Light-quark baryon spectroscopy and transition form factor within ANL-Osaka dynamical coupled-channels approach

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(Osaka U.)

ECT* Workshop “Nucleon Resonances: From Photoproduction to High Photon Virtualities”
ECT*, Trento, Italy, October 12-16, 2015

Outline

PART I:

Overview of ANL-Osaka Dynamical Coupled-Channels (DCC) analysis

- **N* & Δ* spectroscopy via the analysis of πN & γN reactions**
  ➔ HK, Nakamura, Lee, Sato, PRC88(2013)035209; HK, PRC88(2013) 045203

- **Application to neutrino-induced meson production reactions**
  ➔ Nakamura, HK, Sato, arXiv:1506.03403, to appear in PRD

- **Λ* & Σ* spectroscopy via the analysis of $\bar{K}$N reactions**
  ➔ HK, Nakamura, Lee, Sato, PRC90(2014)065204;92(2015)025205

PART II:

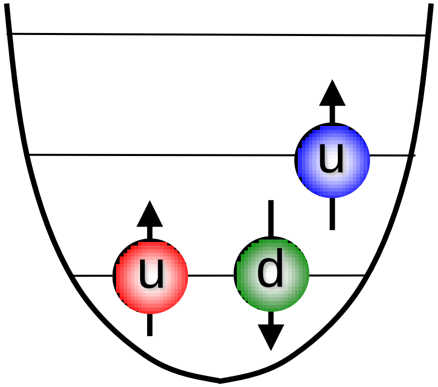
Electromagnetic transition form factor of nucleon resonances (➔ for Toru Sato)

PART I
Overview of ANL-Osaka DCC Analysis

Hadron spectrum and reaction dynamics

✓ **Various *static* hadron models have been proposed to calculate hadron spectrum and form factors.**

- **Quark models, Bag models, Dyson-Schwinger approaches, Holographic QCD,…**
- **Excited hadrons are treated as stable particles. → The resulting masses are *real*.**



Constituent quark model

Hadron spectrum and reaction dynamics

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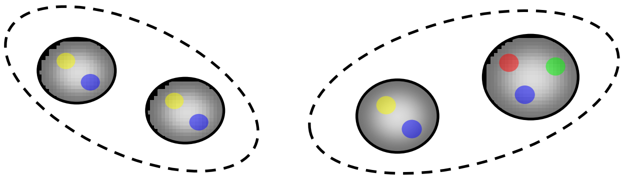
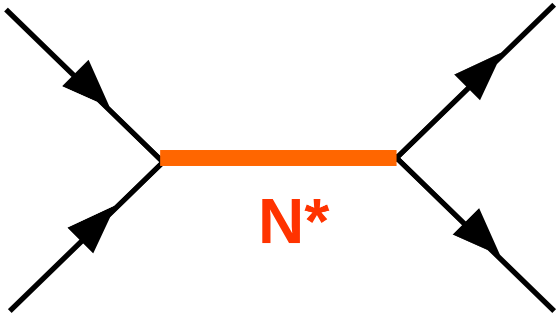
- Excited hadrons are treated as stable particles. → The resulting masses are *real*.

✓ In reality, excited hadrons are "unstable" and can exist only as resonance states in hadron reactions.

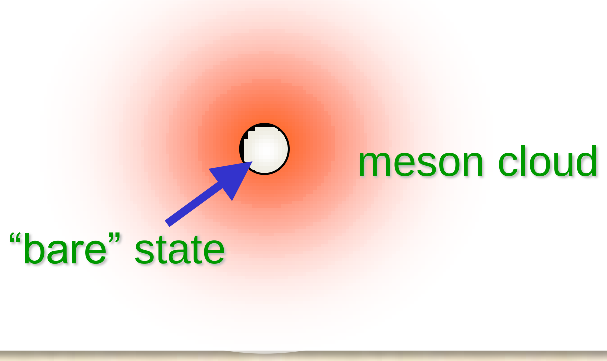
"Mass" becomes complex !!
→ "pole mass"

"molecule-like" states





core (bare state) + meson cloud



Hadron spectrum and reaction dynamics

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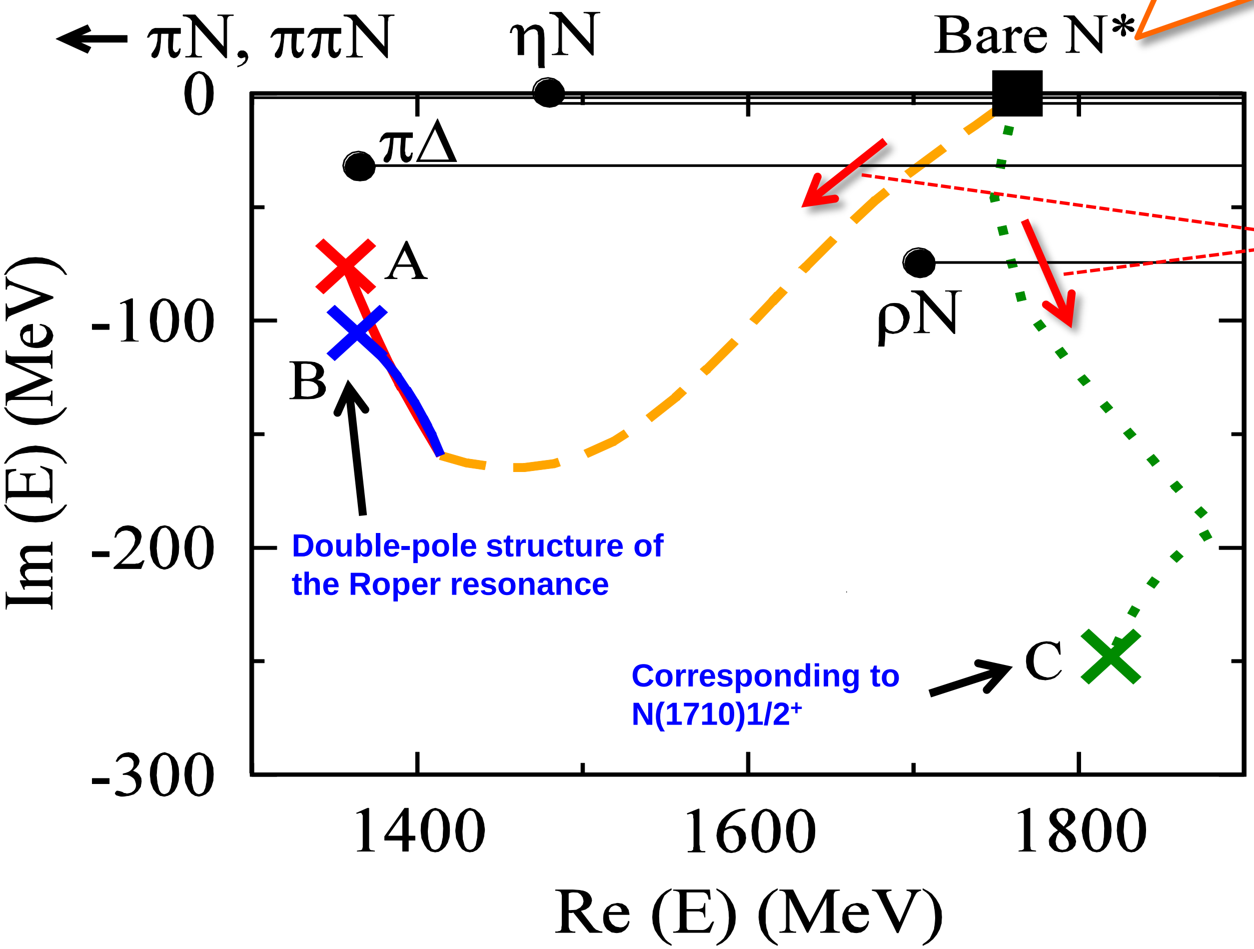
  - ➢ Quark models, Bag models, Dyson-Schwinger approaches, Holographic QCD,…
  - ➢ Excited hadrons are treated as stable particles. → The resulting masses are *real*.
- ✓ In reality, excited hadrons are "unstable" and can exist only as resonance states in hadron reactions.

"Mass" becomes complex !!
→ "pole mass"

What is the role of reaction dynamics in interpreting the spectrum, structure, and dynamical origin of hadrons??

Dynamical origin of P11 N* resonances
(example of nontrivial nature of multichannel reaction dynamics)



Would be related to a baryon state in static hadron models excluding meson-baryon continuums

Move of poles by “gradually” strengthening channel couplings

Double-pole structure of the Roper resonance

Corresponding to N(1710)1/2⁺

Suzuki, Julia-Diaz, HK, Lee, Matsuyama, Sato, PRL104 042302 (2010)

Dynamical origin of P11 N* resonances

(example of nontrivial nature of multichannel reaction dynamics)

To explore role of reaction dynamics for hadron resonances, one needs:

- Modeling appropriately reaction processes with a model Hamiltonian.
  (➔ not a simple "pole + polynomial" parametrization, etc.)

- Solving coupled-channels equations so that the amplitudes satisfy the multichannel unitarity.
  (➔ key to having proper analytic structure [branch points, cuts,…] in complex energy plane)

We employ Dynamical Coupled-Channels approach !!

Dynamical coupled-channels (DCC) model for meson production reactions

For details see Matsuyama, Sato, Lee, Phys. Rep. 439(2007)193
HK, Nakamura, Lee, Sato, PRC(2013)035209

✓ **Partial-wave (LSJ) amplitudes of a → b reaction:**

$$T^{(LSJ)}_{a,b}(p_a, p_b; E) = V^{(LSJ)}_{a,b}(p_a, p_b; E) + \underbrace{\sum_c}_{\text{coupled-channels effect}} \underbrace{\int_0^\infty q^2 dq}_{\text{off-shell effect}} V^{(LSJ)}_{a,c}(p_a, q; E) G_c(q; E) T^{(LSJ)}_{c,b}(q, p_b; E)$$

✓ **Reaction channels:**

$$a, b, c = (\gamma^{(*)}N,\ \pi N,\ \eta N,\ \underbrace{\boxed{\pi\Delta,\ \sigma N,\ \rho N,}}_{\pi\pi N}\ K\Lambda,\ K\Sigma, \omega N \cdots)$$

✓ **Transition Potentials:**

$$V_{a,b} = \underbrace{v_{a,b}}_{\boxed{\text{Exchange potentials}}} + \underbrace{Z_{a,b}}_{\boxed{\text{Z-diagrams}}} + \underbrace{\sum_{N^*} \frac{\Gamma^\dagger_{N^*,a} \Gamma_{N^*,b}}{E - M_{N^*}}}_{\boxed{\text{bare N* states}}}$$

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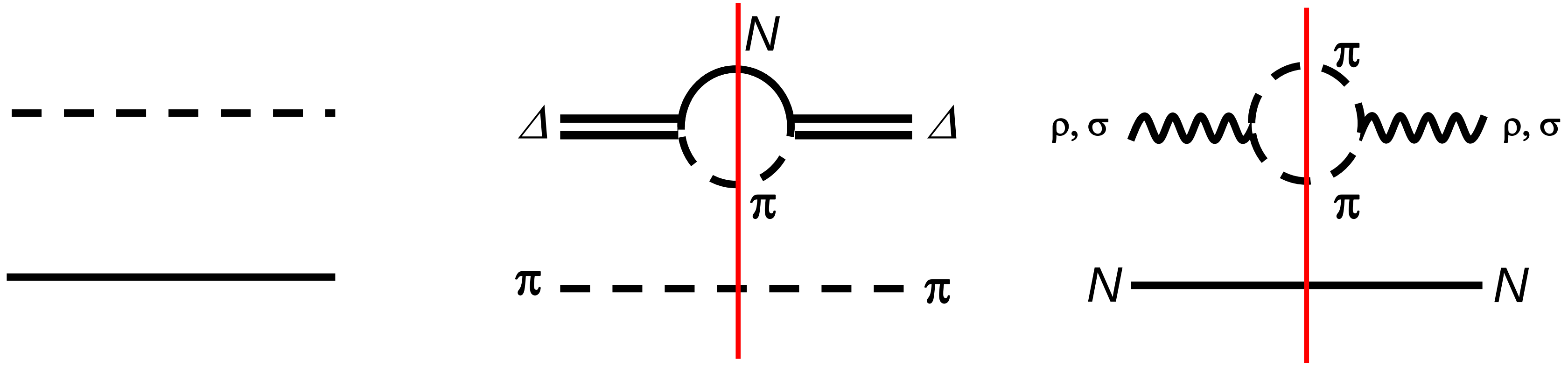
- ✓ **Meson-Baryon Green functions** G_{MB}

$MB = \pi N, \eta N, K\Lambda, K\Sigma, \omega N$

Stable channels

$MB = \pi\Delta, \rho N, \sigma N$

Quasi 2-body channels



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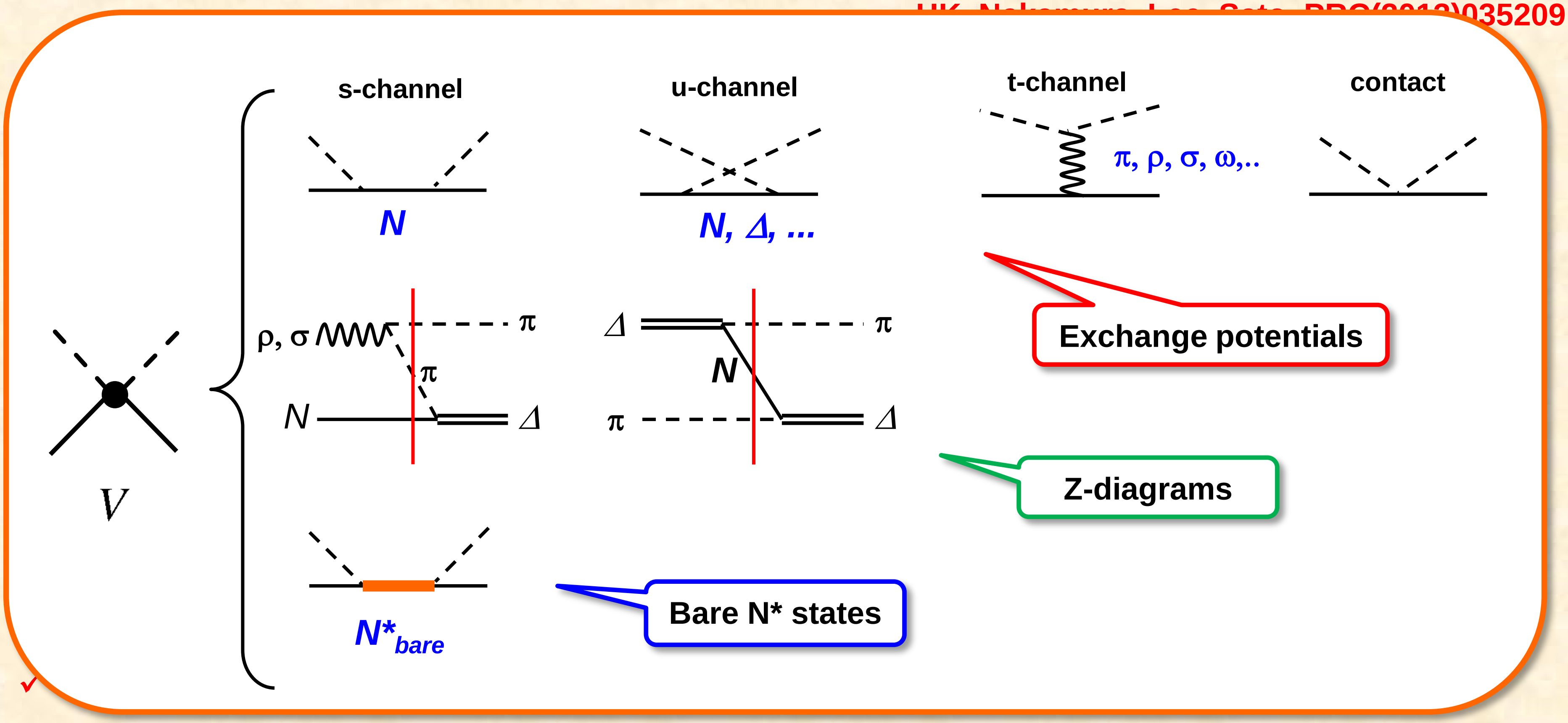

Exchange potentials

Z-diagrams

Bare N* states

$$V_{a,b} = v_{a,b} + Z_{a,b} + \sum_{N^*} \frac{\Gamma^\dagger_{N^*,a}\Gamma_{N^*,b}}{E - M_{N^*}}$$

Exchange potentials

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bare N* states

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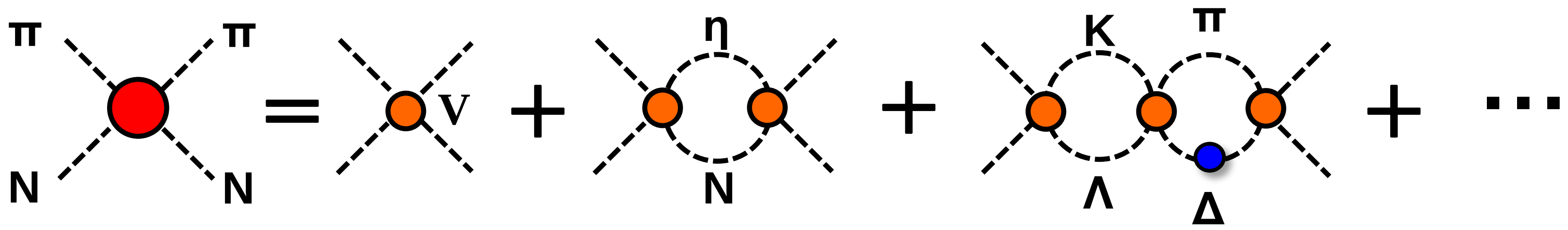
- ✓ **Summing up all possible transitions between reaction channels !!**
  (➔ satisfies multichannel two- and *three*-body unitarity)

e.g.) πN scattering



- ✓ **Momentum integral takes into account off-shell rescattering effects in the intermediate processes.**

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- ✓ **Reaction channels:**

$$a, b, c = (\gamma^{(*)}N$$

Would be related with hadron states of the static hadron models (quark models, DSE, etc.) excluding meson-baryon continuums.

- ✓ **Transition Potentials:**

$$V_{a,b} = v_{a,b} + Z_{a,b} + \sum_{N^*}\frac{\Gamma^\dagger_{N^*,a}\Gamma_{N^*,b}}{E - M_{N^*}}$$

Exchange potentials

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bare N* states

Dynamical coupled-channels (DCC) model for meson production reactions

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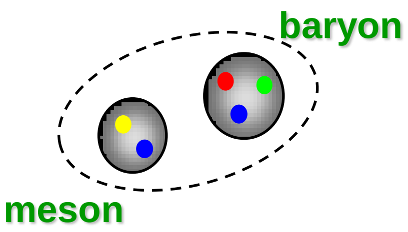
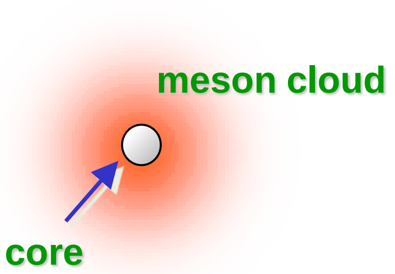
- ✓ **Partial-wave (LSJ) amplitudes of a → b reaction:**

Physical N*s will be a “mixture” of the two pictures:



$$|N^*\rangle = |MB\rangle$$



$$|N^*\rangle = |qqq\rangle + |\mathrm{m.c.}\rangle$$

- ✓ **Transition Potentials:**

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Exchange potentials

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Applications of ANL-Osaka DCC approach to various systems

N* & Δ* spectroscopy

- **Early analyses of πN & γN reactions:**
  PRC76(2007)065201; 77(2008)045205; 78(2008)025204
  PRC79(2009)025206; 80(2009)065203; 81(2010)065207
  PRL104(2010)042302
- **Latest analysis of πN & γN reactions:**
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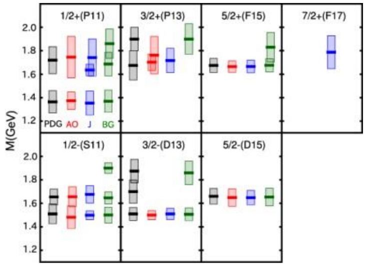
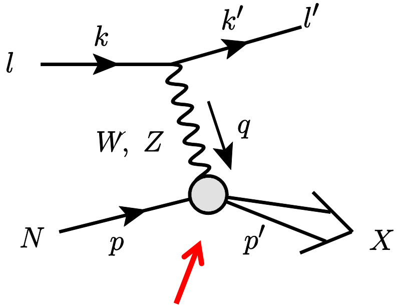
- **Electroproduction analysis & Form factor extraction:**
  PRC80(2009)025207; 82(2010)045206



Neutrino reactions

- **Calculation in $Q^2 = 0$ limit:**
  PRD86(2012)097503
- **Full DCC-model calculation up to W = 2 GeV, $Q^2 = 3$ GeV^2:**
  arXiv:1506.03403 (to appear in PRD)



Weak ("V-A") form factors

ANL-Osaka DCC approach

Λ* & Σ* spectroscopy

- **Λ*, Σ* resonance extractions via analysis of K^-p reactions:**
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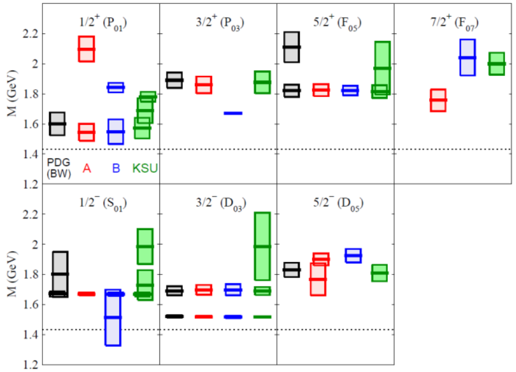
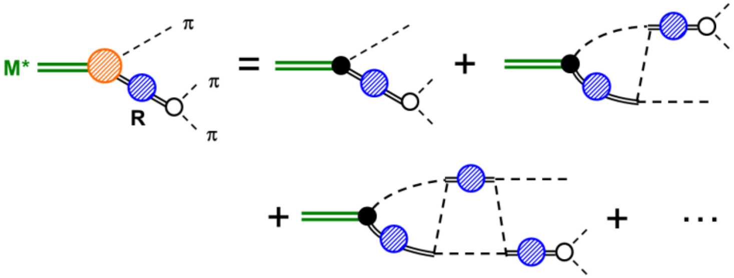


Meson spectroscopy

- **Formulation of 3-body unitary model for decays of mesons:**
  PRD84(2011)114019
- **Application to γp → M*N → (3π)N:**
  PRD86(2012)114012



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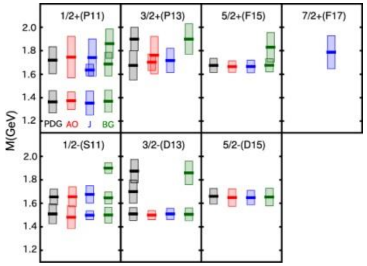

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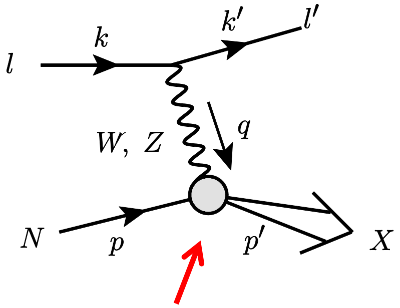

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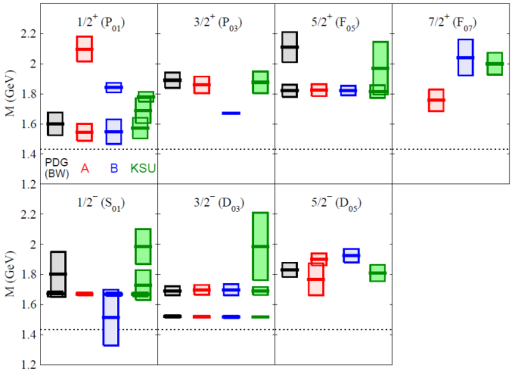

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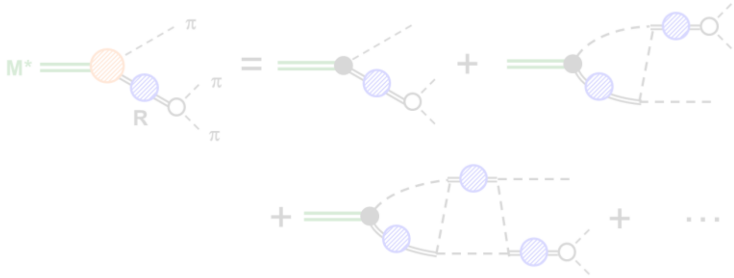

ANL-Osaka DCC approach to N* and Δ*

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$$a,b,c = (\gamma^{(*)}N,\ \pi N,\ \eta N,\ \underbrace{\boxed{\pi\Delta,\ \sigma N,\ \rho N,}}_{\pi\pi N}\ K\Lambda,\ K\Sigma,\cdots)$$

← Region our model can cover →

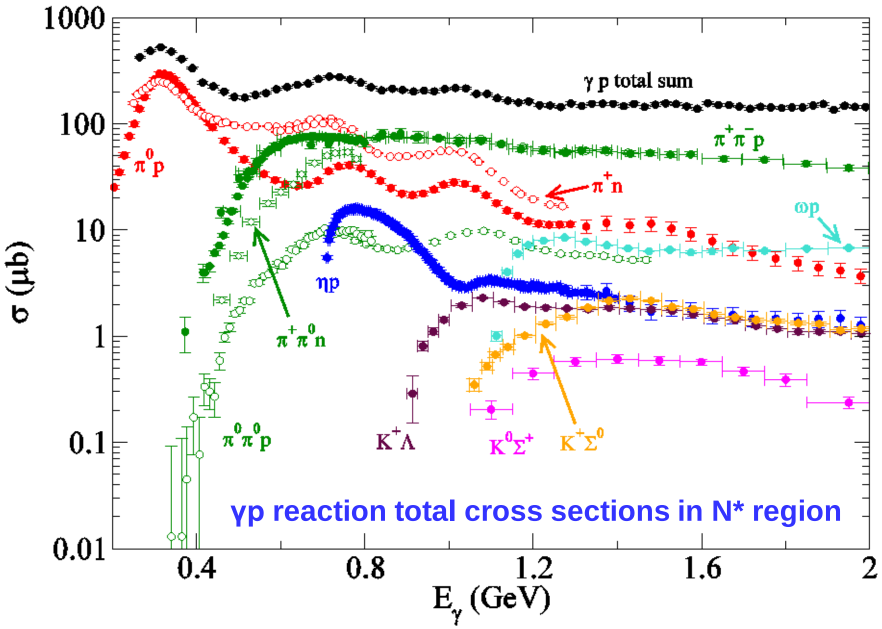
Latest published model (8-channel):

HK, Nakamura, Lee, Sato, PRC88(2013)035209

Constructed by simultaneous analysis of

- πN SAID PW amps. (W < 2.3 GeV)
- πp → ηN, KΛ, KΣ (W < 2.1 GeV)
- γp → πN, ηN, KΛ, KΣ (W < 2.1 GeV)

(including dσ/dΩ & polarization obs. data)



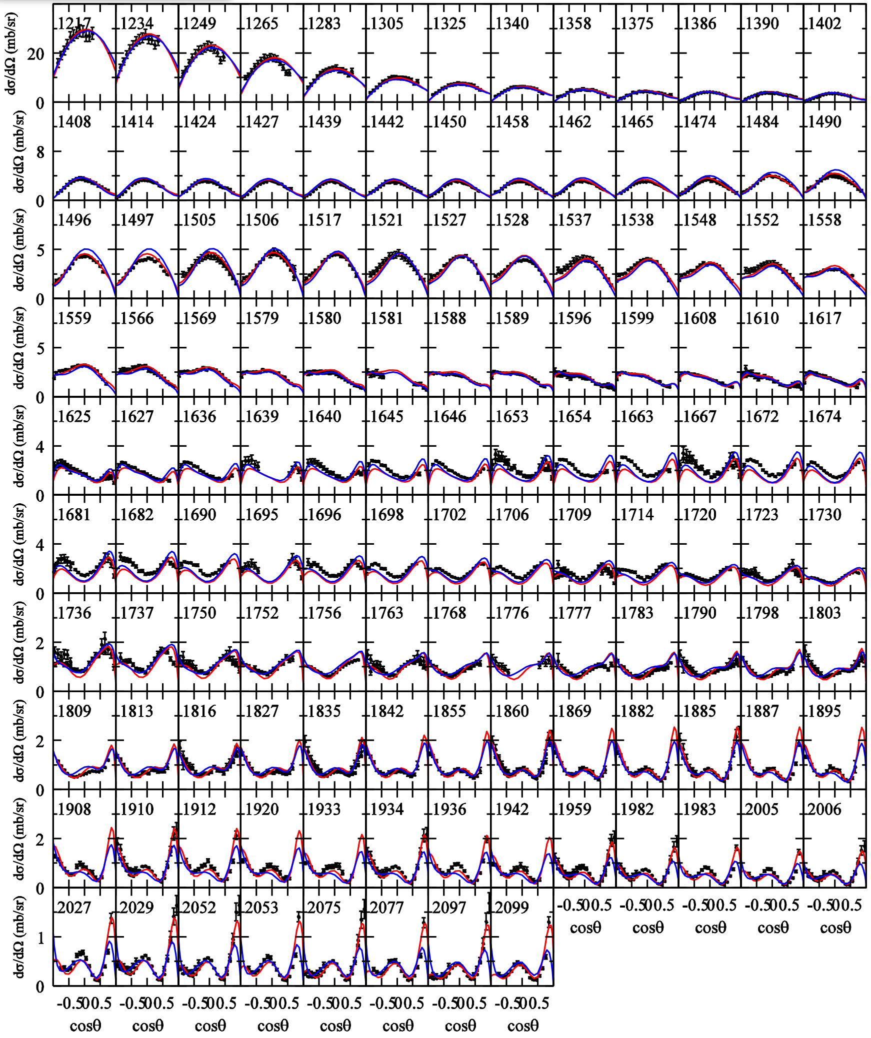
γp reaction total cross sections in N* region

ANL-Osaka DCC approach to N* and Δ*

HK, Nakamura, Lee, Sato, PRC88(2013)035209 (with update)

$\gamma p \rightarrow \pi^0 p$

dσ/dΩ for W < 2.1 GeV



$\gamma p \rightarrow K^+\Lambda$

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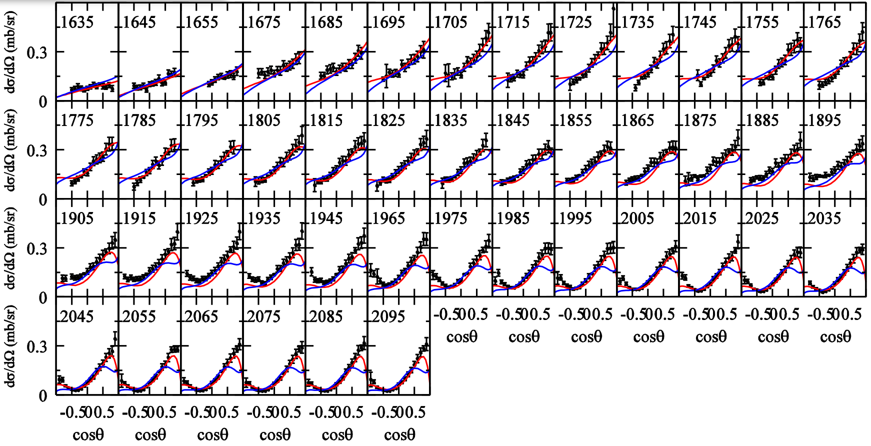
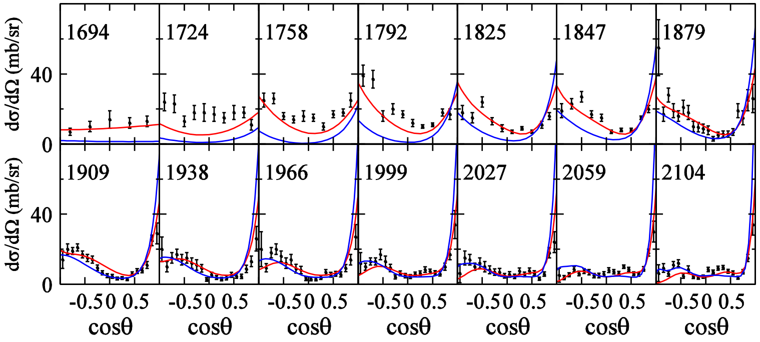


$\pi^- p \rightarrow K^0\Sigma^0$

dσ/dΩ for W < 2.1 GeV



Red: minor updated ver.

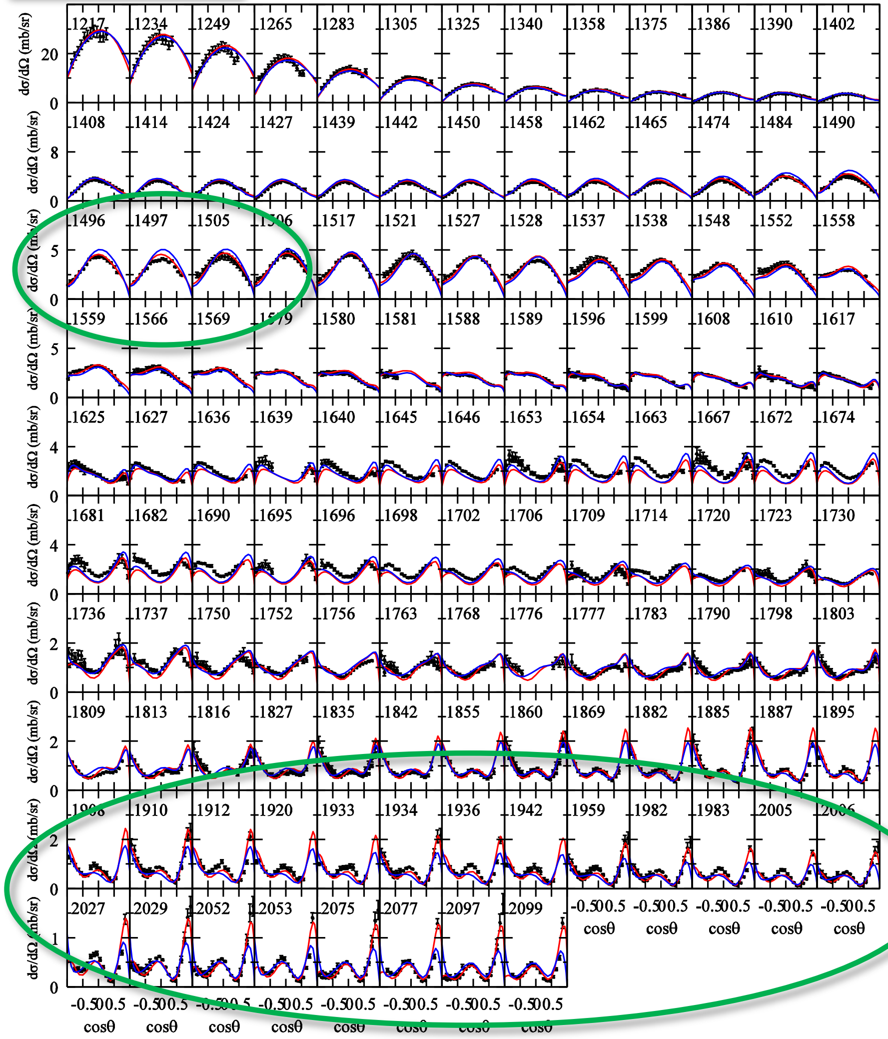
Blue: PRC88(2013)035209

ANL-Osaka DCC approach to N* and Δ*

HK, Nakamura, Lee, Sato, PRC88(2013)035209 (with update)

γp → π^0p

dσ/dΩ for W < 2.1 GeV



γp → $K^+\Lambda$

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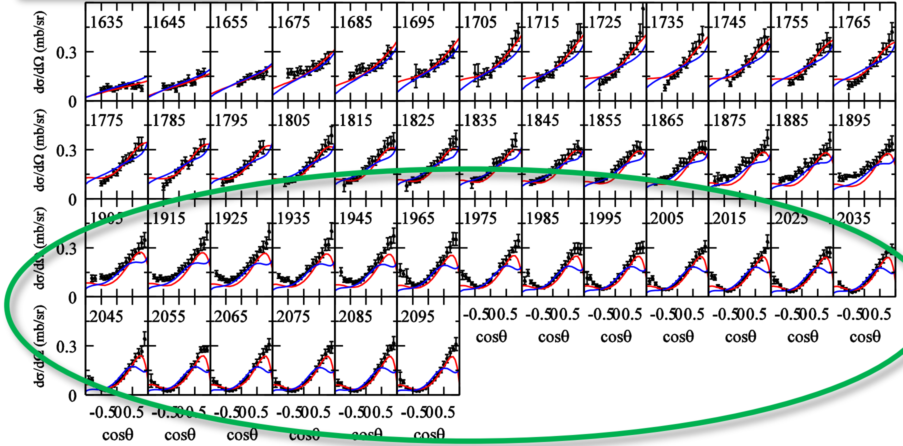

π^-p → $K^0\Sigma^0$

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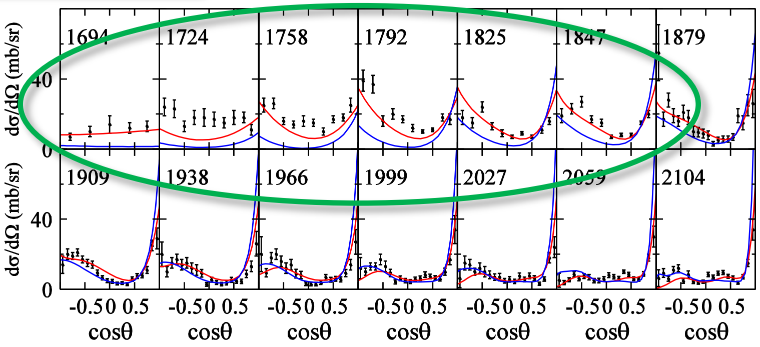

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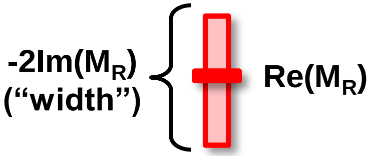
Comparison of N* & Δ* spectrum between multichannel analyses

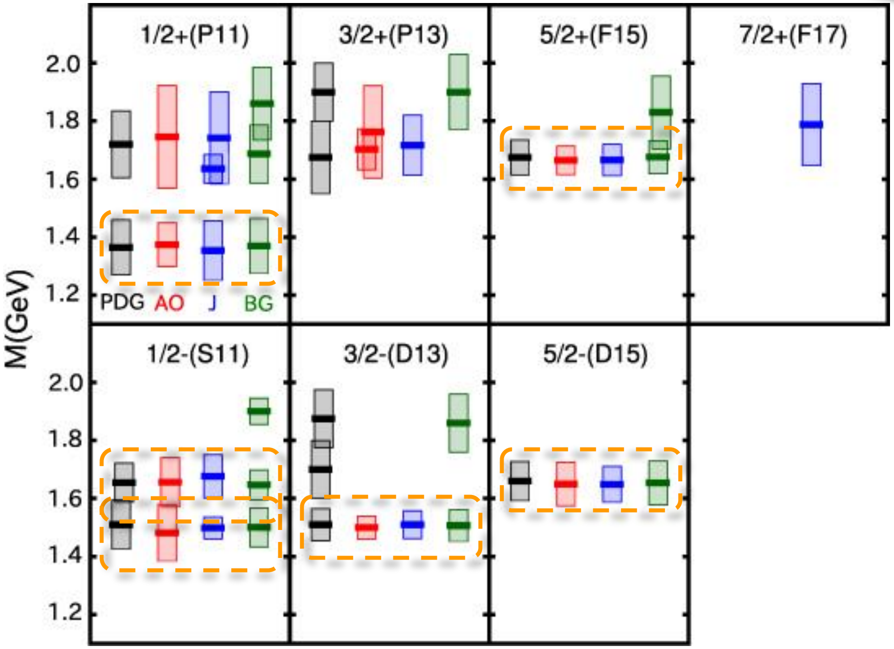
HK, Nakamura, Lee, Sato, PRC88 (2013) 035209

Existence and mass spectrum are now well established for most low-lying resonances !!
(➔ Next task: establish high-mass resonances)

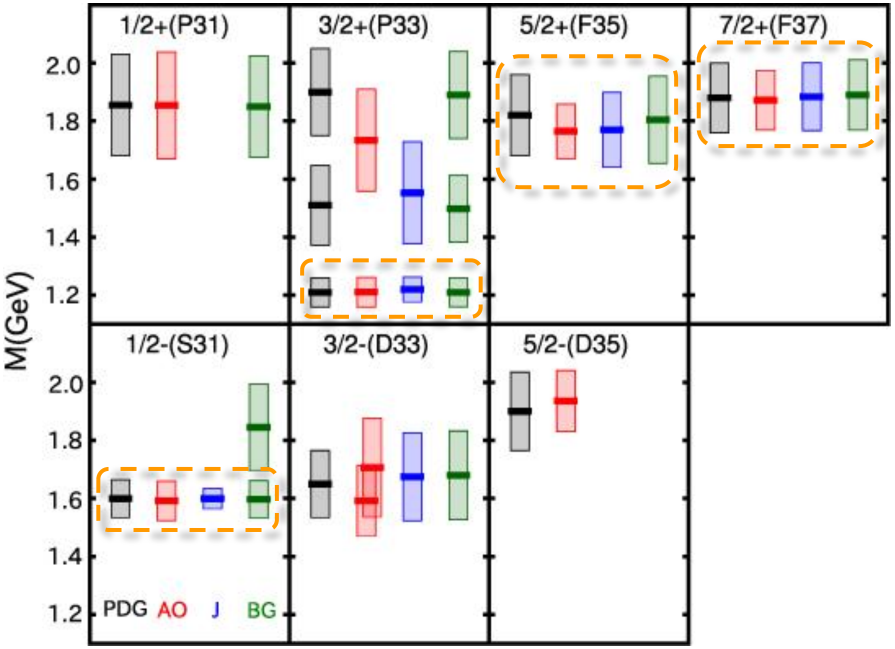


M_R : Resonance pole mass (complex)

$J^P(L_{2I\ 2J})$ "N" resonance (I=1/2)



$J^P(L_{2I\ 2J})$ "Δ" resonance (I=3/2)



NOTE: Presented only N* and Δ* with -2Im(M_R) < 400 MeV

PDG: 4* & 3* states assigned by PDG2012

AO : ANL-Osaka

J : Juelich [EPJA49(2013)44]

BG : Bonn-Gatchina [EPJA48(2012)5]

Comparison of N* & Δ* spectrum between multichannel analyses

HK, Nakamura, Lee, Sato, PRC88 (2013) 035209

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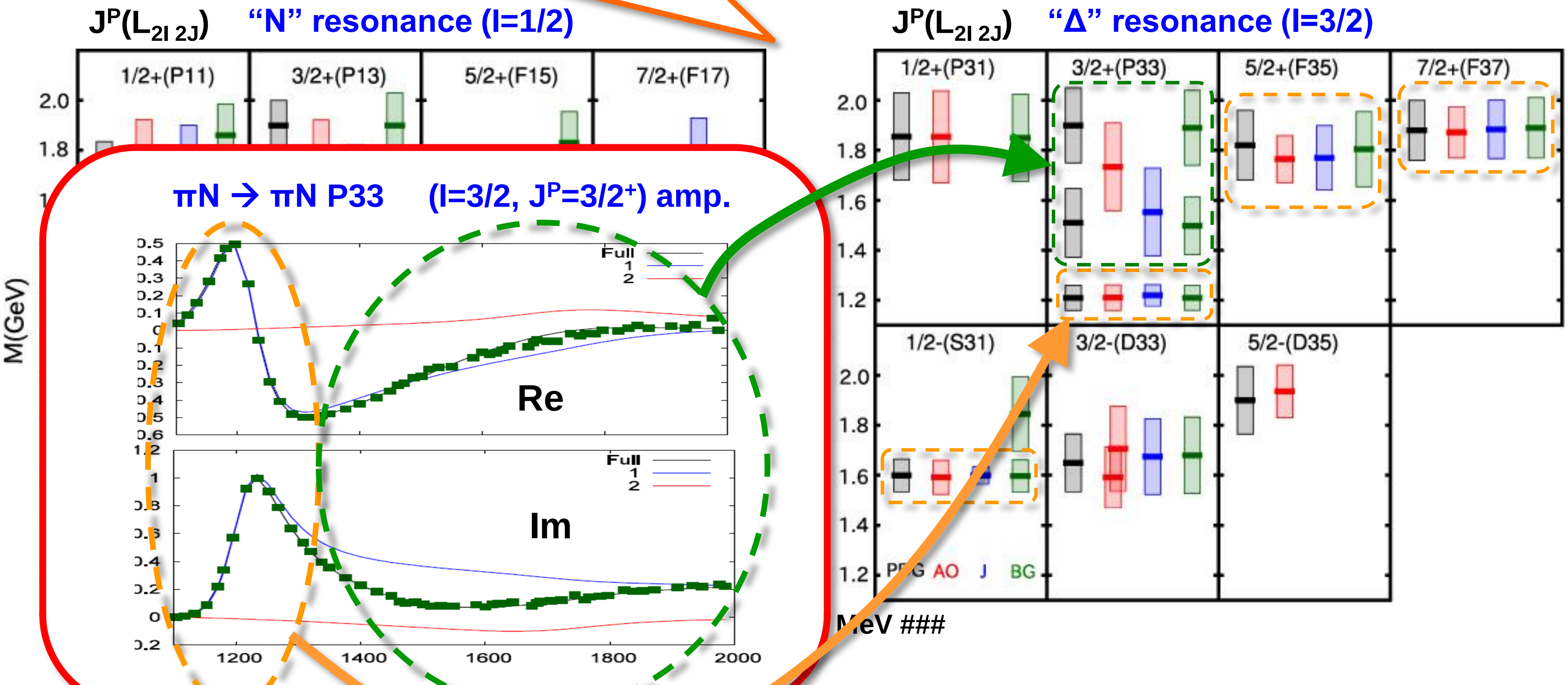
-2Im(M_R) ("width") | Re(M_R)

M_R : Resonance pole mass (complex)



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Need of inelastic reaction data for establishing high-mass N* and Δ* spectrum

To establish the spectrum of high-mass resonances, inelastic reaction (particularly double pion production) data are highly desirable:

πN, γN → ππN, KΛ, KΣ, ηN, η'N, ωN, ΦN,…

Measurements of

πN → ππN, … :

HADES

[➔ e.g., talk by W. Przygoda @NSTAR2015]

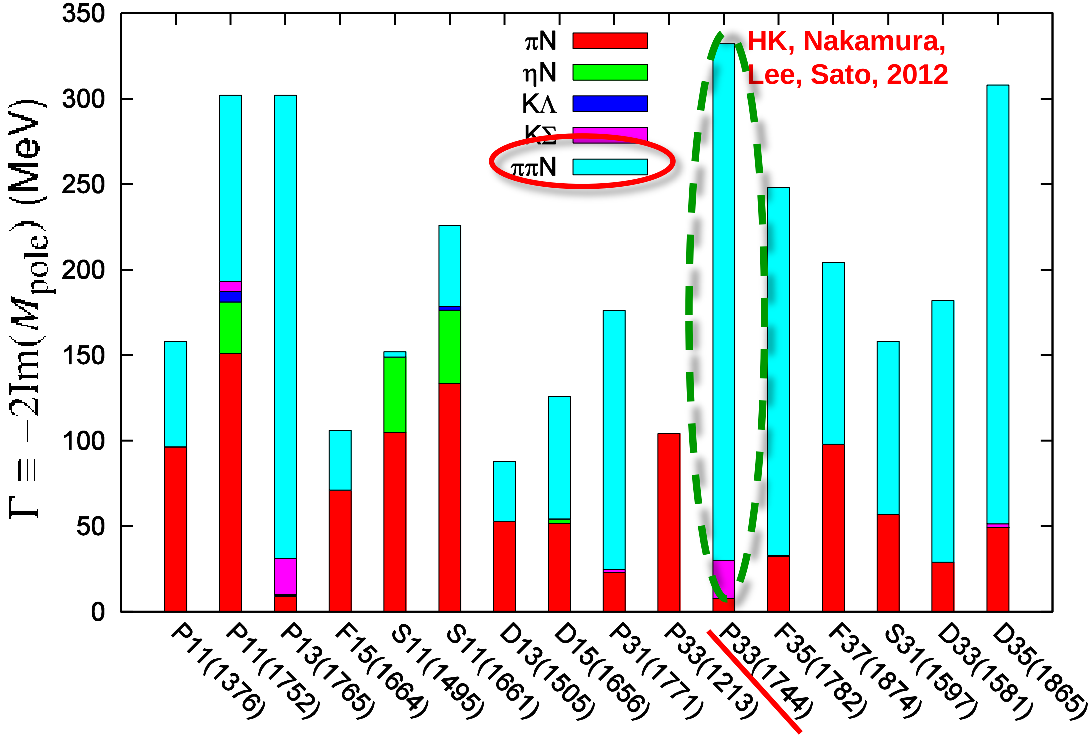
http://www.rcnp.osaka-u.ac.jp/~nstar15/talks/27_P2/27_P2_Przygoda.pdf

J-PARC E45

[➔ e.g., talk by K. Hosomi @NSTAR2015]

http://www.rcnp.osaka-u.ac.jp/~nstar15/talks/27_A2/27_A2_Hosomi.pdf

Partial decay widths of N* and Δ*

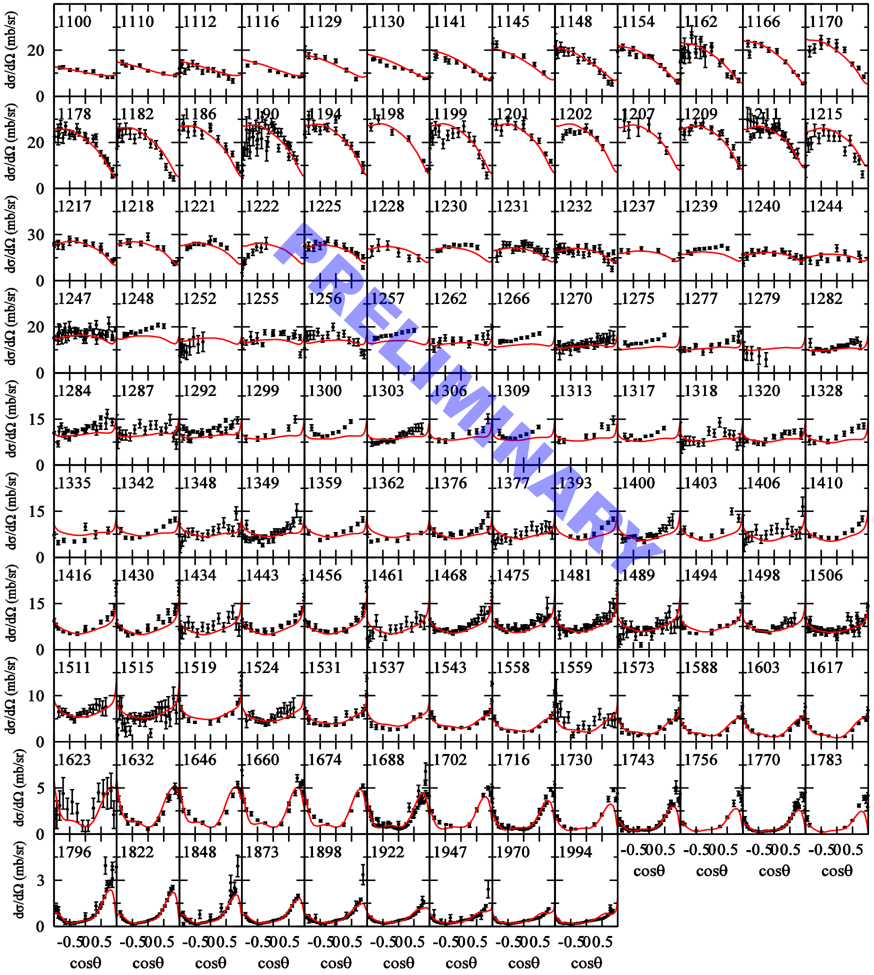


Meson photoproductions off "neutron"

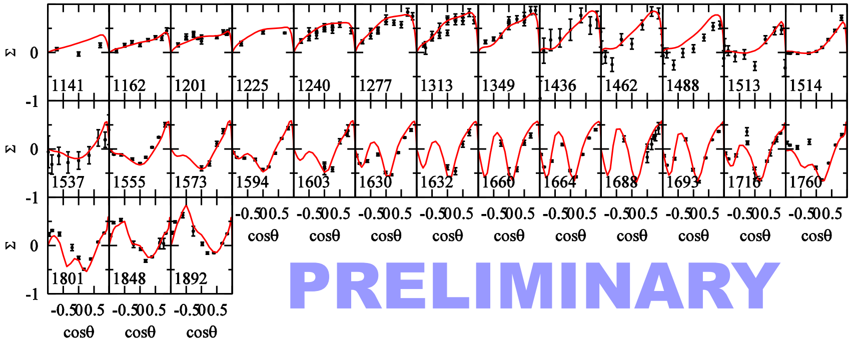
- ✓ Need for **isospin decomposition** of electromagnetic currents.
  - ➔ Necessary for applications to ***NEUTRINO*** reactions

γ 'n' ➔ π^- p

dσ/dΩ for W < 2 GeV



Σ for 1.14 < W < 1.9 GeV



PRELIMINARY

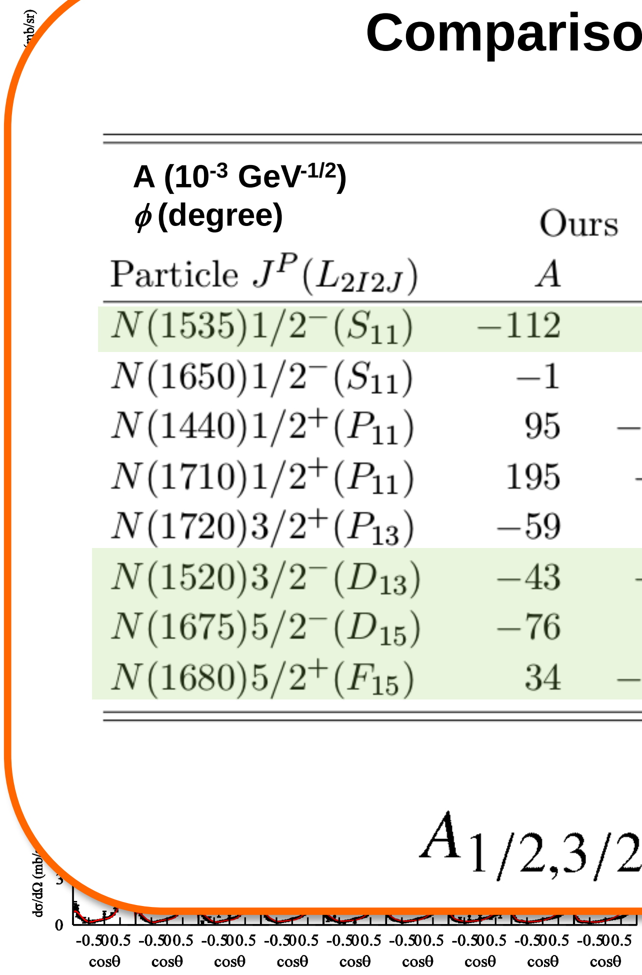
Meson photoproductions off “neutron”

✓ Need for **isospin decomposition** of electromagnetic currents.

➔ Necessary for applications to ***NEUTRINO*** reactions

γ ‘n’ → π^- p

dσ/dΩ for W < 2 GeV



Comparison of γn → N* helicity amplitudes

(PRELIMINARY)

A (10^{-3} GeV$^{-1/2}$) ϕ (degree)	$A_{1/2}$				$A_{3/2}$			
	Ours		BoGa		Ours		BoGa	
Particle $J^P(L_{2I2J})$	A	ϕ	A	ϕ	A	ϕ	A	ϕ
$N(1535)1/2^-(S_{11})$	-112	16	-103 ± 11	8 ± 5	-	-	-	-
$N(1650)1/2^-(S_{11})$	-1	45	25 ± 20	0 ± 15	-	-	-	-
$N(1440)1/2^+(P_{11})$	95	-15	35 ± 12	25 ± 25	-	-	-	-
$N(1710)1/2^+(P_{11})$	195	-8	-40 ± 20	-30 ± 25	-	-	-	-
$N(1720)3/2^+(P_{13})$	-59	6	-80 ± 50	-20 ± 30	-28	-19	-140 ± 65	5 ± 30
$N(1520)3/2^-(D_{13})$	-43	-1	-49 ± 8	-3 ± 8	-110	5	-114 ± 12	1 ± 3
$N(1675)5/2^-(D_{15})$	-76	2	-61 ± 7	-10 ± 5	-38	-5	-89 ± 10	-17 ± 7
$N(1680)5/2^+(F_{15})$	34	-12	33 ± 6	-12 ± 9	-56	-4	-44 ± 9	8 ± 10

BoGa: EPJA49(2013)67

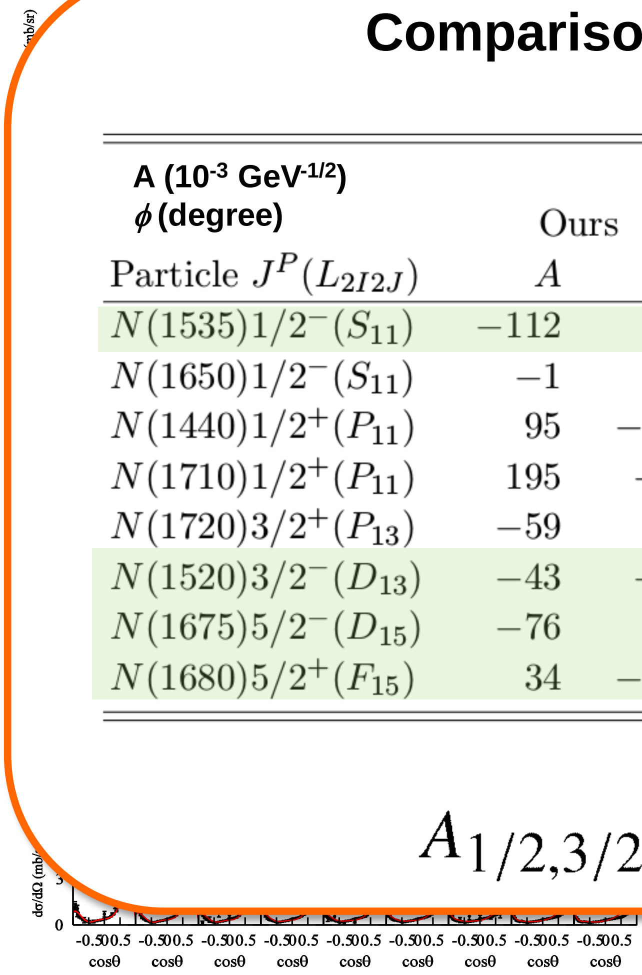
$$A_{1/2,3/2} \equiv A\exp[i\phi] \quad (-90^\circ < \phi < 90^\circ)$$

Meson photoproductions off “neutron”

✓ Need for **isospin decomposition** of electromagnetic currents.
➔ Necessary for applications to ***NEUTRINO*** reactions

γ ‘n’ → π⁻ p

dσ/dΩ for W < 2 GeV



Comparison of γn → N* helicity amplitudes
(PRELIMINARY)

A (10^{-3} GeV$^{-1/2}$)
ϕ (degree)

	$A_{1/2}$				$A_{3/2}$			
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$N(1710)1/2^+(P_{11})$	195	-8	-40 ± 20	-30 ± 25	-	-	-	-
$N(1720)3/2^+(P_{13})$	-59	6	-80 ± 50	-20 ± 30	28	19	140 ± 65	5 ± 30
$N(1520)3/2^-(D_{13})$	-43	-1	-49 ± 8					
$N(1675)5/2^-(D_{15})$	-76	2	-61 ± 7					
$N(1680)5/2^+(F_{15})$	34	-12	33 ± 6					

$$A_{1/2,3/2} \equiv A\exp[$$

Ongoing work:
Analyze deuteron reaction data directly !!

➔ **Extract amplitudes for “neutron-target” reactions and neutron-N* form factors in a fully consistent way in our approach.**
(Talk by Harry Lee)

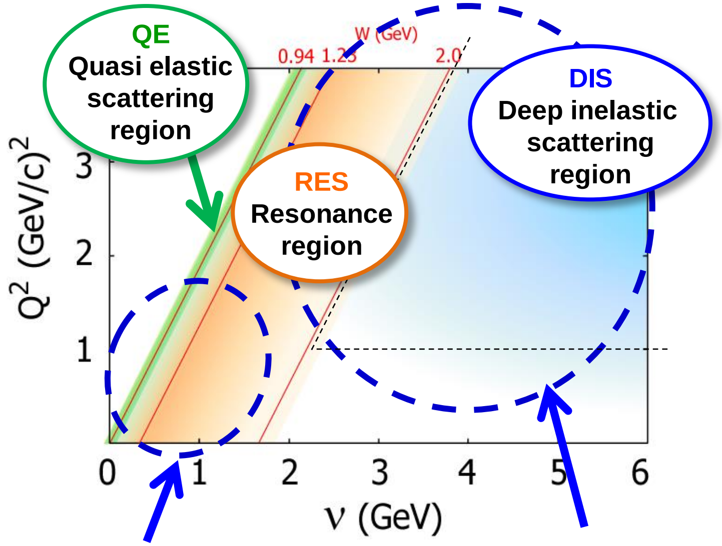
Applications of ANL-Osaka DCC approach to neutrino-induced reactions

Non-zero value of all neutrino-mixing angles θ_{12}, θ_{23}, θ_{13} has now been established !!

Major interest is shifting to determining leptonic CP phase & neutrino mass hierarchy !!

- ✓ **Accurate model to describe neutrino-nucleon/nucleus cross sections (10% or better !!) is necessary for reliable extraction of neutrino parameters from next-generation neutrino-oscillation experiments.**
- ✓ **Relevant kinematical region extends over QE, RES, and DIS regions !!**

  (➔ Combination of expertise from different fields is necessary !!)



T2K (long-baseline exp.)

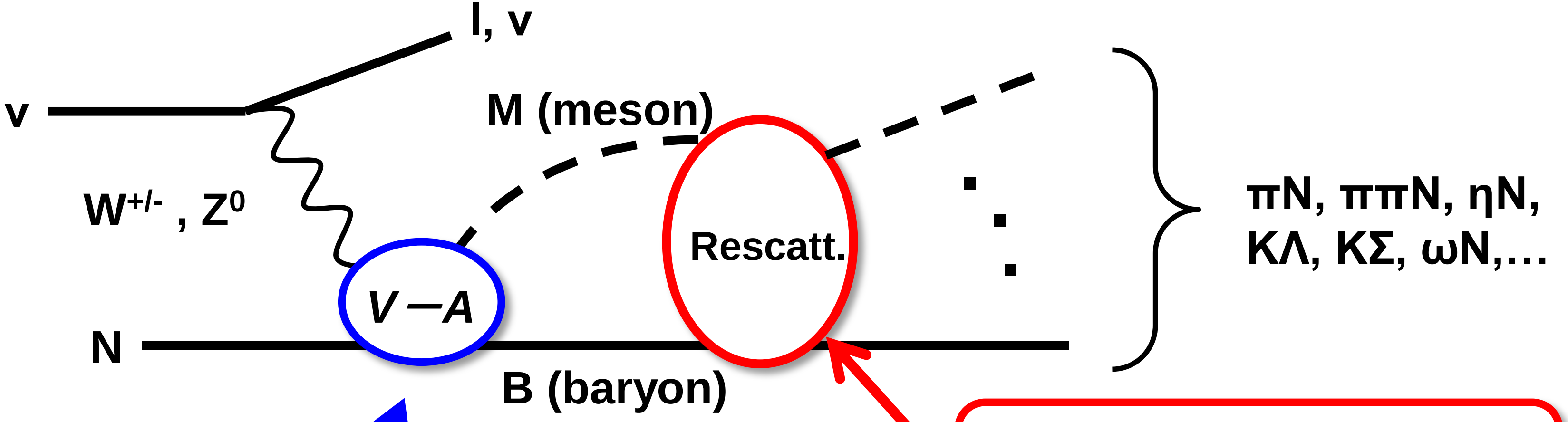
CP phase & mass hierarchy studies with atmospheric exp.

Collaboration@J-PARC Branch of KEK Theory Center
[http://j-parc-th.kek.jp/html/English/e-index.html]

Y. Hayato (ICRR, U. of Tokyo), M. Hirai (Nippon Inst. Tech.)
H. Kamano (RCNP, Osaka U.), S. Kumano (KEK)
S. Nakamura (Osaka U.), K. Saito (Tokyo U. of Sci.)
M. Sakuda (Okayama U.), T. Sato (Osaka U.)
[➔ arXiv:1303.6032]

Neutrino-nucleon reactions within ANL-Osaka DCC approach

Nakamura, HK, Sato, arXiv:1506.03403; to appear in PRD



Determined by plenty of data of
πN → πN, ππN, ηN, KΛ, KΣ,…
γN → πN, ππN, ηN, KΛ, KΣ,…

Need to evaluate transition matrix elements induced by weak interaction

- **Isovector-vector matrix elements:** $\langle MB|V_\mu(Q^2)|N\rangle$

  Determined up to W = 2 GeV; Q^2 = 3 GeV^2

  (Q^2=0) determined with γp & γ"n" data

  (Q^2>0) determined with p(e,eπ)N data & structure function data for inclusive p(e,e')X & "n"(e,e')X

- **Isovector-axial matrix elements:** $\langle MB|A_\mu(q)|N\rangle$

  (Q^2=0) fixed with πN→MB transition matrix elements by making use of PCAC hypothesis

  (Q^2>0) at the moment, Q2 dependence fixed by assuming a dipole form factor:

  $F(Q^2) = [1+(Q^2/M_A^2)]^{-2}$ with M_A=1.02 GeV, etc.

Ultimately, axial part has to be determined with neutrino data, but…

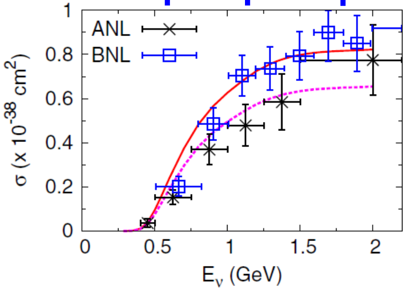
Predicted results for neutrino-induced reactions

Nakamura, HK, Sato, arXiv:1506.03403; to appear in PRD

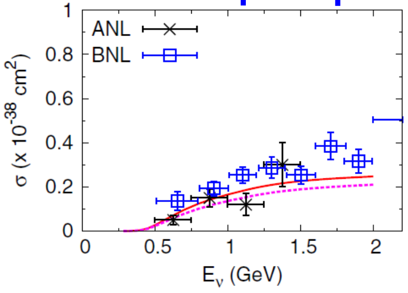
The first-time full coupled-channels calculation of ν-nucleon reactions beyond the Δ(1232) region !!

✓ **Single pion production:**

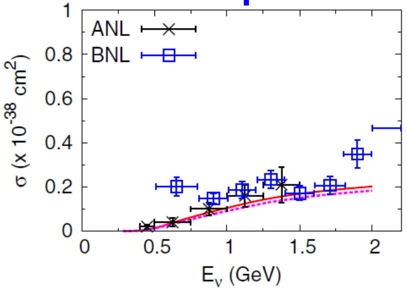
$\nu\, p \rightarrow \mu^- \pi^+ p$



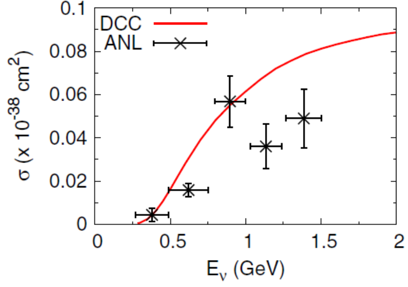
$\nu\, n \rightarrow \mu^- \pi^0 p$



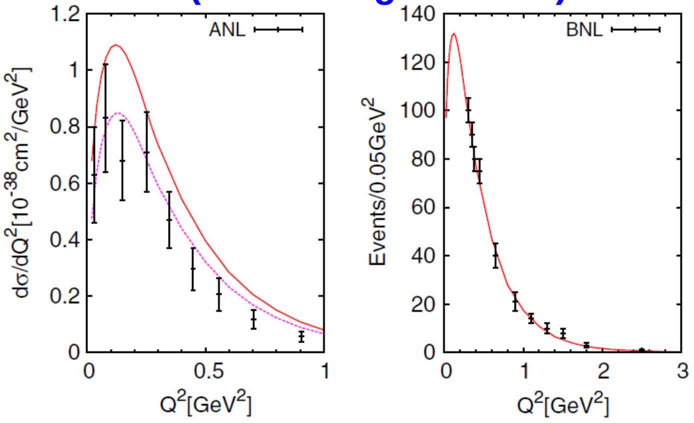
$\nu\, n \rightarrow \mu^- \pi^+ n$



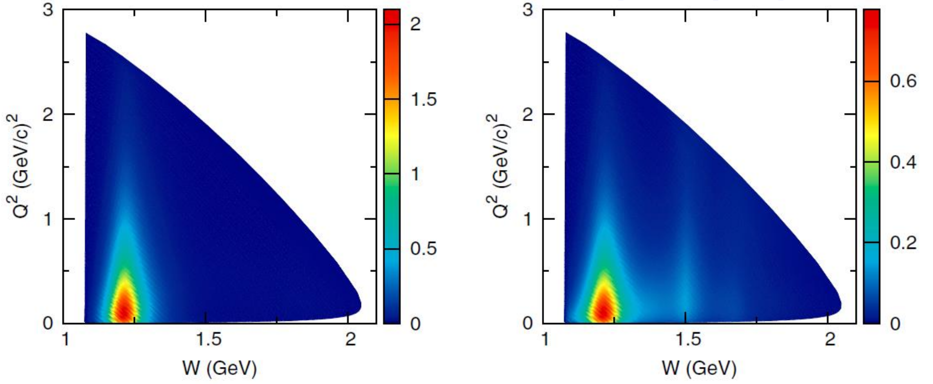
$\nu\, n \rightarrow \nu\, \pi^- p$



$d\sigma/dQ^2$ for $\nu\, p \rightarrow \mu^- \pi^+ p$ (flux averaged for Ev)



$d^2\sigma/dWdQ^2$ at Ev = 2 GeV


$\nu\, p \rightarrow \mu^- \pi^+ p$

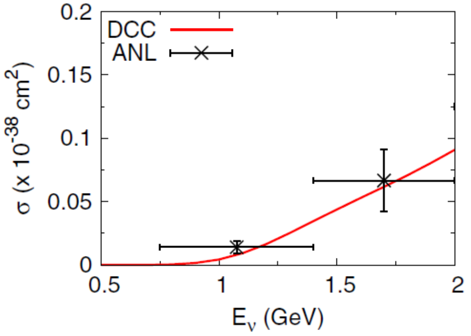
$\nu\, n \rightarrow \mu^- \pi^0 p + \mu^- \pi^+ n$

Predicted results for neutrino-induced reactions

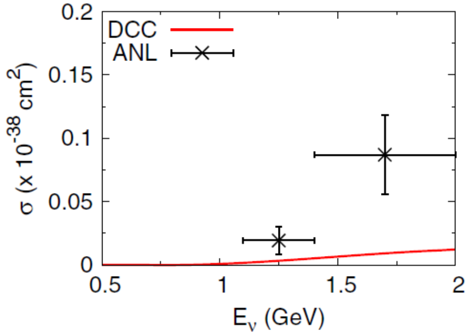
Nakamura, HK, Sato, arXiv:1506.03403; to appear in PRD

✓ **Double pion production:**

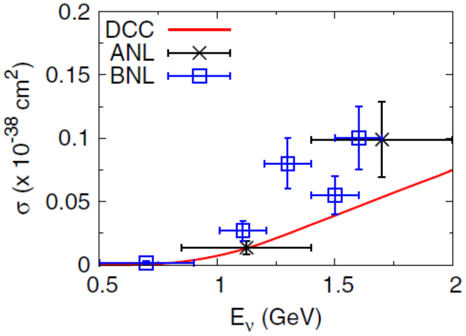
$\nu p \rightarrow \mu^- \pi^+ \pi^0 p$



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

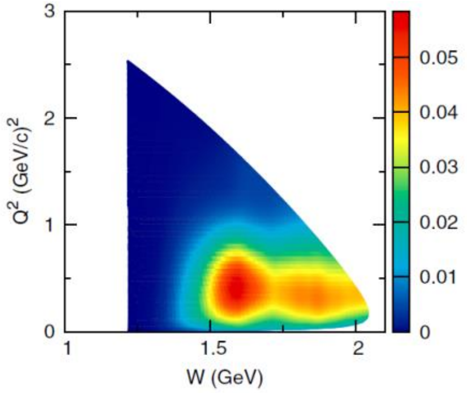


$\nu n \rightarrow \mu^- \pi^+ \pi^- p$

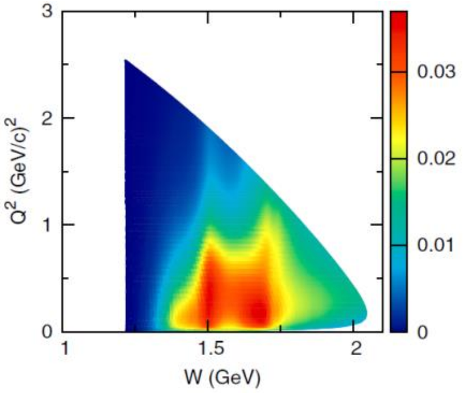


$d\sigma/dWdQ^2$ at $E\nu = 2$ GeV

$\nu p \rightarrow \mu^- \pi^+ \pi^0 p$

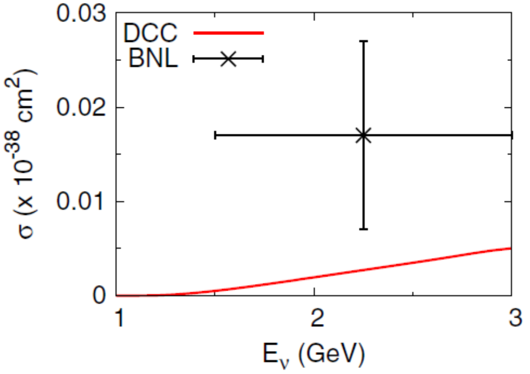


$\nu n \rightarrow \mu^- \pi^+ \pi^- p$



✓ **KΛ production:**

$\nu n \rightarrow \mu^- K^+ \Lambda$



Applications of ANL-Osaka DCC approach to Y* (=Λ*, Σ*) spectroscopy

Current situation of Y*(= Λ*, Σ*) spectroscopy

✓ **Y* resonances are much less understood than N* & Δ* !!**

For example,

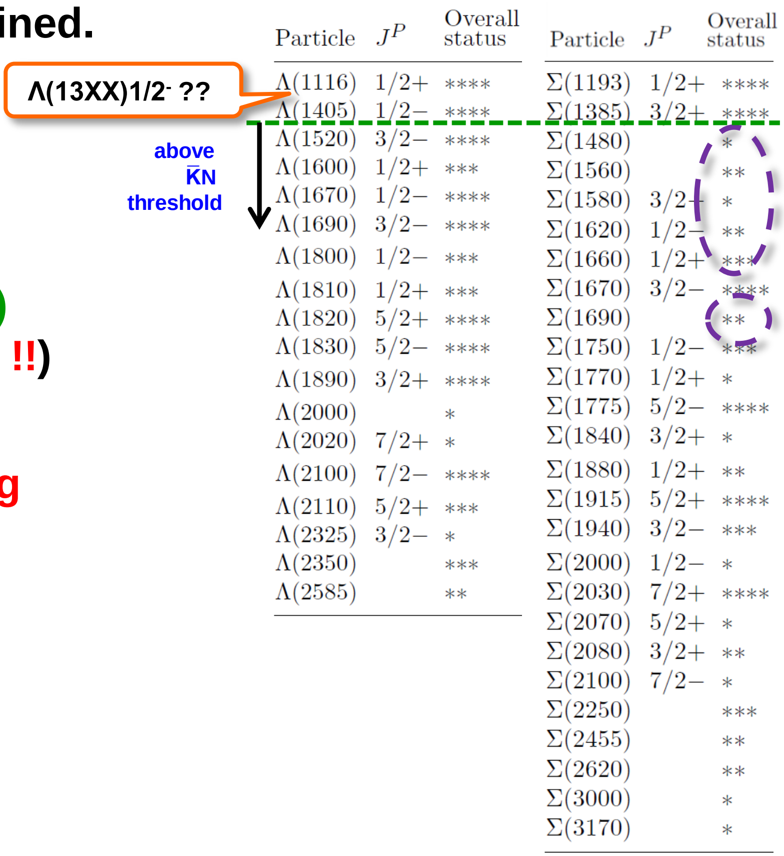
- Even low-lying resonances are not well determined.

  ➔ N* & Δ* spectra are very well established up to M_R < ~ 1.8 GeV.

- Before 2012, PDG listed only Breit-Wigner (BW) mass and width. (➔ “*highly*” model-dependent !!)

  ➔ N* & Δ* case:
  Resonances defined by poles of scattering amplitudes are extensively studied;
  PDG lists BOTH pole and BW parameters.

PDG listing



Λ*

Particle	J^P	Overall status
Λ(1116)	1/2+	****
Λ(1405)	1/2−	****
Λ(1520)	3/2−	****
Λ(1600)	1/2+	***
Λ(1670)	1/2−	****
Λ(1690)	3/2−	****
Λ(1800)	1/2−	***
Λ(1810)	1/2+	***
Λ(1820)	5/2+	****
Λ(1830)	5/2−	****
Λ(1890)	3/2+	****
Λ(2000)		*
Λ(2020)	7/2+	*
Λ(2100)	7/2−	****
Λ(2110)	5/2+	***
Λ(2325)	3/2−	*
Λ(2350)		***
Λ(2585)		**

Σ*

Particle	J^P	Overall status
Σ(1193)	1/2+	****
Σ(1385)	3/2+	****
Σ(1480)		*
Σ(1560)		**
Σ(1580)	3/2−	*
Σ(1620)	1/2−	**
Σ(1660)	1/2+	***
Σ(1670)	3/2−	****
Σ(1690)		**
Σ(1750)	1/2−	***
Σ(1770)	1/2+	*
Σ(1775)	5/2−	****
Σ(1840)	3/2+	*
Σ(1880)	1/2+	**
Σ(1915)	5/2+	****
Σ(1940)	3/2−	***
Σ(2000)	1/2−	*
Σ(2030)	7/2+	****
Σ(2070)	5/2+	*
Σ(2080)	3/2+	**
Σ(2100)	7/2−	*
Σ(2250)		***
Σ(2455)		**
Σ(2620)		**
Σ(3000)		*
Σ(3170)		*

Applications of ANL-Osaka DCC approach to Y* (=Λ*, Σ*) spectroscopy

✓ Comprehensive partial-wave analyses of K^- p reactions to extract *Y* defined by poles* have been accomplished ***just recently*** :

- ➢ Kent State University (KSU) group [Zhang et al., PRC88(2013)035204;035205]
  (➔ 2013, "KSU on-shell parametrization" of S-matrix)
- ➢ Our group [HK, Nakamura, Lee, Sato, PRC90(2014)065204; 92(2015)025205]
  (➔ 2014-2015, Dynamical Coupled-Channels approach)

- Formulates coupled-channels equations for S = -1 sector by replacing

$$(\,\gamma^{(*)}N,\ \pi N,\ \eta N,\ \pi\Delta,\ \sigma N,\ \rho N,\ K\Lambda,\ K\Sigma,\cdots)$$

$$\Downarrow$$

$$(\,\bar{K}N,\ \pi\Sigma,\ \pi\Lambda,\ \eta\Lambda,\ K\Xi,\ \boxed{\pi\Sigma^*,\ \bar{K}^*N,}\ \cdots\ )$$

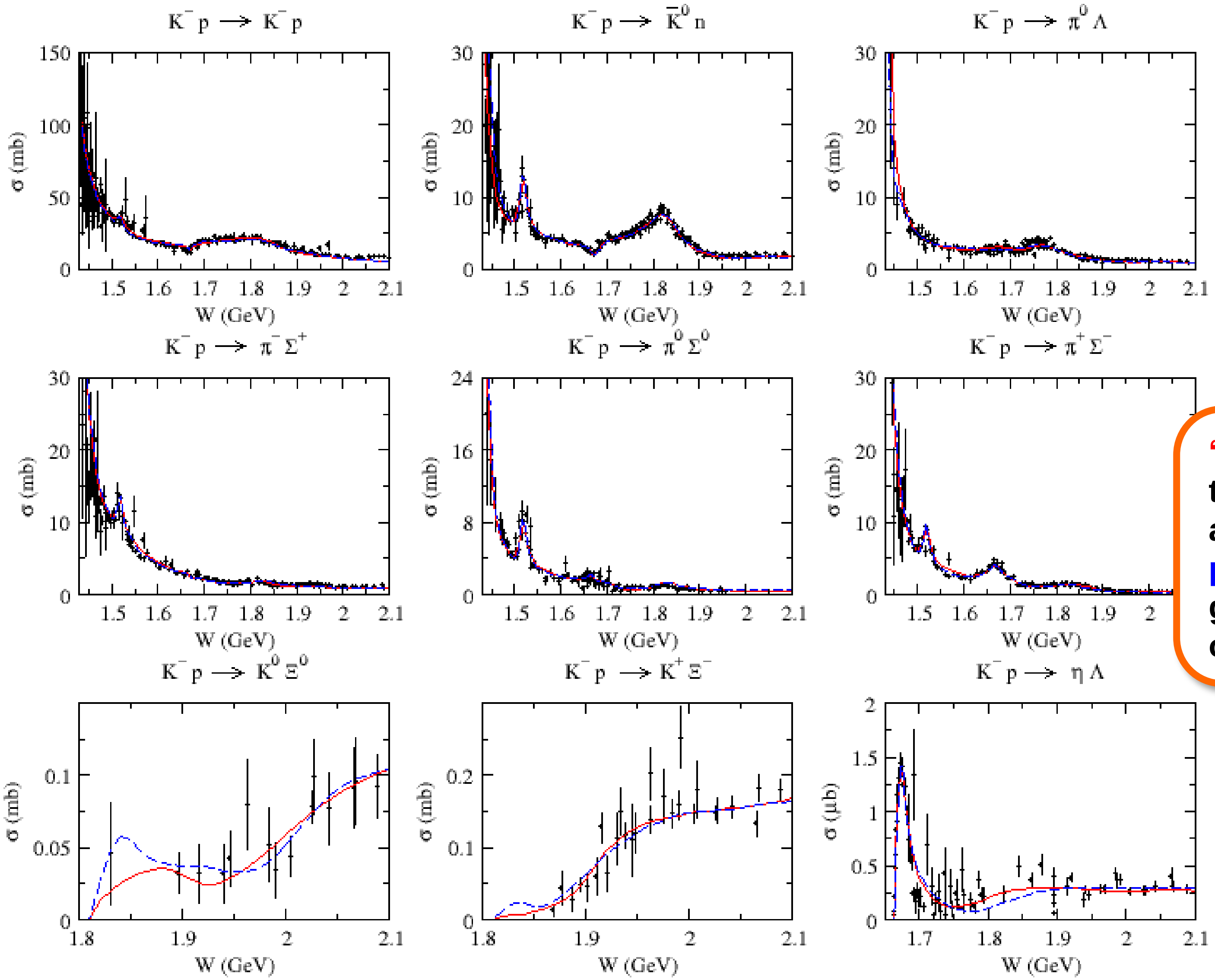
quasi 2-body channels
subsequently decaying
into 3-body ππΛ & πK̄N

- Constructs DCC model by fitting ***ALL*** available data for
  K^- p → K̄N, πΣ, πΛ, ηΛ, KΞ up to W = 2.1 GeV.
  (➔ more than 17,000 data points to fit !!)

Results of the fits

$K^- p \rightarrow MB$ total cross sections

HK, Nakamura, Lee, Sato, PRC90(2014)065204



Red: Model A

Blue: Model B

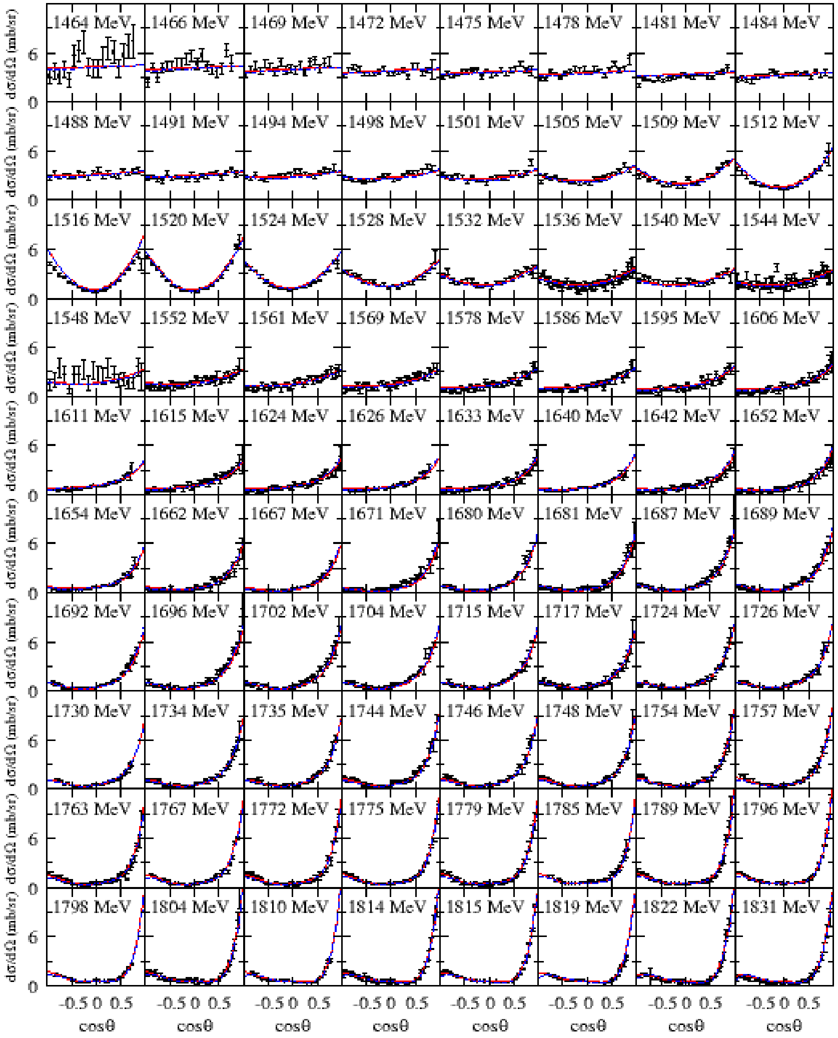
“Incompleteness” of the current database allows us to have two parameter sets that give similar quality of the fit.

Results of the fits

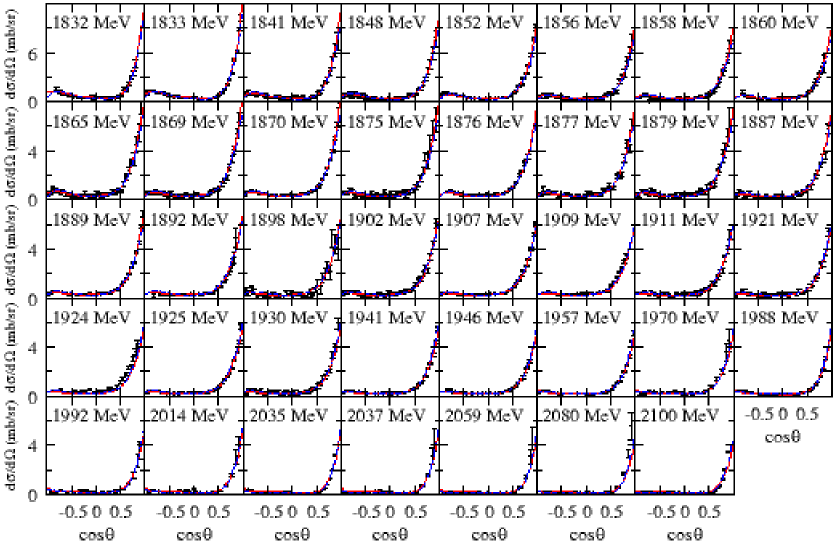
K$^-$ p → K$^-$ p scattering

HK, Nakamura, Lee, Sato, PRC90(2014)065204

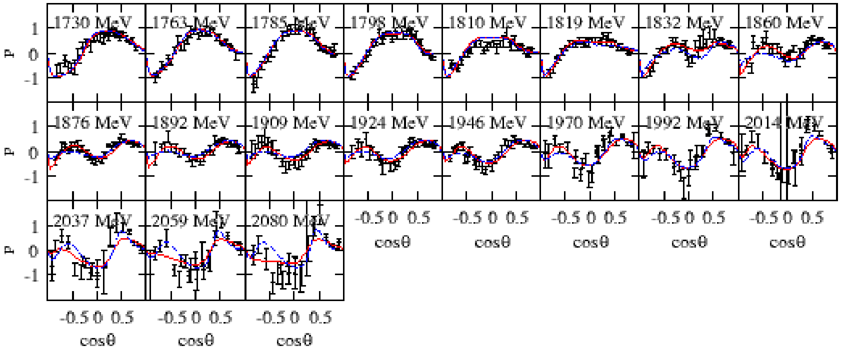
dσ/dΩ (1464 < W < 1831 MeV)



dσ/dΩ (1832 < W < 2100 MeV)



P



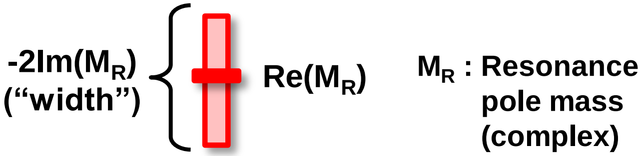
Red: Model A Blue: Model B

Extracted Λ* and Σ* mass spectrum

HK, Nakamura, Lee, Sato, PRC92(2015)025205

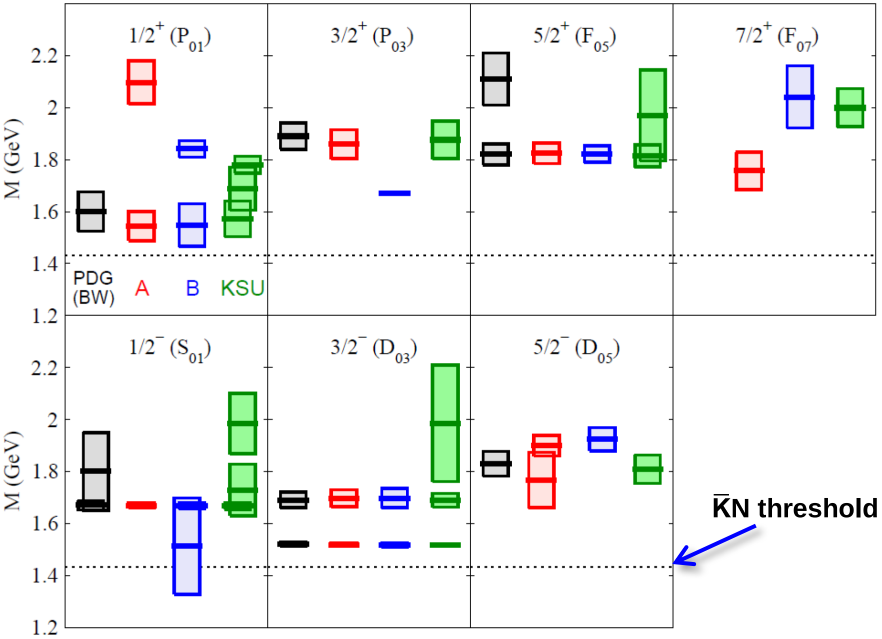
Spectrum for Y* resonances found above the $\bar{K}N$ threshold

Red: Model A
Blue: Model B
Green: KSU
Black: PDG (only 4- & 3-star Y*;
Breit-Wigner)

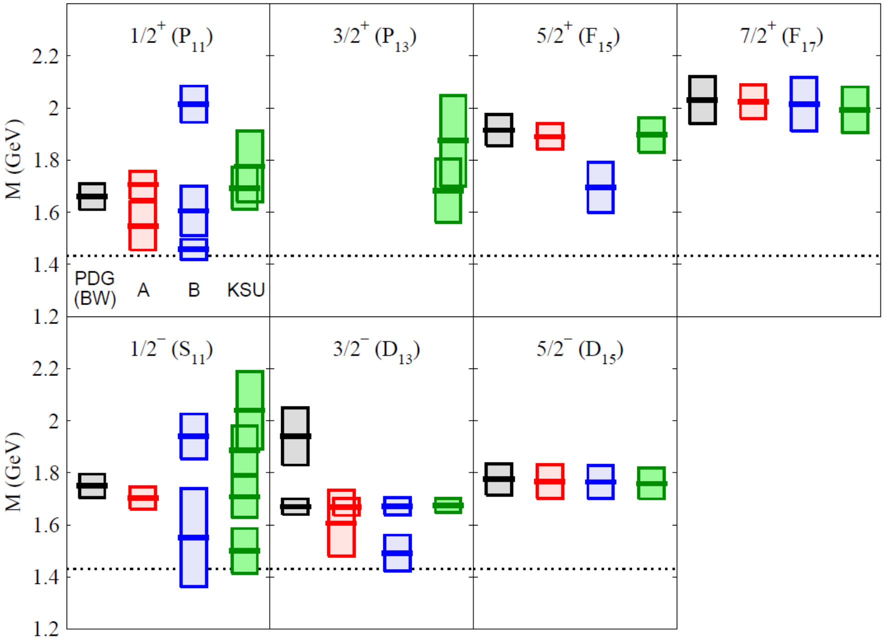


M_R : Resonance pole mass (complex)

$J^P(L_{I\,2J})$ "Λ" resonance (I=0)



$J^P(L_{I\,2J})$ "Σ" resonance (I=1)



Extracted Λ* and Σ* mass spectrum

HK, Nakamura, Lee, Sato, PRC92(2015)025205

Spectrum for Y* resonances found above the $\bar{K}N$ threshold

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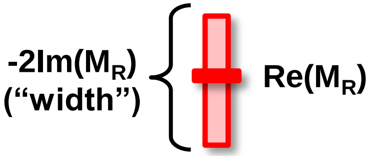
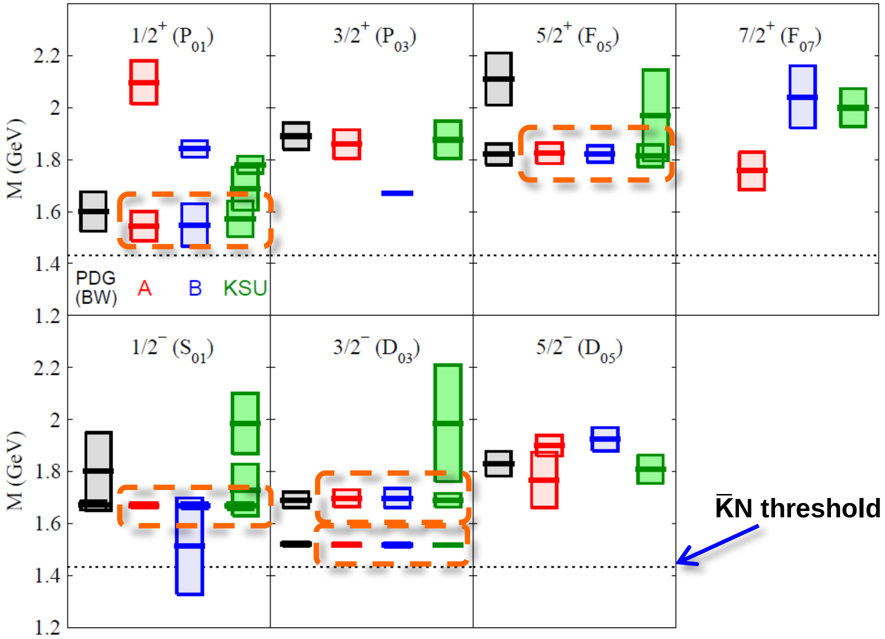


-2Im(M_R)
(“width”)

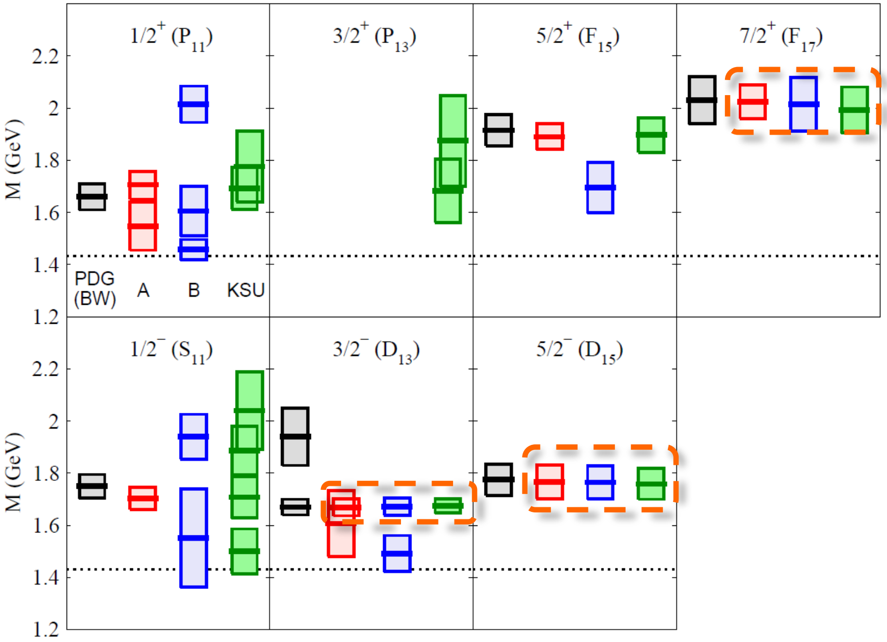
Re(M_R)

M_R : Resonance
pole mass
(complex)

$J^P(L_{I\ 2J})$ “Λ” resonance (I=0)



$J^P(L_{I\ 2J})$ “Σ” resonance (I=1)



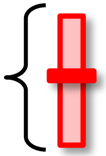
Extracted Λ* and Σ* mass spectrum

HK, Nakamura, Lee, Sato, PRC92(2015)025205

Spectrum for Y* resonances found above the $\bar{K}N$ threshold

Red: Model A
Blue: Model B
Green: KSU
**Black: PDG (only 4- & 3-star Y*;
Breit-Wigner)**

New narrow $3/2^+$ resonance
M = 1671 – 5i MeV
near the ηΛ threshold !!

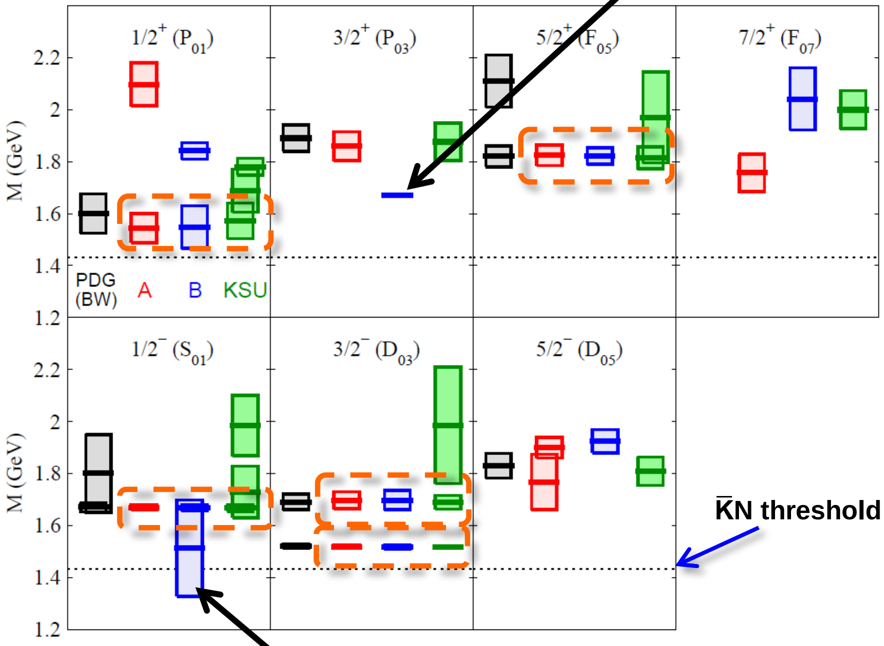


$-2\mathrm{Im}(M_R)$
(“width”)

$\mathrm{Re}(M_R)$

M_R : Resonance pole mass (complex)

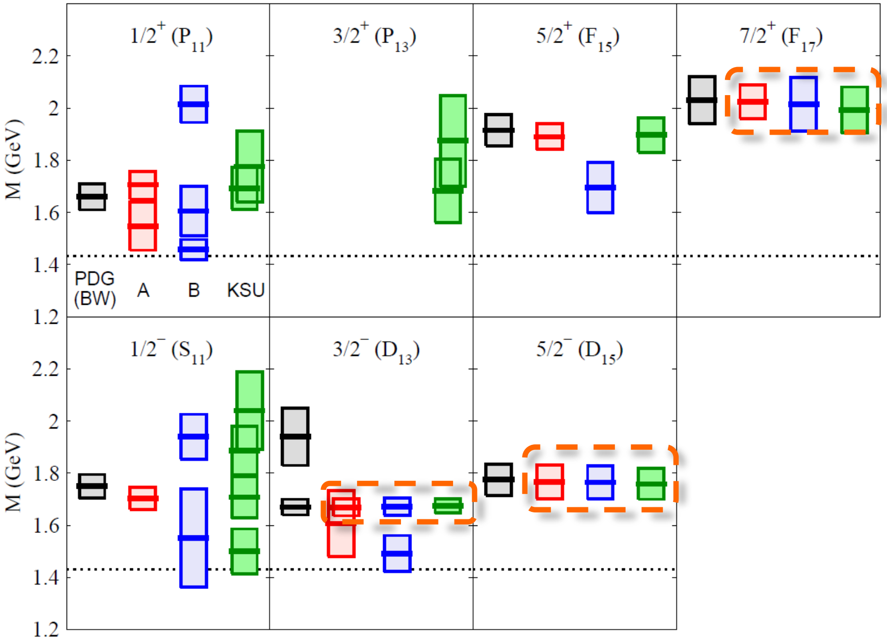
$J^P(L_{I\ 2J})$ “Λ” resonance (I=0)



$\bar{K}N$ threshold

Spin partner of
$\Lambda(1520)3/2^-$??

$J^P(L_{I\ 2J})$ “Σ” resonance (I=1)



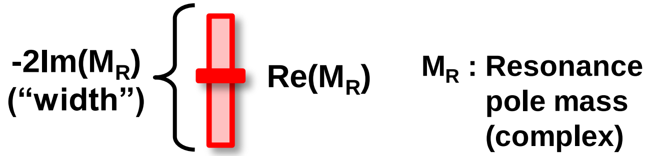
Extracted Λ* and Σ* mass spectrum

HK, Nakamura, Lee, Sato, PRC92(2015)025205

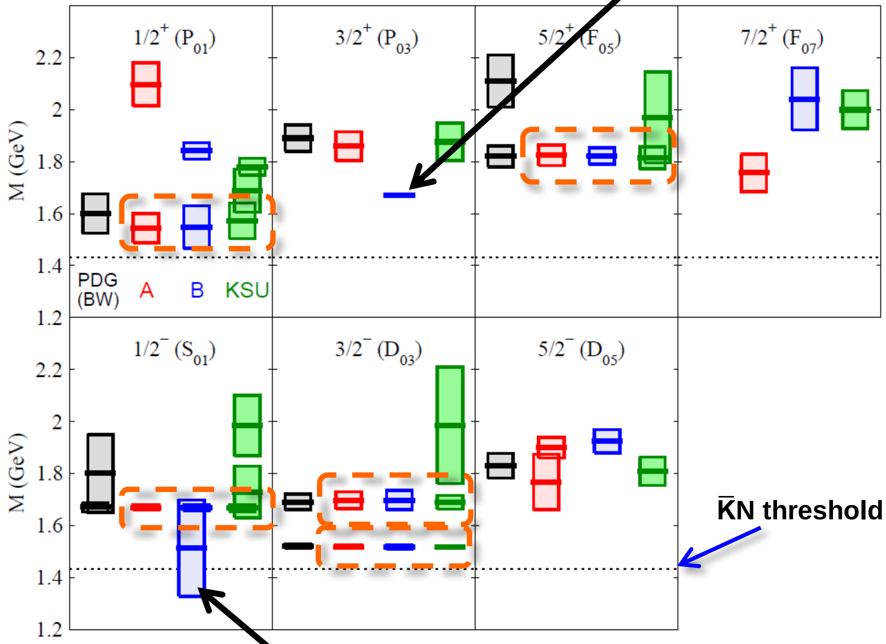
Spectrum for Y* resonances found above the K̄N threshold

Red: Model A
Blue: Model B
Green: KSU
Black: PDG (only 4- & 3-star Y*; Breit-Wigner)

New narrow 3/2$^+$ resonance
M = 1671 – 5i MeV
near the ηΛ threshold !!


-2Im(M_R)
("width")
Re(M_R)
M_R : Resonance pole mass (complex)

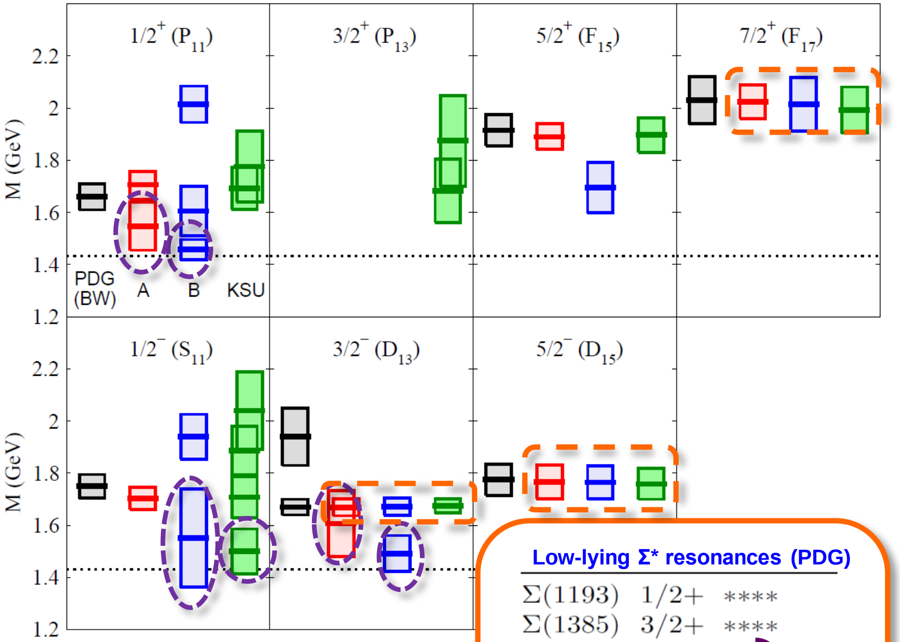
$J^P(L_{I\,2J})$ "Λ" resonance (I=0)



K̄N threshold

Spin partner of Λ(1520)3/2$^-$??

$J^P(L_{I\,2J})$ "Σ" resonance (I=1)



Low-lying Σ* resonances (PDG)

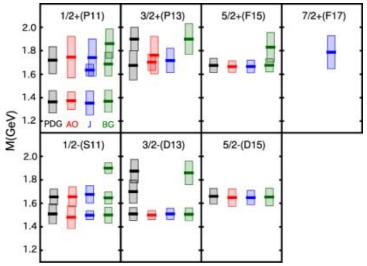
Σ(1193)	1/2+	****
Σ(1385)	3/2+	****
Σ(1480)		*
Σ(1560)		**
Σ(1580)	3/2−	*
Σ(1620)	1/2−	**
Σ(1660)	1/2+	***
Σ(1670)	3/2−	****

?

Summary for PART I

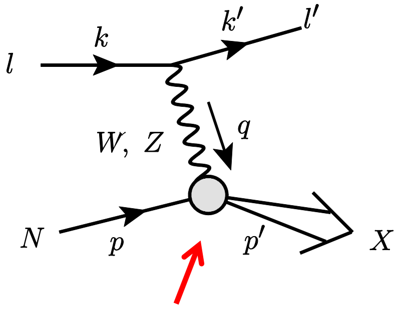
N* & Δ* spectroscopy

- **Early analyses of πN & γN reactions:**
  PRC76(2007)065201; 77(2008)045205; 78(2008)025204
  PRC79(2009)025206; 80(2009)065203; 81(2010)065207
  PRL104(2010)042302
- **Latest analysis of πN & γN reactions:**
  PRC88(2013)035209; 88(2013)045203
- **Electroproduction analysis & Form factor extraction:**
  PRC80(2009)025207; 82(2010)045206



Neutrino reactions

- **Calculation in $Q^2 = 0$ limit:**
  PRD86(2012)097503
- **Full DCC-model calculation up to $W = 2$ GeV, $Q^2 = 3$ GeV^2:**
  arXiv:1506.03403 (to appear in PRD)

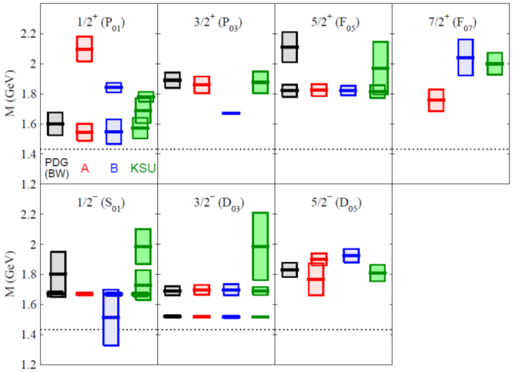


Weak ("V-A") form factors

ANL-Osaka DCC approach

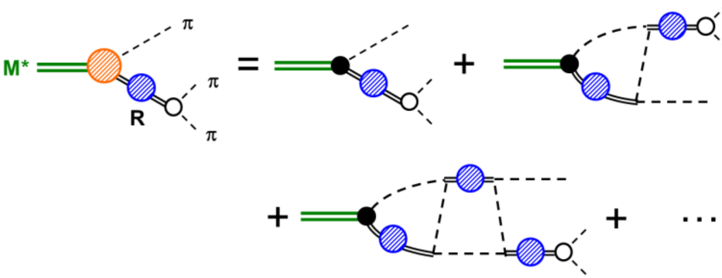
Λ* & Σ* spectroscopy

- **Λ*, Σ* resonance extractions via analysis of K^-p reactions:**
  PRC90(2014)065204; 92(2015)025205



Meson spectroscopy

- **Formulation of 3-body unitary model for decays of mesons:**
  PRD84(2011)114019
- **Application to γp → M*N → (3π)N:**
  PRD86(2012)114012



Summary for PART I

ANL-Osaka DCC approach

N* & Δ* spectroscopy

- Establishing high-mass resonances with Re(M_R) > 1.8 GeV
- Extending channel space to go higher W (ωN, η'N, ΦN, 4-body ρΔ ??, …)
- Analyzing "deuteron-target" reactions.
  → Direct extraction of form factors associated with NEUTRON.

Neutrino reactions

- Applying to nuclear target reactions
- How smoothly connect to DIS and Regge regions ?? (➔ Construction of a unified neutrino reaction model @J-PARC Branch of KEK Theory Center)

Λ* & Σ* spectroscopy

- Establishing low-lying Y* resonances [Λ(1405)$1/2^-$, Λ(13XX)$1/2^-$, Λ(15XX)$1/2^-$??, poorly established Σ*, …] using K^-d reaction data (J-PARC E31)
- Extending to multistrangeness (Ξ, Ω) baryon spectroscopy.
- Applications to hyper nuclei & kaonic nuclei

Meson spectroscopy

- Applying exotic hybrid meson searches (GlueX, CLAS12, COMPASS…)
- Applying heavy-quark systems (XYZ systems, …)

PART II

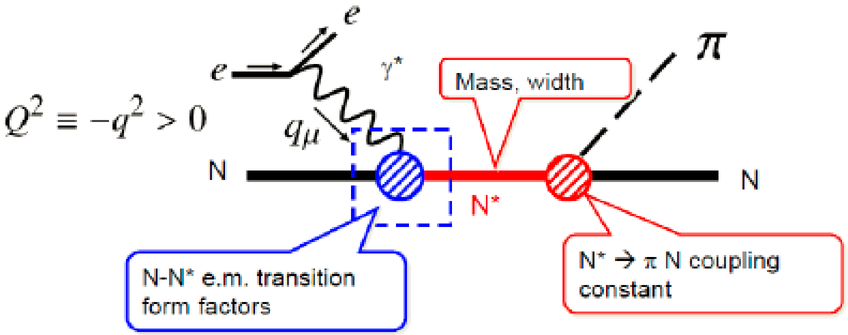
Electromagnetic transition form factor of nucleon resonances

Toru Sato [Hiroyuki Kamano]

Osaka University

Based on S.X. Nakamura, H. Kamano and TS, (PRD92 accepted)
"Dynamical coupled-channels model for neutirno-induced meson productions in resonance region"

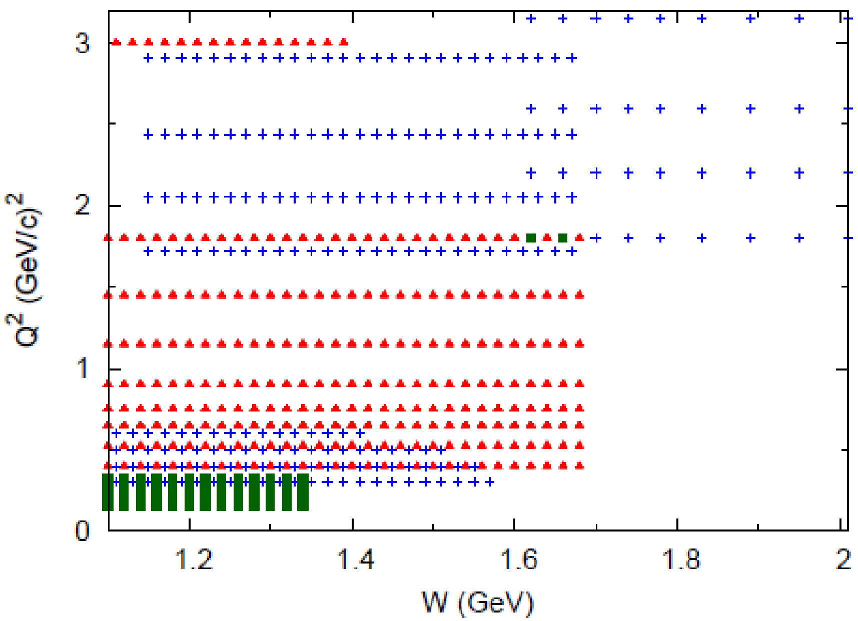
Objective: Extract NN^* transition electromagnetic form factor by analyzing ep data.



Procedure:

- Basic model: coupled-channels model for πN and γp reactions.[H. Kamano et al. PRC88 (2013)]
- Fit $p(e, e'\pi)$ by using 'bare' NN^* transition form factors as parameters.
- Extract transition from factor from the residue of the scattering amplitude at the resonance pole

CLAS data of single pion electroproduction off proton used in the analysis.



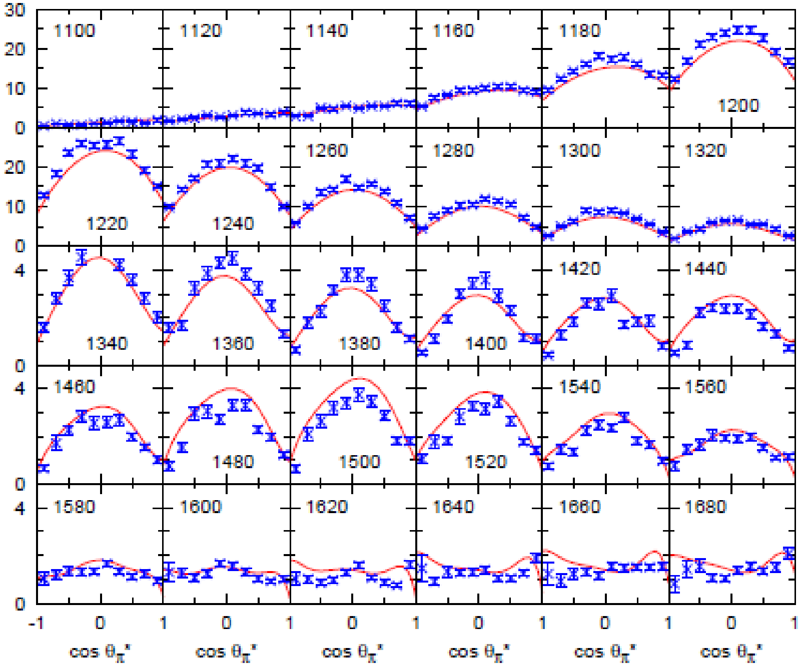
Red triangle[blue cross]: data for $p(e,e'\pi^0)p[p(e,e'\pi^+)n]$

Green square: both π^+,π^0 data are available

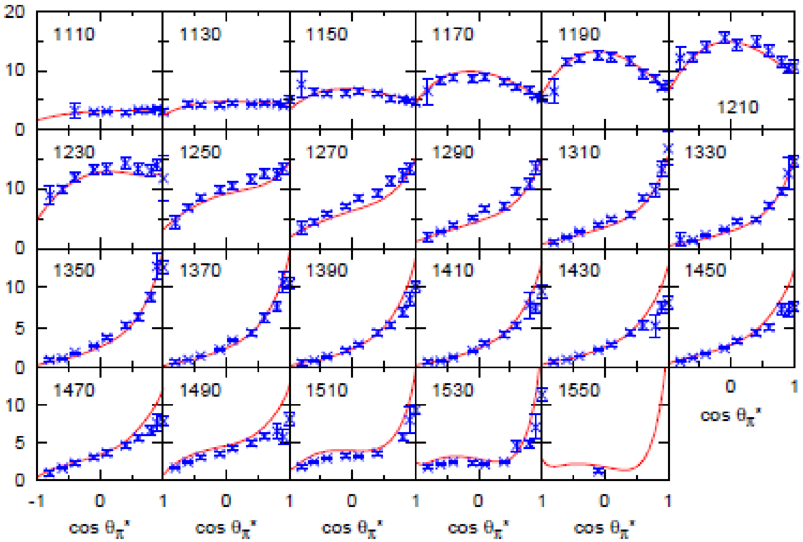
- $W > 1.4GeV$, low Q^2 and $W > 1.7GeV$, $Q^2 < 2GeV^2$: data are not available.
- We fitted also inclusive structure functions in those regions. (M.E. Christy and P.E. Bosted, PRC81 055213)

Quality of fit of our DCC model

Single pion electorproduction $[d\sigma_T/d\Omega^* + \epsilon d\sigma_L/d\Omega^*$ at $Q^2 = 0.4GeV^2]$



$p(e, e'\pi^0)p$

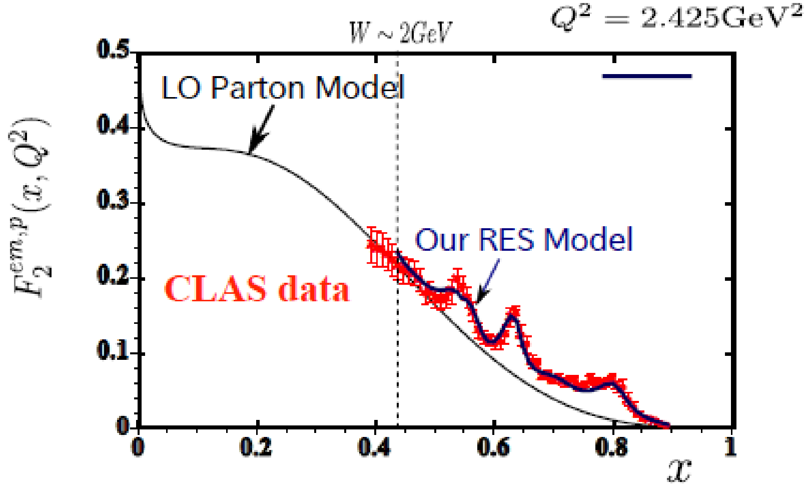


$p(e, e'\pi^+)n$

Data of structure functions for single pion electroproduction are provided by K. Joo and L. C. Smith.

Inclusive cross section $F_2^{em,p}$

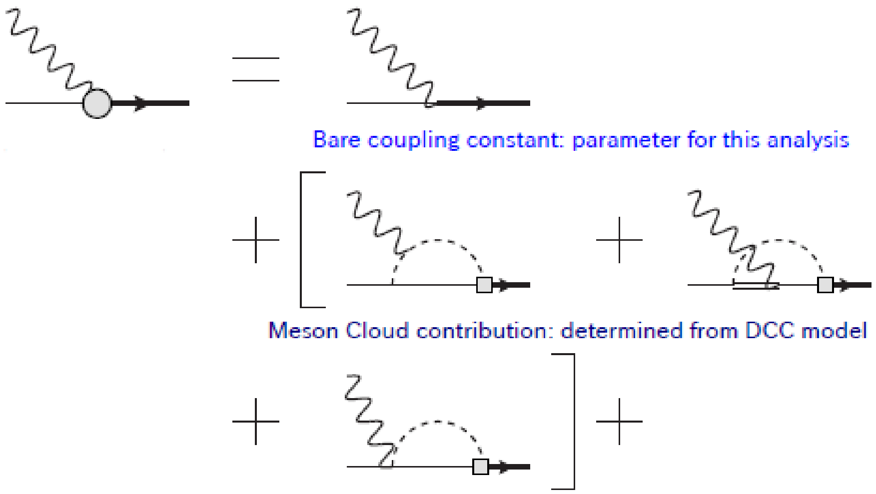
Resonance vs DIS (Inclusive structure function)



Parton model by S. Kumano, DCC by S. Nakamura, data are from http://www.ge.infn.it/ osipenko/results/inclusive/

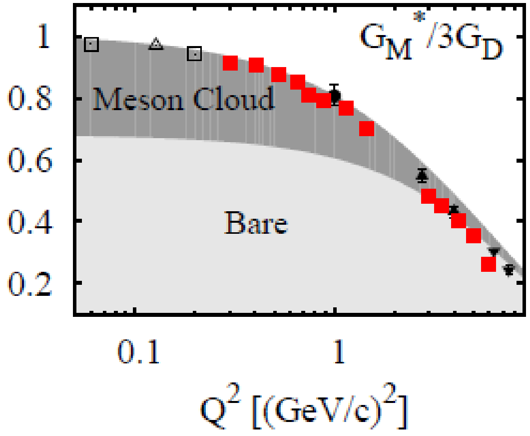
- Total strength of ep reaction is well explained by DCC
- hadronic description(DCC model) matches with parton model around $W \sim 2GeV$
- Similar comparison of Parton model with DCC on Charged current and Neutral current structure functions would be interesting.

Transition form factor in Coupled-channel model



Bare coupling constant: parameter for this analysis

Meson Cloud contribution: determined from DCC model



- 'Bare' electromagnetic coupling constants of N^* are fitting parameters
- Contribution of meson cloud(loop) is prediction of DCC model. (Assuming the Q^2 dependence of relevant electromagnetic form factors are known.)
- strength of 'Bare' might depends on the Fock space(meson-baryon channels) of the DCC model.
- For channel with multi-bare states, the helicity amplitude of resonance is given by the superposition of 'bare' states. This can be automatically done by evaluating the residue of the amplitudes at resonance pole.

How extracted from factors, meson cloud depend on DCC model?

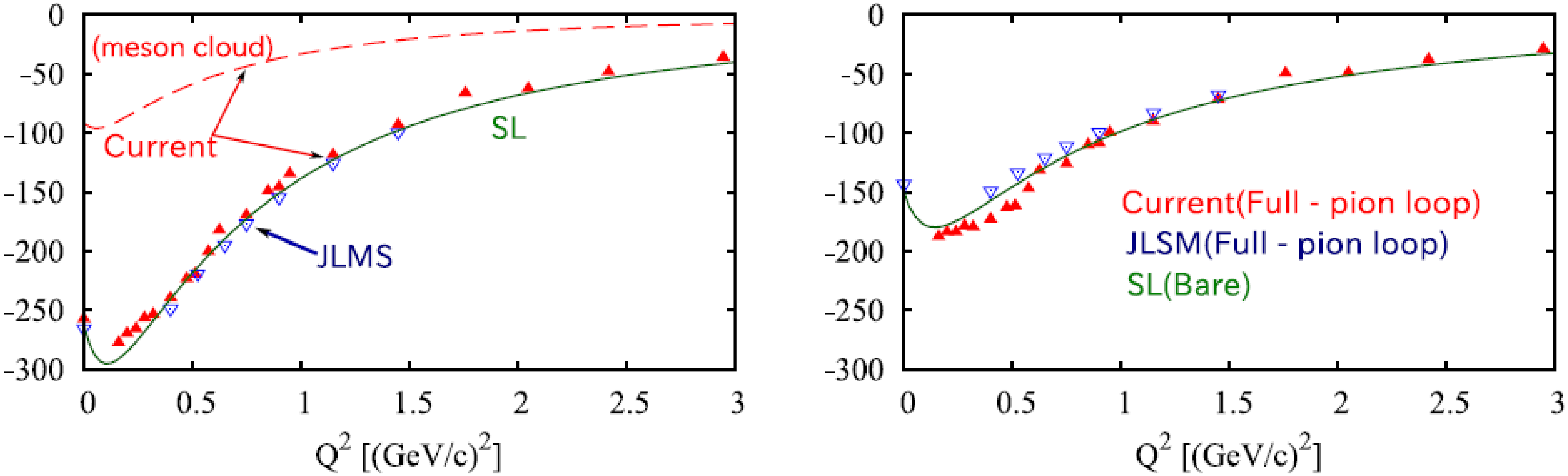
	Channel	Fitted Reactions/Q^2 of $e, e'\pi$
SL(2001)	πN	$\pi(\gamma)N \to \pi N : W < 1.27GeV$ $Q^2 = 2.8, 4GeV^2$
JLMS(2008)	$(\pi + \eta + \pi\pi)N$	$\pi(\gamma)N \to \pi N : W < 2(1.65)GeV$ 0.4,... 1.45 (7 points)
Current(2015)	$(\pi + \eta + \pi\pi)N$ +KY	$\pi(\gamma)N \to \pi, \eta N, KY : W < 2.1(2.)GeV$ 0.16,... 3.0(23 points)

* SL model: Q^2 dependence of form factor is parametrized by two-parameter function.

SL: T. Sato, T. -S. H. Lee, PRC63 (2001)

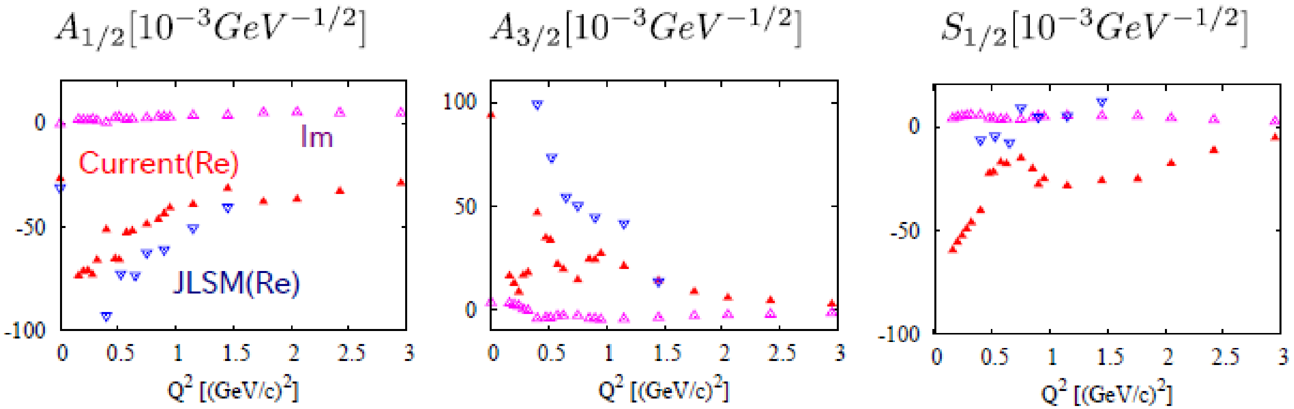
JLMS:B. Julia-Diaz,T.-S. H. Lee,A. Matsuyama, T. Sato,PRC77(2008) B. Julia-Diaz,H.Kamano,T.-S. H. Lee,A. Matsuyama, T. Sato, N. Suzuki, PRC80(2009),N. Suzuki,T. Sato, T.-S. H. Lee, PRC82 (2010)

Transition form factor of $N \to \Delta(3/2^+3/2, 1210 - 50i)$
$[Re(A_{3/2}(Q^2))$ at resonance pole]

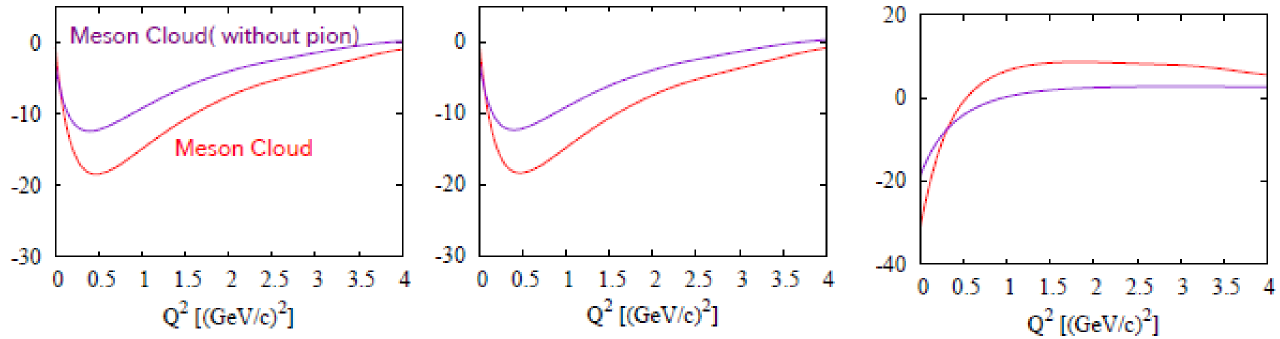


- Left: Full $A_{3/2}$ extracted from DCC models (Current, JLSM, SL) agree well with each other.
- Right: Contribution other than pion-cloud(loop) also agree well.
  In Current model, meson cloud is dominated by pion.
- At least for delta, robust results of form factor $A_{3/2}$ are obtained in DCC approach.

Q^2 dependence of Meson-Cloud $D_{13}(3/2^-1/2, 1505 - 41i)$

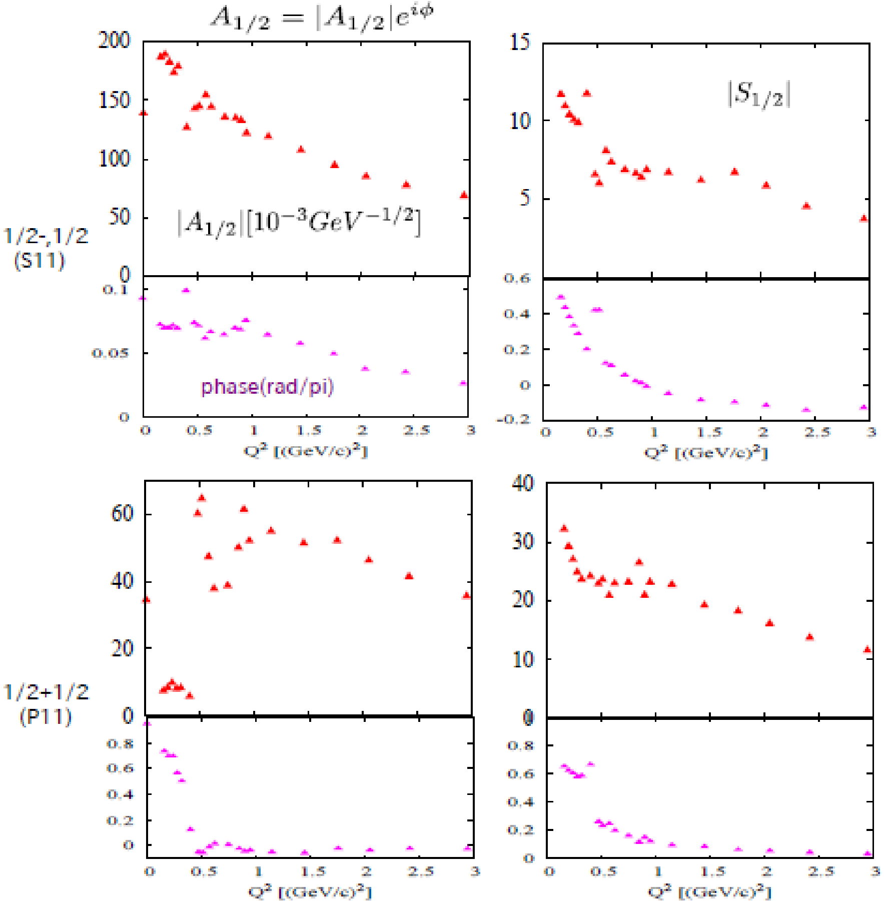


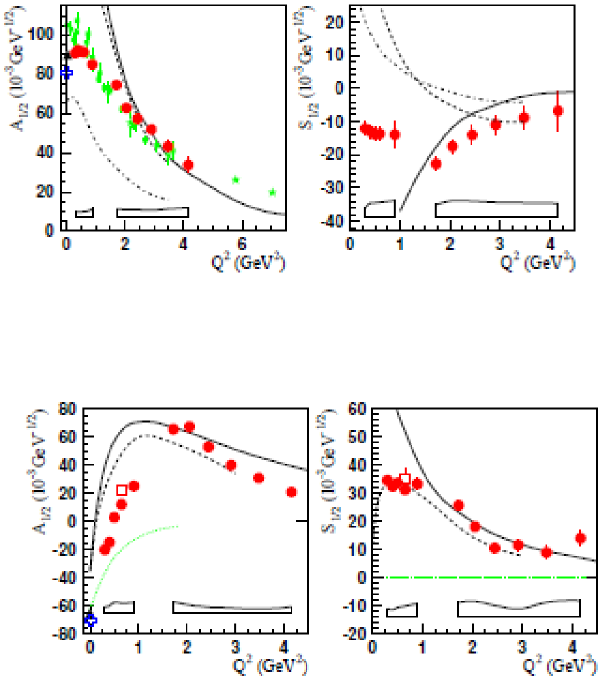
- Qualitatively Current model ~ JLMS
- Imaginary part of form factor is small for this transition



- Meson cloud effects are decreasing in high Q^2.
- Pion and other meson clouds are equally important for N^*_{D13} form factors.

Transition form factors $S_{11}(1/2^{-}1/2, 1495 - 116i)$ $P_{11}(1/2^{+}1/2, 1375 - 74i)$





- qualitatively, $Re(A_{1/2})$ of DCC $\sim A_{1/2}$ of I. Aznauryan et al. (arXiv 1102.0597)
  $Re(A_{1/2})$ of $1/2^{+}1/2(P11)$ changes sign around $Q^2 \sim 0.3 - 0.4GeV^2$
- $Re(S_{1/2}) \sim Im(S_{1/2})$

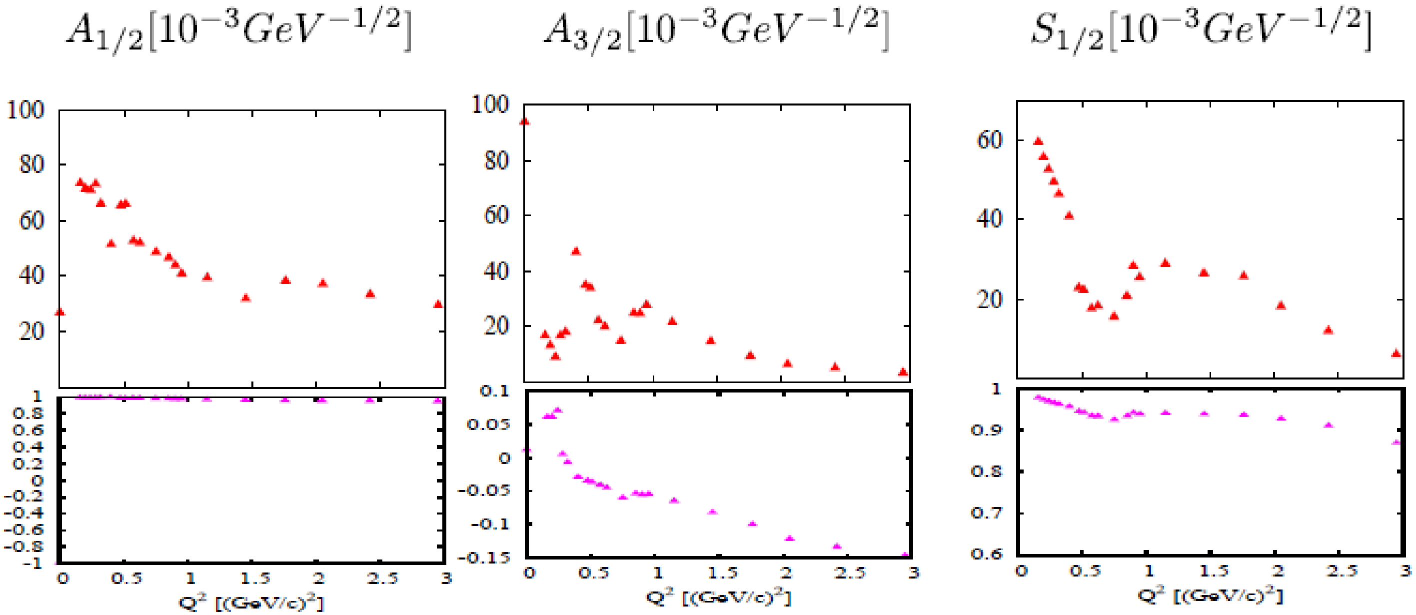
Summary of Part II

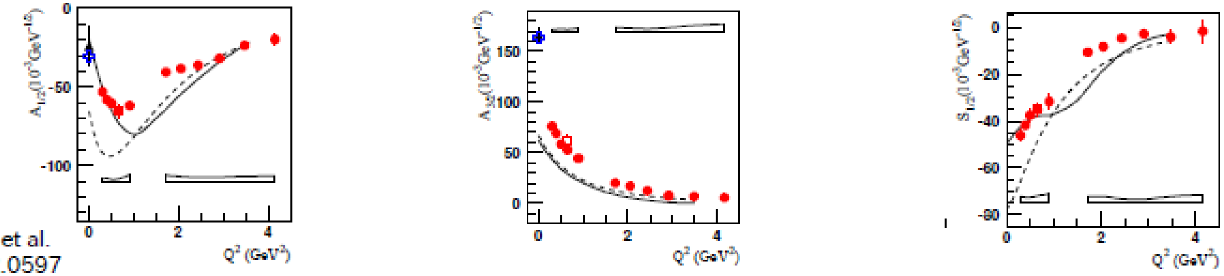
- $\gamma^* N N^*$ transition form factors are extracted by analyzing ep reactions within DCC model.

  Note: The DCC model for $0 < Q^2 < 3GeV^2$ used in this report is developed for the use of neutrino physics, not fine tuned for the study of N^* structure.
- Extracted form factors and pion-loop contributions for $\gamma^* N \Delta_{33}$ transition from our three DCC models agree well with each other.
- Form factors of $(3/2^-, 1/2)D_{13}$,$(1/2^-, 1/2)S_{11}$, $(1/2^+, 1/2)P_{11}$ and other resonances are analyzed. In general, contribution of meson cloud decreases as Q^2 increases and meson-baryon state other than pion-nucleon can be important.
- Analysis on the real/imaginary part of the form factors and relation to the amplitude at real W is in progress.
- On going elaborated analysis of $p(e, e'\pi)N$ up to $Q^2 = 6GeV^2$ will give us more information on the distribution of NN^* transition current .

Back up

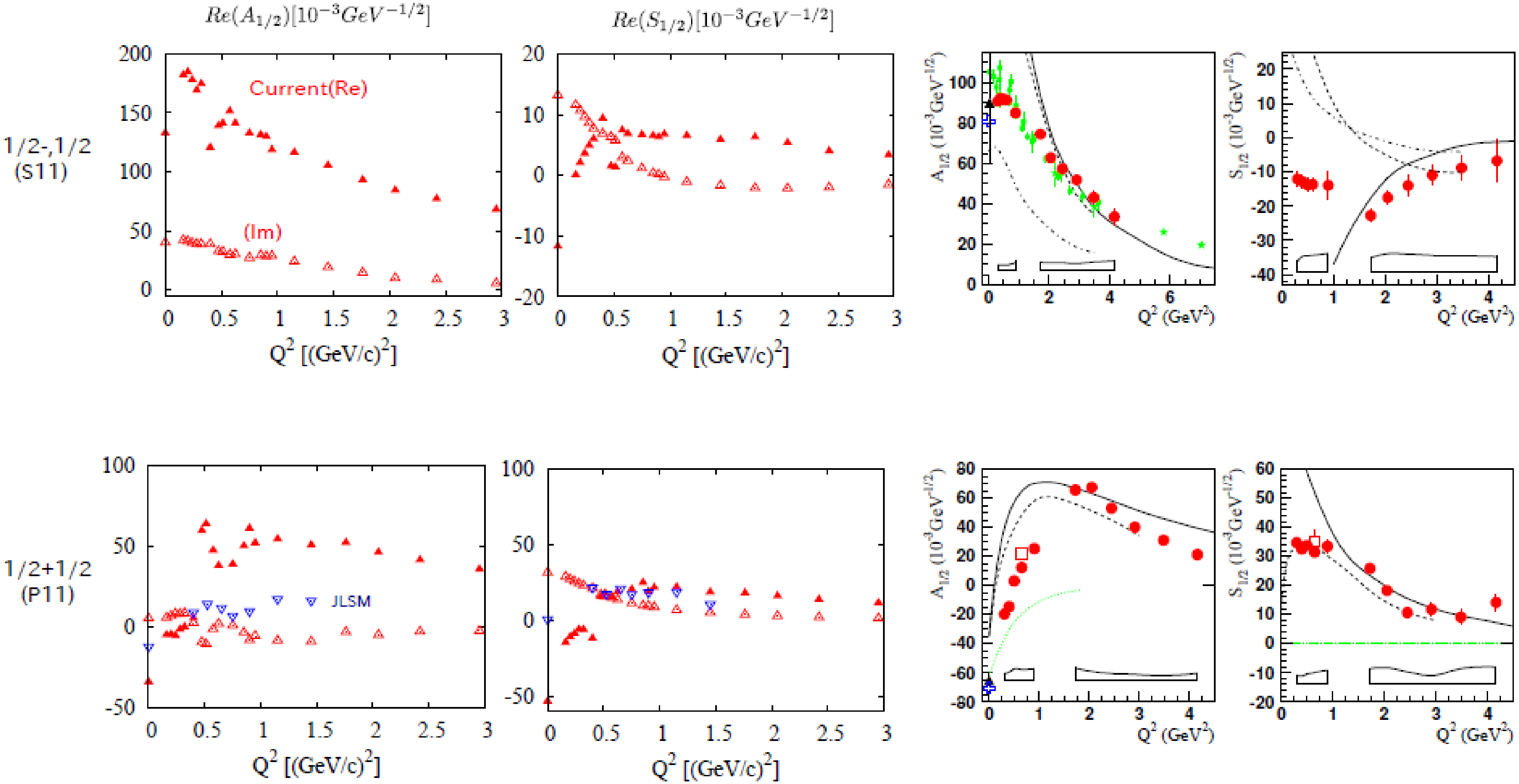
Backup $D_{13}(3/2^-1/2, 1505-41i)$


$A_{1/2}[10^{-3}GeV^{-1/2}]$ $A_{3/2}[10^{-3}GeV^{-1/2}]$ $S_{1/2}[10^{-3}GeV^{-1/2}]$



Aznauryan et al.
arXiv 1102.0597

Transition form factors $S_{11}(1/2^-1/2, 1495 - 116i)$ $P_{11}(1/2^+1/2, 1375 - 74i)$



- qualitatively, $Re(A_{1/2})$ of DCC $\sim A_{1/2}$ of I. Aznauryan et al. (arXiv 1102.0597)
- $Re(S_{1/2}) \sim Im(S_{1/2})$

Multi-resonances and DCC approach

In DCC, (bare) states mix with each other due to coupling with meson-baryon states and the N^* Greens function has off-diagonal element. (Σ is matrix with off-diagonal element.)

$$\begin{aligned} F_{\gamma^*,\pi}(W) &= g_{\pi N N_1^*}(W)(\frac{1}{W-m-\Sigma})_{11}\ g_{\gamma^* N N_1^*}(W) \\ &+ g_{\pi N N_1^*}(W)(\frac{1}{W-m-\Sigma})_{12}\ g_{\gamma^* N N_2^*}(W) + ... + F(non-res,W) \end{aligned}$$

This amplitude cannot be expressed by the sum of individual resonances(diagonal)

$$\neq \sum_i g_{\pi N N_i^*}(W)\frac{1}{W-m_i-\Sigma_i} g_{\gamma^* N N_i^*}(W)$$

Therefore, extracting resonance parameters from DCC amplitude is non-trivial task in this form. However, expansion around resonance pole uniquely determines resonance parameters

$$F_{\gamma^*,\pi}(W) = \frac{\tilde{g}_{\pi N N^*}\tilde{g}_{\gamma^* N N^*}}{W-M+i\Gamma/2} + (non-pole)$$

The helicity amplitude of resonance $\tilde{g}_{\gamma^* N N^*}$ is ginve by the sum of bare states.

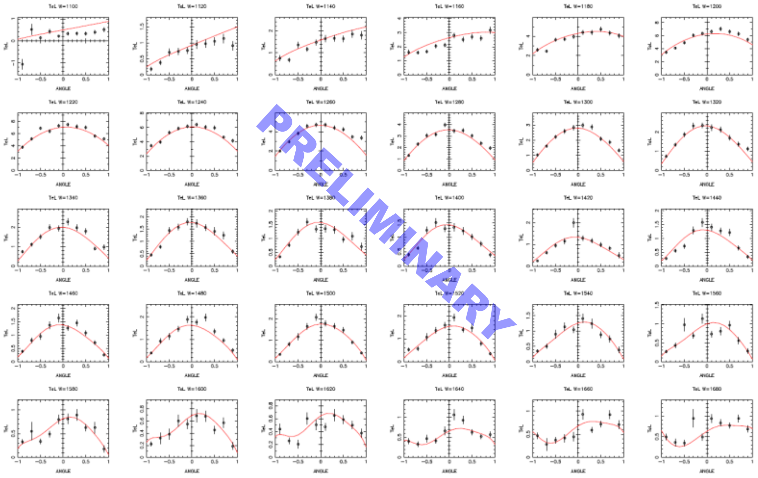
$$\tilde{g}_{\gamma^* N N^*} = \sum_i N_i\ g_{\gamma^* N N_i^*}(W=M-i\Gamma/2)$$

Analysis of electroproduction reactions: Determining N-N* e.m. transition form factors

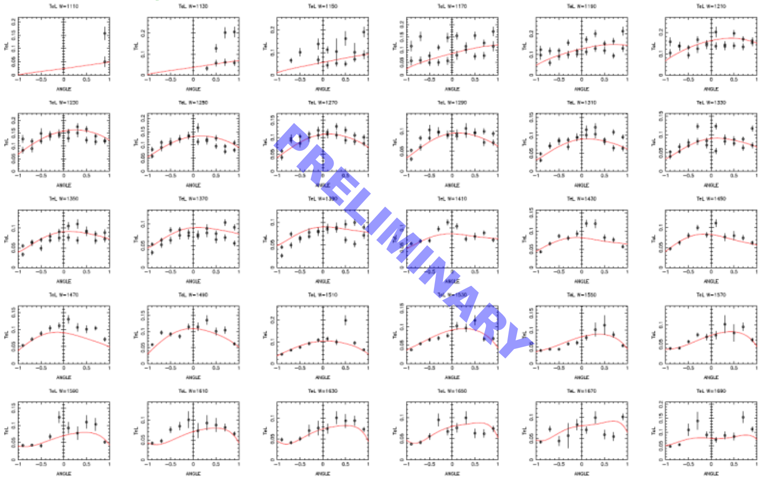
$\sigma_T+\varepsilon\sigma_L$ for ep → eπ^0p

Data for structure functions are provided by K. Joo and L. C. Smith.

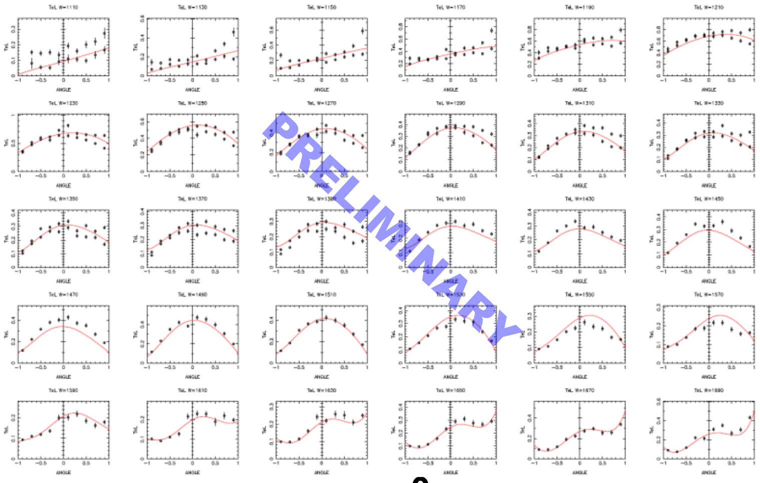
Q^2 = 1.15 GeV^2, 1.10 < W < 1.69 GeV



Q^2 = 5.0 GeV^2, 1.11 < W < 1.69 GeV

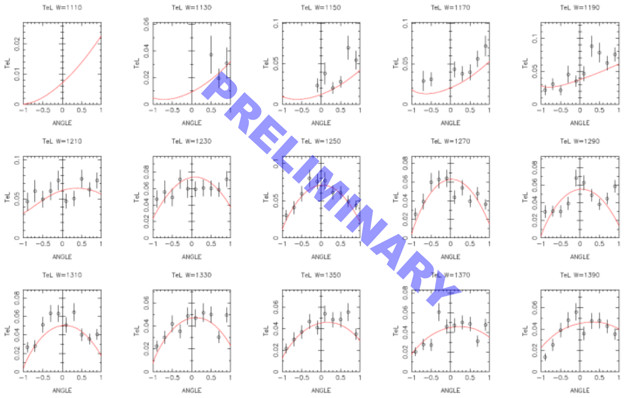


Q^2 = 3.0 GeV^2, 1.11 < W < 1.69 GeV



cosθ

Q^2 = 6.0 GeV^2, 1.11 < W < 1.39 GeV

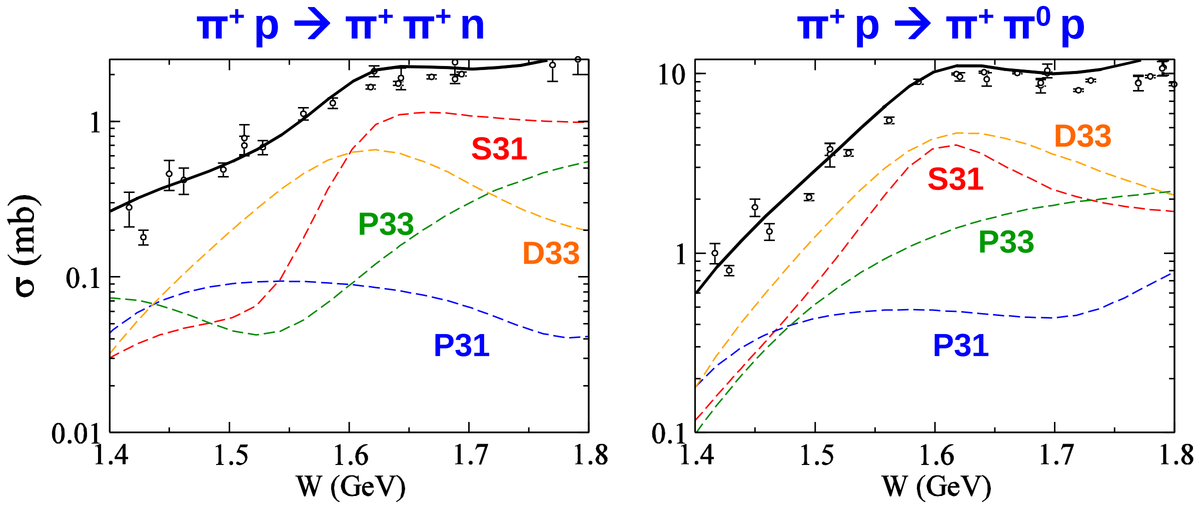


cosθ

Necessity of inelastic reaction data for establishing high-mass N* and Δ* spectrum

To establish the spectrum of high-mass resonances, inelastic reaction (particularly double pion production) data are highly desirable:

πN, γN → ππN, KΛ, KΣ, ηN, η'N, ωN, ΦN,…



HK
PRC88(2013)
045203

π^+ p →ππN will be a key to determining 2nd P33 resonance !!