Extraction of N-N* electromagnetic transition form factors within ANL-Osaka dynamical coupled-channels approach

Hiroyuki Kamano
(KEK)

Collaborators:
T.-S. H. Lee (ANL), S. X. Nakamura (Osaka U.), T. Sato (Osaka U.)

INT Workshop on “Spectrum and Structure of Excited Nucleons from Exclusive Electroproduction”
INT, Seattle, WA, USA, November 14-18, 2016

Outline

1. Background & motivation for studying N-N* electromagnetic transition form factors

2. Current status for electroproduction analysis based on ANL-Osaka Dynamical Coupled-Channels (DCC) approach

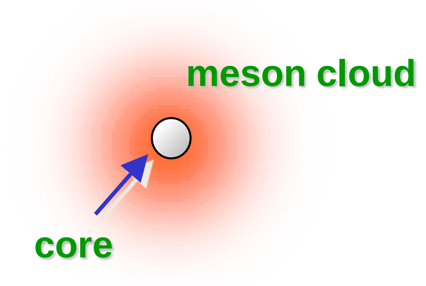
Background & motivation for studying N-N* electromagnetic transition form factors

(1 of 2)

E.M. transition form factors:
Exploring quark-gluon substructure of N* & Δ*

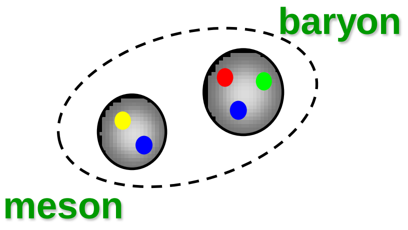
Electromagnetic transition form factors provide crucial information for revealing the structure of N* & Δ* resonances !!

- **Structure of baryon resonances (at long distance scale):**



$$|N^*\rangle = |\text{“core”}\rangle + |\text{m.c.}\rangle$$

$$(\ |\text{“core”}\rangle = |qqq\rangle + |qqqq\bar{q}\rangle + |qqqg\rangle + \cdots\ )$$



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

e.g.) Roper resonance from dynamical reaction models

- **“core” + meson cloud**
  Suzuki et al., PRL104(2010)042302
- **meson-baryon molecule-like state**
  Ronchen et al., EPJA49(2013)44

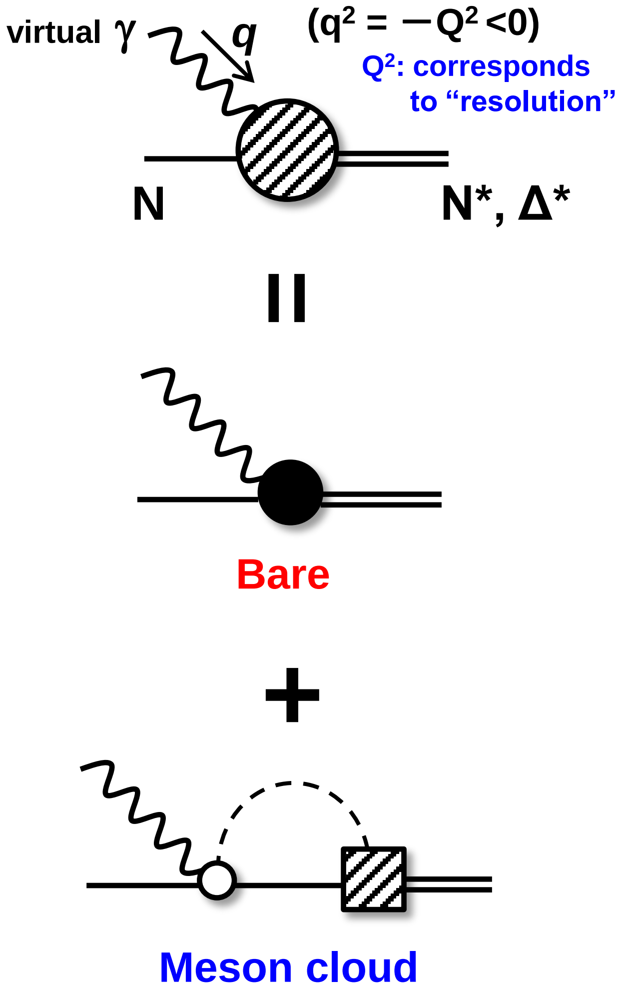
(NOTE: obtained with πN analysis)

Q^2 dependence of the form factors could judge the substructure of the Roper resonance !!

E.M. transition form factors:

Exploring quark-gluon substructure of N* & Δ*

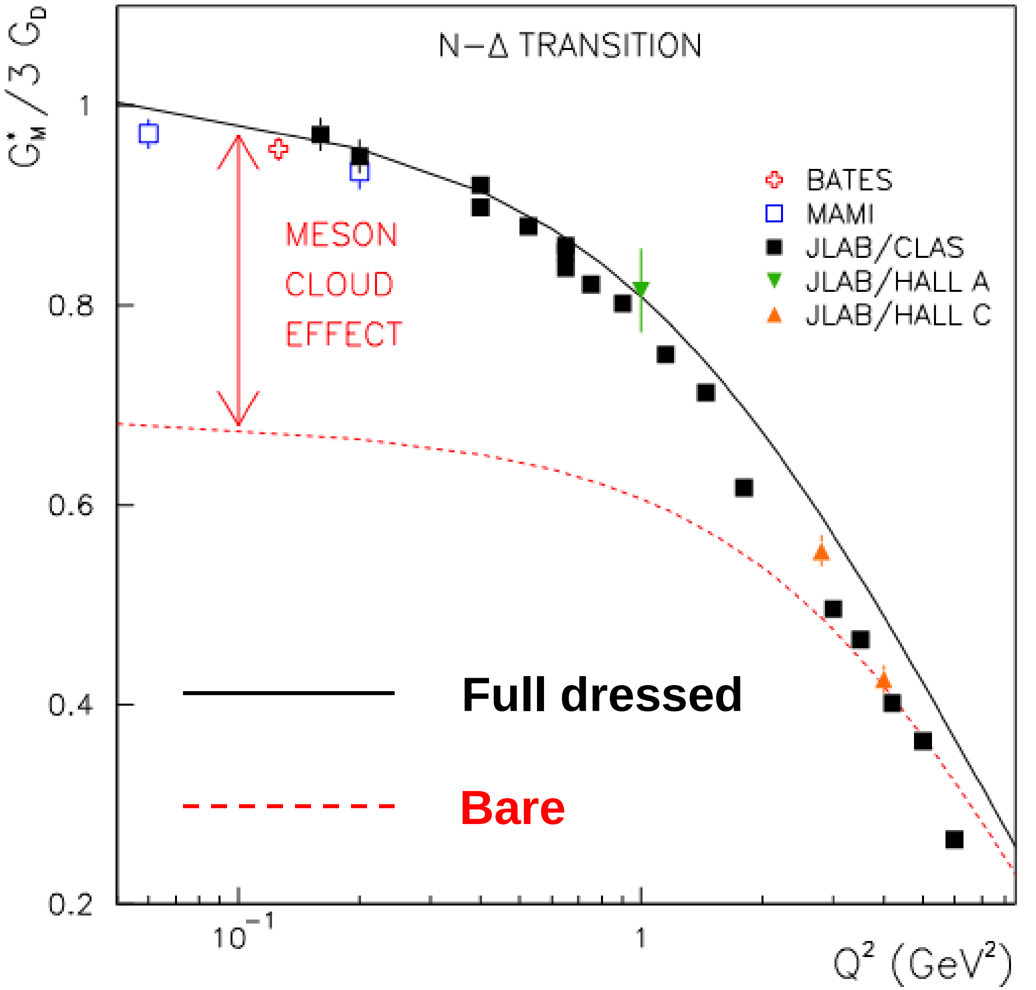
N-N* e.m. transition form factor



$(q^2 = -Q^2 < 0)$

Q^2: corresponds to "resolution"

Re[$G_M(Q^2)$] for γ N → Δ (1232) M1 transition

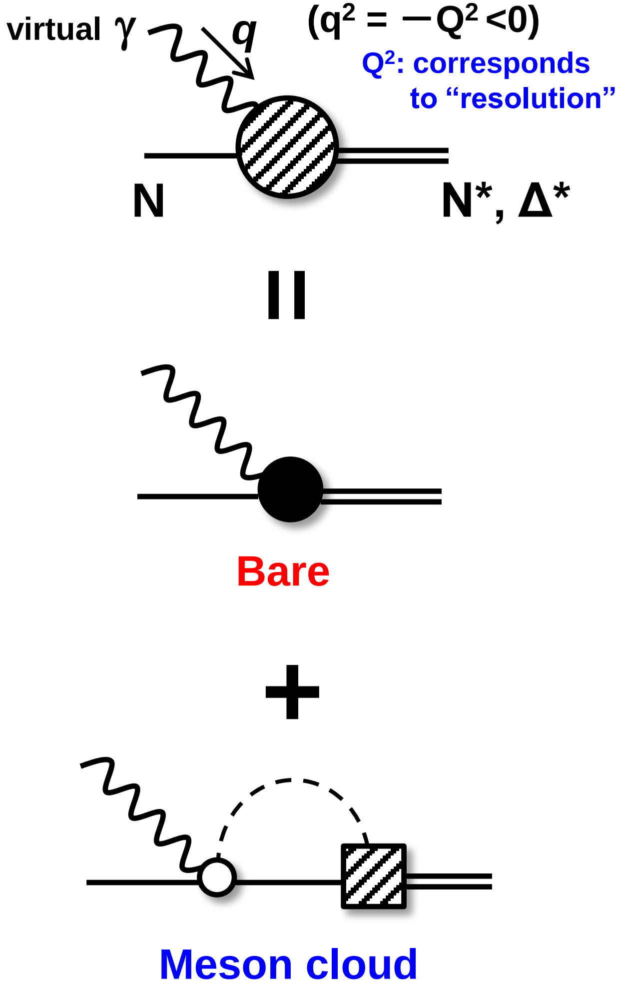


Julia-Diaz, Lee, Sato, Smith, PRC75 015205 (2007)

E.M. transition form factors:

Exploring quark-gluon substructure of N* & Δ*

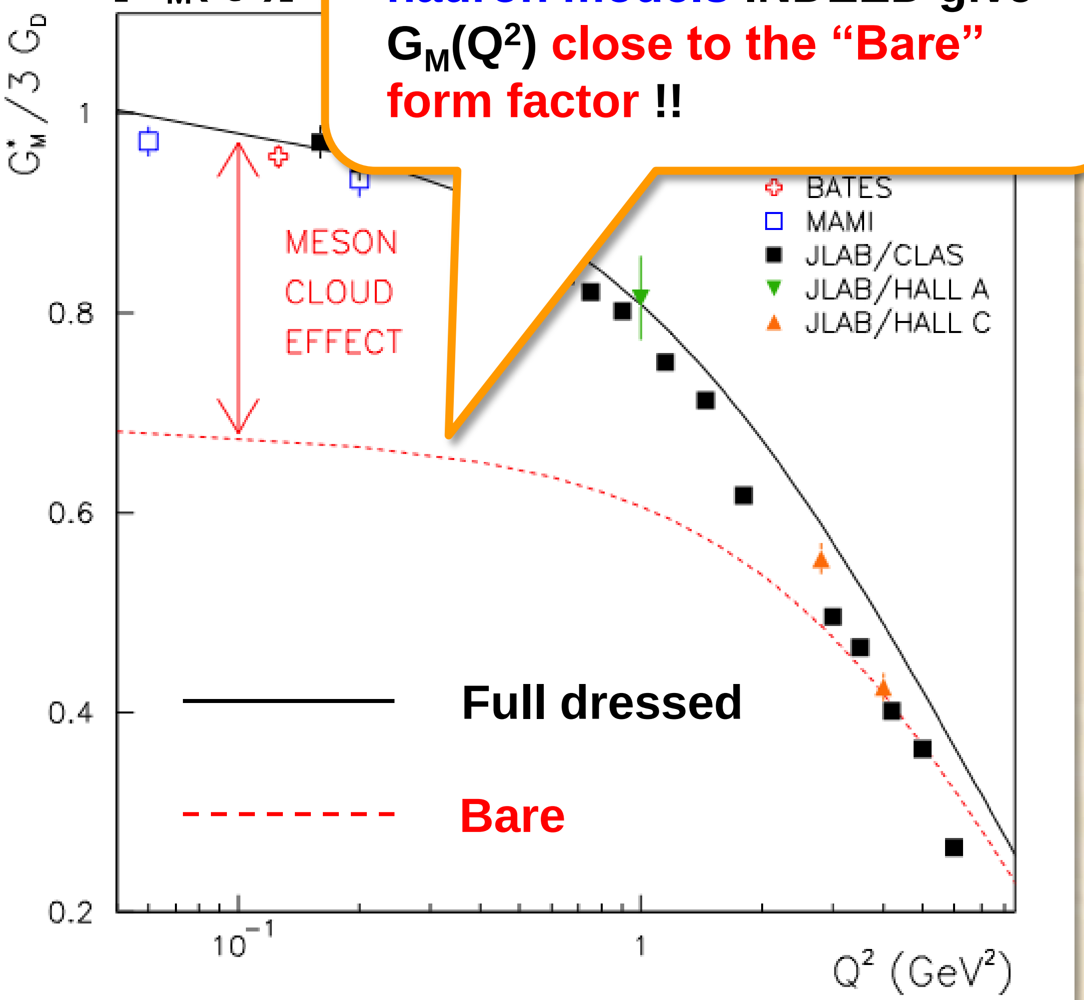
N-N* e.m. transition form factor



($q^2 = -Q^2 < 0$)

Q^2: corresponds to "resolution"

Re[$G_M(Q^2)$] f

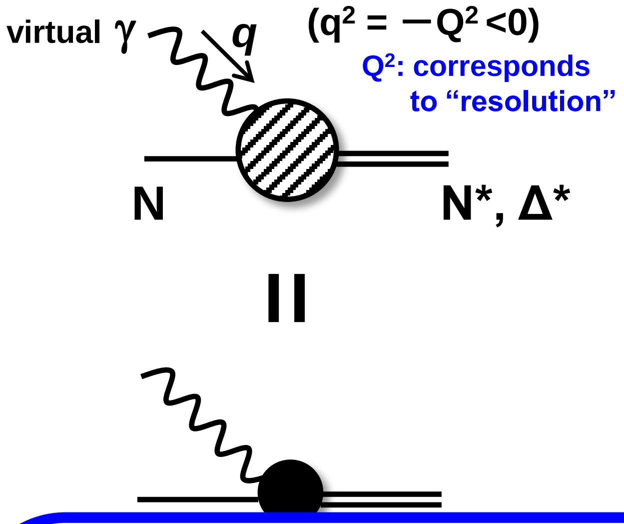


Most of the available **static hadron models** INDEED give $G_M(Q^2)$ **close to the "Bare" form factor** !!

Julia-Diaz, Lee, Sato, Smith, PRC75 015205 (2007)

E.M. transition form factors:
Exploring quark-gluon substructure of N* & Δ*

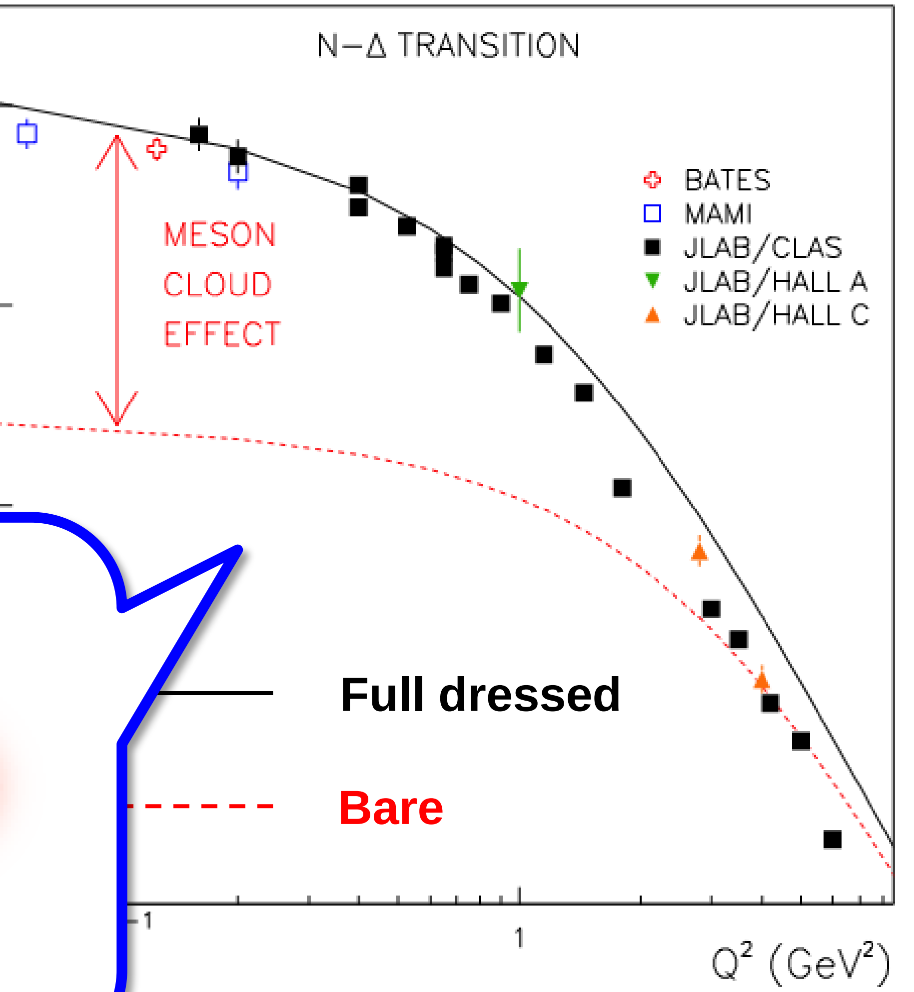
N-N* e.m. transition form factor



$(q^2 = -Q^2 < 0)$

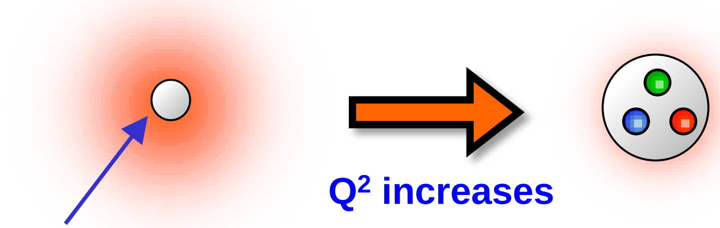
Q^2: corresponds to "resolution"

Re[$G_M(Q^2)$] for γ N → Δ (1232) M1 transition



a-Diaz, Lee, Sato, Smith, PRC75 015205 (2007)

meson cloud

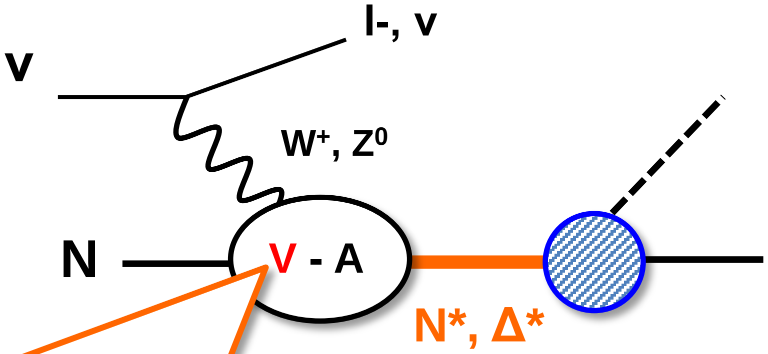


Q^2 increases

"bare" state
(core composed of
"dressed" quarks)

E.M. transition form factors:
Critical input to neutrino physics

- Neutrino-induced meson production reaction:



Vector part of the weak current matrix elements can be precisely determined with exclusive electroproduction data !!

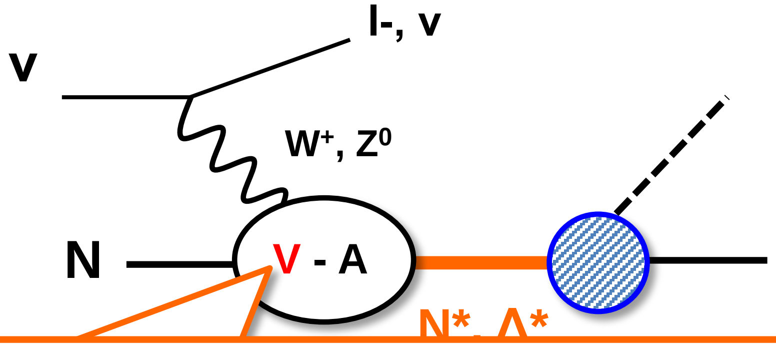
- Data for BOTH proton & deuteron (“neutron”) targets are required to make isospin decomposition of vector current.
  (➔ Ralf’s talk for progress report for electron-deuteron reaction)

✓ Key to precise determination of leptonic CP violation & neutrino mass hierarchy from next-generation neutrino-oscillation expt. at T2K and DUNE etc.

[see. e.g., Alvarez-Ruso et al., New J. Phys. 16(2014)075015]

E.M. transition form factors: Critical input to neutrino physics

- **Neutrino-induced meson production reaction:**



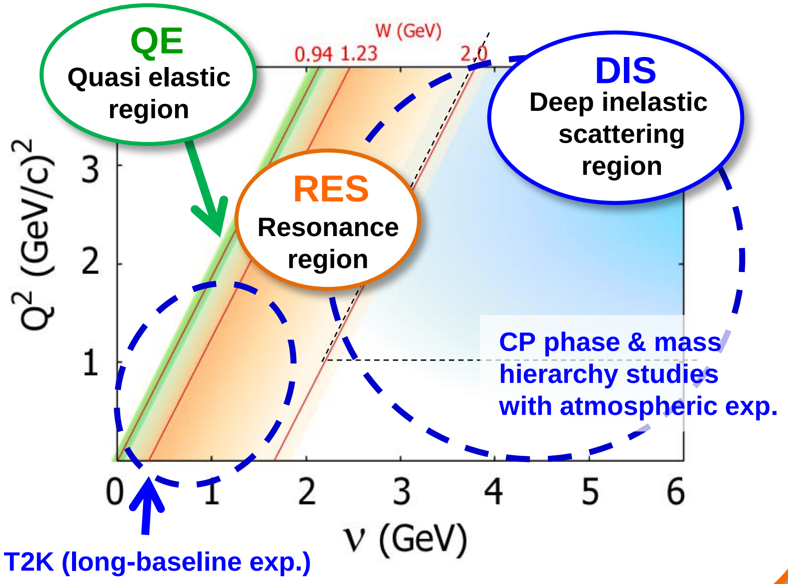
Neutrino collaboration@J-PARC Branch, KEK Theory Center

http://nuint.kek.jp/index_e.html

GOAL:
Construct a unified model comprehensively describing neutrino-nucleon/nucleus reactions over QE, RES, and DIS regions !!

A review article for the neutrino collaboration (to be published in Rep. Prog. Phys.):
Nakamura et al., arXiv:1610.01464

DCC model for neutrino-nucleon reactions:
Nakamura, HK, Sato, PRC92(2015)025205



QE
Quasi elastic region

RES
Resonance region

DIS
Deep inelastic scattering region

CP phase & mass hierarchy studies with atmospheric exp.

T2K (long-baseline exp.)

Current status for electroproduction analysis based on ANL-Osaka DCC approach
(2 of 2)

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:**

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

- ✓ **Reaction channels:**

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

- ✓ **Transition Potentials:**

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

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:**

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

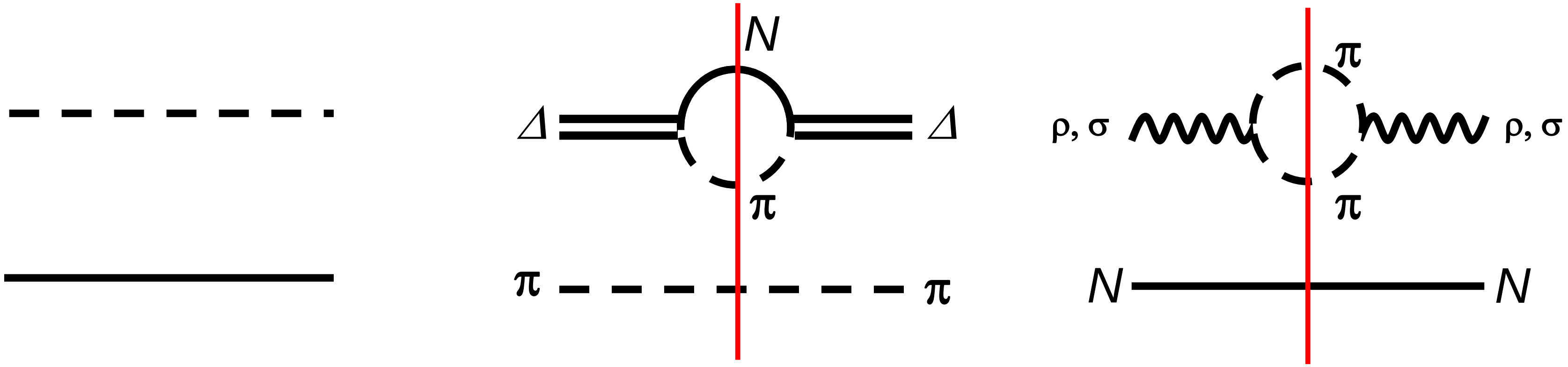
- ✓ **Meson-Baryon Green functions G_{MB}**

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

Stable channels

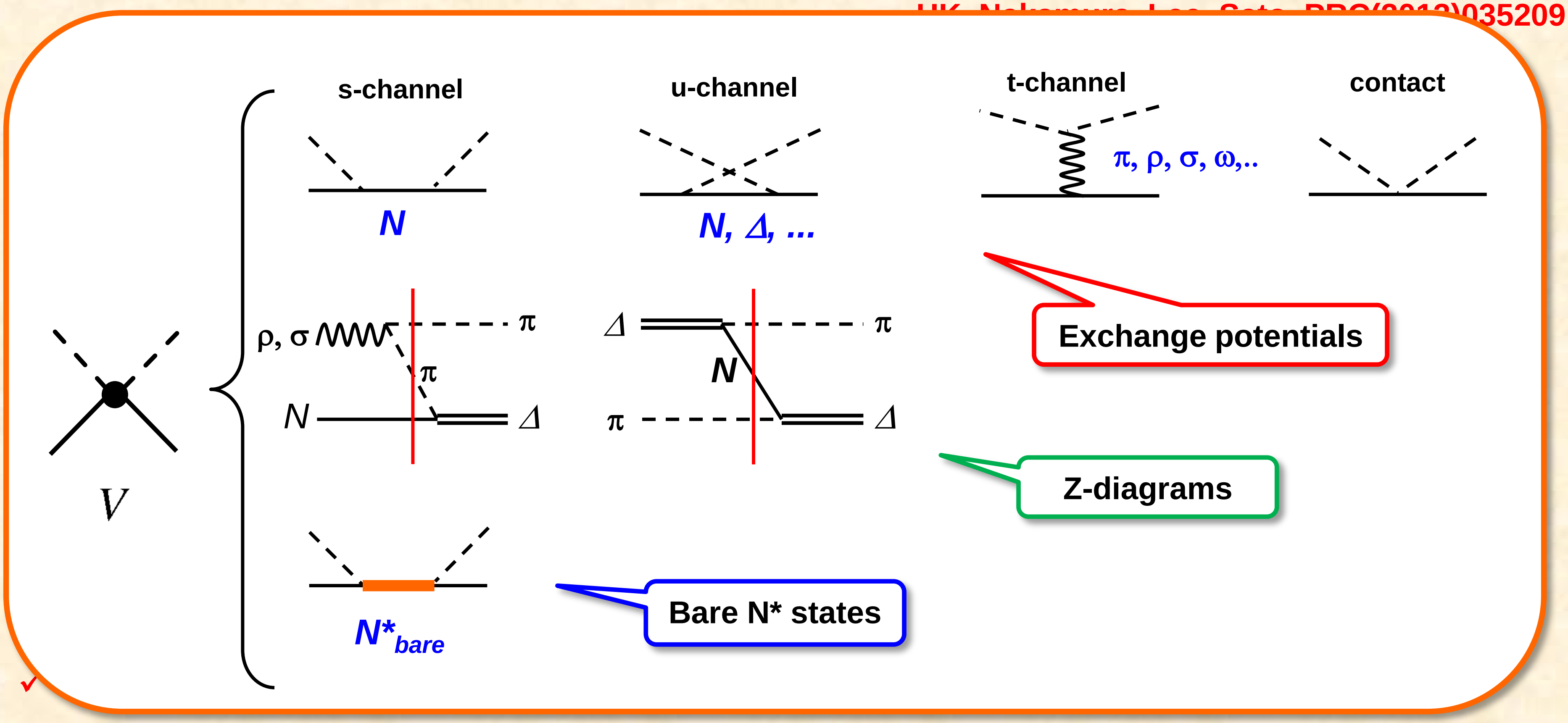
$MB = \pi\Delta, \rho N, \sigma N$

Quasi 2-body channels



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



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

Z-diagrams

bare N* states

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

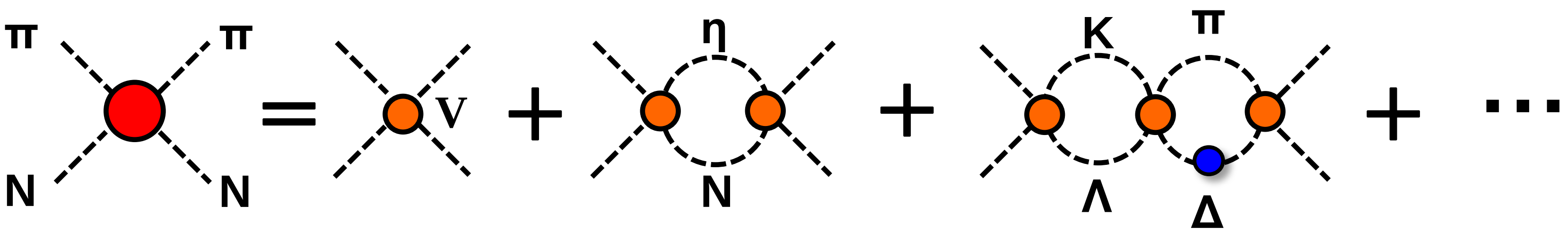
For details see Matsuyama, Sato, Lee, Phys. Rep. 439(2007)193
HK, Nakamura, Lee, Sato, PRC(2013)035209

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

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

✓ **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.**

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:**

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

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

- ✓ **Transition Potentials:**

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

Strategy for N* and Δ* spectroscopy: Analysis of pion- & photon-induced reactions

1) Construct a model by making χ^2-fit of the world data of meson production reactions.

✓ **Latest published model (8-channel):**

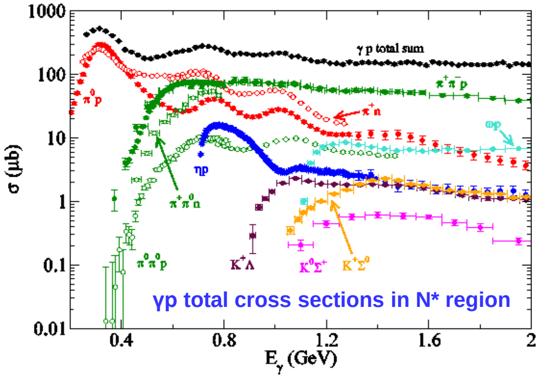
HK, Nakamura, Lee, Sato, PRC88(2013)035209; PRC94(2016)015201

Made simultaneous analysis of

- πN → πN(SAID amp) (W < 2.3 GeV)
- πp → ηN, KΛ, KΣ (W < 2.1 GeV)
- γp → πN, ηN, KΛ, KΣ (W < 2.1 GeV)
- γ 'n' → πN (W < 2 GeV)

→~27,000 data points of both dσ/dΩ & spin-pol. obs.

← Region our model can cover →



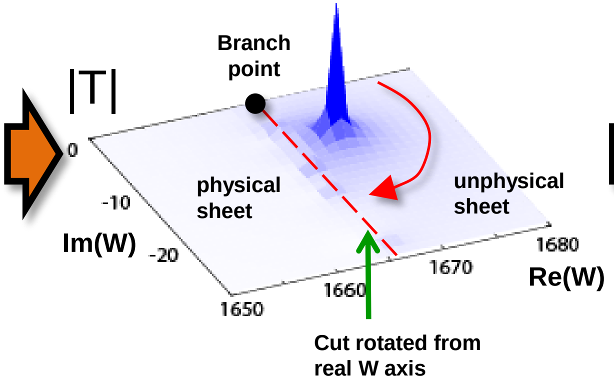
γp total cross sections in N* region

- Use supercomputers to accomplish coupled-channels analyses:

NERSC

Argonne NATIONAL LABORATORY

2) Search *poles* of scattering amplitudes by analytic continuation to a complex energy plane.

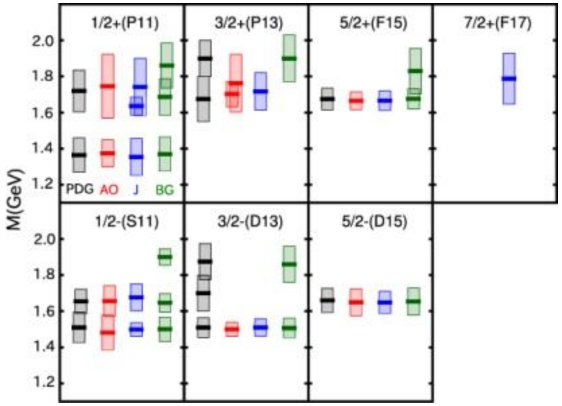


Pole position → (complex) resonance mass

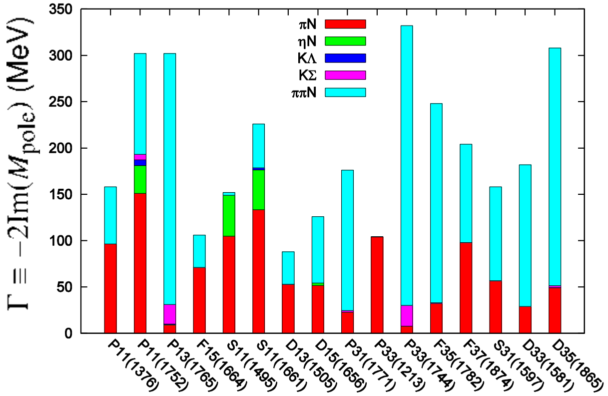
Residues → coupling strengths between resonance and meson-baryon channel

3) Extract resonance parameters defined by poles.

Mass spectrum



Partial decay widths

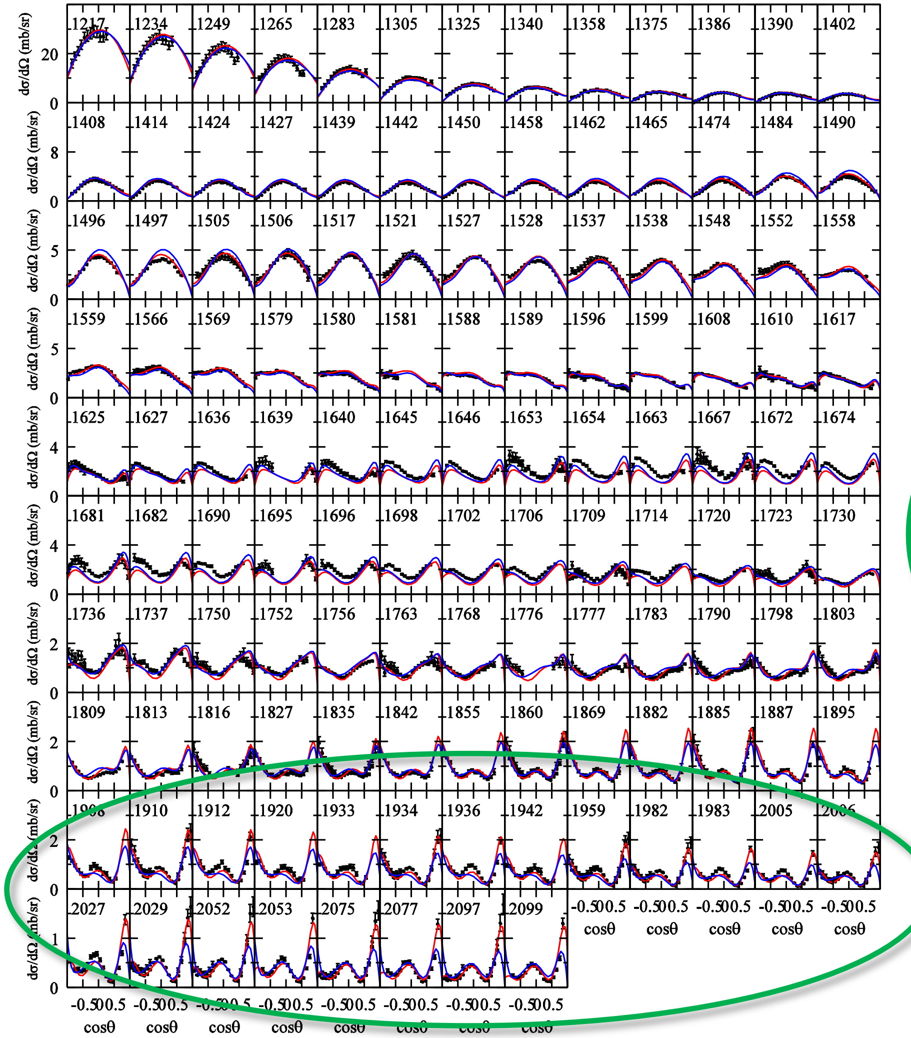


ANL-Osaka DCC approach to N* and Δ*

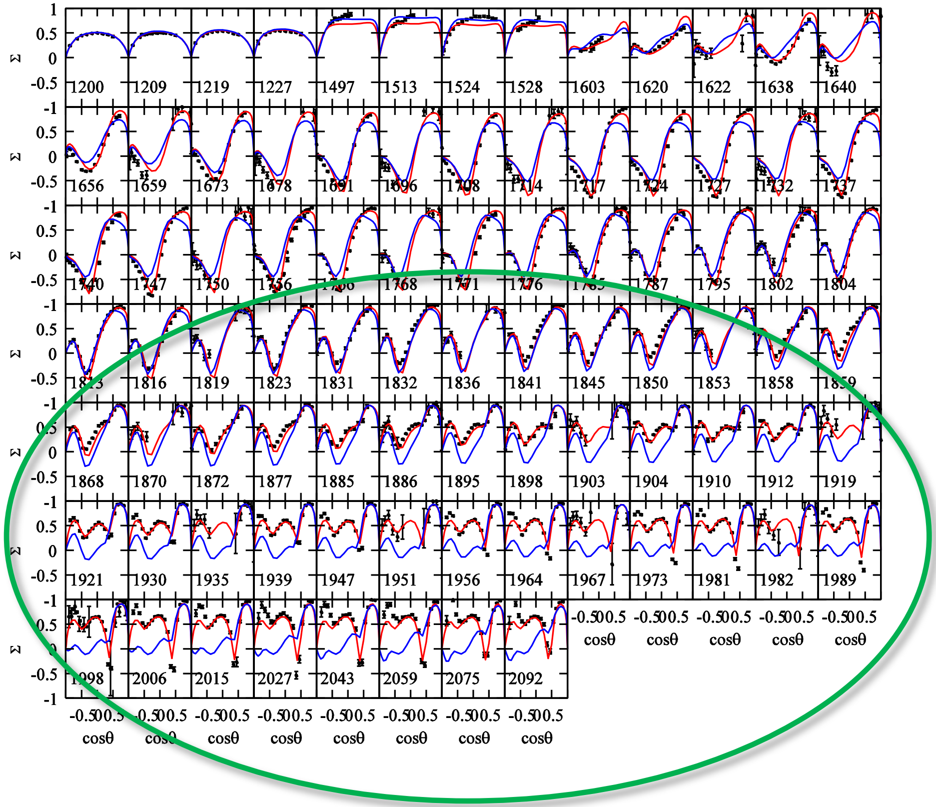
HK, Nakamura, Lee, Sato, PRC88(2013)035209; 94(2016)015201

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

dσ/dΩ for W < 2.1 GeV



Σ for W < 2.1 GeV

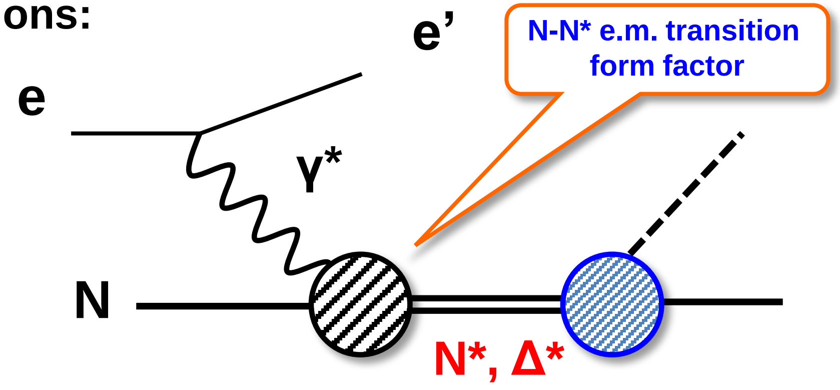


Red: Updated model [PRC94(2016)015201]

Blue: Original model [PRC88(2013)035209]

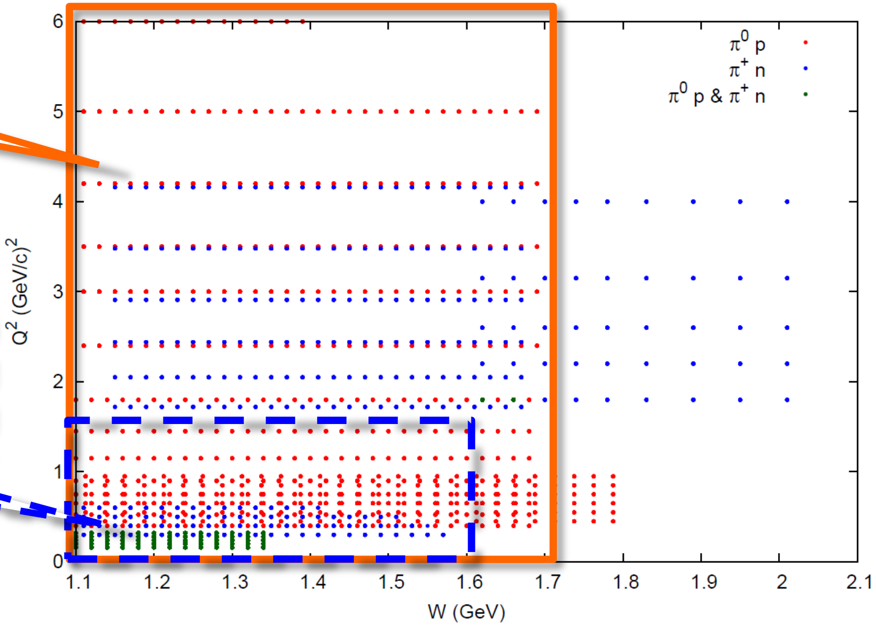
Analysis of electroproduction reactions to determine N-N* e.m. transition form factors

- **Meson electroproductions:**



N-N* e.m. transition form factor

Database for 1π electroproduction@CLAS6 ($Q^2 < 6$ GeV^2)



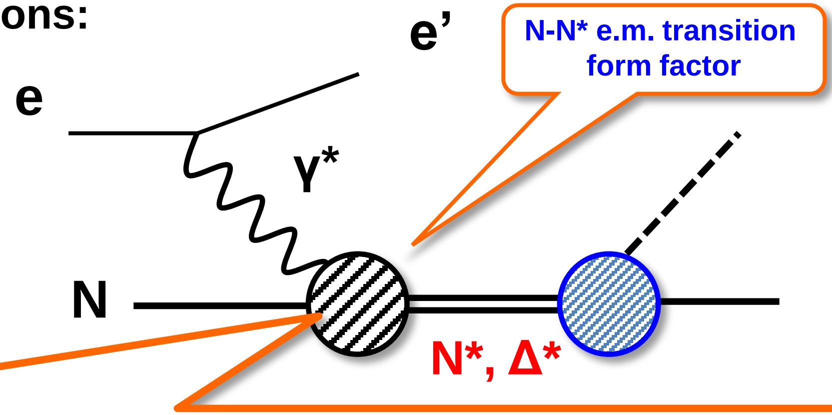
(W,Q^2) region in the current analysis ($Q^2 < 6$ GeV^2, $W < 1.7$ GeV)

(W,Q^2) region in the early analysis:
Julia-Diaz, HK, Lee, Matsuyama, Sato, Suzuki, PRC80(2009)025207

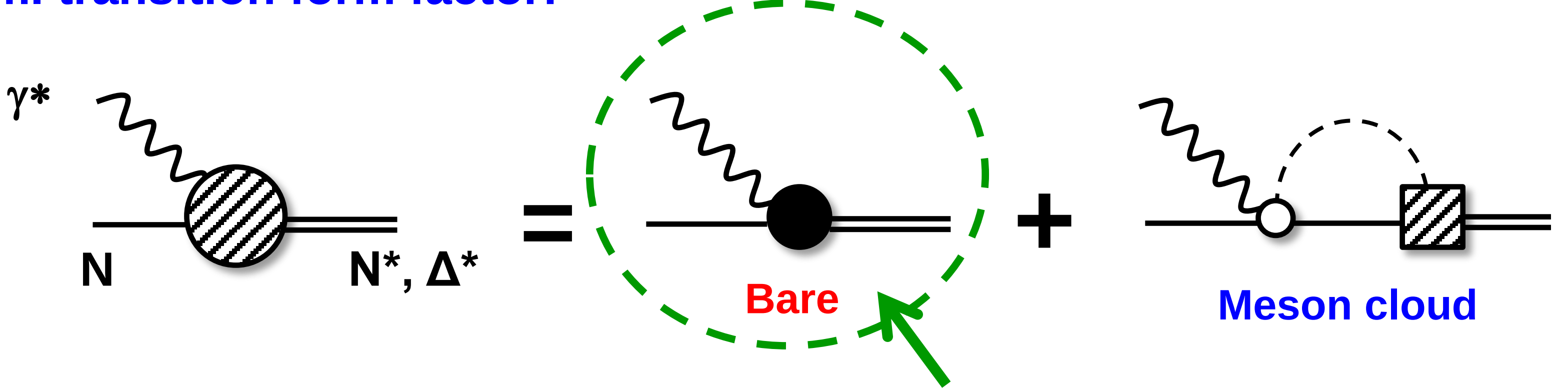
+ ***$K^+\Lambda$, $K^+\Sigma^0$, $\pi\pi N$ electro-production data***

Analysis of electroproduction reactions to determine N-N* e.m. transition form factors

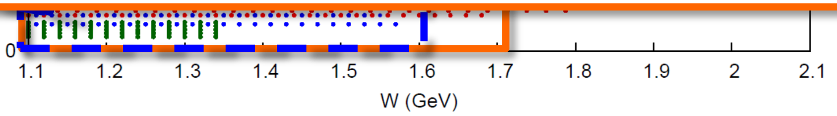
- Meson **electro**productions:



e.m. transition form factor:



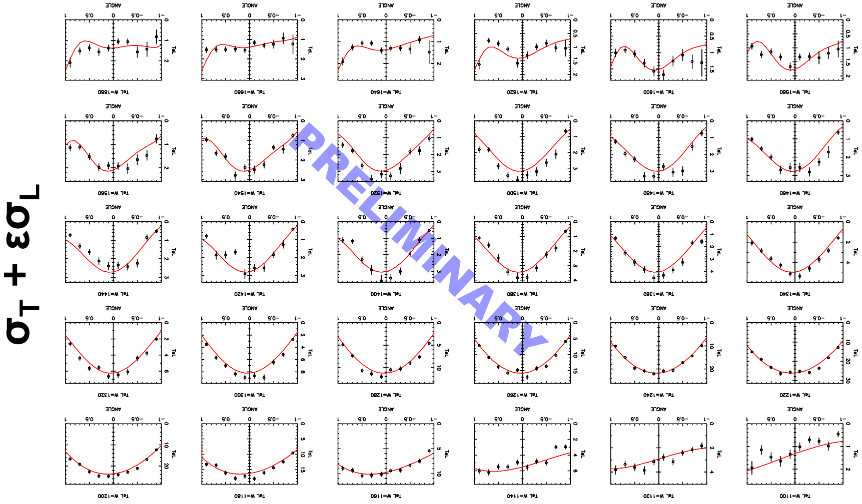
Varies model parameters included only in the "bare" transition form factors.
(Other parameters are fixed with the values obtained in πN & γN analysis.)

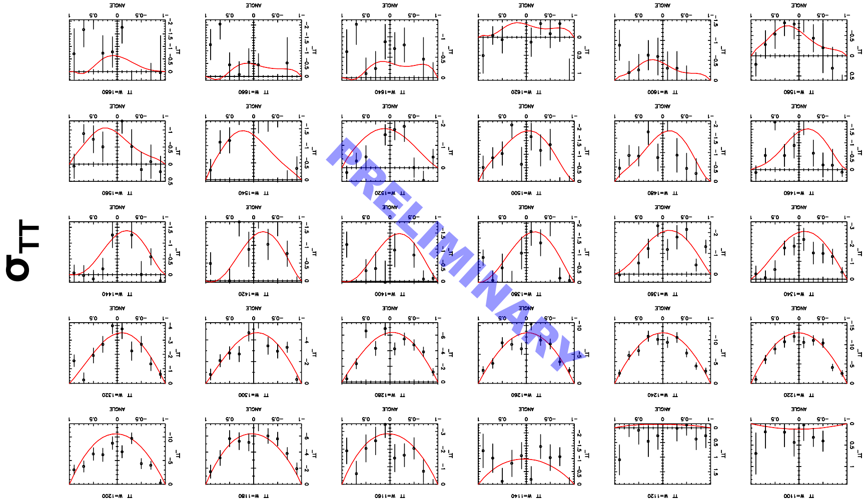


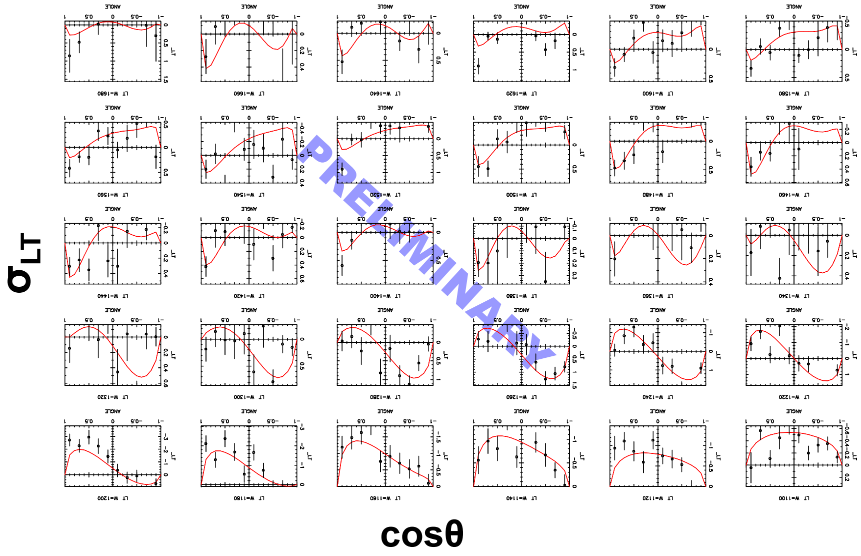
Analysis of single-pion electroproduction reactions

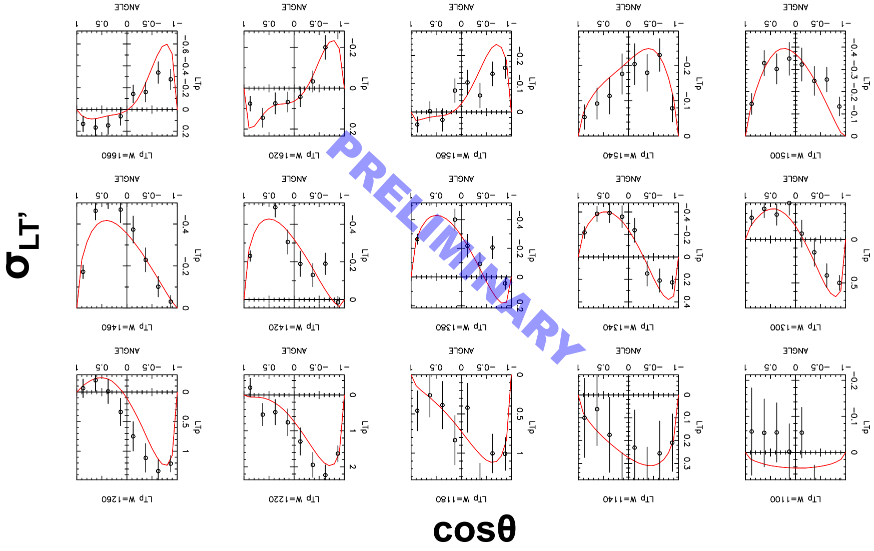
ep → e'π^0p @ Q^2 = 0.4 GeV^2, 1.10 < W < 1.68 GeV

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





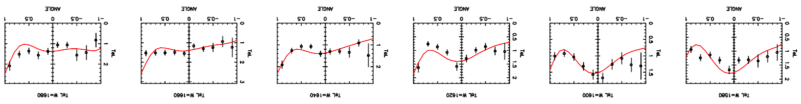


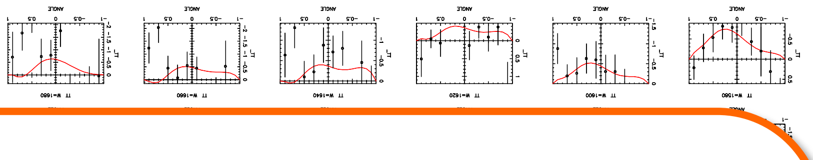


Analysis of single-pion electroproduction reactions

ep → e'π^0p @ Q^2 = 0.4 GeV^2, 1.10 < W < 1.68 GeV

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

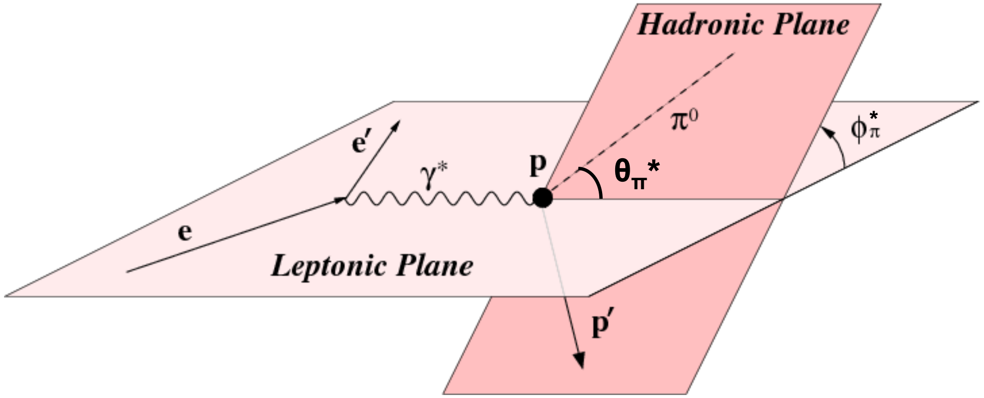


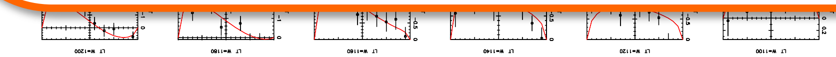


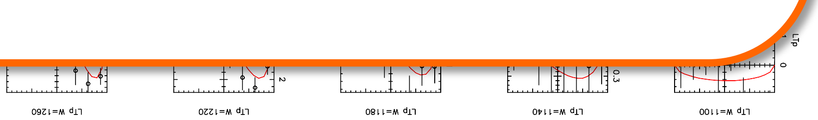
- ✓ **Fivefold differential cross section (one-photon exchange approximation)**

$$\frac{d\sigma^5}{dE_{e'}d\Omega_{e'}d\Omega_\pi^*} = \Gamma_\gamma\left[\sigma_T + \epsilon\sigma_L + \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}\cos\phi_\pi^* + \epsilon\sigma_{TT}\cos 2\phi_\pi^* + h_e\sqrt{2\epsilon(1-\epsilon)}\sigma_{LT'}\sin\phi_\pi^*\right].$$

Strucutre functions: $\sigma_\alpha = \sigma_\alpha(W, Q^2, \cos\theta_\pi^*) \quad (\alpha = T, L, LT, TT, LT')$





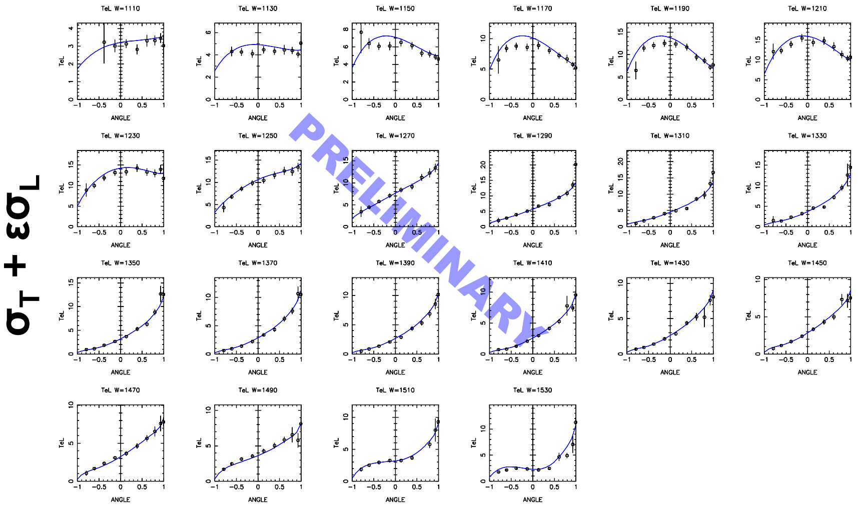


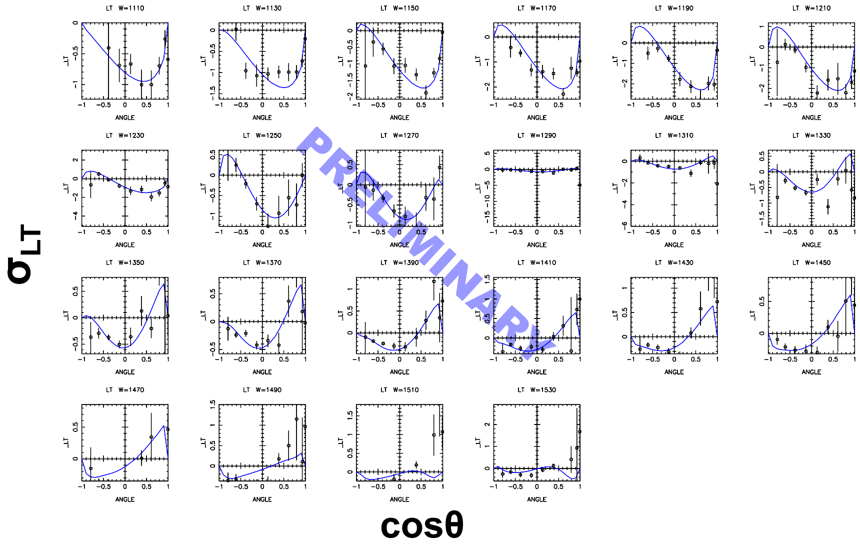
cosθ **cosθ**

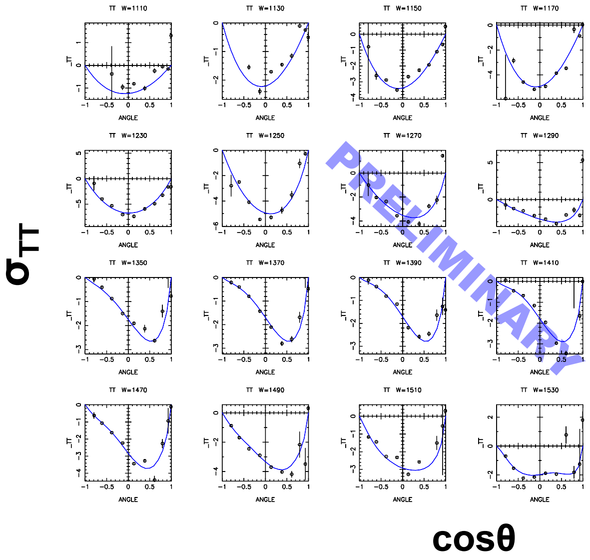
Analysis of single-pion electroproduction reactions

ep → e'π^+n @ Q^2 = 0.4 GeV^2, 1.11 < W < 1.53 GeV

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



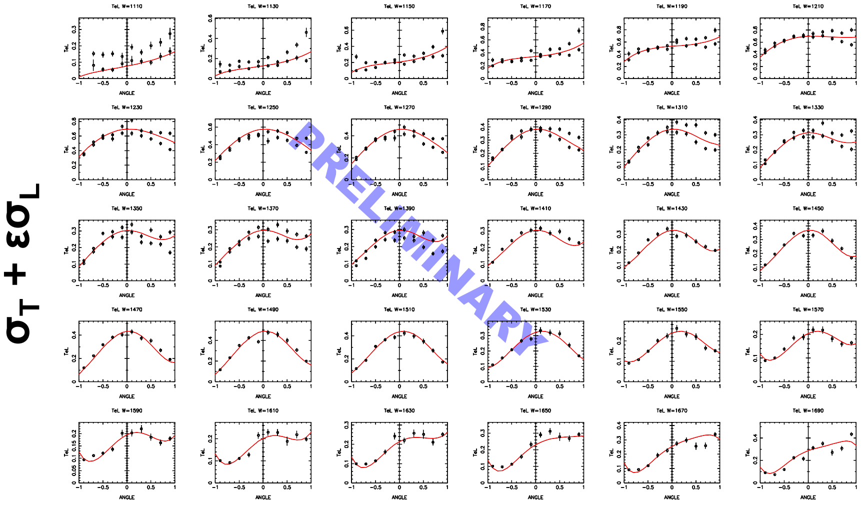


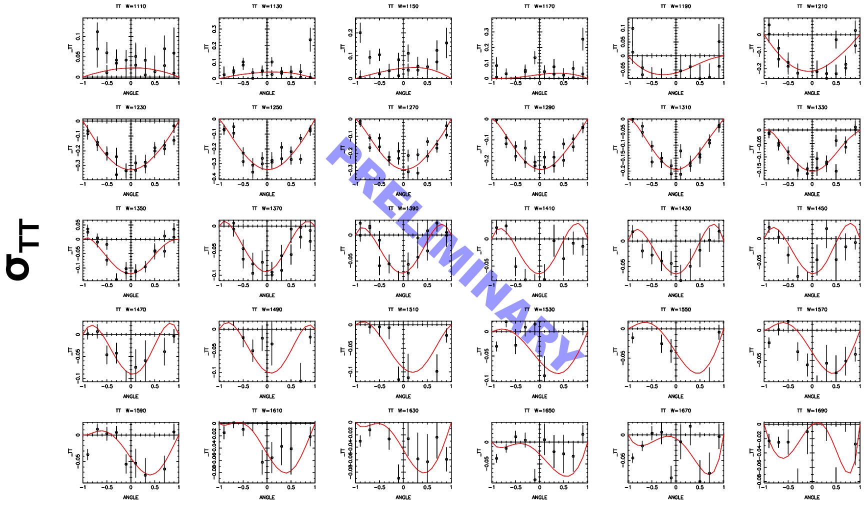


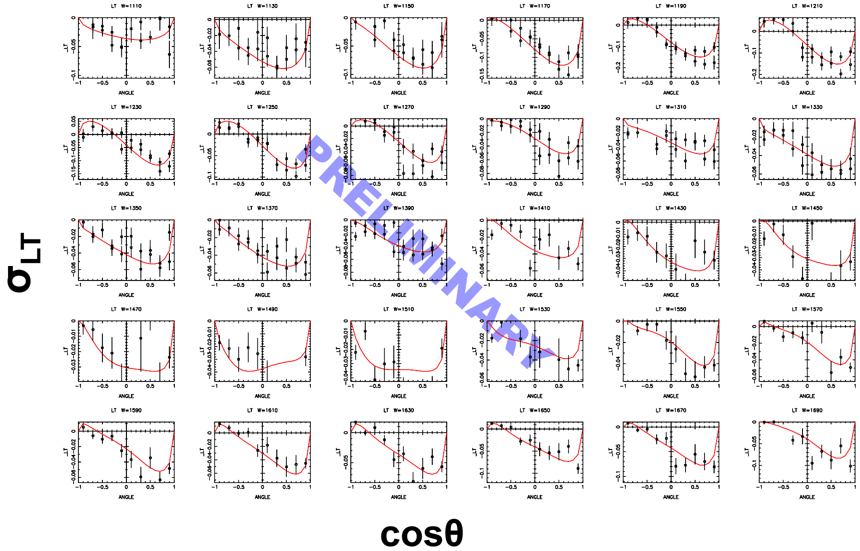
Analysis of single-pion electroproduction reactions

ep → e'π^0p @ Q^2 = 3 GeV^2, 1.10 < W < 1.69 GeV

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



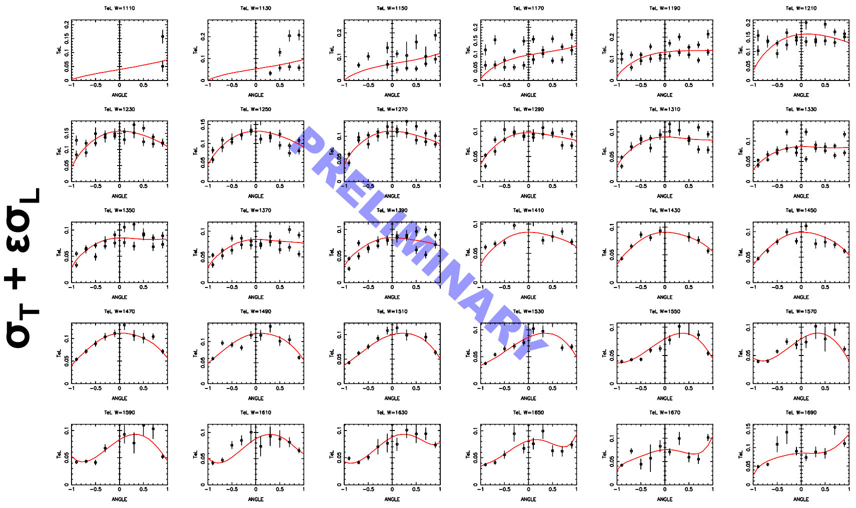


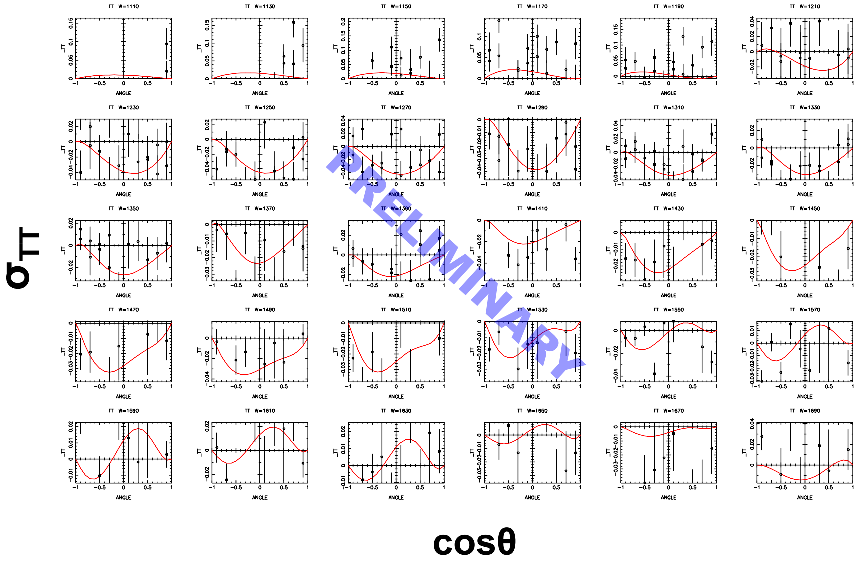


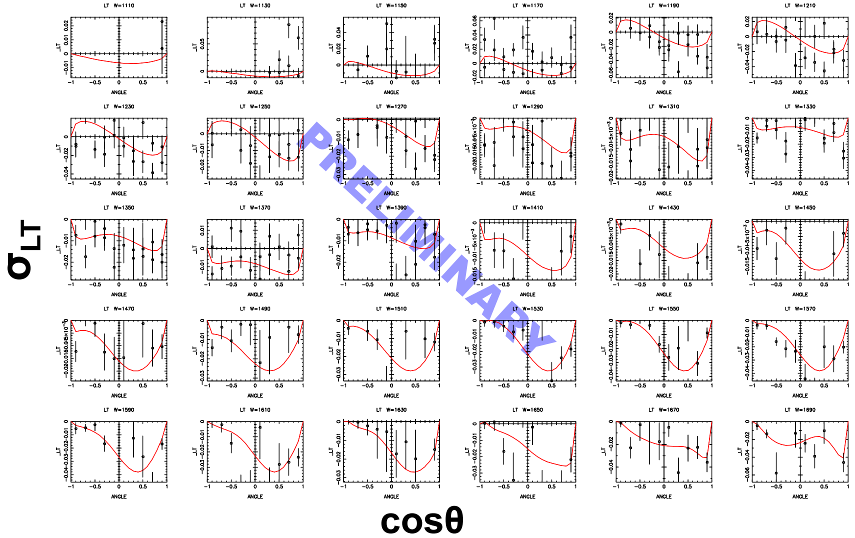
Analysis of single-pion electroproduction reactions

$ep \rightarrow e'\pi^0 p$ @ $Q^2 = 5$ GeV^2, $1.11 < W < 1.69$ GeV

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







Resonance parameters defined by poles of scattering amplitudes

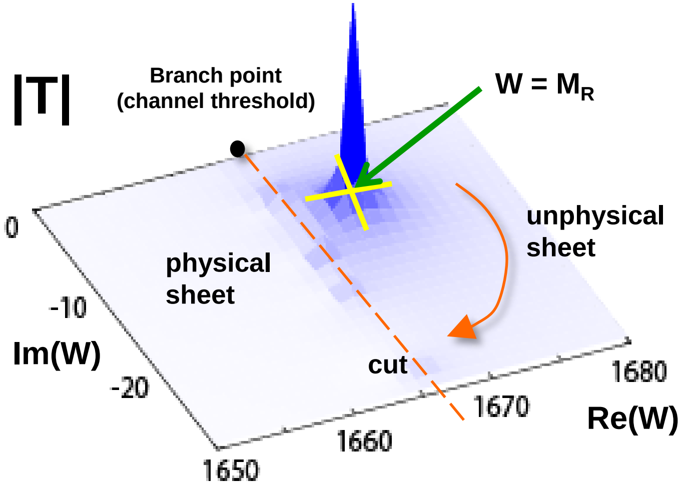
PROPER definition of

- ✓ **Hadron resonance masses (complex)** ➔ **Pole positions of scattering amplitudes in the lower-half of complex-W plane**
- ✓ **Transition amplitudes between resonance and multi-particle states** ➔ **~ Residues$^{1/2}$ at the pole**

Residue at the pole
~ $\langle MB|V|R\rangle \times \underline{\langle R|V|\gamma^* N\rangle}$

E.M. transition form factor

➢ **γ* N → MB reaction T-matrix element**



$$\langle MB|\hat{T}(E)|\gamma^* N\rangle\Big|_{E\to M_R} \to \frac{R_{MB,\gamma^* N}}{E-M_R} + (\text{regular terms})$$

Resonance pole position
(Im(M_R) < 0)

Resonance parameters defined by poles of scattering amplitudes

PROPER definition of

- ✓ **Hadron resonance masses (complex)** → **Pole positions of scattering amplitudes in the lower-half of complex-W plane**
- ✓ **Transition amplitudes between resonance and multi-particle states** → **~ Residues$^{1/2}$ at the pole**

Residue at the pole
~ $\langle MB|V|R\rangle \times \langle R|V|\gamma^* N\rangle$

Resonance theory based on Gamow vectors:
[G. Gamow (1928), R. E. Peierls (1959), …]

“Quantum resonance state is an (complex-)energy eigenstate of the *FULL* Hamiltonian of the *underlying theory* solved under the Purely Outgoing Boundary Condition (POBC).”

Energy eigenvalue = pole energy

Transition matrix elements between resonance and multi-particle states ~ Residues$^{1/2}$ at the pole

Resonance parameters defined by poles of sca

PROPER definition of

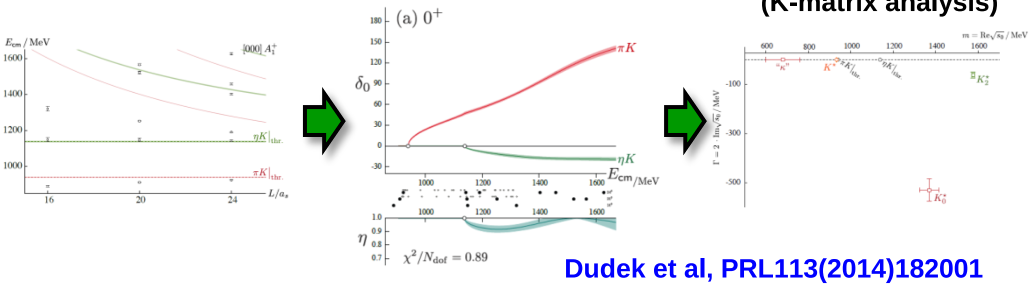
- ✓ Hadron resonance masses (co
- ✓ Transition amplitudes between resonance and multi-particle s

There are attempts to link real energy spectrum of QCD in the finite volume to resonance pole masses.

QCD spectrum in finite volume

Phase shifts & inelasticity (Luescher's formula)

Extracted resonance poles (K-matrix analysis)



Dudek et al, PRL113(2014)182001

(see also an approach based on the HAL QCD method: Inoue et al., NPA881(2012)881; Ikeda et al., arXiv:1602.03465)

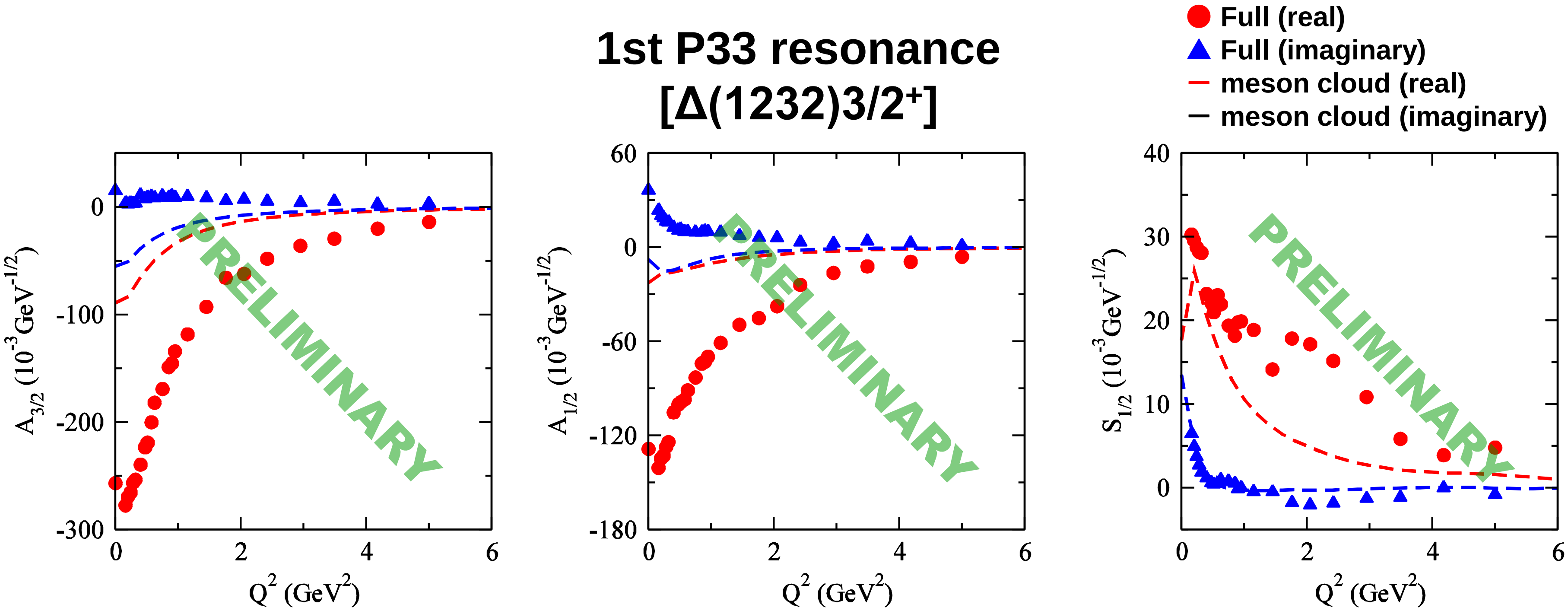
Resonance theory based on Gamow vectors:
[G. Gamow (1928), R. E. Peierls (1959), …]

"Quantum resonance state is an (complex-)energy eigenstate of the *FULL* Hamiltonian of the *underlying theory* solved under the Purely Outgoing Boundary Condition (POBC)."

Energy eigenvalue = pole energy

Transition matrix elements between resonance and multi-particle states ~ Residues$^{1/2}$ at the pole

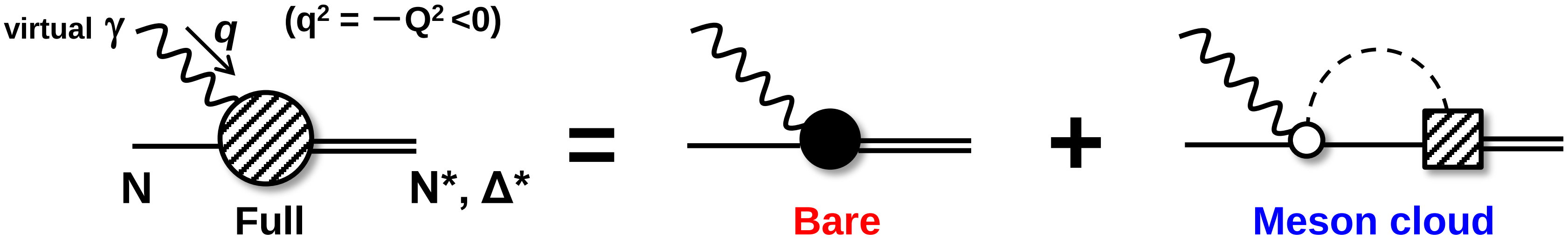
E.M. transition form factors evaluated at the resonance poles



1st P33 resonance
[Δ(1232)3/2$^+$]

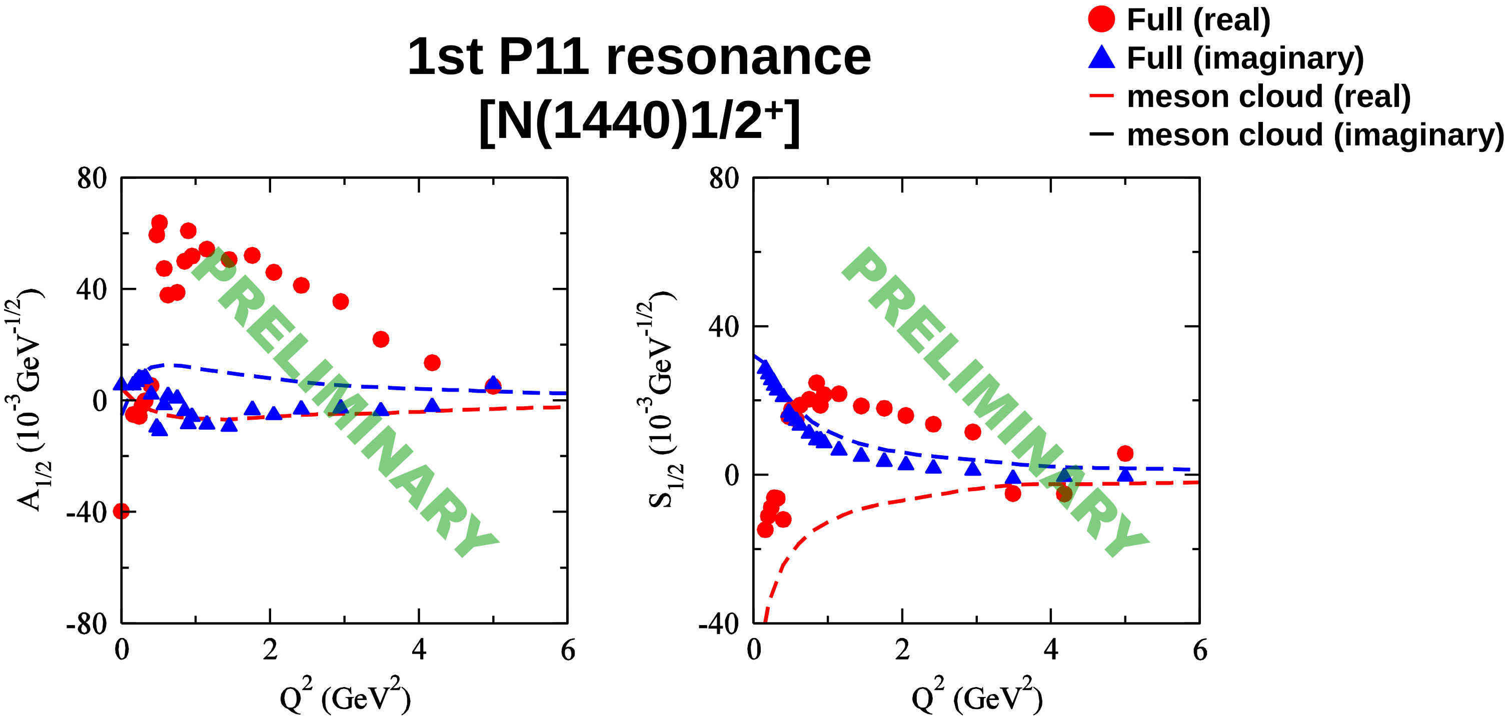
✓ Evaluated at resonance pole position.

➔ Form factors inevitably become complex (fundamental nature of decaying particles).

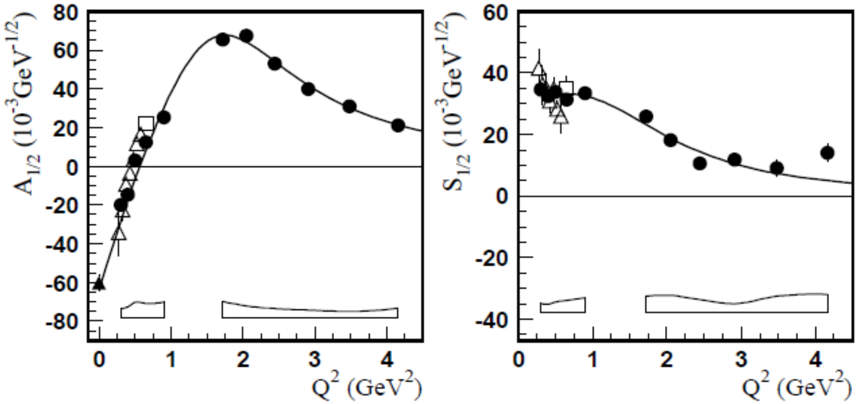


E.M. transition form factors evaluated at the resonance poles

1st P11 resonance [N(1440)1/2$^+$]

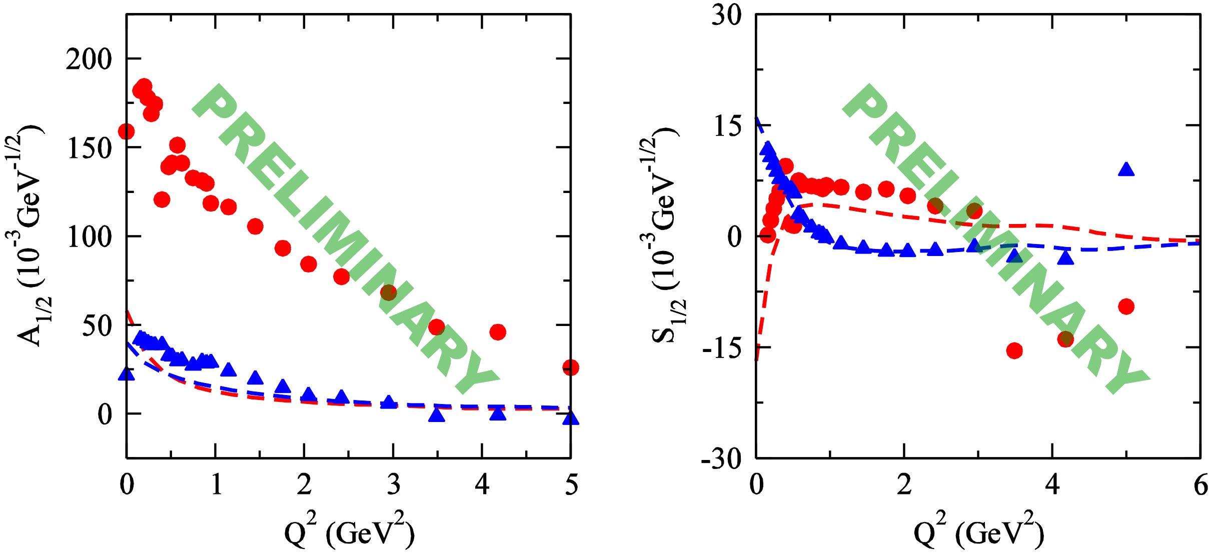


PDG (Breit-Wigner)

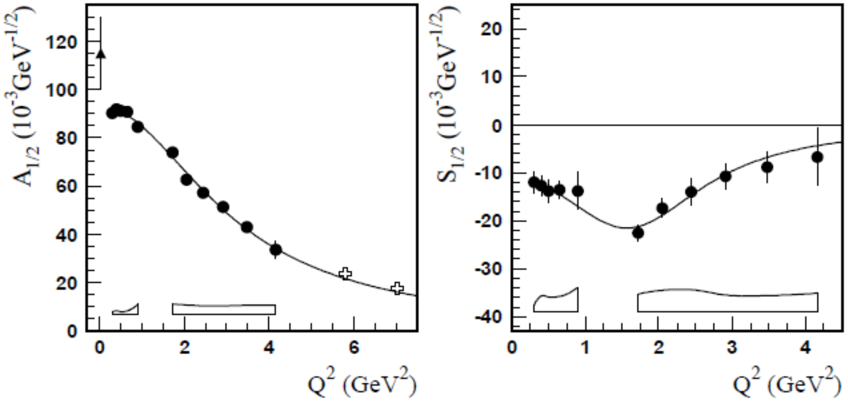


E.M. transition form factors evaluated at the resonance poles

1st S11 resonance
[N(1535)1/2$^-$]



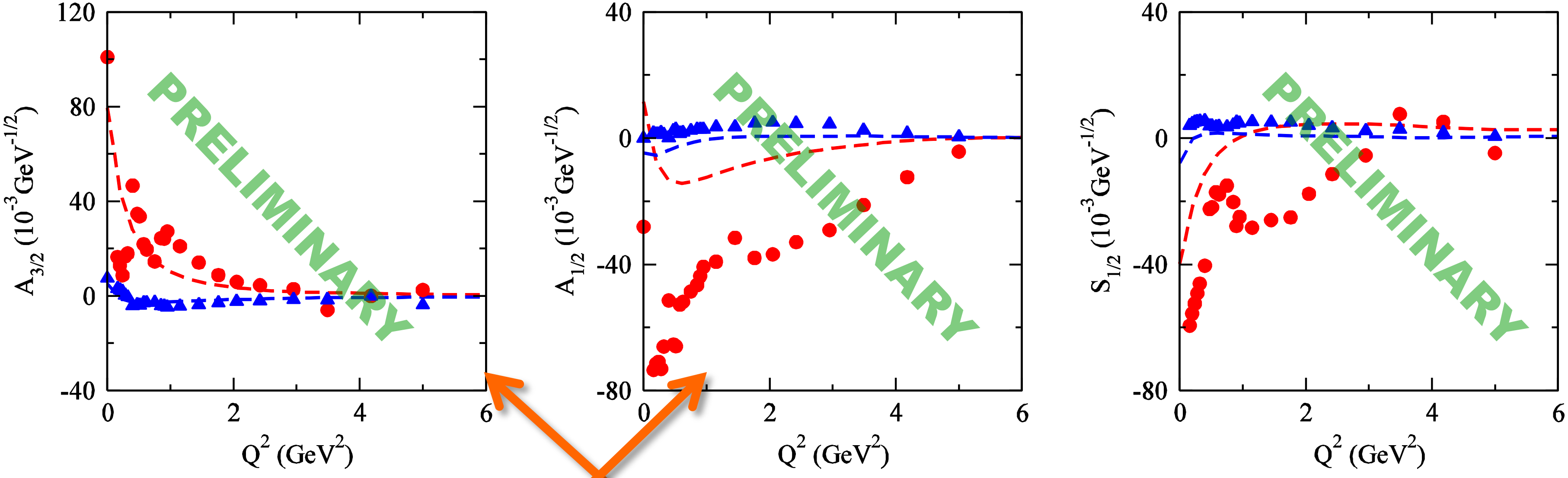
PDG
(Breit-Wigner)



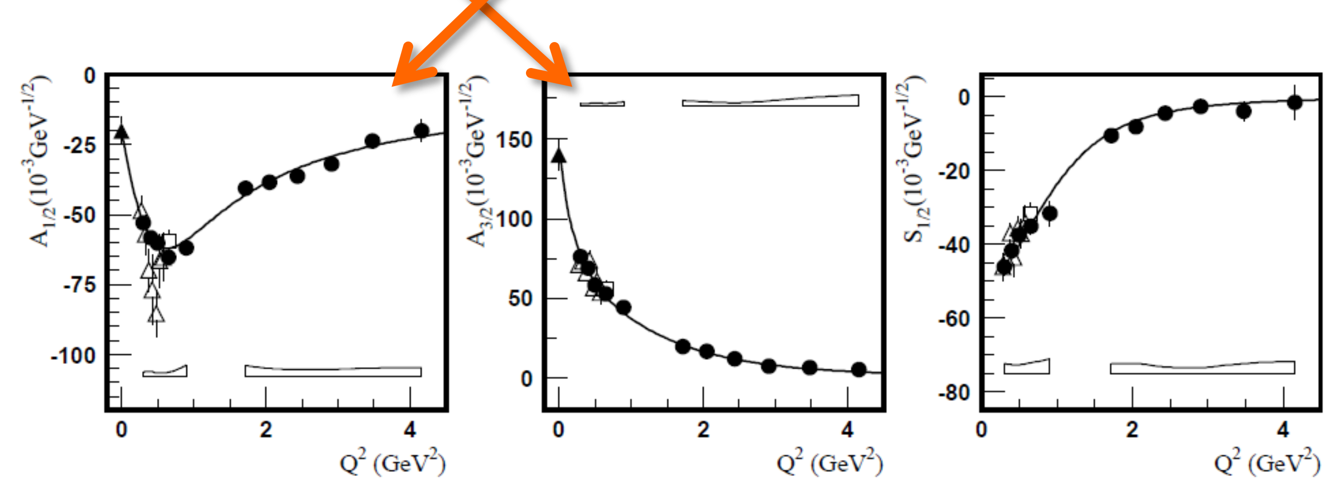
E.M. transition form factors evaluated at the resonance poles

1st D13 resonance
[N(1520)3/2$^-$]

- ● Full (real)
- ▲ Full (imaginary)
- — meson cloud (real)
- — meson cloud (imaginary)



PDG
(Breit-
Wigner)



Summary

Summary

- ✓ N-N* e.m. transition form factors:
  - ➢ Crucial for revealing quark-gluon substructure of N* & Δ* resonances.
  - ➢ Important input to neutrino-induced meson production reactions.
- ✓ Presented current status for 1π electroproduction analysis based on ANL-Osaka DCC approach in the kinematic region of $Q^2 < 6$ GeV^2 & $W < 1.7$ GeV.
- ✓ Presented preliminary results of e.m. transition form factors for Δ(1232)3/2$^+$, N(1440)1/2$^+$, N(1535)1/2$^-$, and N(1520)3/2$^-$.
  - ➢ Form factors defined by poles become complex.
  - ➢ Real parts show similar behavior to BW results when imaginary parts are small.

Future work

- ✓ Extends analysis by including $ep \rightarrow e'KY$ data to determine e.m. transition form factors for higher mass resonances.
- ✓ Prepare for the future high-Q^2 CLAS12 data and ed reaction data.

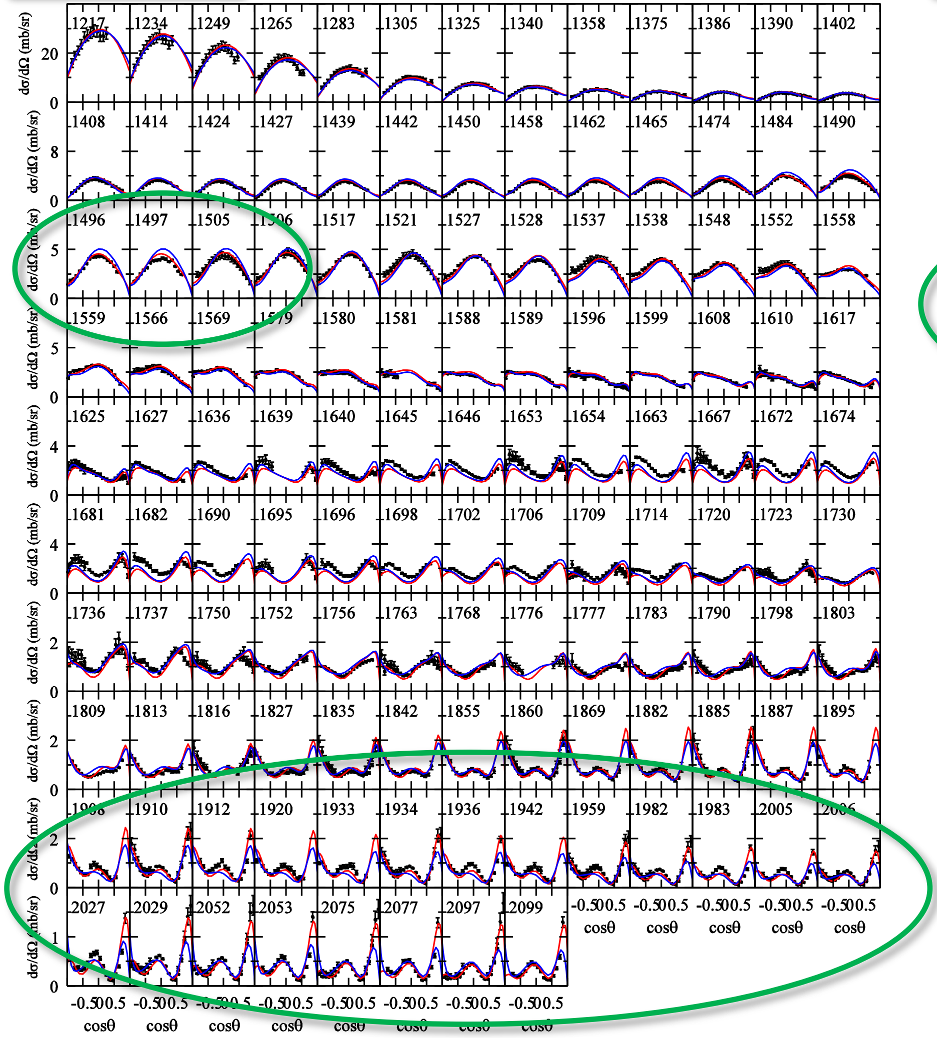
Back up

ANL-Osaka DCC approach to N* and Δ*

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

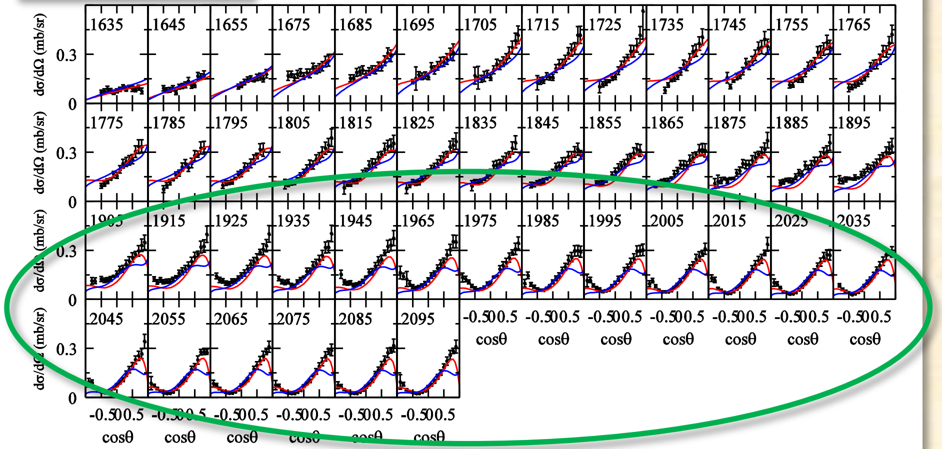
γp → π^{0}p

dσ/dΩ for W < 2.1 GeV



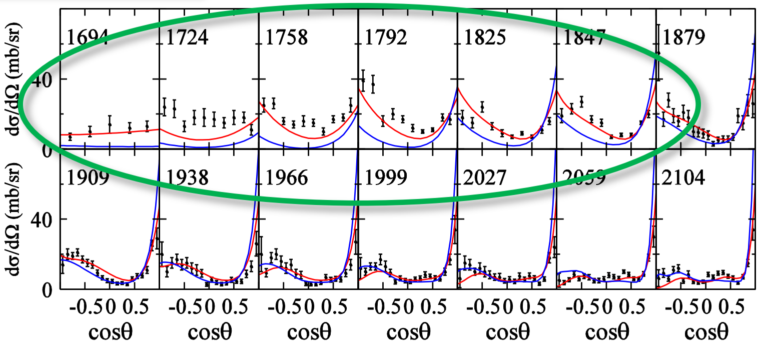
γp → K$^+$Λ

dσ/dΩ for W < 2.1 GeV



π$^-$p → K^{0}Σ^0

dσ/dΩ for W < 2.1 GeV



Red: minor updated ver.

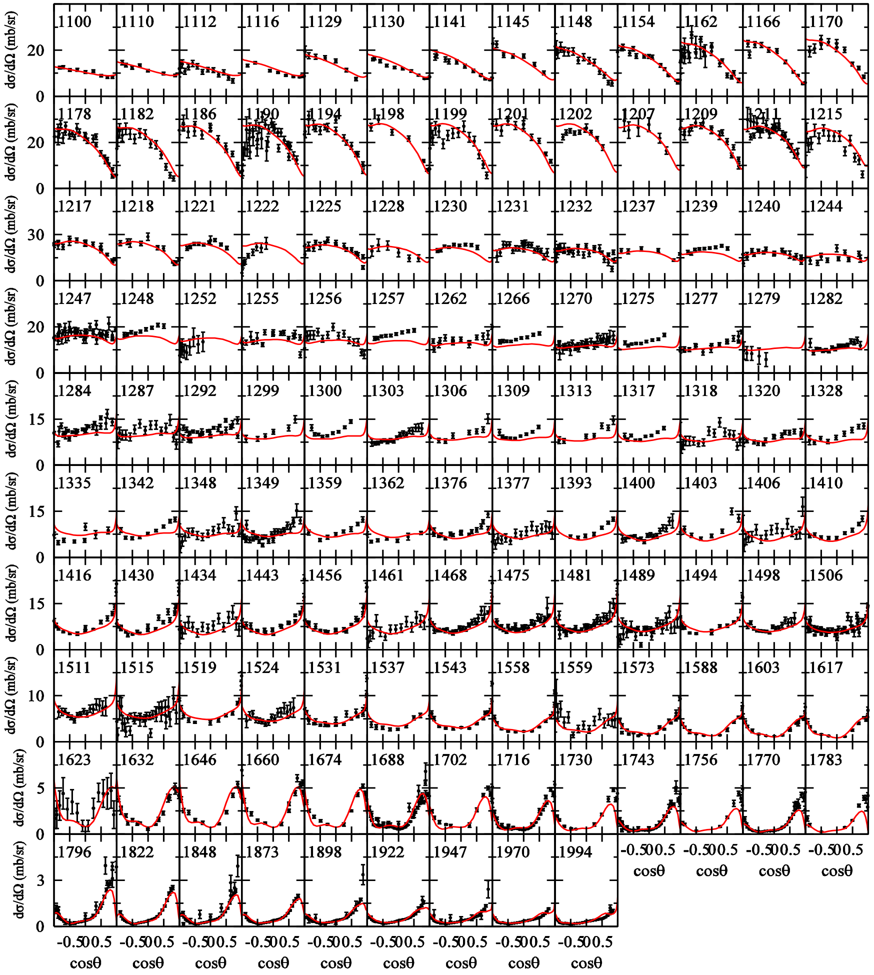
Blue: PRC88(2013)035209

Meson photoproductions off “neutron”

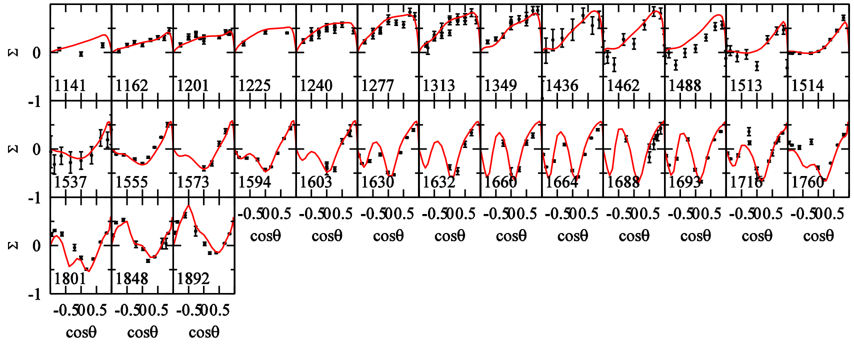
- ✓ Need for **isospin decomposition** of electromagnetic currents.
  - ➔ Necessary for applications to ***NEUTRINO*** reactions

γ ‘n’ → π^- p

dσ/dΩ for W < 2 GeV



Σ for 1.14 < W < 1.9 GeV



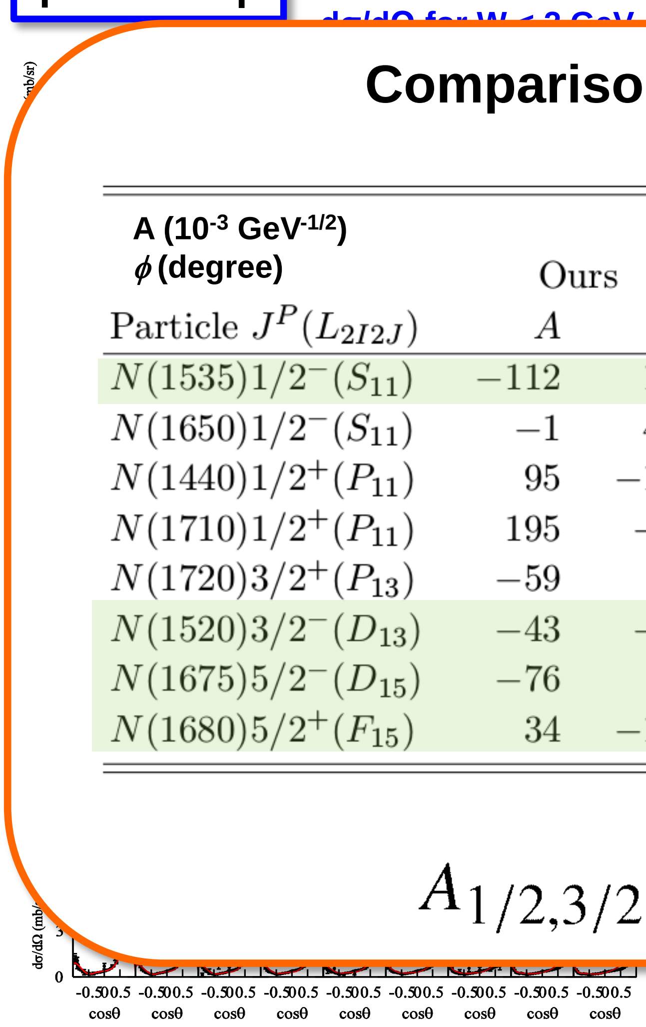
HK, Nakamura, Lee, Sato, PRC94(2016)015201

Meson photoproductions off “neutron”

✓ Need for isospin decomposition of electromagnetic currents.

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

γ ‘n’ → π^- p



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

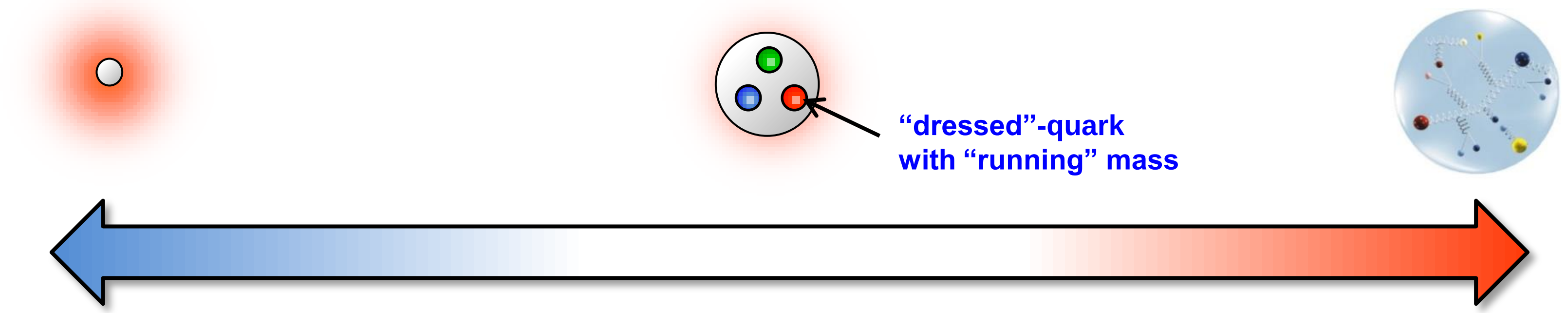
BoGa: EPJA49(2013)67

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

HK, Nakamura, Lee, Sato, PRC94(2016)015201

E.M. transition form factors:

Exploring quark-gluon substructure of N* & Δ*



"dressed"-quark core
obscured by dense meson clouds

Meson clouds become small;
"dressed"-quark core dominates

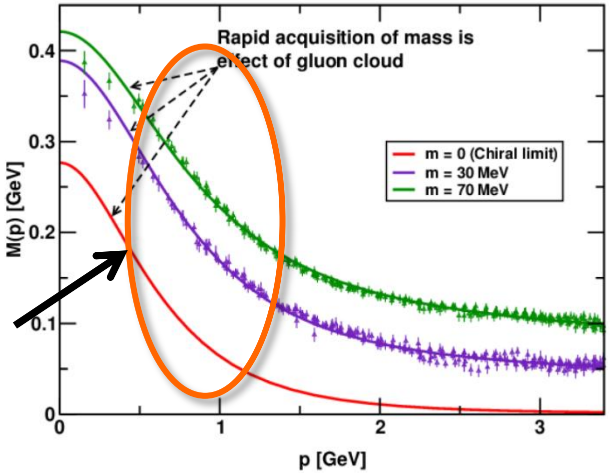
"Partons"

"dressed"-quark
with "running" mass

Q^2: small
(low "resolution")

Q^2: large
(high "resolution")

"constituent" quark ↔ "current" quark



Will be accessed by
CLAS12@JLab
(E12-09-003, E12-06-108A)

Curves: a model based on
Dyson-Schwinger
equations (Landau gauge)

Points: Lattice QCD

e.g.) Cloet, Roberts,
Prog.Part.Nucl.Phys.77(2014)1