Lecture #3: Neutron, hadron and neutrino interactions in matter

Neutron interaction with matter

Neutron interacts via strong interaction with nuclei and also via EM (radiative capture)

- Elastic scattering
- Inelastic scattering
- Radiative capture
- (n,p) and (n,α) reaction

How is a neutral particle such as the neutron detected ?

Interaction with nucleus to giving secondary *charged* particles

e.g. $n + p \rightarrow n + p$ *(elastic scattering)* $E_p = E_n \cos^2\theta_p$

$n + {}^3He \rightarrow p + {}^3H \quad (\sigma_{th} \sim 5330 \text{ barns}, Q = 0.76 \text{ MeV})$

$n + {}^6Li \rightarrow {}^3H + \alpha \quad (\sigma_{th} \sim 940 \text{ barns}, Q = 4.78 \text{ MeV})$

$n + {}^{10}B \rightarrow {}^7Li + \alpha \quad (\sigma_{th} \sim 3840 \text{ barns}, Q = 2.79 \text{ MeV})$

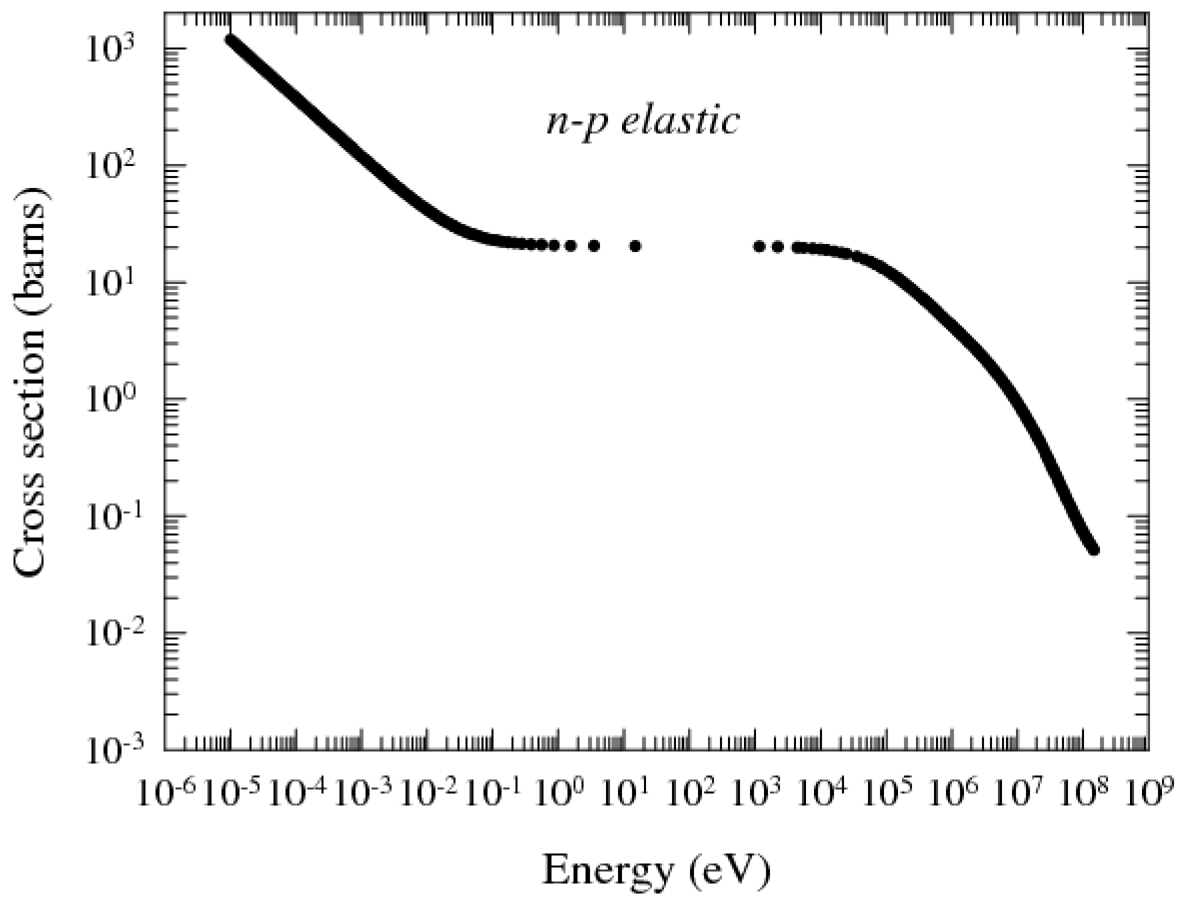
$n + {}^{155,157}Gd \rightarrow {}^{156,158}Gd + \gamma \quad (\sigma_{th} \sim 61 \text{ and } 254 \text{ kbarns resp.},$

$Q = 8.54 \;\&\; 7.94 \text{ MeV})$ *followed by* $\gamma + Z \rightarrow Z + e^+ + e^-$

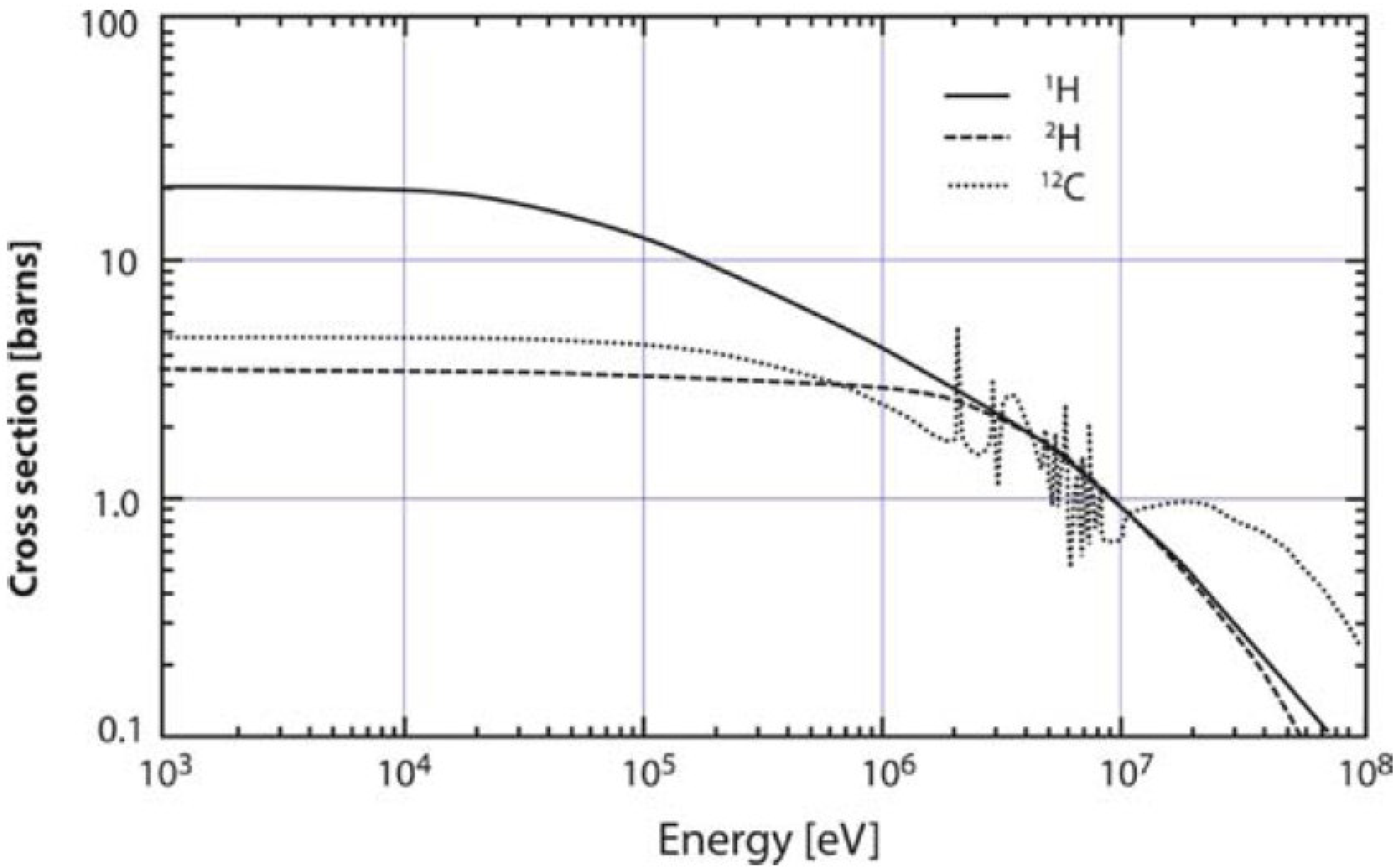
The *charged* particle then interacts with matter causing ionization, electronic excitation and fast $e^{\pm}$ induced emission of Cerenkov photons.

Gas proportional counters use ^{3}He, BF_3 and *scintillation detectors* based on LiF, plastic, liquid scintillators etc.

n-p elastic scattering cross section



Elastic scattering cross section for neutrons on $^{1,2}H$, ^{12}C



from Tavernier , Exp.Tech.Nucl.Part.Phys.(Springer,2010)

Hadronic interactions

Mean free path for nuclear interaction $\lambda = 35\ A^{1/3}$ gm/cm^2

$\lambda = \rho/(n\sigma) = \rho\ /[(\rho/A)\ N_A\ \pi\ r_0^2 A^{2/3} \times 10^{-26}]$

Hadronic showers:

EM component : γ, e^+, e^- , $\pi^0 \rightarrow 2\ \gamma$

Hadronic component: charged hadrons ($\pi^{\pm}$, $K^{\pm}$) ~ 20%

(non EM) **nuclear fragments (p) ~ 25%**

neutrons, soft γs ~ 15%

nuclear breakup ~ 40%

Max. in energy deposit at $x/\lambda = 0.2\ ln\ E(\mathrm{GeV}) + 0.7$

For Fe absorber $\lambda_{had} \approx$ 134 gm/cm^2 $\Rightarrow$ 17 cm

($L_{rad} = \lambda_{EM} \approx$ 13.8 gm/cm^2 $\Rightarrow$ 1.76 cm)

Ranges of **10**, 50, **100**, 500 & **1000** MeV protons in Fe are

0.2, 3.3, **11.3**, 165 & **457** gm/cm^2

Max. energy deposit at 0.7 λ = 11.9 cm for 1 GeV hadron

1.16 λ = 19.7 cm for 10 GeV hadron

1.62 λ = 27.6 cm for 100 GeV hadron

Remember that for $\pi^{\pm}$, $K^{\pm}$ **$c\tau$** ~ 7.8 m, 3.7m resp.

and for π^0 **$c\tau$** ~ 2.5 nm!

Neutrino interactions

Neutrino interactions with matter

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

First calculation of neutrino cross section by Bethe & Peierls *Nature* ***133***, *532 (1934*)

$\sigma_\nu \sim 10^{-44}$ cm^2 $E_\nu^{\,2}$ where E is in MeV

"……*there is no practically possible way of observing the neutrino*"

Relate beta decay half life to σ_ν

$\sigma_\nu = A/t$ where A has dimensions of L^2T^{-1} , $t \sim T$

$\sigma_\nu < (\hbar/p_\nu)^2 \; [\hbar/(p_\nu c)]/t$

If $t \sim 3$ min, $Q_\beta \sim$ 2-3 MeV

$\sigma_\nu \sim 10^{-44}$ cm^2 (Bethe, Peierls)

E-dependence at low energies (Pontecorvo)

$\sigma_\nu \propto (1/E_\nu^2) \;.\; (1/E_\nu) \;.\; E_\nu^5$

$\Rightarrow \sigma_\nu \propto E_\nu^2$ (correct dependence at low energies)

At higher energies $\sigma_\nu \propto E_\nu$

- At low energies (< 100 MeV)

  Charged current (CC) interactions with nucleus

  $\nu_l + N \rightarrow l^- + N'$

  Neutral current (NC) interactions with nucleus $\nu_l + N \rightarrow \nu_l + N$

- Few 100s of MeV

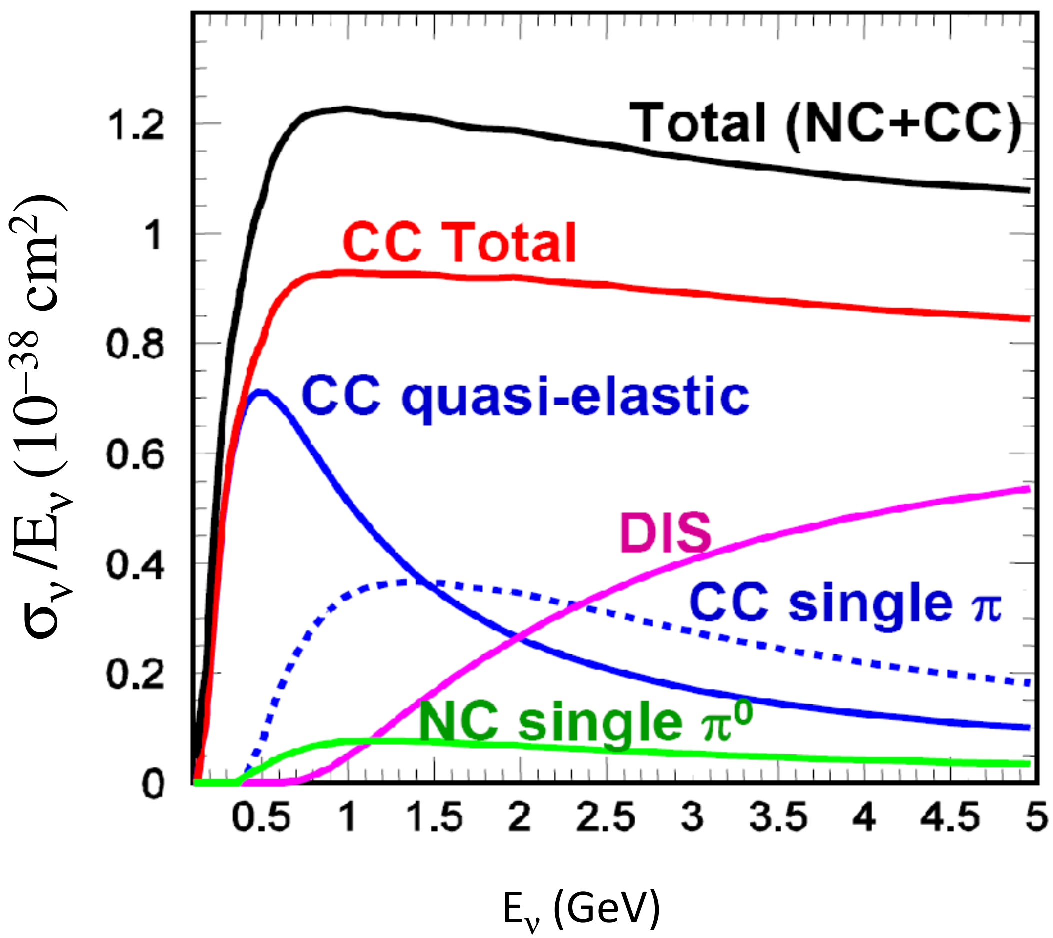
  Quasi-elastic CC interactions with nucleons in nucleus

  Pion production (CC + NC)

- At energies > GeV

  above processes become progressively less important and

  deep inelastic scattering (DIS) dominates



$\nu_\mu + n \rightarrow \mu^- + p$ (CC-QE)

$\nu_\mu + p \rightarrow \mu^- + p + \pi^+$
(CC resonance-1π, 2π..)

$\nu_\mu + q^- (N) \rightarrow \mu^- + q^+ + X$ *(DIS)*

from Mezzetto (ISAPP 2006)

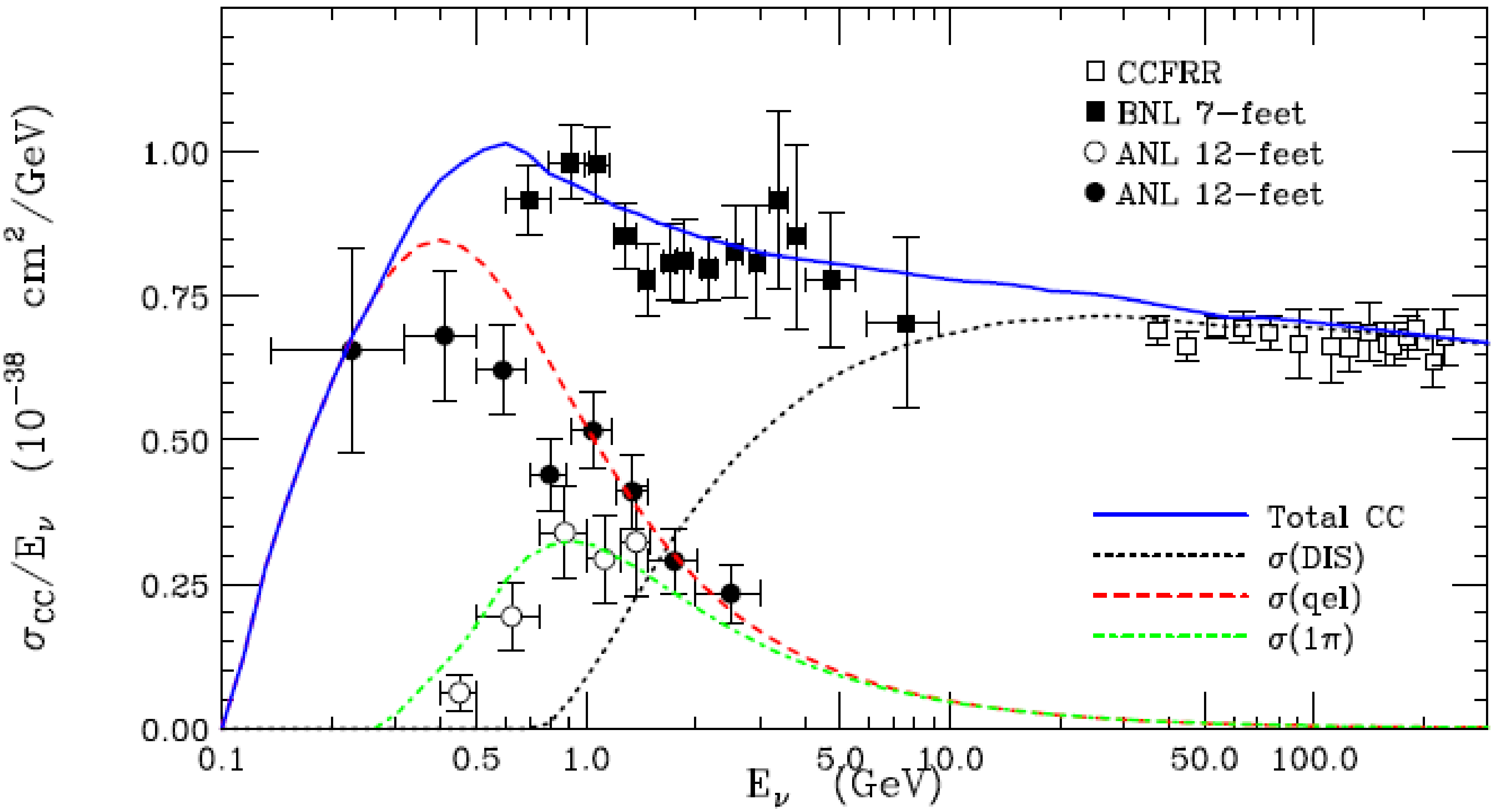
- QE reactions good from the point of view of ease of detection of single muon whose momentum can be determined with good precision

- For stopped muons range $\Rightarrow E_\mu$

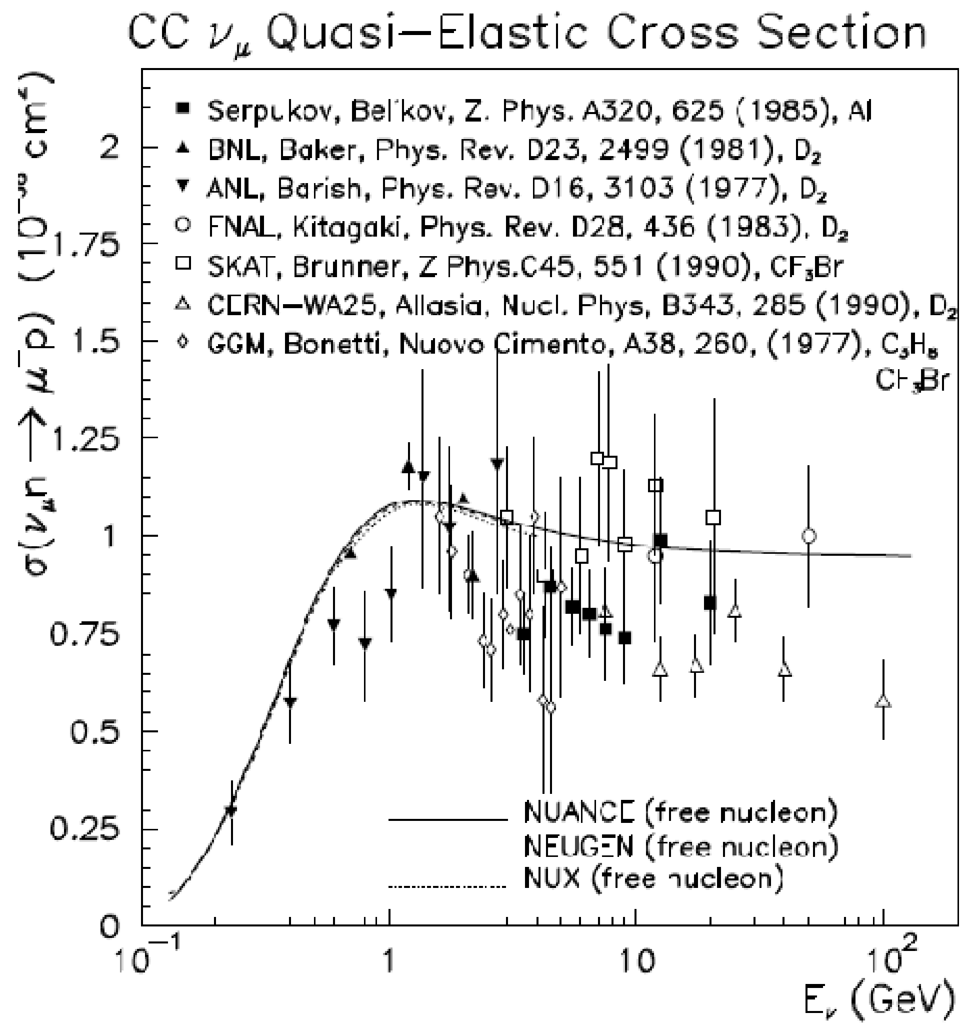
- Muons not stopping in detector (e.g. ICAL), curvature $\Rightarrow p_\mu$, E_μ

  Also increases effective (fiducial) detector volume

- For reactions with hadrons in final state, 4-momentum resolution worse than in QE

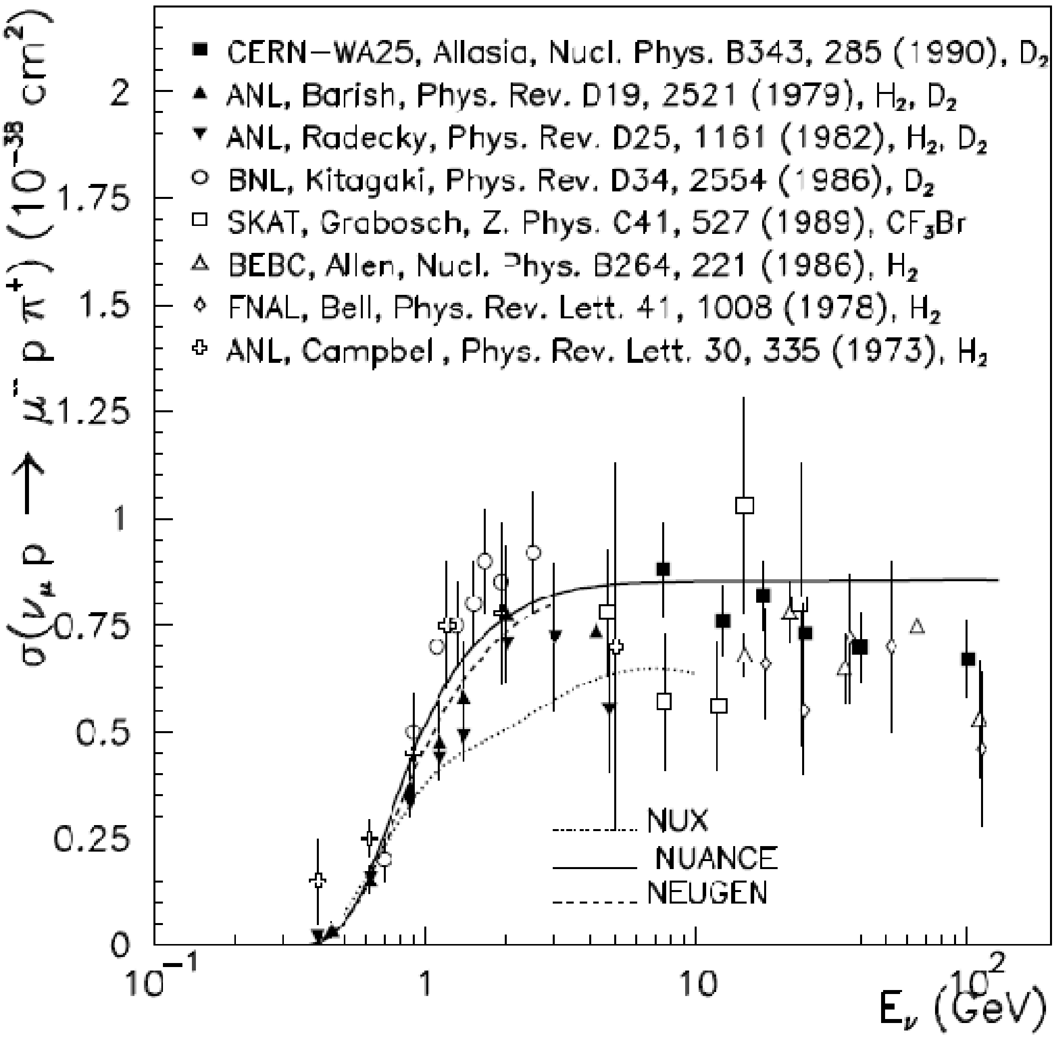


Ref: Zeller, arXiv:hep-ex/0312061 v1, Fig 1



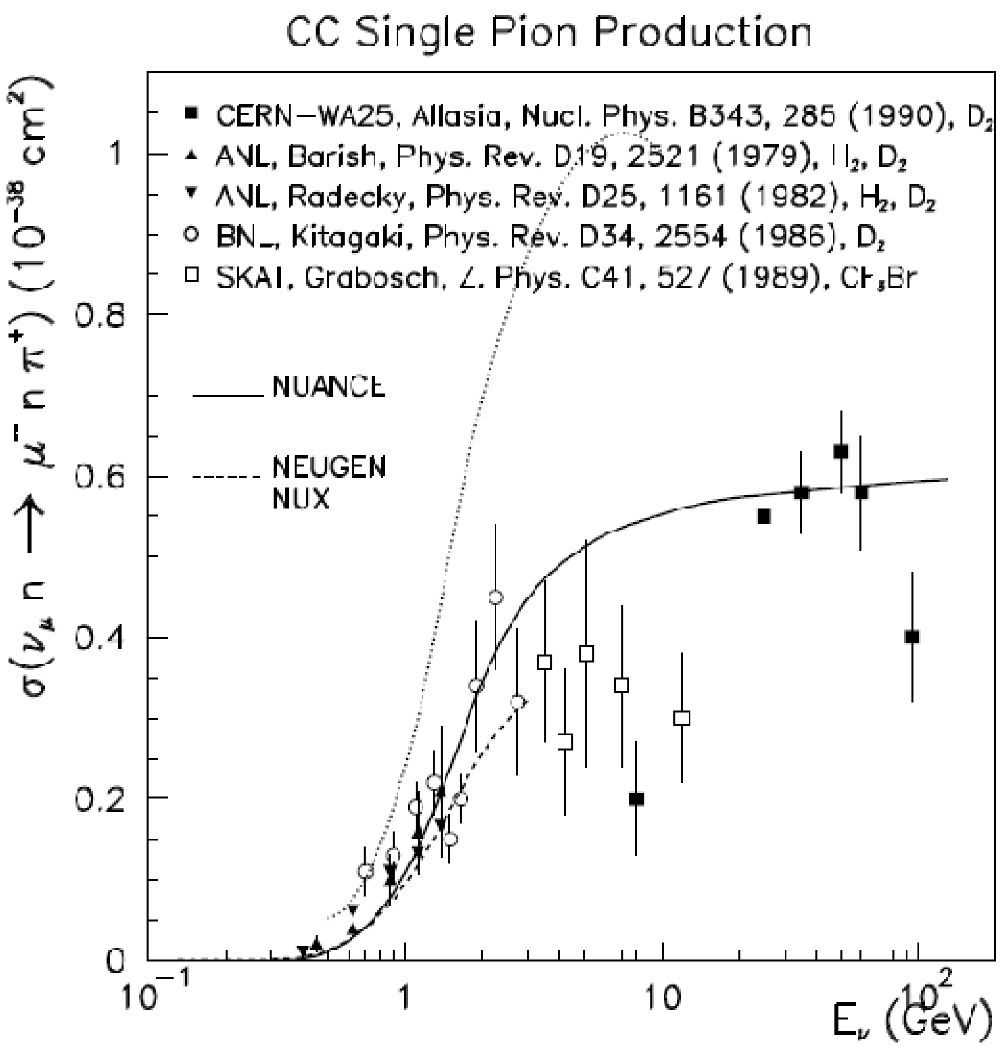
Ref: Zeller, arXiv:hep-ex/0312061 v1, Fig 2

Single Pion production ($\nu_\mu + p \rightarrow \mu^- + p + \pi^+$)

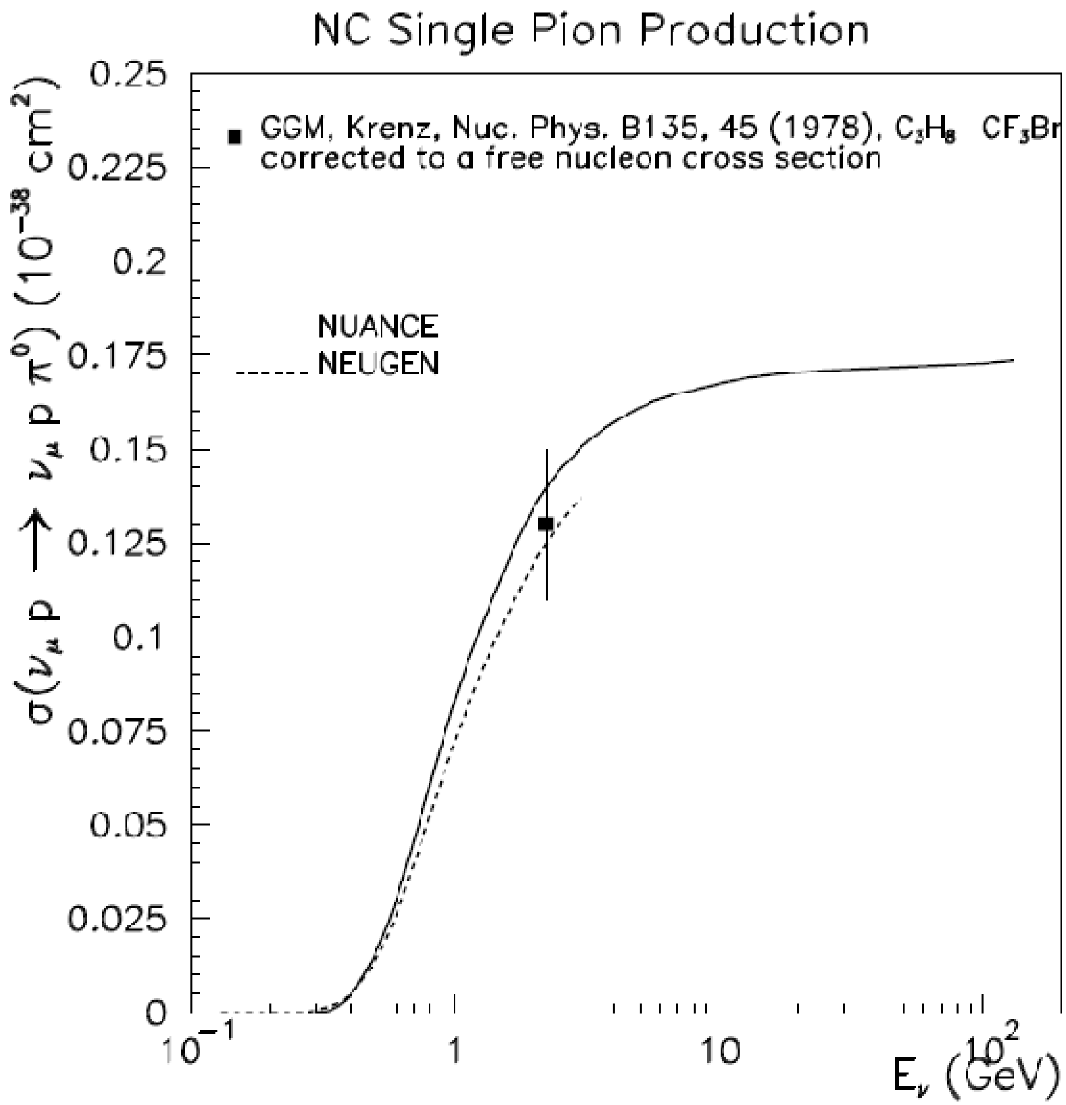


Ref: Zeller, arXiv:hep-ex/0312061 v1, Fig 4

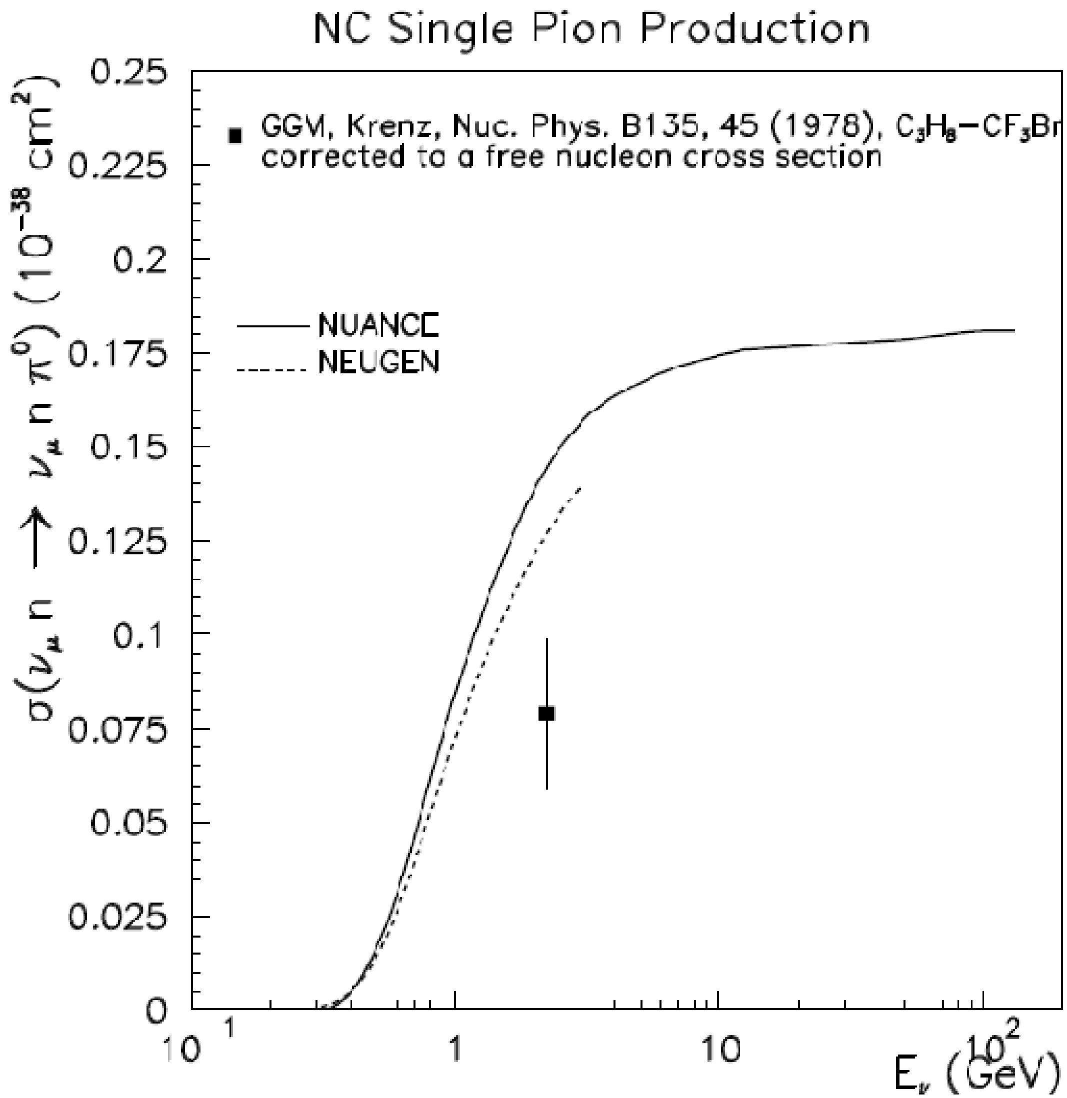
$\nu_\mu + n \longrightarrow \mu^- + n + \pi^+$



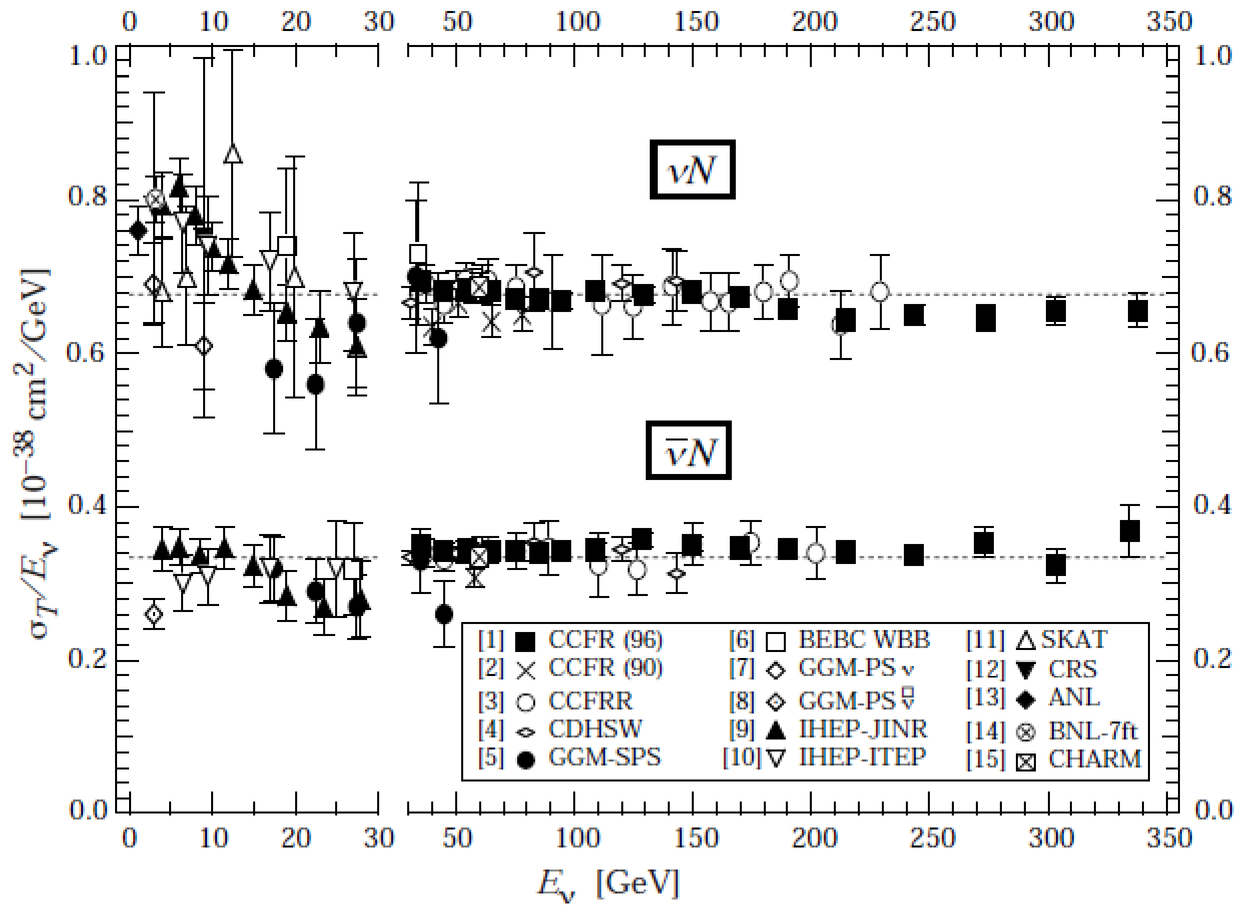
Ref: Zeller, arXiv:hep-ex/0312061 v1



Above slides emphasize the need for more precise data!


NC Single Pion Production
GGM, Krenz, Nuc. Phys. B135, 45 (1978), $C_3H_8-CF_3Br$
corrected to a free nucleon cross section
NUANCE
NEUGEN
$\sigma(\nu_\mu n \rightarrow \nu_\mu n \pi^0)$ $(10^{-38}$ cm$^2)$
E_ν (GeV)
0.25
0.225
0.2
0.175
0.15
0.125
0.1
0.075
0.05
0.025
0
10^{-1}
1
10
10^2

Total Charged Current cross sections for muon neutrinos & anti-neutrinos



RPP 2006