Nucleon emision off nuclei induced by neutrino interactions

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NuFact09
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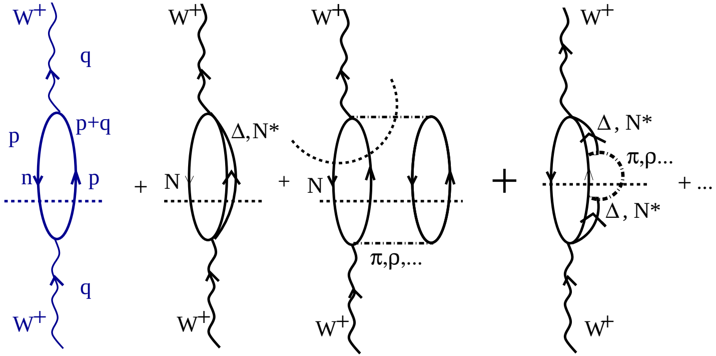
Main Nuclear Effects

- Pauli blocking: Fermi Gas
- Fermi motion: Fermi Gas
- Correlations in excited states: RPA
- Nucleon binding: Nucleon spectral functions (hole states)
- Final State Interactions: Nucleon spectral functions (particle states)
- Nucleon rescattering: Monte Carlo propagation

Self-energy of the Gauge Boson



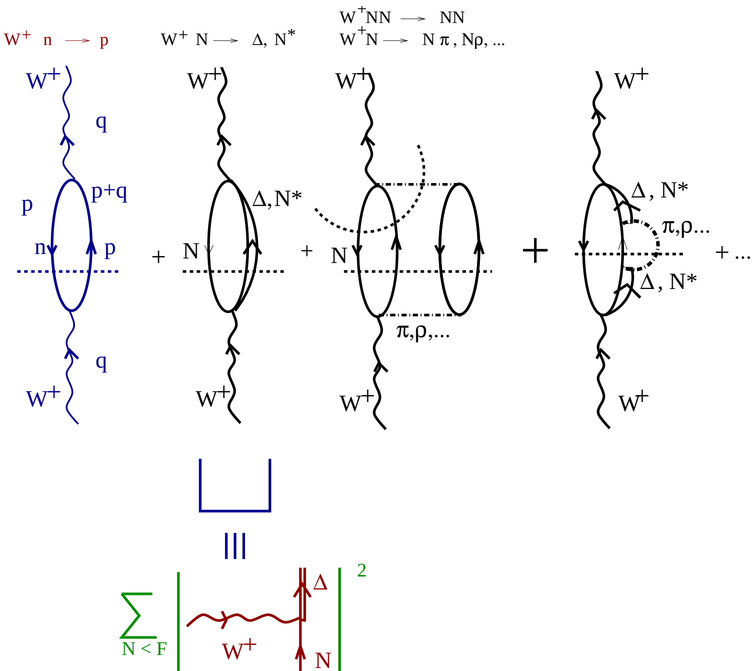
Many Body expansion of

$\boxed{\Pi^{\nu\rho}_{W,Z^0,\gamma}(q,\rho)}$

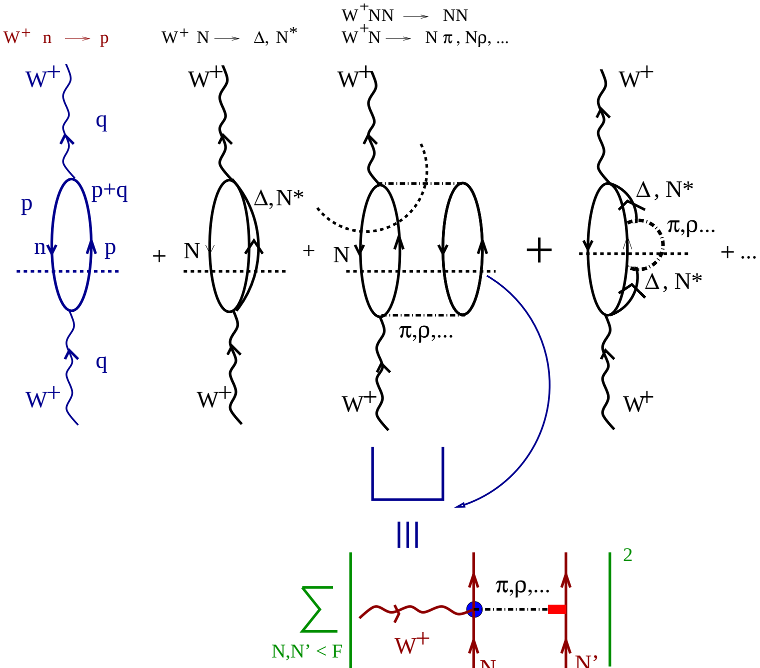
Absorption by **one Nucleon**, 2N,. . .

Real and virtual meson (π, ρ, $\cdots$) productio

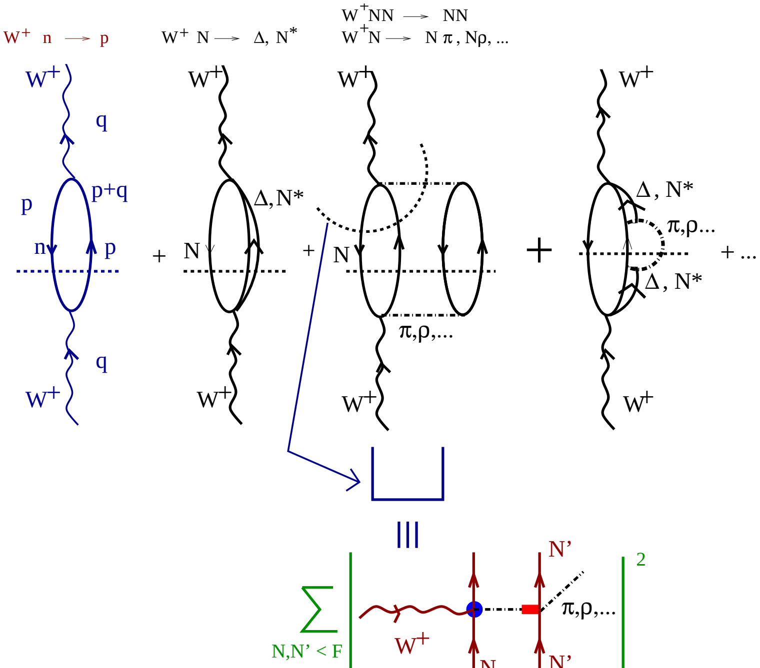
Excitation of Δ or higher resonances



W+ n → p
W+ N → Δ, N*
W+NN → NN
W+N → N π , Nρ, ...
W+
q
p+q
p
n
p
+
Δ,N*
N
+
N
π,ρ,...
+
Δ , N*
π,ρ...
Δ , N*
+ ...
Σ
N < F
Δ
W+
N
2



$W^+ n \longrightarrow p$
$W^+ N \longrightarrow \Delta, N^*$
$W^+NN \longrightarrow NN$
$W^+N \longrightarrow N\pi, N\rho, \ldots$
W+
q
p
p+q
n
p
q
W+
+
N
Δ,N*
+
N
π,ρ,...
+
Δ, N*
π,ρ...
Δ, N*
+ ...
$\sum_{N,N'<F}$
π,ρ,...
W+
N
N'
2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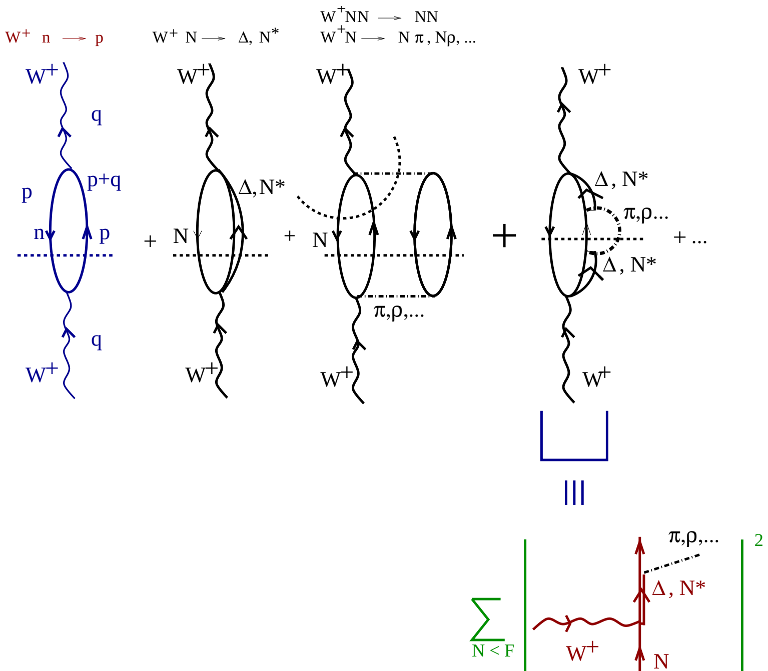
W^+
q
p
p+q
n
p
+
N
Δ,N*
+
N
π,ρ,...
+
Δ , N*
π,ρ...
Δ , N*
+ ...
|||
$\sum_{N,N' < F}$
N'
π,ρ,...
W^+
N
N'
2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W+
q
p
p+q
n
p
W+
Δ,N*
N
+
π,ρ,...
+
Δ, N*
π,ρ...
Δ, N*
+ ...
π,ρ,...
2
Δ, N*
N < F
N

Main features of the model

We work in nuclear matter and get results via LDA

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We work in nuclear matter and get results via LDA
but include whole range of nuclear corrections

- Long (RPA) and short range correlations
- $\Delta(1232)$ degrees of freedom
- Final State Interactions (FSI)
- Nucleon Rescattering (Semi-inclusive Observables)

J. Nieves, J.E. Amaro, M. Valverde, Phys. Rev. C

J. Nieves, M. Valverde, M. J. Vicente Vacas Phys. Rev. C

The Impulse Approximation

General expresion for the cross section

$$d\sigma \sim L^{\mu\nu} W_{\mu\nu}$$

All nuclear physics is on the hadronic tensor

$$\int d^4p^\mu \underbrace{S_h(p^0, \mathbf{p}) S_p(p^0 + q^0, \mathbf{p} + \mathbf{q})}_{\text{NuclearPhysics}} \underbrace{A^{\mu\nu}(p, q)}_{\text{Vertexinteraction}}$$

In Fermi Gas approximation:

$$\int \frac{d^3\mathbf{p}}{2\pi^3} \frac{M}{E_{\mathbf{p}+\mathbf{q}}} \frac{M}{E_{\mathbf{p}}} \Theta\left(k_F(\mathbf{r}) - |\mathbf{p}|\right) \Theta\left(|\mathbf{p}| - k_F(\mathbf{r})\right) \delta\left(q^0 + E_{\mathbf{p}} - E_{\mathbf{p}+\mathbf{q}}\right)$$

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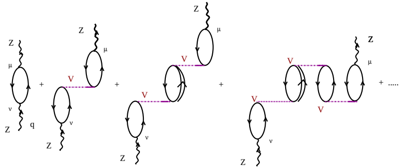
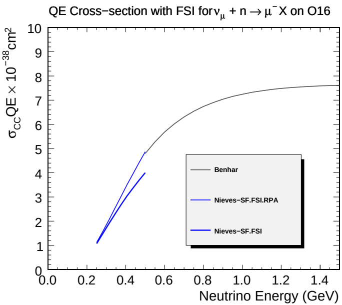
In Fermi Gas approximation:

$$\int d^3\mathbf{r} \int \frac{d^3\mathbf{p}}{2\pi^3} \frac{M}{E_\mathbf{p}} \Theta\left(k_F\left(r\right) - |\mathbf{p}|\right) \frac{M}{E_{\mathbf{p}+\mathbf{q}}} \Theta\left(|\mathbf{p}| - k_F(r)\right) \delta\left(q^0 + E_\mathbf{p} - E_{\mathbf{p}+\mathbf{q}}\right)$$

RPA Response

ph excitation $\longrightarrow$ series of *ph* and Δh excitations.

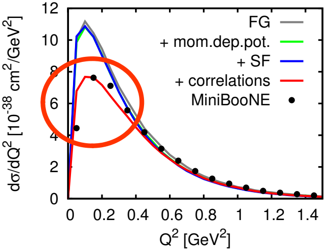


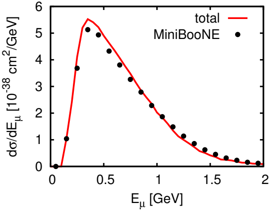


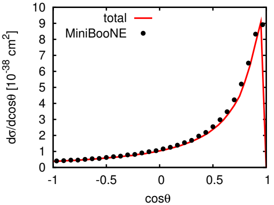
Thanks to S. Dytman and S. Boyd for the plot

MiniBooNE observables

- CCQE (like)
  - full GiBUU in-med mod. + FSI
  - M_A = 1 GeV
  - no parameter tuning
  - in addition: RPA correlations by Nieves et al. PRC73 (2006)
  - compared to MiniBooNE Monte Carlo output (T. Katori)

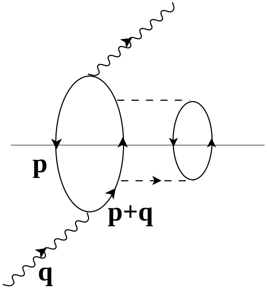






Nucleon Spectral Functions

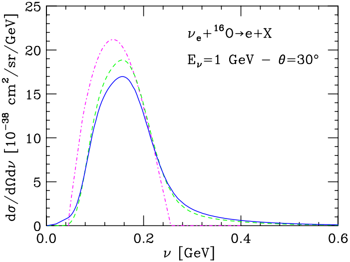
FSI dressing up the nucleon propagator in the *ph* excitation



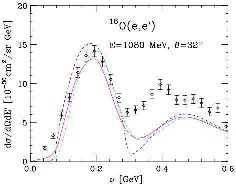
$$S_{p,h}(\omega, \mathbf{p}) = \mp \frac{1}{\pi} \frac{\mathrm{Im}\Sigma(\omega, \mathbf{p})}{\left[\omega - \frac{\mathbf{p}^2}{2M} - \mathrm{Re}\Sigma(\omega, \mathbf{p})\right]^2 + [\mathrm{Im}\Sigma(\omega, \mathbf{p})]^2}$$

- Hole Interacting particles in a Fermi Sea FS
- Particle Interaction of the ejected nucleon with the final *nuclear state*

In the limit $\Sigma \to 0$ we recover Fermi Gas



Qualitatively agreement with Benhar, Farina, Nakamura, Sakuda and Seki [PRD 72 (2005) 053005]



– RPA corrections are not included, but probably small for $|\vec{q}| \geq 500$ MeV

– Pion production and 2N channels should be included in the "dip" and Δ regions.

DWIA Vs. MC Vs. Transport model

DWIA $\rightarrow$ Complex optical potential distorts outgoing nucleon wave

- Complex potential removes all events not in a given nuclear channel
- DWIA understimates cross sections in semi-inclusive reactions
- Does NOT conserve probability (Violates Unitarity)

MC $\rightarrow$ Transport simulation through a cascade model keeps track:

- Change in energy and angle of the emitted nucleon
- Production of secondary nucleons

Transport model $\rightarrow$ Semiclassical transport equation explicitly solved

- Also allows for particle tracking
- E.g. GiBUU

The Cascade Model

- For a given leptonic part kinematics q^μ we randomly select a point in the nucleus where the boson absorption takes place according to the profile $d^5/d\Omega' dE' d^3\mathbf{r}$
- Pick a random nucleon from the local Fermi sea with given momentum $\mathbf{p}$
- Fix the kinematics imposing energy conservation $E = q^0 + \sqrt{\mathbf{p}^2 + M^2 - k_F^2(\mathbf{r})/2M}$
- Pauli Blocking effects are explicitly included

Nucleon propagation in nuclear medium

Move the nucleon through finite steps in a real potential

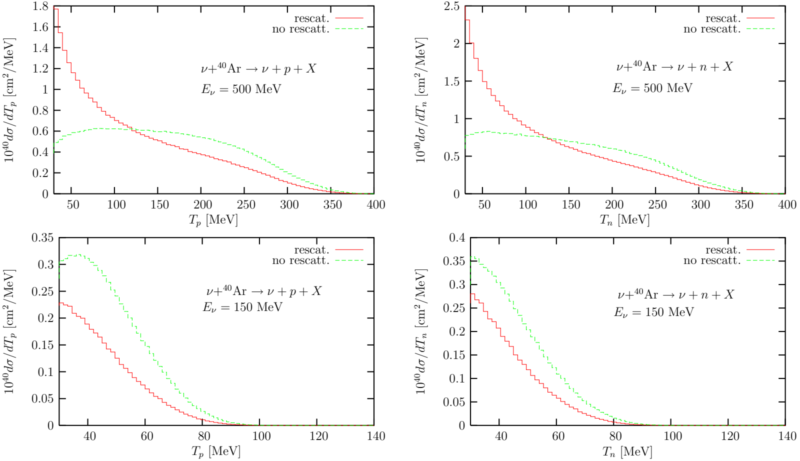
$$V(r) = -k_F(\mathbf{r})/2M$$

Consider a NN collision at every step according to NN elastic cross section and decide if a secondary nucleon is produced

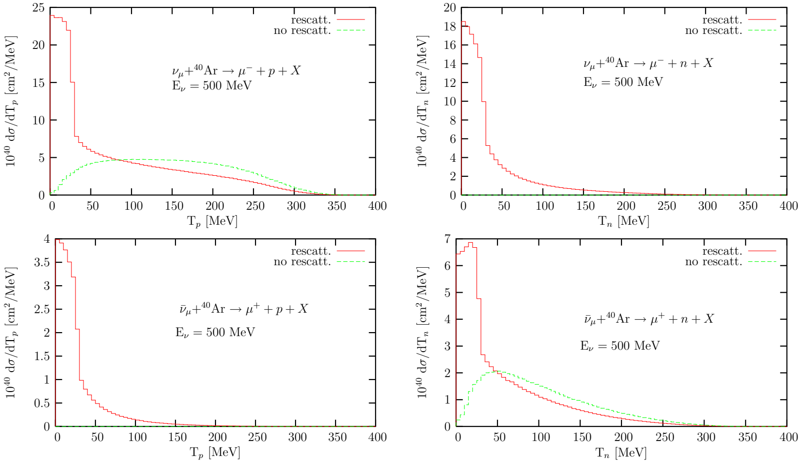
$$\hat{\sigma}^{N_1 N_2} = \int d\Omega_{CM} \frac{d\sigma^{N_1 N_2}}{d\Omega_{CM}} C_T(q,\rho) \Theta\left(\kappa - \frac{|\mathbf{p}\cdot\mathbf{p}_{CM}|}{|\mathbf{p}||\mathbf{p}_{CM}|}\right)$$

Medium renormalization and Pauli blocking effects

$^{40}Ar(\nu, \mu^- + N)$, $^{40}Ar(\bar{\nu}, \mu^+ + N)$



$^{40}Ar(\nu, \nu + N)$



rescatt.
no rescatt.
$\nu_\mu + ^{40}\mathrm{Ar} \to \mu^- + p + X$
$E_\nu = 500$ MeV
$10^{40}\ d\sigma/dT_p\ [\mathrm{cm}^2/\mathrm{MeV}]$
T_p [MeV]
rescatt.
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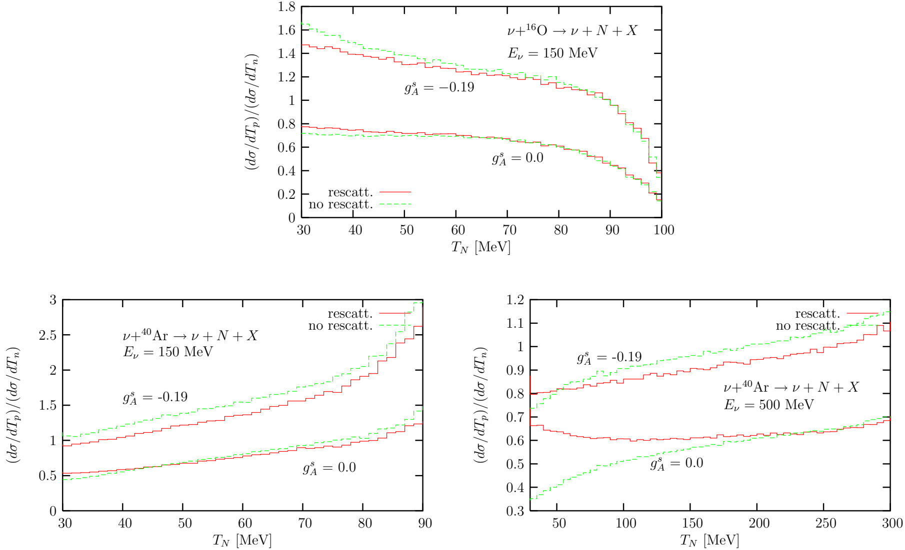
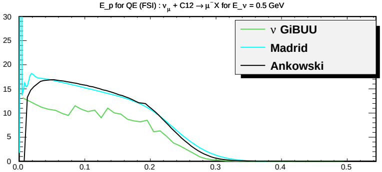
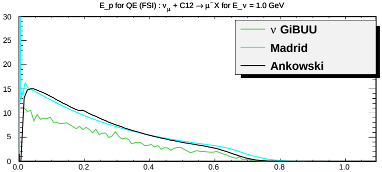
Effects on the extraction of g_A^s

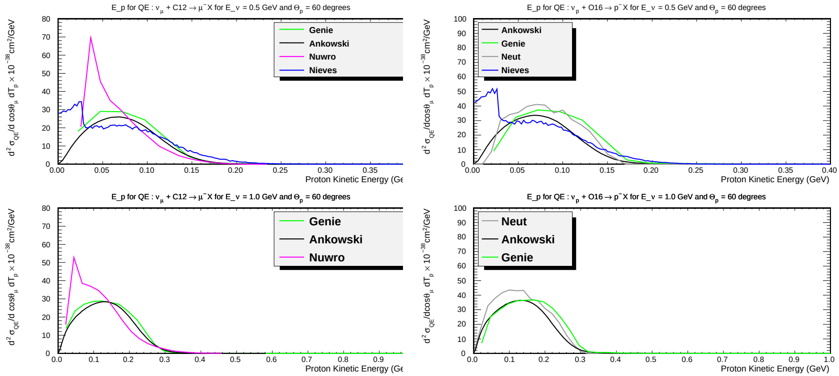


Taken from J.Sobczyk@NuInt09





- GiBUU: Transport Model
- Madrid: Proton in a realistic potential
- Ankowsky: Effective spectral functions
- Nieves: FG + RPA + FSI + Rescattering (No π effects)



E_p for QE : ν_μ + C12 → μ⁻X for E_ν = 0.5 GeV and Θ_p = 60 degrees
Genie
Ankowski
Nuwro
Nieves
Proton Kinetic Energy (GeV)
E_p for QE : ν_p + O16 → p⁻X for E_ν = 0.5 GeV and Θ_p = 60 degrees
Ankowski
Genie
Neut
Nieves
Proton Kinetic Energy (GeV)
E_p for QE : ν_μ + C12 → μ⁻X for E_ν = 1.0 GeV and Θ_p = 60 degrees
Genie
Ankowski
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E_p for QE : ν_p + O16 → p⁻X for E_ν = 1.0 GeV and Θ_p = 60 degrees
Neut
Ankowski
Genie
Proton Kinetic Energy (GeV)

Conclusions

- General qualitative agreement on which nuclear effects are relevant

  ...and how they affect cross sections
- Quantitative agreement not so good

Thanks!

Thanks to Profs. S. Boyd, S. Ditman and J. Sobczyk for permission to use their plots

and to the audience!!