Dynamical coupled-channels study of S = -1 hyperon resonances

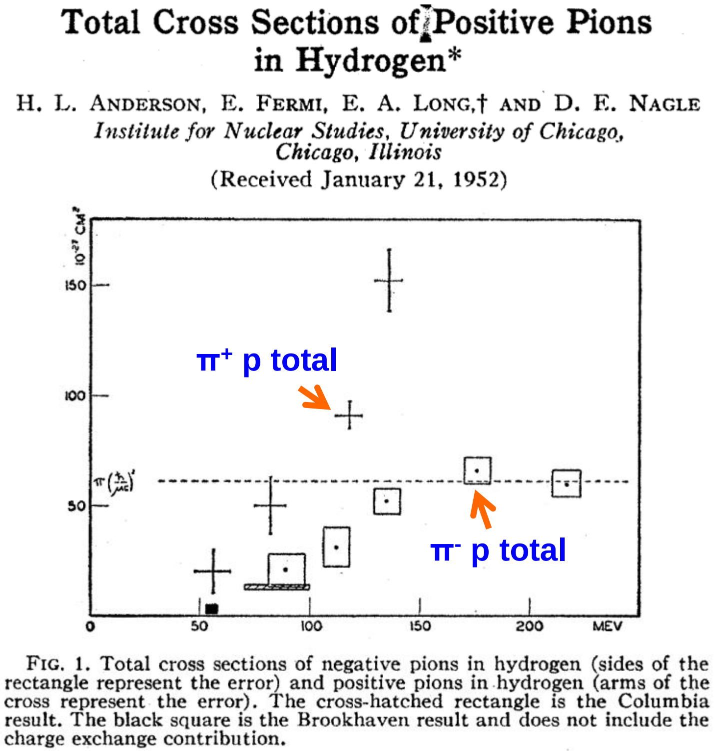
Hiroyuki Kamano
(RCNP, Osaka U.)

[HK, Nakamura, Lee, Sato, PRC90(2014)065204; arXiv:1506.01768 (to appear in PRC)]

KEK理論センター J-PARC分室、JAEA先端基礎研究センター共催研究会
「ストレンジネス核物理の発展方向」, KEK東海キャンパス, Aug. 3-5, 2015

Introduction: Baryon spectroscopy

Discovery of the Δ baryon (1952)



Total Cross Sections of Positive Pions in Hydrogen*

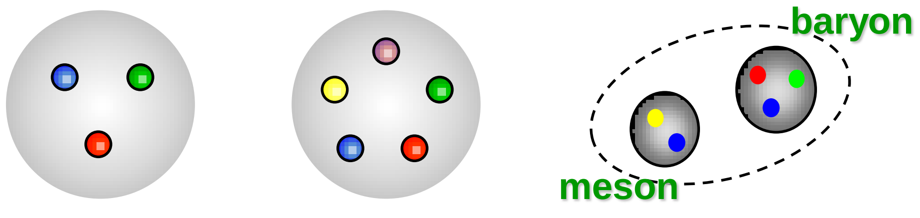
H. L. Anderson, E. Fermi, E. A. Long,† and D. E. Nagle
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 21, 1952)

Fig. 1. Total cross sections of negative pions in hydrogen (sides of the rectangle represent the error) and positive pions in hydrogen (arms of the cross represent the error). The cross-hatched rectangle is the Columbia result. The black square is the Brookhaven result and does not include the charge exchange contribution.

PDG2014 reports ~ 150 baryons.
(NOTE: Existence is still uncertain
for ~ 50% of baryons.)

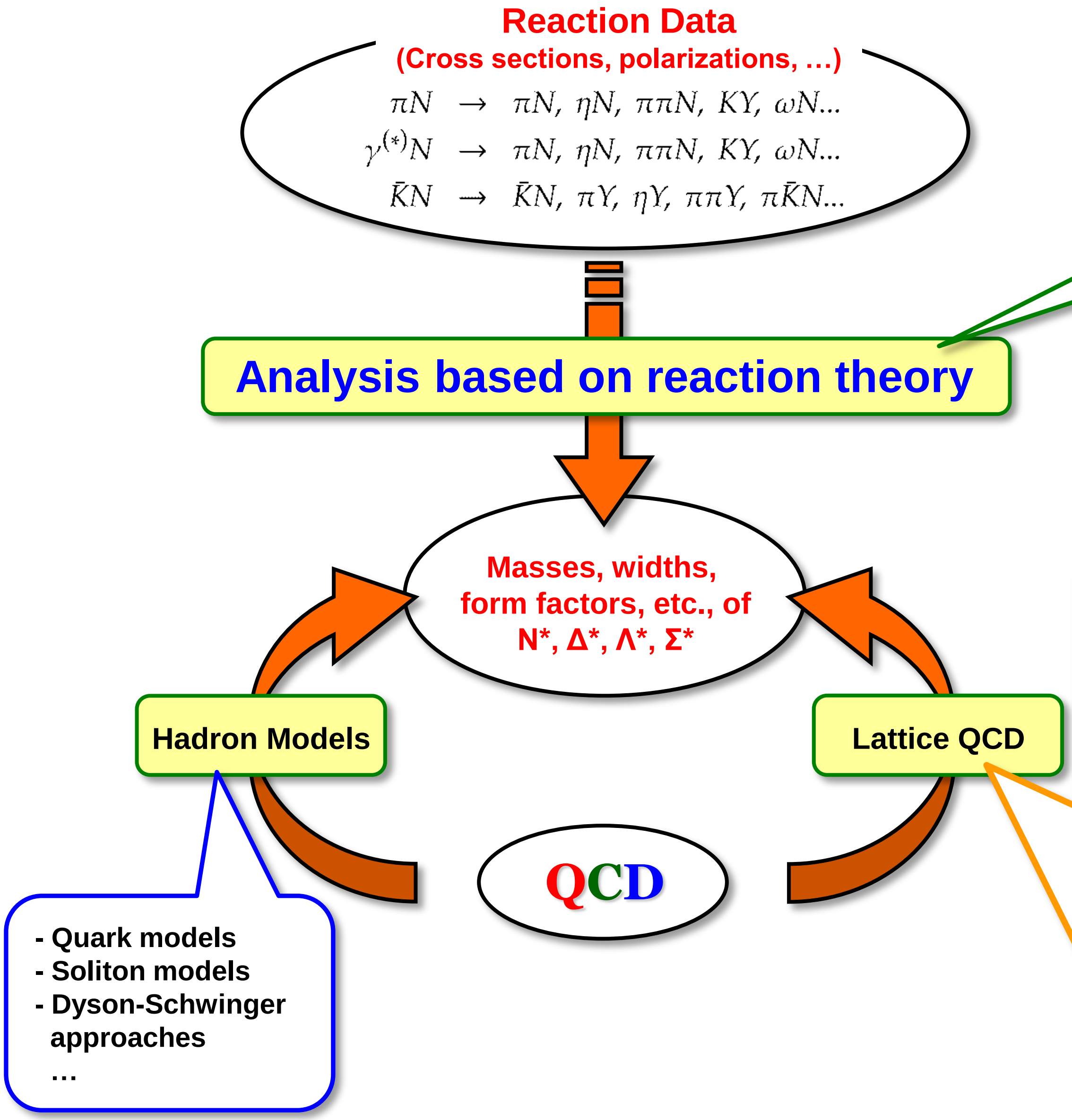
Baryon Spectroscopy: Understanding nature of baryons and their excitations

- Mass, width, spin, parity …?
- Internal structure (form factors)?
- How produced in reaction processes?
- How interact with other particles?



3-quark state multiquark state “molecule-like” state

Approaches to light-quark baryon (N*, Δ*, Λ*, Σ*) spectroscopy



Reaction Data

(Cross sections, polarizations, …)

$$\pi N \rightarrow \pi N,\ \eta N,\ \pi\pi N,\ KY,\ \omega N...$$

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

$$\bar{K} N \rightarrow \bar{K} N,\ \pi Y,\ \eta Y,\ \pi\pi Y,\ \pi\bar{K} N...$$

Analysis based on reaction theory

Our approach !!

Masses, widths, form factors, etc., of N*, Δ*, Λ*, Σ*

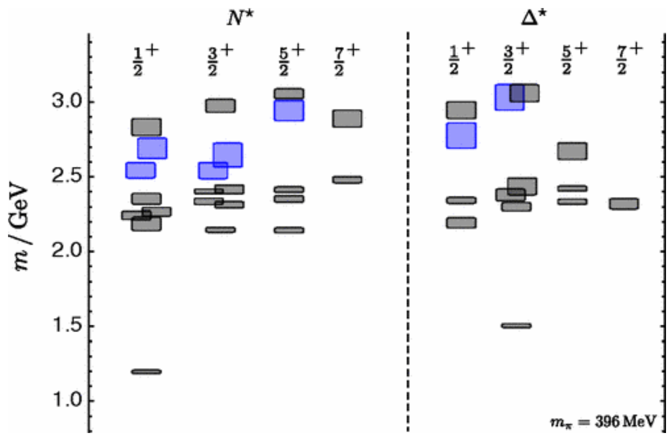
Hadron Models

Lattice QCD

QCD

- Quark models
- Soliton models
- Dyson-Schwinger approaches
  …

“Real” energy spectrum of QCD in a finite box



Dudek, Edwards, PRD85(2012)054016

Current situation of Y*(= Λ*, Σ*) spectroscopy

✓ Y* (= Λ*, Σ*) resonances are much less understood than N* & Δ*.

Λ(13XX)$1/2^-$??

For example:

- Even low-lying resonances are not well determined.

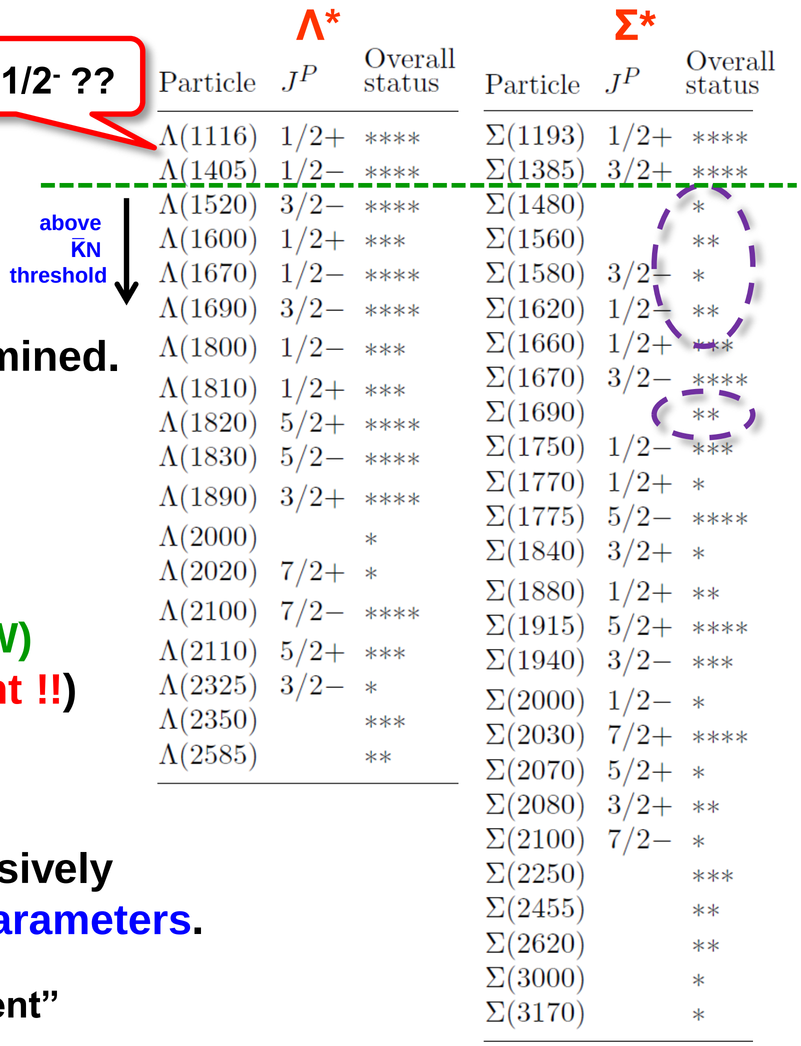
  ➔ N* & Δ* spectra are well established in the mass range 0.94 < M < ~ 1.8 GeV.

- Before 2012, PDG listed only Breit-Wigner (BW) mass and width. (➔ "*highly*" model-dependent !!)

  ➔ N* & Δ* case: Resonance parameters defined by poles of scattering amplitudes are extensively studied; PDG lists BOTH pole and BW parameters.

NOTE: Pole parameters should be "model-independent" and meaningful to compare !!

PDG listing



above $\bar{K}N$ threshold

Λ*

Particle	J^P	Overall status
Λ(1116)	1/2+	****
Λ(1405)	1/2−	****
Λ(1520)	3/2−	****
Λ(1600)	1/2+	***
Λ(1670)	1/2−	****
Λ(1690)	3/2−	****
Λ(1800)	1/2−	***
Λ(1810)	1/2+	***
Λ(1820)	5/2+	****
Λ(1830)	5/2−	****
Λ(1890)	3/2+	****
Λ(2000)		*
Λ(2020)	7/2+	*
Λ(2100)	7/2−	****
Λ(2110)	5/2+	***
Λ(2325)	3/2−	*
Λ(2350)		***
Λ(2585)		**

Σ*

Particle	J^P	Overall status
Σ(1193)	1/2+	****
Σ(1385)	3/2+	****
Σ(1480)		*
Σ(1560)		**
Σ(1580)	3/2−	*
Σ(1620)	1/2−	**
Σ(1660)	1/2+	***
Σ(1670)	3/2−	****
Σ(1690)		**
Σ(1750)	1/2−	***
Σ(1770)	1/2+	*
Σ(1775)	5/2−	****
Σ(1840)	3/2+	*
Σ(1880)	1/2+	**
Σ(1915)	5/2+	****
Σ(1940)	3/2−	***
Σ(2000)	1/2−	*
Σ(2030)	7/2+	****
Σ(2070)	5/2+	*
Σ(2080)	3/2+	**
Σ(2100)	7/2−	*
Σ(2250)		***
Σ(2455)		**
Σ(2620)		**
Σ(3000)		*
Σ(3170)		*

Current situation of Y*(= Λ*, Σ*) spectroscopy

✓ Comprehensive partial-wave analysis of K^- p reactions to extract Y* *defined by poles* has been accomplished ***just recently*** :

- **Kent State University (KSU) group**

  (➔ 2013, "KSU on-shell parametrization" of S-matrix)

  Zhang et al., PRC88(2013)035204, 035205.

- **Our group**

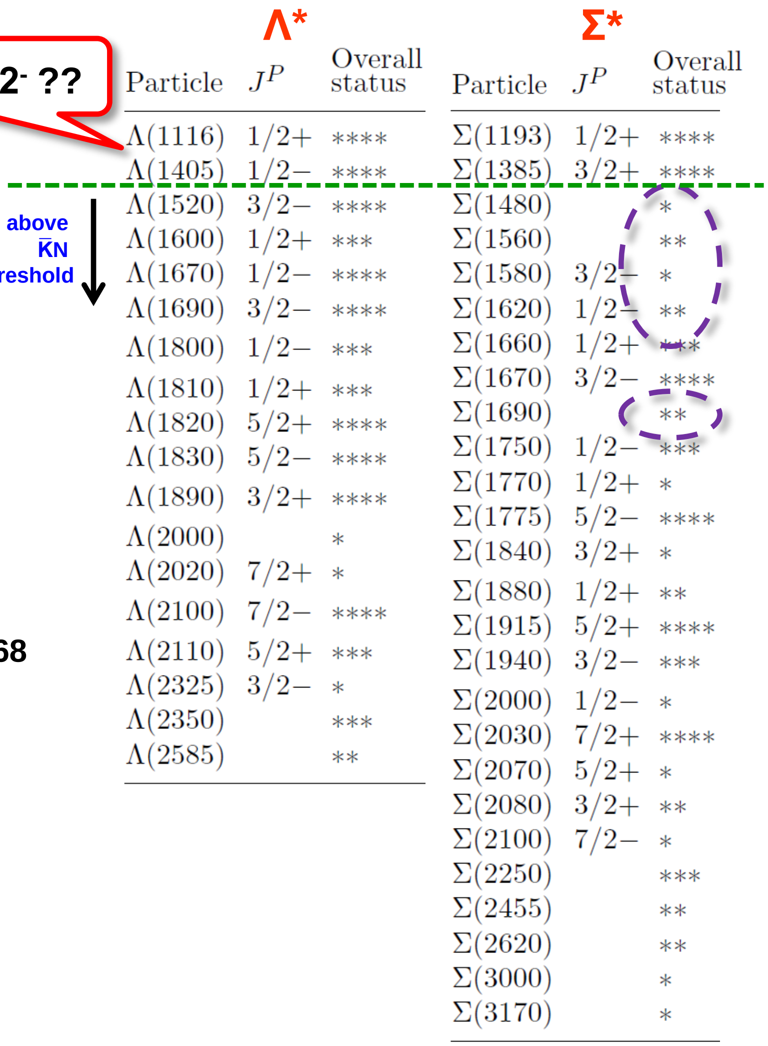
  (➔ 2014-2015, dynamical coupled-channels approach)

  HK, Nakamura, Lee, Sato, PRC90(2014)065204; arXiv:1506.01768

PDG listing

Λ(13XX)$1/2^-$??

above $\bar{K}N$ threshold



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Λ(2110)	5/2+	***
Λ(2325)	3/2−	*
Λ(2350)		***
Λ(2585)		**

Σ*

Particle	J^P	Overall status
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Σ(1480)		*
Σ(1560)		**
Σ(1580)	3/2−	*
Σ(1620)	1/2−	**
Σ(1660)	1/2+	***
Σ(1670)	3/2−	****
Σ(1690)		**
Σ(1750)	1/2−	***
Σ(1770)	1/2+	*
Σ(1775)	5/2−	****
Σ(1840)	3/2+	*
Σ(1880)	1/2+	**
Σ(1915)	5/2+	****
Σ(1940)	3/2−	***
Σ(2000)	1/2−	*
Σ(2030)	7/2+	****
Σ(2070)	5/2+	*
Σ(2080)	3/2+	**
Σ(2100)	7/2−	*
Σ(2250)		***
Σ(2455)		**
Σ(2620)		**
Σ(3000)		*
Σ(3170)		*

Dynamical coupled-channels (DCC) approach for Y* production reactions

HK, Nakamura, Lee, Sato, PRC90(2014)065204

- ✓ **Coupled-channels integral equations for partial-wave amplitudes of a → b reaction:**

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

- ✓ **Reaction channels:**

$$a,b,c = (\,\bar{K}N,\ \pi\Sigma,\ \pi\Lambda,\ \eta\Lambda,\ K\Xi, \boxed{\pi\Sigma^*,\ \bar{K}^*N,}\ \cdots\ )$$

quasi two-body channels

- ✓ **Transition Potentials:**

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

Exchange potentials

Bare Y* states

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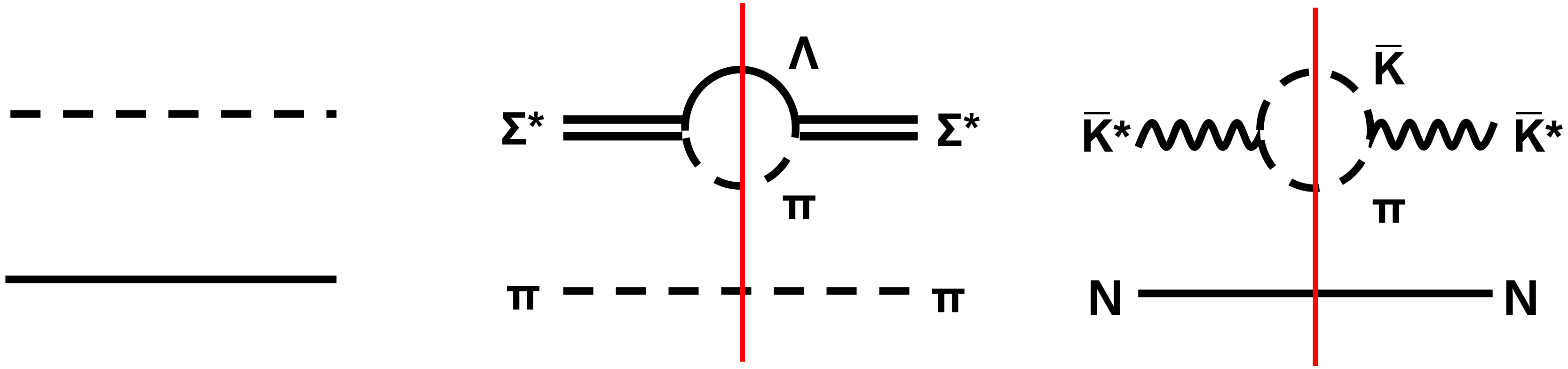
- ✓ **Meson-Baryon Green functions**

$$MB = \bar{K}N, \pi\Sigma, \pi\Lambda, \eta\Lambda, K\Xi$$

Stable channels

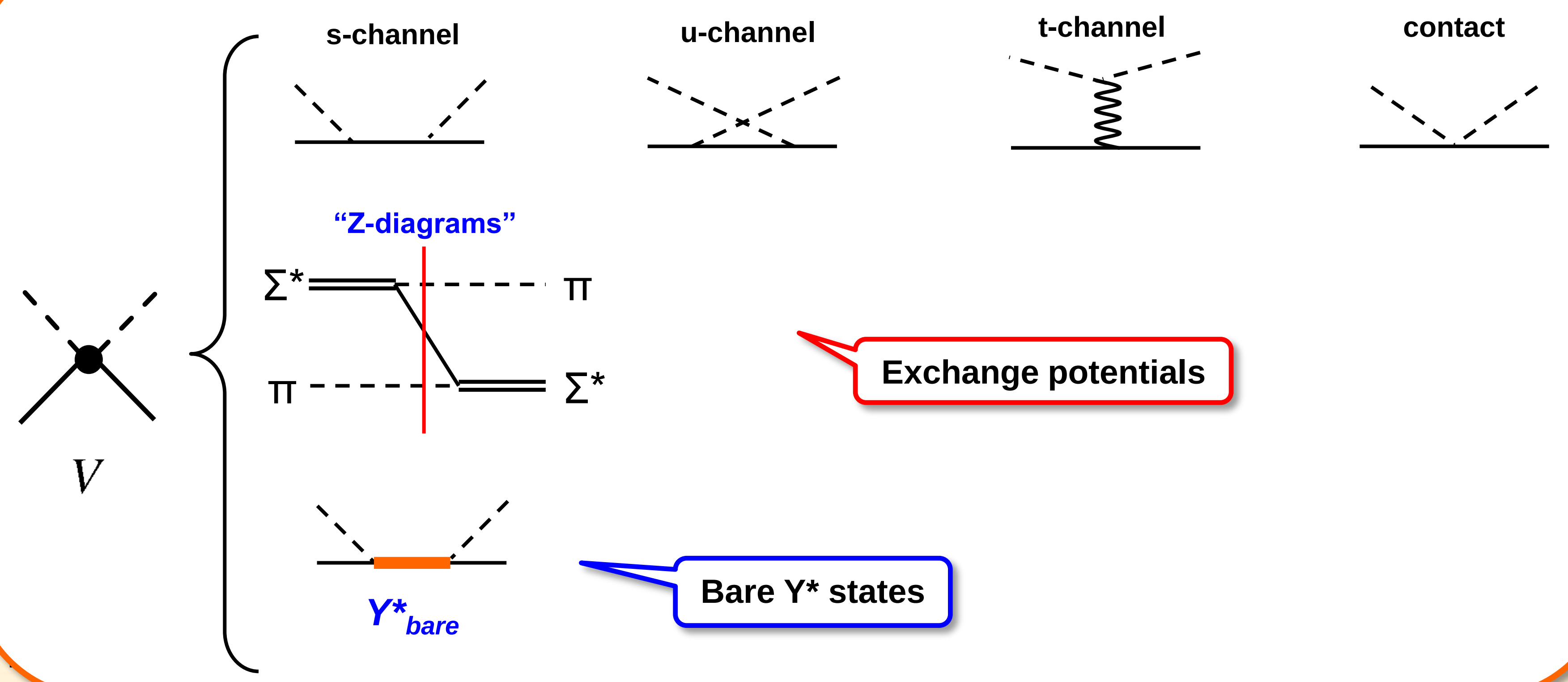
$$MB = \pi\Sigma^*, \bar{K}^*N$$

Quasi 2-body channels



Dynamical coupled-channels (DCC) approach for Y* production reactions

HK, Nakamura, Lee, Sato, PRC90(2014)065204



Exchange potentials

Bare Y* states

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

Exchange potentials

Bare Y* states

Dynamical coupled-channels (DCC) approach for Y* production reactions

HK, Nakamura, Lee, Sato, PRC90(2014)065204

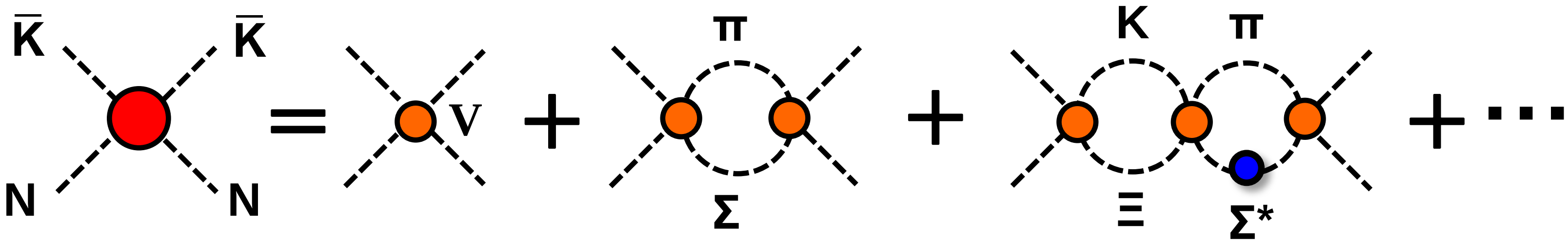
✓ **Coupled-channels integral equations for partial-wave amplitudes of a → b reaction:**

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

✓ **Reaction cha**

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

e.g.) $\bar{K}N$ scattering



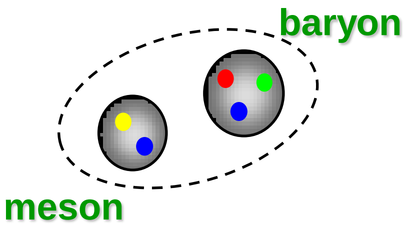
✓ **Momentum integral takes into account off-shell rescattering effects in the intermediate processes.**

Dynamical coupled-channels (DCC) approach for Y* production reactions

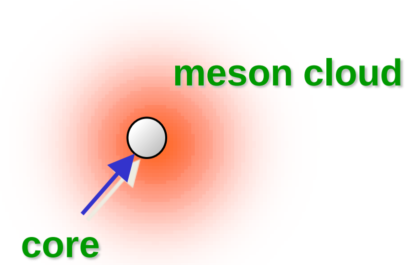
HK, Nakamura, Lee, Sato, PRC90(2014)065204

✓ Coupled-channels integral equations for partial-wave amplitudes of a → b reaction:

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



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



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

✓ Transition Potentials:

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

Exchange potentials

Bare Y* states

Why coupled-channels dynamics is important ??

Multichannel unitary condition for T-matrix elements:

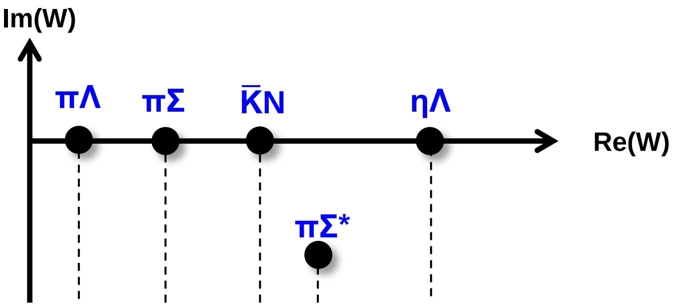
$$T_{ab}(E) - T^{\dagger}_{ab}(E) = -2\pi i \sum_{c} T^{\dagger}_{ac}\delta(E - E_c)T_{cb}(E)$$

1) Ensures "conservation of probabilities" in multichannel reaction processes

- **Key to comprehensive & simultaneous analysis of various reactions in a reliable way !!**

2) Ensures "proper analytic structure" for scattering amplitudes in the complex energy plane (branch points and cuts, etc.)

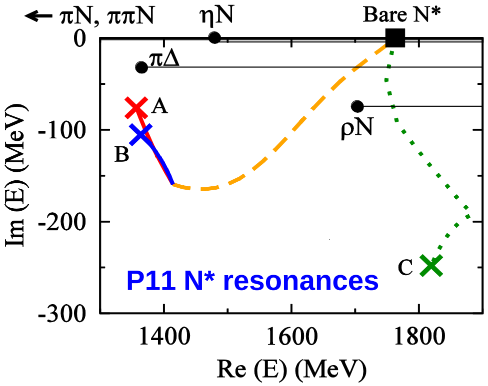
- **Without this, it is likely to get false resonance signals.**



3) Brings nontrivial features allowing ones to have new physics interpretations for various resonance properties

- **Dynamical origin of baryon resonances**

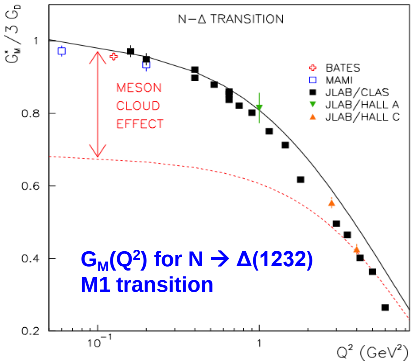
Suzuki, Julia-Diaz, HK, Lee, Matsuyama, Sato PRL104 065203 (2010)



P11 N* resonances

- **Meson cloud effects in form factors**

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



$G_M(Q^2)$ for N → Δ(1232) M1 transition

What we have done so far

With the dynamical coupled-channels approach developed for the S= -1 sector, we made:

- ✓ **Comprehensive analysis of *all* available data of $K^- p \rightarrow \bar{K}N, \pi\Sigma, \pi\Lambda, \eta\Lambda, K\Xi$ up to $W = 2.1$ GeV.**

  [HK, Nakamura, Lee, Sato, PRC90(2014)065204]

  - **Needs supercomputers to accomplish extensive coupled-channels analysis**

    NERSC Argonne NATIONAL LABORATORY

  - **Successfully determined the partial-wave amplitudes of $\bar{K}N \rightarrow \bar{K}N, \pi\Sigma, \pi\Lambda, \eta\Lambda, K\Xi$ for S, P, D, and F waves !!**

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

  [HK, Nakamura, Sato, arXiv:1506.01768 (to appear in PRC)]

Database of our analysis (W < 2.1GeV)

HK, Nakamura, Lee, Sato, PRC90(2014)065204

Issues in the availability of data:

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

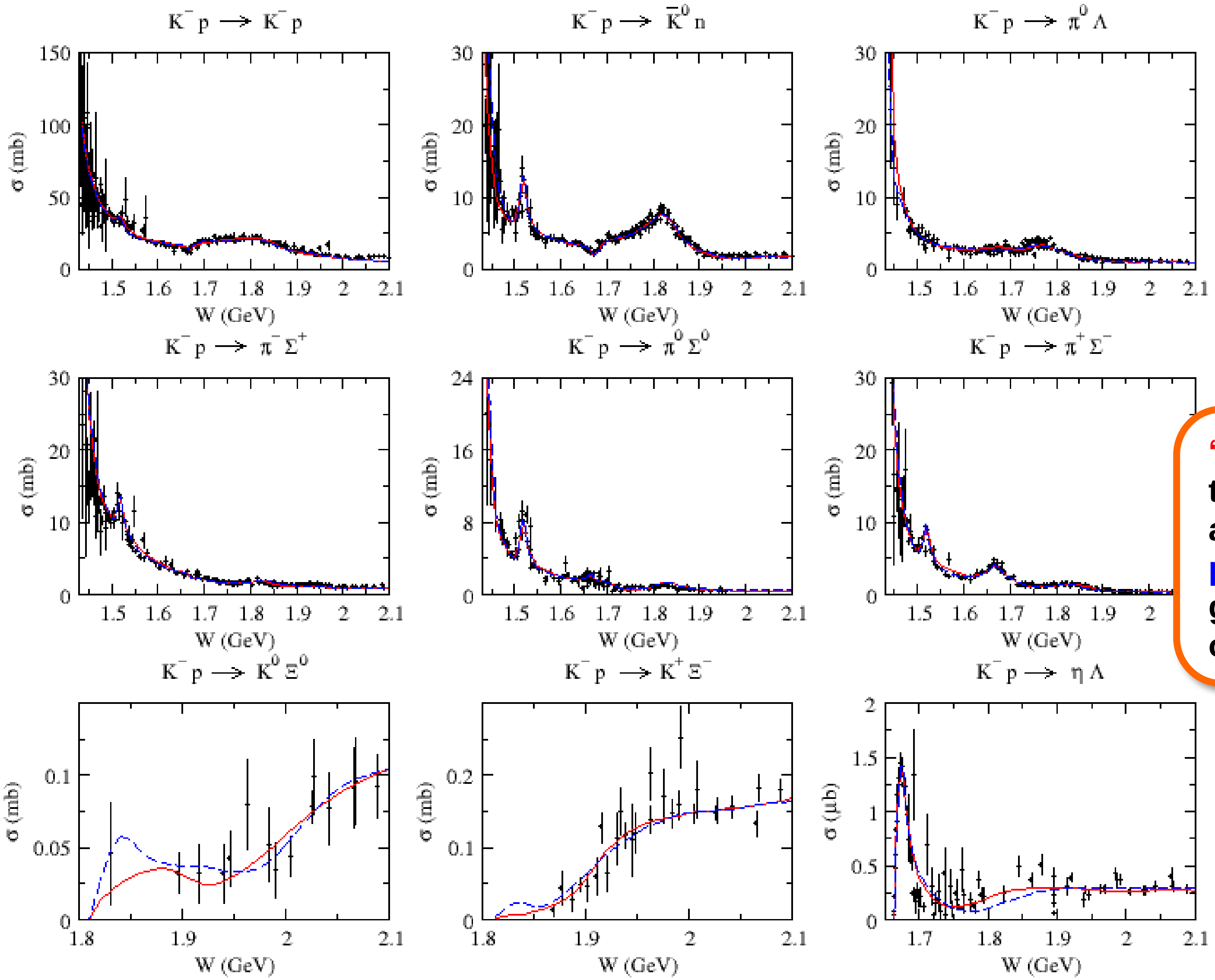
The K$^-$ p reaction data are far from "complete"!!
→ Need help of hadron beam facilities such as J-PARC !!

Reactions	Observables	Number of data	
$K^- p \to K^- p$	$d\sigma/d\Omega$	3962	$d\sigma/d\Omega$: 1465 MeV < W P : 1730 MeV < W β, R, A: No data
	P	510	
	σ	253	
$K^- p \to \bar{K}^0 n$	$d\sigma/d\Omega$	2950	$d\sigma/d\Omega$: 1465 MeV < W P : No data β, R, A: No data
	σ	260	
$K^- p \to \pi^- \Sigma^+$	$d\sigma/d\Omega$	1792	$d\sigma/d\Omega$: 1535 MeV < W P : 1535 MeV < W < 1967 MeV β, R, A: No data
	P	418	
	$P \times d\sigma/d\Omega$	177	
	σ	173	
$K^- p \to \pi^0 \Sigma^0$	$d\sigma/d\Omega$	580	$d\sigma/d\Omega$: 1535 MeV < W < 1763 MeV P : 1535 MeV < W < 1696 MeV β, R, A: No data
	P	196	
	$P \times d\sigma/d\Omega$	189	
	σ	125	
$K^- p \to \pi^+ \Sigma^-$	$d\sigma/d\Omega$	1786	$d\sigma/d\Omega$: 1536 MeV < W P : No data β, R, A: No data
	σ	181	
$K^- p \to \pi^0 \Lambda$	$d\sigma/d\Omega$	2178	$d\sigma/d\Omega$: 1535 MeV < W P : 1535 MeV < W β, R, A: No data
	P	693	
	$P \times d\sigma/d\Omega$	176	
	σ	207	
$K^- p \to \eta \Lambda$	$d\sigma/d\Omega$	160	$d\sigma/d\Omega$: 1664 MeV < W < 1696 MeV P : 1669 MeV < W < 1681 MeV β, R, A: No data
	P	18	
	σ	78	
$K^- p \to K^0 \Xi^0$	$d\sigma/d\Omega$	33	$d\sigma/d\Omega$: 1970 MeV < W < 2070 MeV P : No data β, R, A: No data
	σ	15	
$K^- p \to K^+ \Xi^-$	$d\sigma/d\Omega$	92	$d\sigma/d\Omega$: 1950 MeV < W < 2070 MeV P : No data β, R, A: No data
	σ	27	
Total		17229	

Results of the fits

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

HK, Nakamura, Lee, Sato, PRC90(2014)065204



Red: Model A

Blue: Model B

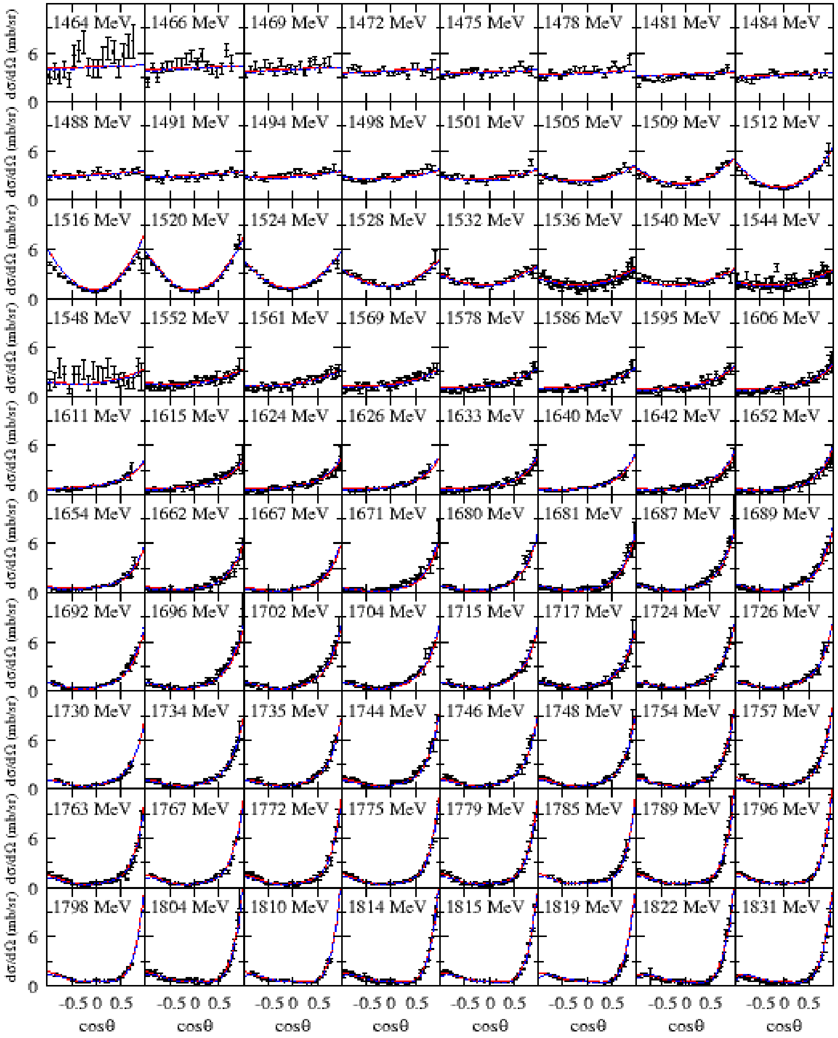
"Incompleteness" of the current database allows us to have two parameter sets that give similar quality of the fit.

Results of the fits

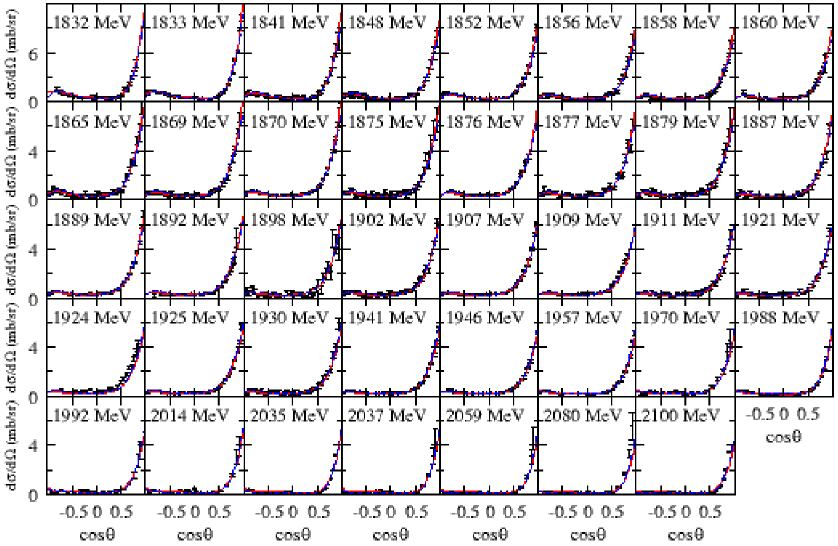
$K^- p \rightarrow K^- p$ scattering

HK, Nakamura, Lee, Sato, PRC90(2014)065204

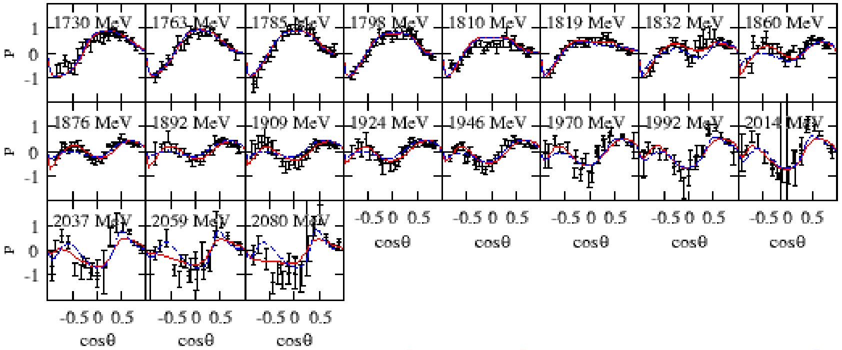
dσ/dΩ (1464 < W < 1831 MeV)



dσ/dΩ (1832 < W < 2100 MeV)



P



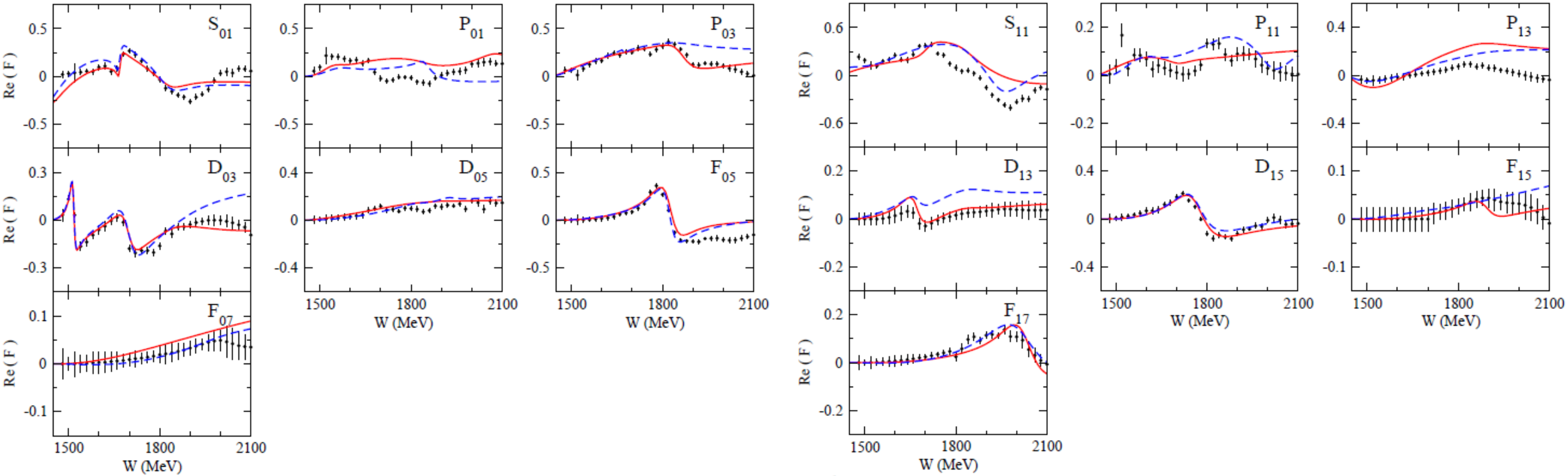
Red: Model A Blue: Model B

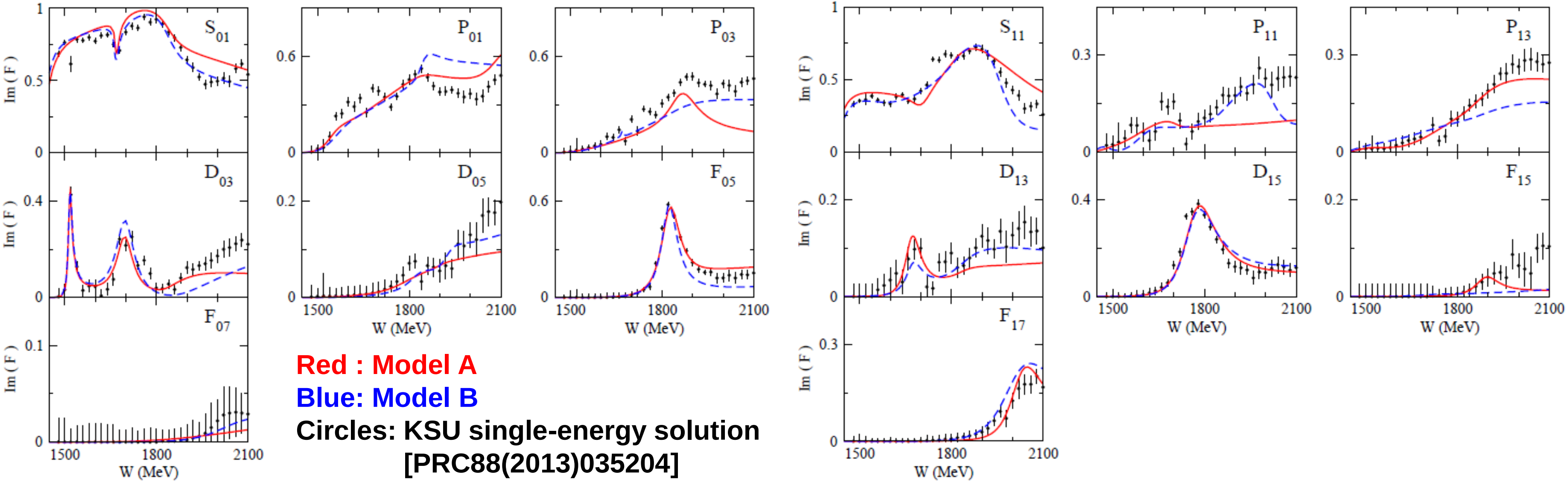
Comparison of extracted partial-wave amplitudes

Extracted $\bar{K}N$ scattering amplitudes

HK, Nakamura, Lee, Sato, PRC90(2014)065204

$L_{I\,2J}$: L = S, P, .. ; I = isospin; J = total angular mom.





Red : Model A

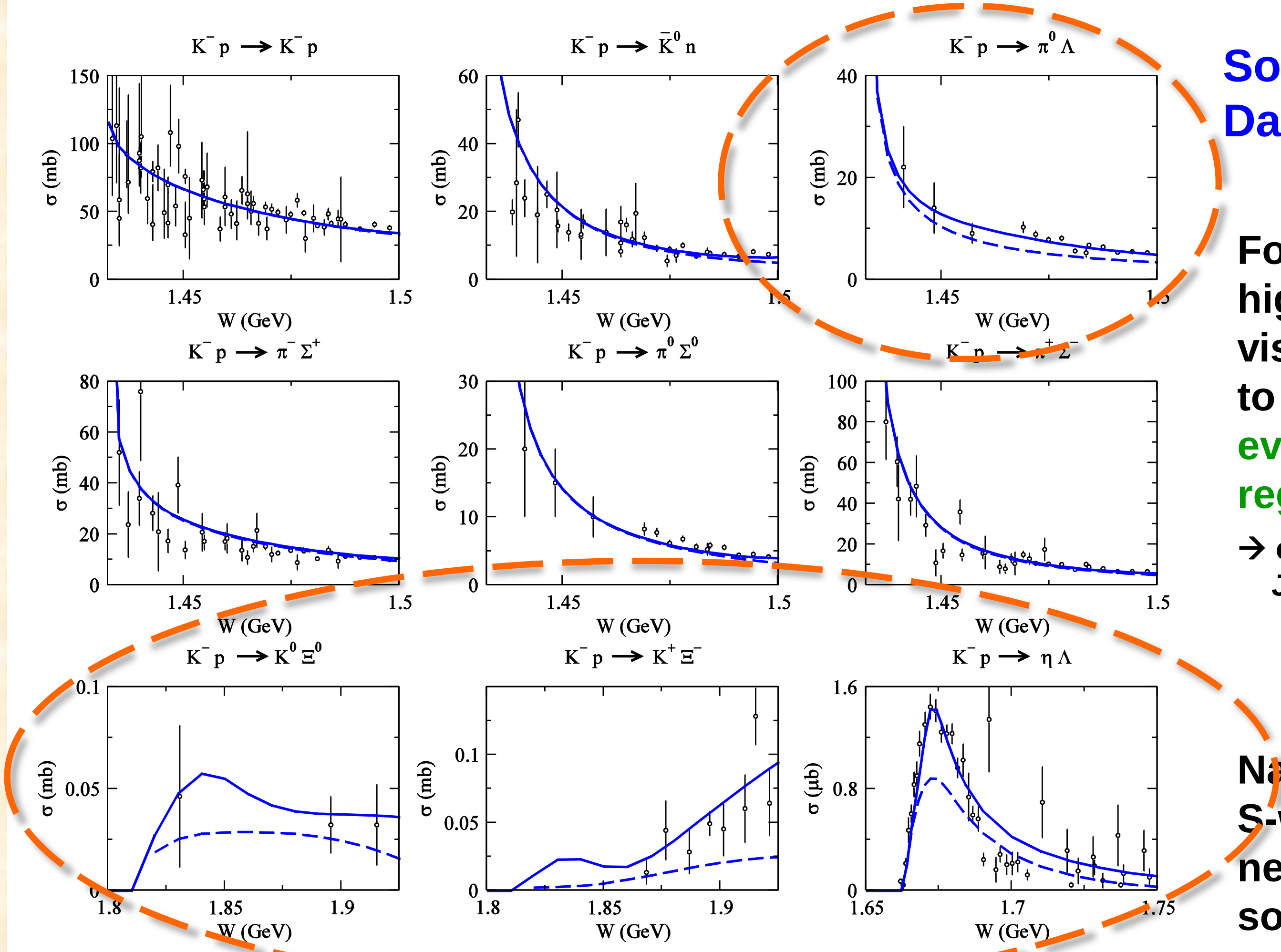
Blue: Model B

Circles: KSU single-energy solution [PRC88(2013)035204]

S-wave dominance ??

K^- p → MB total cross sections near threshold

Model B



Solid: Full
Dashed: S wave only

For K- p → πΛ, ηΛ, KΞ, higher partial waves visibly contribute to the cross sections even in the threshold region.

→ consistent with the observation in Jackson et al., PRC91(2015)065208

Naïve expectation for S-wave dominance near the threshold sometimes does not hold !!

HK, Nakamura, Lee, Sato, PRC90(2014)065204

Extracting Y* resonance parameters

Definitions of

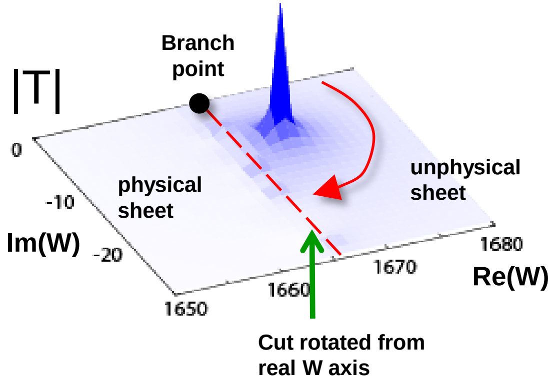
- ✓ **Y* masses (spectrum)** ➔ **Pole positions of the amplitudes**
- ✓ **Y* → MB coupling constants** ➔ **Residues$^{1/2}$ at the pole**

Y* → b coupling constant

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

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

Analytic continuation to complex energy plane:



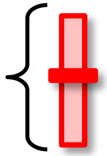
Suzuki, Sato, Lee PRC79(2009)025205; 82(2010)045206

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

Extracted Λ* and Σ* mass spectrum

HK, Nakamura, Lee, Sato, arXiv:1506.01768

Spectrum for Y* resonances found above the $\bar{K}N$ threshold



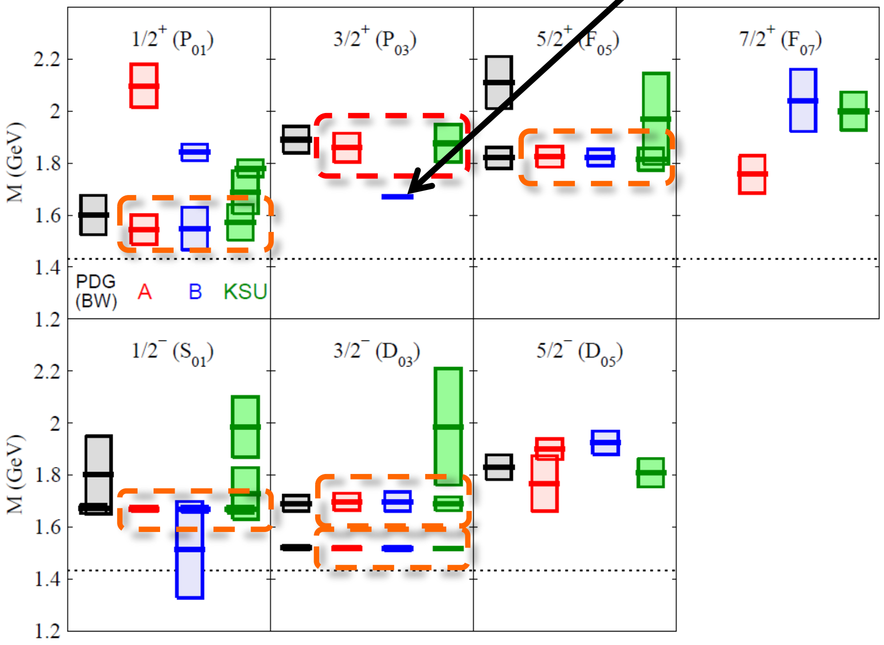
-2Im(M_R) (“width”)

Re(M_R)

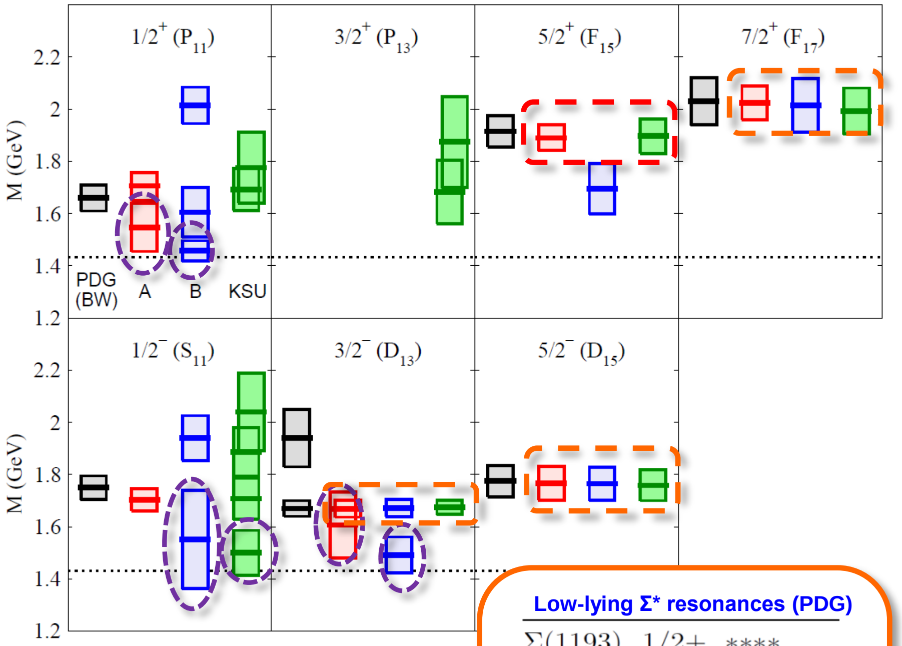
M_R : Resonance pole mass (complex)

New narrow $3/2^+$ resonance
M = 1671 – 5i MeV
near the ηΛ threshold !!

$J^P(L_{I\,2J})$ “Λ” resonance (I=0)



$J^P(L_{I\,2J})$ “Σ” resonance (I=1)



Red: Model A, Blue: Model B,
Green: KSU, Black: PDG(Breit-Wigner)

Low-lying Σ* resonances (PDG)

Σ(1193)	1/2+	****
Σ(1385)	3/2+	****
Σ(1480)		*
Σ(1560)		**
Σ(1580)	3/2−	*
Σ(1620)	1/2−	**
Σ(1660)	1/2+	***
Σ(1670)	3/2−	****

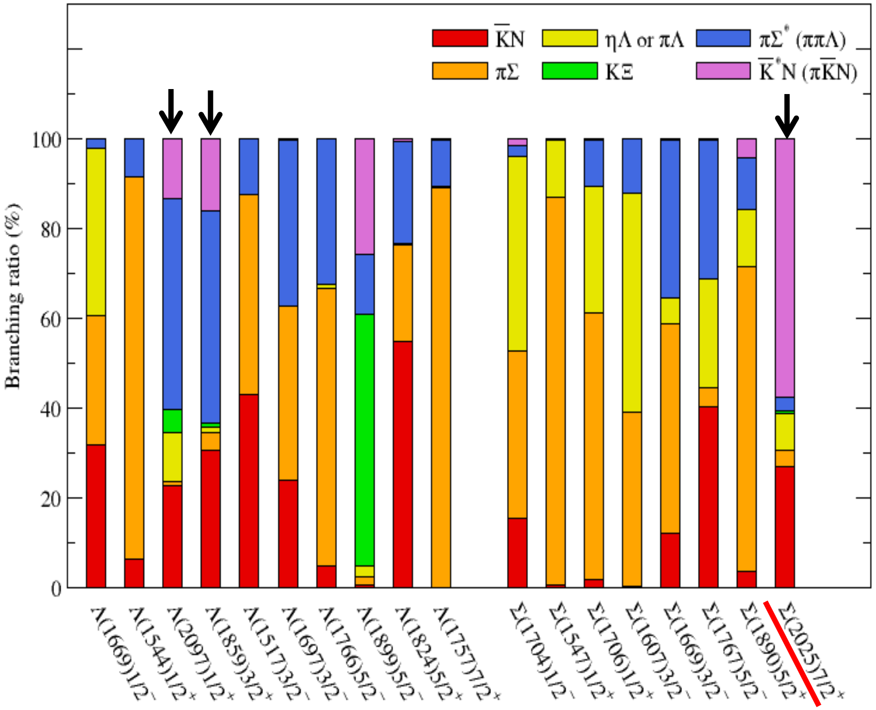
?

Branching ratios

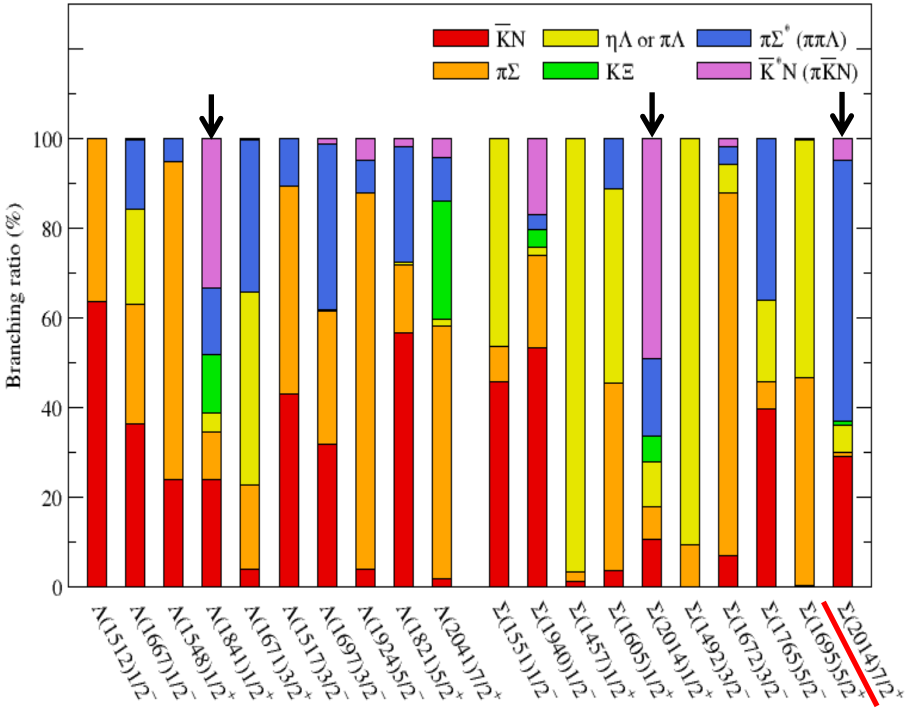
- ✓ **High-mass Y* have large branching ratio to $\pi\Sigma^*$ ($\pi\pi\Lambda$) & $\bar{K}^*N$ ($\pi\bar{K}N$)**
  - ➢ **$K^- p \rightarrow \pi\pi\Lambda$, $\pi\bar{K}N$ data would play a crucial role for establishing high-mass Y*.**

    ➔ Similar to high-mass N* and Δ* case, where ππN channel plays a crucial role.
    (e.g., measurement of πN → ππN reactions at J-PARC E45)

Model A



Model B



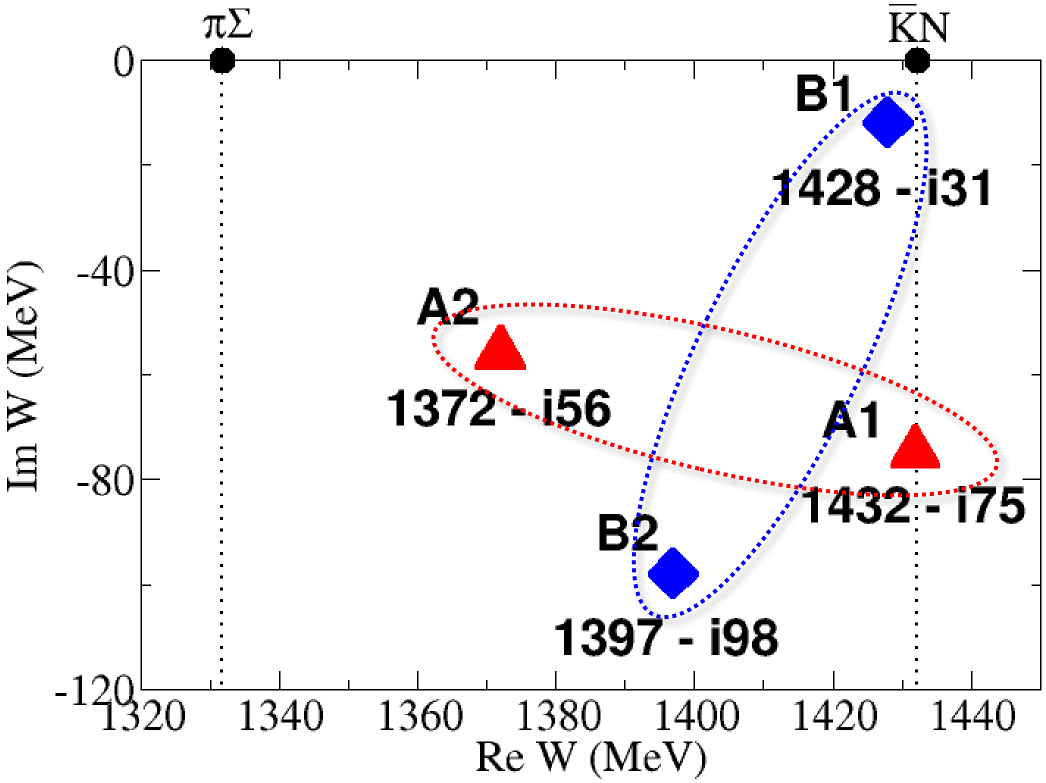
HK, Nakamura, Lee, Sato, arXiv:1506.01768

S-wave resonances below $\bar{K}N$ threshold from the current analysis

HK, Nakamura, Lee, Sato, arXiv:1506.01768

 # NOTE: Further extensive analysis including the data below $\bar{K}N$ threshold is necessary to have *conclusive* results for the $\bar{K}N$ subthreshold region.

“Predicted” Λ* (J^P = 1/2-) resonance poles below $\bar{K}N$ threshold



- ✓ **Two resonance poles are found in both Models A and B.**
  - ➢ **A1 & B1 seem correspond to Λ(1405)**
  - ➢ **Another Λ resonance with mass 30-60 MeV lower than Λ(1405) (A2 & B2) is also found to exist.**

Red triangles: Model A
Blue diamonds: Model B

Summary

✓ **Comprehensive analysis of $K^- p \rightarrow \bar{K}N, \pi\Sigma, \pi\Lambda, \eta\Lambda, K\Xi$ up to W = 2.1 GeV has been accomplished for the first time within a dynamical coupled-channels approach.**

✓ **Partial-wave (S, P, D, and F) amplitudes & Λ^* and Σ^* resonance parameters (pole mass, width,…) have been successfully extracted.**

Visible analysis dependence exits in extracted resonance parameters ➡ **Lack of the K- p reaction data for**

- **polarization observables (P and β, R, A)**
- **the $\bar{K}N$ threshold region**
- **3-body ($\pi\pi\Lambda$, $\pi\bar{K}N$, …) production reaction**
- **…**

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