Quasi-Elastic Neutrino Reactions on Carbon and Lead Nuclei

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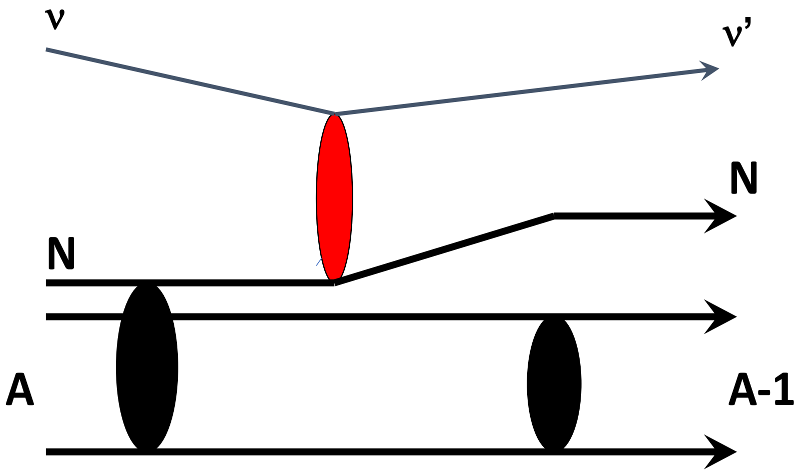
Outline

- Description of the reaction model
- Study the effects of strange quarks on the reaction
- Comparison the results of the model with data
- Prediction of the model for reaction on Lead targets

The cross section for exclusive neutrino-nucleon production is:

$$\frac{d^3\sigma}{d\Omega_\nu d\Omega_N dE_N} = \frac{G_F^2 m_N c^2 p_N c k_f^2 c^2}{8\,(2\pi)^5\,\hbar c} \times \sum_{J_B M_B M} \frac{\mathcal{S}_{J_i J_f}(J_B)}{2J_B+1} |\mathcal{L}^\alpha N_{\alpha M M_B}|^2.$$



$\mathcal{S}_{J_i J_f}(J_B)$: Spectroscopic factor

Lepton and nuclear currents are:

$$\mathcal{L}^{\alpha} = \overline{\nu}(k_f)(\gamma^{\alpha} - \gamma^{\alpha}\gamma^{5})\nu(k_i),$$

$$N_{\alpha M M_B} = \int d^3x \overline{\psi}_M\left(k_p, x\right) j_{\alpha} \psi_{J_B M_B}\left(x\right) e^{\mathbf{q}\cdot\mathbf{x}},$$

The weak current is:

$$\begin{aligned} j^{\mu} \;\; = \;\; & F_1^V(Q^2)\gamma^{\mu} + i\frac{\kappa}{2M}F_2^V(Q^2)\sigma^{\mu\nu}q_{\nu} \\ & -G_A(Q^2)\gamma^{\mu}\gamma^{5}, \end{aligned}$$

Weak isovector Dirac and Pauli form factors are:

$$F_i^{V,p(n)} = \left(\frac{1}{2} - 2\sin^2\theta_W\right) F_i^{p(n)} - \frac{1}{2}F_i^{n(p)} - \frac{1}{2}F_i^s,$$

$$i = 1, 2,$$

$\sin^2\theta_W \simeq 0.23143,$

$$F_1^s(Q^2) = \frac{(\rho^s + \mu^s)\tau}{(1+\tau)(1+Q^2/M_V^2)^2},$$

$$F_2^s(Q^2) = \frac{(\mu^s - \tau\rho^s)}{(1+\tau)(1+Q^2/M_V^2)^2}$$

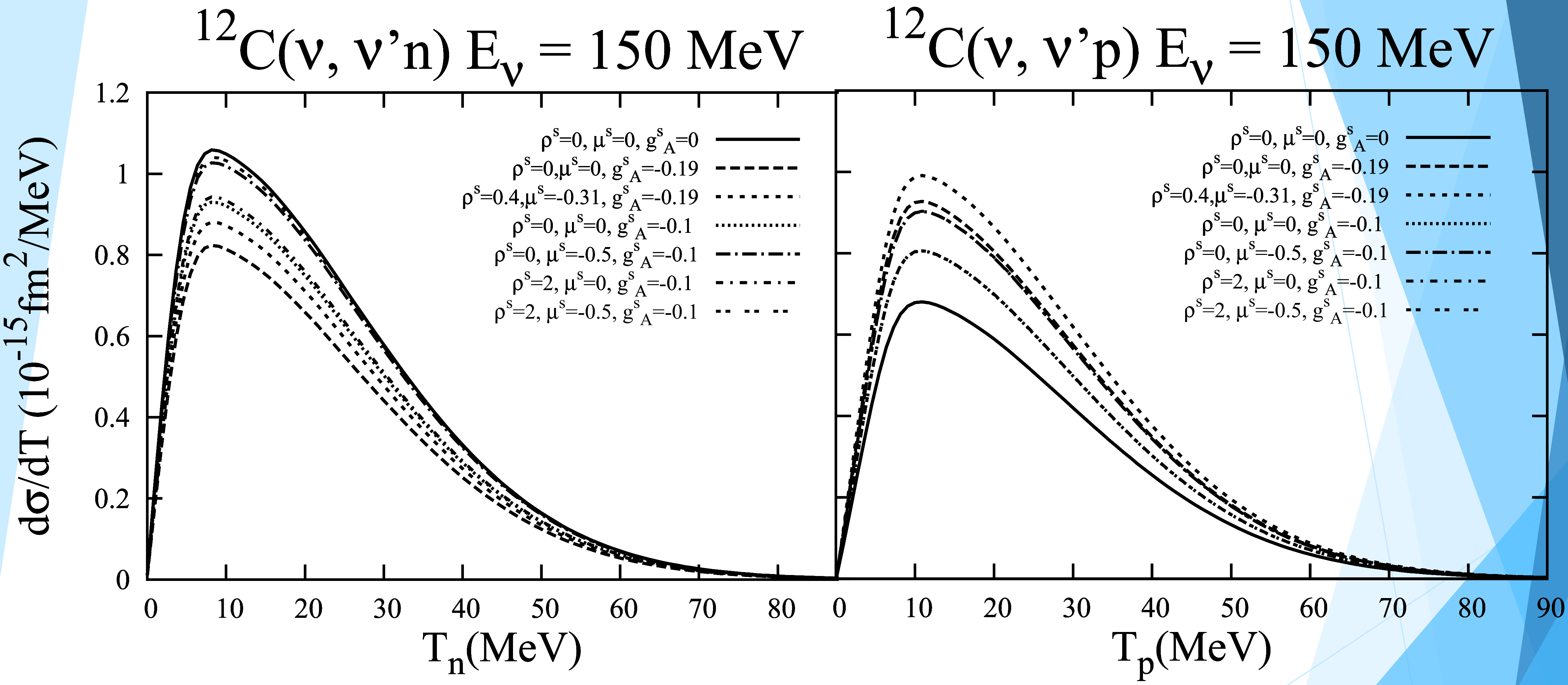
$\tau = Q^2/(4m_N^2),\ \ M_V = 0.843\ \text{GeV},$

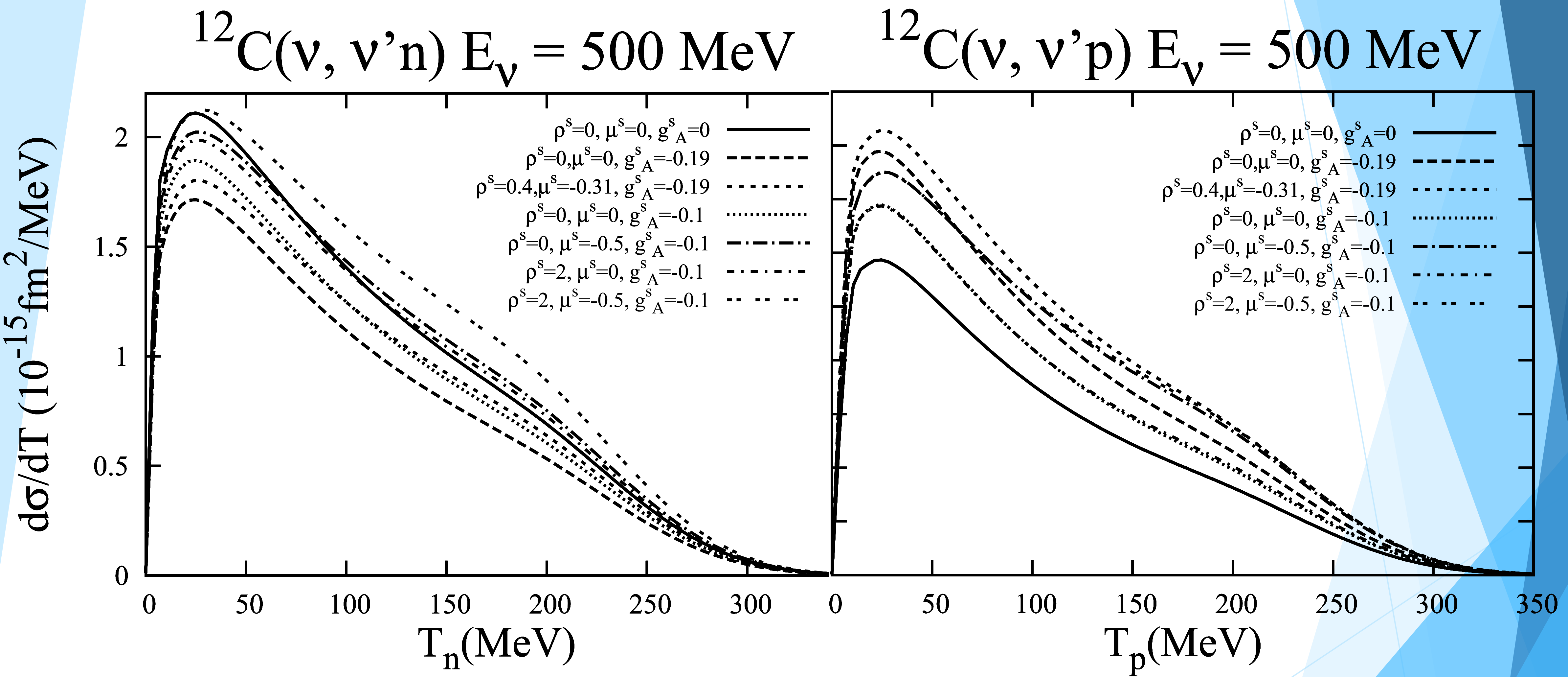
Axial form factor:

$$G_A(Q^2) = \frac{1}{2}(\tau_3 g_A - g_A^s)G(Q^2),$$

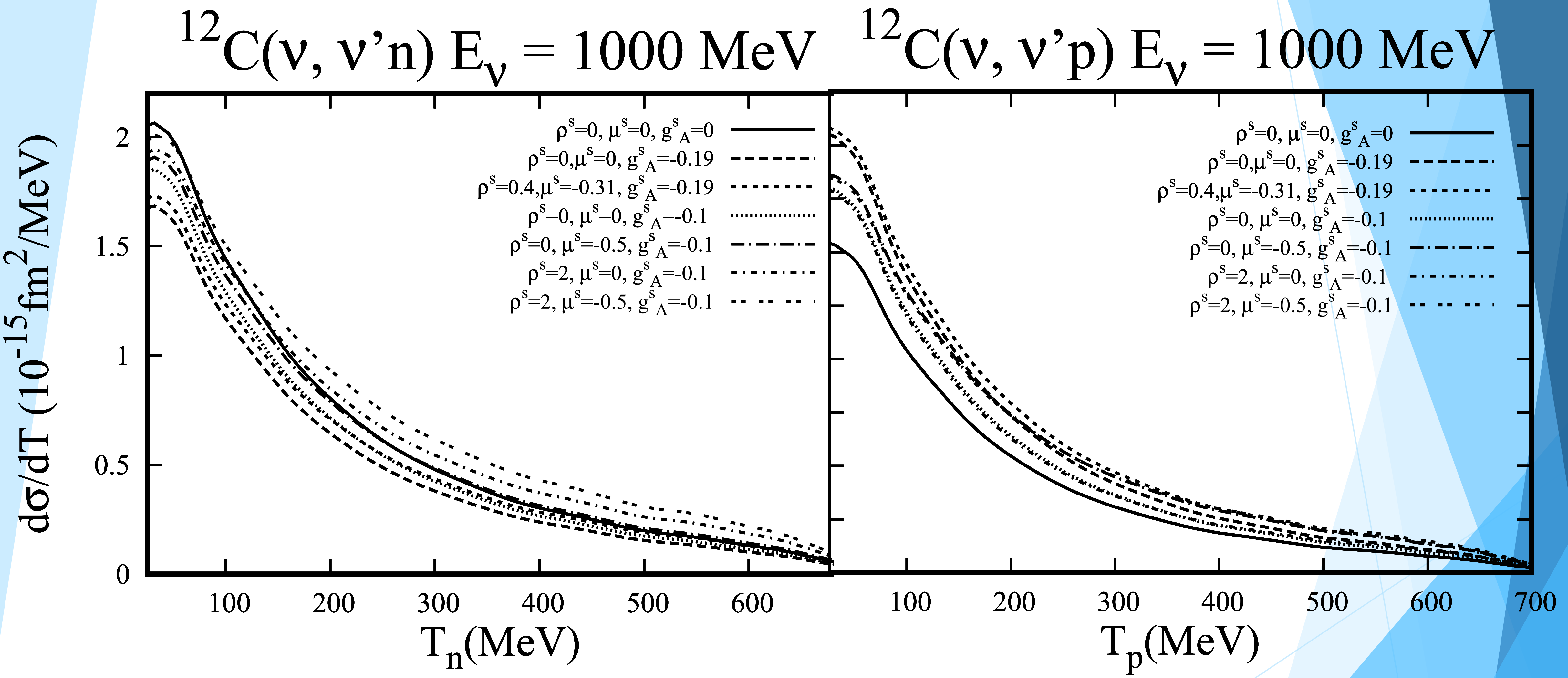
$$g_A \simeq 1.26,\ G = (1 + Q^2/M_A^2)^{-2},$$

$$M_A = (1.026 \pm 0.021)\ \text{GeV, and } \tau_3 = +1\ (-1)$$

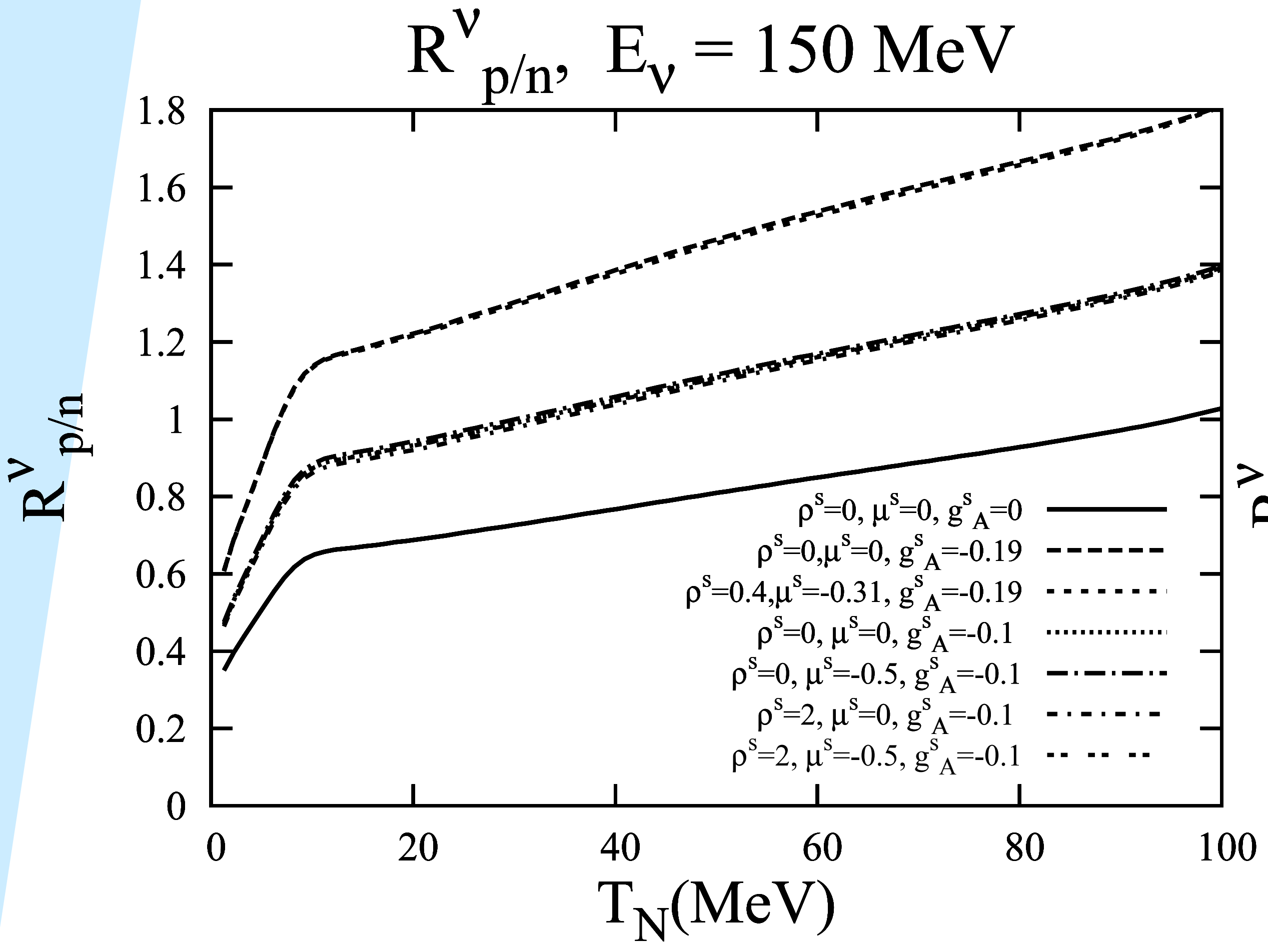

$^{12}C(\nu, \nu'n)\ E_\nu = 150$ MeV
$^{12}C(\nu, \nu'p)\ E_\nu = 150$ MeV
$d\sigma/dT\ (10^{-15} fm^2/MeV)$
$\rho^s=0,\ \mu^s=0,\ g^s_A=0$
$\rho^s=0, \mu^s=0,\ g^s_A=-0.19$
$\rho^s=0.4, \mu^s=-0.31,\ g^s_A=-0.19$
$\rho^s=0,\ \mu^s=0,\ g^s_A=-0.1$
$\rho^s=0,\ \mu^s=-0.5,\ g^s_A=-0.1$
$\rho^s=2,\ \mu^s=0,\ g^s_A=-0.1$
$\rho^s=2,\ \mu^s=-0.5,\ g^s_A=-0.1$
0
0.2
0.4
0.6
0.8
1
1.2
0 10 20 30 40 50 60 70 80
0 10 20 30 40 50 60 70 80 90
T_n(MeV)
T_p(MeV)



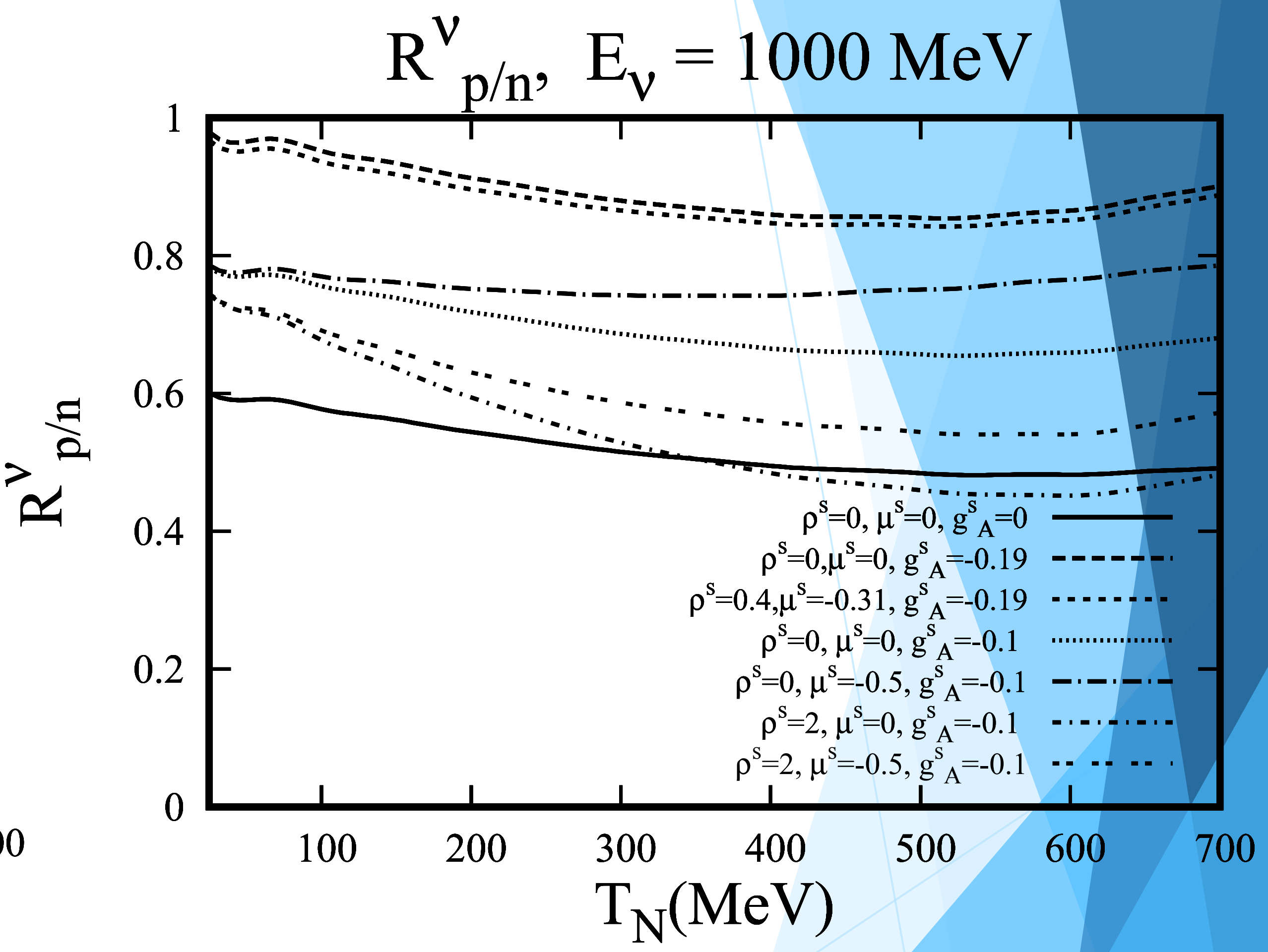
12C(ν, ν'n) Eν = 500 MeV
12C(ν, ν'p) Eν = 500 MeV
dσ/dT (10^-15 fm^2/MeV)
Tn(MeV)
Tp(MeV)
ρs=0, μs=0, gsA=0
ρs=0,μs=0, gsA=-0.19
ρs=0.4,μs=-0.31, gsA=-0.19
ρs=0, μs=0, gsA=-0.1
ρs=0, μs=-0.5, gsA=-0.1
ρs=2, μs=0, gsA=-0.1
ρs=2, μs=-0.5, gsA=-0.1
0
0.5
1
1.5
2
50
100
150
200
250
300
350



12C(ν, ν'n) Eν = 1000 MeV
12C(ν, ν'p) Eν = 1000 MeV
dσ/dT (10-15fm2/MeV)
ρs=0, μs=0, gsA=0
ρs=0,μs=0, gsA=-0.19
ρs=0.4,μs=-0.31, gsA=-0.19
ρs=0, μs=0, gsA=-0.1
ρs=0, μs=-0.5, gsA=-0.1
ρs=2, μs=0, gsA=-0.1
ρs=2, μs=-0.5, gsA=-0.1
0
0.5
1
1.5
2
100
200
300
400
500
600
700
Tn(MeV)
Tp(MeV)



R^ν p/n, E_ν = 150 MeV
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
20
40
60
80
100
T_N(MeV)
R^ν p/n
ρ^s=0, μ^s=0, g^s_A=0
ρ^s=0,μ^s=0, g^s_A=-0.19
ρ^s=0.4,μ^s=-0.31, g^s_A=-0.19
ρ^s=0, μ^s=0, g^s_A=-0.1
ρ^s=0, μ^s=-0.5, g^s_A=-0.1
ρ^s=2, μ^s=0, g^s_A=-0.1
ρ^s=2, μ^s=-0.5, g^s_A=-0.1



R^ν p/n, E_ν = 1000 MeV
1
0.8
0.6
0.4
0.2
0
100
200
300
400
500
600
700
T_N(MeV)
R^ν p/n
ρ^s=0, μ^s=0, g^s_A=0
ρ^s=0,μ^s=0, g^s_A=-0.19
ρ^s=0.4,μ^s=-0.31, g^s_A=-0.19
ρ^s=0, μ^s=0, g^s_A=-0.1
ρ^s=0, μ^s=-0.5, g^s_A=-0.1
ρ^s=2, μ^s=0, g^s_A=-0.1
ρ^s=2, μ^s=-0.5, g^s_A=-0.1

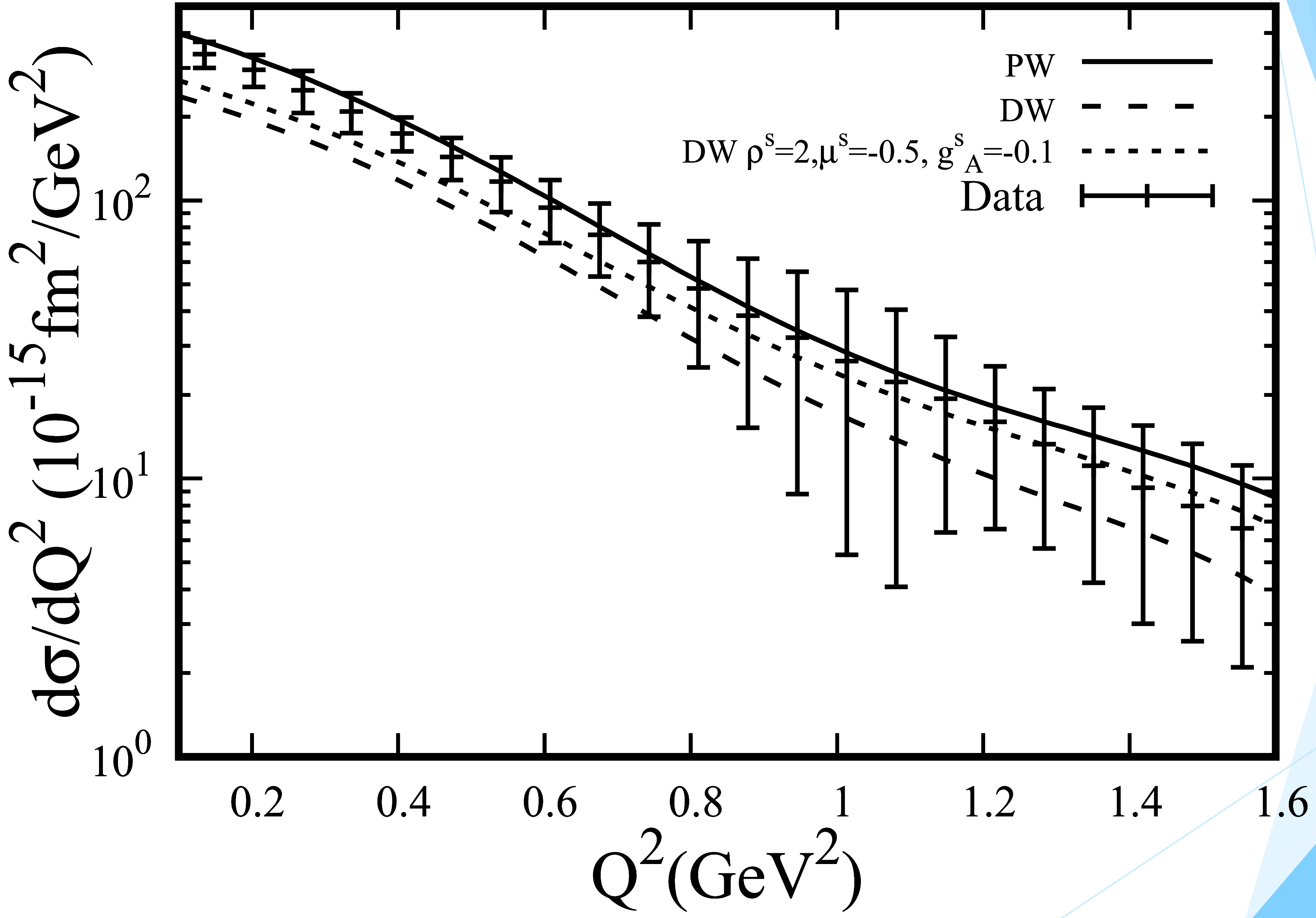
Flux-averaged cross section:

$$\left\langle \frac{d\sigma}{dQ^2} \right\rangle = \int \phi_\nu(E_\nu) \frac{d\sigma}{dQ^2}(E_\nu) \; dE_\nu,$$

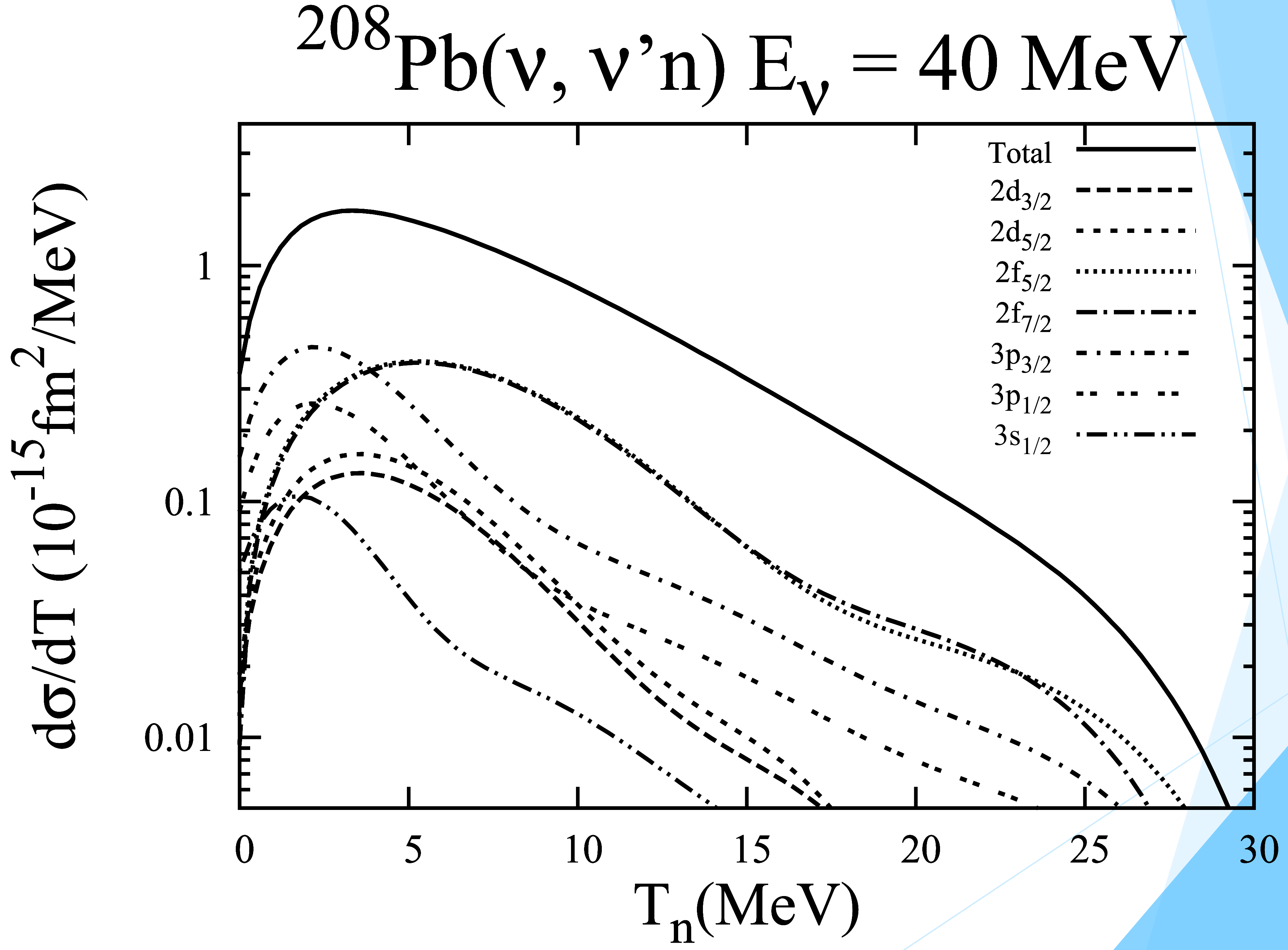
$Q^2 = 2m_N T_N$, $\phi_\nu(E_\nu)$: normalized neutrino flux

$$\frac{d\sigma_{\nu N \to \nu N}}{dQ^2} = \frac{1}{7} C_{\nu p,H} \frac{d\sigma_{\nu p \to \nu p,H}}{dQ^2} + \frac{3}{7} C_{\nu p,C} \frac{d\sigma_{\nu p \to \nu p,C}}{dQ^2} + \frac{3}{7} C_{\nu n,C} \frac{d\sigma_{\nu n \to \nu n,C}}{dQ^2},$$

(νN, ν'N) Reaction



A. A. Aguilar-Arevalo et al (MiniBooNE Collaboration), Phys. Rev. D 82 (2010)



208Pb(ν, ν'n) Eν = 40 MeV
Total
2d3/2
2d5/2
2f5/2
2f7/2
3p3/2
3p1/2
3s1/2
1
0.1
0.01
0
5
10
15
20
25
30
dσ/dT (10-15fm2/MeV)
Tn(MeV)

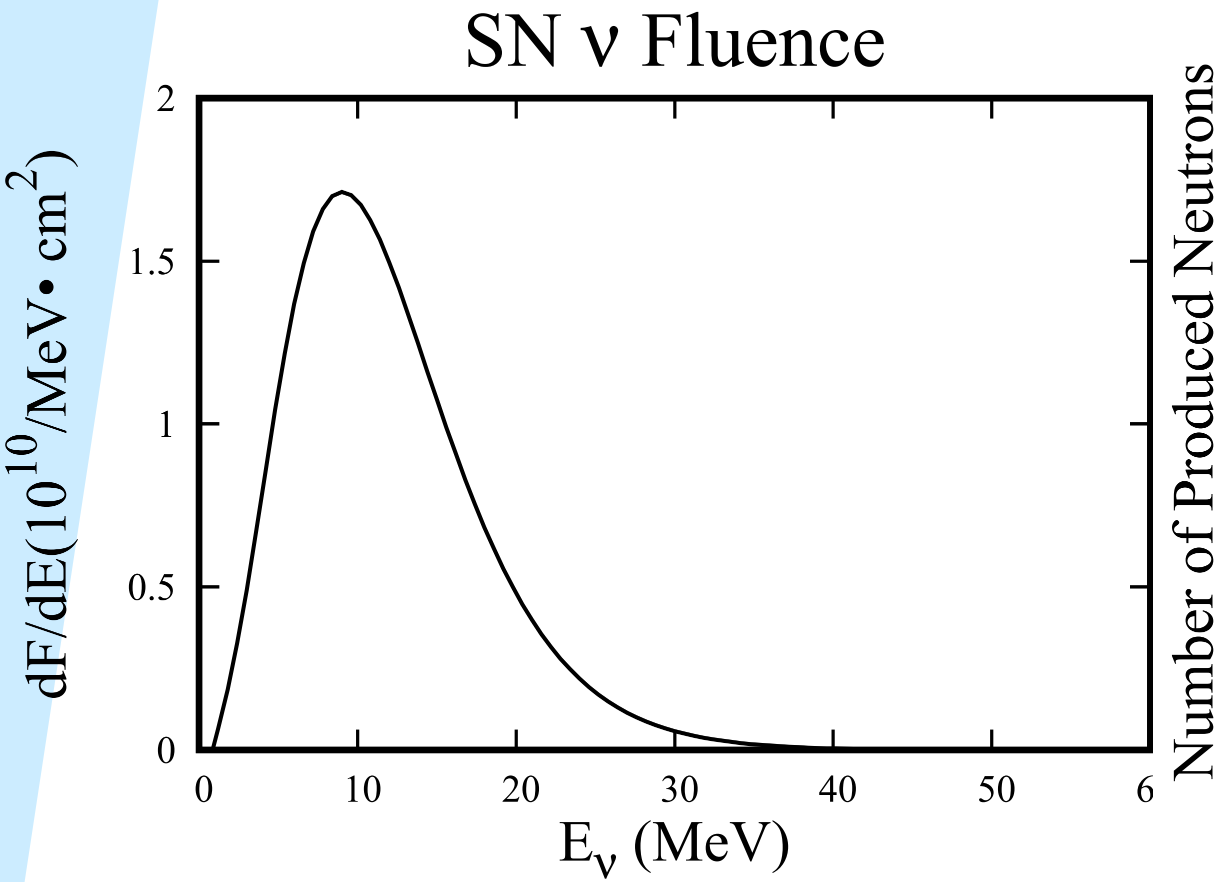
Fluence for each neutrino flavour is obtained from:

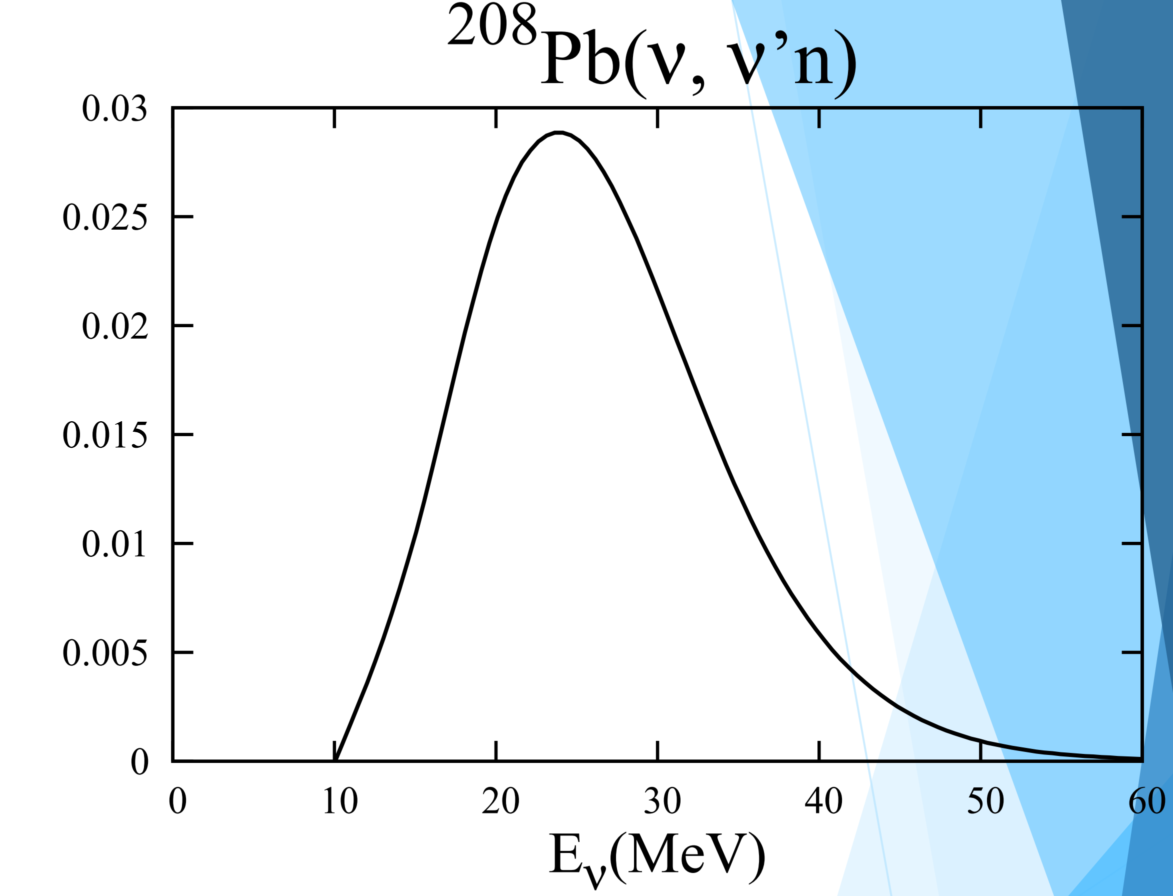
$$\frac{dF_\nu(E)}{dE} = \left(2.35 \times 10^{13}\right) \frac{\mathcal{E}_\nu}{d^2} \frac{E^3}{\langle E_\nu \rangle^5} \exp\left(-\frac{4E}{\langle E_\nu \rangle}\right),$$

The total number of events per atom in the target is :

$$\langle n_{\text{event}} \rangle = \int dE \sigma(E) \frac{dF_\nu(E)}{dE},$$

B. Dasgupta, J.F. Beacom, Phys. Rev. D 83 (2011) 113006





For a supernova (5×10^{52}erg emitting energy and at a distance 10kpc) about 30 neutrons will be produced in HALO_1 where 0.54 is via neutral current quasi-free reactions.

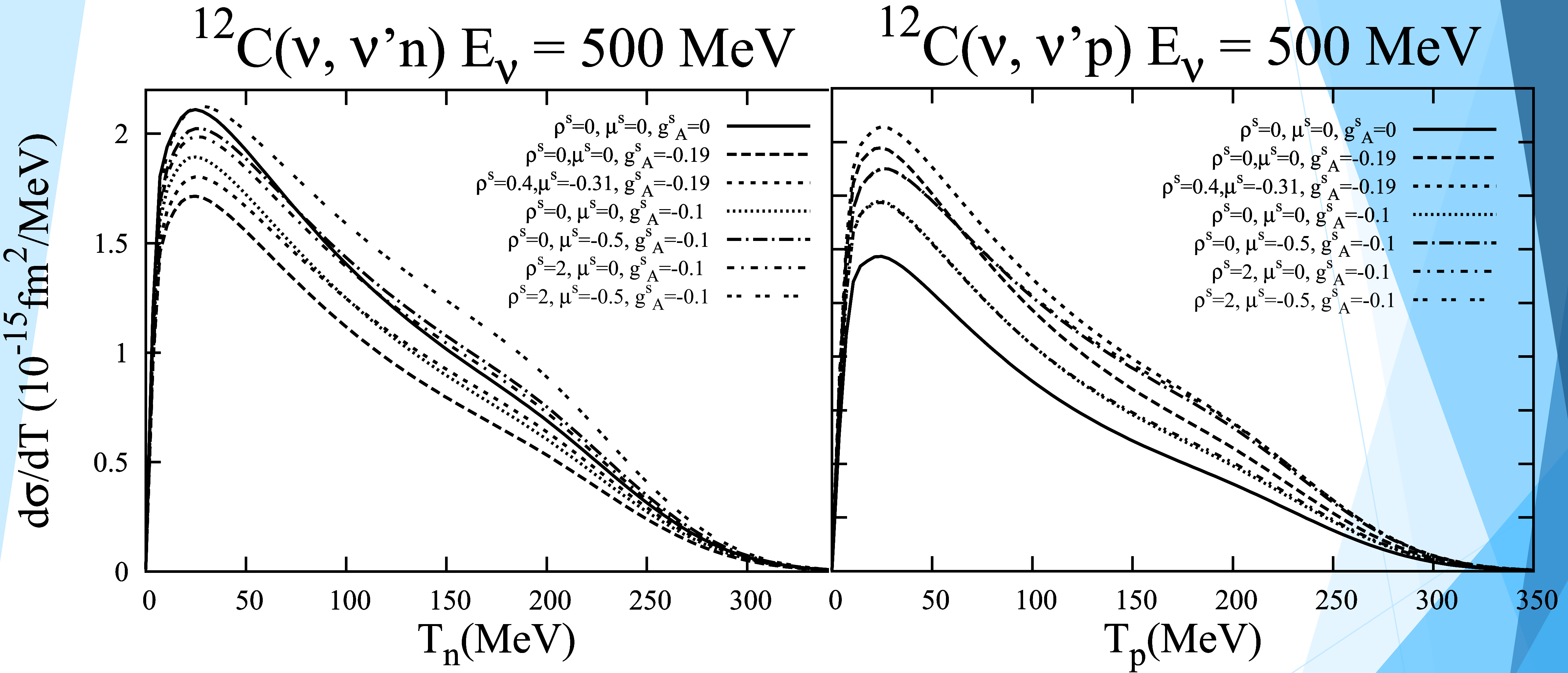
J. Engel, G.C. McLaughlin, C. Volpe, Phys. Rev. D 67 (2003) 013005

Summary

- g_A^s has the most effect on the cross section.
- ρ^s has no effect on $(\nu, \nu' p)$ cross section and small effect on $(\nu, \nu' n)$ cross section.
- $R_{p/n}$ is grouped with different g_A^s values.
- PW calculations reproduced the MiniBooNE data, however DW lies below the data for $Q^2 < 0.5$ GeV^2.
- In a standard supernova about 30 neutrons will be produced in HALO_1 where 0.54 is via neutral current quasi-free reactions

Collaborators: James Finlay, Soheyl Massoudi, Charles Nokes and Marc de Montigny

Reference: Journal of Physics G, Vol.45, No.2(2017)025201



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$^{12}C(\nu, \nu'p)\ E_\nu = 500$ MeV
$d\sigma/dT\ (10^{-15} fm^2/MeV)$
$\rho^s=0, \mu^s=0, g^s_A=0$
$\rho^s=0, \mu^s=0, g^s_A=-0.19$
$\rho^s=0.4, \mu^s=-0.31, g^s_A=-0.19$
$\rho^s=0, \mu^s=0, g^s_A=-0.1$
$\rho^s=0, \mu^s=-0.5, g^s_A=-0.1$
$\rho^s=2, \mu^s=0, g^s_A=-0.1$
$\rho^s=2, \mu^s=-0.5, g^s_A=-0.1$
T_n(MeV)
T_p(MeV)

E_ν	σ_{PW}	σ_{1n} (Ref.[67])
10	0.00	0.02
15	0.411	0.6
20	2.27	2.0
25	7.05	4.6
30	16.3	8.7
35	30.9	14.4
40	52.2	21.5
45	81.3	29.7
50	119	38.6
55	167	47.9
60	224	57.4

Table 1: Total cross sections (in units of 10^{-15} fm^2) of the neutral-current neutrino quasi-elastic scattering on ^{208}Pb with neutron knockout for various energies in MeV of the incoming neutrino. σ_{PW} is computed by using the relativistic plane-wave impulse approximation, and the last column shows the results for $\nu \to \nu$ from Table 1 in Ref.[67].

$$g_A^s = -0.08 \pm 0.05$$

$$\rho^s = -0.10 \pm 0.08 \pm 0.02 \text{ and } \mu^s = 0.056 \pm 0.023 \pm 0.017.$$

TABLE I. Neutrino cross sections in units of 10^{-40} cm^2 as a function of energy (MeV) for emission of one and two neutrons, and summed over all decay channels, obtained with the Skyrme force SIII. We include the charged-current channel for neutrinos, and the neutral-current channel for both neutrinos and antineutrinos.

	$\nu_e \rightarrow e$			$\nu \rightarrow \nu$			$\bar{\nu} \rightarrow \bar{\nu}$		
E_ν	1n	2n	total	1n	2n	total	1n	2n	total
5			0.39×10^{-7}			0.67×10^{-11}			0.66×10^{-11}
10	0.29×10^{-11}		0.09	0.002		0.007	0.002		0.007
15	0.91		1.54	0.06		0.08	0.05		0.08
20	4.96		6.51	0.20		0.27	0.18		0.24
25	14.66	0.45	17.63	0.46	0.03	0.62	0.40	0.03	0.54
30	25.05	3.15	32.22	0.87	0.15	1.22	0.73	0.13	1.04
35	29.27	10.85	45.37	1.44	0.42	2.15	1.18	0.36	1.79
40	33.56	23.68	64.10	2.15	0.93	3.48	1.73	0.76	2.82
45	37.91	38.97	85.33	2.97	1.74	5.25	2.34	1.39	4.17
50	42.54	53.79	106.16	3.86	2.93	7.50	2.99	2.26	5.82
55	47.17	71.63	130.09	4.79	4.56	10.24	3.65	3.42	7.78
60	52.02	90.05	154.64	5.74	6.63	13.50	4.31	4.85	10.04
65	56.31	108.73	178.75	6.71	9.17	17.25	4.97	6.54	12.57
70	60.39	129.14	204.17	7.69	12.17	21.49	5.62	8.47	15.34
75	64.03	150.40	229.88	8.67	15.59	26.14	6.25	10.62	18.31
80	67.04	170.75	253.92	9.65	19.39	31.16	6.86	12.94	21.42
85	69.69	191.16	277.58	10.58	23.51	36.43	7.44	15.39	24.61
90	71.95	211.73	300.95	11.45	27.90	41.88	7.97	17.93	27.82
95	73.91	231.25	323.03	12.23	32.47	47.39	8.45	20.51	31.00

$$^{3}He + n \rightarrow p + t + 764keV$$

which produces a back-to-back proton-triton pair, with the proton carrying 573 keV of kinetic energy and the triton having 191 keV.