Meson production reactions for investigating hadron structure: New opportunities at J-PARC

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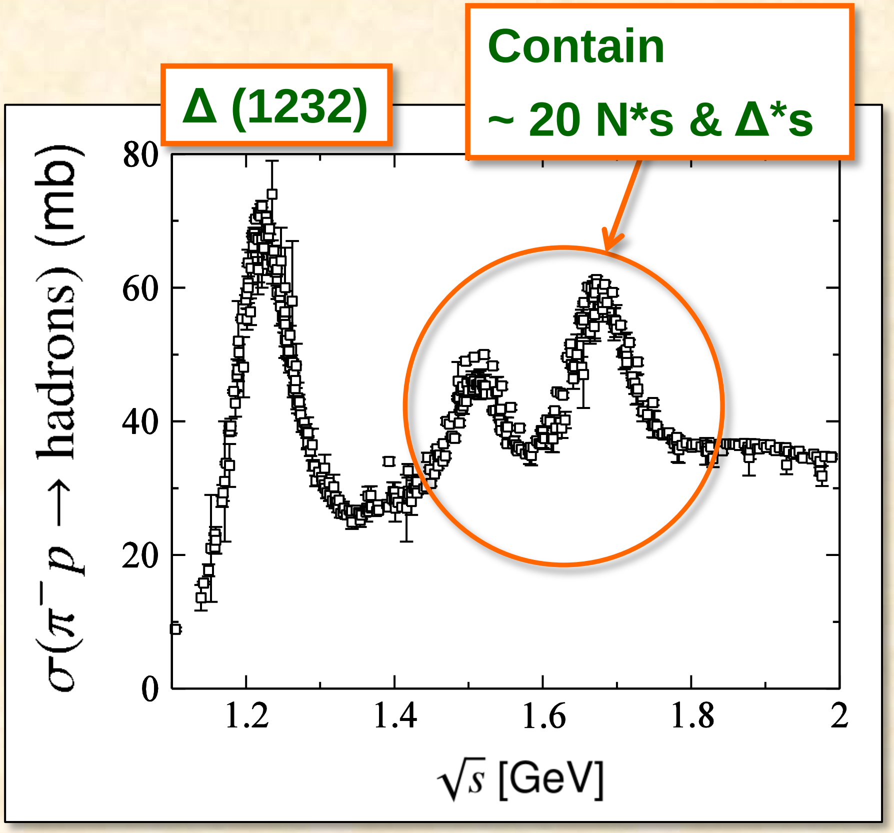
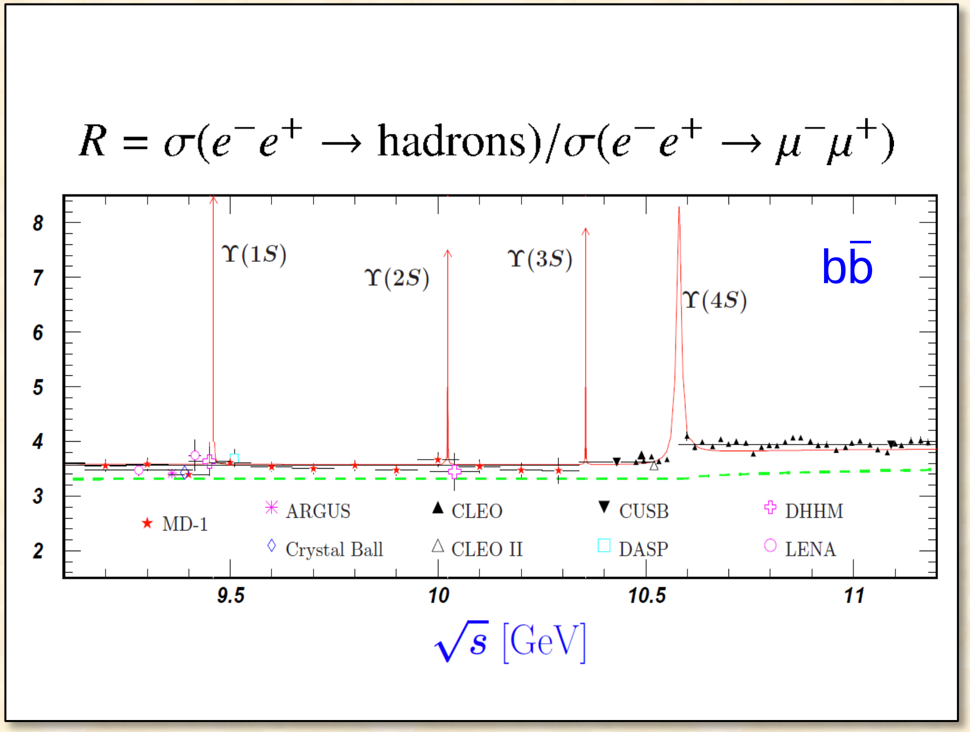
Workshop on J-PARC Hadron Physics
Feb 10-12, 2014

Light-flavor baryon spectroscopy : Physics of broad & overlapping resonances





- ✓ **Width: a few hundred MeV.**
- ✓ **Resonances are highly overlapping in energy except Δ(1232).**

- ✓ **Width: ~10 keV to ~10 MeV**
- ✓ **Each resonance peak is clearly separated.**

N* states and PDG *s

Particle	J^P	Status overall	πN	γN	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
N	$1/2^+$	****									
$N(1440)$	$1/2^+$	****	****	****		***				*	***
$N(1520)$	$3/2^-$	****	****	****	***					***	***
$N(1535)$	$1/2^-$	****	****	****	****					**	*
$N(1650)$	$1/2^-$	****	****	***	***			***	**	**	***
$N(1675)$	$5/2^-$	****	****	***	*			*		*	***
$N(1680)$	$5/2^+$	****	****	****	*	**				***	***
$N(1685)$	$?^?$	*									
$N(1700)$	$3/2^-$	***	***	**	?			*	*	*	***
$N(1710)$	$1/2^+$	***	***	***	***		**	***	**	*	**
$N(1720)$	$3/2^+$	****	****	***	***			**	**	**	*
$N(1860)$	$5/2^+$	**	**							*	*
$N(1875)$	$3/2^-$	***	*	***			**	***	**		***
$N(1880)$	$1/2^+$	**	*	*		**		*			
$N(1895)$	$1/2^-$	**	*	**	? **			**	*		
$N(1900)$	$3/2^+$	***	**	***	**		**	***	**	*	**
$N(1990)$	$7/2^+$	**	**	**					*		
$N(2000)$	$5/2^+$	**	*	**	**			**	*	**	
$\Delta(1232)$	$3/2^+$	****	****	****	F						
$\Delta(1600)$	$3/2^+$	***	***	***	? o					*	***
$\Delta(1620)$	$1/2^-$	****	****	***		r				***	***
$\Delta(1700)$	$3/2^-$	****	****	****		b				**	***
$\Delta(1750)$	$1/2^+$	*	*		?		i				
$\Delta(1900)$	$1/2^-$	**	**	**			d		**	**	**
$\Delta(1905)$	$5/2^+$	****	****	****			d		***	**	**
$\Delta(1910)$	$1/2^+$	****	****	**				e	*	*	**
$\Delta(1920)$	$3/2^+$	***	***	**				n	***		**
$\Delta(1930)$	$5/2^-$	***	***		?						
$\Delta(1940)$	$3/2^-$	**	*	**	F				(seen	in	$\Delta\eta$)
$\Delta(1950)$	$7/2^+$	****	****	****	o				***	*	***
$\Delta(2000)$	$5/2^+$	**			?	r					**

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$\Delta(1910)$	$1/2^+$	****	****	**				e	*	*	**
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All of these studies essentially agree on the existence and (most) properties of the 4-star states. For the 3-star and lower states, however, even a statement of existence is problematic.

—— **Arndt, Briscoe, Strakovsky, Workman PRC 74 045205 (2006)**

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Most of the N*s were determined from

$$\pi N \to \pi N\ ,\quad \gamma N \to \pi N$$

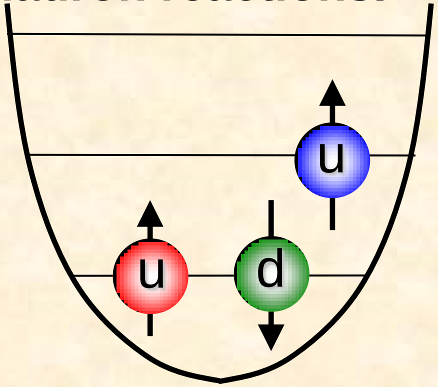
Need *comprehensive analysis* of

$$\pi N,\ \eta N,\ \pi\pi N,\ KY,\ \omega N, \ldots$$

channels !!

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



Constituent quark model

Hadron spectrum and reaction dynamics

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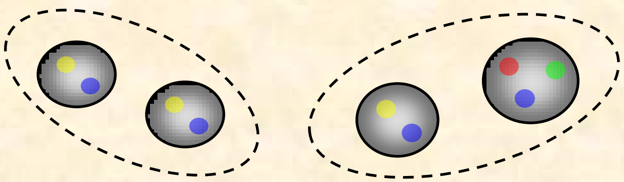
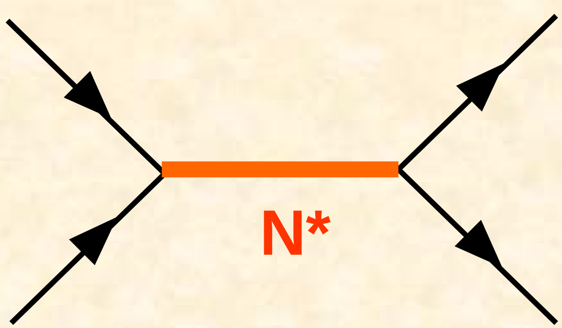
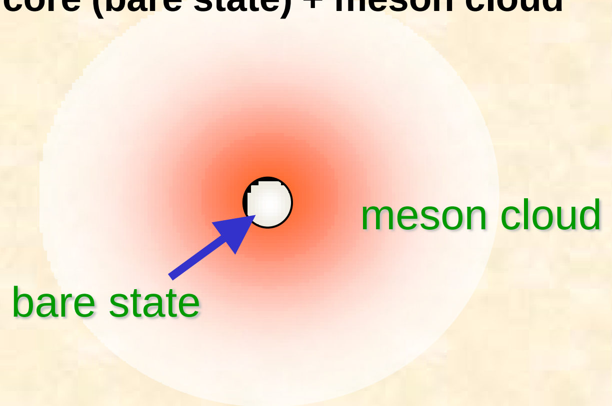
“Mass” becomes complex !!
→ “pole mass”

“molecule-like” states





core (bare state) + meson cloud



Hadron spectrum and reaction dynamics

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What is the role of reaction dynamics in interpreting the hadron spectrum, structures, and dynamical origins ??

Approaches to N* spectroscopy

Reaction Data

$$\pi N \rightarrow \pi N,\ \eta N,\ \pi\pi N,\ KY,\ \omega N...$$
$$\gamma^{(*)} N \rightarrow \pi N,\ \eta N,\ \pi\pi N,\ KY,\ \omega N...$$


JLab, ELSA, MAMI, SPring-8, ELPH,…

Analysis based on reaction theory

Mass, width, form factors, etc of N* & Δ*

QCD-inspired Hadron Models

Lattice QCD

QCD

Constituent quark models
Soliton models
Holographic QCD etc

N* spectroscopy with **multichannel unitary reaction models** has made a significant progress.

✓ **Multichannel unitary condition:**

$$T_{ab}(E) - T^{\dagger}_{ab}(E) = -2\pi i \sum_c T^{\dagger}_{ac}\delta(E - E_c)T_{cb}(E)$$
$$a, b, c \;=\; (\gamma^{(*)}N,\ \pi N,\ \eta N,\ \pi\pi N,\ K\Lambda,\ K\Sigma,\ \omega N\cdots)$$

- Ensures conservation of probability.
- Defines analytic structure (branch points, cuts) of the amplitudes in complex-E plane.

ANL-Osaka/EBAC-JLab, Bonn-Gatchina, Carnegie Mellon-Berkely, Dubna-Mainz-Taipei, VPI/GWUGeorge, Giessen, Juelich, Karlsruhe-Helsinki, …

Our 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, PRC88 (2013) 035209

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

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

✓ **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:**

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

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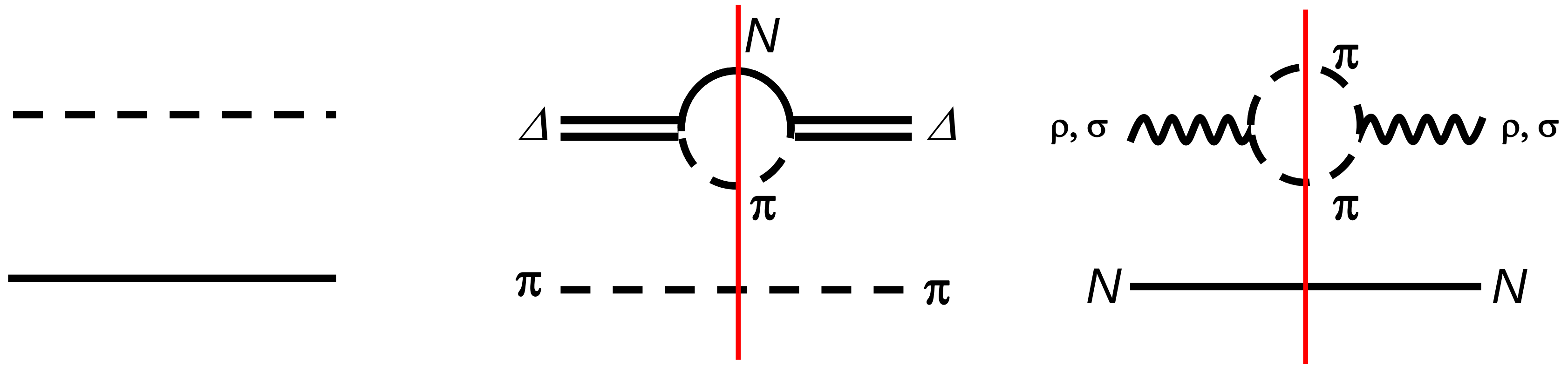
✓ **Meson-Baryon Green functions** G_{MB}

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

Stable channels

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

Quasi 2-body channels



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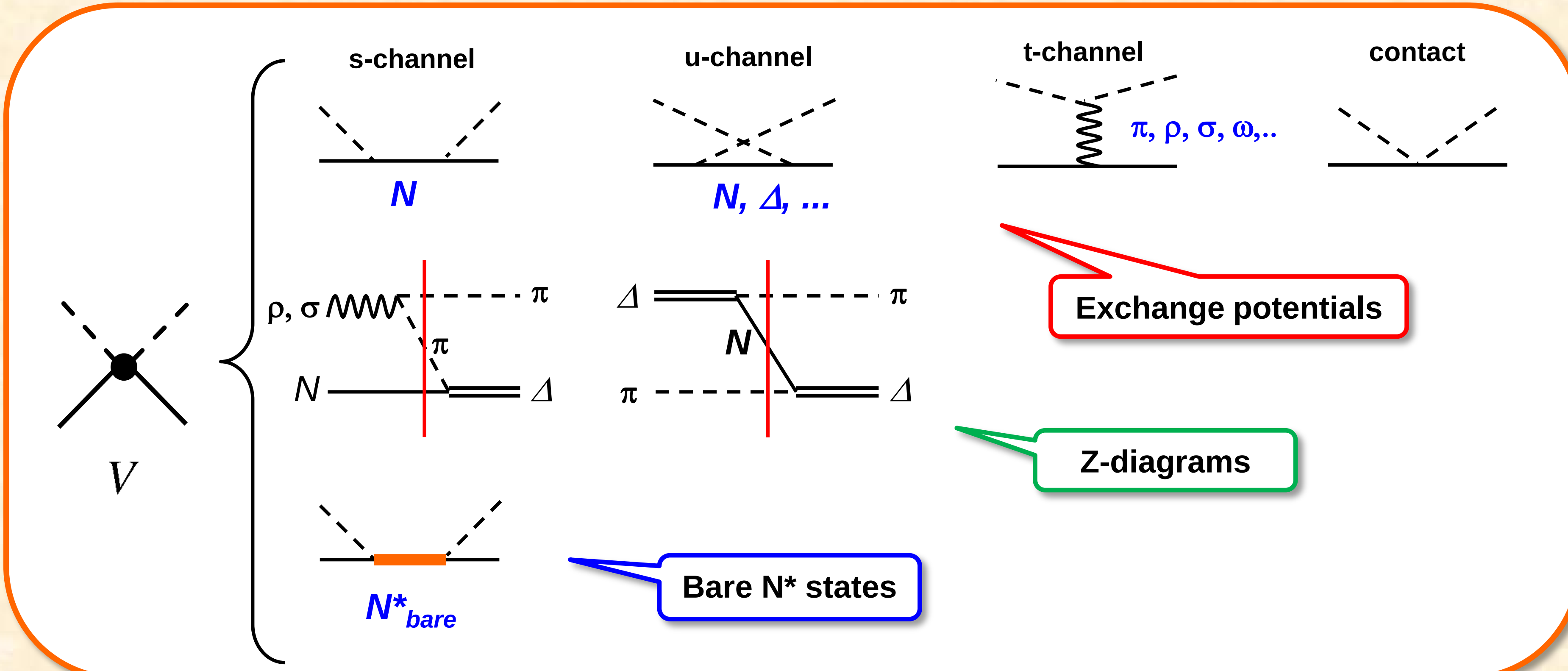

$$V_{a,b} = v_{a,b} + Z_{a,b} + \sum_{N^*} \frac{\Gamma^{\dagger}_{N^*,a}\Gamma_{N^*,b}}{E - M_{N^*}}$$

Exchange potentials | Z-diagrams | bare N* states

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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:**

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

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

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

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

Exchange potentials $\quad$ Z-diagrams $\quad$ bare N* states

Strategy for the N* spectroscopy

Step 1

Couplings, cutoffs, masses of bare N*s, etc.

Determine model parameters by performing χ^2-fit of the world data of meson production reactions.

Step 2

Extract resonance parameters (pole masses, form factors etc.) from the constructed model by making the analytic continuation of the amplitudes to the complex energy plane.

Step 3

Examine role of multichannel reaction dynamics in understanding the spectrum, internal structure and production mechanisms of the N* resonances.

Our analyses of meson production reactions

Fully combined **analysis of πN , $\gamma N \rightarrow \pi N$, ηN , $K\Lambda$, $K\Sigma$ reactions !!**

	2006 – 2009 (EBAC/JLab)	2010 – 2013 (ANL-Osaka)
✓ # of coupled channels	6 channels ($\gamma N,\pi N,\eta N,\pi\Delta,\rho N,\sigma N$)	8 channels ($\gamma N,\pi N,\eta N,\pi\Delta,\rho N,\sigma N,K\Lambda,K\Sigma$)
✓ $\pi p \rightarrow \pi N$	< 2 GeV	< 2.3 GeV
✓ $\gamma p \rightarrow \pi N$	< 1.6 GeV	< 2.1 GeV
✓ $\pi p \rightarrow \eta N$	< 2 GeV	< 2.1 GeV
✓ $\gamma p \rightarrow \eta p$	—	< 2.1 GeV
✓ $\pi p \rightarrow K\Lambda, K\Sigma$	—	< 2.1 GeV
✓ $\gamma p \rightarrow K^+\Lambda, K\Sigma$	—	< 2.1 GeV

Julia-Diaz, Lee, Matsuyama, Sato, PRC76 (2007) 065201; Julia-Diaz, et al., PRC77 (2008) 045205

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

Database for ANL-Osaka DCC analysis

πN → πN PWA from SAID

Partial wave		Partial wave		
S_{11}	65×2	S_{31}	65×2	
P_{11}	65×2	P_{31}	61×2	
P_{13}	61×2	P_{33}	65×2	
D_{13}	61×2	D_{33}	59×2	
D_{15}	61×2	D_{35}	40×2	
F_{15}	48×2	F_{35}	43×2	
F_{17}	32×2	F_{37}	44×2	
G_{17}	42×2	G_{37}	32×2	
G_{19}	28×2	G_{39}	32×2	
H_{19}	34×2	H_{39}	31×2	
Sum	994		944	1938

πp → ηN, KΛ, KΣ observables

	$d\sigma/d\Omega$	P	β	Sum
$\pi^- p \to \eta p$	294	–	–	294
$\pi^- p \to K^0 \Lambda$	544	262	43	849
$\pi^- p \to K^0 \Sigma^0$	160	70	–	230
$\pi^+ p \to K^+ \Sigma^+$	552	312	7	871
Sum	1550	644	50	2244

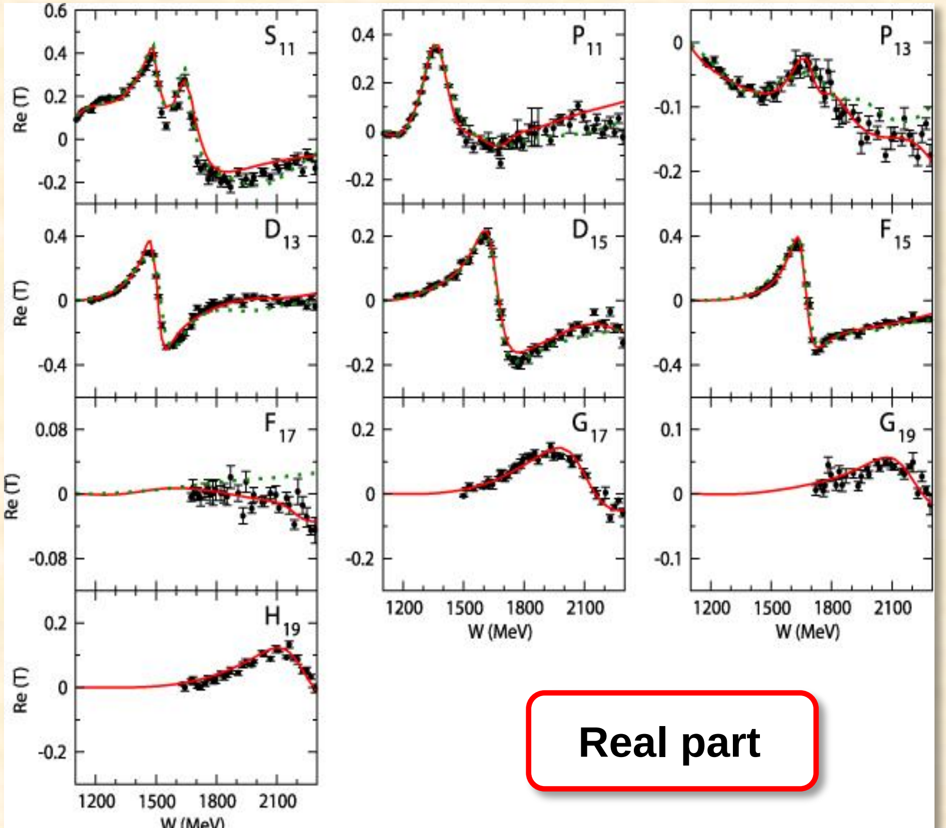
HK, Nakamura, Lee, Sato
PRC88 (2013) 035209

22,348 data of unpolarized & polarized observables to fit !!

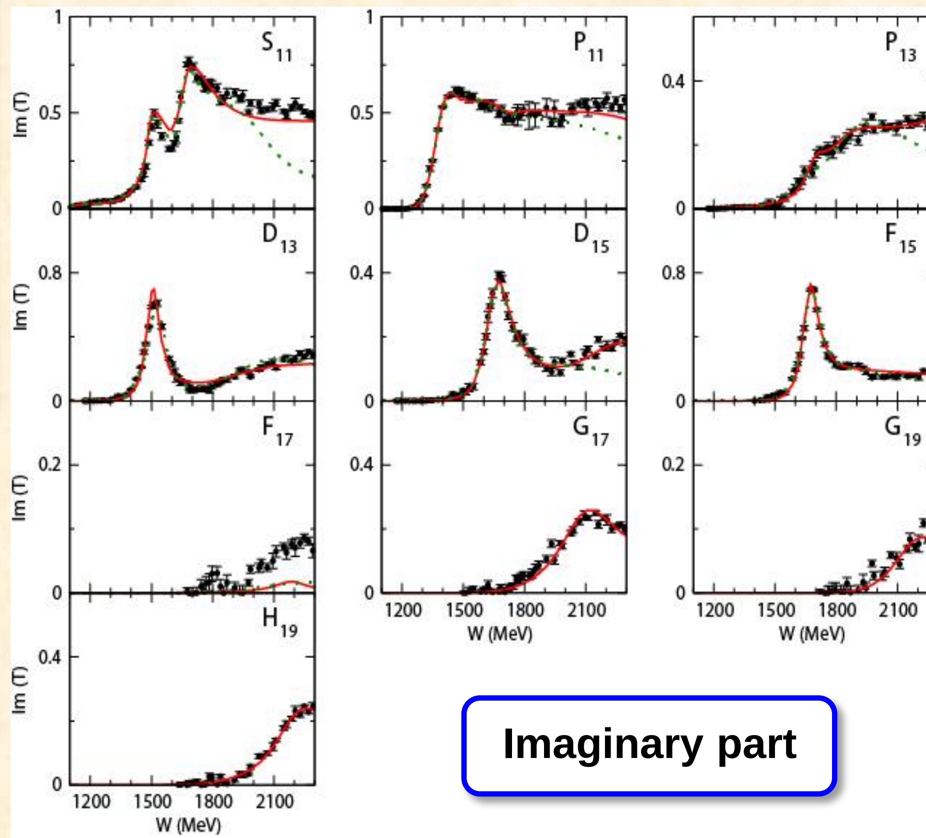
γp → πN, ηp, KΛ, KΣ observables

	$d\sigma/d\Omega$	Σ	T	P	$\hat{E}$	G	H	$O_{x'}$	$O_{z'}$	C_x	C_z	Sum
$\gamma p \to \pi^0 p$	4381	1128	380	589	140	125	49	7	7	–	–	6806
$\gamma p \to \pi^+ n$	2315	747	678	222	231	86	128	–	–	–	–	4407
$\gamma p \to \eta p$	3221	235	50	–	–	–	–	–	–	–	–	3506
$\gamma p \to K^+ \Lambda$	800	86	66	865	–	–	–	66	66	79	79	2107
$\gamma p \to K^+ \Sigma^0$	758	62	–	169	–	–	–	–	–	40	40	1069
$\gamma p \to K^0 \Sigma^+$	220	15	–	36	–	–	–	–	–	–	–	271
Sum	11 695	2273	1174	1881	371	211	177	73	73	119	119	18166

Partial wave amplitudes of πN scattering



$$I = \frac{1}{2}$$



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

previous 6ch DCC-analysis
(fitted to $\pi N \rightarrow \pi N$ data only up to
W = 2 GeV and F wave)
[Julia-Diaz et al., PRC76 (2007) 065201]

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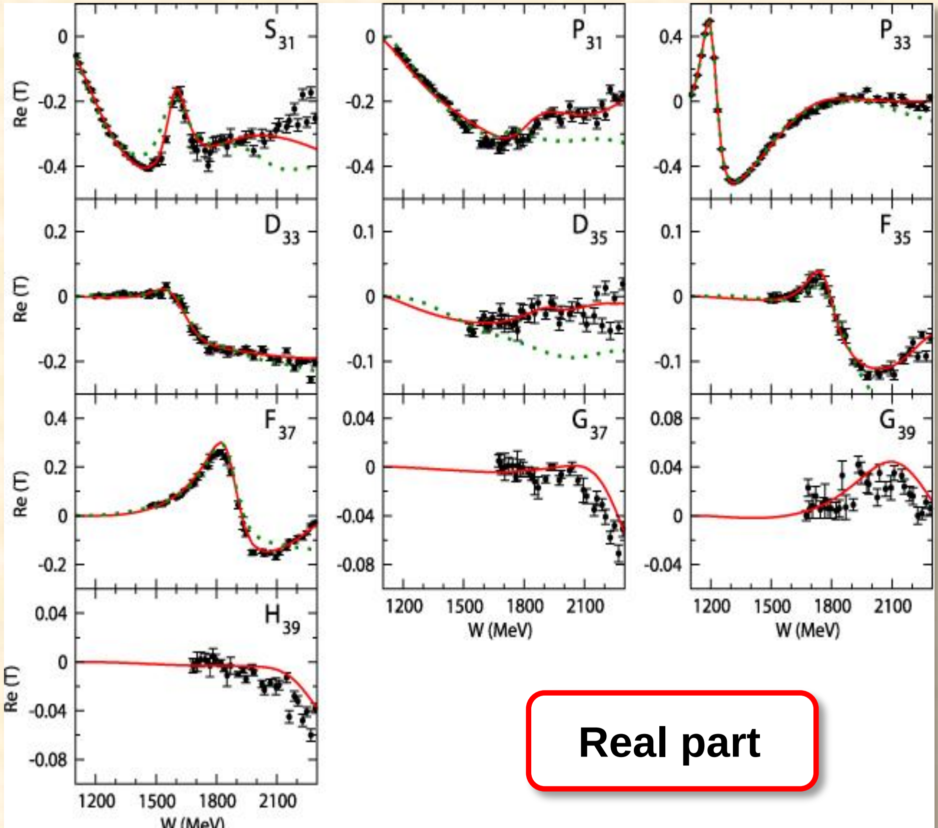
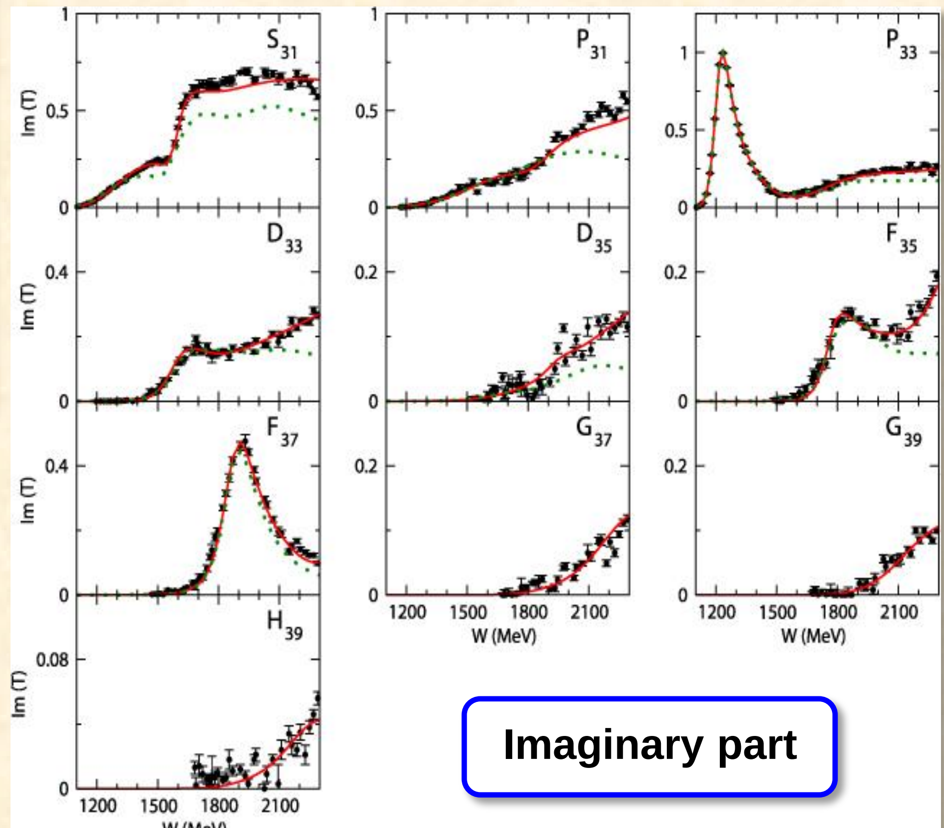


$$I = \frac{3}{2}$$



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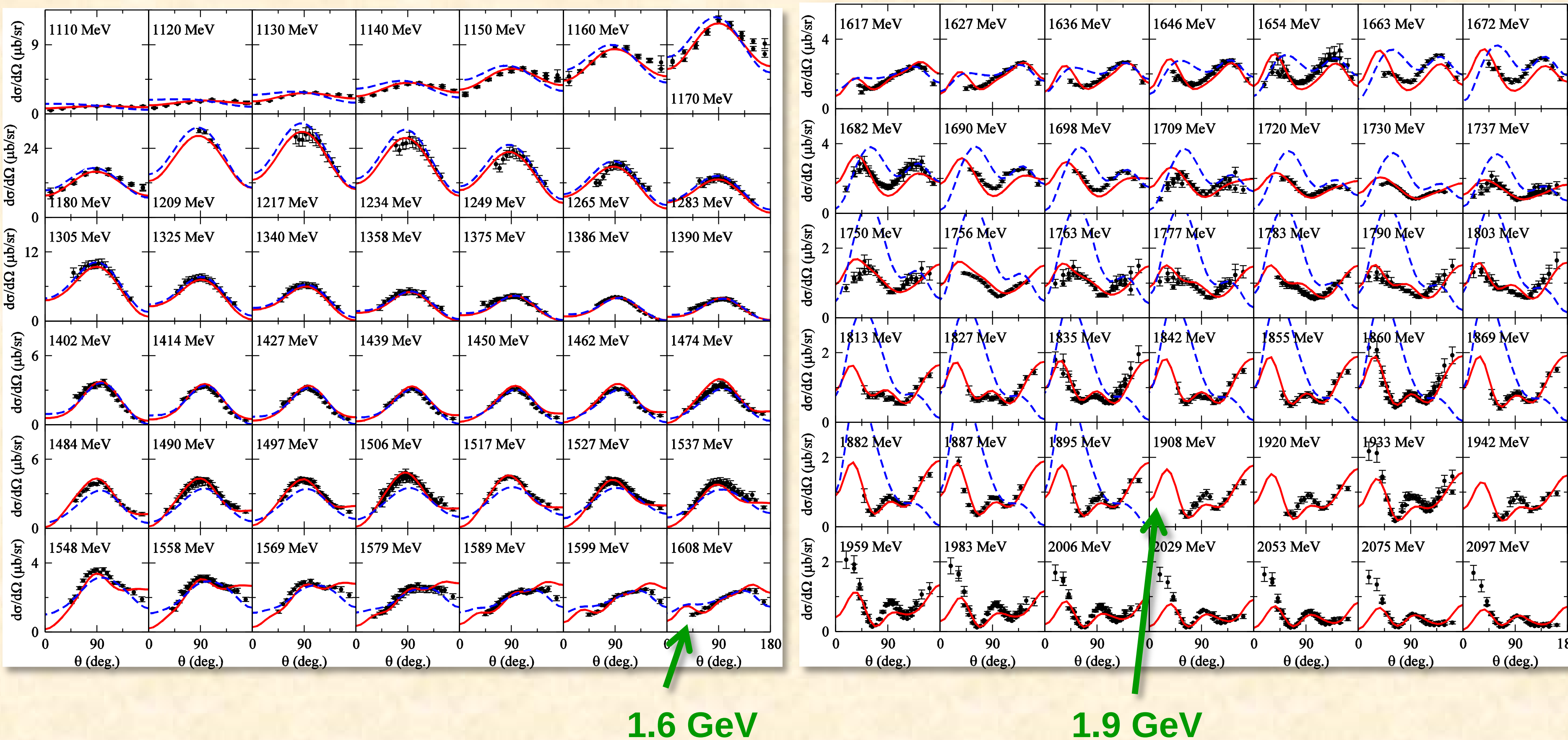
γ p → π^0 p reaction

Differential cross section (W = 1.08-2.1 GeV)



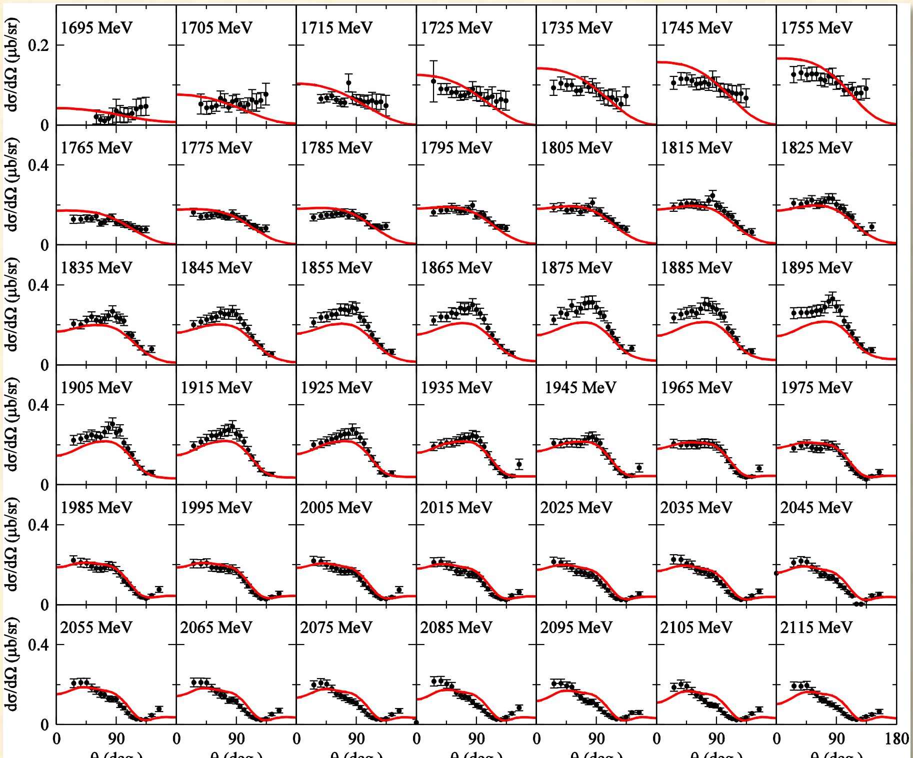
8ch DCC-analysis
[HK, Nakamura, Lee, Sato, PRC88 (2013) 035209]

previous 6ch DCC-analysis
(fitted to γN → πN data only up to W = 1.6 GeV)
[Julia-Diaz et al., PRC77 (2008) 045205]

$\gamma\, p \rightarrow K^+ \Sigma^0$ reaction

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

DCS



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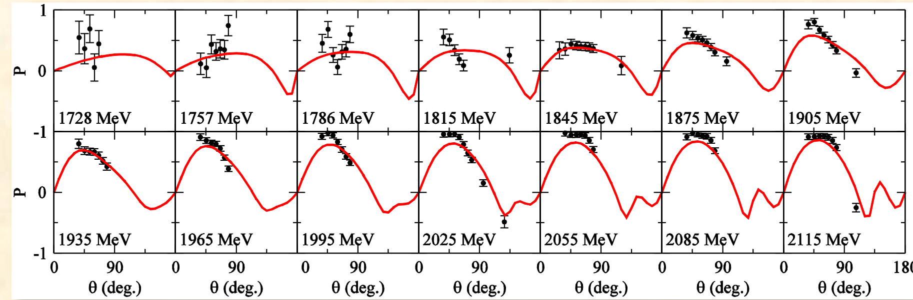
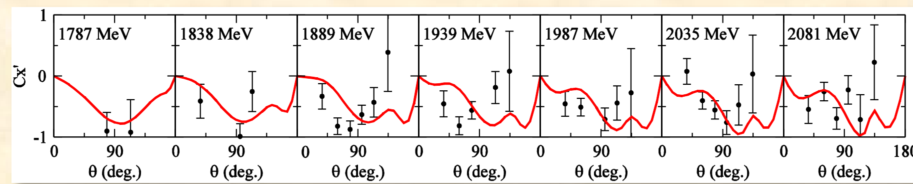
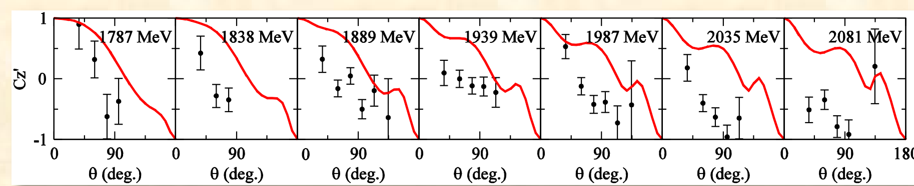
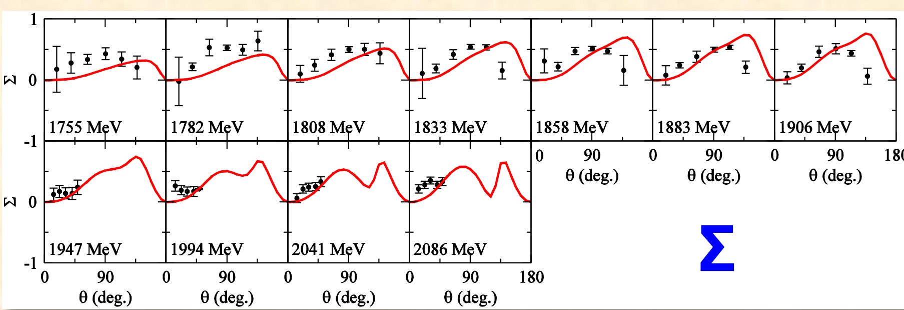


Cx’



Cz’





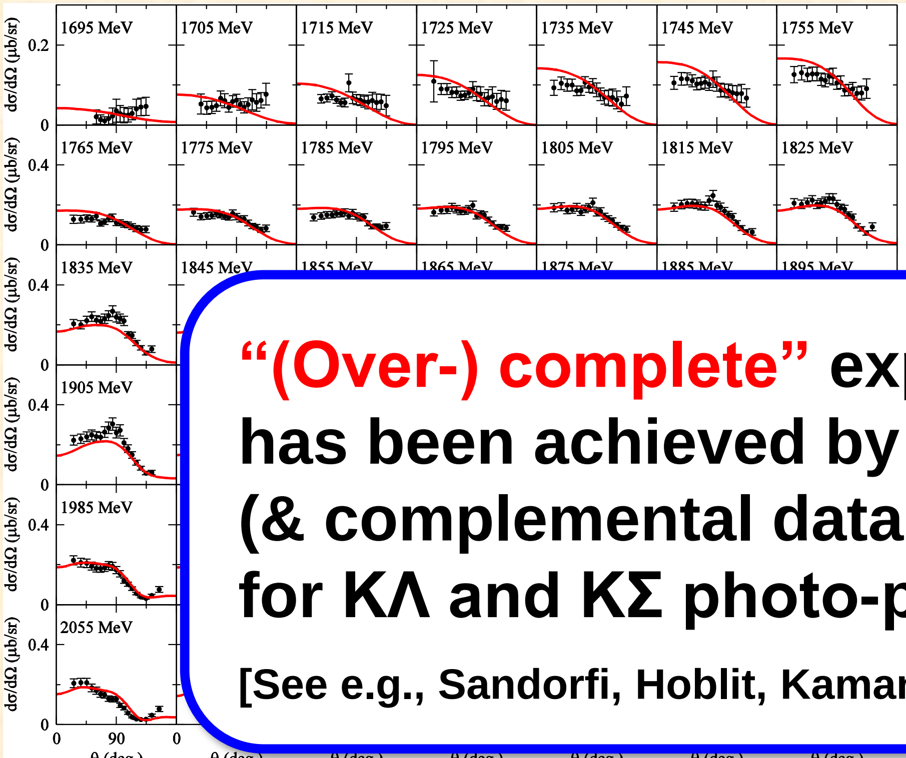
Σ

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

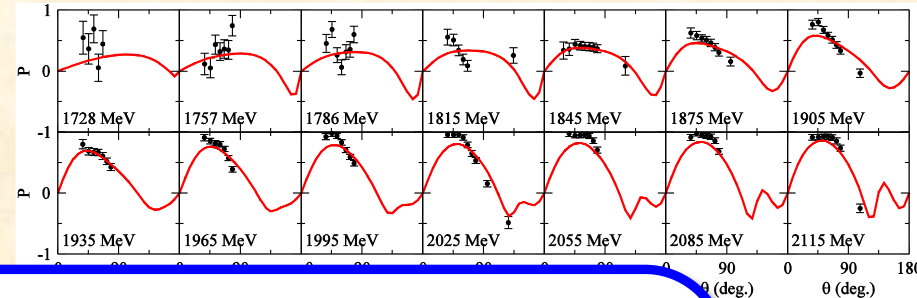
γ p → K⁺ Σ⁰ reaction

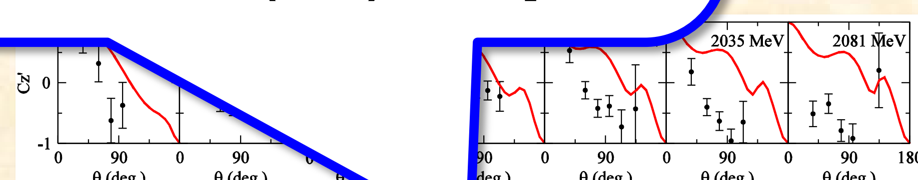
8ch DCC-analysis
[HK, Nakamura, Lee, Sato, PRC88 (2013) 035209]

DCS



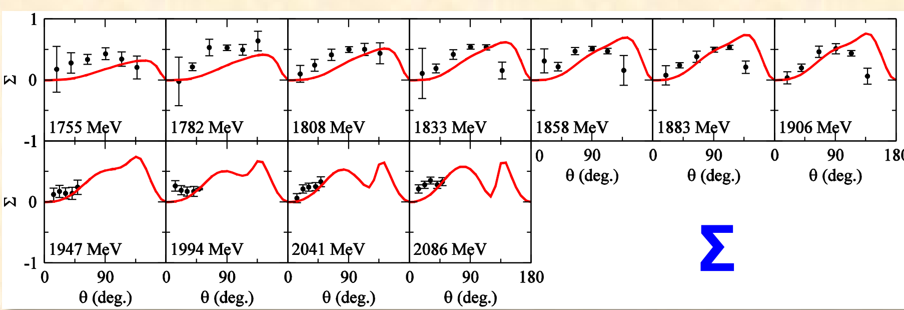
P





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

[See e.g., Sandorfi, Hoblit, Kamano, Lee, JPG38(2011)053001]



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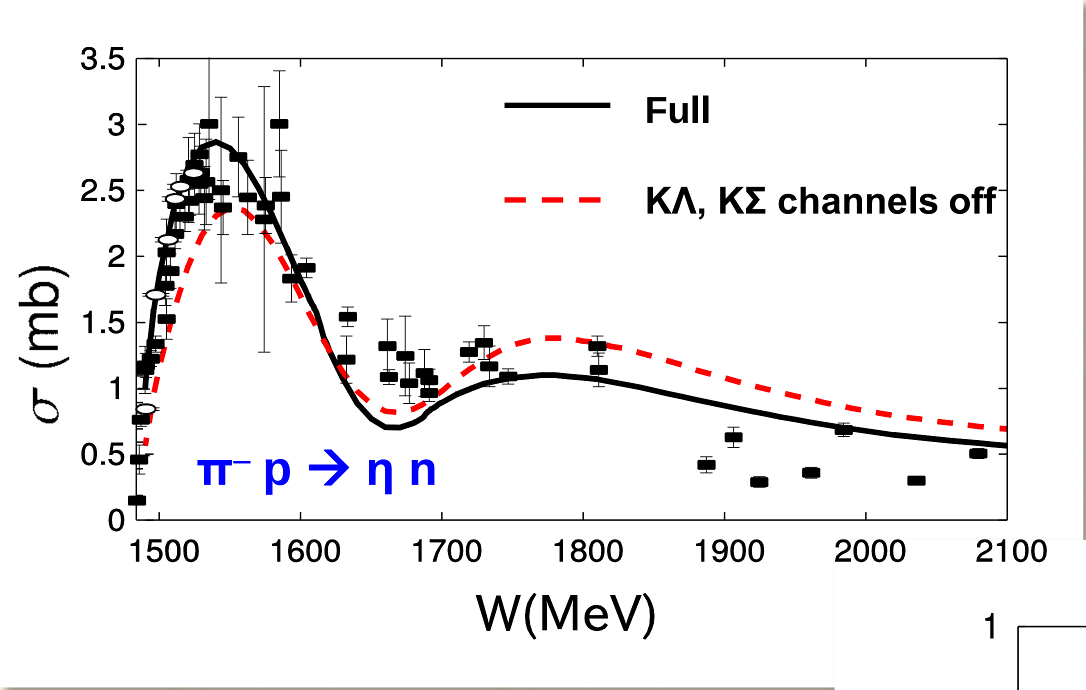
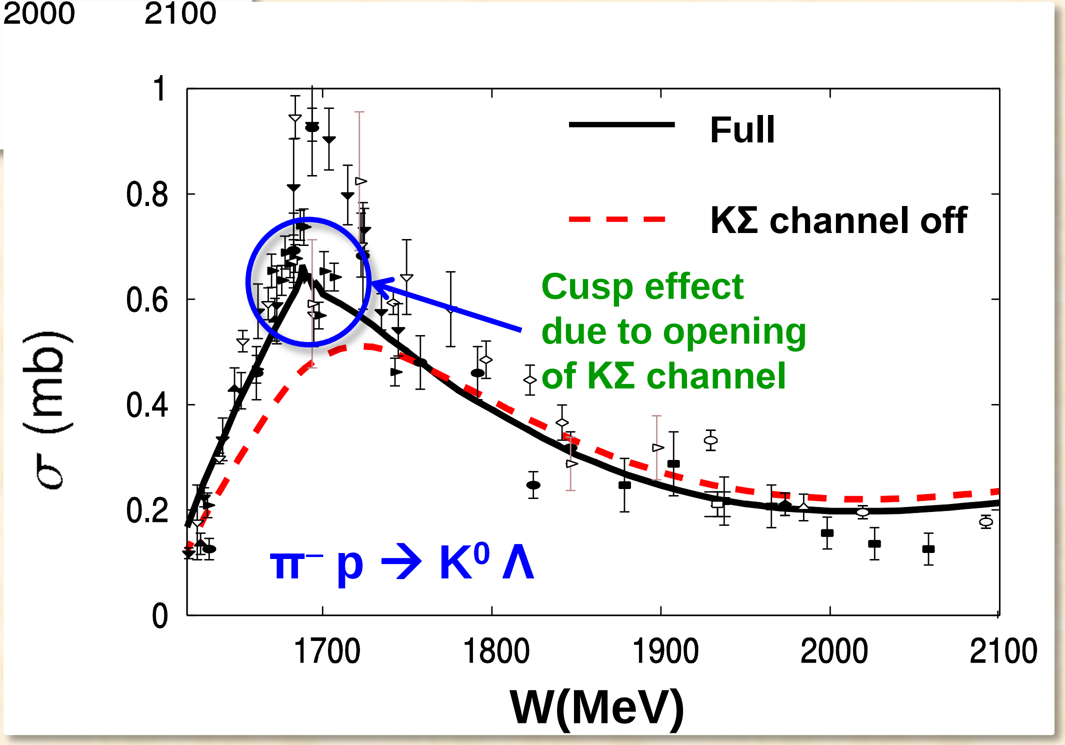
T, E, F, G, H, Ox’, Oz’, Lx’, Lz’, Tx’, Tz’

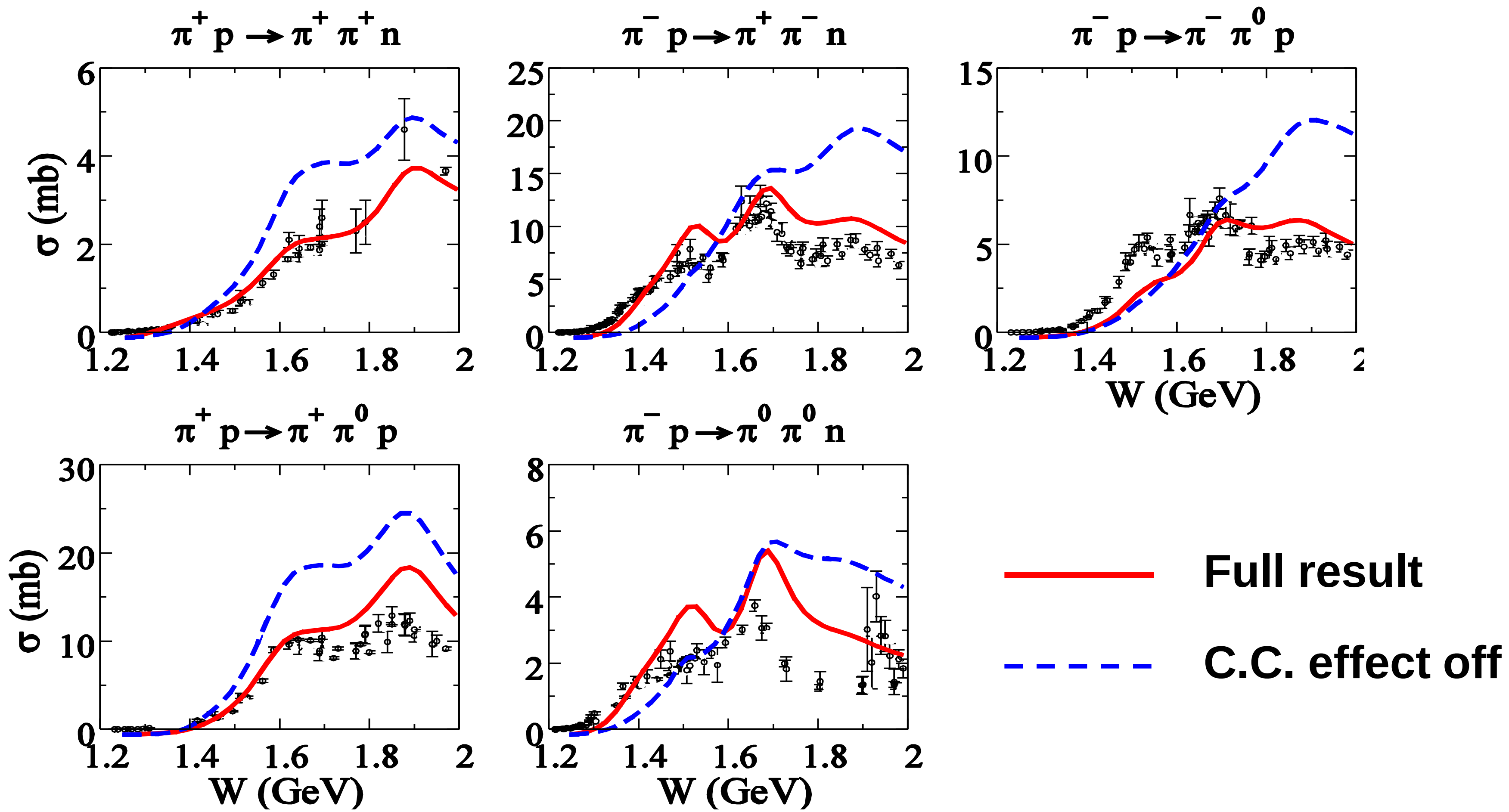
Coupled-channels effect on observables





Coupled-channels effect on observables

Predicted πN → ππN total cross sections with our DCC model



HK, Julia-Diaz, Lee, Matsuyama, Sato, PRC79 (2008) 025206
HK, PRC88 (2013) 045203

Extracting N* resonance parameters

Definitions of

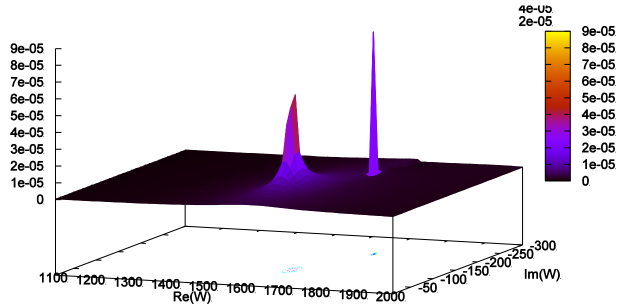
- ✓ **N* masses (spectrum) ➔ Pole positions of the amplitudes**
- ✓ **N* → MB, γN coupling constants ➔ Residues[1/2] at the pole**

N* → b coupling constant

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

N* pole position (Im(E_0) < 0)

Analytic continuation to (lower-half) complex energy plane.



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

Extracting N* resonance parameters

Definitions of

- ✓ N* masses (spectrum) ➔ Pole positions of the amplitudes
- ✓ N* → MB, γN coupling constants ➔ Residues$^{1/2}$ at the pole

Consistent with the resonance theory based on Gamow vectors

G. Gamow (1928), R. E. Peierls (1959), …
For a brief introduction of Gamov vectors, see, e.g., de la Madrid et al, quant-ph/0201091

➔ Resonances are (complex-energy) eigenstates of the Hamiltonian of the underlying fundamental theory with the purely outgoing boundary condition !!

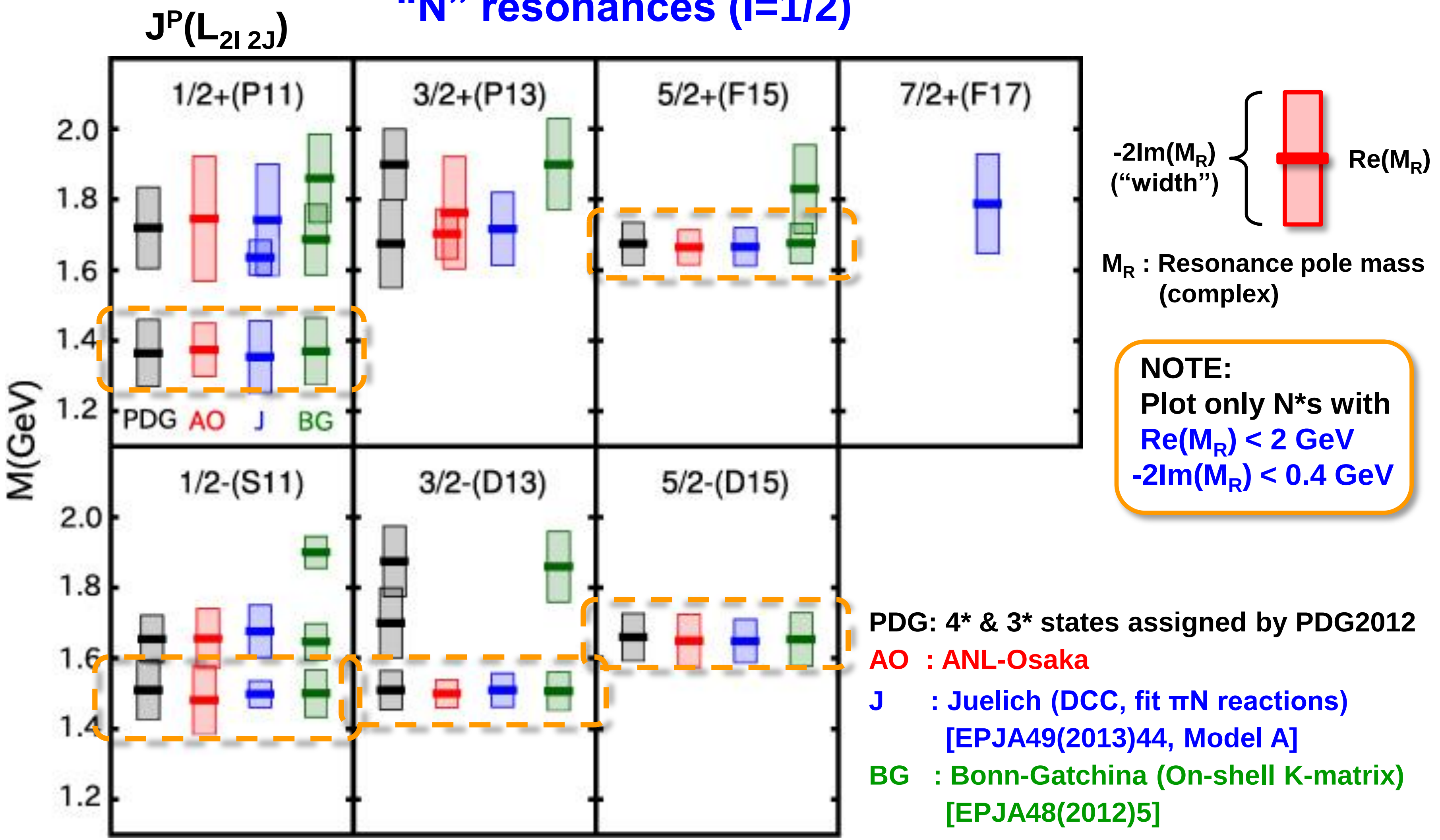
(complex) energy eigenvalues = pole values

transition matrix elements = (residue)$^{1/2}$ of the poles

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 (DCC, fit πN reactions) [EPJA49(2013)44, Model A]
BG : Bonn-Gatchina (On-shell K-matrix) [EPJA48(2012)5]

Comparison of N* spectrum with other multichannel analyses

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

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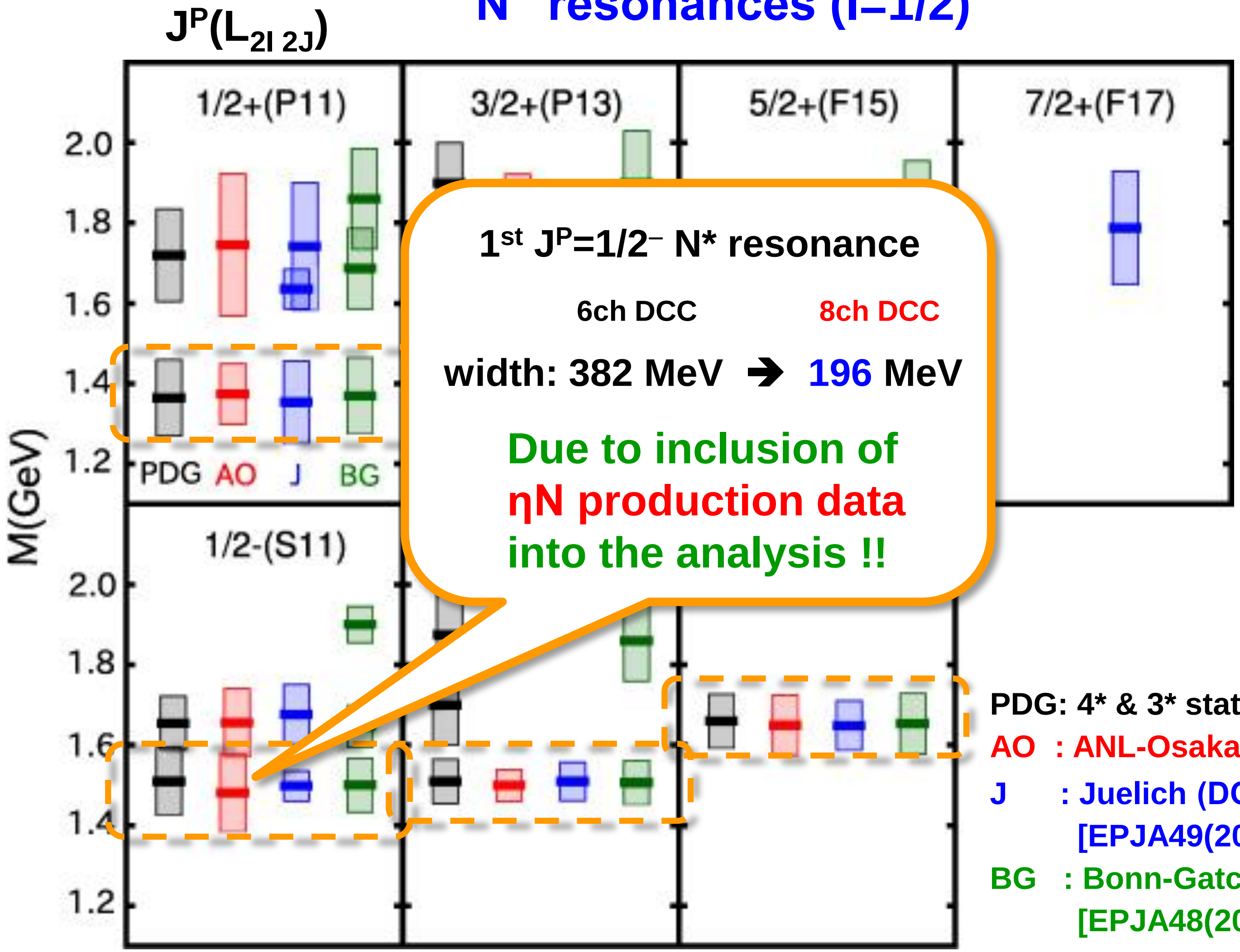

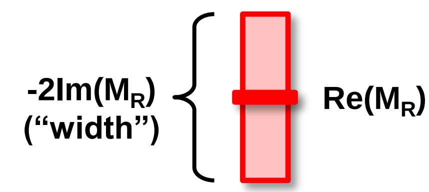

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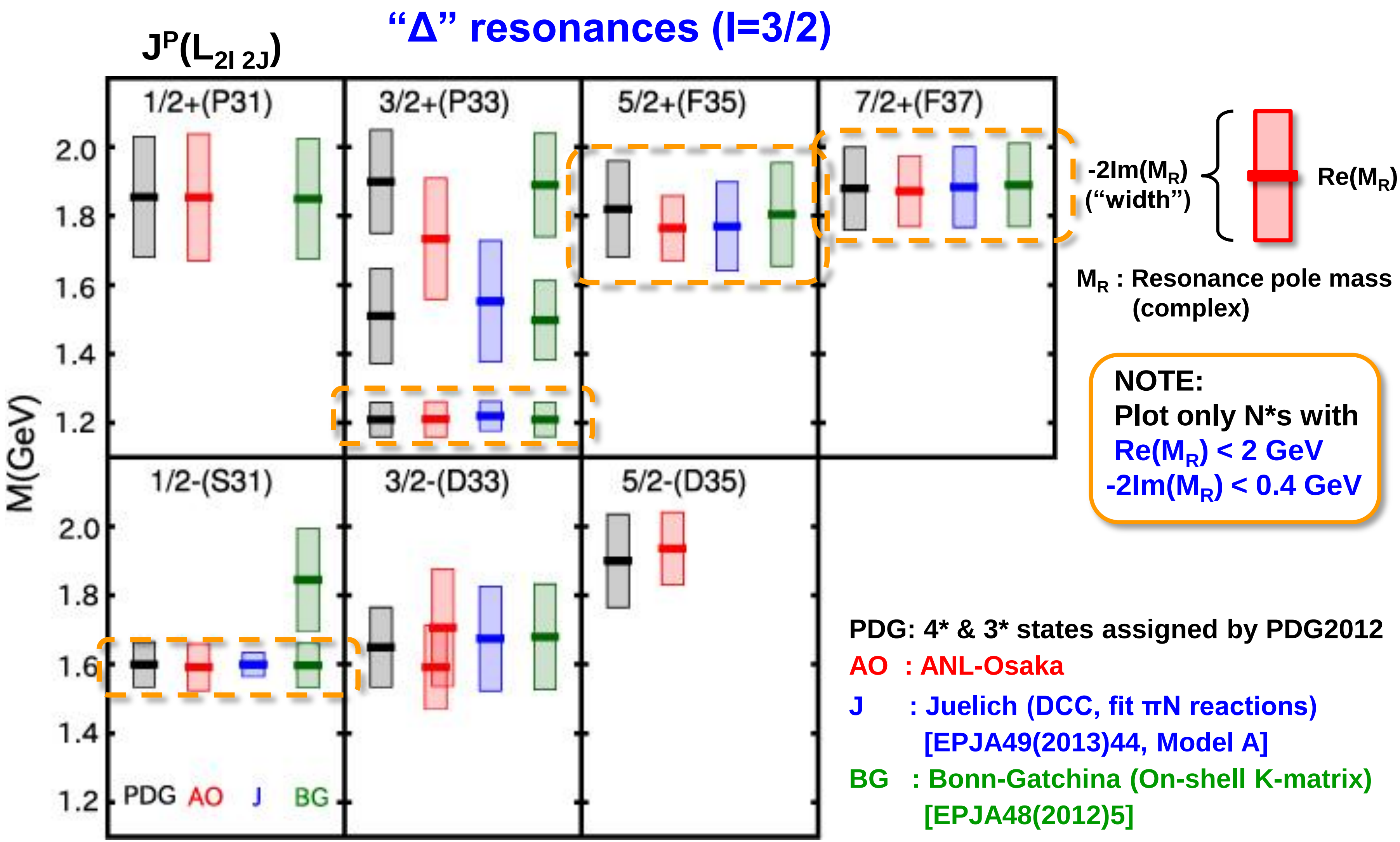
HK, Nakamura, Lee, Sato, PRC88 (2013) 035209



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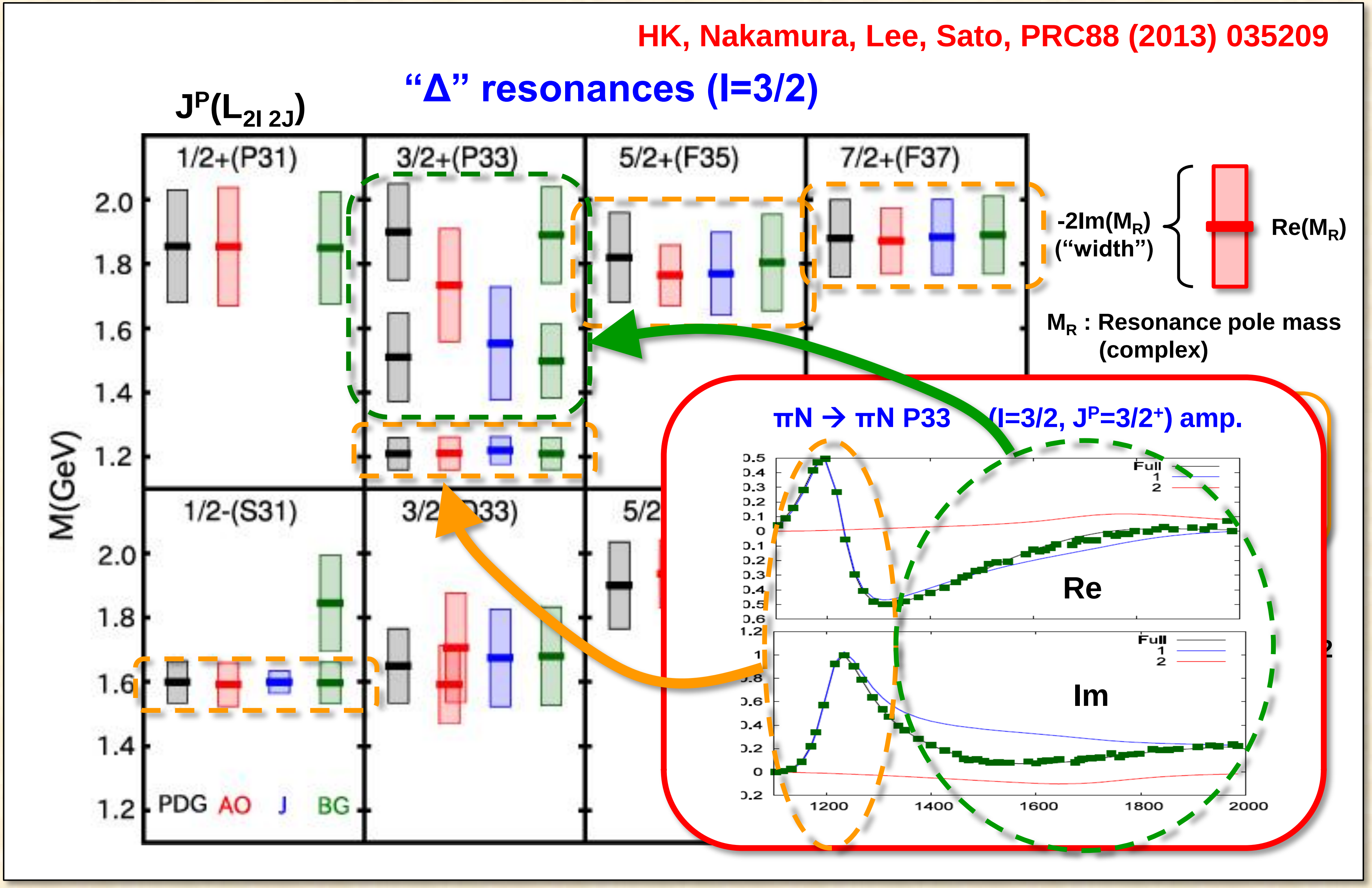
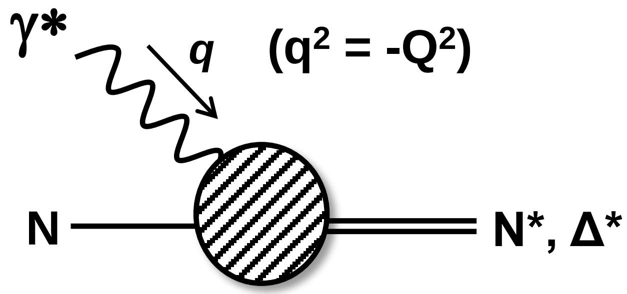
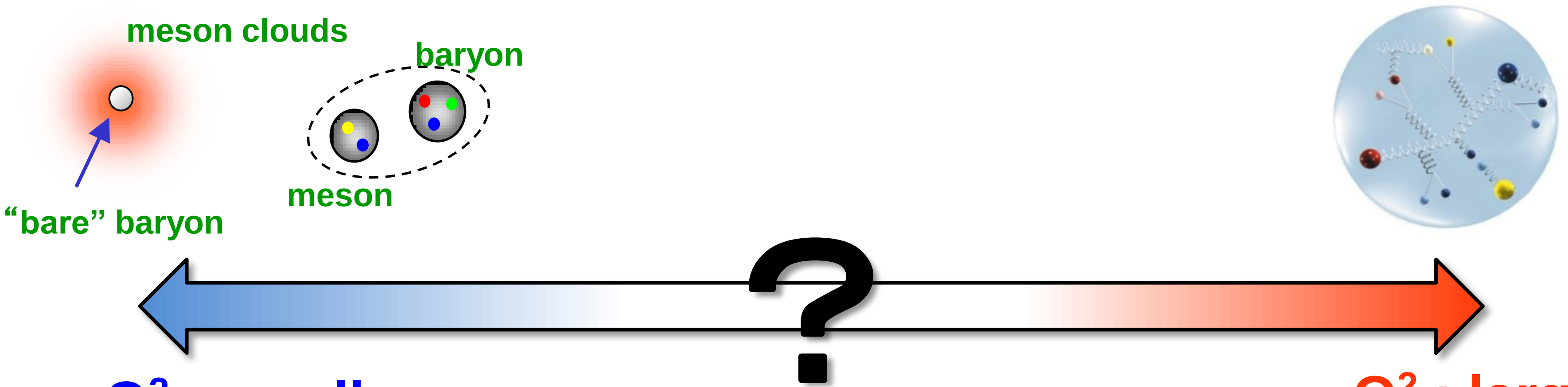


Transition form factors and baryon structure



N-N* electromagnetic transition form facctor

“hadronic” picture **“partonic” picture**



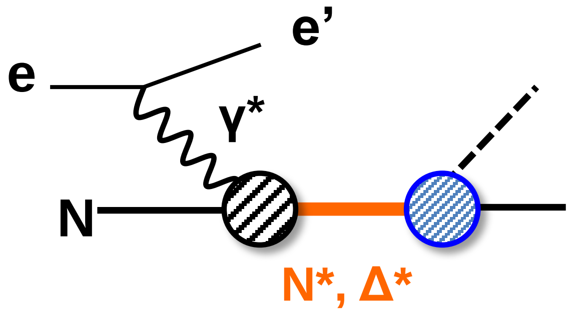
Q^2 : small **Q^2 : large**

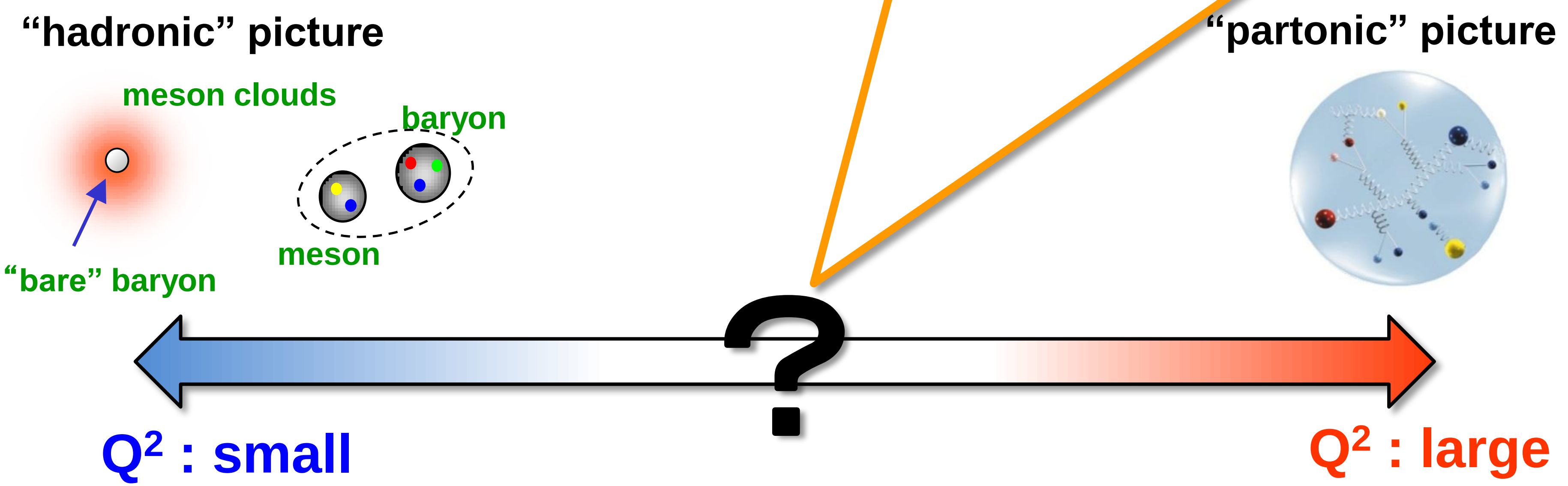
How effective d.o.f.’s describing baryon change with Q^2 ?

Transition form factors and baryon structure

Measurement of p(e,e'π)N &
p(e,e'ππ)N for $5 < Q^2 < 10$ (GeV/c)^2.

➔ JLab CLAS12 experiment
(E12-09-003)

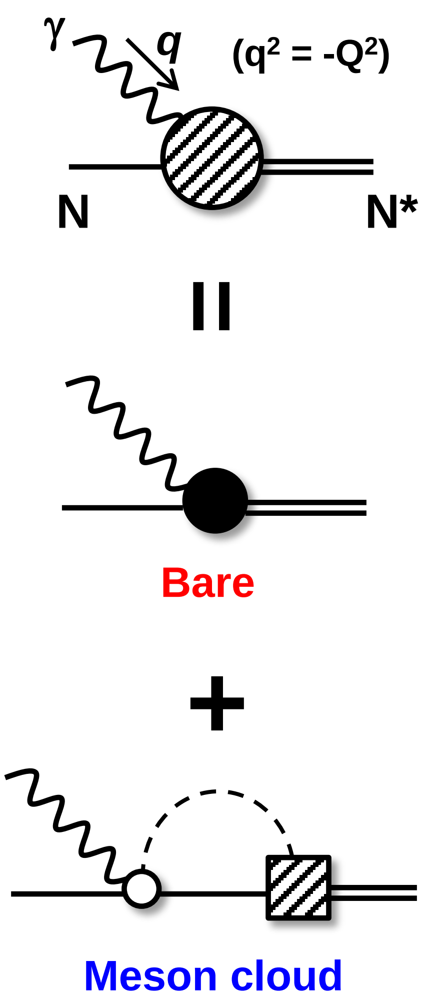


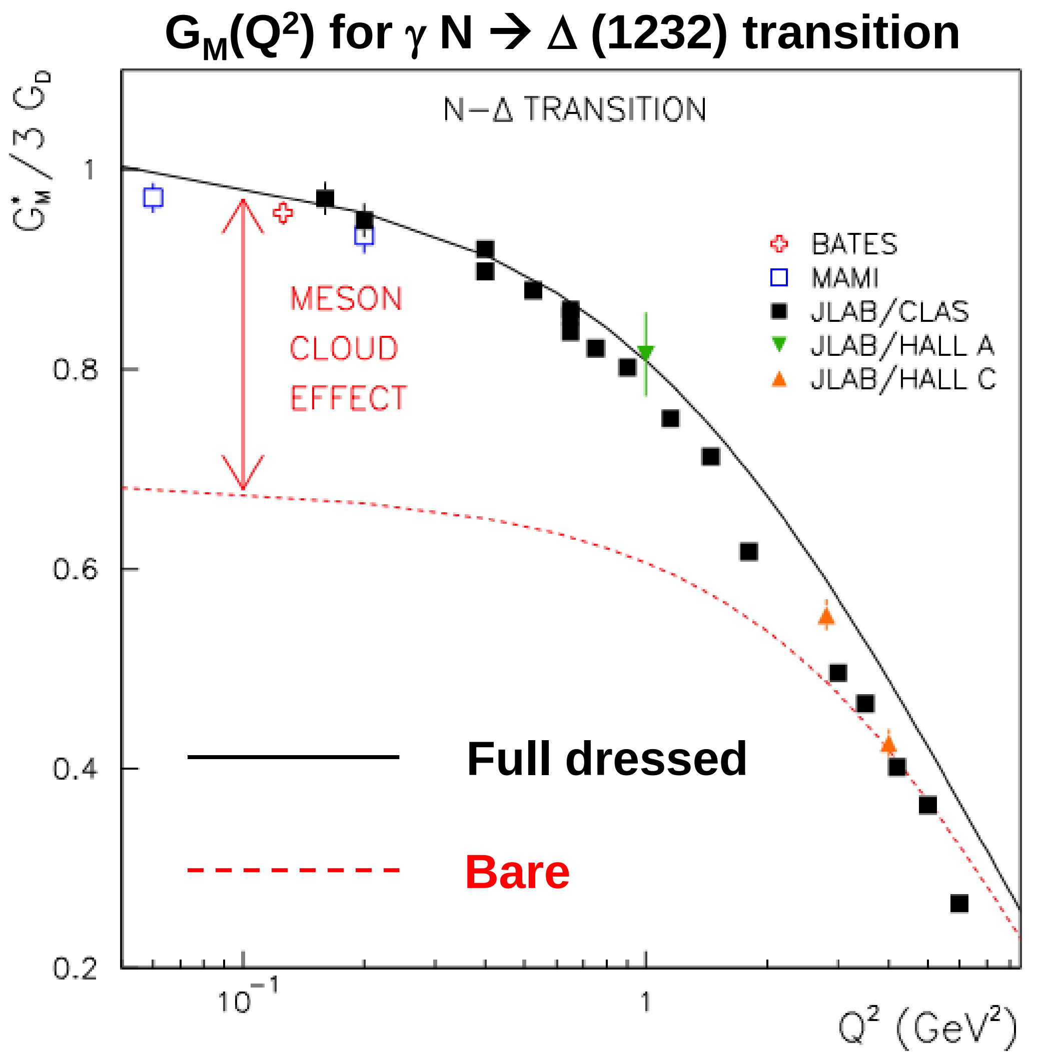


How effective d.o.f.'s describing baryon change with Q^2 ?

Transition form factors and baryon structure

N-N* e.m. transition form factor

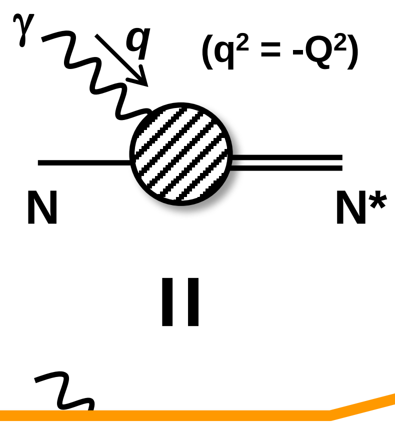


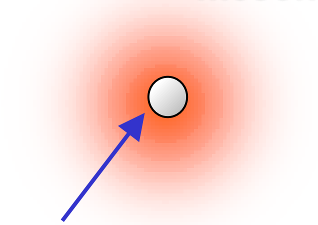


Julia-Diaz, Lee, Sato, Smith, PRC75 (2007) 015205

Transition form factors and baryon structure

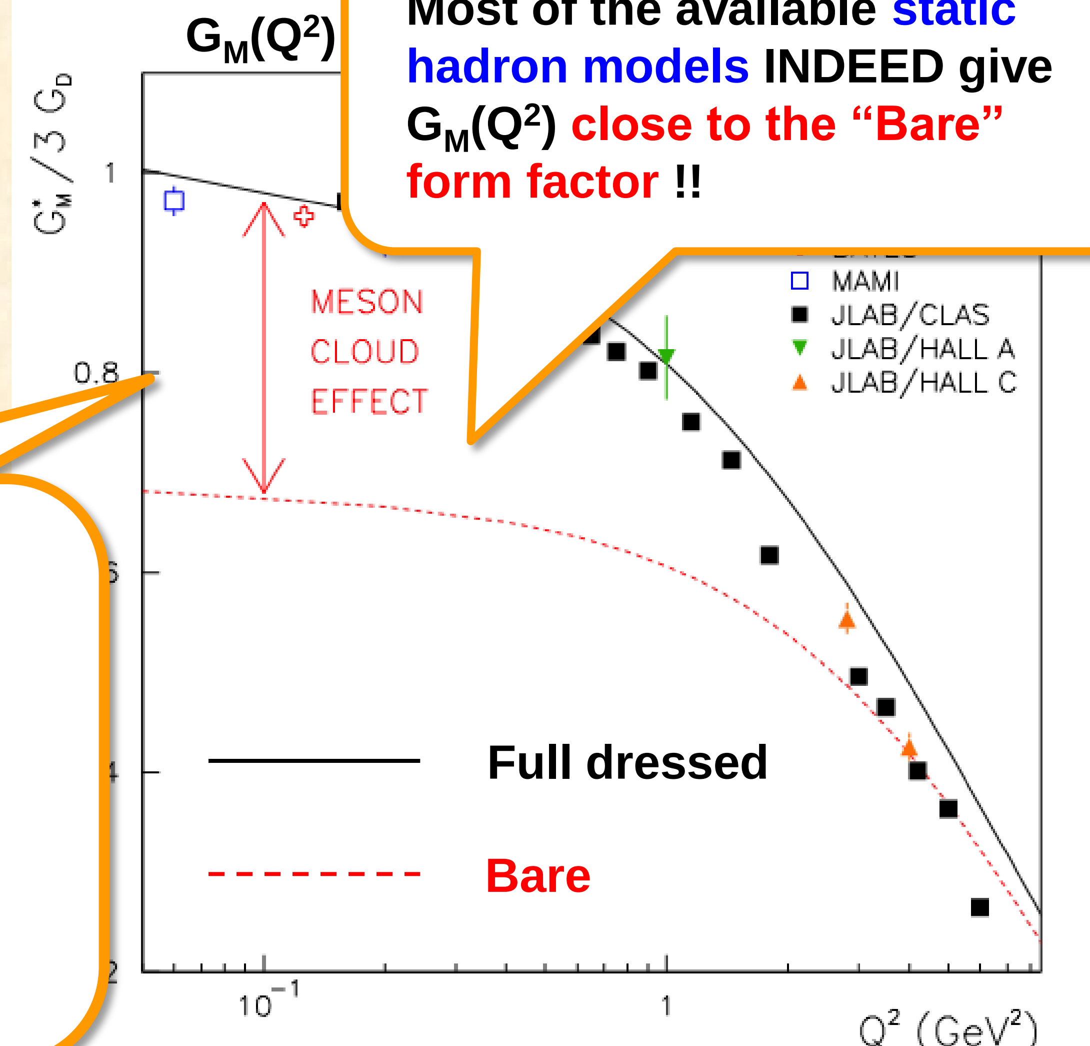
N-N* e.m. transition form factor





$\Delta(1232)$ at low Q^2

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



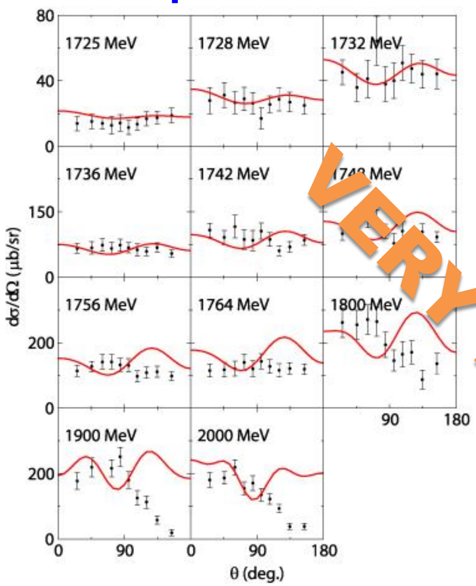
Julia-Diaz, Lee, Sato, Smith, PRC75 (2007) 015205

Ongoing & future projects on N* spectroscopy with ANL-Osaka DCC approach

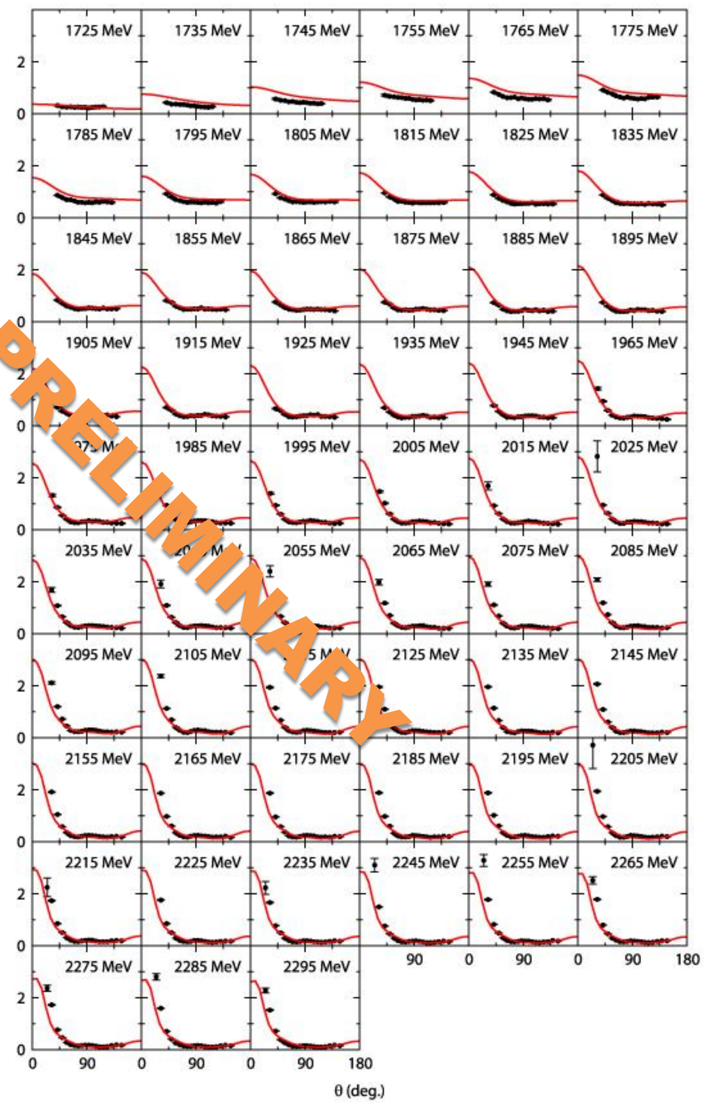
Extending DCC analysis	2006-2009	2010-2013 [PRC88(2013)035209]	2014-
✓ # of coupled channels	6 channels ($\gamma N,\pi N,\eta N,\pi\Delta,\rho N,\sigma N$)	8 channels (6ch + $K\Lambda$, $K\Sigma$)	9 channels (8ch + ωN)
✓ $\pi p \rightarrow \pi N$	< 2 GeV	< 2.3 GeV	< 2.5 GeV
✓ $\gamma p \rightarrow \pi N$	< 1.6 GeV	< 2.1 GeV	< 2.3 GeV
✓ $\pi p \rightarrow \eta p$	< 2 GeV	< 2.1 GeV	< 2.3 GeV
✓ $\gamma p \rightarrow \eta p$	—	< 2.1 GeV	< 2.3 GeV
✓ $\pi p \rightarrow K\Lambda, K\Sigma$	—	< 2.1 GeV	< 2.3 GeV
✓ $\gamma p \rightarrow K\Lambda, K\Sigma$	—	< 2.1 GeV	< 2.3 GeV
✓ $\pi^- p \rightarrow \omega n$	—	—	< 2.3 GeV
✓ $\gamma p \rightarrow \omega p$	—	—	< 2.3 GeV

Ongoing & future projects on N* spectroscopy with ANL-Osaka DCC approach

$\pi^- p \rightarrow \omega n$ DCS



$\gamma p \rightarrow \omega p$ DCS



Combined analysis including ωN data is *in progress* !!

2014-

9 channels

(8ch + ωN)

< 2.5 GeV

< 2.3 GeV

< 2.3 GeV

< 2.3 GeV

< 2.3 GeV

< 2.3 GeV

< 2.3 GeV

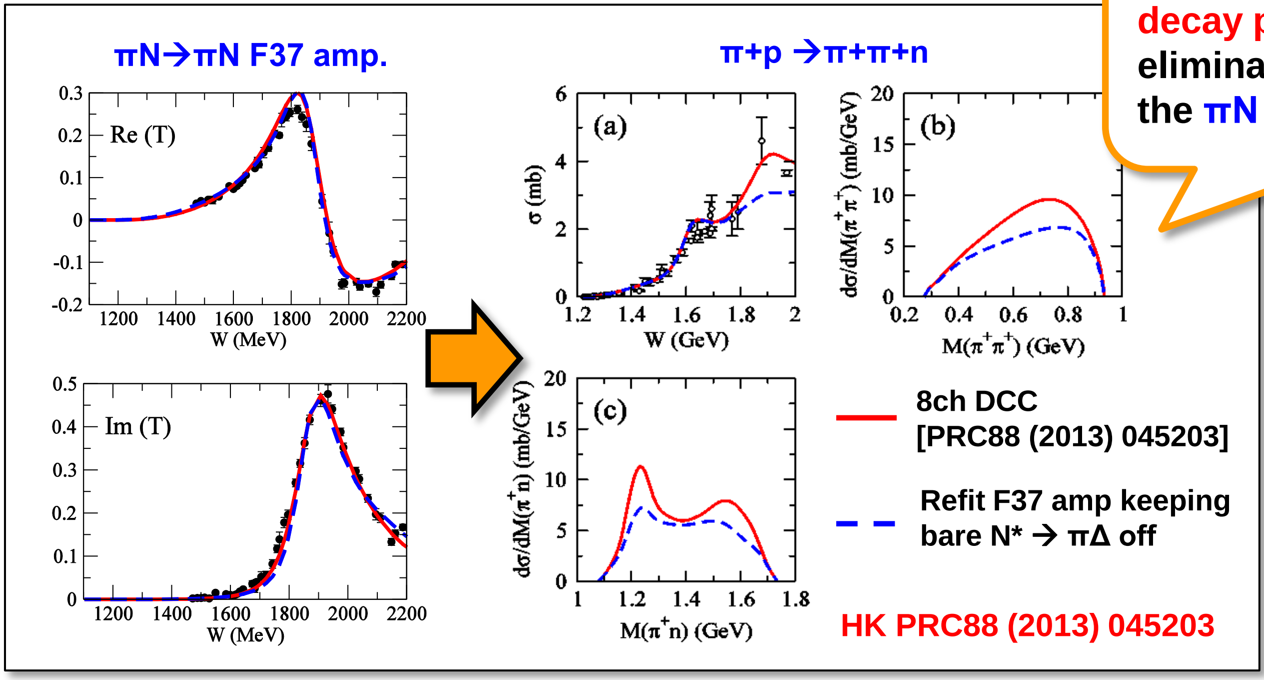
< 2.3 GeV

Ongoing & future projects on N* spectroscopy with ANL-Osaka DCC approach

After the 9-channel analysis, next task is to include ππN data !!

- ➢ **ππN has the largest cross section in πN and γN reactions above W = 1.6 GeV.**
- ➢ **Most N*s decay dominantly to ππN.**

Ambiguity over N* → ππN decay processes can be eliminated by the πN → ππN data !!



Ongoing & future projects on N* spectroscopy with ANL-Osaka DCC approach

After the 9-channel analysis, next task is to include ππN data !!

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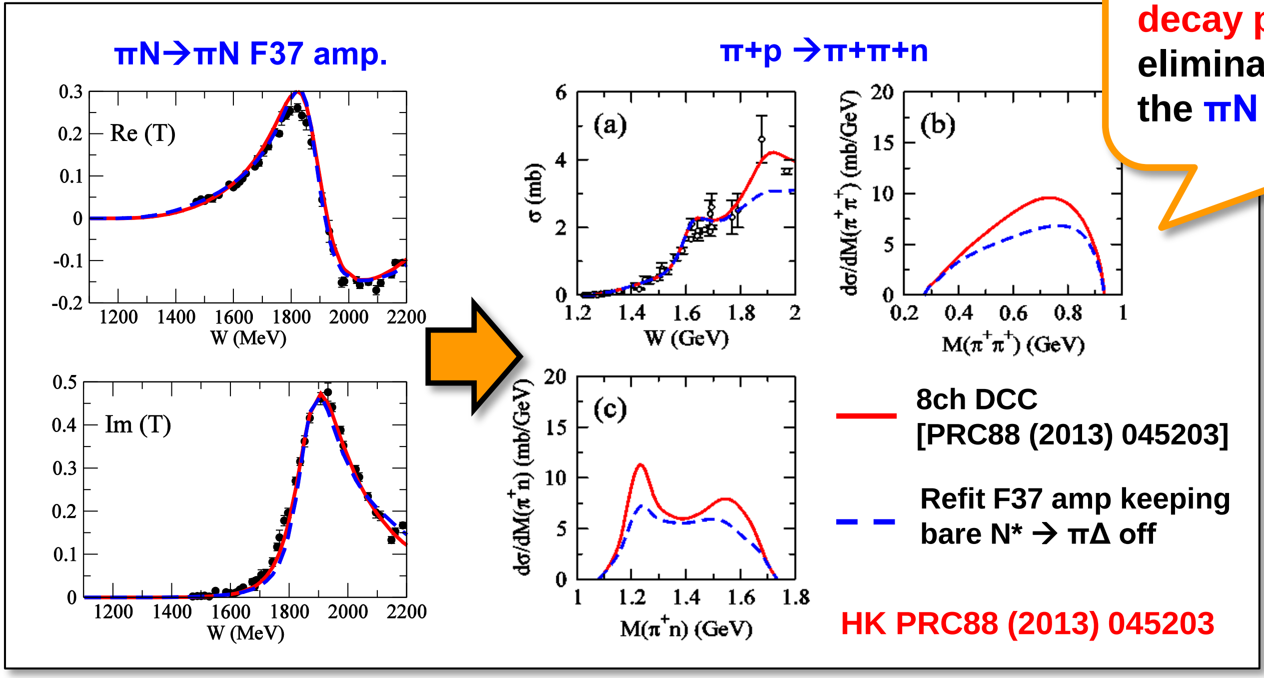


Ambiguity over N* → ππN decay processes can be eliminated by the πN → ππN data !!

Measurements of πN → ππN has been approved at J-PARC !!!
[K. Hicks and H. Sako et al., J-PARC E45]

New opportunity at J-PARC

✓ Need more extensive and accurate data of

- $\pi N \rightarrow \pi\pi N$
- $\pi N \rightarrow K\Lambda$ (~ 1,000 data points)
- $\pi N \rightarrow K\Sigma$ (~ 2,200)
- $\pi N \rightarrow \eta N$ (~ 350)
- $\pi N \rightarrow \omega N$ (~ 200)

Approved (J-PARC E45
K. Hicks & H. Sako et al.)

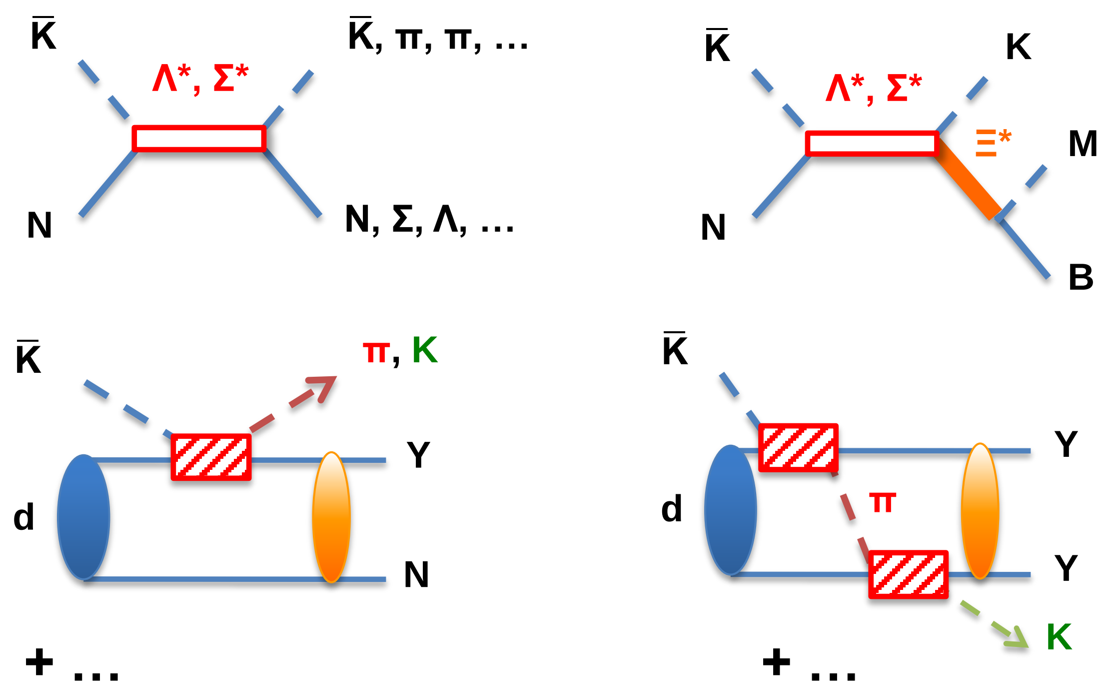
- Much less than $\pi N \rightarrow \pi N$ (~ 30,000)
- Lack of sufficient data leaves sizable uncertainty in pinning down N* mass spectrum and N* → ηN, ωN, KY, ππN decay dynamics

J-PARC is a unique facility to resolve this issue !!

New opportunity at J-PARC: Y* spectroscopy with Kaon beams

Y* spectroscopy with *Kaon*-induced reactions

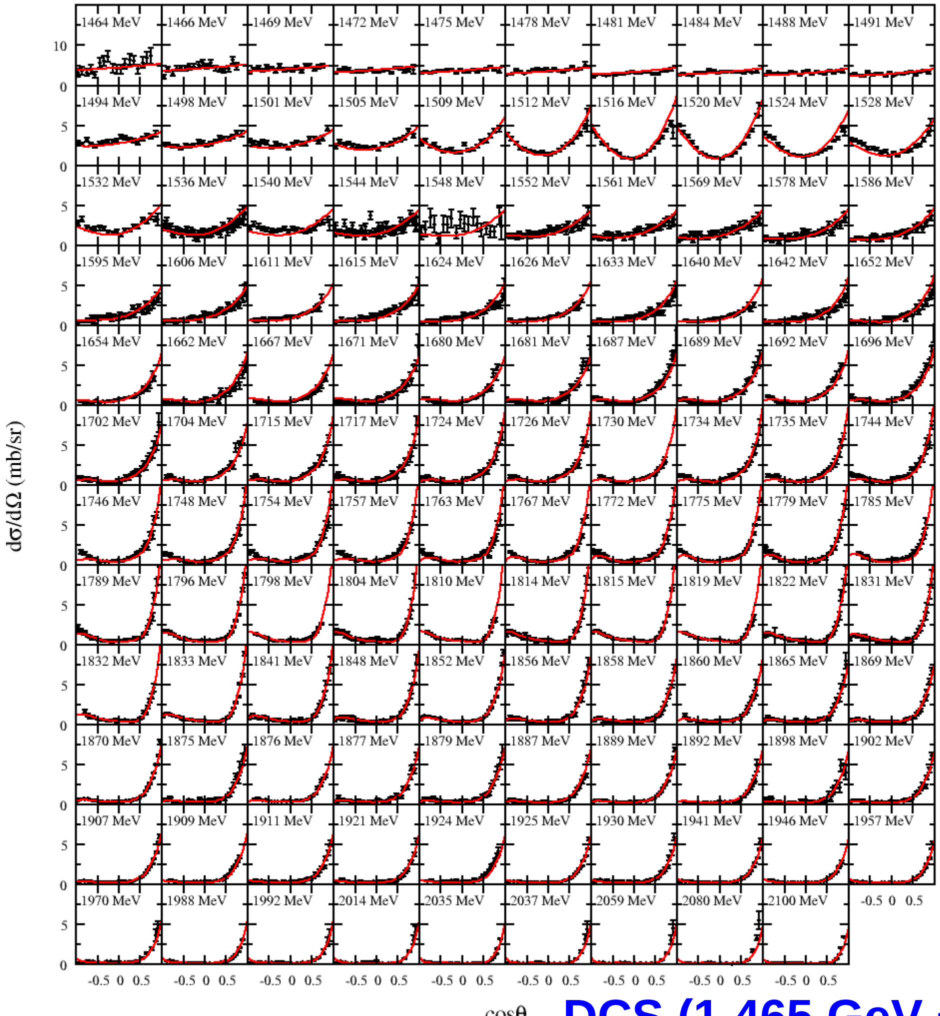
- The simplest reactions for studying Y*.
- Deuteron reactions allow direct access to Λ(1405) region and study of YN and YY interactions.



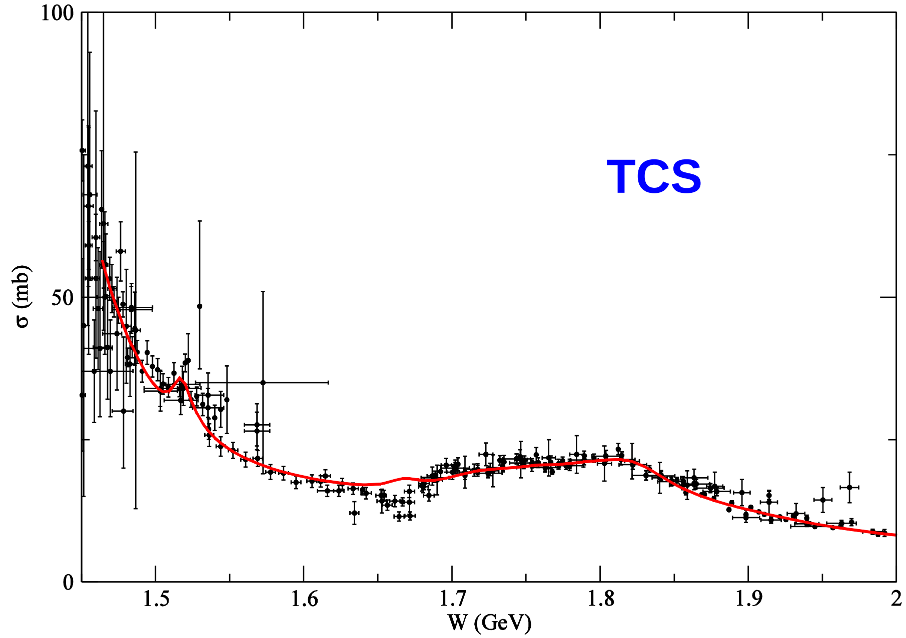
(Noumi et al., J-PARC E31)

New opportunity at J-PARC: Y* spectroscopy with Kaon beams

Y* spectroscopy with *Kaon*-induced reactions



K⁻ p → K⁻ p

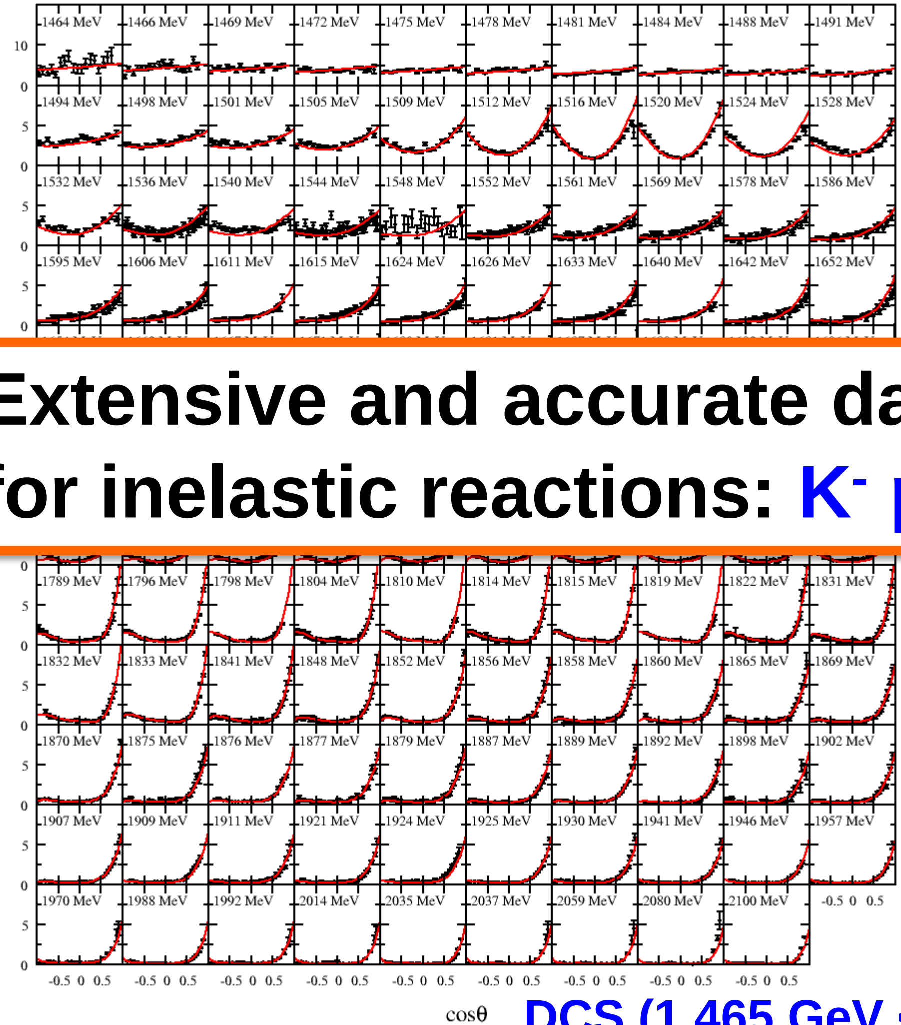


PRELIMINARY

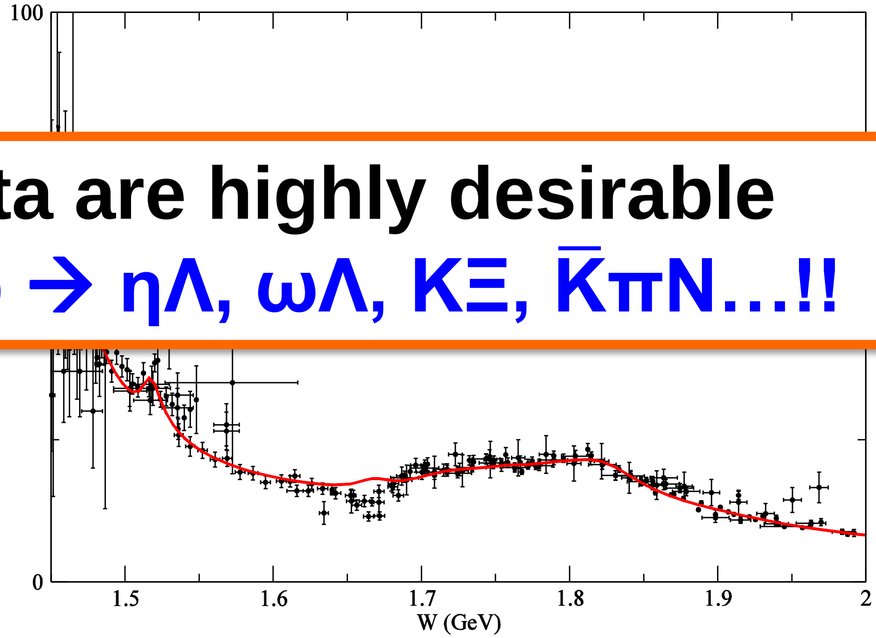
DCS (1.465 GeV < W < 2.1 GeV)

New opportunity at J-PARC: Y* spectroscopy with Kaon beams

Y* spectroscopy with *Kaon*-induced reactions



K$^-$ p → K$^-$ p



Extensive and accurate data are highly desirable for inelastic reactions: K$^-$ p → ηΛ, ωΛ, KΞ, $\bar{K}$πN…!!

PRELIMINARY

DCS (1.465 GeV < W < 2.1 GeV)

Conclusion

1. To establish N* spectrum,
   extensive and accurate data of $\pi N \rightarrow \eta N$, ωN, KY…
   are necessary.

2. To establish Y* spectrum,
   extensive and accurate data of $\bar{K}N$ and $\bar{K}d$ reactions
   are necessary.

We rely on J-PARC for measuring these *crucial* reactions !!