Isospin decomposition of the $\gamma^{(*)}N \rightarrow N^*$ transitions as input for constructing models of neutrino-induced reactions in the nucleon resonance region

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(KEK Theory Center)

Collaborators:
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S. X. Nakamura (Osaka U.)
T. Sato (Osaka U.)

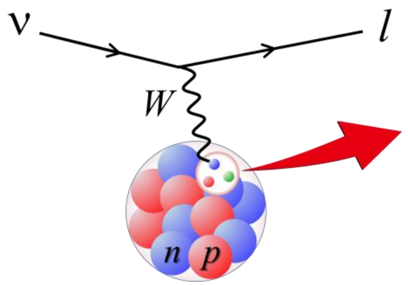
NuFact2016, ICISE, Quy Nhon, Vietnam, Aug. 21-27, 2016

Outline

- ✓ **Background and motivation for studying neutrino-induced reactions**
  - ➢ **Research project at J-PARC Branch of KEK Theory Center [http://nuint.kek.jp/index_e.html]**

- ✓ **Determining $\gamma^{(*)}$ N ➔ N* transition form factors via Dynamical Coupled-Channels (DCC) analysis of e-, γ-, and π-induced meson production reactions in the nucleon resonance region**

Introduction



Why are neutrino-nucleus reactions important ?

[see e.g., recent review by Alvarez-Ruso, Hayato, and Nieves, New J. Phys. 16(2014)075015]

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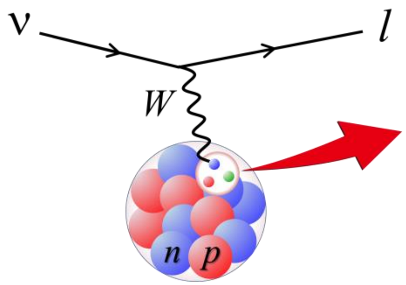

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✓ **Need of accurate knowledge of neutrino reaction cross sections for**

- **reliable extraction of neutrino parameters via oscillation experiments**
- **search for physics beyond the standard model**
- **understanding dynamics of core-collapse supernovae**

➔ **Interests relevant to particle physics and astrophysics**

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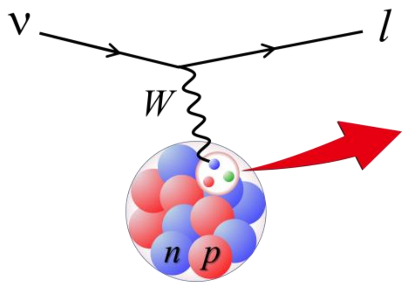

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- provides information totally independent from that obtained with electromagnetic probes

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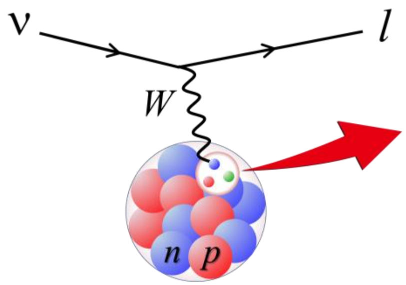

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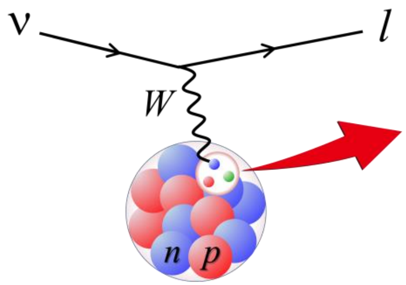

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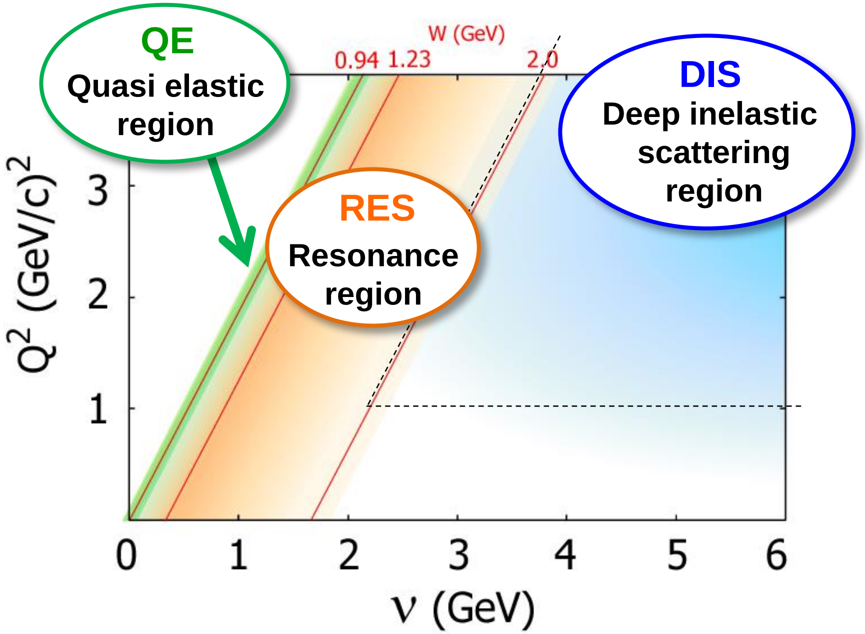
Kinematical regions of neutrino-nucleus reactions for accelerator and atmospheric experiments

Relevant kinematical region extends over QE, RES, and DIS !!

$E\nu = \mathcal{O}(10^{-1} - 10^{1})$ GeV

- ✓ Need a reaction model that **comprehensively** describes the **entire** kinematical region.
- ✓ However, each region is governed by rather **different physics mechanisms** !!



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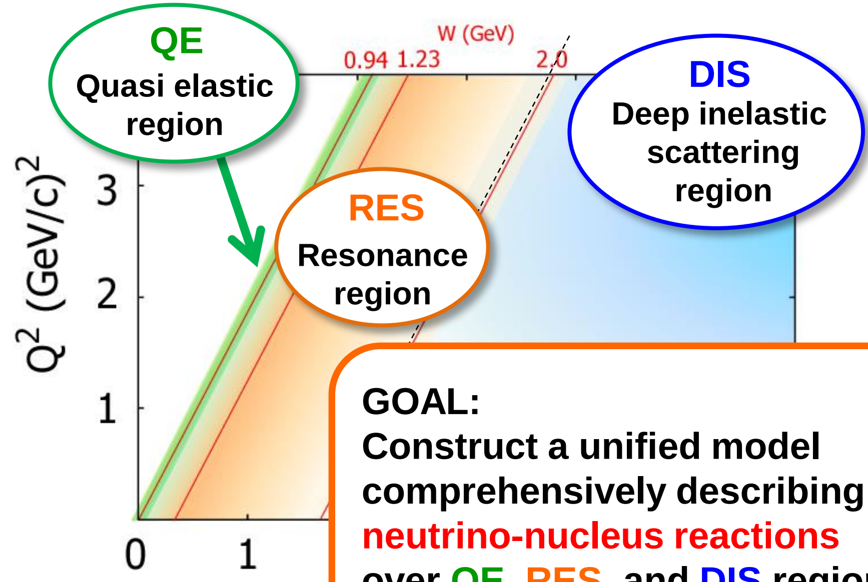


GOAL:
Construct a unified model comprehensively describing **neutrino-nucleus reactions** over QE, RES, and DIS regions !!

Combination of expertise from different fields is required !!

➔ **Collaboration@J-PARC Branch, KEK Theory Center**

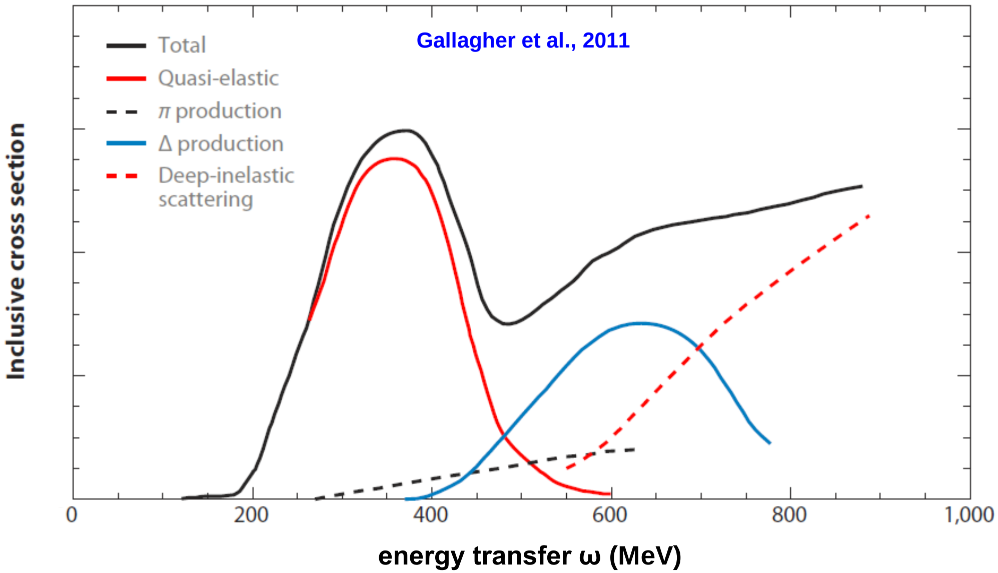
Participants:

[QE, RES] H. Kamano, S. Nakamura, T. Sato
[DIS] M. Hirai, S. Kumano, K. Saito
[EXP] Y. Hayato, M. Sakuda

http://nuint.kek.jp/index_e.html
arXiv:1303.6032

A review article will be published in Reports on Progress in Physics.

Current understanding of neutrino-nucleus reaction cross sections



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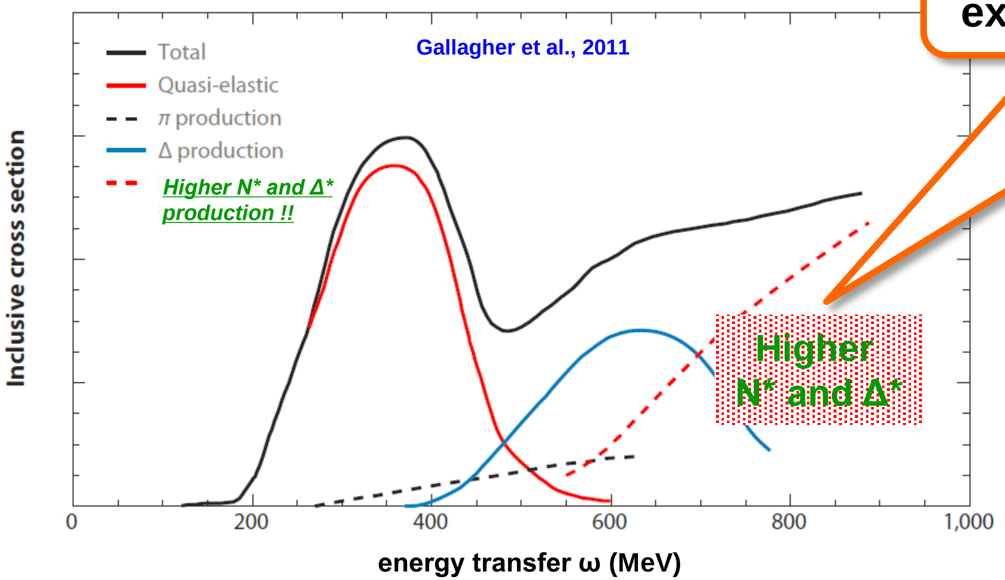
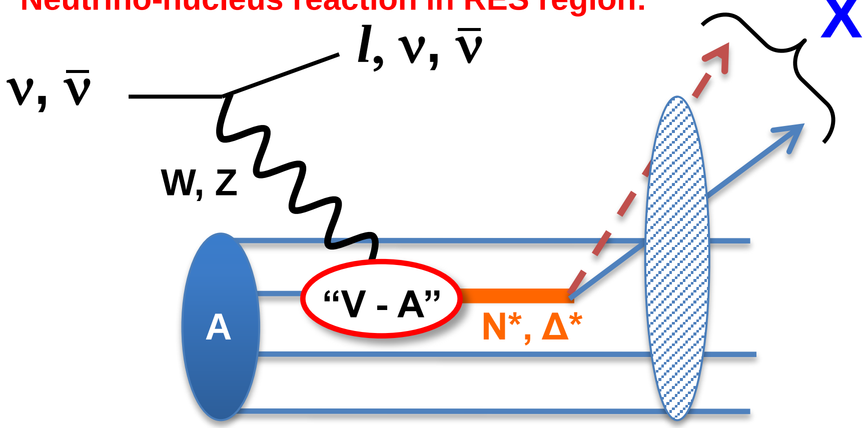


In reality, ~ 50 N* and Δ* baryons exist up to ω ~ 2 - 3 GeV !!

✓ Higher N* and Δ* productions result in various (multi-)meson productions:

X = πN, ππN, ηN, KΛ, KΣ, ωN, …

Neutrino-nucleus reaction in RES region:



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GOAL for RES region:

Develop a microscopic model accurately describing *exclusive* (multi-)meson-production neutrino-nucleus reactions.

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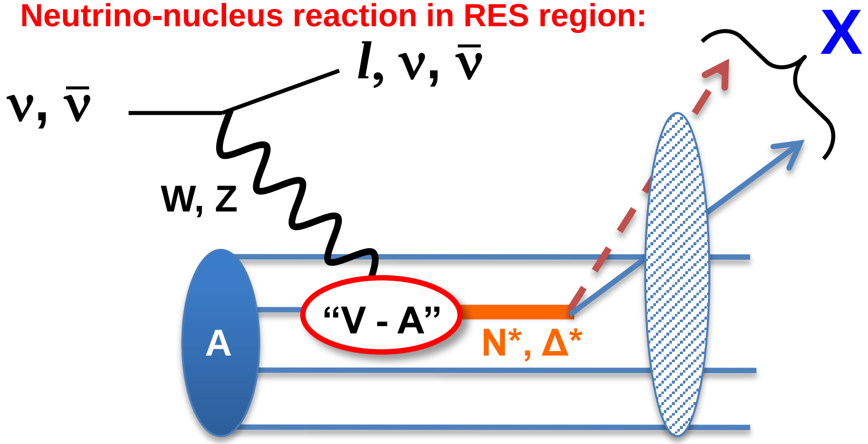

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Develop a microscopic model accurately describing *exclusive* (multi-)meson-production neutrino-nucleus reactions.

Before going to nuclear target reactions, one has to develop a reliable model *at the nucleon level* !!

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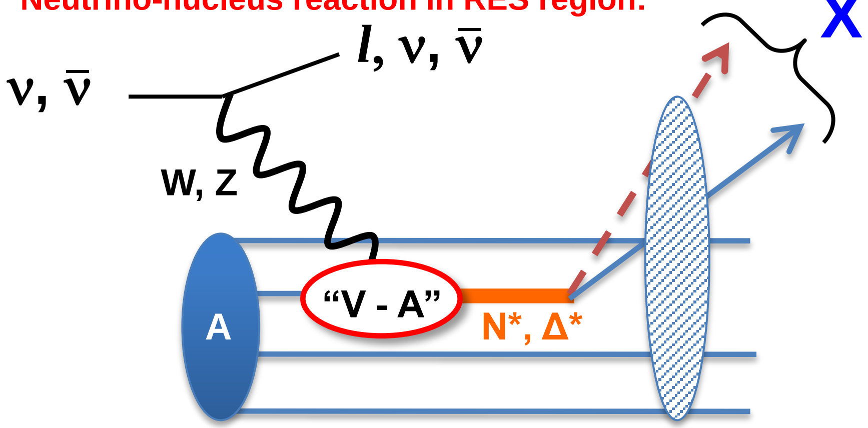
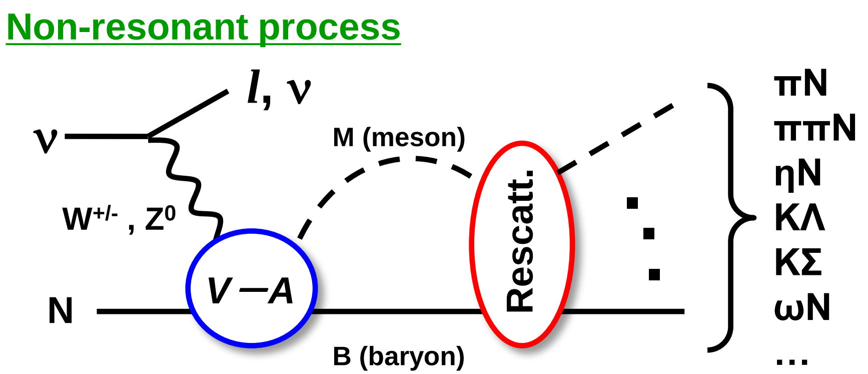
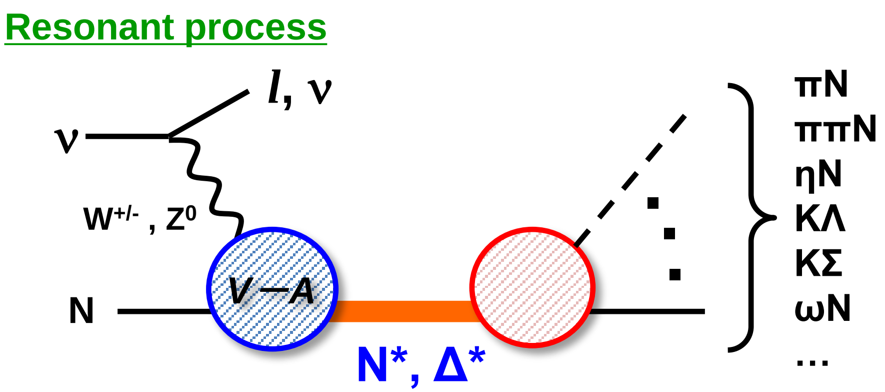


"Ingredients" of neutrino-nucleon reaction in the nucleon resonance region





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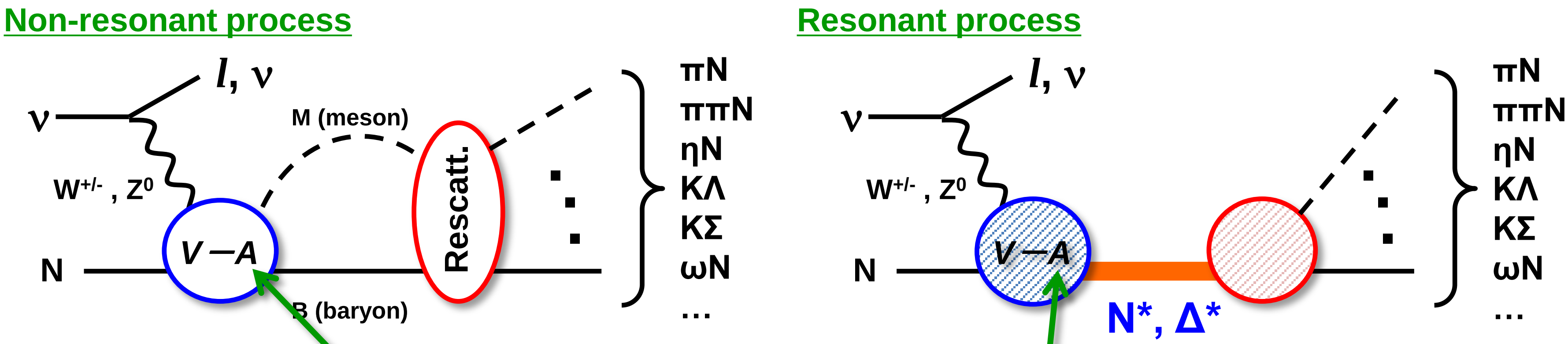

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πN reaction model + PCAC hypothesis
For general Q^2:
Has to be determined by analyzing neutrino reactions

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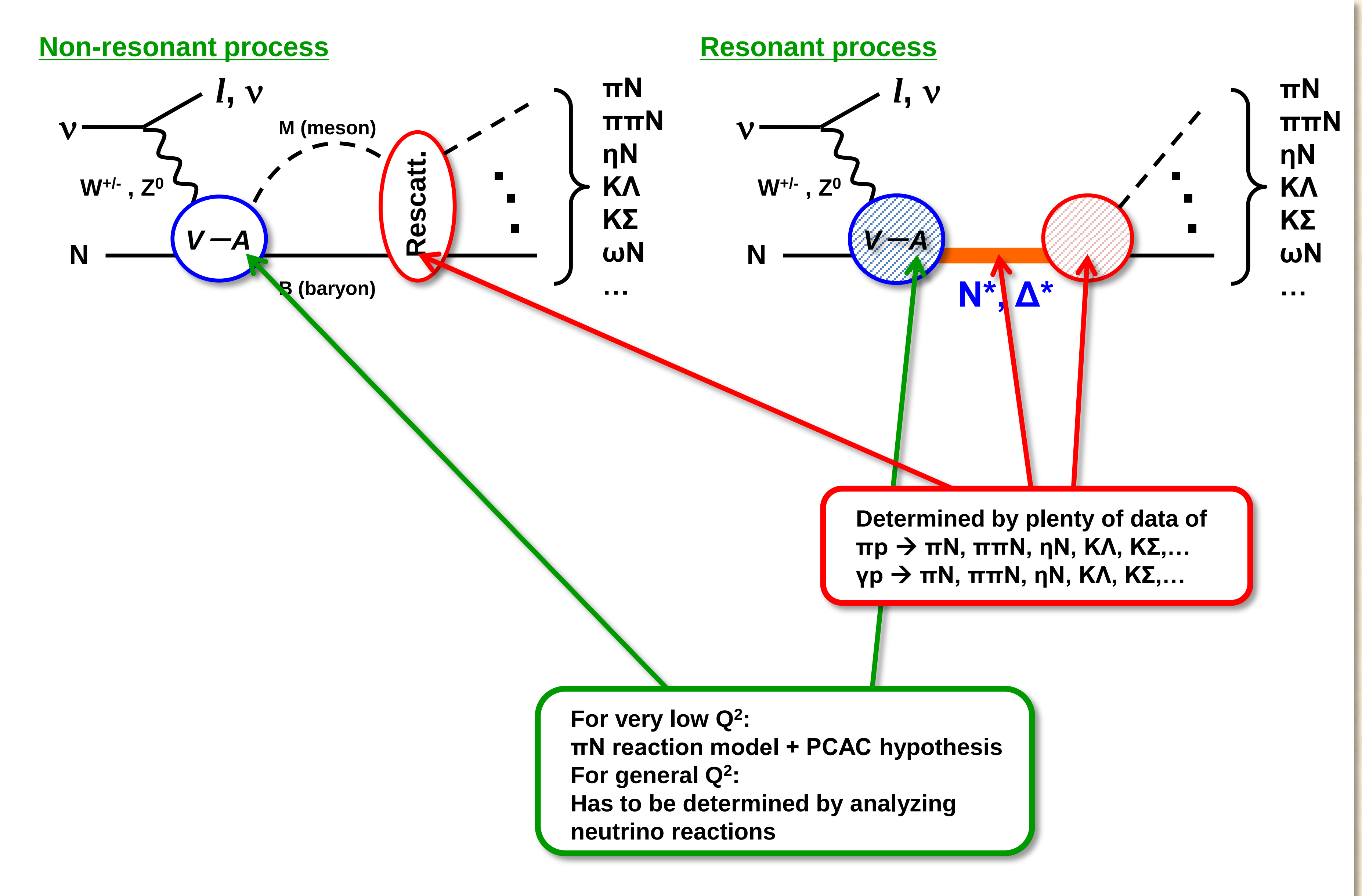

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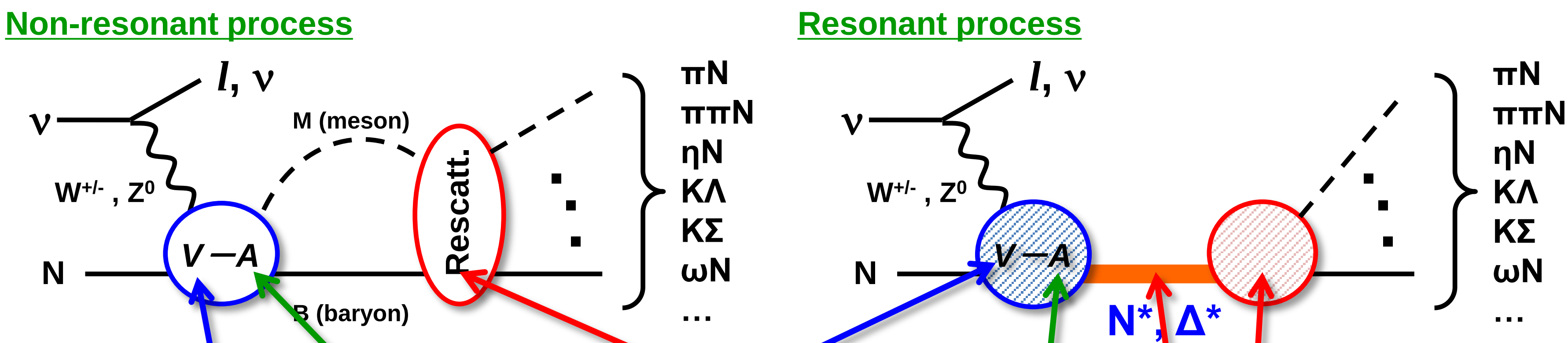

Determined with the data of
($Q^2=0$) γN → πN, ππN, ηN, KΛ, KΣ,…
($Q^2>0$) eN → e’πN, e’ππN, e’ηN, e’KΛ, e’KΣ,…

Both proton & “neutron” target data are necessary
to obtain vector-current matrix elements
from those of electromagnetic current !!

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

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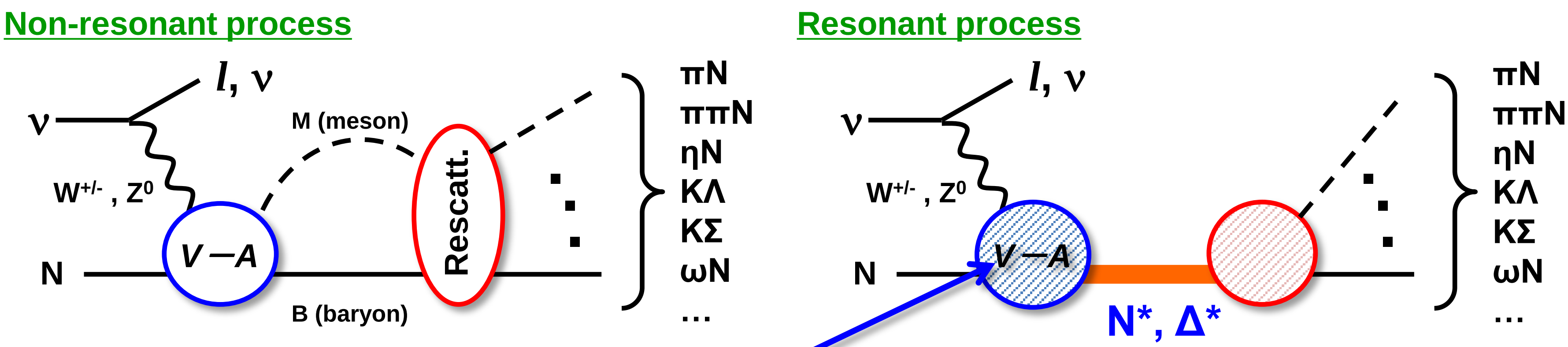

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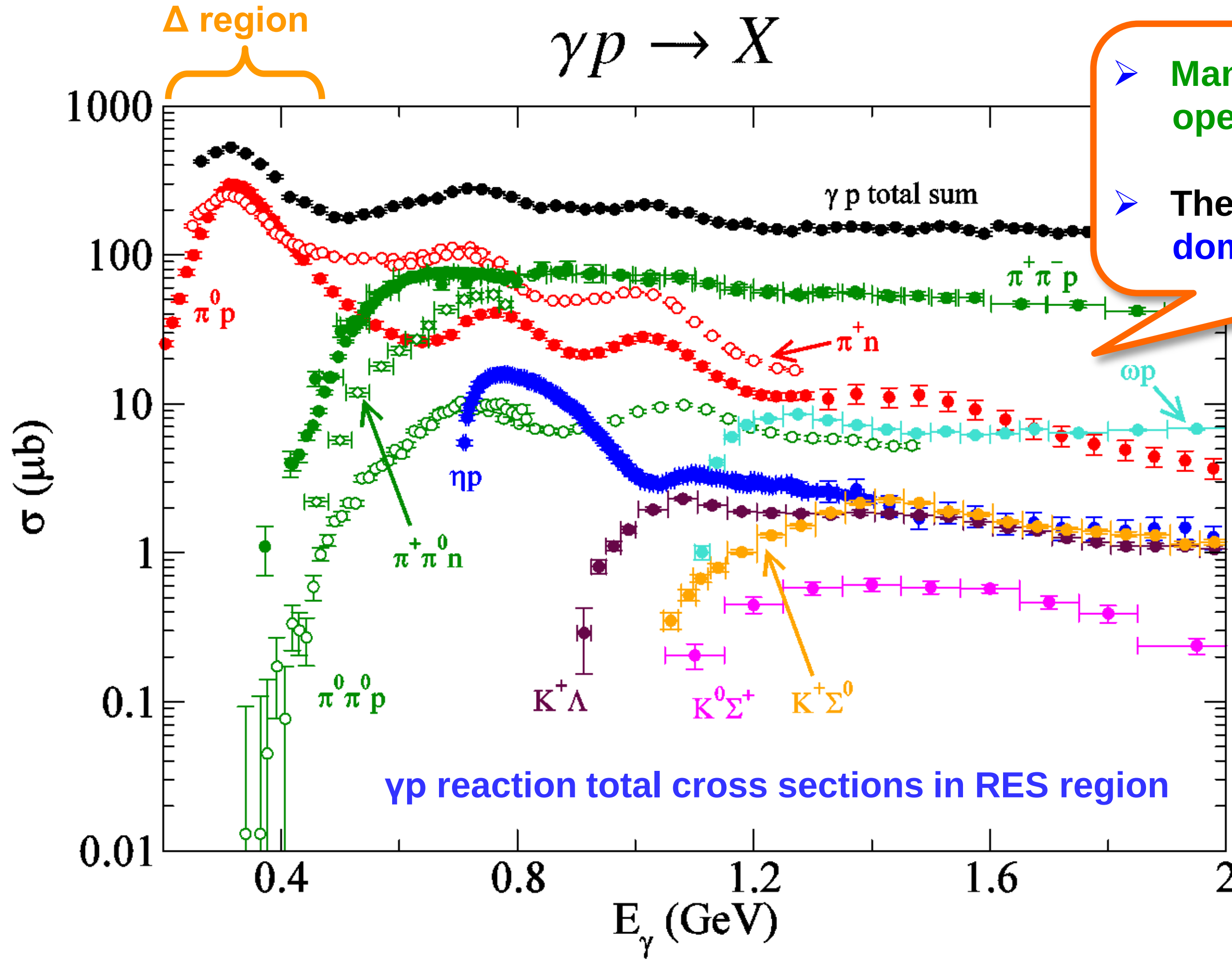
Inelastic channels in resonance region



- **Many inelastic channels open** above the Δ region.
- The **ππN channel become dominant** above Eγ = 0.8 GeV.

Need developing a reliable reaction model that satisfies multi-channel unitarity including 3-body ππN channel !!

ANL-Osaka DCC model for meson production reactions in N* and Δ* region

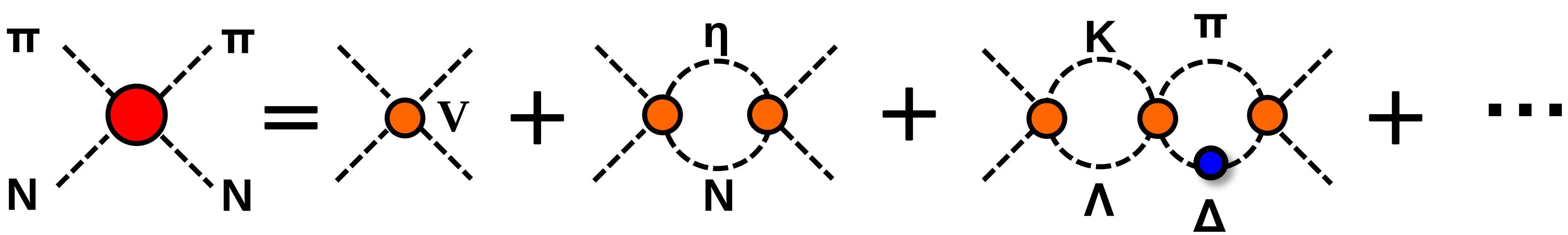
Dynamical Coupled-Channels model [Matsuyama, Sato, Lee, Phys. Rep. 439(2007)193]

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

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

✓ **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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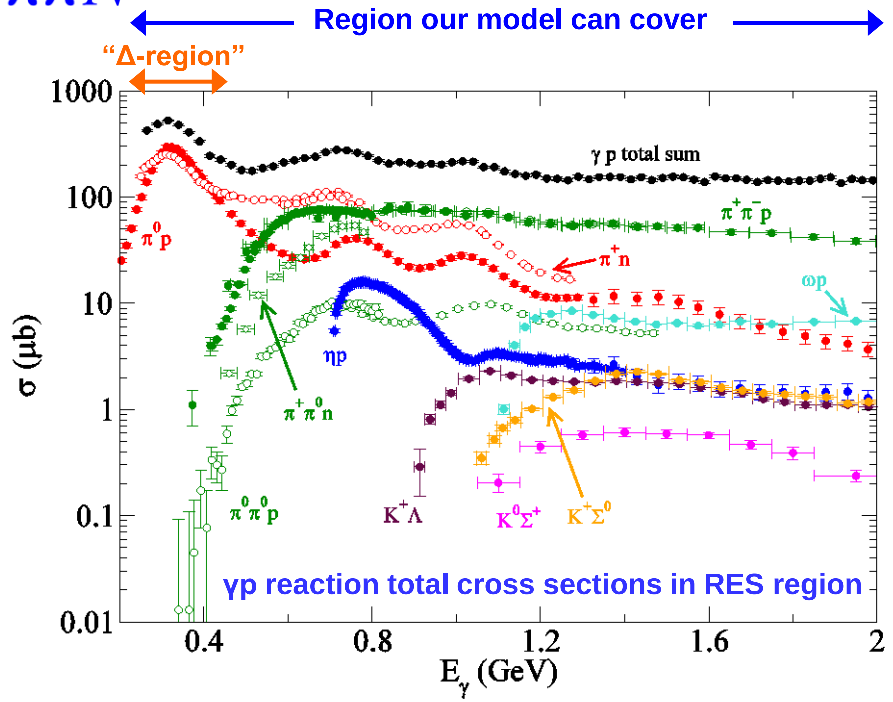
✓ **Latest published model (8 channels):**

HK, Nakamura, Lee, Sato, PRC88(2013)035209 [updated in PRC94(2016)015201]

- Constructed by simultaneous analysis of
  - πN scattering (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)
- Fit ~27,000 data points including dσ/dΩ & spin-polarization observables.

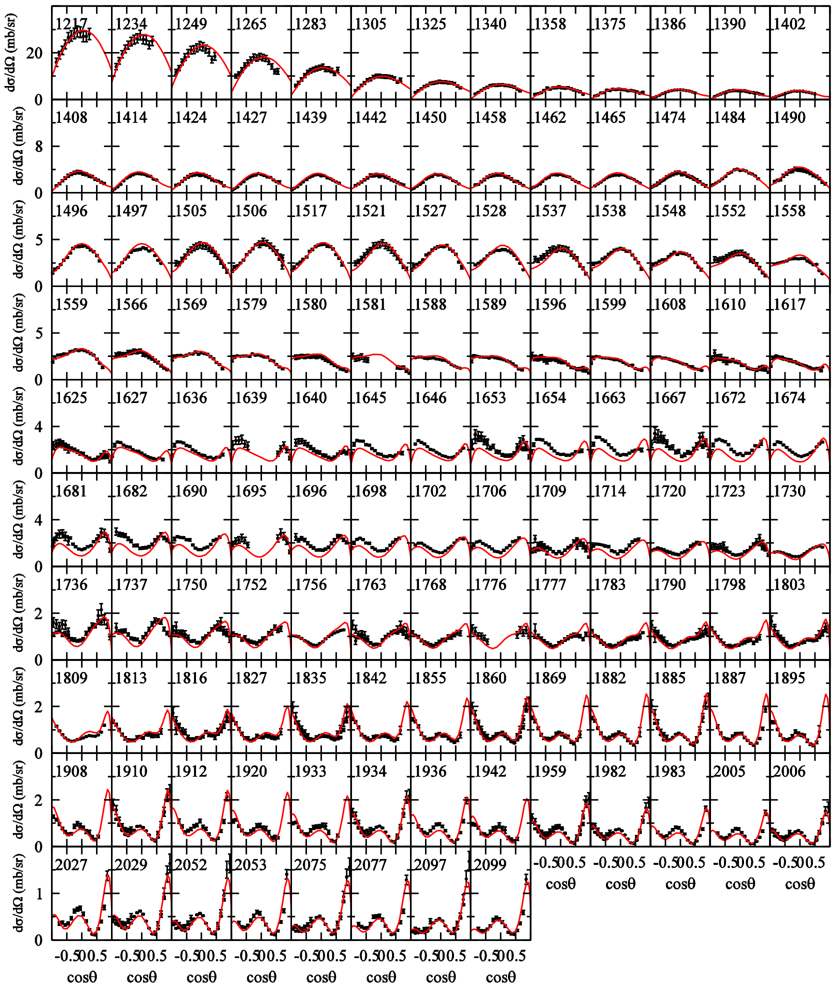


Results of the fits

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

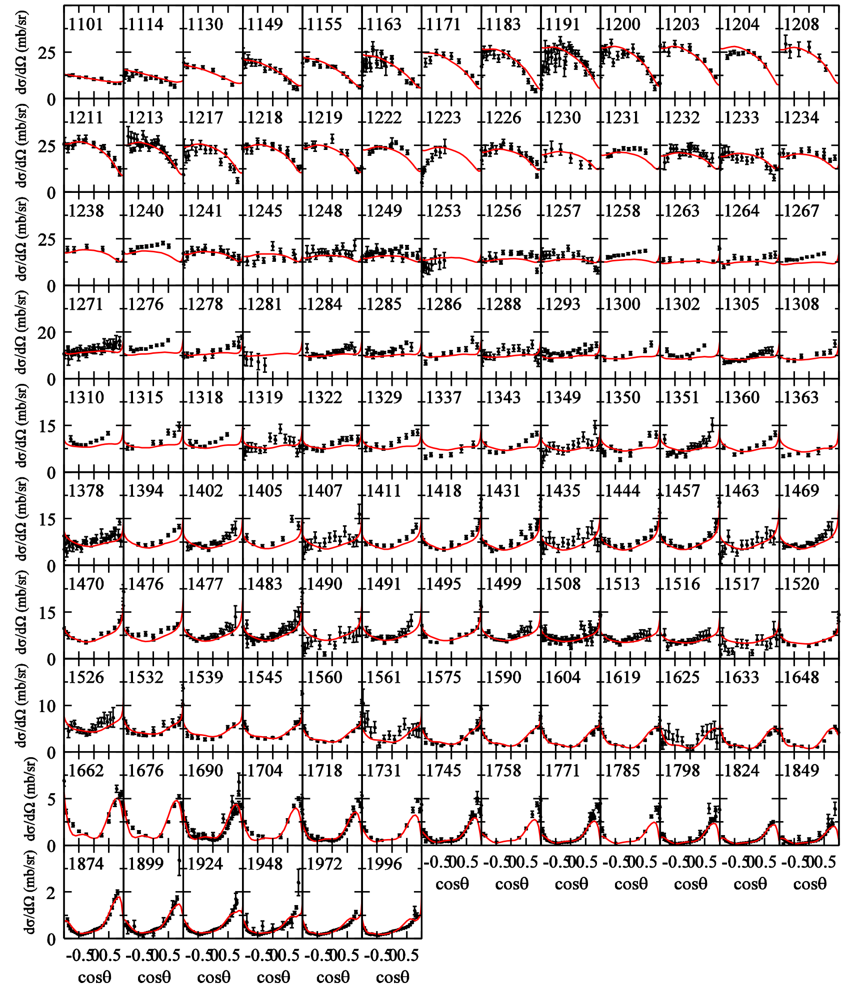
$\gamma p \rightarrow \pi^0 p$

$d\sigma/d\Omega$ for W < 2.1 GeV



γ 'n' $\rightarrow \pi^- p$

$d\sigma/d\Omega$ for W < 2 GeV



Extracting resonance parameters

Proper definitions of

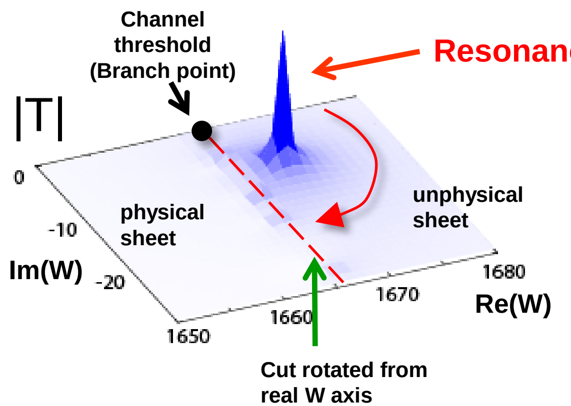
- ✓ **N* & Δ* mass and width** ➔ **Pole positions of the amplitudes**
- ✓ **g_{N^*MB}, g_{Δ^*MB}** ➔ **Residues[1/2] at the pole**
  $\gamma^{(*)}$ N → N*, Δ* form factors

Resonance coupling constants or $\gamma^{(*)}$ N → N*, Δ* form factors

$$\langle p_a|\hat{T}(E)|p_b\rangle\Big|_{E\to E_0} \rightarrow \frac{\bar{\Gamma}(E_0,p_a)\bar{\Gamma}(E_0,p_b)}{E-E_0} + (\text{regular terms})$$

N*, Δ* pole position (Im(E_0) < 0)

Analytic continuation to complex energy plane:



Suzuki, Sato, Lee PRC79(2009)025205; 82(2010)045206

Helicity amplitudes for $\gamma^{(*)}N \rightarrow N^*, \Delta^*$ transition at photon point (Q^2=0)

Comparison of $\gamma p \rightarrow N^*, \Delta^*$ helicity amplitudes ($A^p_{1/2,3/2}$)

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

A (10^{-3} GeV$^{-1/2}$)
ϕ (degree)

	$A^p_{1/2}$				$A^p_{3/2}$			
	Ours		BoGa		Ours		BoGa	
Particle $J^P(L_{2I2J})$	A	ϕ	A	ϕ	A	ϕ	A	ϕ
$N(1535)1/2^-(S_{11})$	161	8	116 ± 10	7 ± 6	-	-	-	-
$N(1650)1/2^-(S_{11})$	36	-28	33 ± 7	-9 ± 15	-	-	-	-
$N(1440)1/2^+(P_{11})$	-40	-9	-44 ± 7	-38 ± 5	-	-	-	-
$N(1710)1/2^+(P_{11})$	-47	-24	55 ± 18	-10 ± 65	-	-	-	-
$N(1720)3/2^+(P_{13})$	131	7	110 ± 45	0 ± 40	-34	12	-150 ± 35	65 ± 35
$N(1520)3/2^-(D_{13})$	-28	0	-21 ± 4	0 ± 5	101	4	132 ± 9	2 ± 4
$N(1675)5/2^-(D_{15})$	9	21	24 ± 3	-16 ± 5	49	-12	26 ± 8	-19 ± 6
$N(1680)5/2^+(F_{15})$	-44	-11	-13 ± 4	-25 ± 22	60	-2	134 ± 5	-2 ± 4
$\Delta(1620)1/2^-(S_{31})$	105	1	52 ± 5	-9 ± 9	-	-	-	-
$\Delta(1910)1/2^+(P_{31})$	-1	-90	23 ± 9	40 ± 90	-	-	-	-
$\Delta(1232)3/2^+(P_{33})$	-133	-16	-131 ± 3.5	-19 ± 2	-257	-3	-254 ± 4.5	-9 ± 1
$\Delta(1700)3/2^-(D_{33})$	128	19	170 ± 20	50 ± 15	120	47	170 ± 25	45 ± 10
$\Delta(1905)5/2^+(F_{35})$	37	-8	25 ± 5	-23 ± 15	-24	-81	-50 ± 4	0 ± 10
$\Delta(1950)7/2^+(F_{37})$	-69	-14	-72 ± 4	-7 ± 5	-83	2	-96 ± 5	-7 ± 5

Definition of $A_{1/2}$, $A_{3/2}$:

$$A_{3/2}(Q^2) \equiv \langle R|\, J^\mu_{\mathrm{e.m.}}(Q^2)\, \varepsilon_\mu^{(\lambda_\gamma=+1)}\, |N(\lambda_N = -1/2)\rangle$$

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BoGa: EPJA48(2012)15

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$\Delta(1232)3/2^+(P_{33})$	-133	-16	-131 ± 3.5	-19 ± 2	-257	-3	-254 ± 4.5	-9 ± 1
$\Delta(1700)3/2^-(D_{33})$	128	19	170 ± 20	50 ± 15	120	47	170 ± 25	45 ± 10
$\Delta(1905)5/2^+(F_{35})$	37	-8	25 ± 5	-23 ± 15	-24	-81	-50 ± 4	0 ± 10
$\Delta(1950)7/2^+(F_{37})$	-69	-14	-72 ± 4	-7 ± 5	-83	2	-96 ± 5	-7 ± 5

Definition of $A_{1/2}$, $A_{3/2}$:

$$A_{3/2}(Q^2) \equiv \langle R|\, J^\mu_{\mathrm{e.m.}}(Q^2)\, \varepsilon_\mu^{(\lambda_\gamma=+1)}\, |N(\lambda_N = -1/2)\rangle$$

$$A_{1/2}(Q^2) \equiv \langle R|\, J^\mu_{\mathrm{e.m.}}(Q^2)\, \varepsilon_\mu^{(\lambda_\gamma=+1)}\, |N(\lambda_N = +1/2)\rangle$$

($R = N^*, \Delta^*$; λ_x = helicity of particle x)

Ours: PRC94(2016)015201
BoGa: EPJA48(2012)15

Helicity amplitudes for $\gamma^{(*)}N \rightarrow N^*, \Delta^*$ transition at photon point ($Q^2=0$)

Comparison of $\gamma p \rightarrow N^*, \Delta^*$ helicity amplitudes ($A^p_{1/2,3/2}$)

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

$A^p_{1/2}$		$A^p_{3/2}$	
Ours	BoGa	Ours	BoGa

Measure dσ/dΩ & *ALL* possible spin-polarization observables !!

"(Over-)complete" experiments are being performed for γp reactions at JLab, ELSA, MAMI, ...

New extensive & accurate data can be used for eliminating analysis dependence in the extracted $\gamma N \rightarrow N^*, \Delta^*$ helicity amplitudes !!

Definition of $A_{1/2}$, $A_{3/2}$:

$$A_{3/2}(Q^2) \equiv \langle R|\, J^{\mu}_{\mathrm{e.m.}}(Q^2)\, \varepsilon^{(\lambda_\gamma=+1)}_{\mu}\, |N(\lambda_N=-1/2)\rangle$$

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Comparison of $\gamma n \rightarrow N^*, \Delta^*$ helicity amplitudes ($A^n_{1/2,3/2}$)

(Note: $A^p = A^n$ for Δ^*)

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

A (10^{-3} GeV$^{-1/2}$) ϕ (degree)	$A^n_{1/2}$				$A^n_{3/2}$			
	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

Ours: PRC94(2016)015201
BoGa: EPJA49(2013)67

Helicity amplitudes for $\gamma^{(*)}N \rightarrow N^*, \Delta^*$ transition at photon point ($Q^2=0$)

Comparison of $\gamma n \rightarrow N^*, \Delta^*$ helicity amplitudes ($A^n_{1/2,3/2}$)
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$N(1535)1/2^-(S_{11})$	-112	16	-103 ± 11	8 ± 5	-	-	-	-
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Ours: PRC94(2016)015201
BoGa: EPJA49(2013)67

For N* with I = 1/2:

$$A^{\text{iso vector}}_{1/2,3/2} = \left(A^p_{1/2,3/2} - A^n_{1/2,3/2}\right)/(-2\sqrt{3})$$

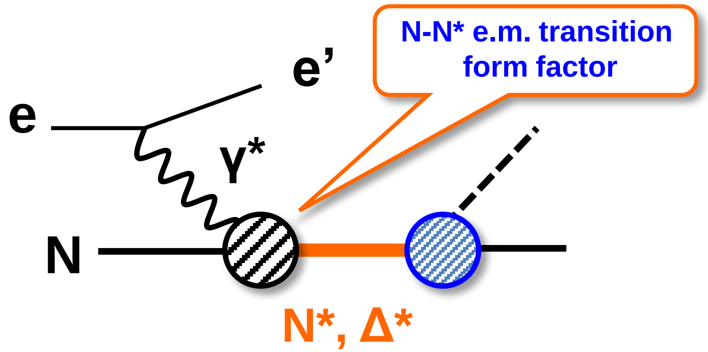
$$A^{\text{iso scalar}}_{1/2,3/2} = \left(A^p_{1/2,3/2} + A^n_{1/2,3/2}\right)/2$$

For Δ* with I = 3/2:

$$A^{\text{iso vector}}_{1/2,3/2} = \sqrt{3/2}A^p_{1/2,3/2} = \sqrt{3/2}A^n_{1/2,3/2}$$

Analysis of electroproduction reactions: Determining e.m. transition form factors at finite Q^2

- Meson electroproductions:

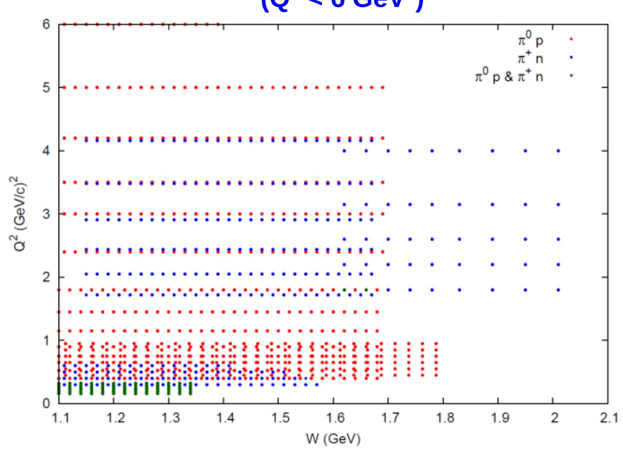


✓ **electron-proton reactions**

Extensive data from CLAS are available for
$ep \rightarrow e'\pi N$, $e'K\Lambda$, $e'K\Sigma$, $e'\pi\pi N$ with $Q^2 < 6$ GeV^2

(New measurements at higher Q^2 will be performed at CLAS12.)

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



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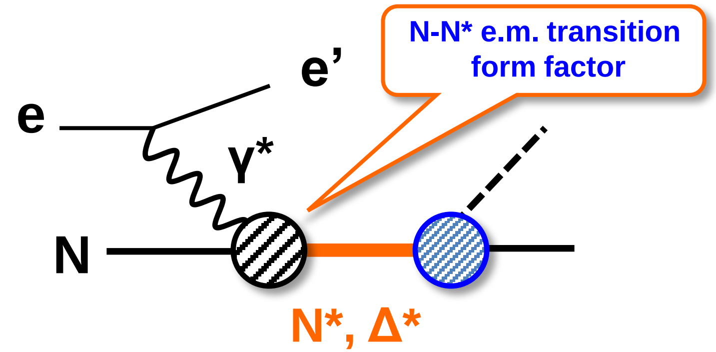

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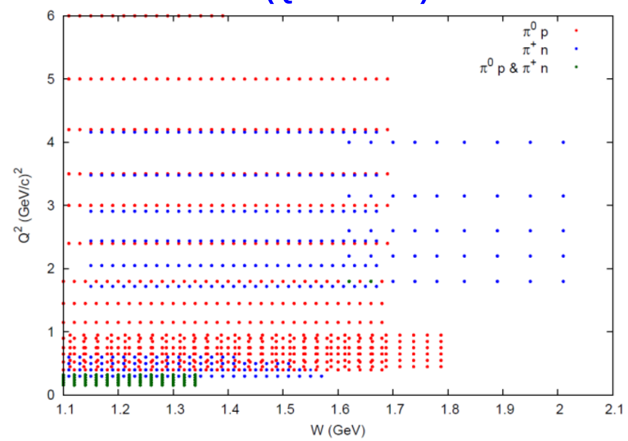


✓ electron-'neutron' reactions

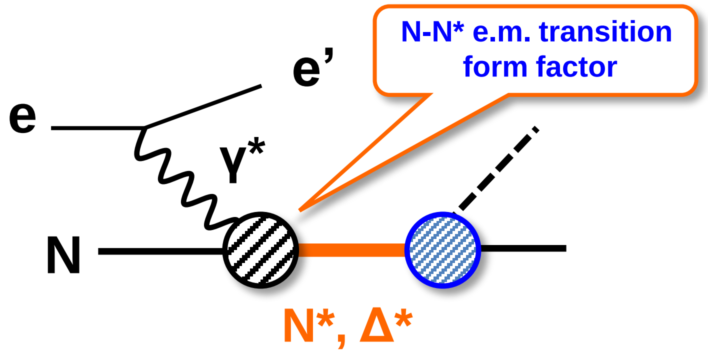
Only empirical F2 structure function for inclusive e 'n' → e'X is available.
[Bosted, Christy, PRC77(2008)065206]

Analysis to obtain exclusive e 'n' → e'πN cross section is underway at CLAS.
New data will be available in the near future.

R. Gothe, talk@ECT* workshop(2015)
[http://boson.physics.sc.edu/~gothe/ect*-15/talks/Ralf-Gothe.pdf]

Analysis of electroproduction reactions: Determining e.m. transition form factors at finite Q^2

- Meson electroproductions:



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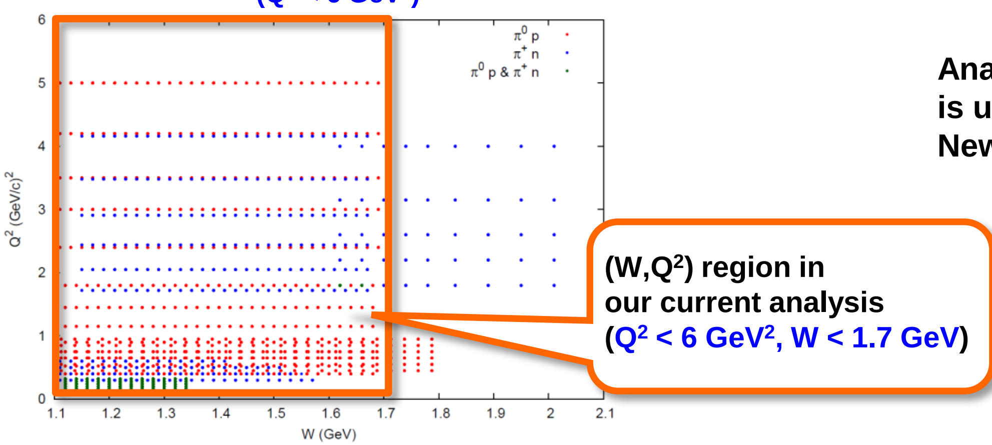

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Analysis of electroproduction reactions: Determining e.m. transition form factors at finite Q^2

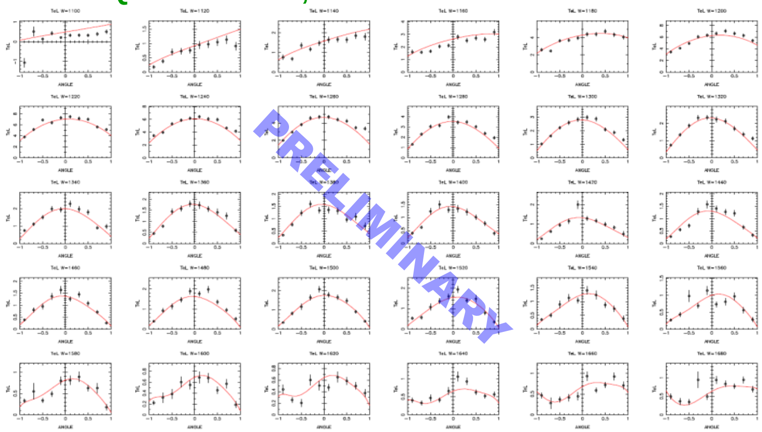
$$\frac{d\sigma^5}{dE_{e'}d\Omega_{e'}d\Omega^*_\pi} = \Gamma_\gamma\left[\sigma_T + \epsilon\sigma_L + \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}\cos\phi^*_\pi + \epsilon\sigma_{TT}\cos 2\phi^*_\pi + h_e\sqrt{2\epsilon(1-\epsilon)}\sigma_{LT'}\sin\phi^*_\pi\right].$$

$$\sigma_\alpha = \sigma_\alpha(W, Q^2, \cos\theta^*_\pi)$$

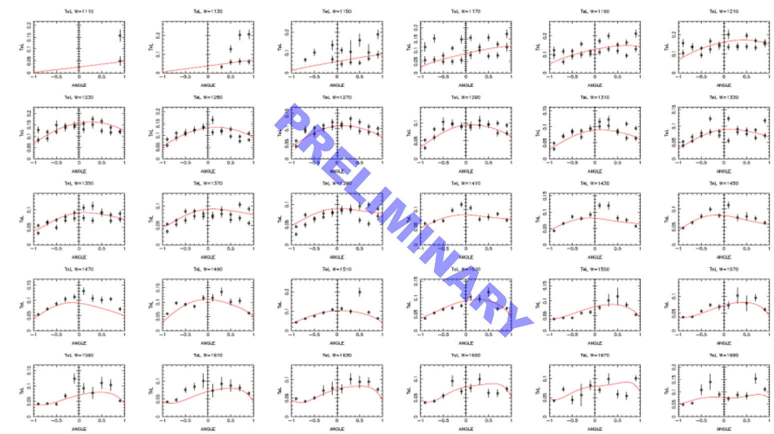
$\sigma_T+\varepsilon\sigma_L$ for $ep \rightarrow e\pi^0 p$

Data for structure functions are obtained with the help of K. Joo and L. C. Smith.

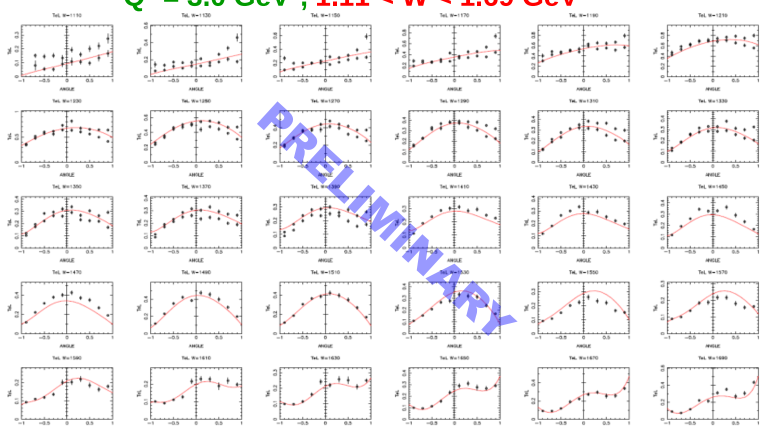
Q^2 = 1.15 GeV^2, 1.10 < W < 1.69 GeV



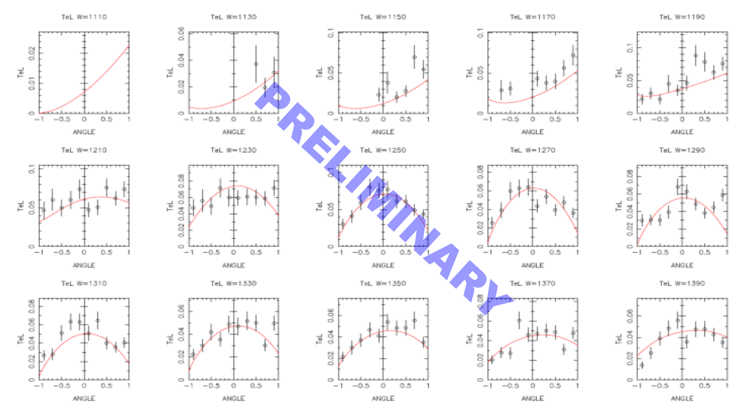
Q^2 = 5.0 GeV^2, 1.11 < W < 1.69 GeV



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



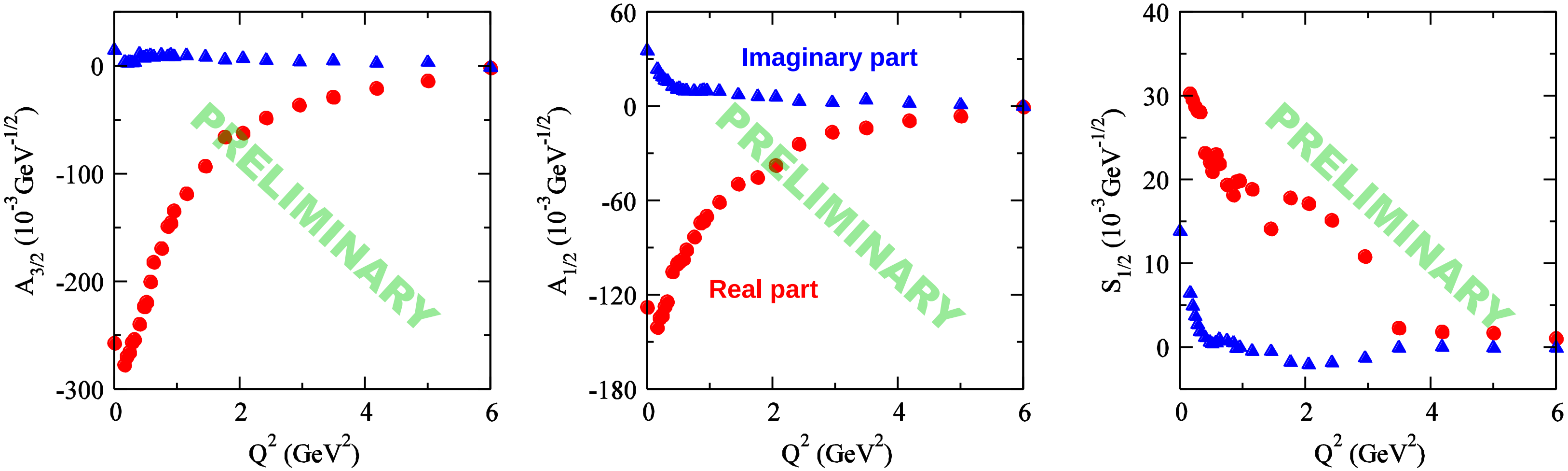
Q^2 = 6.0 GeV^2, 1.11 < W < 1.39 GeV



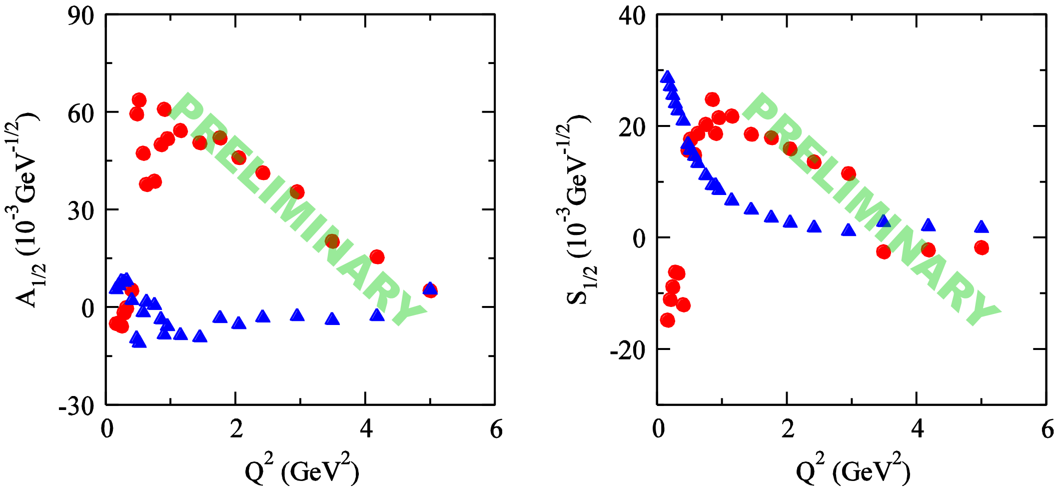
cosθ **cosθ**

Extracted $\gamma^{(*)} p \rightarrow N^*, \Delta^*$ transition form factors at finite Q^2 (evaluated at resonance poles)

$\gamma^{(*)} p \rightarrow \Delta(1232)3/2^+$



$\gamma^{(*)} p \rightarrow N(1440)1/2^+$



Definition of $A_{1/2}$, $A_{3/2}$, $S_{1/2}$:

$$A_{3/2}(Q^2) \equiv \langle R | \, J^{\mu}_{\rm e.m.}(Q^2) \, \varepsilon_{\mu}^{(\lambda_\gamma=+1)} \, | N(\lambda_N = -1/2) \rangle$$

$$A_{1/2}(Q^2) \equiv \langle R | \, J^{\mu}_{\rm e.m.}(Q^2) \, \varepsilon_{\mu}^{(\lambda_\gamma=+1)} \, | N(\lambda_N = +1/2) \rangle$$

$$S_{1/2}(Q^2) \equiv \langle R | \, J^{\mu}_{\rm e.m.}(Q^2) \, \varepsilon_{\mu}^{(\lambda_\gamma=\;0)} \, | N(\lambda_N = -1/2) \rangle$$

Summary

✓ **Determining $\gamma(*)$ N → N*, Δ* transition form factors via DCC analysis of π-, γ-, e-induced meson productions**

- **Primary motivation comes from studying quark-gluon substructure of N* & Δ* resonances, but it can also be important input to constructing a model for neutrino reactions.**

- **There are still visible uncertainties for extracted form factors, particularly for high-mass resonances.**

- **New extensive and accurate data from JLab, ELSA, MAMI,... will further improve our reaction model and greatly reduce uncertainties in extracted form factors.**

Summary

✓ **Determining $\gamma(*)\ N \rightarrow N^*, \Delta^*$ transition form factors via DCC analysis of π-, γ-, e-induced meson productions**

- Primary motivation comes from **studying quark-gluon substructure of N* & Δ* resonances**, but it can also be **important input to constructing a model for neutrino reactions**.
- There are still visible uncertainties for extracted form factors, particularly for high-mass resonances.
- New extensive and accurate data from JLab, ELSA, MAMI,... will further improve our reaction model and greatly reduce uncertainties in extracted form factors.

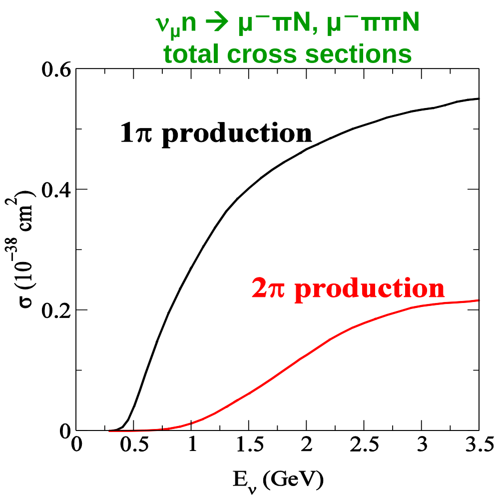
✓ **Neutrino collaboration at J-PARC Branch of KEK Theory Center.**

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

- Developed DCC model for neutrino-nucleon reactions in resonance region. [Nakamura, HK, Sato, PRD92(2015)074024]

  - assumed certain Q^2 dependence for axial matrix elements.

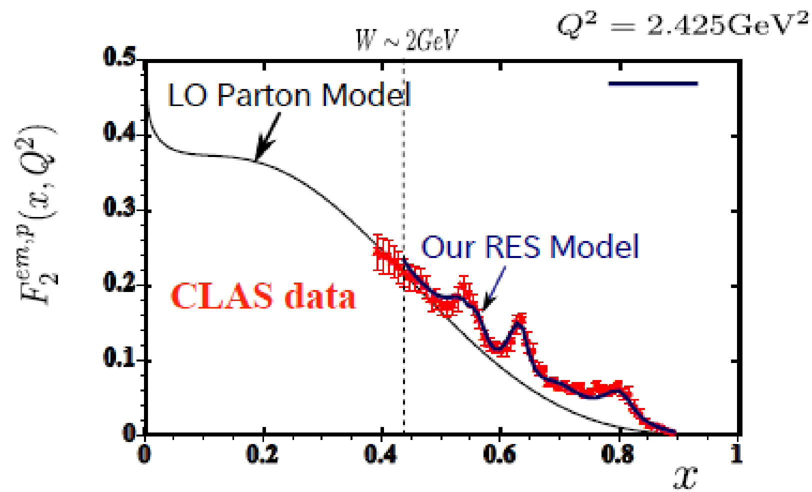
  - evaluated vector matrix elements using empirical F_2 structure functions for inclusive electron-'neutron' reaction.



Back up

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

Resonance vs DIS (Inclusive structure function)

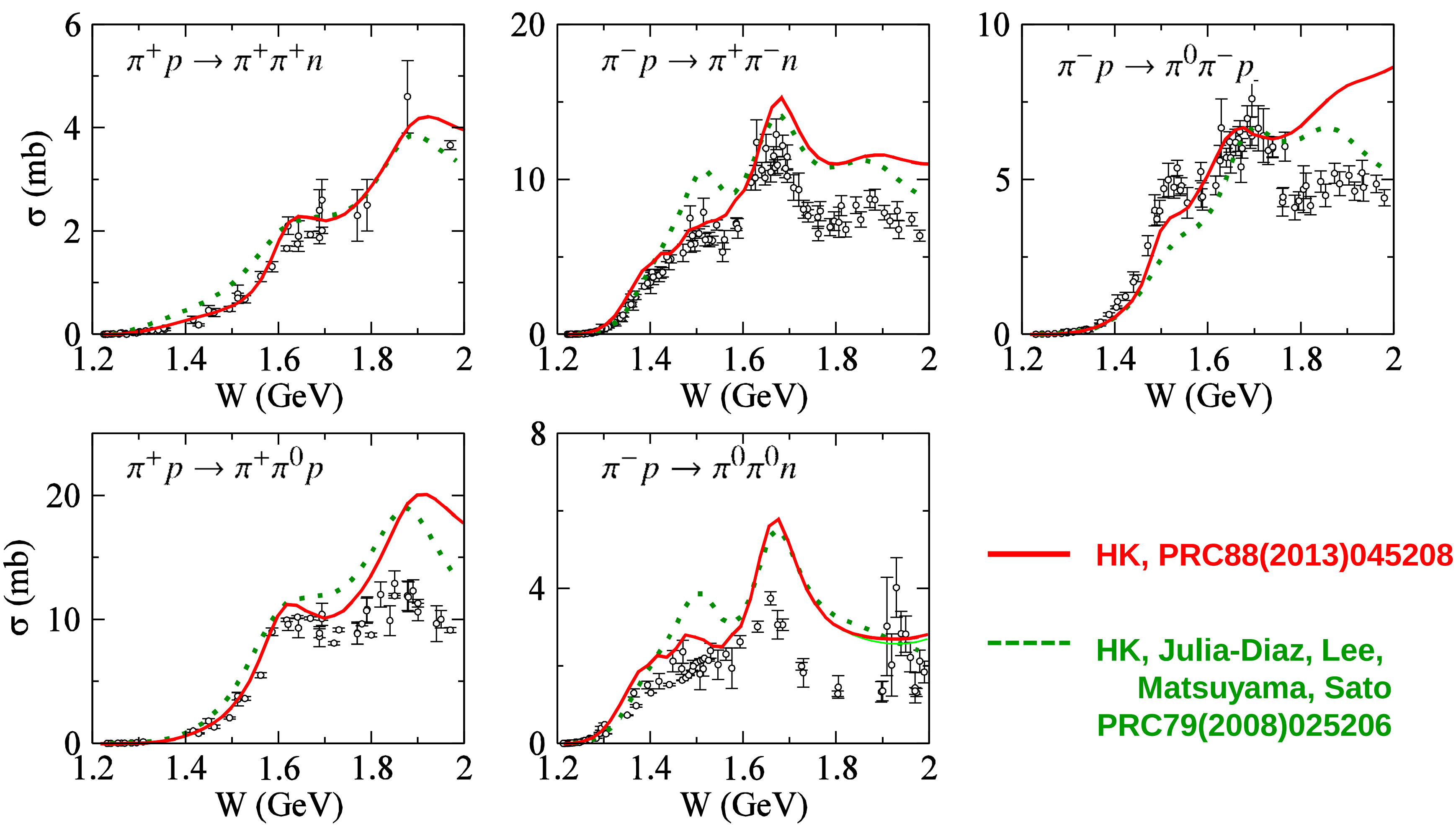


Parton model by S. Kumano, DCC by S. Nakamura, data are from http://www.ge.infn.it/ osipenko/results/inclusive/

- 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.

ANL-Osaka DCC approach to N* & Δ*

Predicted πN → ππN total cross sections with our DCC model

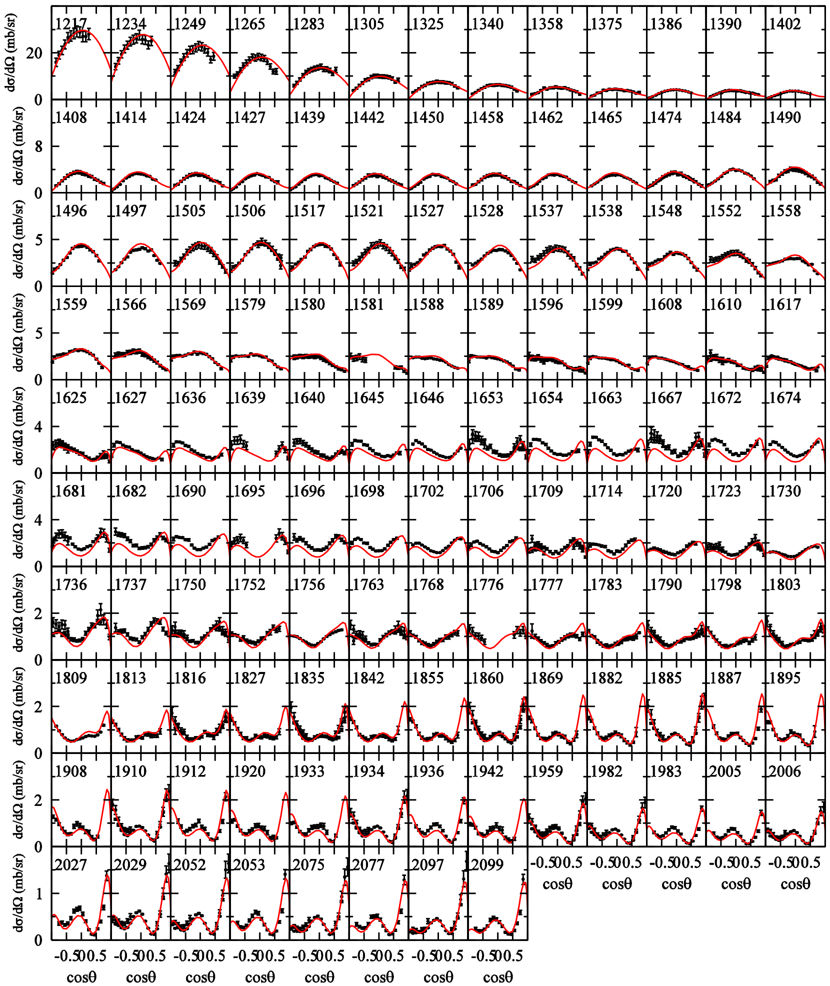


ANL-Osaka DCC approach to N* & Δ*

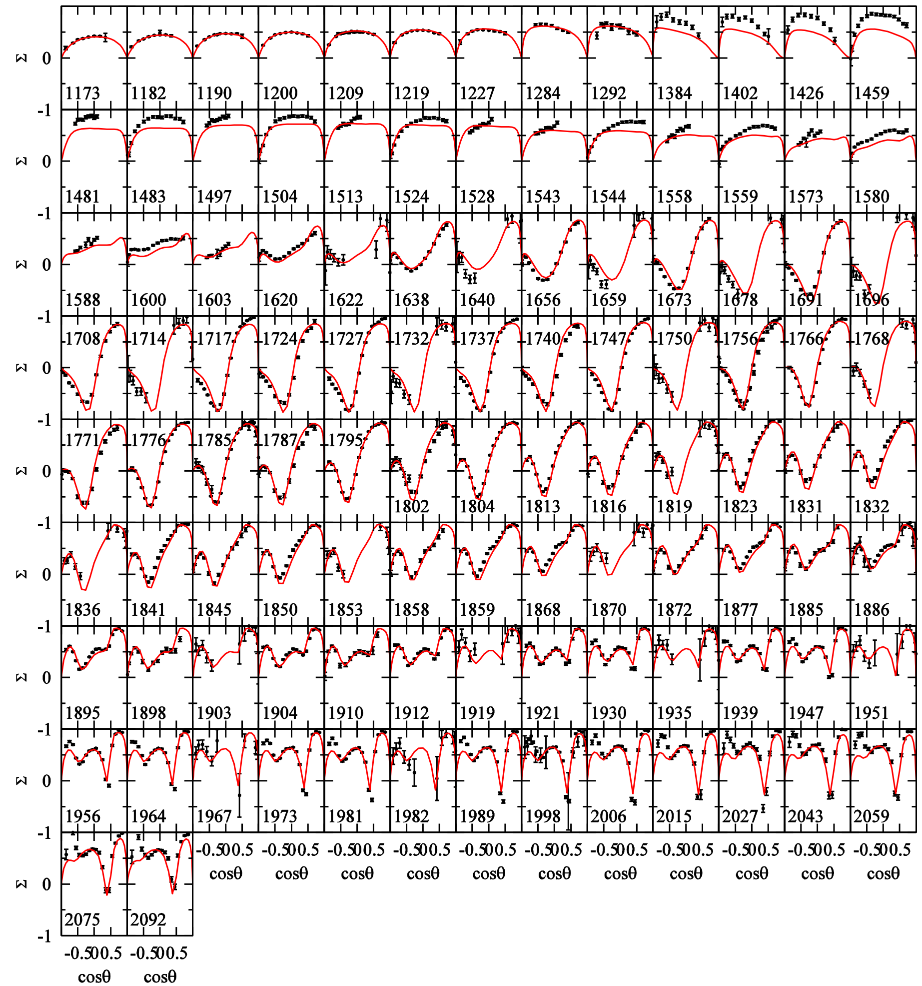
γp → π^0p

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

dσ/dΩ for W < 2.1 GeV



Σ for W < 2.1 GeV



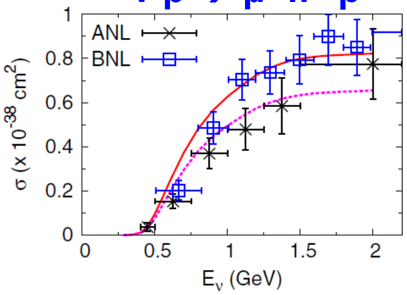
Predicted results for neutrino-induced reactions

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

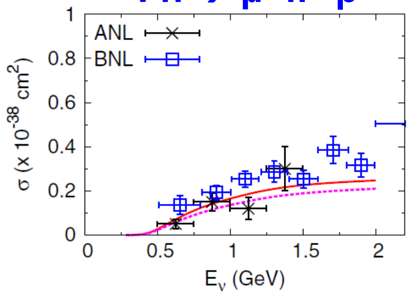
The first-time full coupled-channels calculation of ν-nucleon reactions beyond the Δ(1232) region !!

✓ **Single pion production:**

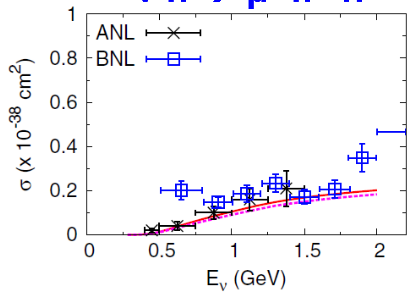
$\nu\, p \rightarrow \mu^-\, \pi^+\, p$



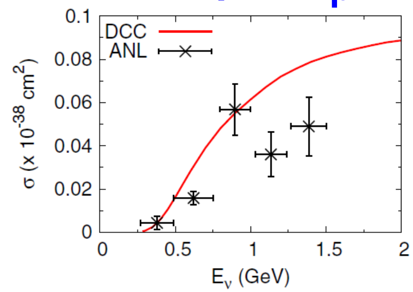
$\nu\, n \rightarrow \mu^-\, \pi^0\, p$



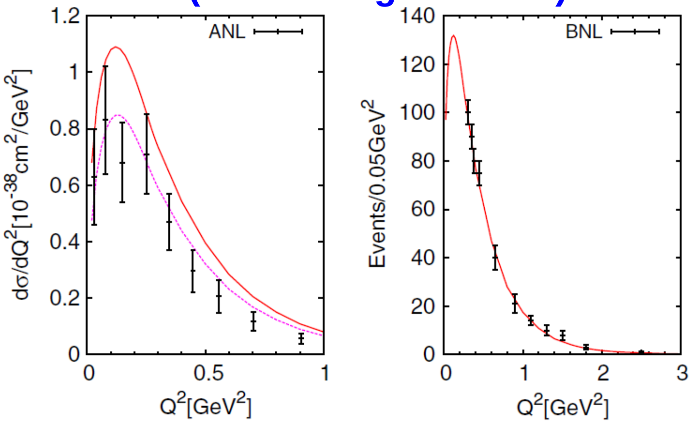
$\nu\, n \rightarrow \mu^-\, \pi^+\, n$



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

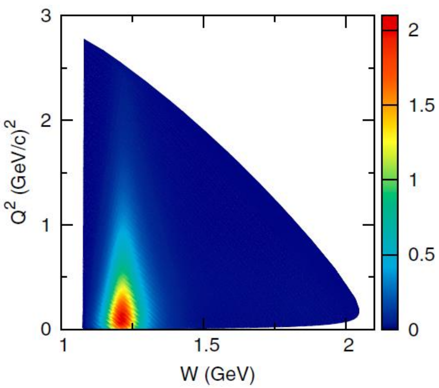


$d\sigma/dQ^2$ for $\nu\, p \rightarrow \mu^-\, \pi^+\, p$
(flux averaged for Ev)

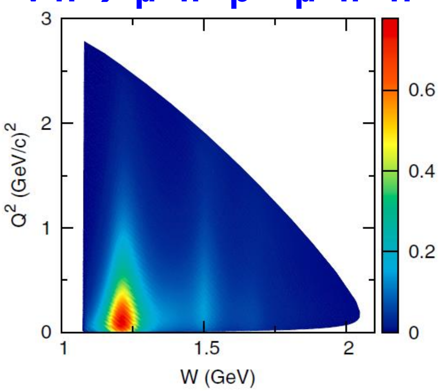


$d^2\sigma/dWdQ^2$ at Ev = 2 GeV

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



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

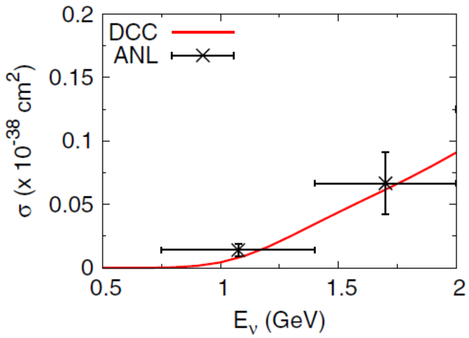


Predicted results for neutrino-induced reactions

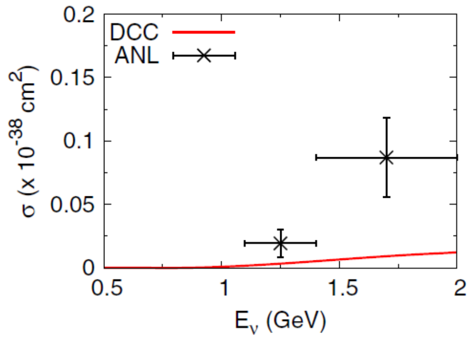
Nakamura, HK, Sato, arXiv:1506.03403; to appear in PRD

✓ **Double pion production:**

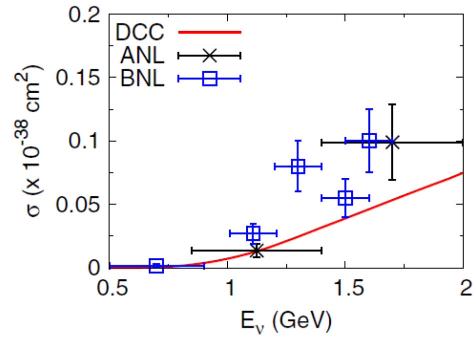
$\nu\, p \rightarrow \mu^-\, \pi^+\, \pi^0\, p$



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

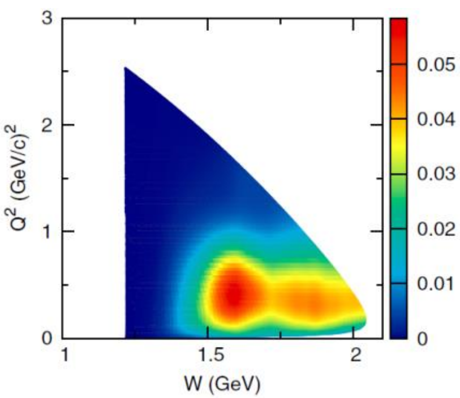


$\nu\, n \rightarrow \mu^-\, \pi^+\, \pi^-\, p$

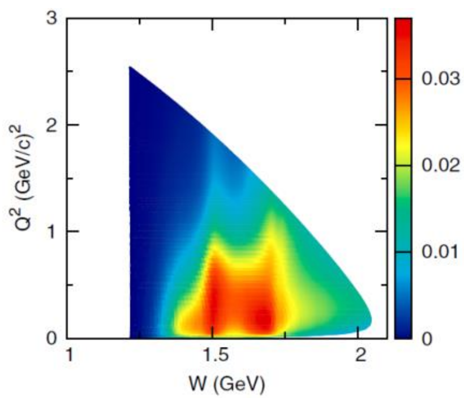


$d\sigma/dWdQ^2$ at $E\nu$ = 2 GeV

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

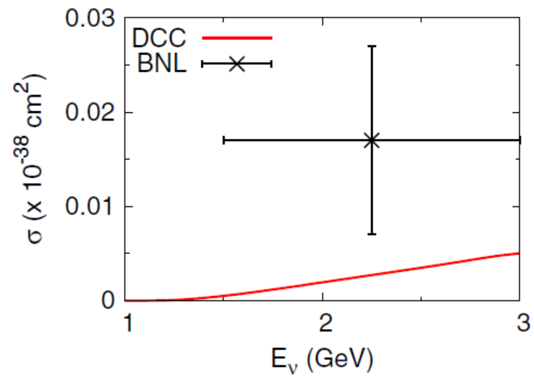


$\nu\, n \rightarrow \mu^-\, \pi^+\, \pi^-\, p$



✓ **KΛ production:**

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



Matching resonance and DIS regions (rough idea)

Consider at the nucleon level for the first attempt

✓ **Currently, Q^2 dependence of $\langle MB|A_\mu(q)|N\rangle$ in the RES region has large flexibility because of no enough neutrino data to fix them.**

✓ **Use DIS information as an additional constraint on Q^2 dependence of $\langle MB|A_\mu(q)|N\rangle$ in the RES region.**