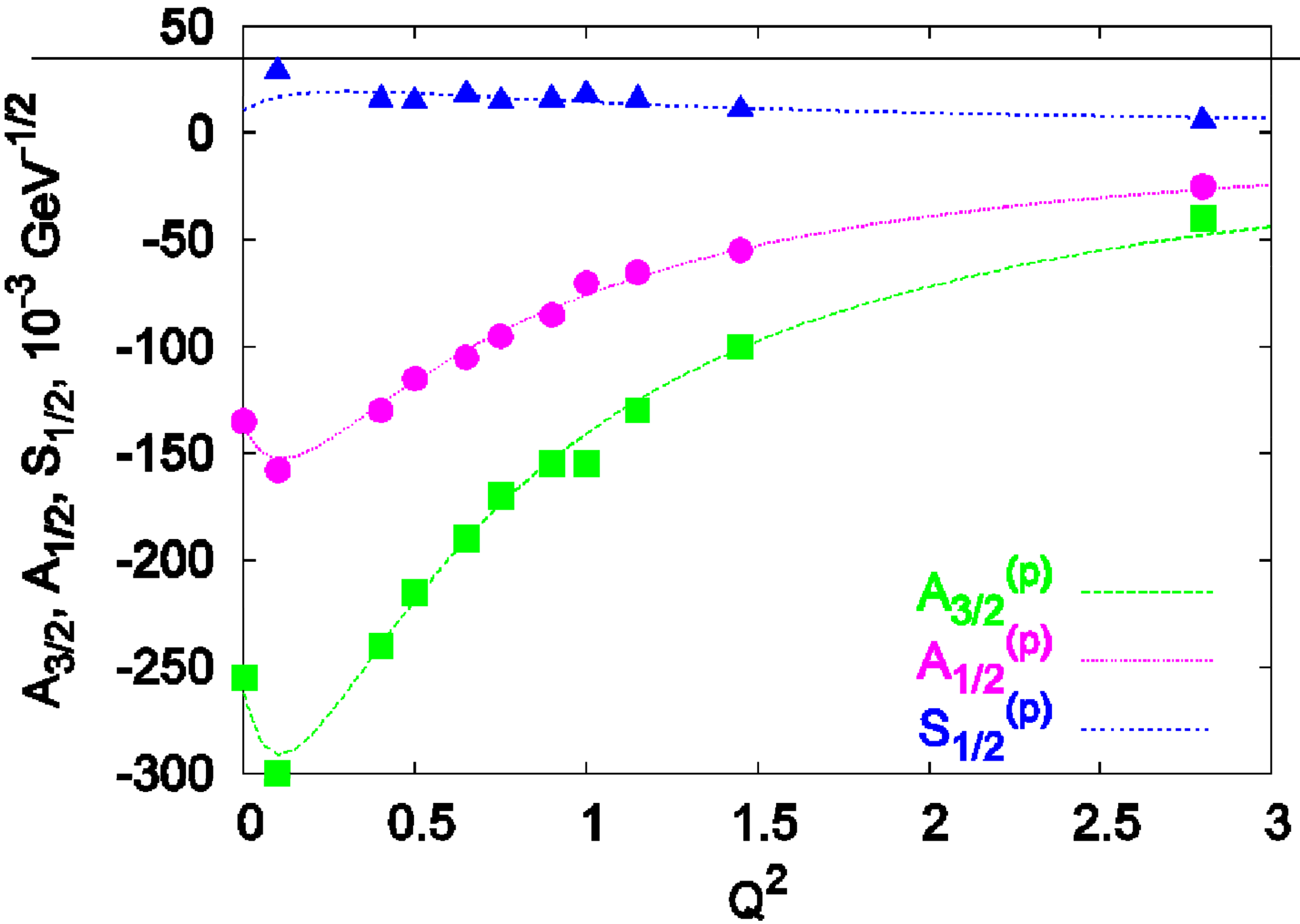


which depend on the transfered momentum

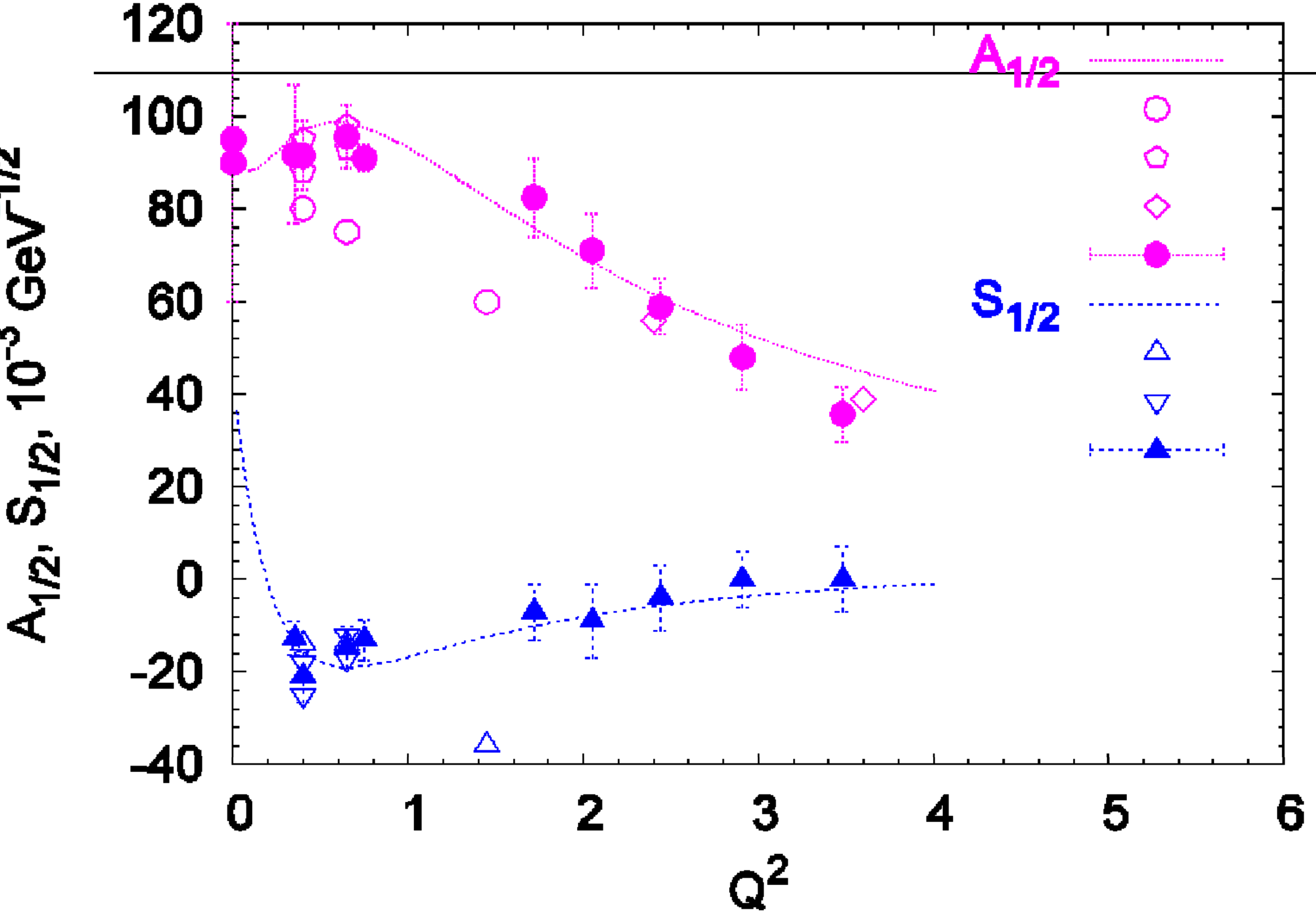
These form factors are independent of the flavor of the incoming nutrino (and correspondingly outgoing muon). So one can simulate them for ν_μ and then use for ν_e and ν_τ.

Question: how many form factors do we need for each resonance?

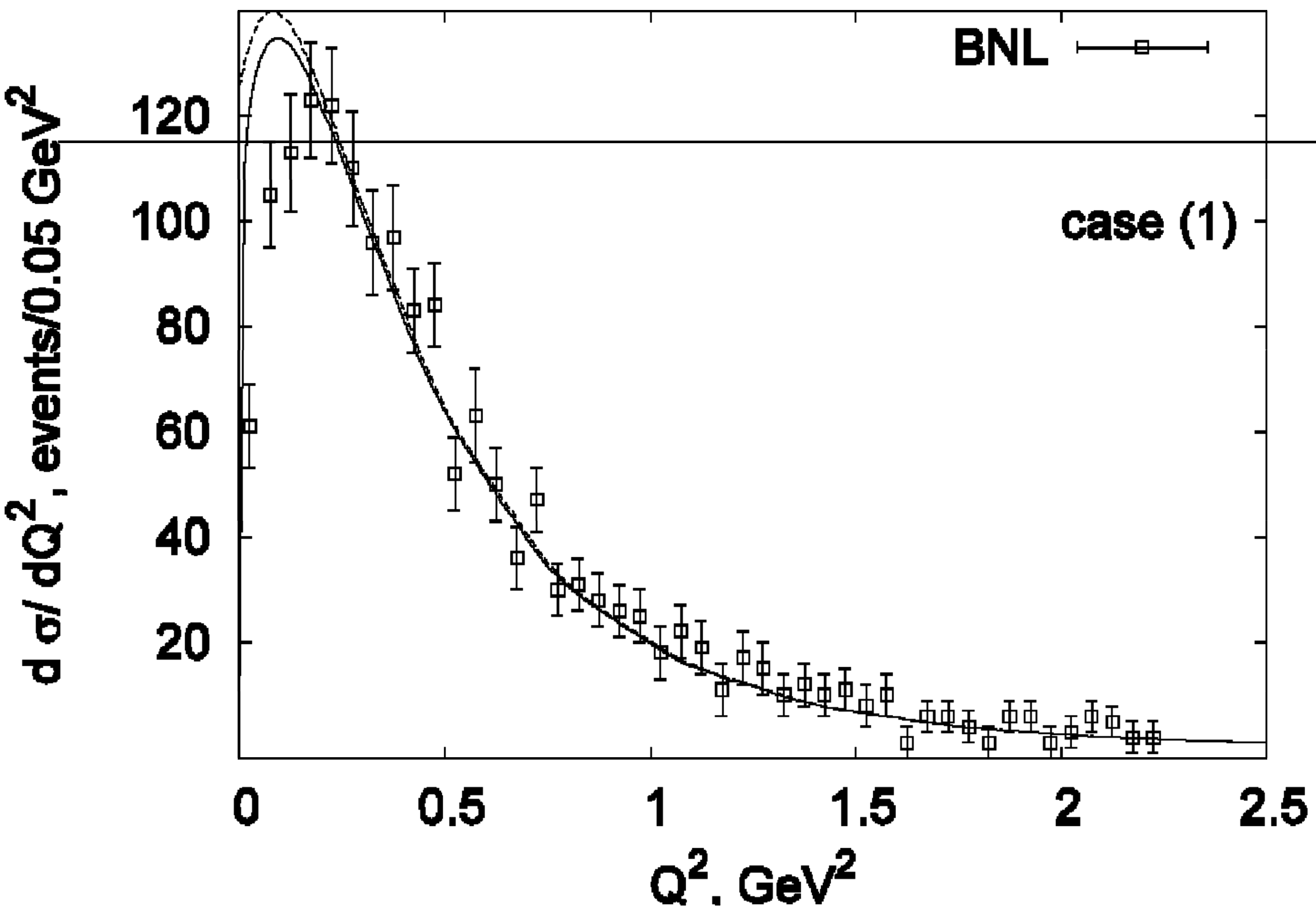
- For the delta excitation two vector form factors (magnetic dipole dominance) and one axial are sufficient.



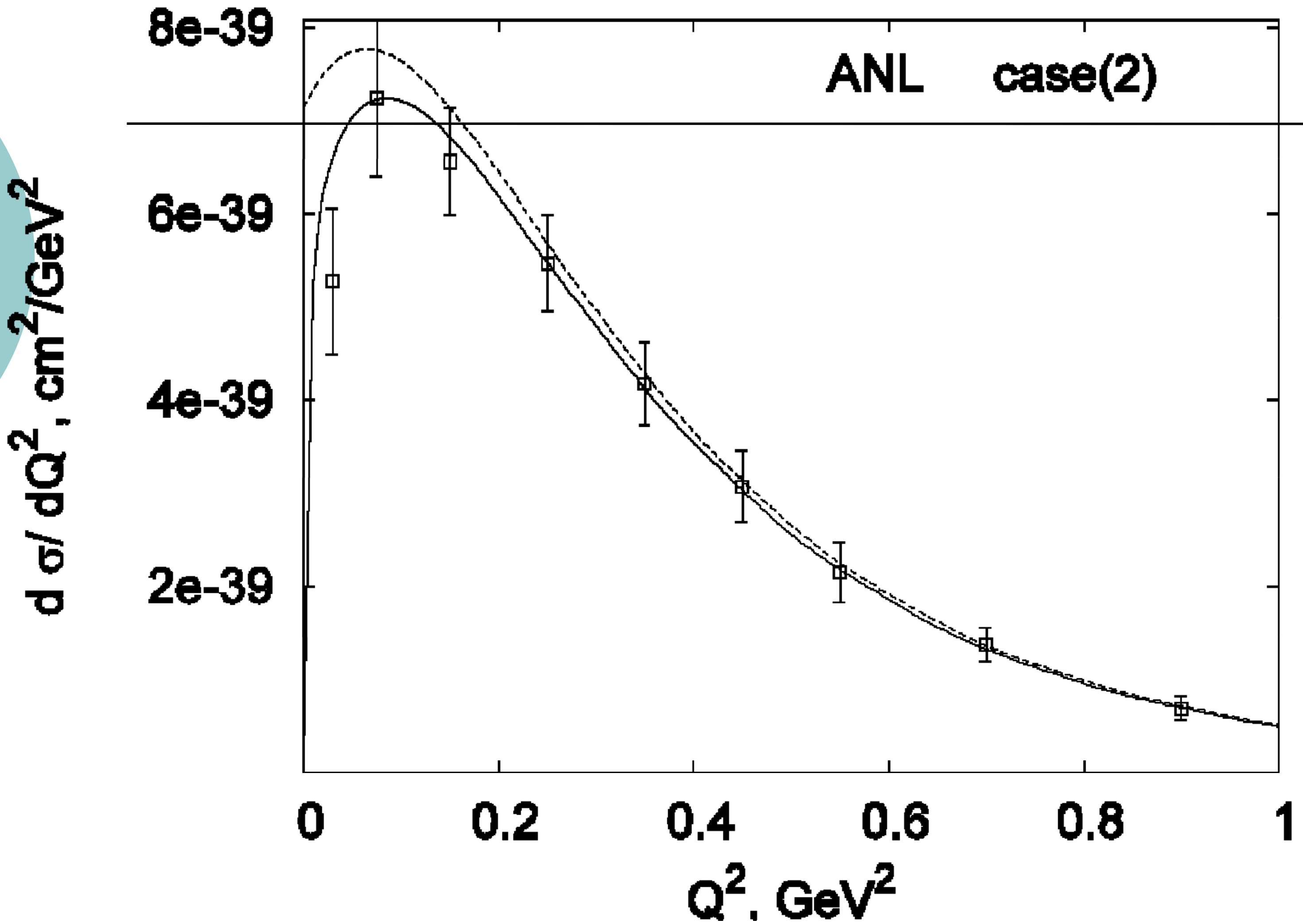
50
0
-50
-100
-150
-200
-250
-300
$A_{3/2}$, $A_{1/2}$, $S_{1/2}$, 10^{-3} GeV$^{-1/2}$
0
0.5
1
1.5
2
2.5
3
Q^2
$A_{3/2}^{(p)}$
$A_{1/2}^{(p)}$
$S_{1/2}^{(p)}$



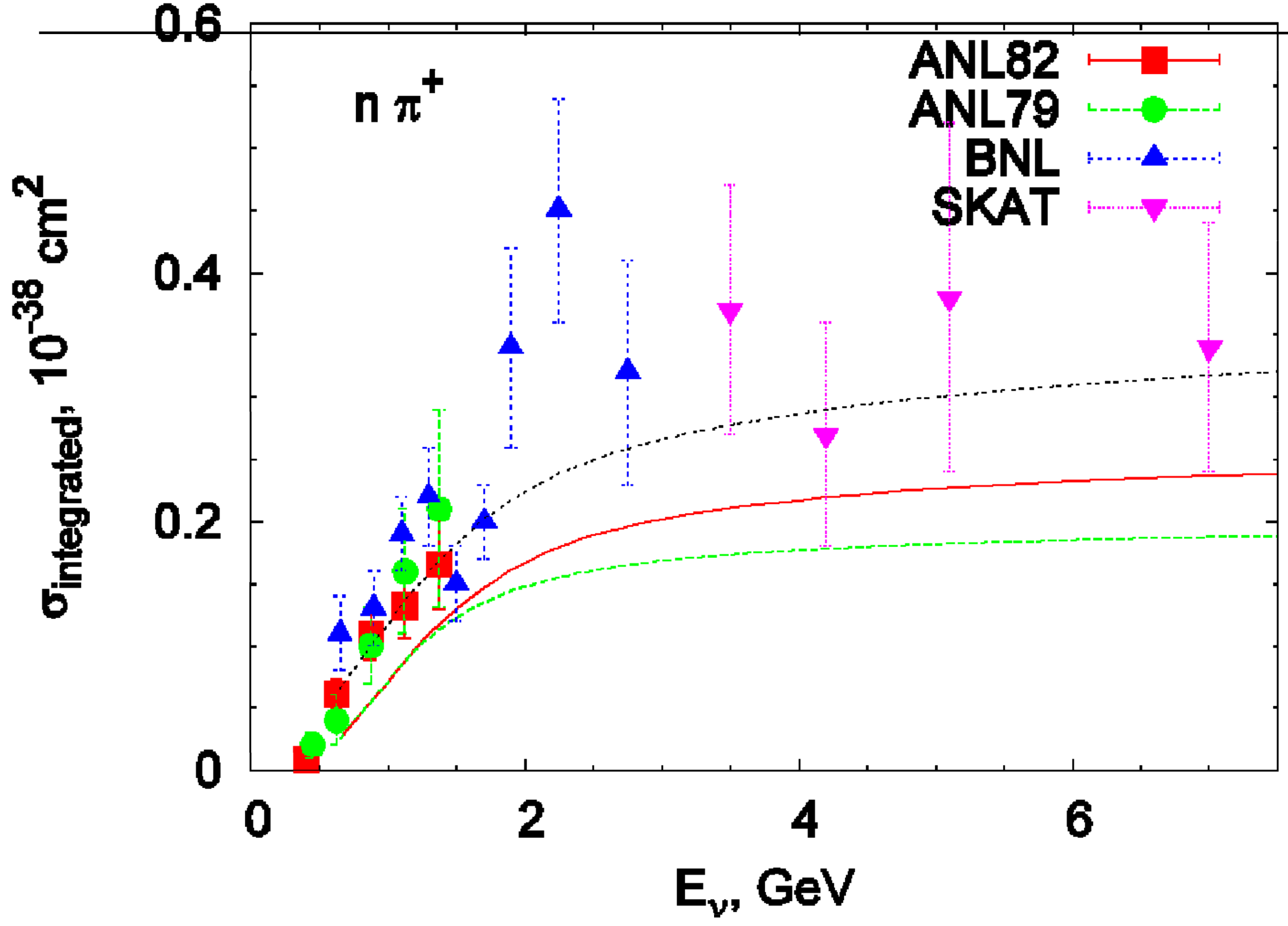
120
100
80
60
40
20
0
-20
-40
0
1
2
3
4
5
6
Q2
A1/2, S1/2, 10-3 GeV-1/2
A1/2
S1/2



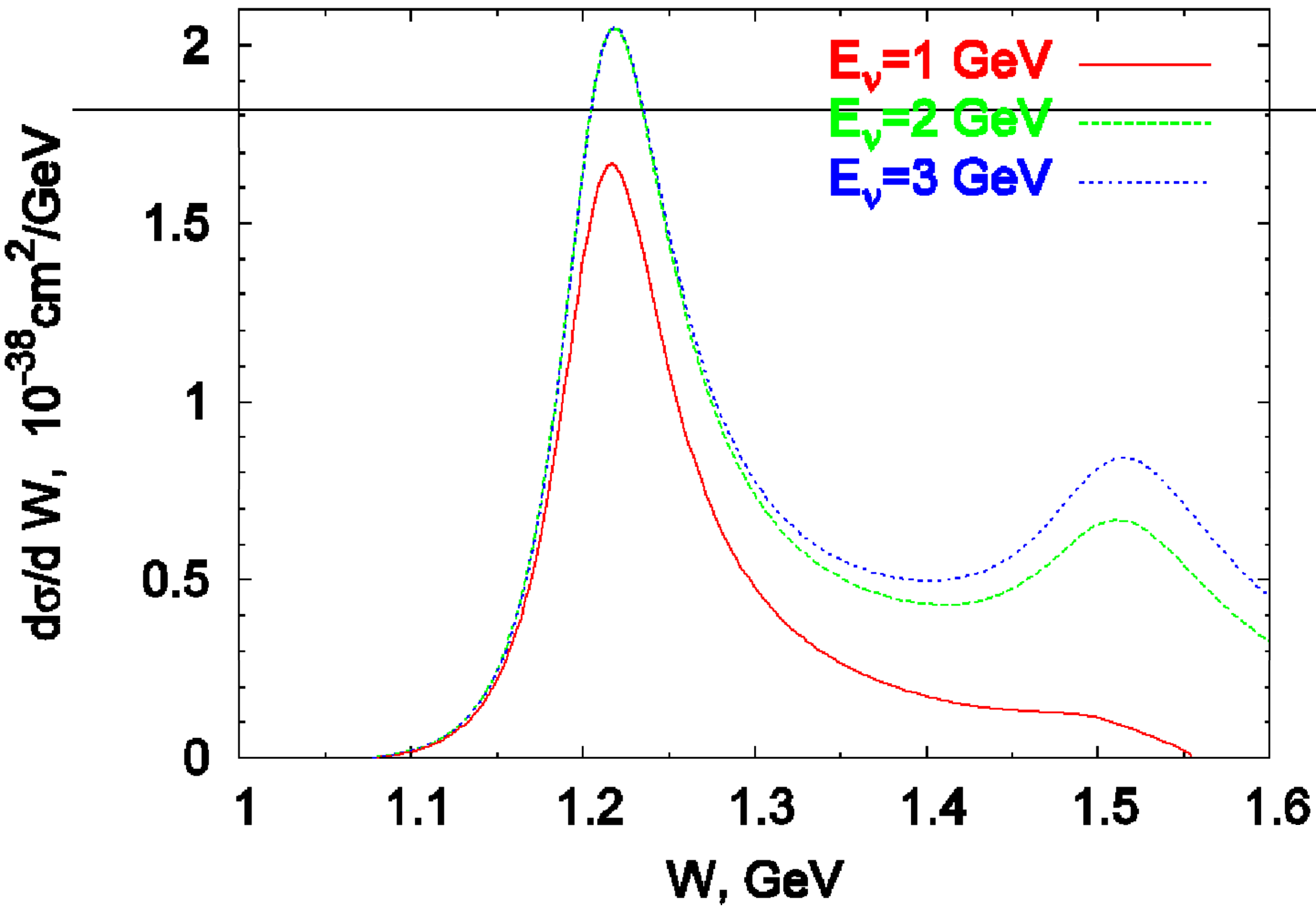
BNL
case (1)
d σ/ dQ², events/0.05 GeV²
Q². GeV²
0
0.5
1
1.5
2
2.5
20
40
60
80
100
120



8e-39
6e-39
4e-39
2e-39
ANL case(2)
d σ/ dQ2, cm2/GeV2
0
0.2
0.4
0.6
0.8
1
Q2, GeV2

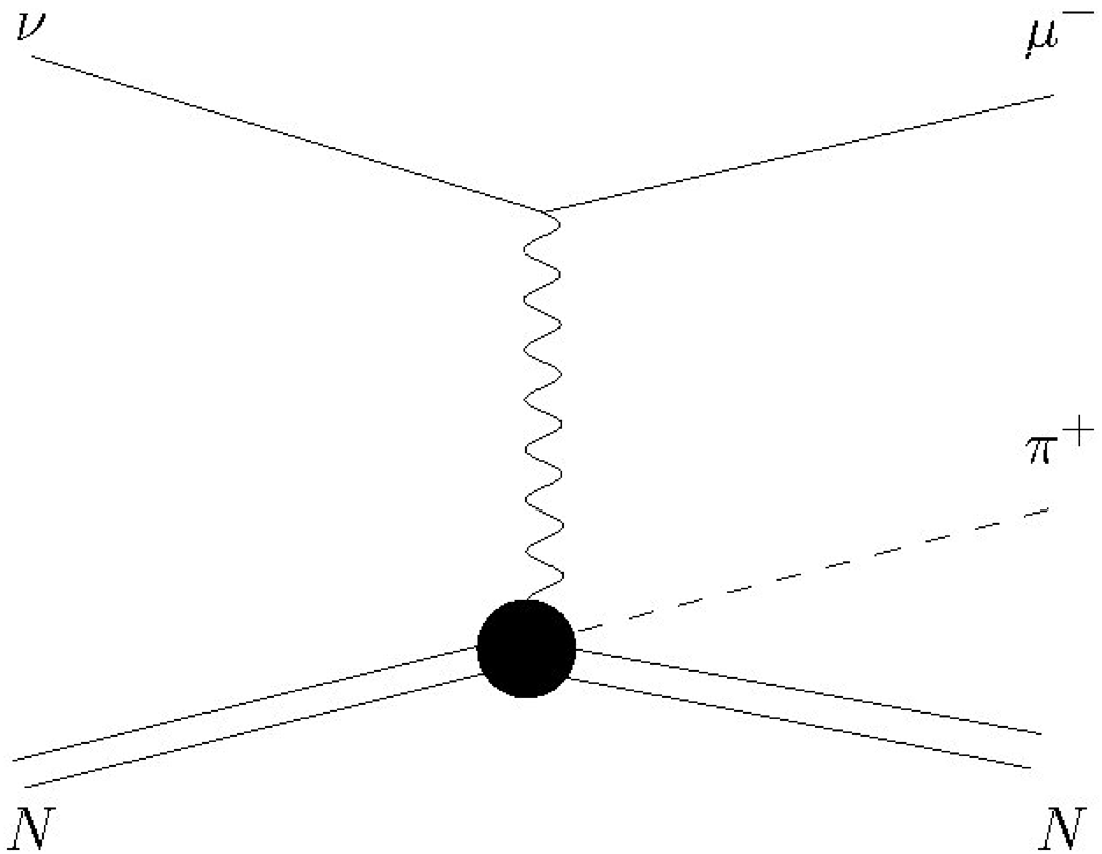


n π+
ANL82
ANL79
BNL
SKAT
0.6
0.4
0.2
0
0
2
4
6
σintegrated, 10-38 cm2
Eν, GeV



E_ν=1 GeV
E_ν=2 GeV
E_ν=3 GeV
dσ/d W, 10^{-38}cm^2/GeV
W, GeV
0
0.5
1
1.5
2
1
1.1
1.2
1.3
1.4
1.5
1.6

Coherent pion production
(Gounaris,Kartavtsev, EAP; Schalla)



Coherent pion production

PART I: Gounaris, Kartavtsev, Paschos [**PRD74** (2006) 054007]

$$-iA_\rho^+ = \frac{f_\pi\sqrt{2}q_\rho}{Q^2+m_\pi^2}T(\pi^+N \to \pi^+N) - R_\rho$$

The first amplitude is the pion pole, which varies rapidly for small Q^2 and R^ρ is the amplitude for the rest which is a smooth function of Q^2.

PCAC gives the relation

$$-iq^\rho A_\rho^+ = \frac{\sqrt{2}f_\pi m_\pi^2}{Q^2+m_\pi^2}T(\pi^+N \to \pi^+N)$$

while the definition of the amplitudes gives

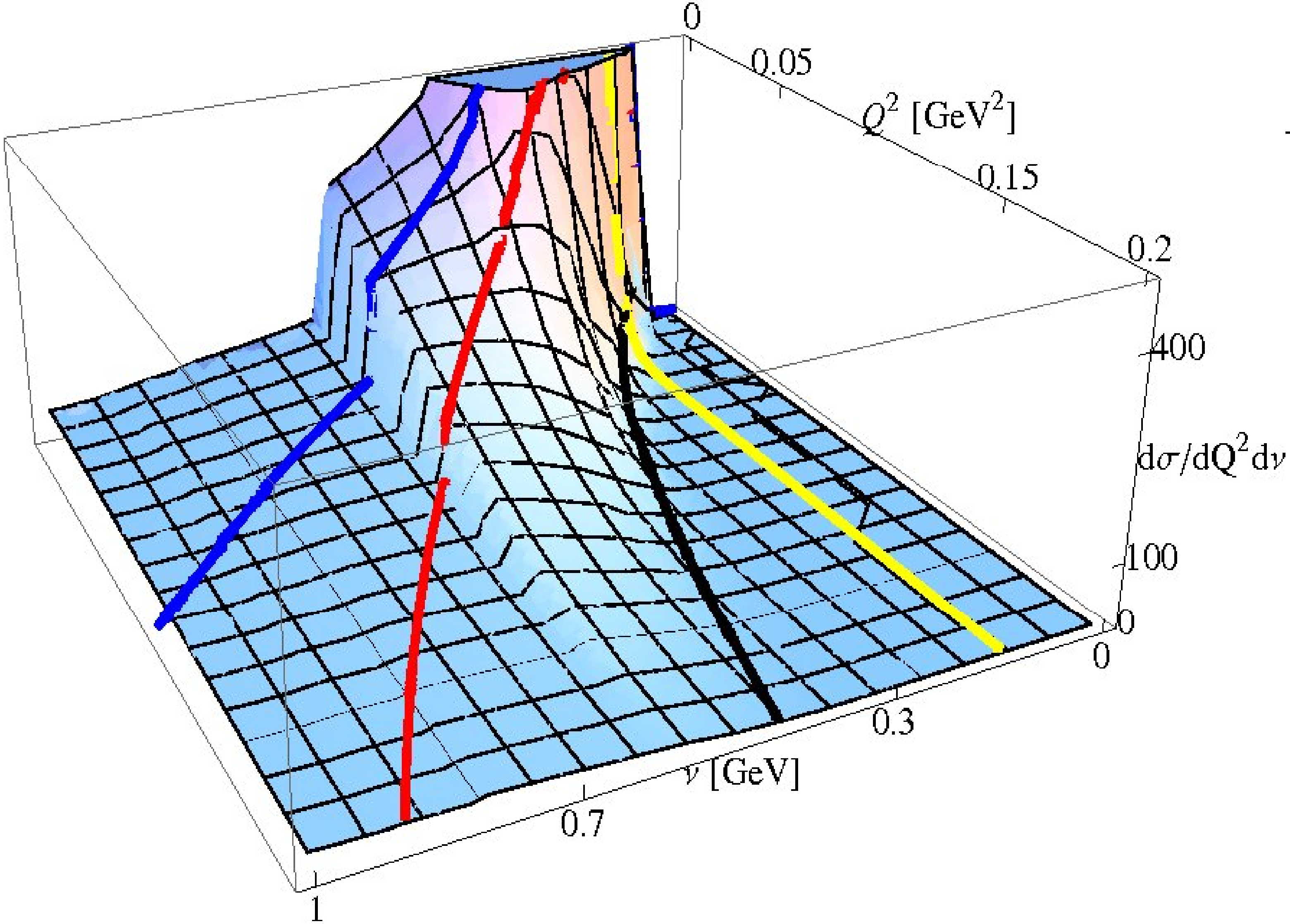
$$-iq^\rho A_\rho^+ = -\frac{\sqrt{2}f_\pi Q^2}{Q^2+m_\pi^2}T(\pi^+N \to \pi^+N) - q^\rho R_\rho$$

Comparing the last two equations $\Longrightarrow (A) = (B)$

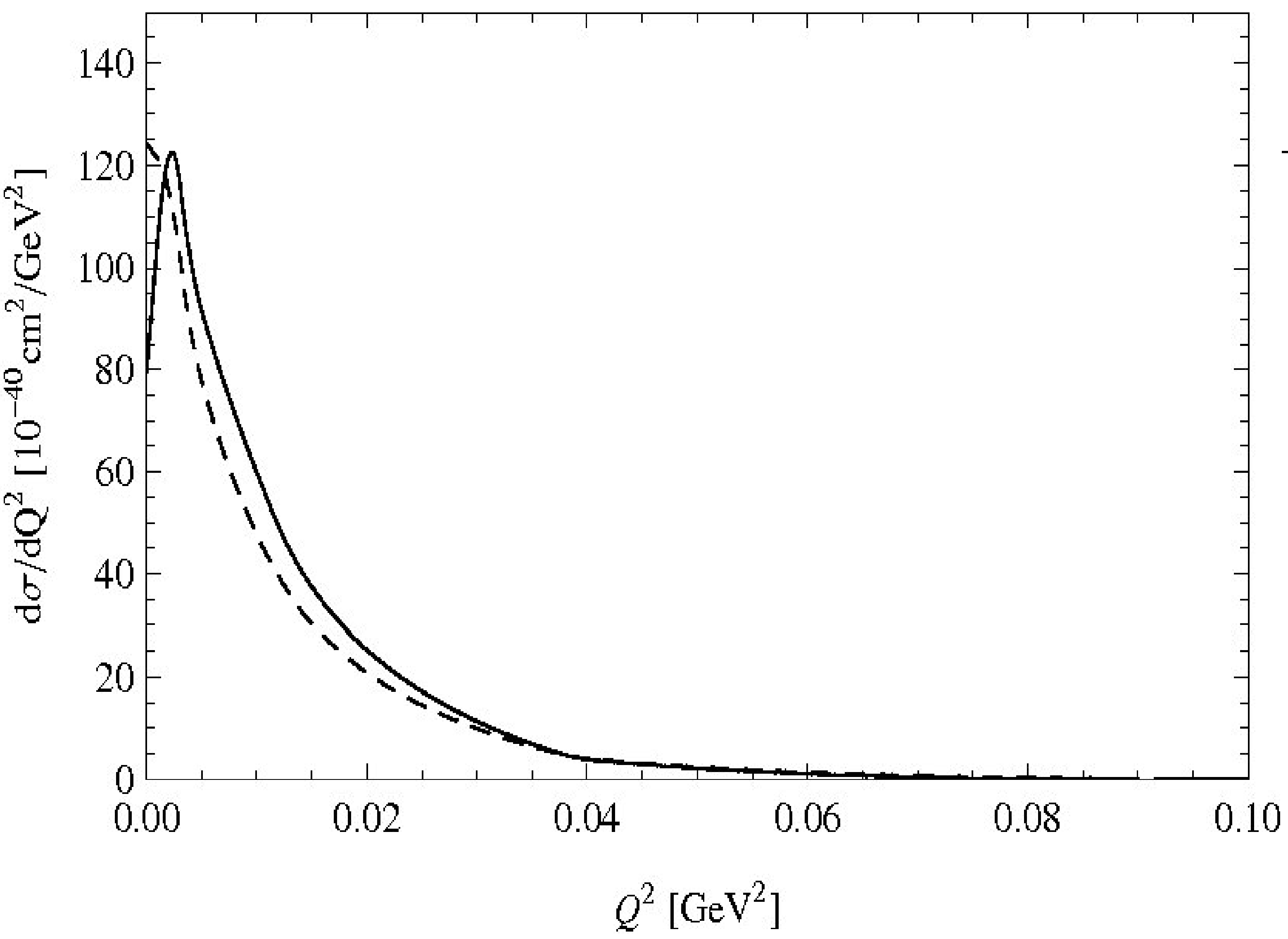
$$q^\rho R_\rho = -\sqrt{2}f_\pi T(\pi^+N \to \pi^+N)$$

Condition

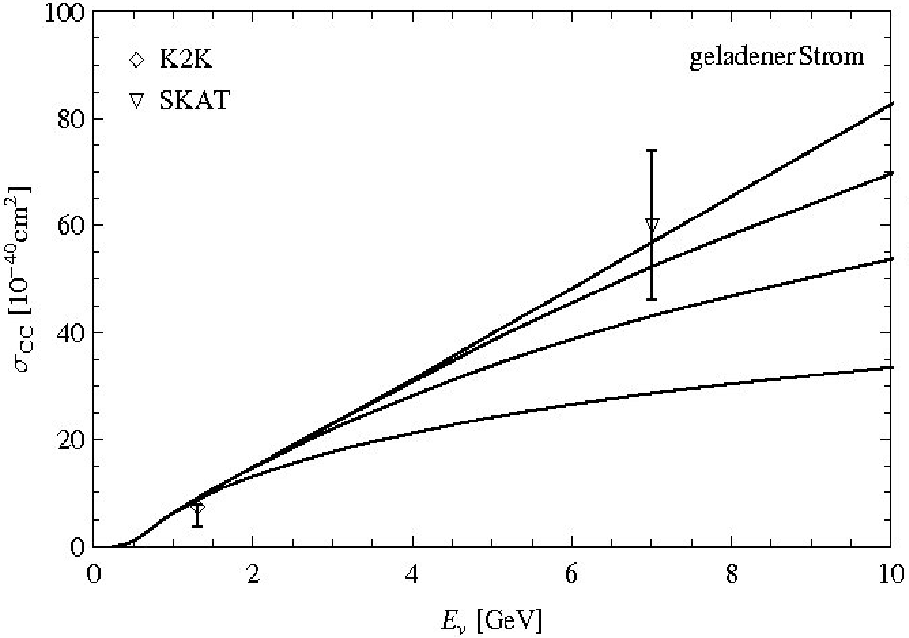
- For its validity it must satisfy the condition
  $v >> \{Q^2/M\}$
- $v = \{Q^2/M\} * \xi$
  The region $\xi > 1.0$ covers practically the entire cross section



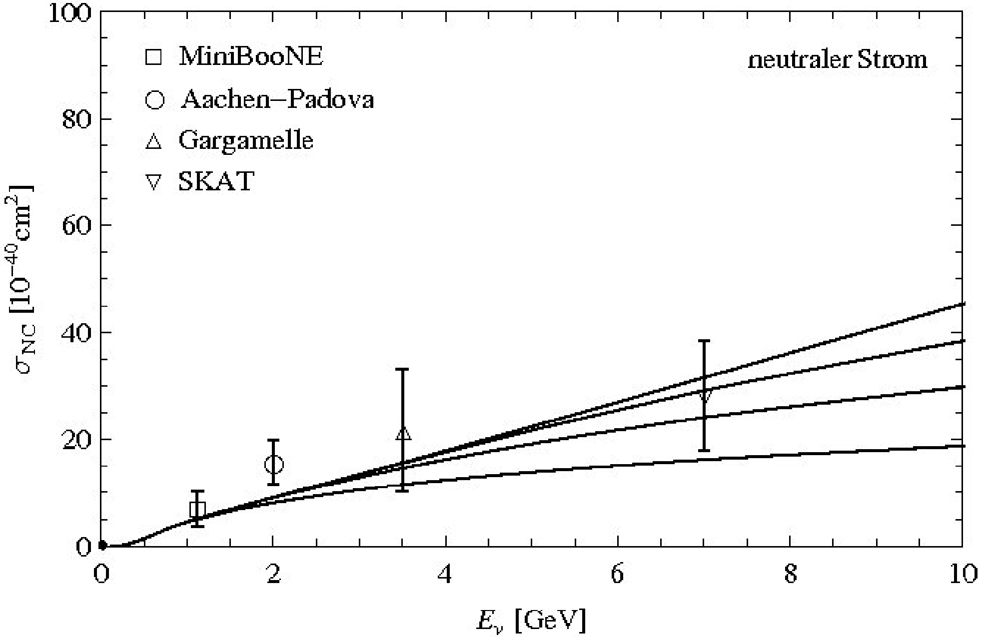
0
0.05
Q^2 [GeV^2]
0.15
0.2
400
dσ/dQ^{2}dν
100
0
0
0.3
ν [GeV]
0.7
1



140
120
100
80
60
40
20
0
0.00
0.02
0.04
0.06
0.08
0.10
dσ/dQ² [10⁻⁴⁰cm²/GeV²]
Q² [GeV²]



K2K
SKAT
geladener Strom
σ_{CC} [10^{-40}cm^2]
E_ν [GeV]
0
20
40
60
80
100
0
2
4
6
8
10



MiniBooNE
Aachen–Padova
Gargamelle
SKAT
neutraler Strom
σ_{NC} [10^{-40}cm^2]
E_ν [GeV]
0
20
40
60
80
100
0
2
4
6
8
10

Improvements

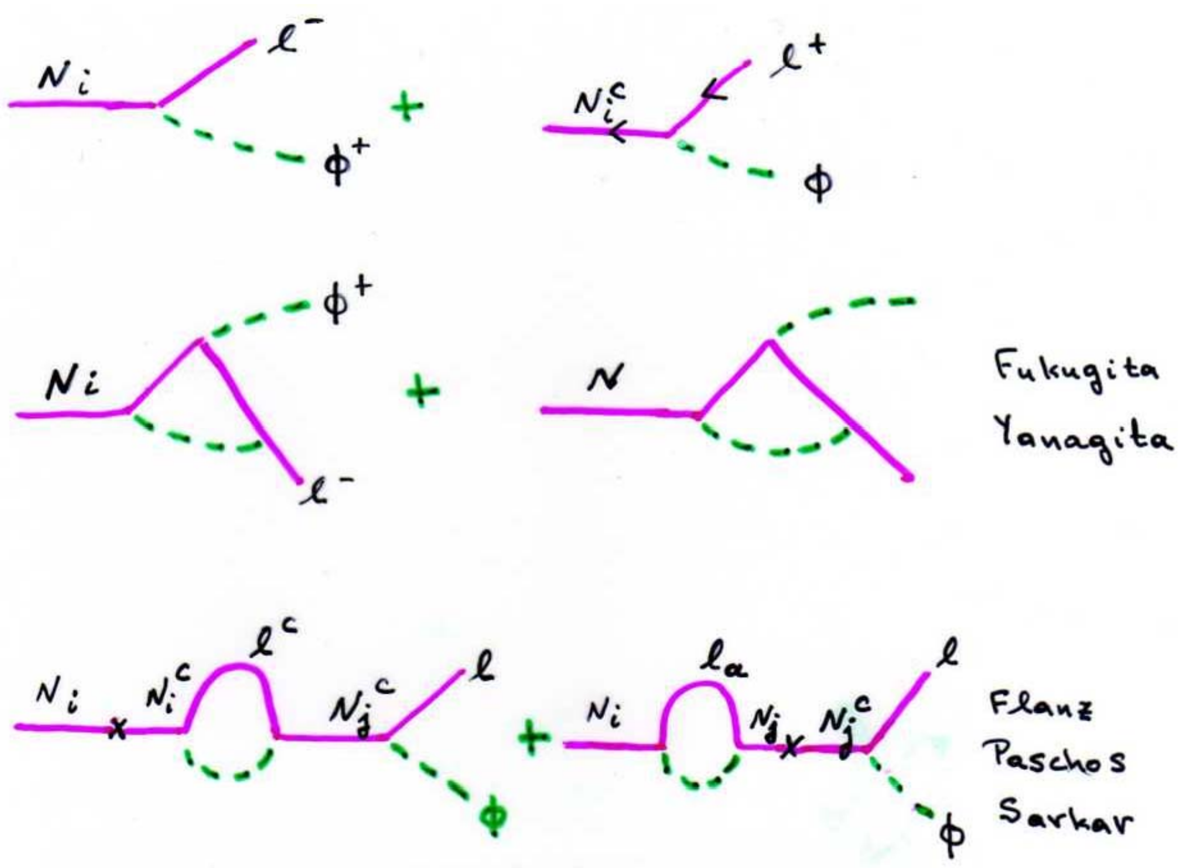
- Two changes from older works by Adler and by Rein, Sehgal
- (1) modifies Q^2-dependence and overall rate.
- (2) for its validity it must satisfy conditions for validity of PCAC
  $\nu >> \xi^2 * \{Q^2/M\}$; figure shows that the condition is satisfied even for xi=1.0

Relevance for Leptogenesis

- The evidence for neutrino masses makes leptogenesis a favoured mechanism to explain the baryon asymmetry.
- There are new terms in the Lagrangian

$$\mathcal{L} = \overline{N}_i h_{ij} \nu_{Lj} + \frac{1}{2} (N_i)^C (M_R)_{ij} N_j + \text{h.c.}$$

which produce the diagrams :

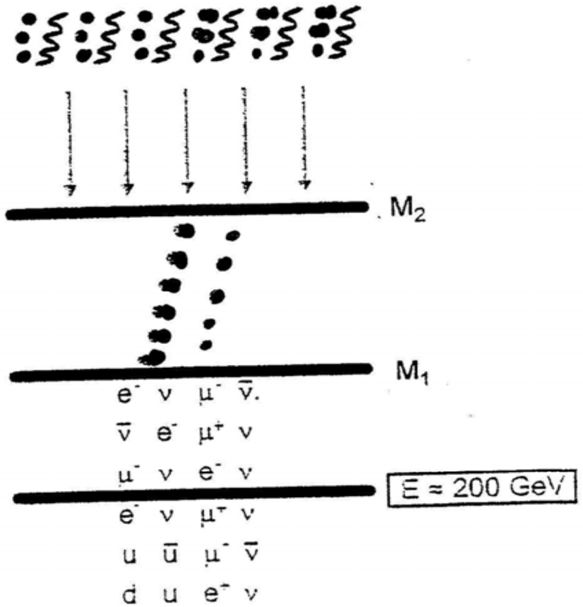


THERE ARE STATES WITH UNEQUAL

CONTENT OF PARTICLE and ANTIPARTICLE

$\Uparrow$ N_i $\qquad\qquad$ $\Uparrow$ N_i^c

TIME DEVELOPMENT



$$\delta = \frac{n_\ell - n_{\ell c}}{n_\ell + n_\ell^c}$$

The oscillation of a $j = 2$ neutrino to an $i = 1$ neutrino and its decay to the αth light lepton or antilepton produces the asymmetry,

$$\delta = 4\sqrt{2}\pi \left(\frac{M_i}{M_j}\right) \frac{\text{Re }(h_{\alpha j} h^*_{\alpha i}) \ \ \text{Im}(h_{\alpha j} h^*_{\alpha i})}{|h_{\alpha i}|^2 + |h_{\alpha j}|^2} \tag{4}$$

We shall include this lepton asymmetry in the evolution of the lepton number determined by the Boltzmann equation.

Two solutions

- 1) Solution in a uniform density of energy and particles ---> a constant change of the density

- 2) Solution with density fluctuations---> the higher density regions are enhanced

The s-channel process

$$N_i + L \to h \to Q + u$$

$$\hat{\sigma}_h(s) = \frac{m_Q^2 (g^\dagger g)_{ii}}{2\pi v^2} \left[\frac{s - M_i^2}{s} \right]^2$$

The reaction density for the decay $N_1 \to Y$, where Y is a general final state, is defined by

$$< \Gamma >= \int d\Pi_{N_i} d\Pi_Y (2\pi)^4 \delta^{(4)}(p_Y - p_{N_i}) f_\psi^{eq} |\mathcal{M}(N_i \to Y)|^2;$$

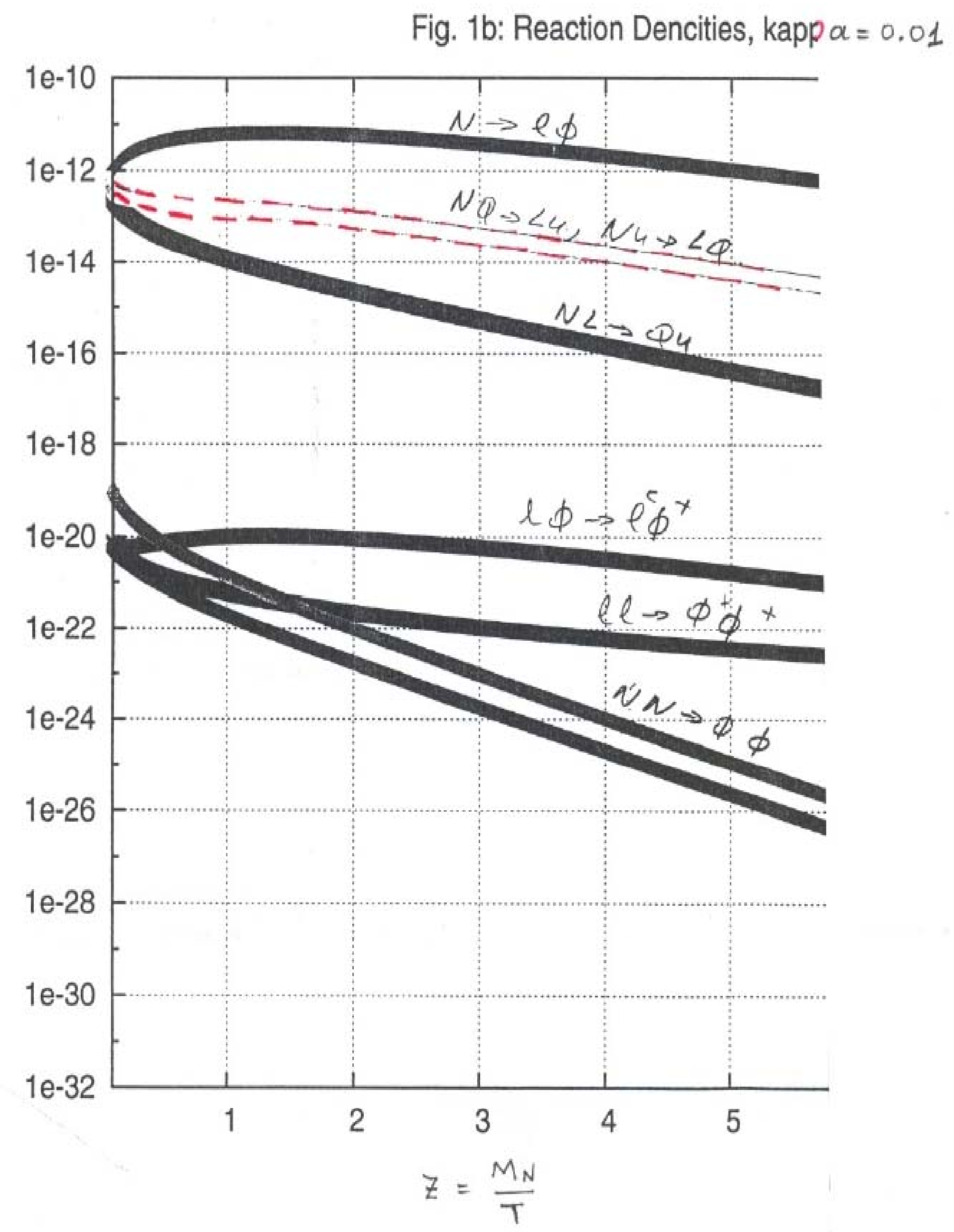


Fig. 1b: Reaction Dencities, kappa = 0.01
1e-10
1e-12
1e-14
1e-16
1e-18
1e-20
1e-22
1e-24
1e-26
1e-28
1e-30
1e-32
1
2
3
4
5
z = M_N / T

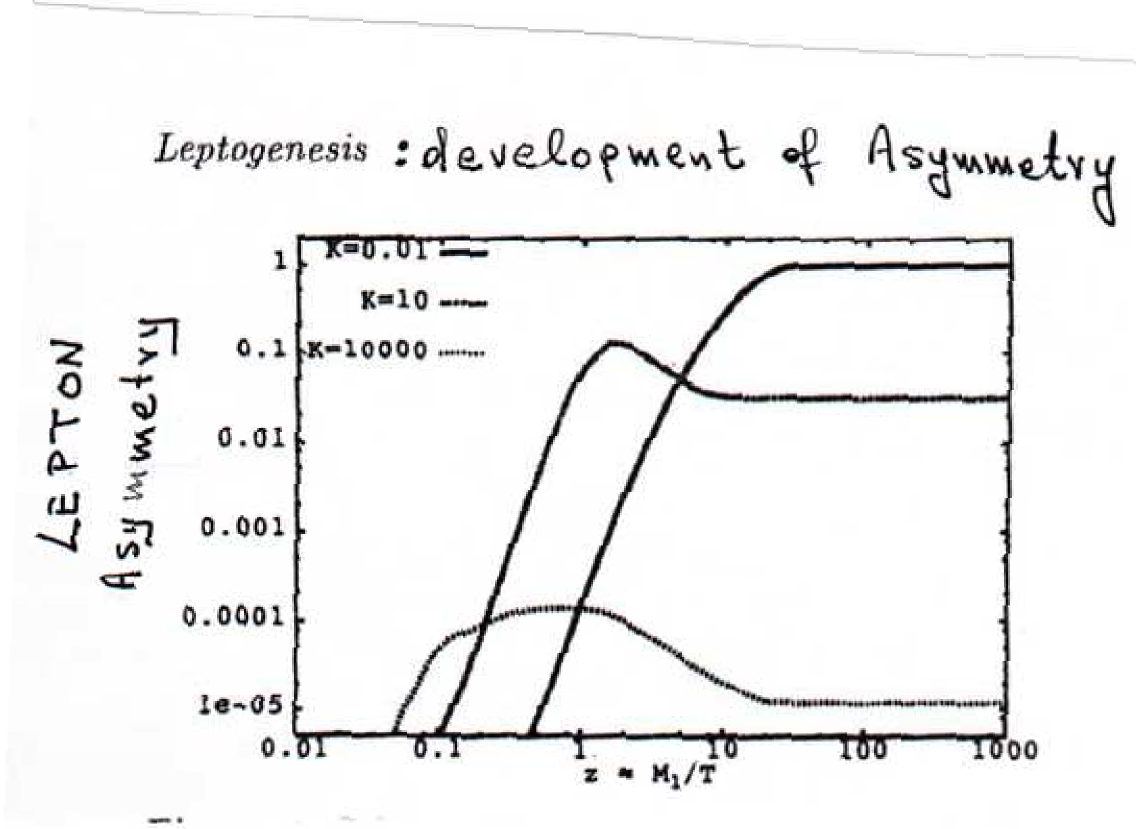
$$\frac{dY_{\Psi_1}}{dz} = -\gamma K z \left\{ Y_{\Psi_1} - Y_{\Psi_1}^{EQ} \right\}$$

$$\gamma_L := \left[g_* Y_{\Psi_1}^{EQ} \langle \Gamma_{\Psi_1} \rangle + 2 n_\gamma \langle \sigma' v \rangle \right] / \Gamma_{\Psi_1}(z = 1)$$

with $K = \frac{\langle \Gamma \rangle}{H}$ and $z = \frac{M}{T}$

Solution in a uniform Universe

- With   K=<Γ>/H



- When the temperature reaches an energy equal to the rest mass of the light Majorana neutrino, this particle is non-relativistic and in addition it decouples, i.e. it just decays.

- The time development in the various regions depends on the reaction and decay densities.

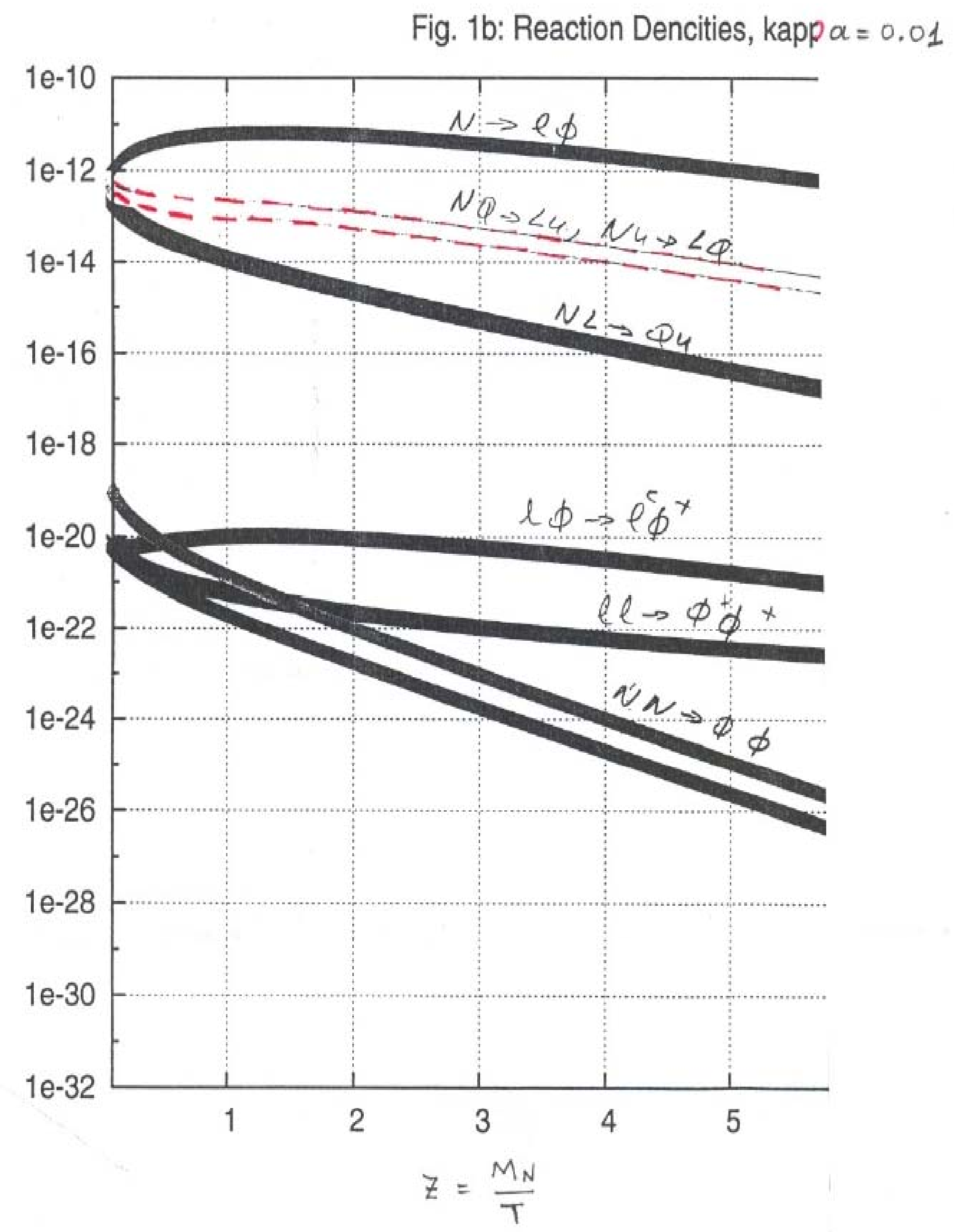


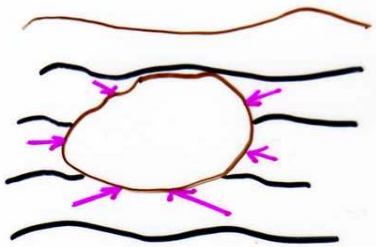
Fig. 1b: Reaction Dencities, kappa = 0.01
1e-10
1e-12
1e-14
1e-16
1e-18
1e-20
1e-22
1e-24
1e-26
1e-28
1e-30
1e-32
1
2
3
4
5

GROWTH OF DENSITY FLUCTUATIONS at LEPTOGENESIS.

Usual solution for lepton asymmetry in a uniform background of particles.

Assume different energy distribution

$\Rightarrow$ Regions of higher density



At the time of radiation internal pressure is large to wash out any growth

Except for Majorana neutrinos; they non-relativistic and decouple

1) Assuming découpling and $\rho_M / \rho_0 \approx \frac{\delta_M}{\delta_0} \approx 1/100$

2) $H = \frac{\dot{R}}{R} = \frac{1}{2t}$; $R(t)$ scale parameter

Define :

$$\rho(x,t) = \rho_0(1+\delta_0) + \rho_M(1+\delta_M)$$

ρ_0 : Uniform density of light particles

ρ_M : " " of Majoranas

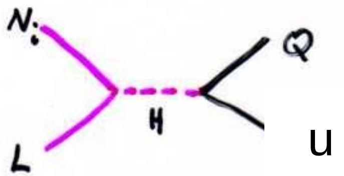
δ_0, δ_m their respective fluctuations

Then
$$\frac{d^2\delta_m}{dt^2} + 2H\frac{d\delta_M}{dt} \approx \frac{1}{4}\left(\frac{\rho_M}{\rho_0} - 2\frac{\langle\Gamma\rangle}{H}\right)\frac{1}{t^2}\delta_M$$

Solution:

$$\delta_M(t) = C_1 t^n + C_2 t^{-n} + \text{Const.}$$

with $n \approx 1/10$



$$\hat{\sigma}_H(s) = \frac{m_Q^2 (h^\dagger h)_{ii}}{2\pi v^2} \left[\frac{s - M_i^2}{M_i^2} \right]^2$$

$$\frac{d^2\delta_M}{dt^2} + 2H(t)\frac{d\delta_M}{dt} \approx \frac{1}{4}\left(\frac{\rho_M}{\rho_0} - 2\frac{<\Gamma>}{H}\right)\frac{1}{t^2}\delta_M$$

This is homogeneous in time and has the solution

$$\delta_M(t) = C_1 t^n + \text{ constant}$$

$$\text{with } n \approx \frac{1}{2}\sqrt{\frac{\rho_M}{\rho_0}}$$

Conclusions

1)In regions of higher densities the lepton asymmetry is enhanced.
We must study its time development

2)Neutrino interactions are better understood and they should lead to:
i)relations among the couplings,
ii) determination of their properties (masses, mixings,....)