Phenomenology of weak meson production

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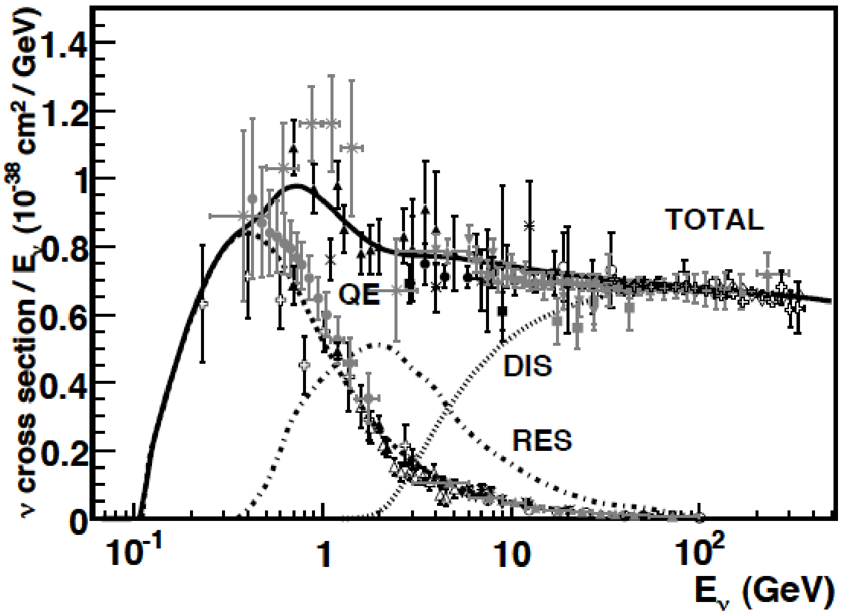
Introduction

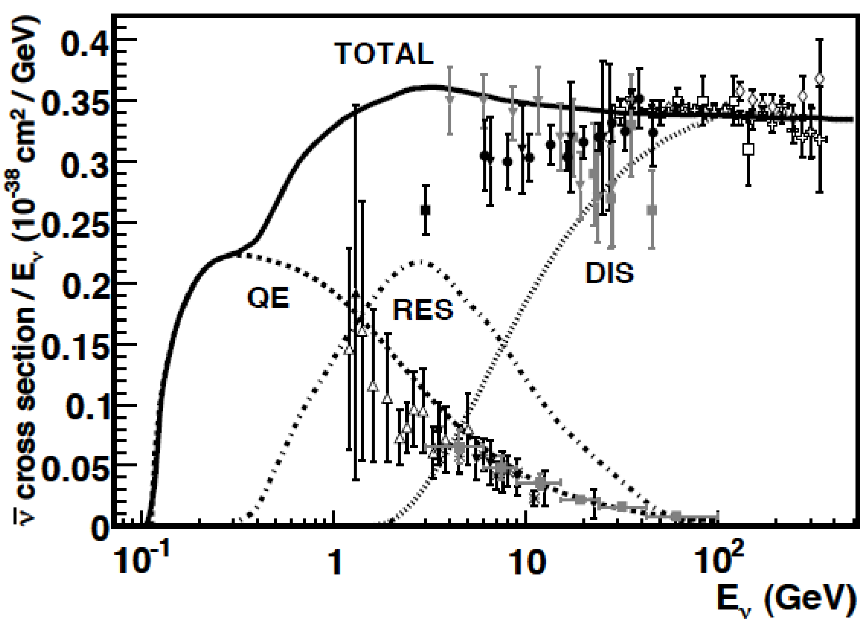
- Neutrino interactions with matter are at the heart all experiments seeking to unravel its nature.
- Oscillation experiments (with accelerator ν in the few-GeV region): T2K, NOvA, MicroBooNE, Hyper-K, DUNE/LBNF
  - Good understanding of neutrino interactions are important for:
    - ν detection, E_ν reconstruction, ν flux calibration
    - determination of (irreducible) backgrounds
    - reduction of systematic errors
    - needed in the quest for CP violation and ν mass hierarchy
  - Precision of 1-5% in ν cross sections are required

Introduction

- Neutrino interactions with matter are at the heart of many interesting and relevant physical processes
  - Astrophysics
    - Dynamics of the core-collapse in supernovae
    - r-process nucleosynthesis
  - Physics Beyond the Standard Model
    - Non-standard ν interactions
  - **Hadronic physics**
    - Nucleon and Nucleon-Resonance (N-Δ, N-N*) axial form factors
    - Strangeness content of the nucleon spin
  - Nuclear physics
    - Information about: nuclear correlations, MEC, spectral functions
    - Complement electron scattering studies

Introduction





CC cross sections:
world data and NUANCE generator
Formaggio, Zeller, Rev. Mod. Phys. (2012)

Weak meson production

$$\nu_l\, N \to l\, \pi\, N'$$

- CC:
$$\nu_\mu\, p \to \mu^-\, p\, \pi^+, \qquad \overline{\nu}_\mu\, p \to \mu^+\, p\, \pi^-$$
$$\nu_\mu\, n \to \mu^-\, p\, \pi^0, \qquad \overline{\nu}_\mu\, p \to \mu^+\, n\, \pi^0$$
$$\nu_\mu\, n \to \mu^-\, n\, \pi^+, \qquad \overline{\nu}_\mu\, n \to \mu^+\, n\, \pi^-$$
  - source of CCQE-like events (in nuclei)
  - needs to be subtracted for a good E_ν reconstruction
- NC:
$$\nu_\mu\, p \to \nu_\mu\, p\, \pi^0, \qquad \overline{\nu}_\mu\, p \to \overline{\nu}_\mu\, p\, \pi^0$$
$$\nu_\mu\, p \to \nu_\mu\, n\, \pi^+, \qquad \overline{\nu}_\mu\, n \to \overline{\nu}_\mu\, n\, \pi^0$$
$$\nu_\mu\, n \to \nu_\mu\, n\, \pi^0, \qquad \overline{\nu}_\mu\, n \to \overline{\nu}_\mu\, n\, \pi^0$$
$$\nu_\mu\, n \to \nu_\mu\, p\, \pi^-, \qquad \overline{\nu}_\mu\, n \to \overline{\nu}_\mu\, p\, \pi^-$$
  - e-like background to $\nu_\mu \to \nu_e$ (T2K)

Weak meson production

- ΔS = 0 e.g. $\nu_l \, p(n) \to l^- \, K^+ \, \Sigma^+(\Lambda)$ Nakamura et al.,arXiv:1506.03403
- ΔS = 1 :
  - Cabibbo suppressed but with lower thresholds than ΔS = 0
  - Kaon: $$\begin{aligned} \nu_l \, p &\to l^- \, K^+ \, p \\ \nu_l \, n &\to l^- \, K^0 \, p \\ \nu_l \, n &\to l^- \, K^+ \, n \end{aligned}$$
    - Background for proton decay p $\to \nu$ K^+

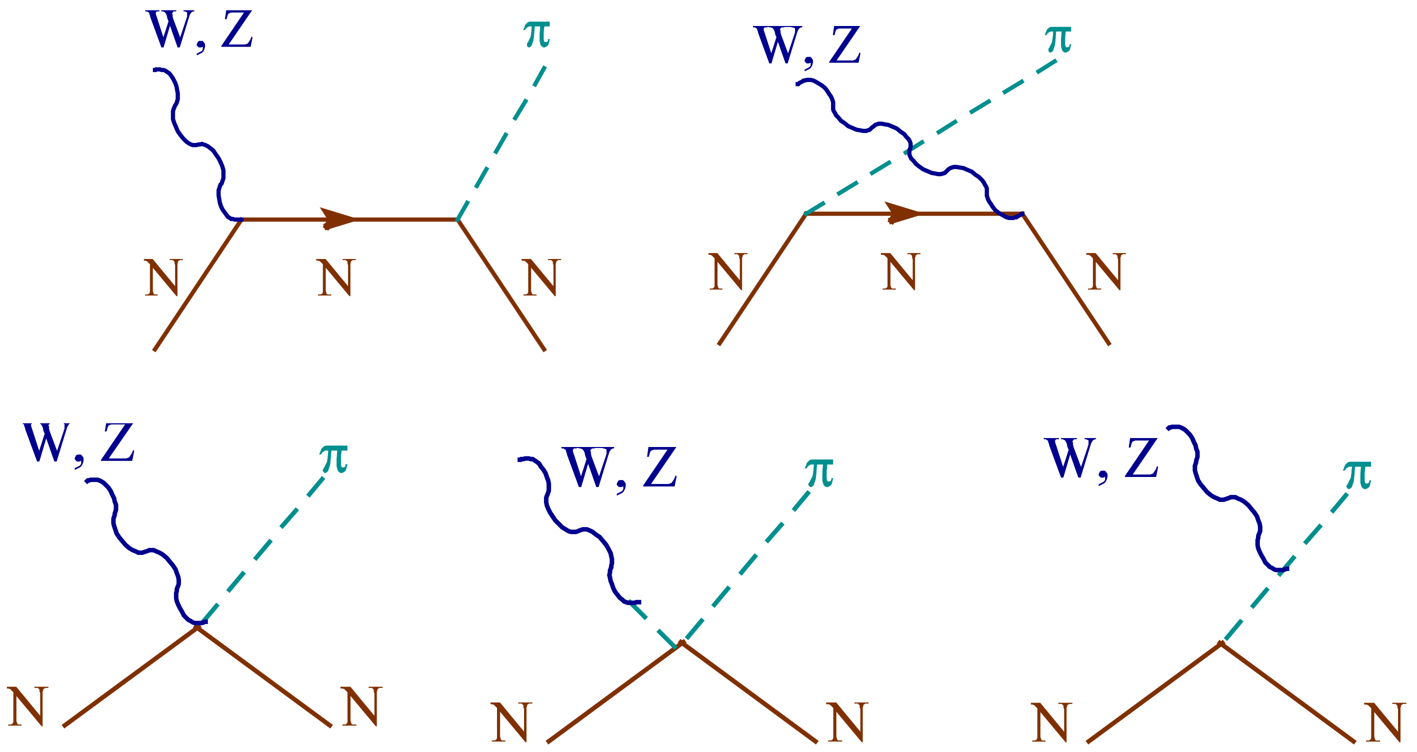
Weak meson production

- ΔS = -1 :
  - Cabibbo suppressed but with lower thresholds than ΔS = 0
  - antiKaon: $$\begin{aligned} \bar{\nu}_l \, p &\rightarrow l^+ \, K^- \, p \\ \bar{\nu}_l \, p &\rightarrow l^+ \, \bar{K}^0 \, n \\ \bar{\nu}_l \, n &\rightarrow l^+ \, K^- \, n \end{aligned}$$
  - $\Sigma \, \pi$: $$\begin{aligned} \bar{\nu}_l \, p &\rightarrow l^+ \, \Sigma^0 \, \pi^0 \\ \bar{\nu}_l \, p &\rightarrow l^+ \, \Sigma^+ \, \pi^- \\ \bar{\nu}_l \, p &\rightarrow l^+ \, \Sigma^- \, \pi^+ \end{aligned}$$
  - can proceed through the excitation of Λ or Σ resonances
    - in particular: Λ(1405)

1π production on the nucleon

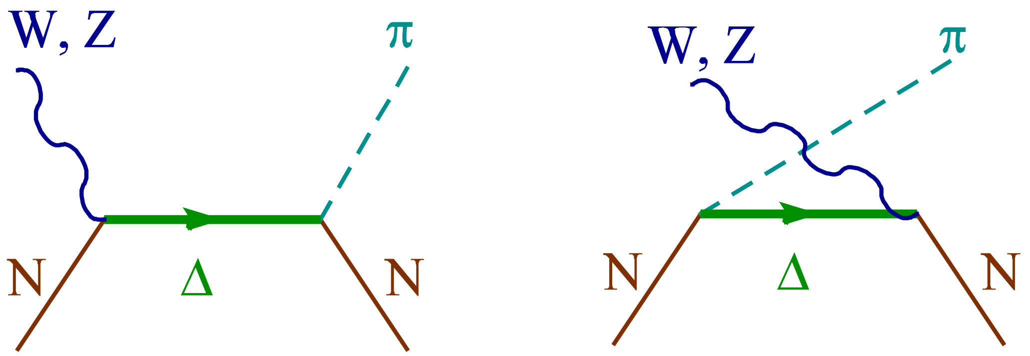
$$\nu_l \, N \rightarrow l \, \pi \, N'$$

- From Chiral symmetry:



1π production on the nucleon

- Δ (1232) excitation:



- N-Δ transition current:

$$J^\mu = \bar{\psi}_\mu \left[\left(\frac{C_3^V}{M}(g^{\beta\mu} \not{q} - q^\beta \gamma^\mu) + \frac{C_4^V}{M^2}(g^{\beta\mu} q \cdot p' - q^\beta p'^\mu) + \frac{C_5^V}{M^2}(g^{\beta\mu} q \cdot p - q^\beta p^\mu) \right) \gamma_5 \right.$$
$$\left. + \frac{C_3^A}{M}(g^{\beta\mu} \not{q} - q^\beta \gamma^\mu) + \frac{C_4^A}{M^2}(g^{\beta\mu} q \cdot p' - q^\beta p'^\mu) + C_5^A g^{\beta\mu} + \frac{C_6^A}{M^2} q^\beta q^\mu \right] u$$

- Vector form factors $\Leftrightarrow$ Helicity amplitudes

1π production on the nucleon

- N-Δ transition current

$$J^\mu = \bar{\psi}_\mu \left[\left(\frac{C_3^V}{M}(g^{\beta\mu}\not{q} - q^\beta\gamma^\mu) + \frac{C_4^V}{M^2}(g^{\beta\mu}q\cdot p' - q^\beta p'^\mu) + \frac{C_5^V}{M^2}(g^{\beta\mu}q\cdot p - q^\beta p^\mu) \right)\gamma_5 \right.$$
$$\left. + \frac{C_3^A}{M}(g^{\beta\mu}\not{q} - q^\beta\gamma^\mu) + \frac{C_4^A}{M^2}(g^{\beta\mu}q\cdot p' - q^\beta p'^\mu) + C_5^A g^{\beta\mu} + \frac{C_6^A}{M^2}q^\beta q^\mu \right] u$$

- Helicity amplitudes can be extracted from data on π photo- and electro-production

$$A_{1/2} = \sqrt{\frac{2\pi\alpha}{k_R}} \left\langle R, J_z = 1/2 \left| \epsilon_\mu^+ J^\mu_{\mathrm{EM}} \right| N, J_z = -1/2 \right\rangle \zeta$$

$$A_{3/2} = \sqrt{\frac{2\pi\alpha}{k_R}} \left\langle R, J_z = 3/2 \left| \epsilon_\mu^+ J^\mu_{\mathrm{EM}} \right| N, J_z = 1/2 \right\rangle \zeta$$

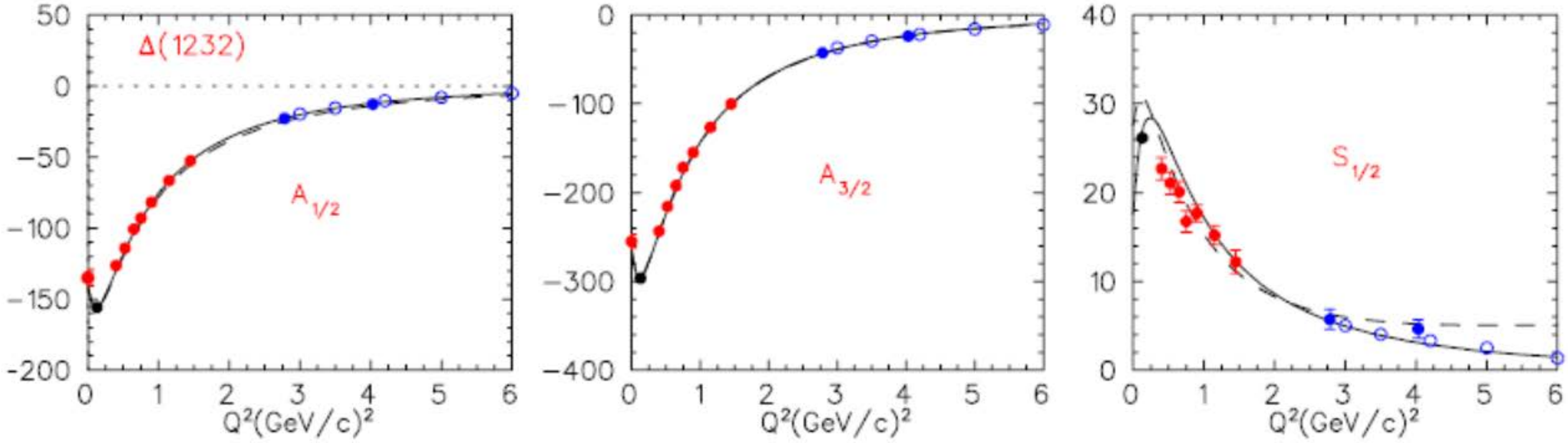
$$S_{1/2} = -\sqrt{\frac{2\pi\alpha}{k_R}} \frac{|\mathbf{q}|}{\sqrt{Q^2}} \left\langle R, J_z = 1/2 \left| \epsilon_\mu^0 J^\mu_{\mathrm{EM}} \right| N, J_z = 1/2 \right\rangle \zeta$$

1π production on the nucleon

- N-Δ transition current

$$J^\mu = \bar\psi_\mu \left[\left(\frac{C_3^V}{M}(g^{\beta\mu}\not q - q^\beta\gamma^\mu) + \frac{C_4^V}{M^2}(g^{\beta\mu} q\cdot p' - q^\beta p'^\mu) + \frac{C_5^V}{M^2}(g^{\beta\mu} q\cdot p - q^\beta p^\mu) \right)\gamma_5 \right.$$
$$\left. + \frac{C_3^A}{M}(g^{\beta\mu}\not q - q^\beta\gamma^\mu) + \frac{C_4^A}{M^2}(g^{\beta\mu} q\cdot p' - q^\beta p'^\mu) + C_5^A g^{\beta\mu} + \frac{C_6^A}{M^2} q^\beta q^\mu \right] u$$

- Helicity amplitudes can be extracted from data on π photo- and electro-production Tiator et al., EPJ Special Topics 198 (2011)



1π production on the nucleon

- N-Δ transition current

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  - Axial form factors

$$C_6^A = C_5^A \frac{M^2}{m_\pi^2 + Q^2} \leftarrow \text{PCAC}$$

$$C_5^A = C_5^A(0) \left(1 + \frac{Q^2}{M_{A\Delta}^2} \right)^{-2}$$

  - Constraints from ANL and BNL data on $\nu_\mu \, d \to \mu^- \, \pi^+ \, p \, n$
    - with large normalization (flux) uncertainties
  - ANL and BNL data do not constrain $C^A_{3,4}$: consistent with zero
    Hernandez et al., PRD81(2010)

1π production on the nucleon

- N-Δ axial form factors: determination of $C^A_5(0)$ and $M_{A\,\Delta}$
- $$C_5^A = C_5^A(0)\left(1+\frac{Q^2}{M_{A\Delta}^2}\right)^{-2}$$
- From ANL and BNL data on $\nu_\mu\, d \to \mu^-\, \pi^+\, p\, n$

- Graczyk et al., PRD 80 (2009)
  - Deuteron effects
  - Non-resonant background absent
  - $C^A_5(0) = 1.19 \pm 0.08$, $M_{A\,\Delta} = 0.94 \pm 0.03$ GeV

- Hernandez et al., PRD 81 (2010)
  - Deuteron effects
  - $C^A_5(0) = 1.00 \pm 0.11$, $M_{A\,\Delta} = 0.93 \pm 0.07$ GeV
  - 20% reduction of the GT relation $C_5^A(0) = \frac{g_{\Delta N\pi} f_\pi}{\sqrt{6}M} \approx 1.2 \leftarrow$ off diagonal GT relation

1π production on the nucleon

- Watson's theorem
  - Unitarity
  - Time reversal invariance

$$\sum_M \langle M|T|F\rangle^* \langle M|T|I\rangle = -2\mathrm{Im}\langle F|T|I\rangle \in \mathbb{R}$$

- For W N $\rightarrow$ π N
  - assuming that |M⟩ = |F⟩ = |π N⟩
  - schematically:

$$\langle \pi N|T|\pi N\rangle^* \langle \pi N|T|W N\rangle = -2\mathrm{Im}\langle \pi N|T|W N\rangle \in \mathbb{R}$$

$$\langle \pi N|T|\pi N\rangle \approx \langle \pi N|T_{\mathrm{strong}}|\pi N\rangle$$

1π production on the nucleon

- Watson's theorem
  - Unitarity
  - Time reversal invariance

- For W N $\rightarrow$ π N

$$\sum_\rho \sum_L \frac{2L+1}{2J+1} (L,1/2,J;0,-\lambda')(L,1/2,J;0,-\rho)\langle J,M;L,1/2|T_{\rm str}|J,M;L,1/2\rangle^* \langle J,M;0,\rho|T|0,0;r,\lambda\rangle \in \mathbb{R}.$$

- For the dominant J=3/2, I=3/2, L=1 $\Leftrightarrow$ P_{33} partial wave

$$\left[\sum_\rho (1,1/2,3/2;0,-\rho)\,(1,1/2,3/2;0,-\rho)\,\langle 3/2,M;0,\rho|T|0,0;r,\lambda\rangle\right] e^{-i\delta_{P_{33}}} \in \mathbb{R}$$

writting $T = T_\Delta + T_B e^{-i\delta(W,q^2)}$ we impose Watson's theorem.

- This approach has been applied for π photo and electroproduction

  Olsson, NPB78 (1974)
  Carrasco, Oset, NPA536 (1992)
  Gil, Nieves, Oset, NPA627 (1997)

1π production on the nucleon

- Watson's theorem
  - Unitarity
  - Time reversal invariance

- For W N $\rightarrow$ π N

$$\sum_\rho \sum_L \frac{2L+1}{2J+1} (L,1/2,J;0,-\lambda')(L,1/2,J;0,-\rho)\langle J,M;L,1/2|T_{\rm str}|J,M;L,1/2\rangle^* \langle J,M;0,\rho|T|0,0;r,\lambda\rangle \in \mathbb{R}$$

- For the dominant J=3/2, I=3/2, L=1 $\Leftrightarrow$ P_{33} partial wave

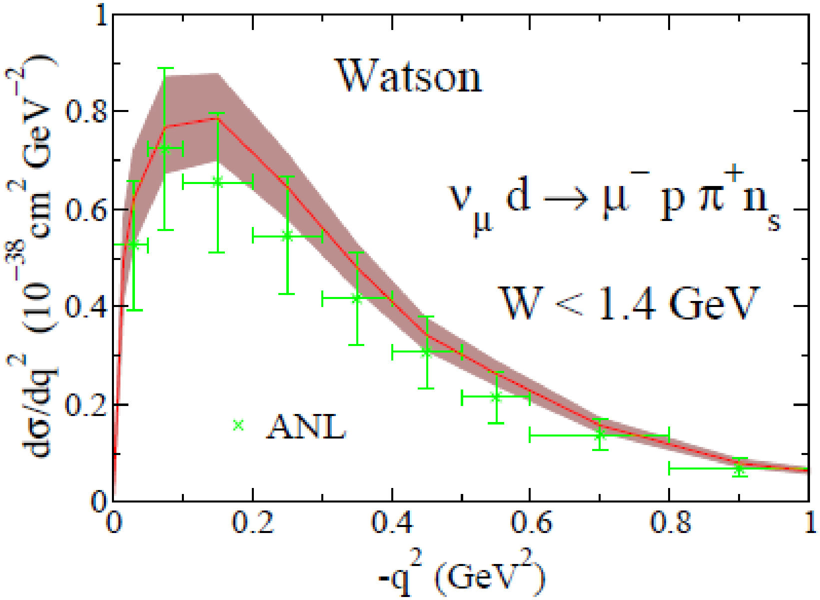
$$\left[\sum_\rho (1,1/2,3/2;0,-\rho)\,(1,1/2,3/2;0,-\rho)\,\langle 3/2,M;0,\rho|T|0,0;r,\lambda\rangle\right] e^{-i\delta_{P_{33}}} \in \mathbb{R}$$

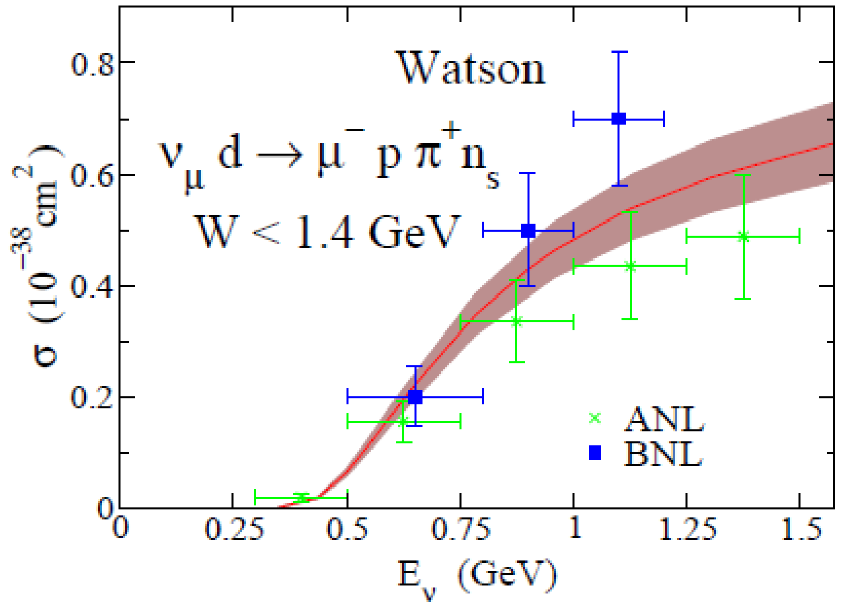
writting $T = T_\Delta + T_B e^{-i\delta(W,q^2)}$ we impose Watson's theorem.

- This approach has been applied for π photo and electroproduction
- In weak production two phases δ_V and δ_A are needed

1π production on the nucleon

- Fit to ANL and BNL data with W < 1.4 GeV

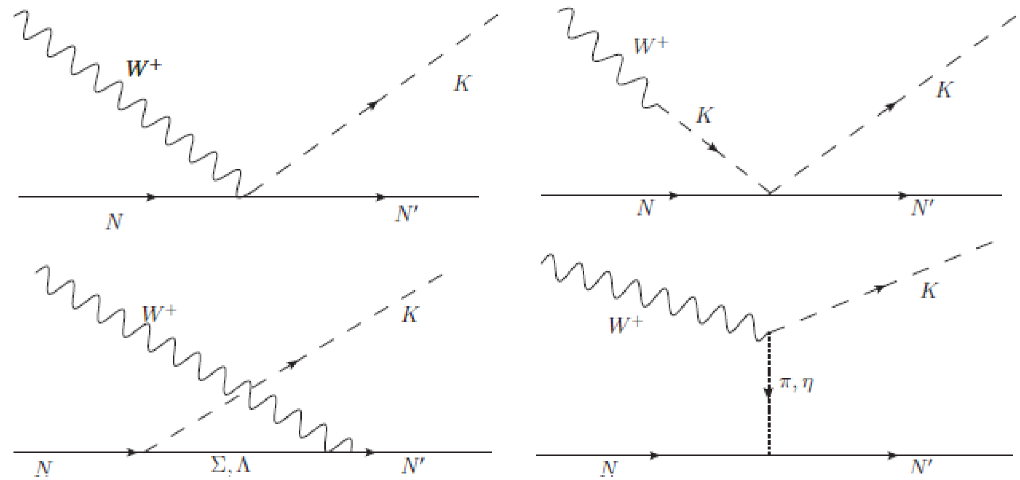




- $C^A_5(0) = 1.12 \pm 0.11$, $M_{A\Delta} = 0.95 \pm 0.06$ GeV
- Consistent with the off-diagonal GT relation $C_5^A(0) = \frac{g_{\Delta N\pi} f_\pi}{\sqrt{6}M} \approx 1.2$

Strangeness production

- $\Delta S = 1$:
$$\begin{aligned} \nu_l\, p &\rightarrow l^- K^+ p \\ \nu_l\, n &\rightarrow l^- K^0 p \\ \nu_l\, n &\rightarrow l^- K^+ n \end{aligned}$$



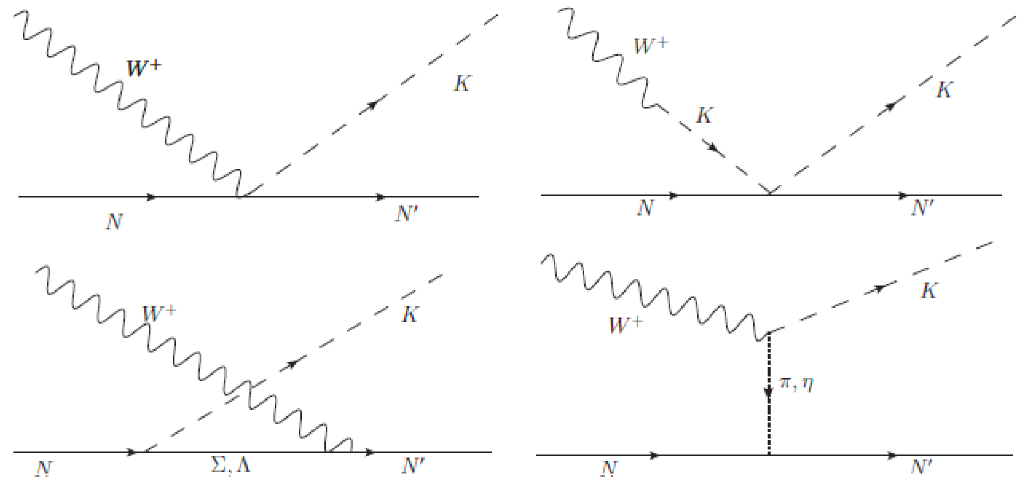
- Rafi Alam et al., PRD 82 (2010)

- SU(3) symmetric chiral Lagrangian
- Physical hadron masses
- s-channel baryon pole diagrams absent
- Couplings depend on V_{us}, D, F, f_π
  - fixed by nucleon and hyperon semileptonic decay and pion decay
- Global dipole form factor

$$F(q^2) = \left(1 - \frac{q^2}{M_F^2}\right)^{-2}$$ $M_F = 1 \pm 0.1$ GeV

Strangeness production

- $\Delta S = 1$: $\nu_l\, p \rightarrow l^- K^+ p$
  $\nu_l\, n \rightarrow l^- K^0 p$
  $\nu_l\, n \rightarrow l^- K^+ n$



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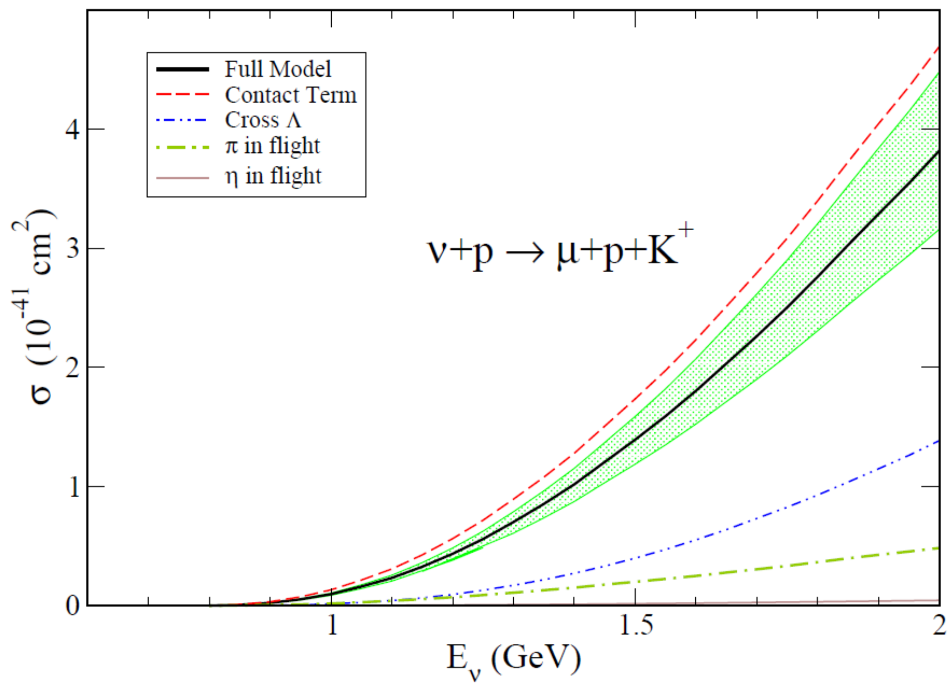
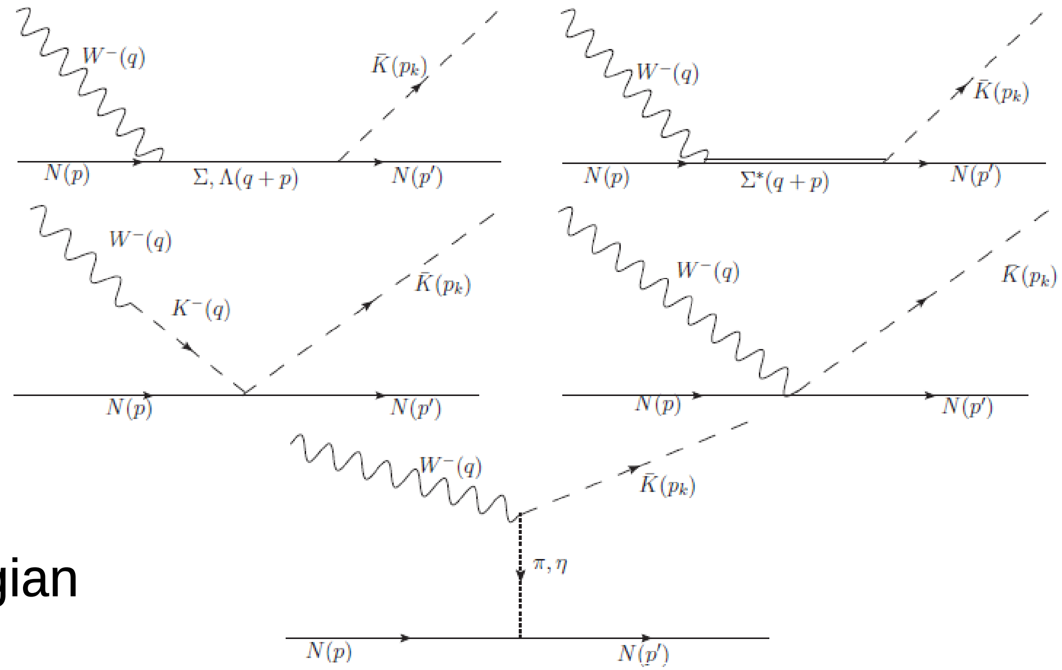


Strangeness production

- ΔS = -1: $\bar{\nu}_l\, p \rightarrow l^+ K^- p$
  $\bar{\nu}_l\, p \rightarrow l^+ \bar{K}^0 n$
  $\bar{\nu}_l\, n \rightarrow l^+ K^- n$



- Rafi Alam et al., PRD 85 (2012)

- SU(3) symmetric chiral Lagrangian
- Physical hadron masses
- s-channel baryon pole diagrams present
  - spin 3/2 Σ(1385)
- Couplings depend on V_{us} and D, F, f_π $\leftarrow$ fixed by semileptonic decays
- Global dipole form factor

$$F(q^2) = \left(1 - \frac{q^2}{M_F^2}\right)^{-2}$$ $M_F = 1 \pm 0.1$ GeV

Strangeness production

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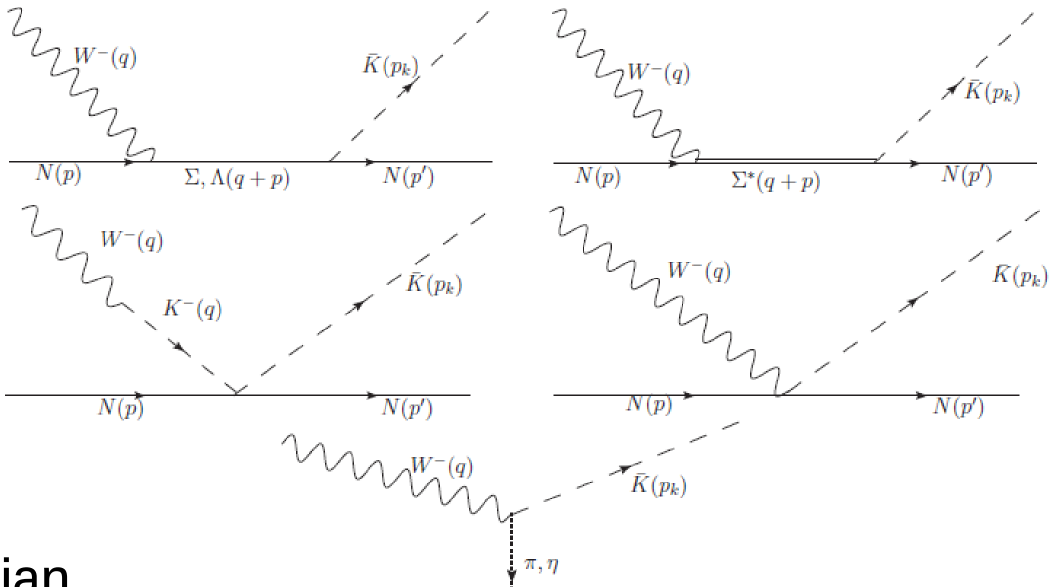

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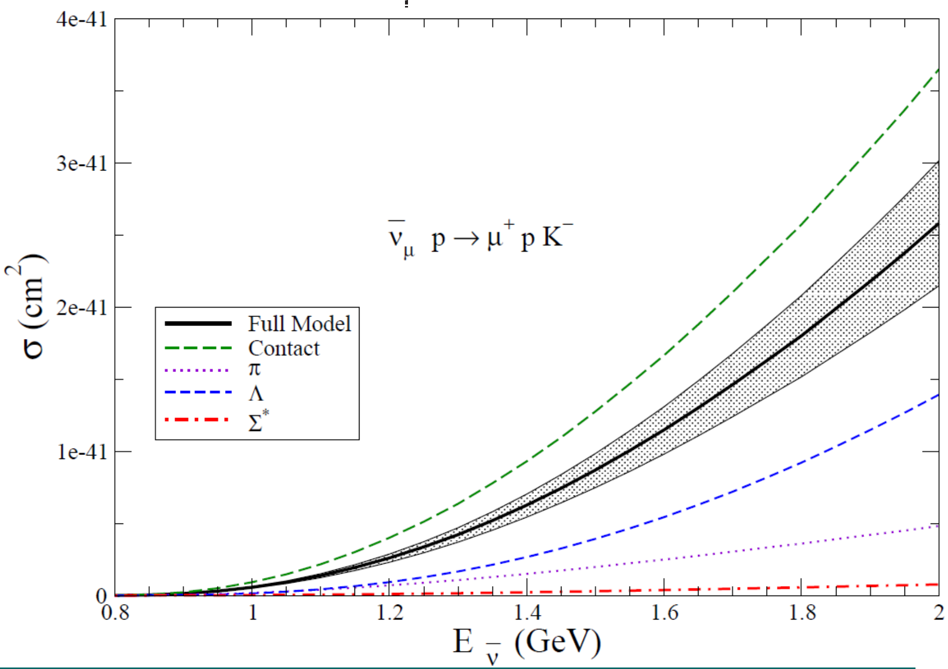

Strangeness production

- $\bar{\nu}_l \, p \to l^+ \, \phi \, B$ Ren et al., PRC91 (2015)

$$\phi \, B = K^- p, \, \bar{K}^0 n, \, \pi^0 \Lambda, \, \pi^0 \Sigma^0, \, \eta \, \Lambda, \, \eta \, \Sigma^0, \, \pi^+ \Sigma^-, \, \pi^- \Sigma^+, \, K^+ \Xi^-, \, K^0 \Xi^0$$

- SU(3) symmetric chiral Lagrangian
- Physical hadron masses
- Couplings depend on V_{us} and D, F, f_π $\leftarrow$ fixed by semileptonic decays
- Global dipole form factor

$$F(q^2) = \left(1 - \frac{q^2}{M_F^2}\right)^{-2}$$ $M_F = 1 \pm 0.1$ GeV

- s-wave projection
- Unitarization in coupled channels

Strangeness production

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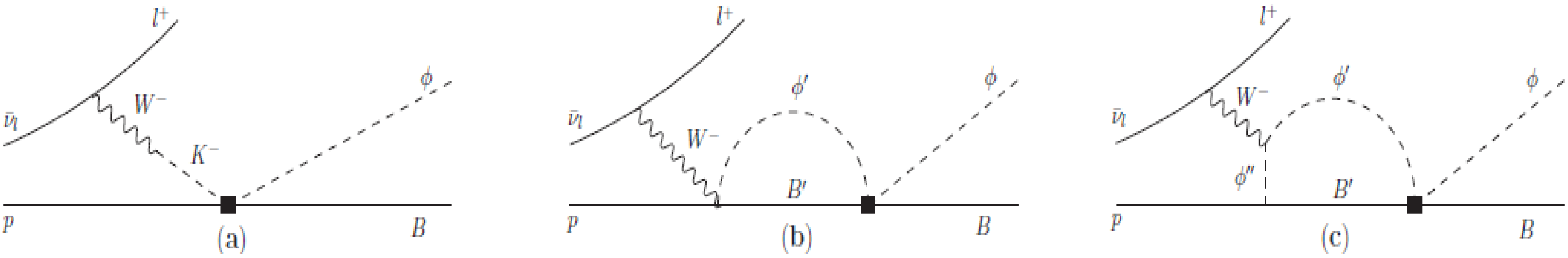
- Unitarization in coupled channels



- T: Solution of the Bethe-Salpeter eq. in coupled channels

$$T = V + VGT = [1 - VG]^{-1} V$$

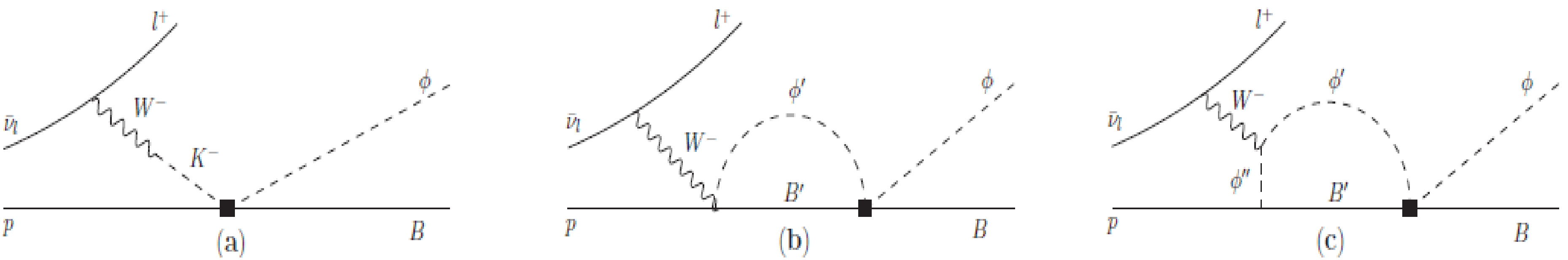
- V: from leading order chiral Lagrangian
- Cut-off regularization of the loop functions with q_{max} = 630 MeV
- Oset, Ramos, NPA635 (1998)

Strangeness production

- $\bar{\nu}_l\, p \to l^+\, \phi\, B$ Ren et al., PRC91 (2015)

$$\phi\, B = K^- p,\, \bar{K}^0 n,\, \pi^0 \Lambda,\, \pi^0 \Sigma^0,\, \eta \Lambda,\, \eta \Sigma^0,\, \pi^+ \Sigma^-,\, \pi^- \Sigma^+,\, K^+ \Xi^-,\, K^0 \Xi^0$$

- Unitarization in coupled channels



- Λ(1405) dynamically generated
- Two poles: M$\approx$ 1385 MeV, $\Gamma \approx$ 150 MeV
  M$\approx$ 1420 MeV, $\Gamma \approx$ 40 MeV
- Suggested by Dalitz et al.(60ies) and obtained in many theoretical studies

Oller, Meissner, PLB500(2001); Jido et al. NPA725(2003); Borasoy et al. PRC74(2006); Geng, Oset, EPJA34(2007; Hyodo, Jido, Prog.Part.Nucl.Phys.67(2012); Guo, Oller PRC87(2013); Roca, Oset PRC87(2013); Mai, Meissner, EPJA51(2015); ...

Strangeness production

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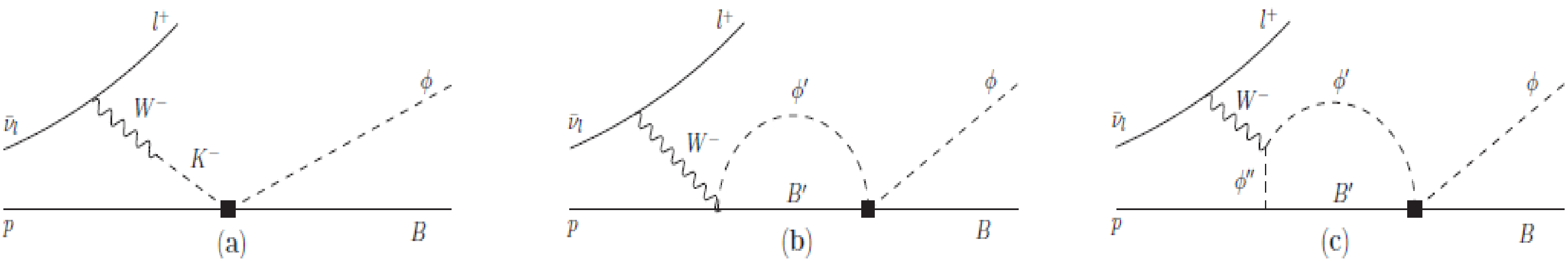
- Unitarization in coupled channels

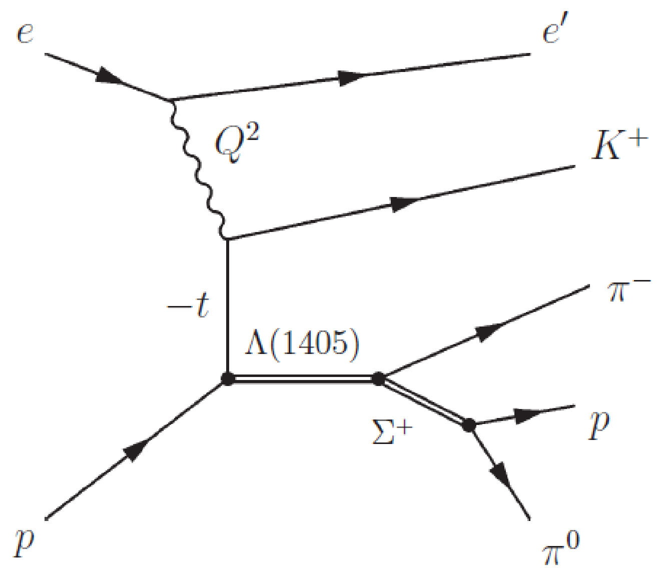


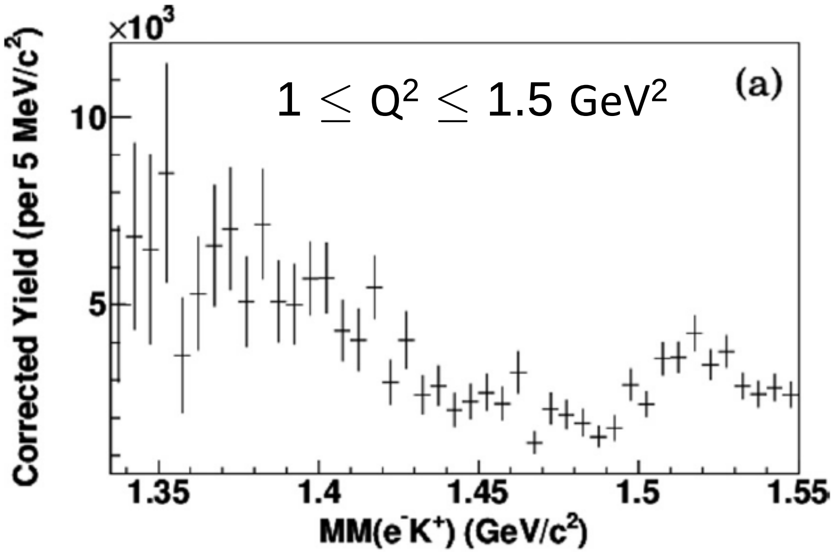
- Λ(1405) dynamically generated
- Two poles: M≈ 1385 MeV, $\Gamma \approx$ 150 MeV
  M≈ 1420 MeV, $\Gamma \approx$ 40 MeV
- Suggested by Dalitz et al.(60ies) and obtained in many theoretical studies
- Consistent with data:

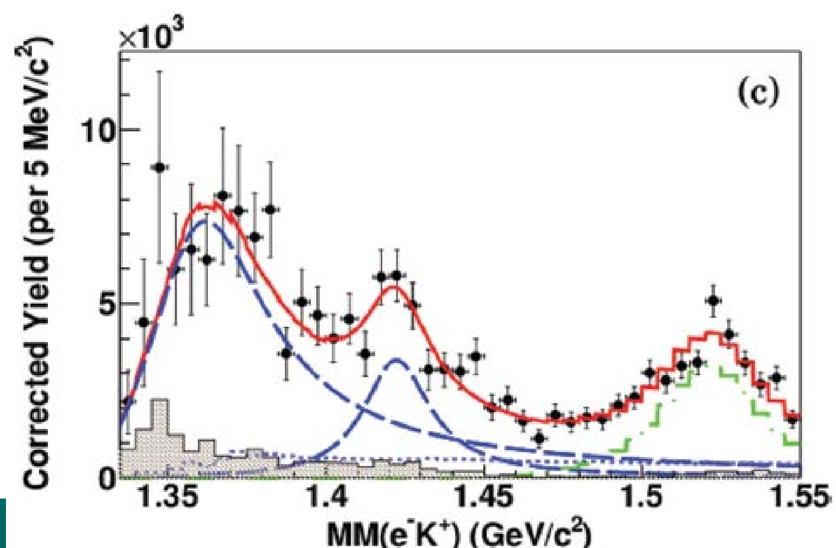
$$K^- \, p \to \phi \, B, \, K^- \, p \to \pi^0 \, \pi^0 \, \Sigma^0, \, p \, p \to p \, K^- \, \Lambda(1405), \, \gamma \, p \to K^+ \, \pi \, \Sigma,$$
$$e \, p \to e' \, K^+ \, \Lambda(1405)$$

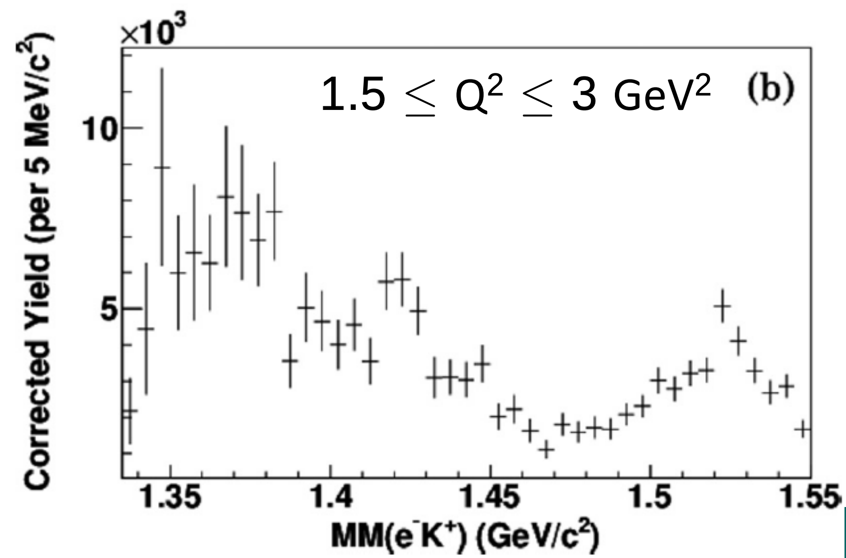
Strangeness production

- $e\,p \to e'\,K^+\,\Lambda(1405)$ Lu et al. (CLAS), PRC88(2013)









Strangeness production

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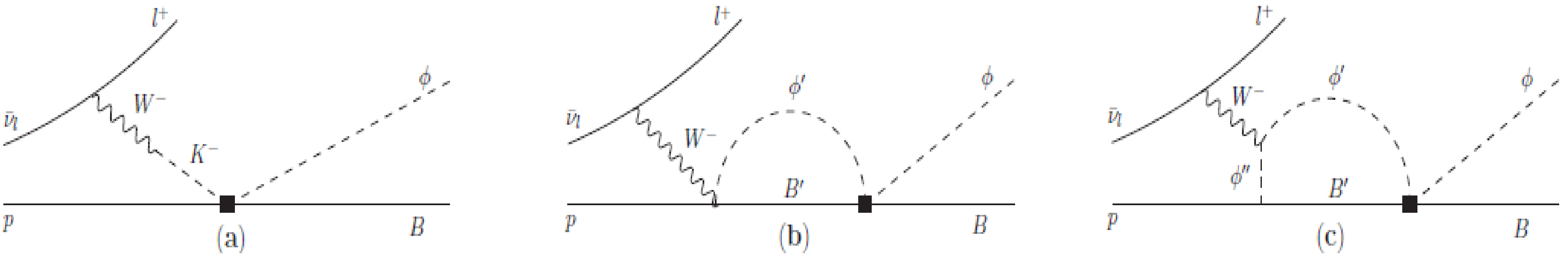
$$\phi\, B = K^-\, p,\ \bar{K}^0\, n,\ \pi^0\, \Lambda,\ \pi^0\, \Sigma^0,\ \eta\, \Lambda,\ \eta\, \Sigma^0,\ \pi^+\, \Sigma^-,\ \pi^-\, \Sigma^+,\ K^+\, \Xi^-,\ K^0\, \Xi^0$$

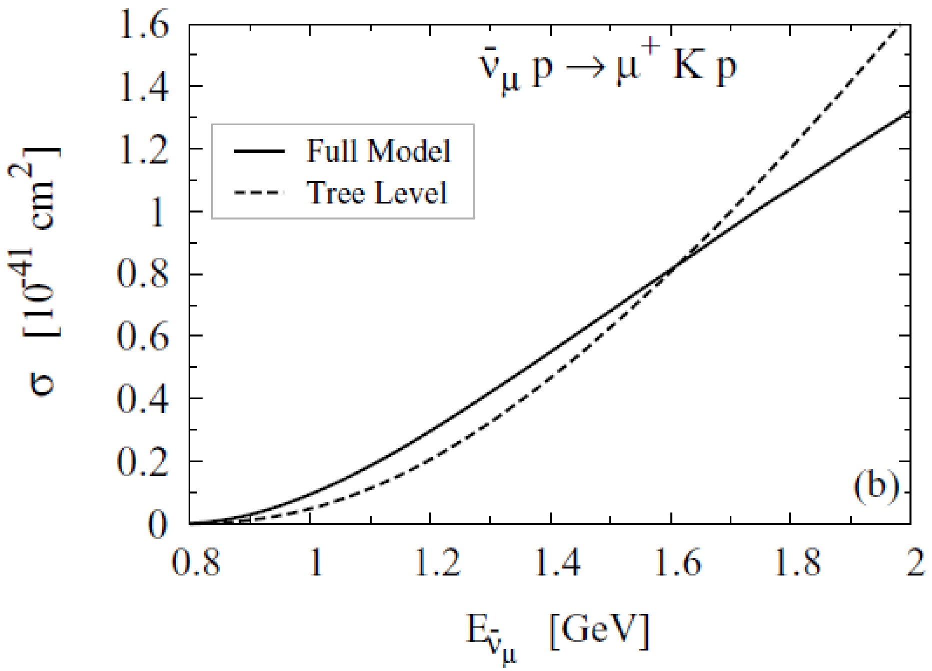
- Unitarization in coupled channels

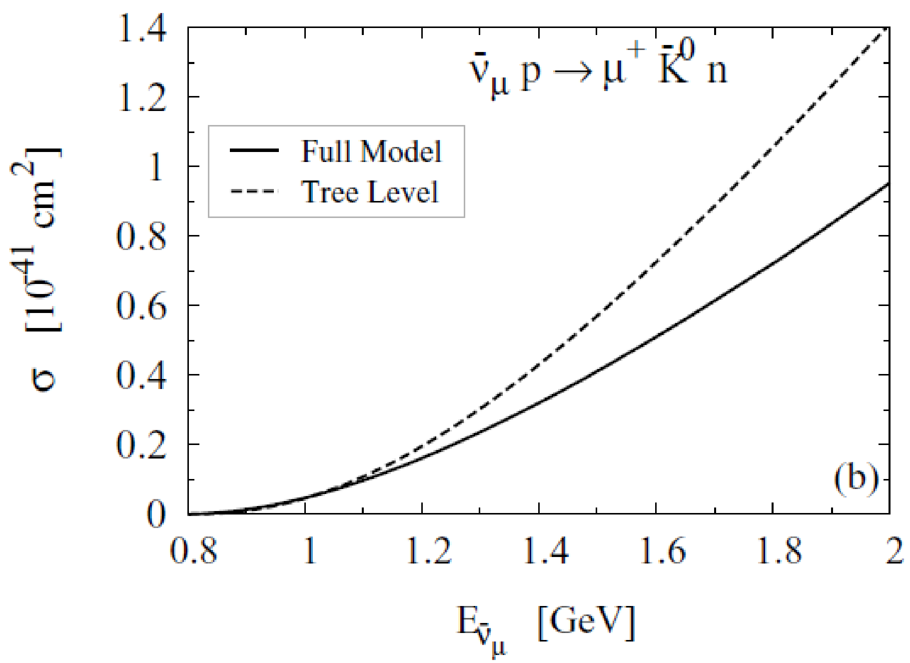


- Λ(1405) dynamically generated
- Two poles: M$\approx$ 1385 MeV, $\Gamma \approx$ 150 MeV
  M$\approx$ 1420 MeV, $\Gamma \approx$ 40 MeV
- $\bar{\nu}_l\, p \to l^+\, \Lambda(1405)$ vs $\gamma\, p \to K^+\, \pi\, \Sigma,\ e\, p \to e'\, K^+\, \Lambda(1405)$
  - no lineshape distortion due to $K^+\Lambda$(1405) FSI
  - but Cabibbo suppressed

Strangeness production

- $\bar{\nu}_l \, p \to l^+ \, \bar{K} \, N$ Ren et al., PRC91 (2015)

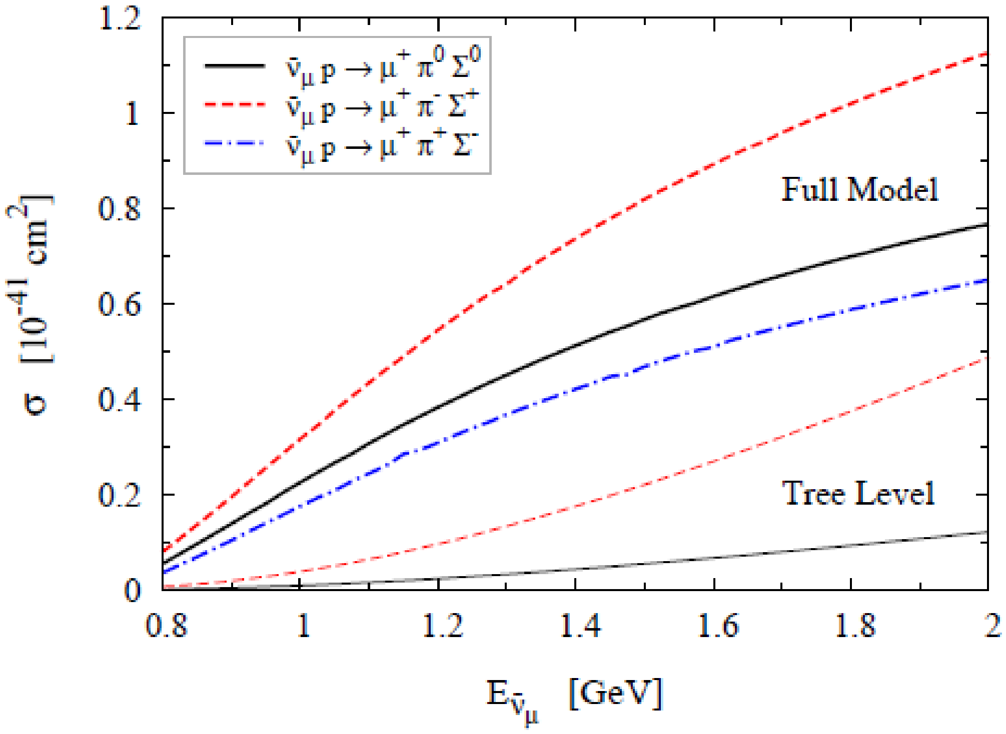




- Unitarization effects are not large: mostly a reduction of the cross section

Strangeness production

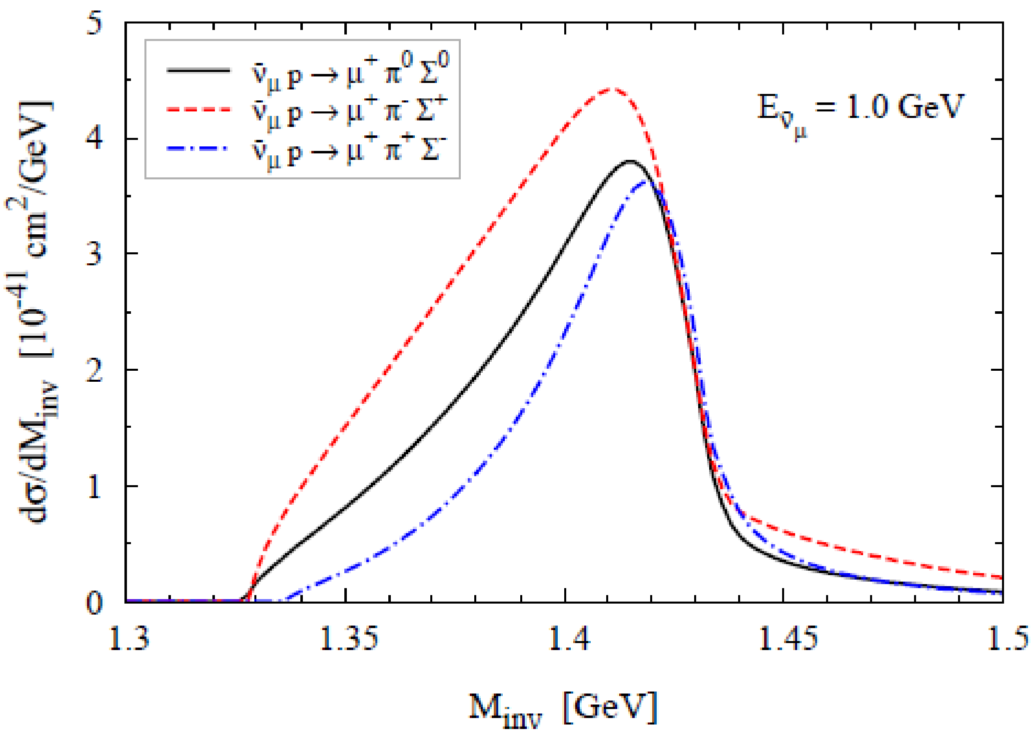
- $\bar{\nu}_l \, p \rightarrow l^+ \, \Sigma \, \pi$ Ren et al., PRC91 (2015)



- Cross sections largely driven by the $\Lambda(1405)$ resonance

Strangeness production

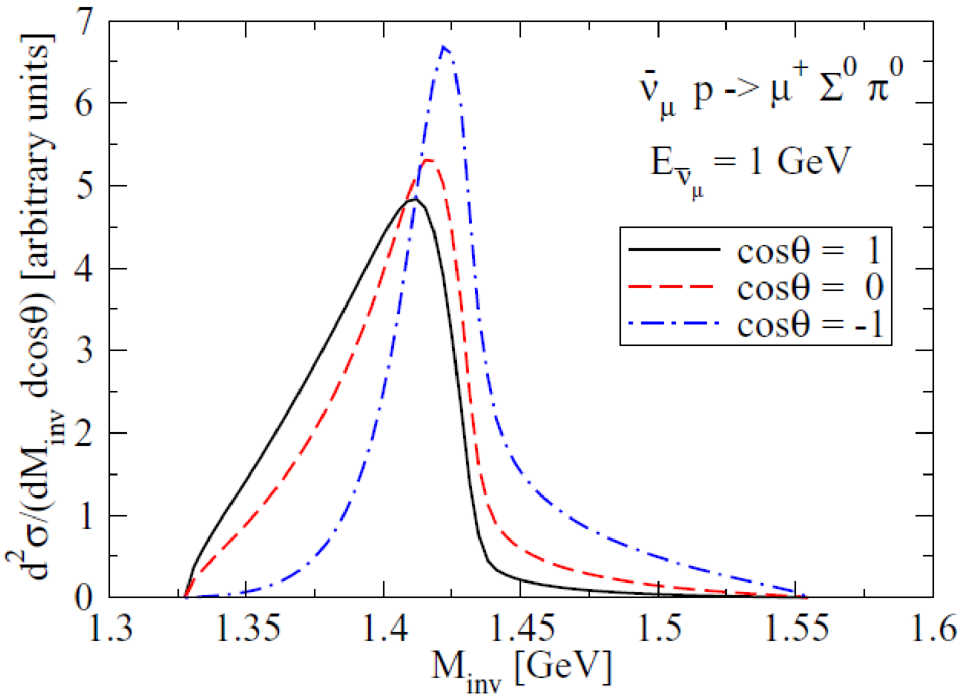
- $\bar{\nu}_l \, p \to l^+ \, \Sigma \, \pi$ Ren et al., PRC91 (2015)



- Cross sections largely driven by the $\Lambda(1405)$ resonance
- Differences in strength vs the $\pi^0 \Sigma^0$ channel from the I=1 amplitude
- Single asymmetric peak with more weight from the 1420 MeV pole

Strangeness production

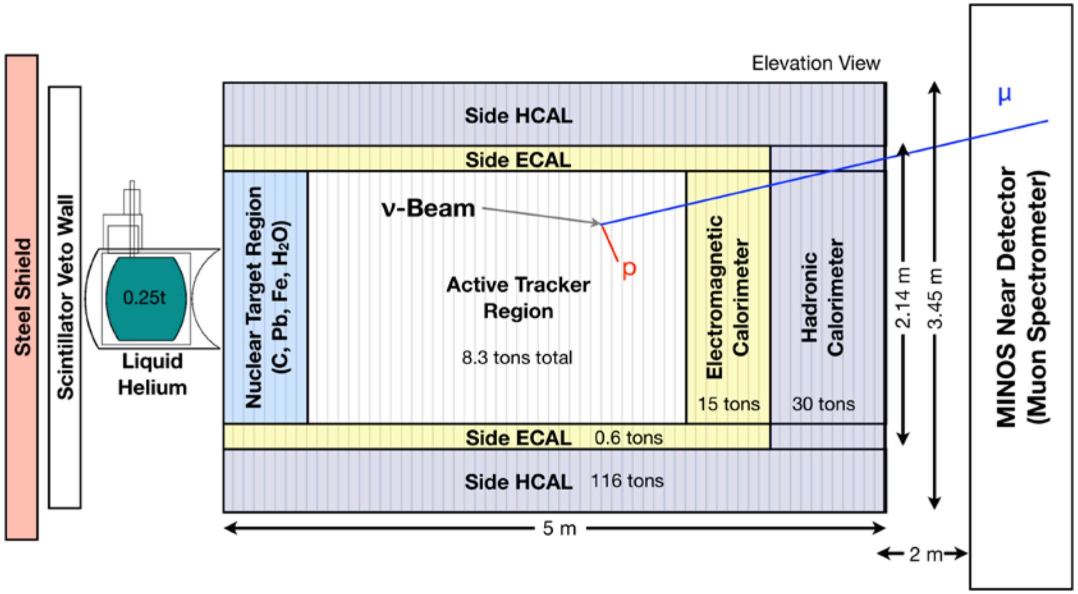
- $\bar{\nu}_l \, p \rightarrow l^+ \, \Sigma \, \pi$ Ren et al., PRC91 (2015)

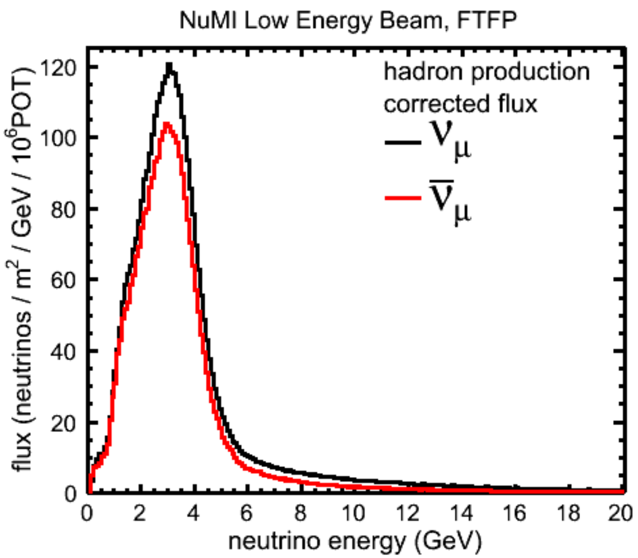


- Single asymmetric peak with more weight from the 1420 MeV pole
- Backwards: $\sim$ Breit-Wigner resonance with M $\approx$ 1420 MeV, $\Gamma \approx$ 40 MeV
- Although $d^2\sigma(\cos\theta = -1) \sim d^2\sigma(\cos\theta = 1)/14$

Strangeness production

- $\bar{\nu}_l \, p \to l^+ \, \Sigma \, \pi$ @ MINERvA (FNAL)





- $\approx$ 2000 $\pi\Sigma$ pairs @ scintillator

Conclusions

- ν scattering on nucleons and nuclei is relevant for oscillation studies
- Interesting for hadron and nuclear physics
- This is the case, in particular, for weak meson production
- Weak pion production and $|\Delta S| = 1$ reactions discussed
- Models are improved by unitarization
- Weak pion production: consistency with the off-diagonal G-T relation for the N-Δ transition is restored by imposing the Watson's theorem
- Weak production of $\Lambda(1405)$ studied for the first time
- New ν-N measurements are highly desirable