Establishing mass spectrum of S=-1 hyperon resonances via a dynamical coupled-channels analysis of $K^- p$ reactions

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In collaboration with
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[HK, Nakamura, Lee, Sato, PRC90(2014)065204; PRC92(2015)025205]

HYP2015, Tohoku University, Sendai, Japan, September 7-12, 2015

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

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

For example:

- ➢ **Even low-lying resonances are not well determined.**

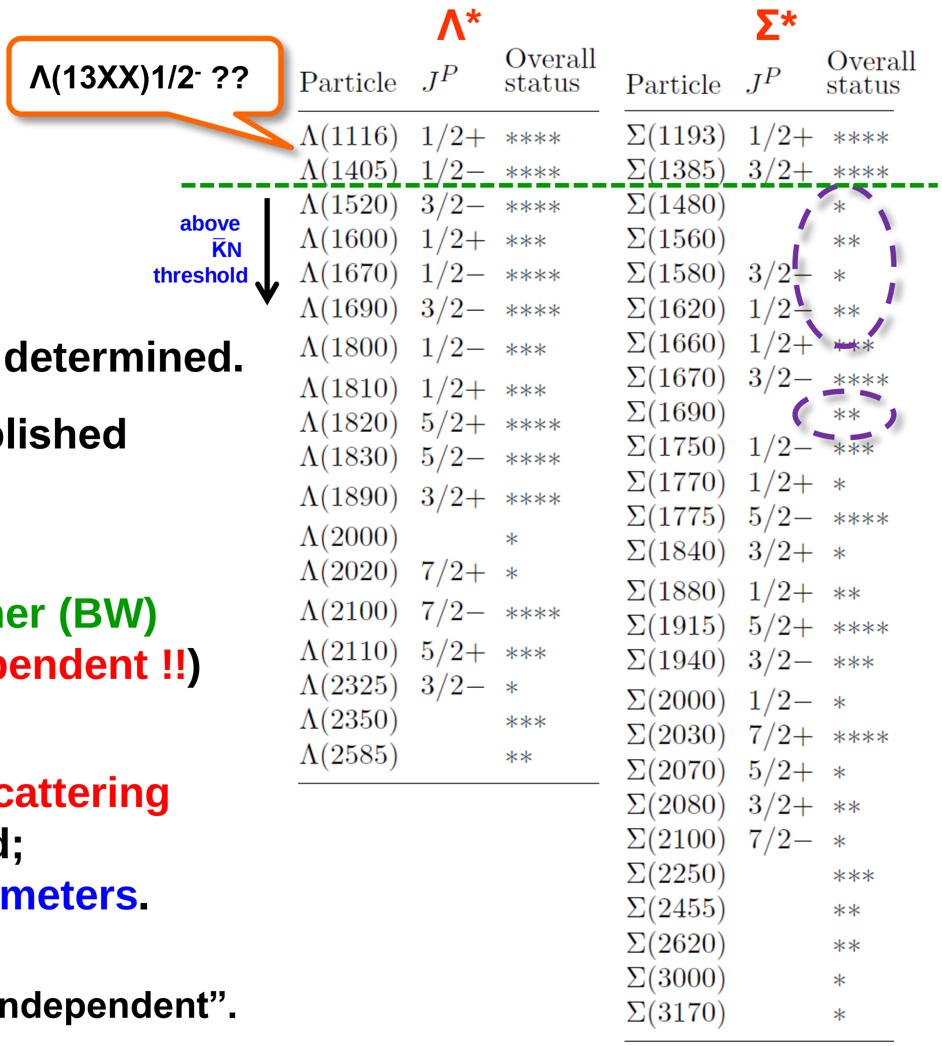
  ➔ N* & Δ* spectra are very well established up to $M_R <\sim 1.8$ GeV.

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

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

NOTE: Pole parameters should be "model-independent".

PDG listing



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 analyses of K^- p reactions to extract Y* *defined by poles* have 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; 92(2015)025205

PDG listing

$\Lambda(13XX)1/2^-$??

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+	***
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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)		*

Dynamical Coupled-Channels (DCC) approach to Λ* & Σ* productions

Dynamical Coupled-Channels (DCC) model:

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

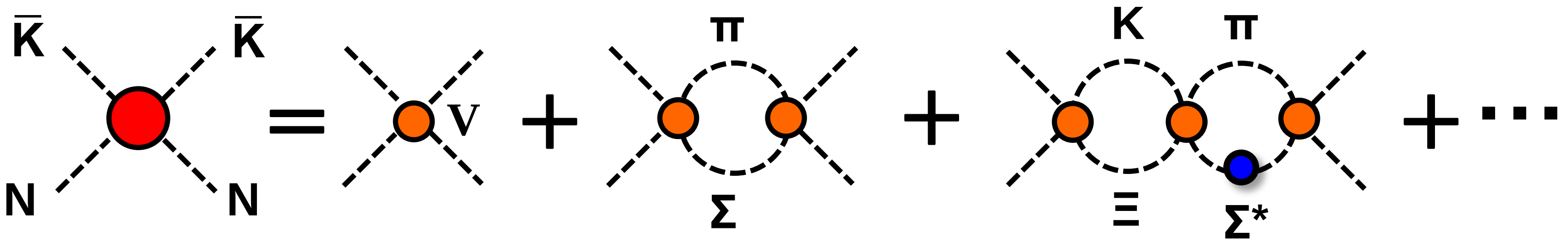
$$T^{(LSJ)}_{a,b}(p_a,p_b;E) = V^{(LSJ)}_{a,b}(p_a,p_b;E) + \underbrace{\sum_c}_{\text{CC effect}} \underbrace{\int_0^\infty q^2 dq}_{\text{off-shell effect}} V^{(LSJ)}_{a,c}(p_a,q;E)G_c(q;E)T^{(LSJ)}_{c,b}(q,p_b;E)$$

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

quasi two-body channels of
three-body ππΛ & πK̄N

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

e.g.) K̄N scattering



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

What we have done so far

With the DCC approach developed for the S= -1 sector, we made:

Supercomputers are necessary for the analysis !!

NERSC

Argonne NATIONAL LABORATORY

- ✓ **Comprehensive analysis of *ALL* available data (more than 17,000 data points) 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]

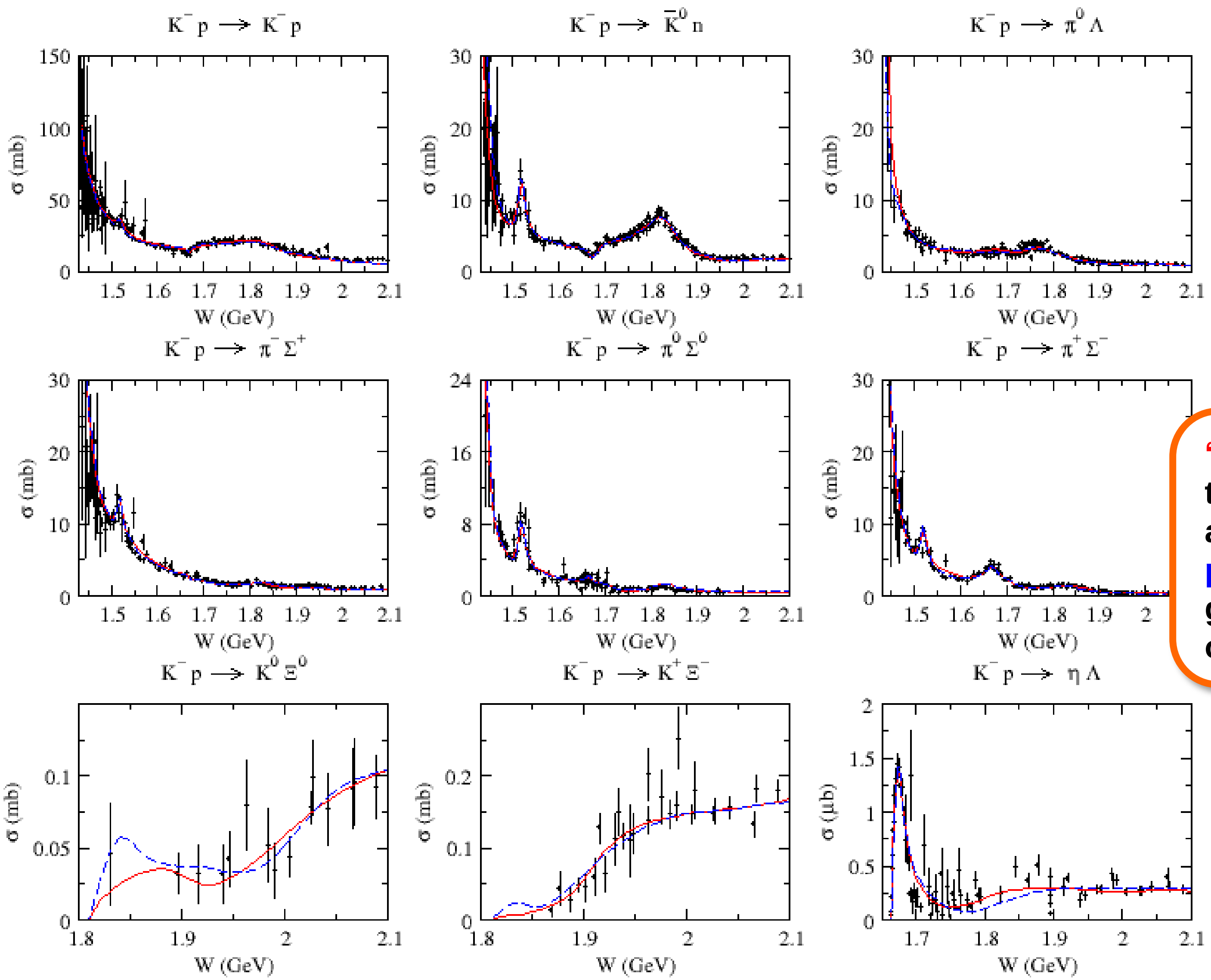
- ✓ **Determination of threshold parameters (scattering lengths, effective ranges,…); the partial-wave amplitudes of $\bar{K}N \rightarrow \bar{K}N, \pi\Sigma, \pi\Lambda, \eta\Lambda, K\Xi$ for S, P, D, and F waves.**
  [HK, Nakamura, Lee, Sato, PRC90(2014)065204]

- ✓ **Extraction of $Y^* = (\Lambda^*, \Sigma^*)$ resonance parameters (mass, width, couplings, …) defined by poles of scattering amplitudes.**
  [HK, Nakamura, Lee, Sato, PRC92(2015)025205]

Results of the fits

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

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



Red: Model A

Blue: Model B

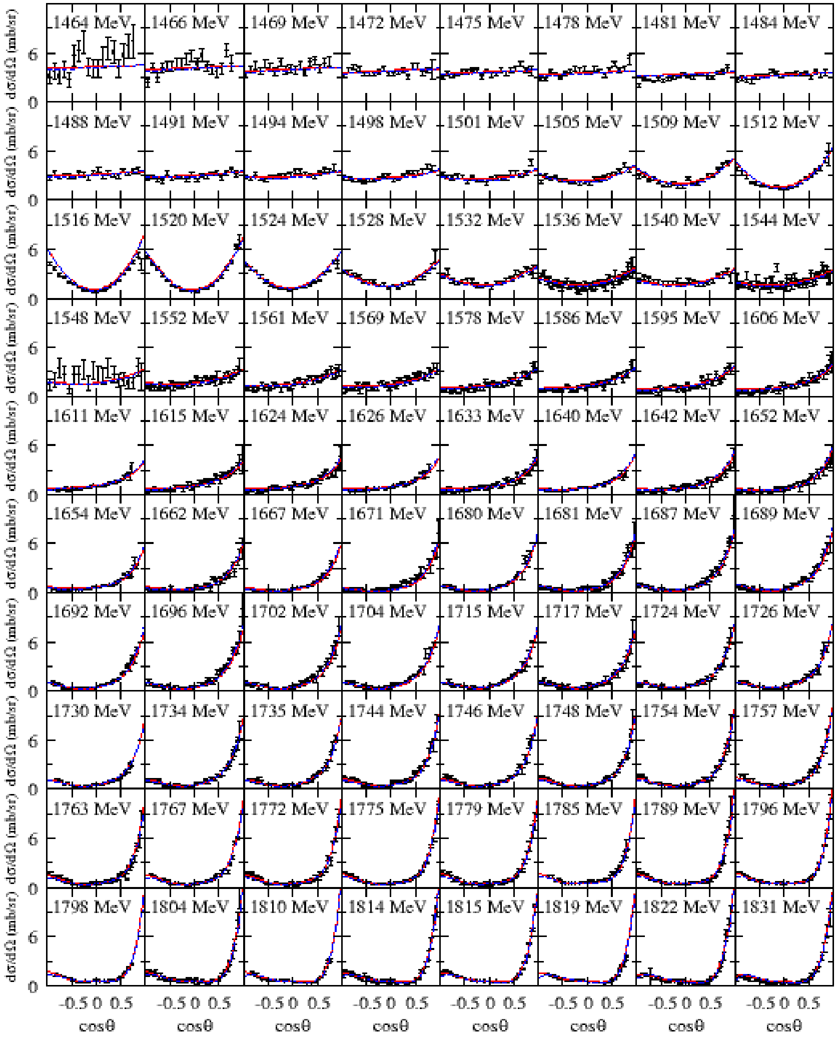
"Incompleteness" of the current database allows us to have two parameter sets that give similar quality of the fit.

Results of the fits

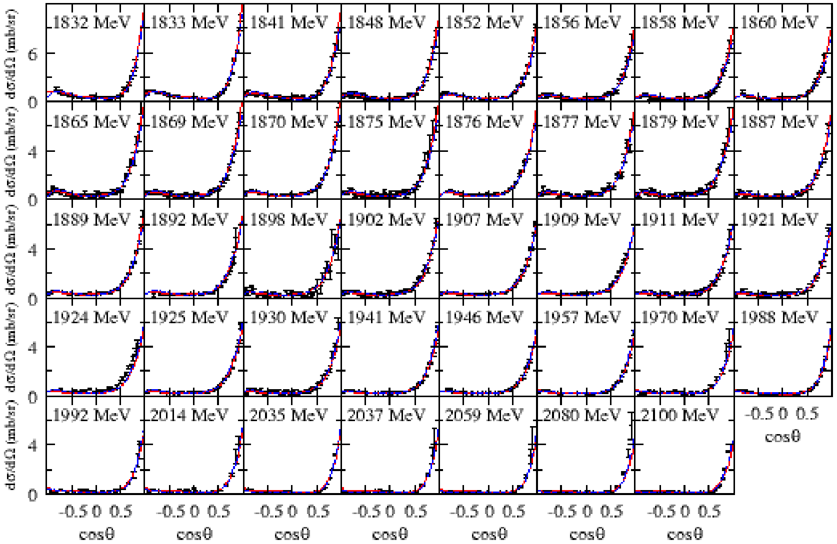
K$^-$ p → K$^-$ p scattering

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

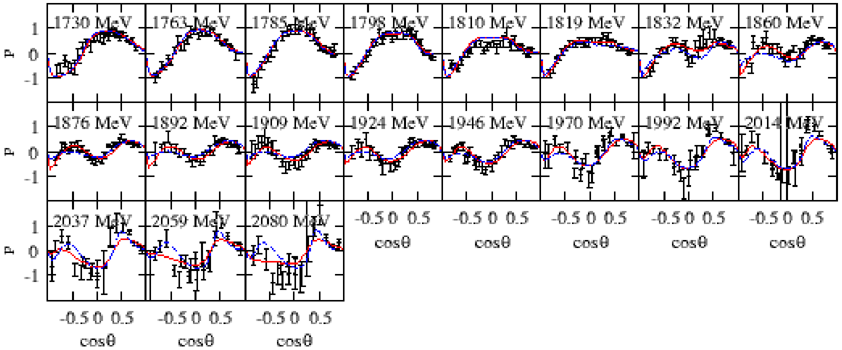
dσ/dΩ (1464 < W < 1831 MeV)



dσ/dΩ (1832 < W < 2100 MeV)



P (1730 < W < 2080 MeV)



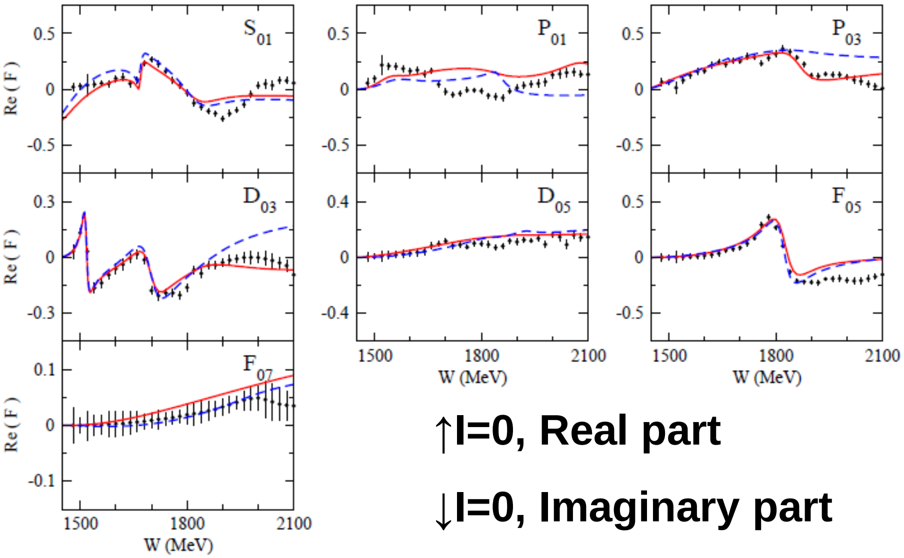
Red: Model A Blue: Model B

Comparison of extracted partial-wave amplitudes

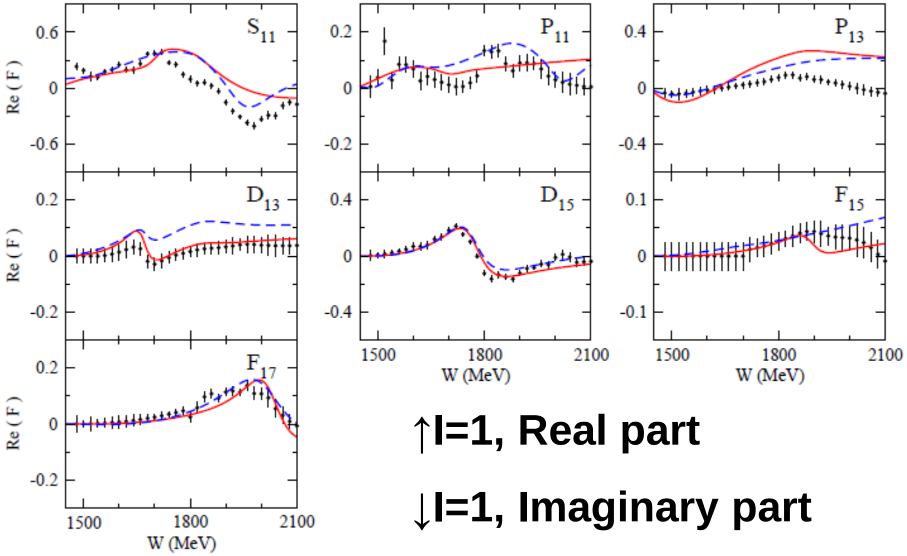
Extracted $\bar{K}N$ scattering amplitudes

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

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



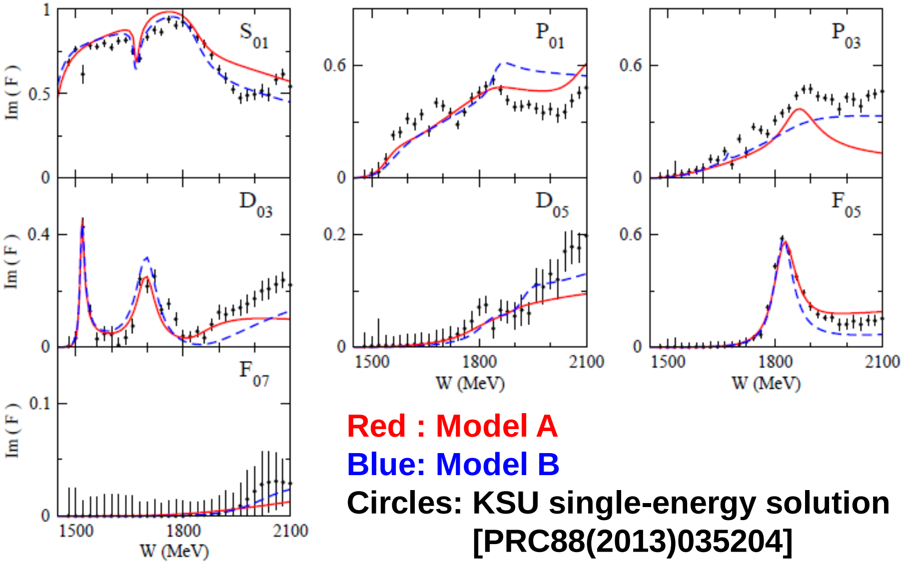
↑I=0, Real part

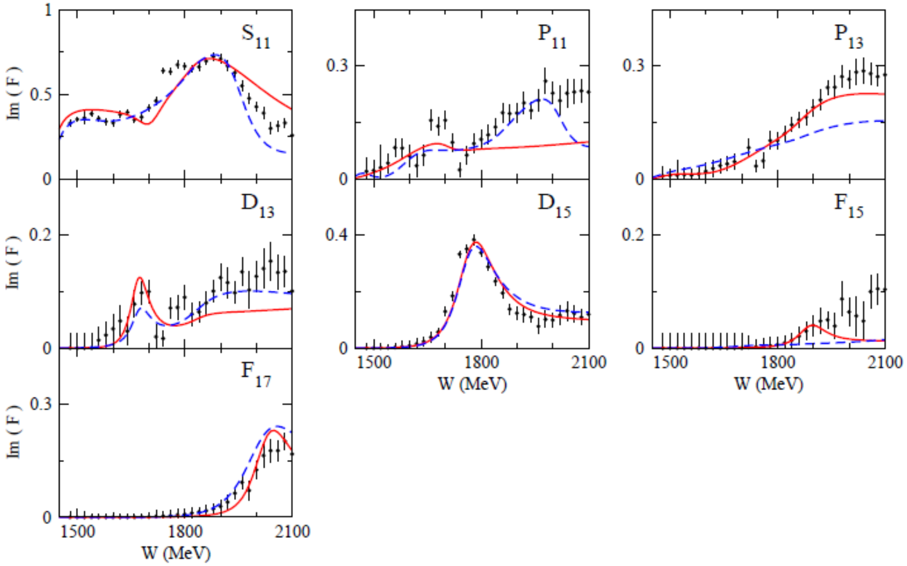


↑I=1, Real part

↓I=0, Imaginary part

↓I=1, Imaginary part





Red : Model A

Blue: Model B

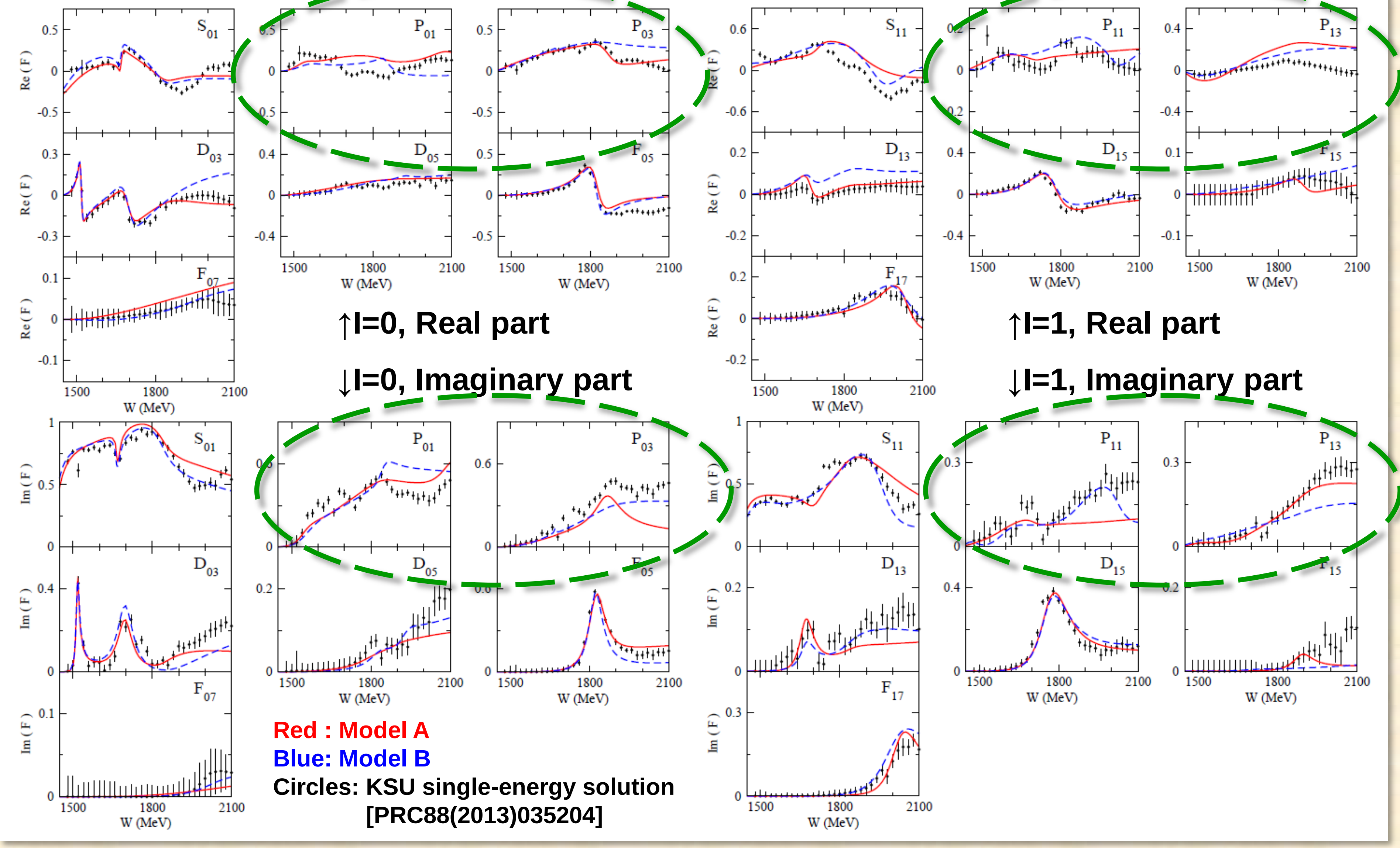
Circles: KSU single-energy solution [PRC88(2013)035204]

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.



↑I=0, Real part

↓I=0, Imaginary part

↑I=1, Real part

↓I=1, Imaginary part

Red : Model A

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

Comparison of extracted partial-wave amplitudes

Extracted $\bar{K}N$ scattering amplitudes

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

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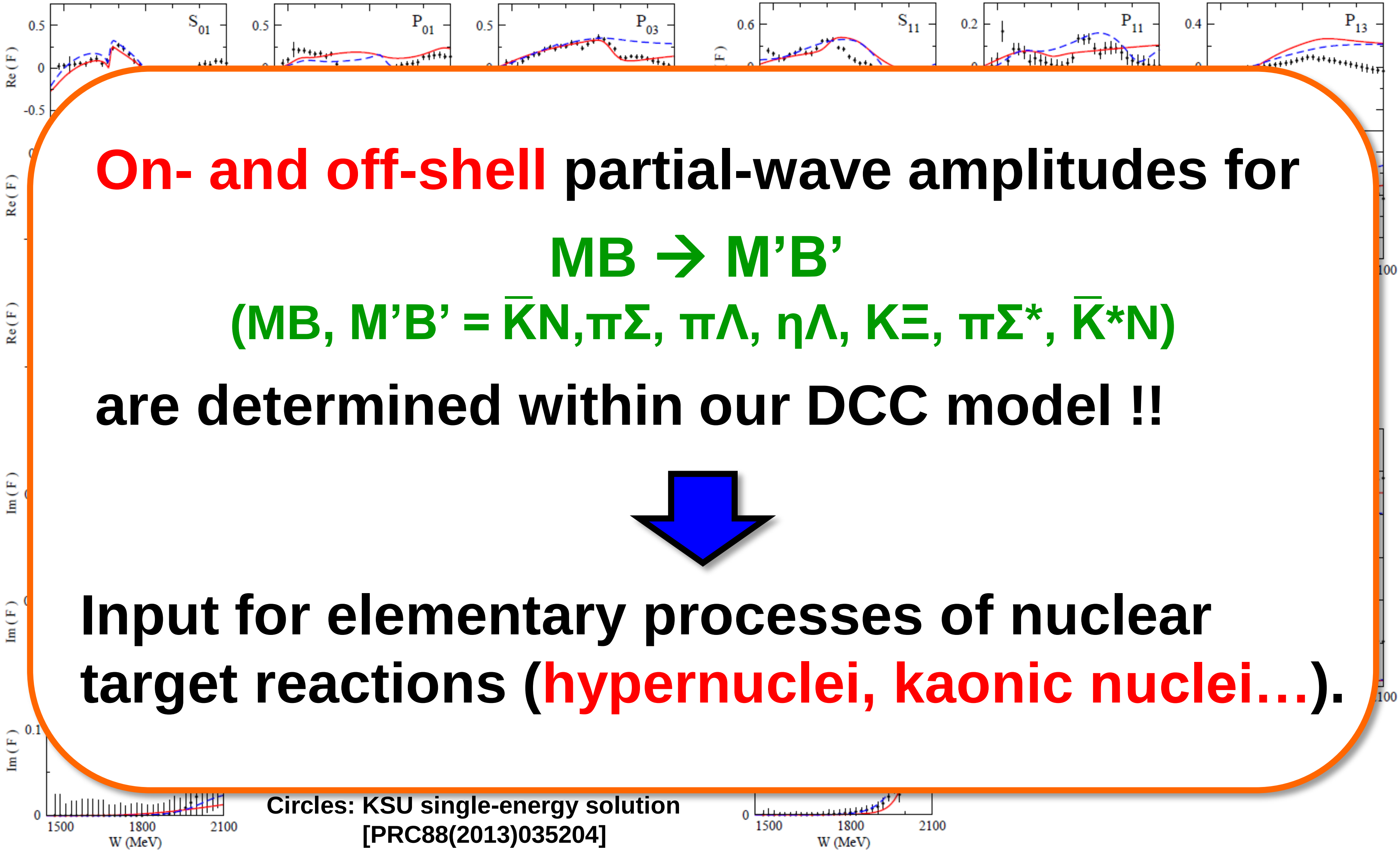


On- and off-shell partial-wave amplitudes for

MB → M'B'

(MB, M'B' = $\bar{K}N$,πΣ, πΛ, ηΛ, KΞ, πΣ*, $\bar{K}$*N)

are determined within our DCC model !!

Input for elementary processes of nuclear target reactions (hypernuclei, kaonic nuclei…).

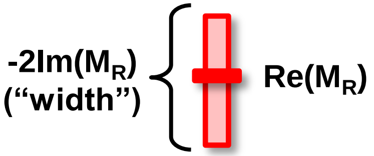
Circles: KSU single-energy solution [PRC88(2013)035204]

Extracted Λ* and Σ* mass spectrum

HK, Nakamura, Lee, Sato, PRC92(2015)025205

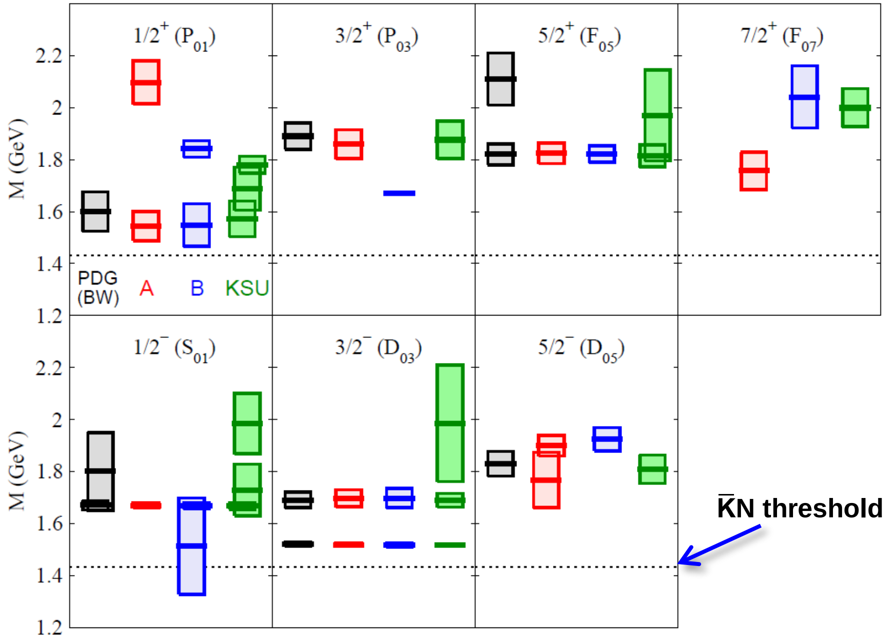
Spectrum for Y* resonances found above the $\bar{K}N$ threshold

Red: Model A
Blue: Model B
Green: KSU
Black: PDG (only 4- & 3-star Y*;
Breit-Wigner)

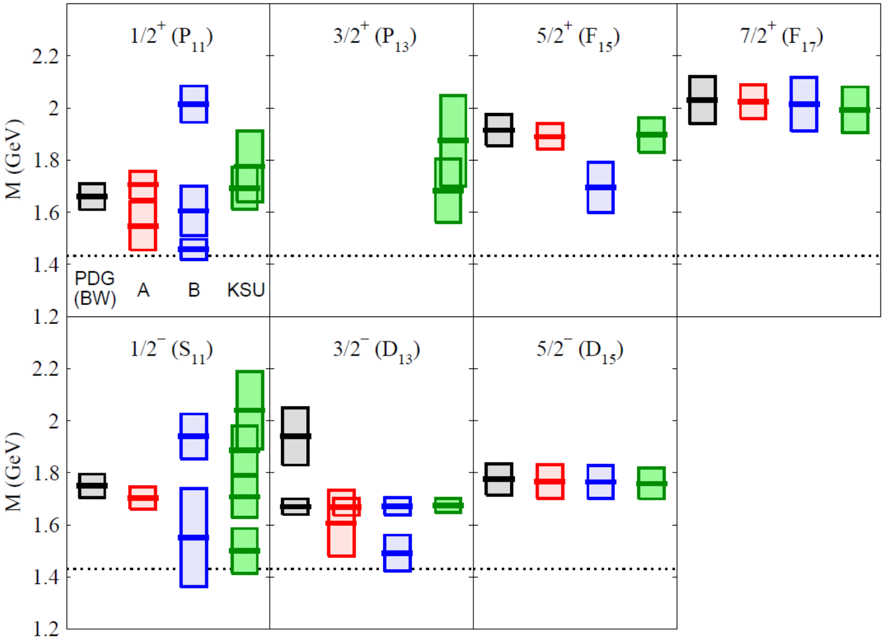


M_R : Resonance
pole mass
(complex)

$J^P(L_{I\,2J})$ "Λ" resonance (I=0)



$J^P(L_{I\,2J})$ "Σ" resonance (I=1)



Extracted Λ* and Σ* mass spectrum

HK, Nakamura, Lee, Sato, PRC92(2015)025205

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

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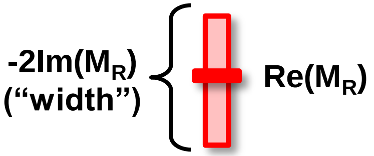
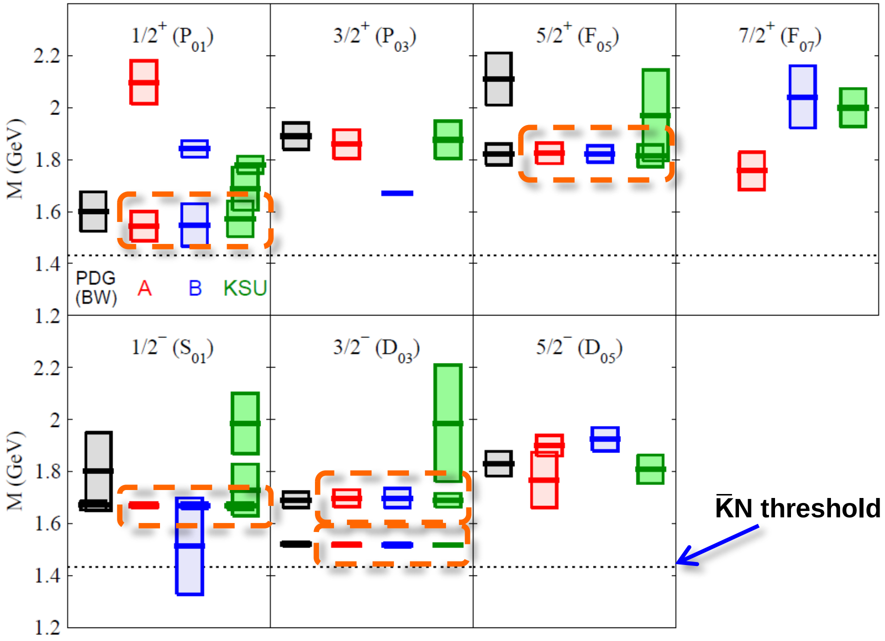
Breit-Wigner)

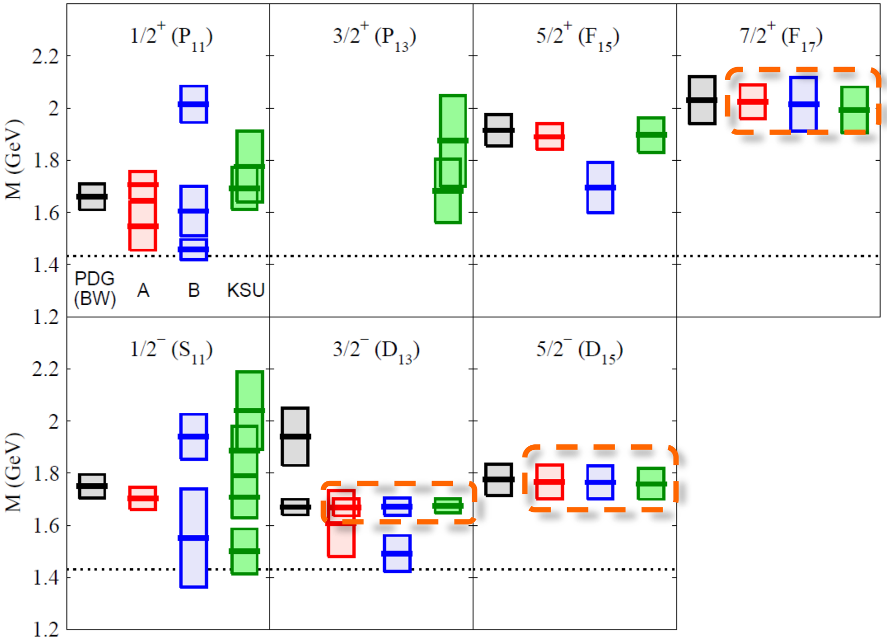


M_R : Resonance pole mass (complex)

$J^P(L_{I\,2J})$ "Λ" resonance (I=0)



$J^P(L_{I\,2J})$ "Σ" resonance (I=1)



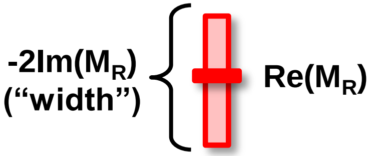
Extracted Λ* and Σ* mass spectrum

HK, Nakamura, Lee, Sato, PRC92(2015)025205

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

Red: Model A
Blue: Model B
Green: KSU
Black: PDG (only 4- & 3-star Y*; Breit-Wigner)

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

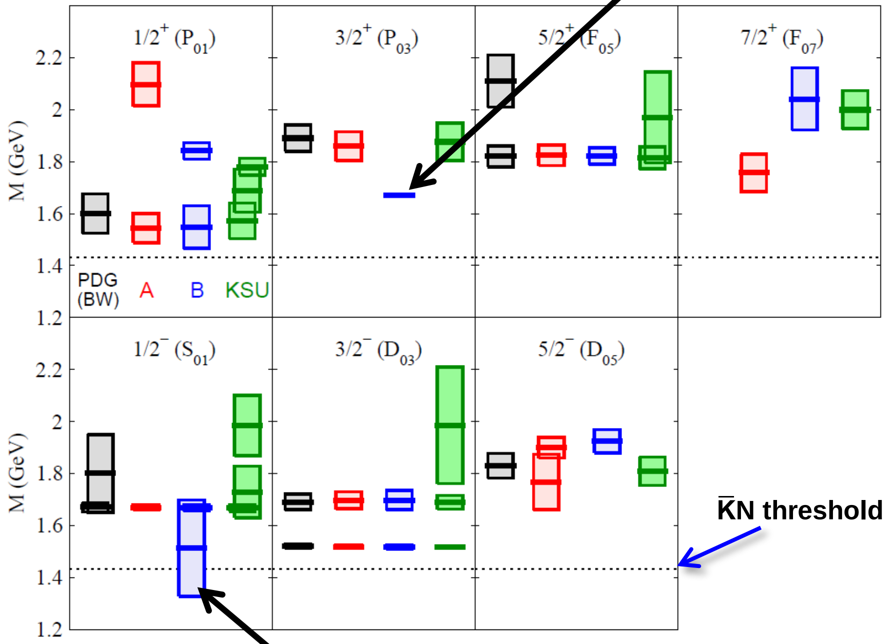


$-2\mathrm{Im}(M_R)$ (“width”)

$\mathrm{Re}(M_R)$

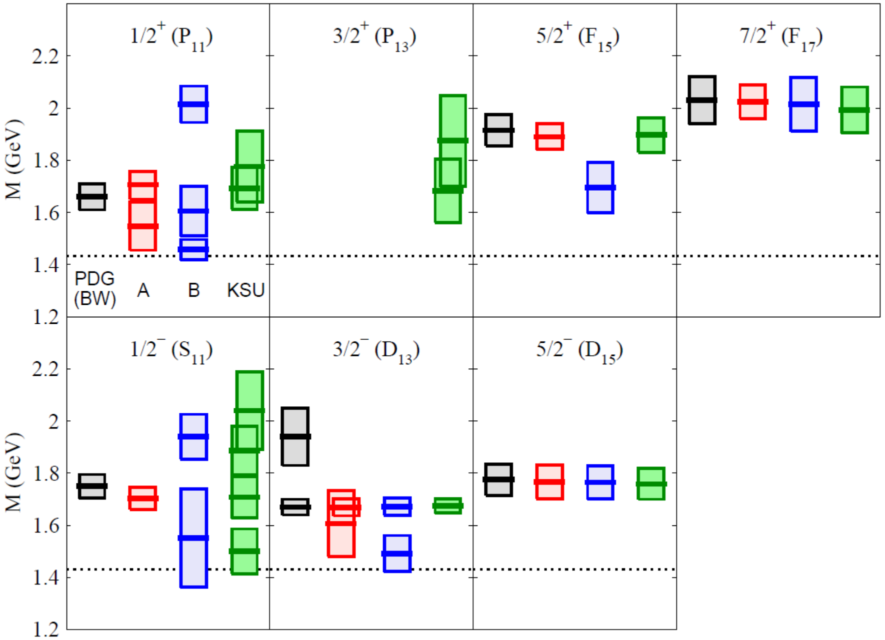
M_R : Resonance pole mass (complex)

$J^P(L_{I\,2J})$ “Λ” resonance (I=0)



$\bar{K}N$ threshold

$J^P(L_{I\,2J})$ “Σ” resonance (I=1)



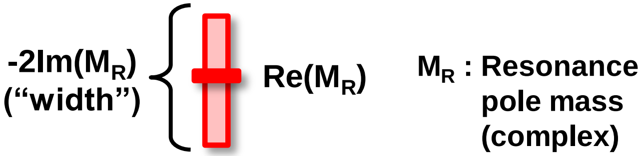
Spin partner of Λ(1520)3/2⁻ ??

Extracted Λ* and Σ* mass spectrum

HK, Nakamura, Lee, Sato, PRC92(2015)025205

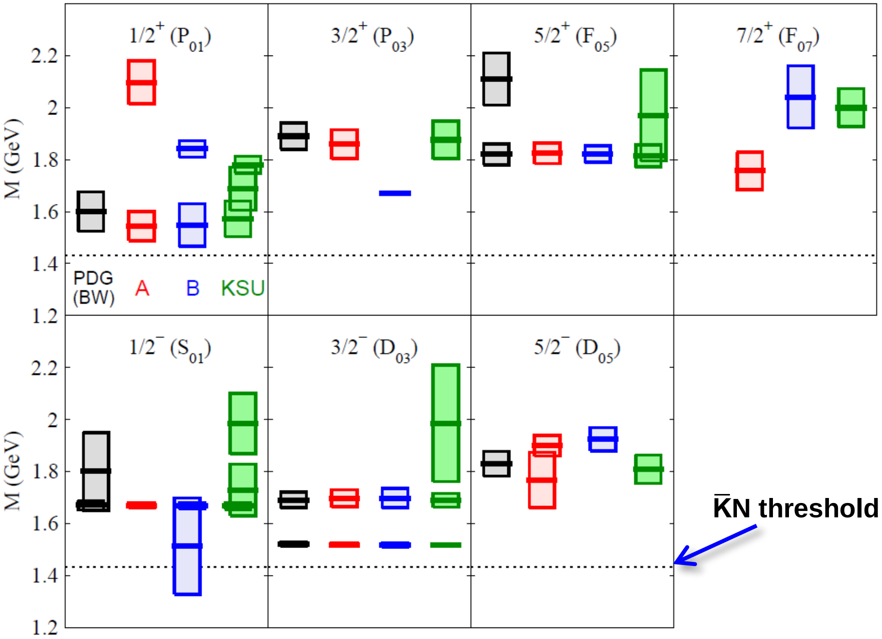
Spectrum for Y* resonances found above the K̄N threshold

Red: Model A
Blue: Model B
Green: KSU
Black: PDG (only 4- & 3-star Y*;
Breit-Wigner)



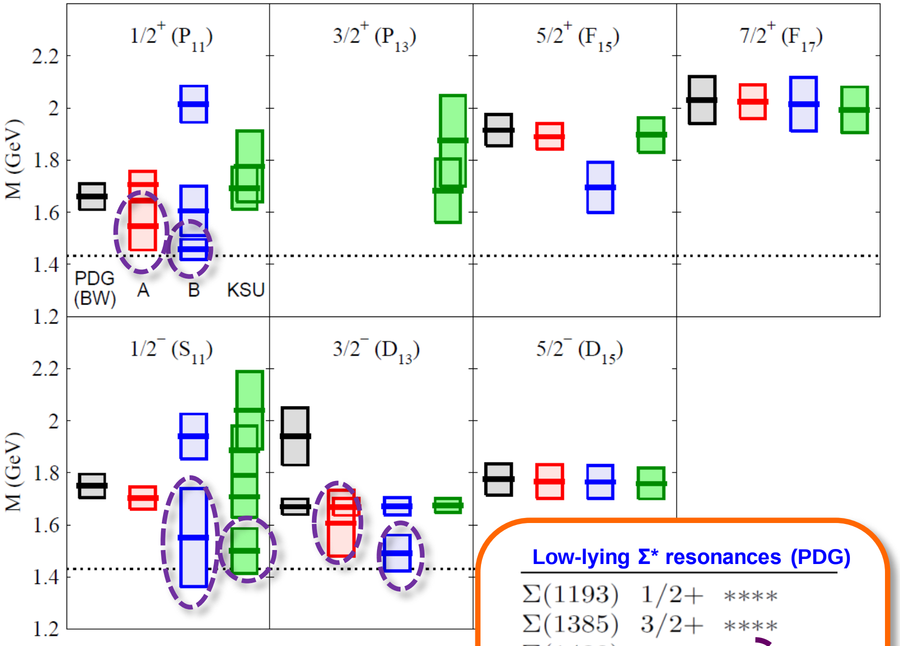
M_R : Resonance pole mass (complex)

$J^P(L_{I\,2J})$ "Λ" resonance (I=0)



K̄N threshold

$J^P(L_{I\,2J})$ "Σ" resonance (I=1)



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−	****

?

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 !!

Back up

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

HK, Nakamura, Lee, Sato, PRC92(2015)025205

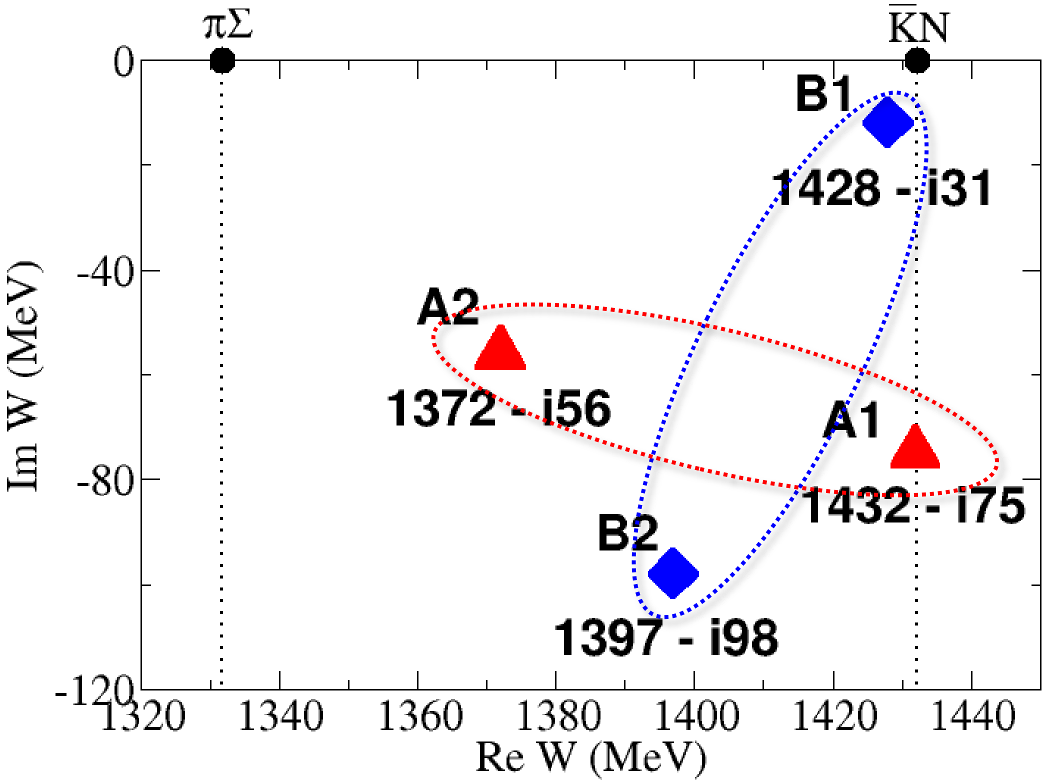
NOTE: Further extensive analysis including the data below $\bar{K}N$ threshold is necessary to have *conclusive* results for the $\bar{K}N$ subthreshold region.

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

HK, Nakamura, Lee, Sato, PRC92(2015)025205

 # 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.**

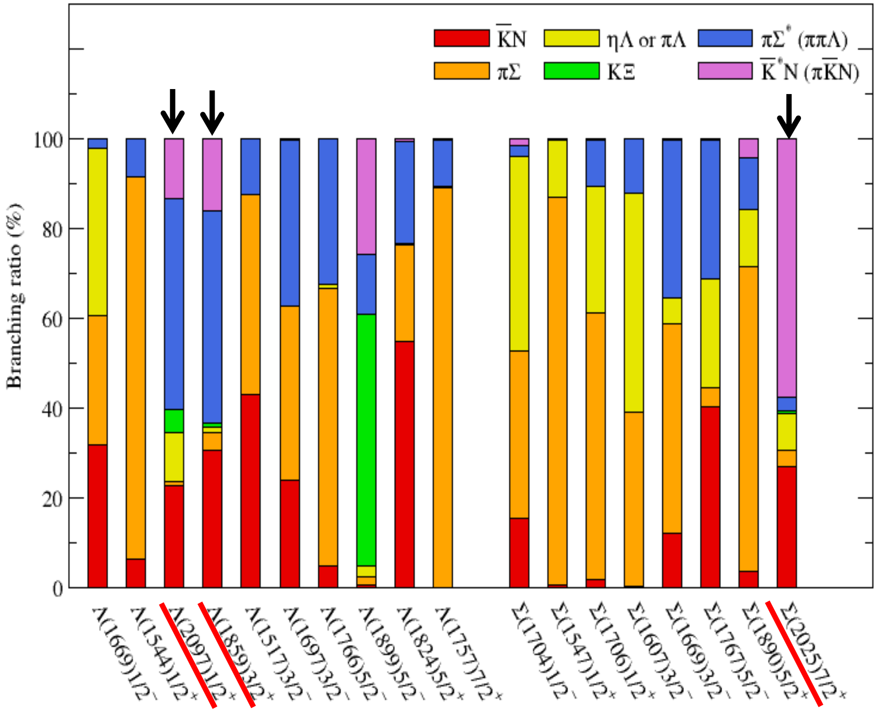
Red triangles: Model A
Blue diamonds: Model B

Importance of 2 → 3 reactions: Branching ratio high-mass Y* resonances

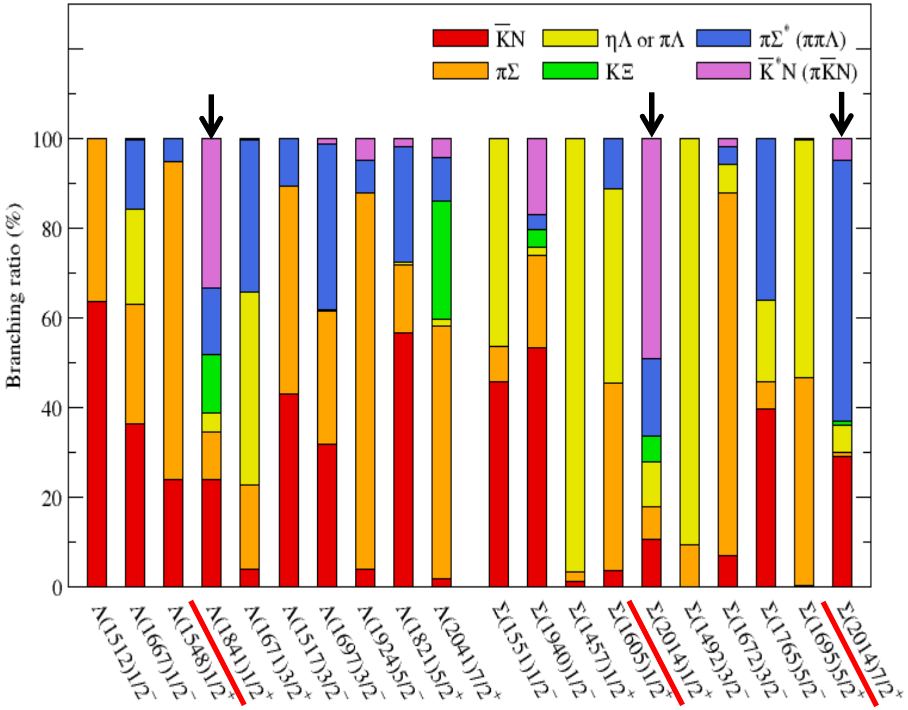
- ✓ **High-mass Y* have large branching ratio to $\pi\Sigma^*$ ($\pi\pi\Lambda$) & $\bar{K}^*N$ ($\pi\bar{K}N$)**
  - ➢ **$K^- p \to \pi\pi\Lambda, \pi\bar{K}N$ data would play a crucial role for establishing high-mass Y*.**

    ➔ 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

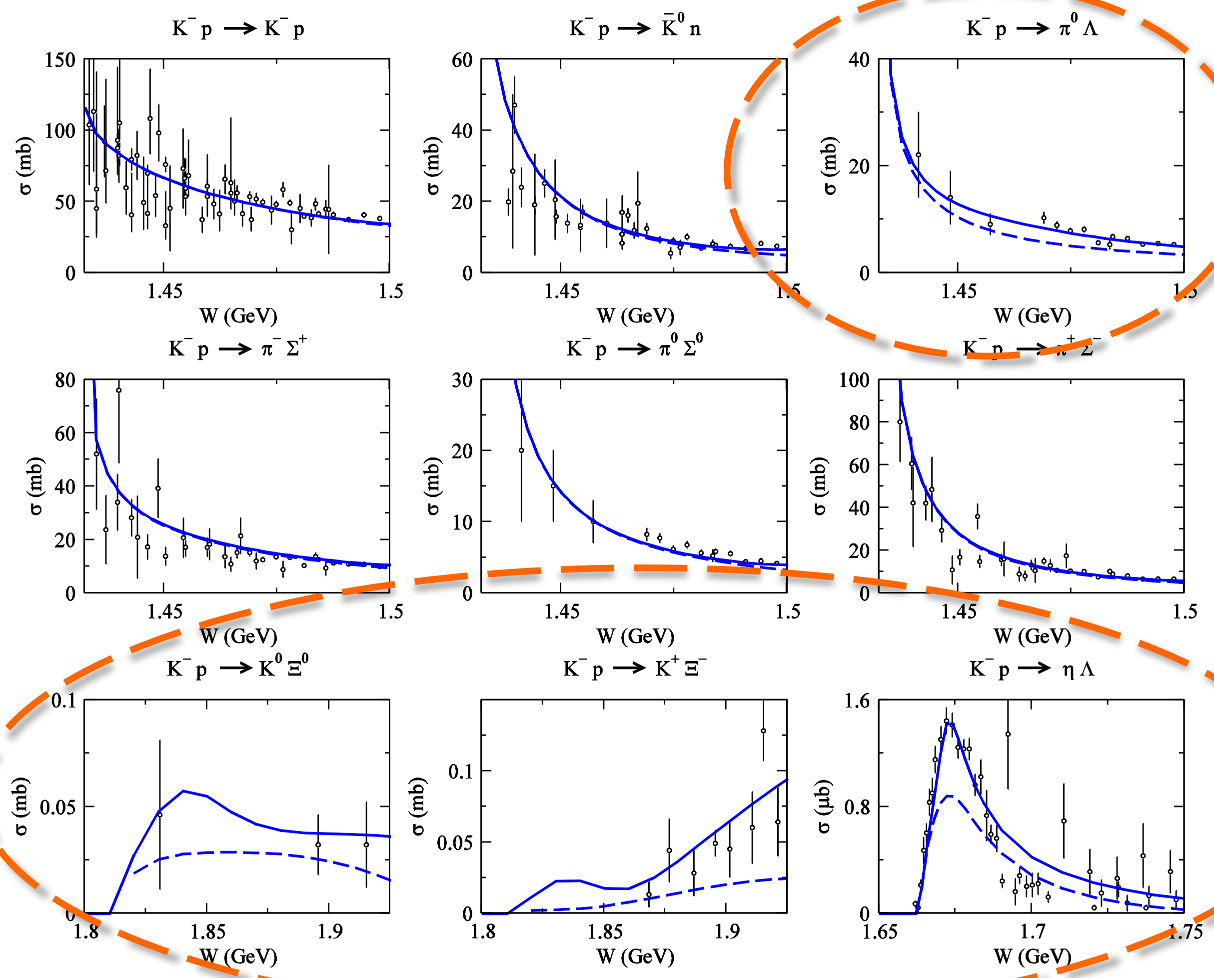


HK, Nakamura, Lee, Sato, PRC92(2015)025205

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

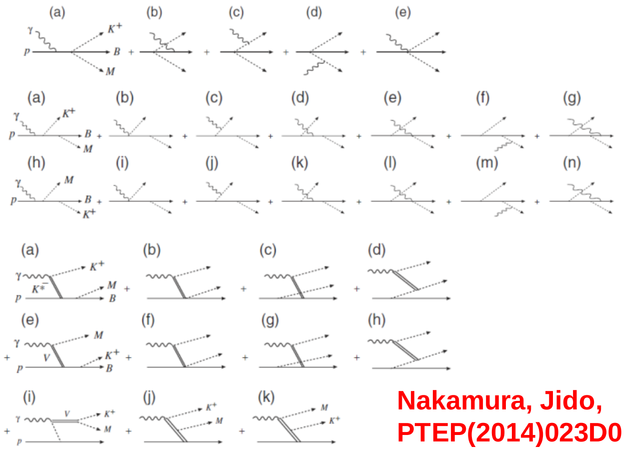
Naïve expectation for S-wave dominance near the threshold sometimes does not hold !!

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

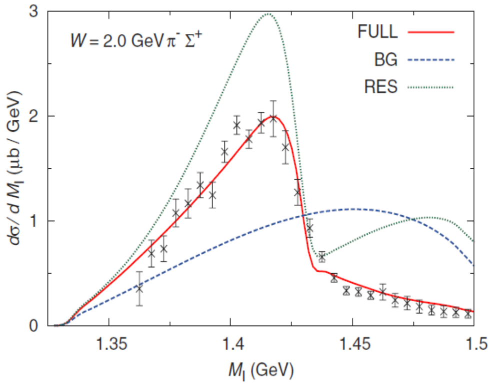
How we study the region below the $\bar{K}N$ threshold ?

E.g.) $\gamma p \rightarrow K^+\pi\Sigma$ @CLAS

At the CLAS energy, many production processes contribute and sizably affect mass distributions as backgrounds.



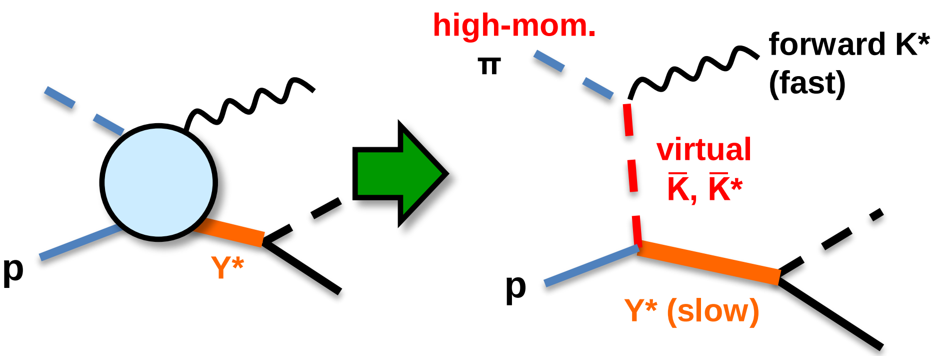
Nakamura, Jido, PTEP(2014)023D01



Large model dependence from complicated production processes.

→ Makes unambiguous determination of Λ(1405) difficult.

Forward p(π, K*)X reactions with high-momentum pion beam (➔ J-PARC E50)



- For forward K* (small t), the processes are dominated by diffractive t-channel exchange processes.
- We DO have fully unitarized $\bar{K}N \rightarrow MB$ and $\bar{K}^*N \rightarrow MB$ half off-shell amplitudes !!
- 12 GeV JLab can do a similar measurement by replacing incident π by high-energy photon.
- Useful also for determining low-lying Σ* resonances

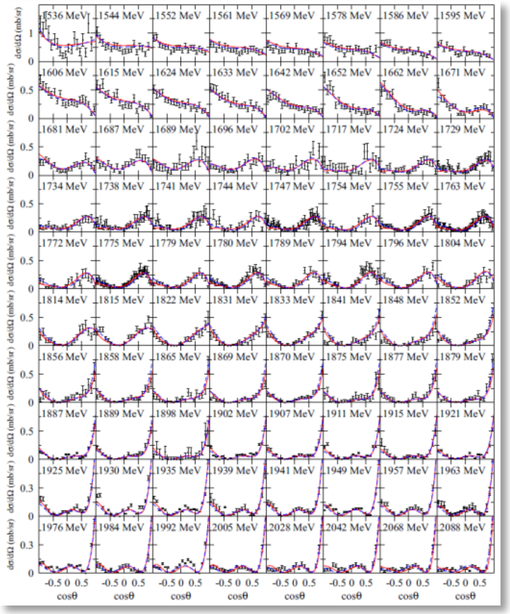
Low-lying Σ* resonances(PDG)

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−	****

?

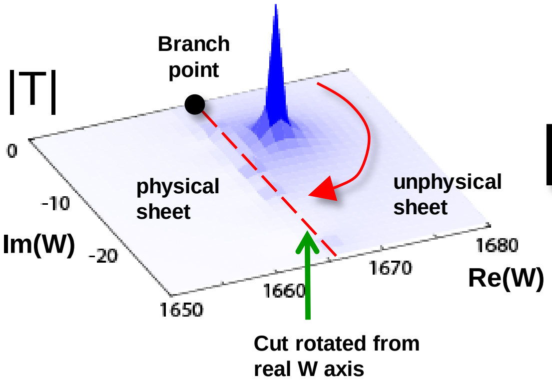
Our strategy for light-quark baryon spectroscopy

1) Construct a model by making χ^2-fit of the world data of meson production reactions:



- **Partial-wave amplitudes, scattering length,… etc. are extracted.**
- **Use supercomputers to accomplish coupled-channels analyses:**

2) Search *poles* of determined scattering amplitudes by making analytic continuation to a complex energy plane.

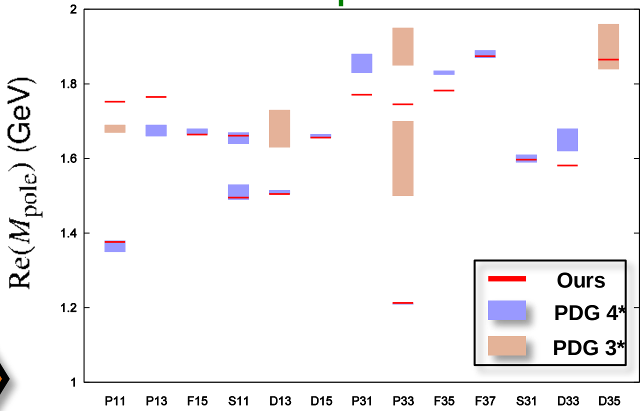


Pole position → (complex) resonance mass

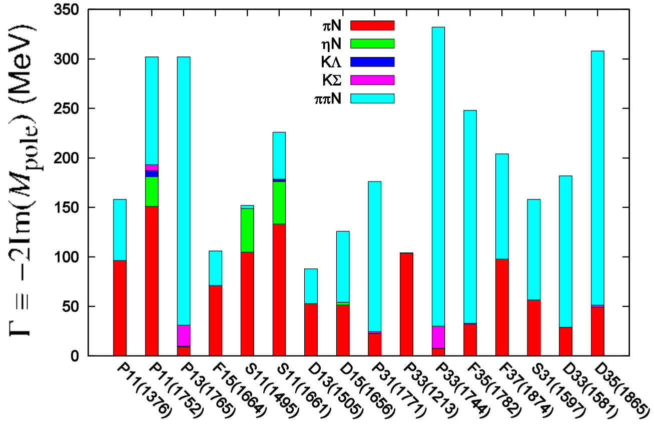
Residues → coupling strengths between Y* and MB

3) Extract resonance parameters defined by poles.

Mass spectrum



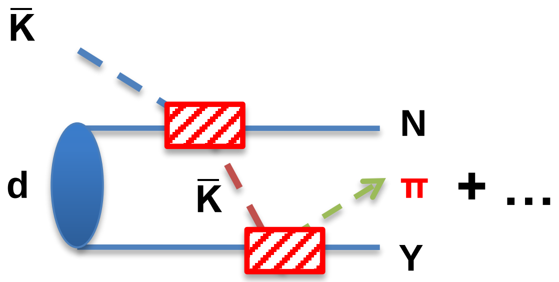
Decay width



Future works

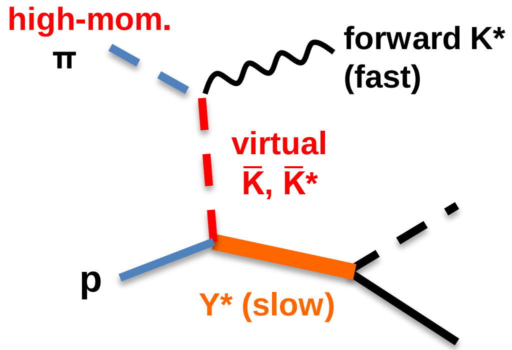
- ✓ Extension of our analysis: tackling on Λ(1405) as well as low-lying Σ* resonances

J-PARC E31



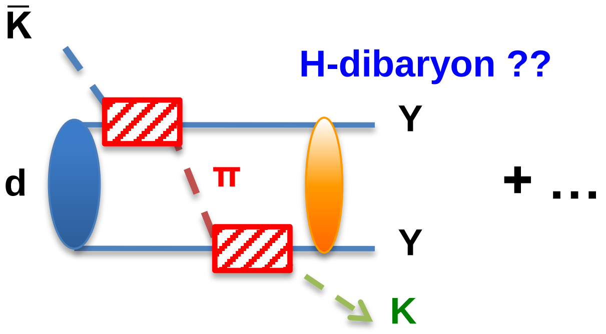
Forward p(π, K*)X reactions with high-momentum pion beam (➔ J-PARC E50)

(Processes are expected to be dominated by diffractive t-channel exchange processes.)



- ✓ Studying YY interactions

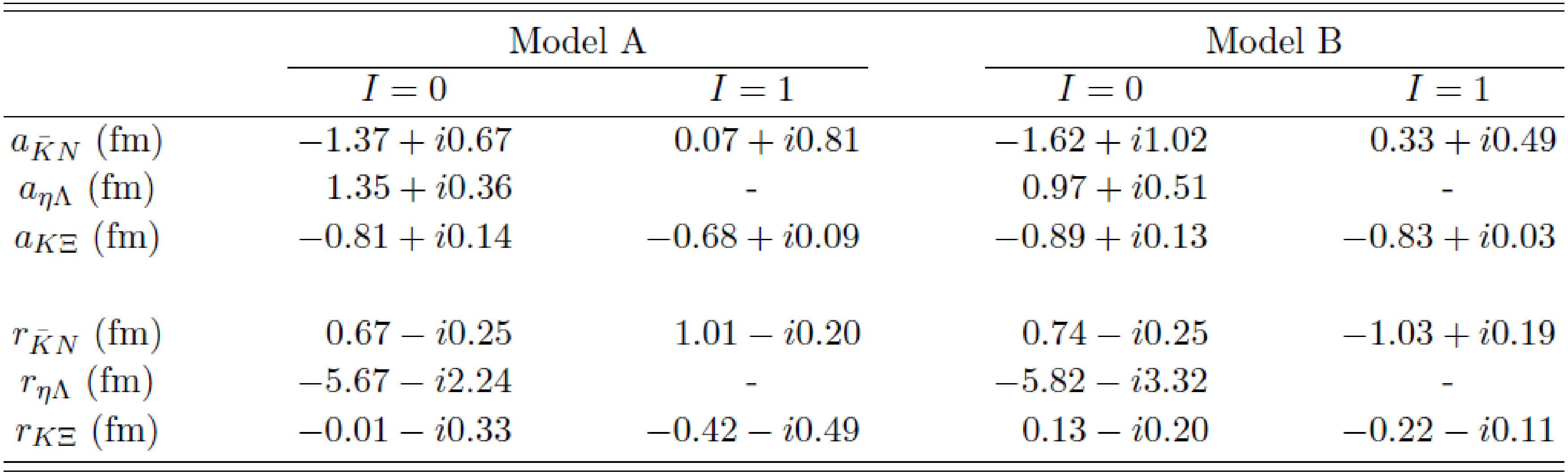
J-PARC E42



Extracted scattering lengths and effective ranges

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

Scattering length and effective range



	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)	$-0.01-i0.33$	$-0.42-i0.49$	$0.13-i0.20$	$-0.22-i0.11$

$a_{K\text{-}p}$ = -0.65 + i0.74 fm (Model A)
$a_{K\text{-}p}$ = -0.65 + i0.76 fm (Model B)

Database of our analysis (W < 2.1GeV)

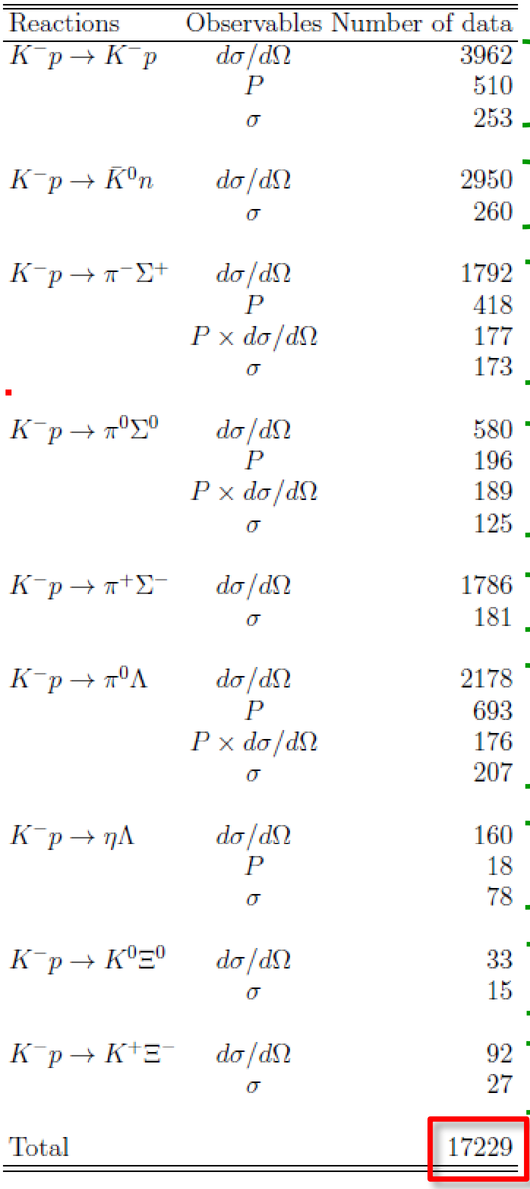
HK, Nakamura, Lee, Sato, PRC90(2014)065204

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 !!

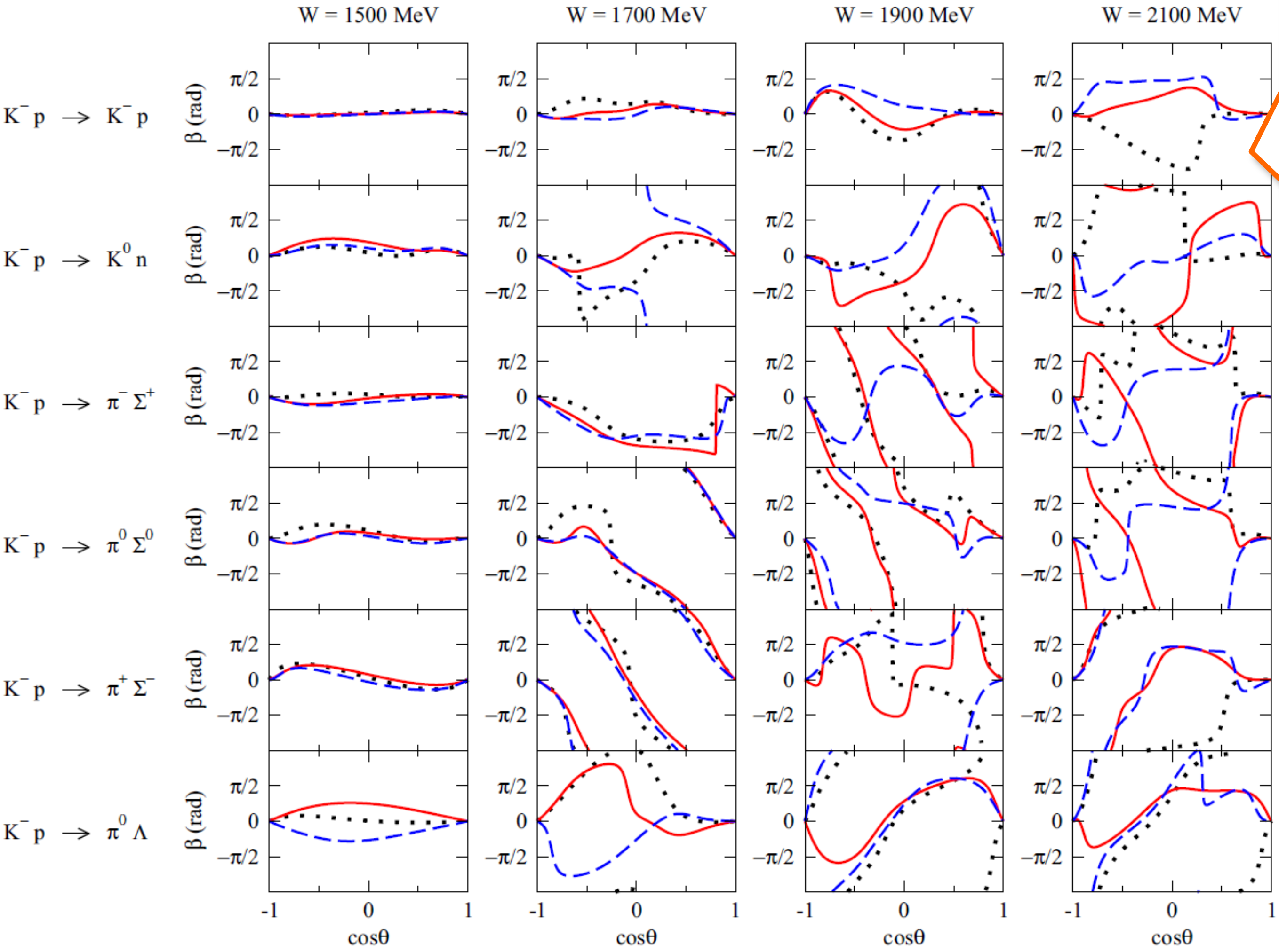


Reactions	Observables	Number of data	
$K^-p \to K^-p$	$d\sigma/d\Omega$	3962	$d\sigma/d\Omega$: 1465 MeV < W P : 1730 MeV < W β, R, A: No data
	P	510	
	σ	253	
$K^-p \to \bar{K}^0 n$	$d\sigma/d\Omega$	2950	$d\sigma/d\Omega$: 1465 MeV < W P : No data β, R, A: No data
	σ	260	
$K^-p \to \pi^-\Sigma^+$	$d\sigma/d\Omega$	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	

Predicted spin-rotation angle β

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

Currently no data for spin-rotation angle β



Analysis dependence is clearly seen !!

Measurement of β will give strong constraints on 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