Weak pion production on nuclei

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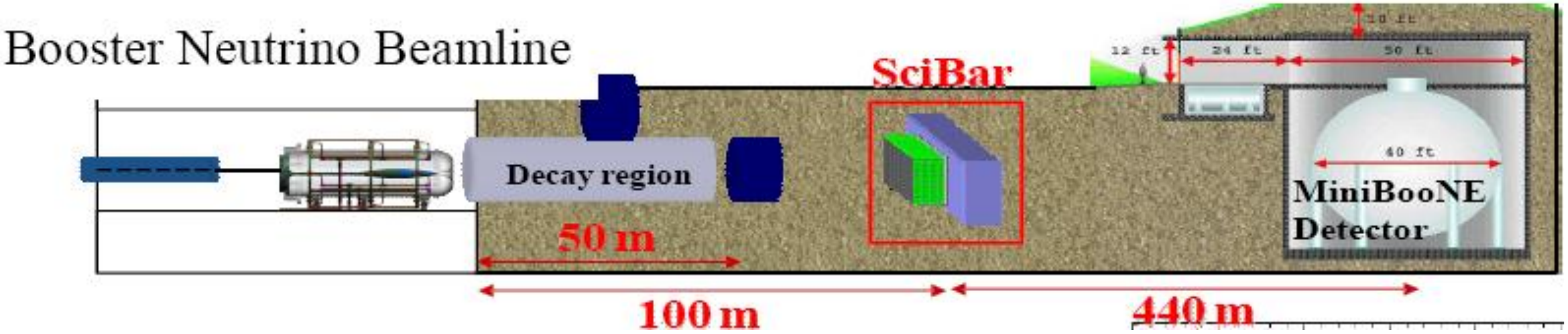
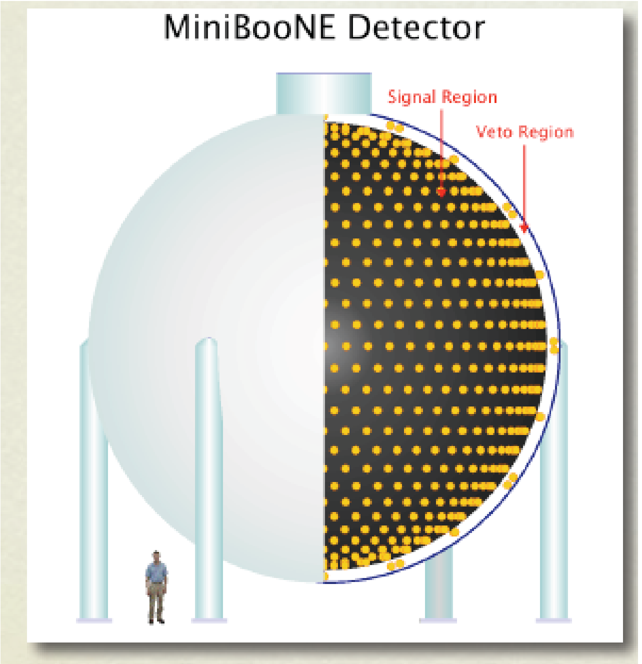
Motivation

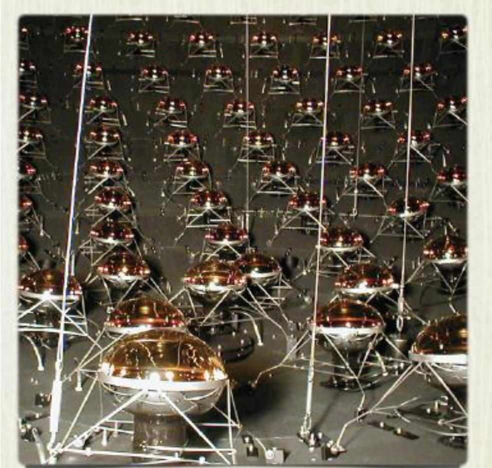
- Neutrino oscillation experiments search a distortion in the neutrino flux at a detector positioned far away (L) from the source.

SciBooNE (FNAL E954)



$p + A \rightarrow \pi^{\pm} X \qquad \pi^{\pm} \rightarrow \mu\nu_{\mu}$ (BR~100%)

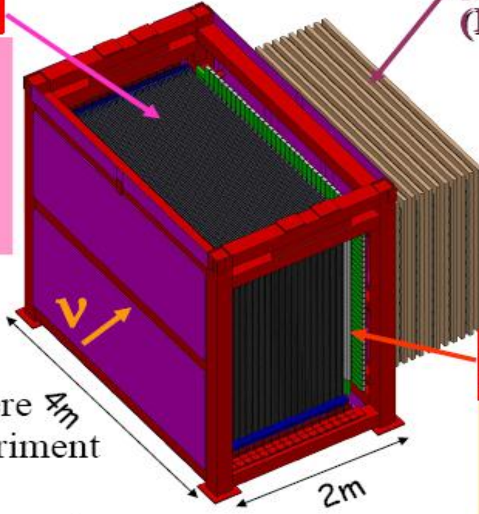



MiniBooNE Detector

SciBooNE detector

SciBar

- 14,336 scintillator bars (15 tons)
- detect all charged particles
- p/π separation using dE/dx



Muon Range Detector (MRD)

- 12 2”-thick steel + scintillator planes
- measure muon momentum with range up to 1.2 GeV/c

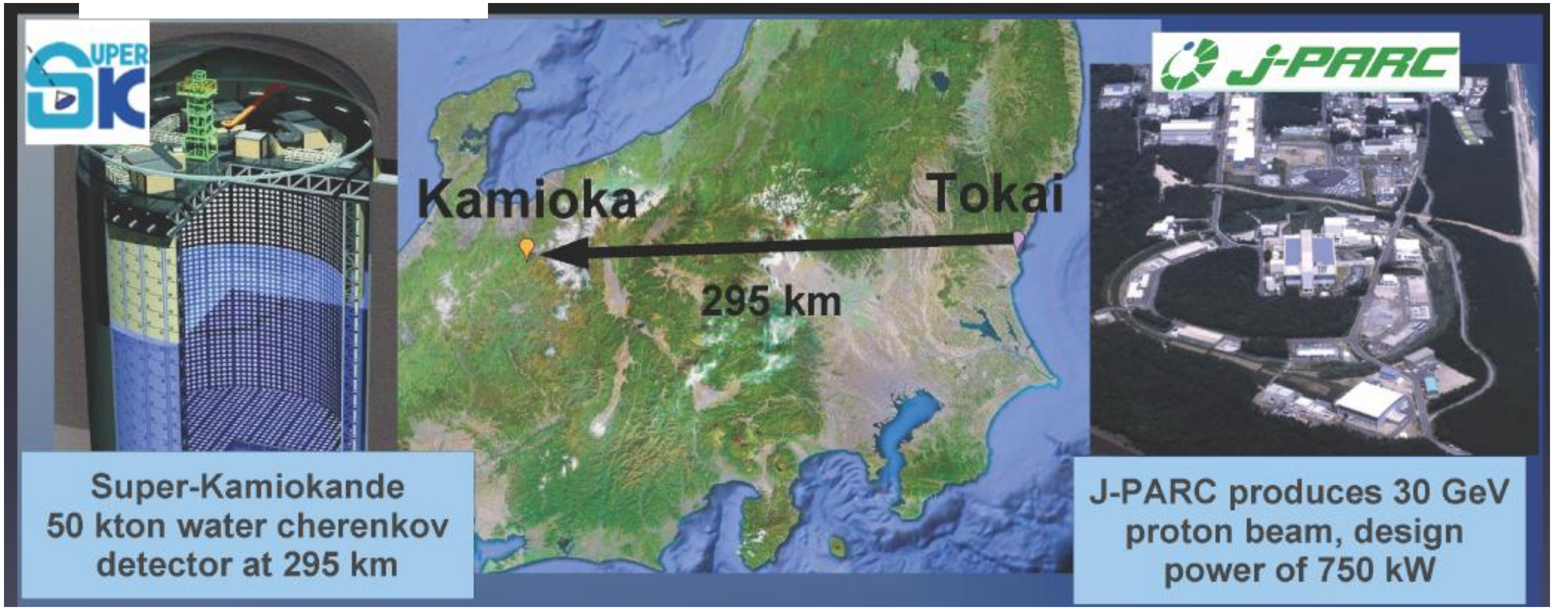
Electron Catcher (EC)

- spaghetti calorimeter
- 2 planes (11 X_0)
- identify π^0 and ν_e

SciBar and EC were used in K2K experiment

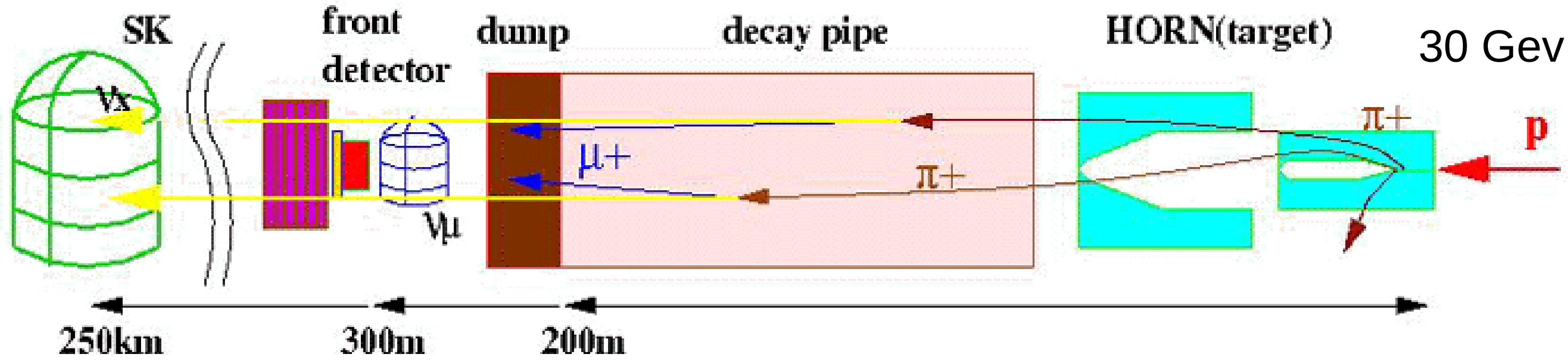
No NCπ0 measurement by such a full active scintillating detector

T2K

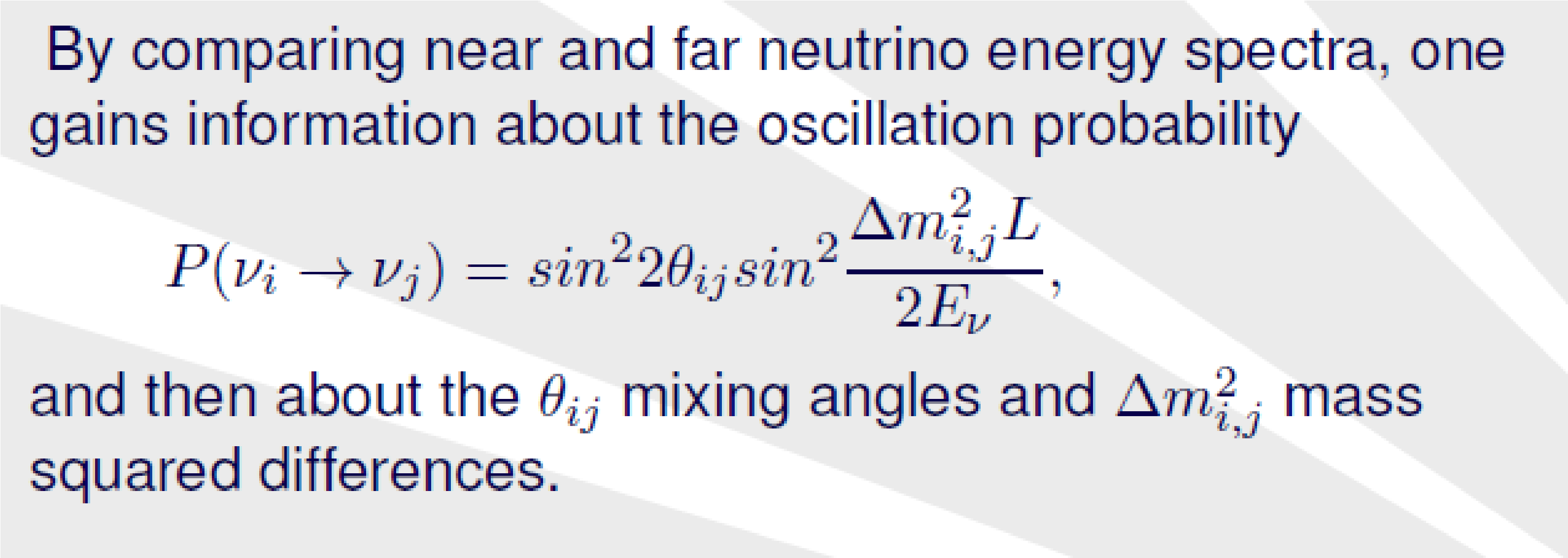


Super-Kamiokande
50 kton water cherenkov
detector at 295 km

J-PARC produces 30 GeV
proton beam, design
power of 750 kW



30 Gev



By comparing near and far neutrino energy spectra, one gains information about the oscillation probability

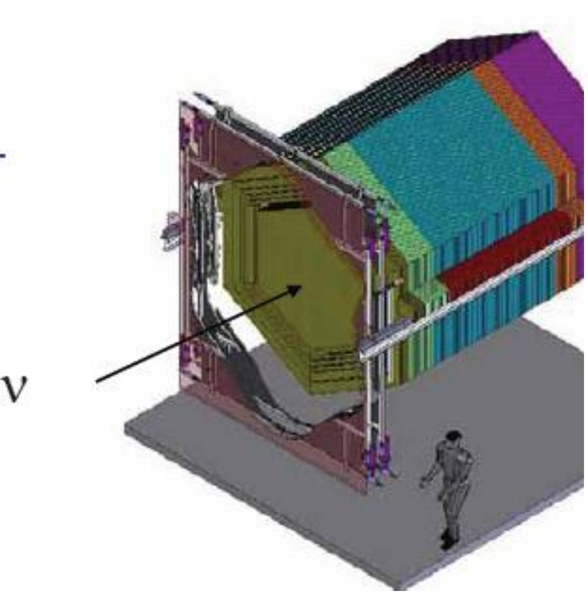
$$P(\nu_i \rightarrow \nu_j) = sin^2 2\theta_{ij} sin^2 \frac{\Delta m^2_{i,j} L}{2E_\nu},$$

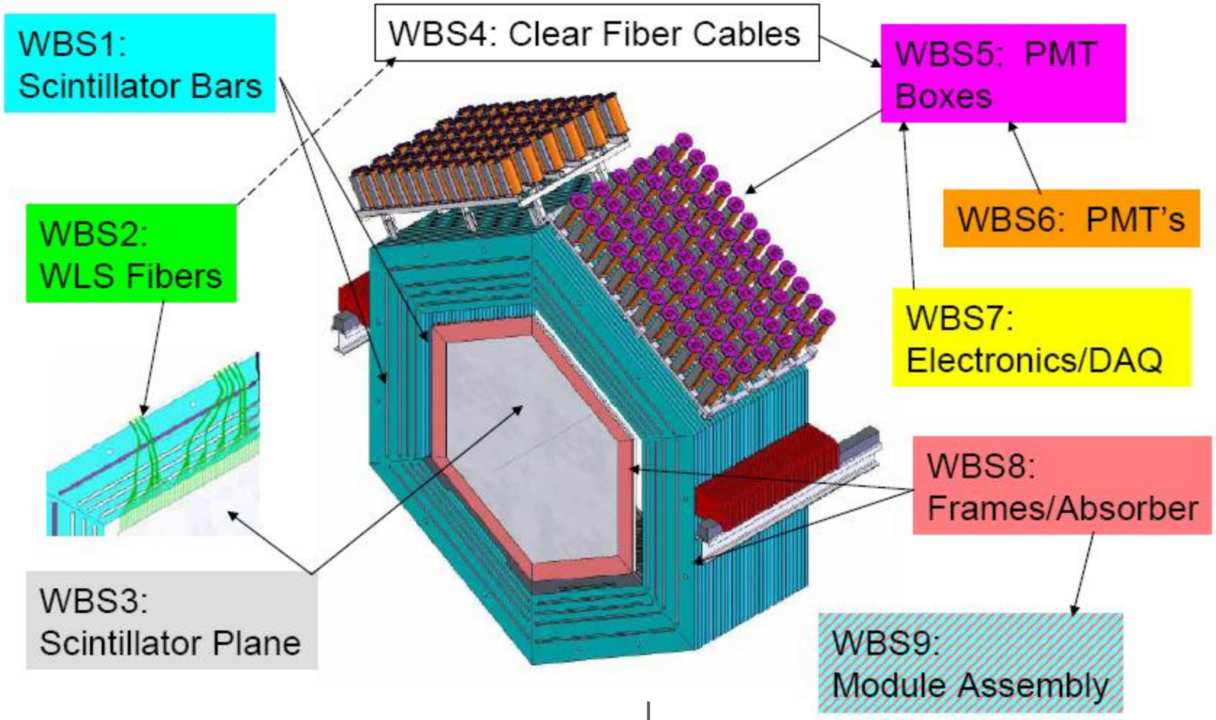
and then about the θ_{ij} mixing angles and $\Delta m^2_{i,j}$ mass squared differences.

- On the other hand and also using NUMI beam

This year began to run a powerfull tool to study axial structure of the nucleon and resonances: MINERvA (Main Injector Experiment for ν -A Scattering, which is a detector to study ν-A interactions with several nuclei and unpreceding detail

Overview of MINERvA Detector





WBS1: Scintillator Bars

WBS2: WLS Fibers

WBS3: Scintillator Plane

WBS4: Clear Fiber Cables

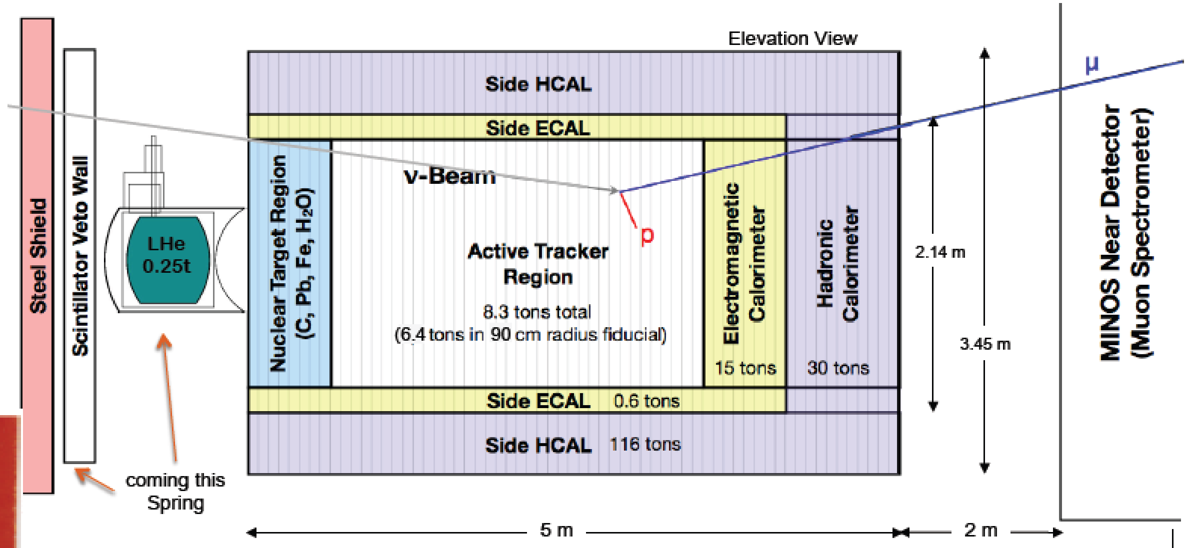
WBS5: PMT Boxes

WBS6: PMT's

WBS7: Electronics/DAQ

WBS8: Frames/Absorber

WBS9: Module Assembly

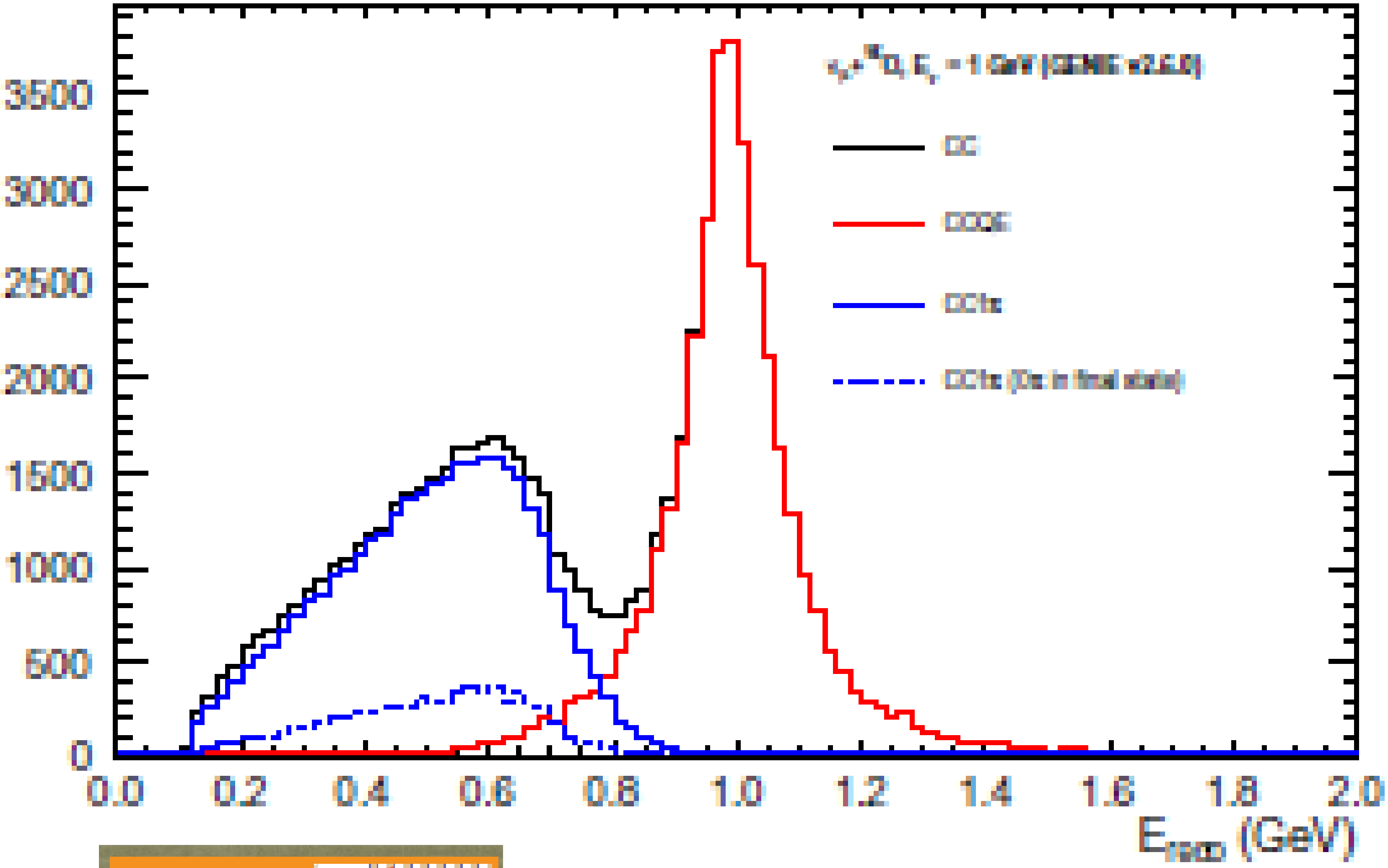


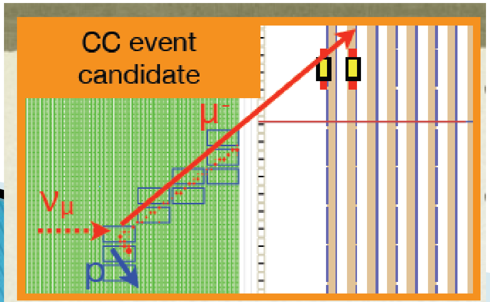
CCQE reaction $\nu_l n \to l^- p$ in the nucleus target is used as signal event or/and to reconstruct the neutrino energy.

Neutrino energy, is not directly measurable but reconstructed from reactions products through two-body kinematics, exact only for free nucleons.

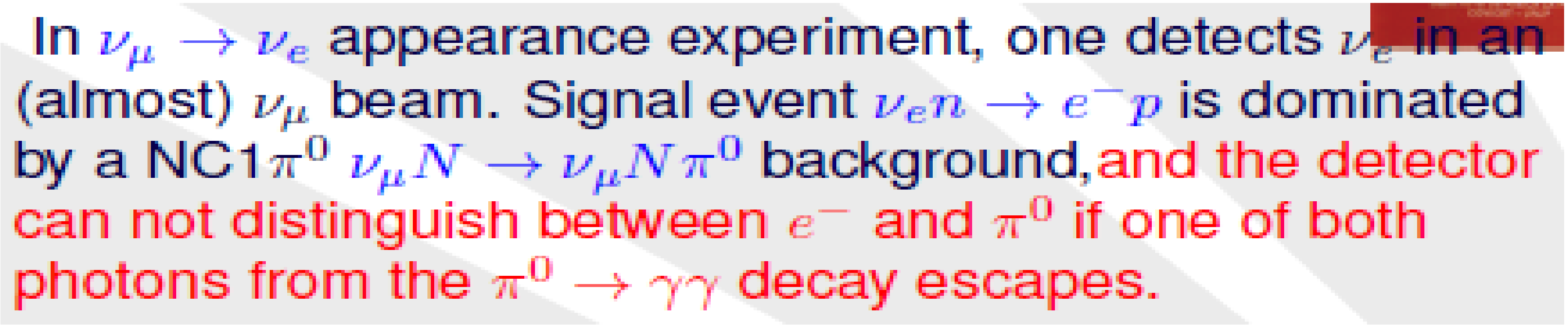
Competition of another processes could lead misidentification of the arriving neutrinos.

Disappearance searching experiments $\nu_\mu \to \nu_x$ uses $\nu_\mu n \to \mu^- p$ CCQE reaction to detect an arriving neutrino and reconstruct its energy. E_ν determination could be wrong for a fraction of CC1π^+ background events (20%) $\nu_\mu p \to \mu^- p \pi^+$, that can mimic a CCQE one if the pion is absorbed in the target and/or not detected.



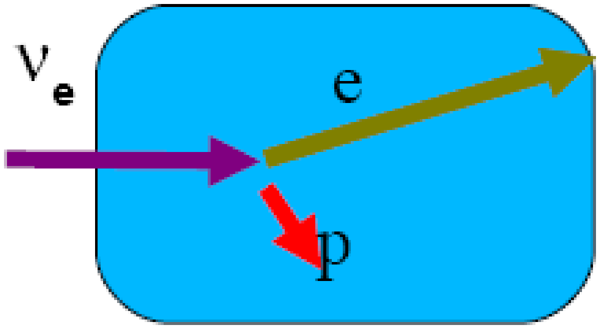


CC event candidate

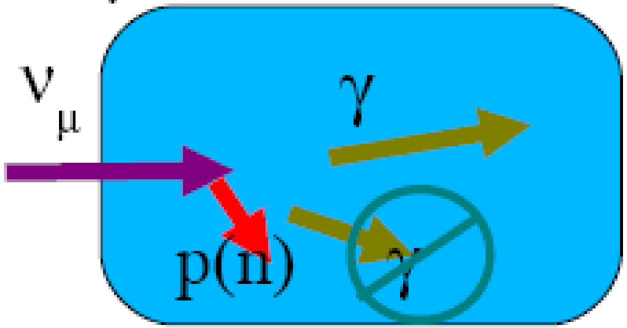


In $\nu_\mu \to \nu_e$ appearance experiment, one detects ν_e in an (almost) ν_μ beam. Signal event $\nu_e n \to e^- p$ is dominated by a NC1π^0 $\nu_\mu N \to \nu_\mu N \pi^0$ background, and the detector can not distinguish between e^- and π^0 if one of both photons from the $\pi^0 \to \gamma\gamma$ decay escapes.

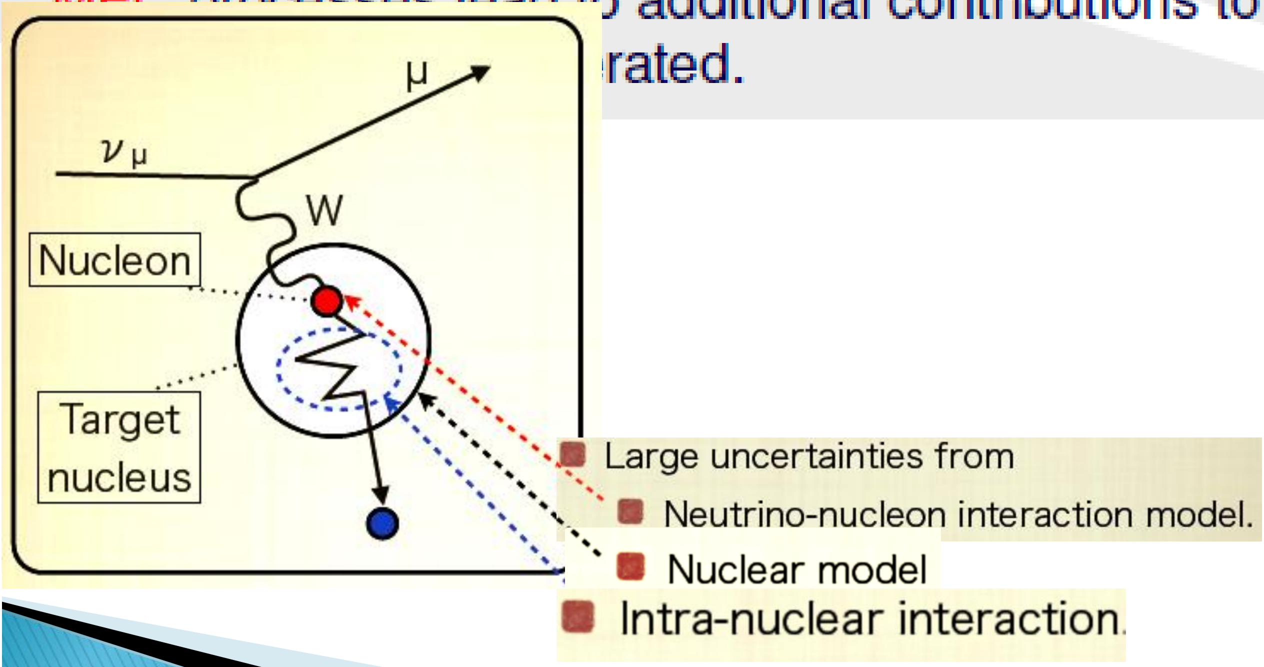
The ν_e signal : electron



The background from NCπ^0 :
One γ from π^0 , miss another γ

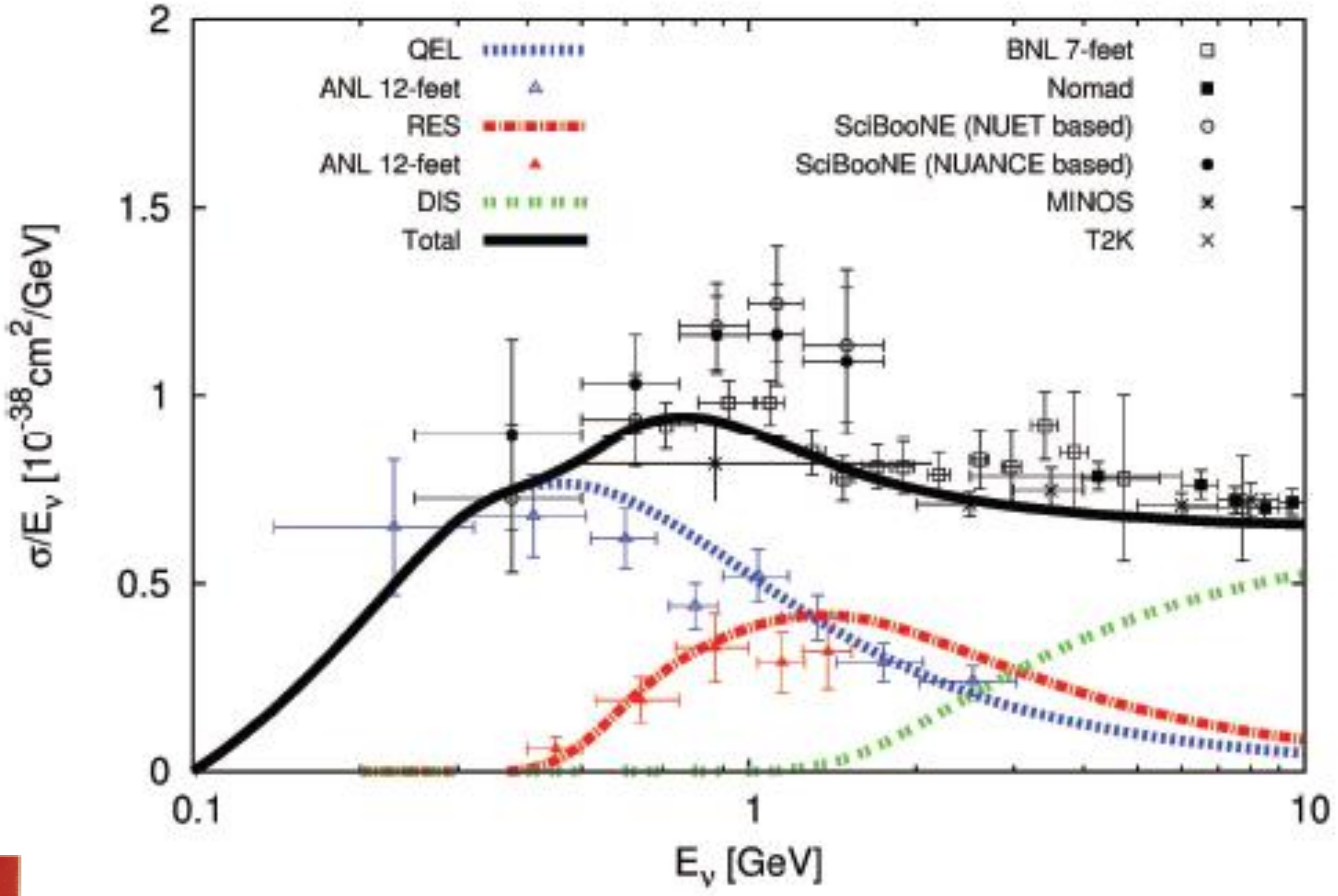


- A precise knowledge of cross sections is a prerequisite in order to make simulations in event generators to substract fake 1π events in QE countings.
- Nuclear effects: Smearing of the reconstructed energy by the momentum distribution of the target bound nucleons (GSC+Bounding). FSI of the emerging nucleon generate energy lost,change of direction,charge transfer or multiple nucleon knock out(np-nh). All these affecting QE events determination.
- MEC processes lead to additional contributions to rated.

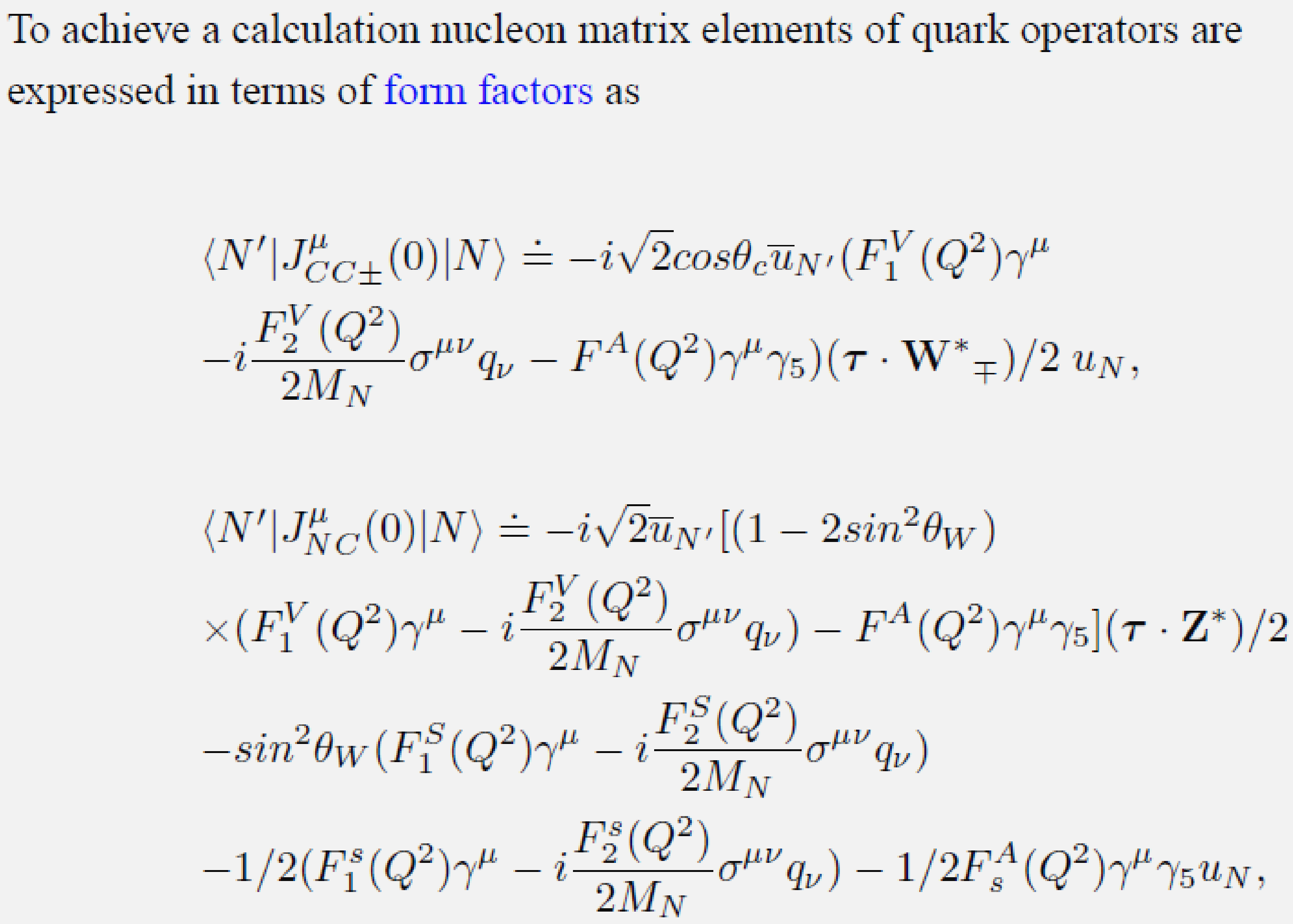


- Large uncertainties from
  - Neutrino-nucleon interaction model.
  - Nuclear model
- Intra-nuclear interaction.

Inclusive cross section



CCQE



To achieve a calculation nucleon matrix elements of quark operators are expressed in terms of form factors as

$$\langle N'|J^{\mu}_{CC\pm}(0)|N\rangle \doteq -i\sqrt{2}cos\theta_c \overline{u}_{N'}(F_1^V(Q^2)\gamma^{\mu}$$
$$-i\frac{F_2^V(Q^2)}{2M_N}\sigma^{\mu\nu}q_{\nu} - F^A(Q^2)\gamma^{\mu}\gamma_5)(\boldsymbol{\tau}\cdot\mathbf{W^*}_{\mp})/2\; u_N,$$

$$\langle N'|J^{\mu}_{NC}(0)|N\rangle \doteq -i\sqrt{2}\overline{u}_{N'}[(1-2sin^2\theta_W)$$
$$\times(F_1^V(Q^2)\gamma^{\mu} - i\frac{F_2^V(Q^2)}{2M_N}\sigma^{\mu\nu}q_{\nu}) - F^A(Q^2)\gamma^{\mu}\gamma_5](\boldsymbol{\tau}\cdot\mathbf{Z}^*)/2$$
$$-sin^2\theta_W(F_1^S(Q^2)\gamma^{\mu} - i\frac{F_2^S(Q^2)}{2M_N}\sigma^{\mu\nu}q_{\nu})$$
$$-1/2(F_1^s(Q^2)\gamma^{\mu} - i\frac{F_2^s(Q^2)}{2M_N}\sigma^{\mu\nu}q_{\nu}) - 1/2F_s^A(Q^2)\gamma^{\mu}\gamma_5 u_N,$$

Effective model

where the

F_i^V fixed through the CVC hypothesis

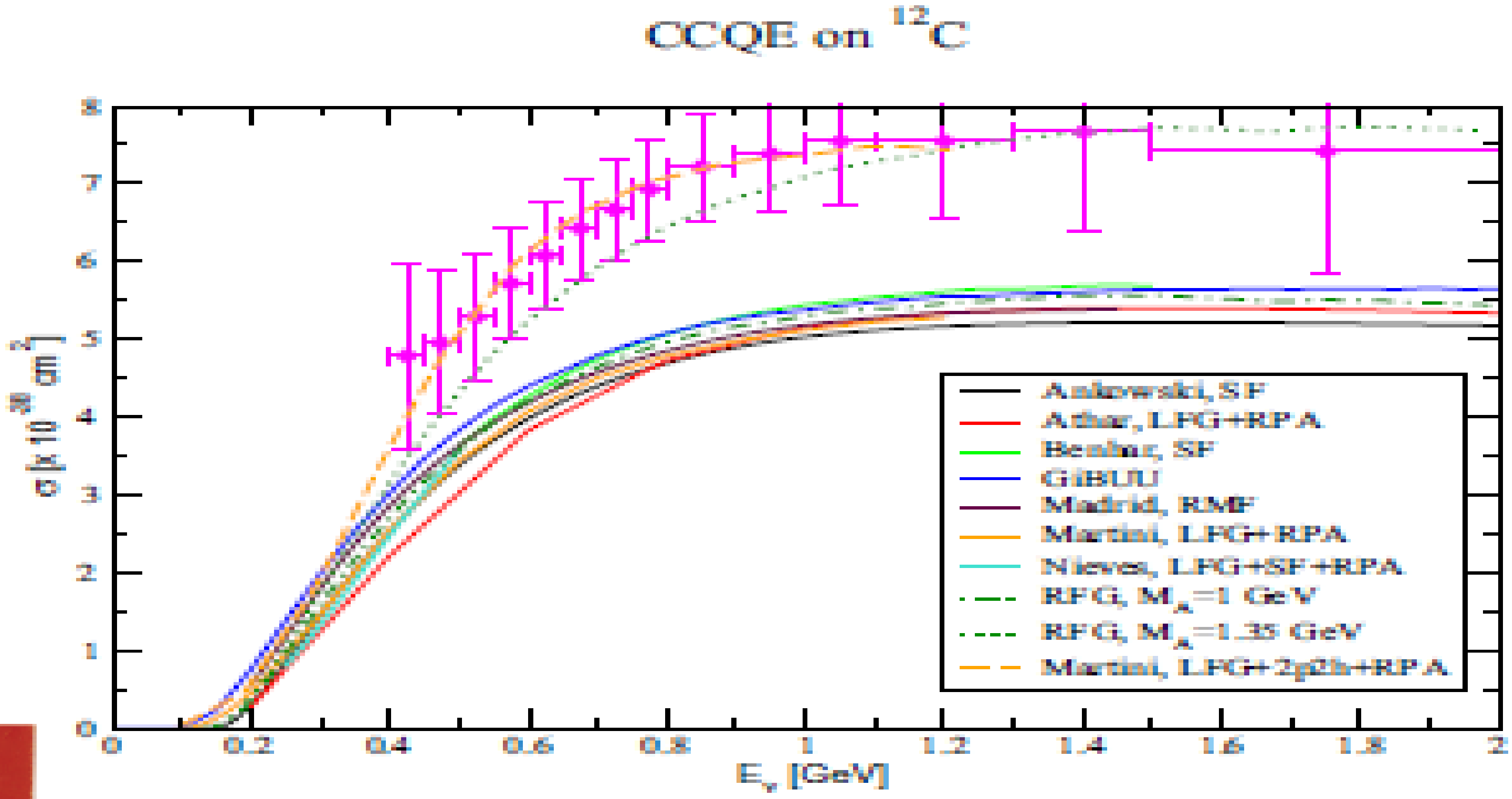
F^A using the PCAC hypotesis

F_i^S are the isoscalar electromagnetic form factors

F_i^s, F_A^s are the strange form factors obtained from parity violating electron scattering.

$$F_A(Q^2) = \frac{G_A}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}.$$

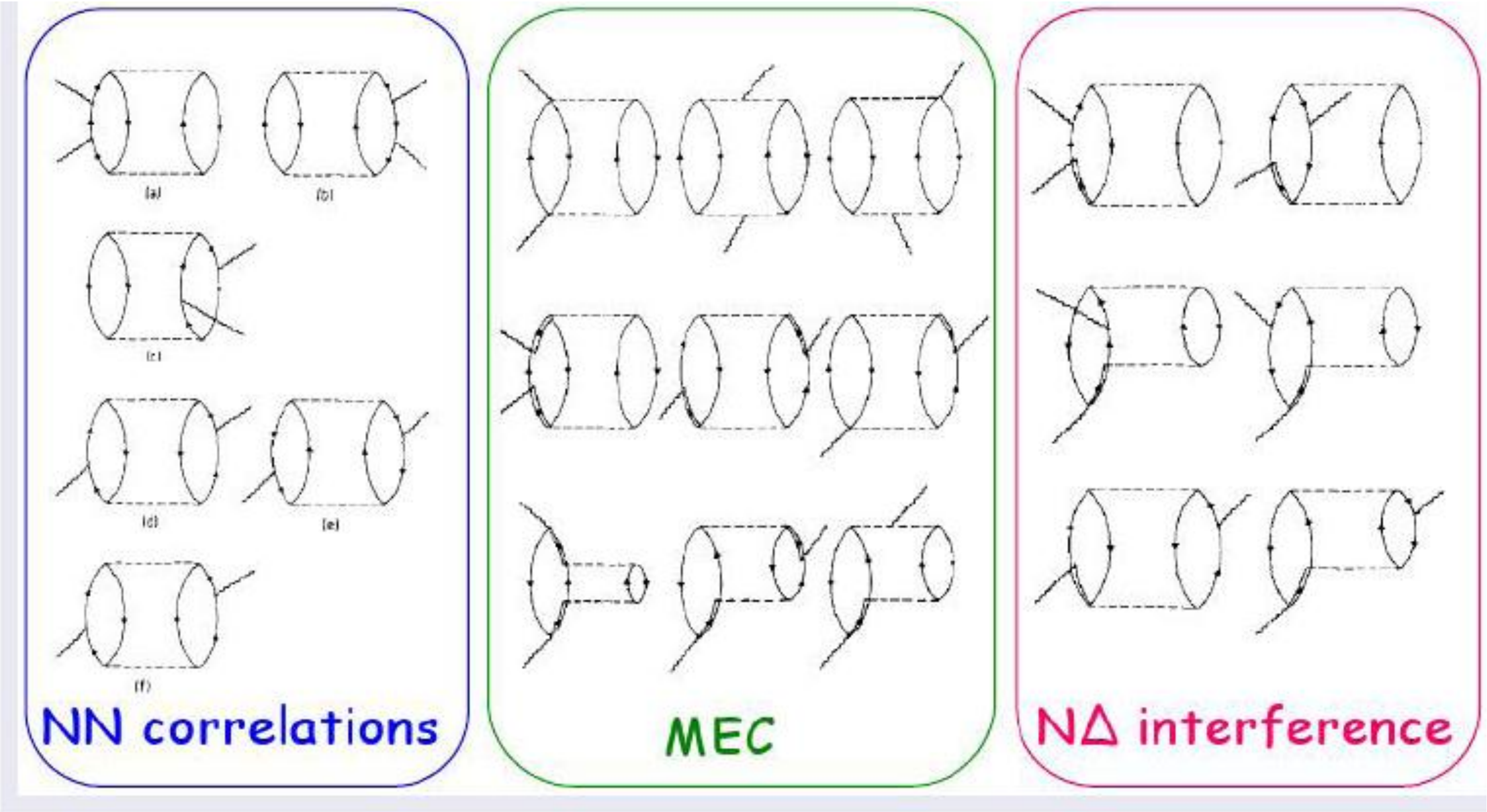
$$F_A(0) \equiv G_A \approx 1.26.$$



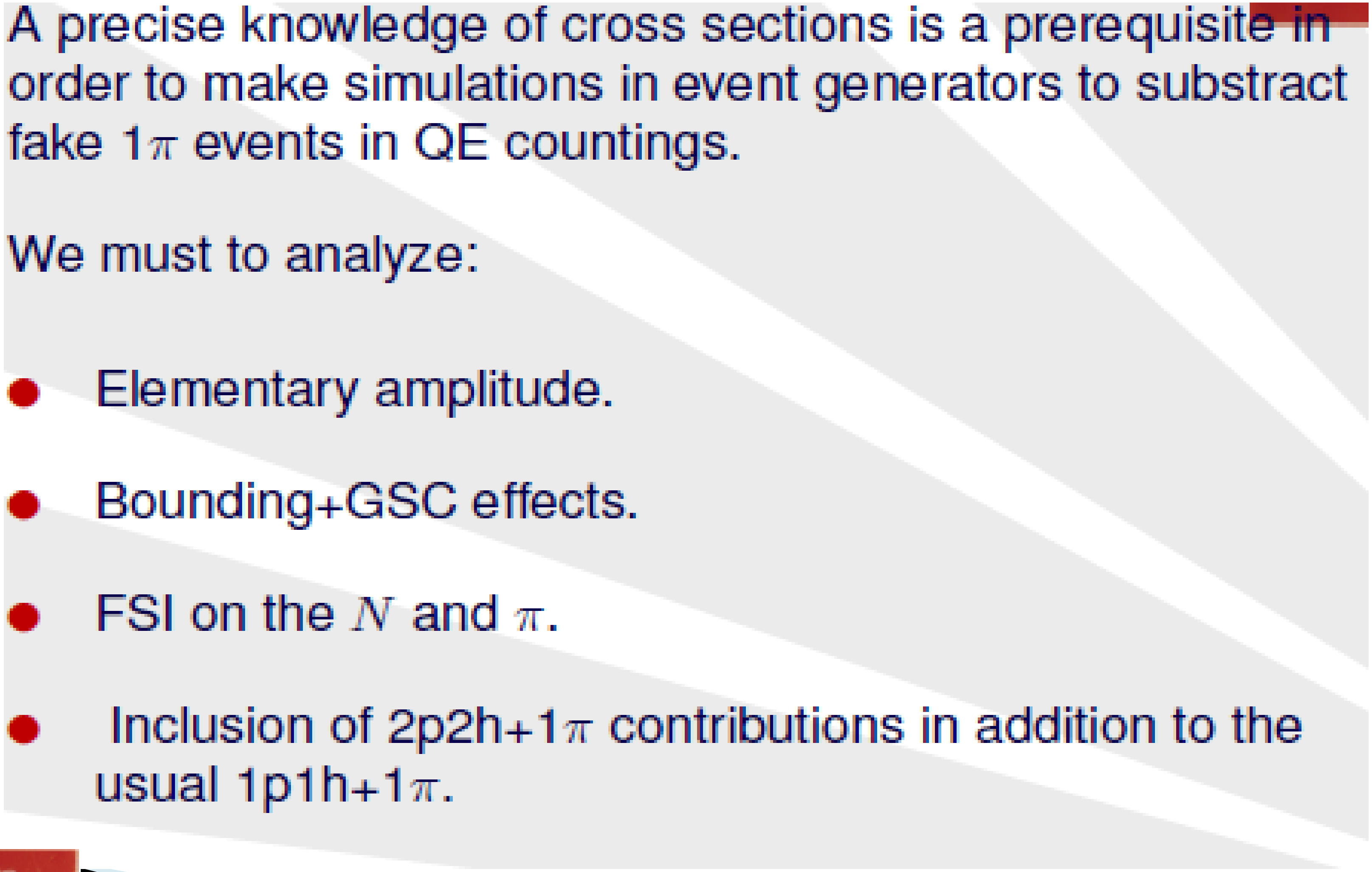
The problem of CCQE axial mass leads us to theoretical frameworks going beyond simple theory of CCQE and Impulse Approximation presented before.

At the energies of Mentioned experiments Δ(1232 MeV) gives main resonance contribution

2p-2h contribution comes from the nuclear matter Δ pionless decay and from the diagrams:



1 π process



A precise knowledge of cross sections is a prerequisite in order to make simulations in event generators to substract fake 1π events in QE countings.

We must to analyze:

- Elementary amplitude.
- Bounding+GSC effects.
- FSI on the N and π.
- Inclusion of 2p2h+1π contributions in addition to the usual 1p1h+1π.

Elementary amplitude

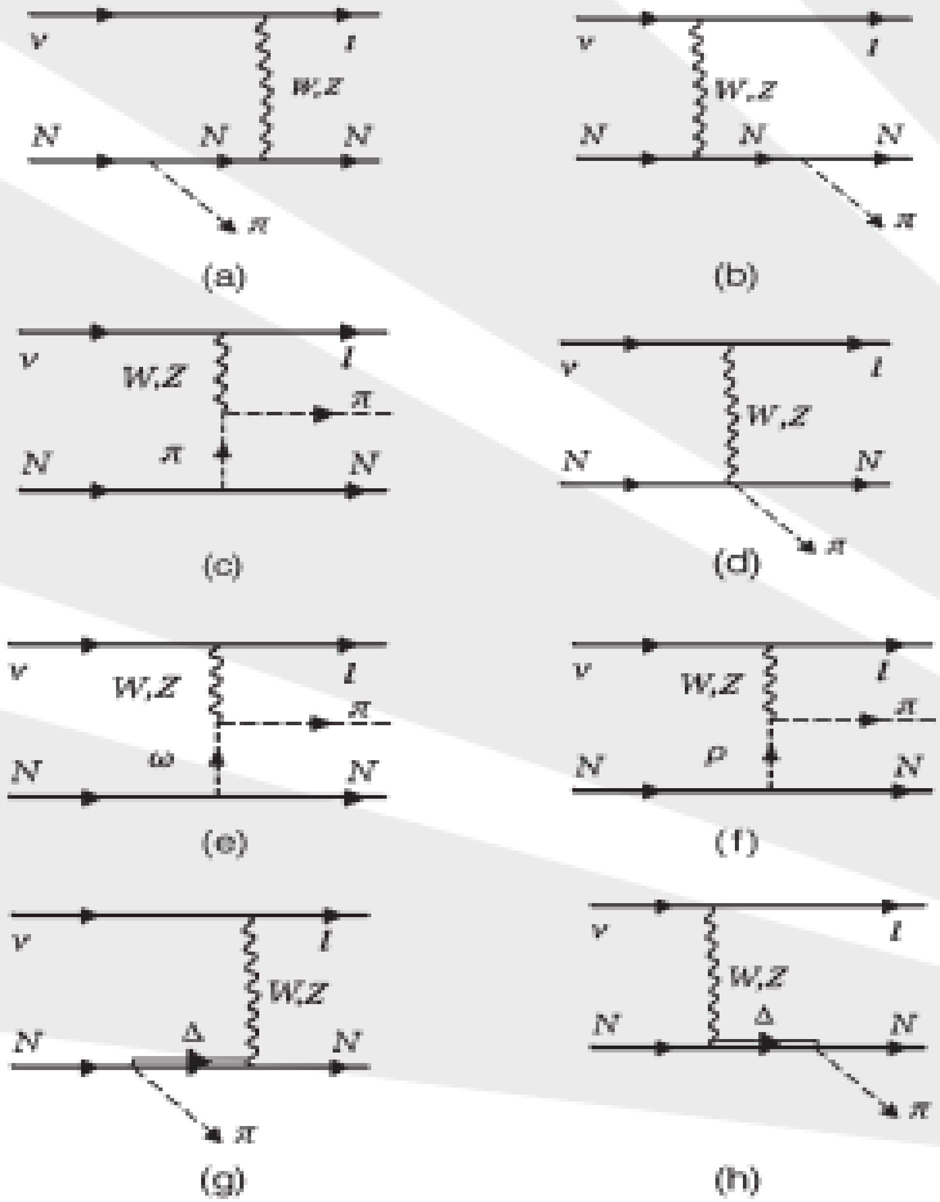
For the $\nu N \to l N' \pi$ process

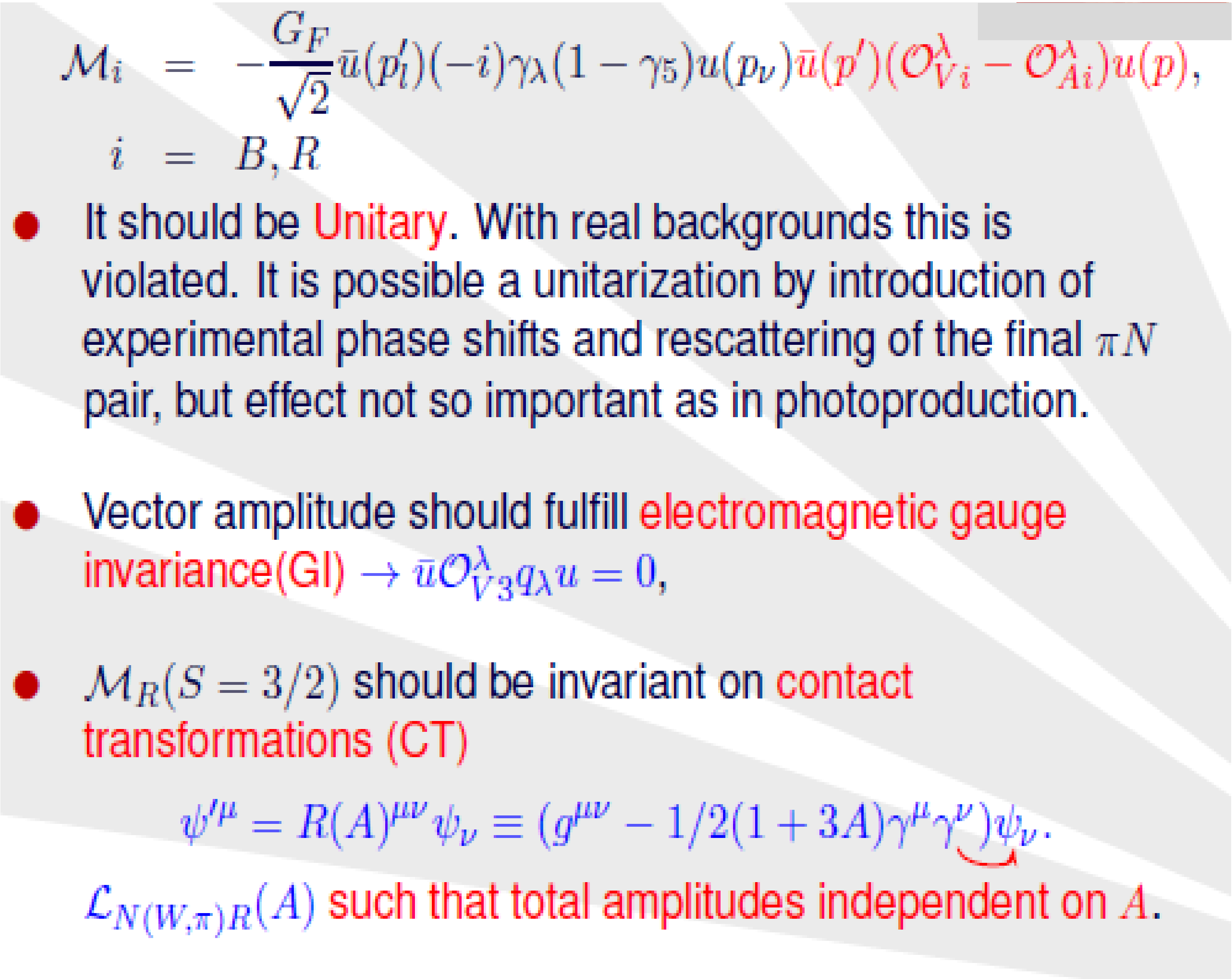
$$\sigma(E\nu^{CM}) = \frac{F^{CC/NC}}{(2\pi)^4 E_\nu^{CM}\sqrt{s}} \int_{E_l-}^{E_l^+} dE_l^{CM} \int_{E_\pi^-}^{E_\pi^+} dE_\pi^{CM} \int_{-1}^{+1} dcos\theta$$

$$\int_0^{2\pi} d\eta \frac{1}{16} \sum_{spin} |\mathcal{M}|^2 ,$$

where $E_\nu^{CM} = \frac{m_N E_\nu^{Lab}}{\sqrt{2E_\nu^{Lab} m_N + m_N^2}}$ and

$$\mathcal{M} = \mathcal{M}_B + \sum_R \mathcal{M}_R, \quad R \equiv \Delta, N^*.$$


ν
l
W,Z
N
π
Δ
ω
ρ
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)



$$\begin{aligned}\mathcal{M}_i &= -\frac{G_F}{\sqrt{2}}\bar{u}(p_l')(-i)\gamma_\lambda(1-\gamma_5)u(p_\nu)\bar{u}(p')(\mathcal{O}^\lambda_{Vi}-\mathcal{O}^\lambda_{Ai})u(p),\\ i &= B,R\end{aligned}$$

- It should be Unitary. With real backgrounds this is violated. It is possible a unitarization by introduction of experimental phase shifts and rescattering of the final πN pair, but effect not so important as in photoproduction.

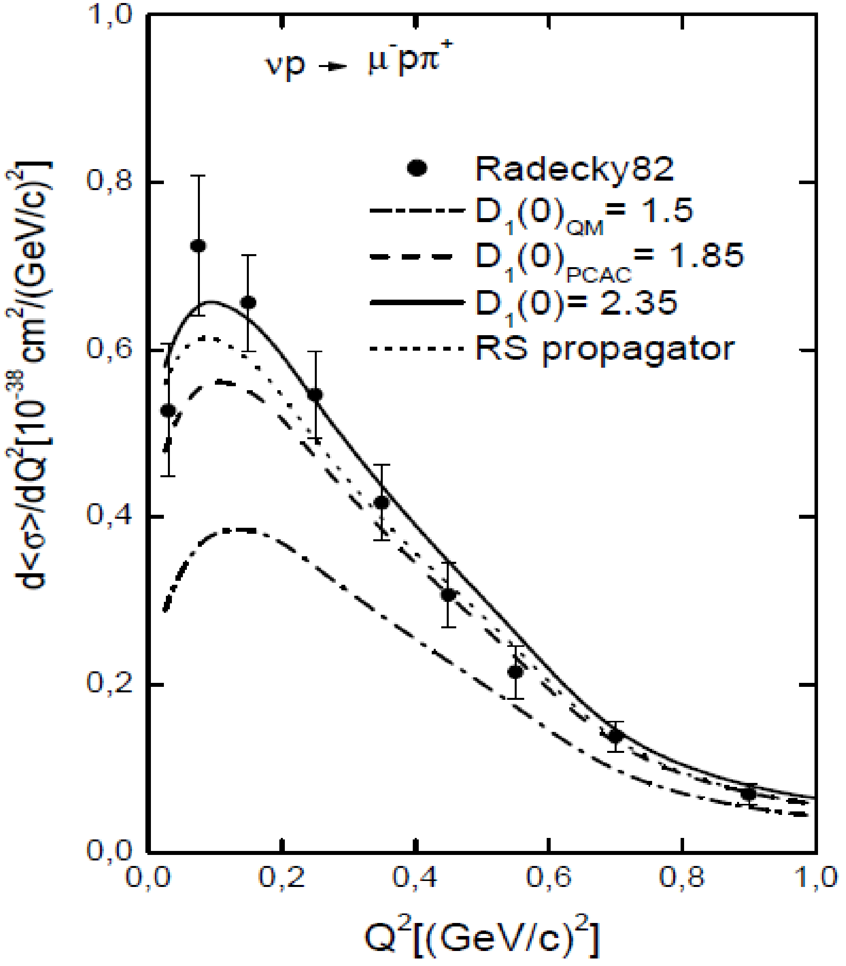
- Vector amplitude should fulfill electromagnetic gauge invariance(GI) → $\bar{u}\mathcal{O}^\lambda_{V3}q_\lambda u = 0$,

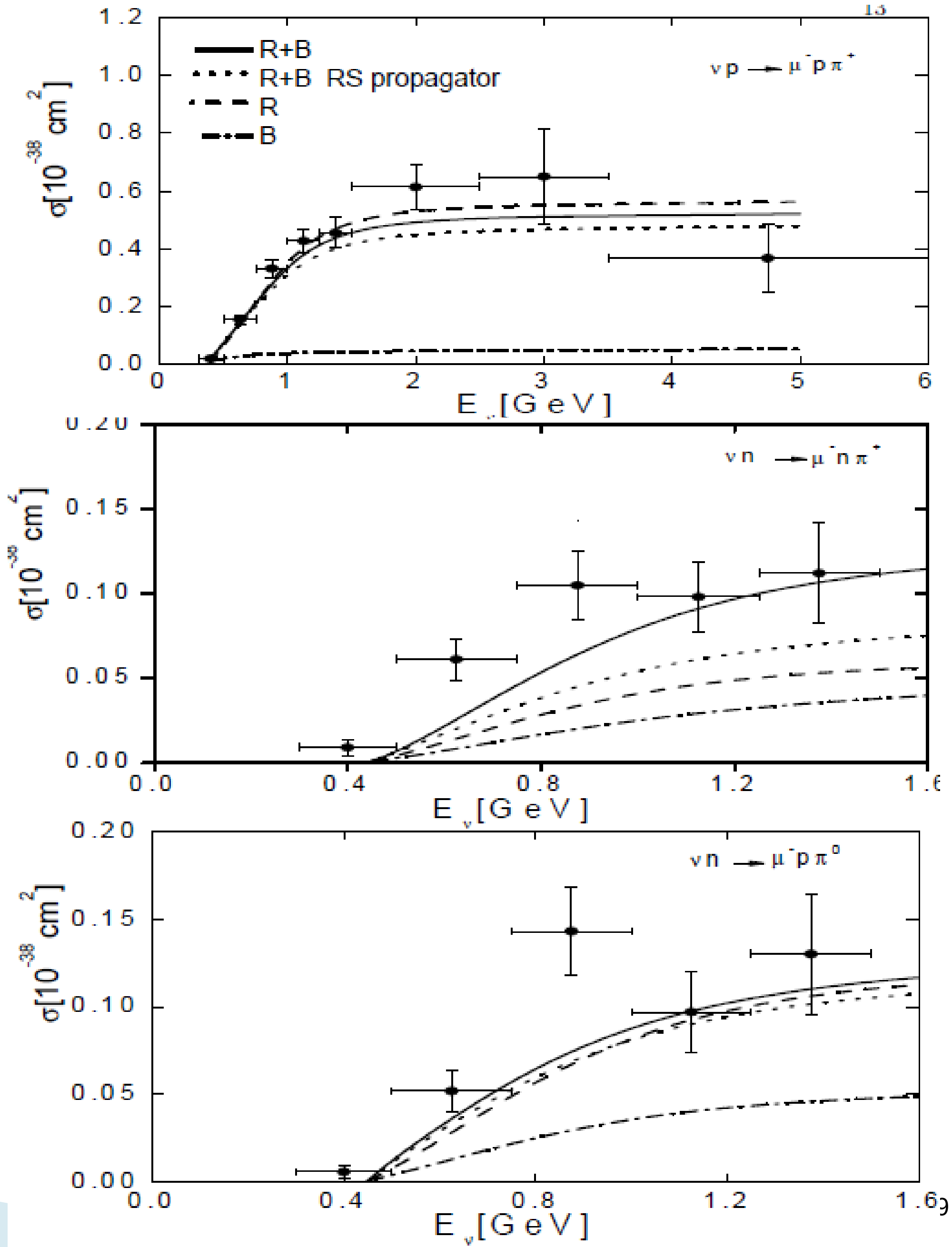
- $\mathcal{M}_R(S=3/2)$ should be invariant on contact transformations (CT)

$$\psi'^\mu = R(A)^{\mu\nu}\psi_\nu \equiv (g^{\mu\nu} - 1/2(1+3A)\gamma^\mu\gamma^\nu)\psi_\nu .$$

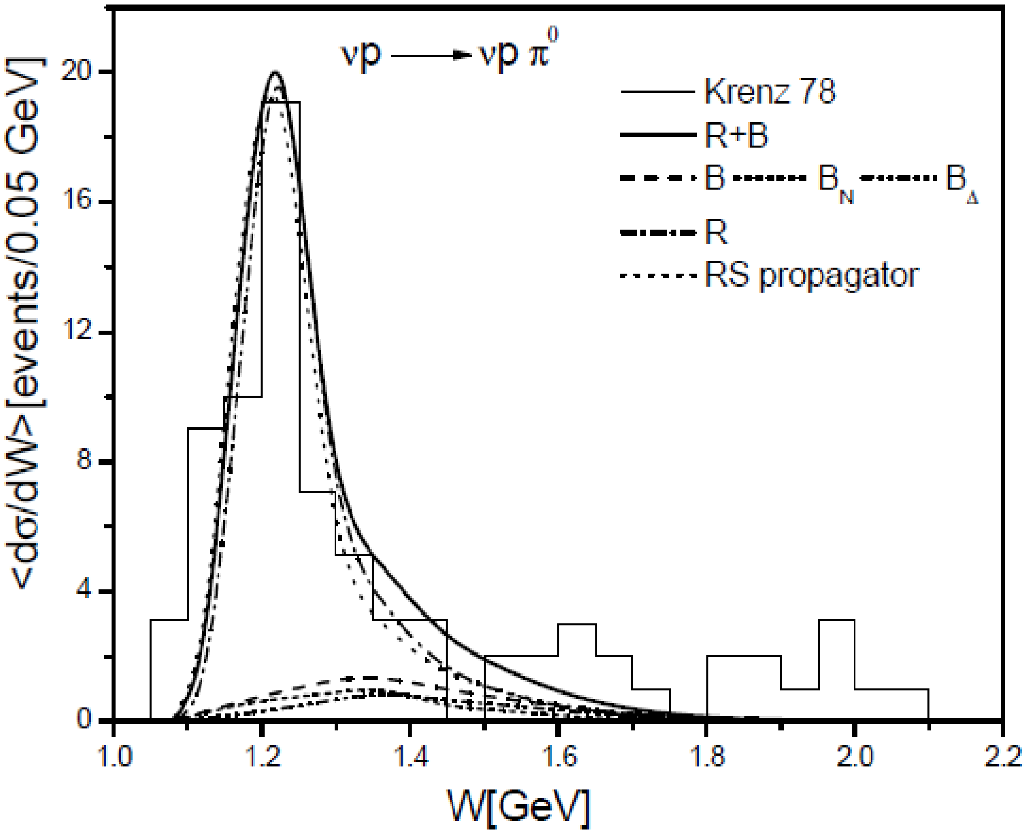
$\mathcal{L}_{N(W,\pi)R}(A)$ such that total amplitudes independent on A.

Prediction for CC

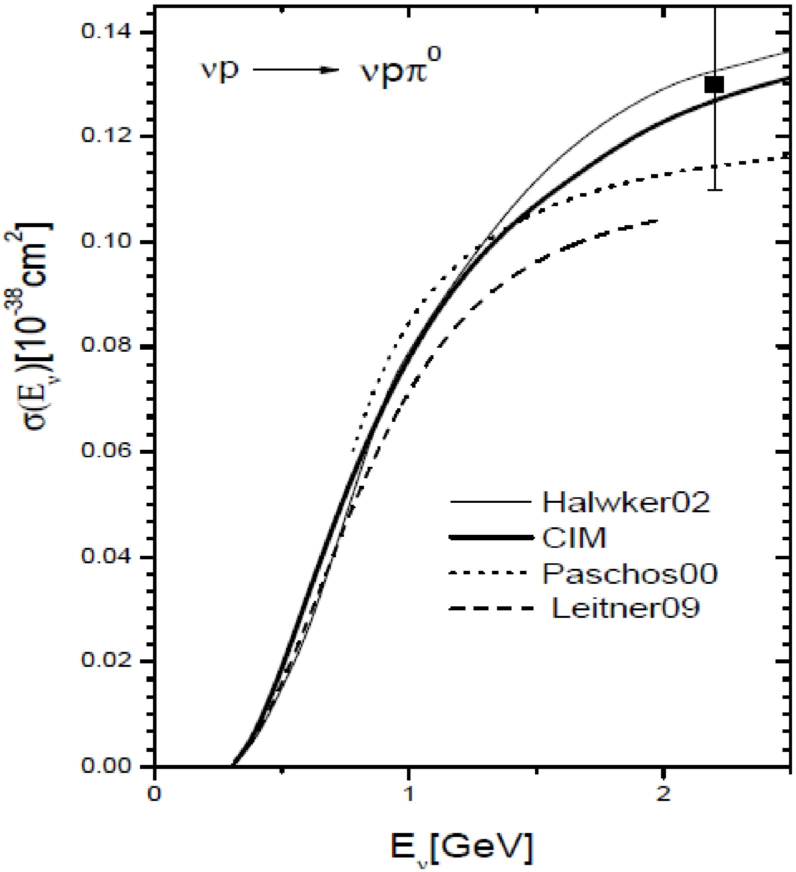




and for NC



νp → νp π^0
Krenz 78
R+B
B
B_N
B_Δ
R
RS propagator
<dσ/dW>[events/0.05 GeV]
W[GeV]
0
4
8
12
16
20
1.0
1.2
1.4
1.6
1.8
2.0
2.2



νp → νpπ^0
Halwker02
CIM
Paschos00
Leitner09
σ(E_ν)[10^-38 cm^2]
E_ν[GeV]
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0
1
2

Binding and FSI

Impulse approximation

$$d\sigma_{\nu,A} = 2d^3k\left(1-\frac{|\mathbf{k}|cos\theta_{\nu,\mathbf{k}}}{E(\boldsymbol{k}_\nu)}\right)n_A(\boldsymbol{k})\sum_m d\sigma(\nu,N_B)^{CM}$$

- Binding within the RHA of QHD I (σ,ω mesons), for N and Δ (universal coupling)

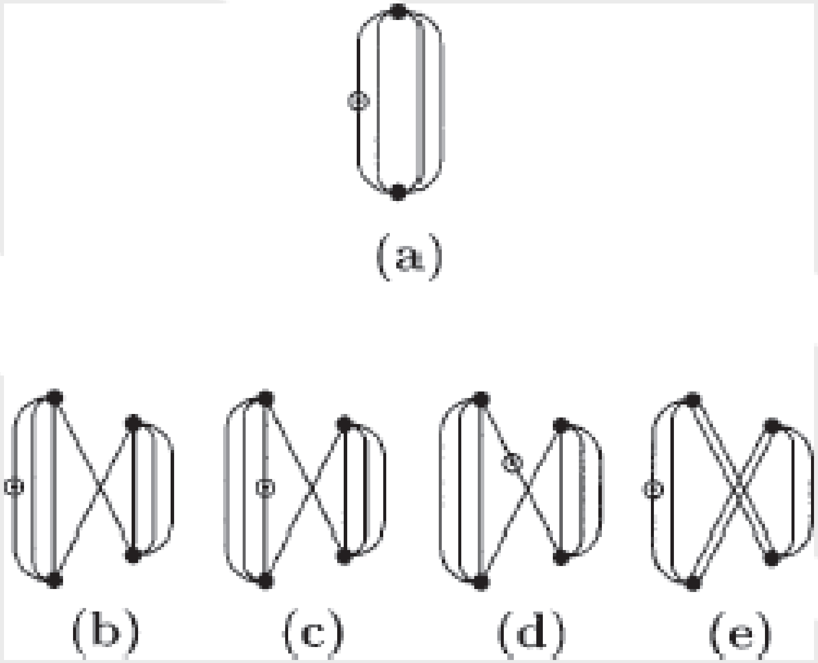
$$\psi_N(x) = \int dp^3\sum_{m_s m_t}\sqrt{\frac{m_N^*}{(2\pi)^3E^*(\mathrm{p})}}\left[u(\mathrm{p}m_s m_t)a_{\mathbf{p}m_s m_t}e^{ip\cdot x}+b^\dagger_{\mathbf{p}m_s m_t}v(\mathrm{p}m_s m_t)e^{-ip\cdot x}\right]$$

$$p_0 = C_V^2\frac{\rho_B}{m_N^2}+E^*(\mathbf{p})\equiv\Sigma_0^V(C_V)+E^*(\mathbf{p}),$$

$$E^*(\mathbf{p})=\sqrt{\mathbf{p}^2+m_N^{*2}},\ m_N^*\equiv m_N+\Sigma^S(C_S,m_N^*)$$

- GSC (2p2h+4p4h) in ground state, through perturbation theory in nuclear matter

$$n^{m_t}(\mathrm{p}) \quad = \quad \frac{3N^{m_t}}{4\pi \mathrm{p}_F^3}\left[\theta(1-\mathrm{p}) + \delta n^{(2)}(\mathrm{p}) + \delta n^{(4C)}(\mathrm{p})\right],$$



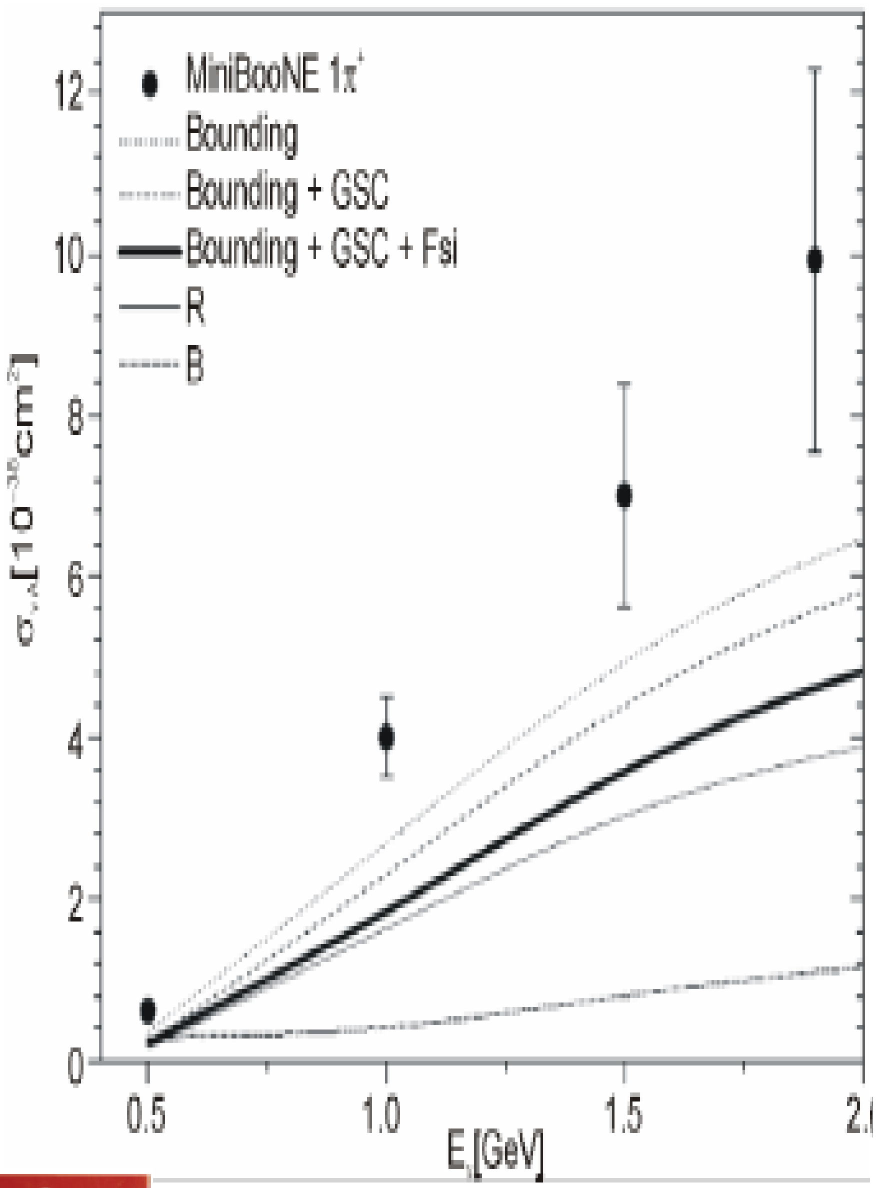
FSI on nucleons is taken (Toy model !) through the used effective fields within the RHA also for final N. While for pions we use the Eikonal approach in its simplest version, that is $\phi_\pi \to \phi^*_\pi$, where

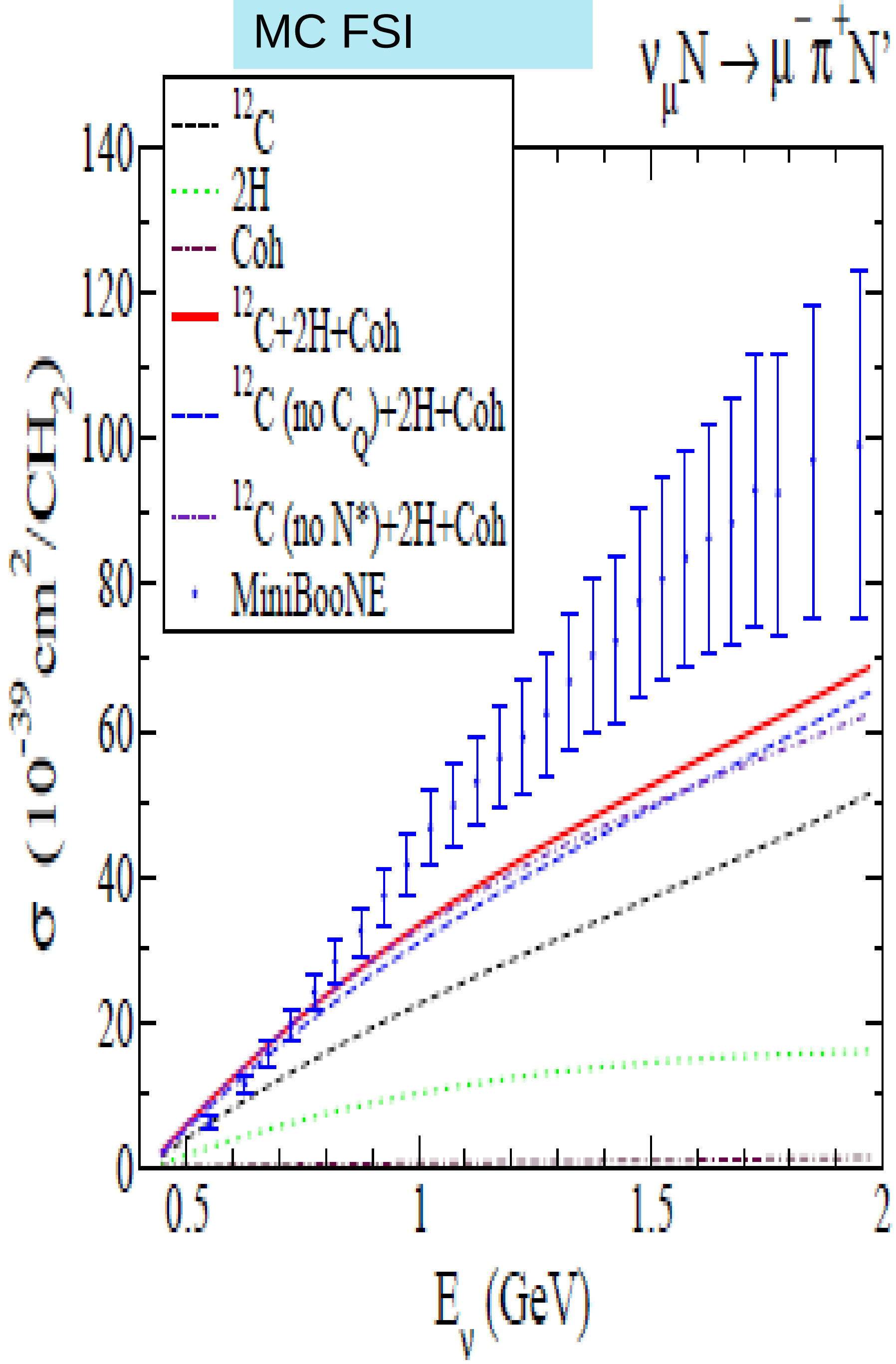
$$\phi^*_\pi(\mathbf{r}) \sim e^{-i\mathbf{p}_\pi\cdot\mathbf{r}} e^{-i/v_\pi \int_{z_\pi}^{\infty} V_{opt}(\mathbf{b},\mathbf{z}')d\mathbf{z}'}, \mathbf{r} = (\mathbf{b}, \mathbf{z}'),$$

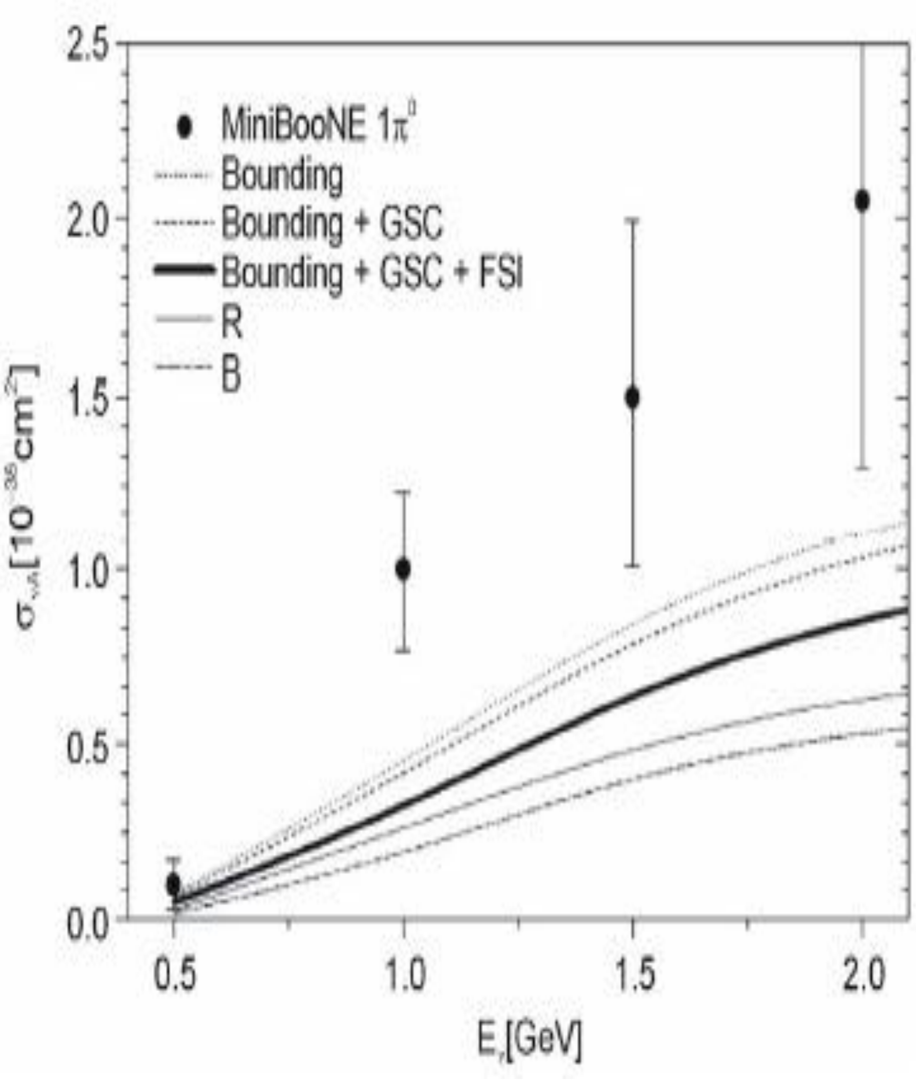
Assuming a mean distance of trip for π in nucleus, constant nucleon density and the Δ-h model for the π-optical potential we get

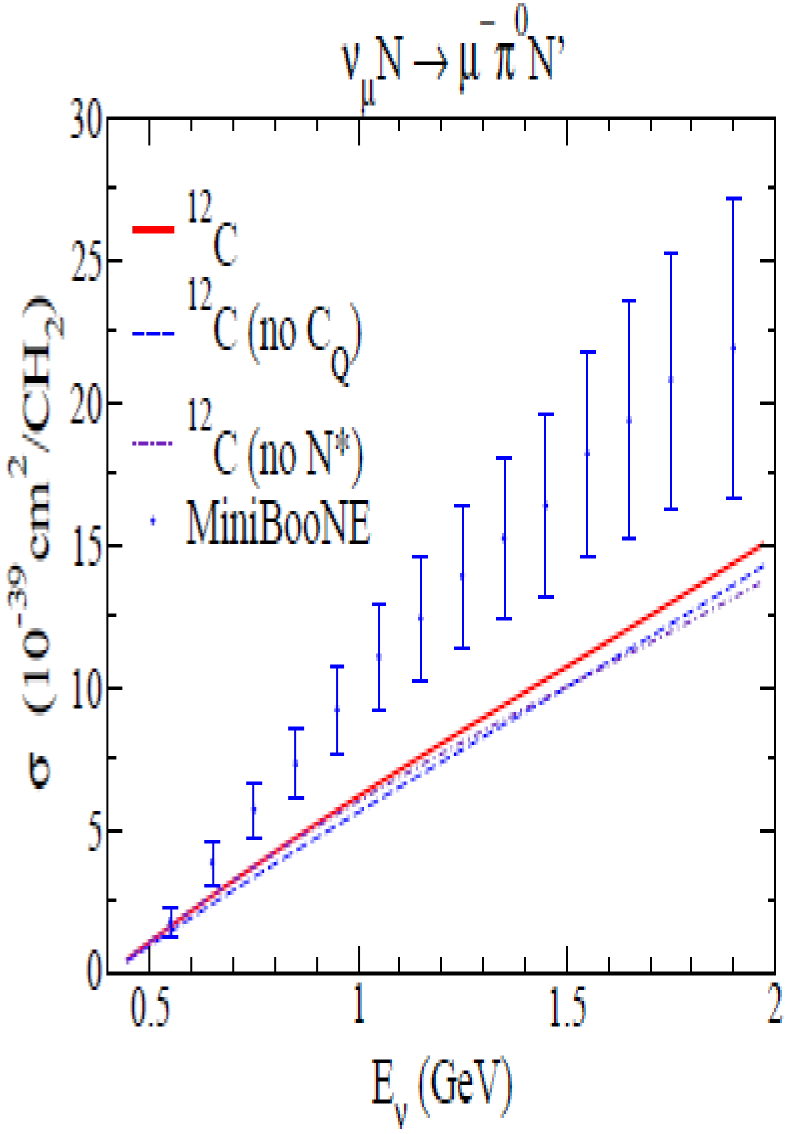
$$\begin{aligned}
\phi^*_\pi(\mathbf{r}) &\sim e^{-i\mathbf{p}_\pi\cdot\mathbf{r}} e^{-i\lambda(s)|\mathbf{p}_\pi|<d>}, \\
\lambda(s) &= \frac{2}{9}\left(\frac{f_{\pi N\Delta}}{m_\pi}\right)^2 \frac{m_N^2 \rho_0 T}{s(\sqrt{s} - m^*_\Delta + 1/2\Gamma^*_\Delta)}, \\
< d > &= \sqrt{R^2 - 2/3 < r >^2},\ \ R = r_0 A^{1/3}, < r >= cA^{1/3}.
\end{aligned}$$

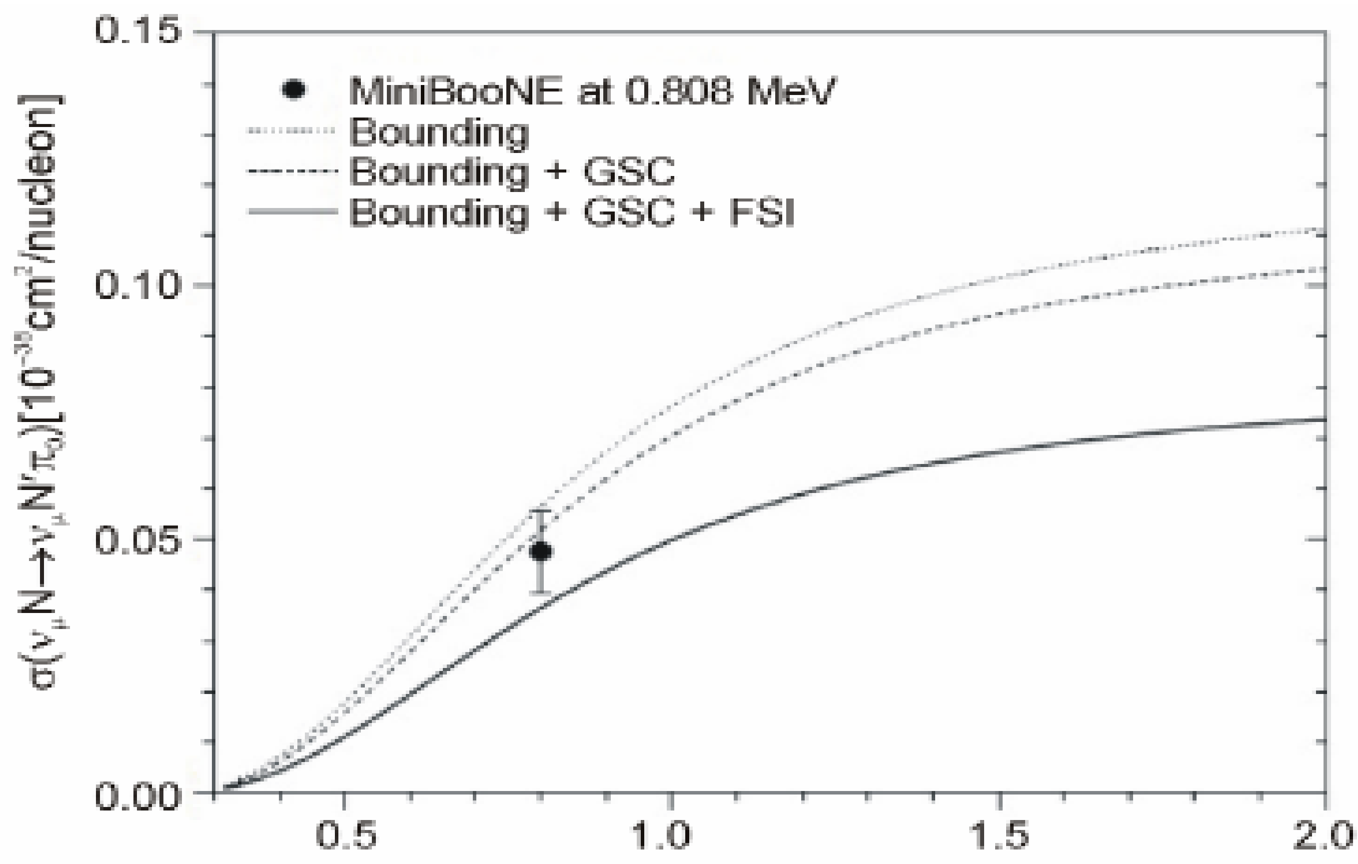
MC FSI


MiniBooNE 1π+
Bounding
Bounding + GSC
Bounding + GSC + Fsi
R
B
σ_{1π}[10^{-38}cm^2]
0
2
4
6
8
10
12
0.5
1.0
1.5
2.(
E_ν[GeV]

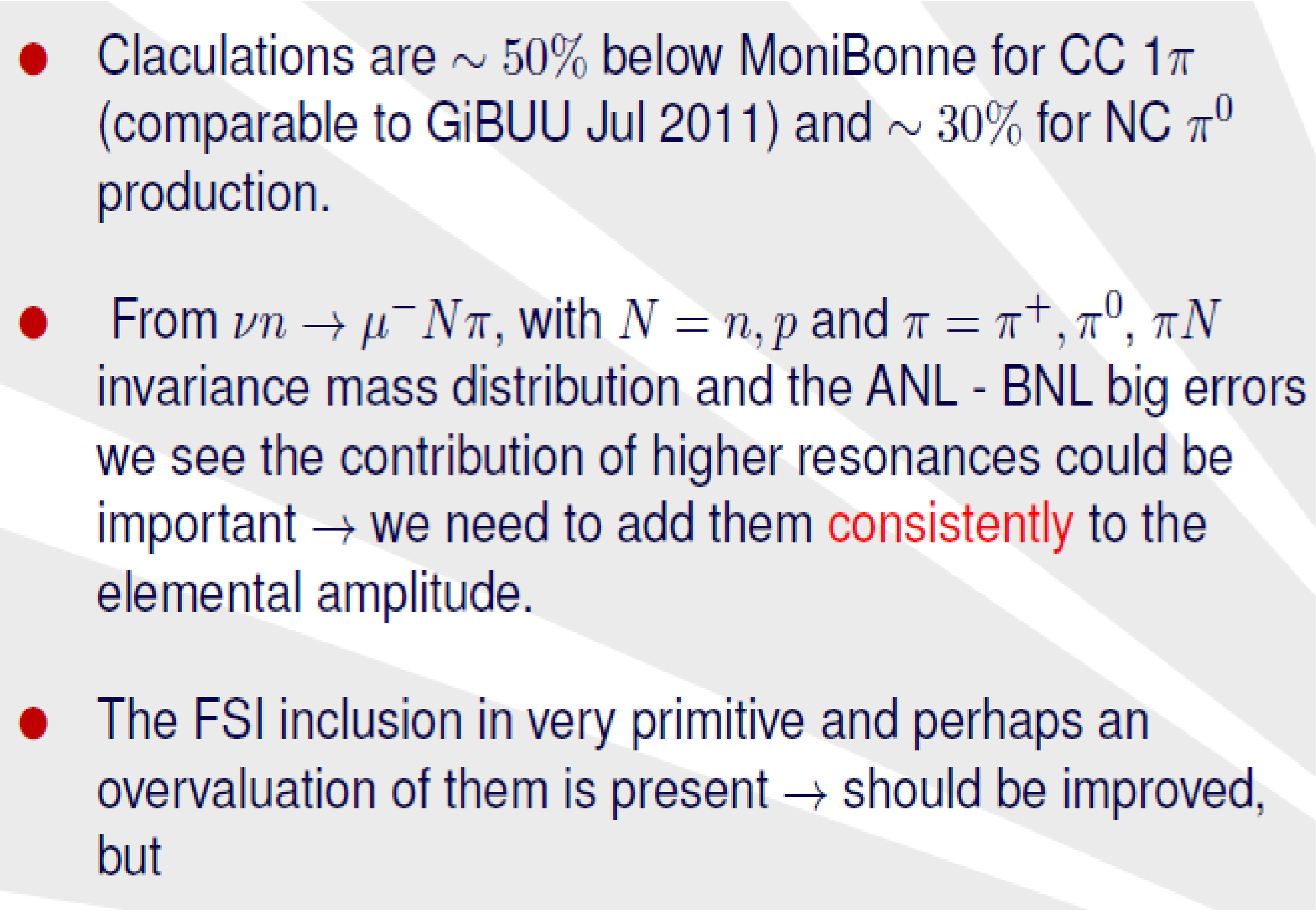

$\nu_\mu N \rightarrow \mu^- \pi^+ N'$
^{12}C
2H
Coh
^{12}C+2H+Coh
^{12}C (no C_Q)+2H+Coh
^{12}C (no N*)+2H+Coh
MiniBooNE
σ (10^{-39} cm^2/CH_2)
0
20
40
60
80
100
120
140
0.5
1
1.5
2
E_ν (GeV)


MiniBooNE $1\pi^0$
Bounding
Bounding + GSC
Bounding + GSC + FSI
R
B
$\sigma_{\nu A}[10^{-38}\mathrm{cm}^2]$
2.5
2.0
1.5
1.0
0.5
0.0
0.5
1.0
1.5
2.0
E_ν[GeV]

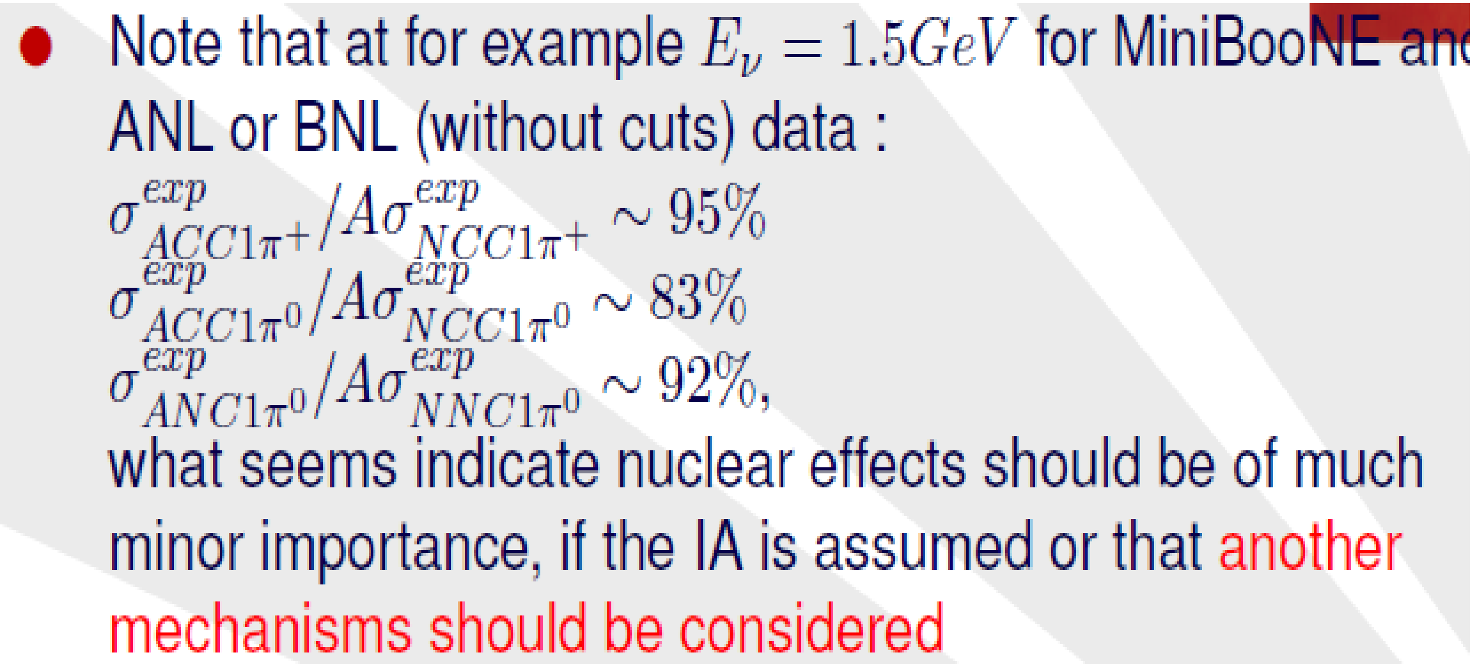

$\nu_\mu N \rightarrow \mu^- \pi^0 N'$
^{12}C
^{12}C (no C_Q)
^{12}C (no N*)
MiniBooNE
σ (10^{-39} cm^2/CH$_2$)
30
25
20
15
10
5
0
0.5
1
1.5
2
E_ν (GeV)


0.15
0.10
0.05
0.00
0.5
1.0
1.5
2.0
$\sigma(\nu_\mu N \rightarrow \nu_\mu N' \pi_0)[10^{-38}cm^2/nucleon]$
● MiniBooNE at 0.808 MeV
Bounding
Bounding + GSC
Bounding + GSC + FSI

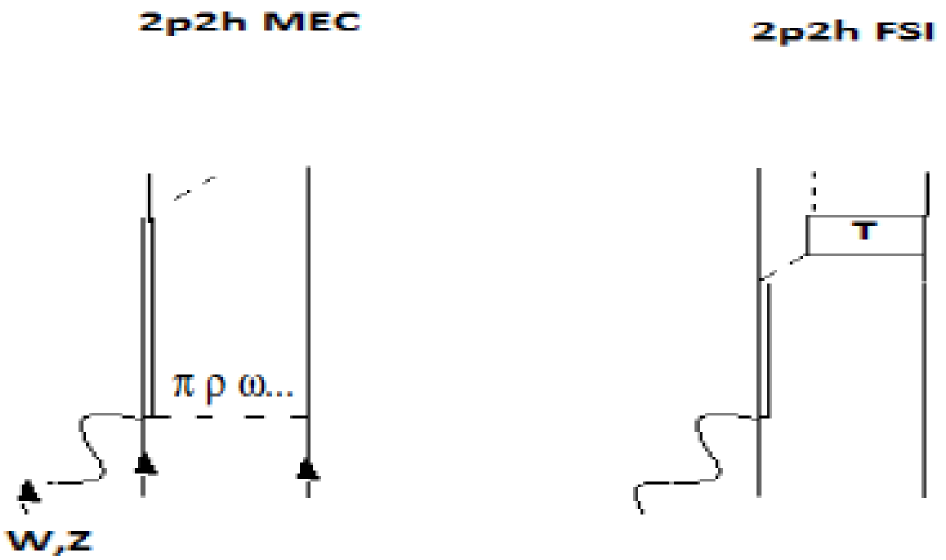
Conclusions



- Claculations are $\sim 50\%$ below MoniBonne for CC 1π (comparable to GiBUU Jul 2011) and $\sim 30\%$ for NC π^0 production.
- From $\nu n \to \mu^- N\pi$, with $N = n, p$ and $\pi = \pi^+, \pi^0$, πN invariance mass distribution and the ANL - BNL big errors we see the contribution of higher resonances could be important → we need to add them consistently to the elemental amplitude.
- The FSI inclusion in very primitive and perhaps an overvaluation of them is present → should be improved, but

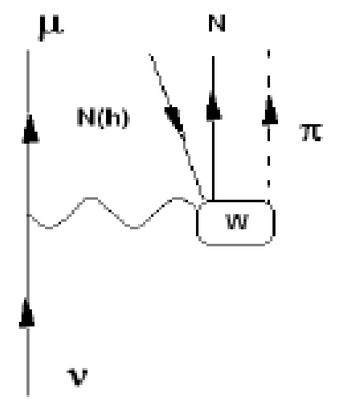


- Note that at for example $E_\nu = 1.5 GeV$ for MiniBooNE an
ANL or BNL (without cuts) data :
$\sigma^{exp}_{ACC1\pi^+}/A\sigma^{exp}_{NCC1\pi^+} \sim 95\%$
$\sigma^{exp}_{ACC1\pi^0}/A\sigma^{exp}_{NCC1\pi^0} \sim 83\%$
$\sigma^{exp}_{ANC1\pi^0}/A\sigma^{exp}_{NNC1\pi^0} \sim 92\%,$
what seems indicate nuclear effects should be of much minor importance, if the IA is assumed or that another mechanisms should be considered



That is

Until now we have included



but also we should include