N* and Y* physics within a dynamical coupled-channels approach

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Workshop on “Progress on J-PARC hadron physics in 2014”
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Introductory remarks about light-quark baryon spectroscopy

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 complicated interference.

✓ To disentangle the above complications and establish resonance mass spectrum, one must accomplish:

- Comprehensive partial-wave analysis (PWA) of various meson-production reactions over the wide energy region using multichannel reaction framework.

  ➔ Multichannel reaction framework satisfying unitarity is indispensable for extracting the *correct* resonance information from data.

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

- ***Very wide energy*** and ***kinematical (angles, Q2,…) regions***,
- both ***unpolarizaed*** and ***polarized*** observables.

Recent experimental and theoretical efforts for N* and Δ* 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* and Δ*

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

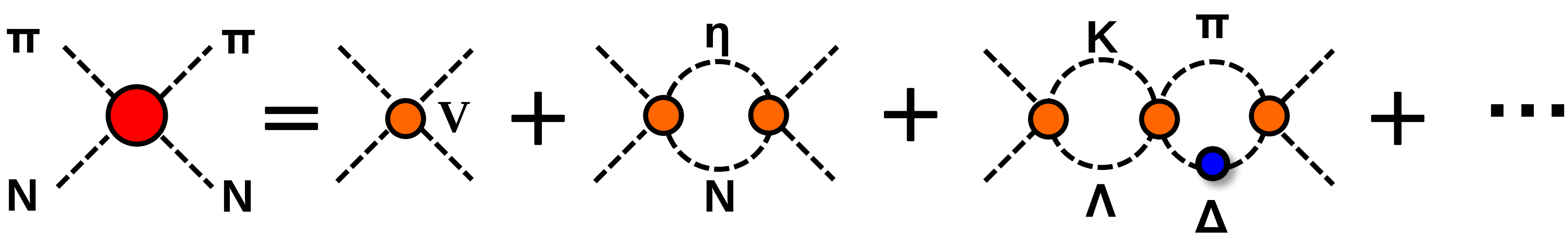
$$T_{a,b}^{(LS\,J)}(p_a,p_b;E) \;=\; V_{a,b}^{(LS\,J)}(p_a,p_b;E)+\underline{\sum_c}\int_0^\infty q^2dqV_{a,c}^{(LS\,J)}(p_a,q;E)G_c(q;E)T_{c,b}^{(LS\,J)}(q,p_b;E)$$

Coupled-channels effect

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

✓ **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* and Δ*

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

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

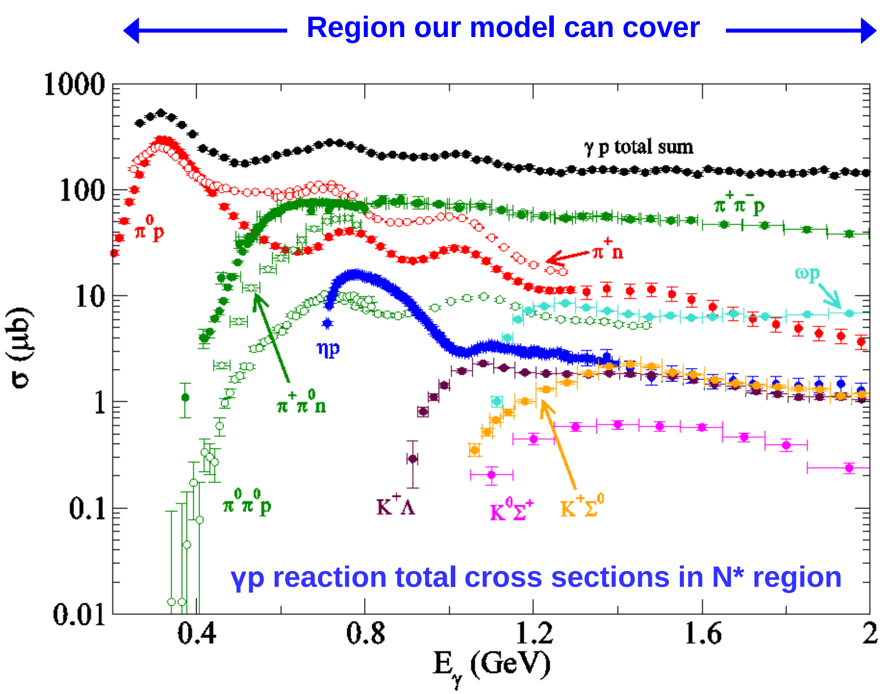
Latest published model for N* and Δ*:

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)**

~23,000 data points to analyze



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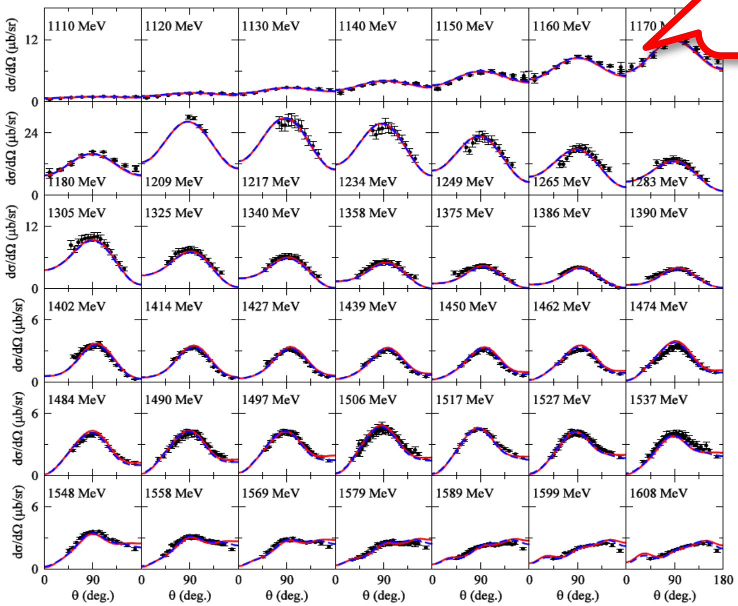
dσ/dΩ γ p → π^0 p



1. Construct model (determine amplitudes) by fitting data

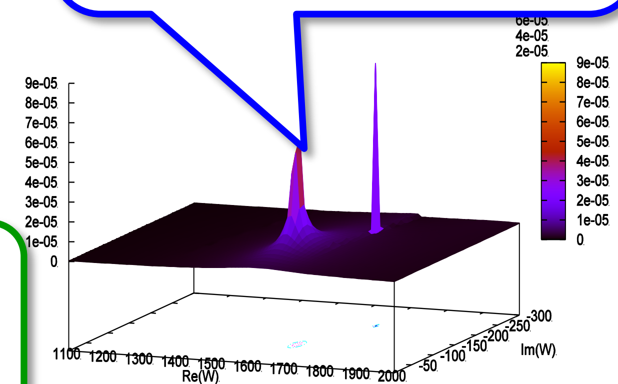
2. Analytic continuation of determined amplitudes to complex energy plane !!

Suzuki et al (2009)

3. Resonances are obtained as poles of amplitudes in complex energy plane !!

mass & width = pole value

coupling constants = $(\text{residue})^{1/2}$ at the pole



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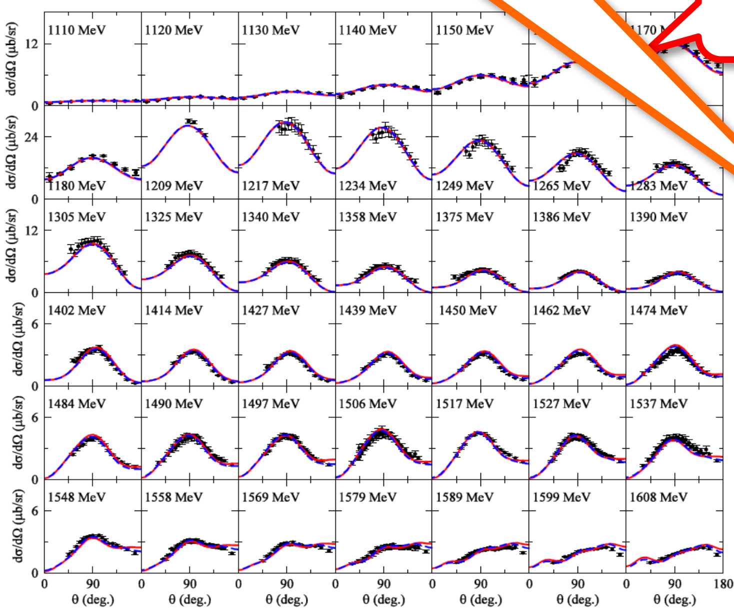
Coupled-channels effect

$$N,\ \pi N,\ \eta N,\ \underbrace{\boxed{\pi\Delta,\ \sigma N,\ \rho N}}_{\pi\pi N}\ K\Lambda,\ K\Sigma,\cdots)$$

(Multichannel) unitarity is a key to making *"correct"* analytic continuation !!

dσ/dΩ γ p →



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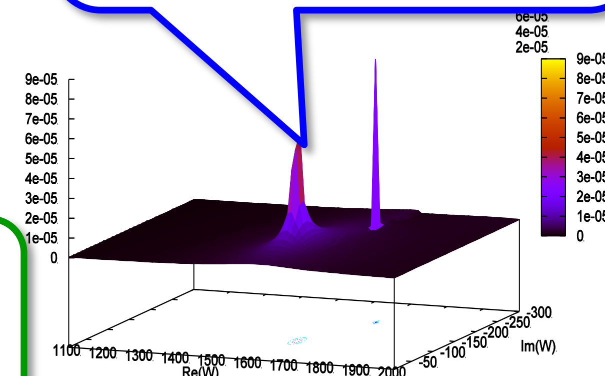
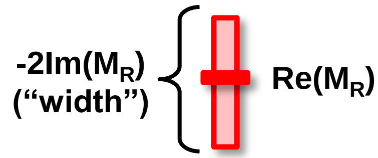


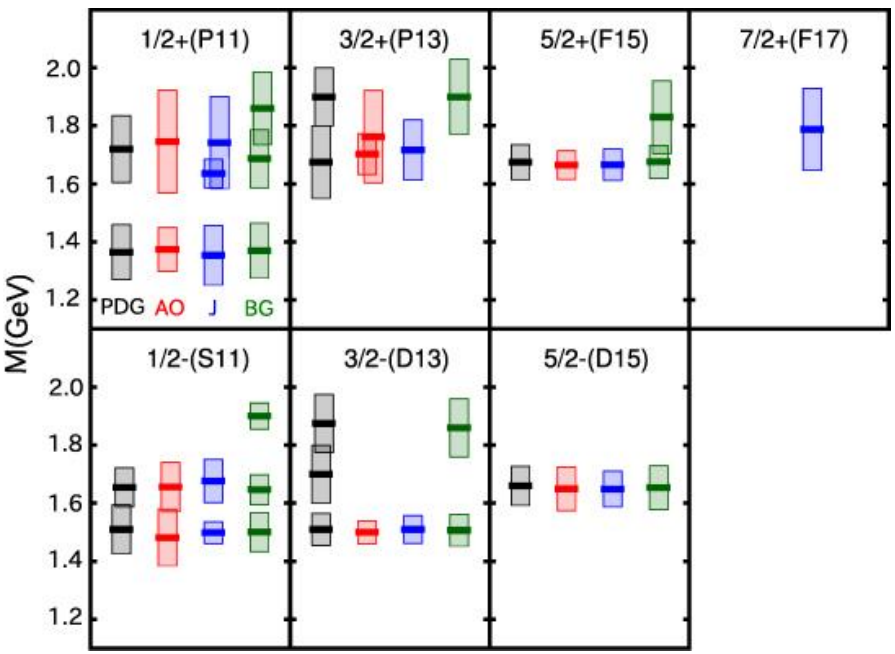
Comparison of N* & Δ* spectrum between multichannel analyses

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

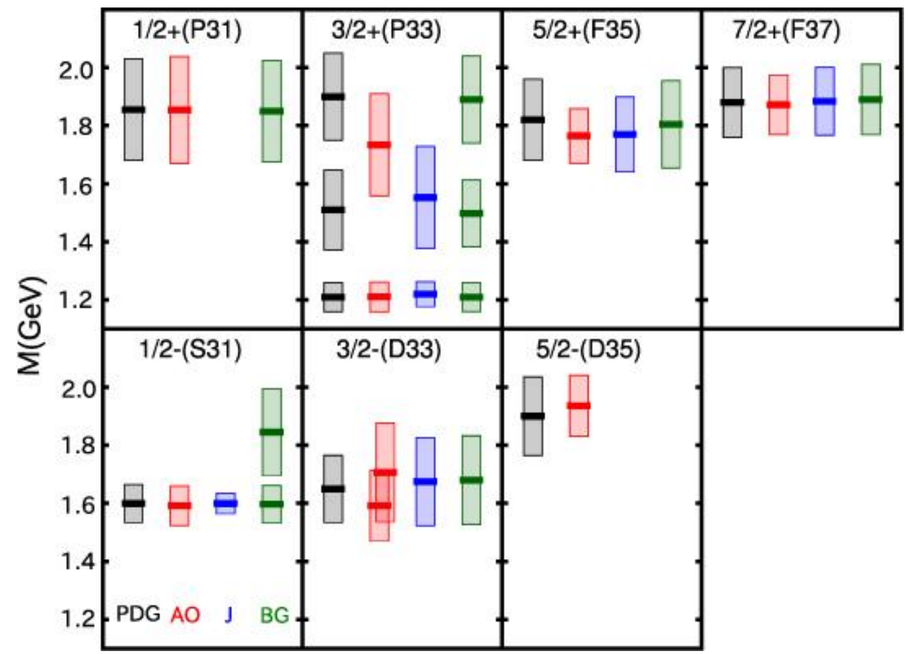


M_R : Resonance pole mass (complex)

$J^P(L_{2I\ 2J})$ "N" resonance (I=1/2)



$J^P(L_{2I\ 2J})$ "Δ" resonance (I=3/2)



PDG: 4* & 3* states assigned by PDG2012

AO : ANL-Osaka (Ours, DCC)

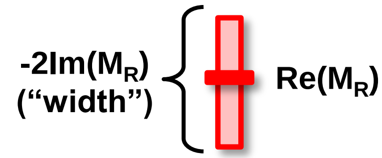
J : Juelich [DCC, πN reaction only, EPJA49(2013)44]

BG : Bonn-Gatchina [on-shell K-matrix, EPJA48(2012)5]

Comparison of N* & Δ* spectrum between multichannel analyses

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

Spectrum for low-lying states with $\mathrm{Re}(M_R) < 1.6$ GeV is now well established !!
(One exception is 2nd P33, Roper-like state of Δ)



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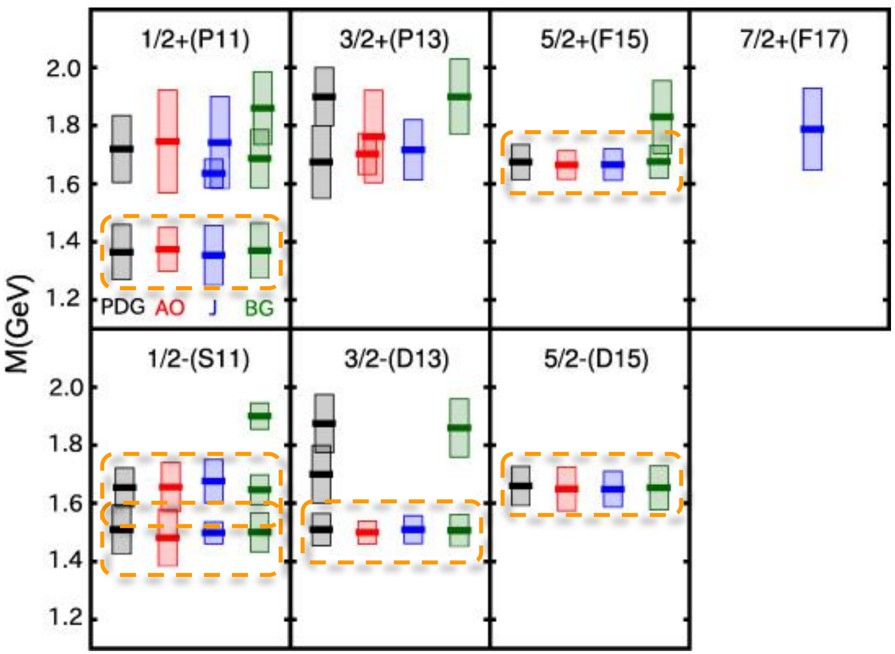

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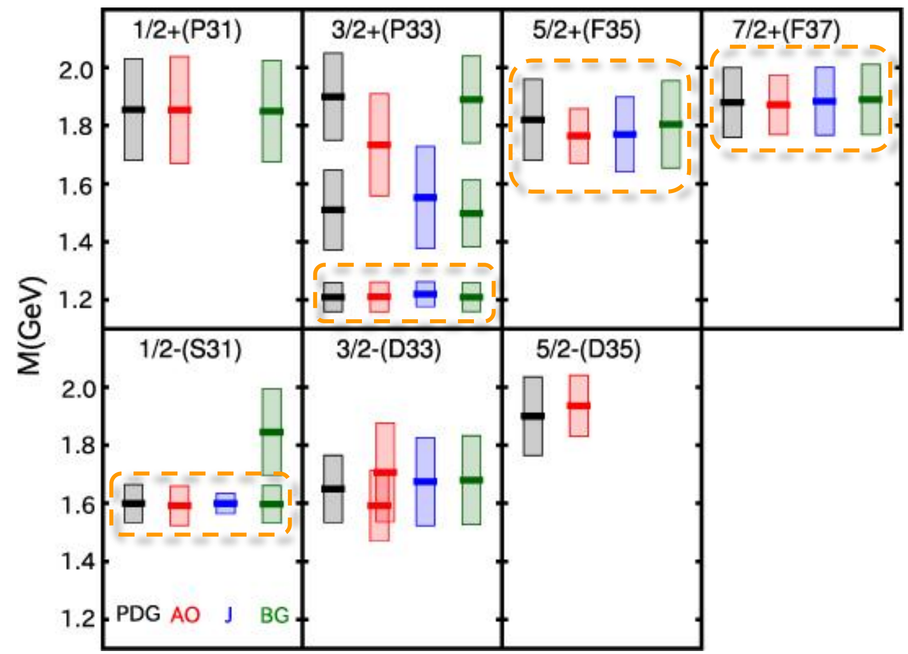

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What I expect of J-PARC for establishing N* spectrum

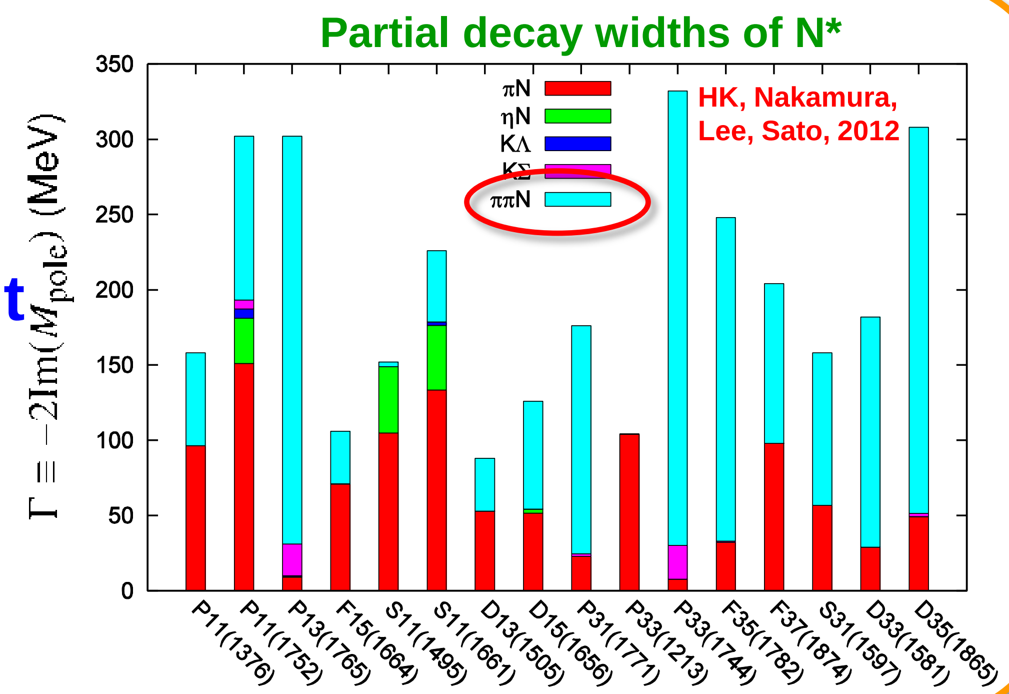
To tackle the spectrum of **high-mass N* resonances** ($1.6 < M_R < \sim 3$ GeV), **inelastic πN reaction data** are *highly* desirable:

πN → ππN, KΛ, KΣ, ηN, η'N, ωN, ΦN,…

Measurement of
πN → ππN, KY:

Hicks and Sako et al.,
J-PARC E45 experiment

Expected to make a significant impact on the high-mass N* spectroscopy !!



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

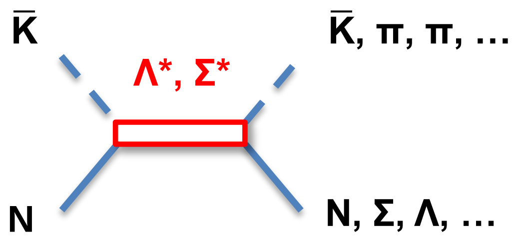
- ✓ **Much less understood than N* and Δ* baryons.**

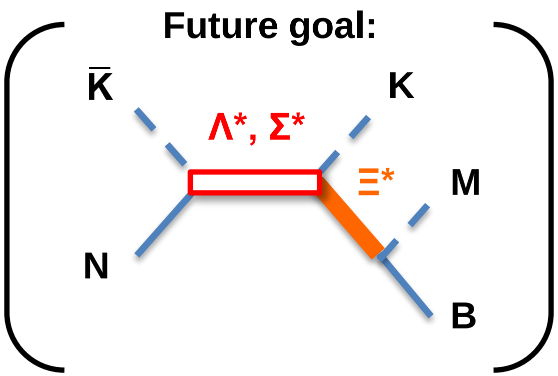
- ✓ **PDG(2012) lists only Y* mass spectrum defined by the "*highly model-dependent*" Breit-Wigner mass and width.**

- ✓ **Comprehensive & systematic PWA to extract *Y* resonances defined by poles of scattering amplitudes*:**
  - ➢ **KSU group (2013, on-shell K-matrix approach)**
  - ➢ **Our group (2014, dynamical approach)**

Y* spectroscopy using anti-Kaon beam

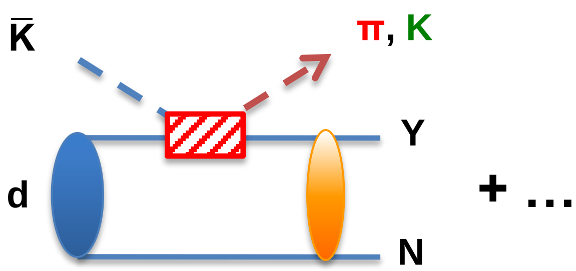
- The **simplest** reactions for **studying Y***.

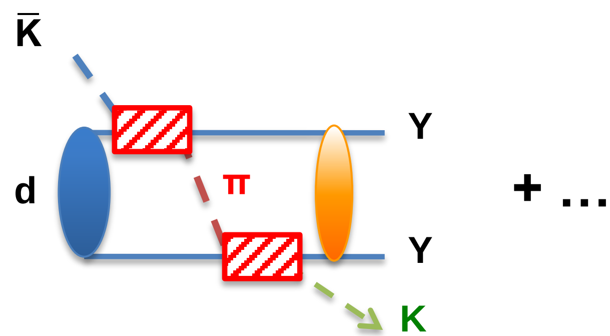




- Deuteron reactions allow direct access to **Λ(1405) region** and study of **YN** and **YY** interactions.

(Noumi et al., J-PARC E31)





Y* spectroscopy using anti-Kaon beam

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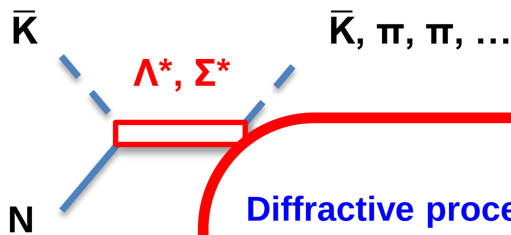
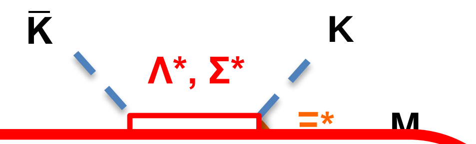


Future goal:



- Deuteron reactions allow dire
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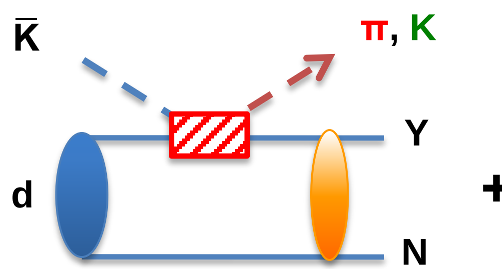
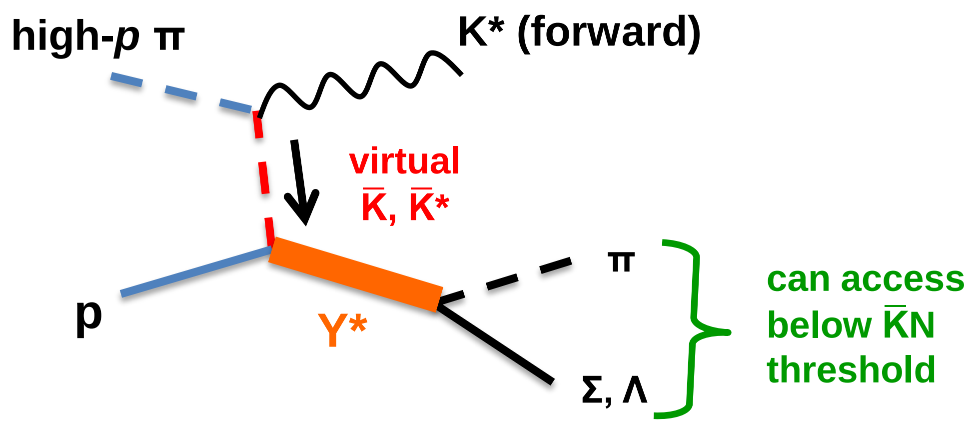


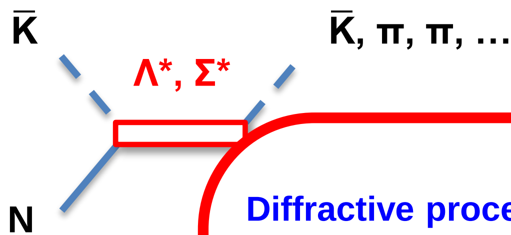
Diffractive processes with high-momentum pion beam:



(Noumi et al., J-PARC E50)

Y* spectroscopy using anti-Kaon beam

- The simplest reactions for studying Y*.



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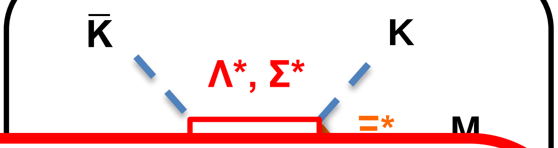

- Deuteron reactions allow dire
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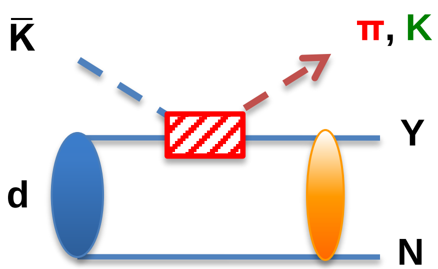
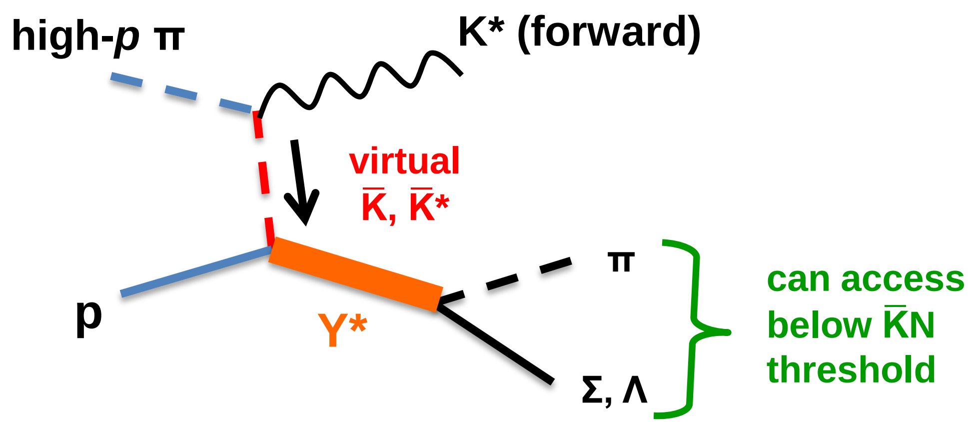
(Noumi et al.,
J-PARC E31)



+

Diffractive processes with high-momentum pion beam:



(Noumi et al., J-PARC E50)

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

What we have done so far

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

✓ Simultaneous analysis of *all* available polarized and unpolarized data of $K^- p \rightarrow \bar{K}N$, $\pi\Sigma$, $\pi\Lambda$, $\eta\Lambda$, $K\Xi$ from the threshold up to W = 2.1 GeV, by including L = 0(S), 1(P), 2(D), 3(F) partial waves.

(HK, Nakamura, Lee, Sato, arXiv:1407.6839, to appear in PRC)

✓ Extraction of Λ^* and Σ^* mass spectrum defined by poles of scattering amplitudes.

(HK, Nakamura, Lee, Sato, in preparation)

Database of our analysis (W < 2.1GeV)

HK, Nakamura, Lee, Sato, arXiv:1407.6839 (with updates) to appear in PRC

<u>Issues in the availability of data</u>:

- ✓ Most data are from 60-70's.
- ✓ Kinematical coverage is rather sparse for most reactions.
- ✓ No data for spin rotations (β, R, A).
- ✓ No data near the threshold for K- p → $\bar{K}$N, πΣ, πΛ.

The K^- p reaction data are far from "complete"!!
→ Need help of hadron beam facilities such as J-PARC !!

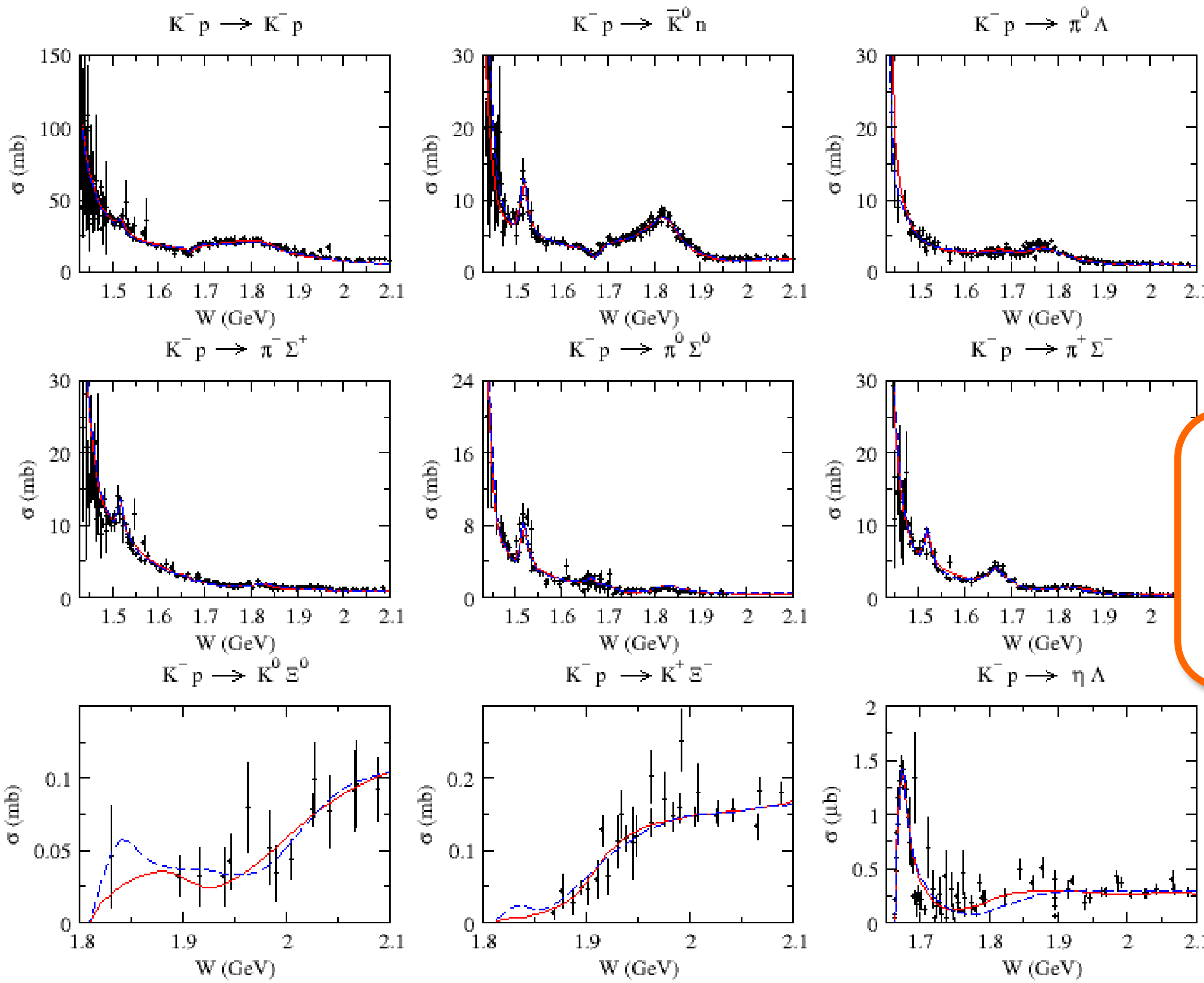
Reactions	Observables	Number of data
$K^-p \to K^-p$	$d\sigma/d\Omega$	3962
	P	510
	σ	253
$K^-p \to \bar{K}^0 n$	$d\sigma/d\Omega$	2950
	σ	260
$K^-p \to \pi^-\Sigma^+$	$d\sigma/d\Omega$	1792
	P	418
	$P \times d\sigma/d\Omega$	177
	σ	173
$K^-p \to \pi^0\Sigma^0$	$d\sigma/d\Omega$	580
	P	196
	$P \times d\sigma/d\Omega$	189
	σ	125
$K^-p \to \pi^+\Sigma^-$	$d\sigma/d\Omega$	1786
	σ	181
$K^-p \to \pi^0\Lambda$	$d\sigma/d\Omega$	2178
	P	693
	$P \times d\sigma/d\Omega$	176
	σ	207
$K^-p \to \eta\Lambda$	$d\sigma/d\Omega$	160
	P	18
	σ	78
$K^-p \to K^0\Xi^0$	$d\sigma/d\Omega$	33
	σ	15
$K^-p \to K^+\Xi^-$	$d\sigma/d\Omega$	92
	σ	27
Total		17229

- $K^-p \to K^-p$: $d\sigma/d\Omega$: 1465 MeV < W; P : 1730 MeV < W; β, R, A: No data
- $K^-p \to \bar{K}^0 n$: $d\sigma/d\Omega$: 1465 MeV < W; P : No data; β, R, A: No data
- $K^-p \to \pi^-\Sigma^+$: $d\sigma/d\Omega$: 1535 MeV < W; P : 1535 MeV < W < 1967 MeV; β, R, A: No data
- $K^-p \to \pi^0\Sigma^0$: $d\sigma/d\Omega$: 1535 MeV < W < 1763 MeV; P : 1535 MeV < W < 1696 MeV; β, R, A: No data
- $K^-p \to \pi^+\Sigma^-$: $d\sigma/d\Omega$: 1536 MeV < W; P : No data; β, R, A: No data
- $K^-p \to \pi^0\Lambda$: $d\sigma/d\Omega$: 1535 MeV < W; P : 1535 MeV < W; β, R, A: No data
- $K^-p \to \eta\Lambda$: $d\sigma/d\Omega$: 1664 MeV < W < 1696 MeV; P : 1669 MeV < W < 1681 MeV; β, R, A: No data
- $K^-p \to K^0\Xi^0$: $d\sigma/d\Omega$: 1970 MeV < W < 2070 MeV; P : No data; β, R, A: No data
- $K^-p \to K^+\Xi^-$: $d\sigma/d\Omega$: 1950 MeV < W < 2070 MeV; P : No data; β, R, A: No data

Results of the fits

$K^- p \rightarrow$ MB total cross sections

HK, Nakamura, Lee, Sato, arXiv:1407.6839 (with updates)
to appear in PRC



Red: Model A

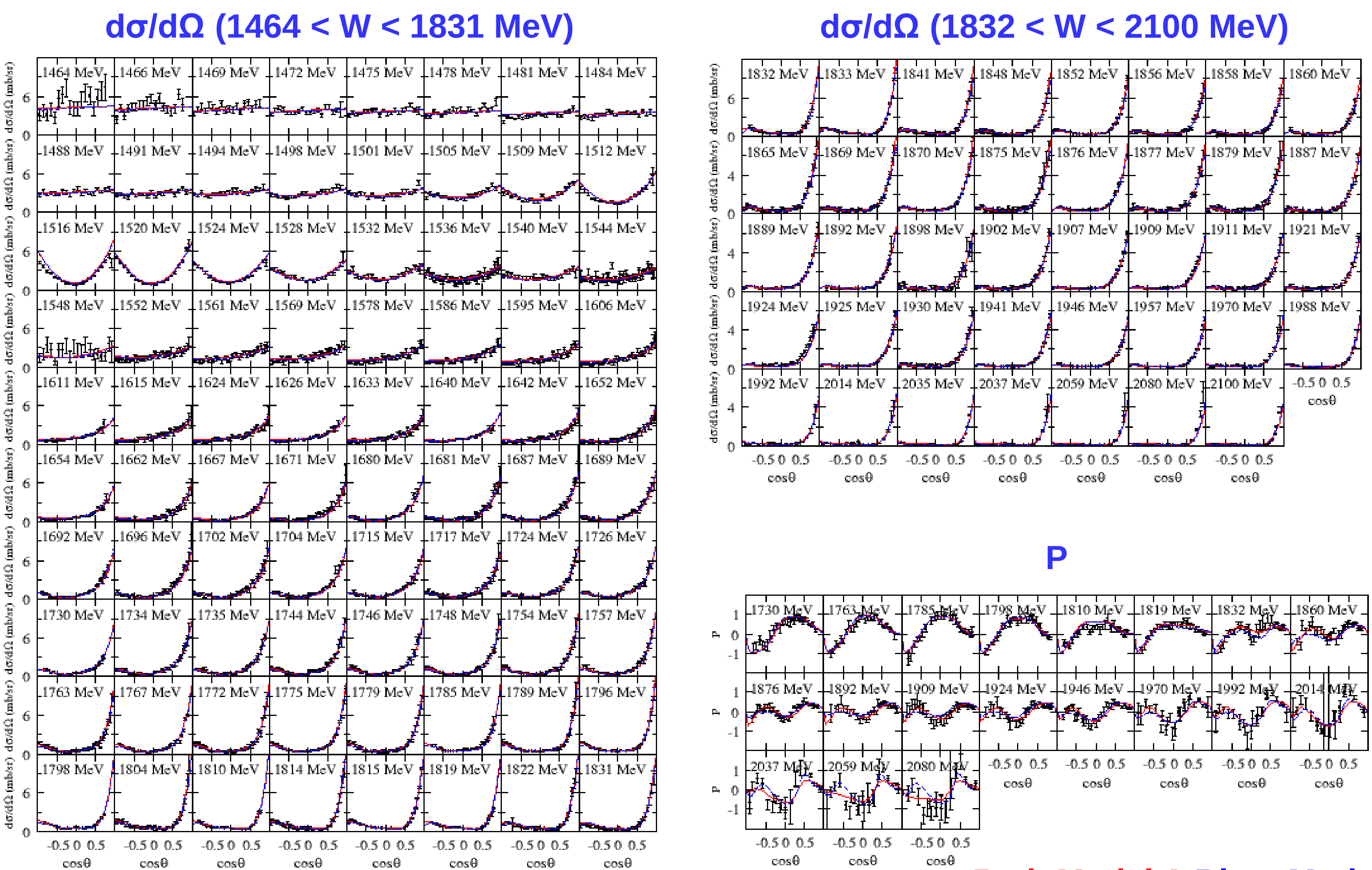
Blue: Model B

"Incompleteness" of the current database allows us to have two parameter sets that give similar quality of the fit.

Results of the fits

$K^- p \rightarrow K^- p$ scattering

HK, Nakamura, Lee, Sato, arXiv:1407.6839 (with updates)
to appear in PRC



Red: Model A Blue: Model B

What I expect of J-PARC for establishing Y* spectrum

There is no doubt that K^- p reactions are simplest and most suitable for the Y* spectroscopy.

However, the kinematical coverage and accuracy of K^- p reaction data are still very much limited.

- no data for spin-rotation observables (β, R, A),
- no data near the $\bar{K}N$ threshold,
- …

J-PARC is a unique facility to overcome this unsatisfactory situation !!

Back up

Extracted scattering lengths and effective ranges

HK, Nakamura, Lee, Sato, arXiv:1407.6839 (with updates)
to appear in PRC

	Model A		Model B	
	$I=0$	$I=1$	$I=0$	$I=1$
$a_{\bar{K}N}$ (fm)	$-1.37+i0.67$	$0.07+i0.81$	$-1.62+i1.02$	$0.33+i0.49$
$a_{\eta\Lambda}$ (fm)	$1.35+i0.36$	-	$0.97+i0.51$	-
$a_{K\Xi}$ (fm)	$-0.81+i0.14$	$-0.68+i0.09$	$-0.89+i0.13$	$-0.83+i0.03$
$r_{\bar{K}N}$ (fm)	$0.67-i0.25$	$1.01-i0.20$	$0.74-i0.25$	$-1.03+i0.19$
$r_{\eta\Lambda}$ (fm)	$-5.67-i2.24$	-	$-5.82-i3.32$	-
$r_{K\Xi}$ (fm)	$-0.01-i0.33$	$-0.42-i0.49$	$0.13-i0.20$	$-0.22-i0.11$

✓ **Visible model-dependency (sizable for some) is observed.**

➔ **This obviously reflects the lack of the data near the threshold !!**

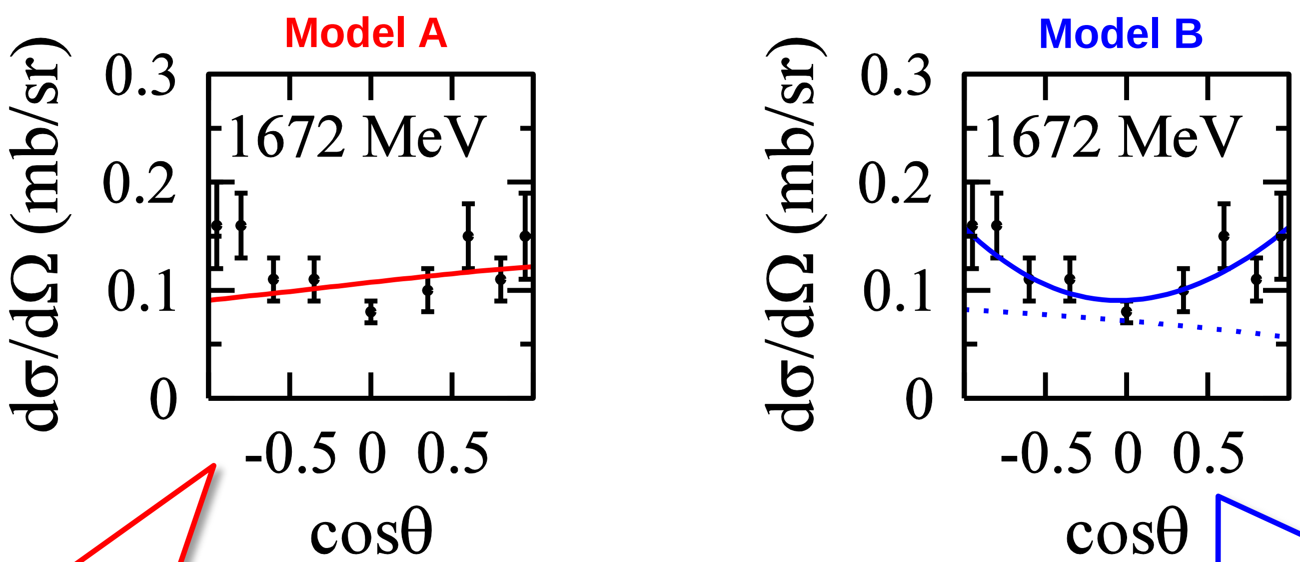
✓ **Both models give almost the same value for a(K^-p), a(K^-p) = -0.65 + i0.74 fm for Model A & -0.65 + i0.76 fm for Model B, which are consistent with recent extracted value in Ikeda et al NPA881(2012)98, yet the isospin components give rather different values between the two models.**

P03 resonance just above the ηΛ threshold

HK, Nakamura, Lee, Sato, arXiv:1407.6839 (with updates) to appear in PRC

✓ dσ/dΩ of K- p → ηΛ @W=1672 MeV (just 8 MeV above the threshold)

- Even in the region close to the threshold, dσ/dΩ **shows a clear angular dependence.**



S-wave dominated Model A seems not reproduce the angular distribution well.

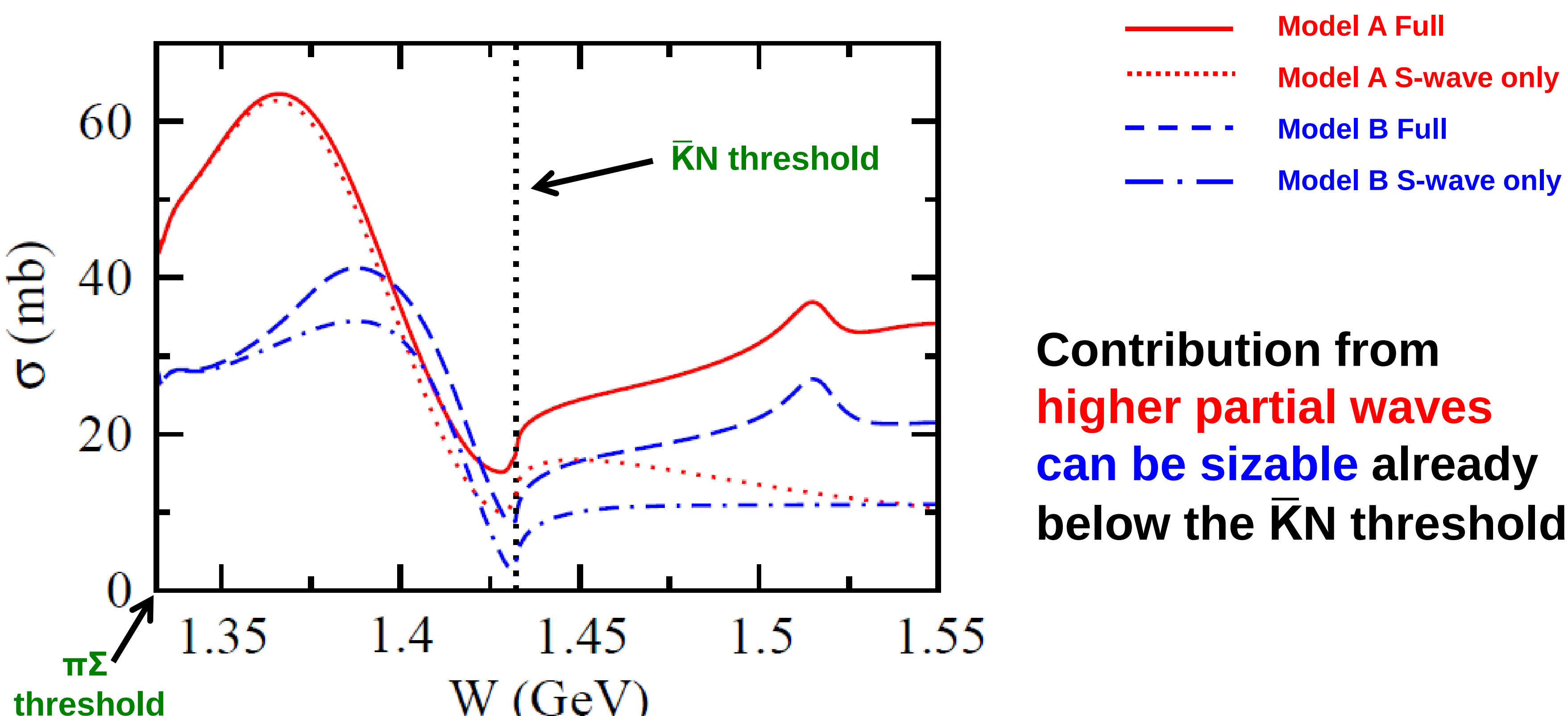
Narrow P03 resonance (only seen in Model B) seems important for angular dependence. (If it is turned off, dσ/dΩ becomes dotted curve.)

Predicted πΣ scattering total cross section at low energies

HK, Nakamura, Lee, Sato, arXiv:1407.6839 (with updates)
to appear in PRC

- ✓ **Predicted total cross sections of πΣ scatterings from the threshold up to W = 1.55 GeV**

$$\pi^{+/-}\Sigma^{-/+} \longrightarrow \pi^{+/-}\Sigma^{-/+}$$

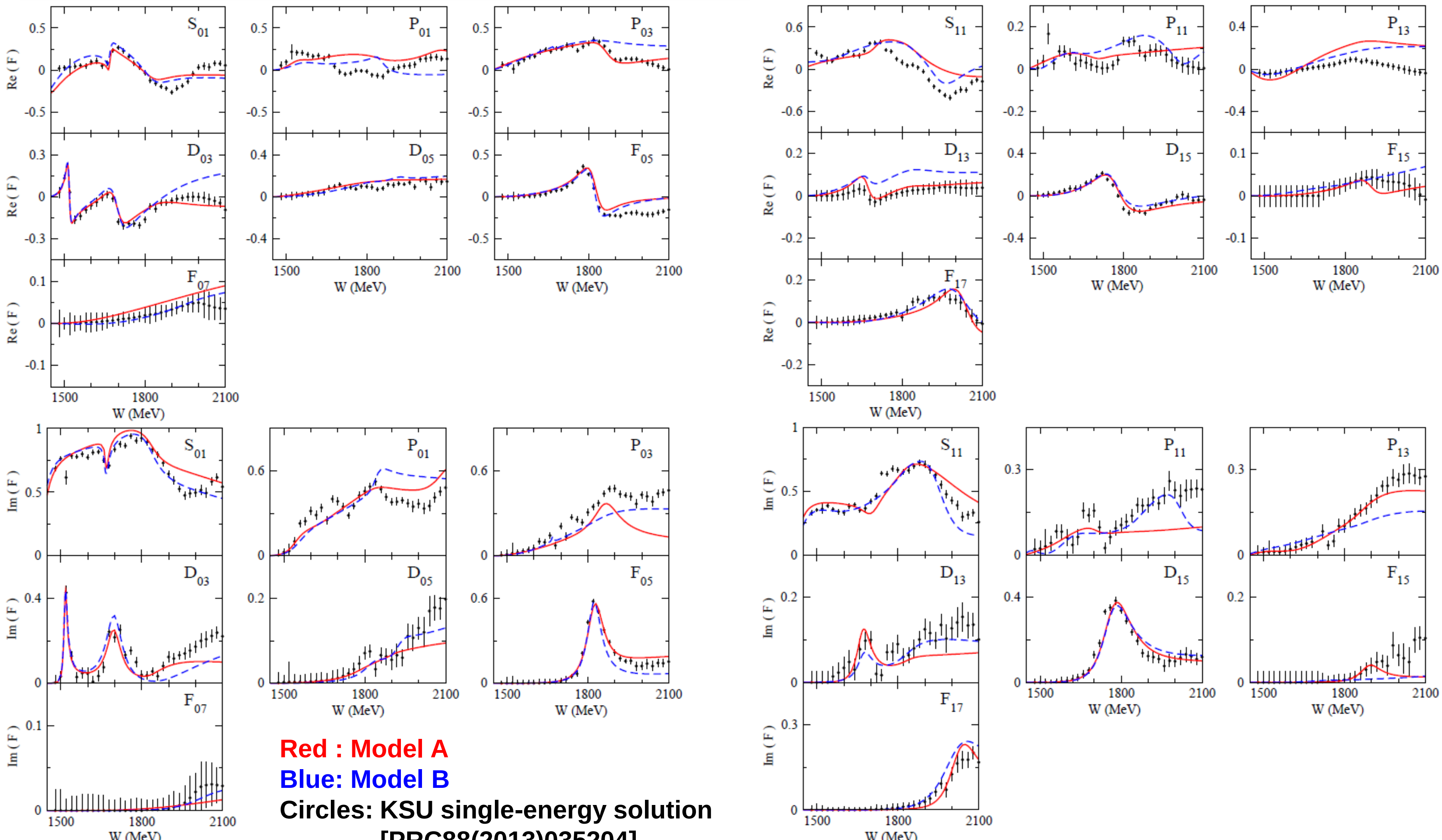


Contribution from **higher partial waves can be sizable** already below the K̄N threshold !!

Comparison of extracted partial-wave amplitudes

Extracted $\bar{K}N$ scattering amplitudes

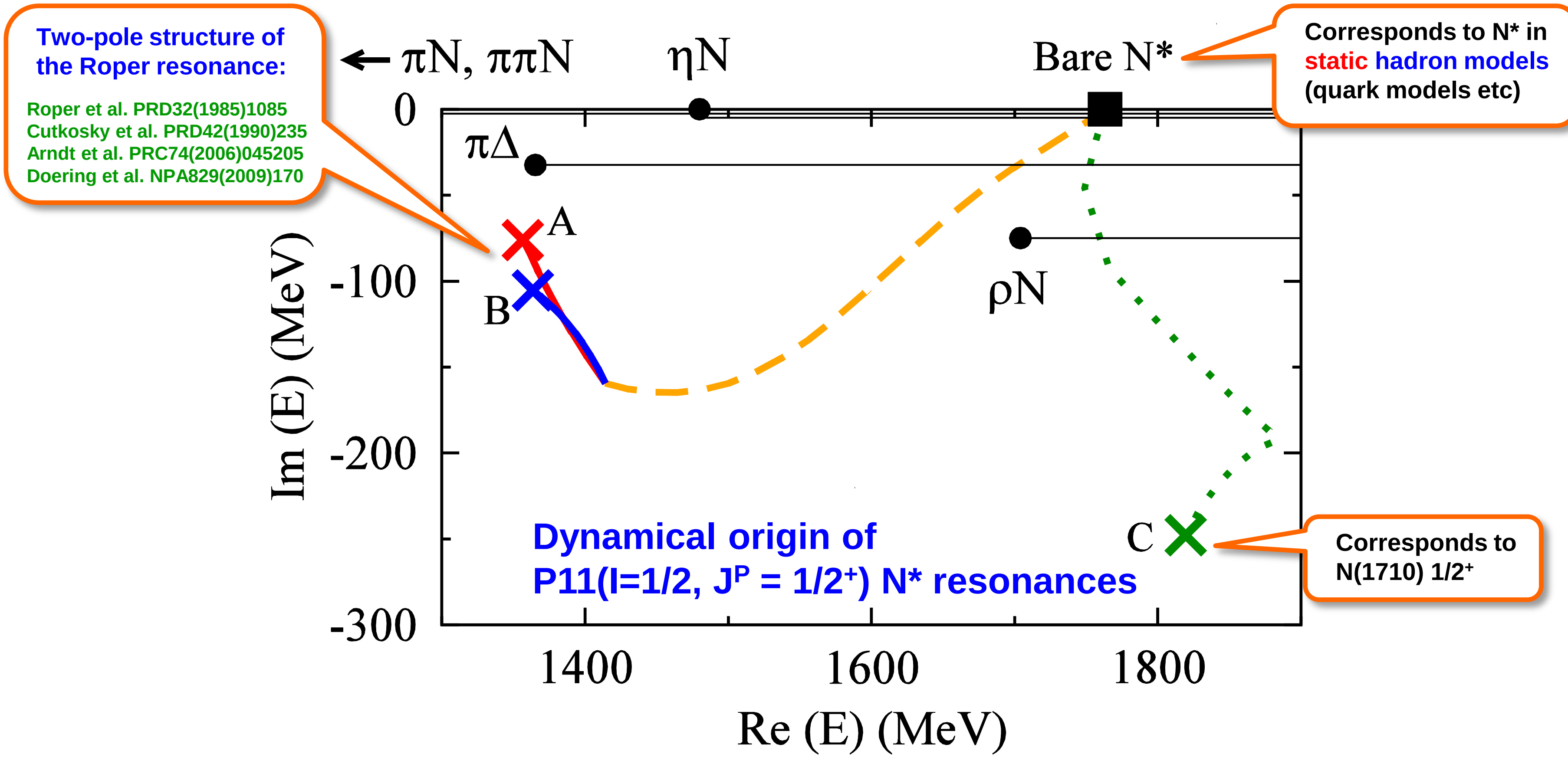
HK, Nakamura, Lee, Sato, arXiv:1407.6839 (with updates)
to appear in PRC



Red : Model A
Blue: Model B
Circles: KSU single-energy solution
[PRC88(2013)035204]

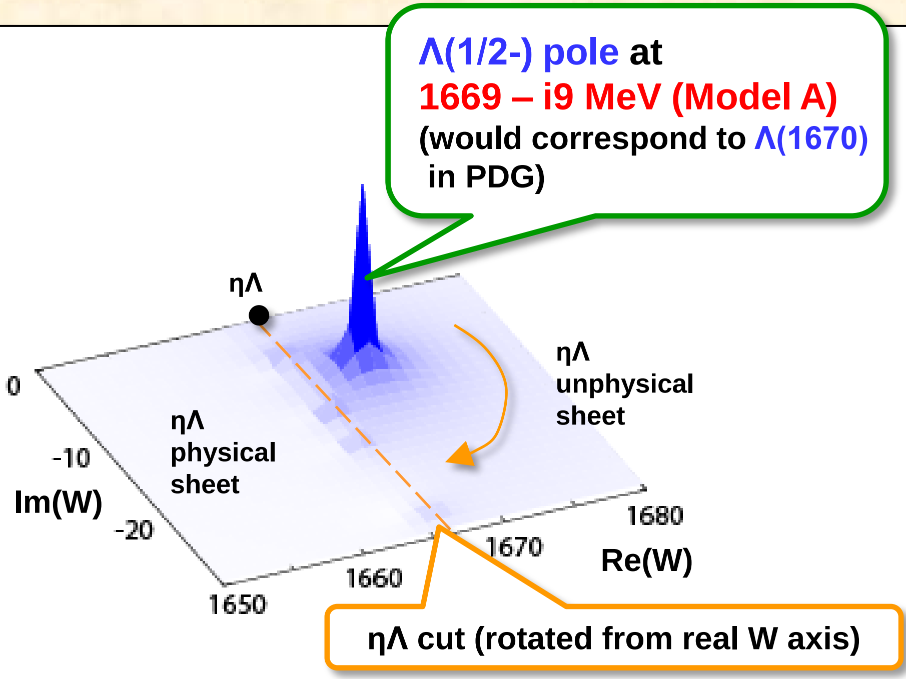
Why DCC approach ??

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

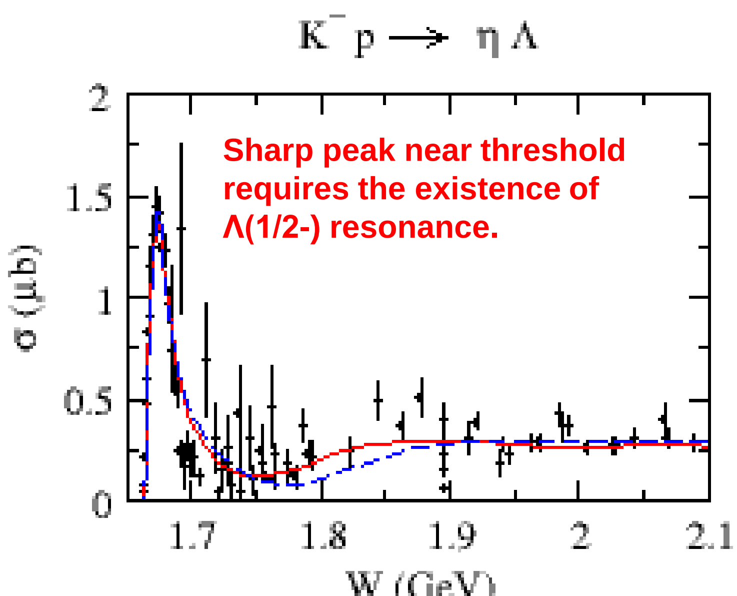


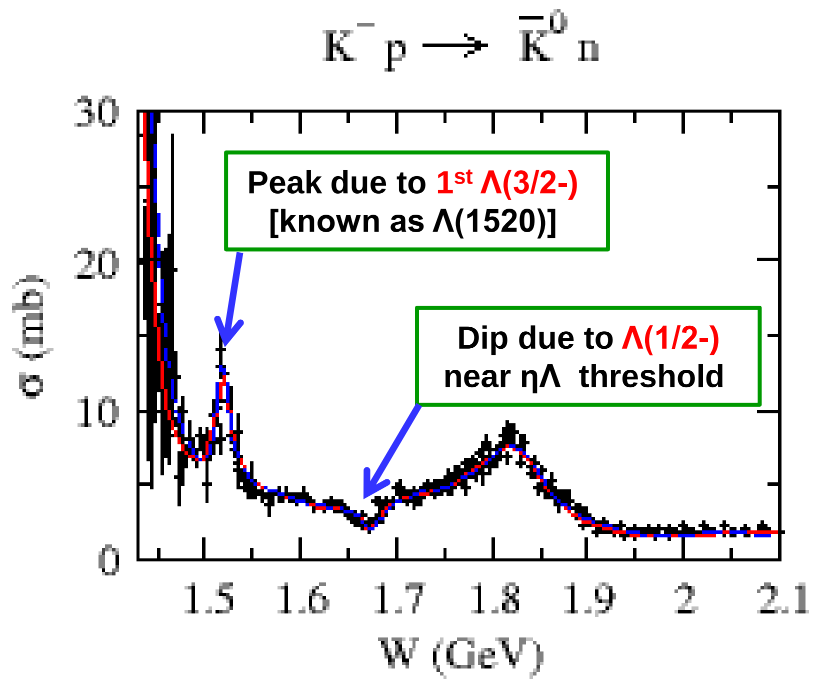
- Coupling to reaction channels can produce a sizable mass shift.
- Multichannel reaction dynamics can give rise to *many* physical resonances from a single bare state.

Λ(1/2-) resonance near the ηΛ threshold



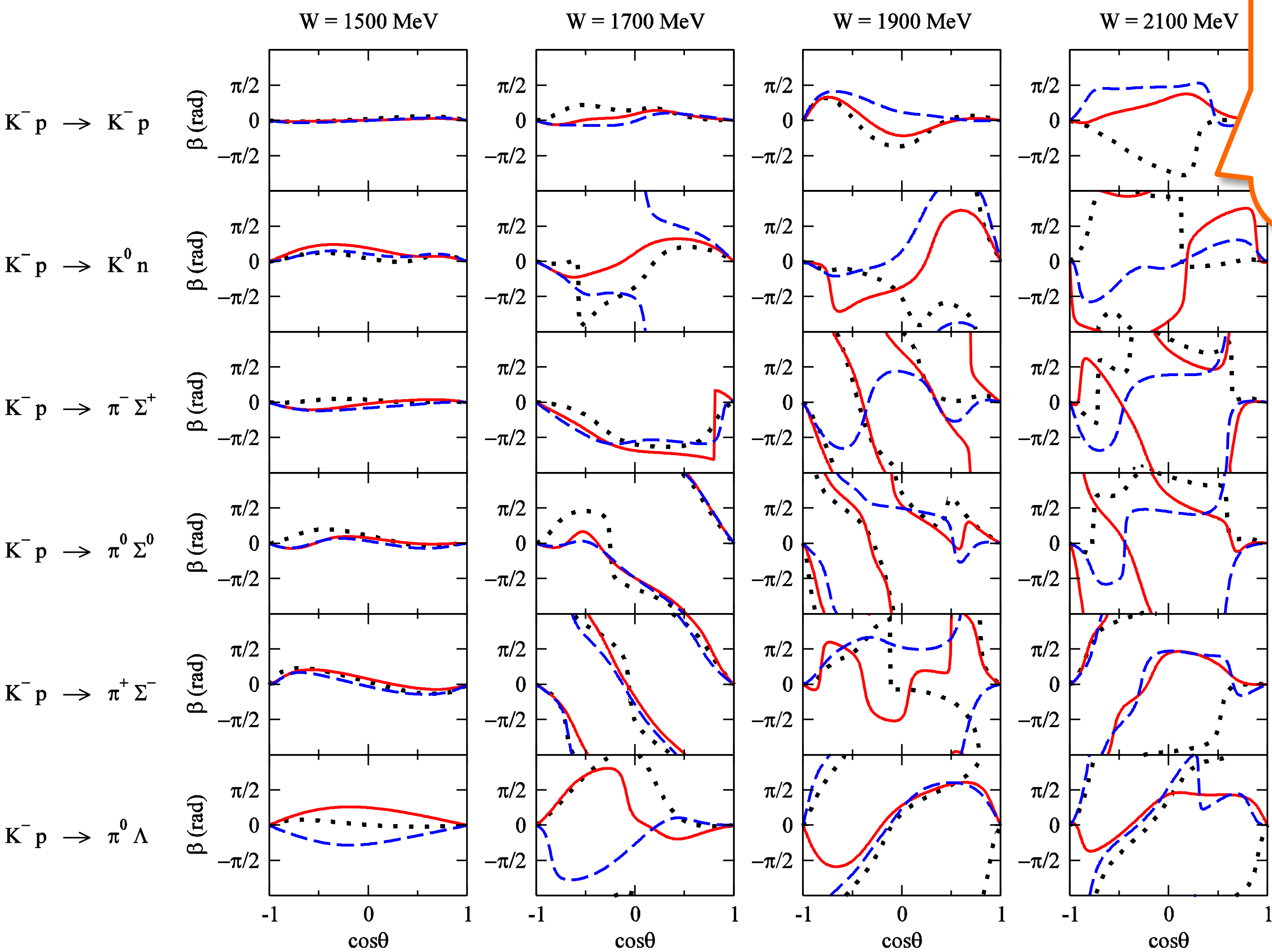
- ✓ Next higher excited states of Λ(1405).
- ✓ K- p → ηΛ data make the existence of this Λ(1/2-) stable and model-independent.
- ✓ Dip at W ~ 1670 MeV seen in K- p → MB total cross sections is produced by this Λ(1/2-). [ηΛ cusp effect is hindered by the large contribution from Λ(1/2-).]





Predicted spin-rotation angle β

HK, Nakamura, Lee, Sato, arXiv:1407.6839 (with updates) to appear in PRC



Model dependence is clearly seen in observables not yet measured.

Measurement of such observables will give strong constraints on the Y* spectrum !!

Red: Model A

Blue: Model B

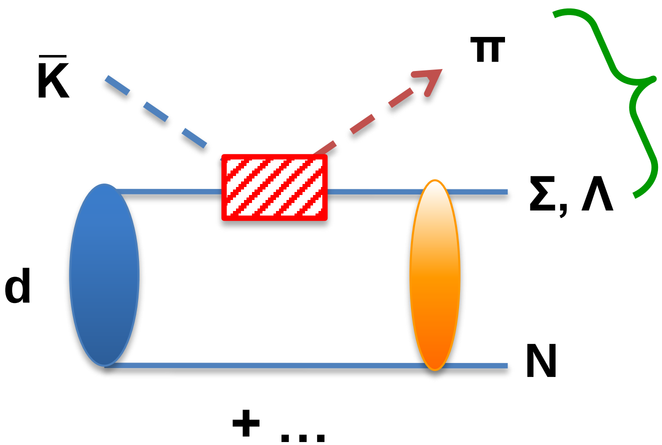
Black: KSU

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

NOTE:
β is modulo 2π

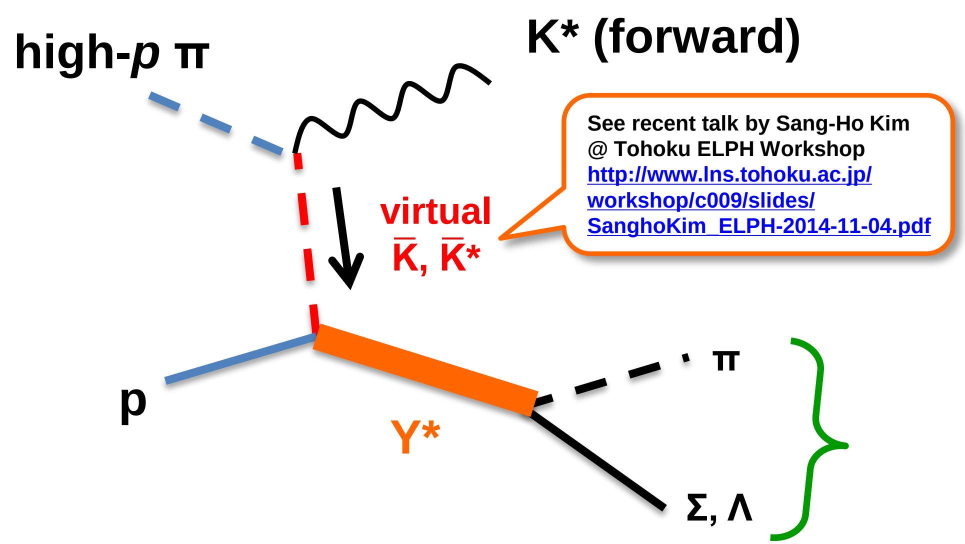
How do we access the region below $\bar{K}N$ threshold with J-PARC?

✓ Deuteron-target reactions:



(Noumi et al., J-PARC E31)

✓ Diffractive processes with high-momentum (pion) beam:



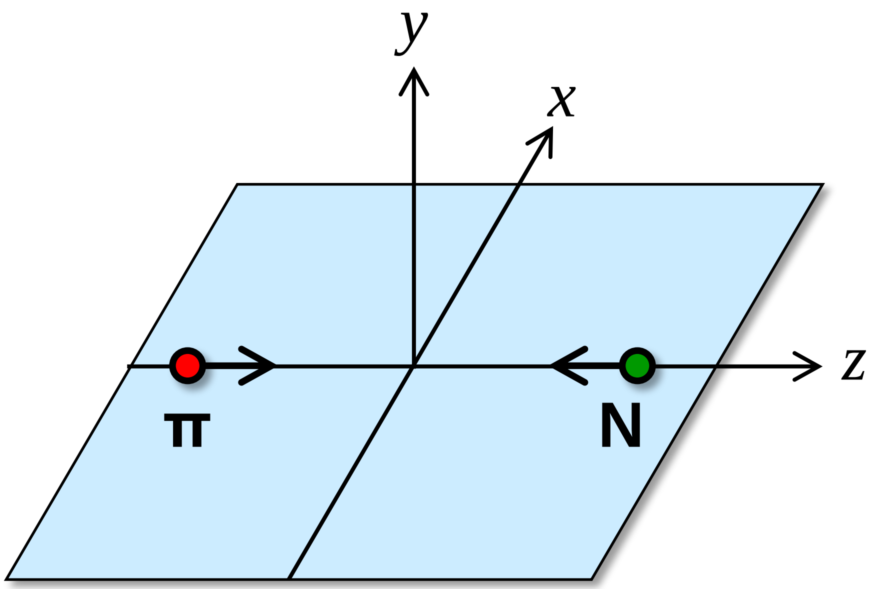
(Noumi et al., J-PARC E50)

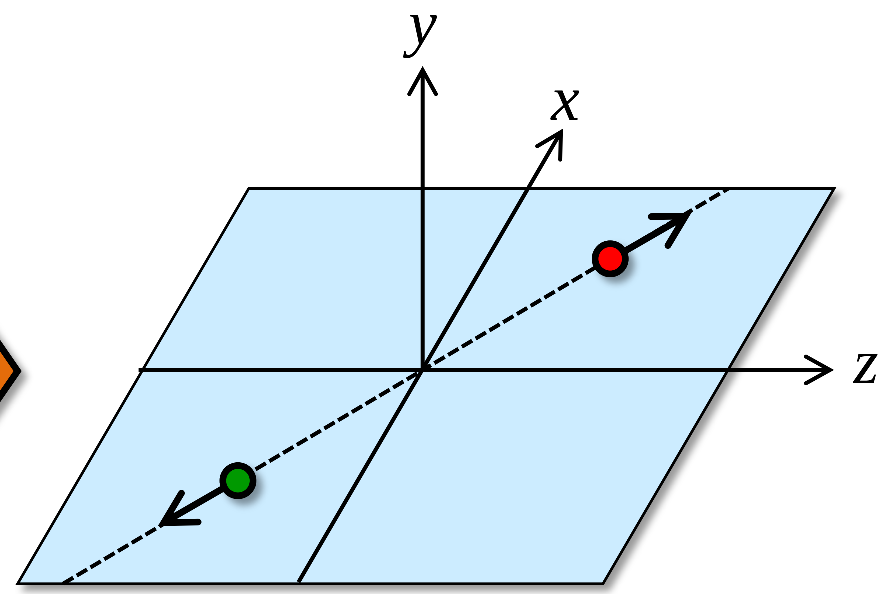
We DO have off-shell $\bar{K}N \rightarrow$ MB and $\bar{K}^*N \rightarrow$ MB amplitudes not only for *S wave* but also for *P, D,* and *F waves* !!

Polarization observables for spin-0 + spin-1/2 ➔ spin-0 + spin-1/2 reactions

Wolfenstein, Phys. Rev. 96(1954)1654
Kelly, Sandusky, Cutkosky, PRD10(1974)2309
Saxon, Whittaker, Z. Phys. C9(1981)35
Supek et al., PRD47(1993)1762

e.g.) πN scattering (in c.m. frame)





Suppose target nucleon polarization points z-axis (➔ parallel to pion momentum):

$$\vec{P}_{N_T} = P_{N_T}\,\hat{z}$$

Polarization of the recoil nucleon is then expressed as

$$\begin{aligned}\vec{P}_{N_R} &= P\,\hat{y}\\ &+ P_{N_T}\sqrt{1-P^2}\,\sin\beta\,\hat{x}\\ &+ P_{N_T}\sqrt{1-P^2}\,\cos\beta\,\hat{z}\end{aligned}$$

$$\left(R = \sqrt{1-P^2}\,\sin\beta,\quad A = \sqrt{1-P^2}\,\cos\beta\right)$$

Note: Various conventions are taken for β, R, A in literatures.

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:**

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

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coupled-channels effect

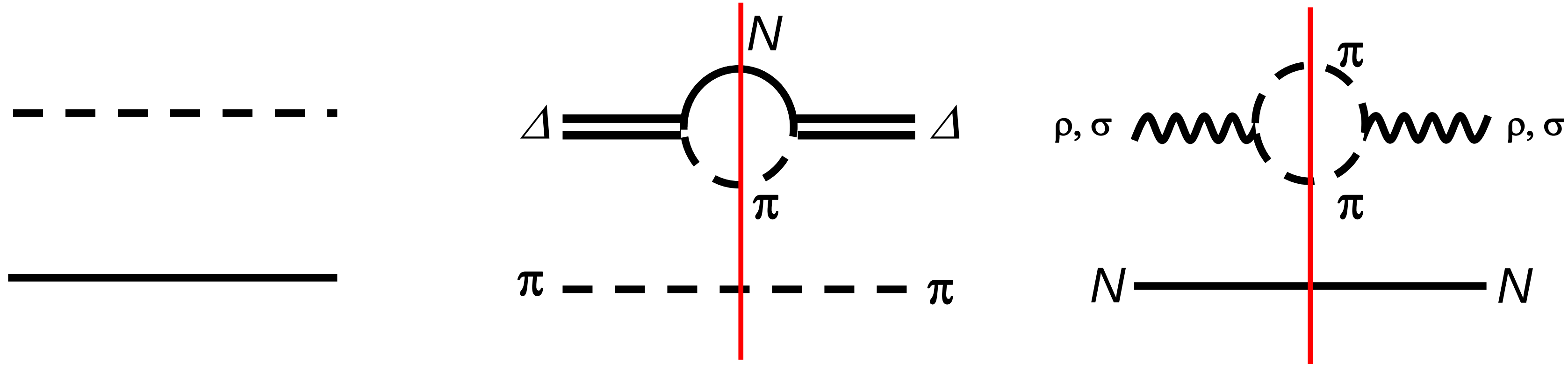
✓ **Meson-Baryon Green functions** G_{MB}

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

Stable channels

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

Quasi 2-body channels



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- ✓ **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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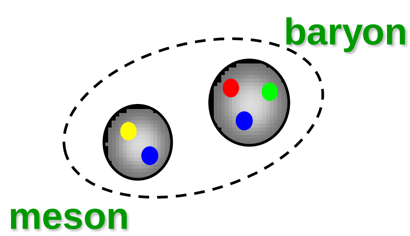
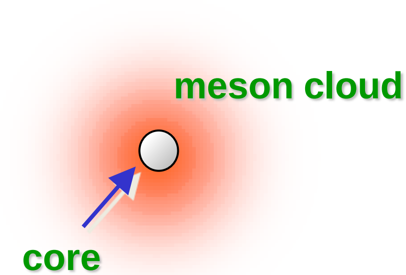
For details see Matsuyama, Sato, Lee, Phys. Rep. 439 (2007)193
HK, Nakamura, Lee, Sato, PRC88 (2013) 035209

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

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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