N* and Y* baryon spectroscopy using high momentum pion beam (+ kaon beam)

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Mini workshop on "Structure and productions of charmed baryons II"
KEK Tokai Campus, Tokai, Aug. 7-9, 2014

Outline

1. **Brief description of ANL-Osaka Dynamical Coupled-Channels (DCC) approach & N* spectroscopy from the analysis of πN and γN reactions**
   (HK, Nakamura, Lee, Sato, PRC88(2013)035209)

2. **Y* (= Λ*, Σ*) spectroscopy using Kaon beam**
   (HK, Nakamura, Lee, Sato, arXiv:1407.6839; in preparation)

3. **Applications of ANL-Osaka DCC approach to forward p(π, ρ or K*)X with high-momentum pion beam**
   (HK in preparation)

Brief description of ANL-Osaka DCC approach & N* spectroscopy from the analysis of πN and γN reactions (1 of 3)

Introductory remarks

N*, Δ*, Λ*, Σ*

✓ "Light-quark baryon spectroscopy"

= "Physics of very broad and highly overlapping resonances"

➢ Resonances are strongly correlated with each other in the reaction processes over the wide energy region.

➢ Resonances appear in the cross sections as rather complicated interference.

✓ To disentangle the above complications and establish resonance mass spectrum, the followings must be accomplished:

➢ Simultaneous partial-wave analysis of various meson-production reactions over the wide energy range within multichannel reaction framework.

➢ Careful investigation of the analysis results in an comprehensive manner.

✓ This requires extensive and accurate data of various meson production reactions that covers:

➢ ***wide energy*** and ***kinematical (angles, Q2,…) regions***.

➢ both ***unpolarizaed*** and ***polarized*** observables.

Introductory remarks

Experimental and theoretical efforts for N* spectroscopy

Experiments

JLab, ELSA, MAMI, GRAAL, SPring-8, ELPH, …

Theoretical analyses
with multichannel framework

ANL-Osaka/EBAC-JLab
Bonn-Gatchina
Carnegie-Mellon-Berkeley
Dubna-Mainz-Taipei
Giessen
GWU/VPI
Juelich
Karlsruhe-Helsinki
…

✓ **Multichannel unitary condition:**

$$T_{ab}(E) - T^{\dagger}_{ab}(E) = -2\pi i \sum_c T^{\dagger}_{ac}\delta(E-E_c)T_{cb}(E)$$

$$a,b,c \;=\; (\gamma^{(*)}N,\ \pi N,\ \eta N,\ \pi\pi N,\ K\Lambda,\ K\Sigma,\ \omega N\cdots)$$

ANL-Osaka DCC approach to N*

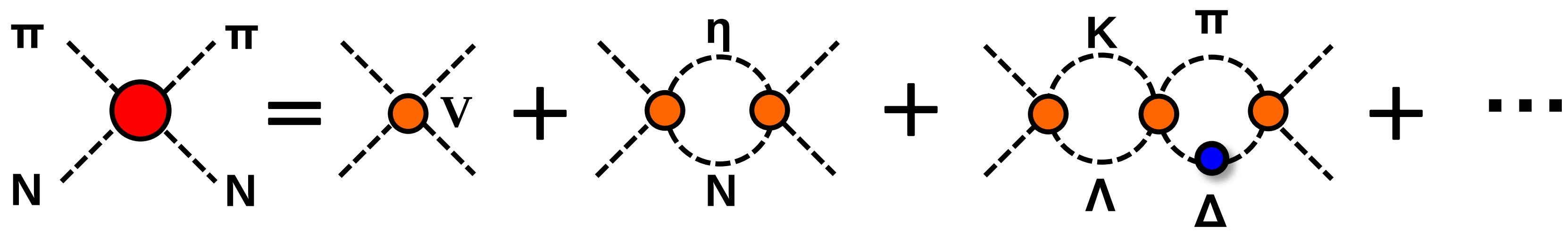
Dynamical coupled-channels model [Matsuyama, Sato, Lee, Phys. Rep. 439(2007)193]

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

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

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

e.g.) πN scattering



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

ANL-Osaka DCC approach to N*

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

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

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

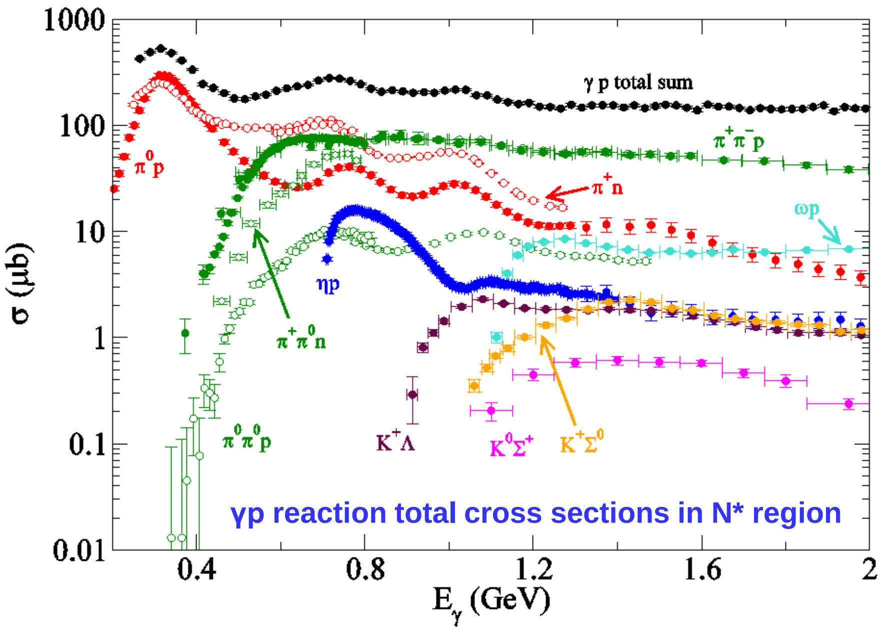
Latest published model:

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

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)**

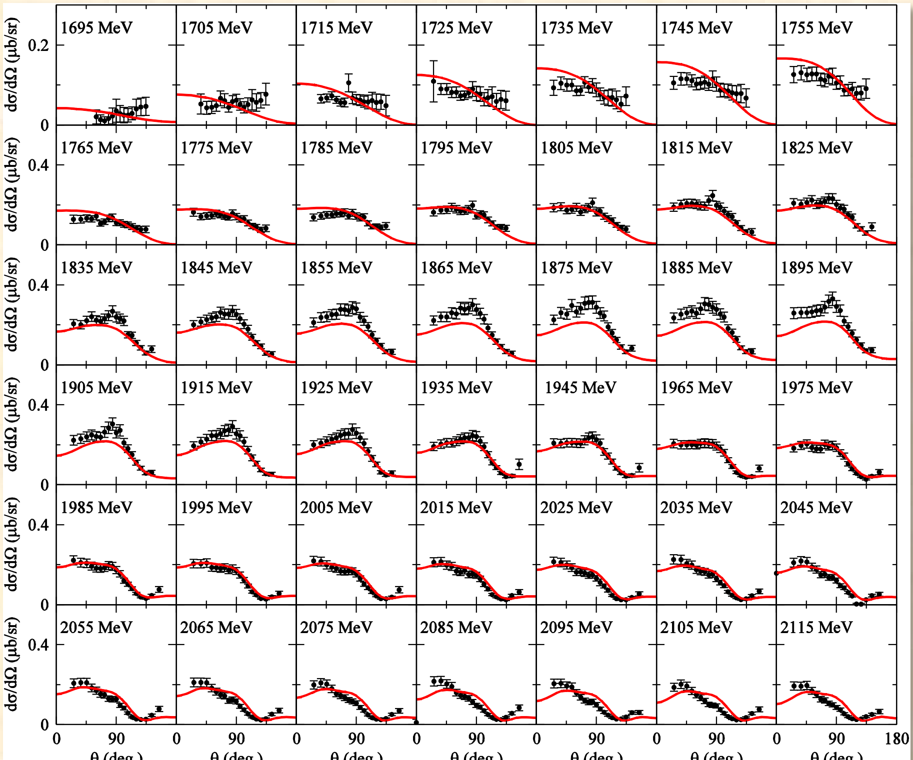
Region our model can cover



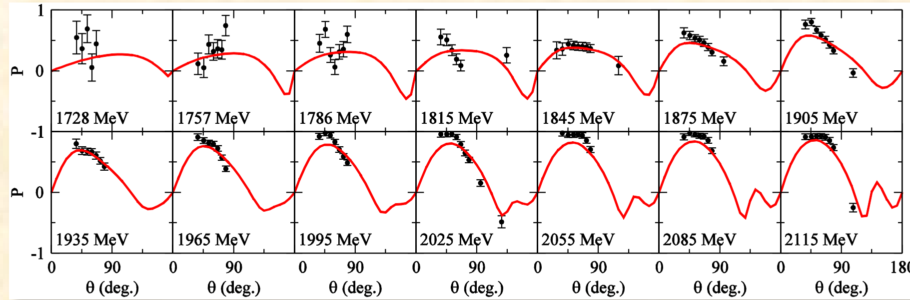
γ p → $K^+ \Sigma^0$ reaction

8ch DCC-analysis
[HK, Nakamura, Lee, Sato, PRC88 (2013) 035209]

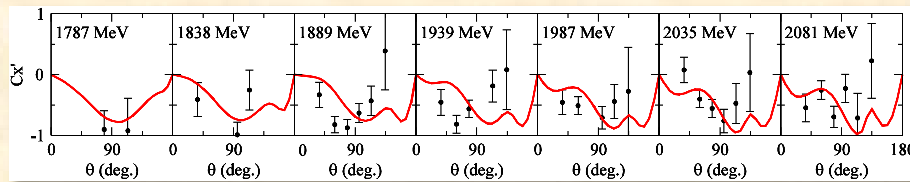
DCS



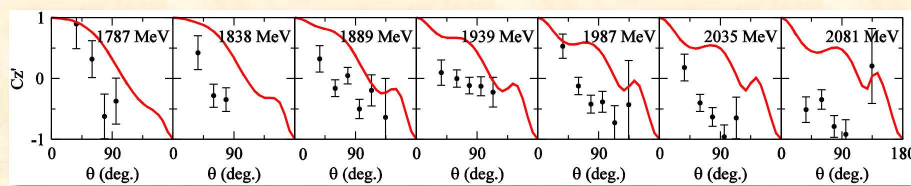
P

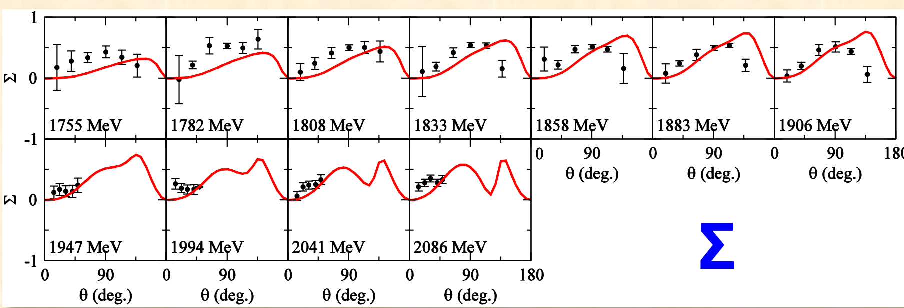


Cx’



Cz’





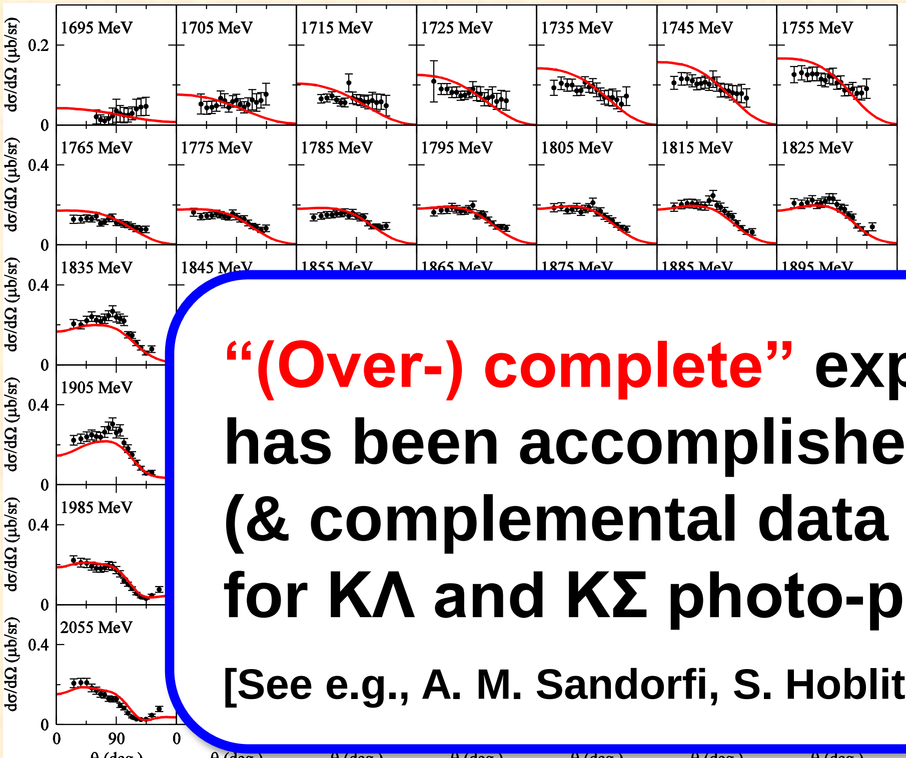
Σ

At present, **NO** data are available for the other 11 observables (as of 2013):
T, E, F, G, H, Ox’, Oz’, Lx’, Lz’, Tx’, Tz’

γ p → $K^+ \Sigma^0$ reaction

8ch DCC-analysis
[HK, Nakamura, Lee, Sato, PRC88 (2013) 035209]

DCS



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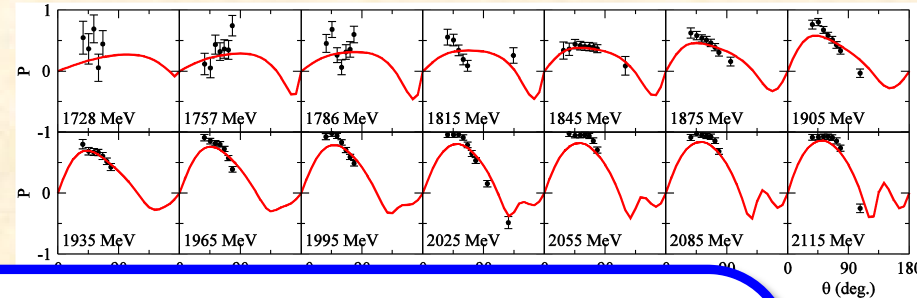
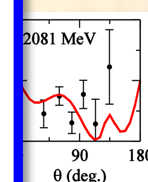
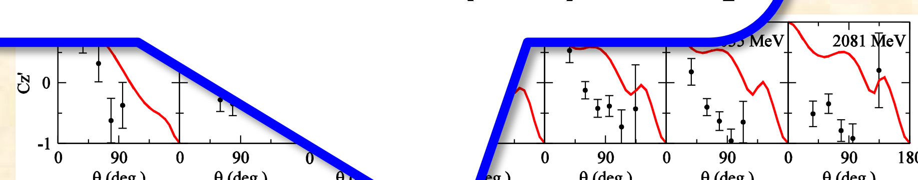
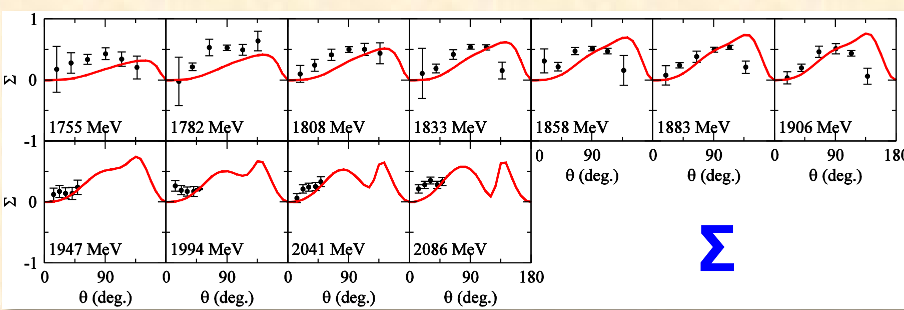






"(Over-) complete" experiments
has been accomplished by CLAS
(& complemental data from ELSA, MAMI,..)
for KΛ and KΣ photo-productions !!!

[See e.g., A. M. Sandorfi, S. Hoblit, HK, T.-S. H. Lee, JPG38(2011)053001]



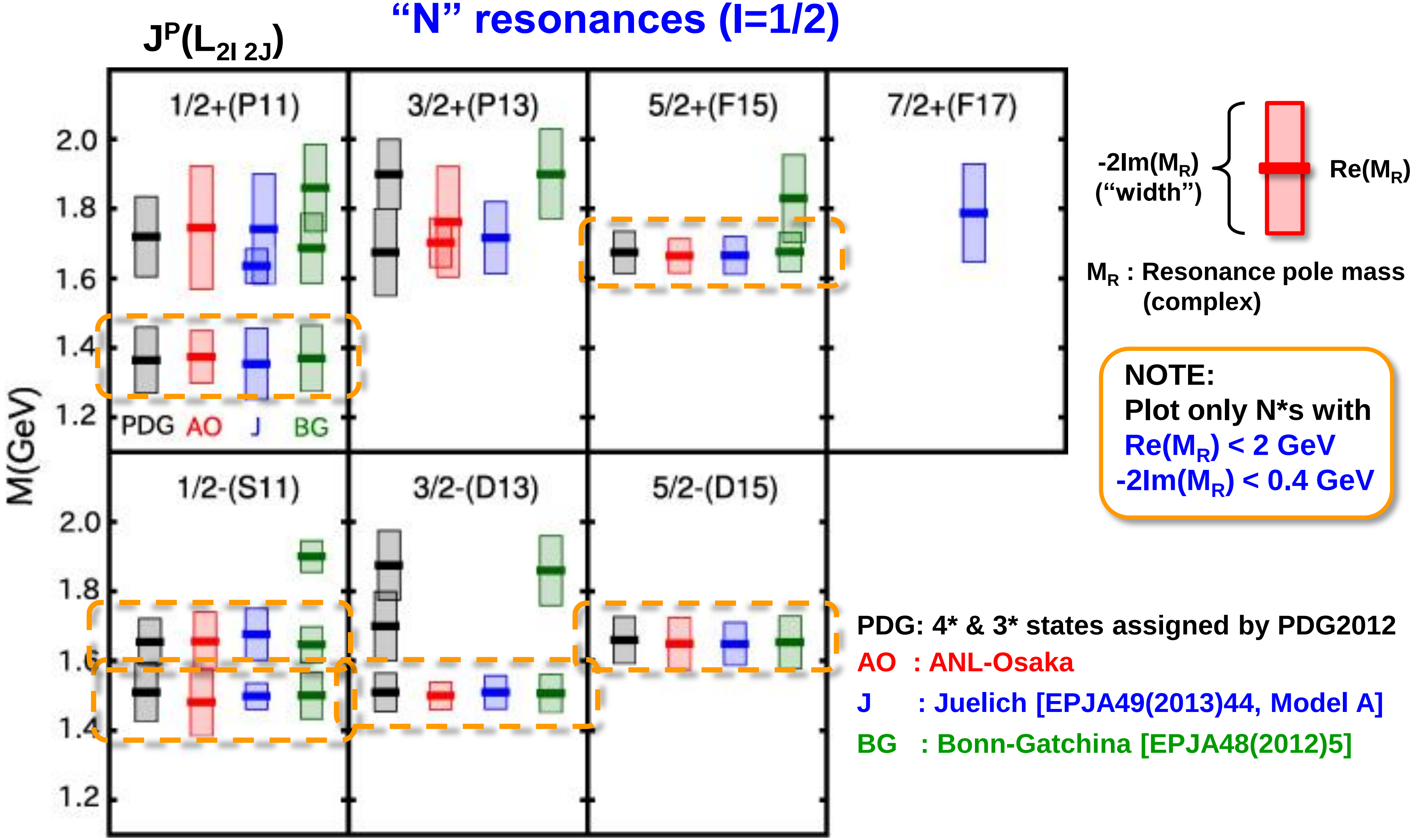
Σ

At present, NO data are available for the other 11 observables (as of 2013):
T, E, F, G, H, Ox', Oz', Lx', Lz', Tx', Tz'

Comparison of N* spectrum with other multichannel analyses

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

"N" resonances (I=1/2)



M_R : Resonance pole mass (complex)

NOTE:
Plot only N*s with
Re(M_R) < 2 GeV
-2Im(M_R) < 0.4 GeV

PDG: 4* & 3* states assigned by PDG2012
AO : ANL-Osaka
J : Juelich [EPJA49(2013)44, Model A]
BG : Bonn-Gatchina [EPJA48(2012)5]

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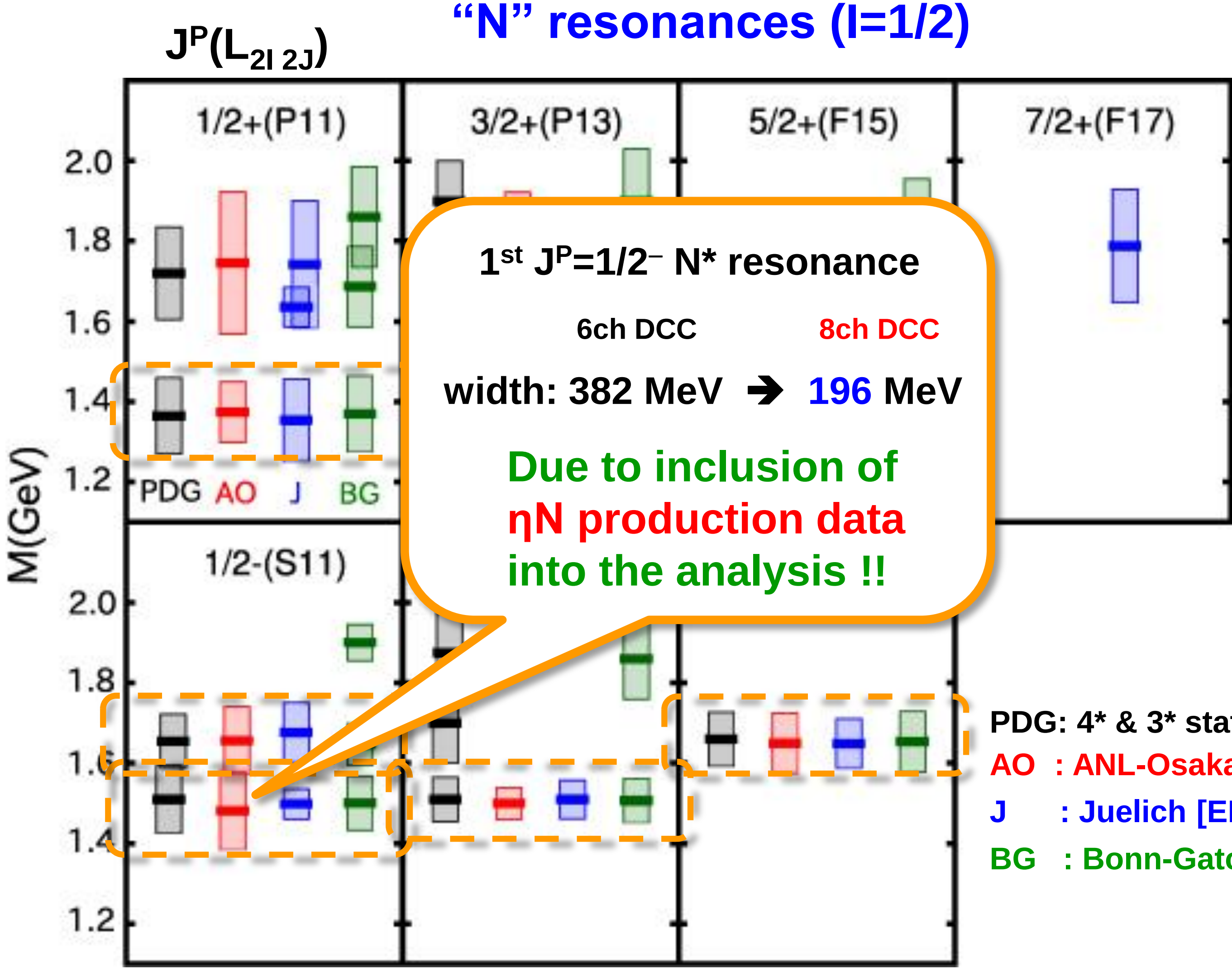


1^{st} J^P=1/2⁻ N* resonance

6ch DCC → 8ch DCC

width: 382 MeV → 196 MeV

Due to inclusion of ηN production data into the analysis !!

M_R : Resonance pole mass (complex)

NOTE:
Plot only N*s with
Re(M_R) < 2 GeV
-2Im(M_R) < 0.4 GeV

PDG: 4* & 3* states assigned by PDG2012

AO : ANL-Osaka

J : Juelich [EPJA49(2013)44, Model A]

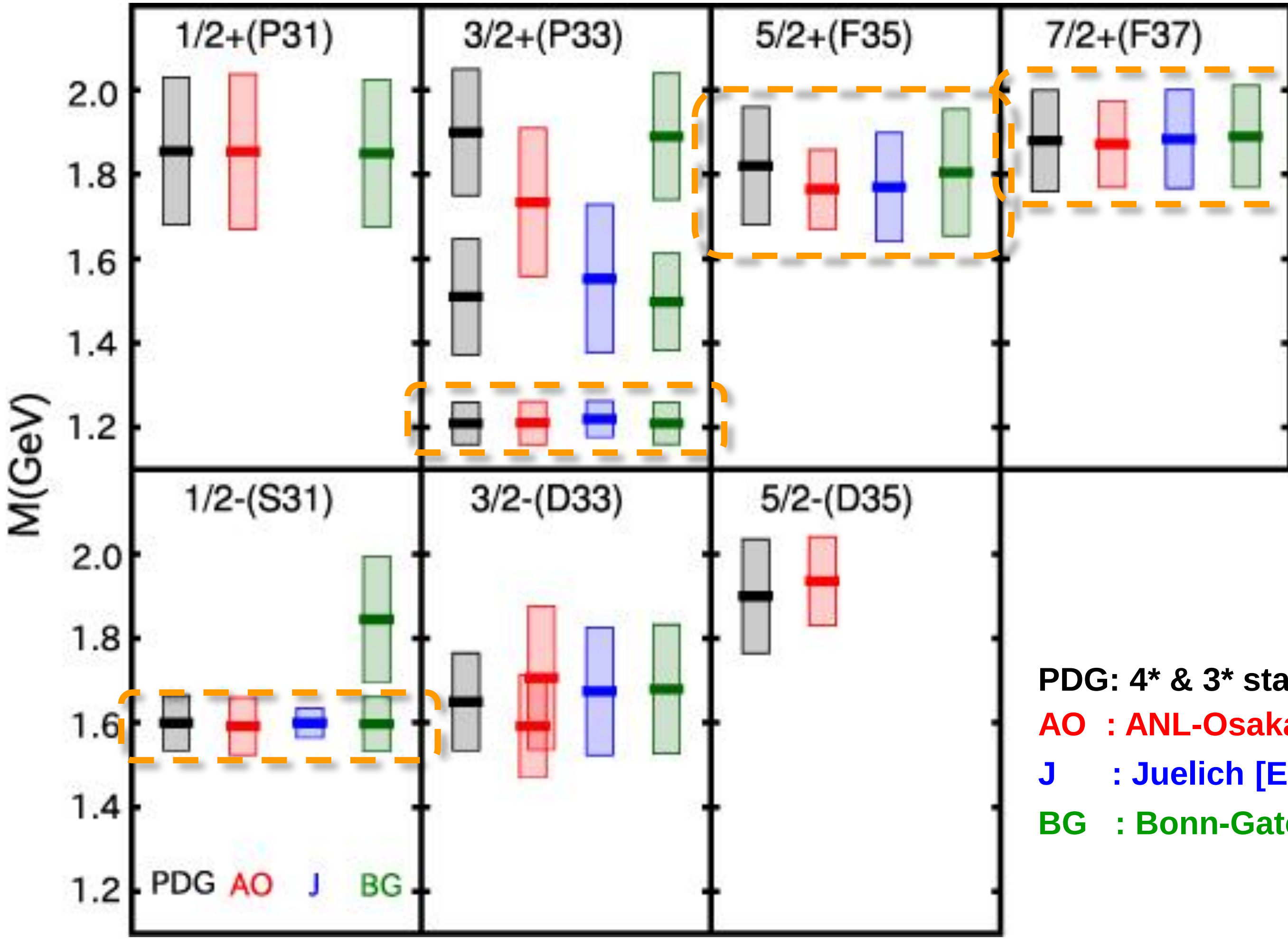
BG : Bonn-Gatchina [EPJA48(2012)5]

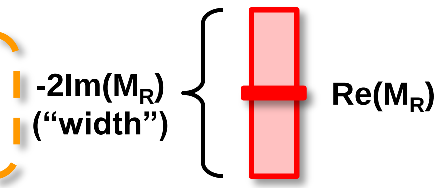
Comparison of N* spectrum with other multichannel analyses

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

"Δ" resonances (I=3/2)

$J^P(L_{2I\ 2J})$





M_R : Resonance pole mass (complex)

NOTE:
Plot only N*s with
$Re(M_R)$ < 2 GeV
$-2Im(M_R)$ < 0.4 GeV

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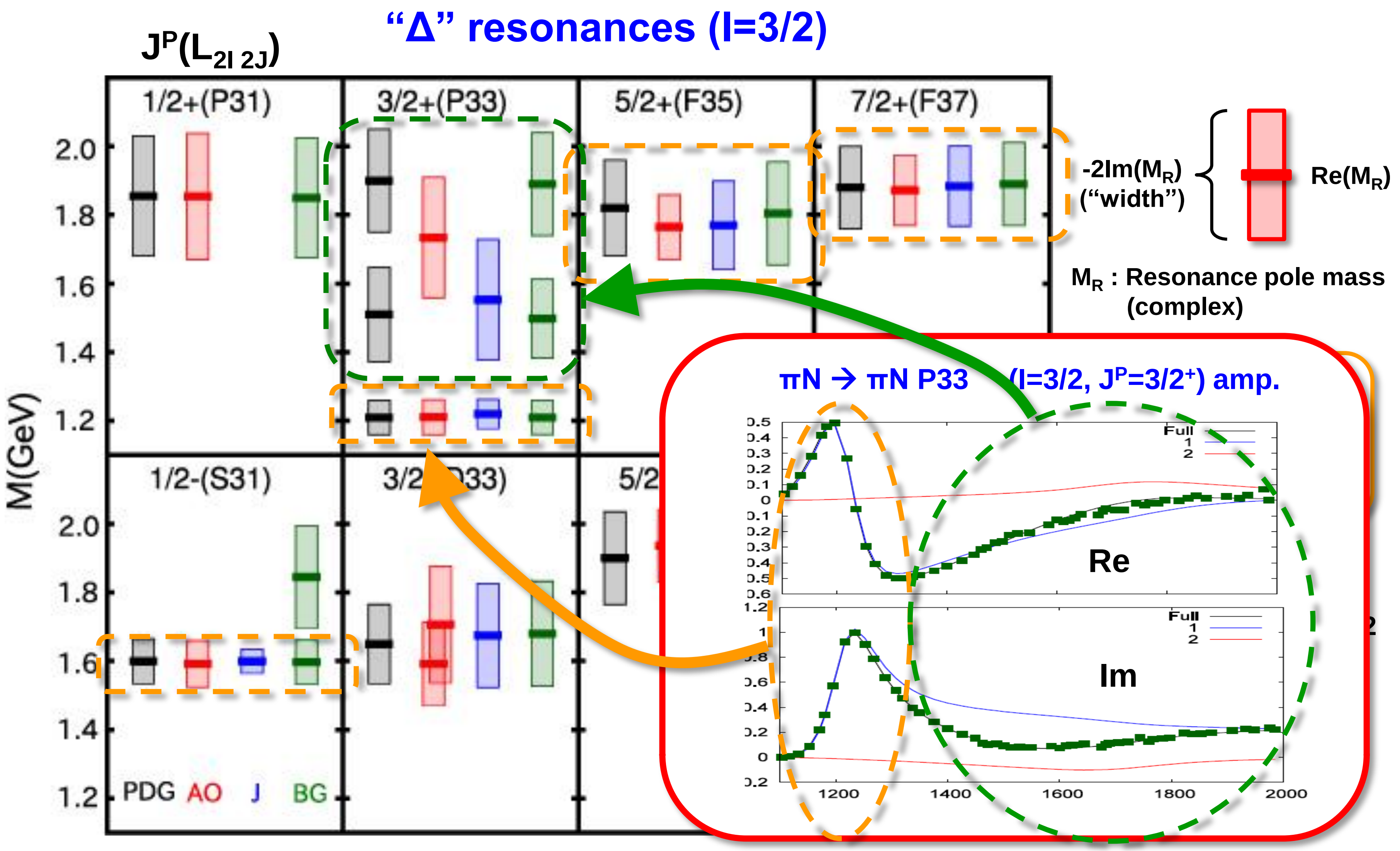
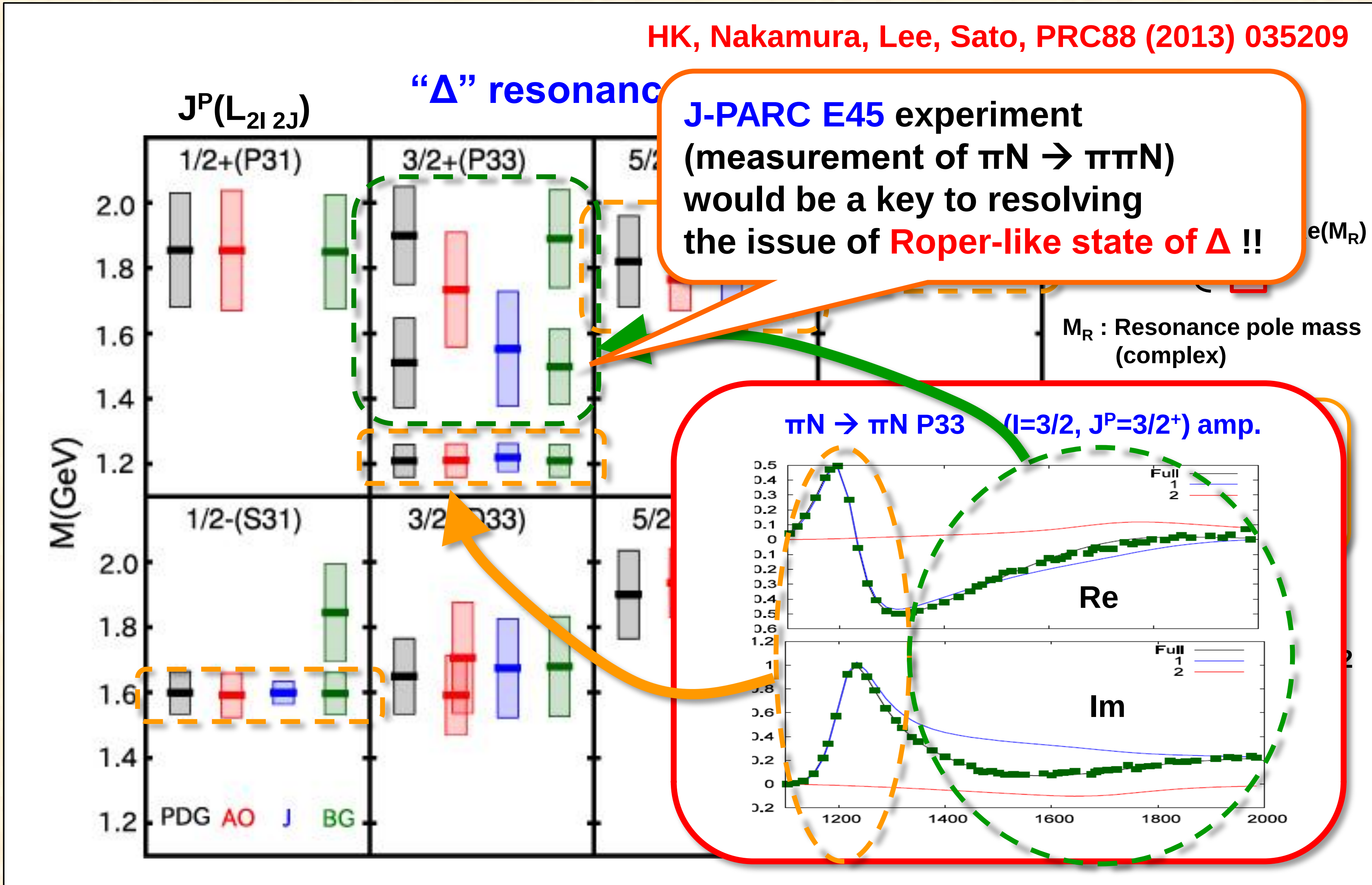
Comparison of N* spectrum with other multichannel analyses

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



Comparison of N* spectrum with other multichannel analyses

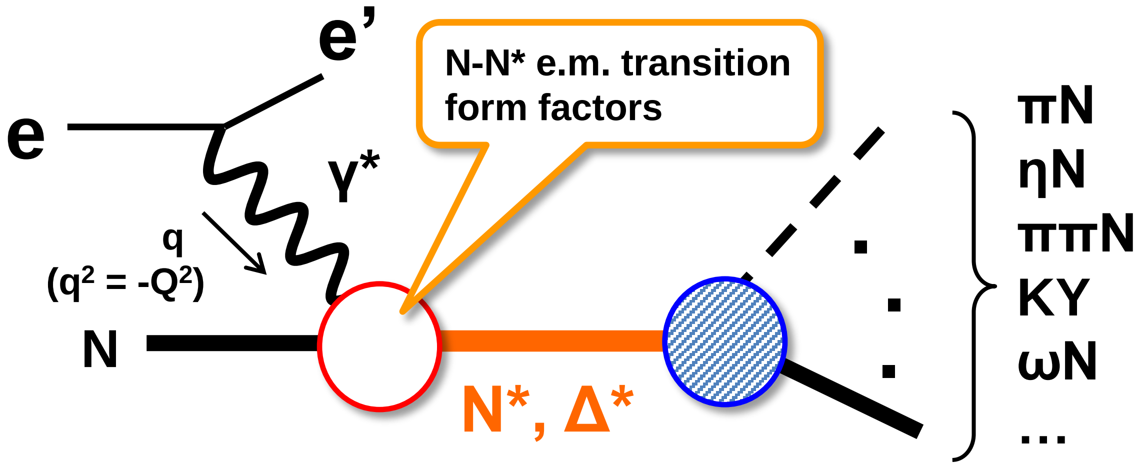


Short summary and remarks (1/3)

Main interests in N* in the near future (in my view):

- ✓ Establishing the spectrum for **high-mass N*s** (1.7 < M < 2.5 GeV)
  - ➢ **LEPS2** can play a **key** role !!
    (with their polarized photons; hopefully also polarized targets and recoil particles)

- ✓ **Quantitative study** of quark-gluon substructure of N* via the Q^2 dependence of **N-N* e.m. transition form factors**.
  - ➢ Form factors are extracted from meson **electro**-productions.
  - ➢ This is a main N* program at **CLAS12**.
    (R. Gothe et al., JLab E12-09-003; D. Carman et al., a new proposal in preparation)



Y* (= Λ*, Σ*) spectroscopy using Kaon beam (2 of 3)

Applications of ANL-Osaka DCC approach to Y* spectroscopy

Current status of Y* spectroscopy (some points may be missed) **:**

- ✓ **Much less understood than N* and Δ* baryons.**

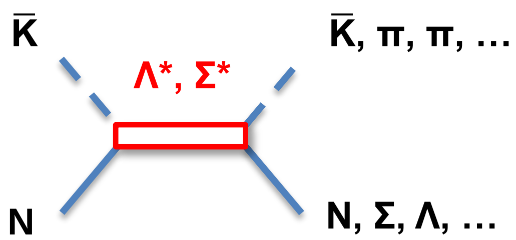
- ✓ **PDG lists only Y* mass spectrum defined by the "*highly model-dependent*" Breit-Wigner mass and width.**

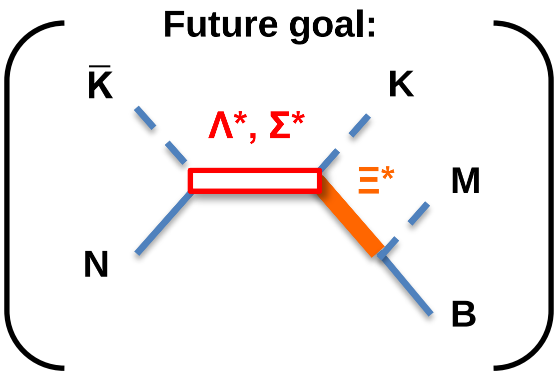
- ✓ **Systematic partial-wave analysis to extract *Y** *defined as poles of scattering amplitudes* was first performed by the KSU group (2013, on-shell K-matrix approach), and then by our group (2014, dynamical approach).**

Applications of ANL-Osaka DCC approach to Y* spectroscopy

✓ Y* spectroscopy using anti-Kaon beams

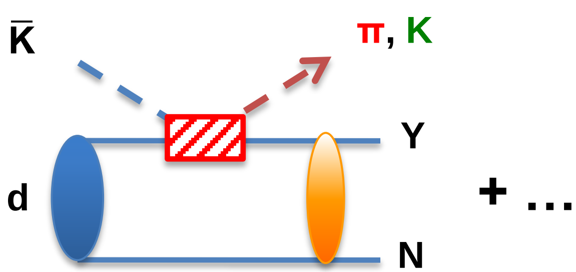
- The simplest reactions for studying Y*.

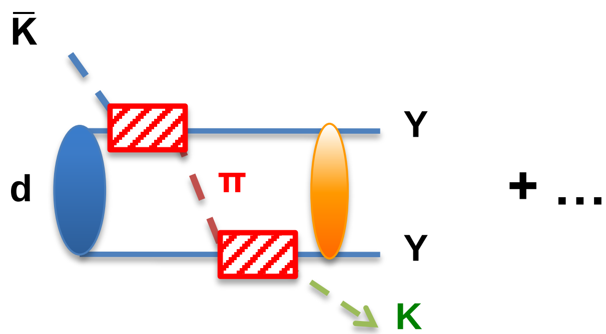




- Deuteron reactions allow direct access to Λ(1405) region and study of YN and YY interactions.

(Noumi et al., J-PARC E31)





Most importantly, J-PARC can measure all of these reactions!!

Applications of ANL-Osaka DCC approach to Y* spectroscopy

What we have done so far:

- ✓ Formulation of coupled-channels equations with $\bar{K}N$, $\pi\Sigma$, $\pi\Lambda$, $K\Xi$, $\pi\Sigma^*(\pi\pi\Lambda)$, $\bar{K}^*N(\pi\bar{K}N)$ channels

- ✓ Simultaneous analysis of available polarized and unpolarized data of $K^-p \rightarrow \bar{K}N, \pi\Sigma, \pi\Lambda, K\Xi$ from the threshold up to W = 2.1 GeV. (~ 17,000 data to fit)
  (HK, Nakamura, Lee, Sato, arXiv:1407.6839)

- ✓ Extraction of Λ^* and Σ^* mass spectrum defined by poles of scattering amplitudes. (HK, Nakamura, Lee, Sato, in preparation)

Applications of ANL-Osaka DCC approach to Y* spectroscopy

Database (mostly comes from 60-70's)

HK, Nakamura, Lee, Sato, arXiv:1407.6839

Reactions	Observables	Number of data	χ^2/data Model A	χ^2/data Model B
$K^-p \to K^-p$	$d\sigma/d\Omega$	3962	4.26	4.18
	P	510	2.26	2.17
	σ	253	2.50	2.72
$K^-p \to \bar{K}^0 n$	$d\sigma/d\Omega$	2950	3.79	3.15
	σ	260	1.93	2.98
$K^-p \to \pi^-\Sigma^+$	$d\sigma/d\Omega$	1792	5.83	5.55
	P	418	2.37	2.22
	$P \times d\sigma/d\Omega$	177	2.21	2.80
	σ	173	2.75	4.86
$K^-p \to \pi^0\Sigma^0$	$d\sigma/d\Omega$	580	6.24	8.15
	P	196	5.43	5.13
	$P \times d\sigma/d\Omega$	189	1.26	1.30
	σ	125	1.90	1.86
$K^-p \to \pi^+\Sigma^-$	$d\sigma/d\Omega$	1786	3.46	4.06
	σ	181	1.37	1.71
$K^-p \to \pi^0\Lambda$	$d\sigma/d\Omega$	2178	2.68	4.12
	P	693	1.46	1.66
	$P \times d\sigma/d\Omega$	176	1.43	1.38
	σ	207	2.23	2.51
$K^-p \to K^0\Xi^0$	σ	15	0.63	0.61
$K^-p \to K^+\Xi^-$	σ	27	1.60	1.52
Total		16848	3.67	3.81

Kinematical region covered (up to W < 2.1 GeV):

$d\sigma/d\Omega$: 1465 MeV < W
P : 1730 MeV < W
β, R, A: No data

$d\sigma/d\Omega$: 1465 MeV < W
P : No data
β, R, A: No data

$d\sigma/d\Omega$: 1535 MeV < W
P : 1535 MeV < W < 1967 MeV
β, R, A: No data

$d\sigma/d\Omega$: 1535 MeV < W < 1763 MeV
P : 1535 MeV < W < 1696 MeV
β, R, A: No data

$d\sigma/d\Omega$: 1536 MeV < W
P : No data
β, R, A: No data

$d\sigma/d\Omega$: 1535 MeV < W
P : 1535 MeV < W
β, R, A: No data

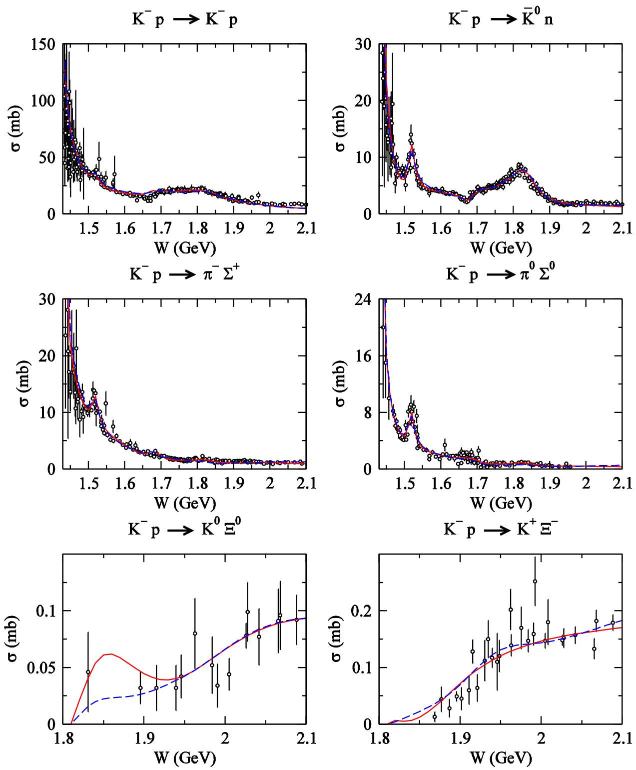
No data for $d\sigma/d\Omega$, P , β, R, A

Applications of ANL-Osaka DCC approach to Y* spectroscopy

HK, Nakamura, Lee, Sato, arXiv:1407.6839

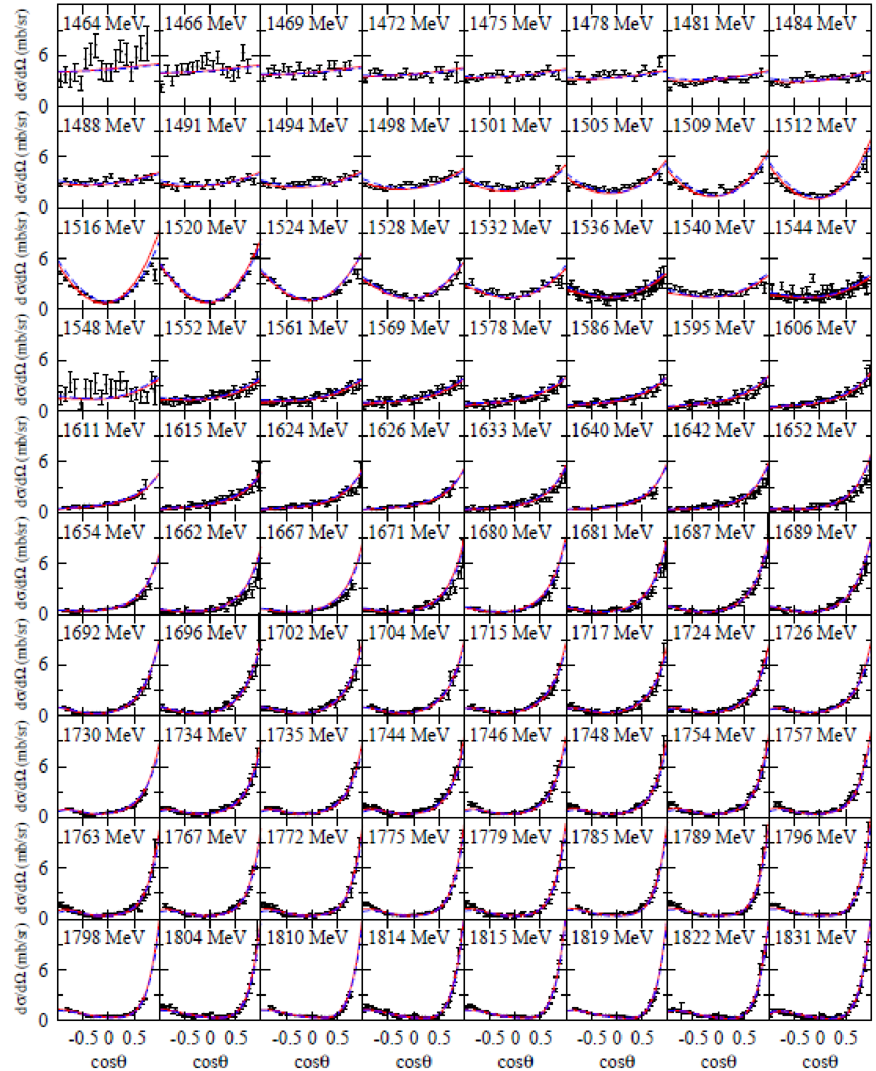
Results of the fit

TCS



Red: Model A

Blue: Model B

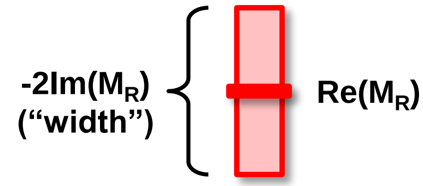


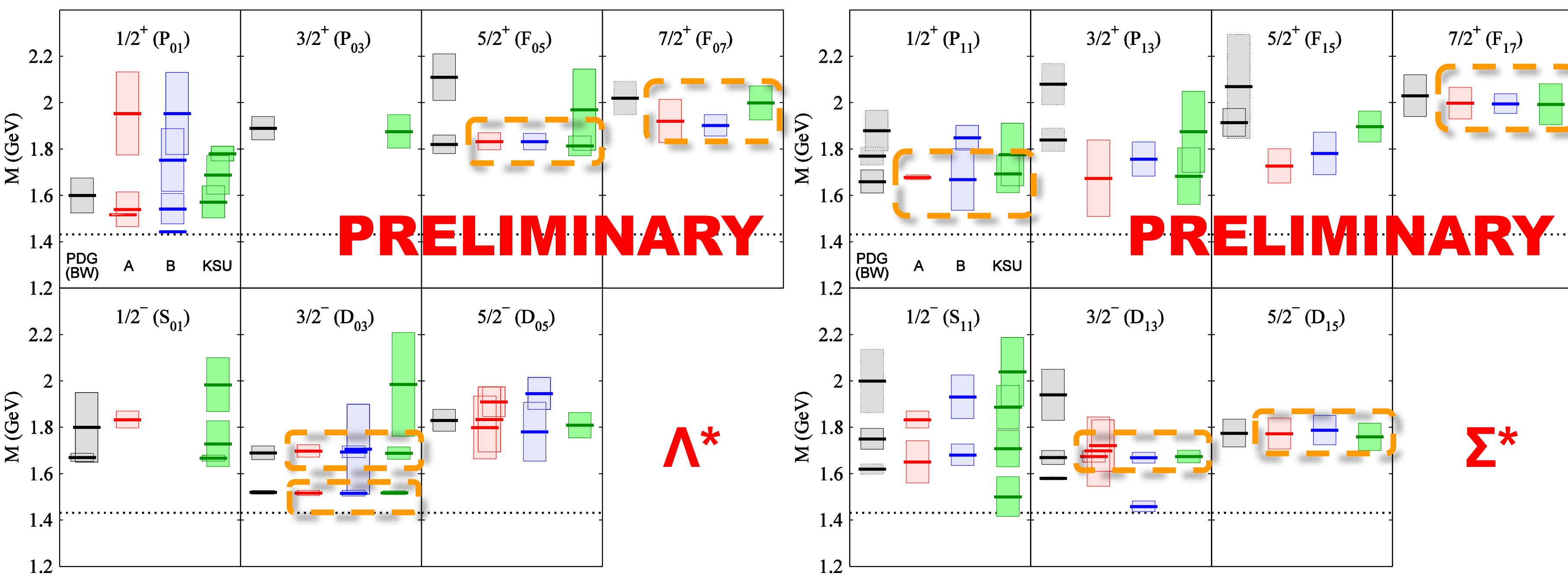
DCS for K-p → K-p

Applications of ANL-Osaka DCC approach to Y* spectroscopy

HK, Nakamura, Lee, Sato, in preparation

Extracted S = -1 Y* mass spectrum
(Here only Y*s above $\bar{K}N$ threshold are presented.)

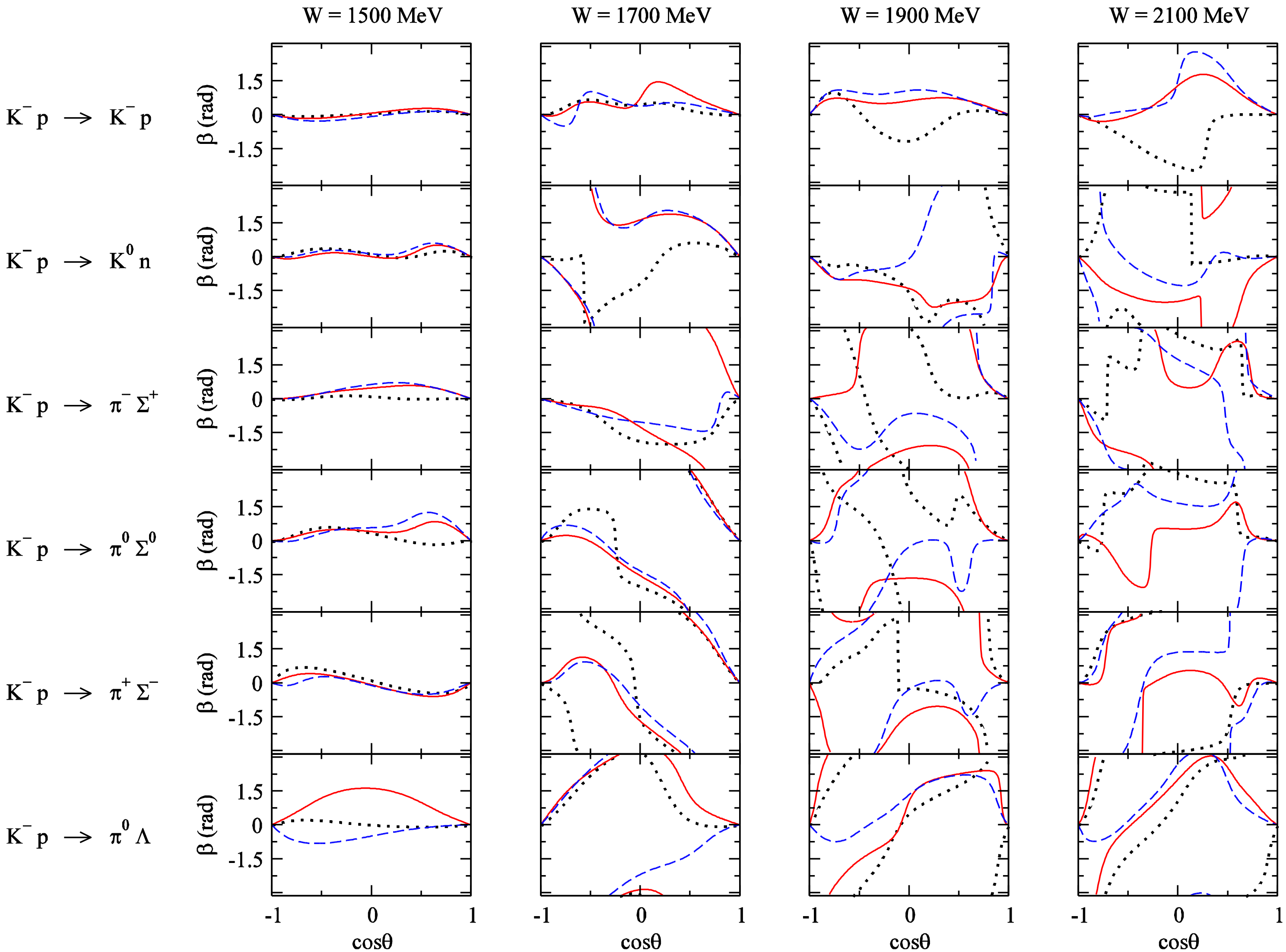




Red: Model A, Blue: Model B, Green: KSU [PRC88(2013)035205], Black: PDG(Breit-Wigner)

Predicted spin-rotation angle β

HK, Nakamura, Lee, Sato, arXiv:1407.6839



Red: Model A

Blue: Model B

Black: KSU

The KSU results are computed by us using their amplitudes in PRC88(2013)035204.

NOTE:
β is modulo 2π

Short summary and remarks (2/3)

- ✓ Systematic partial wave analyses to extract Y* defined by poles have been done recently by KSU and our groups.
- ✓ The K- p reaction data are still far from “complete”.
  (Limitation of kinematical coverage, no spin-rotation parameters,…)
  - ➢ Extracted Y* mass spectrum still contains sizable ambiguities !!
- ✓ To eliminate the ambiguities, one needs:
  - ➢ Polarization observables
    (*P* in wider kinematical region, spin-rotations β, R, or A)
  - ➢ Data near the $\bar{K}N$ threshold
    (Almost no differential cross section data below W = 1.5 GeV)
  - ➢ Data for inelastic reactions: K- p → ηΛ, KΞ, π$\bar{K}$N, ππΛ,…

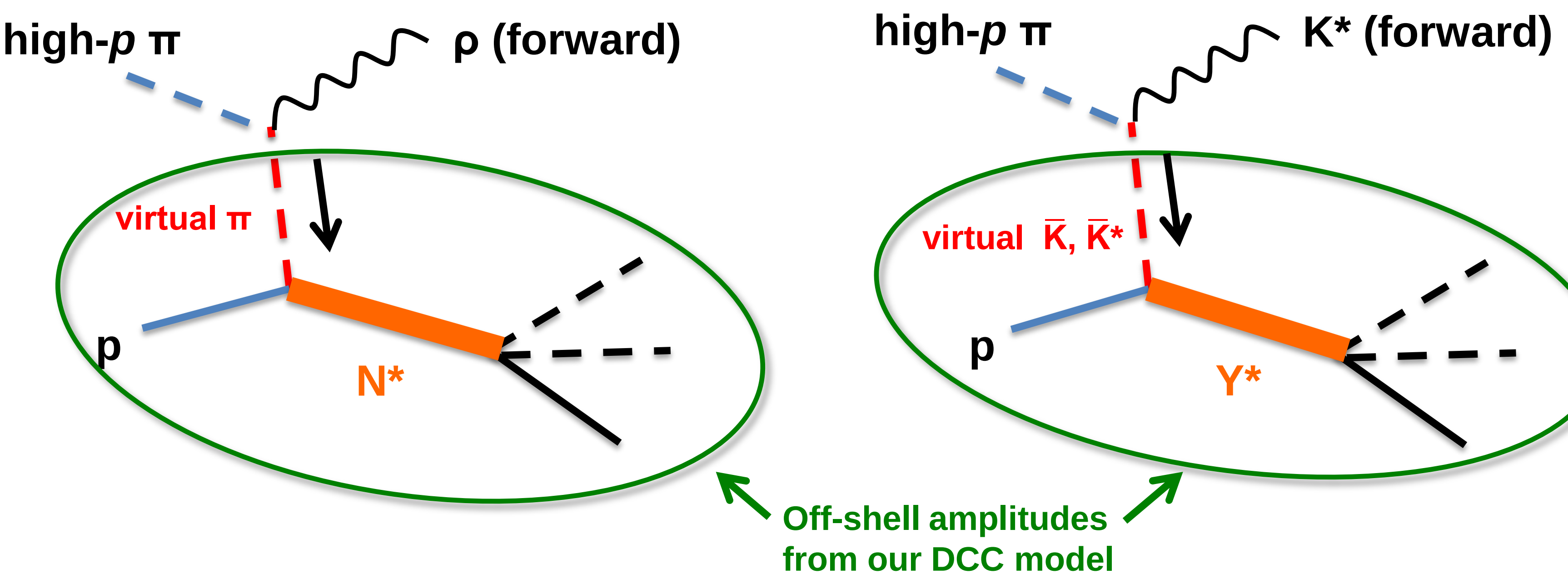
Applications of ANL-Osaka DCC approach to p(π, ρ or K*)X with high-momentum pion beam (3 of 3)

Applications of ANL-Osaka DCC approach to forward p(π,V)X reactions

✓ **Forward p(π,ρ)X & p(π, K*)X reactions with high-momentum pions (Ishikawa-san's talk at RCNP May 1st, 2012)**

- **New opportunity** of light-quark baryon spectroscopy using diffractive processes
  (→ another useful source for addressing the $\bar{K}$N subthreshold region!!)

- May be able to be used for determining **N-N* and N-Y* transition form factors** by **axial currents** (from virtual-πNN*, virtual-$\bar{K}$NY* vertices + PCAC).

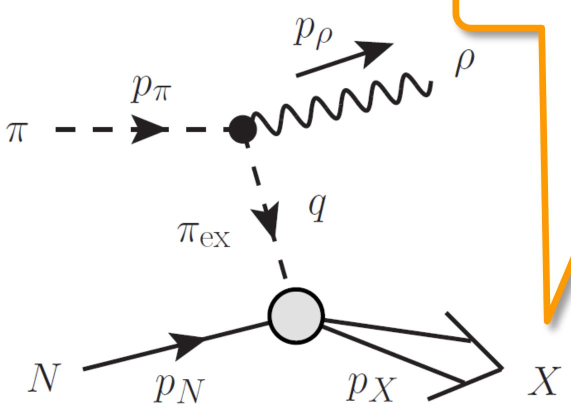


Applications of ANL-Osaka DCC approach to forward p(π,V)X reactions

Formulation:

X=πN, ηN, ππN, KY,…

HK, in preparation



$$\frac{d\sigma}{dt dW^2} = \frac{\sqrt{\lambda(W^2, m_N^2, t)}}{32\pi^2 \lambda(s, m_N^2, m_\pi^2)} |D_{\pi_{\rm ex}}|^2 \times \left(\sum_{S_\rho^z} |F^{(S_\rho^z)}_{\rho\pi_{\rm ex},\pi}(t)|^2\right) (I_\rho I_\rho^z, I_{\pi_{\rm ex}} I_\pi^z - I_\rho^z | I_\pi I_\pi^z)^2 \times \underline{\sigma_{X,\pi_{\rm ex}N}}.$$

Cross section for (half-off-shell) π_{ex} N → X reaction

→ Calculated with our DCC model

- **ρππ vertex function:**

$$\sum_{S_\rho^z} \left|F^{(S_\rho^z)}_{\rho\pi_{\rm ex},\pi}(t)\right|^2 = 2g^2_{\rho\pi\pi}\left(m_\rho^2 - 2(t+m_\pi^2) + \frac{(t-m_\pi^2)^2}{M_\rho^2}\right)[F(t)]^2. \qquad F(t) = \left(\frac{\Lambda^2_{\rho\pi\pi} - m_\pi^2}{\Lambda^2_{\rho\pi\pi} - t}\right)$$

$g_{\rho\pi\pi} = 6.04$ (from $\rho \to \pi\pi$ decay) $\qquad \Lambda_{\rho\pi\pi} = 900$ MeV [PRC24(1981)2611]

- **π propagator (Reggeized) [e.g., Guidal et al, NPA627(1997)645]:**

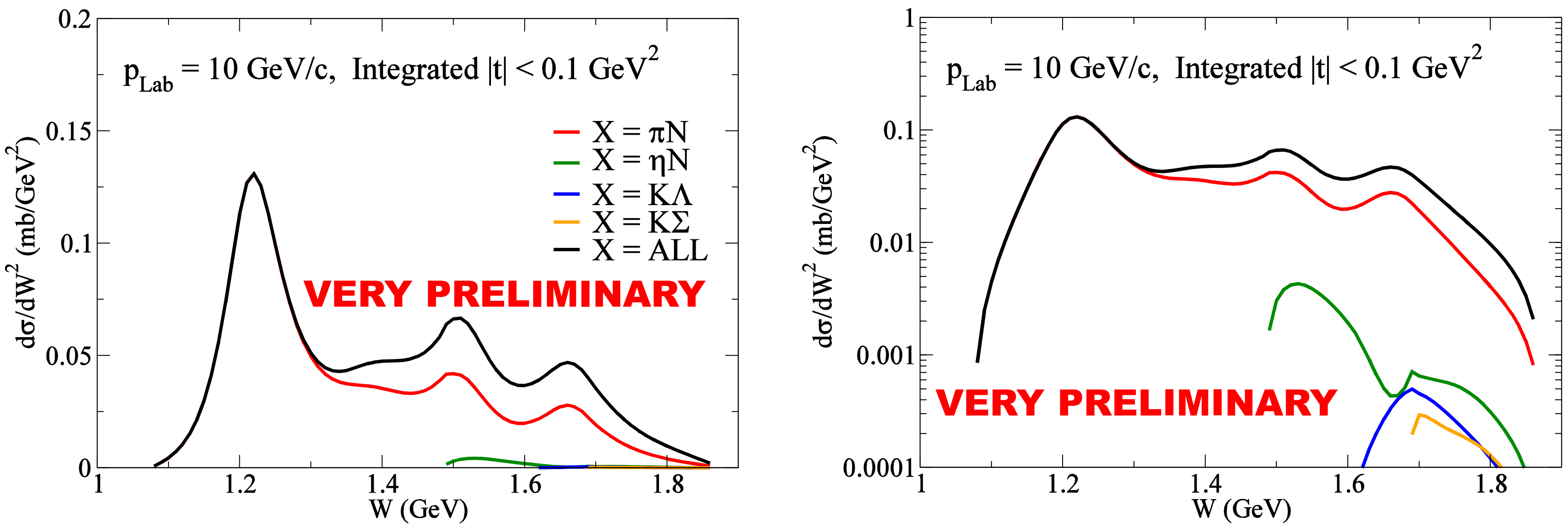
$$D_{\rm ex} = \left(\frac{s}{s_0}\right)^{\alpha(t)} \frac{\pi\alpha'}{\sin(\pi\alpha(t))} \frac{S + e^{-i\pi\alpha(t)}}{2} \frac{1}{\Gamma(1+\alpha(t))}$$

Applications of ANL-Osaka DCC approach to forward p(π,V)X reactions

$$\frac{d\sigma}{dW^2} \equiv \int_{-t_{\min}}^{-t_{\max}=0.1GeV^2} d(-t)\,\frac{d\sigma}{d(-t)dW^2}$$

HK, in preparation

$\pi^- p \rightarrow \rho^0 X$

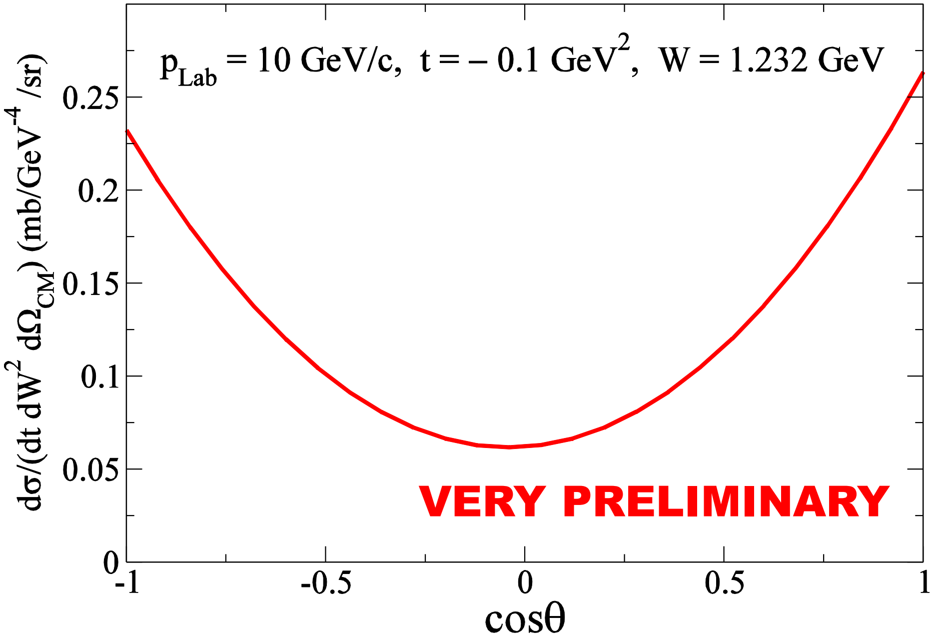


Contributions of X = ηN, KΛ, KΣ are much smaller than X = πN, ππN.

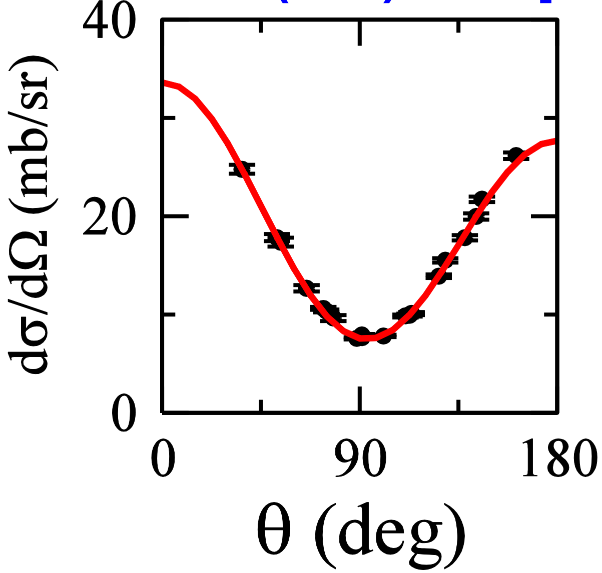
Applications of ANL-Osaka DCC approach to forward p(π,V)X reactions

HK, in preparation

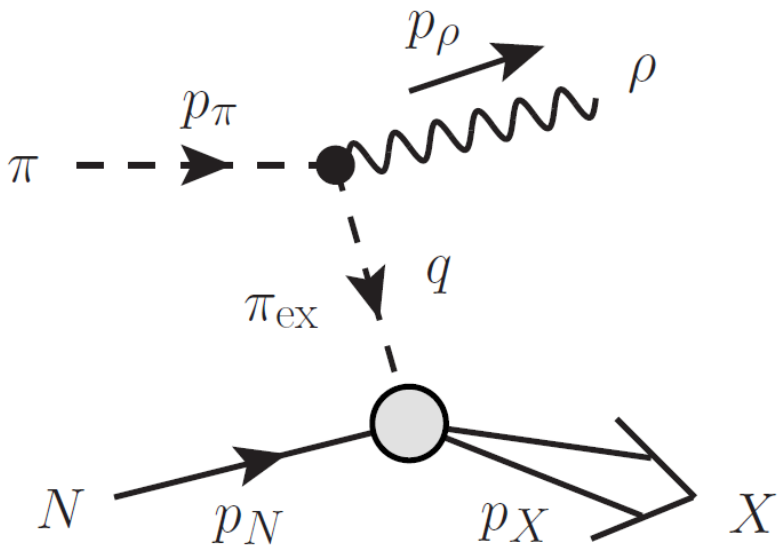
Angular distribution for $\pi^+ p \to \rho^0 X$ with $X = \pi^+ p$



DCS of π+ p scattering at W = 1.232 GeV [HK, Nakamura, Lee, Sato PRC88(2013)035209]



Short summary and remarks (3/3)



- An attempt to using forward p(π,ρ)X for light-quark baryon spectroscopy is underway within our DCC model.
- Application to p(π,K*)X will also be possible using our DCC model for K- p reactions !!