Comprehensive study of S = -1 hyperon resonances via the coupled-channels analysis of $K^- p$ and $K^- d$ reactions

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(KEK)

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

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)		**

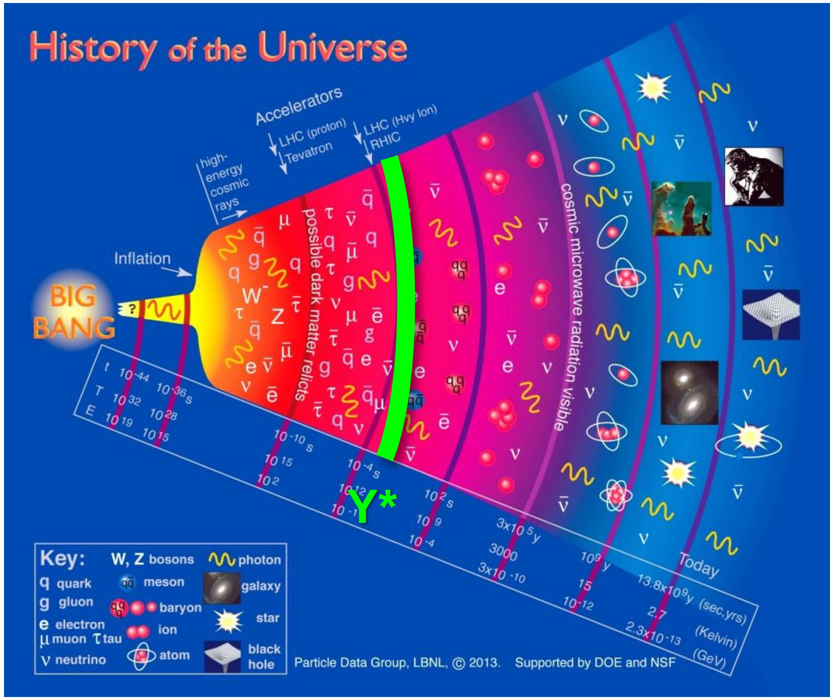
Σ*

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)		*

➔ Not well established

➔ Spin-parity not assigned

Establishing Y* spectrum is crucial also for understanding thermodynamic properties below the QCD crossover.
[Bazavov et al., PRL113(2014)072001]



Possibility of producing secondary K_L beam are being discussed at JLab (See e.g., arXiv:1604.02141)

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Σ(1660)	1/2+	***
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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−	*
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Σ(2070)	5/2+	*
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Σ(2455)		**
Σ(2620)		**
Σ(3000)		*
Σ(3170)		*

➔ Not well established

➔ Spin-parity not assigned

✓ **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.

  ➔ Reanalysis of KSU single-energy solution using an on-shell K-matrix model (Femandez-Ramirez et al., arXiv:1510.07065)

- **Our group**

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

  HK, Nakamura, Lee, Sato, PRC90(2014)065204; 92(2015)025205

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

Dynamical Coupled-Channels (DCC) model:

[Matsuyama, Sato, Lee, PR439(2007)193; HK, Nakamura, Lee, Sato, PRC88(2013)035209;90(2014)065204]

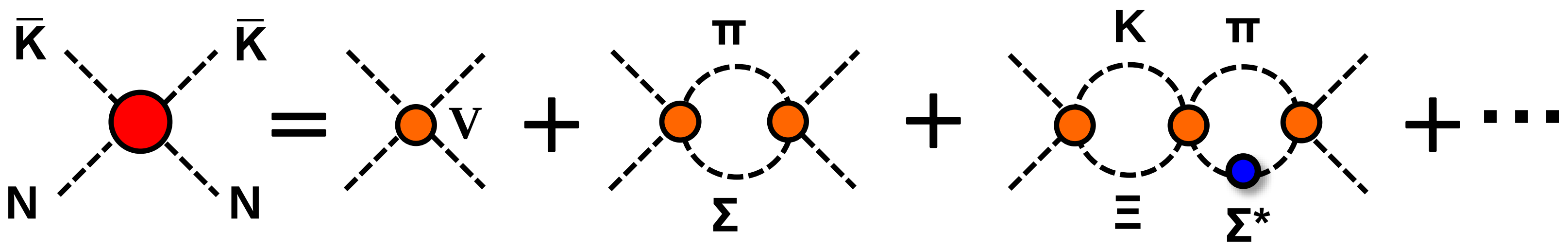
$$T^{(LSJ)}_{a,b}(p_a,p_b;E) = V^{(LSJ)}_{a,b}(p_a,p_b;E) + \underbrace{\sum_c}_{\text{CC effect}} \underbrace{\int_0^\infty q^2 dq}_{\text{off-shell effect}} V^{(LSJ)}_{a,c}(p_a,q;E) G_c(q;E) T^{(LSJ)}_{c,b}(q,p_b;E)$$

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

quasi two-body channels of three-body ππΛ & π$\bar{K}$N

- ✓ **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.**

What we have done so far

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

Supercomputers are necessary for the analysis !!

- ✓ **Comprehensive analysis of *ALL* available data (more than 17,000 data points) of $K^- p \to \bar{K}N, \pi\Sigma, \pi\Lambda, \eta\Lambda, K\Xi$ up to W = 2.1 GeV.**
  [HK, Nakamura, Lee, Sato, PRC90(2014)065204]

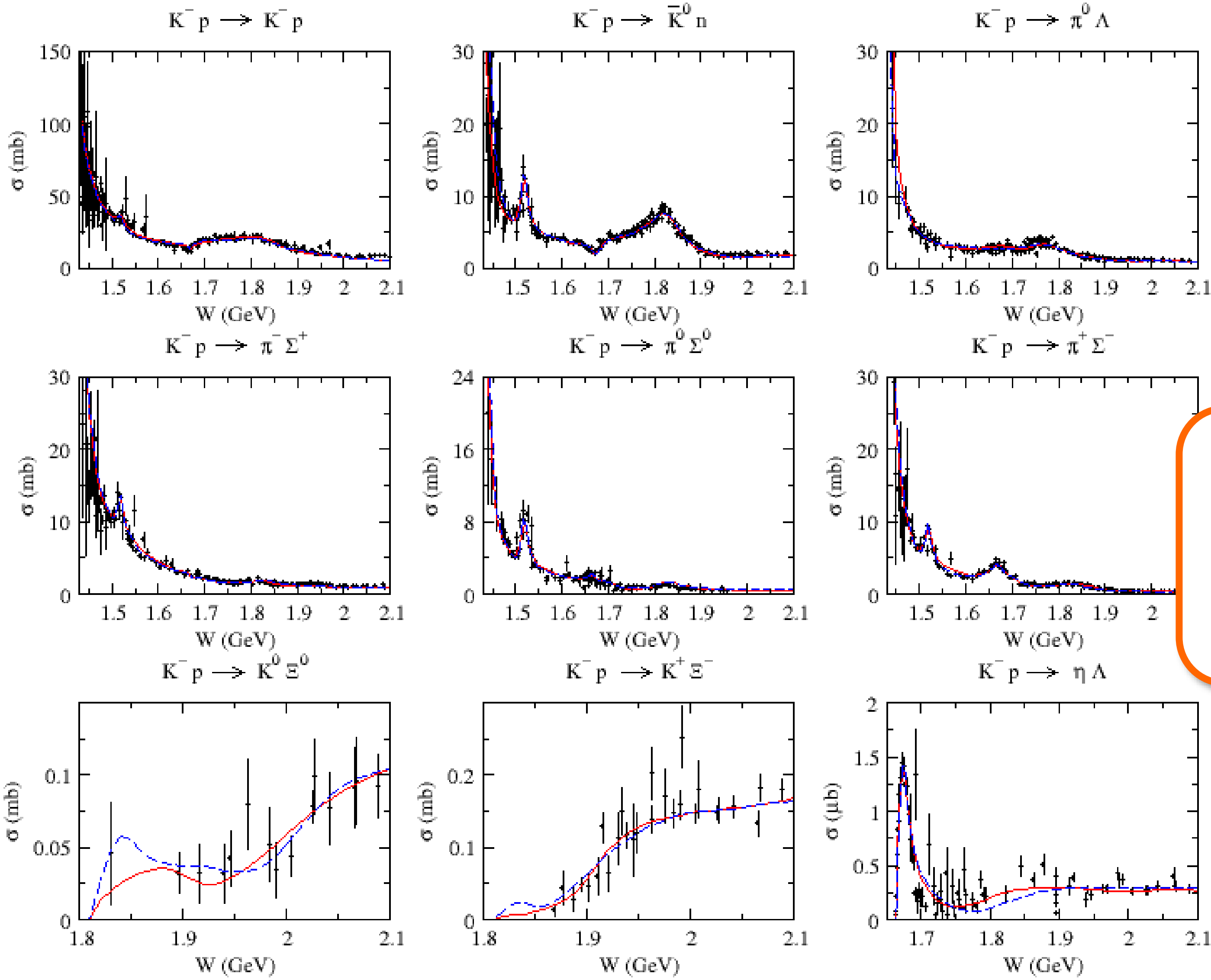
- ✓ **Determination of threshold parameters (scattering lengths, effective ranges,…); the partial-wave amplitudes of $\bar{K}N \to \bar{K}N, \pi\Sigma, \pi\Lambda, \eta\Lambda, K\Xi$ for S, P, D, and F waves.**
  [HK, Nakamura, Lee, Sato, PRC90(2014)065204]

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

Results of the fits

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

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



Red: Model A

Blue: Model B

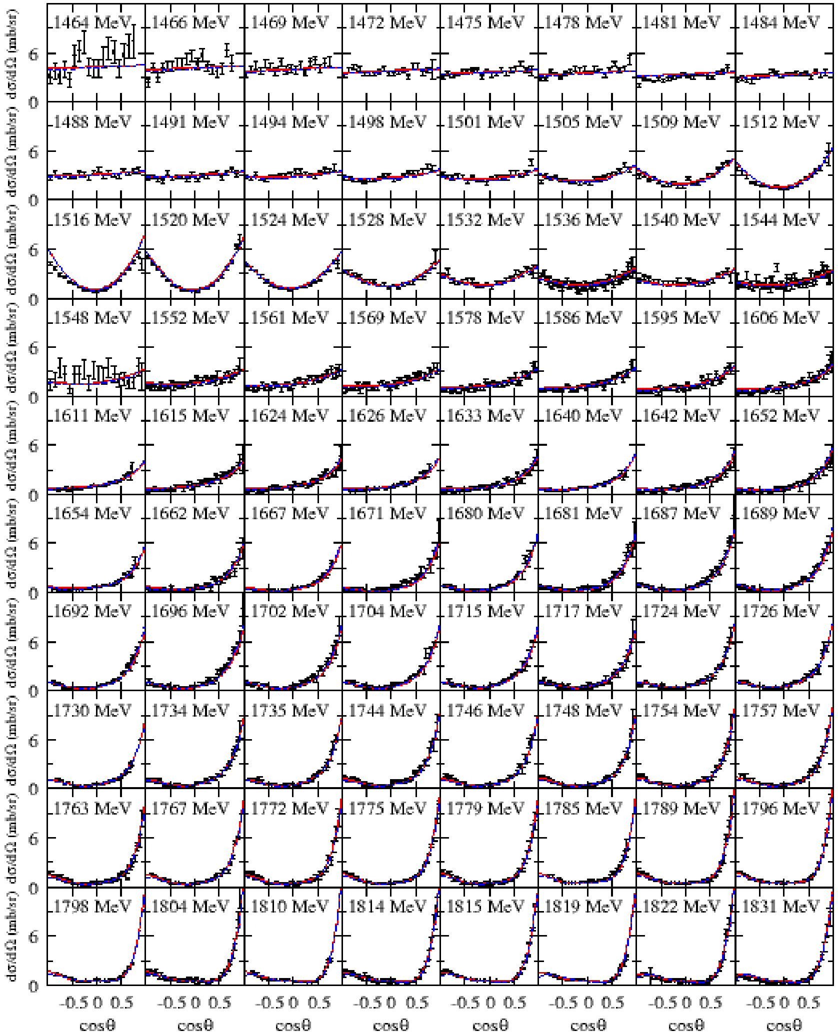
"Incompleteness" of the current database allows us to have two parameter sets that give similar quality of the fit.

Results of the fits

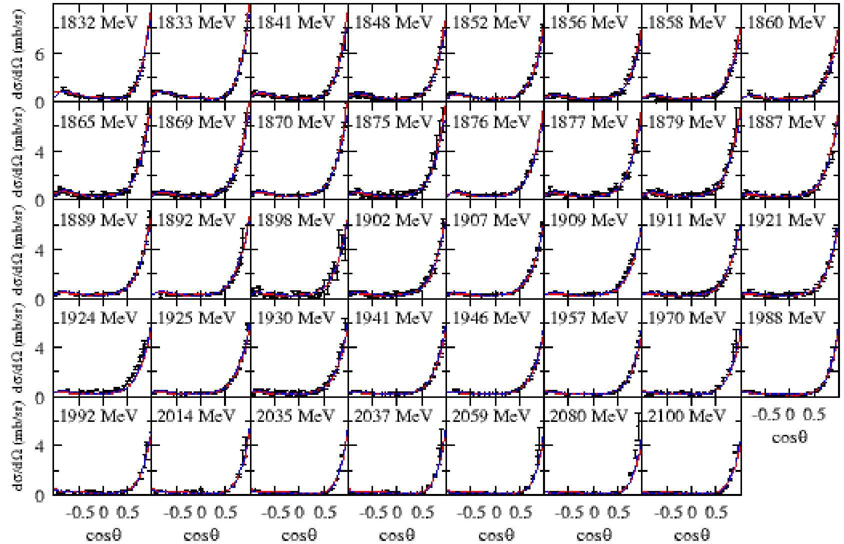
K⁻ p → K⁻ p scattering

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

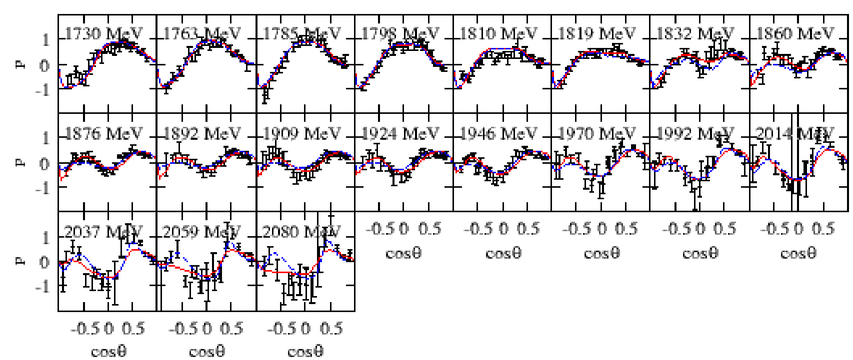
dσ/dΩ (1464 < W < 1831 MeV)



dσ/dΩ (1832 < W < 2100 MeV)



P (1730 < W < 2080 MeV)



Red: Model A Blue: Model B

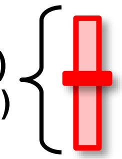
Extracted Λ* and Σ* mass spectrum

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

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

Red: Model A
Blue: Model B
Green: KSU[PRC88(2013)035205]
Black: PDG (only 4- & 3-star Y*; Breit-Wigner)

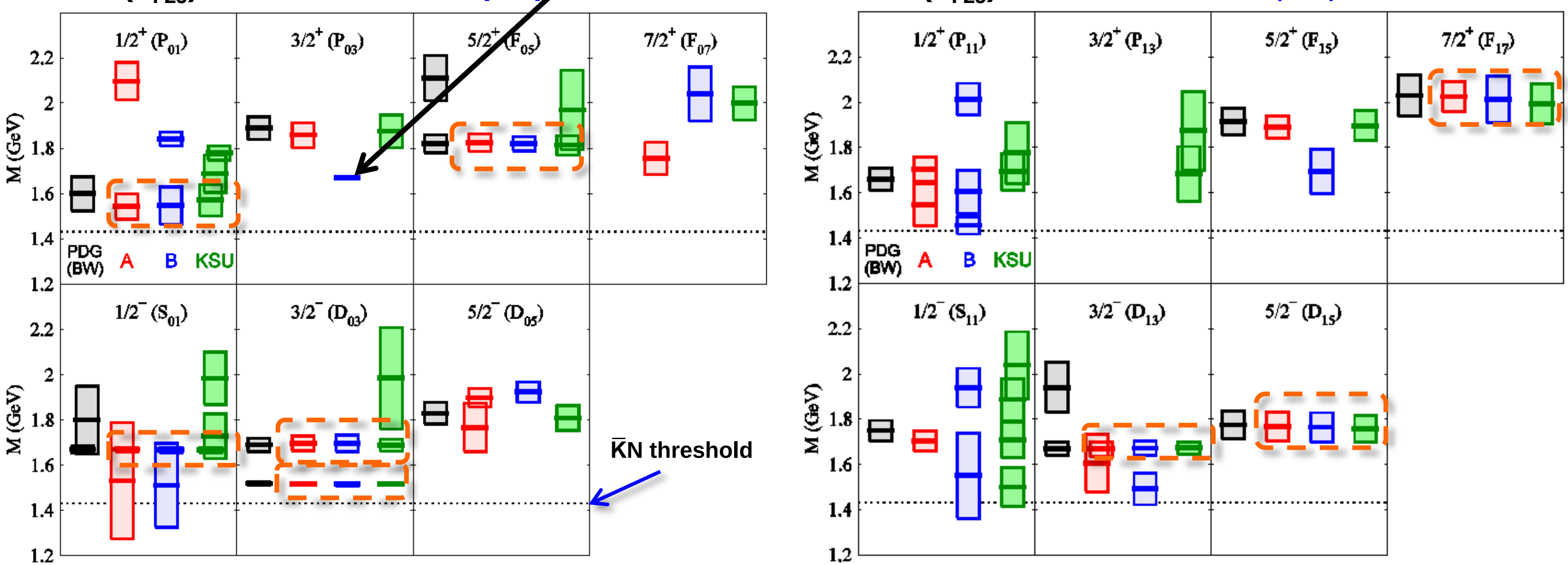
New narrow $3/2^+$ resonance
$M = 1671 - 5i$ MeV
near the ηΛ threshold !!



M_R : Resonance pole mass (complex)

$J^P(L_{I\,2J})$ "Λ" resonance (I=0)

$J^P(L_{I\,2J})$ "Σ" resonance (I=1)



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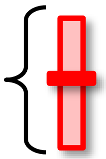
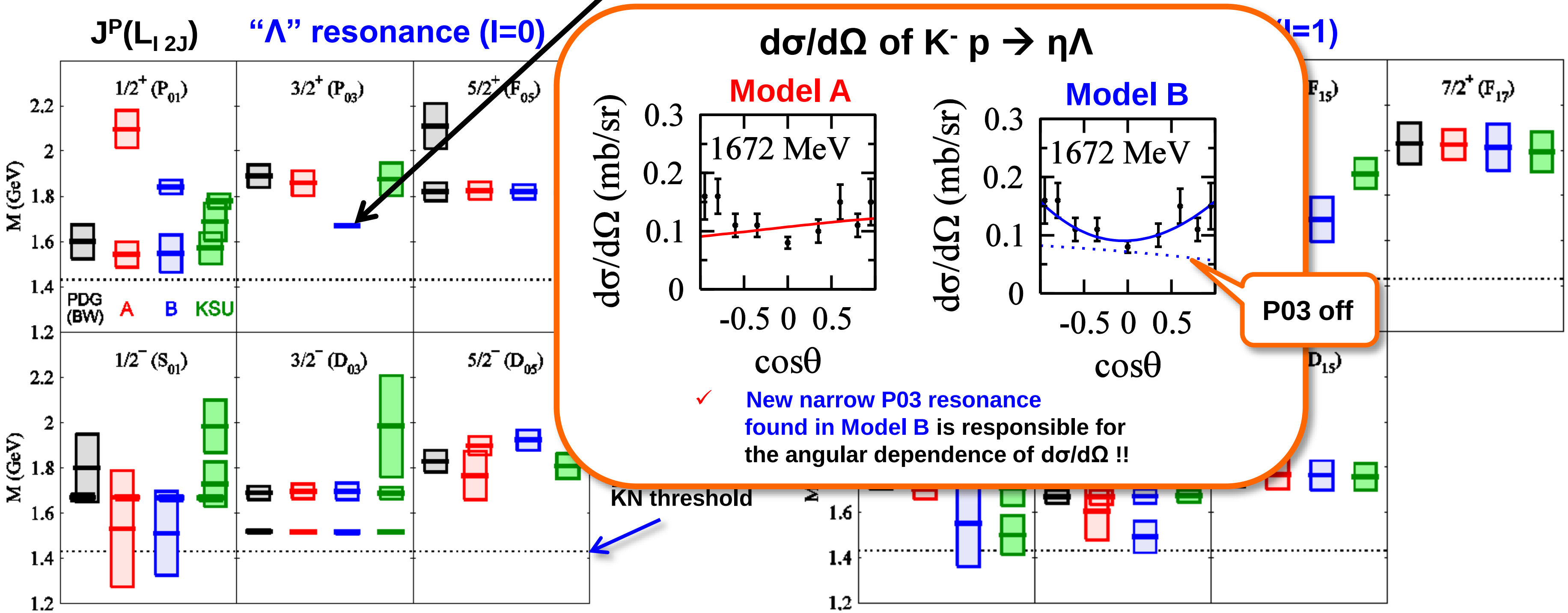
-2Im(M_R) (“width”)



Re(M_R)

M_R : Resonance pole mass (complex)



Extracted Λ* and Σ* mass spectrum

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

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

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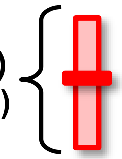

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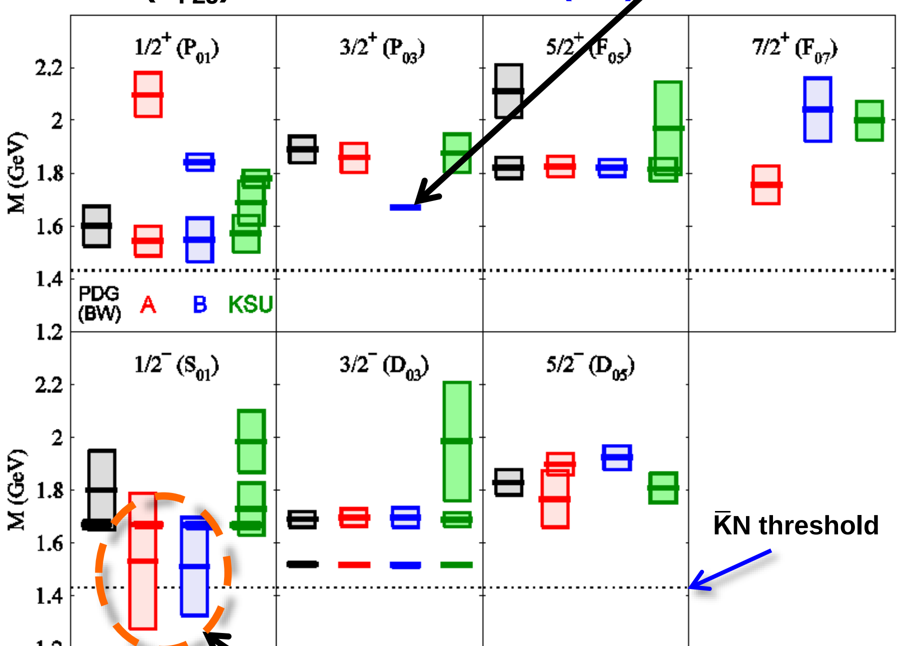
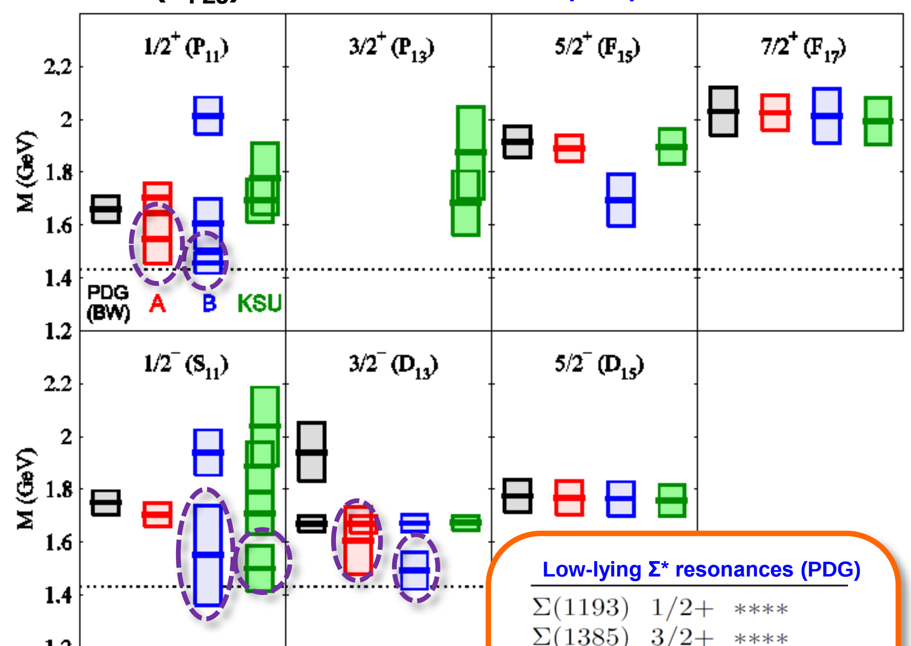


Spin partner of Λ(1520)$3/2^-$??

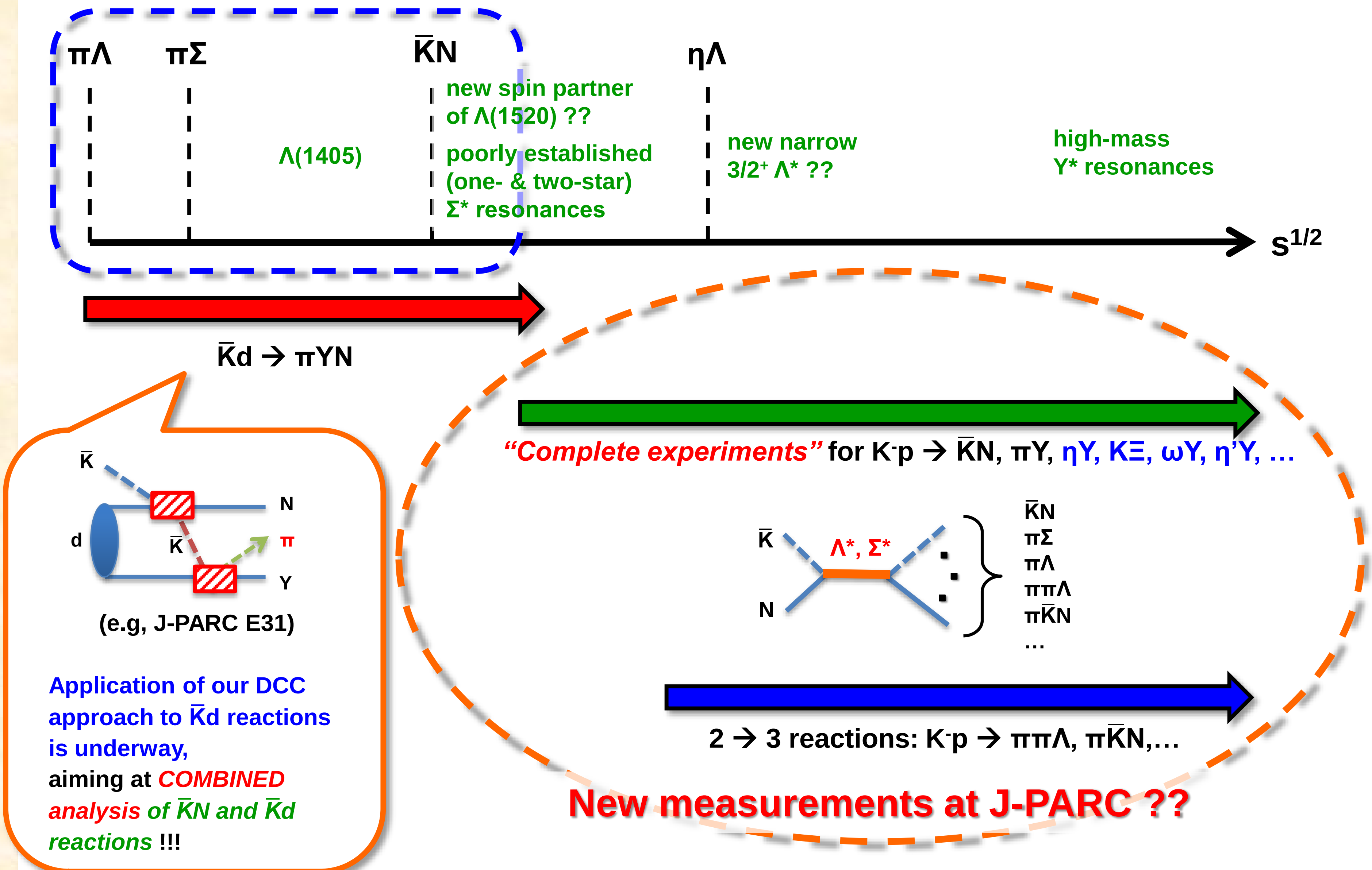


Low-lying Σ* resonances (PDG)

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−	****

?

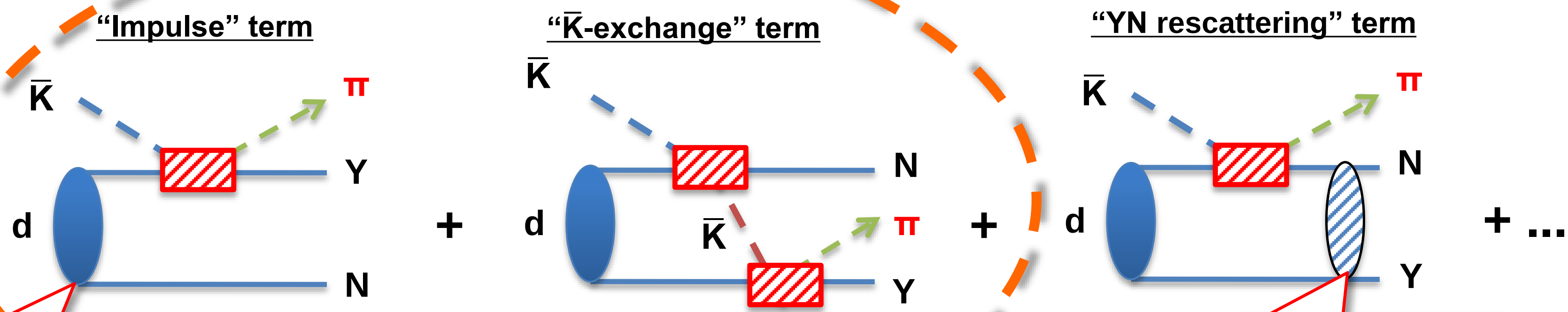
Strategy for establishing Y* resonances using antikaon-induced reactions



Model for deuteron-target reactions

- ✓ **Multistep processes are treated in a sequential manner.**

- ✓ **Off-shell amplitudes for meson-baryon sub-processes (▨) are taken from our dynamical coupled-channels model.** HK, Nakamura, Lee, Sato, PRC90(2014)065203



Use, e.g., deuteron w.f. from ANL-V18 potential [PRC51(1995)38]

Completely dominates the reaction processes at the kinematics with $\theta_N \sim 0$. (➔ J-PARC E31)

- ✓ **Unique feature of our work:**

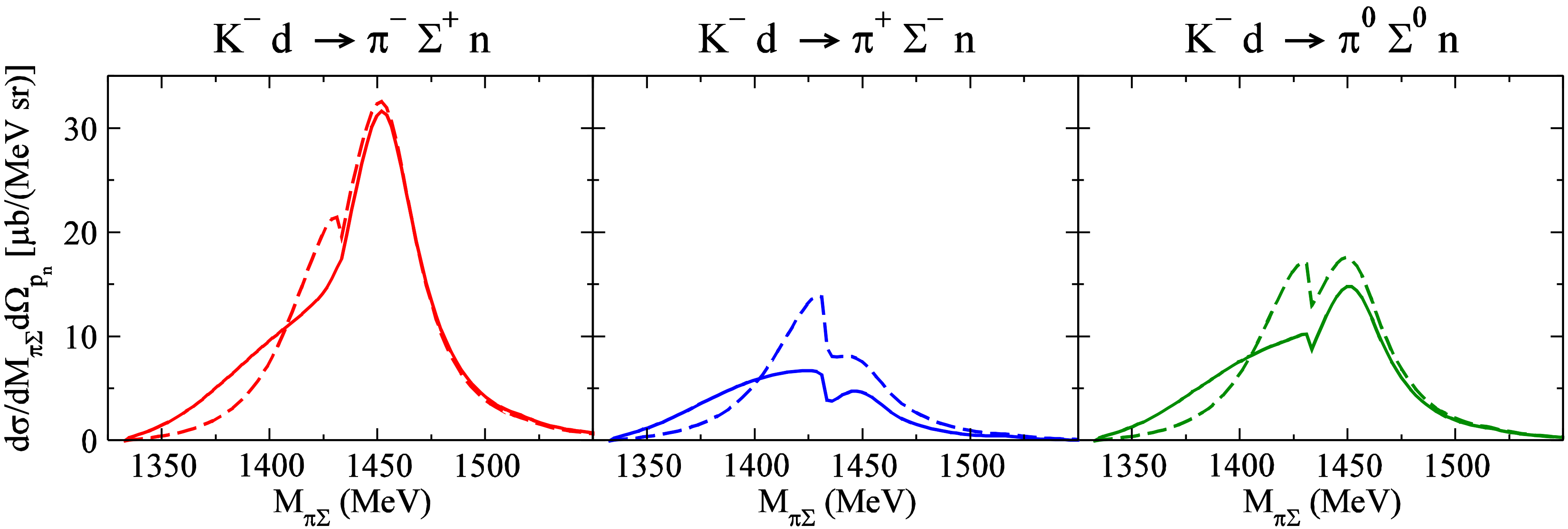
  For elementary meson-baryon subprocesses, we employ amplitudes that are

  - ➢ **well-tested by K^- p → $\bar{K}$N, πΣ, πΛ, ηΛ, KΞ *up to W = 2.1 GeV*.**
  - ➢ **not only for S wave, but also P, D, F waves.**

Results for $K^- d \rightarrow (\pi\Sigma)_0 n$

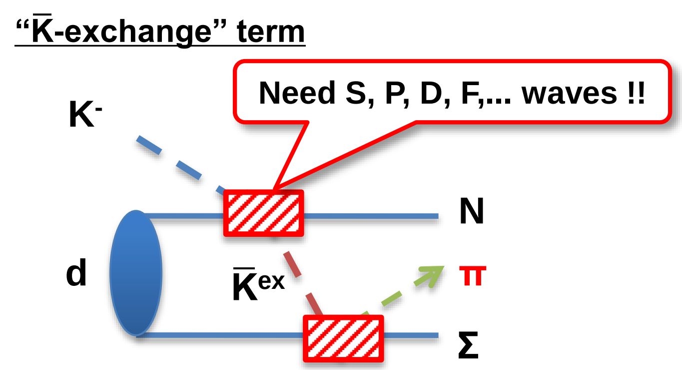
HK, Lee, arXiv:1608.03470

p_{K^-} = 1 GeV, θ_n = 0 deg.



Model A (Full)

Model B (Full)



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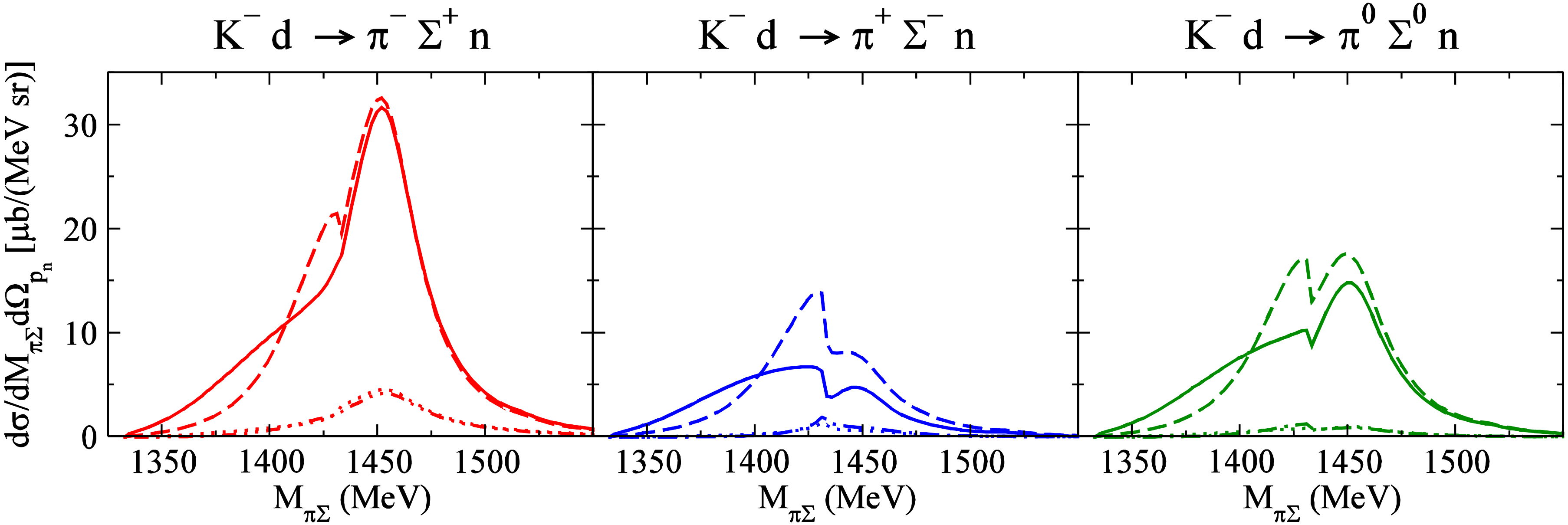
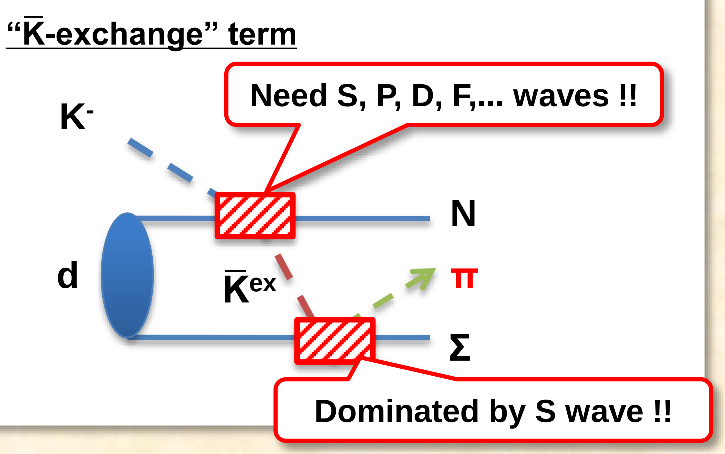


- Model A (Full)
- Model B (Full)
- Model A (only S-wave for $\bar{K}N \to \bar{K}^{ex} N$)
- Model B (only S-wave for $\bar{K}N \to \bar{K}^{ex} N$)



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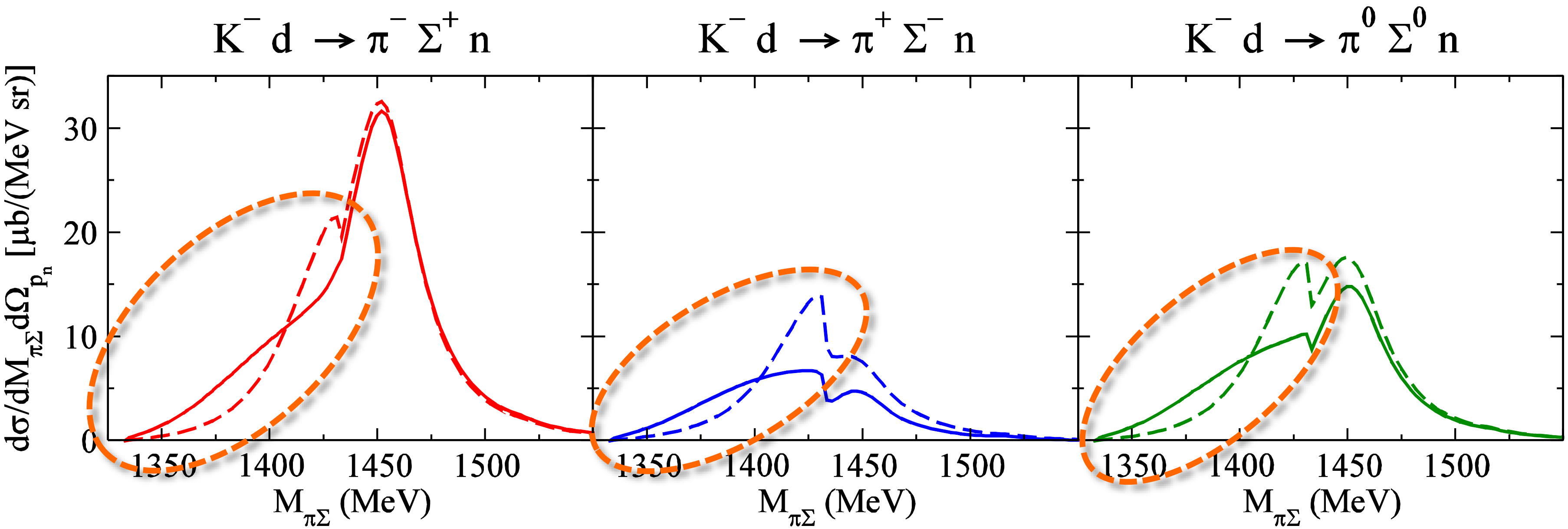
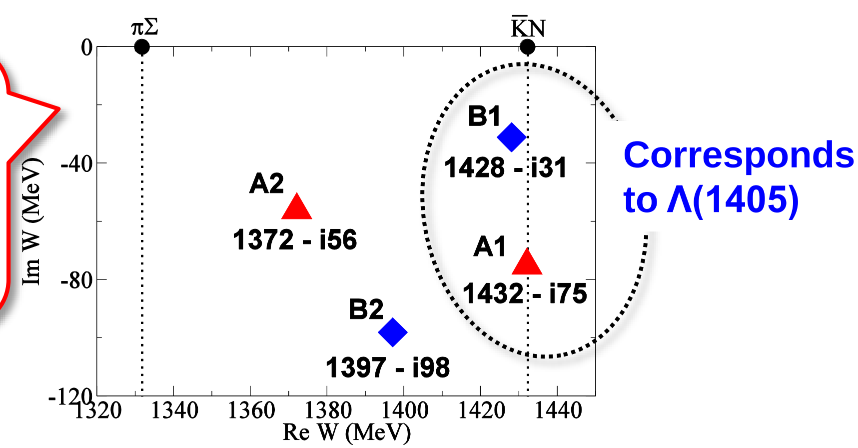


Model A (Full)

Model B (Full)

Pole positions of S-wave ($J^P=1/2^-$) Λ resonances below $\bar{K}N$ threshold [HK et al, PRC92(2015)025205]



Summary

✓ Accomplished comprehensive analysis of $K^- p \rightarrow \bar{K}N, \pi\Sigma, \pi\Lambda, \eta\Lambda, K\Xi$ up to W = 2.1 GeV for the first time within a DCC approach.

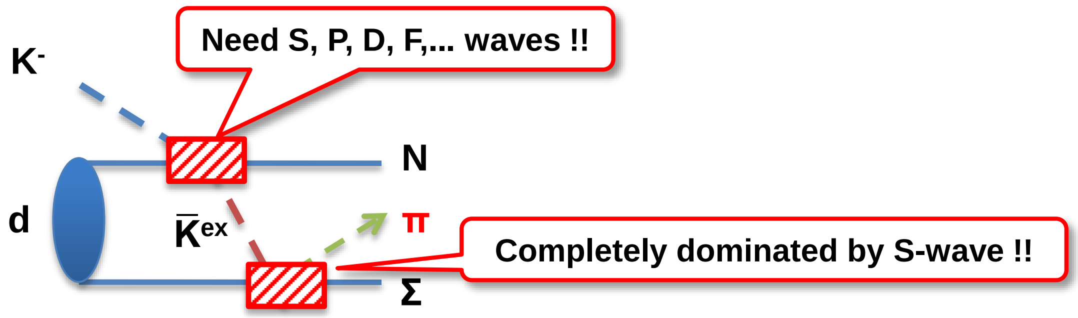
✓ Successfully extracted partial-wave amplitudes (up to F wave) and Y* resonance parameters defined by poles of amplitudes.

- New narrow $J^P = 3/2^+$ Λ* resonance (M_R = 1672-i5 MeV) located near the ηΛ threshold
- New $J^P = 1/2^-$ Λ* resonance (Re M_R ~ 1520 MeV) with mass close to $\Lambda(1520)3/2^-$
- Unestablished low-lying Σ* resonances just above $\bar{K}N$ threshold

✓ Application to $K^- d$ reactions

- Use of appropriate meson-baryon amplitudes is crucial for computing cross sections.
- Λ(1405) is found to be sensitive to DCS (➔ what about other low-lying resonances ??)

“$\bar{K}$-exchange” term



Summary

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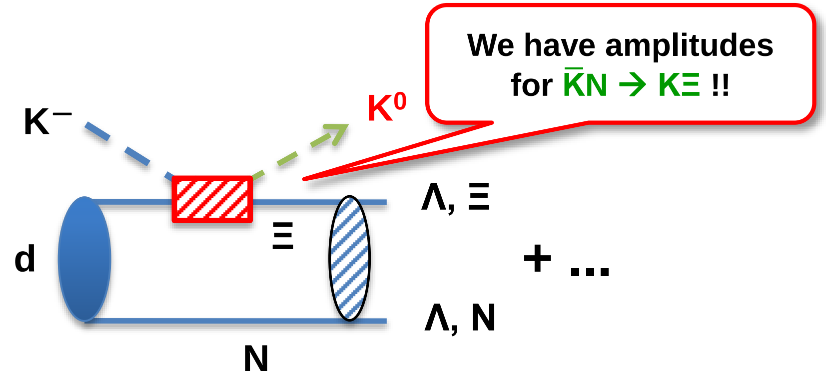
- ✓ Successfully extracted partial-wave amplitudes (up to F wave) and Y^* resonance parameters defined by poles of amplitudes.
  - ➢ New narrow $J^P = 3/2^+$ Λ^* resonance (M_R = 1672-i5 MeV) located near the $\eta\Lambda$ threshold
  - ➢ New $J^P = 1/2^-$ Λ^* resonance (Re M_R ~ 1520 MeV) with mass close to $\Lambda(1520)3/2^-$
  - ➢ Unestablished low-lying Σ^* resonances just above $\bar{K}N$ threshold

- ✓ Application to $K^- d$ reactions
  - ➢ Use of appropriate meson-baryon amplitudes is crucial for computing cross sections.
  - ➢ $\Lambda(1405)$ is found to be sensitive to DCS (➔ what about other low-lying resonances ??)

Next work:

- ✓ Study of YY interaction (including H dibaryon) via $K^- d \to K^0\Lambda\Lambda, K^0\Xi N$

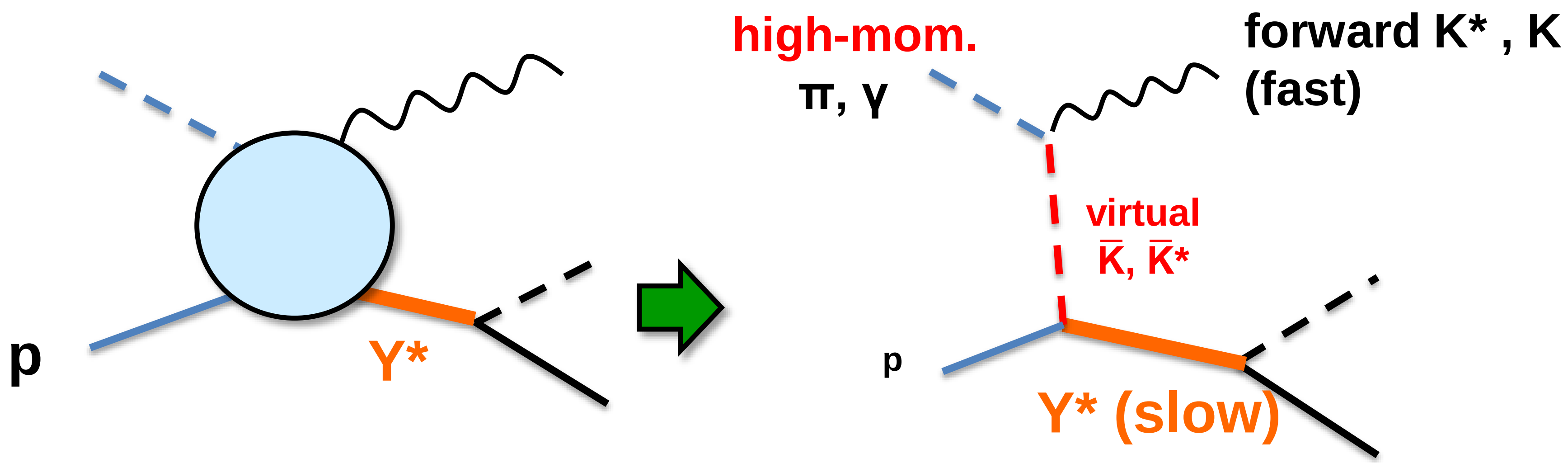


Back up

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

Other possible reactions that can access the region below $\bar{K}N$ threshold

Forward p(γ, K)X reactions (➔ L. Guo, CLAS12)
Forward p(π, K*)X reactions with high-momentum pion beam (➔ J-PARC)



In theoretical analysis point of view,
these reactions may be more "economical" than K^- d reactions.

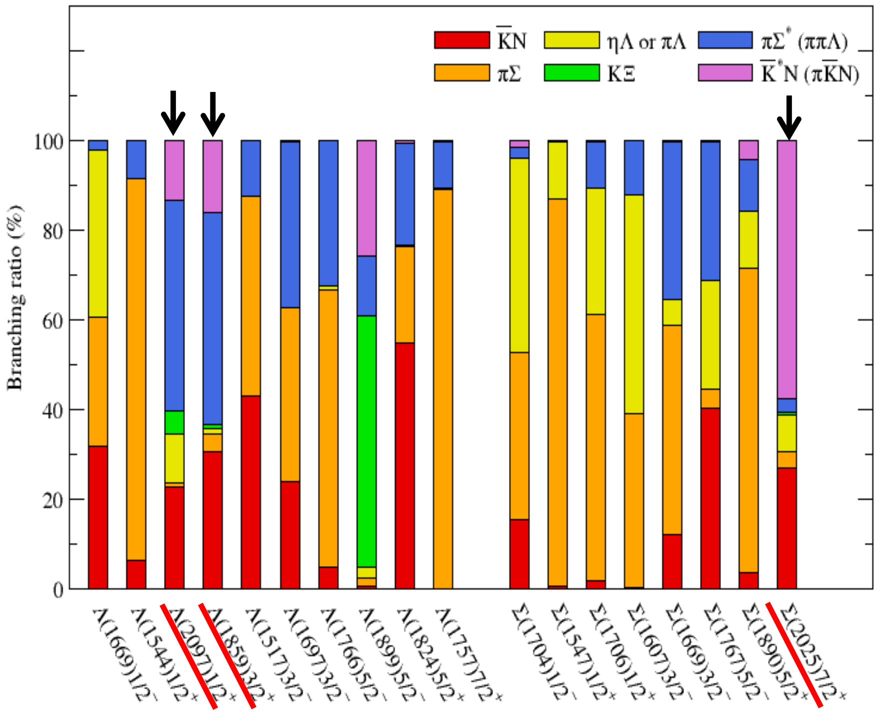
Importance of 2 → 3 reactions: Branching ratios of high-mass Y* resonances

✓ **High-mass Y* have large branching ratio to $\pi\Sigma^*$ ($\pi\pi\Lambda$) & $\bar{K}^*N$ ($\pi\bar{K}N$)**

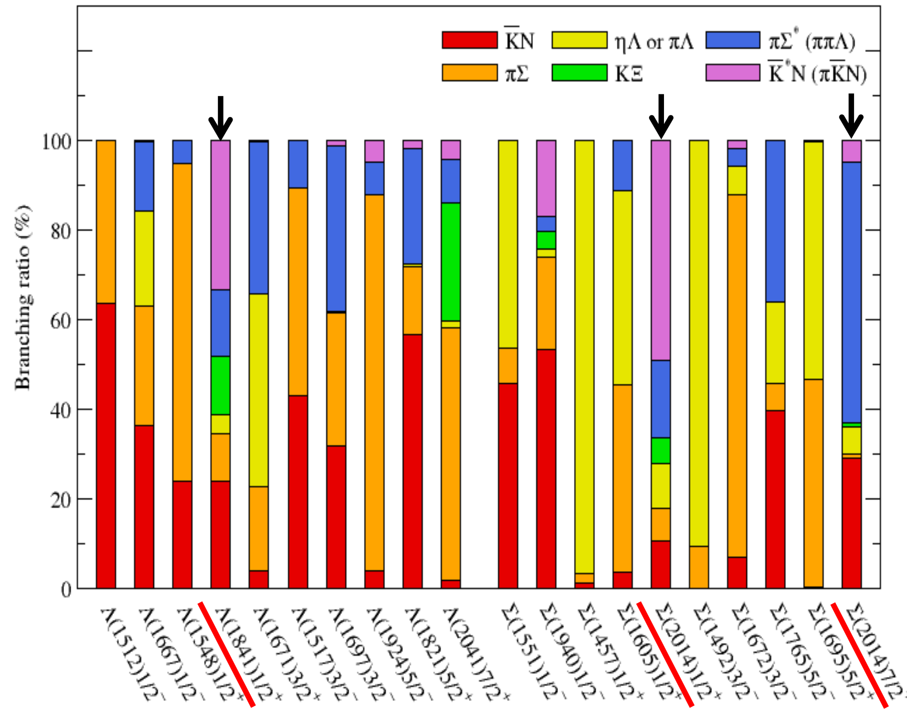
➢ **$K^- p \to \pi\pi\Lambda, \pi\bar{K}N, \ldots$ data would play a crucial role for establishing high-mass Y*.**

➔ 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

Extracted scattering lengths and effective ranges

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

Scattering length and effective range

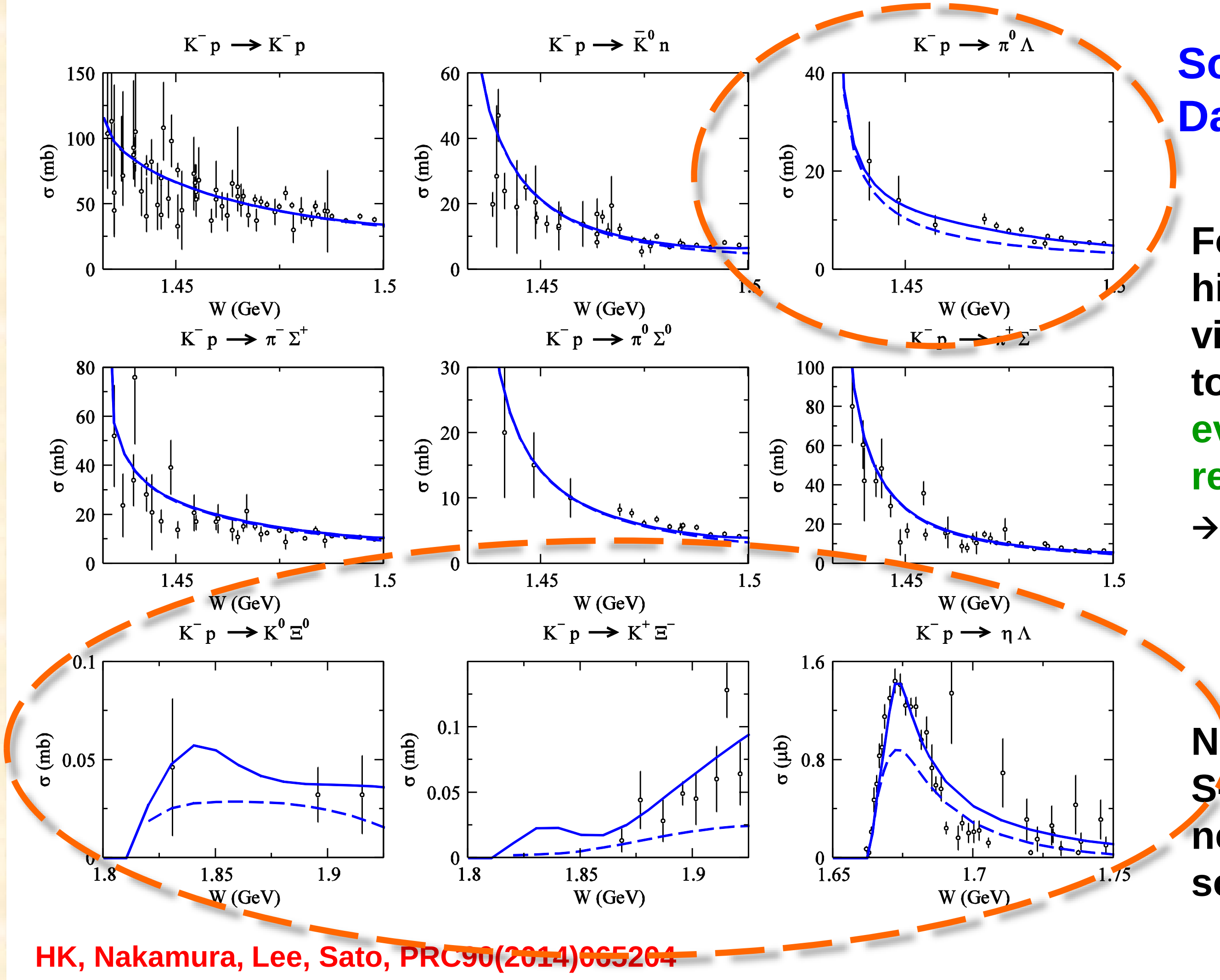
	Model A		Model B	
	$I=0$	$I=1$	$I=0$	$I=1$
$a_{\bar{K}N}$ (fm)	$-1.37+i0.67$	$0.07+i0.81$	$-1.62+i1.02$	$0.33+i0.49$
$a_{\eta\Lambda}$ (fm)	$1.35+i0.36$	-	$0.97+i0.51$	-
$a_{K\Xi}$ (fm)	$-0.81+i0.14$	$-0.68+i0.09$	$-0.89+i0.13$	$-0.83+i0.03$
$r_{\bar{K}N}$ (fm)	$0.67-i0.25$	$1.01-i0.20$	$0.74-i0.25$	$-1.03+i0.19$
$r_{\eta\Lambda}$ (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^-p} = -0.65 + i0.74 fm (Model A)
a_{K^-p} = -0.65 + i0.76 fm (Model B)

S-wave dominance ??

K⁻ p → MB total cross sections near threshold

Model B



Solid: Full
Dashed: S wave only

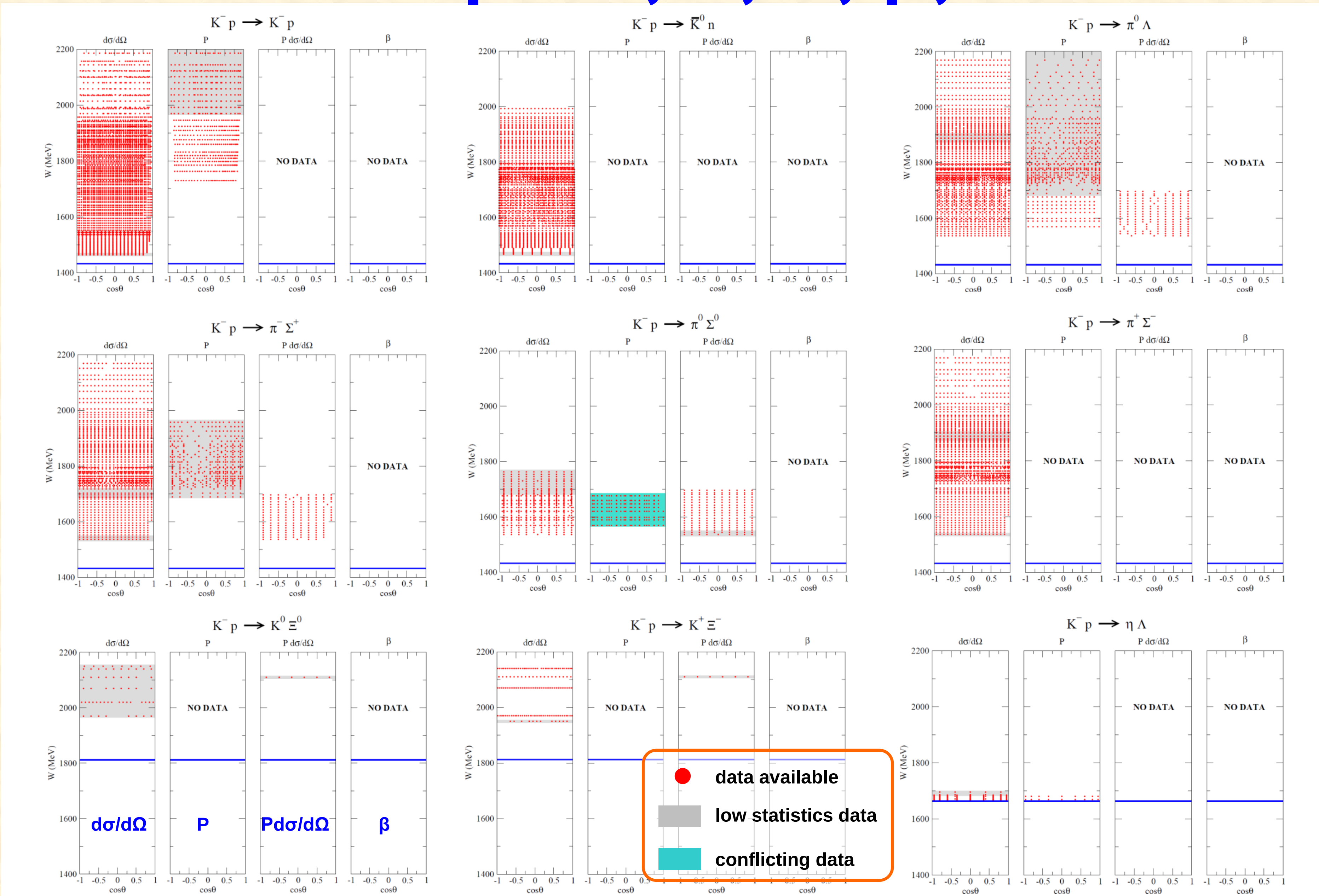
For K- p → πΛ, ηΛ, KΞ, higher partial waves visibly contribute to the cross sections even in the threshold region.

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

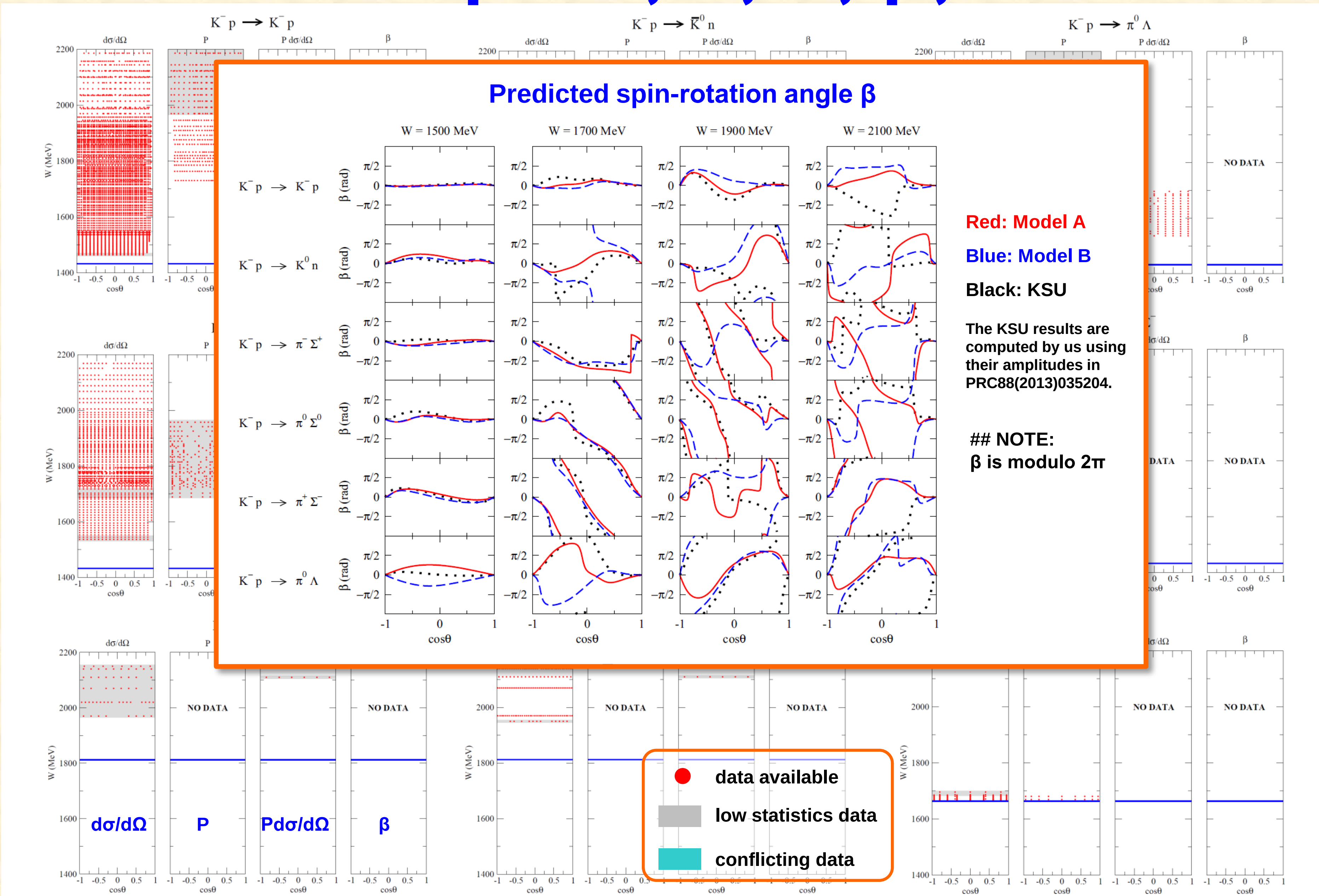
Naïve expectation for S-wave dominance near the threshold sometimes does not hold !!

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

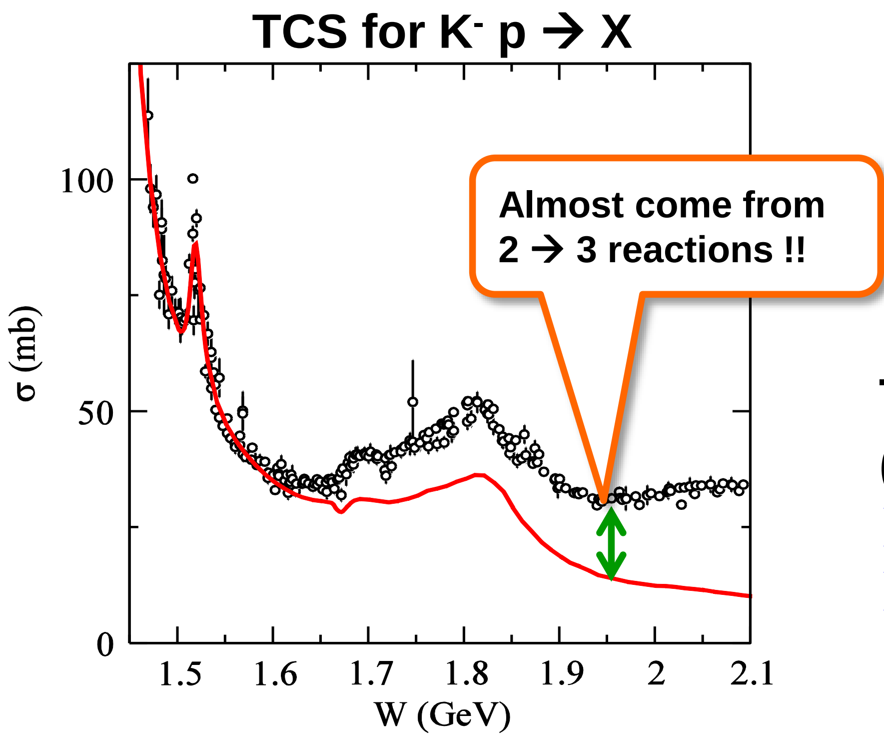
Kinematical (W, cosθ) coverage of available $K^- p \to \bar{K}N, \pi\Sigma, \pi\Lambda, \eta\Lambda, K\Xi$ data



Kinematical (W, cosθ) coverage of available $K^- p \to \bar{K}N, \pi\Sigma, \pi\Lambda, \eta\Lambda, K\Xi$ data



Importance of 2 → 3 reactions: Dominance of cross sections at high W



Sum of $K^- p \to \bar{K}N$, $\pi\Sigma$, $\pi\Lambda$, $\eta\Lambda$, $K\Xi$
(Computed with Model A)

TCS for 2 → 3 reactions
($K^- p \to \pi\pi\Lambda$, $\pi\bar{K}N$,…):

- significant above W ~ 1.7 GeV.
- even larger than the 2 → 2 TCS above W ~ 1.9 GeV !!

Effects of 3-body channels on Y* resonance parameters are expected to be sizable.

However, at present essentially no differential cross section data are available for 2 → 3 reactions that can be used for detailed partial wave analyses !!