Dynamical coupled-channels approach to light-flavor baryon spectroscopy

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Outline

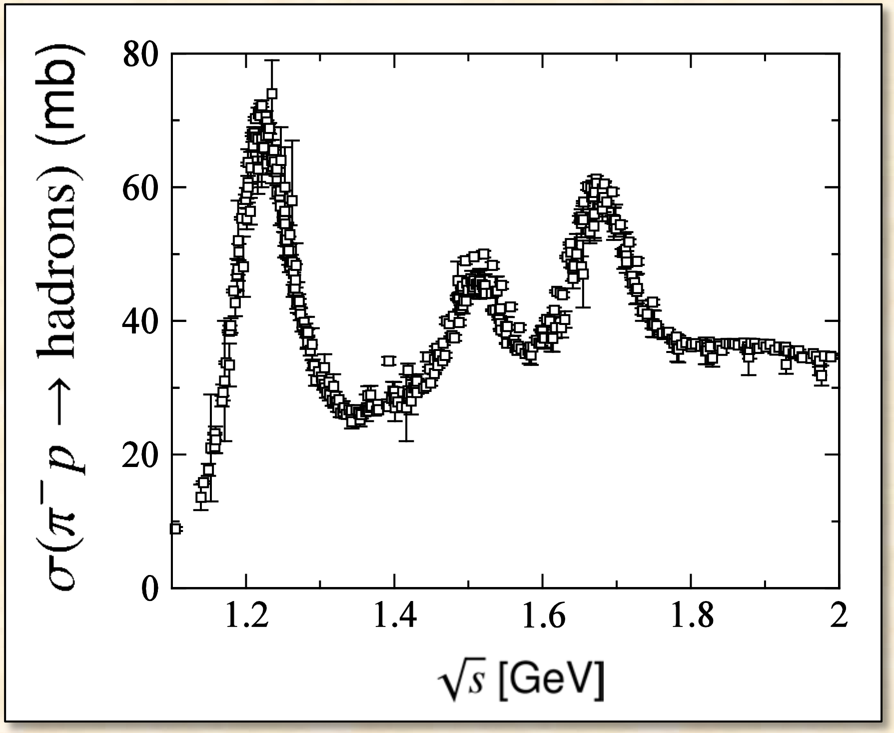
1. Background and motivation for N* spectroscopy

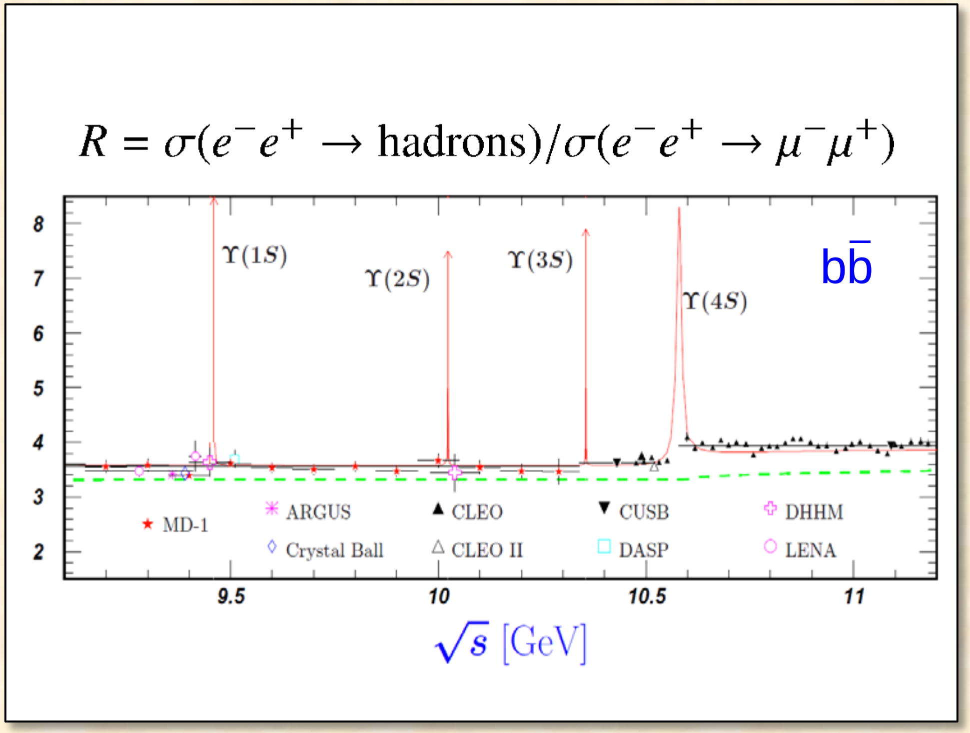
2. Results of ANL-Osaka Dynamical Coupled-Channels (DCC) analysis of πN and γN reactions
   - Brief description of ANL-Osaka DCC model
   - Results of 6-channel DCC analysis (2006-2009)
   - Results of 8-channel DCC analysis (2010-2012) ➔ arXiv: 1305.4351

3. Ongoing projects and future plans with ANL-Osaka DCC approach

4. Summary

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

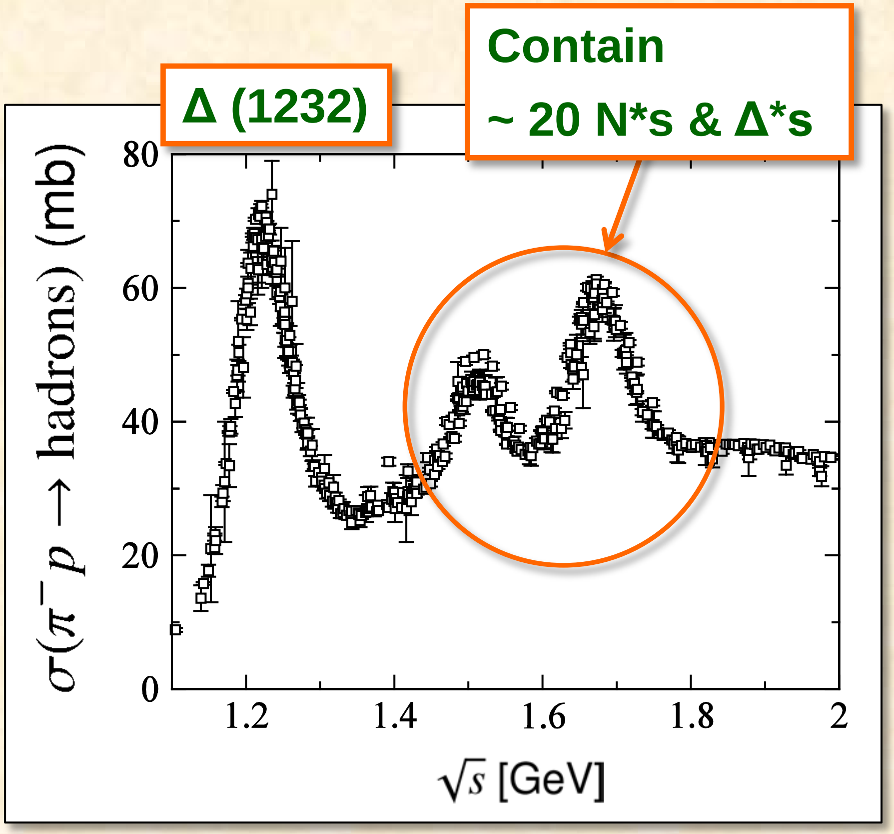


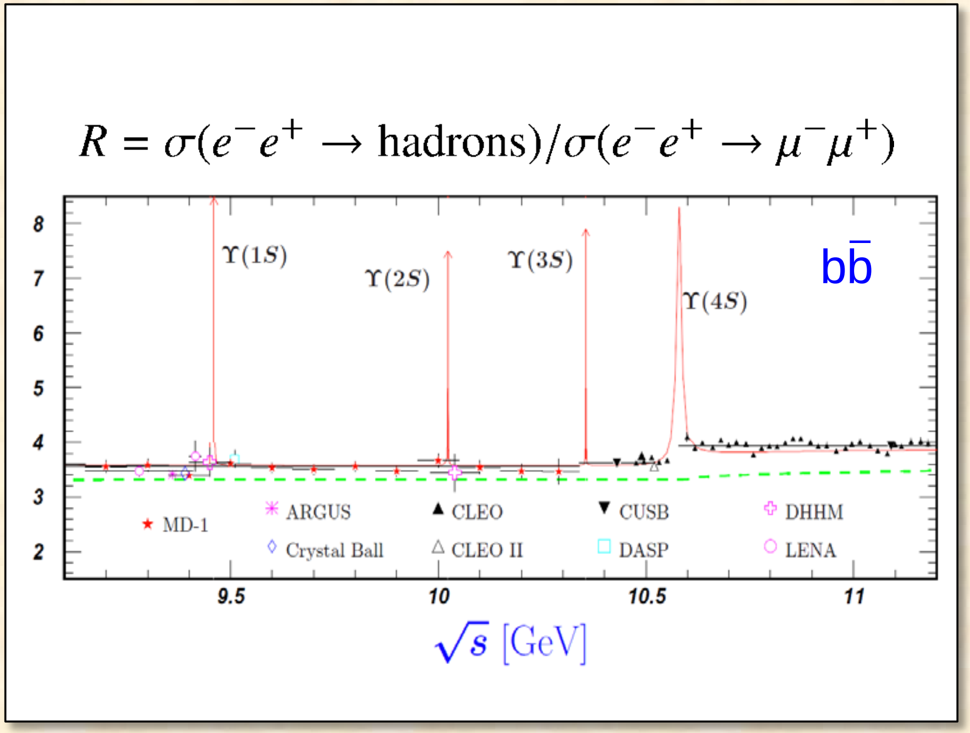


- ✓ **Width: a few hundred MeV.**
  [(width/mass) ~ *0.1 - 0.2*]
- ✓ **Resonances are highly overlapping in energy except Δ(1232).**

- ✓ **Width: ~10 keV to ~10 MeV**
  [(width/mass) ~ 10^{-3} - 10^{-4}]
- ✓ **Each resonance peak is clearly separated.**

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





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N* states and PDG *s

Particle	J^P	overall	Status πN	γN	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
N	$1/2^+$	****									
$N(1440)$	$1/2^+$	****	****	****		***				*	***
$N(1520)$	$3/2^-$	****	****	****	***					***	***
$N(1535)$	$1/2^-$	****	****	****	****					**	*
$N(1650)$	$1/2^-$	****	****	***	***			***	**	**	***
$N(1675)$	$5/2^-$	****	****	***	*			*		*	***
$N(1680)$	$5/2^+$	****	****	****	*	**				***	***
$N(1685)$	$?^?$	*									
$N(1700)$	$3/2^-$	***	***	**	*			*	*	*	***
$N(1710)$	$1/2^+$	***	***	***	***		**	***	**	*	**
$N(1720)$	$3/2^+$	****	****	***	***			**	**	**	*
$N(1860)$	$5/2^+$	**	**							*	*
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$N(1880)$	$1/2^+$	**	*	*		**		*			
$N(1895)$	$1/2^-$	**	*	**	**			**	*		
$N(1900)$	$3/2^+$	***	**	***	**		**	***	**	*	**
$N(1990)$	$7/2^+$	**	**	**					*		
$N(2000)$	$5/2^+$	**	*	**	**			**	*	**	
$\Delta(1232)$	$3/2^+$	****	****	****	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	$\Delta\eta$)
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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

$$\pi N \rightarrow \pi N \;, \quad \gamma N \rightarrow \pi N$$

Need *comprehensive analysis* of

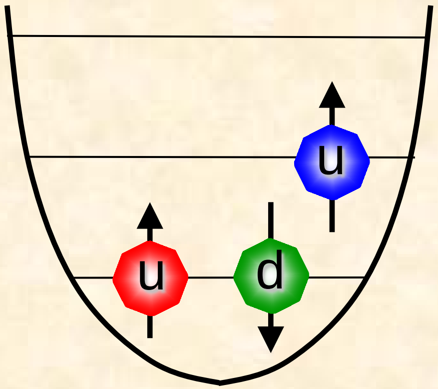
$$\pi N,\ \eta N,\ \pi\pi N,\ KY,\ \omega N, \ldots$$

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*.**



Constituent quark model

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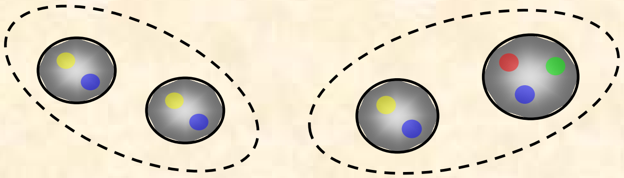
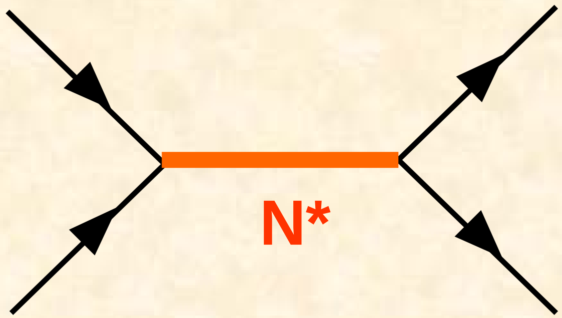
- ✓ **In reality, excited hadrons are “unstable” and can exist only as resonance states in hadron reactions.**

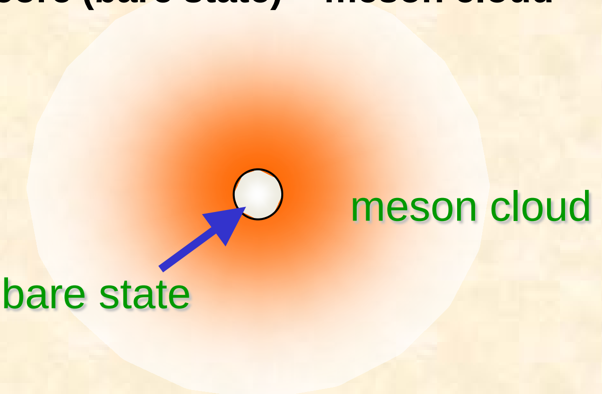
“Mass” becomes complex !!
→ “pole mass”

“molecule-like” states





core (bare state) + meson cloud



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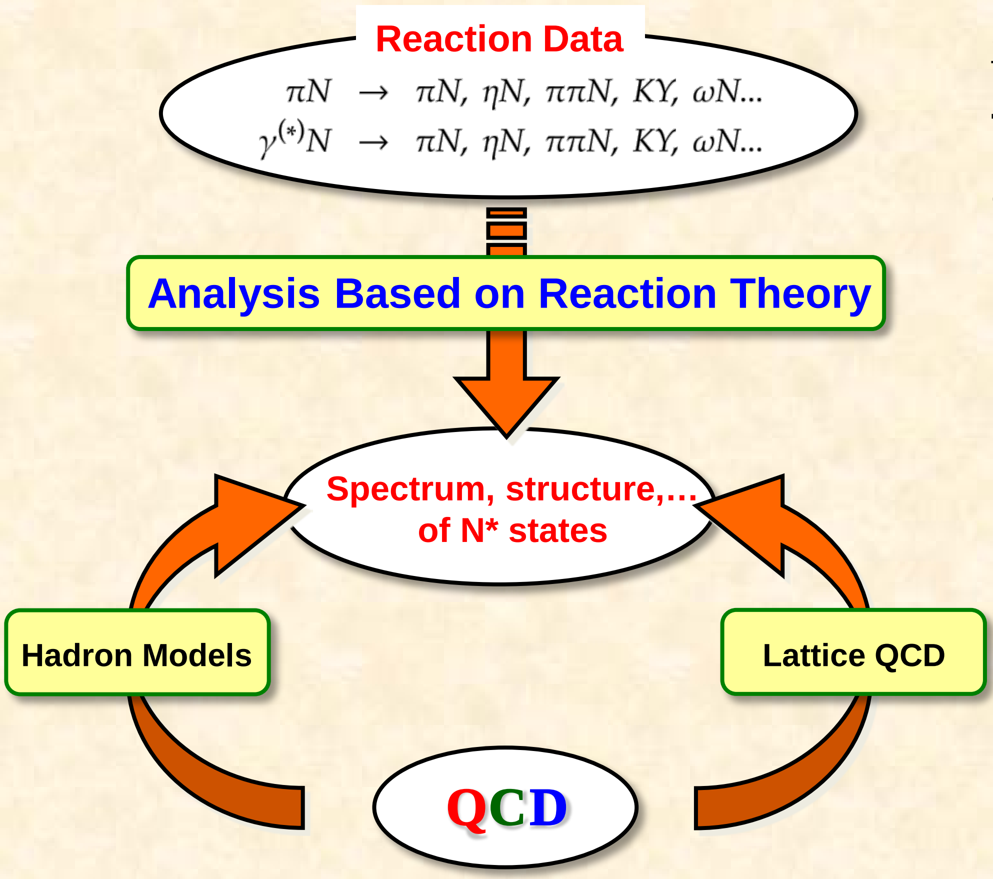
What is the role of reaction dynamics in interpreting the hadron spectrum, structures, and dynamical origins ??

N* spectroscopy with ANL-Osaka Dynamical Coupled-Channels (DCC) approach

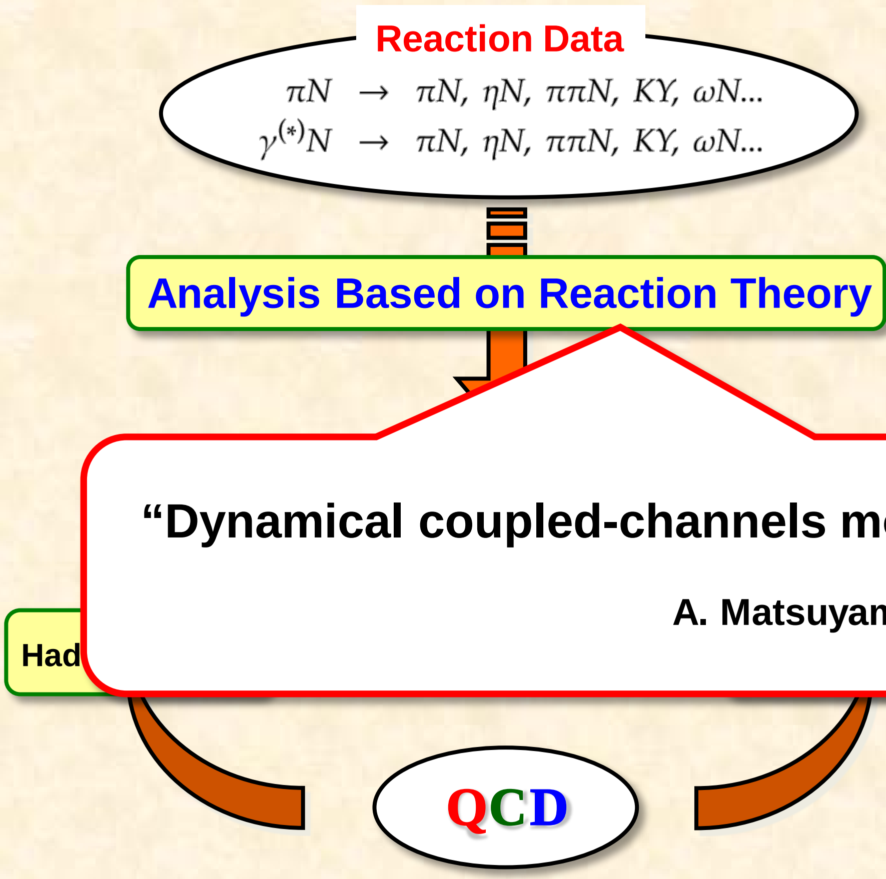


Objectives and goals:

Through the comprehensive analysis of world data of πN, γN, N(e,e') reactions,

- ✓ **Determine N* spectrum (pole masses)**
- ✓ **Extract N* form factors (e.g., N-N* e.m. transition form factors)**
- ✓ **Provide reaction mechanism information necessary for interpreting N* spectrum, structures and dynamical origins**

N* spectroscopy with ANL-Osaka Dynamical Coupled-Channels (DCC) approach



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structures and dynamical origins

"Dynamical coupled-channels model of meson production reactions"

A. Matsuyama, T. Sato, T.-S.H. Lee Phys. Rep. 439 (2007) 193

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

For details see Matsuyama, Sato, Lee, Phys. Rep. 439,193 (2007)

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

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

coupled-channels effect

- **Reaction channels:**

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

$\pi\pi N$

- **Transition Potentials:**

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

Exchange potentials

Z-diagrams

bare N* states

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coupled-channels effect

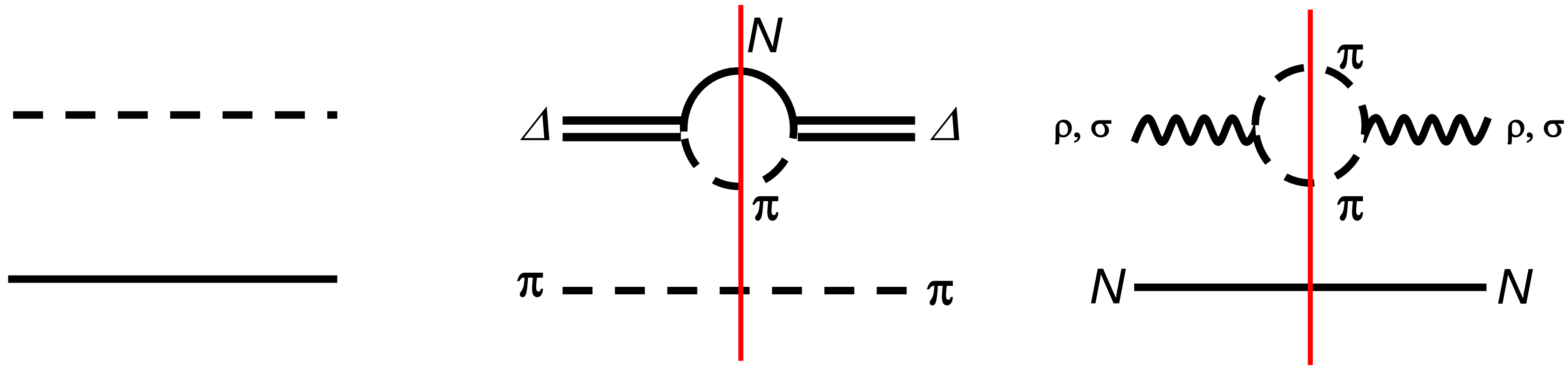
✓ **Meson-Baryon Green functions** G_{MB}

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

Stable channels

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

Quasi 2-body channels



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Exchange potentials | Z-diagrams | bare N* states

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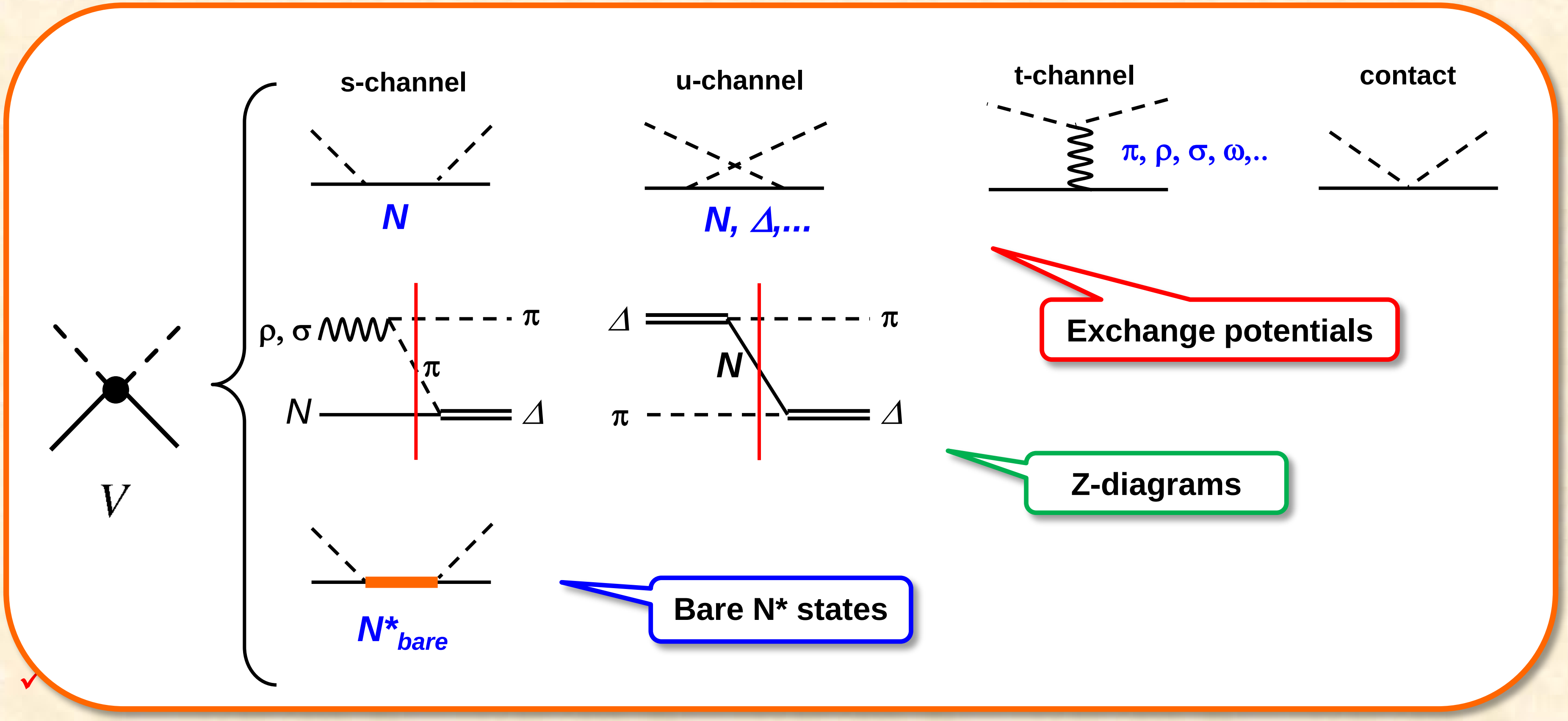

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coupled-channels effect

- **Reaction channels:**

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

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

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Exchange potentials | Z-diagrams | bare N* states

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Exchange potentials | Z-diagrams | bare N* states

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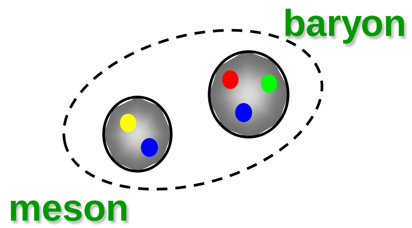
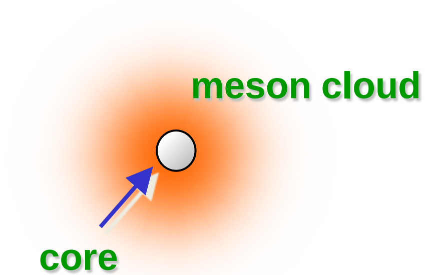
✓ **Partial wave (LSJ) amplitudes of a → b reaction:**

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



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



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

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Exchange potentials | Z-diagrams | bare N* states

DCC analysis (2006-2009)

γN, πN, ηN, πΔ, ρN, σN coupled-channels calculations were performed.

Hadronic part

✓ π N → π N : Analyzed to construct a hadronic part of the model up to W = 2 GeV
Julia-Diaz, Lee, Matsuyama, Sato, PRC76 065201 (2007)

✓ π N → η N : Analyzed to construct a hadronic part of the model up to W = 2 GeV
Durand, Julia-Diaz, Lee, Saghai, Sato, PRC78 025204 (2008)

✓ π N → π π N : Fully dynamical coupled-channels calculation up to W = 2 GeV
Kamano, Julia-Diaz, Lee, Matsuyama, Sato, PRC79 025206 (2009)

Electromagnetic part

✓ $\gamma^{(*)}$ N → π N : Analyzed to construct a E.M. part of the model up to W = 1.6 GeV and Q^2 = 1.5 GeV^2
(photoproduction) Julia-Diaz, Lee, Matsuyama, Sato, Smith, PRC77 045205 (2008)
(electroproduction) Julia-Diaz, Kamano, Lee, Matsuyama, Sato, Suzuki, PRC80 025207 (2009)

✓ γ N → π π N : Fully dynamical coupled-channels calculation up to W = 1.5 GeV
Kamano, Julia-Diaz, Lee, Matsuyama, Sato, PRC80 065203 (2009)

Extraction of N* parameters

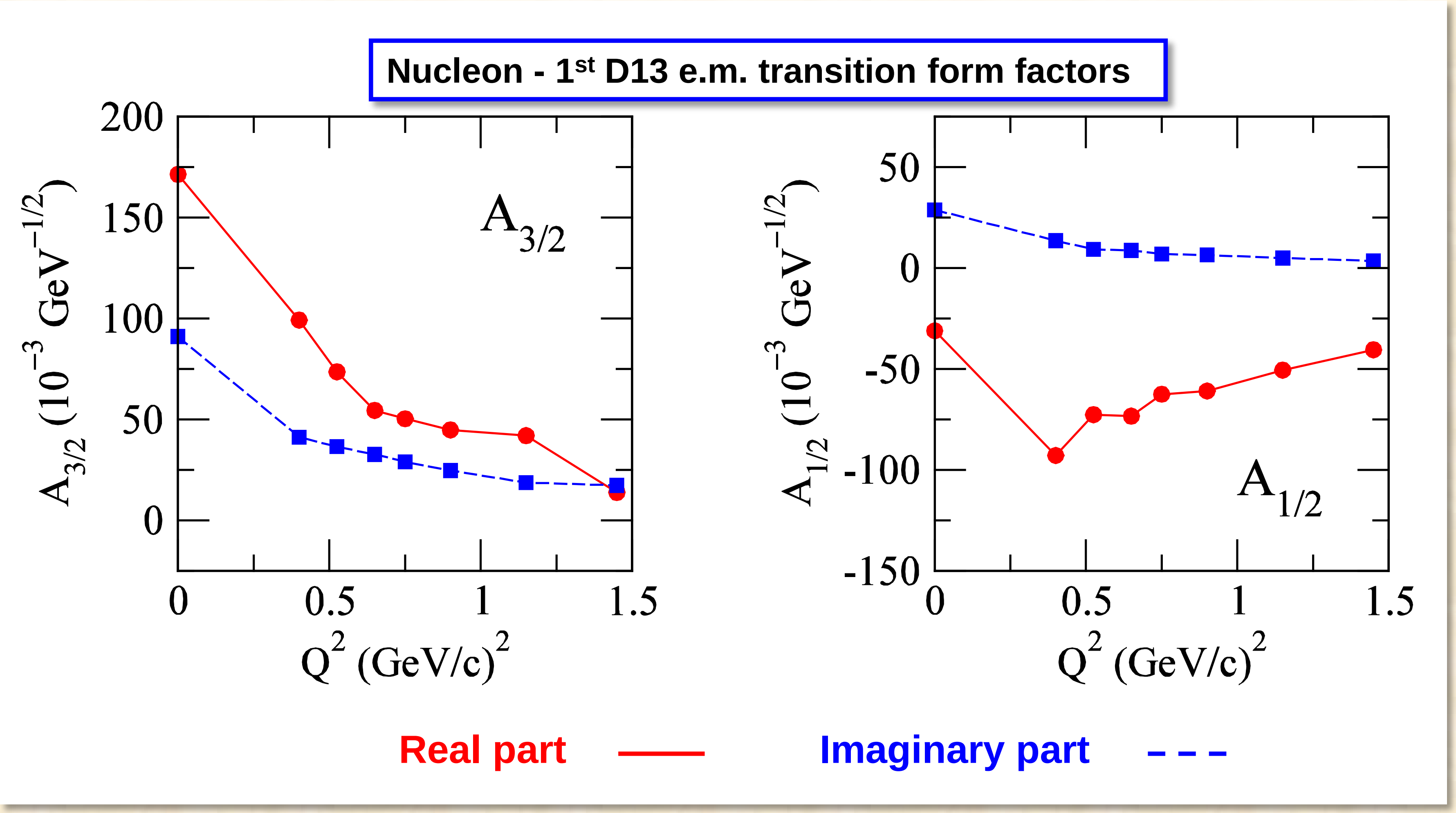
✓ Extraction of N* pole positions & new interpretation on the dynamical origin of P11 resonances
Suzuki, Julia-Diaz, Kamano, Lee, Matsuyama, Sato, PRL104 065203 (2010)

✓ Stability and model dependence of P11 resonance poles extracted from pi N → pi N data
Kamano, Nakamura, Lee, Sato, PRC81 065207 (2010)

✓ Extraction of γN → N* electromagnetic transition form factors
Suzuki, Sato, Lee, PRC79 025205 (2009); PRC82 045206 (2010)

Consequences of reaction dynamics (1/3): Complex nature of resonance parameters

Extracted from analyzing the p(e,e'π)N data (~ 20,000) from CLAS



Julia-Diaz, Kamano, Lee, Matsuyama, Sato, Suzuki PRC80 025207 (2009)
Suzuki, Sato, Lee, PRC82 045206 (2010)

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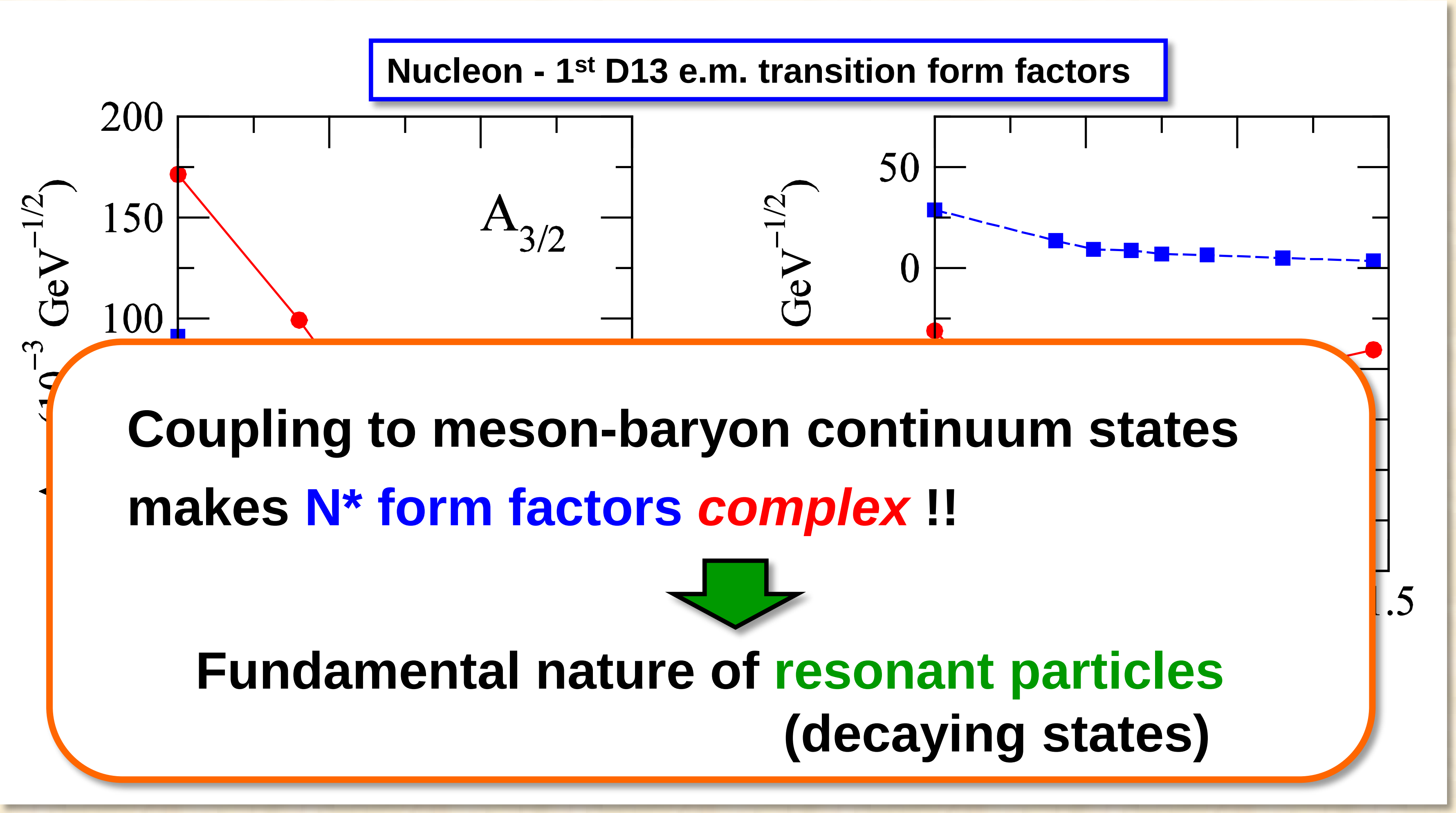


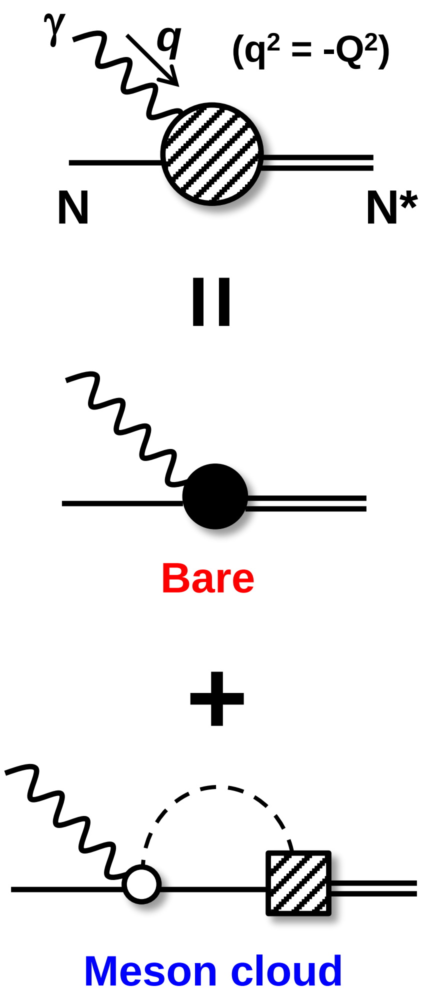
Coupling to meson-baryon continuum states makes N* form factors *complex* !!

Fundamental nature of resonant particles (decaying states)

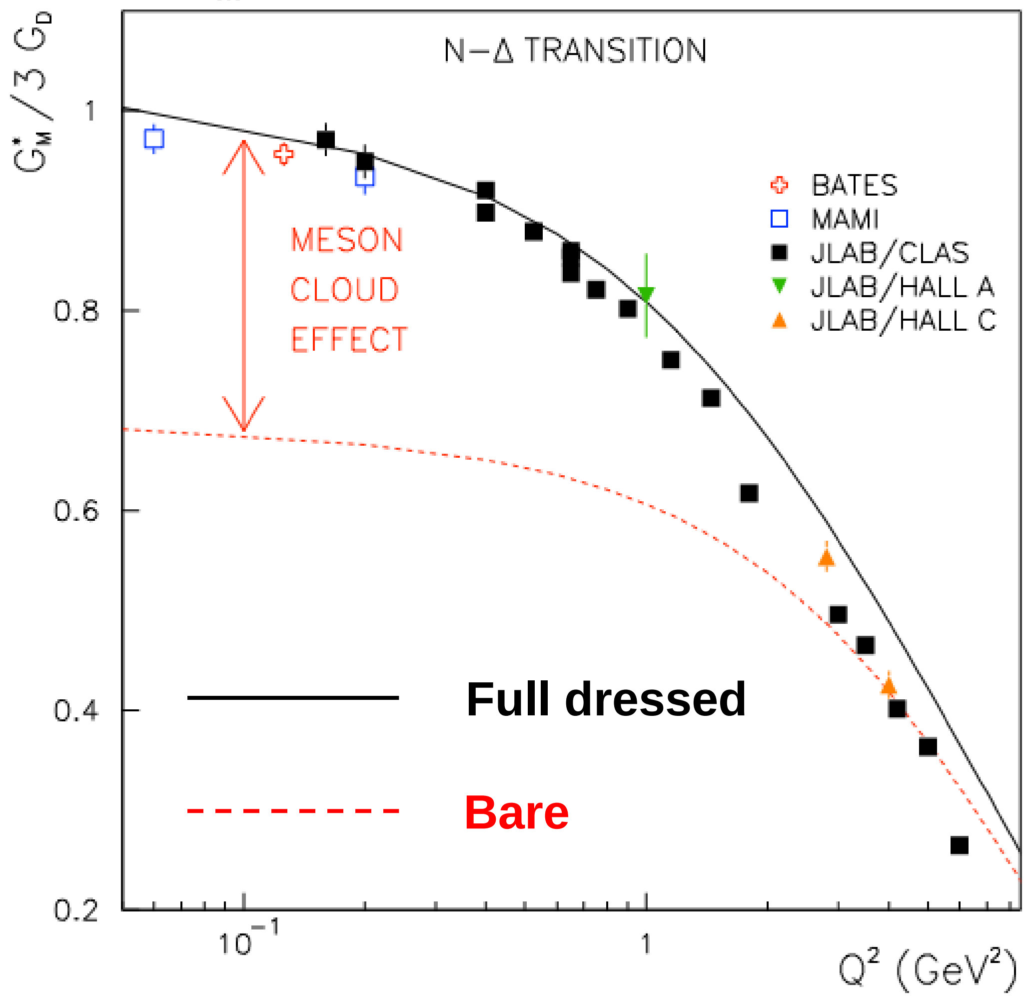
Julia-Diaz, Kamano, Lee, Matsuyama, Sato, Suzuki PRC80 025207 (2009)
Suzuki, Sato, Lee, PRC82 045206 (2010)

Consequences of reaction dynamics (2/3): Meson cloud effect

N-N* e.m. transition form factor

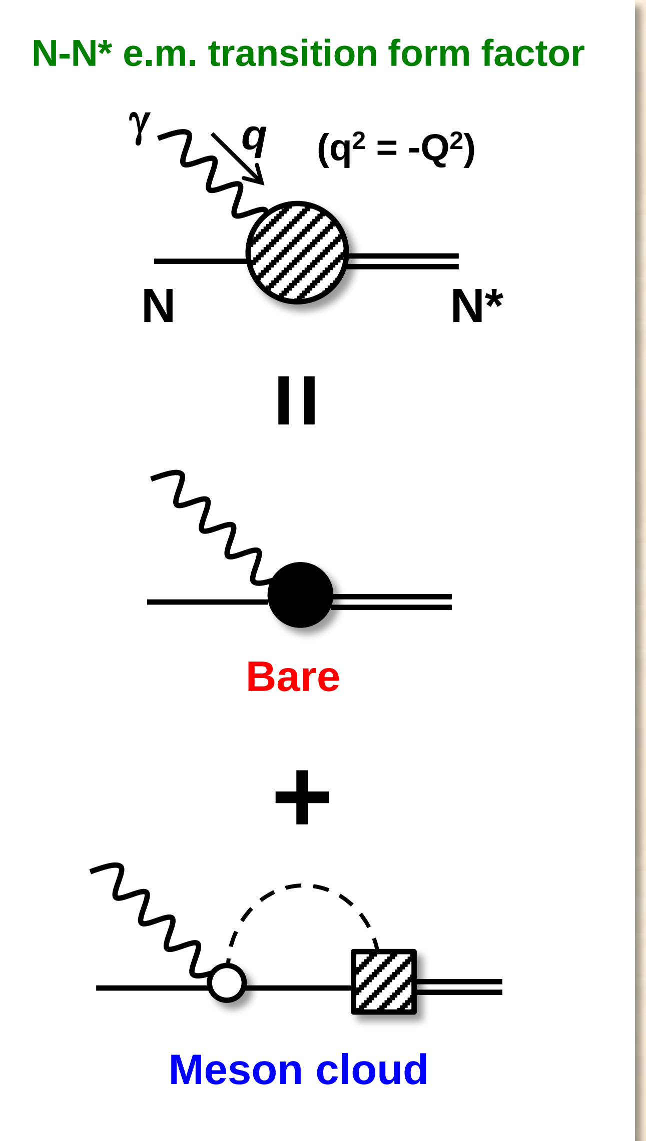


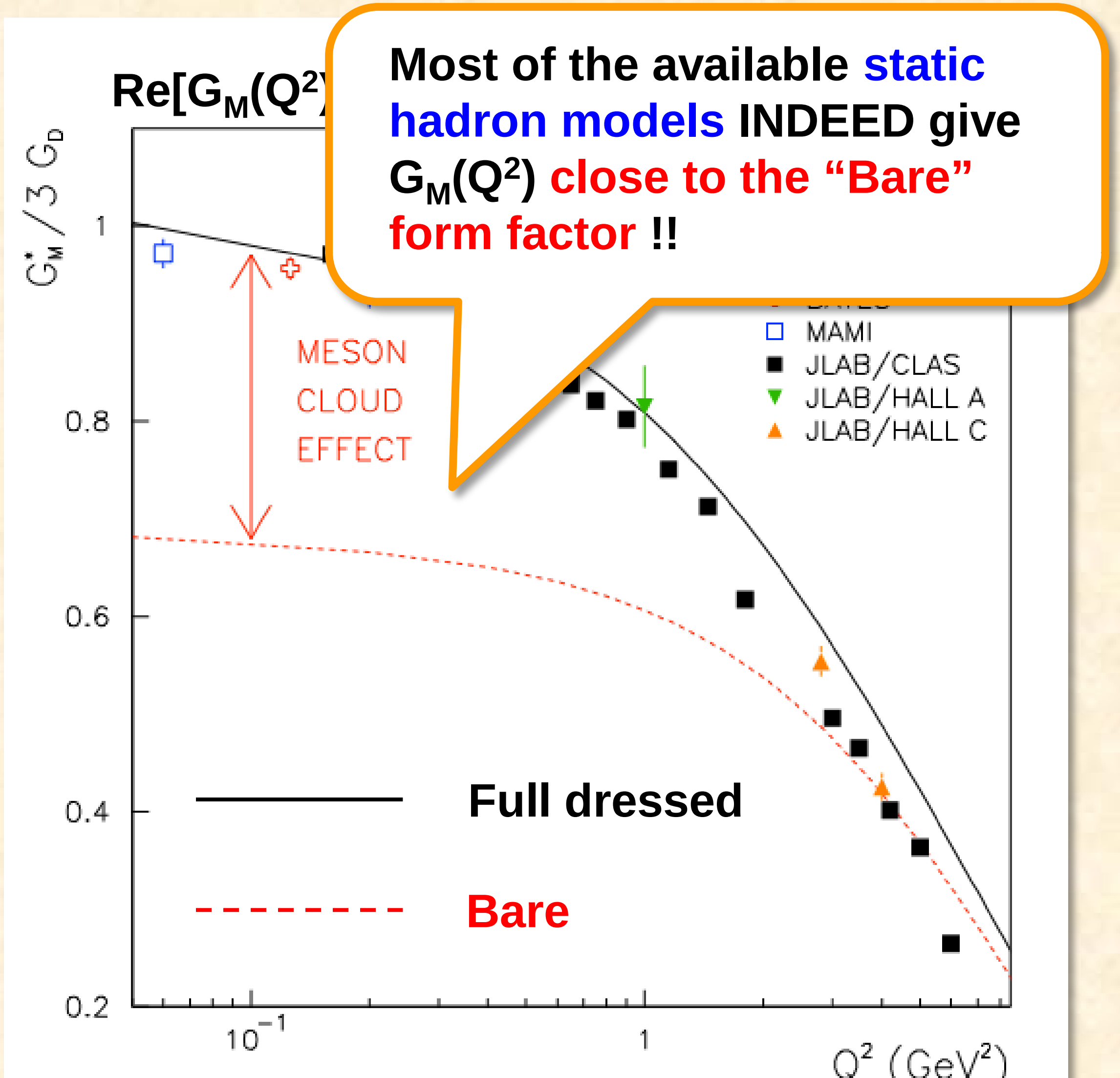
Re[$G_M(Q^2)$] for γ N → Δ (1232) transition



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

Consequences of reaction dynamics (2/3): Meson cloud effect





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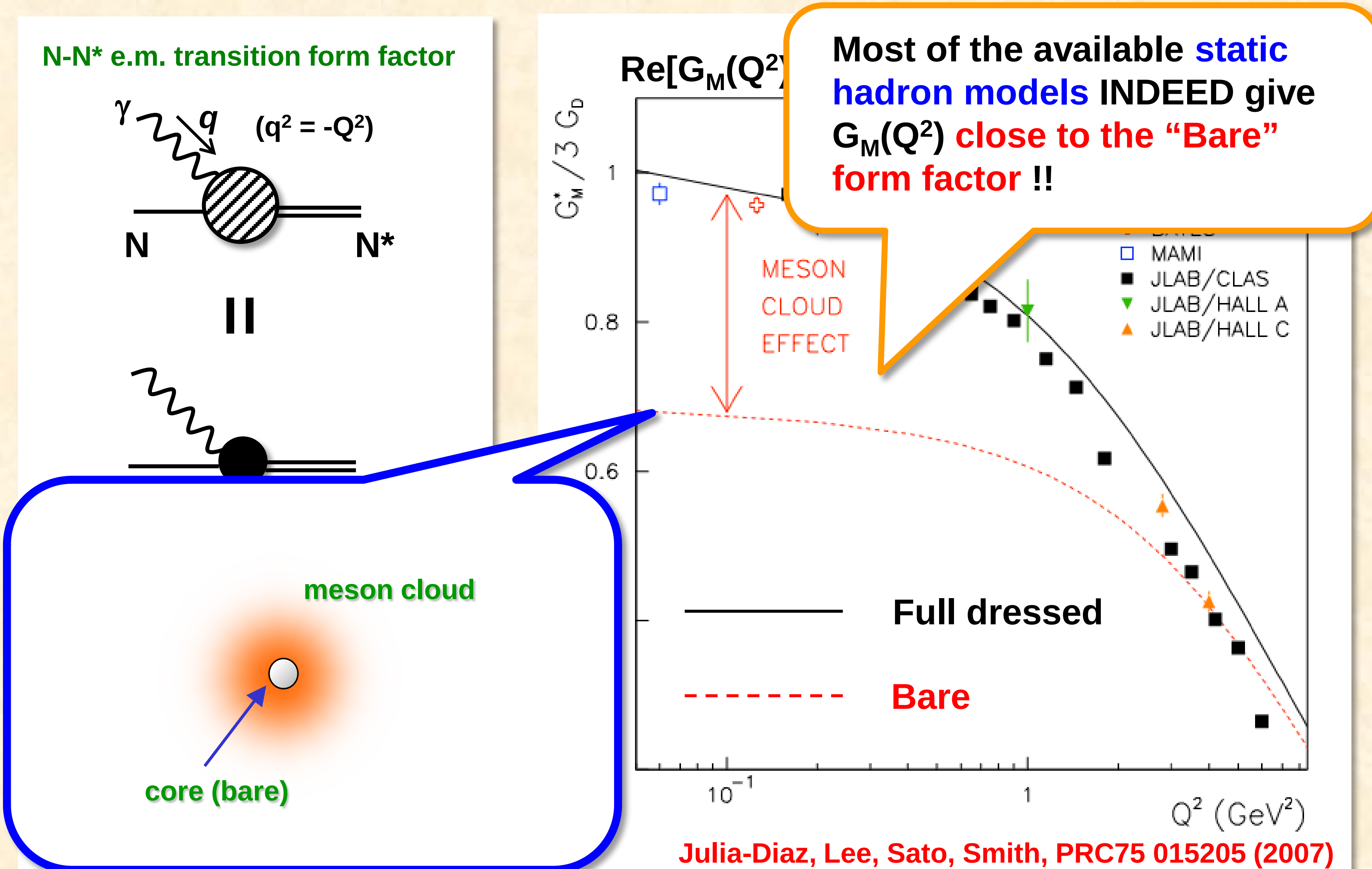
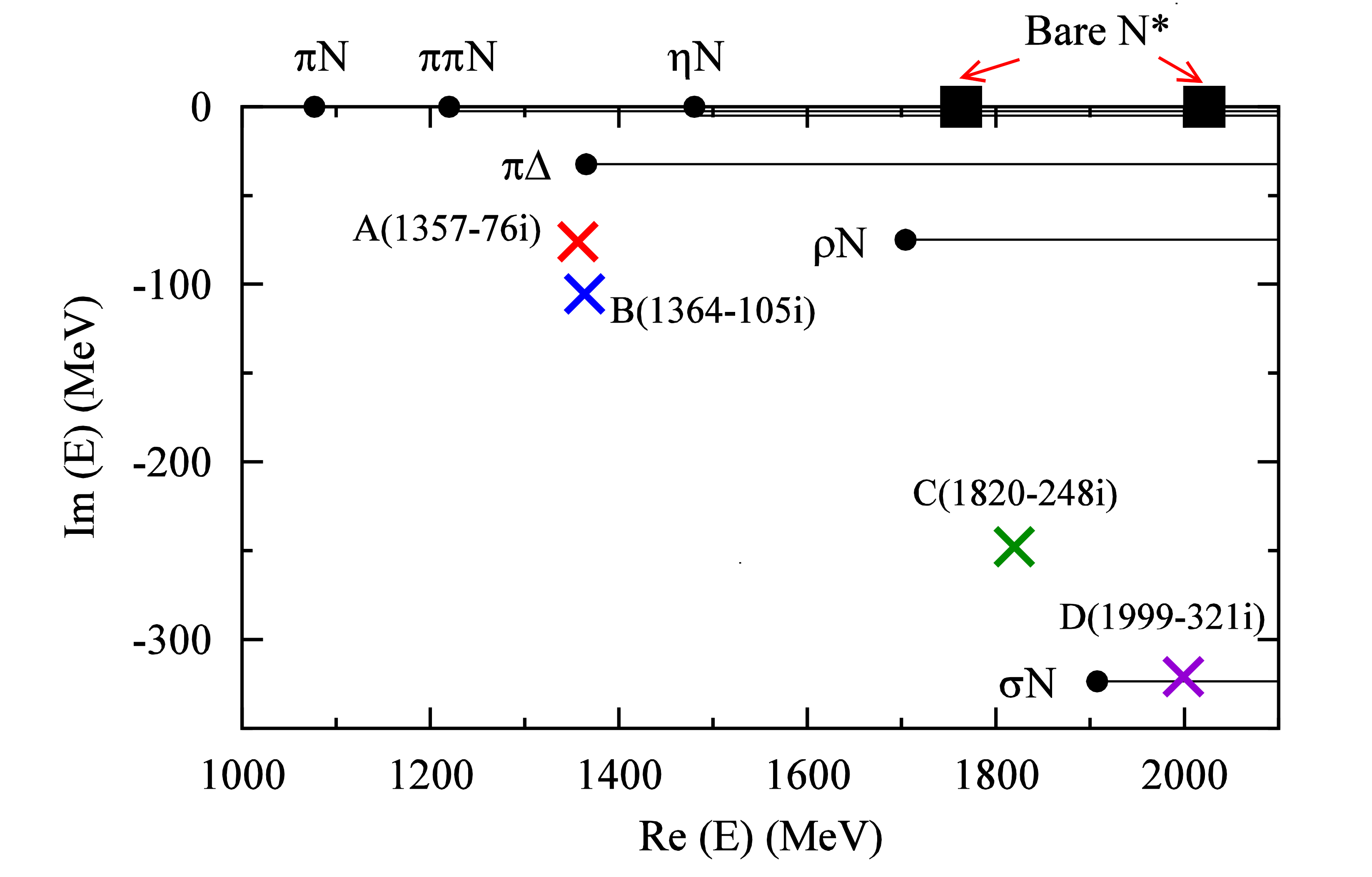


Consequences of reaction dynamics (3/3): Dynamical origin of nucleon resonances

Suzuki, Julia-Diaz, Kamano, Lee, Matsuyama, Sato, PRL104 065203 (2010)

(Complex) pole masses and dynamical origin of I=1/2, $J^P = 1/2^+$ resonances



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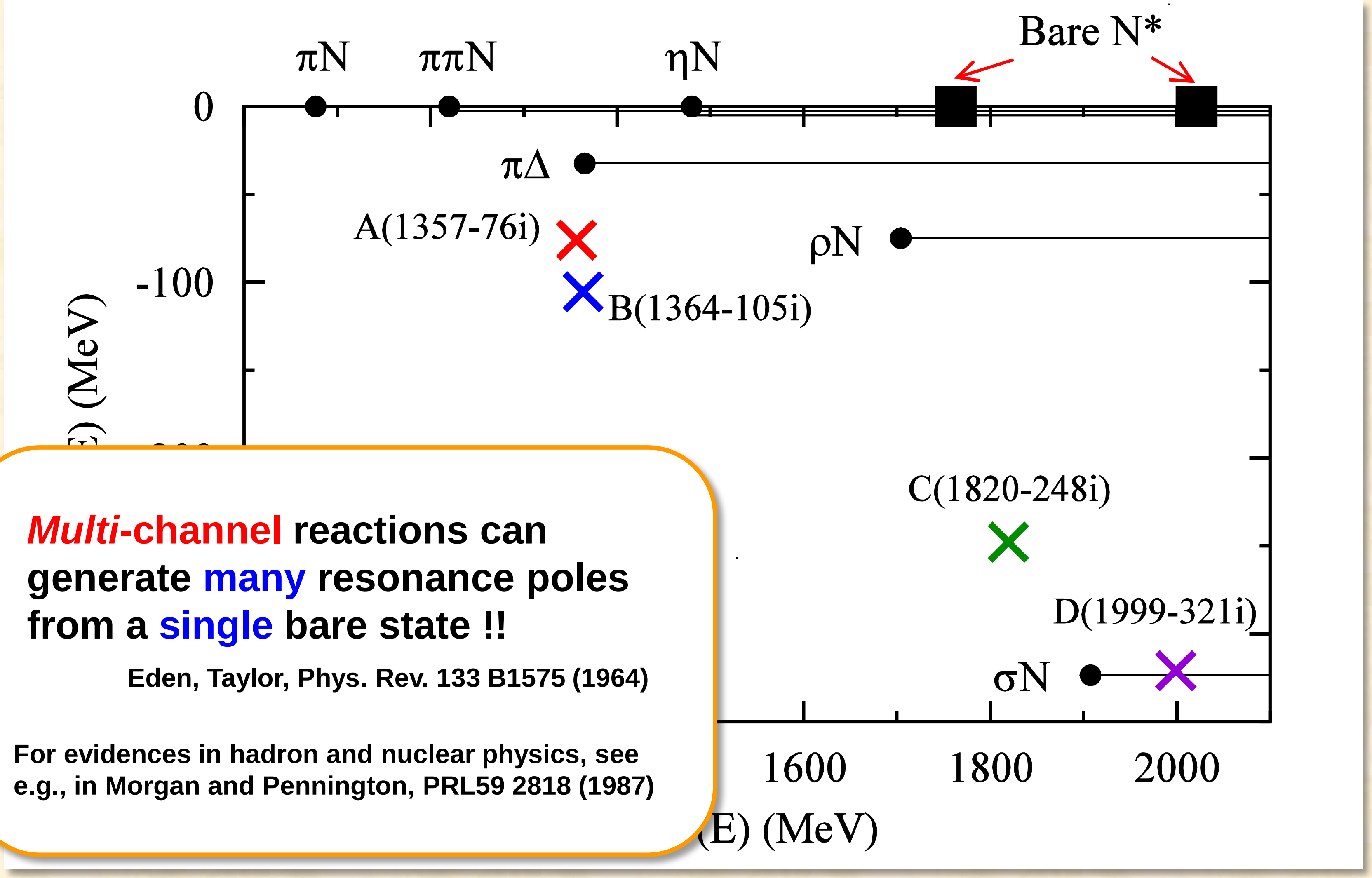


***Multi*-channel reactions can generate many resonance poles from a single bare state !!**

Eden, Taylor, Phys. Rev. 133 B1575 (1964)

For evidences in hadron and nuclear physics, see e.g., in Morgan and Pennington, PRL59 2818 (1987)

ANL-Osaka DCC analysis

Fully combined **analysis of πN , γN → πN , ηN , KΛ, KΣ reactions !!**

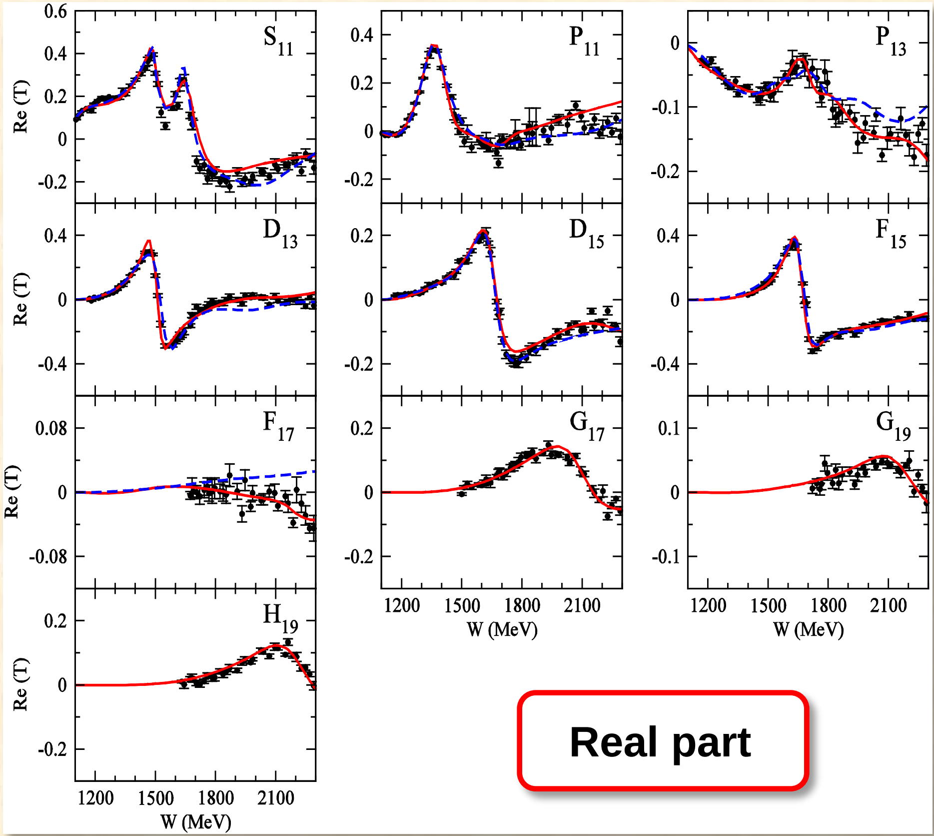
(more than 22,000 data of unpolarized & polarized observables to fit)

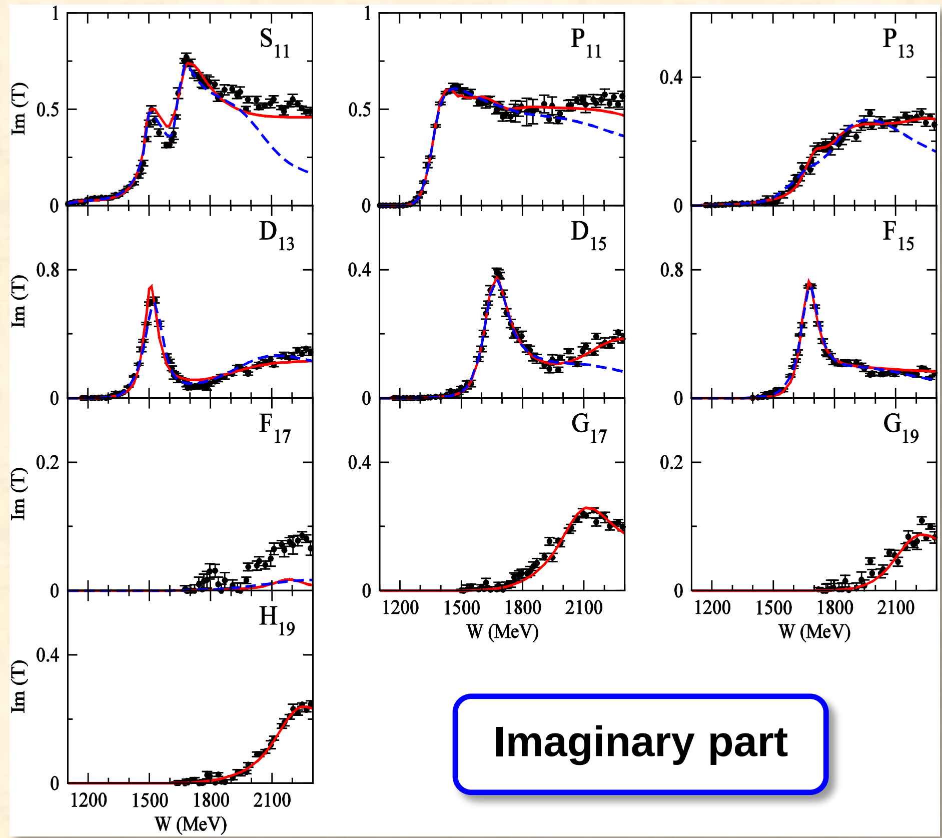
	2006 - 2009	2010 - 2012
✓ # of coupled channels	6 channels (γN,πN,ηN,πΔ,ρN,σN)	8 channels (γN,πN,ηN,πΔ,ρN,σN,KΛ,KΣ)
✓ πp → πN	< 2 GeV	< 2.3 GeV
✓ γp → πN	< 1.6 GeV	< 2.1 GeV
✓ πp → ηN	< 2 GeV	< 2.1 GeV
✓ γp → ηp	—	< 2.1 GeV
✓ πp → KΛ, KΣ	—	< 2.1 GeV
✓ γp → K^+Λ, KΣ	—	< 2.1 GeV

Kamano, Nakamura, Lee, Sato
arXiv:1305.4351

Partial wave amplitudes of πN scattering

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

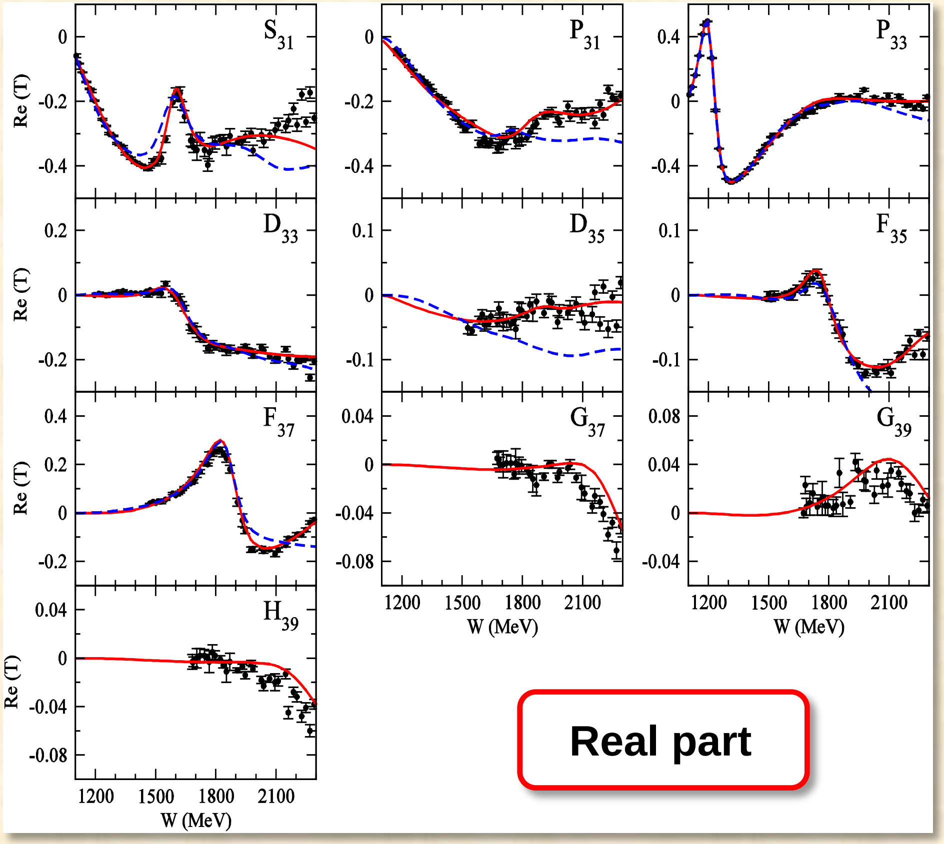




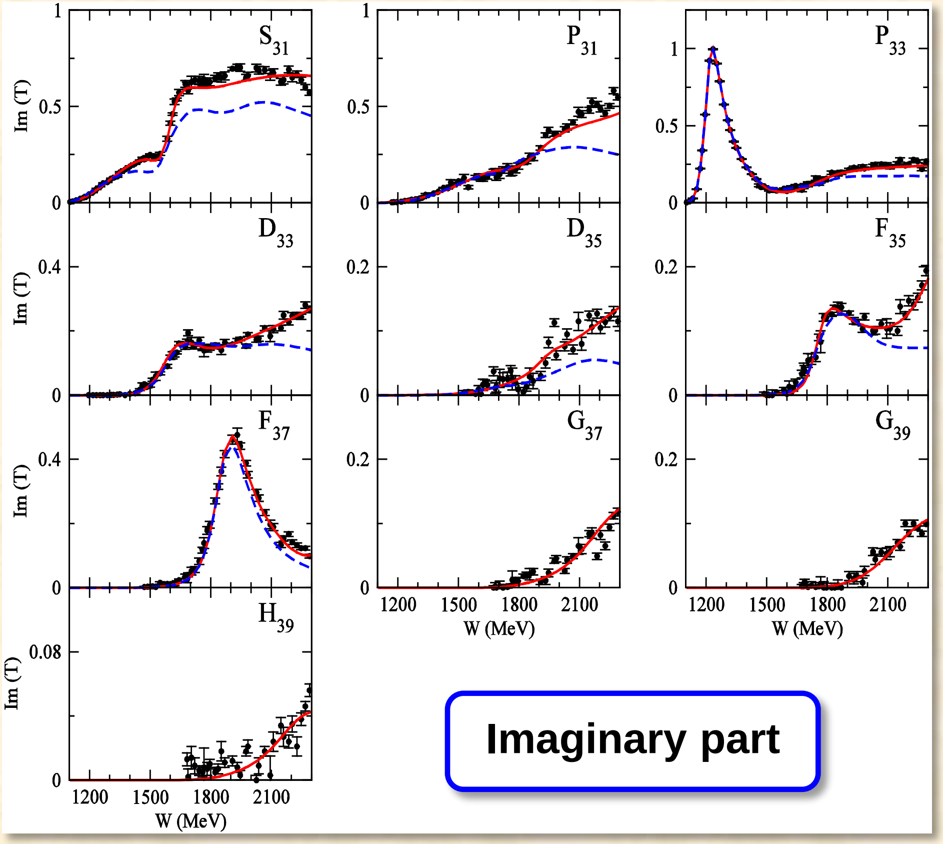
8ch DCC-analysis
(Kamano, Nakamura, Lee, Sato, arXiv:1305.4351)

previous 6ch DCC-analysis
(fitted to πN → πN data only up to
W = 2 GeV and F wave)
[PRC76 065201 (2007)]

Partial wave amplitudes of πN scattering



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



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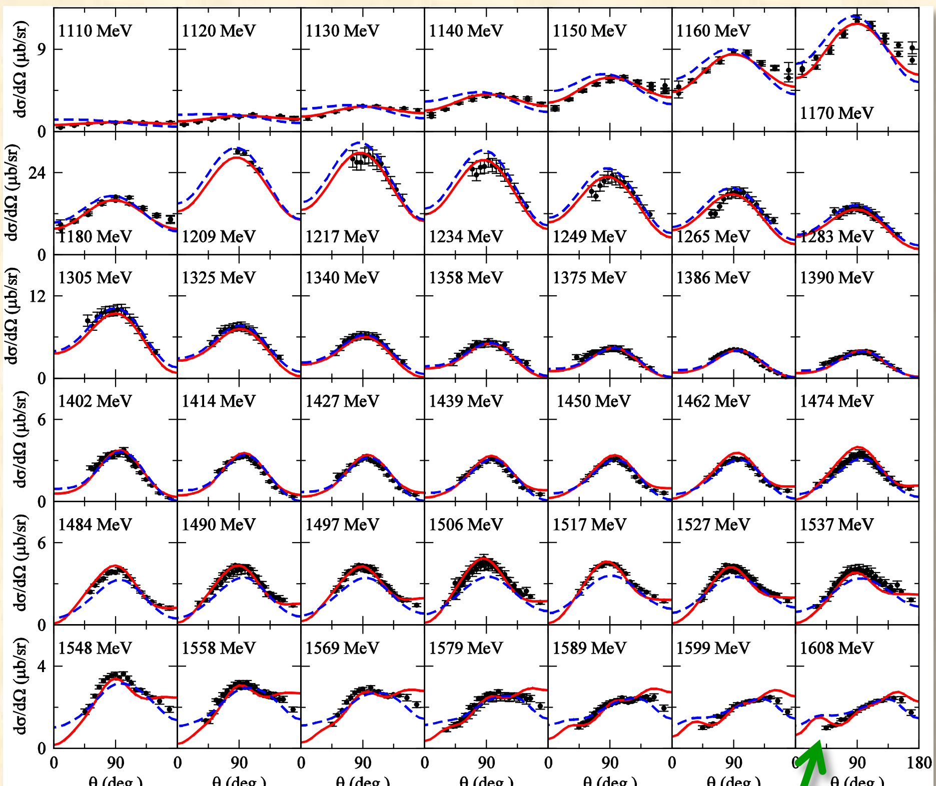
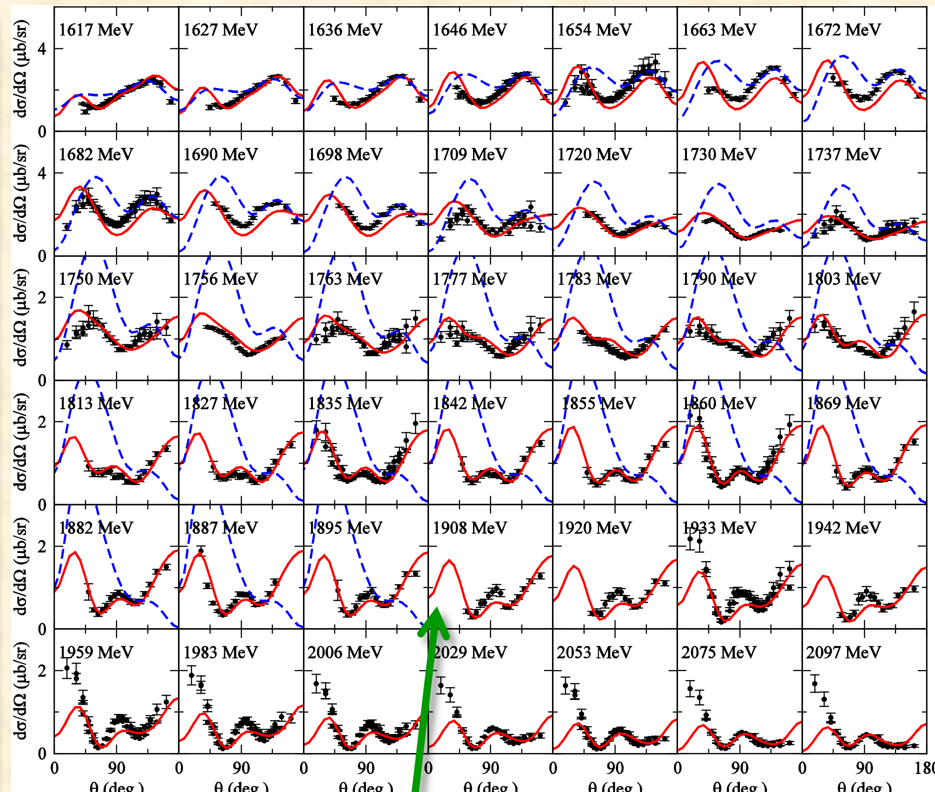
[PRC76 065201 (2007)]

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

DCS





1.6 GeV

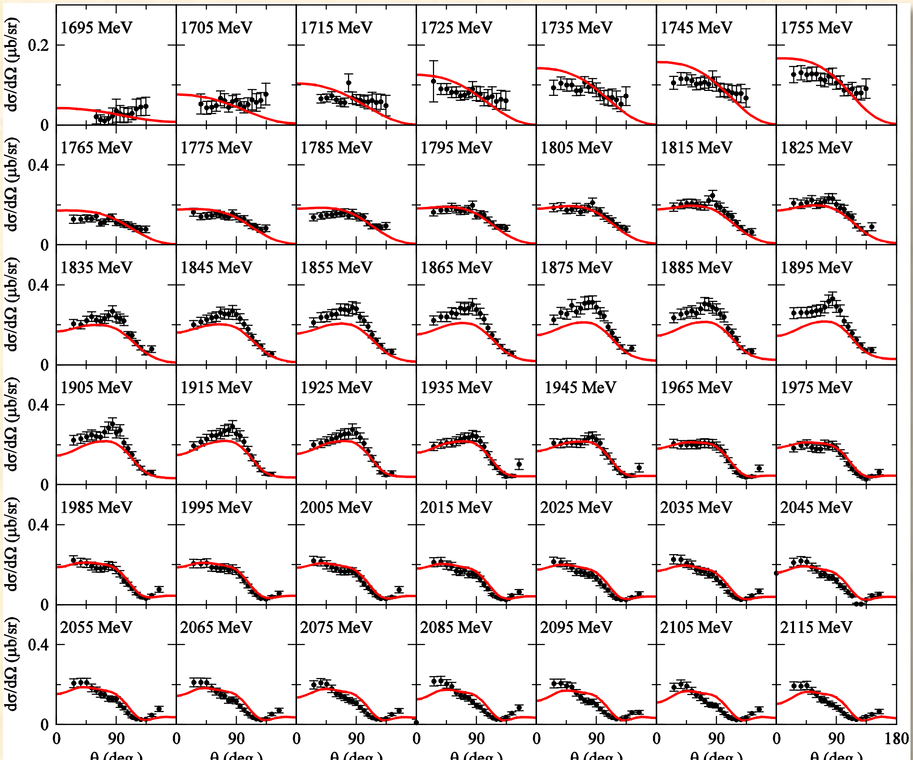
1.9 GeV

8ch DCC-analysis
(Kamano, Nakamura, Lee, Sato, arXiv:1305.4351)

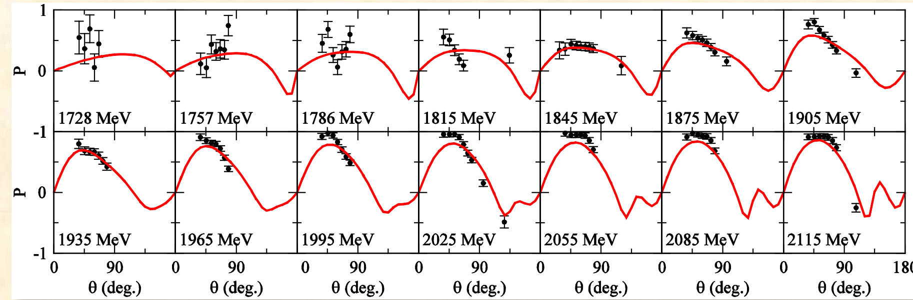
previous 6ch DCC-analysis
(fitted to $\gamma N \rightarrow \pi N$ data only up to W = 1.6 GeV)
[PRC77 045205 (2008)]

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

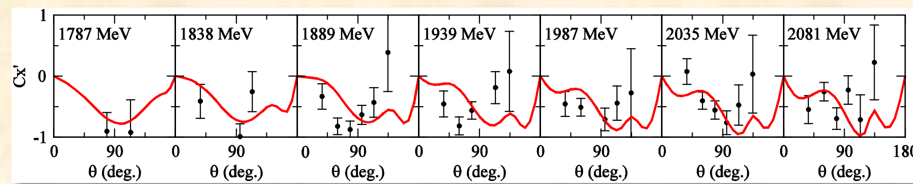
DCS

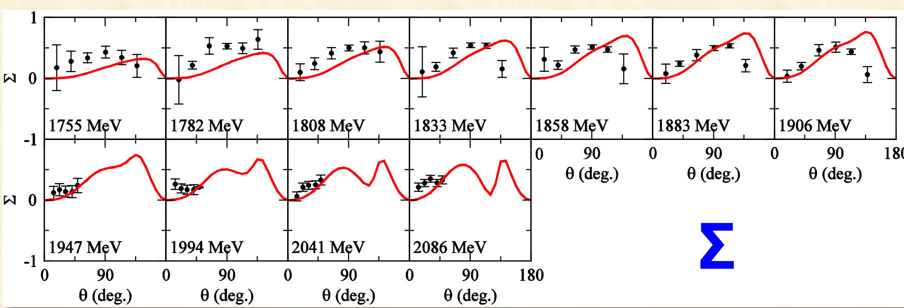


P



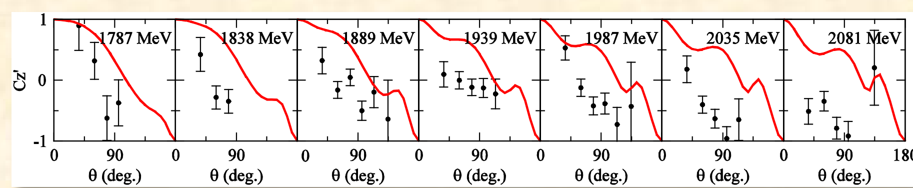
Cx’





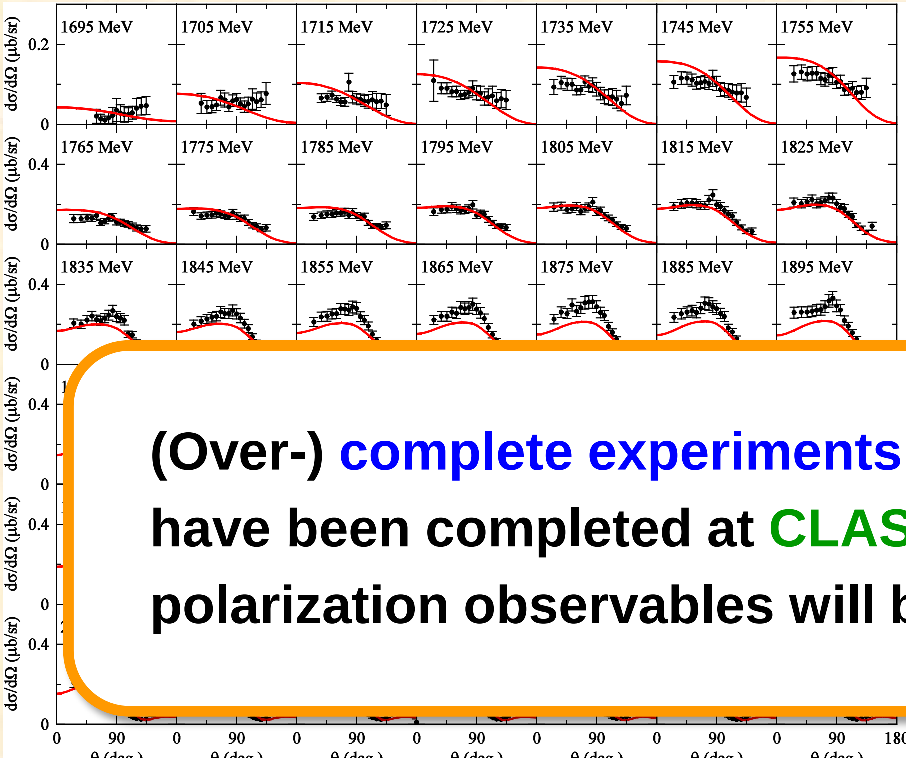
Σ

Cz’

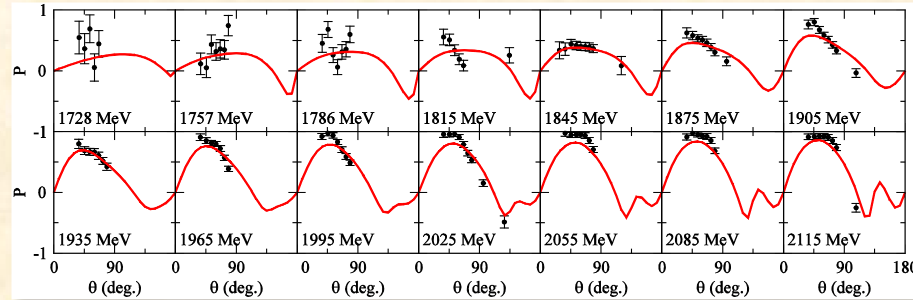


$\gamma\, p \rightarrow K^{+}\, \Sigma^{0}$ reaction

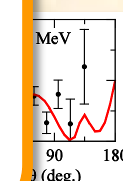
DCS



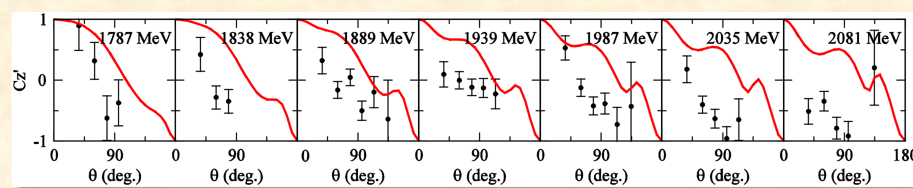
P

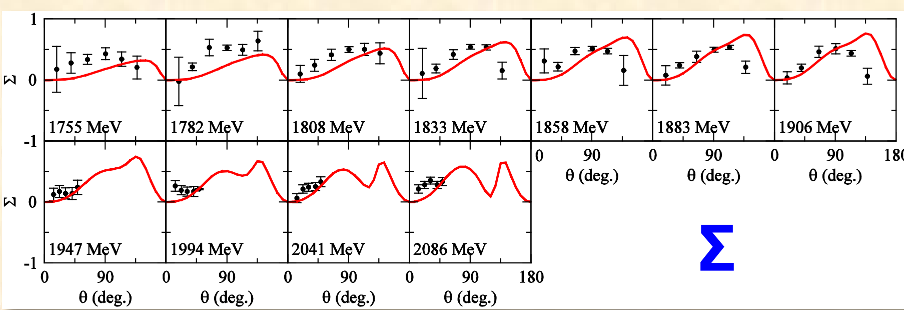


(Over-) complete experiments of KΛ & KΣ photoproductions have been completed at CLAS and the extensive data of polarization observables will be available soon !!



Cz’





Σ

Definition of N* parameters

Definitions of

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

N* → b decay vertex

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

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

Make an analytic continuation to (lower-half) complex energy plane.

Suzuki, Sato, Lee PRC79(2009)025205

Definition of N* parameters

Definitions of

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N* → b

Consistent with the resonance theory based on Gamow vectors

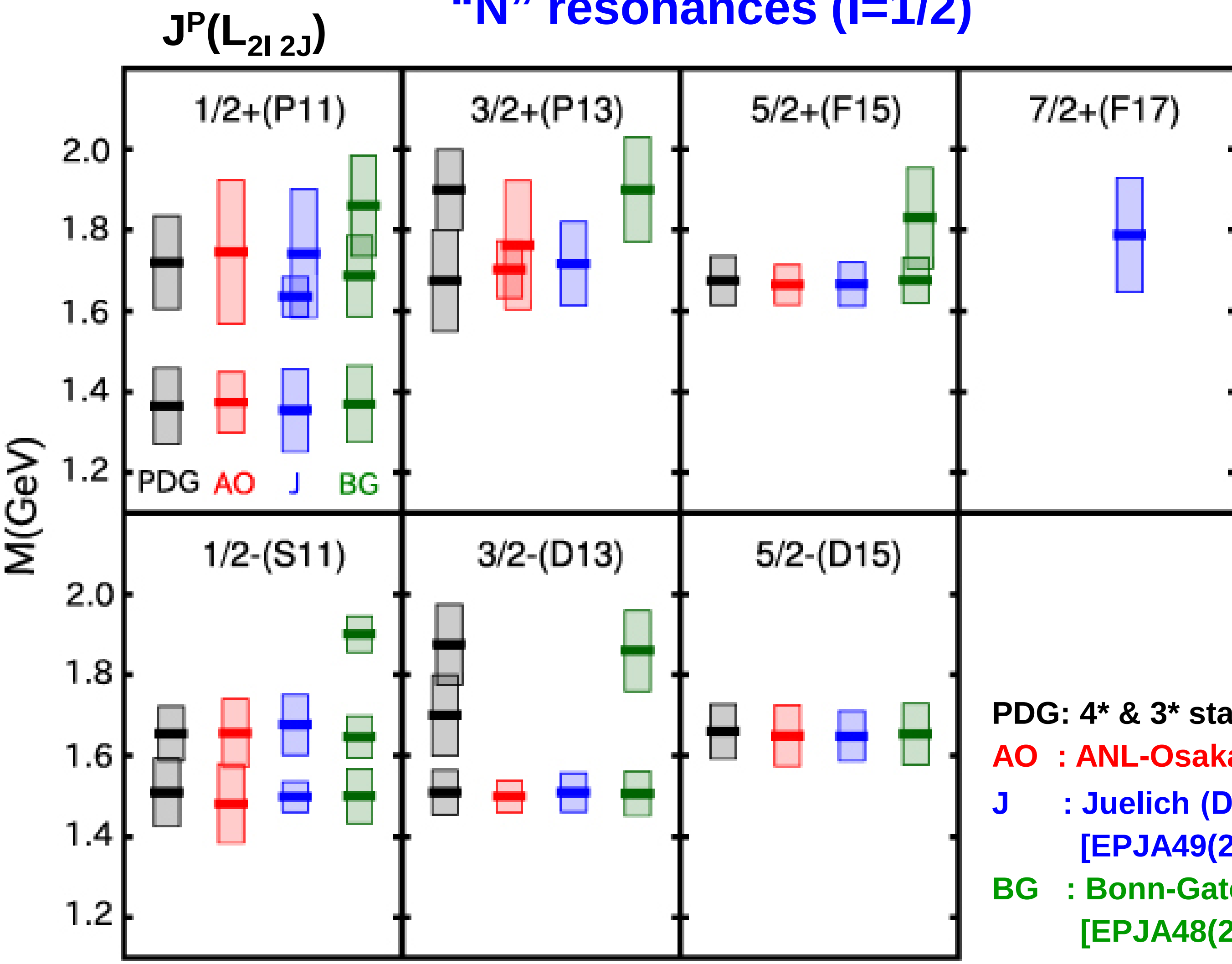
G. Gamow (1928), R. E. Peierls (1959), …
A brief introduction of Gamov vectors: de la Madrid et al, quant-ph/0201091

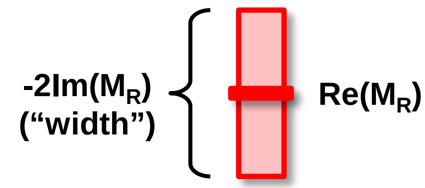
(complex) energy eigenvalues	**=**	**pole values**
transition matrix elements	**=**	**(residue)$^{1/2}$ of the poles**

Spectrum of N* resonances

Kamano, Nakamura, Lee, Sato, arXiv:1305.4351

"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 only) [EPJA49(2013)44, Model A]
BG : Bonn-Gatchina (on-shell K-matrix) [EPJA48(2012)5]

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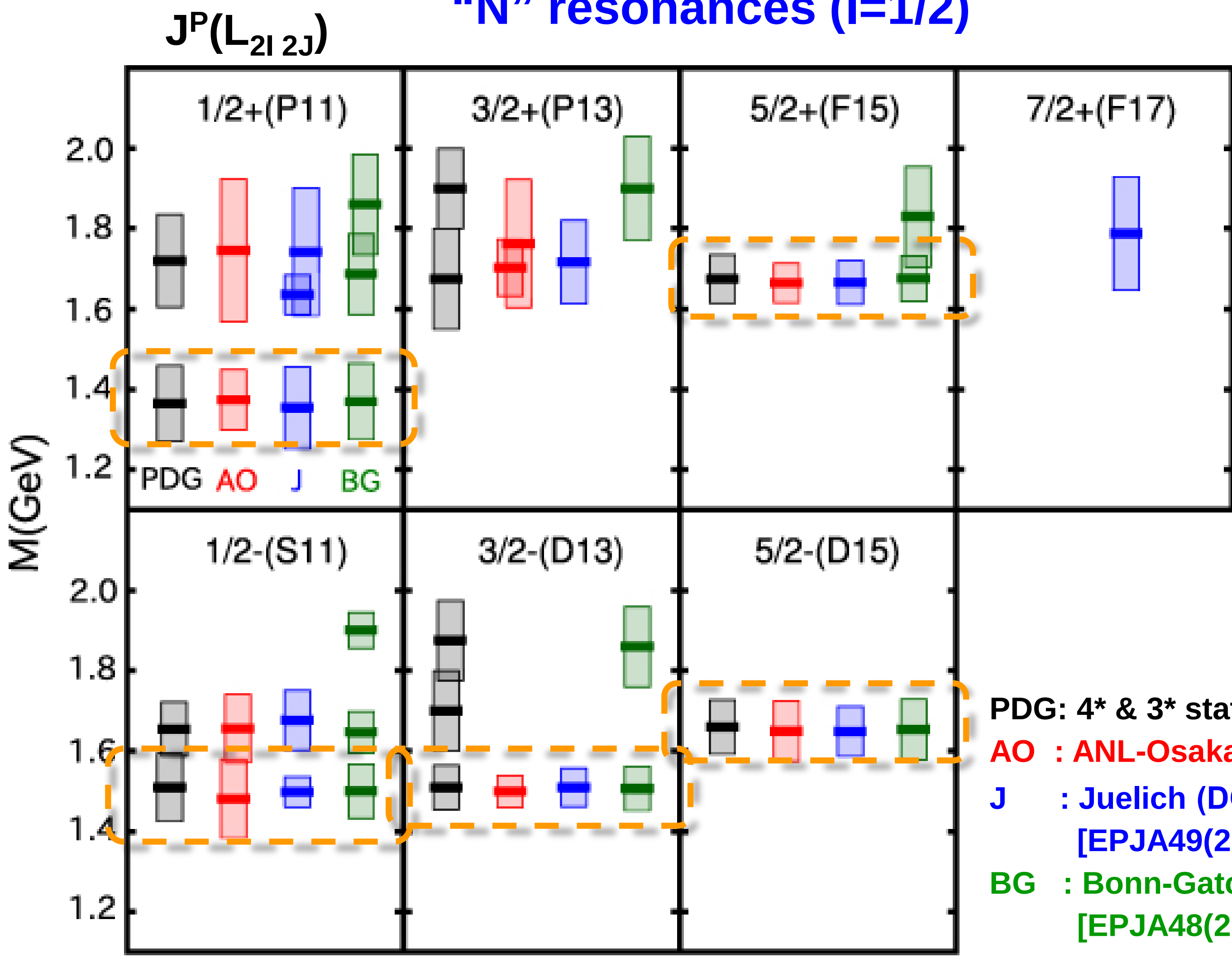

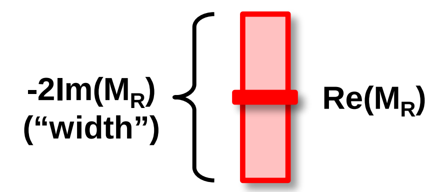

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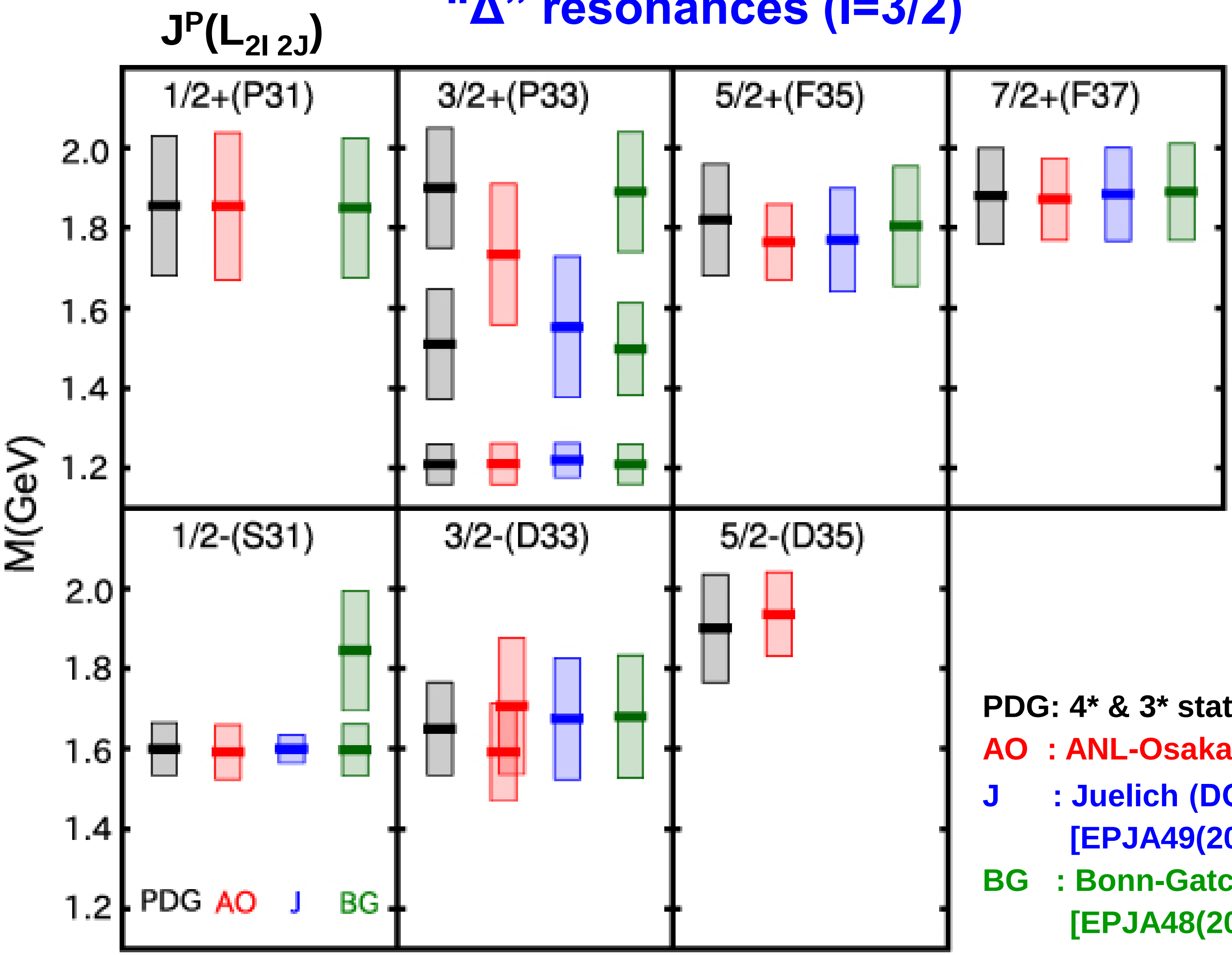
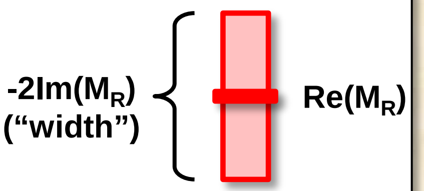
Spectrum of N* resonances

Kamano, Nakamura, Lee, Sato, arXiv:1305.4351

"Δ" resonances (I=3/2)





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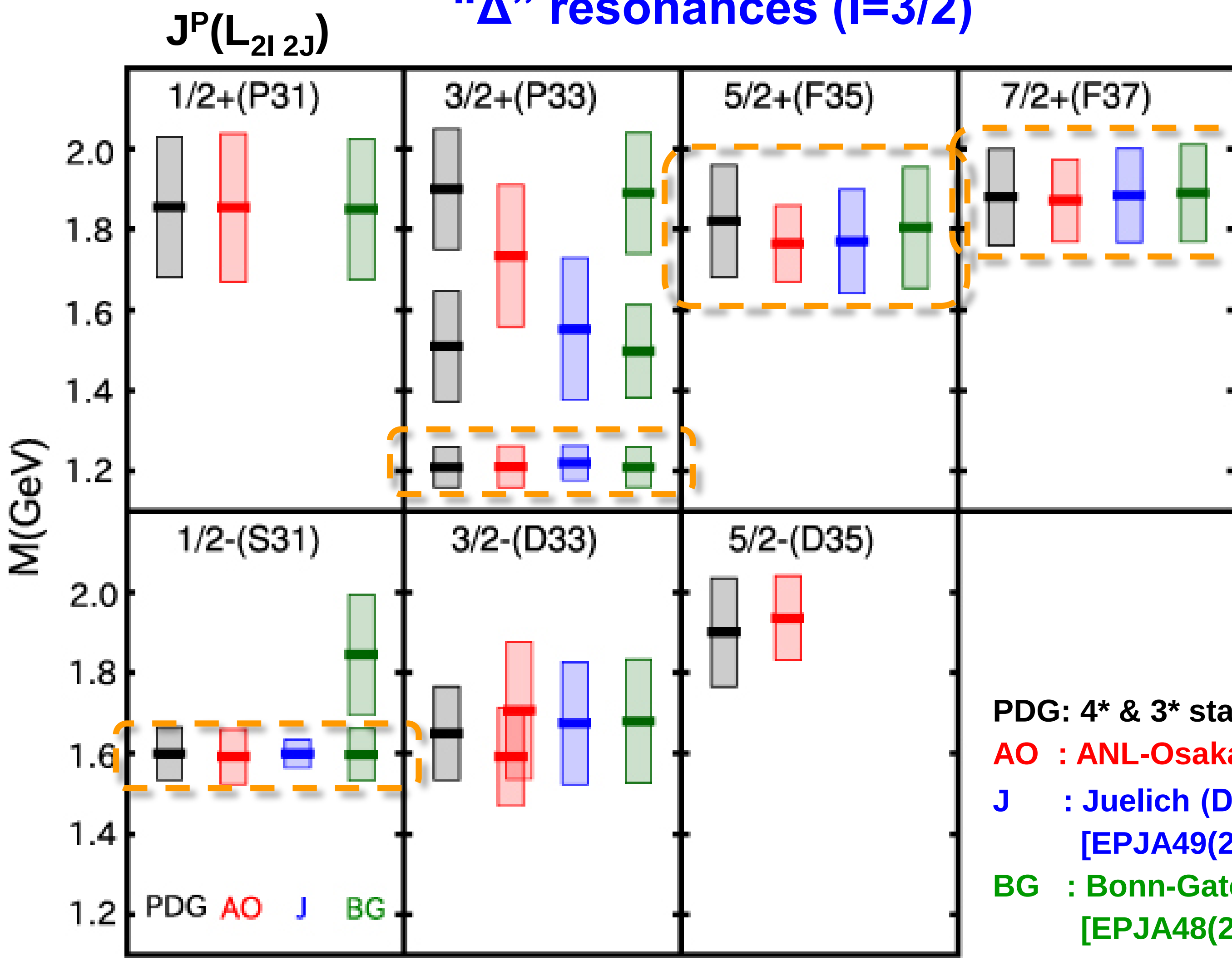

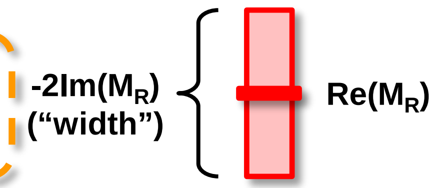

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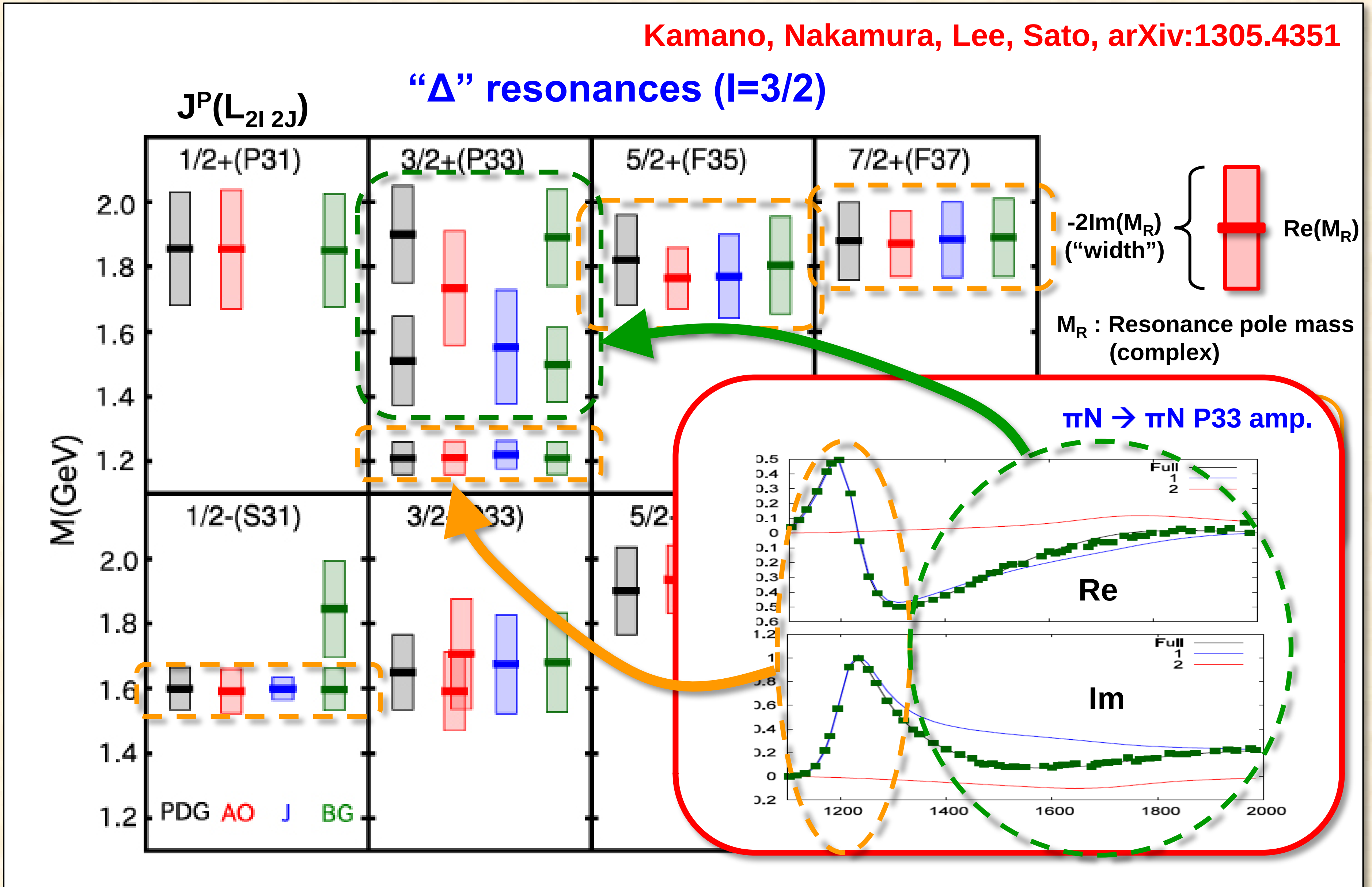
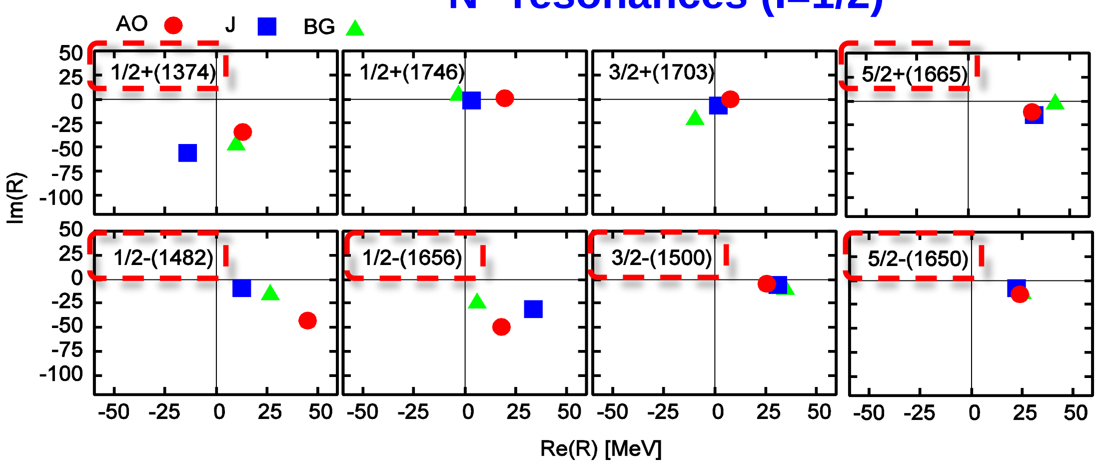


Residues of πN scattering amplitudes at resonance poles

Kamano, Nakamura, Lee, Sato, arXiv:1305.4351

J^P (Re[M_R])

"N" resonances (I=1/2)



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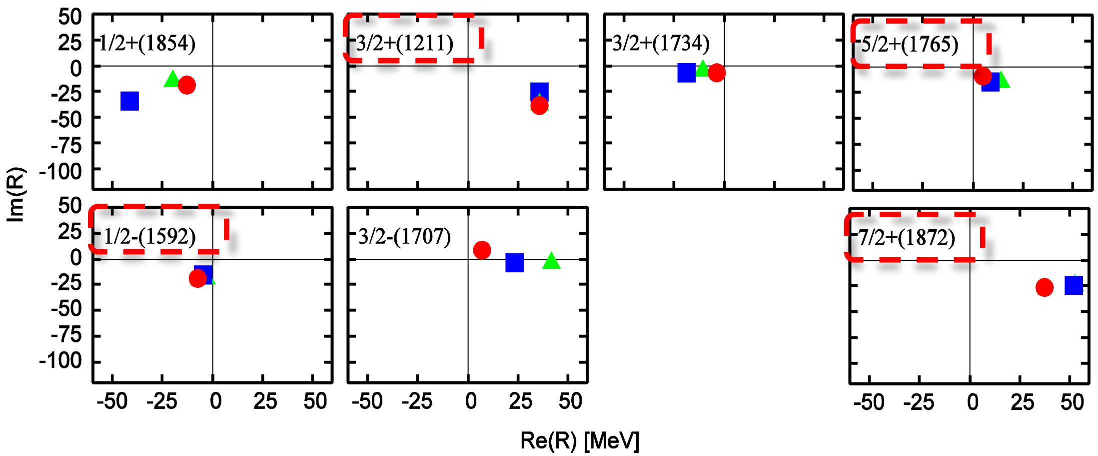

Residue

$$\mathcal{F}_{\pi N,\pi N}(W \to M_R) = -\frac{R_{\pi N,\pi N}}{W - M_R} + \cdots$$

Interpreted as *square* of "N*Nπ coupling constant" (complex value !!)

$$R_{\pi N,\pi N} \equiv (g_{N^*,\pi N})^2$$

= resonances showing good agreement for pole masses

Helicity amplitudes of γp → N* transition at resonance poles

Kamano, Nakamura, Lee, Sato, arXiv:1305.4351

Particle $J^P(L_{2I2J})$	ANL-Osaka				Bonn-Gatchina [23]			
	$A_{3/2}$		$A_{1/2}$		$A_{3/2}$		$A_{1/2}$	
(10^{-3} GeV$^{-1/2}$)	Re	Im	Re	Im	Re	Im	Re	Im
$N(1482)\ 1/2^-(S_{11})$	-	-	159.	24.	-	-	115.1	14.1
$N(1656)\ 1/2^-(S_{11})$	-	-	29.	−28.	-	-	32.6	−5.2
$N(1374)\ 1/2^+(P_{11})$	-	-	−49.	10.	-	-	−34.7	27.1
$N(1746)\ 1/2^+(P_{11})$	-	-	−24.	83.	-	-	54.2	−9.6
$N(1703)\ 3/2^+(P_{13})$	70.	−8.	−234.	−8.	63.4	135.9	110.0	0.0
$N(1763)\ 3/2^+(P_{13})$	−44.	1.	126.	−72.	-	-	-	-
$N(1500)\ 3/2^-(D_{13})$	93.	11.	−38.	−2.	131.9	4.6	−21.0	0.0
$N(1702)\ 3/2^-(D_{13})$	40.	−36.	11.	23.	−37.	0.0	3.8	43.8
$N(1650)\ 5/2^-(D_{15})$	30.	−13.	5.	−2.	24.6	−8.5	23.1	−6.6
$N(1665)\ 5/2^+(F_{15})$	38.	2.	−53.	5.	133.9	−4.7	−11.8	5.5
$\Delta(1592)\ 1/2^-(S_{31})$	-	-	113.	−2.	-	-	51.4	−8.1
$\Delta(1702)\ 1/2^-(S_{31})$	-	-	35.	3.	-	-	29.5	51.1
$\Delta(1854)\ 1/2^+(P_{31})$	-	-	−51.	9.	-	-	17.6	14.8
$\Delta(1211)\ 3/2^+(P_{33})$	−257.	12.	−129.	34.	−250.9	39.7	−123.9	42.6
$\Delta(1734)\ 3/2^+(P_{33})$	18.	135.	23.	68.	−39.6	10.6	−34.1	40.6
$\Delta(1592)\ 3/2^-(D_{33})$	−89.	−76.	−123.	−38.	-	-	-	-
$\Delta(1707)\ 3/2^-(D_{33})$	32.	−121.	20.	−56.	120.2	120.2	109.3	130.2
$\Delta(1936)\ 5/2^-(D_{35})$	34.	−9.	50.	−19.	-	-	-	-
$\Delta(1765)\ 5/2^+(F_{35})$	0.	−18.	−1.	−8.	−50.0	0.0	23.0	−9.8
$\Delta(1872)\ 7/2^+(F_{37})$	−76.	−2.	−61.	10.	−95.3	11.7	−71.5	8.8

Good agreement:
1st P33

Qualitative agreement:
1st S11
2nd S11
1st P11
1st D13
1st D15
1st S31
1st F37

Helicity amplitudes of γp → N* transition at resonance poles

Kamano, Nakamura, Lee, Sato, arXiv:1305.4351

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$N(1482)$ $1/2^-(S_{11})$	-	-	159.	24.	-	-	115.1	14.1
$N(1656)$ $1/2^-(S_{11})$	-	-	29.	−28.	-	-	32.6	−5.2
$N(1374)$ $1/2^+$[illegible]			[illegible]	[illegible]			[illegible]	[illegible]
$N(1746$								
$N(170$								
$N(176$								
$N(150$								
$N(170$								
$N(165$								
$N(166$								
$\Delta(159$								
$\Delta(1702)$								
$\Delta(1854)$ $1/2^+(P_{31})$	-	-	−51.	9.	-	-	17.6	14.8
$\Delta(1211)$ $3/2^+(P_{33})$	−257.	12.	−129.	34.	−250.9	39.7	−123.9	42.6
$\Delta(1734)$ $3/2^+(P_{33})$	18.	135.	23.	68.	−39.6	10.6	−34.1	40.6
$\Delta(1592)$ $3/2^-(D_{33})$	−89.	−76.	−123.	−38.	-	-	-	-
$\Delta(1707)$ $3/2^-(D_{33})$	32.	−121.	20.	−56.	120.2	120.2	109.3	130.2
$\Delta(1936)$ $5/2^-(D_{35})$	34.	−9.	50.	−19.	-	-	-	-
$\Delta(1765)$ $5/2^+(F_{35})$	0.	−18.	−1.	−8.	−50.0	0.0	23.0	−9.8
$\Delta(1872)$ $7/2^+(F_{37})$	−76.	−2.	−61.	10.	−95.3	11.7	−71.5	8.8

Good agreement:
1st P33

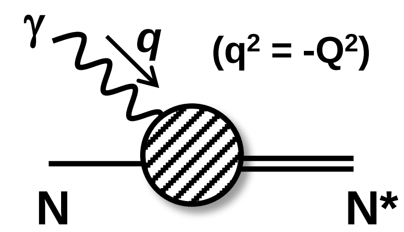
Qualitative agreement:
1st S11

Extracted resonance coupling constants and helicity amplitudes seem much more sensitive to the analysis performed than the resonance pole masses !!

Ongoing projects & future plans with ANL-Osaka DCC approach (1/4)

Further study of N* spectroscopy with the current ANL-Osaka DCC model

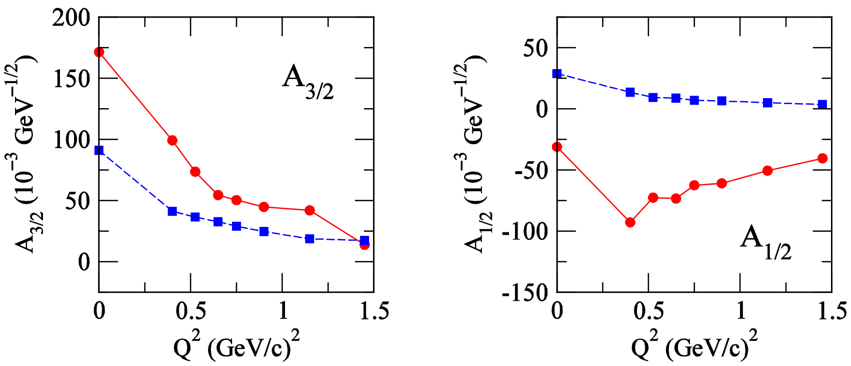
- **Extraction of N-N* e.m. transition form factors via the analysis of electroproduction reactions**
  - **Extend our early analysis [PRC80(2009)025207] of p(e,e'π)N data from CLAS6 to higher Q^2 region: 1.5 → 6.0 $(GeV/c)^2$**
  - **(Hopefully) see how the transition between hadron and quark-gluon degrees of freedom occurs as Q^2 increases.**



N-N* e.m. transition form factor

Expected to be a crucial source of information on internal structure of N*s !!

e.g.) Nucleon - 1st D13 e.m. transition form factors



● Real
■ Imaginary

Julia-Diaz, Kamano, Lee, Matsuyama, Sato, Suzuki PRC80(2009)025207
Suzuki, Sato, Lee, PRC82(2010)045206

Ongoing projects & future plans with ANL-Osaka DCC approach (1/4)

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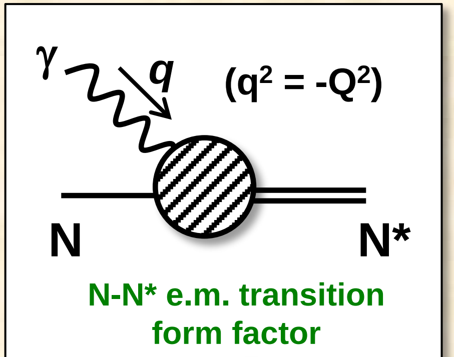
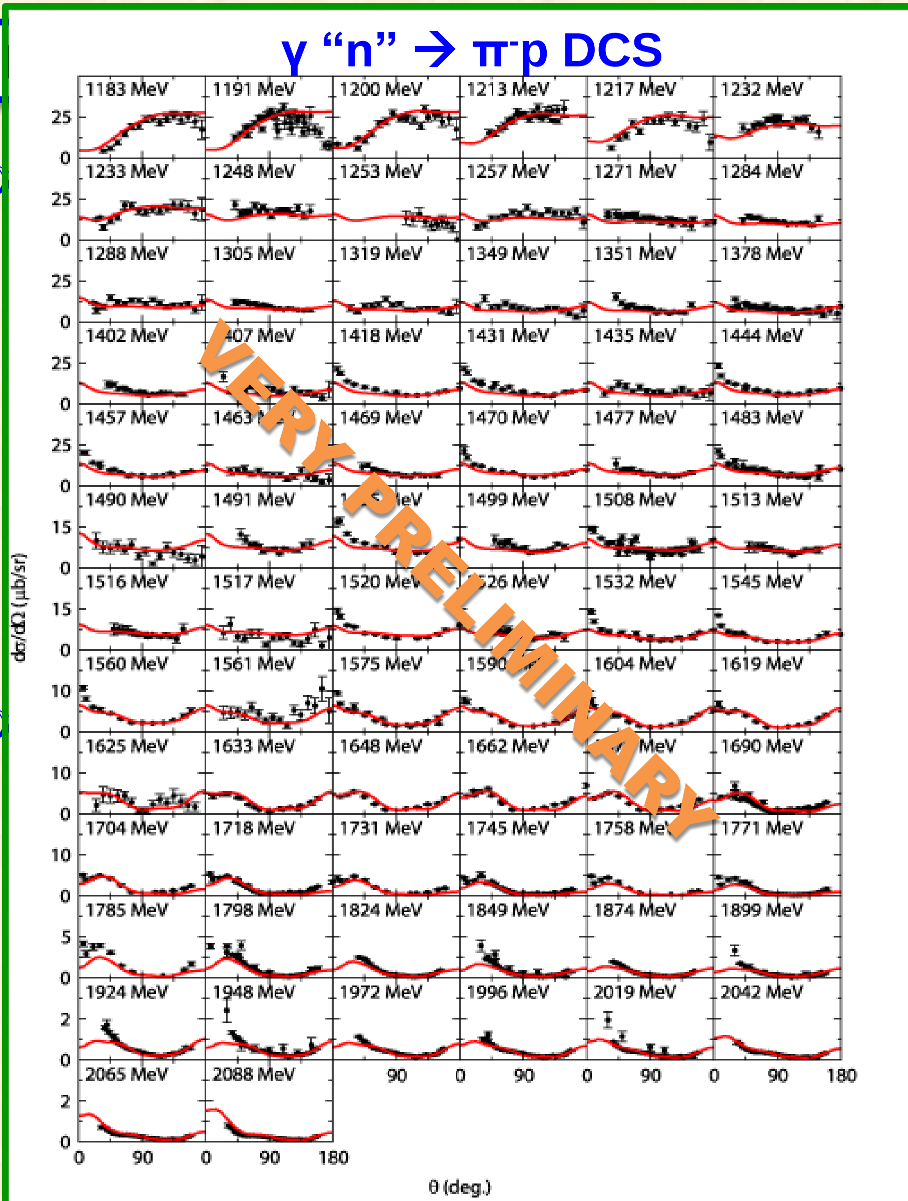


Expected to be a crucial source of information on internal structure of N*s !!

- **Study of photoproduction reactions off a "neutron" target**
  - **For I=1/2 N* states, *BOTH* proton-N* and neutron-N* e.m. transition form factors are needed for decomposing to isoscalar and isovector form factors.**

    ➔ Necessary for *neutrino-induced* reactions !!
  - **Explore a possible existence of N* states that strongly couple to "neutron"-target photoproductions.**

Ongoing projects & future plans with ANL-Osaka DCC approach (1/4)



he current ANL-Osaka DCC model

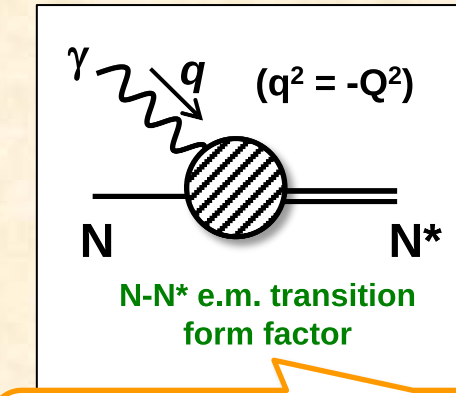
actors via the analysis of

5207] of

gion: 1.5 → 6.0 $(GeV/c)^2$

hadron and

Q^2 increases.



Expected to be a crucial source of information on internal structure of N*s !!

a “neutron” target

eutron-N* e.m. transition form factors are

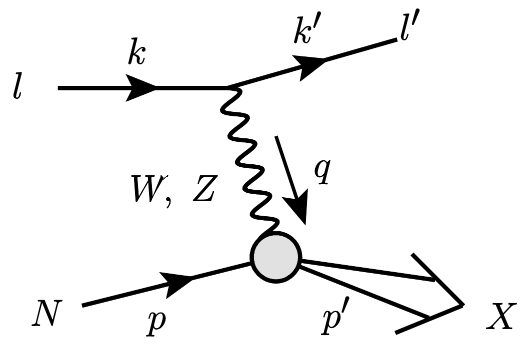
isovector form factors.

ctions !!

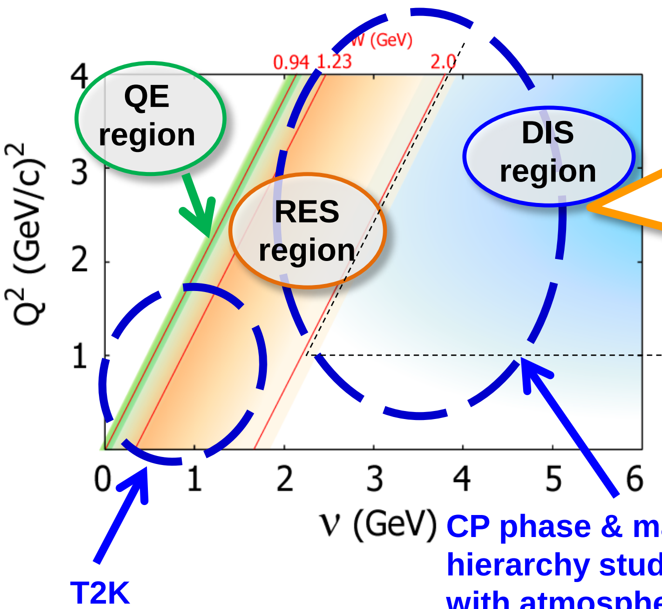
hat strongly couple to “neutron”-target

Ongoing projects & future plans with ANL-Osaka DCC approach (2/4)

Application to neutrino-induced reactions in GeV-energy region



Precise knowledge of neutrino-nucleon/nucleus interactions is necessary for reliable extractions of neutrino parameters (CP phase, mass hierarchy, etc.) from the future neutrino-oscillation experiments.



Need to tackle *overlapping regions* between QE, RES, and DIS regions !!

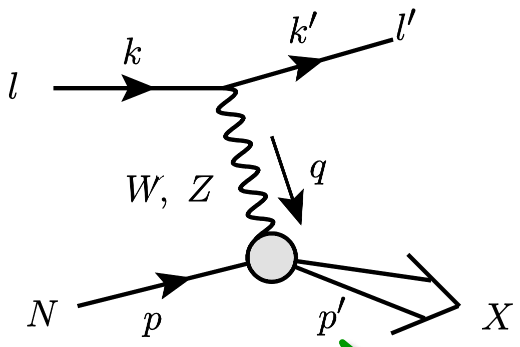
Collaboration@J-PARC Branch of KEK Theory Center

Y. Hayato (ICRR, U. of Tokyo), M. Hirai (Tokyo U. of Sci.)
H. Kamano (RCNP, Osaka U.), S. Kumano (KEK)
S. Nakamura (YITP, Kyoto U.), K. Saito (Tokyo U. of Sci.)
M. Sakuda (Okayama U.), T. Sato (Osaka U.)

[➔ arXiv:1303.6032]

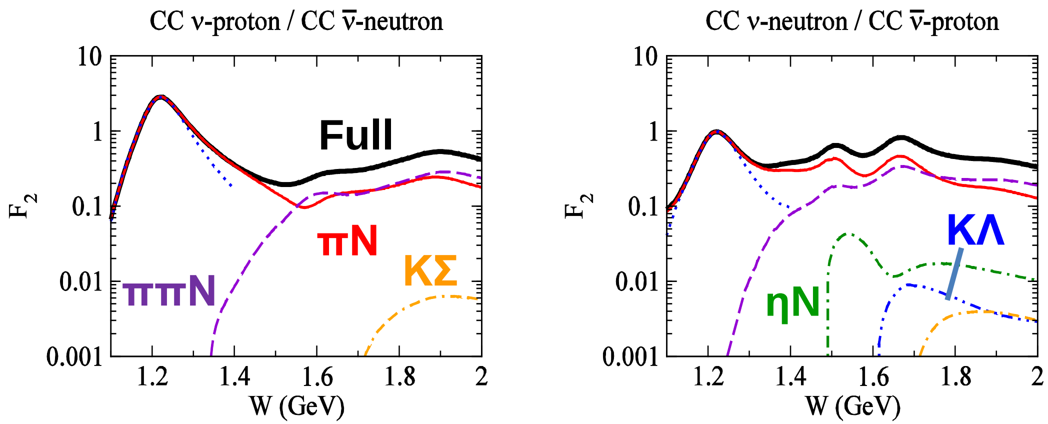
Ongoing projects & future plans with ANL-Osaka DCC approach (2/4)

Application to neutrino-induced reactions in GeV-energy region



Precise knowledge of neutrino-nucleon/nucleus interactions is necessary for reliable extractions of neutrino parameters (CP phase, mass hierarchy, etc.) from the future neutrino-oscillation experiments.

First application of 8ch DCC model to neutrino-nucleon reactions in N* region (forward angle limit)



Kamano, Nakamura, Lee, Sato, PRD86(2012)097503

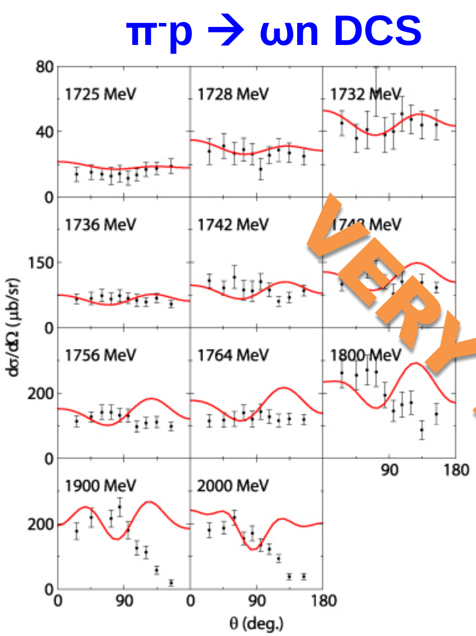
Ongoing projects & future plans with ANL-Osaka DCC approach (3/4)

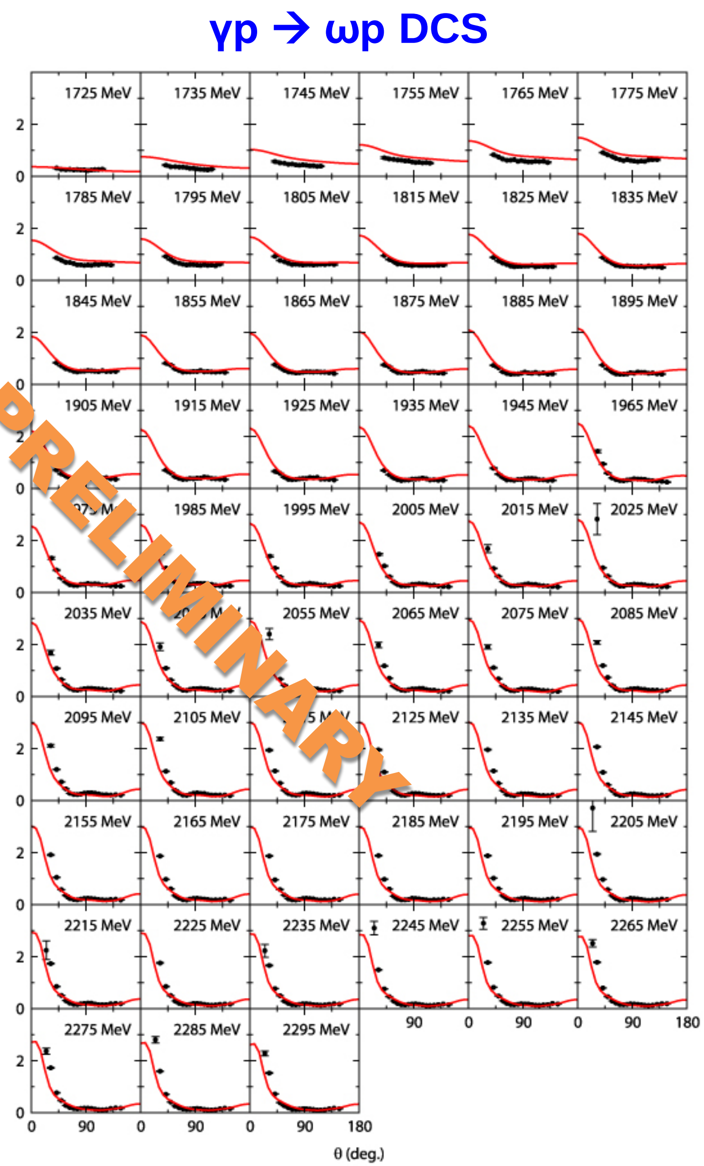
Extending DCC analysis	2006-2009	2010-2012 (arXiv:1305.4351)
✓ # of coupled channels	6 channels ($\gamma N, \pi N, \eta N, \pi\Delta, \rho N, \sigma N$)	8 channels (6ch + $K\Lambda$, $K\Sigma$)
✓ $\pi p \rightarrow \pi N$	< 2 GeV	< 2.3 GeV
✓ $\gamma p \rightarrow \pi N$	< 1.6 GeV	< 2.1 GeV
✓ $\pi p \rightarrow \eta p$	< 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

Ongoing projects & future plans with ANL-Osaka DCC approach (3/4)

Extending DCC analysis	2006-2009	2010-2012 (arXiv:1305.4351)	2013-
✓ # of coupled channels	6 channels (γN,πN,ηN,πΔ,ρN,σN)	8 channels (6ch + KΛ, KΣ)	9 channels (8ch + ωN)
✓ πp → πN	< 2 GeV	< 2.3 GeV	< 2.5 GeV
✓ γp → πN	< 1.6 GeV	< 2.1 GeV	< 2.3 GeV
✓ πp → ηp	< 2 GeV	< 2.1 GeV	< 2.3 GeV
✓ γp → ηp	—	< 2.1 GeV	< 2.3 GeV
✓ πp → KΛ, KΣ	—	< 2.1 GeV	< 2.3 GeV
✓ γp → KΛ, KΣ	—	< 2.1 GeV	< 2.3 GeV
✓ $\pi^- p$ → ωn	—	—	< 2.3 GeV
✓ γp → ωp	—	—	< 2.3 GeV

Ongoing projects & future plans with ANL-Osaka DCC approach (3/4)





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

2013-

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

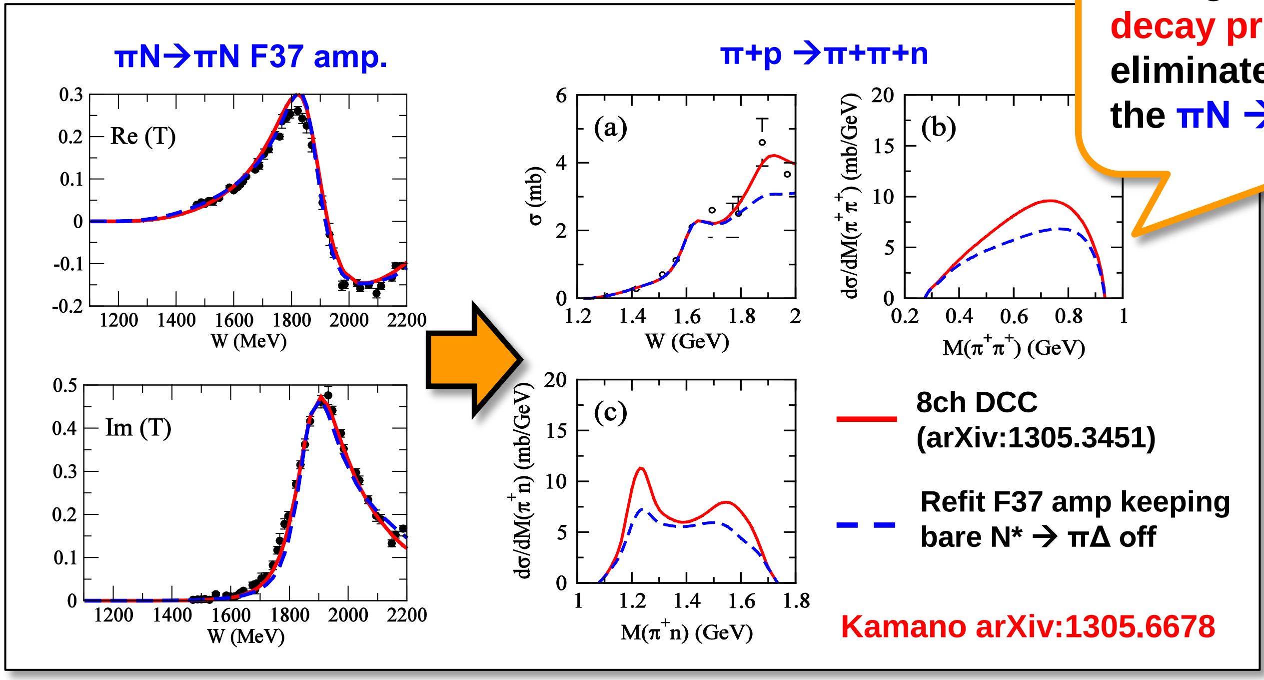
Ongoing projects & future plans with ANL-Osaka DCC approach (3/4)

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.**

  (Precise data of πN → ππN will be available from J-PARC [K. Hicks et al., J-PARC P45])
- **Most N*s decay dominantly to ππN.**

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



Ongoing projects & future plans with ANL-Osaka DCC approach (3/4)

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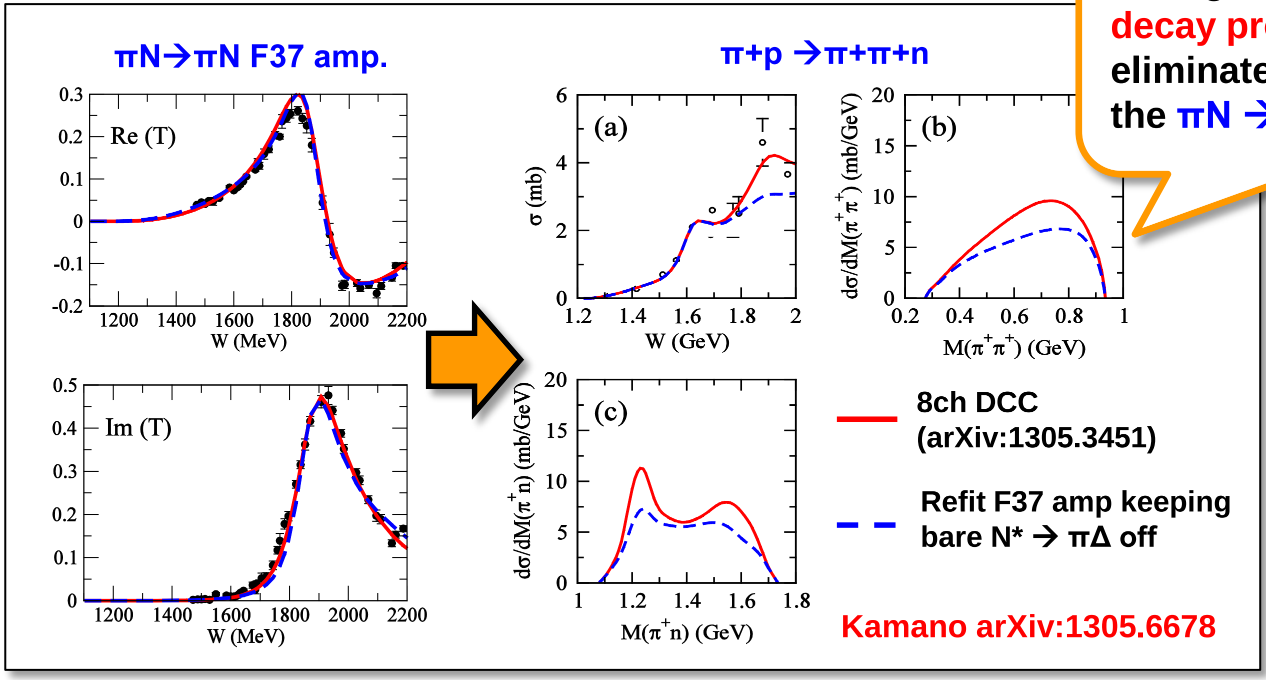


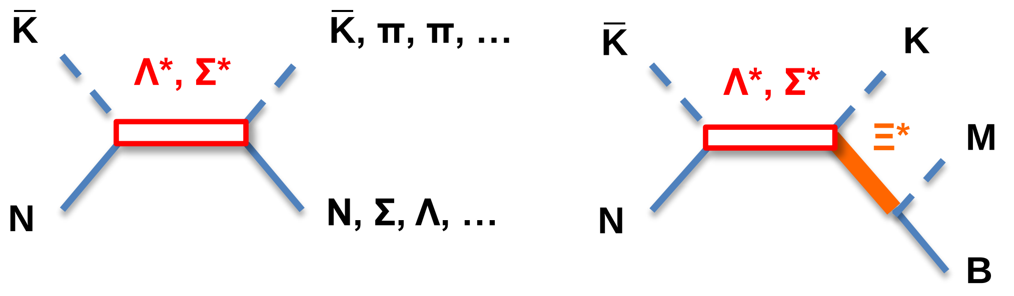
Ambiguity over N* → ππN decay processes can be eliminated by the πN → ππN data !!

Before the combined analysis including ππN data, need further improvement/tune of the analysis code.

Ongoing projects & future plans with ANL-Osaka DCC approach (4/4)

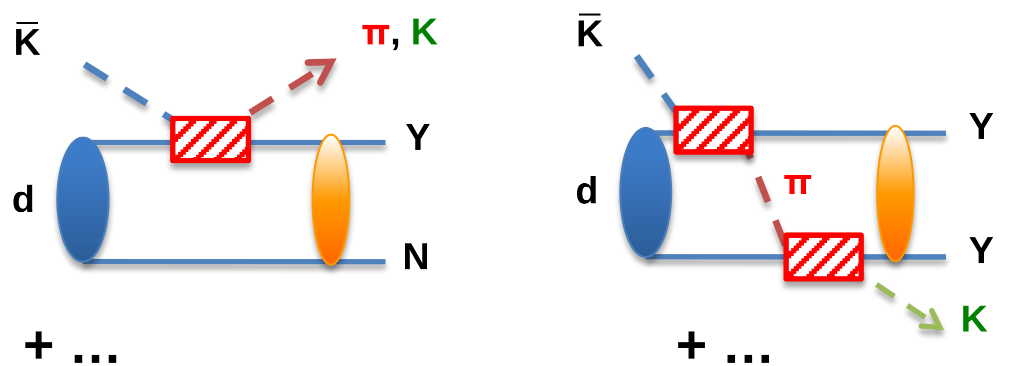
Y* spectroscopy via DCC analysis of kaon-induced reactions

➢ **Nucleon target**



- ✓ **Simplest reaction processes to study Y* resonances.**
- ✓ **Extensive data would become available from J-PARC after the extension of Hadron Hall.**

➢ **Deuteron target**



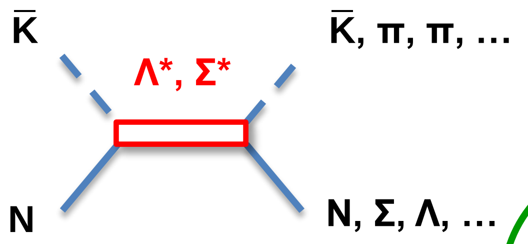
(Noumi et al., J-PARC E31)

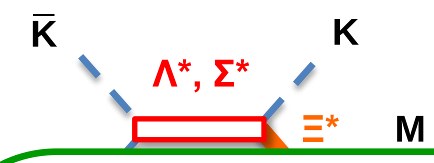
- ✓ **Directly accessible to Λ(1405) region below $\bar{K}$N threshold.**
- ✓ **Expected to be a crucial source of information on YN and YY interactions**

Ongoing projects & future plans with ANL-Osaka DCC approach (4/4)

Y* spectroscopy via DCC analysis of kaon-induced reactions

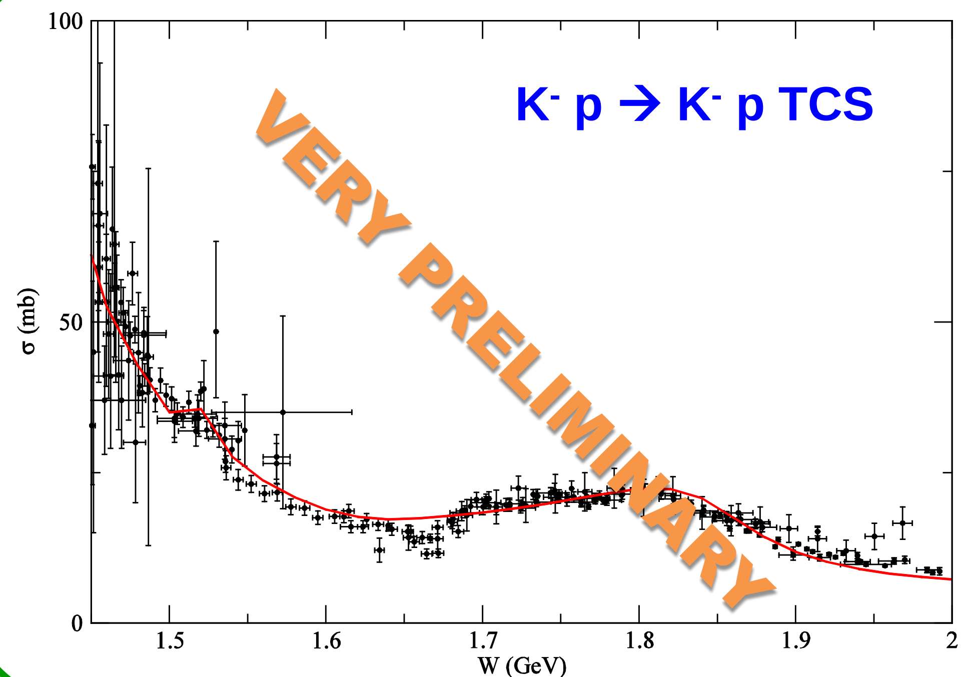
➢ **Nucleon target**



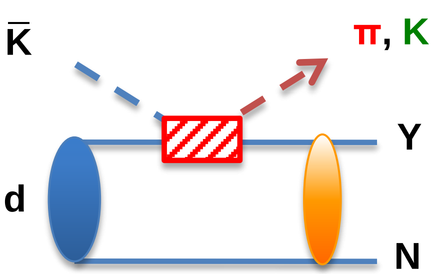


✓ Simplest reaction processes to study Y* resonances.

✓ Extensive data would become
…ARC after
…ron Hall.



➢ **Deuteron target**



+ …

(Noumi et al., J-PARC E31)

… Λ(1405)
…shold.

…cial
…n on
…ns

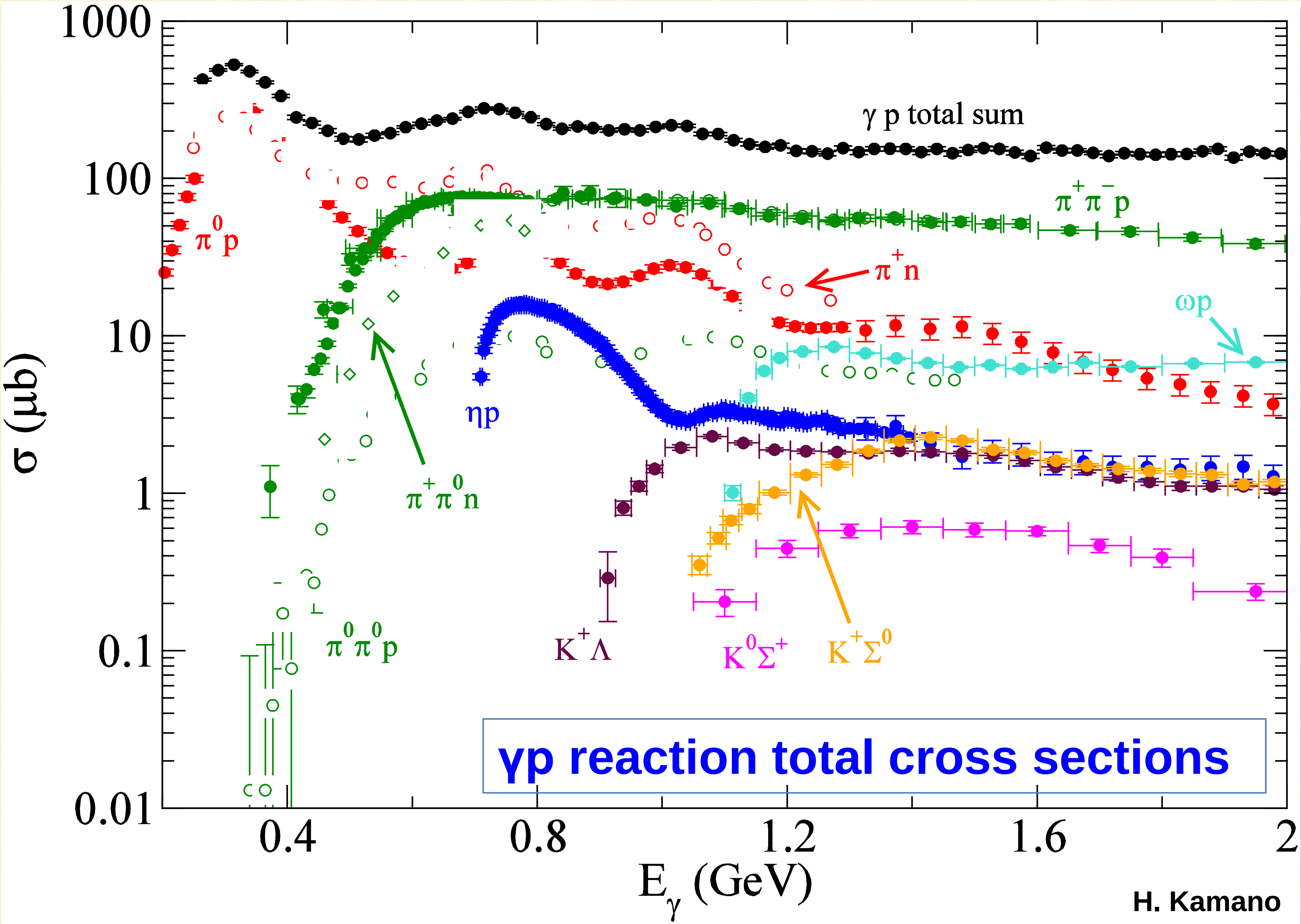
Summary

- ✓ Performed a fully combined analysis of pion- and photon-induced πN, ηN, KΛ, KΣ production reactions with the ANL-Osaka Dynamical Coupled-Channels approach.
- ✓ Revealed the role of nontrivial multichannel reaction dynamics in understanding the nature of N* resonances.
- ✓ The extracted N* parameters (pole masses, residues,…) are compared with other multi-channel analyses:
  - ➢ Extracted resonance masses agree well for almost all the 1st excited states in each partial wave, while sizable differences are found for several higher excited states.
  - ➢ Compared with pole masses, residues ("coupling constants") are more sensitive to the analysis performed.
- ✓ Further applications and extensions of the ANL-Osaka DCC model are in progress.
- ✓ N* spectroscopy is an ideal laboratory for studying "resonance", a universal phenomena over a wide range of areas of physics !!

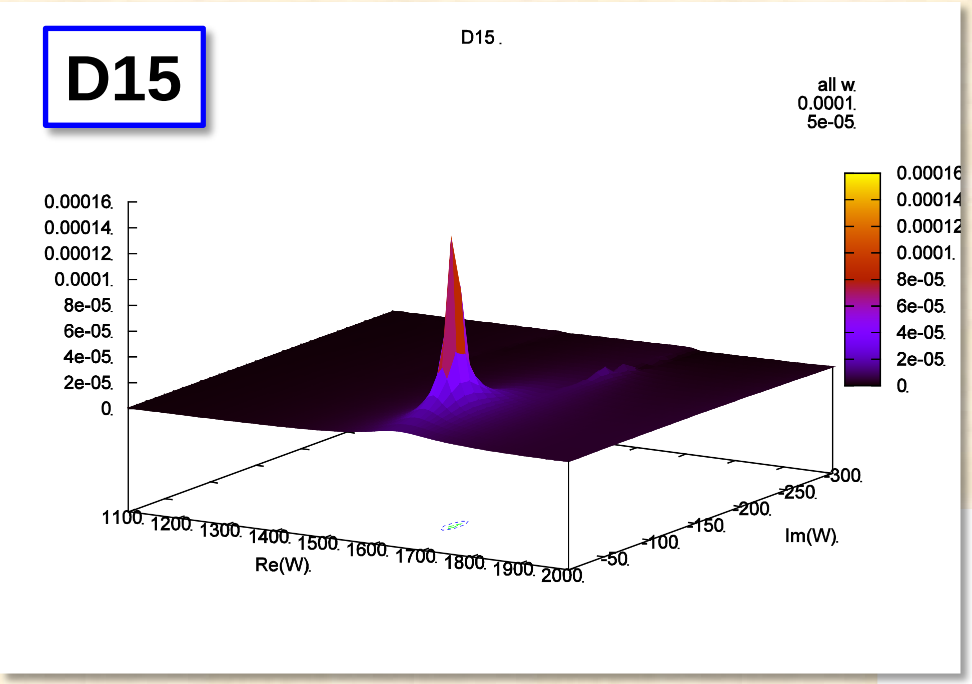
e.g.) YITP workshop on "Resonances and non-Hermitian systems in quantum mechanics" (Dec., 2012)
http://hatano-lab.iis.u-tokyo.ac.jp/hatano/NonHermite/Top.html

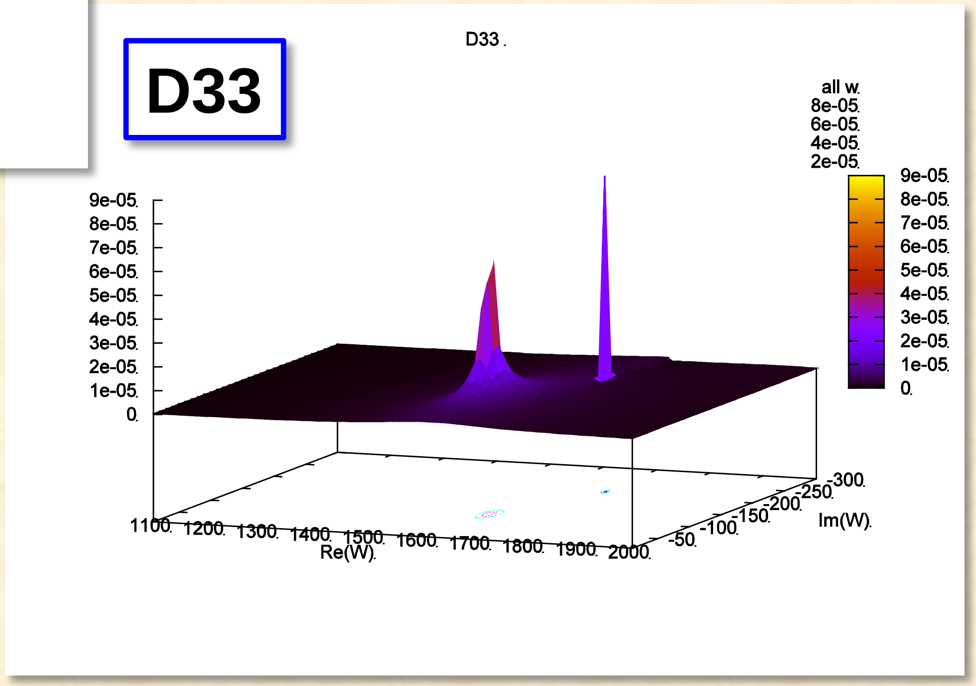
back up

Reaction channels relevant to N* spectroscopy



Resonance poles of πN partial wave amplitude in complex energy plane





Conventions for coupling constants

- α → β reaction amplitude at resonance pole position M_R is expressed as

$$\mathcal{F}_{\beta,\alpha}(W \to M_R) = -\frac{R_{\beta,\alpha}}{W - M_R} + \cdots .$$

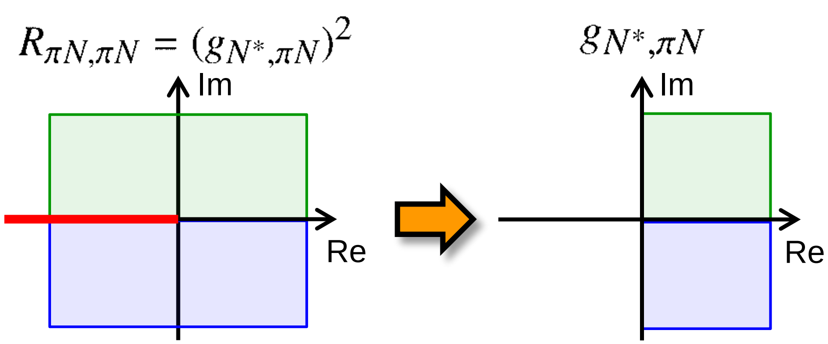
- The residue is then interpreted as the product of "coupling constants" of N*-β and N*-α:

$$R_{\beta,\alpha} \equiv g_{\beta,N^*} \times g_{\alpha,N^*}.$$

- If one tries to get the coupling constants from the residues, the constants can be determined up to a sign. We fix the sign ambiguity by choosing the phase of the pi N scattering residue as

$$-\pi < \arg[R_{\pi N,\pi N}] < \pi.$$

This corresponds to taking the real part of πNN* coupling constants always positive: Re(g_N*,πN) > 0.
With this convention, the relative signs of all coupling constants are uniquely fixed.



Phenomenological prescriptions of constructing conserved-current matrix elements

As commonly done in *practical* calculations in nuclear and particle physics, currently we take a phenomenological prescription to construct conserved current matrix elements [T. Sato, T.-S. H. Lee, PRC60 055201 (2001)]:

$$J^\mu \to J^\mu - \frac{q \cdot J}{n \cdot q} n^\mu$$

J^μ : Full e.m. current matrix elements obtained by solving DCC equations

q^μ : photon momentum $\quad$ n^μ : an arbitrary four vector

- ✓ **A similar prescription is applied, e.g., in Kamalov and Yang, PRL83, 4494 (1999).**

- ✓ **There are also other prescriptions that enable practical calculations satisfying current conservation or WT identity:**
  - **Gross and Riska, PRC36, 1928 (1987)**
  - **Ohta, PRC40, 1335 (1989)**
  - **Haberzettl, Nakayama, and Krewald, PRC74, 045202 (2006).**

Database used for the analysis

✓ **πN → πN Partial wave amp. (SAID EIS)**

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

✓ **πN → 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

✓ **γN → πN, ηN, 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	11695	2273	1174	1881	371	211	177	73	73	119	119	18166

Total 22,348 data points

N* resonances from analyses with the old 6ch and current 8ch models

6ch DCC analysis [PRL104(2010)042302]

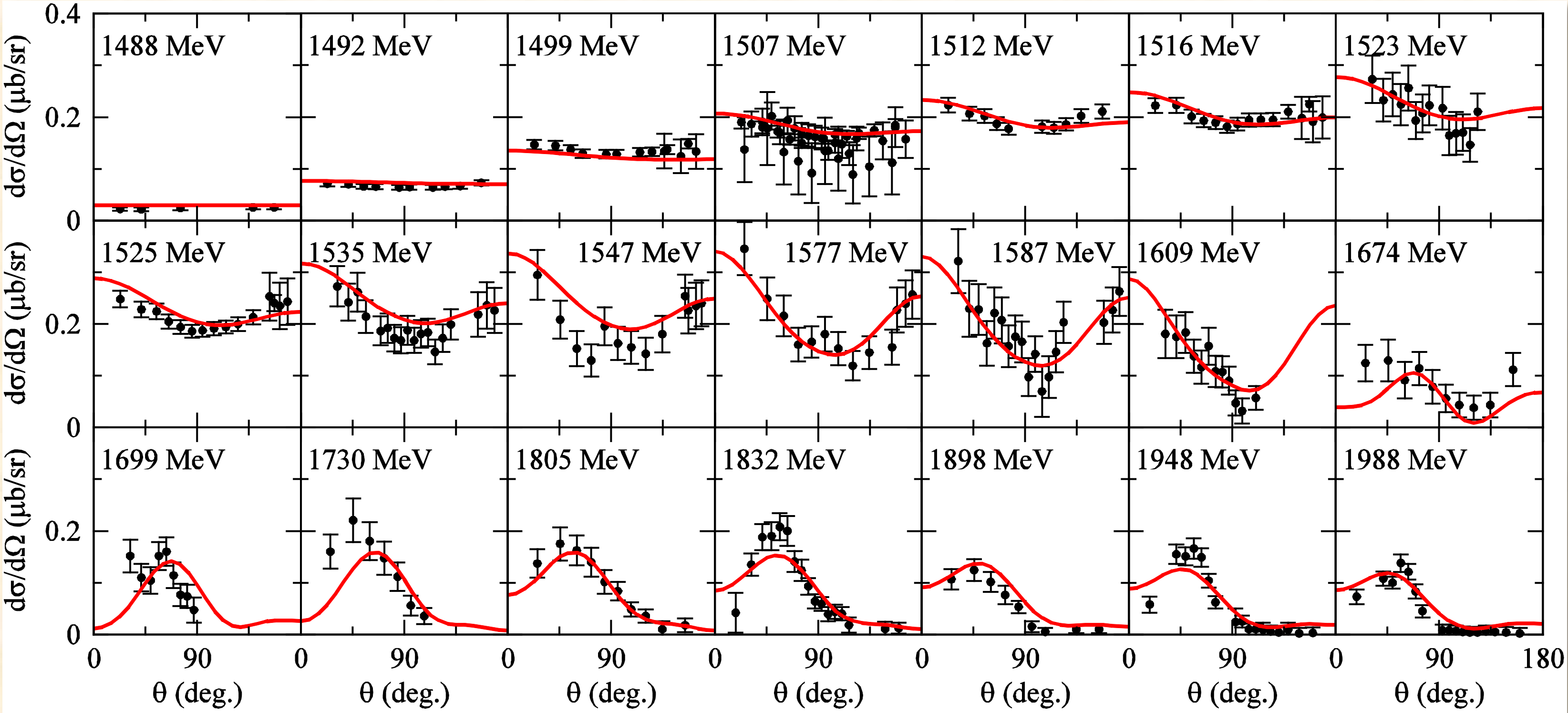
	M_R
S_{11}	(1540, 191)
	(1642, 41)
P_{11}	(1357, 76)
	(1820, 248)
P_{13}	· ·
D_{13}	(1521, 58)
D_{15}	(1654, 77)
F_{15}	(1674, 53)
S_{31}	(1563, 95)
P_{31}	· ·
P_{33}	(1211, 50)
	· ·
D_{33}	(1604, 106)
F_{35}	(1738, 110)
	(1928, 165)
F_{37}	(1858, 100)

8ch DCC analysis [arXiv:1305.4351]

	$J^P(L_{2I2J})$	M_R
N-baryons		
	$1/2^-(S_{11})$	$(1482, 98)^*$
		(1656, 85)
	$1/2^+(P_{11})$	(1374, 76)
		(1746, 177)
	$3/2^+(P_{13})$	(1703, 70)
		(1763, 159)
	$3/2^-(D_{13})$	(1501, 39)
		$(1702, 141)^*$
	$5/2^-(D_{15})$	(1650, 75)
	$5/2^+(F_{15})$	(1665, 49)
Δ-baryons		
	$1/2^-(S_{31})$	(1592, 68)
		$(1702, 193)^*$
	$1/2^+(P_{31})$	(1854, 184)
	$3/2^+(P_{33})$	(1211, 51)
		(1734, 176)
	$3/2^-(D_{33})$	(1592, 122)
		(1707, 170)
	$5/2^-(D_{35})$	(1936, 105)
	$5/2^+(F_{35})$	(1765, 94)
	$7/2^+(F_{37})$	(1872, 103)

π- p → ηn reaction

DCS

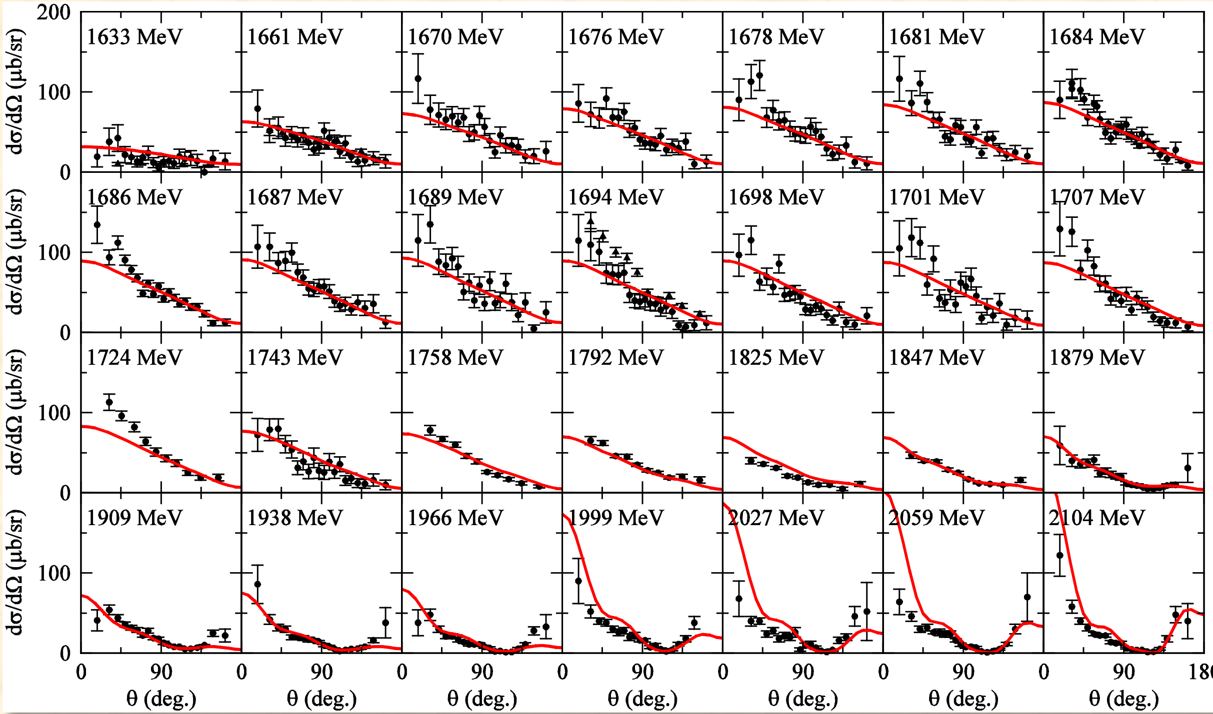


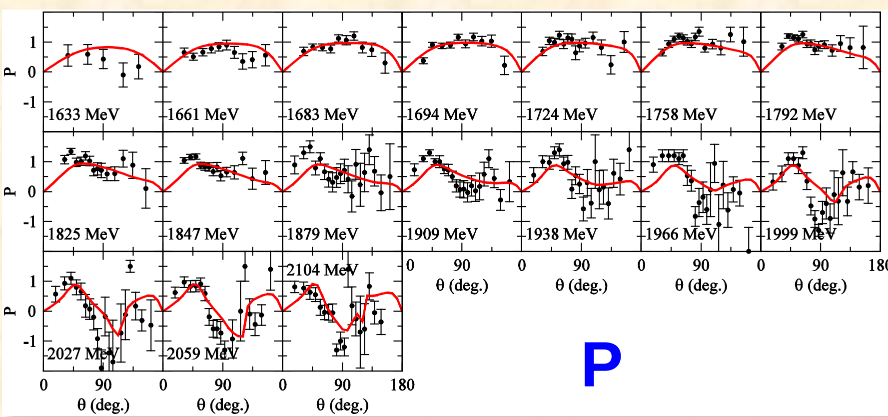
NOTE:
It is known that there is an inconsistency on the normalization of the π-p → ηn data between different experiments.

The data used in our analysis are carefully selected according to the discussion by Durand et al. PRC78 025204.

π- p → $K^0 \Lambda$ reaction

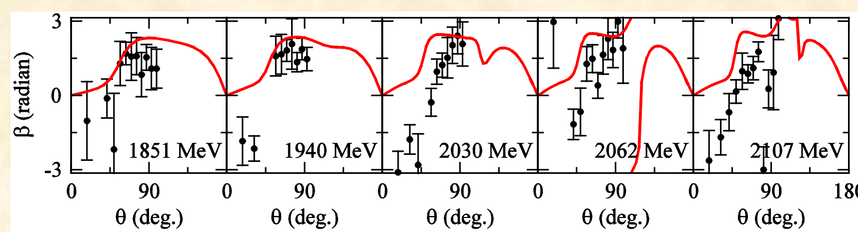
DCS



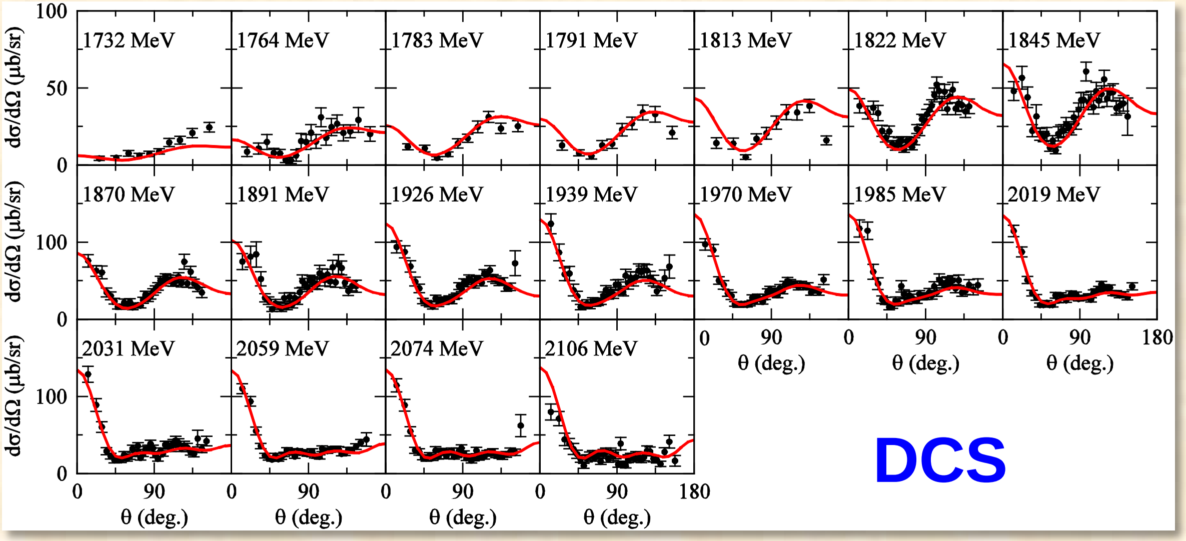


P

β

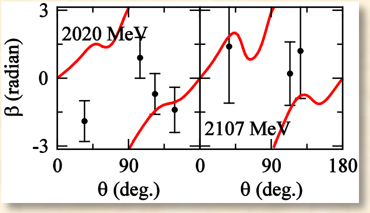


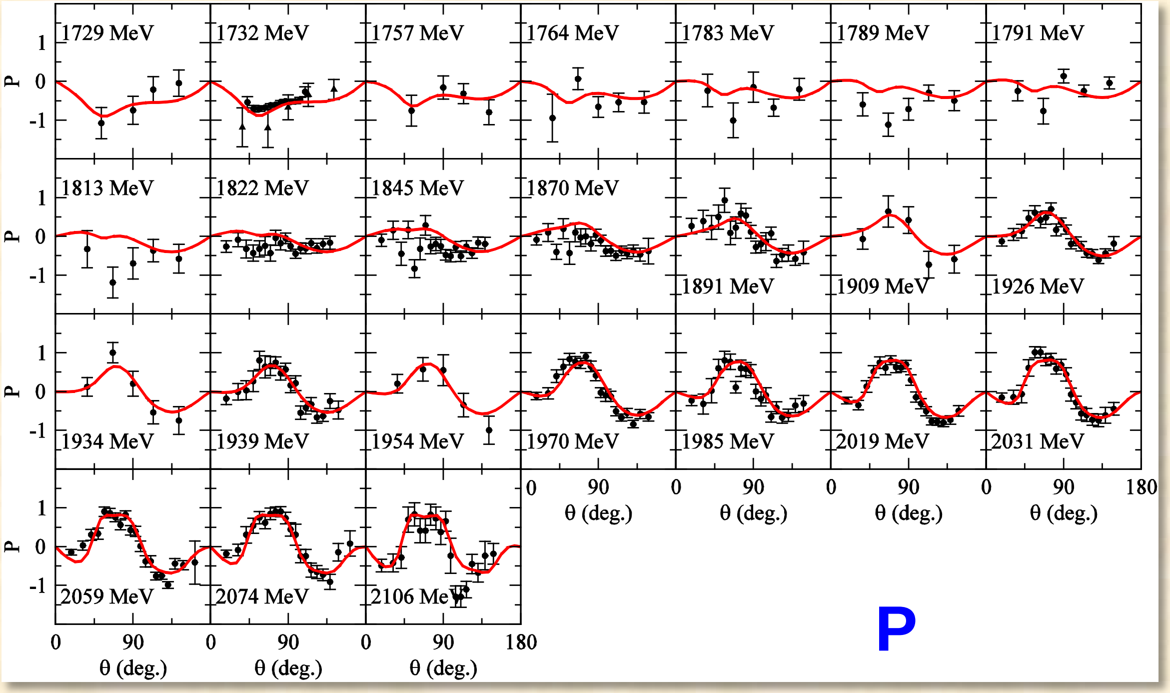
$\pi^+ p \rightarrow K^+ \Sigma^+$ reaction



DCS

β



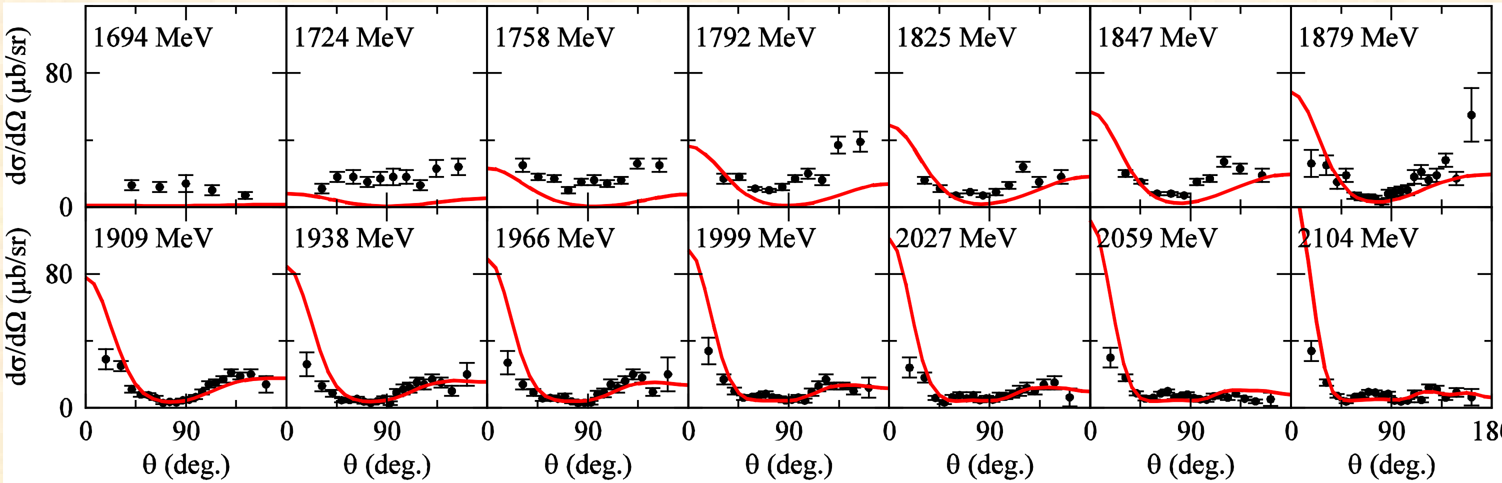


P

Note: spin-rotation β is modulo 2π

π^- p → K^0 Σ^0 reaction

DCS



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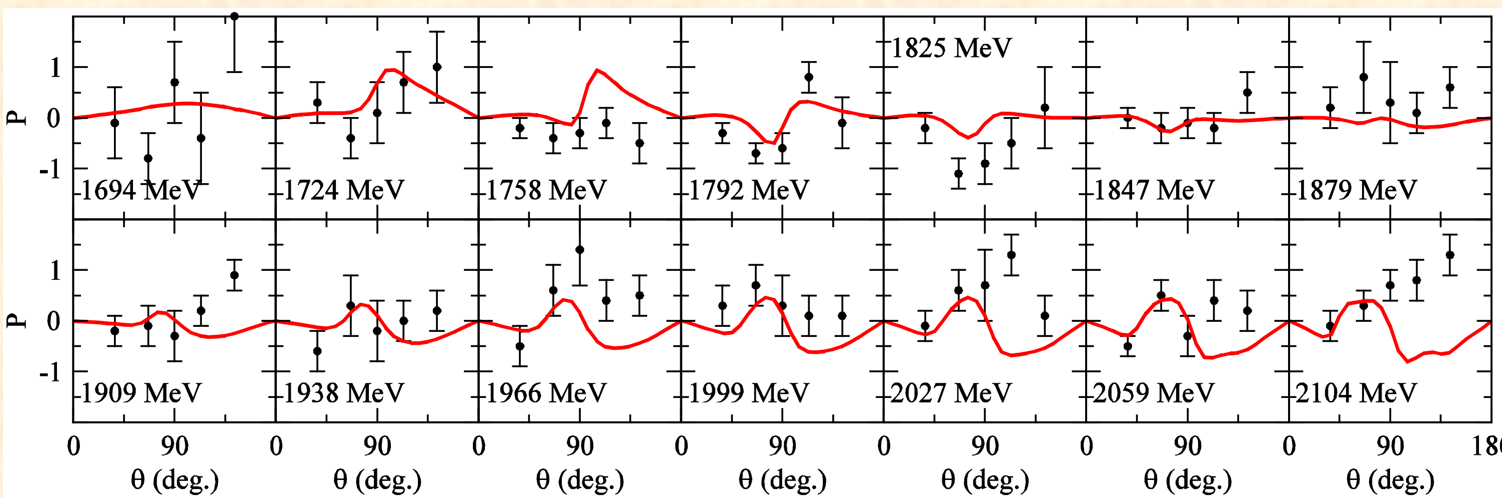
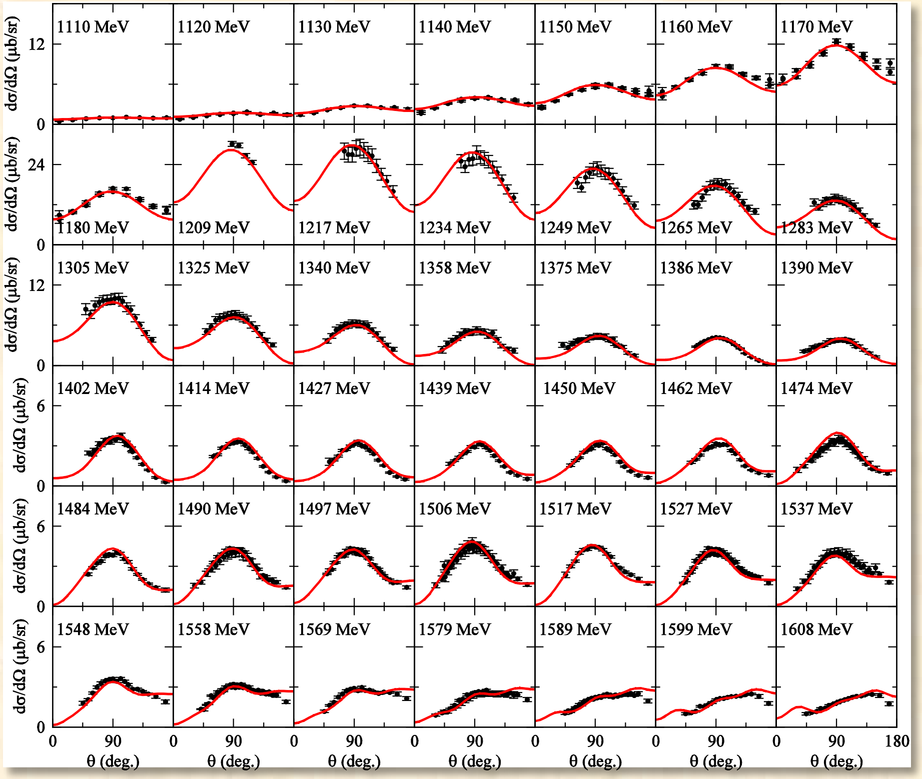
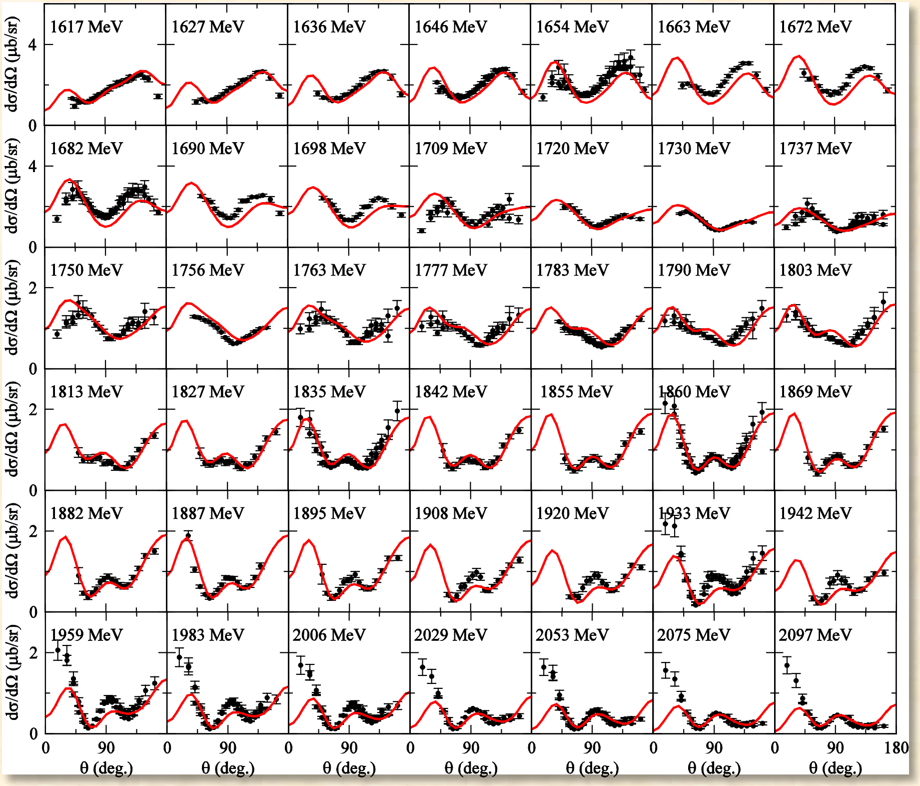


γ p → π^0 p reaction (1/3)

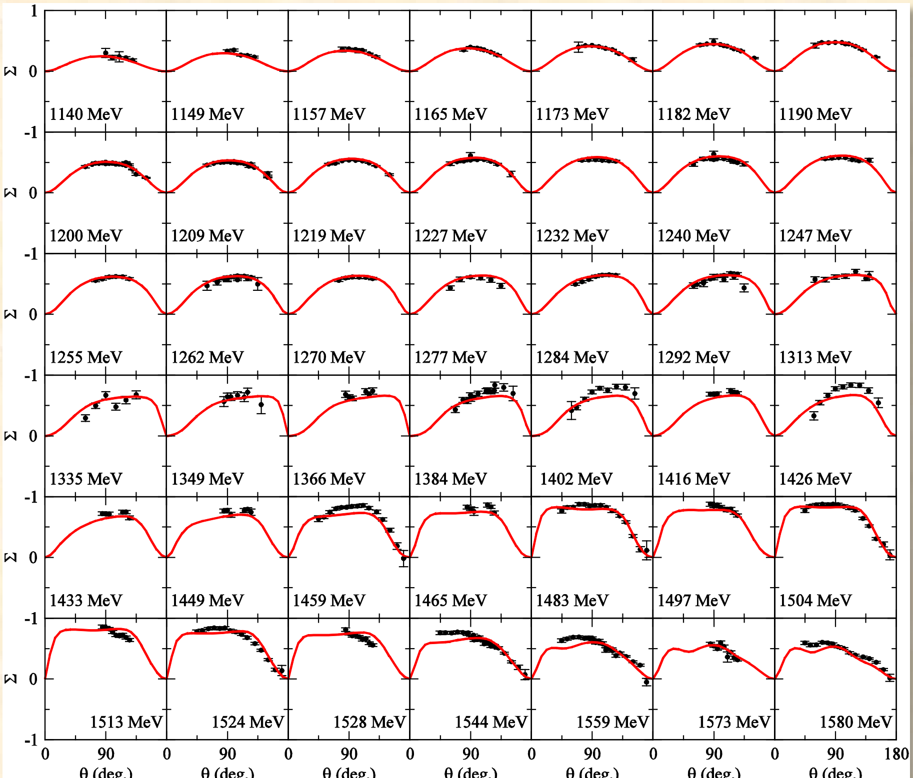
DCS

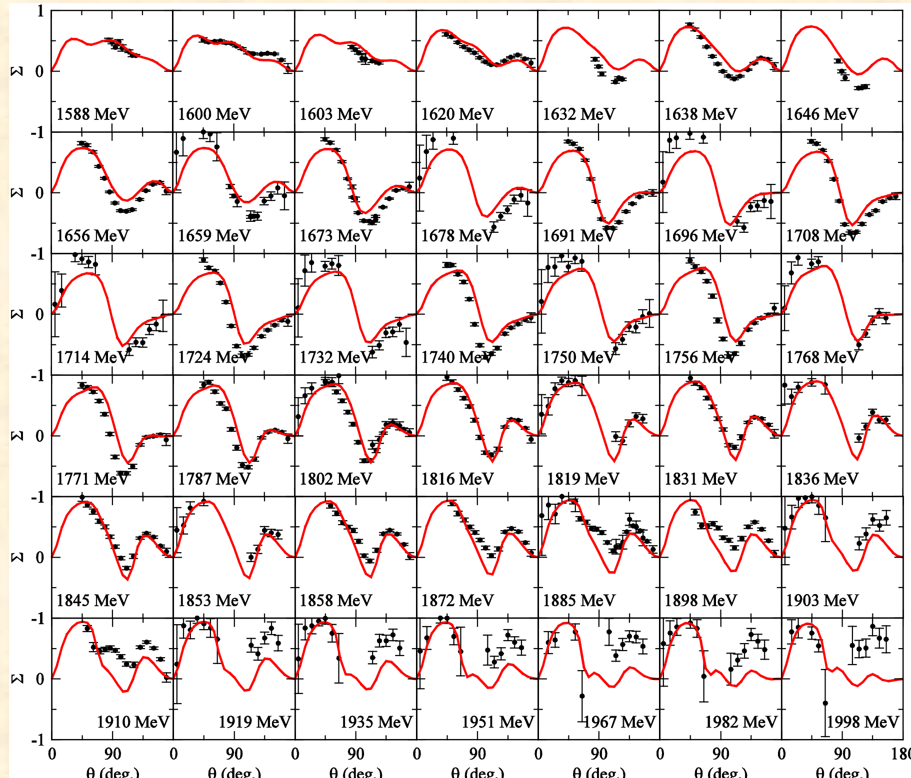




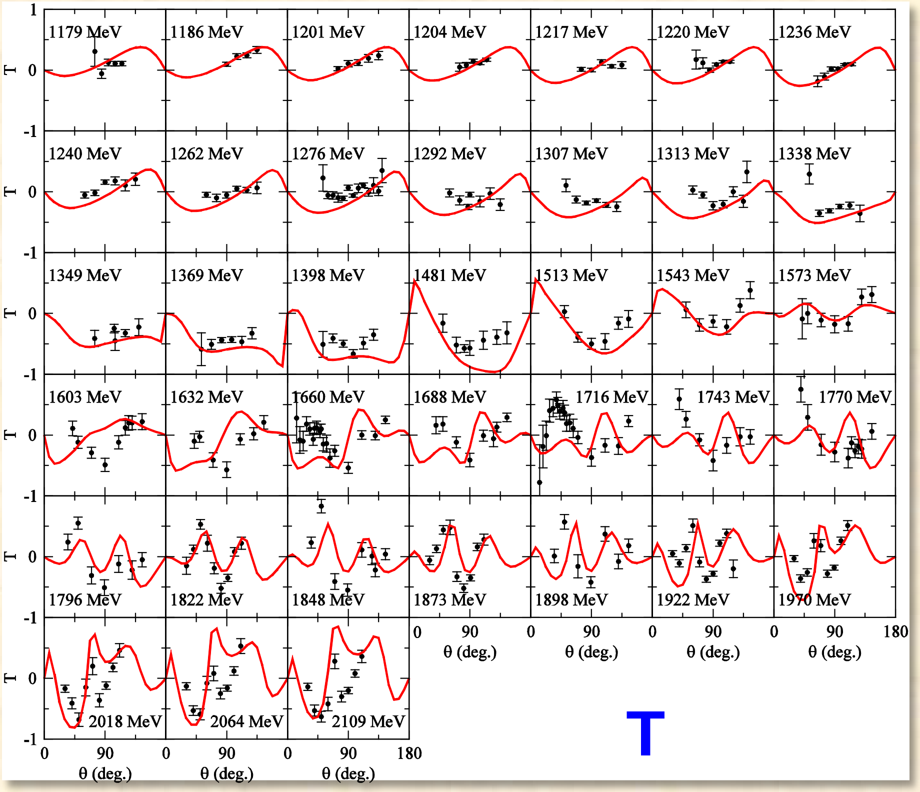
$\gamma\ p \rightarrow \pi^0\ p$ reaction (2/3)

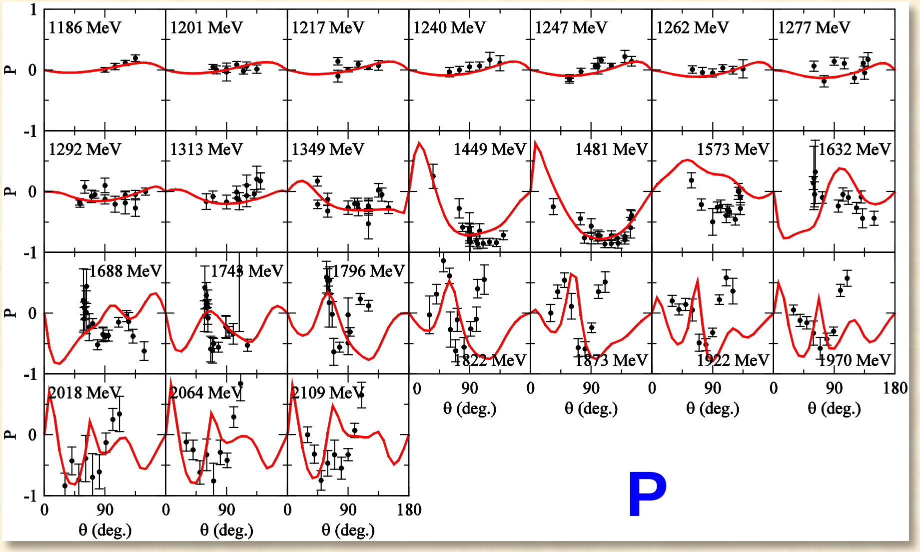
Σ

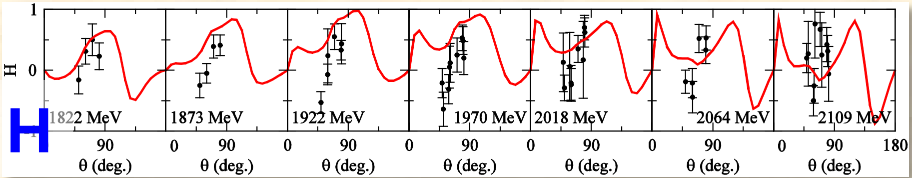


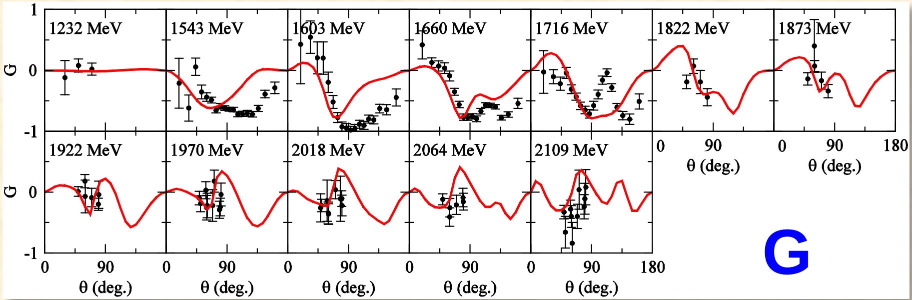


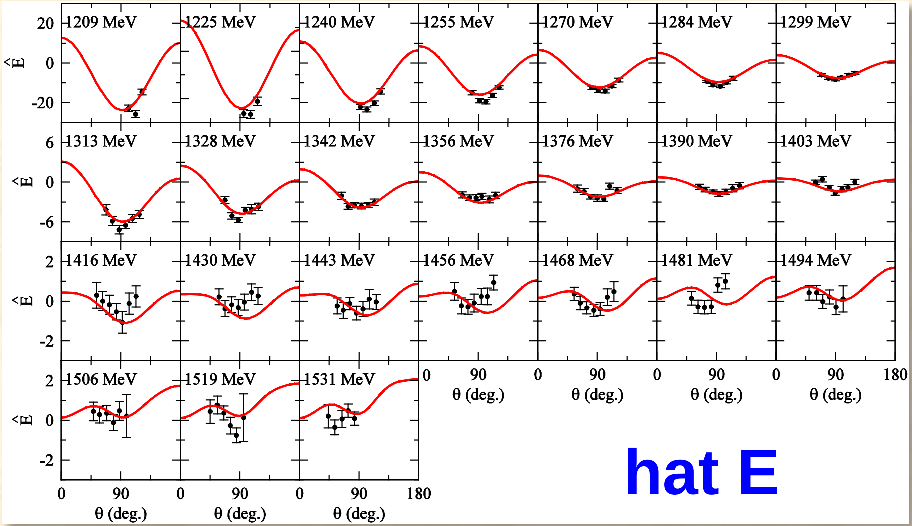
$\gamma\, p \rightarrow \pi^0\, p$ reaction (3/3)





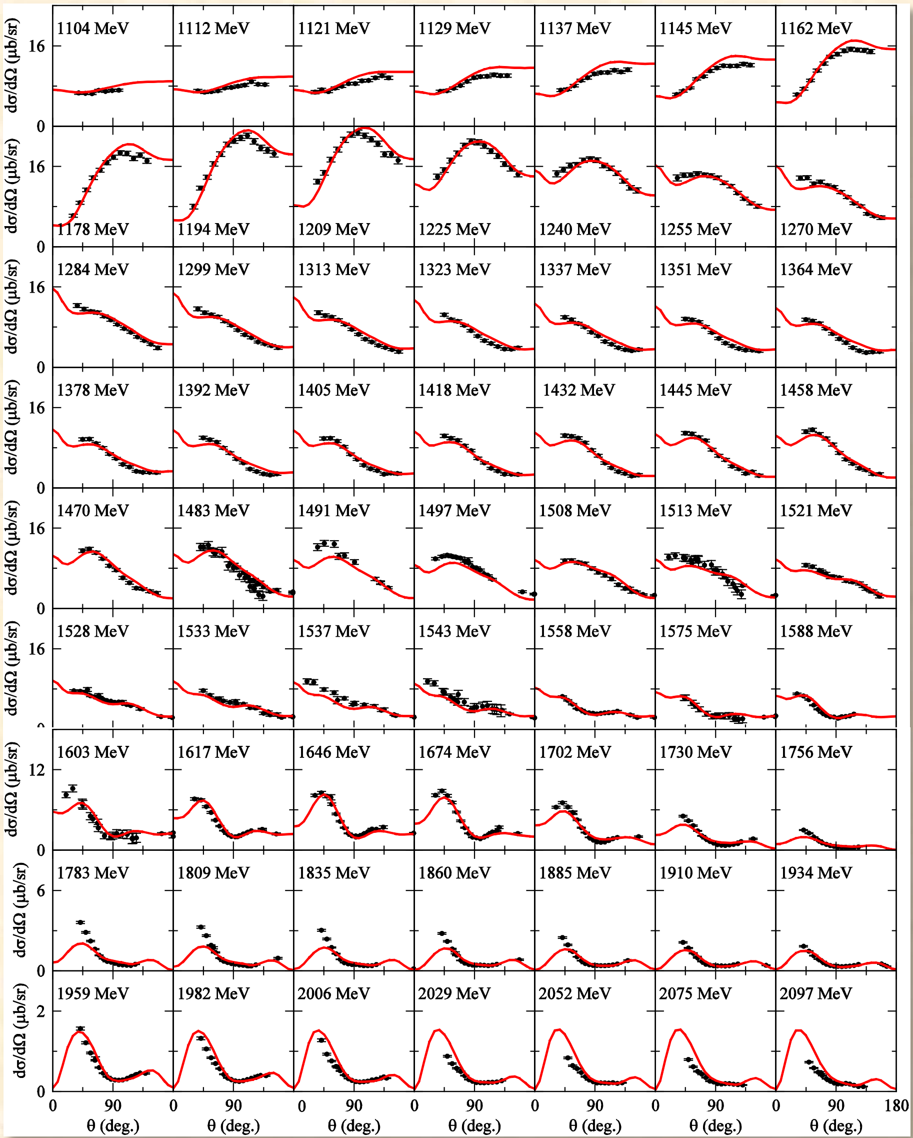






γ p → π+ n reaction (1/3)

DCS



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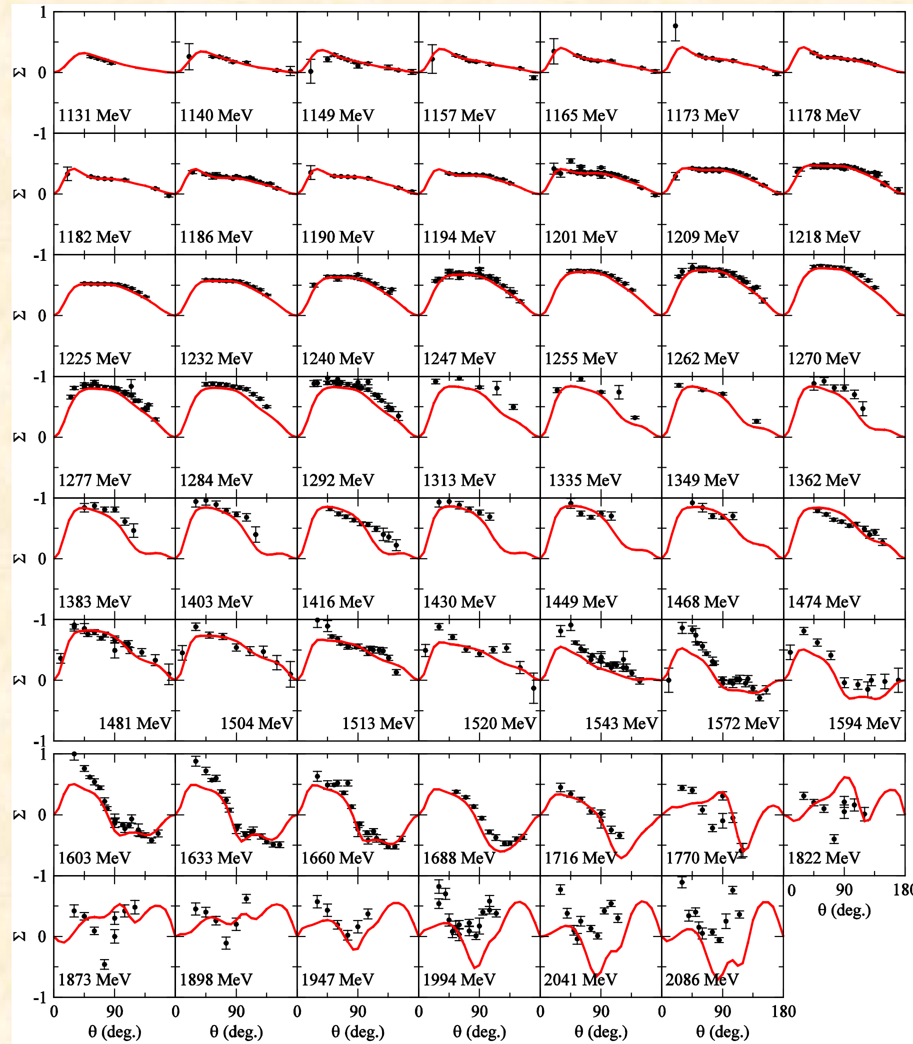
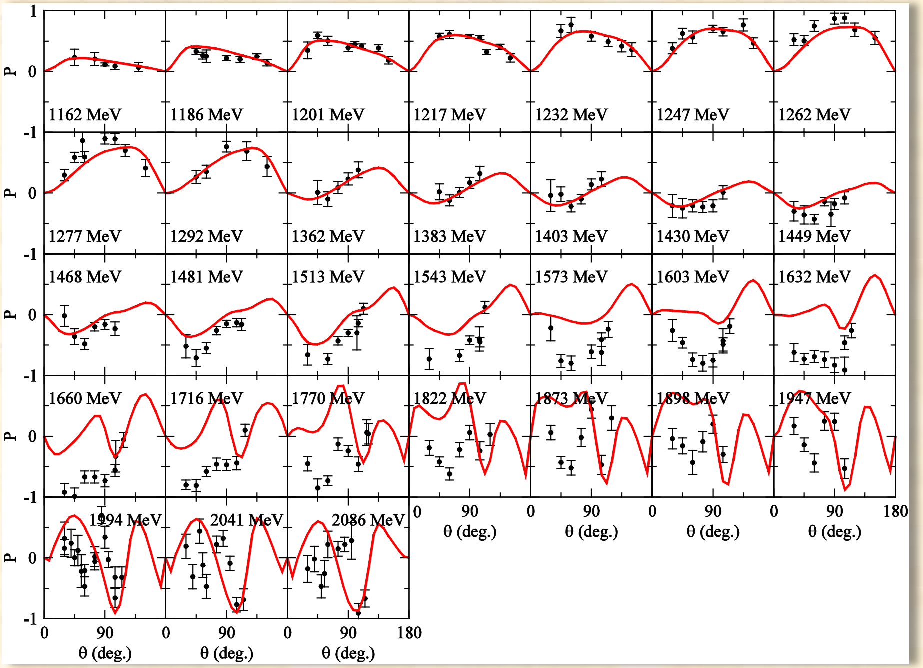
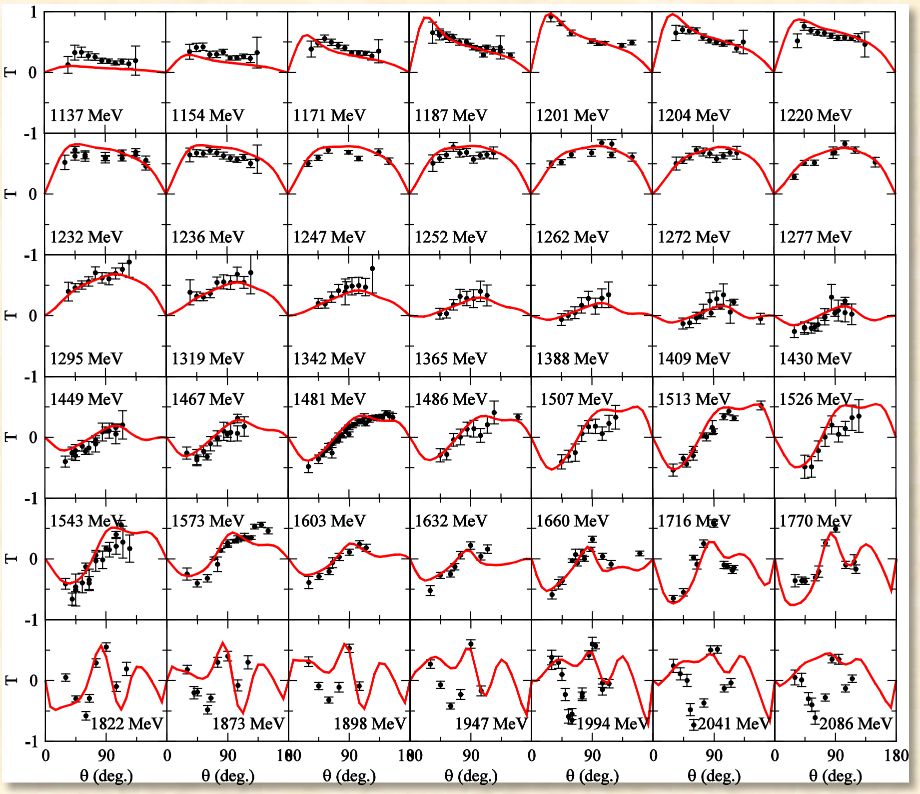


γ p → π^+ n reaction (2/3)

P

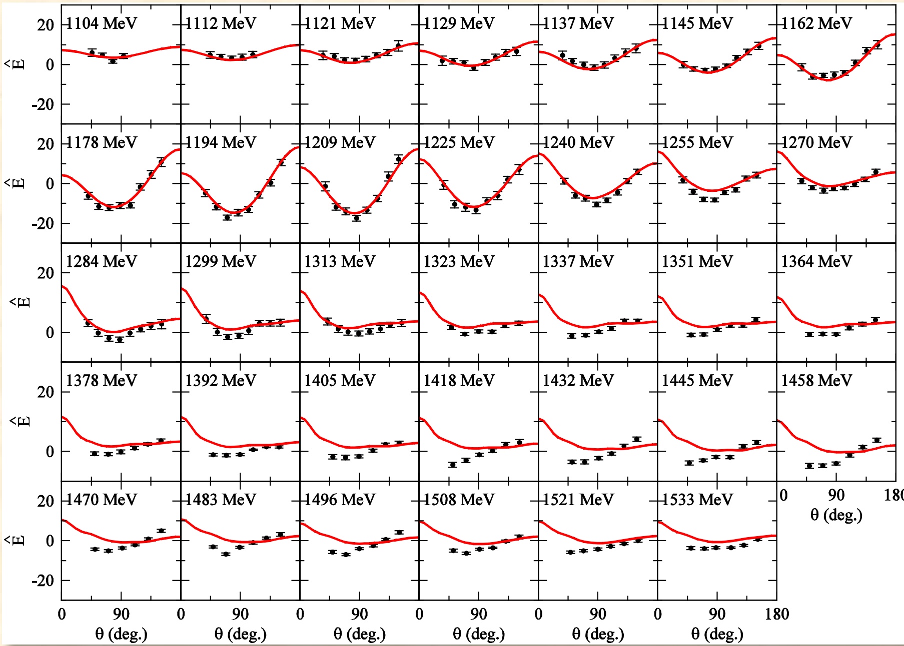


T

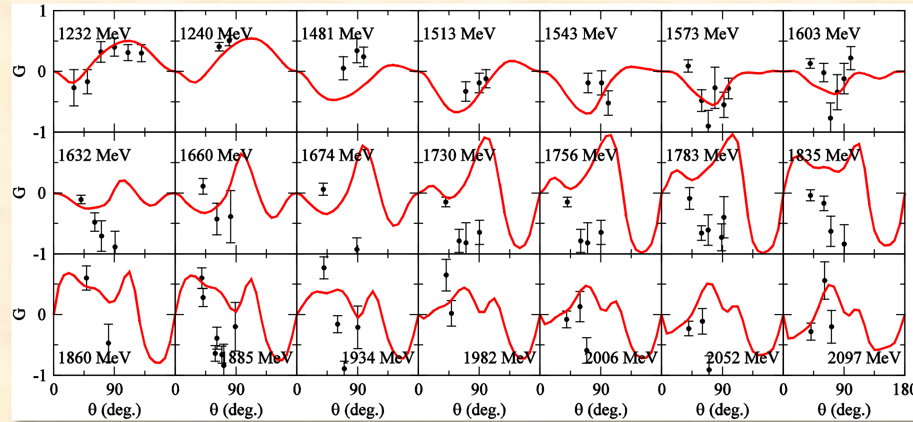


$\gamma\, p \rightarrow \pi^{+}\, n$ reaction (3/3)

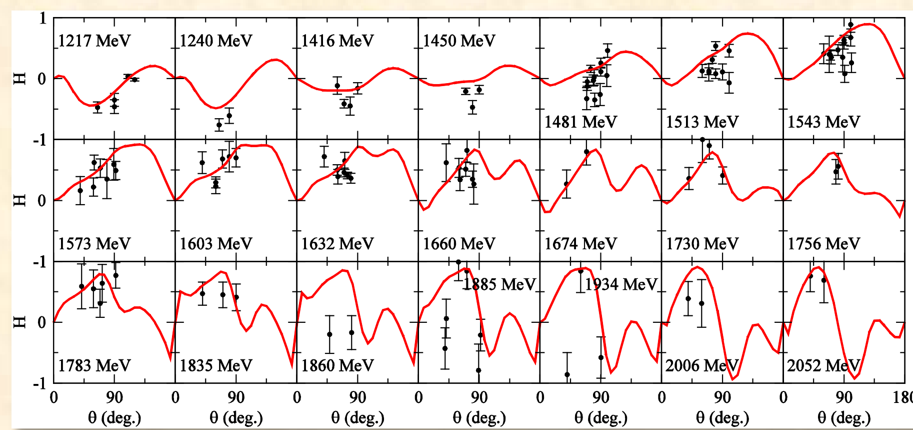
hat E



G

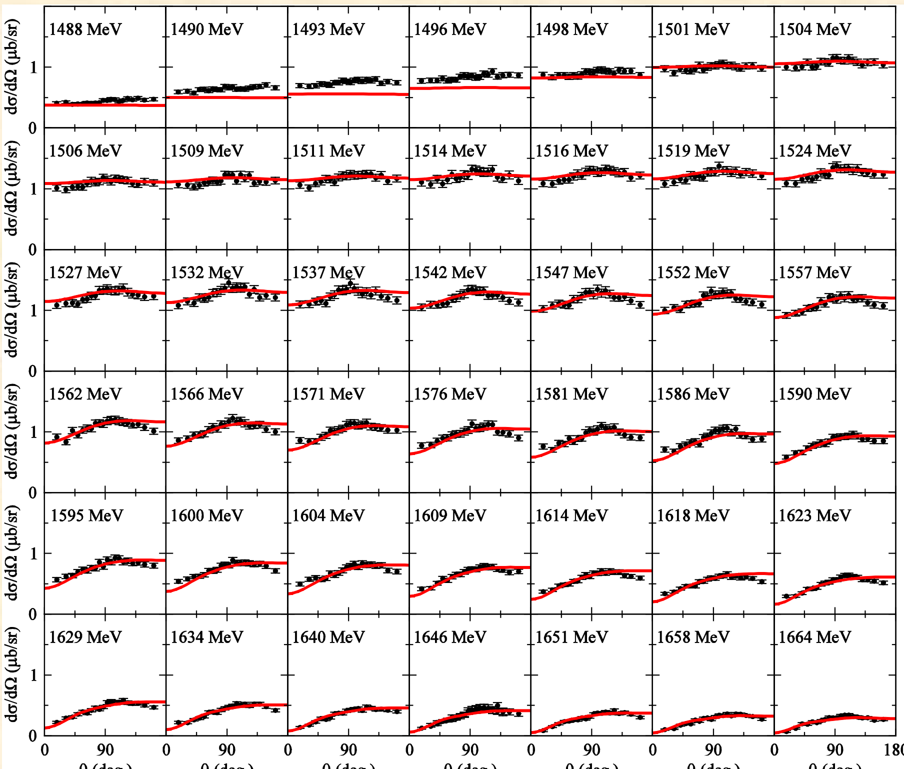


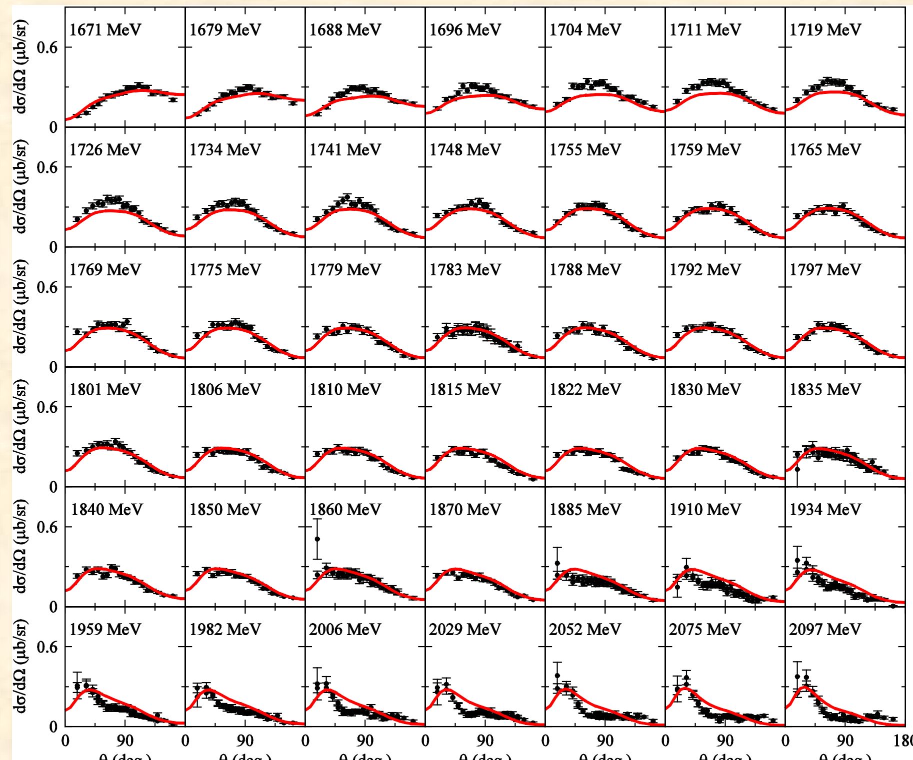
H



γ p → η p reaction (1/2)

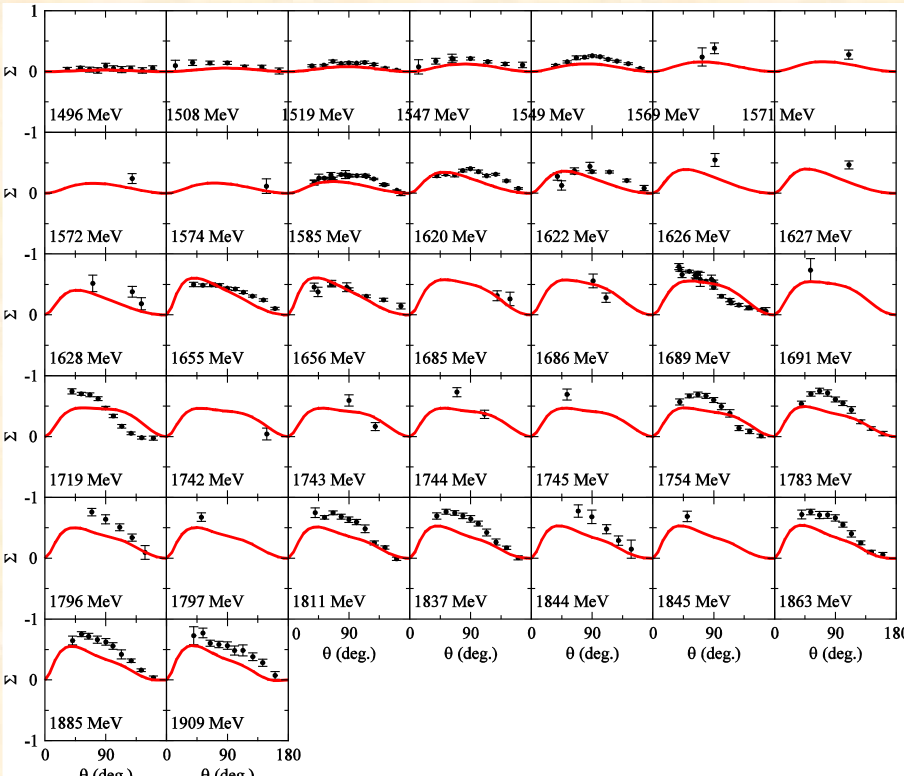
DCS





γ p → η p reaction (2/2)

Σ



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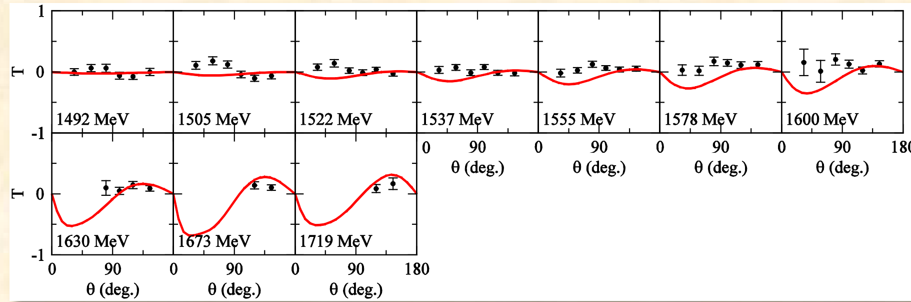
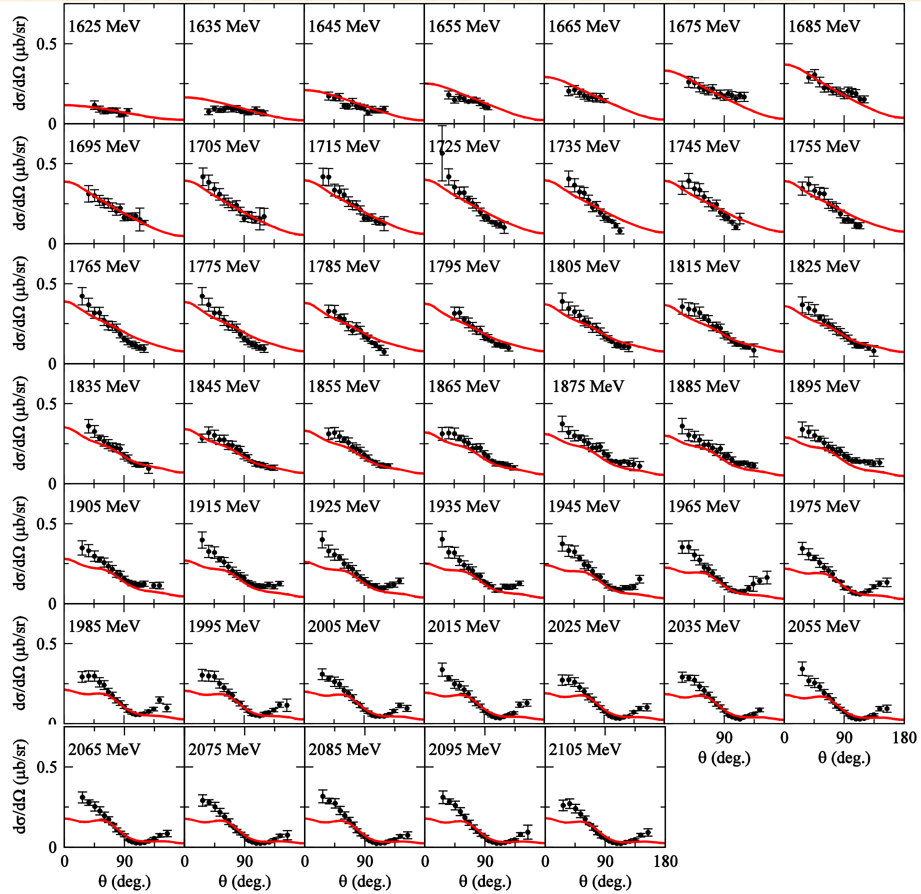
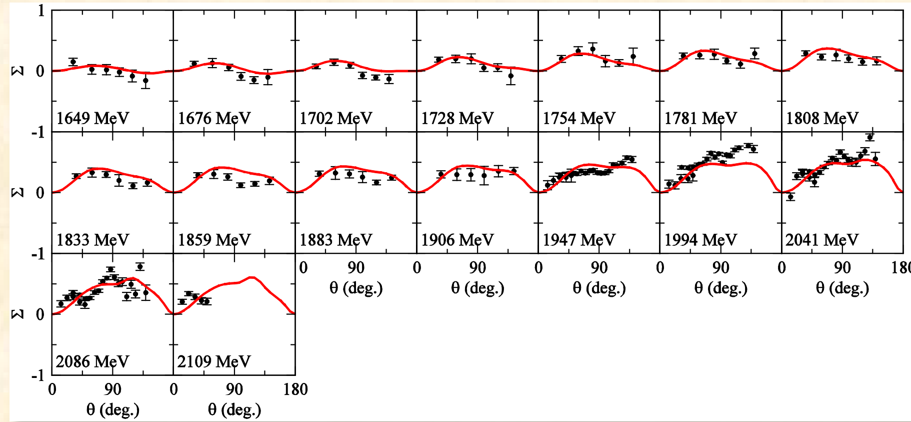


γ p → K$^+$ Λ reaction (1/2)

DCS



Σ



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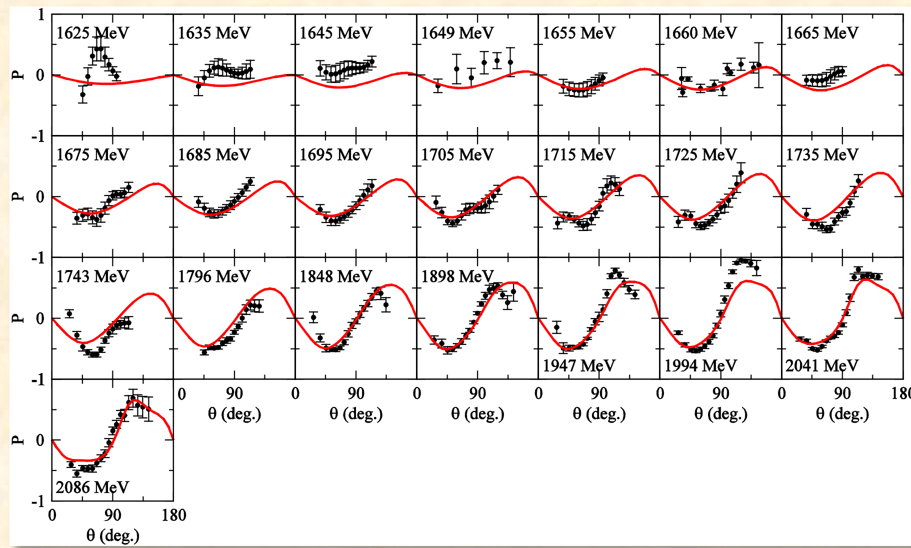
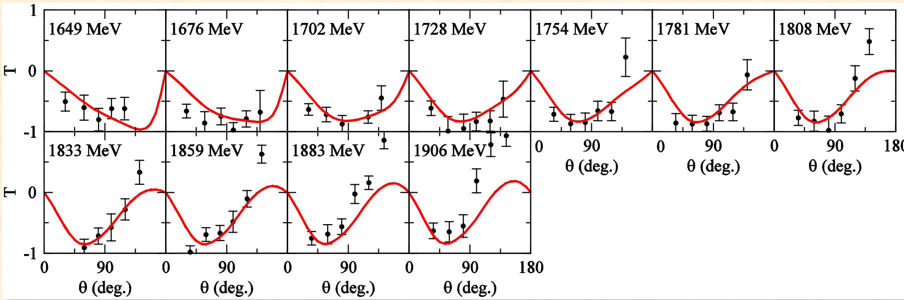
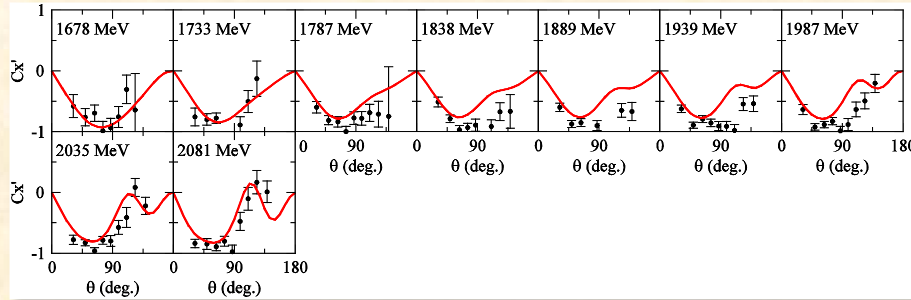


$\gamma\, p \rightarrow K^{+} \Lambda$ reaction (2/2)

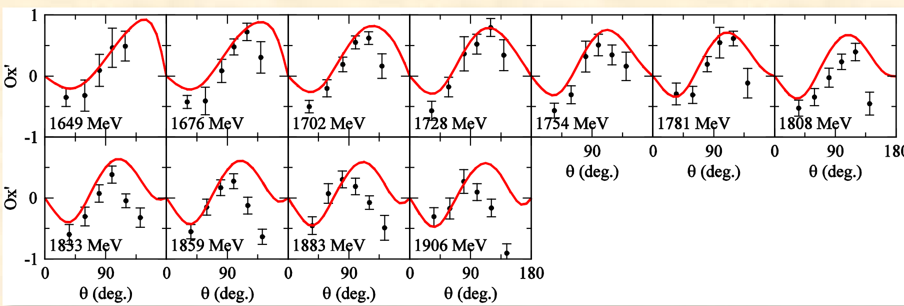
T



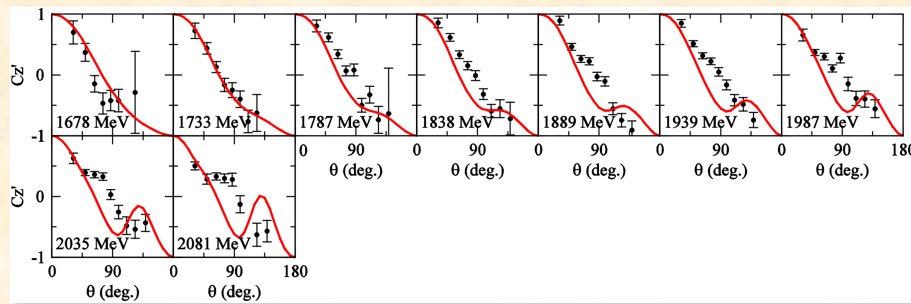
Cx’



Ox’



Cz’



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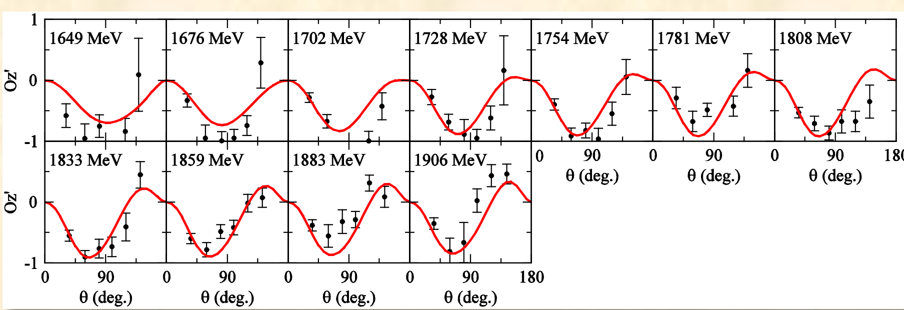
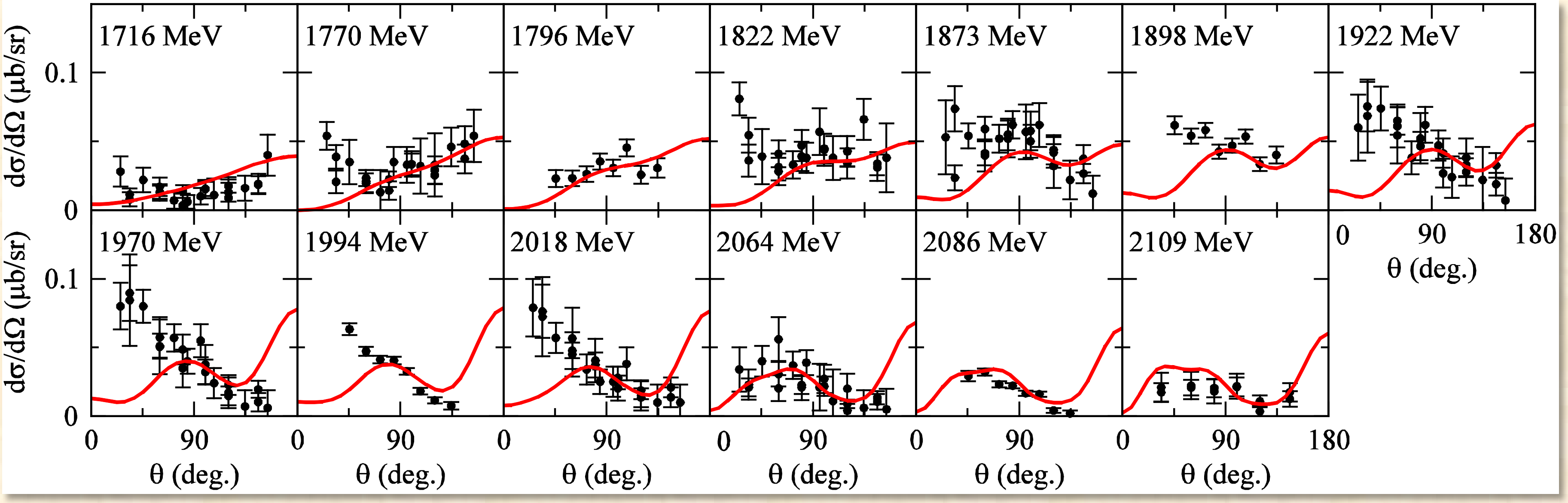


γ p → $K^0 \Sigma^+$ reaction

DCS



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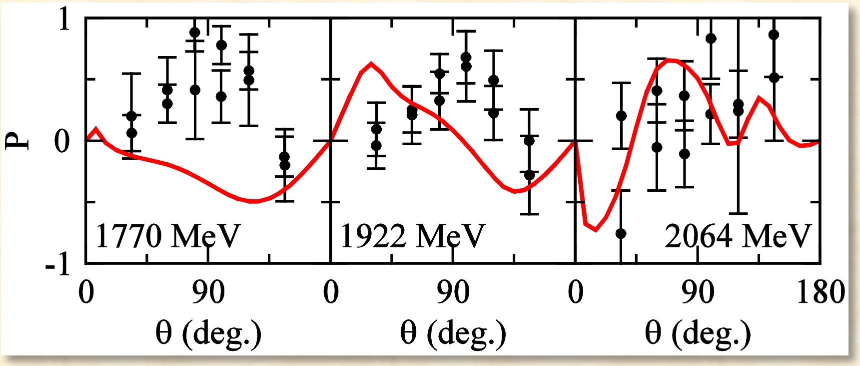

Σ