Neutrino Induced Pion Production Reaction

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N. Suzuki, A. Matsuyama, B. Julia-Diaz

JSPS:16K05354,19H05104,25105010

Motivation

- Neutrino Physics:
  current and future long base line neutrino experiments, atmospheric neutrino observation

$$< \sigma_{\nu A} >= \int dE_\nu \sigma_{\nu A}(E_\nu)\phi_\nu(E_\nu)$$

$$\begin{array}{rcl} \text{T2K} & E_\nu \sim & 0.6 \pm 0.2 (GeV) \\ \text{Dune} & & 2 \pm 2 \\ \text{atmospheric(MH)} & & \text{a few} \quad \sim 10 \end{array}$$

  reaction mechanism in the GeV energy range: QE and RES, DIS

- Hadron/nuclear physics: probe for axial vector structure of nucleon/nuclei $\leftrightarrow$ beta-decay, muon/electron capture (in a different W, Q^2 region)

$$\begin{aligned} J^\mu_{em} &= V^\mu_3 + V^\mu_{IS} \\ J^\mu_{CC} &= V^\mu_{1+i2} - A^\mu_{1+i3} \end{aligned}$$

Model of neutrino induced pion production reaction

Neutrino induced pion production

- Neutrino induced single pion production (Charged Current: CC)

$$
\begin{aligned}
\nu p \rightarrow & \quad l^-\pi^+ p & : |I = 3/2, I_z = 3/2 > \\
\nu n \rightarrow & \quad l^-\pi^+ n & : \sqrt{\frac{2}{3}}|3/2, 1/2 > + \frac{1}{\sqrt{3}}|3/2, 1/2 > \\
\rightarrow & \quad l^-\pi^0 p & : -\frac{1}{\sqrt{3}}|3/2, 1/2 > + \sqrt{\frac{2}{3}}|3/2, 1/2 > \\
\bar{\nu} n \rightarrow & \quad l^+\pi^- n & \\
\bar{\nu} p \rightarrow & \quad l^+\pi^- p & \\
\rightarrow & \quad l^+\pi^0 n &
\end{aligned}
$$

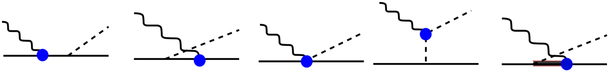
- Inclusive cross section (massless lepton)

$$
\frac{d\sigma}{d\Omega_l dE_l} = \frac{(G_F V_{ud})^2 p_l^2}{2\pi^2}[W_2 \cos^2(\theta/2) + (2W_1 \pm W_3 \frac{E_\nu + E_l}{M}) \sin^2(\theta/2)]
$$

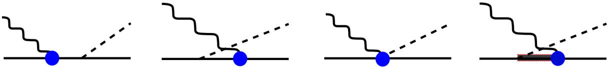
Neutrino induced pion production in $\Delta(1232)$ region

- Non-resonant mechanism

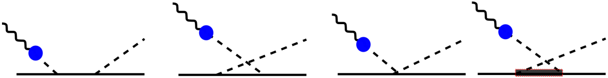
Vector:



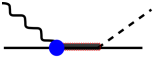
Axial Vector:



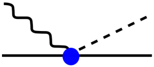
(pion pole)



- s-channel resonance excitation

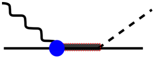


- Contact interaction



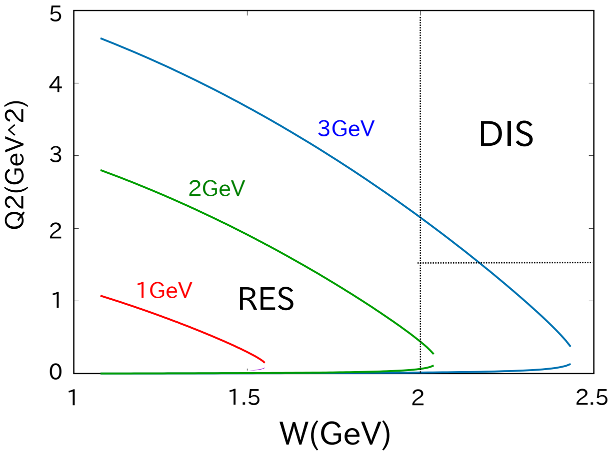
$$
\begin{array}{llll}
V^\mu & \sim \frac{g_A}{2f_\pi}\gamma^\mu\gamma_5 \boldsymbol{\tau}\times\boldsymbol{\pi} & \sim \boldsymbol{\sigma}\ (\boldsymbol{\tau}\times\boldsymbol{\pi})_{1+i2} & E_{0+} \\
A^\mu & \sim \frac{1}{2f_\pi}\gamma^\mu \boldsymbol{\tau}\times\boldsymbol{\pi} & \sim 1\ (\boldsymbol{\tau}\times\boldsymbol{\pi})_{1+i2}\delta_{\mu,0} & \mathcal{S}_{0+}
\end{array}
$$

- $\Delta(1232)$ excitation



$$
\begin{array}{llll}
V^\mu & \sim & \dfrac{G_M^{N\Delta}}{2M} i\boldsymbol{S}\times\boldsymbol{q}\ T_{1+i2} & \text{M1} \\
A^\mu & \sim & G_A^{N\Delta}\boldsymbol{S}\ T_{1+i2} & \text{GT}
\end{array}
$$

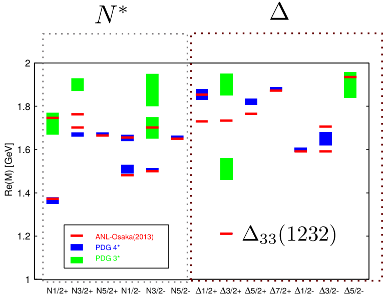
GeV neutrino and reaction mechanism

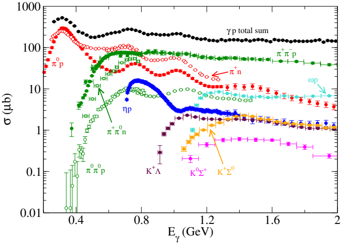


$$W = \sqrt{(p+q)^2}, Q^2 = -q^2 = -(p_\nu - p_l)^2$$

Feature of meson production reactions $m_N + m_\pi < W < 2GeV$

- meson production through N^* and Δ resonances $M_R < 2GeV$ and non-resonant mechanism.





- opening of $\eta N, \pi\pi N, K\Lambda, K\Sigma, , ,$ channels
  $\rightarrow$ multi-channel unitarity including three-body($\pi\pi N$).

Neutrino induced meson production

- Unitarity:

$$Im(\mathcal{F}_{\pi N,\gamma^* N}) = \sum_{n=\pi N,\pi\pi N,\eta N,..} (\mathcal{F}_{n,\pi N})^* \mathcal{F}_{n,\gamma^* N}$$

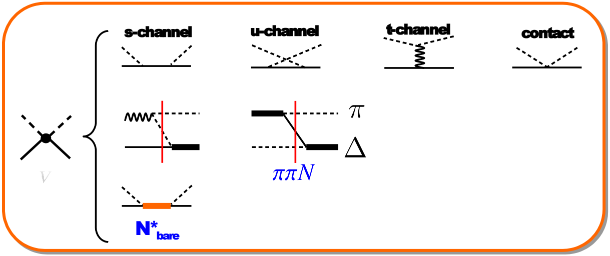
  - HNV : Below 2π, Watson Theorem: $M^\alpha = |M^\alpha| e^{i\delta^\alpha_{\pi N}}, \quad \alpha = JLI$
  - SL, ANL-Osaka: solve Lippmann-Schwinger equation.

- Q^2 dependence of coupling constants. $G_V^{N,\Delta}(Q^2), G_A^{N,\Delta}(Q^2)$

  analysis of data on electron and neutrino induced pion production reactions

Model developed for N^* physics: spectrum of nucleon excited states,transition form factors(ANL-Osaka Coupled channel model)

- include N^*, Δ resonances
- coupled channel model $\pi N, \eta N, \pi\pi N(\sigma N, \rho N, \pi\Delta), K\Lambda, K\Sigma$
- Satisfy three body($\pi\pi N$) unitarity



$$\rightarrow \quad T = V + V G_0 T$$

ANL-Osaka DCC model

- The model is constructed by fitting available data on pion, photon, electron induced meson production reaction

  $\pi N \to MB$:strong interaction dynamics(resonance, non-resonance)
  $\gamma^* p, \gamma^* n \to MB$:iso-vector,iso-scalar vector current

- the model is extended for axial vector current.

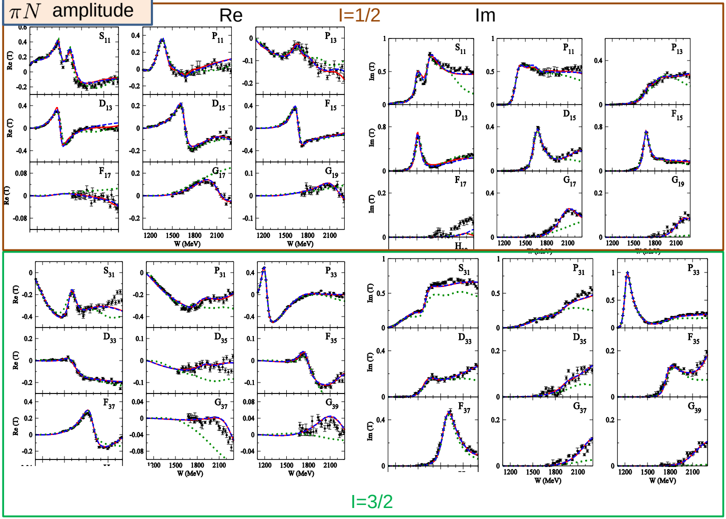
  vector current vertex $\to$ axial vector current assuming PCAC and dipole $N - N^*\Delta$ transition form factors.

  H. Kamano,S.X. Nakamura L, TS PRC88,035209(2013),
  H. Kamano,S.X. Nakamura,T.-S. H. Lee,TS PRC94 015291 (2016)

  S. X. Nakamura,H. Kamano, TS,PRD92 07402(2015)

$\to$ meson production of CC and NC currents

πN amplitude

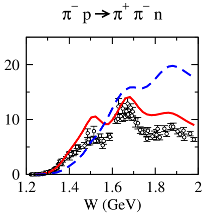


pi N → pi pi N reaction

Kamano, Julia-Diaz, Lee, Matsuyama, Sato, PRC79 025206 (2009)

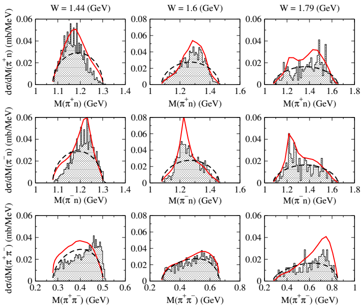
Parameters used in the calculation are from πN → πN analysis.

$$\pi^- p \rightarrow \pi^+ \pi^- n$$



Full result

C.C. effect off

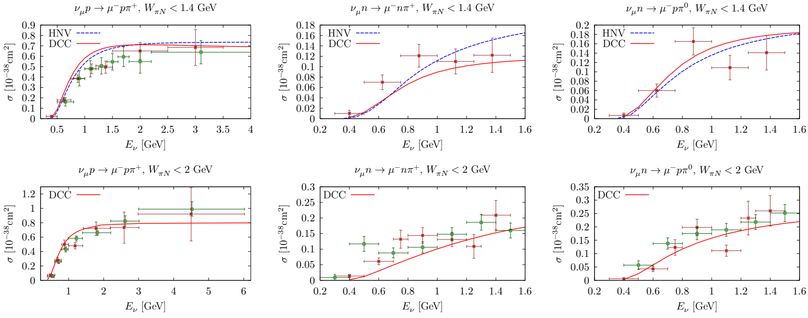


Full result **Phase space**

Data handled with the help of R. Arndt

Single pion production

Single pion production in $\Delta(1232)$ region

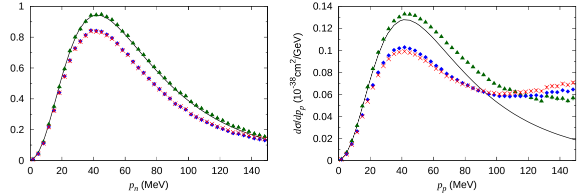


J. Sobczyk,E. Hernandez,S.X. Nakamura, J. Nieves,T. Sato PRD98(2018)073001

- Re-analyzed ANL/BNL data, C. Wilkinson et al. PRD90
- ANL-Osaka DCC,PRD92, Hernandez,Nieves,Valverde PRD76

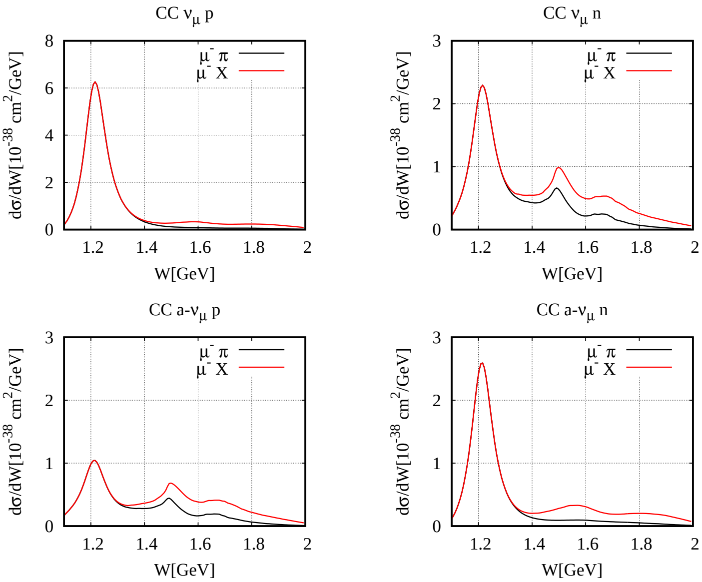
Caution on $\sigma(\nu N)$ of ANL/BNL data extracted from $\sigma(\nu d)$.
About $10 \sim 30\%$ correction due to FSI effects should be corrected S. Nakamura, H. Kamano, T. Sato PRD99,031301(R)(2019)

Momentum distribution of spectator nucleon ($\nu_\mu d \to \mu^- \pi^+ p n$)

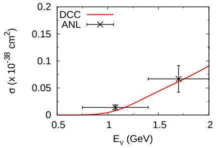


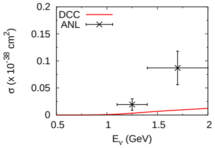
IA, IA+NN-resc,IA+NN-resc+πN-resc

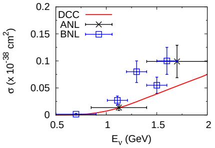
$d\sigma/dW \;\; E_\nu = 2GeV$



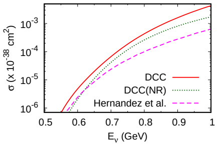
$\nu_\mu p \to \mu^- \pi^+ \pi^- p$ $\qquad$ $\nu_\mu p \to \mu^- \pi^+ \pi^+ n$ $\qquad$ $\nu_\mu n \to \mu^- \pi^+ \pi^- n$

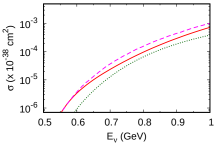


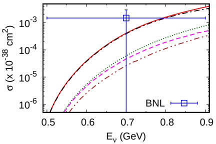




Near threshold(compare with Hernandez et al.(D(1232)+N(1440))







Brief summary:Models of neutrino induced pion production

Summary of models for neutrino reaction in RES

	Res	Non-res	Unit.	1pi	2pi	Tot
RS	Delta,N*	-	X	O		O
LPP	Delta,N*	X	X	O		O
HVM	Delta(1232)	chiral	O	O		
	Delta(1232)+N(1440)	chiral	X	O	O	
Giessen	Delta, N*	phen.	X	O		O
ANL-Osaka	Delta, N*	O	O	O	O	O

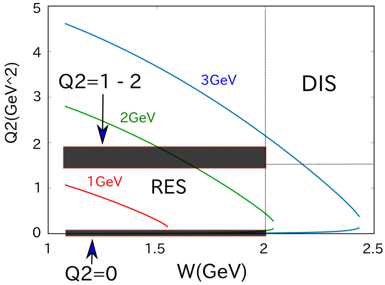
RS: D. Rein, L. M. Sehgal AP133(81), LPP: O. Lalakulich,E.A. Paschos,G. Piranlshvili,PRD74(2006)
HNV: E. Hernandez,J. Nieves,M. Valverde PRD76(2007) Giessen: T. Leitner,O.Buss,L.Alvarez-Ruso,U. Mosel,PRC79(2009)
ANL-Osaka DCC:S.X.Nakamura,H. Kamano,TS,PRD92(2015) ,TS,D. Uno,T.-S.H.Lee PRC67(2003)

R. Gonzales-Jimenes et al. PRD95,113007(2017)+Regge

Axial Vector Current

How good DCC model, Axial vector current?

- $Q^2 = 0$: F_2^{CC} and pi-N cross section.
- $Q^2 \sim 1 - 2GeV^2$: Is DCC model smoothly interpolates to DIS ?



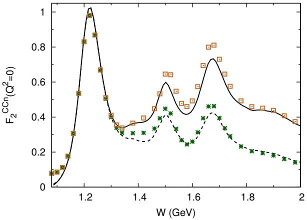
F_2^{CC} and pi-N cross section

Axial Vector current F_2^{CC} (total cross section) at $Q^2 = 0$

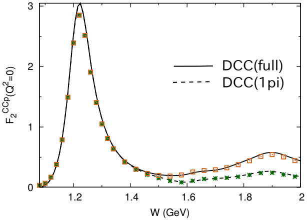
DCC model : 1π dash, a Total solid

πN cross section data: 1π green, a Total brown

$$F_2^{CC}(Q^2 = 0) = \frac{2f_\pi^2}{\pi}\sigma(\pi + N)$$



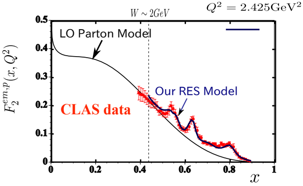
Neutron

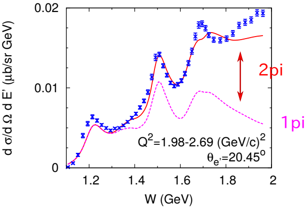


Proton

- Description of axial vector current at $Q^2 = 0$ is consistent with pion scattering data.

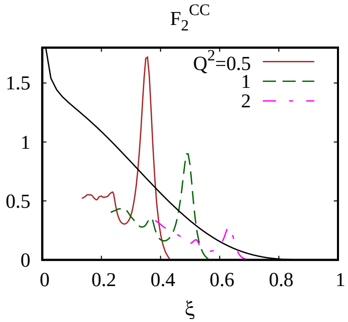
Is DCC model smoothly interpolates to DIS ?





- EM for proton

Is DCC model smoothly interpolates to DIS ?



$$F_2^{\alpha} = \frac{F_{2p}^{\alpha} + F_{2n}^{\alpha}}{2} \quad \alpha = EM, CC$$

- $m_N + m_\pi < W < 2GeV$
- around $W \sim 2GeV, Q^2 = 1 \sim 2GeV^2$, $F_2^{CC} \sim |V|^2$.

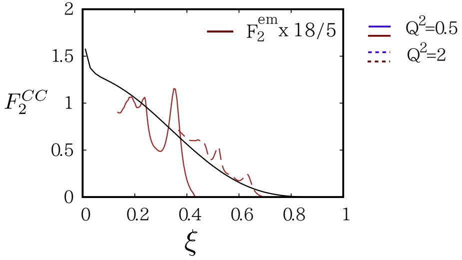
Parton Distribution vs DCC model

- Parton Picture(Isospin-symmetry, neglect s)

$$
\begin{aligned}
F_2^{EM} &= \frac{x}{2}([(\frac{2}{3})^2 u_p + (\frac{1}{3})^2 d_p] + [(\frac{2}{3})^2 u_n + (\frac{1}{3})^2 d_n]) = x\frac{5}{18}(u+d) \\
F_2^{CC} &= \frac{x}{2}(d_p + d_n)(1+1) = x(u+d) = \frac{18}{5}F_2^{EM}
\end{aligned}
$$

- Hadron picture

$$
\begin{aligned}
F_2^{EM} &\sim \sum_f |<f|V_3 + V_{IS}|N>|^2 \\
F_2^{CC} &\sim \sum_f [|<f|V_{1+i2}|N>|^2 + |<f|A_{1+i2}|N>|^2]
\end{aligned}
$$



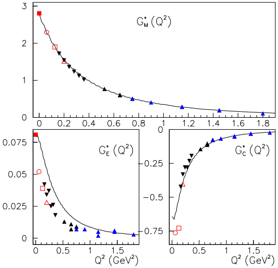
- $F_2^{em} \times 18/5$ of ANL-Osaka Model.

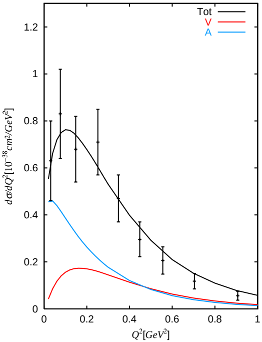
$$\frac{18}{5}F_2^{em}(\text{ANL-OSAKA}) \approx F_2^{CC}(\text{PDF}) = x(u + \bar{u} + d + \bar{d})$$

- contribution of A in DCC-model around large W, Q^2 might be too weak.

Possible solution: transition form factor

$\Delta(1232)$: Left EM, Right CC

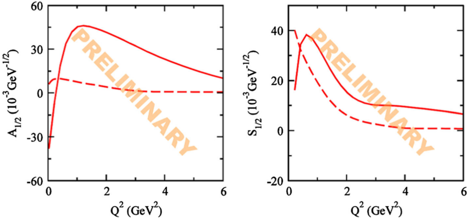




PRC75,015205(2007)(EM), PRC67,65201 (2003)(CC)

Example of transition form factors $N^*(1/2, 1/2^+)$

- Vector(EM): Helicity amplitudes extracted from the residue of partial wave amplitude(DCC-model) at resonance pole (figure from H. Kamano)



- Axial Vector (Quark model)

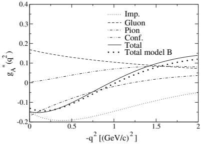
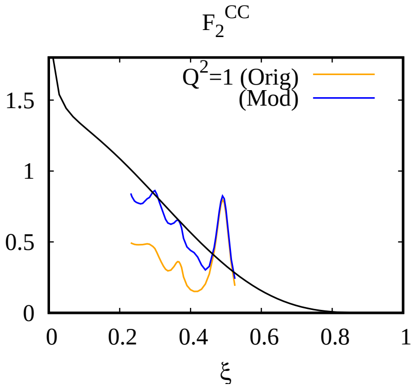


FIG. 7. Axial form factor $g_A^*(q^2)$. Notation as in the upper panel of Fig. 3.

PRC75,065203 (2007) D. Barquilla-Cano, A.J. Buchmann, E. Hernandez

Simple Exercise of DCC model

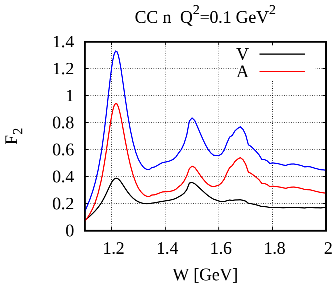
$$A_A^\lambda(Q^2) = A_A^\lambda(0) \times \frac{A_V^\lambda(Q^2)}{A_V^\lambda(0)} \quad \text{except} \quad P_{33}$$



Summary

- ANL-OSAKA DCC model is extended to describe weak meson production reaction up to $W < 2GeV$.
- Neutrino induced single pon production in N^*, Δ resonance region is studied using ANL-Osaka model.
  Comparison with Neutrino event generators(NEUT, GENIE,NuWro,..) and other models will be very useful.
- Model of axial vector current is examined.
  At $Q^2 = 0$, DCC model reproduce πN data.
  Comparison with PDF at high Q^2, suggests need for more strength at high W region.
  Improving axial transition form factors will be helpful.
  PV asymmetry , in principle, gives information of axial vector current.

Contribution of A and V at $Q^2 = 0.1$

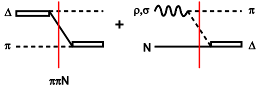


Scattering amplitude of pion and photon induced meson production amplitudes are given by solving coupled channel LS equation(3-dim reduction) in momentum space

$$T_{\beta,\alpha}(k',k,W) = V_{\beta,\alpha}(k',k)+\sum_{\gamma}\int dq q^2 V_{\beta,\gamma}(k',q)G^0_{\gamma}(q,W)T_{\gamma,\alpha}(q,k,W)$$

Scattering amplitudes satisfy two-body and three-body unitarity

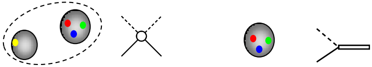
particle exchange interaction $Z(E)$ =



After manupilation of the formula

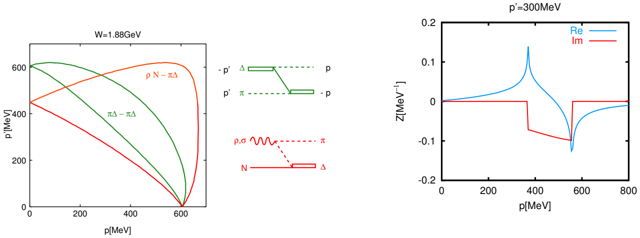
$$T_{\alpha,\beta}(W) \;=\; t^{nr}_{\alpha,\beta}(W) + \sum_{i,j}\bar{\Gamma}_{\alpha,i}(W)\left[\frac{1}{W-m_0-\Sigma(W)}\right]_{ij}\bar{\Gamma}_{\beta,j}(W)$$

α,β Meson-Baryon channel i,j Resonances



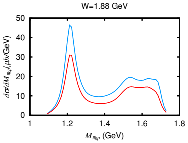
Singularity structure of $Z(E)$

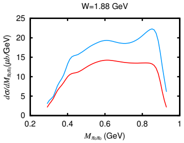
$< \pi\Delta : p'|Z(E)|\pi\Delta : p > \quad l_{\pi\Delta} = 0, j = 3/2$



- Rapid momentum dependence of $Z \to t$(non-res)
- Numerical complication: Contour rotation method is not valid for $\pi\pi N$ production $\to$ Spline-interpolation method (A. Matsuyama for πNN)

Invariant mass distribution ($\gamma p \to \pi^0\pi^0 p$ at W$= 1.88$GeV)





Full $Z(E) = 0$

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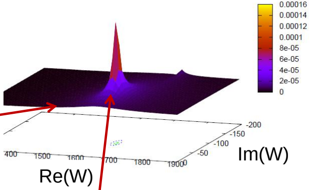
Extraction of resonance parameters

Observables: cross section, polarization

Coupled channel reaction model of meson production reactions

Partial wave amplitude

$\mathcal{F}(W)$



Analytic continuation to complex W

Characterize resonance from pole and residue of the amplitude

$$< f|\mathcal{F}(W)|i > \sim \frac{< f|V|\phi_R >< \tilde{\phi}_R|V|i >}{W - M + i\Gamma/2}$$

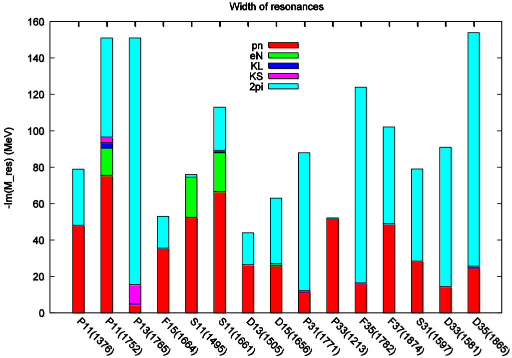
Resonance parameter

Pole position → mass, width

Residue → Form factors, coupling constants

Half width $\Gamma/2 = -Im(E_{res})$

current model



Some freedom exists on the definition of partial width from the residue of the amplitude. The numbers should be taken as a one estimation of the MB-res coupling strength .