Strange particle production from nucleon

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Introduction

The study of neutrino induced weak interactions is not only important to understand the analysis of the various oscillation experiments, but also it is important to understand the hadronic weak currents, estimation of atmospheric backgrounds for nucleon decay searches, strange quark content of the nucleon, etc.

The total νN CC scattering cross section

$$\sigma^{TOTAL} = \sigma^{QEL} \oplus \sigma^{INEL} \oplus \sigma^{DIS}$$

$$\sigma^{INEL} = \sigma^{1\pi} \oplus \sigma^{2\pi} \oplus \ldots \oplus \sigma^{YK} \oplus \sigma^{1K} \oplus \ldots \oplus \sigma^{1Y}$$

Exclusive ν-N channels comprise 3 categories:

1. Single kaon production($\Delta S=1$)

2. Single hyperon production($\Delta S=1$)

3. Charged and neutral current induced associated particle production ($\Delta S=0$).

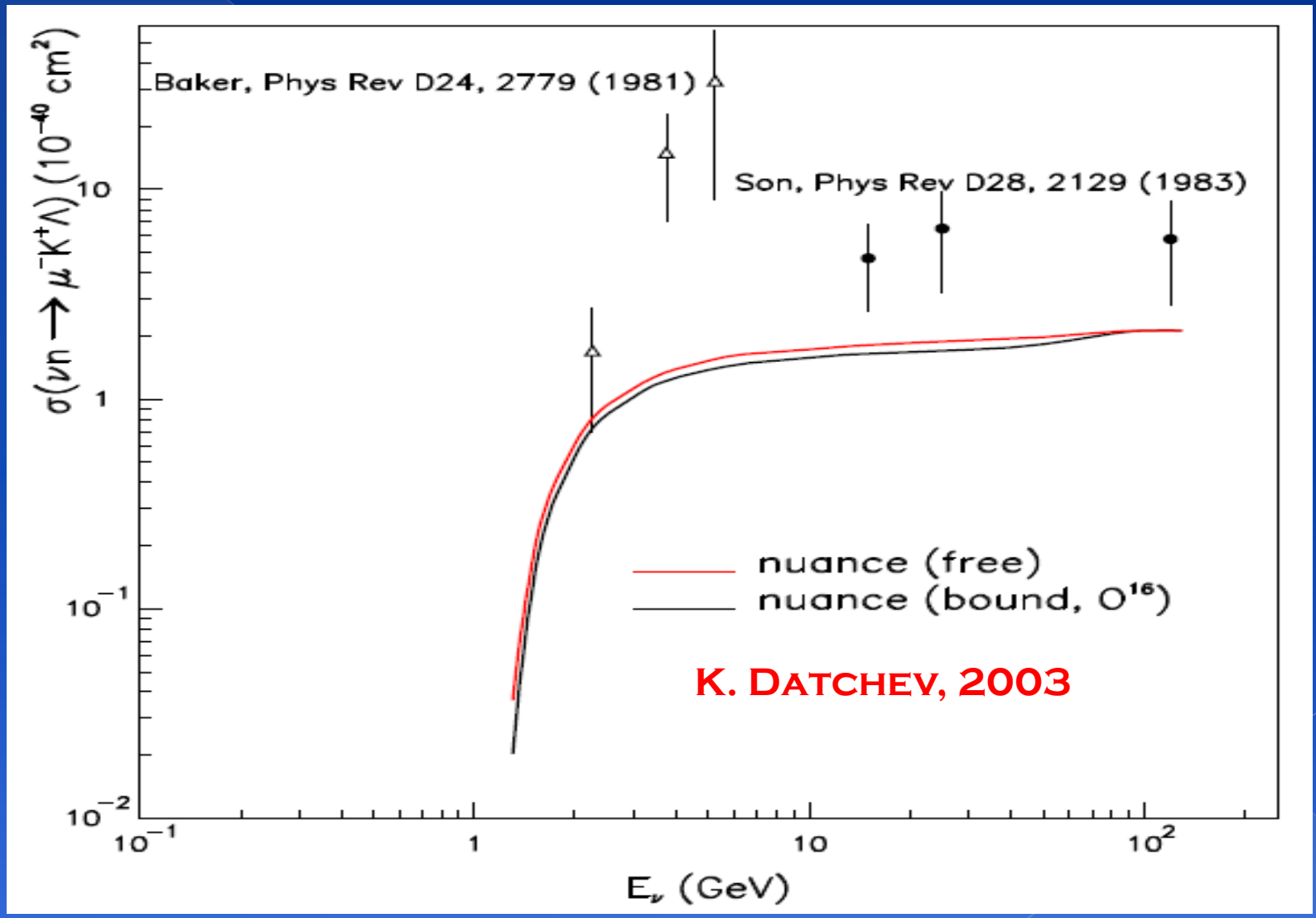
MINERvA is going to study strange particle production reactions . Their study would facilitate the understanding of the structure of hadronic weak current and the estimation of the atmospheric neutrino backgrounds for oscillation searches besides determining precisely ν-A cross sections.

Kaon Production at Minerva, 3 Tons and 4 Years

Reaction	Events(in Thousands)
Δ S=1	Charged Current
$\nu_\mu + p \longrightarrow \mu^- + K^+ + p$	16.0
$\nu_\mu + n \longrightarrow \mu^- + K^0 + p$	2.5
$\nu_\mu + p \longrightarrow \mu^- + K^{0n} + p$	2.0
Δ S=0	Charged Current
$\nu_\mu + n \longrightarrow \mu^- + K^+ + \Lambda^0$	10.5
$\nu_\mu + n \longrightarrow \mu^- + K^+ + \Lambda^0 + \pi^0$	9.5
$\nu_\mu + n \longrightarrow \mu^- + \pi^+ + \Lambda^0 + K^0$	6.5
$\nu_\mu + n \longrightarrow \mu^- + \pi^+ + \Lambda^0 + K^0$	5.0
$\nu_\mu + n \longrightarrow \mu^- + K^+ + K^- + p$	1.5
Δ S=0	Neutral Current
$\nu_\mu + p \longrightarrow \nu_\mu + K^+ + \Lambda^0$	3.5
$\nu_\mu + n \longrightarrow \nu_\mu + K^0 + \Lambda^0$	1.0

Data Points with NUANCE Theoretical estimate for $\nu_\mu + n \rightarrow \mu^- + K^+ + \Lambda^0$

MC includes only resonant kaon production based on RS models for pi prodn.



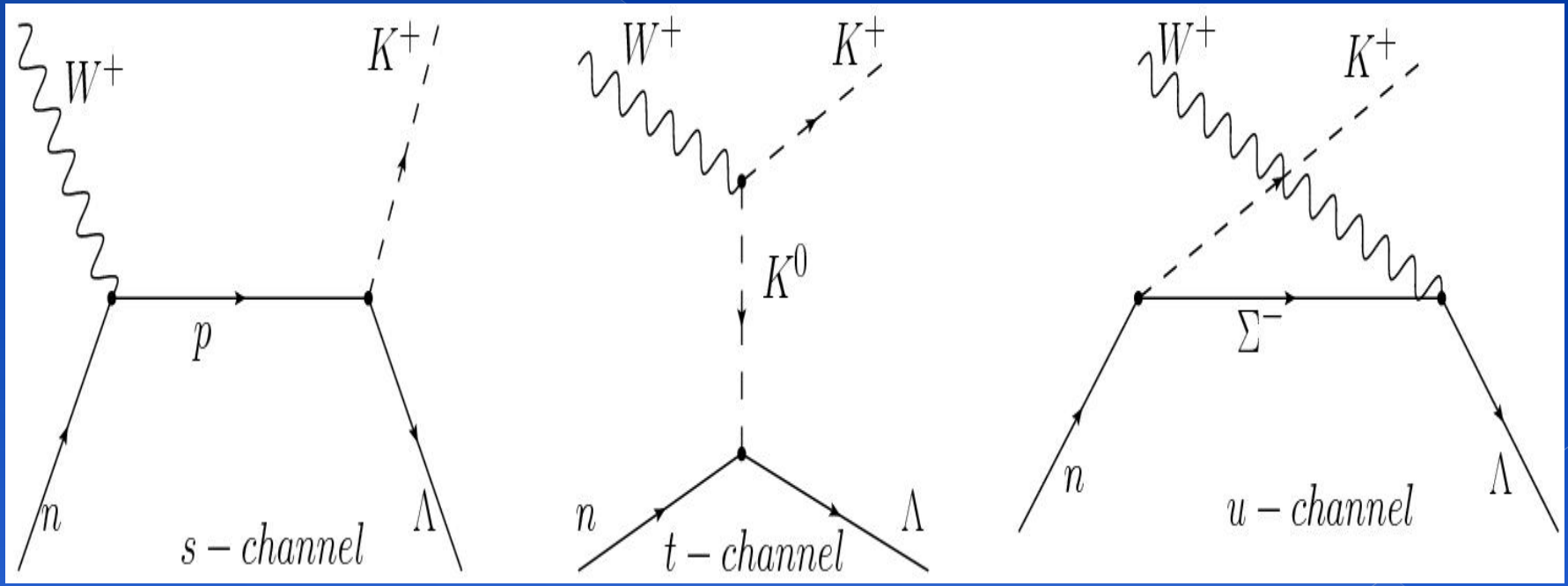
R. E. Shrock (Phys. Rev. D 12, 2049, 1975) used a resonant Born model and estimated the charged and neutral $\nu_\mu + N \rightarrow \mu^- + K + \Lambda^0$ and $\nu_\mu + N \rightarrow \mu^- + K^+ + \Sigma$ cross sections (~ 10^{-40} cm^2) in the neutrino energy region up to 3 GeV.

A. A. Amer (Phys. Rev. D 18, 2290, 1978) used a harmonic oscillator quark model to estimate cross section for $K^+ \Lambda$ production 1.35 – 2.65 ~ 10^{-41} cm^2 which is almost an order of magnitude smaller than the measured result.

H. K. Dewan (Phys. Rev. D 24, 2369, 1981) has studied Associated Production as well as S.C. C.C. reactions $\nu_\mu + N \rightarrow \mu^- + Y + \pi$ and $\nu_\mu + N \rightarrow \mu^- + N + K$ using Born approximations with hyperon-nucleon transition form factors determined from the Cabibbo theory with SU(3) symmetry.

Adera, Van Der Ventel, van Niekerk and T. Mart PRC 82 (2010) 025501

They have studied differential cross section for ν induced C. C. Associated Particle Production using Born term approximation in the framework of Cabibbo theory and SU(3) symmetry.



Chiral perturbation theory (ChPT) is the effective field theory (EFT) of the Strong interactions at low energies.

- **Here one writes a general Lagrangian, consisting of all terms allowed from the symmetry principles and then calculates the matrix elements with this Lagrangian to any given order of perturbation theory.**

The lowest order SU(3) chiral Lagrangian describing the pseudoscalar mesons in the presence of an external current is given by:

S. Scherer---- Adv. Nucl. Phys. 27 (2003) 277

$$\mathcal{L}_M^{(2)} = \frac{f_\pi^2}{4}\mathrm{Tr}[D_\mu U (D^\mu U)^\dagger] + \frac{f_\pi^2}{4}\mathrm{Tr}(\chi U^\dagger + U\chi^\dagger),$$

U is the SU(3) representation of meson fields

$$U(x) = exp\left(i\frac{\phi(x)}{f_\pi}\right)$$

$$\phi(x) = \begin{pmatrix} \pi^0 + \frac{1}{\sqrt{3}}\eta & \sqrt{2}\pi^+ & \sqrt{2}K^+ \\ \sqrt{2}\pi^- & -\pi^0 + \frac{1}{\sqrt{3}}\eta & \sqrt{2}K^0 \\ \sqrt{2}K^- & \sqrt{2}\bar{K}^0 & -\frac{2}{\sqrt{3}}\eta \end{pmatrix},$$

The second term of the Lagrangian incorporates explicit breaking of chiral symmetry coming from the quark masses.

Lowest order Chiral Lagrangian for the baryon octet in the presence of external current

$$\mathcal{L}_{MB}^{(1)} = \mathrm{Tr}\left[\bar{B}\left(i\not{D} - M\right)B\right] - \frac{D}{2}\mathrm{Tr}\left(\bar{B}\gamma^{\mu}\gamma_5\{u_{\mu}, B\}\right) - \frac{F}{2}\mathrm{Tr}\left(\bar{B}\gamma^{\mu}\gamma_5[u_{\mu}, B]\right),$$

where D=0.804, F=0.463 , B is the SU(3) Baryon Octet($1/2^{+}$) field

$$B = \sum_{a=1}^{8}\frac{\lambda_a B_a}{\sqrt{2}} = \begin{pmatrix} \frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & \Sigma^+ & p \\ \Sigma^- & -\frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\Lambda \end{pmatrix}$$

where each entry is a Dirac field

Single Kaon Production

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$$\nu_l + p \longrightarrow l^- + K^+ + p$$
$$\nu_l + n \longrightarrow l^- + K^0 + p$$
$$\nu_l + n \longrightarrow l^- + K^+ + n$$

PRD 85 (2012) 013014

$$\bar{\nu}_l + p \longrightarrow l^+ + K^- + p$$
$$\bar{\nu}_l + p \longrightarrow l^+ + \bar{K}^0 + n$$
$$\bar{\nu}_l + n \longrightarrow l^+ + K^- + n$$

The basic reaction for the neutrino induced charged current kaon production is

$$\nu_l(k) + N(p) \rightarrow l^+(k') + K^-(p_k) + N(p')$$

for which the differential scattering cross section is given by

$$d^9\sigma = \frac{1}{4ME(2\pi)^5} \frac{d\vec{k}'}{(2E_l)} \frac{d\vec{p}'}{(2E'_p)} \frac{d\vec{p}_k}{(2E_K)} \delta^4(k+p-k'-p'-p_k) \bar{\Sigma}\Sigma |\mathcal{M}|^2,$$

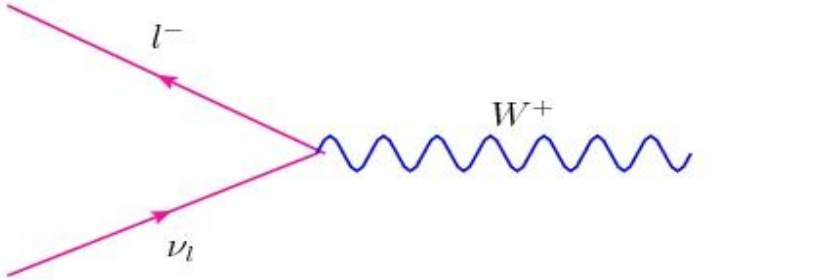
where M is the matrix element given by

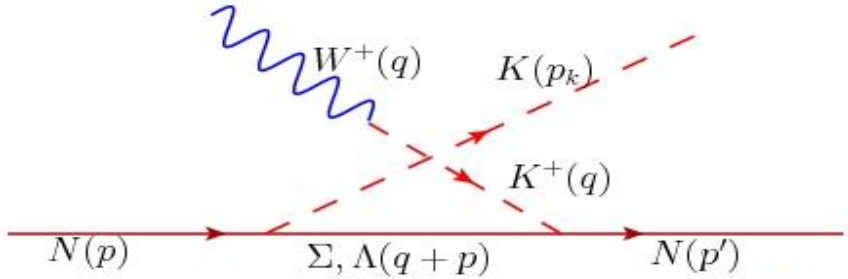
$$\mathcal{M} = \frac{G_F}{\sqrt{2}} j_\mu^{(L)} J^\mu(H) = \frac{g}{2\sqrt{2}} j_\mu^{(L)} \frac{1}{M_W^2} \frac{g}{2\sqrt{2}} J^\mu(H),$$

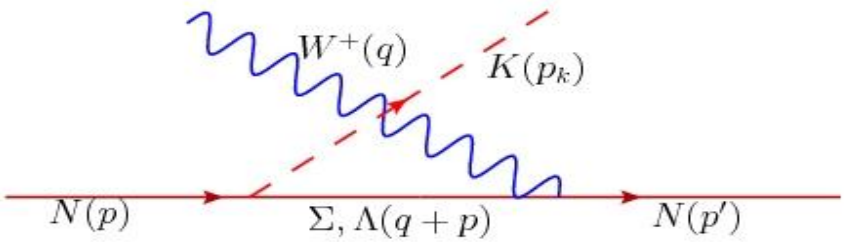
the leptonic current is given by,

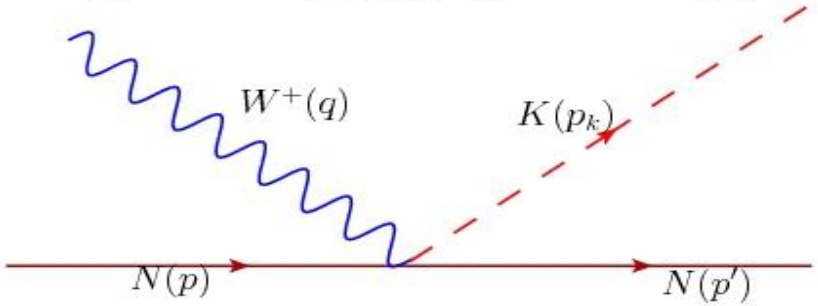
$$\mathcal{L} = -\frac{g}{2\sqrt{2}} \left[W_\mu^+ \bar{\nu}_l \gamma^\mu (1-\gamma^5)\, l + W_\mu^- \bar{l}\, \gamma^\mu (1-\gamma^5) \nu_l \right]$$

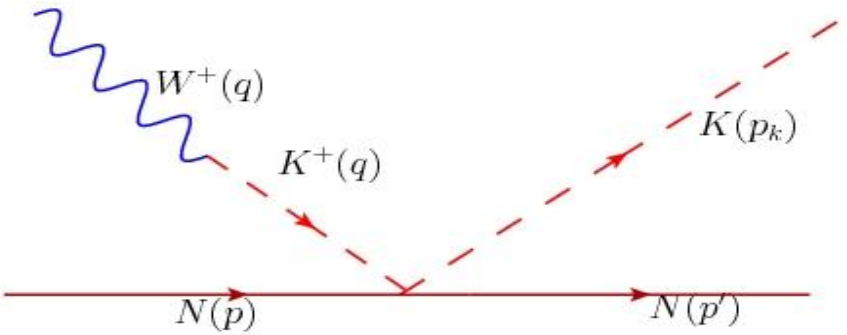
Feynman diagrams for the neutrino induced process: u-channel Kaon in flight , u-channel, contact term, Kaon in flight, pion/eta in flight

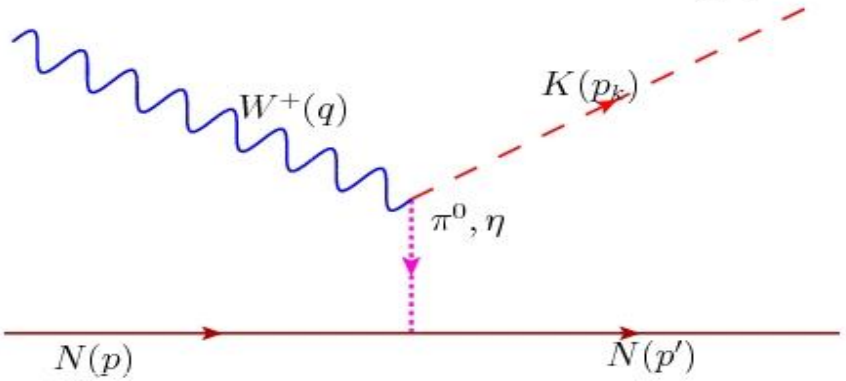




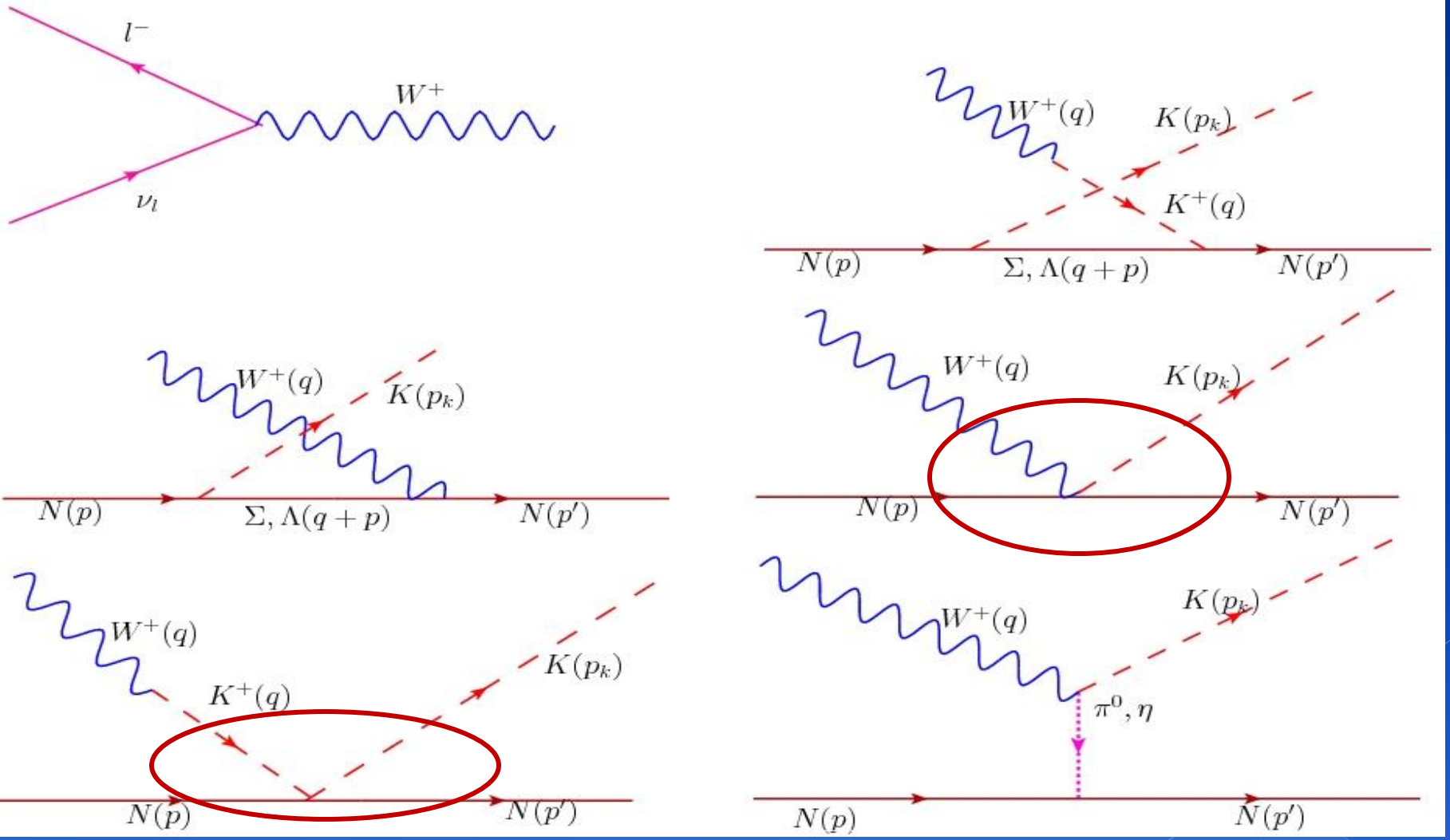








Feynman diagrams for the neutrino induced process: u-channel Kaon in flight , u-channel, contact term, Kaon in flight, pion/eta in flight



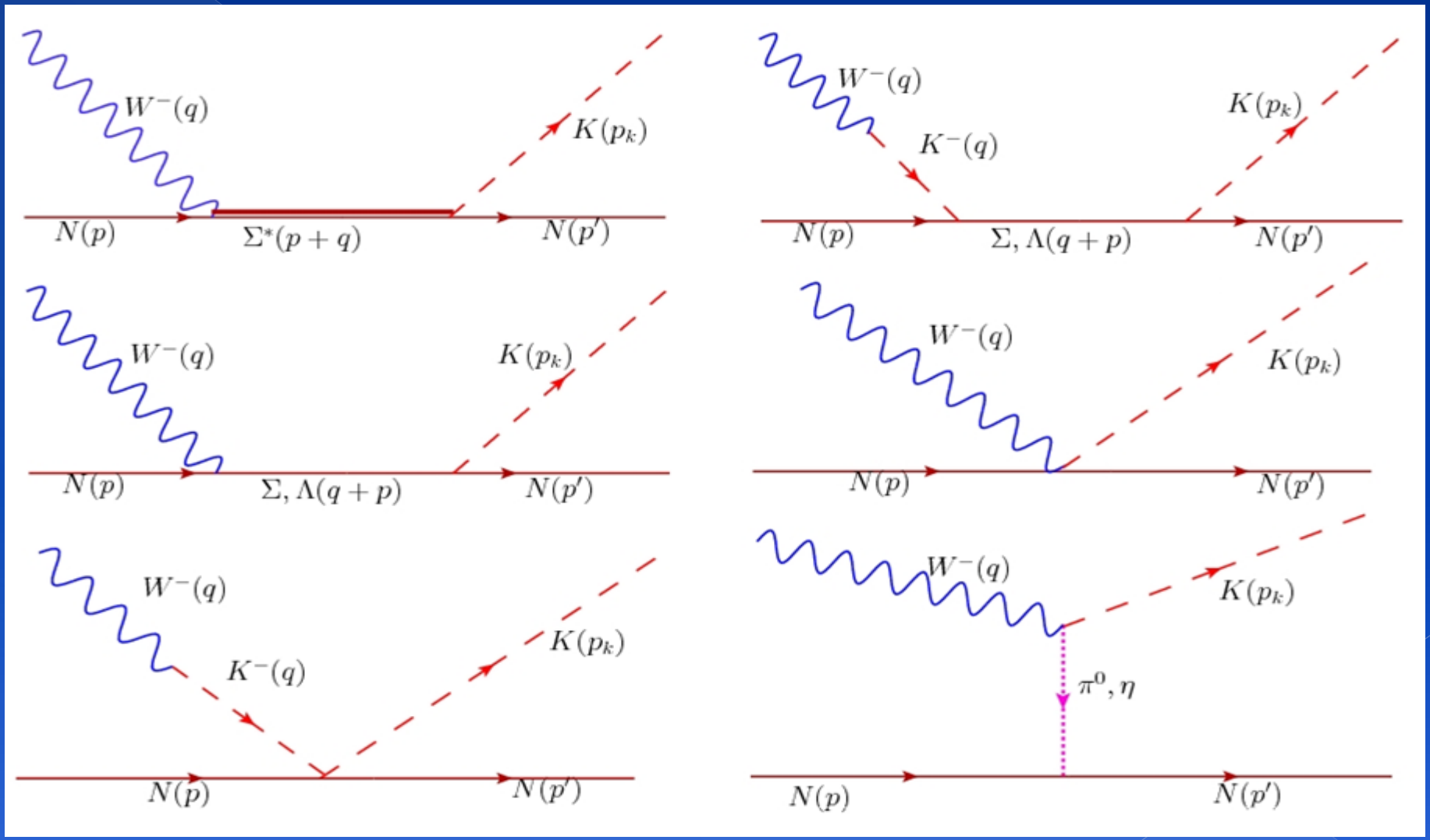
Contributions to the hadronic current for neutrino induced process

$$
\begin{aligned}
j^{\mu}\big|_{CT} &= -iA_{CT}V_{us}\frac{\sqrt{2}}{2f_{\pi}}\bar{N}(p')(\gamma^{\mu}+\gamma^{\mu}\gamma^{5}B_{CT})N(p),\\
j^{\mu}\big|_{Cr\Sigma} &= iA_{Cr\Sigma}V_{us}\frac{\sqrt{2}}{2f_{\pi}}\bar{N}(p')\left(\gamma^{\mu}+i\frac{\mu_p+2\mu_n}{2M}\sigma^{\mu\nu}q_{\nu}+(D-F)(\gamma^{\mu}-\frac{q^{\mu}}{q^2-M_k^2}\not{q})\gamma^{5}\right)\\
&\quad\times\frac{\not{p}-\not{p}_k+M_{\Sigma}}{(p-p_k)^2-M_{\Sigma}^2}\not{p}_k\gamma^{5}N(p),\\
j^{\mu}\big|_{Cr\Lambda} &= iA_{Cr\Lambda}V_{us}\frac{\sqrt{2}}{4f_{\pi}}\bar{N}(p')\left(\gamma^{\mu}+i\frac{\mu_p}{2M}\sigma^{\mu\nu}q_{\nu}-\frac{D+3F}{3}(\gamma^{\mu}-\frac{q^{\mu}}{q^2-M_k^2}\not{q})\gamma^{5}\right)\\
&\quad\times\frac{\not{p}-\not{p}_k+M_{\Lambda}}{(p-p_k)^2-M_{\Lambda}^2}\not{p}_k\gamma^{5}N(p),\\
j^{\mu}\big|_{KP} &= iA_{KP}V_{us}\frac{\sqrt{2}}{4f_{\pi}}\bar{N}(p')(\not{q}+\not{p}_k)N(p)\frac{1}{q^2-M_k^2}q^{\mu},\\
j^{\mu}\big|_{\pi} &= iA_{\pi P}V_{us}(D+F)\frac{\sqrt{2}}{2f_{\pi}}\frac{M}{(q-p_k)^2-M_{\pi}^2}\bar{N}(p')\gamma^{5}.(q^{\mu}-2{p_k}^{\mu})N(p),\\
j^{\mu}\big|_{\eta} &= iA_{\eta P}V_{us}(D-3F)\frac{\sqrt{2}}{2f_{\pi}}\frac{M}{(q-p_k)^2-M_{\eta}^2}\bar{N}(p')\gamma^{5}.(q^{\mu}-2{p_k}^{\mu})N(p),
\end{aligned}
$$

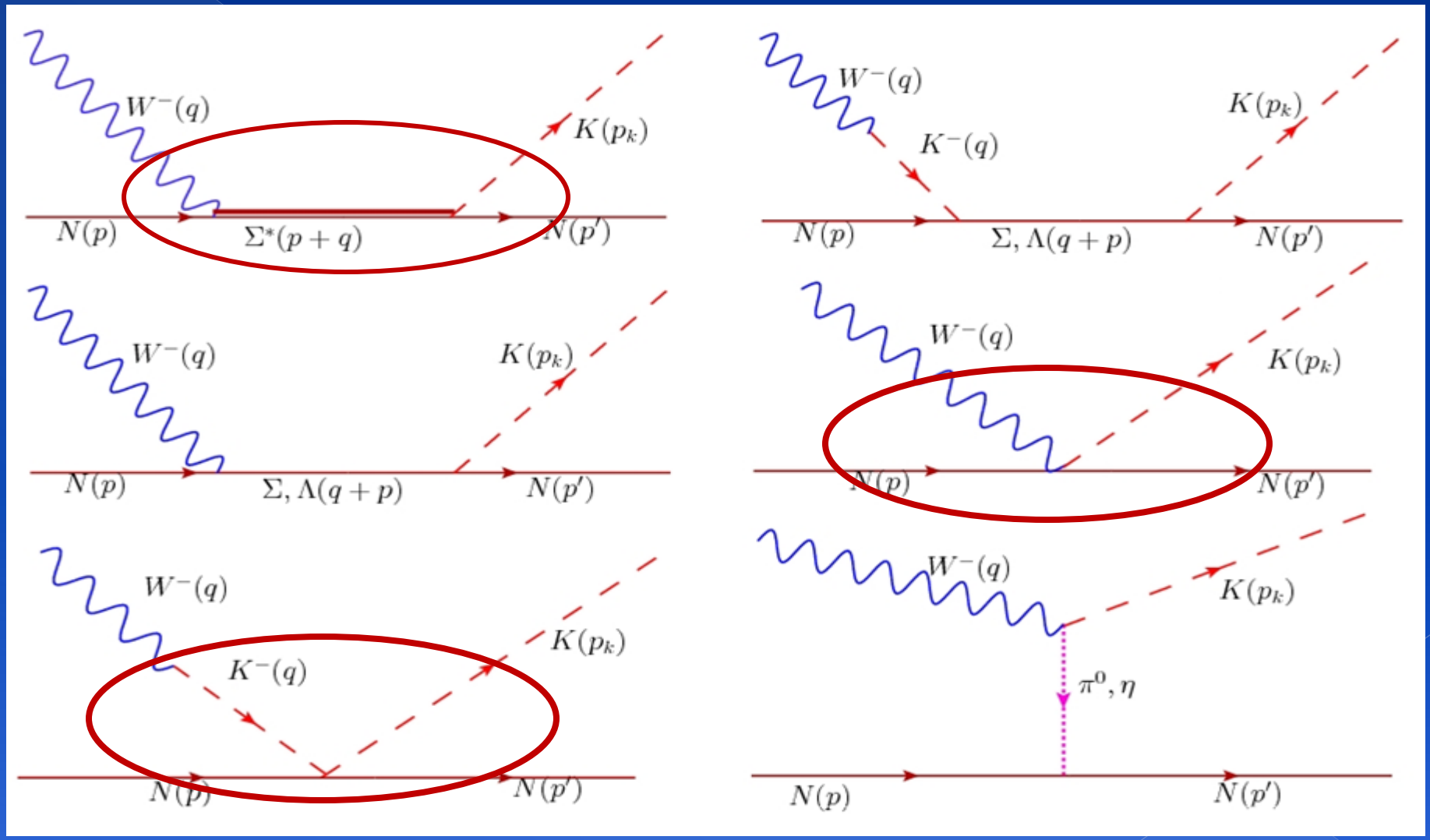
The parameters appearing in the hadronic currents

Process	A_{CT}	B_{CT}	$A_{Cr\Sigma}$	$A_{Cr\Lambda}$	A_{KP}	$A_{\pi P}$	$A_{\eta P}$
$\nu n \to lKn$	1	D-F	-(D-F)	0	1	1	1
$\nu p \to lKp$	2	-F	-(D-F)/2	(D+3F)	2	-1	1
$\nu n \to lKp$	1	-D-F	(D-F)/2	(D+3F)	1	-2	0

Feynman diagrams for the anti-neutrino induced process: Σ-resonance, s-channel Kaon in flight , s-channel, contact term, Kaon in flight, pion/eta in flight



Feynman diagrams for the anti-neutrino induced process: Σ-resonance, s-channel Kaon in flight , s-channel, contact term, Kaon in flight, pion/eta in flight



The interaction between the baryon decuplet, the baryon octet and the meson octet is given by

$$\mathcal{L}_{dec} = \mathcal{C}\left(\epsilon^{abc}\bar{T}^{\mu}_{ade}u^{d}_{\mu,b}B^{e}_{c} + h.c.\right),$$

T^{ade}_{μ} is the SU(3) representation for the spin 3/2 decuplet field with the following associations:

$T^{111}=\Delta^{++}$, $T^{112}=\Delta^{+}/\sqrt{3}$, $T^{122}=\Delta^{0}/\sqrt{3}$, $T^{222}=\Delta^{-}$, $T^{113}=\Sigma^{*+}/\sqrt{3}$,
$T^{123}=\Sigma^{*0}/\sqrt{6}$, $T^{223}=\Sigma^{*-}/\sqrt{3}$, $T^{133}=\Xi^{*0}/\sqrt{3}$, $T^{233}=\Xi^{*-}/\sqrt{3}$ and $T^{333}=\Omega^{-}$

C is fitted from the Δ^{++} decay and found to be = 0.996 ~ 1.0

$$\begin{aligned}\langle\Sigma^{*};P=p+q\,|V^{\mu}|N;p\rangle &= V_{us}\bar{\psi}_{\alpha}(\vec{P})\Gamma^{\alpha\mu}_{V}(p,q)\,u(\vec{p}),\\ \langle\Sigma^{*};P=p+q\,|A^{\mu}|N;p\rangle &= V_{us}\bar{\psi}_{\alpha}(\vec{p})\Gamma^{\alpha\mu}_{A}(p,q)\,u(\vec{p}),\end{aligned}$$

$$j^{\mu} \propto p^{\alpha}_{k}\bar{N}(p')\mathcal{P}_{\alpha\beta}\Gamma^{\beta\mu}(p,q)N(p)$$

$$\begin{aligned}\Gamma^{\alpha\mu}_{V}(p,q) &= \left[\frac{C^{V}_{3}}{M}(g^{\alpha\mu}\not{q}-q^{\alpha}\gamma^{\mu})+\frac{C^{V}_{4}}{M^{2}}(g^{\alpha\mu}q\cdot P-q^{\alpha}P^{\mu})+\frac{C^{V}_{5}}{M^{2}}(g^{\alpha\mu}q\cdot p-q^{\alpha}p^{\mu})+C^{V}_{6}g^{\mu\alpha}\right]\gamma_{5}\\ \Gamma^{\alpha\mu}_{A}(p,q) &= \left[\frac{C^{A}_{3}}{M}(g^{\alpha\mu}\not{q}-q^{\alpha}\gamma^{\mu})+\frac{C^{A}_{4}}{M^{2}}(g^{\alpha\mu}q\cdot P-q^{\alpha}P^{\mu})+C^{A}_{5}g^{\alpha\mu}+\frac{C^{A}_{6}}{M^{2}}q^{\mu}q^{\alpha}\right]\end{aligned}$$

Spin 3/2 Rarita-Schwinger projection operator

$$P^{\mu\nu}(P) = \sum_{spins} \psi^{\mu}\bar{\psi}^{\nu} = -(\not{P} + M_{\Sigma^*}) \left[g^{\mu\nu} - \frac{1}{3}\gamma^{\mu}\gamma^{\nu} - \frac{2}{3}\frac{P^{\mu}P^{\nu}}{M^2_{\Sigma^*}} + \frac{1}{3}\frac{P^{\mu}\gamma^{\nu} - P^{\nu}\gamma^{\mu}}{M_{\Sigma^*}} \right],$$

We take the P-wave width for the decay of Σ^* -> $\Lambda\pi$ (87%)

$$\Gamma_{\Sigma^* \to Y, meson} = \frac{C_Y}{192\pi} \left(\frac{\mathcal{C}}{f_\pi} \right)^2 \frac{(W + M_Y)^2 - m^2}{W^5} \lambda^{3/2}(W^2, M_Y^2, m^2)\, \Theta(W - M_Y - m).$$

The factor C_Y is 1 for Λ and $\frac{2}{3}$ for N and Σ

And total width for Σ^* is :

$$\Gamma_{\Sigma^*} = \Gamma_{\Sigma^* \to \Lambda\pi} + \Gamma_{\Sigma^* \to \Sigma\pi} + \Gamma_{\Sigma^* \to N\bar{K}}$$

Contributions to the hadronic current for anti-neutrino induced process

$$J^\mu|_{CT} = iA_{CT}V_{us}\frac{\sqrt{2}}{2f_\pi}\bar{N}(p')\,(\gamma^\mu + B_{CT}\,\gamma^\mu\gamma_5)\,N(p)$$

$$J^\mu|_{\Sigma} = iA_{\Sigma}(D-F)V_{us}\frac{\sqrt{2}}{2f_\pi}\bar{N}(p')\not{p}_k\gamma_5\frac{\not{p}+\not{q}+M_\Sigma}{(p+q)^2-M_\Sigma^2}\left(\gamma^\mu + i\frac{(\mu_p+2\mu_n)}{2M}\sigma^{\mu\nu}q_\nu\right.$$
$$+ \left.(D-F)\left\{\gamma^\mu - \frac{q^\mu}{{q^2-M_k}^2}\not{q}\right\}\gamma^5\right)N(p)$$

$$J^\mu|_{\Lambda} = iA_{\Lambda}V_{us}(D+3F)\frac{1}{2\sqrt{2}f_\pi}\bar{N}(p')\not{p}_k\gamma^5\frac{\not{p}+\not{q}+M_\Lambda}{(p+q)^2-M_\Lambda^2}\left(\gamma^\mu + i\frac{\mu_p}{2M}\sigma^{\mu\nu}q_\nu\right.$$
$$- \left.\frac{(D+3F)}{3}\left\{\gamma^\mu - \frac{q^\mu}{{q^2-M_k}^2}\not{q}\right\}\gamma^5\right)N(p)$$

$$J^\mu|_{KP} = iA_{KP}V_{us}\frac{\sqrt{2}}{2f_\pi}\bar{N}(p')\not{q}\,N(p)\frac{q^\mu}{q^2-M_k^2}$$

$$J^\mu|_{\pi} = iA_{\pi}\frac{M\sqrt{2}}{2f_\pi}V_{us}(D+F)\frac{2{p_k}^\mu - q^\mu}{(q-p_k)^2-{m_\pi}^2}\bar{N}(p')\gamma_5 N(p)$$

$$J^\mu|_{\eta} = iA_{\eta}\frac{M\sqrt{2}}{2f_\pi}V_{us}(D-3F)\frac{2{p_k}^\mu - q^\mu}{(q-p_k)^2-{m_\eta}^2}\bar{N}(p')\gamma_5 N(p)$$

$$J^\mu|_{\Sigma^*} = -iA_{\Sigma^*}\frac{\mathcal{C}}{f_\pi}\frac{1}{\sqrt{6}}\,V_{us}\,\frac{p_k^\lambda}{P^2-M_{\Sigma^*}^2+i\Gamma_{\Sigma^*}M_{\Sigma^*}}\,\bar{N}(p')P_{RS_{\lambda\rho}}(\Gamma_V^{\rho\mu}+\Gamma_A^{\rho\mu})N(p)$$

Values of the parameters appearing in the hadronic currents

Process	B_{CT}	A_{CT}	A_{Σ}	A_{Λ}	A_{KP}	A_{π}	A_{η}	A_{Σ^*}
$\bar{\nu}n \to l^+K^-n$	D-F	1	-1	0	-1	1	1	2
$\bar{\nu}p \to l^+K^-p$	-F	2	$-\frac{1}{2\sqrt{2}}$	1	-2	-1	1	1
$\bar{\nu}p \to l^+\bar{K}^0n$	-D-F	1	$\frac{1}{2\sqrt{2}}$	1	-1	-2	0	-1

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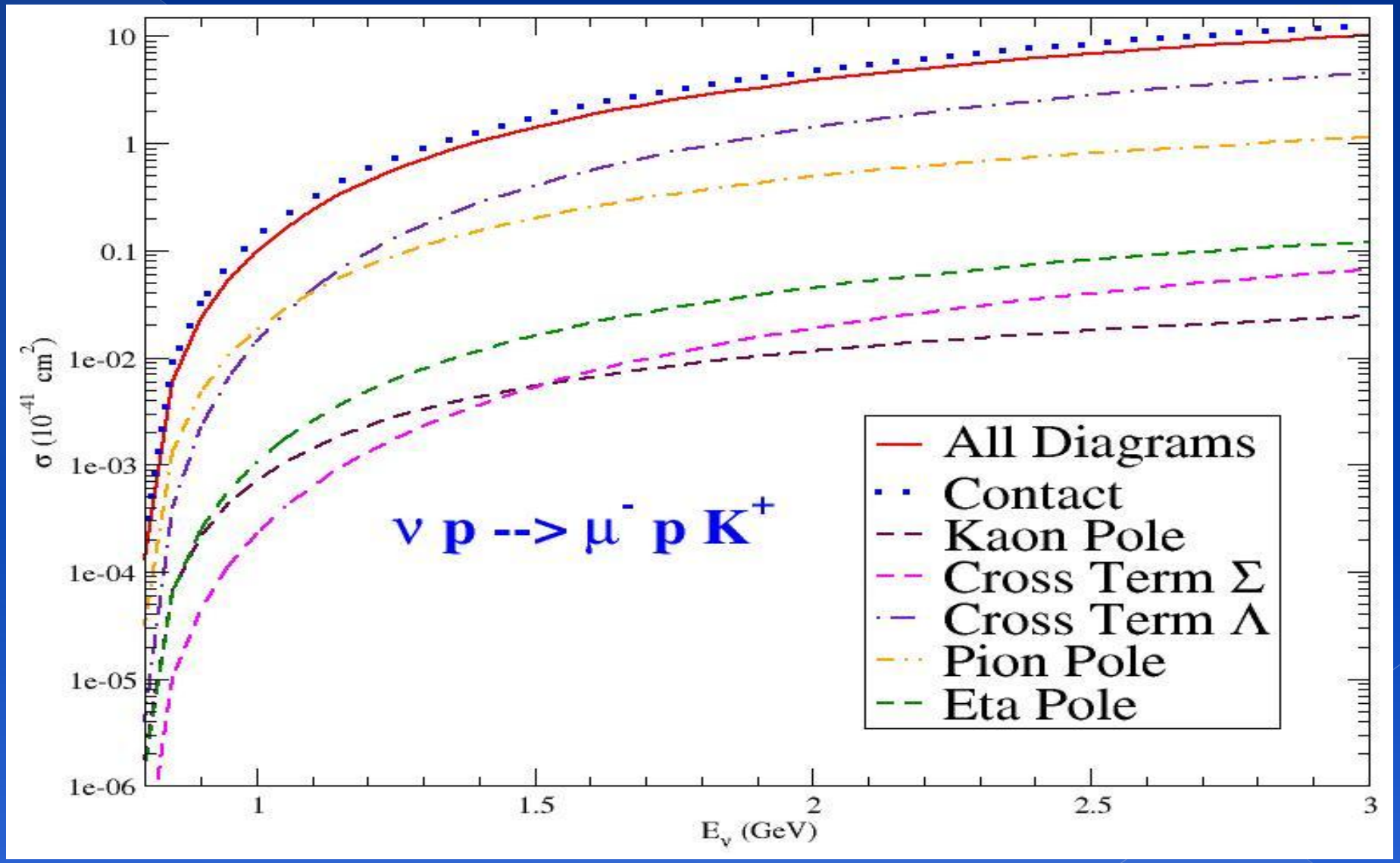

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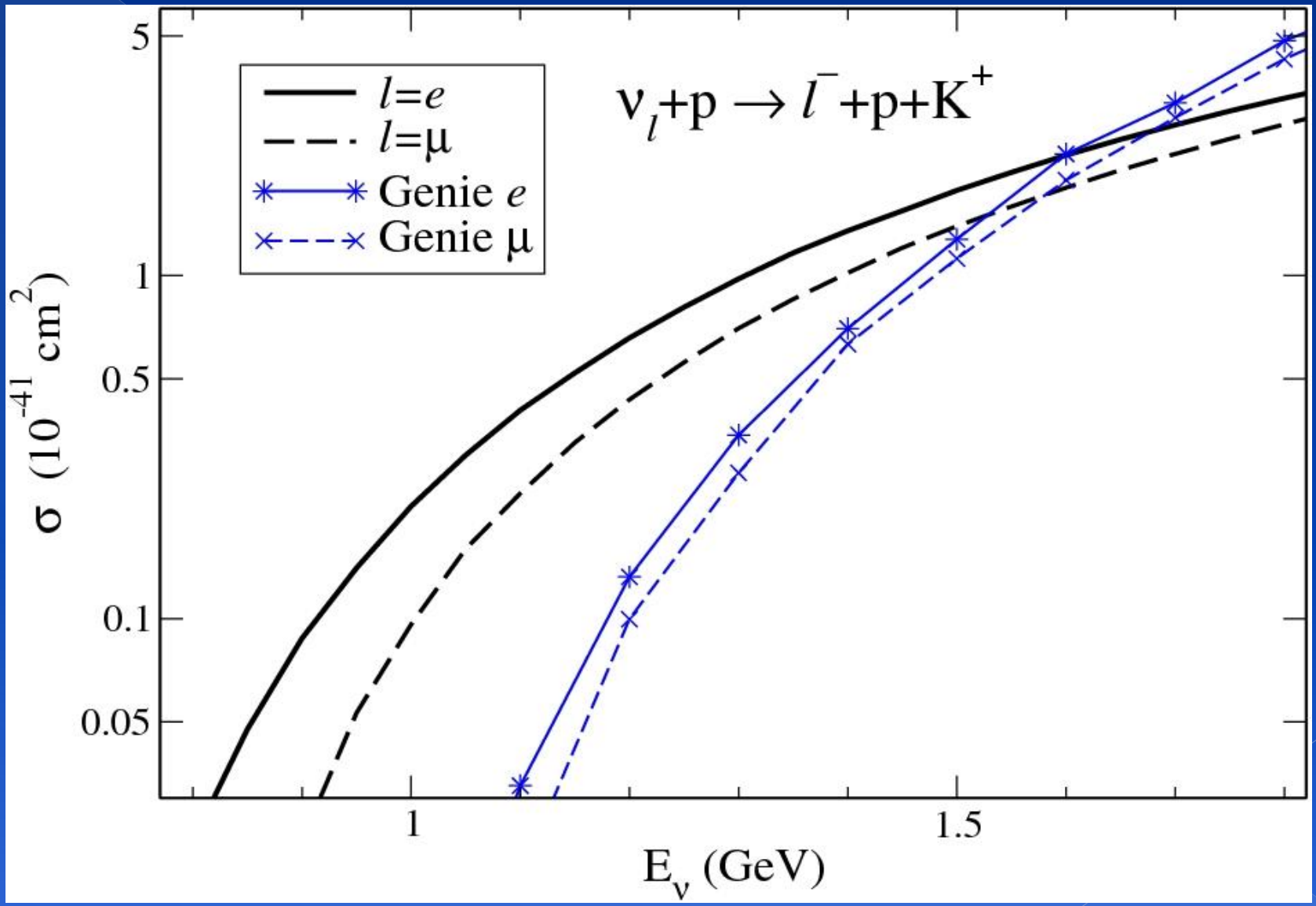

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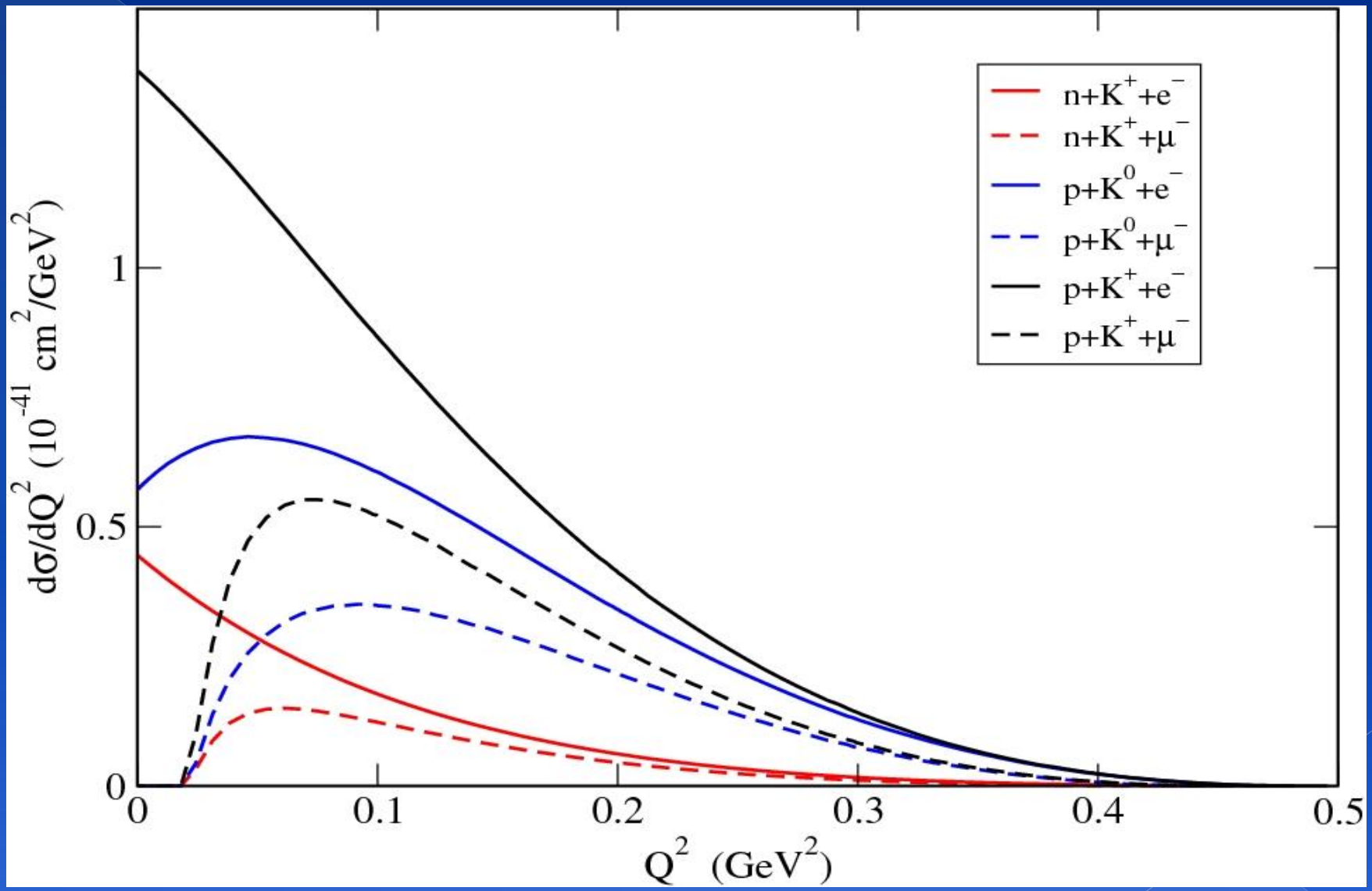
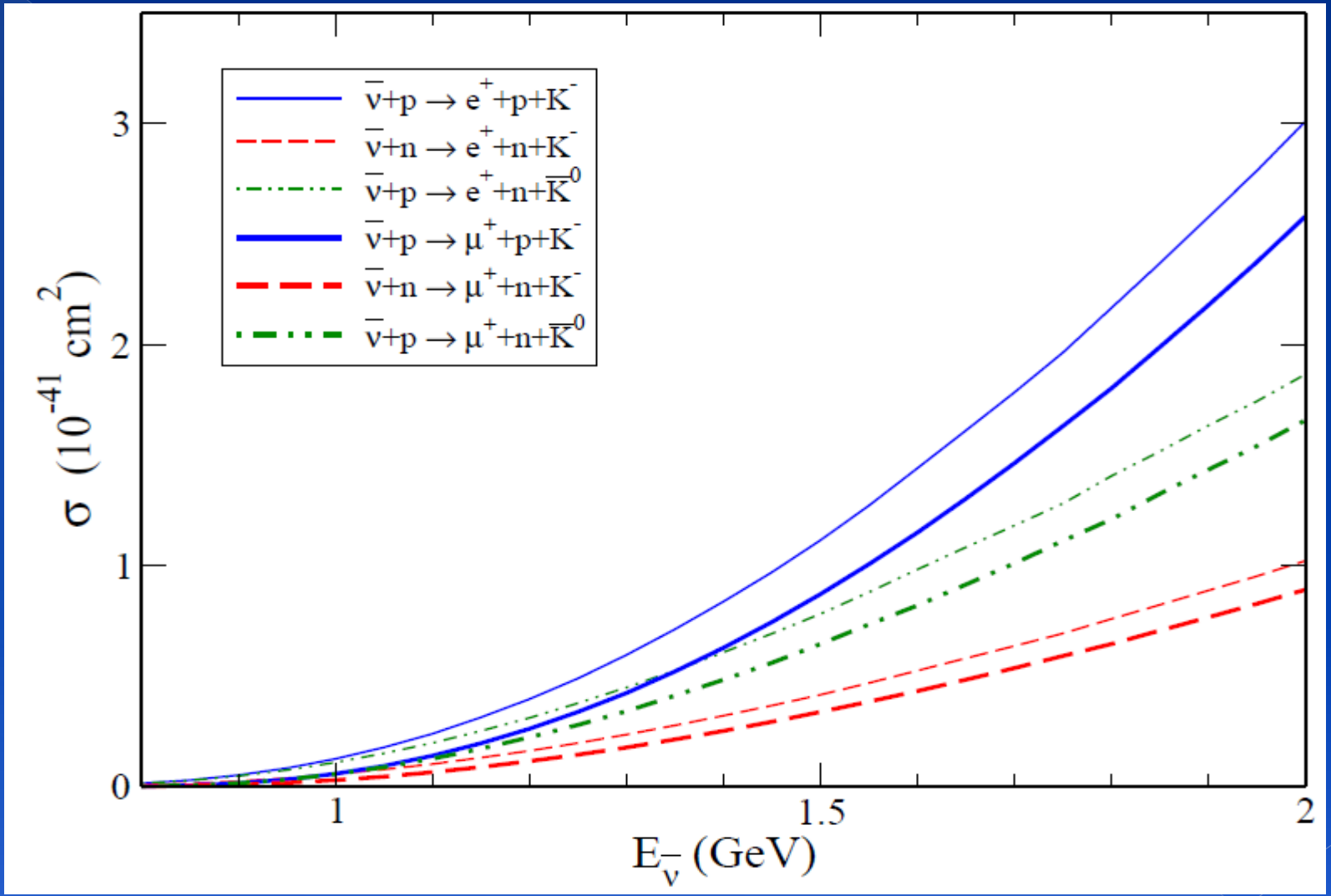


Cross Section for the processes $\bar{\nu}_e N \to e^+ N' \bar{K}$ and $\bar{\nu}_\mu N \to \mu^+ N' \bar{K}$



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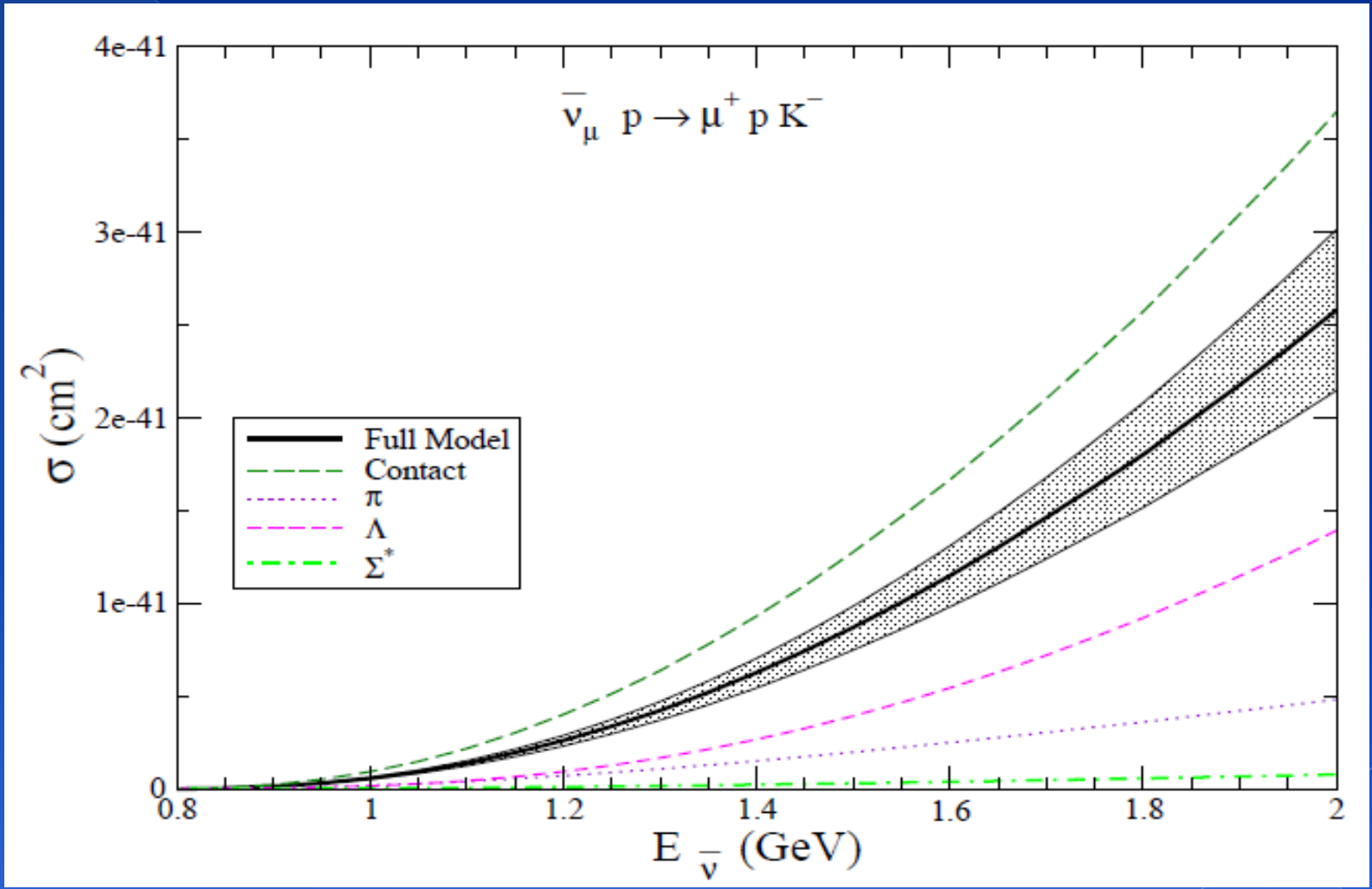
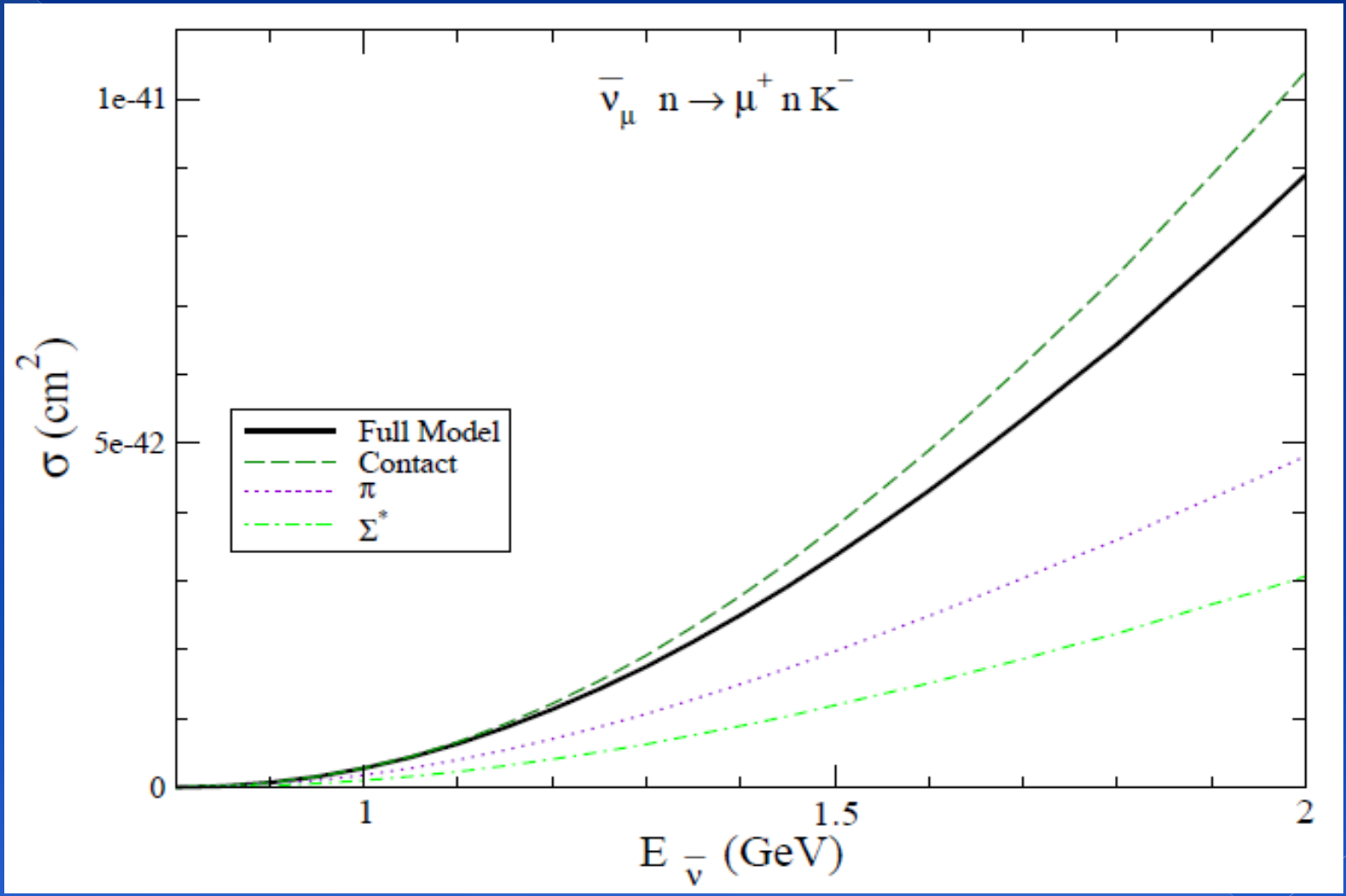
Cross Section for the process $\bar{\nu}_\mu p \to \mu^+ p K^-$



Cross Section for the process $\bar{\nu}_\mu n \to \mu^+ n K^-$



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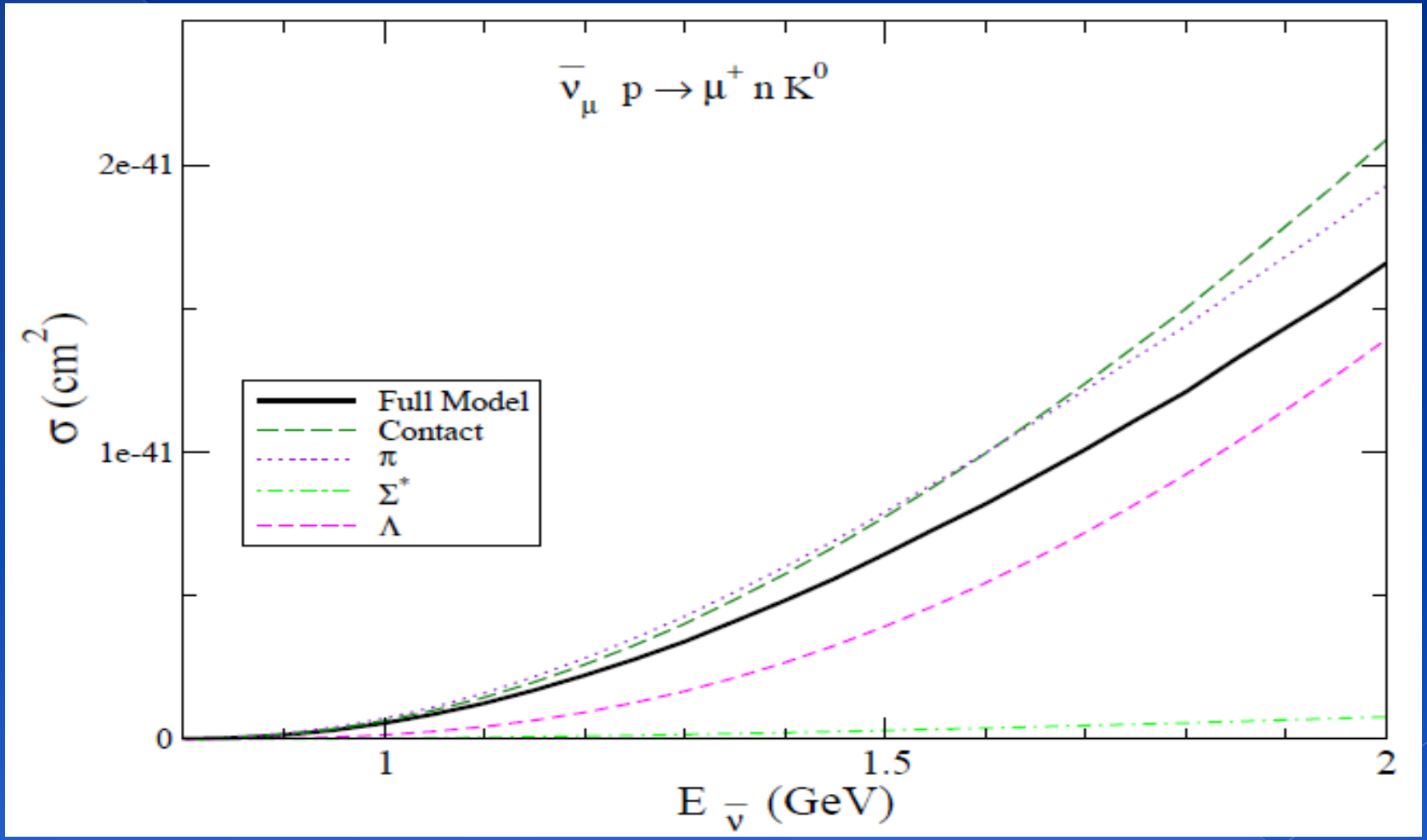
Cross section for the process $\bar{\nu}_\mu p \to \mu^+ n K^0$



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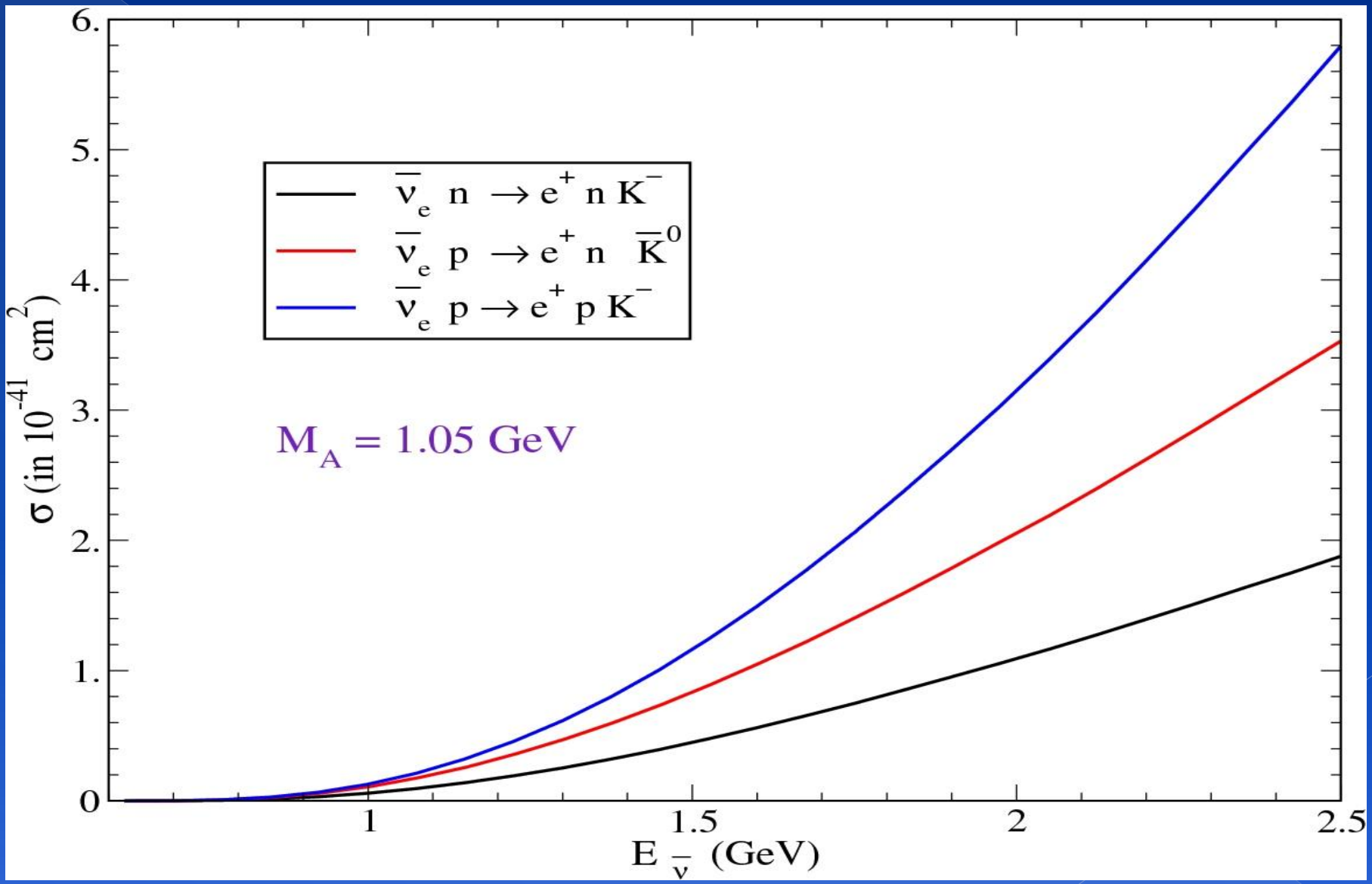
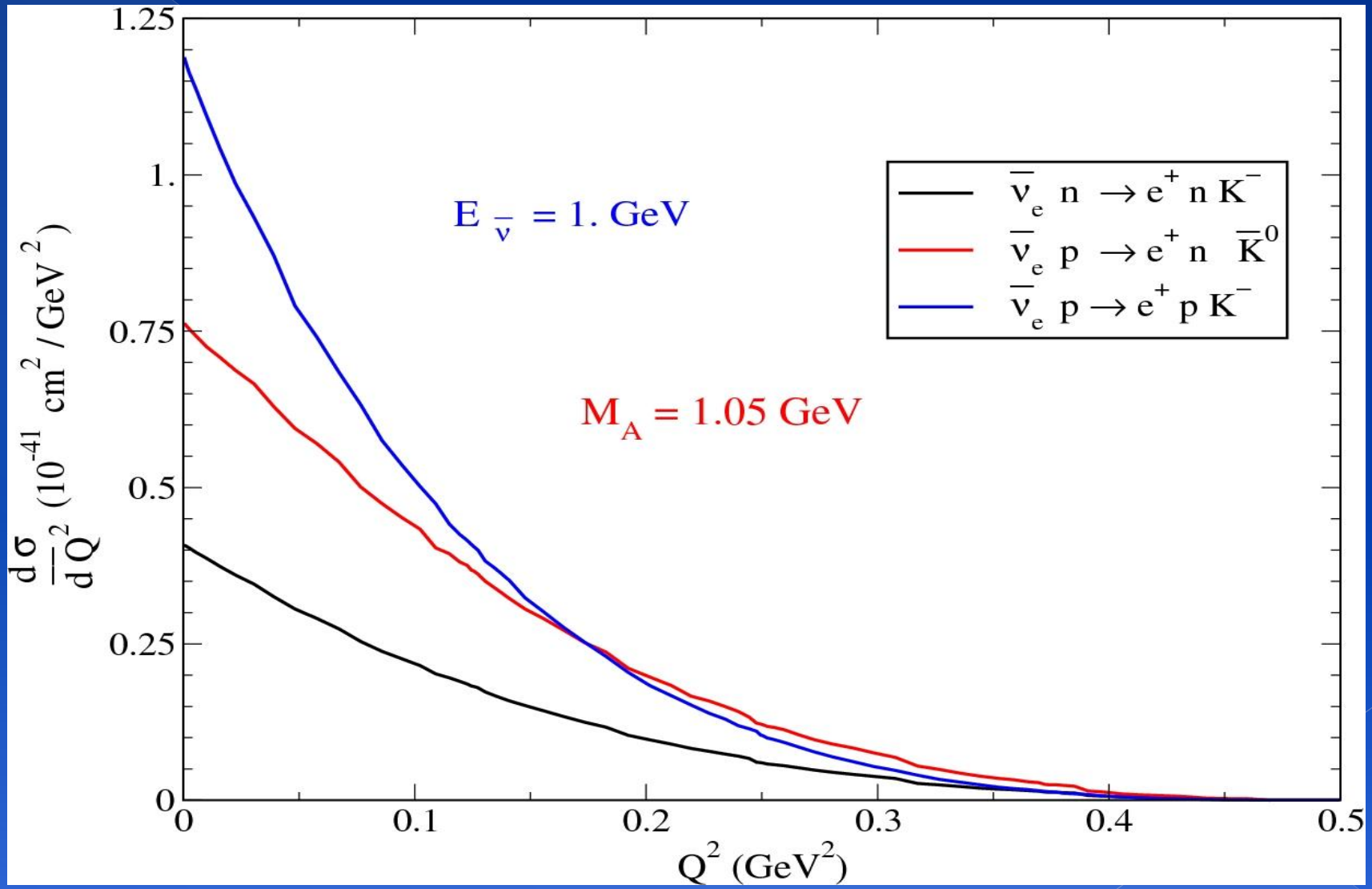
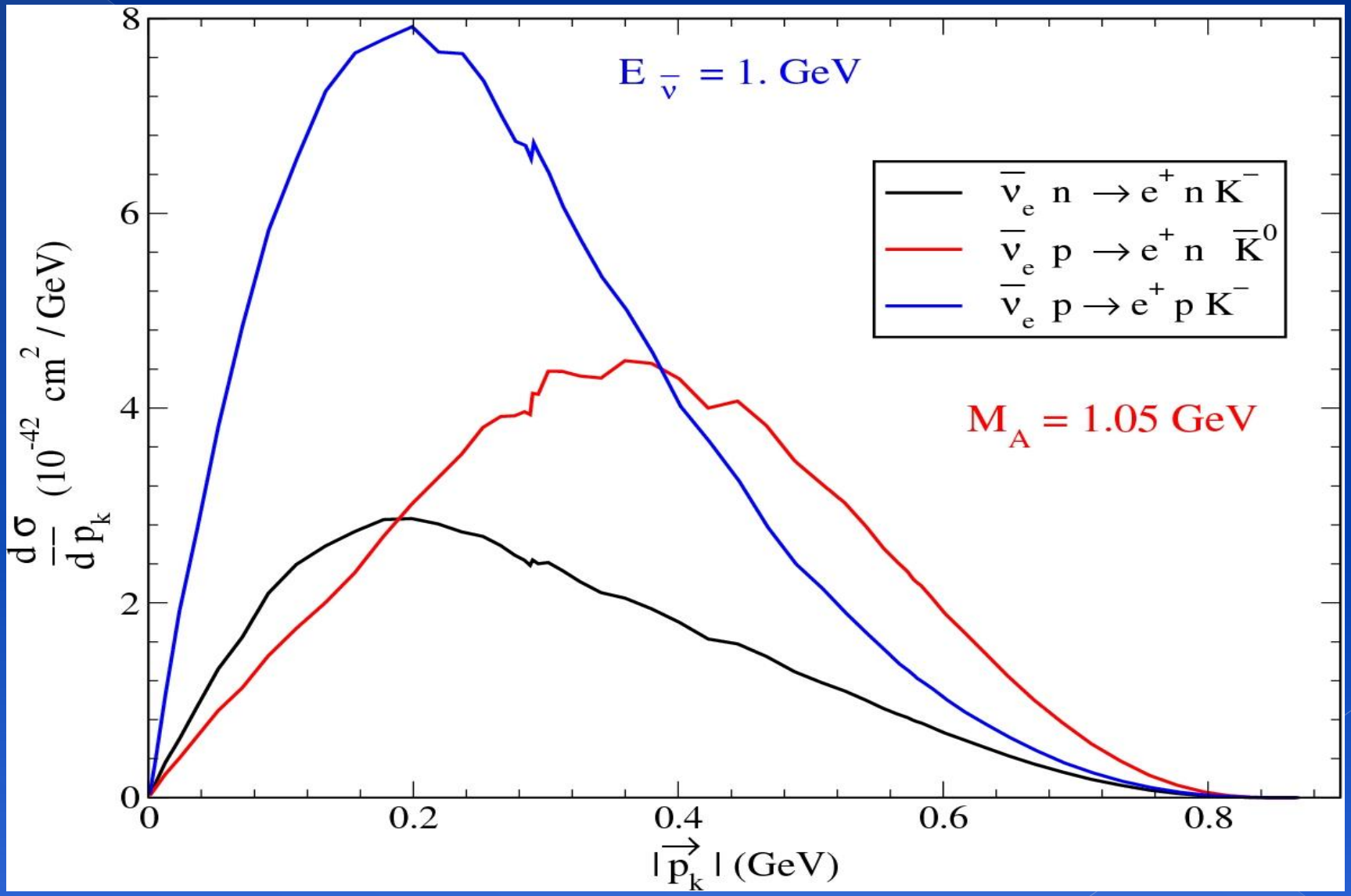


Q^2 distribution




$E_{\bar{\nu}} = 1.\ GeV$
$\bar{\nu}_e\ n \rightarrow e^+\ n\ K^-$
$\bar{\nu}_e\ p \rightarrow e^+\ n\ \bar{K}^0$
$\bar{\nu}_e\ p \rightarrow e^+\ p\ K^-$
$M_A = 1.05\ GeV$
$\frac{d\sigma}{d p_k}\ (10^{-42}\ cm^2\ /\ GeV)$
$|\vec{p_k}|\ (GeV)$
0
2
4
6
8
0
0.2
0.4
0.6
0.8

Associated Production

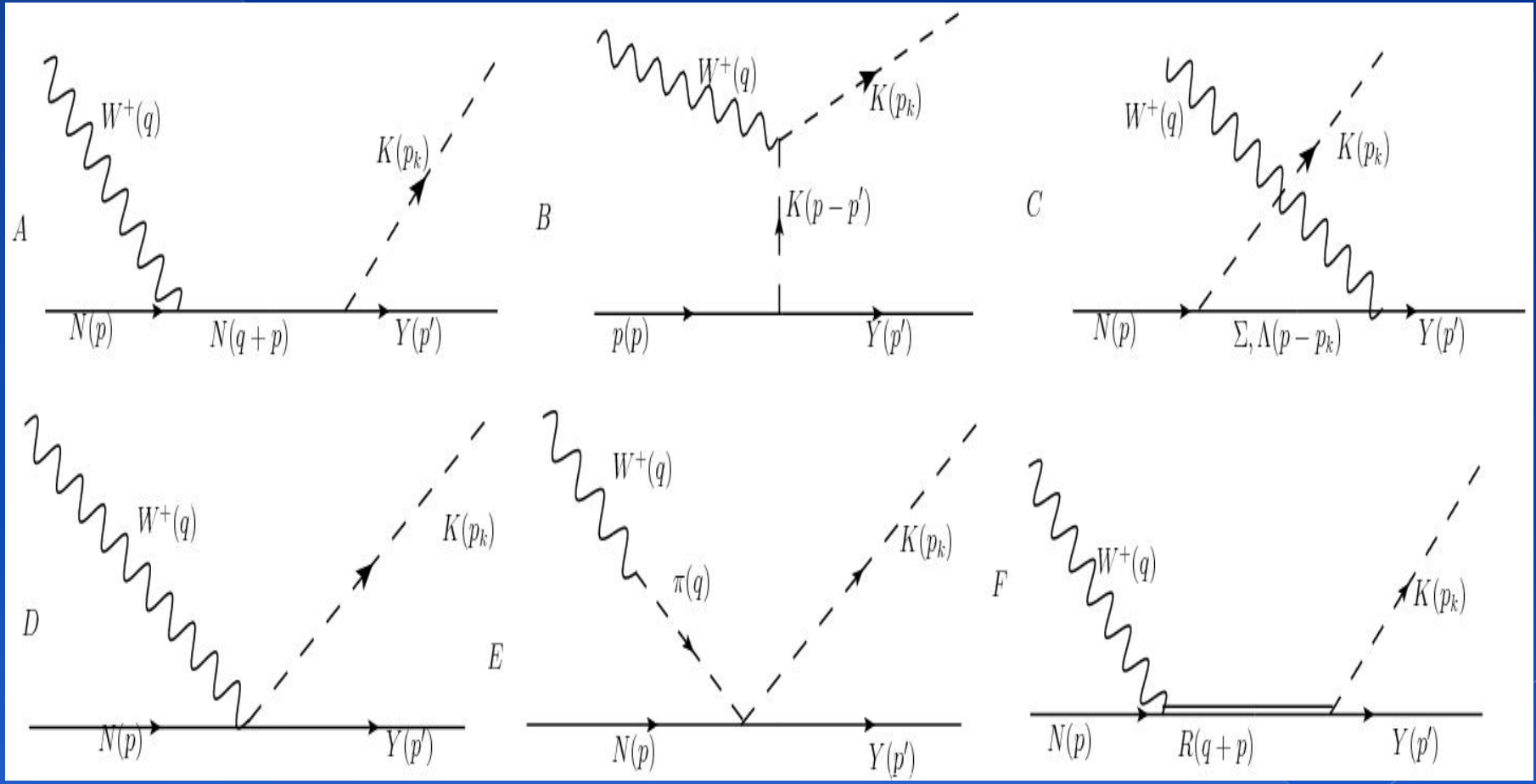
Neutrino

$$\nu_l n \longrightarrow l^- K^0 \Sigma^+$$
$$\nu_l n \longrightarrow l^- K^+ \Lambda^0$$
$$\nu_l n \longrightarrow l^- K^+ \Sigma^0$$
$$\nu_l p \longrightarrow l^- K^+ \Sigma^+$$

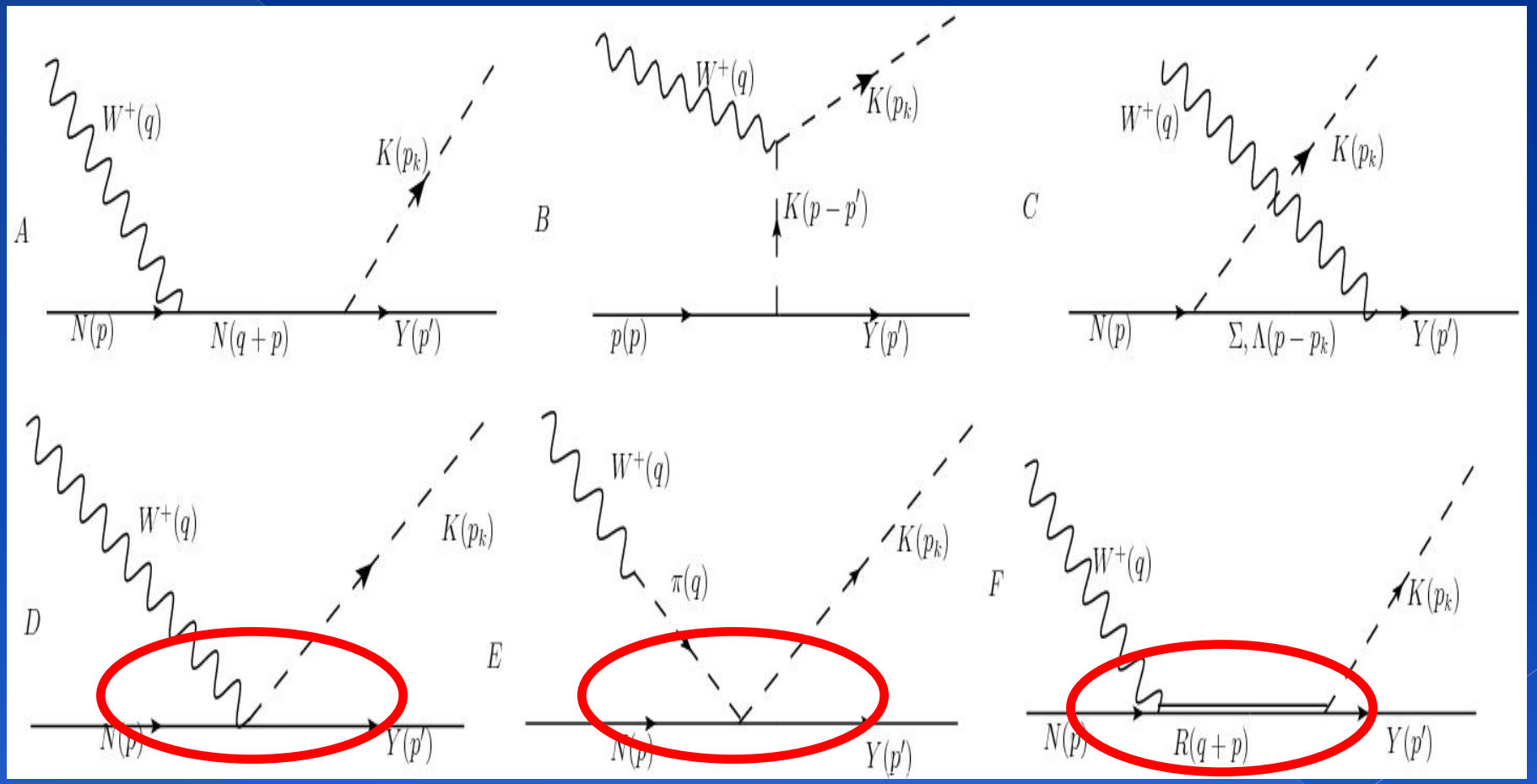
Antineutrino

$$\bar{\nu}_l p \longrightarrow l^+ \Sigma^- K^+$$
$$\bar{\nu}_l p \longrightarrow l^+ \Lambda^0 K^0$$
$$\bar{\nu}_l p \longrightarrow l^+ \Sigma^0 K^0$$
$$\bar{\nu}_l n \longrightarrow l^+ \Sigma^0 K^-$$

Feynman diagrams for the neutrino induced process



Feynman diagrams for the neutrino induced process



Contributions to the hadronic current for neutrino induced process

$$j^\mu|_{SY} = iA_S V_{ud}\frac{\sqrt{2}}{2f_\pi}\,\bar{u}_Y(p')\not{p}_k\gamma^5\frac{\not{p}+\not{q}+M}{(p+q)^2-M^2}\left(\gamma^\mu+i\frac{\mu_p-\mu_n}{2M}\sigma^{\mu\nu}q_\nu-(D+F)\left(\gamma^\mu-\frac{\not{q}q^\mu}{q^2-m_\pi^2}\right)\gamma^5\right)$$

$$j^\mu|_{U\Sigma} = iA_\Sigma V_{ud}\frac{\sqrt{2}}{2f_\pi}\,\bar{u}_Y(p')\left(\gamma^\mu+iz\frac{2\mu_p+\mu_n}{4M}\sigma^{\mu\nu}q_\nu-F^a\left(\gamma^\mu-\frac{\not{q}q^\mu}{q^2-m_\pi^2}\right)\gamma^5\right)\frac{\not{p}-\not{p}_k+M_\Sigma}{(p-p_k)^2-M_\Sigma^2}\not{p}_k\gamma^5 u_N(p)$$

$$j^\mu|_{U\Lambda} = iA_\Lambda V_{ud}\frac{D+3F}{3\sqrt{2}f_\pi}\,\bar{u}_Y(p')\left(i\frac{3\mu_n}{4M}\sigma^{\mu\nu}q_\nu+D\left(\gamma^\mu-\frac{\not{q}q^\mu}{q^2-m_\pi^2}\right)\gamma^5\right)\frac{\not{p}-\not{p}_k+M_\Lambda}{(p-p_k)^2-M_\Lambda^2}\not{p}_k\gamma^5 u_N(p)$$

$$j^\mu|_{T} = iA_T V_{ud}\frac{\sqrt{2}}{2f_\pi}(M+M_Y)\,\bar{u}_Y(p')\gamma_5\,u_N(p)\;\frac{q^\mu-2p_k^\mu}{(p-p')^2-m_k^2}$$

$$j^\mu|_{CT} = iA_{CT} V_{ud}\frac{\sqrt{2}}{2f_\pi}\,\bar{u}_Y(p')\left(\gamma^\mu+B_{CT}\,\gamma^\mu\gamma^5\right)u_N(p)$$

$$j^\mu|_{\pi F} = iA_\pi V_{ud}\frac{\sqrt{2}}{4f_\pi}\,\bar{u}_Y(p')(\not{q}+\not{p}_k)u_N(p)\frac{q^\mu}{q^2-m_\pi^2}$$

[a] for $\nu_l n \to l^- K^+ \Lambda$ replace F by D

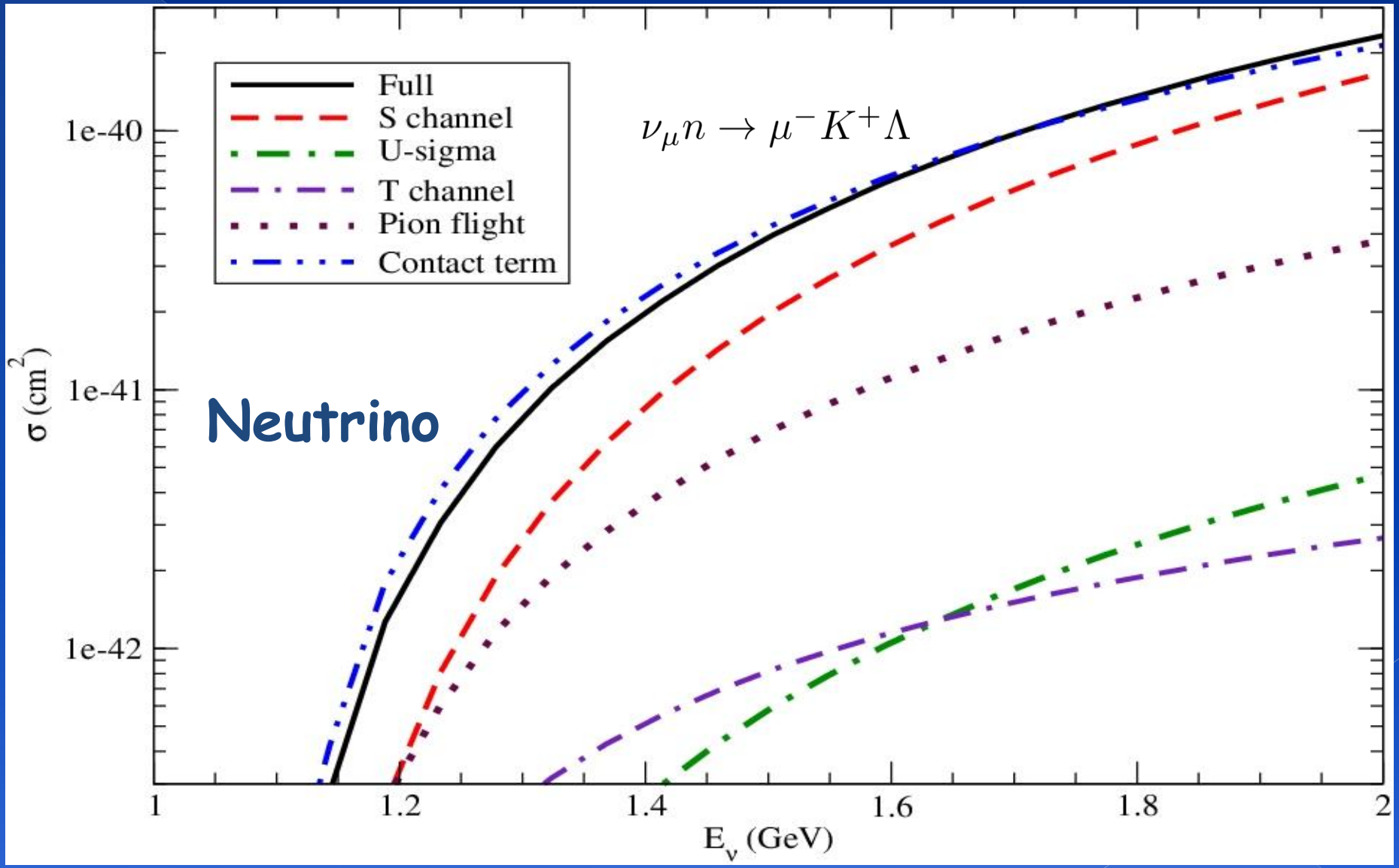
Neutrino

Process	A_S	A_Σ	A_Λ	A_T	A_{CT}	B_{CT}	A_π
$\nu_l n \to l^- K^0 \Sigma^+$	$D-F$	$D-F$	1	0	0	0	0
$\nu_l n \to l^- K^+ \Lambda$	$-\frac{(D+3F)}{\sqrt{6}}$	$-\sqrt{\frac{2}{3}}(D-F)$	0	$-\frac{D+3F}{\sqrt{6}}$	$-\sqrt{\frac{3}{2}}$	$-F-\frac{D}{3}$	$\sqrt{\frac{3}{2}}$
$\nu_l n \to l^- K^+ \Sigma^0$	$\frac{(D-F)}{\sqrt{2}}$	$\sqrt{2}(D-F)$	0	$-\frac{D-F}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}$	$D-F$	$\frac{-1}{\sqrt{2}}$
$\nu_l p \to l^- K^+ \Sigma^+$	0	$F-D$	1	$D-F$	-1	$D-F$	1

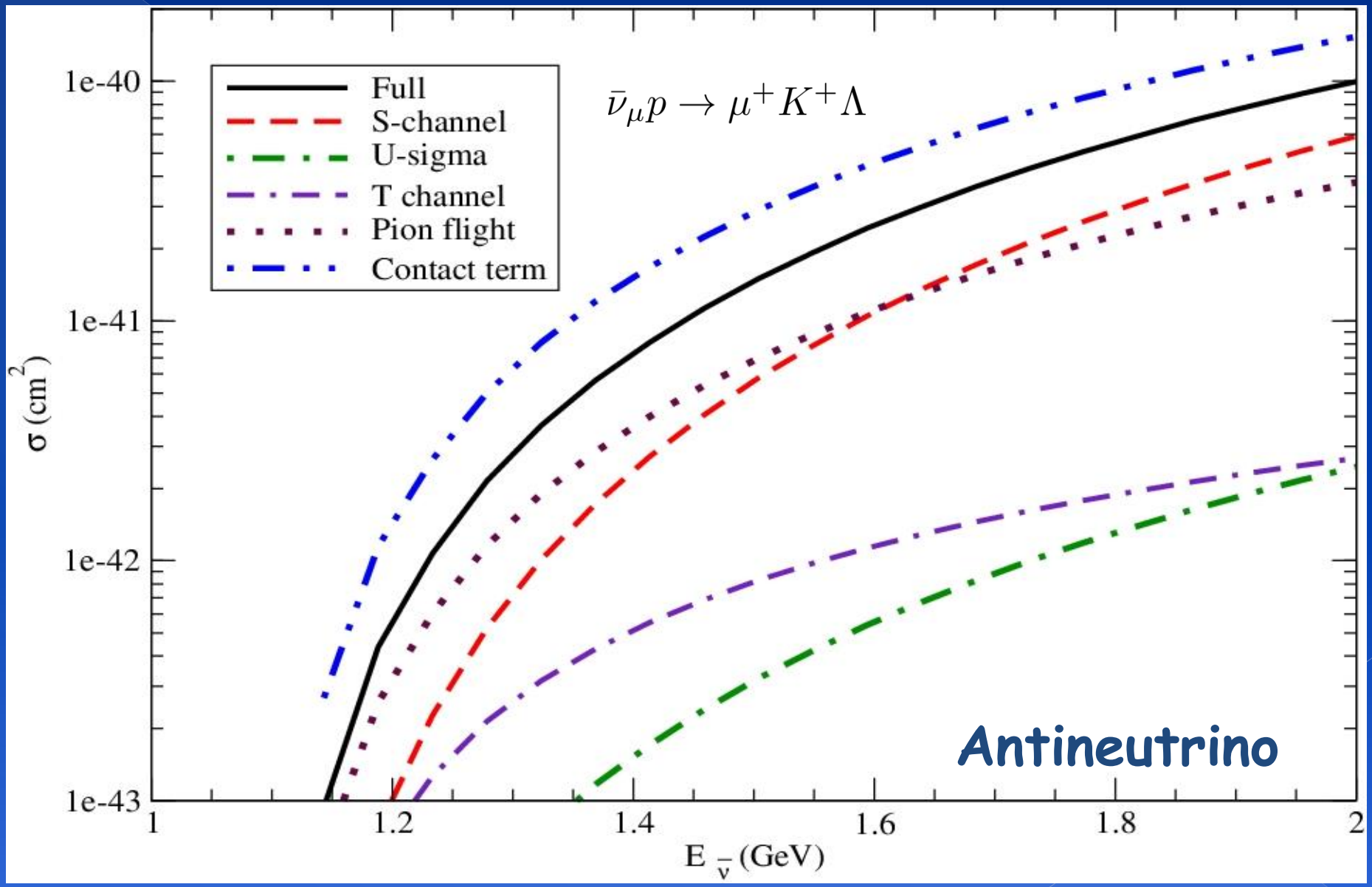
Antineutrino

Process	A_S	A_Σ	A_Λ	A_T	A_{CT}	B_{CT}	A_π
$\bar{\nu}_l p \to l^+ \Sigma^- K^+$	$D-F$	$D-F$	1	0	0	0	0
$\bar{\nu}_l p \to l^+ \Lambda^0 K^0$	$-\frac{(D+3F)}{\sqrt{6}}$	$-\sqrt{\frac{2}{3}}(D-F)$	0	$-\frac{(D+3F)}{\sqrt{6}}$	$-\sqrt{\frac{3}{2}}$	$-\frac{D}{3}-F$	$\sqrt{\frac{3}{2}}$
$\bar{\nu}_l p \to l^+ \Sigma^0 K^0$	$\frac{(F-D)}{\sqrt{2}}$	$\sqrt{2}(F-D)$	0	$\frac{D-F}{\sqrt{2}}$	$-\frac{1}{\sqrt{2}}$	D - F	$\sqrt{\frac{1}{2}}$
$\bar{\nu}_l n \to l^+ \Sigma^0 K^-$	0	$F-D$	1	$D-F$	-1	$D-F$	-1

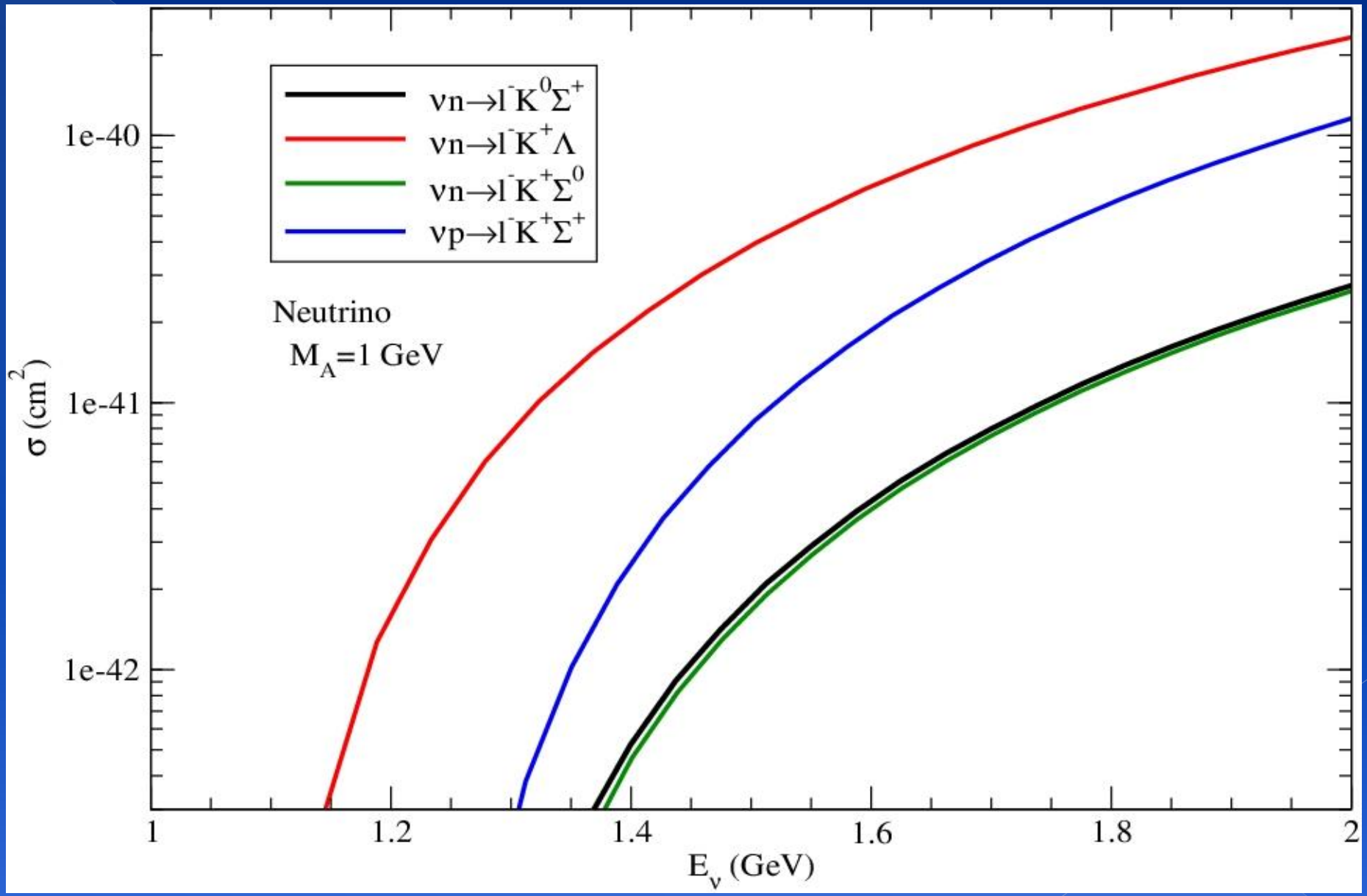
Cross Section vs E

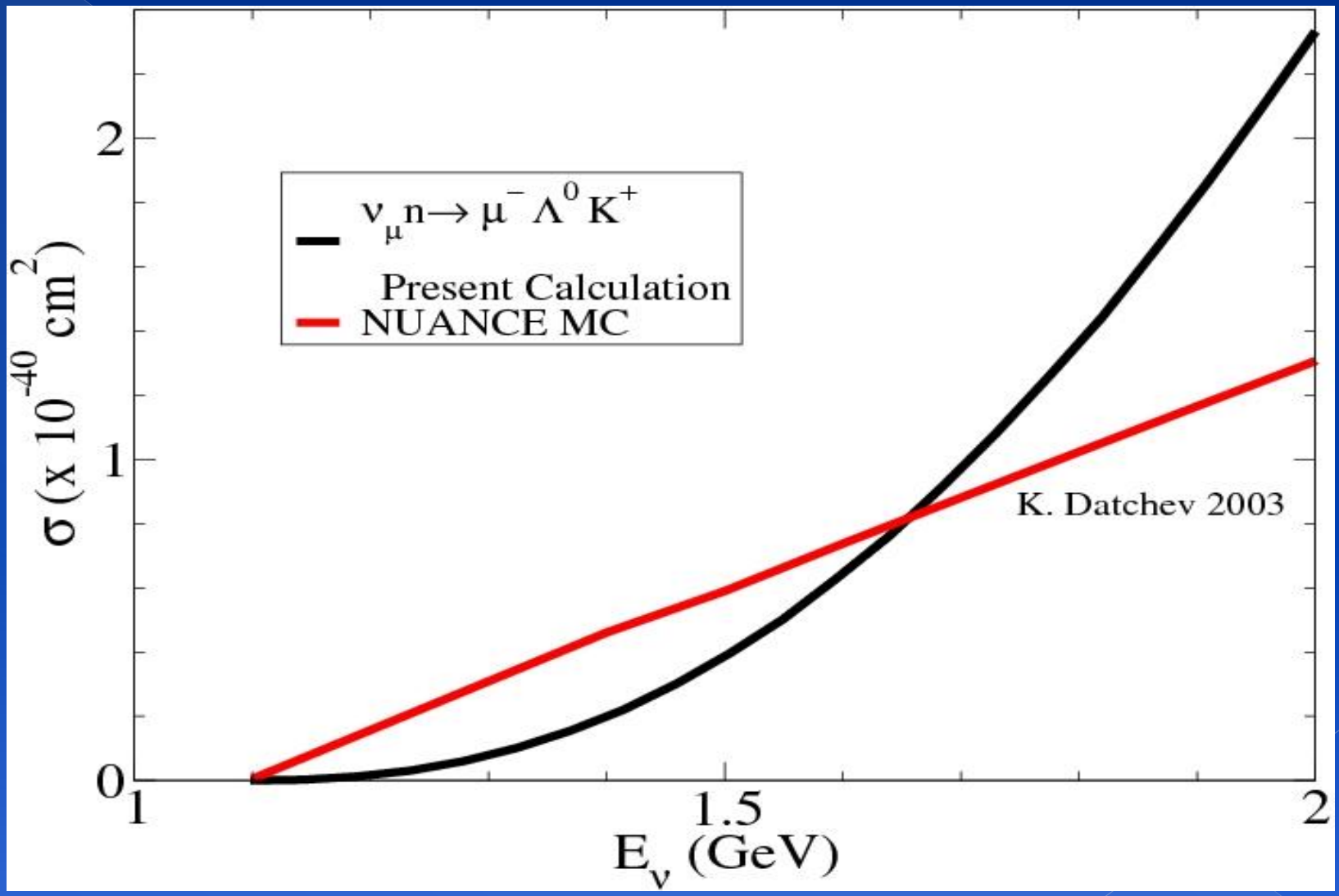


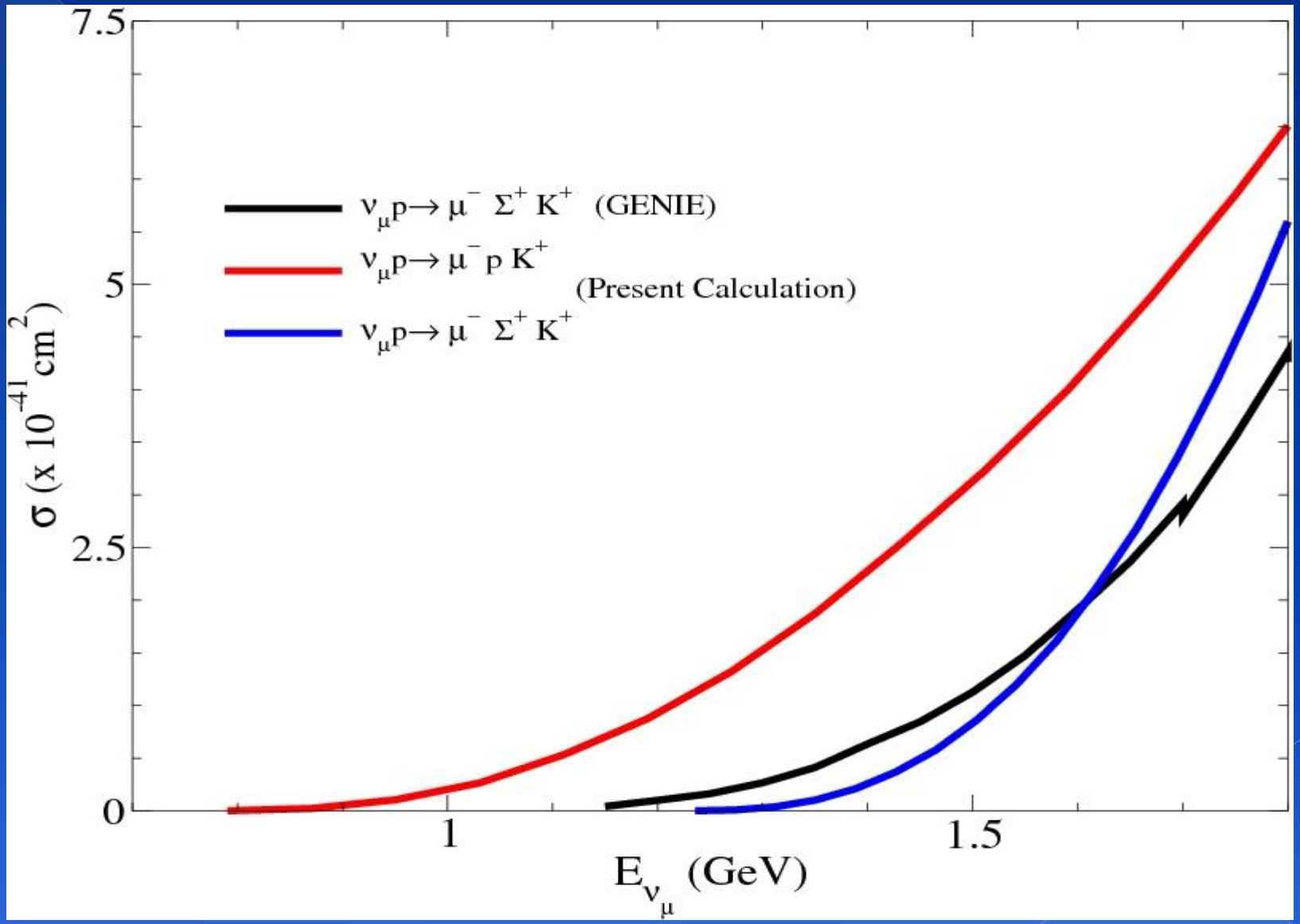
Cross Section Vs E



Cross Section Vs E (Full contribution)



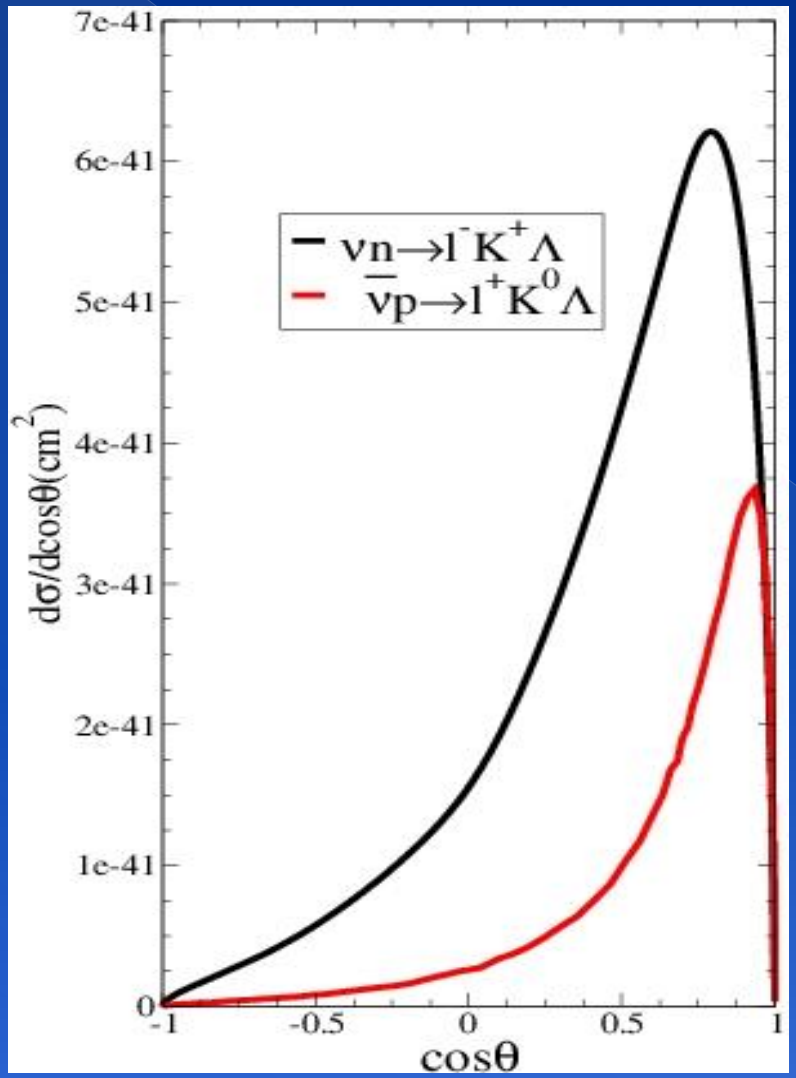

$\nu_\mu n \rightarrow \mu^- \Lambda^0 K^+$
Present Calculation
NUANCE MC
K. Datchev 2003
σ (x 10^{-40} cm^2)
0
1
2
1
1.5
2
E_ν (GeV)


7.5
5
2.5
0
1
1.5
σ (x 10^{-41} cm^2)
E_{ν_μ} (GeV)
$\nu_\mu p \rightarrow \mu^- \Sigma^+ K^+$ (GENIE)
$\nu_\mu p \rightarrow \mu^- p K^+$
(Present Calculation)
$\nu_\mu p \rightarrow \mu^- \Sigma^+ K^+$

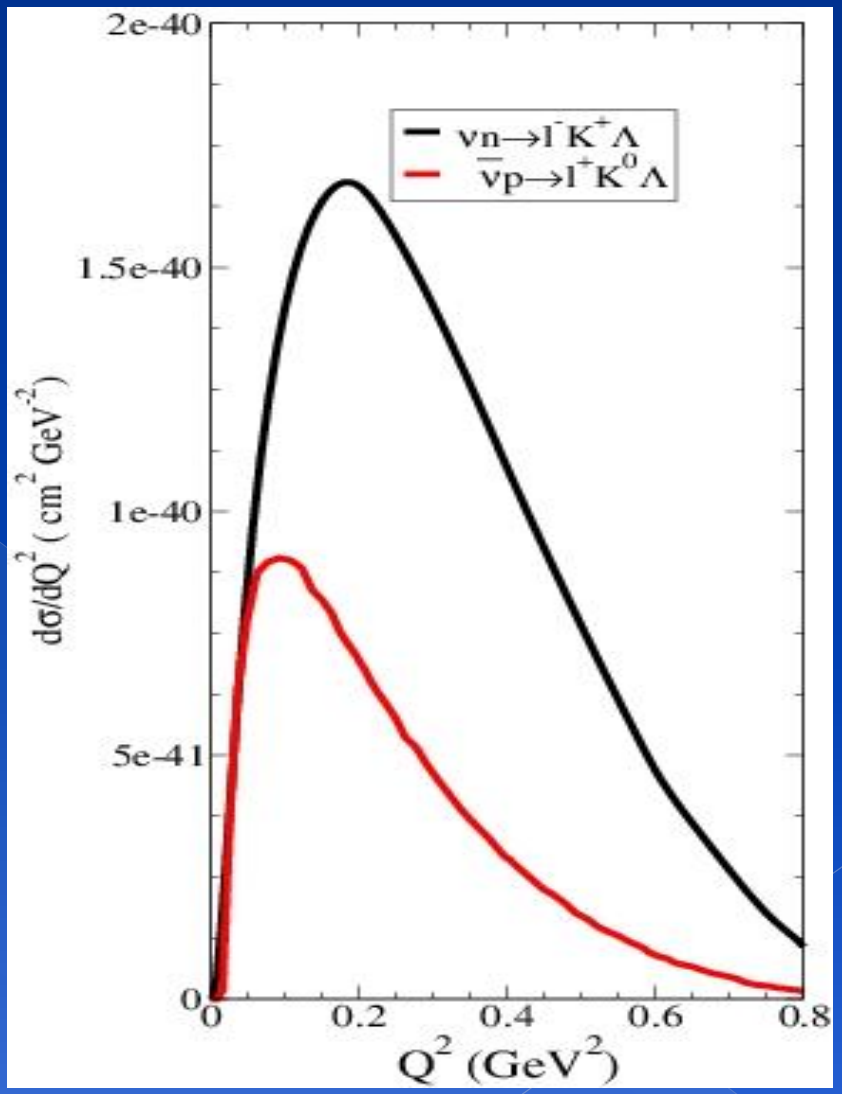
Resonances

Particle	Decay	%	I(J^P)
N(1650)	Λ K	3-11	$\frac{1}{2}(\frac{1^-}{2})$
N(1710)	Λ K	5-25	$\frac{1}{2}(\frac{1^+}{2})$
N(1720)	Λ K	1-15	$\frac{1}{2}(\frac{3^+}{2})$

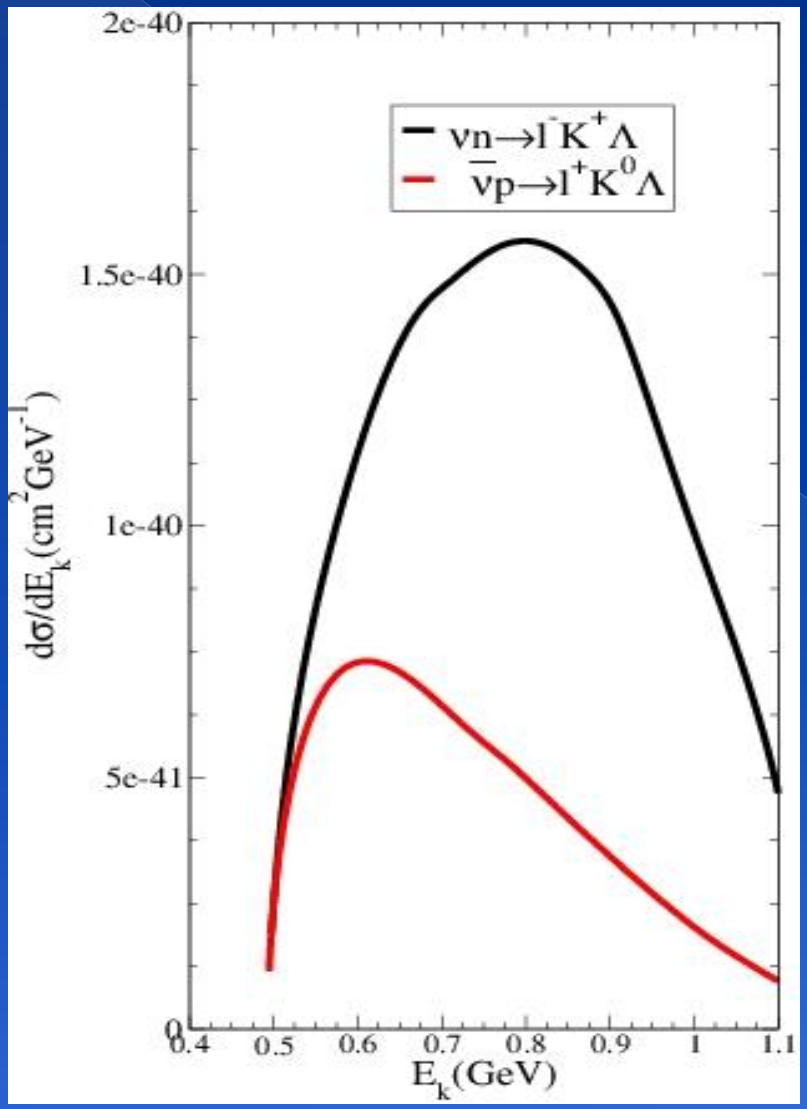
Angular distribution



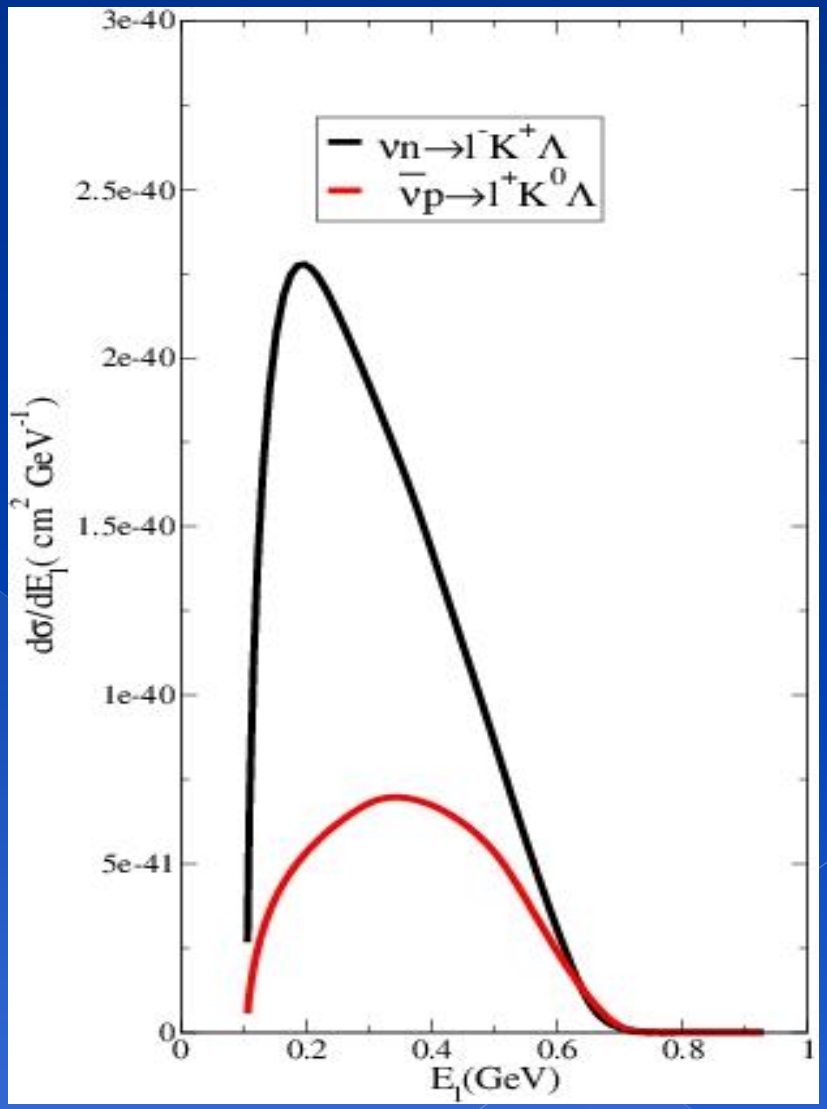
Q^2 distribution



E_k distribution



E_l distribution



Eta Production

Charged current ν(anti-ν) induced eta production

$$\nu_e(k) + N(p) \rightarrow e^-(k') + N'(p') + \eta(p_\eta)$$

$$\bar{\nu}_e(k) + N(p) \rightarrow e^+(k') + N'(p') + \eta(p_\eta)$$

The expression for the differential cross section in the laboratory (lab) frame for the above process is given by,

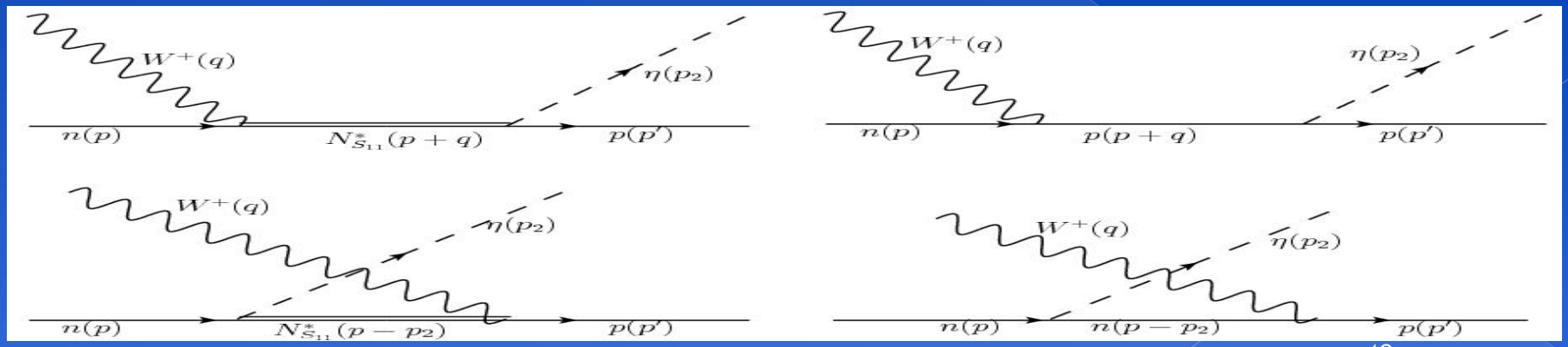
$$d^9\sigma = \frac{1}{4ME(2\pi)^5}\frac{d\vec{k}'}{(2E_l)}\frac{d\vec{p}'}{(2E'_p)}\frac{d\vec{p}_\eta}{(2E_\eta)}\delta^4(k+p-k'-p'-p_\eta)\bar{\Sigma}\Sigma|\mathcal{M}|^2,$$

where the transition amplitude is written as

$$\mathcal{M} = \frac{G_F}{\sqrt{2}}j_\mu^{(L)}J^{\mu\,(H)} = \frac{g}{2\sqrt{2}}j_\mu^{(L)}\frac{1}{M_W^2}\frac{g}{2\sqrt{2}}J^{\mu\,(H)},$$

$$j_\mu^L = \bar{u}(k')\gamma^\mu(1-\gamma_5)\nu_l \ ,$$

We have obtained the hadronic current for s-channel and u-channel nucleon Born terms and s-channel and u-channel resonant S11(1535) and S11(1650) terms.



$$j^{\mu}{}_{s} = i\frac{D-3F}{2\sqrt{3}f_{\pi}}V_{ud}\bar{u}_{p}(p')\not{p}_{\eta}\gamma^{5}\frac{\not{p}+\not{q}+M}{(p+q)^{2}-M^{2}}\mathcal{J}^{\mu}_{N}u_{n}(p)$$

$$j^{\mu}{}_{u} = i\frac{D-3F}{2\sqrt{3}f_{\pi}}V_{ud}\bar{u}_{p}(p')\mathcal{J}^{\mu}_{N}\frac{\not{p}-\not{p}_{\eta}+M}{(p-p_{\eta})^{2}-M^{2}}\not{p}_{\eta}\gamma^{5}u_{n}(p)$$

$$j^{\mu}_{s}{}^{R} = i\frac{g_{\eta NS_{11}}V_{ud}}{f_{\pi}}\bar{u}_{p}(p')\frac{\not{p}+\not{q}+M_{R}}{(p+q)^{2}-M_{R}^{2}+i\Gamma_{R}M_{R}}\mathcal{J}^{\mu}_{R}\gamma^{5}u_{n}(p)$$

$$j^{\mu}_{u}{}^{R} = i\frac{g_{\eta NS_{11}}V_{ud}}{f_{\pi}}\bar{u}_{p}(p')\tilde{\mathcal{J}}^{\mu}_{R}\gamma^{5}\frac{\not{p}-\not{p}_{\eta}+M_{R}}{(p-p_{\eta})^{2}-M_{R}^{2}+i\Gamma_{R}M_{R}}u_{n}(p)$$

where

$$\mathcal{J}^{\mu}_{N} = f_{1}^{V}(Q^{2})\gamma^{\mu}+f_{2}^{V}(Q^{2})\,i\,\sigma^{\mu\rho}\frac{q_{\rho}}{2M_{N}}-\left(f^{A}(Q^{2})\gamma^{\mu}+f^{P}(Q^{2})q^{\mu}\right)\gamma^{5}$$

$$\mathcal{J}^{\mu}_{R} = \frac{F_{1}^{V}(Q^{2})}{4M_{N}^{2}}(Q^{2}\gamma^{\mu}+\not{q}q^{\mu})+\frac{F_{2}^{V}(Q^{2})}{2M_{N}}i\sigma^{\mu\rho}q_{\rho}-\left(F^{A}(Q^{2})\gamma^{\mu}+F^{P}(Q^{2})q^{\mu}\right)\gamma^{5}$$

$$\tilde{\mathcal{J}}^{\mu} = \gamma^{0}\mathcal{J}^{\mu\dagger}\gamma^{0}$$

$f_{1,2}{}^{V}$ are isovector form factors for the nucleons which are expressed in terms of Dirac and Pauli form factors, which in turn are expressed in terms of electric and magnetic Sach's form factors. We have taken BBBA05 parametrisation.

$$f_1^V(Q^2) = f_1^p(Q^2) - f_1^n(Q^2); \qquad f_2^V(Q^2) = f_2^p(Q^2) - f_2^n(Q^2)$$

$$f^A(Q^2) = \frac{f^A(0)}{(1+\frac{Q^2}{M_A^2})^2}; \qquad f^P(Q^2) = \frac{2M}{m_\pi^2+Q^2} f^A(Q^2)$$

$$F_1^V(Q^2) = F_1^p(Q^2) - F_1^n(Q^2); \qquad F_2^V(Q^2) = F_2^p(Q^2) - F_2^n(Q^2)$$

$$F^A(Q^2) = \frac{F^A(0)}{(1+\frac{Q^2}{M_A^2})^2}; \qquad F^P(Q^2) = \frac{M_R - M_N}{m_\pi^2+Q^2} F^A(Q^2)$$

$$f^A(0) = 1.26, \quad F^A(0) = 2g_\pi^* \text{ where } g_\pi^* \sim 0.106$$

The total width is taken as

$$\Gamma_R(1535) = 0.42\,\Gamma_{N^*\to N\eta} + 0.46\,\Gamma_{N^*\to N\pi} + 0.12\,\Gamma_{N^*\to X}$$
$$\Gamma_R(1650) = 0.10\,\Gamma_{N^*\to N\eta} + 0.70\,\Gamma_{N^*\to N\pi} + 0.20\,\Gamma_{N^*\to X}$$

We have taken the following form for S-wave decay width

$$\Gamma_R(S11 \to Nm) = \frac{g_m^2 p_m^{CM}}{8\pi f_\pi^2} \frac{[(W^2 - M^2)^2 - m^2(2M_R^2 + M^2 - W^2 - 2MM_R)]}{W^2}$$

$$p_m^{CM} = \frac{\sqrt{\lambda(W^2, m^2, M_N^2)}}{2W}$$

For S11-1535, $g_{\eta N S_{11}} = 0.286$ and for S11-1650, $g_{\eta N S_{11}} = 0.0867$

$$A_{\frac{1}{2}}^{p,n} = \sqrt{\frac{2\pi\alpha}{M_N} \frac{(M_R + M_N)^2 + Q^2}{M_R^2 - M_N^2}} \left(\frac{Q^2}{4M_N^2} F_1^{p,n}(Q^2) + \frac{M_R - M_N}{2M_N} F_2^{p,n}(Q^2) \right)$$

$$S_{\frac{1}{2}}^{p,n} = \sqrt{\frac{\pi\alpha}{M_N} \frac{(M_R - M_N)^2 + Q^2}{M_R^2 - M_N^2} \frac{(M_R - M_N)^2 + Q^2}{4M_R M_N}} \left(\frac{M_R - M_N}{2M_N} F_1^{p,n}(Q^2) - F_2^{p,n}(Q^2) \right)$$

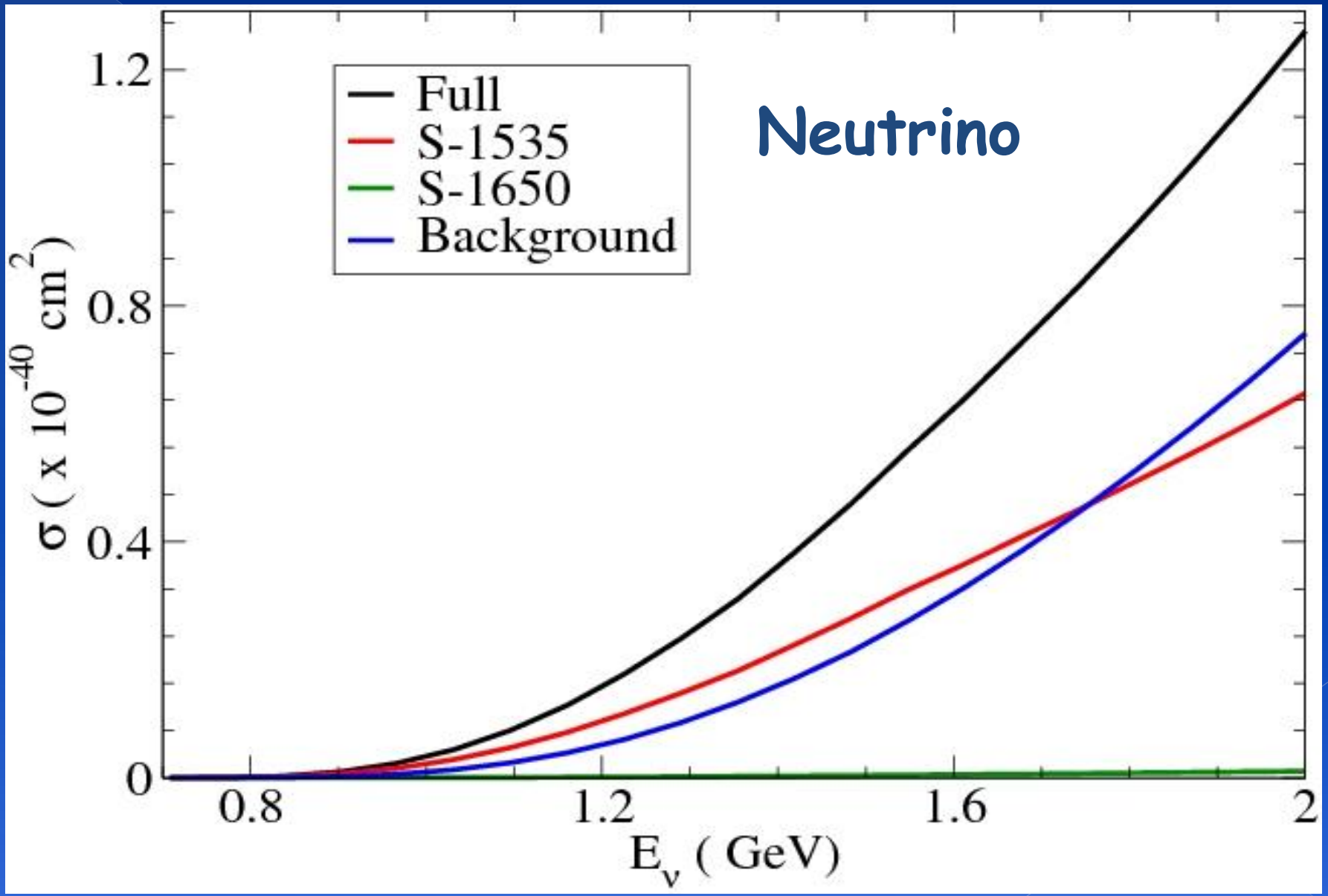
S11(1535)

$$
\begin{aligned}
A^p_{1/2}(Q^2) &= 69.2 \times 10^{-3}(1. + 1.61364Q^2)\ e^{-0.75879Q^2}, \\
S^p_{1/2}(Q^2) &= -16.5 \times 10^{-3}(1. + 2.8261Q^2)\ e^{-0.73735Q^2}, \\
A^n_{1/2}(Q^2) &= -52.79 \times 10^{-3}(1. + 2.86297Q^2)\ e^{-1.68723Q^2}, \\
S^n_{1/2}(Q^2) &= 29.66 \times 10^{-3}(1. + 0.35874Q^2)\ e^{-1.55Q^2}
\end{aligned}
$$

S11(1650)

$$
\begin{aligned}
A^p_{1/2}(Q^2) &= 33.3 \times 10^{-3} \times (1. + 1.45Q^2)\ e^{0.62Q^2}, \\
S^p_{1/2}(Q^2) &= -3.5 \times 10^{-3} \times (1. + 2.88\ Q^2)\ e^{0.76Q^2}, \\
A^n_{1/2}(Q^2) &= 9.3 \times 10^{-3} \times (1. + 0.13\ Q^2)\ e^{1.55Q^2}, \\
S^n_{1/2}(Q^2) &= 10.0 \times 10^{-3} \times (1. - 0.5\ Q^2)\ e^{1.55Q^2}
\end{aligned}
$$

Preliminary



Conclusions

1. We have obtained cross sections for the single kaon production, eta production and associated particle production at the neutrino energies of 1-2 GeV.

2. We find the contribution of contact term to be significant in single kaon production as well as in the associated particle production.

3. Contribution of S11(1535) resonance to neutrino induced eta production is not dominant one, unlike the electromagnetic interactions.

4. Results of the associated particle production also require the contribution of resonant channels, which we are planning to include.

THANK
YOU!

Appendix

$D_\mu U$ is covariant derivative given as,

$$D_\mu U \equiv \partial_\mu U - i r_\mu U + i U l_\mu$$

with l_μ and r_μ as left and right handed external currents.

For the charged current case,

$$r_\mu = 0, \quad l_\mu = -\frac{g}{\sqrt{2}}(W_\mu^+ T_+ + W_\mu^- T_-),$$

g is the weak gauge coupling related with Fermi coupling constant G_F as,

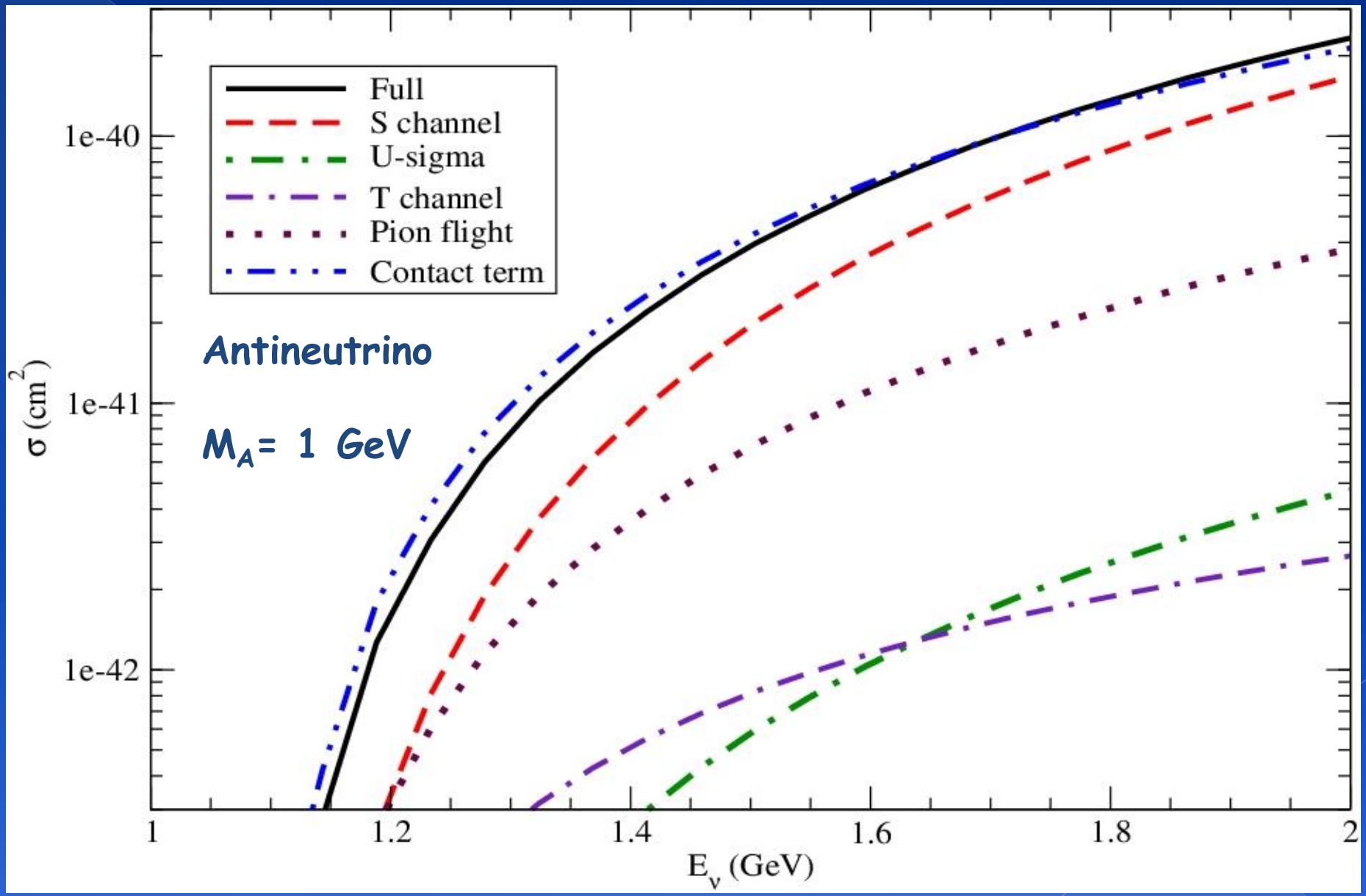
$$G_F = \sqrt{2}\frac{g^2}{8M_W^2} = 1.16639(1) \times 10^{-5}\,\mathrm{GeV}^{-2}$$

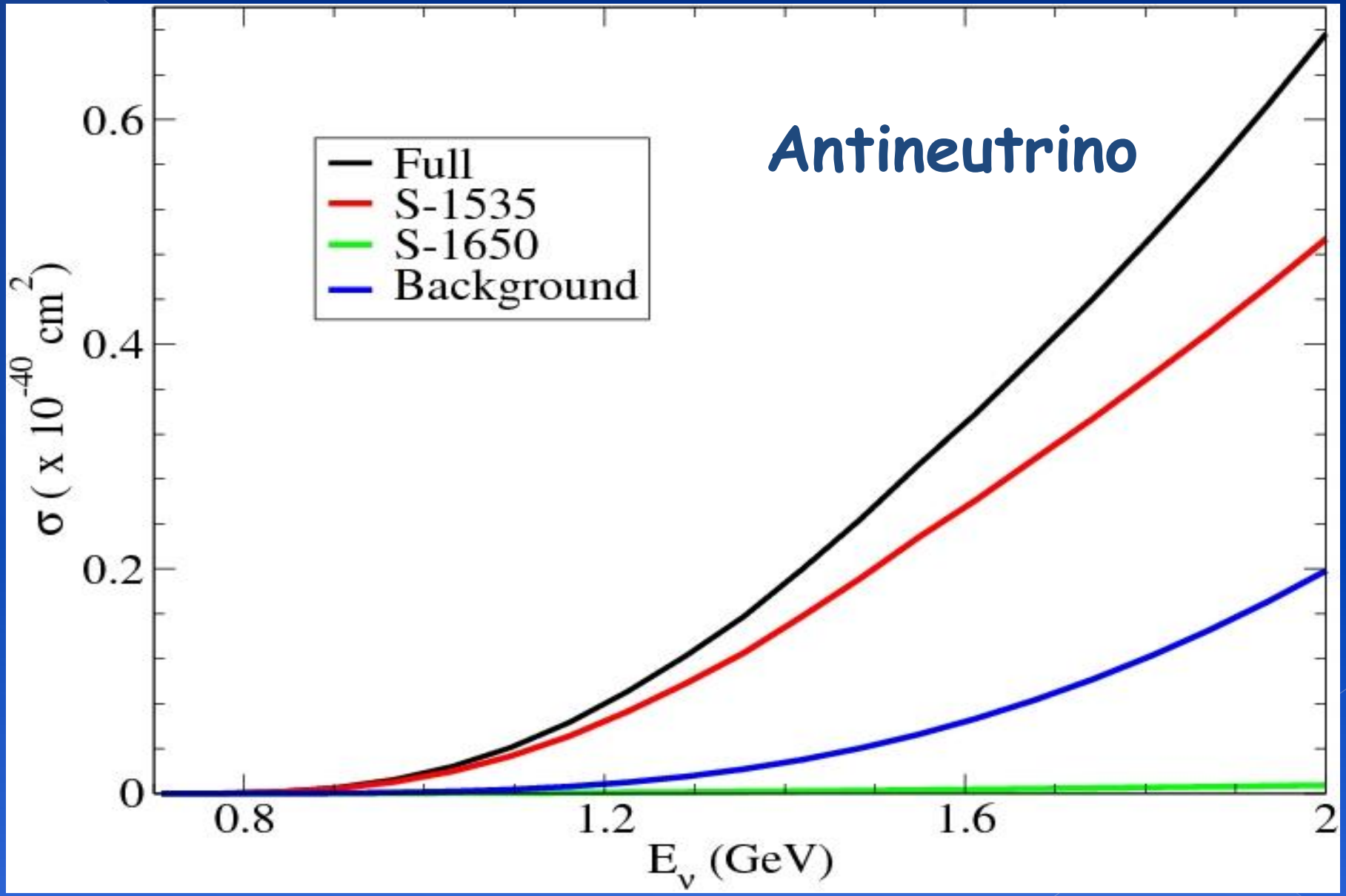
$$T_+ = \begin{pmatrix} 0 & V_{ud} & V_{us} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}; \quad T_- = \begin{pmatrix} 0 & 0 & 0 \\ V_{ud} & 0 & 0 \\ V_{us} & 0 & 0 \end{pmatrix}.$$

V_{ij} denote the elements of the CKM quark mixing matrix describing the transformation between the mass eigen states of the QCD and the weak eigen states.

$|V_{ud}|=0.9735 \pm 0.0008$ and $|V_{us}|=0.2196 \pm 0.0023$

Cross Section Vs E (Full contribution)




Antineutrino
Full
S-1535
S-1650
Background
σ (x 10^-40 cm^2)
0
0.2
0.4
0.6
0.8
1.2
1.6
2
E_ν (GeV)