NuSTEC Neutrino Generator School

Lecture T7

Neutrino production of resonances

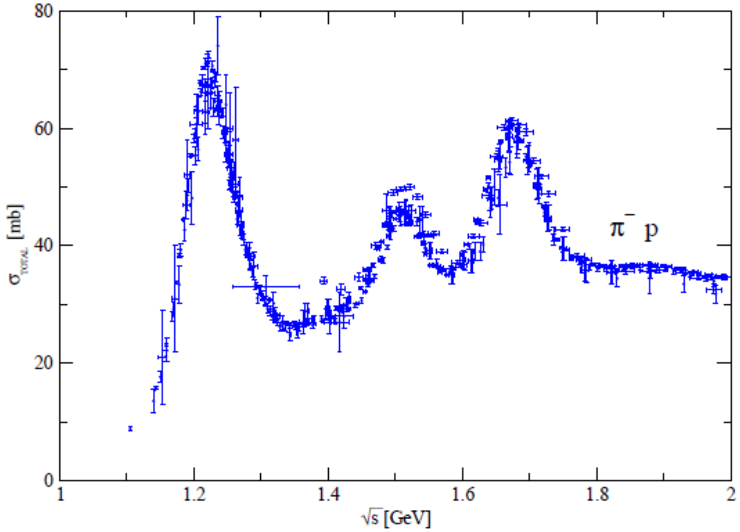
Luis Alvarez Ruso

Outline

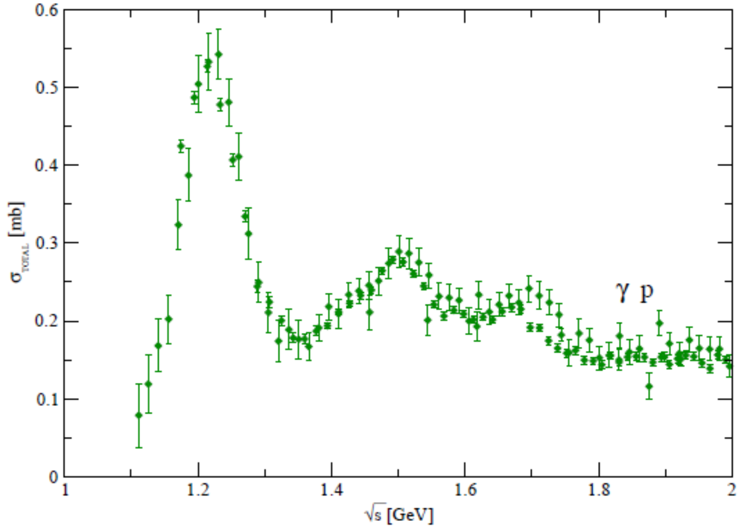
- Baryon resonance properties
- Partial Wave Analyses: MAID
- Weak resonance excitation
- The Rein-Sehgal model
- Non-resonant background

Baryon resonances

- Nucleons are extended objects $\Rightarrow$ excitation spectrum



$$\pi N \to R \to \pi N,\ \pi\pi N,\ \eta N,\ \Lambda K\ \ldots$$

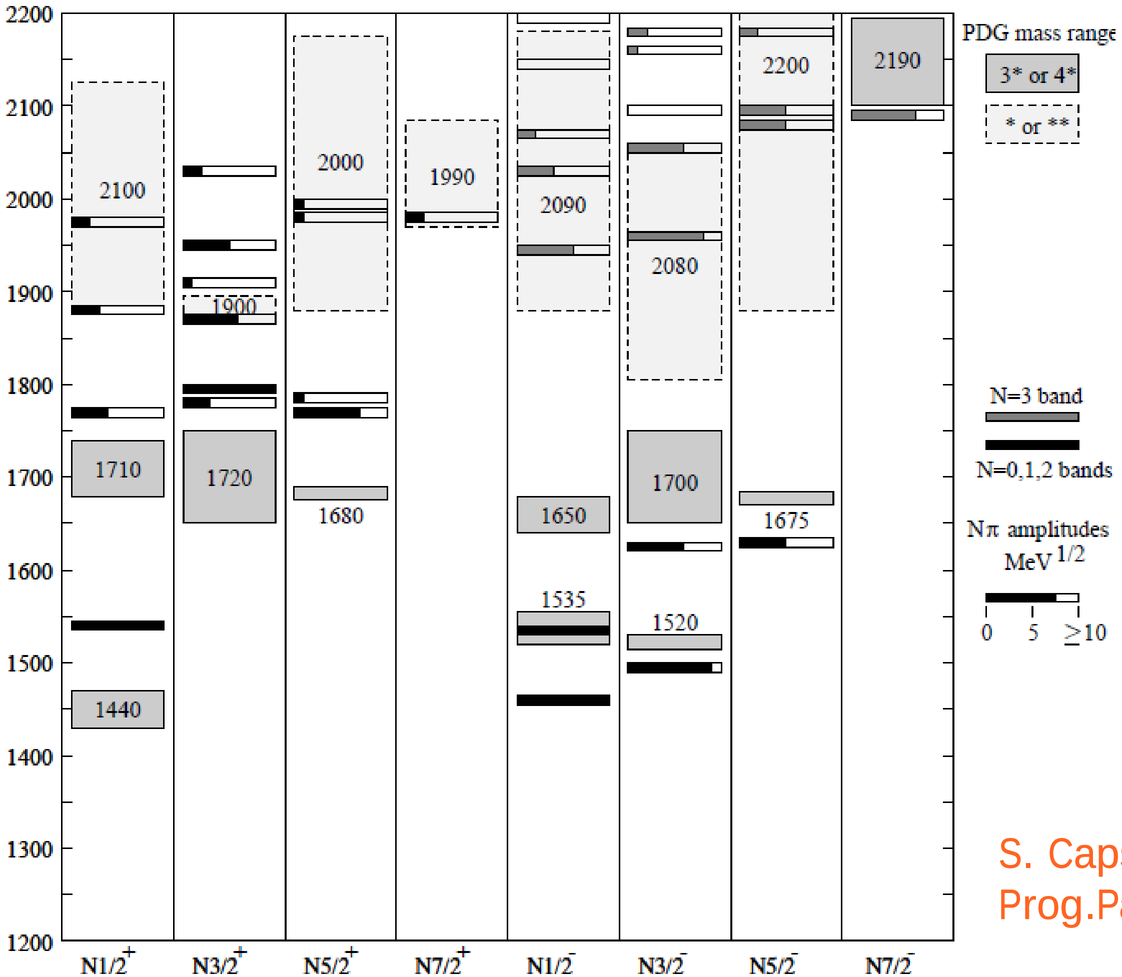


$$\gamma N \to R \to \pi N,\ \pi\pi N,\ \eta N,\ \Lambda K\ \ldots$$

From PDG database

Baryon resonances

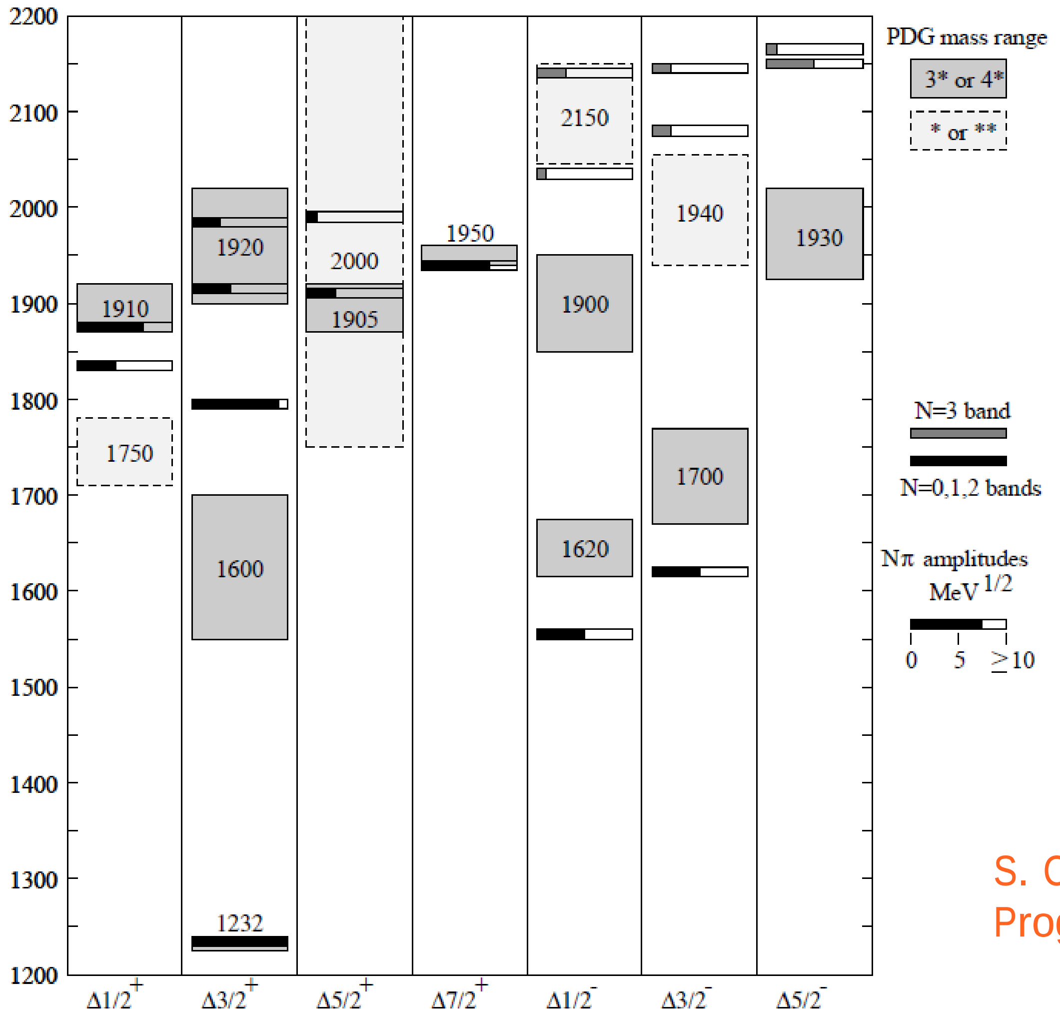
- Nucleons are extended objects ⇒ excitation spectrum
  - N (I = ½) states: N(1440)P_{11} , N(1520)D_{13} , N(1535)S_{11} , ...



S. Capstick, W. Roberts, Prog.Part.Nucl.Phys.45(2000)241

Baryon resonances

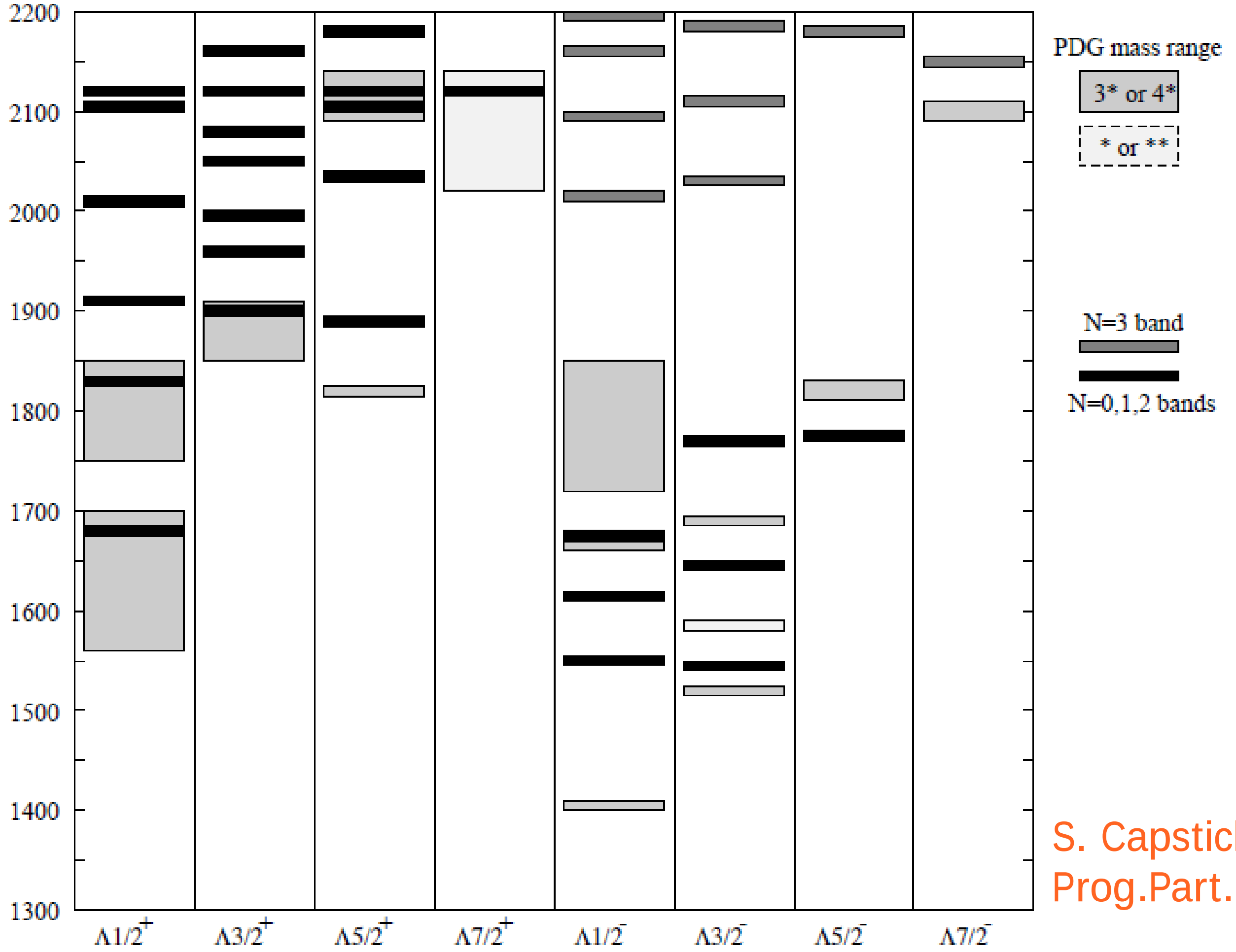
- Nucleons are extended objects ⇒ excitation spectrum
  - Δ (I = 3/2) states: $\Delta(1232)P_{33}$, ...



S. Capstick, W. Roberts, Prog.Part.Nucl.Phys.45(2000)241

Baryon resonances

- Nucleons are extended objects ⇒ excitation spectrum
  - Λ (S=-1, I = 0) states: Λ(1405) , ...



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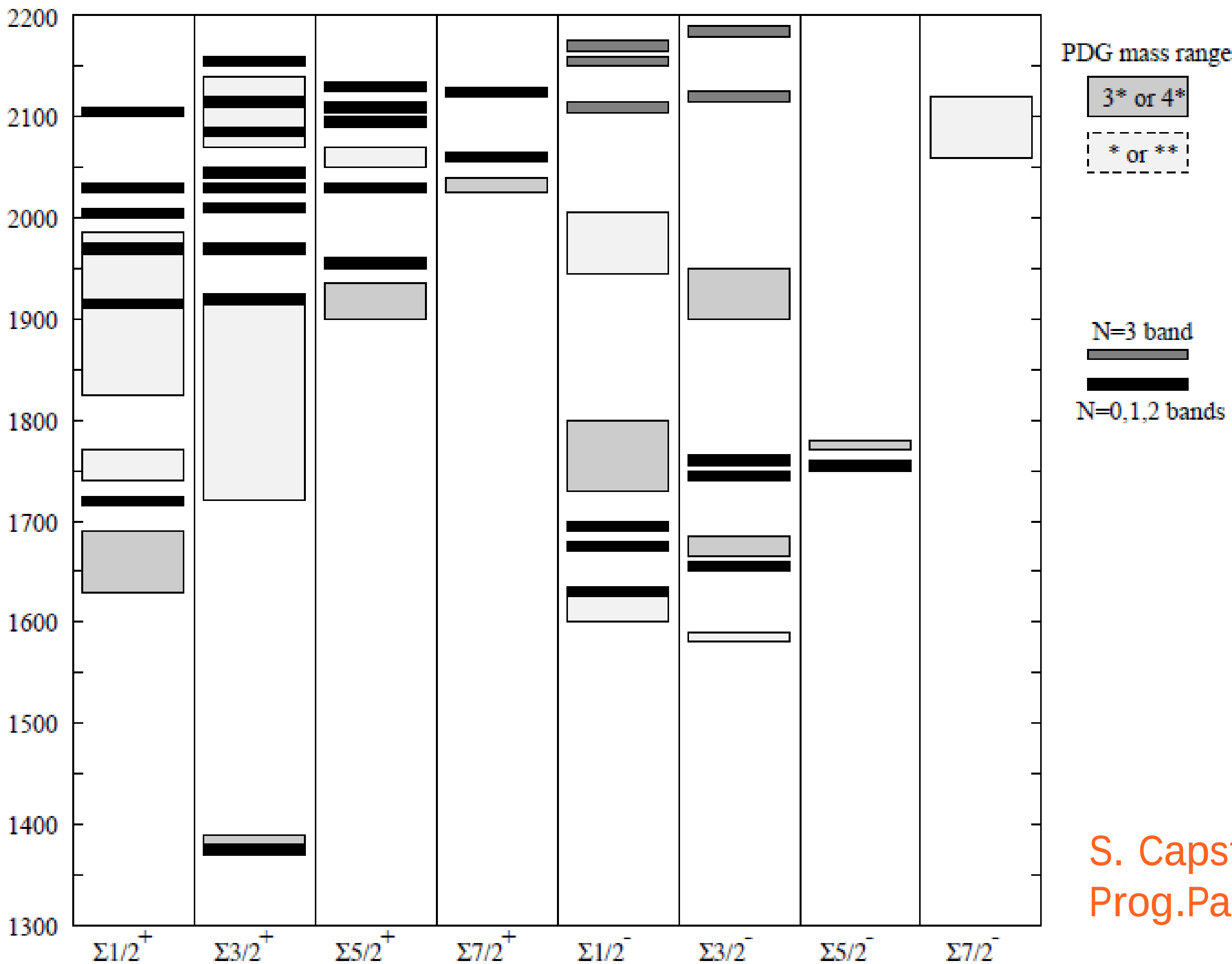
Baryon resonances

- Nucleons are extended objects ⇒ excitation spectrum
  - Σ (S=-1, I = 1) states: Σ(1385) , ...



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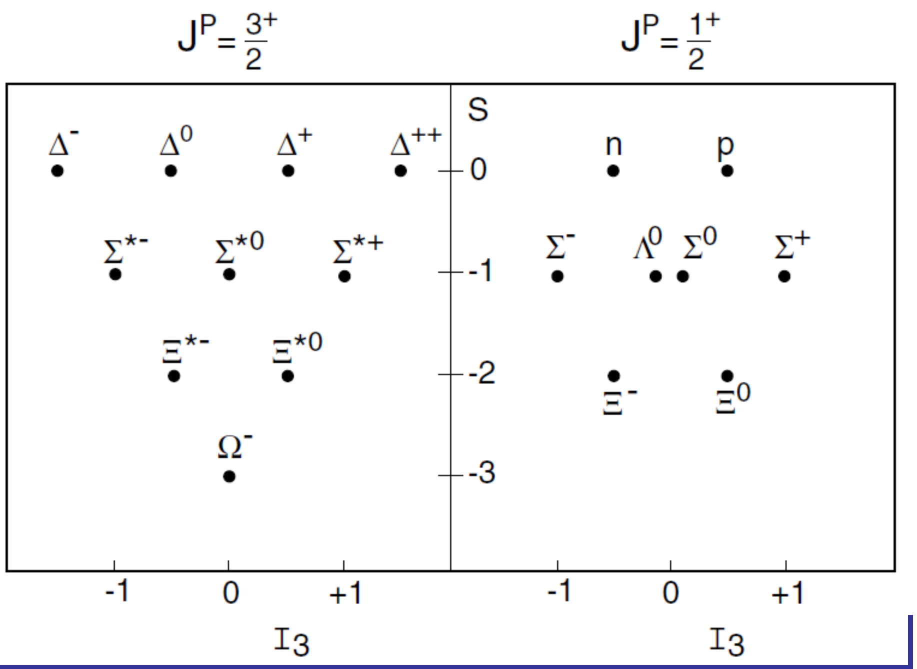
Baryon resonances

- Nucleons are extended objects ⇒ excitation spectrum
  - N (I = ½) states: $N(1440)P_{11}$, $N(1520)D_{13}$, $N(1535)S_{11}$, ...
  - Δ (I = 3/2) states: $\Delta(1232)P_{33}$, ...
  - Λ (S=-1, I = 0) states: $\Lambda(1405)$, ...
  - Σ (S=-1, I = 1) states: $\Sigma(1385)$, ...
  - Ξ (S=-2, I=1/2)
  - Ω (S=-3, I=0)
  - ...
- Constituent quark models:
  - Color singlet (qqq)
  - 3x3x3=10+8+8+1



Baryon resonances

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  - N (I = ½) states: $N(1440)P_{11}$, $N(1520)D_{13}$, $N(1535)S_{11}$, ...
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  - Λ (S=-1, I = 0) states: $\Lambda(1405)$, ...
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  - ...
- Constituent quark models:
  - "Missing" resonances
  - N(1440) is lighter than N(1535)
- There are dynamically generated states: $\Lambda(1405)$, N(1535) , ...

Baryon resonances

- Constituent quark models:
  - "Missing" resonances
  - N(1440) is lighter than N(1535)

In a Quark Model with an oscillator V:

$E = \hbar\omega\left(n + \frac{3}{2}\right)$ with $n = 2n_r + l$

$$n = 0 \quad l = 0 \quad \Rightarrow N\ (J^P = 1/2^+)$$

$$n = 1 \quad l = 1 \quad \Rightarrow N^*(J^P = 1/2^-)$$

$$n = 2 \quad l = 0 \quad \Rightarrow N^*(J^P = 1/2^+)$$

Baryon resonances

- Nucleons are extended objects $\Rightarrow$ excitation spectrum
  - N (I = ½) states: N(1440)P_{11} , N(1520)D_{13} , N(1535)S_{11} , ...
  - Δ (I = 3/2) states: Δ(1232)P_{33} , ...
  - Λ (S=-1, I = 0) states: Λ(1405) , ...
  - Σ (S=-1, I = 1) states: Σ(1385) , ...
  - Ξ (S=-2, I=1/2)
  - Ω (S=-3, I=0)
  - ...
- Constituent quark models:
  - "Missing" resonances
  - N(1440) is lighter than N(1535)
- There are dynamically generated states: Λ(1405) , N(1535) , ...

Baryon resonances

- Resonance properties
  - Quantum numbers
  - Mass, width, branching ratios
  - Originally from π N $\rightarrow$ π N
  - Electromagnetic properties $\leftrightarrow$ γ N $\rightarrow$ π N, γ^* N $\rightarrow$ π N

$$\sigma(W) = \sigma_0 \frac{M^2 B_{in} B_{out} \Gamma^2}{(W^2 - M^2)^2 + M^2\Gamma^2} \Rightarrow \begin{cases} W_R \approx M + i\frac{\Gamma}{2} \\ B_{in},\ B_{out} \end{cases}$$

  - But
    - Resonances overlap: N(1440)P_{11} , N(1520)D_{13} , N(1535)S_{11}
    - Resonances might not produce a peak in the (certain) cross section
      - N(1440)P_{11}
      - Σ(1385) : peak in the π Λ invariant mass in K^- p $\rightarrow$ π^- π^+ Λ
    - Γ = Γ(W) $\sim$ $q_{cm}{}^l$
    - Background/resonance separation is model dependent
    - Need for Partial Wave Analyses

MAID

- Unitary isobar model for $\gamma^* N \to N \pi$ Tiator et al., EPJ Special Topics 198 (2011)

$$T_{\gamma\pi}(W,Q^2) = T^B_{\gamma\pi}(W,Q^2) + T^R_{\gamma\pi}(W,Q^2)$$

- For each partial wave α :

$$T^{B,\alpha}_{\gamma\pi}(W,Q^2) = V^{B,\alpha}_{\gamma\pi}(W,Q^2)\,[1 + iT^{\alpha}_{\pi N}(W)]$$

$V^{B,\alpha}_{\gamma\pi}(W,Q^2) \leftarrow$ Born terms, phenomenological model

$T^{\alpha}_{\pi N}(W) \leftarrow$ πN elastic amplitude, from SAID

$$T^{R,\alpha}_{\gamma\pi} = -\bar{A}^R_\alpha(W,Q^2)\frac{f_{\gamma N}(W)\Gamma_{\rm tot}(W)f_{\pi N}(W)}{W^2 - M_R^2 + iM_R\Gamma_{\rm tot}(W)}e^{i\phi_R(W,Q^2)}$$

$f_{\pi N}(W) \leftarrow$ Breit-Wigner factor for resonance decay

$f_{\gamma N}(W) \leftarrow$ γNR vertex

$\phi_R(W,Q^2) \leftarrow$ adjusted to fulfill Watson theorem

$\bar{A}^R_\alpha(W,Q^2) \leftarrow$ Multipole amplitudes

MAID

- Unitary isobar model for $\gamma^* N \to N \pi$ Tiator et al., EPJ Special Topics 198 (2011)

$$T_{\gamma\pi}(W,Q^2) = T^B_{\gamma\pi}(W,Q^2) + T^R_{\gamma\pi}(W,Q^2)$$

- For each partial wave α :

$$T^{R,\alpha}_{\gamma\pi} = -\bar{\mathcal{A}}^R_\alpha(W,Q^2)\frac{f_{\gamma N}(W)\Gamma_{\mathrm{tot}}(W)f_{\pi N}(W)}{W^2 - M_R^2 + iM_R\Gamma_{\mathrm{tot}}(W)}e^{i\phi_R(W,Q^2)}$$

$\bar{\mathcal{A}}^R_\alpha(W,Q^2) \leftarrow$ Multipole amplitudes

  - j=l + ½ :

$$\begin{aligned} A_{1/2} &= -\frac{1}{2}\left[(l+2)\bar{E}_{l+} + l\bar{M}_{l+}\right] \\ A_{3/2} &= \frac{1}{2}\sqrt{l(l+2)}(\bar{E}_{l+} - \bar{M}_{l+}) \\ S_{1/2} &= -\frac{l+1}{\sqrt{2}}\bar{S}_{l+} \end{aligned}$$

MAID

- Unitary isobar model for $\gamma^* N \to N \pi$ Tiator et al., EPJ Special Topics 198 (2011)

$$T_{\gamma\pi}(W,Q^2) = T^B_{\gamma\pi}(W,Q^2) + T^R_{\gamma\pi}(W,Q^2)$$

- For each partial wave α :

$$T^{R,\alpha}_{\gamma\pi} = -\bar{\mathcal{A}}^R_\alpha(W,Q^2)\frac{f_{\gamma N}(W)\Gamma_{\rm tot}(W)f_{\pi N}(W)}{W^2 - M_R^2 + iM_R\Gamma_{\rm tot}(W)}e^{i\phi_R(W,Q^2)}$$

$\bar{\mathcal{A}}^R_\alpha(W,Q^2) \leftarrow$ Multipole amplitudes

- j=l - ½ :

$$A_{1/2} = \frac{1}{2}\left[(l+1)\bar{M}_{l-} - (l-1)\bar{E}_{l-}\right]$$

$$A_{3/2} = -\frac{1}{2}\sqrt{(l-1)(l+1)}(\bar{E}_{l-} + \bar{M}_{l-})$$

$$S_{1/2} = -\frac{l}{\sqrt{2}}\bar{S}_{l-}$$

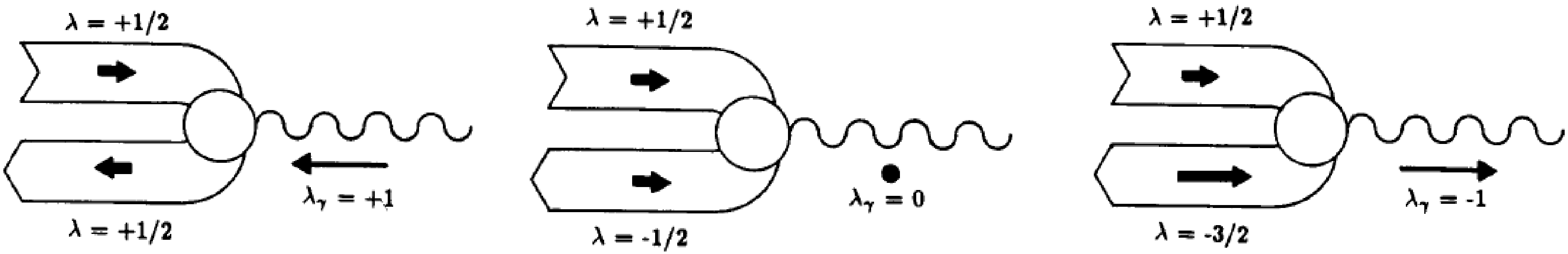
MAID

- Helicity amplitudes

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

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

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

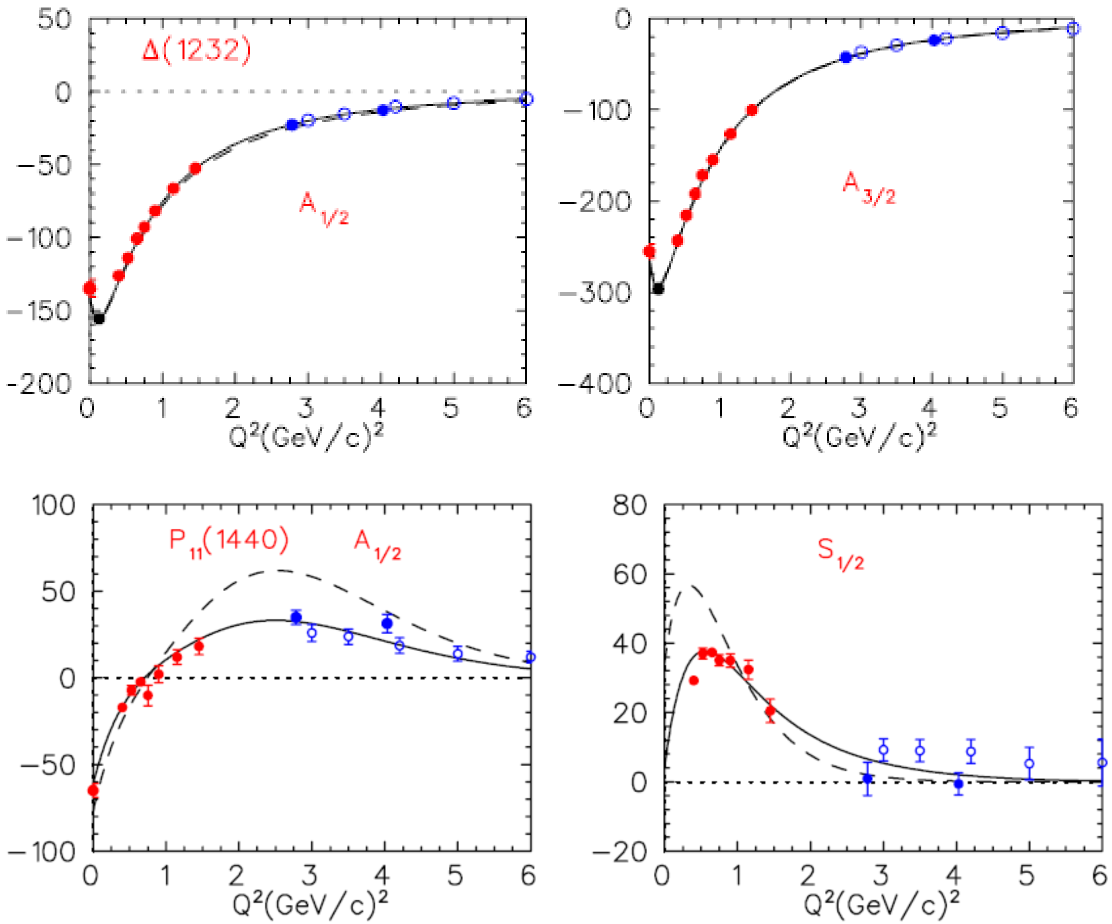


$A_{1/2}$ $S_{1/2}$ $A_{3/2}$

MAID

- Transition N-R e.m. helicity amplitudes extracted for all 4-star resonaces with W < 1.8 GeV
- For example:

Tiator et al., EPJ Special Topics 198 (2011)



MAID

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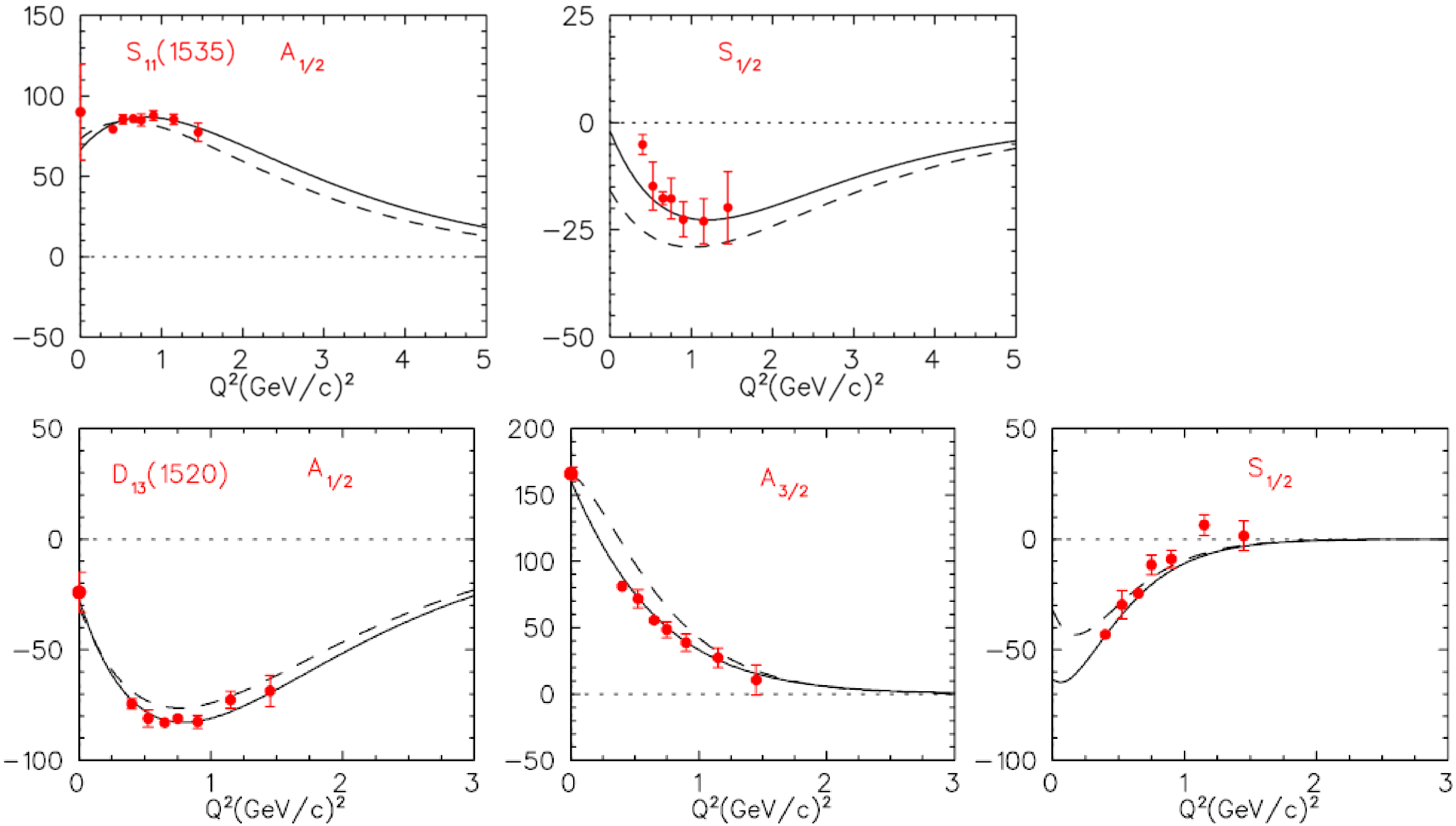

Weak Resonance excitation

- Resonances contribute to:
  - the inclusive $\nu_l \, N \to l \, X$ cross section
  - several exclusive channels: $\nu_l \, N \to l \, N' \, \pi$

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

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

    $\nu_l \, N \to l \, \Lambda(\Sigma) \, \bar{K}$

  - At $E_\nu \sim 1$ GeV (MiniBooNE, SciBooNE, T2K,...) Δ(1232) is dominant
  - At E_ν>1 GeV (MINERνA) N* become also important

Weak Resonance excitation

- CC R excitation: $\nu_l(k)\, N(p) \to l^-(k')\, R(p')$

$$\frac{d\sigma}{dk_0' d\Omega'} = \frac{1}{32\pi^2} \frac{|\vec{k'}|}{k_0 M_N} \mathcal{A}(p') |\bar{\mathcal{M}}|^2$$ ← Inclusive cross section

$$\mathcal{A}(p') = \frac{M^*}{\pi} \frac{\Gamma(p')}{(p'^2 - M^{*2})^2 + M^{*2}\Gamma^2(p')}$$

$\Gamma(p')$ ← total momentum dependent width

$$\mathcal{M} = \frac{G_F \cos\theta_C}{\sqrt{2}} l^\alpha J_\alpha$$

$$l^\alpha = \bar{u}(k')\gamma^\alpha(1-\gamma_5)u(k)$$ ← leptonic current

$$J_\alpha = V_\alpha - A_\alpha$$ ← hadronic current
can be parametrized in terms of
N-R transition form factors

Weak Resonance excitation

- $\Delta(1232)$ $J^P=3/2^+$

$$J_\alpha = \bar{u}^\mu(p') \left[\left(\frac{C_3^V}{M_N}(g_{\alpha\mu}\not{q} - q_\alpha\gamma_\mu) + \frac{C_4^V}{M_N^2}(g_{\alpha\mu} q\cdot p' - q_\alpha p'_\mu) + \frac{C_5^V}{M_N^2}(g_{\alpha\mu} q\cdot p - q_\alpha p_\mu) \right) \gamma_5 + \frac{C_3^A}{M_N}(g_{\alpha\mu}\not{q} - q_\alpha\gamma_\mu) + \frac{C_4^A}{M_N^2}(g_{\alpha\mu} q\cdot p' - q_\beta p'_\mu) + C_5^A g_{\alpha\mu} + \frac{C_6^A}{M_N^2} q_\alpha q_\mu \right] u(p)$$

C^V_{3-5}, C^A_{3-6} $\leftarrow$ N-Δ transition form factors

- Rarita-Schwinger fields: spin 3/2

$$u_\mu(p, s_\Delta) = \sum_{\lambda, s} \left(1\lambda \frac{1}{2} s \middle| \frac{3}{2} s_\Delta \right) \epsilon_\mu(p,\lambda) u(p,s)$$

- Eq. of motion: $(\not{p} - M_\Delta)\, u_\mu = 0$

- with constrains: $\gamma^\mu u_\mu = p^\mu u_\mu = 0$

Weak Resonance excitation

- Second resonance peak: N*(1440), N*(1520), N*(1535)
  - N*(1440) $J^P=1/2^+$

$$J_\alpha = \bar{u}(p')\left[\frac{F_1^V}{(2M_N)^2}(\not{q}q_\alpha - q^2\gamma_\alpha) + i\frac{F_2^V}{2M_N}\sigma_{\alpha\beta}q^\beta - F_A\gamma_\alpha\gamma_5 - \frac{F_P}{M_N}\gamma_5 q_\alpha\right]u(p)$$

  - N*(1535) $J^P=1/2^-$

$$J_\alpha = \bar{u}(p')\left[\frac{F_1^V}{(2M_N)^2}(\not{q}q_\alpha - q^2\gamma_\alpha)\gamma_5 + i\frac{F_2^V}{2M_N}\sigma_{\alpha\beta}q^\beta\gamma_5 - F_A\gamma_\alpha - \frac{F_P}{M_N}q_\alpha\right]u(p)$$

  - N*(1520) $J^P=3/2^-$

$$J_\alpha = \bar{u}^\mu(p')\left[\frac{C_3^V}{M_N}(g_{\alpha\mu}\not{q} - q_\alpha\gamma_\mu) + \frac{C_4^V}{M_N^2}(g_{\alpha\mu}q\cdot p' - q_\alpha p'_\mu) + \frac{C_5^V}{M_N^2}(g_{\alpha\mu}q\cdot p - q_\alpha p_\mu)\right.$$
$$\left. + \left(\frac{C_3^A}{M_N}(g_{\alpha\mu}\not{q} - q_\alpha\gamma_\mu) + \frac{C_4^A}{M_N^2}(g_{\alpha\mu}q\cdot p' - q_\beta p'_\mu) + C_5^A g_{\alpha\mu} + \frac{C_6^A}{M_N^2}q_\alpha q_\mu\right)\gamma_5\right]u(p)$$

Weak Resonance excitation

- Vector CC and NC form factors can be expressed in terms of EM ones
  - CC: $F^V_{1,2} = F^p_{1,2} - F^n_{1,2}$
  - NC: $\tilde{F}^{p(n)}_{1,2} = \left(\frac{1}{2} - 2\sin^2\theta_W\right) F^{p(n)}_{1,2} - F^{n(p)}_{1,2}$
  - The same applies for $C^V_{1,2,3}$
- Helicity amplitudes from π photo- and electro-production data

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

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

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

- Helicity amplitudes $\Rightarrow$ EM form factors

Weak Resonance excitation

- Axial transition form factors
  - Poorly known (if at all...)
  - PCAC: $q^\alpha A_\alpha \approx 0$
  - π-pole dominance of the pseudoscalar form factor: C_6^A

- $\Delta(1232)$ $J^P=3/2^+$

PCAC $\Rightarrow$ $C_6^A = -\frac{M_N^2}{q^2} C_5^A$

Using $\mathcal{L}_{\Delta N\pi} = -\frac{g_{\Delta N\pi}}{f_\pi} \bar{\Delta}_\mu (\partial^\mu \vec{\pi}) \vec{T}^\dagger N$ $\quad g_{\Delta N\pi} \Leftrightarrow \Gamma(N^* \to N\pi)$

π-pole dominance $\Rightarrow$ $C_6^A = -\sqrt{\frac{2}{3}} g_{N^*N\pi} F(q^2) \frac{M_N^2}{q^2 - m_\pi^2}$ $\quad F(0) = 1$

Therefore $C_5^A(0) = \sqrt{\frac{2}{3}} g_{\Delta N\pi} \leftarrow$ Goldberger-Treiman relation

$C_4^A = -\frac{1}{4} C_5^A \qquad C_3^A = 0 \leftarrow$ Adler model

Weak Resonance excitation

- Axial transition form factors
  - $\Delta(1232)$ $J^P=3/2^+$
  - Constraints from ANL and BNL data on $\nu_\mu \, d \to \mu^- \, \pi^+ \, p \, n$
    - with large normalization (flux) uncertainties
  - 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
    - Non-resonant background fixed by chiral symmetry
    - $C^A_5(0) = 1.00 \pm 0.11$ GeV, $M_{A\,\Delta} = 0.93 \pm 0.07$ GeV
    - 20 % reduction of the GT relation: $C^A_5(0) \approx 1.2$
    - But Watson's theorem is not fulfilled
  - ANL and BNL data do not constrain $C^A_{3,4}$

Weak Resonance excitation

- Axial transition form factors
  - Poorly known (if at all...)
  - PCAC: $q^\alpha A_\alpha \approx 0$
  - π-pole dominance of the pseudoscalar form factor: F_P

- N*(1440) $J^P=1/2^+$

PCAC $\Rightarrow$ $$F_P = -\frac{(M^* + M_N)M_N}{q^2} F_A$$

Using $$\mathcal{L}_{N^*N\pi} = -\frac{g_{N^*N\pi}}{f_\pi} \bar{N}^* \gamma_\mu \gamma_5 (\partial^\mu \vec{\pi}) \vec{\tau} N \qquad g_{N^*N\pi} \Leftrightarrow \Gamma(N^* \to N\pi)$$

π-pole dominance $\Rightarrow$ $$F_P = -2 g_{N^*N\pi} F(q^2) \frac{(M^* + M_N)M_N}{q^2 - m_\pi^2} \qquad F(0) = 1$$

Therefore $F_A(0) = 2 g_{N^*N\pi}$ $\leftarrow$ Goldberger-Treiman relation

Educated guess: $$F_A(q^2) = F_A(0)\left(1 - \frac{q^2}{{M_A}^2}\right)^{-2} \qquad M_A = 1\ \mathrm{GeV}$$

Weak Resonance excitation

- Axial transition form factors
  - Poorly known (if at all...)
  - PCAC: $q^{\alpha} A_{\alpha} \approx 0$
  - π-pole dominance of the pseudoscalar form factor: F_P

- N*(1535) $J^P=1/2^-$

PCAC $\Rightarrow$ $$F_P = -\frac{(M^* - M_N)M_N}{q^2} F_A$$

Using $$\mathcal{L}_{N^* N\pi} = -\frac{g_{N^* N\pi}}{f_\pi} \bar{N}^* \gamma_\mu (\partial^\mu \vec{\pi}) \vec{\tau} N$$ $$g_{N^* N\pi} \Leftrightarrow \Gamma(N^* \to N\pi)$$

π-pole dominance $\Rightarrow$ $$F_P = -2 g_{N^* N\pi} F(q^2) \frac{(M^* - M_N)M_N}{q^2 - m_\pi^2} \qquad F(0) = 1$$

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Weak Resonance excitation

- Axial transition form factors
  - Poorly known (if at all...)
  - PCAC: $q^\alpha A_\alpha \approx 0$
  - π-pole dominance of the pseudoscalar form factor: C_6^A

- N*(1520) $J^P=3/2^-$

PCAC $\Rightarrow$ $C_6^A = -\frac{M_N^2}{q^2 - m_\pi^2} C_5^A$

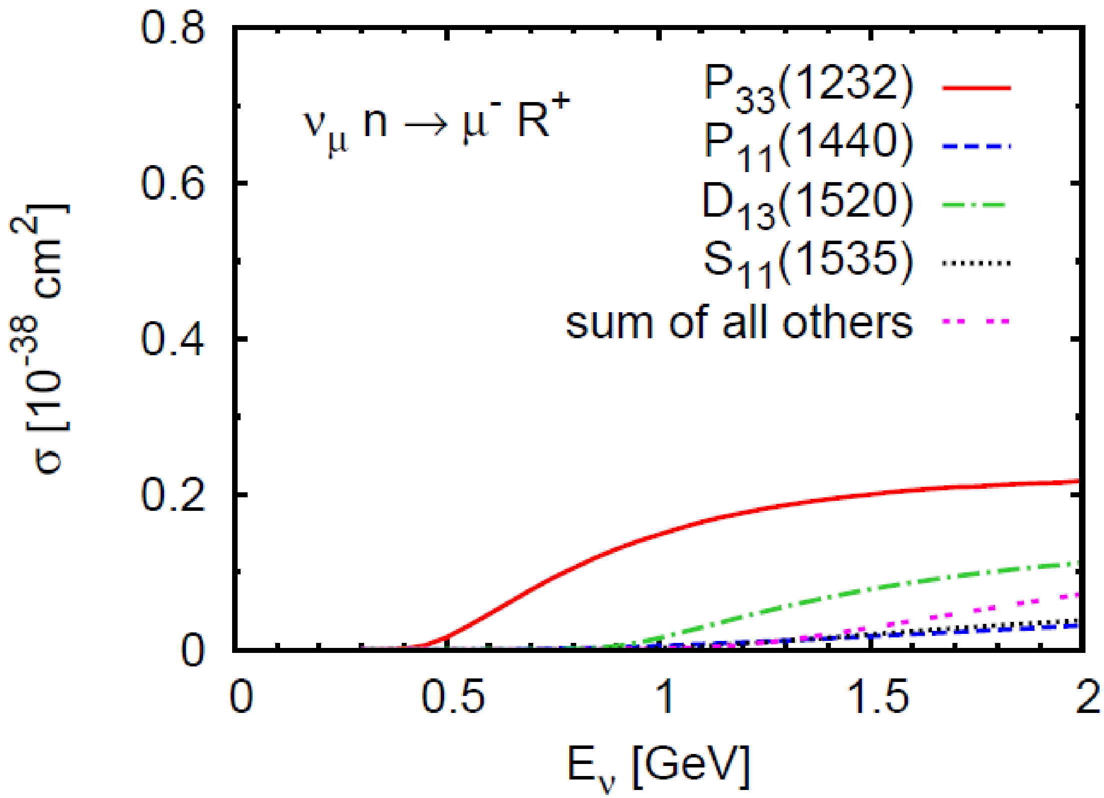
Using $\mathcal{L}_{N^* N\pi} = -\frac{g_{N^* N\pi}}{f_\pi} \bar{N}_\mu^* \gamma_5 (\partial^\mu \vec{\pi}) \vec{\tau} N$ $\quad g_{N^* N\pi} \Leftrightarrow \Gamma(N^* \to N\pi)$

π-pole dominance $\Rightarrow$ $C_6^A = 2 g_{N^* N\pi} F(q^2) \frac{M_N^2}{q^2 - m_\pi^2}$ $\quad F(0) = 1$

Therefore $C_5^A(0) = -2 g_{N^* N\pi}$ $\leftarrow$ Goldberger-Treiman relation

Educated guess: $C_5^A(q^2) = C_5^A(0) \left(1 - \frac{q^2}{{M_A}^2}\right)^{-2}$ $M_A = 1 \text{ GeV}$ $\quad C_3^4 = C_4^A = 0$

Inclusive resonance production



T. Leitner, O. Buss, LAR, U. Mosel, PRC 79 (2009)
T. Leitner, PhD Thesis, 2009

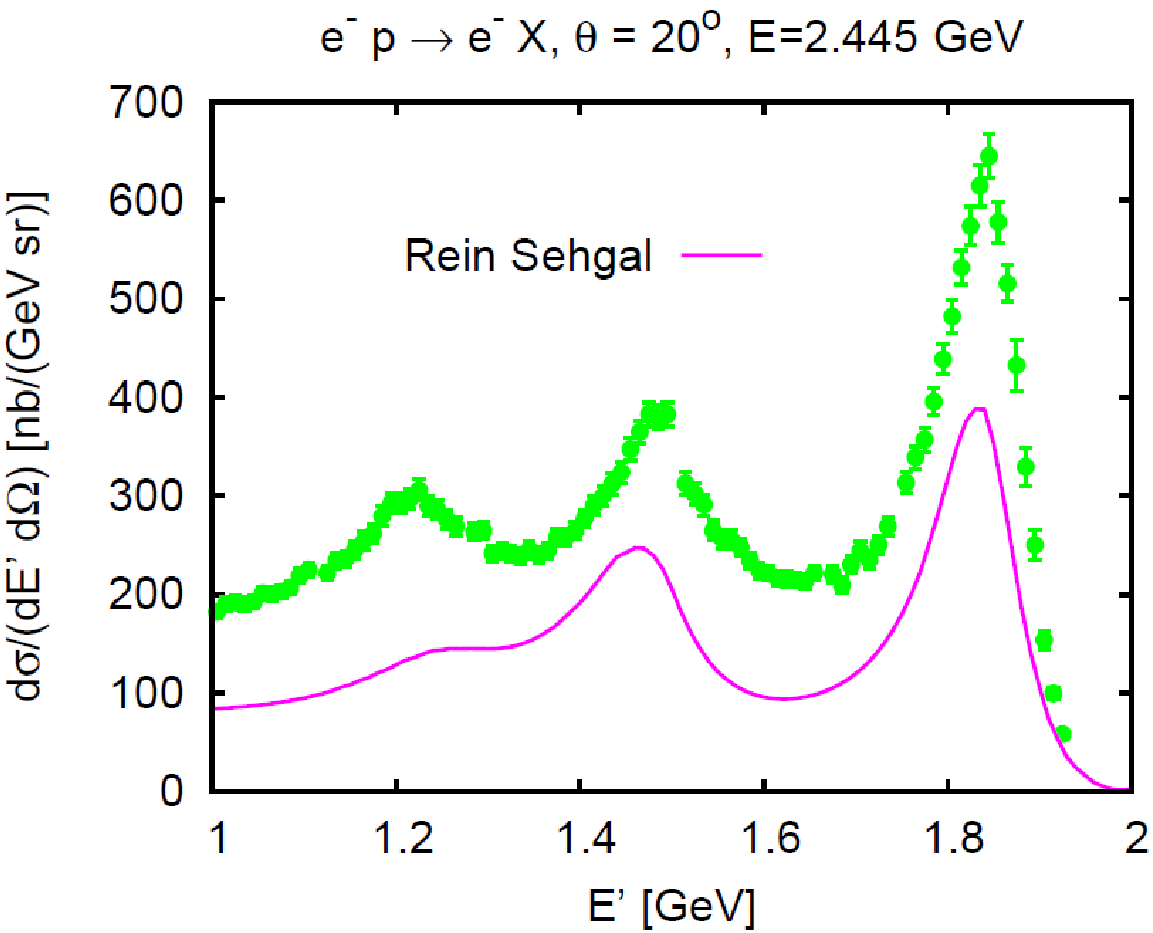
- At E_ν = 2 GeV, CCN*(1520)/CCΔ $\sim$ 0.5, CCN*(1440,1535)/CCΔ $\sim$ 0.22
- N*(1520) is important for $\nu_l\, N \to l\, N'\, \pi$

Resonances in ν generators

- Rein-Sehgal model: Rein, Sehgal, Ann. Phys. 133 (1981) 79.
  - Used by almost all MC generators
  - Relativistic quark model of Feynman-Kislinger-Ravndal with SU(6) spin-flavor symmetry
  - Helicity amplitudes for 18 baryon resonances
  - Lepton mass = 0
    - Corrections: Kuzmin et al., Mod. Phys. Lett. A19 (2004)
      Berger, Sehgal, PRD 76 (2007)
      Graczyk, Sobczyk, PRD 77 (2008)
    - Poor description of π electroproduction data on p

Resonances in ν generators

- Rein-Sehgal model: Rein, Sehgal, Ann. Phys. 133 (1981) 79.



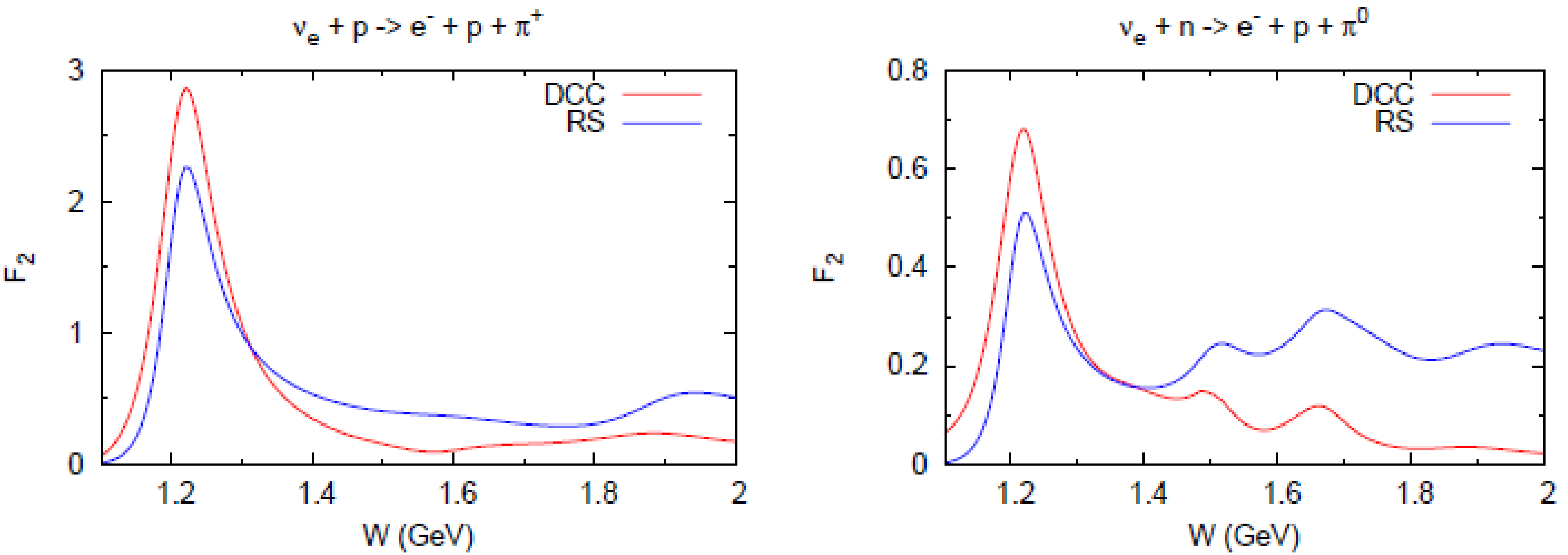
avndal with SU(6)

Leitner et al., POS NUFACT08

2004)

Resonances in ν generators

- Rein-Sehgal model: Rein, Sehgal, Ann. Phys. 133 (1981) 79.
  - Used by almost all MC generators



- Also unsatisfactory in the axial sector: Kamano et al., PRD86 (2012)

PCAC (at $Q^2 \to 0$): π N $\to$ X $\Leftrightarrow$ F_2

Non-resonant background

- Specific for each excusive process
- Background terms interfere with the resonant contributions
- $\nu_l \, N \rightarrow l \, N' \, \pi$
- In Rein-Sehgal model: Rein, Sehgal, Ann. Phys. 133 (1981) 79.

“we have represented the background by a resonance amplitude of P11 character (like the nucleon), with the Breit-Wigner factor replaced by an adjustable constant. The corresponding cross section is added incoherently to the resonant cross section.”

- General principles:
  - CVC, PCAC
  - Threshold behavior dictated by chiral symmetry of QCD

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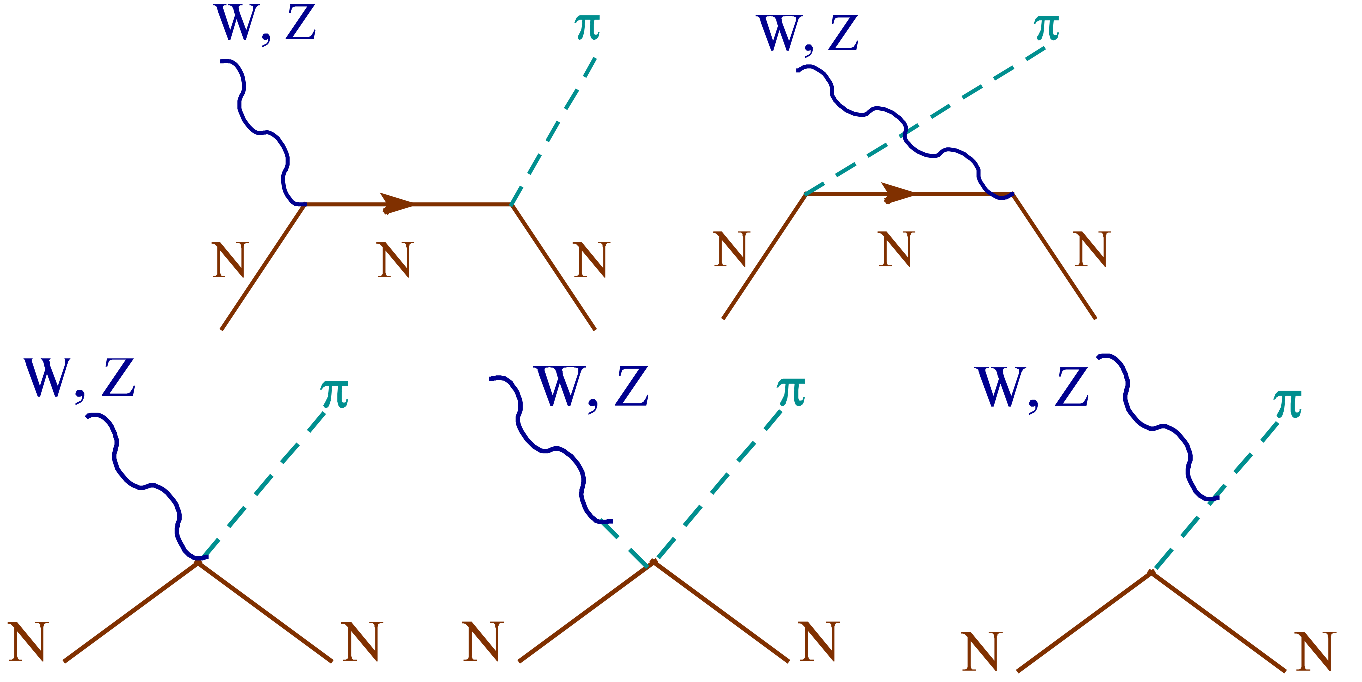

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