Dynamical coupled-channels study of S=-1 hyperon resonances and possible new experiments at J-PARC

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Tokai, March 2th-4th, 2016

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

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

- ✓ **Most of Σ*s are poorly established.**
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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+	****
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Σ(2250)		***
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Σ(2620)		**
Σ(3000)		*
Σ(3170)		*

PDG listing

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    Resonances defined by poles of scattering amplitudes are extensively studied;
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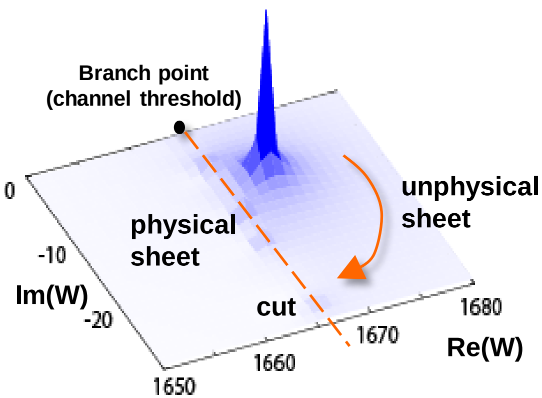

Resonance theory based on Gamow vectors:
[G. Gamow (1928), R. E. Peierls (1959), …]

"Quantum resonance state is an (complex-)energy eigenstate of the *FULL* Hamiltonian of the *underlying theory* imposed by Purely Outgoing Boundary Condition (POBC)."

Energy eigenvalue	=	Pole energy
Transition matrix elements btwn res. & scatt. states	~	Residues$^{1/2}$ at the pole

<u>Extracting poles of amplitudes from reaction data is nothing but obtaining *"exact"* energy eigenvalues of QCD !!!</u>

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✓ **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

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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]

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

CC effect

off-shell effect

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

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

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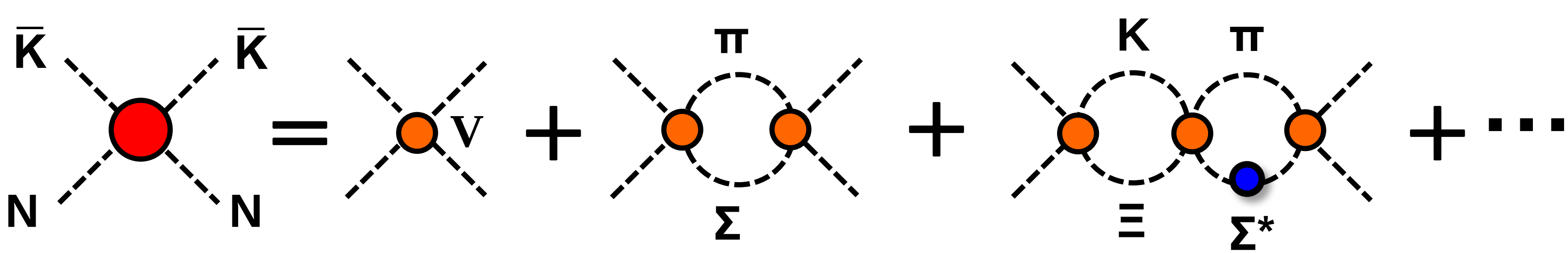
quasi two-body channels of three-body ππΛ & π$\bar{K}$N

- ✓ **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 !!

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]

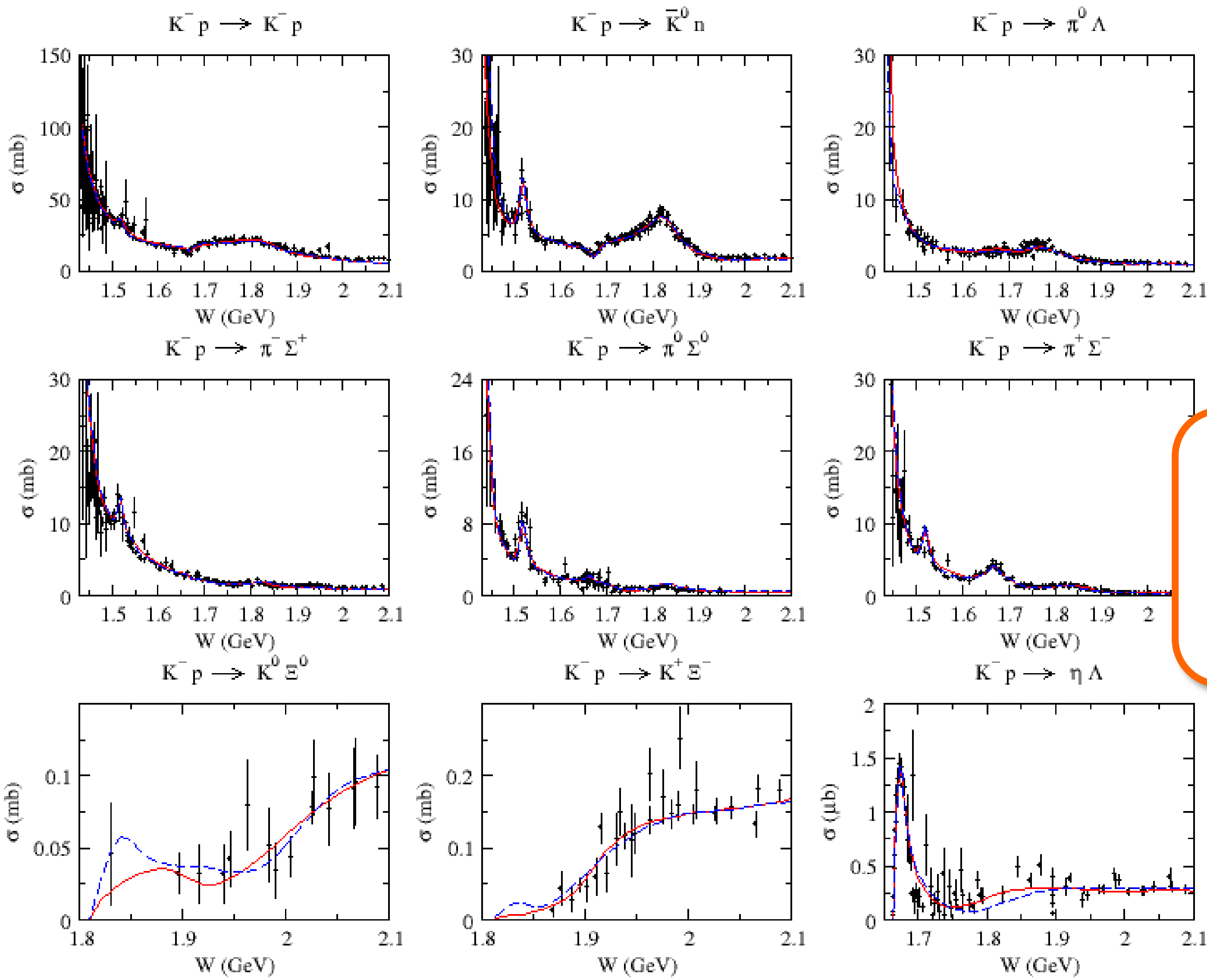
- ✓ **Determination of threshold parameters (scattering lengths, effective ranges,…); the partial-wave amplitudes of $\bar{K}N \rightarrow \bar{K}N$, $\pi\Sigma$, $\pi\Lambda$, $\eta\Lambda$, $K\Xi$ for S, P, D, and F waves.**
  [HK, Nakamura, Lee, Sato, PRC90(2014)065204]

- ✓ **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 → MB total cross sections

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



Red: Model A

Blue: Model B

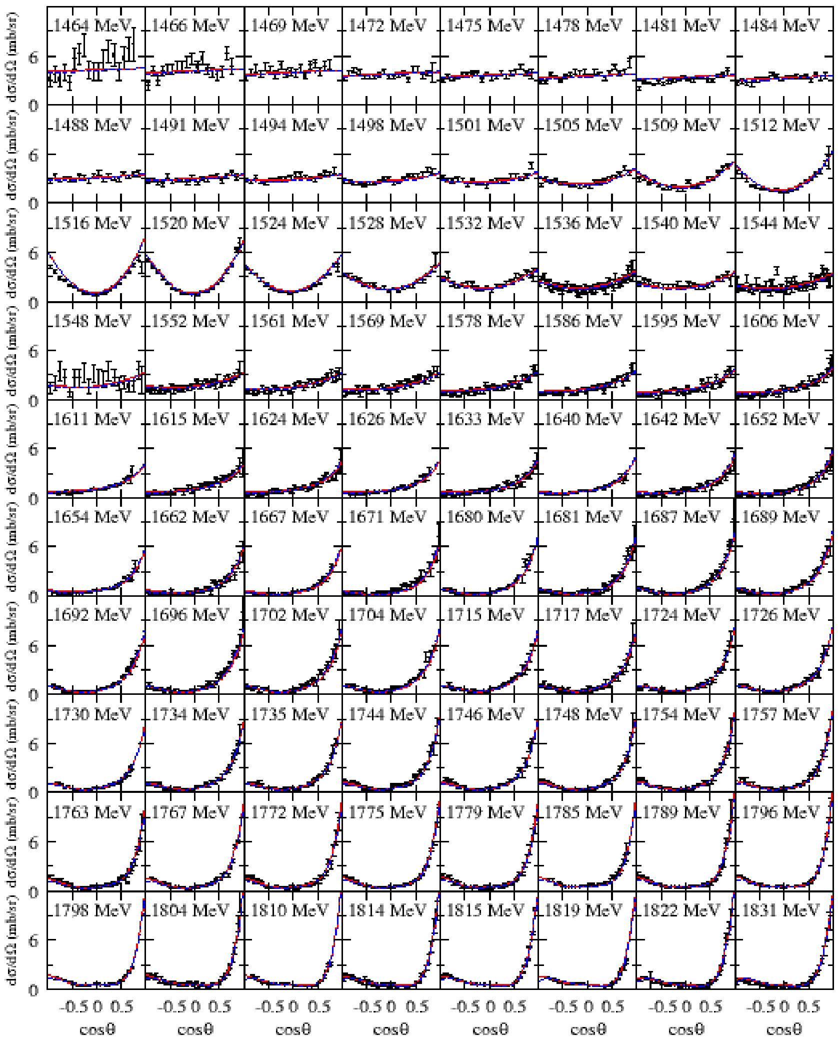
"Incompleteness" of the current database allows us to have two parameter sets that give similar quality of the fit.

Results of the fits

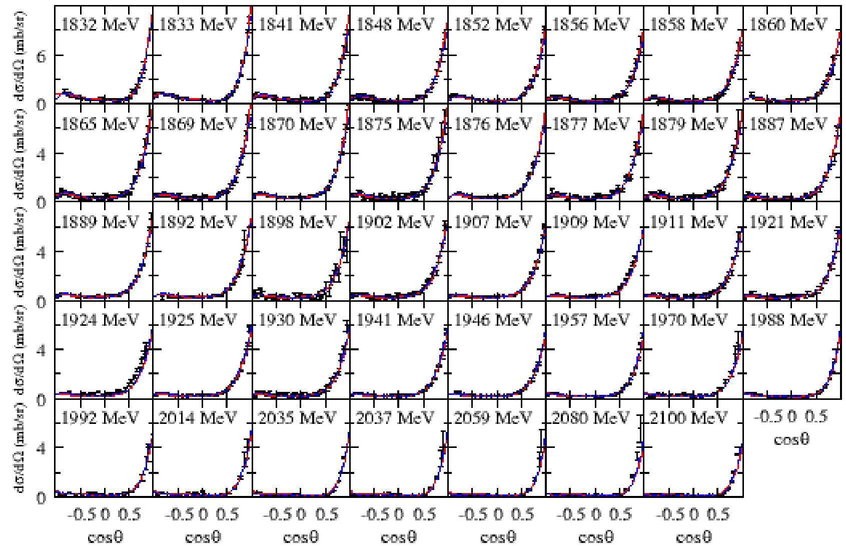
K⁻ p → K⁻ p scattering

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

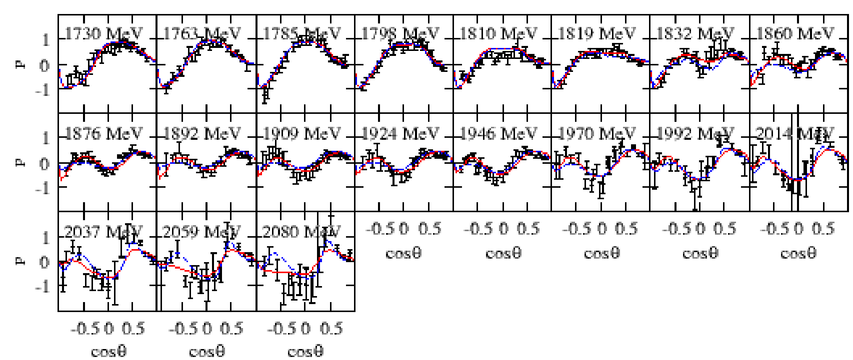
dσ/dΩ (1464 < W < 1831 MeV)



dσ/dΩ (1832 < W < 2100 MeV)



P (1730 < W < 2080 MeV)



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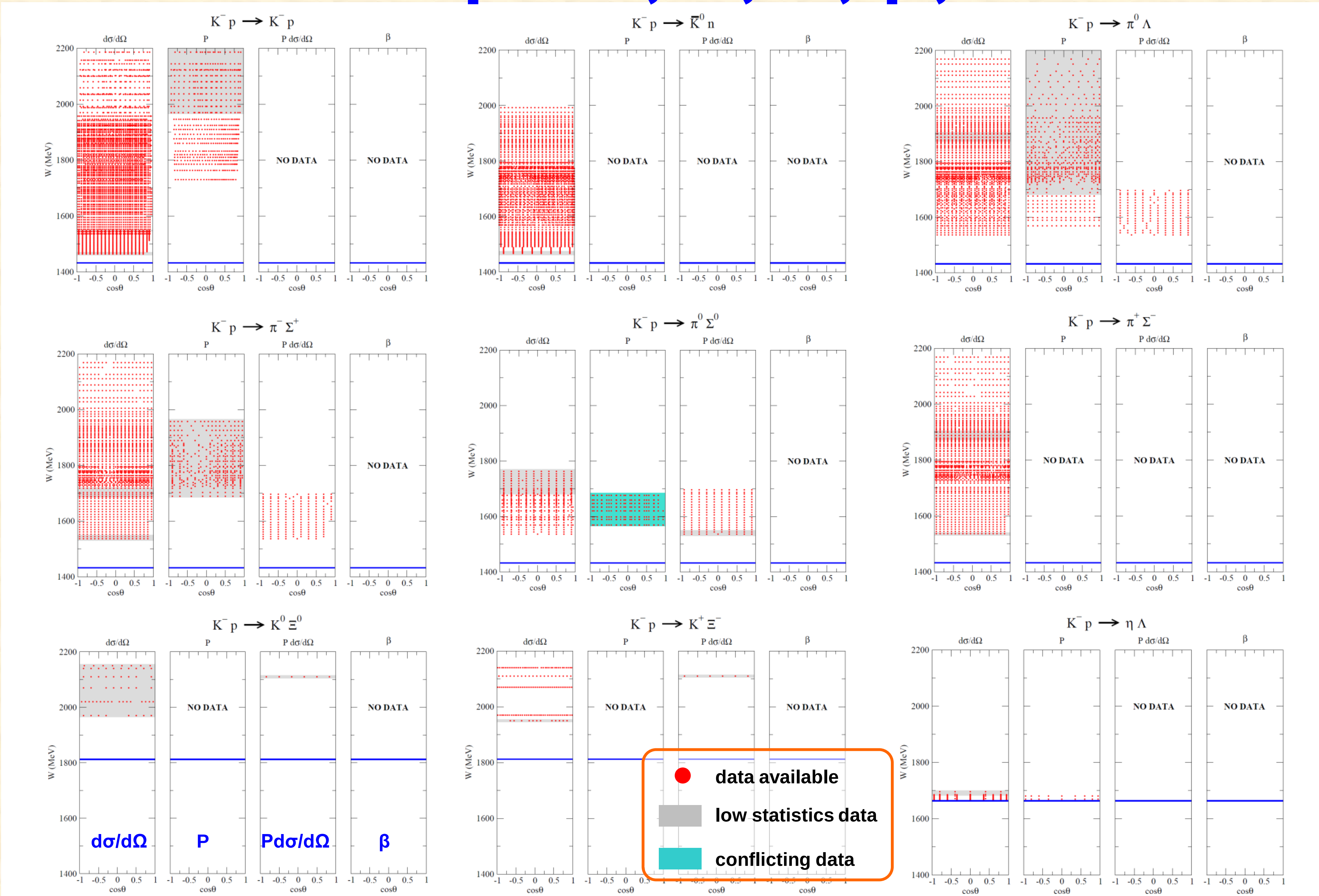
Kinematical (W, cosθ) coverage of available $K^- p \to \bar{K}N$, $\pi\Sigma$, $\pi\Lambda$, $\eta\Lambda$, $K\Xi$ data



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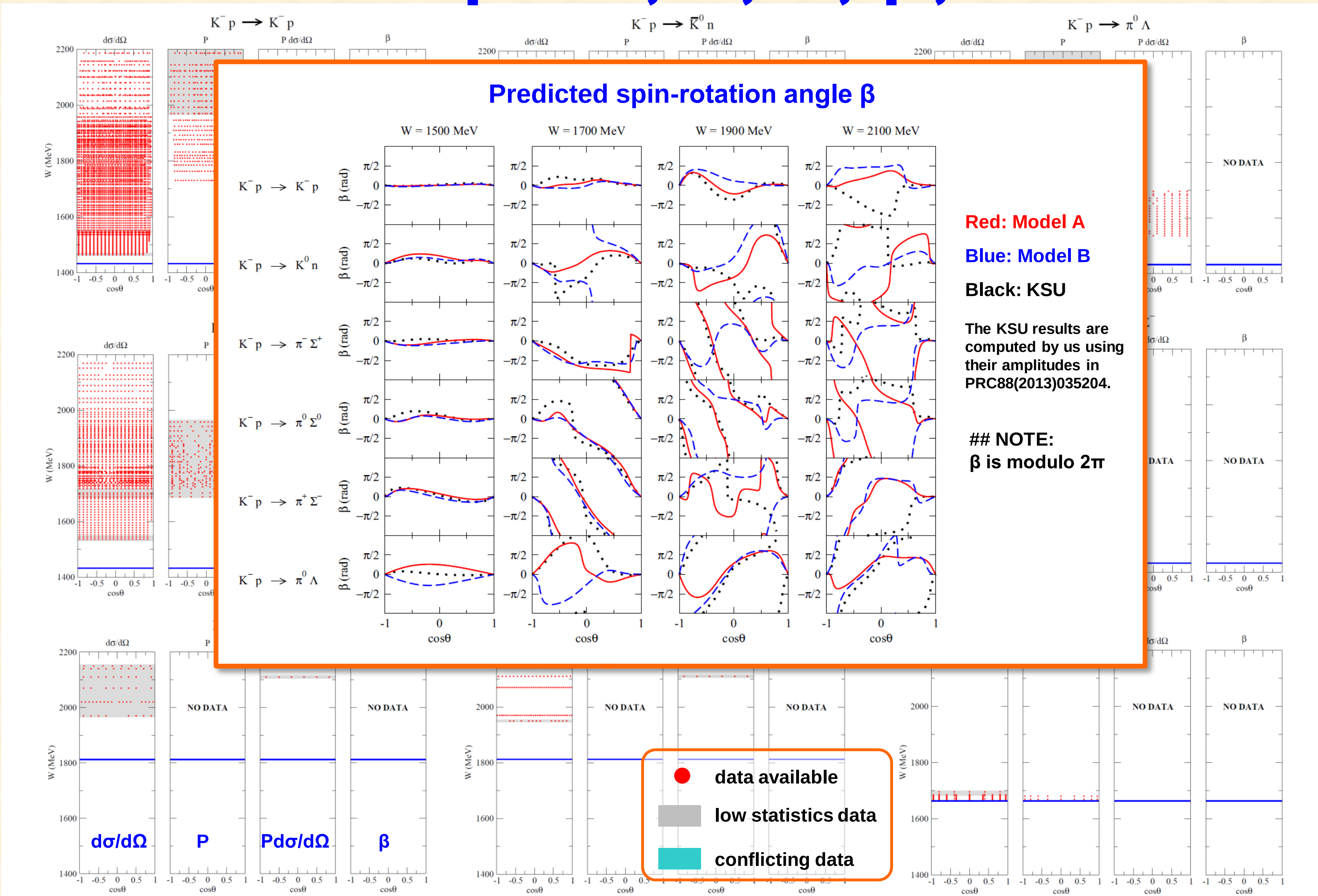

Extracted Λ* and Σ* mass spectrum

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

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

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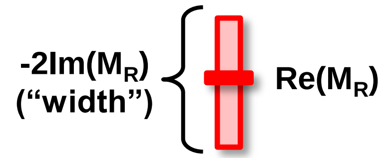
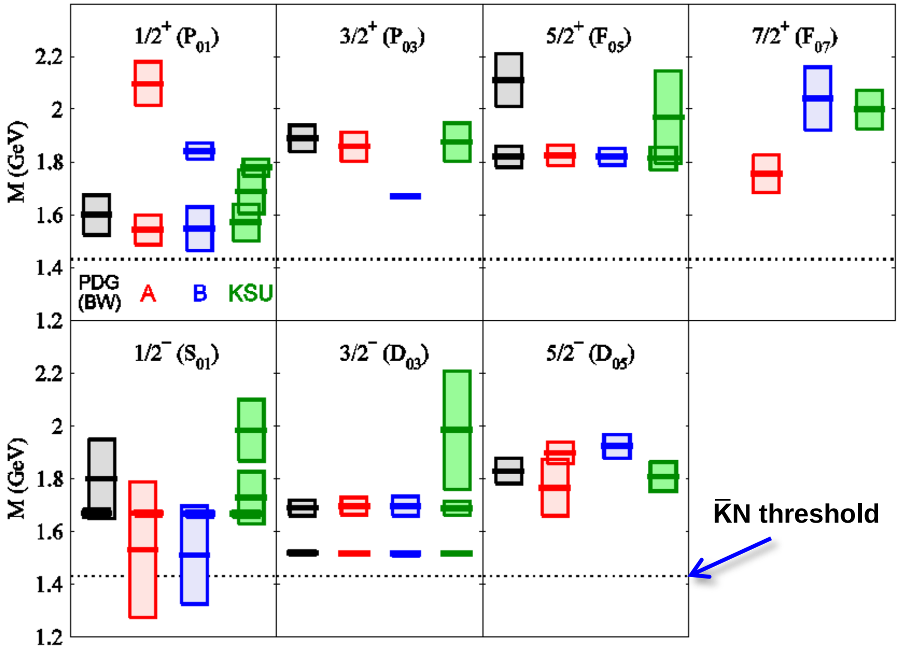
Green: KSU[PRC88(2013)035205]
Black: PDG (only 4- & 3-star Y*; Breit-Wigner)

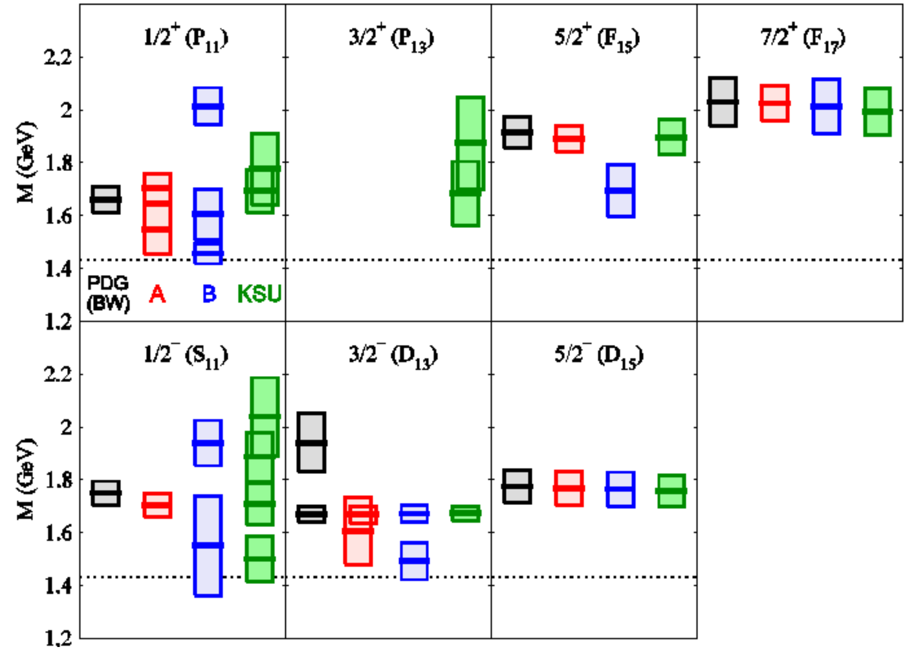


M_R : Resonance pole mass (complex)

$J^P(L_{I\,2J})$ "Λ" resonance (I=0)



$J^P(L_{I\,2J})$ "Σ" resonance (I=1)



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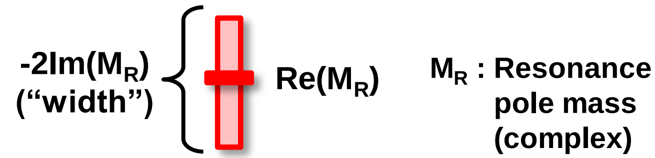

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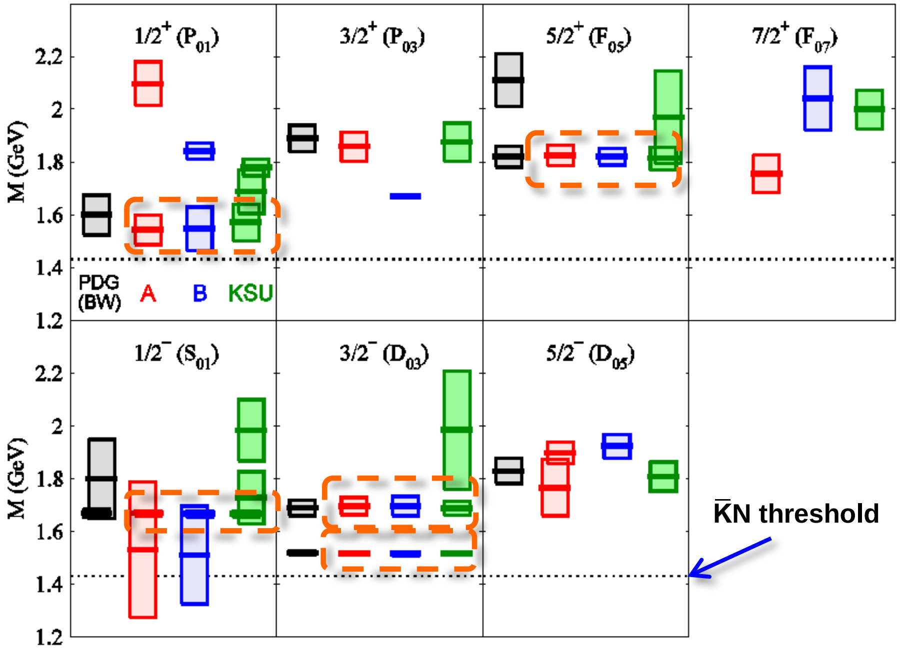

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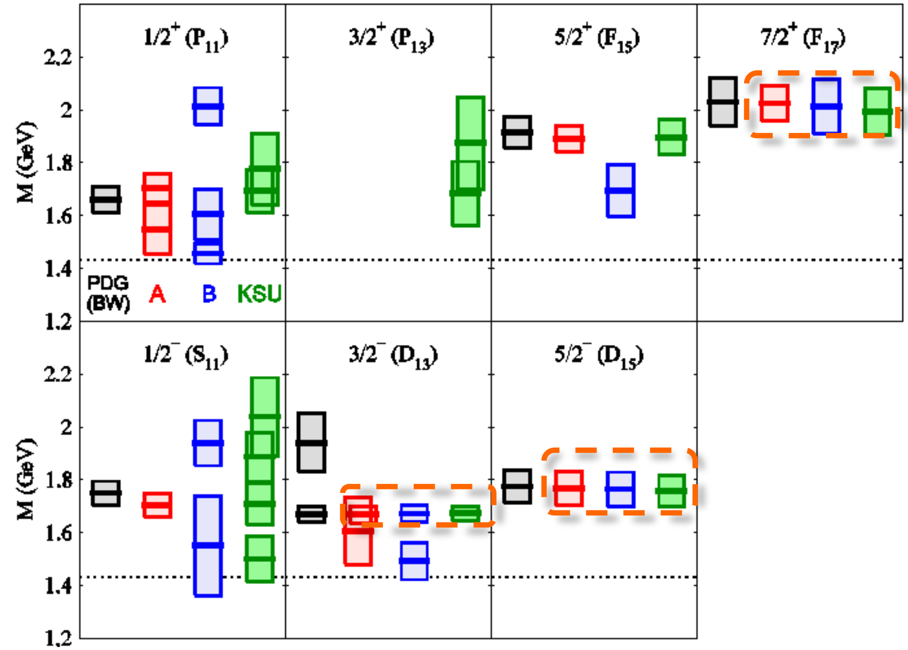

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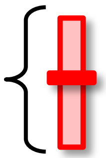
New narrow $3/2^+$ resonance
M = 1671 – 5i MeV
near the ηΛ threshold !!

-2Im(M_R) ("width")



Re(M_R)

M_R : Resonance pole mass (complex)

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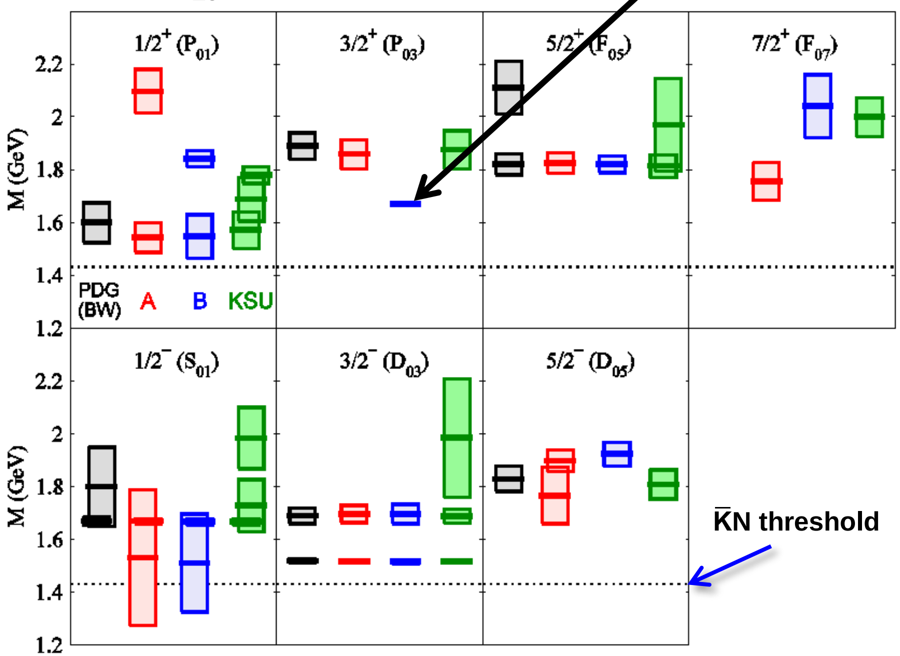

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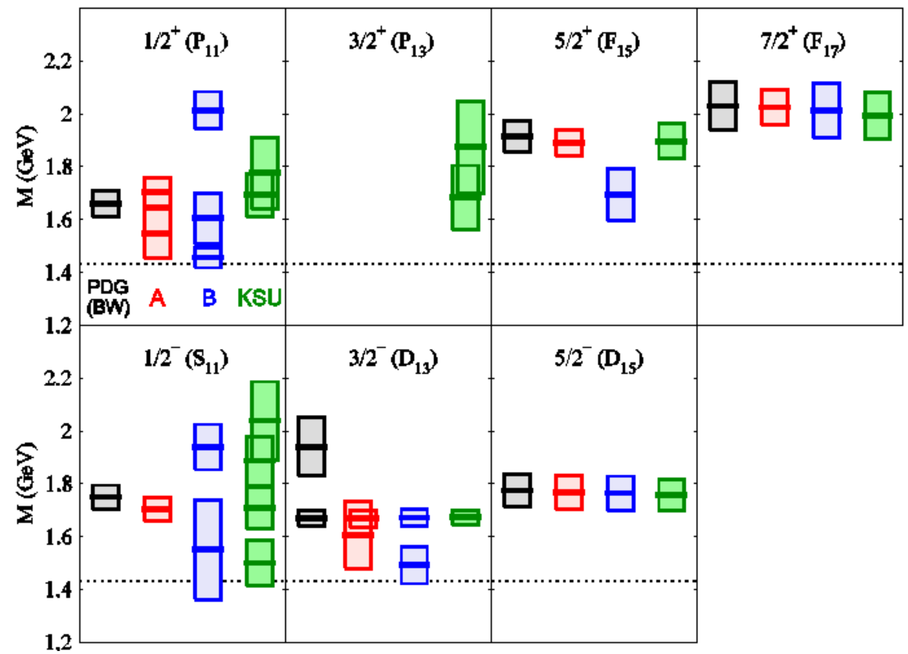

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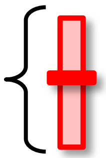
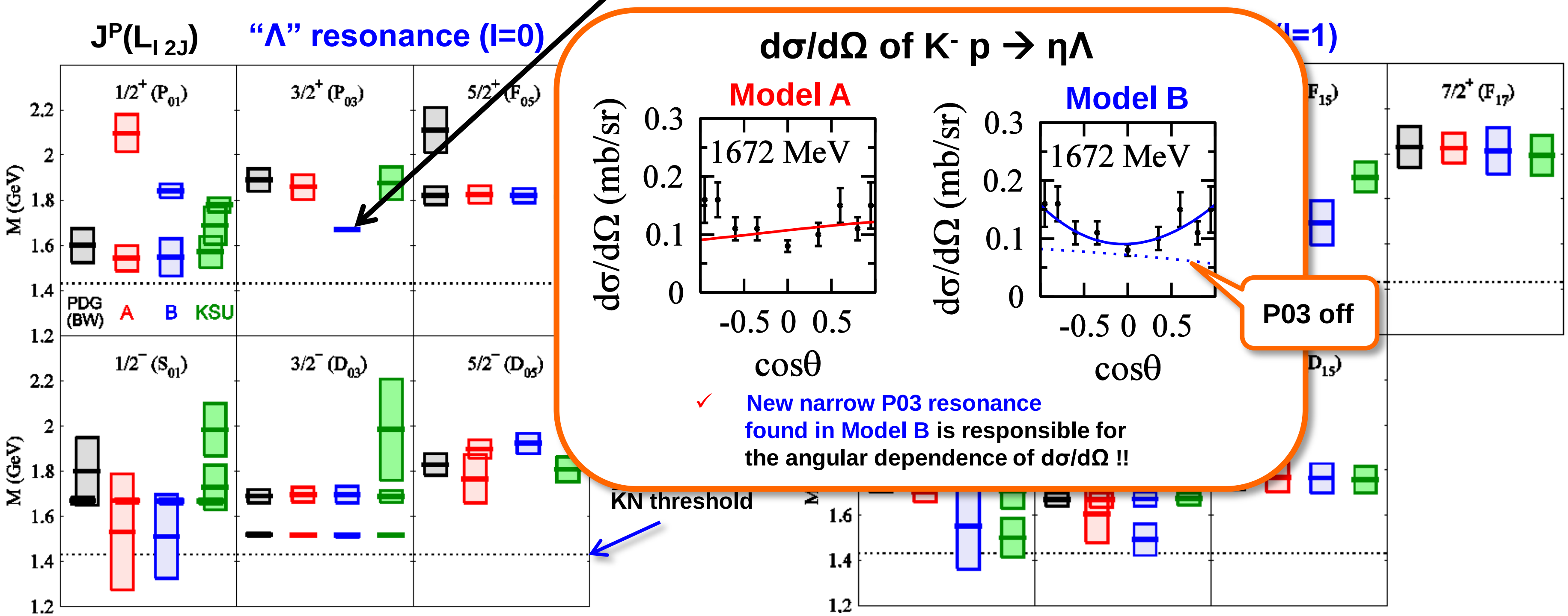
New narrow $3/2^+$ resonance
M = 1671 – 5i MeV
near the ηΛ threshold !!

-2Im(M_R) (“width”)



Re(M_R)

M_R : Resonance pole mass (complex)



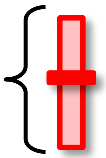
Extracted Λ* and Σ* mass spectrum

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)

-2Im(M_R)
("width")

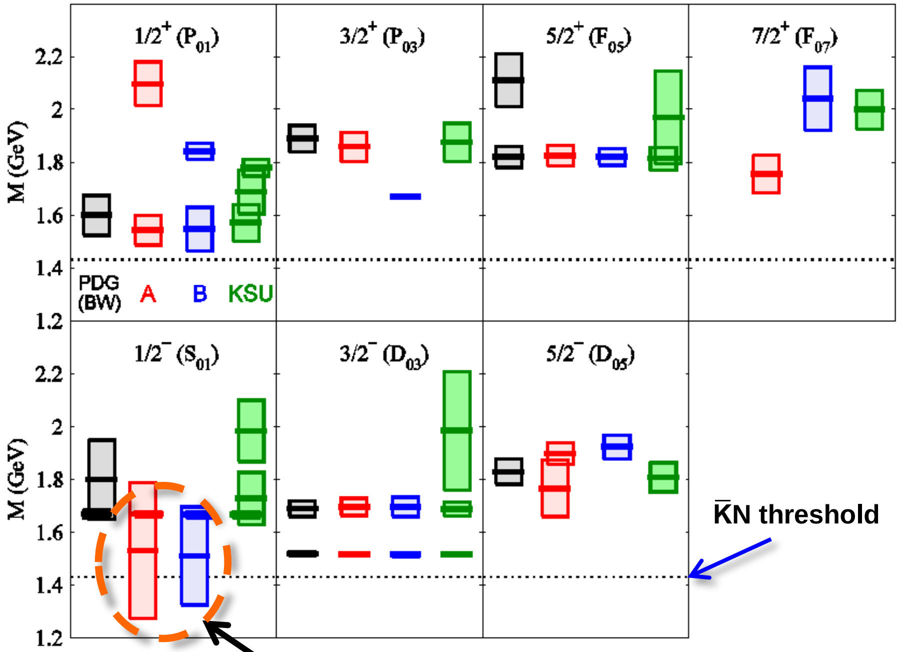


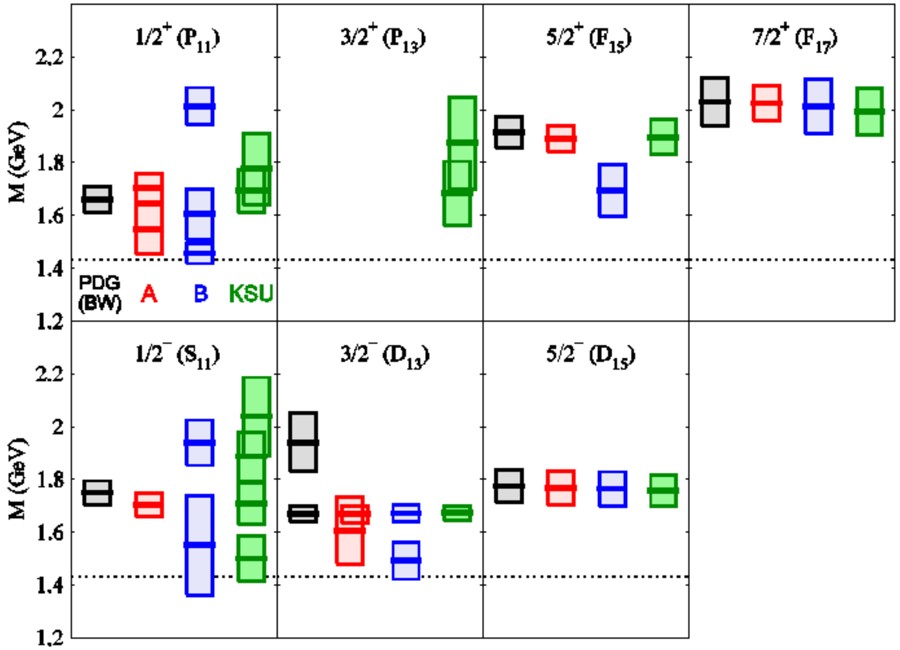
Re(M_R)

M_R : Resonance pole mass (complex)

$J^P(L_{I\ 2J})$ "Λ" resonance (I=0)

$J^P(L_{I\ 2J})$ "Σ" resonance (I=1)





Spin partner of
Λ(1520)3/2⁻ ??

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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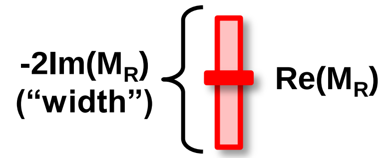
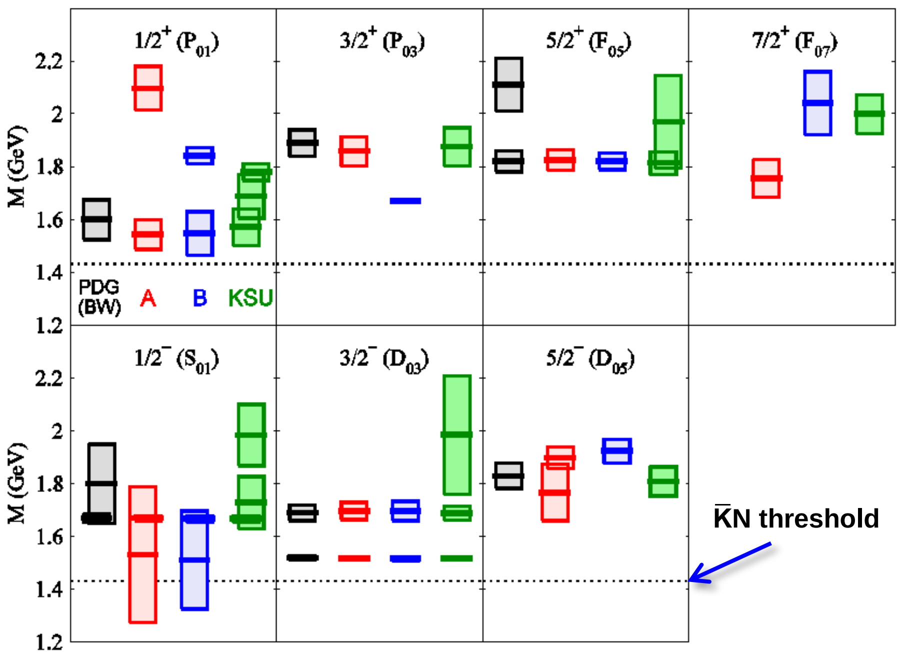
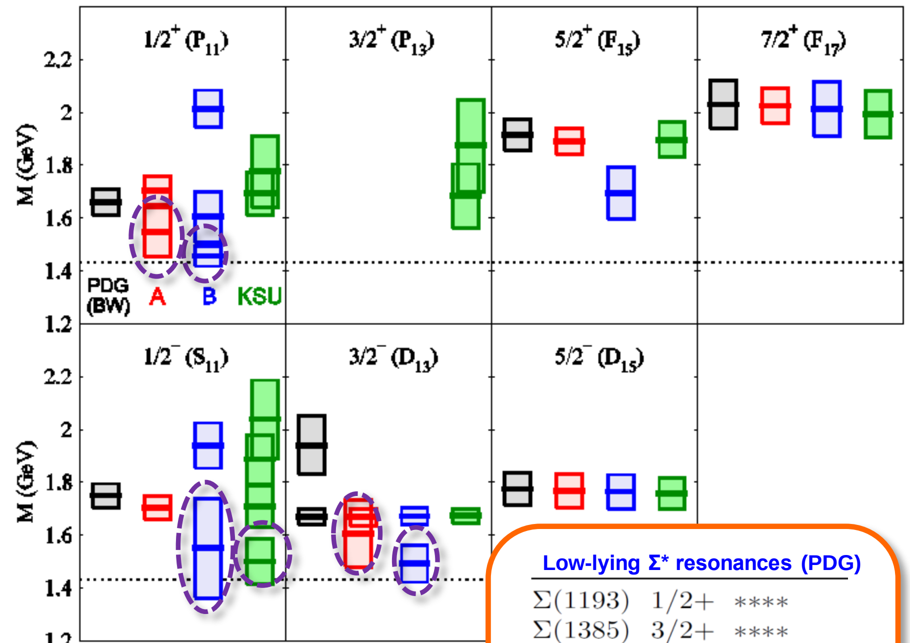


M_R : Resonance pole mass (complex)

$J^P(L_{I\ 2J})$ “Λ” resonance (I=0)



$J^P(L_{I\ 2J})$ “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−	****

?

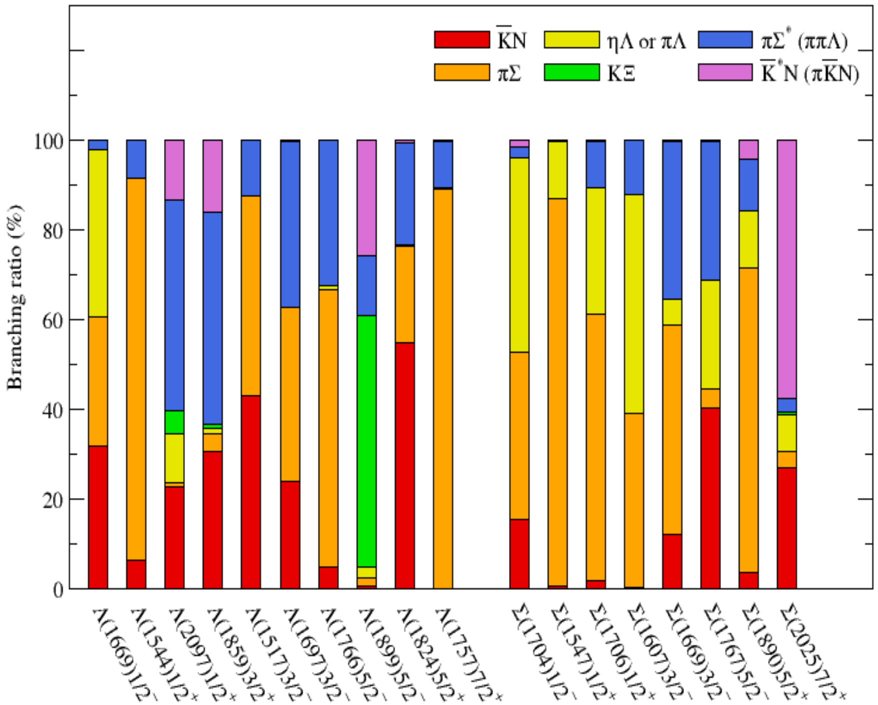
Importance of 2 → 3 reactions: Branching ratios of high-mass Y* resonances

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

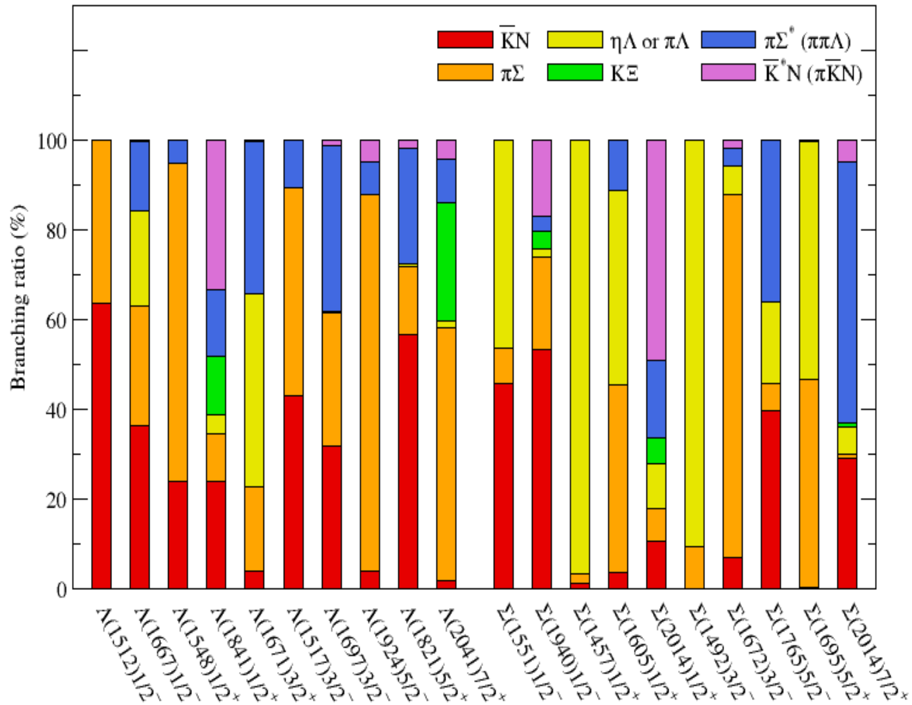
➢ **$K^- p \to \pi\pi\Lambda, \pi\bar{K}N$,… data would play a crucial role for establishing high-mass Y*.**

➔ 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

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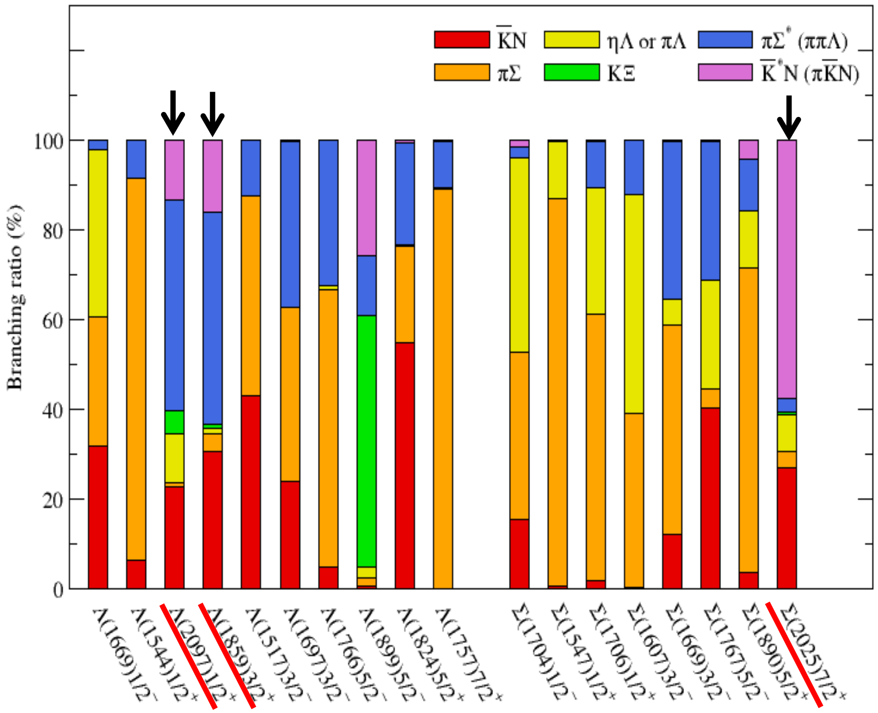
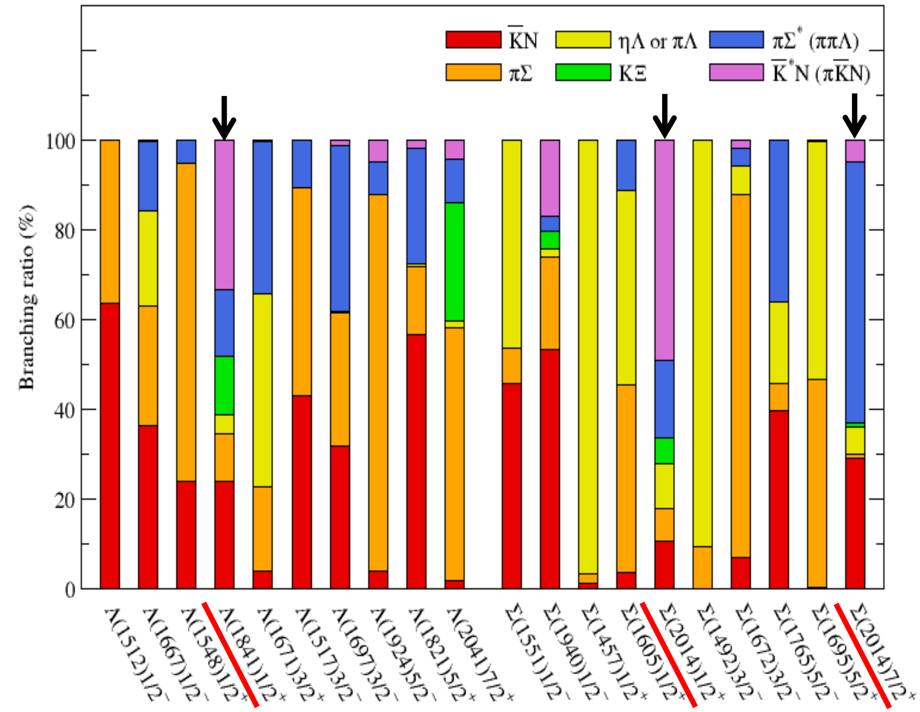


Model B



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

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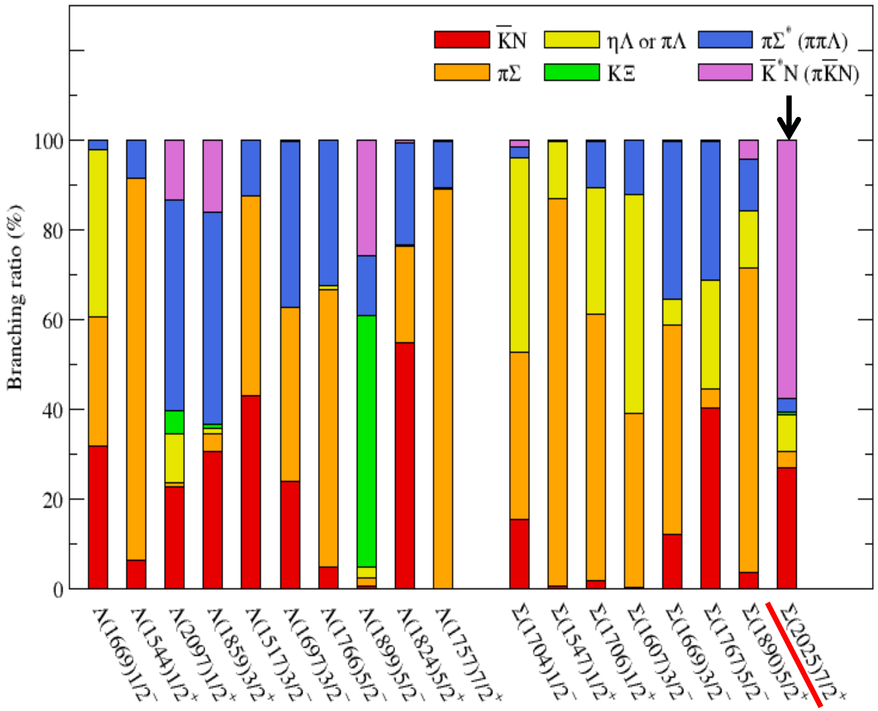
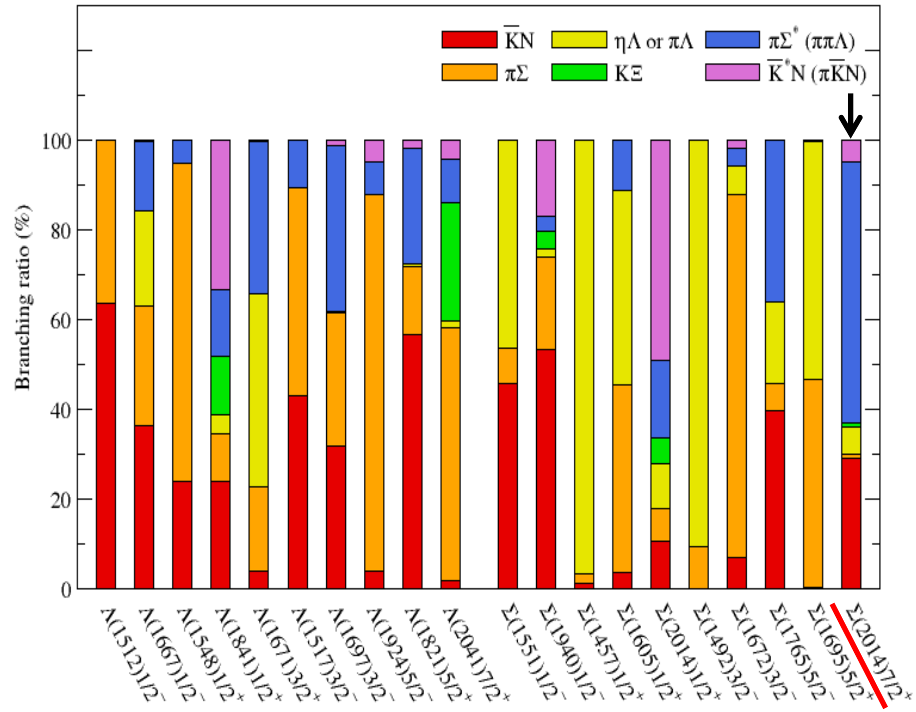
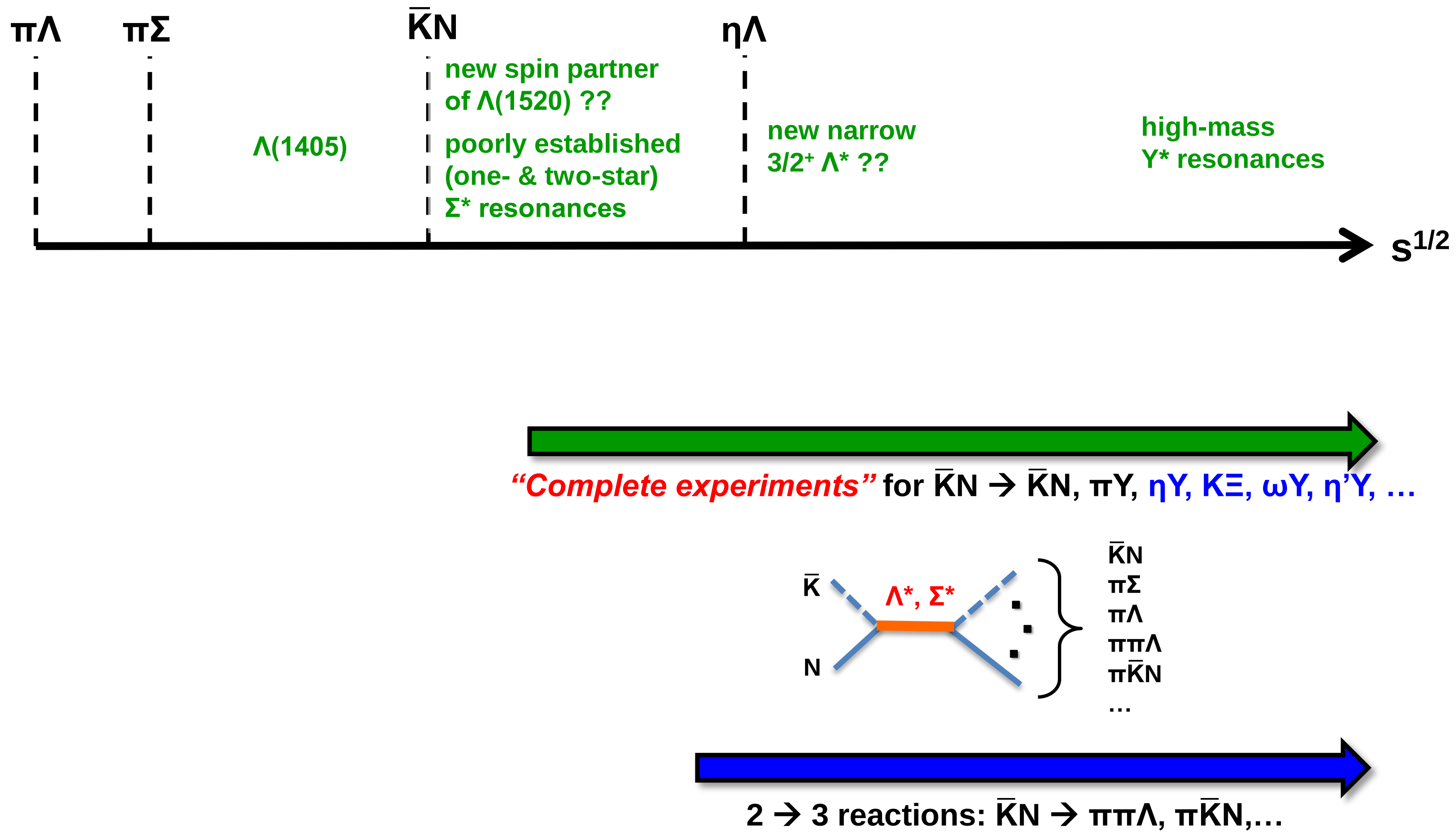


Model B



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

Strategy for establishing Y* resonances using antikaon-induced reactions



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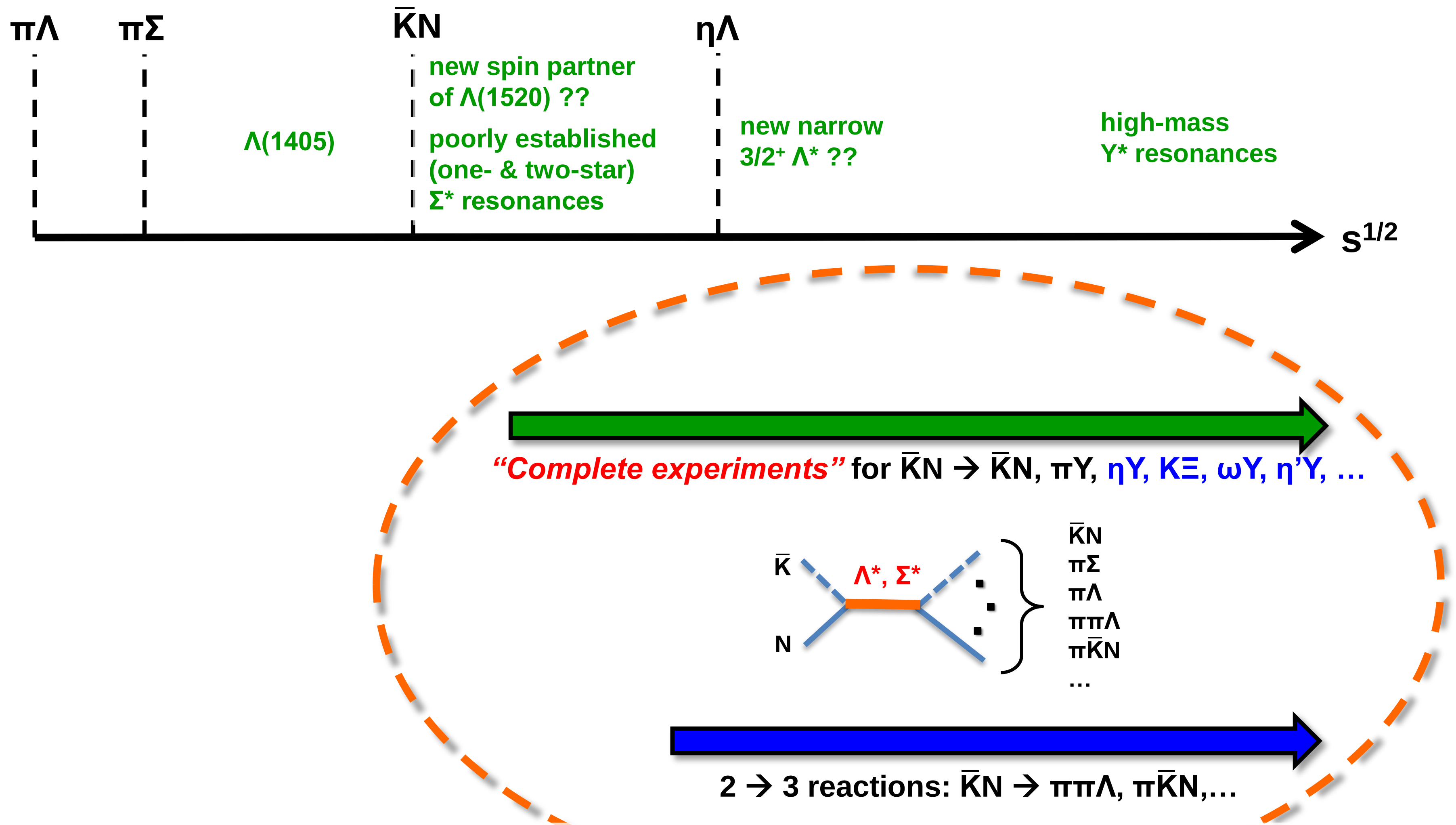

New measurements at J-PARC ??

[discussions with H. Sako, K. Hicks et al.]

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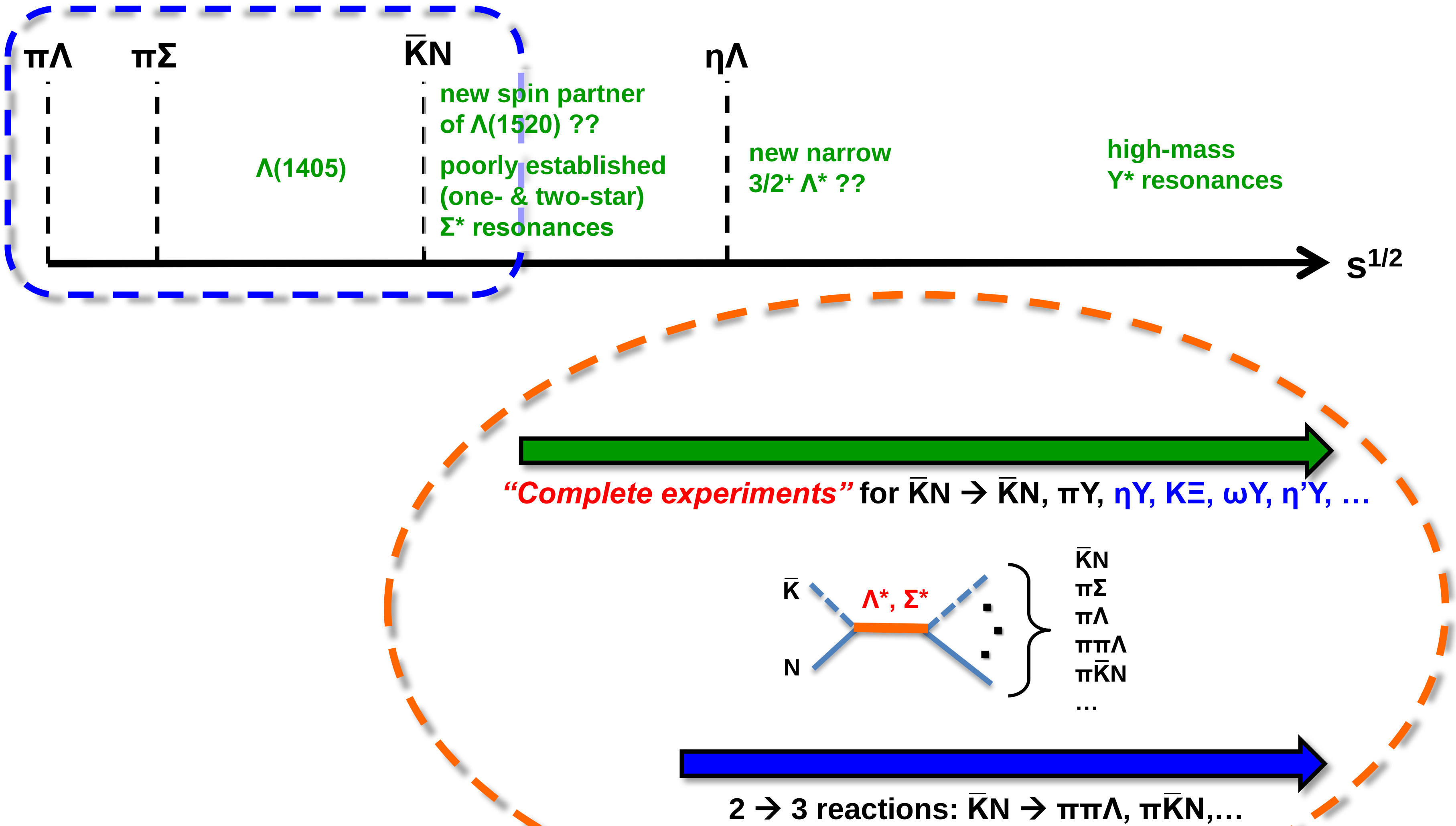

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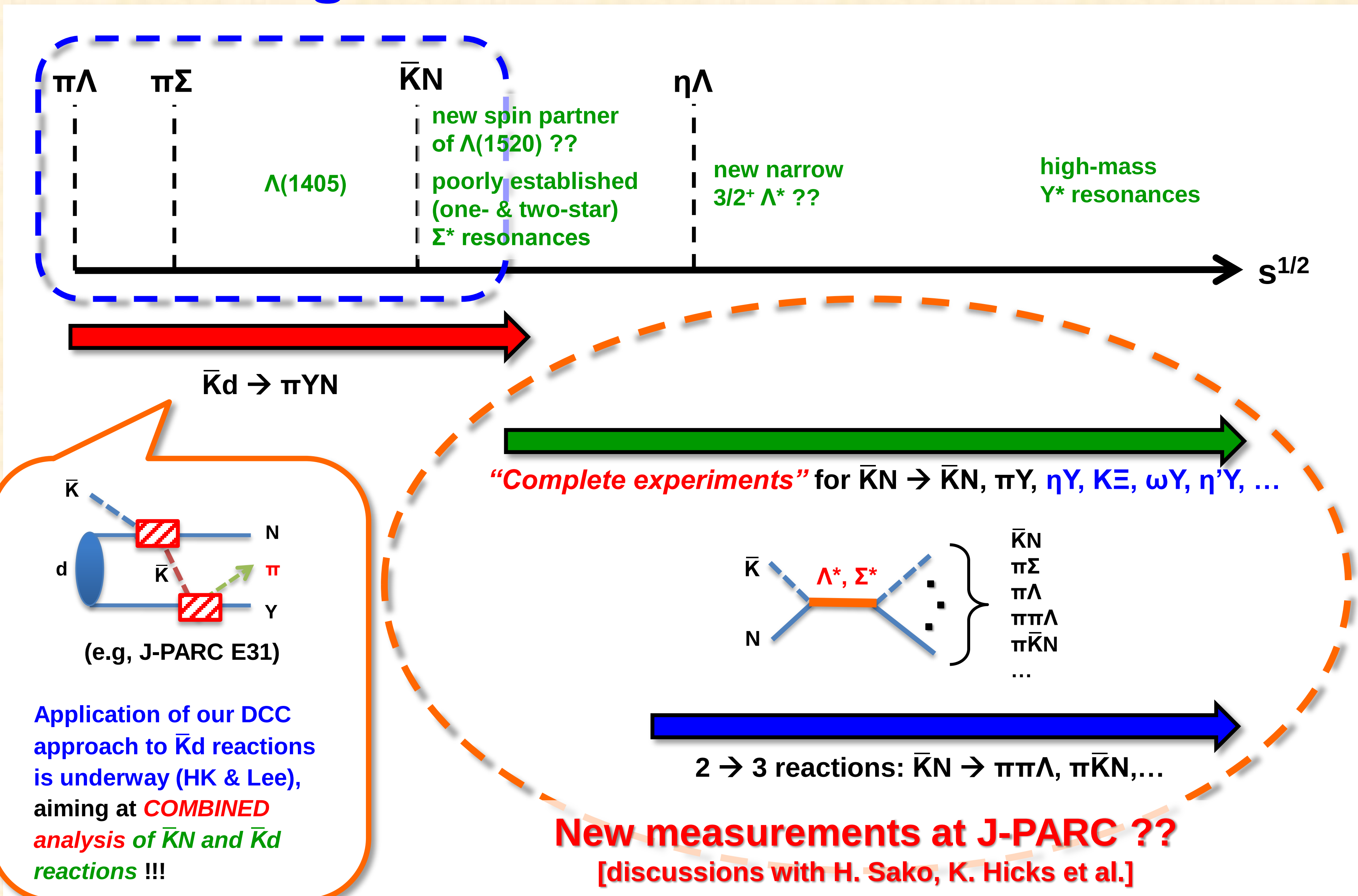

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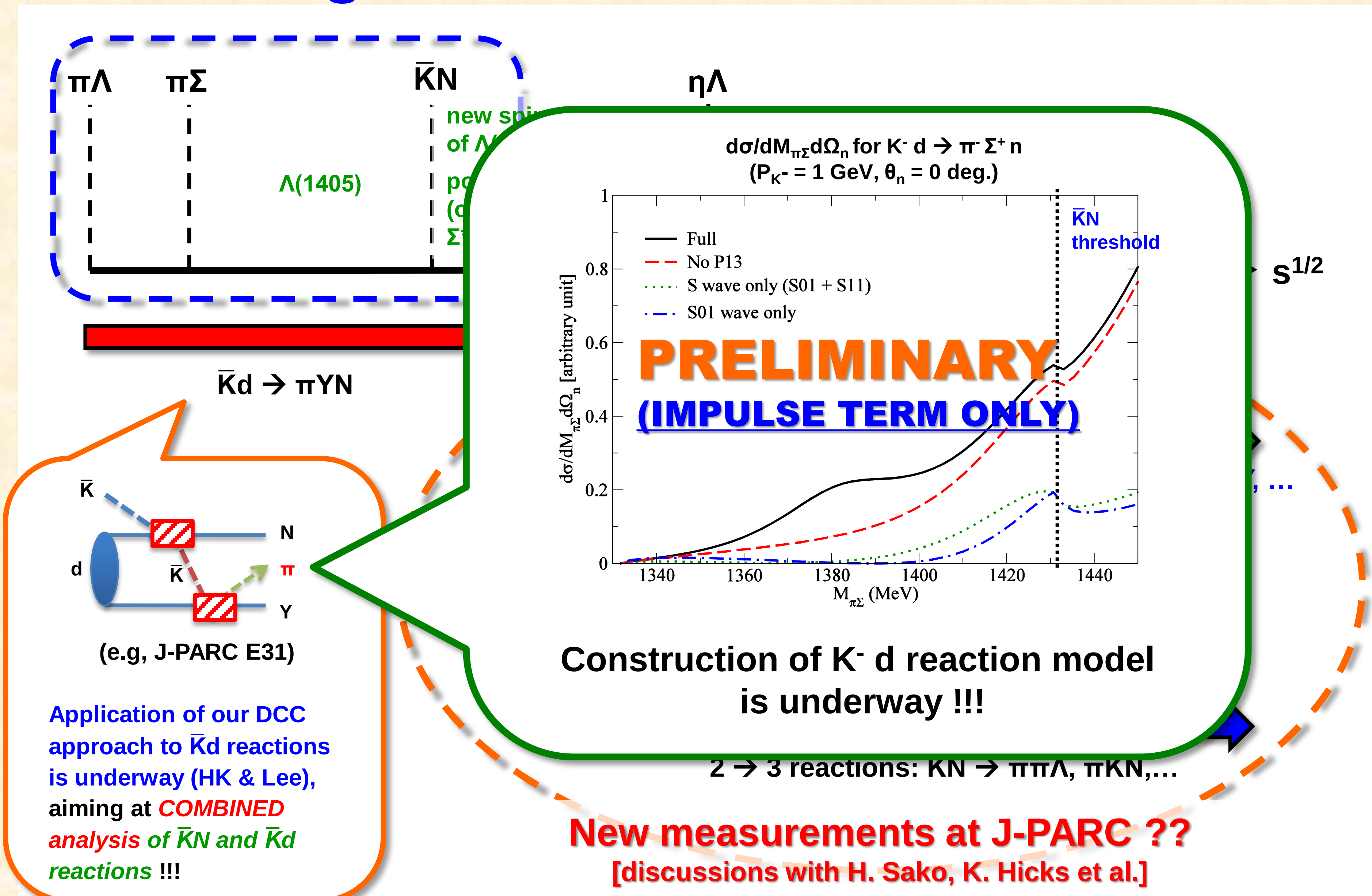

Summary

- ✓ 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 dynamical coupled-channels 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

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- ✓ New accurate data for both $\bar{K}N$ and $\bar{K}d$ reactions are much appreciated !!!
  - ➢ "Complete experiments" for 2 → 2 reaction ($\bar{K}N \rightarrow \bar{K}N$, $\pi\Sigma$, $\pi\Lambda$, $\eta\Lambda$, $K\Xi$, $\eta\Sigma$, $\eta'Y$, ωY, ΦY,…)
  - ➢ 2 → 3 reaction ($\bar{K}N \rightarrow \pi\pi Y$, $\pi\bar{K}N$,…) to determine high-mass Y*
  - ➢ Deuteron-target reaction ($\bar{K}d \rightarrow \pi YN$, …) to determine low-lying Y*

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 dynamical coupled-channels approach.

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- ✓ New accurate data for both $\bar{K}N$ and $\bar{K}d$ reactions are much appreciated !!!
  - "Complete experiments" for 2 → 2 reaction ($\bar{K}N \rightarrow \bar{K}N$, πΣ, πΛ, ηΛ, KΞ, ηΣ, η'Y, ωY, ΦY,…)
  - 2 → 3 reaction ($\bar{K}N \rightarrow \pi\pi Y$, $\pi\bar{K}N$,…) to determine high-mass Y*
  - Deuteron-target reaction ($\bar{K}d \rightarrow \pi YN$, …) to determine low-lying Y*

The help of J-PARC is definitely needed for "complete" determination of Y* resonance mass spectrum !!!

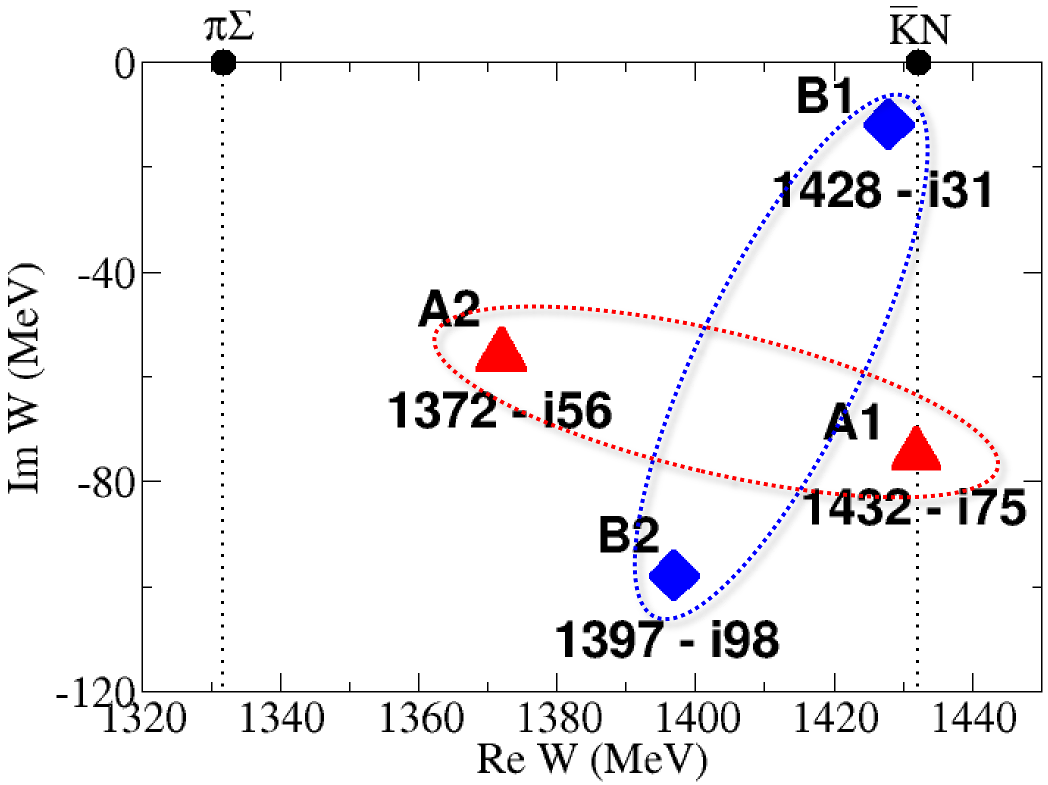
Back up

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.

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



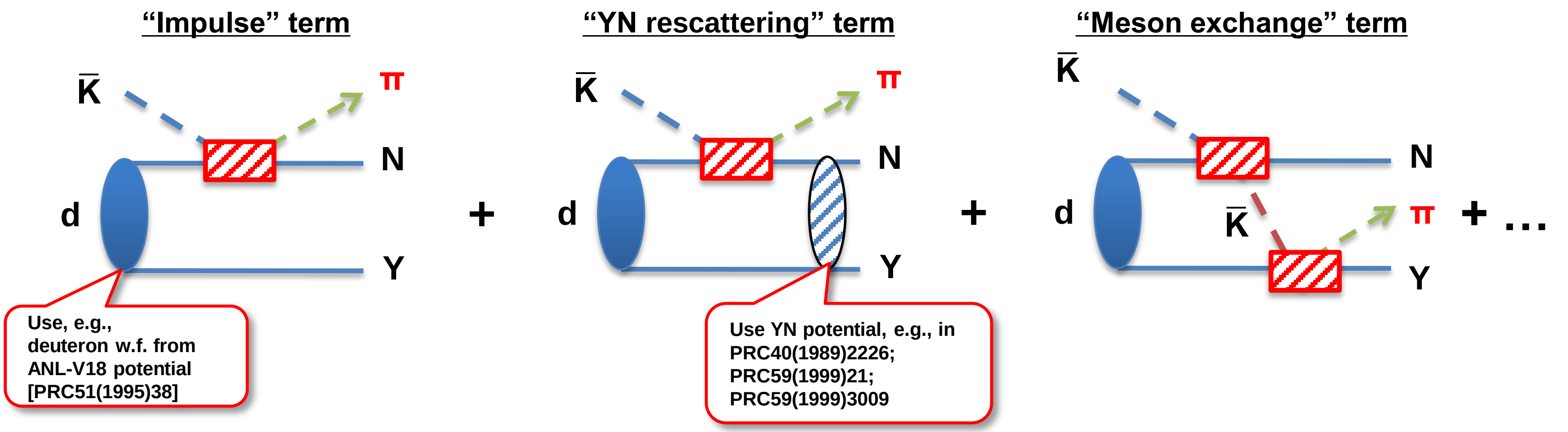
✓ Two resonance poles are found in both Models A and B.

- 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

Model for deuteron-target reactions

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

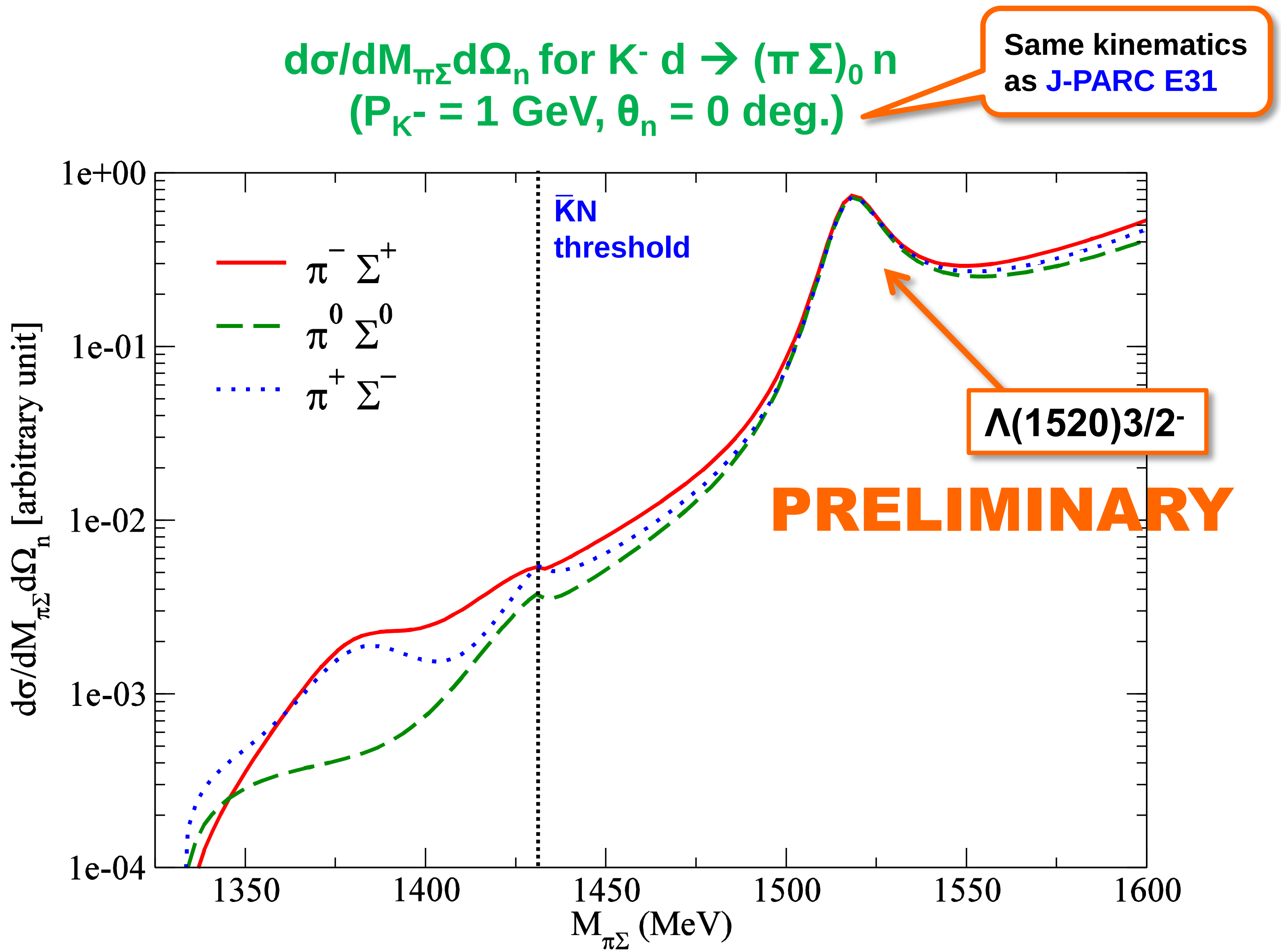


Unique feature of our work:

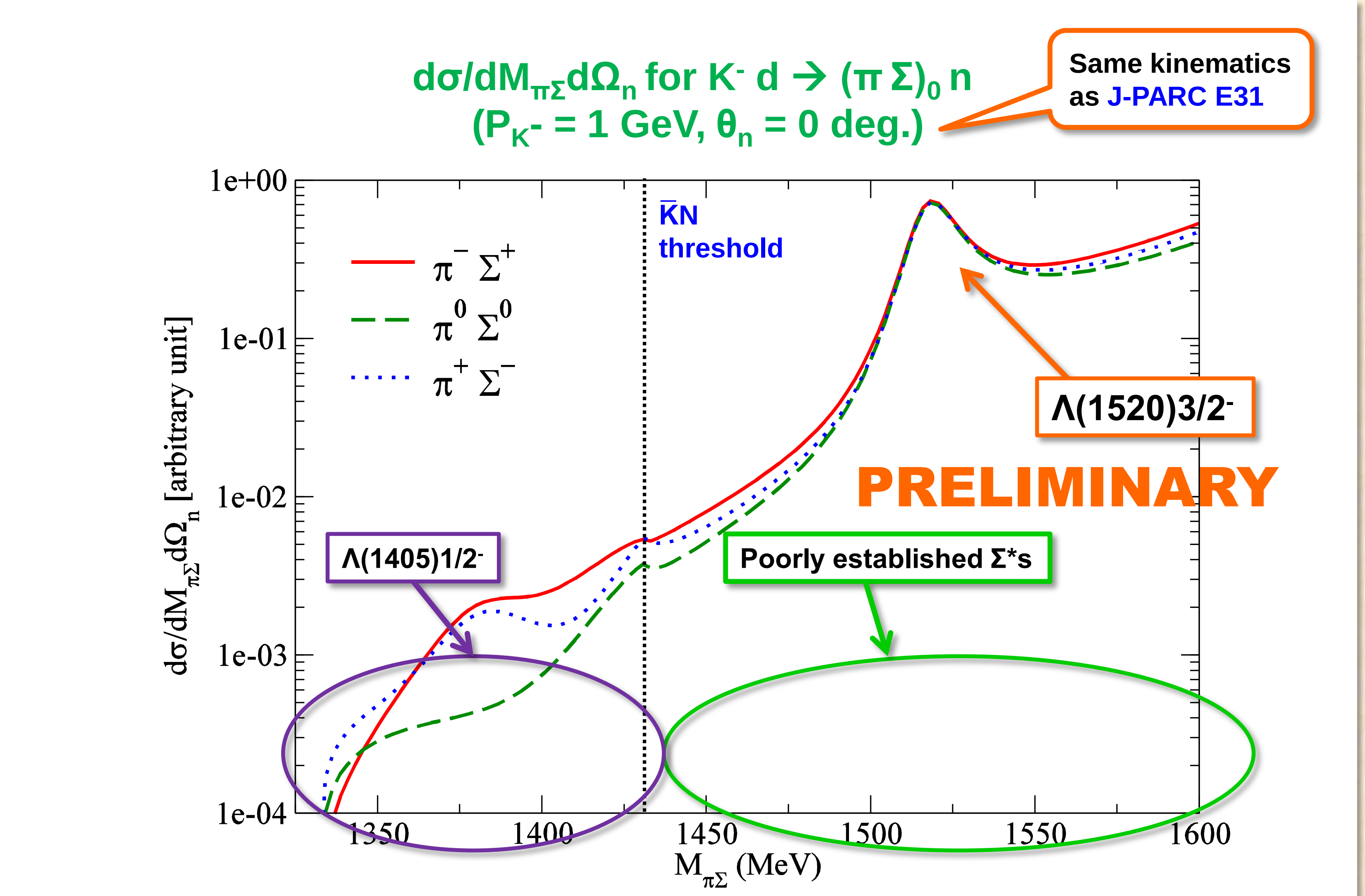
For meson-baryon sub-processes, we have *full-off-shell* amplitudes

- ➢ **well-tested by $K^- p \rightarrow \bar{K}N$, $\pi\Sigma$, $\pi\Lambda$, $\eta\Lambda$, $K\Xi$ up to W = 2.1 GeV.**
- ➢ **not only for S wave, but also P, D, F waves.**

Results (IMPULSE TERM ONLY !!)



Results (IMPULSE TERM ONLY !!)



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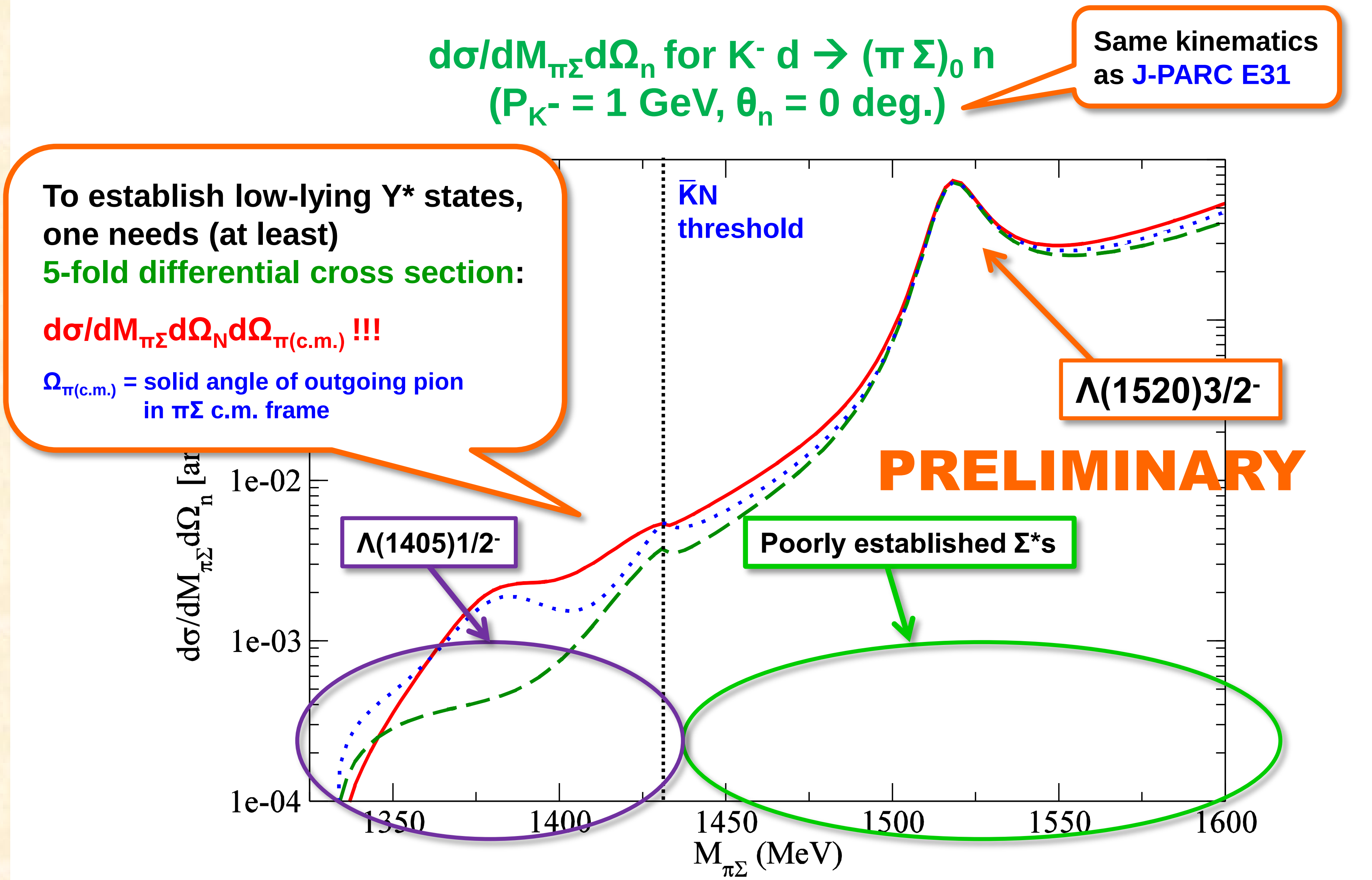
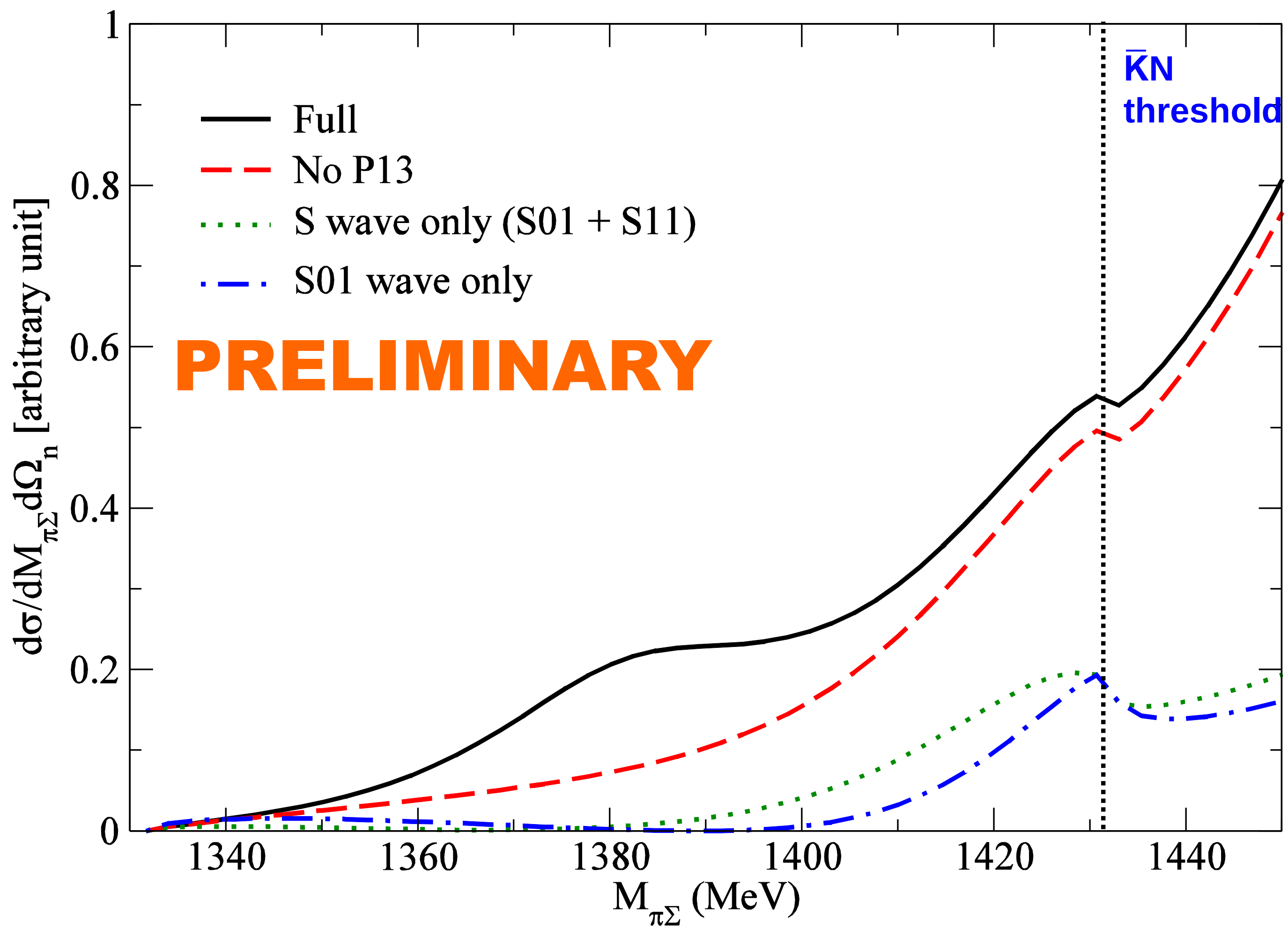


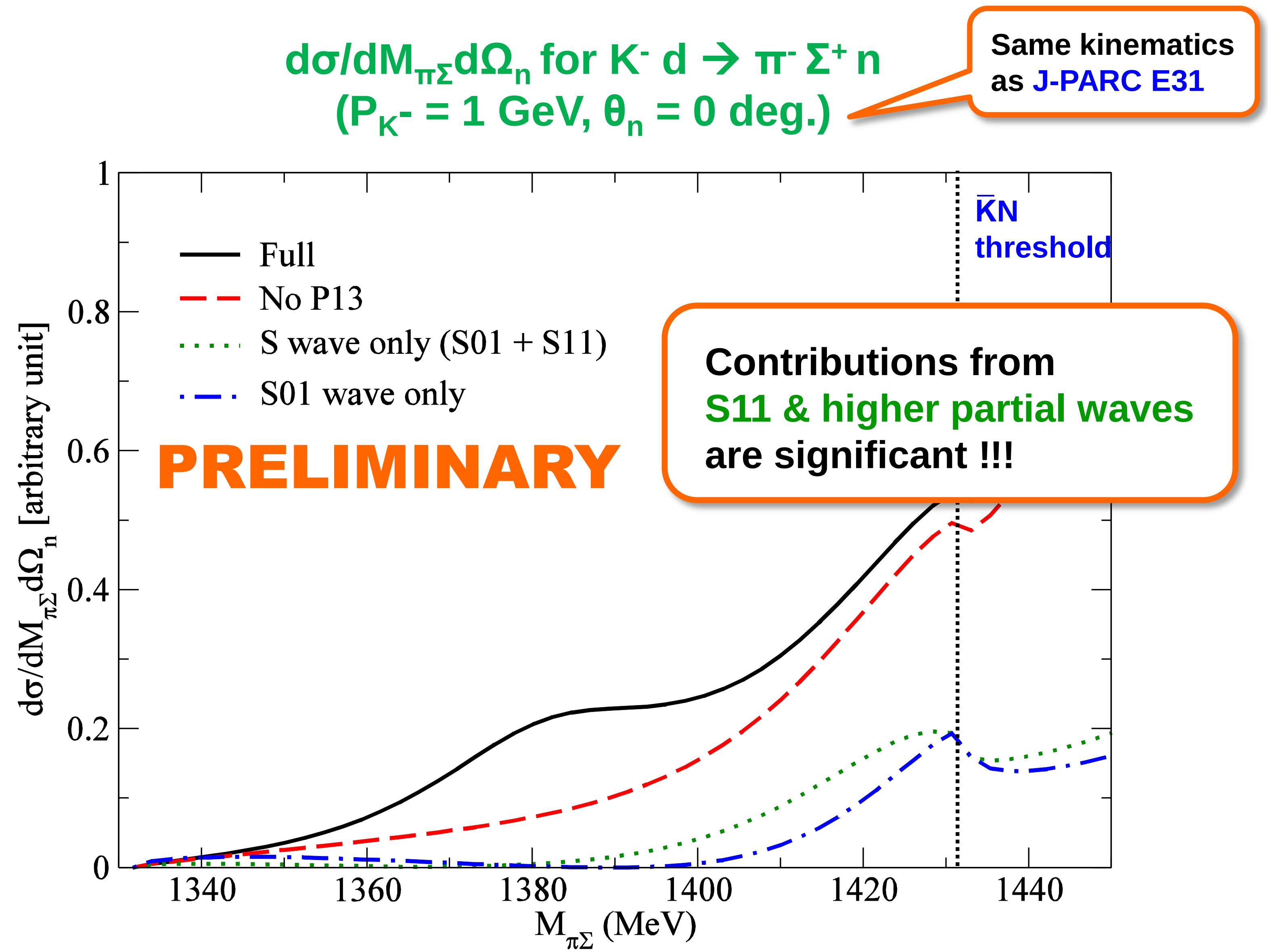
Results (IMPULSE TERM ONLY !!)

$d\sigma/dM_{\pi\Sigma}d\Omega_n$ for $K^- d \rightarrow \pi^- \Sigma^+ n$
(P_{K^-} = 1 GeV, θ_n = 0 deg.)

Same kinematics as J-PARC E31



Results (IMPULSE TERM ONLY !!)



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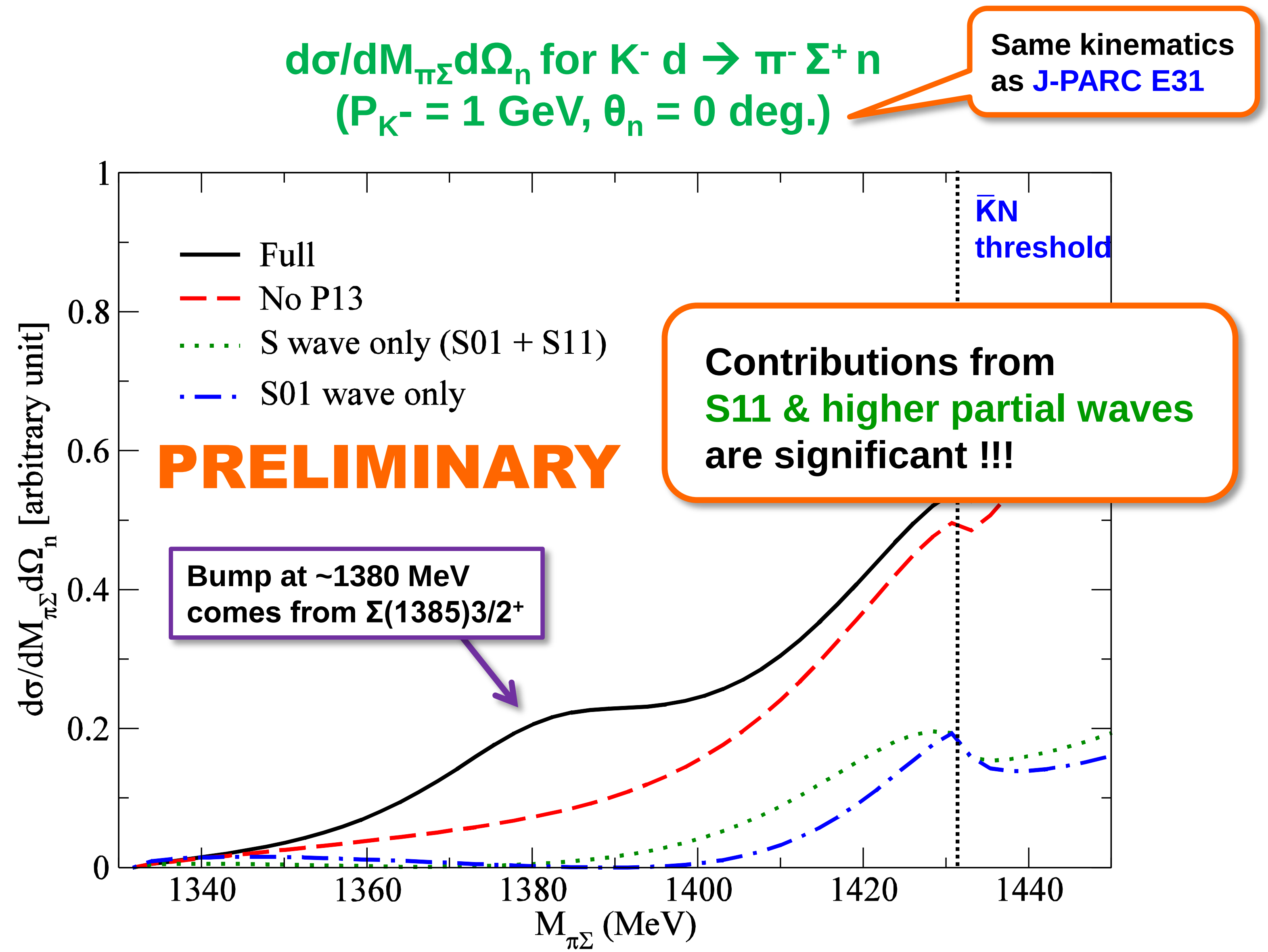
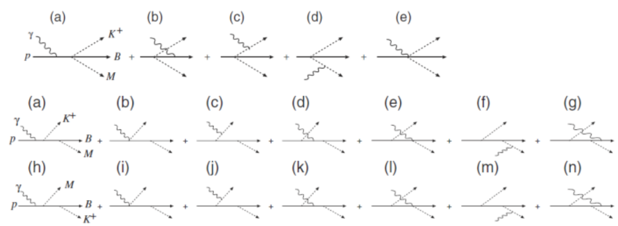
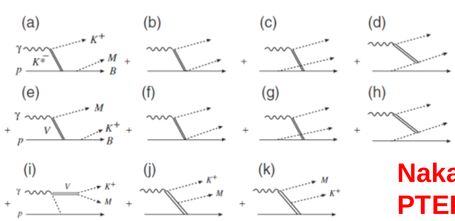


How we study the region below the $\bar{K}N$ threshold ?

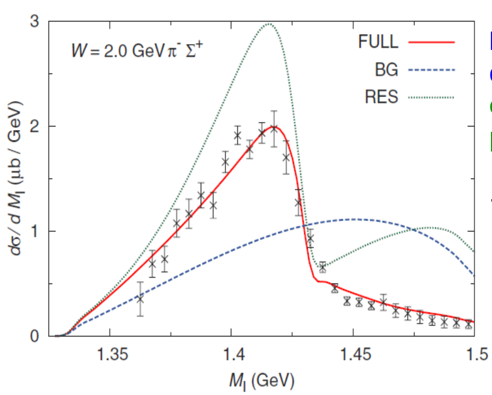
$\gamma p \rightarrow K^+\pi\Sigma$ @CLAS

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





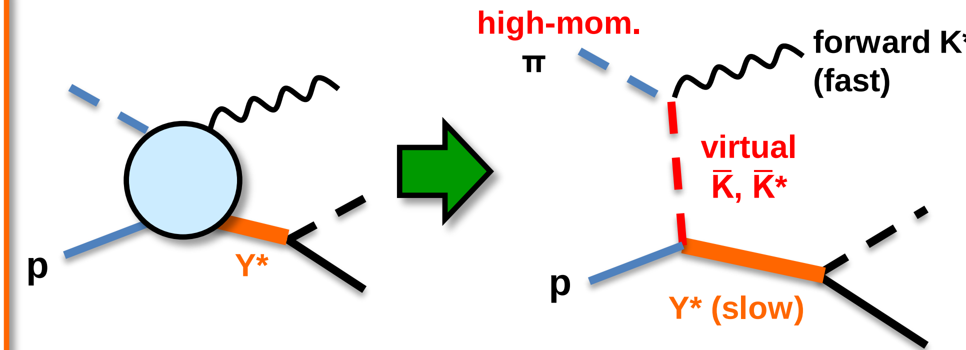
Nakamura, Jido, PTEP(2014)023D01



Large model/analysis 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−	****

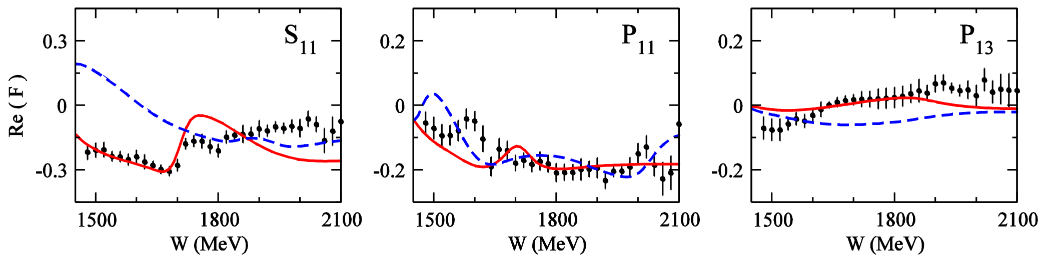
} ? (Σ(1480)–Σ(1620))

New data can eliminate analysis dependence ??

Extracted $\bar{K}N \to \pi\Lambda$ amplitudes

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

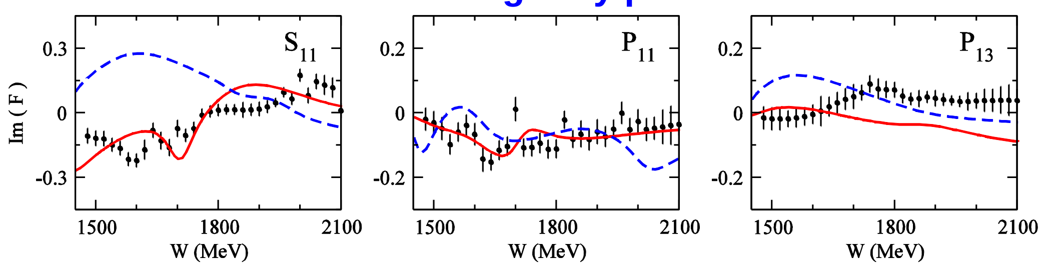
Real parts

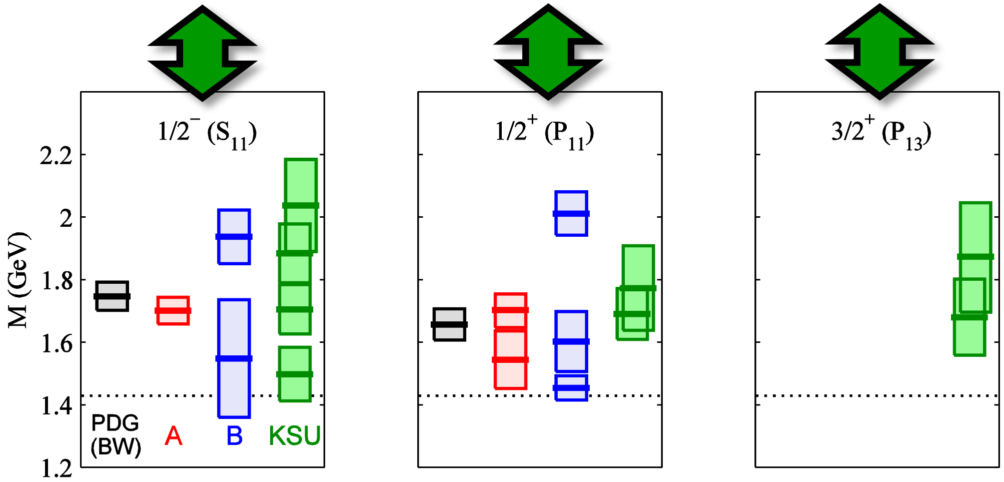


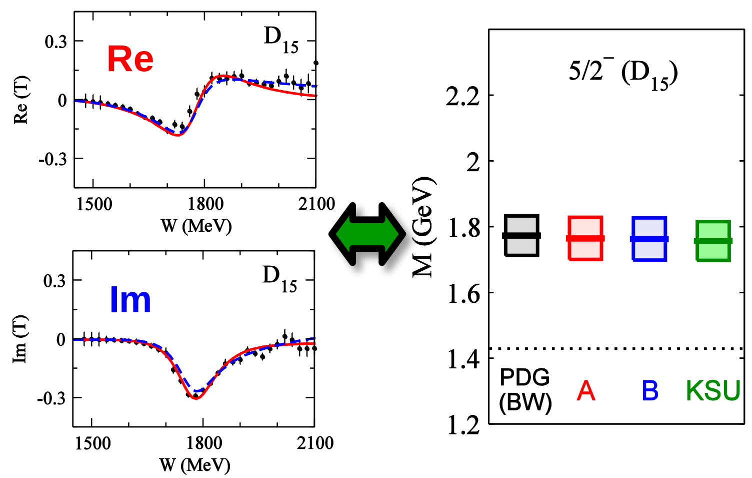
$L_{I\,2J}$: L = S,P,.. ; I = isospin;
J = Total angular mom.

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

Imaginary parts



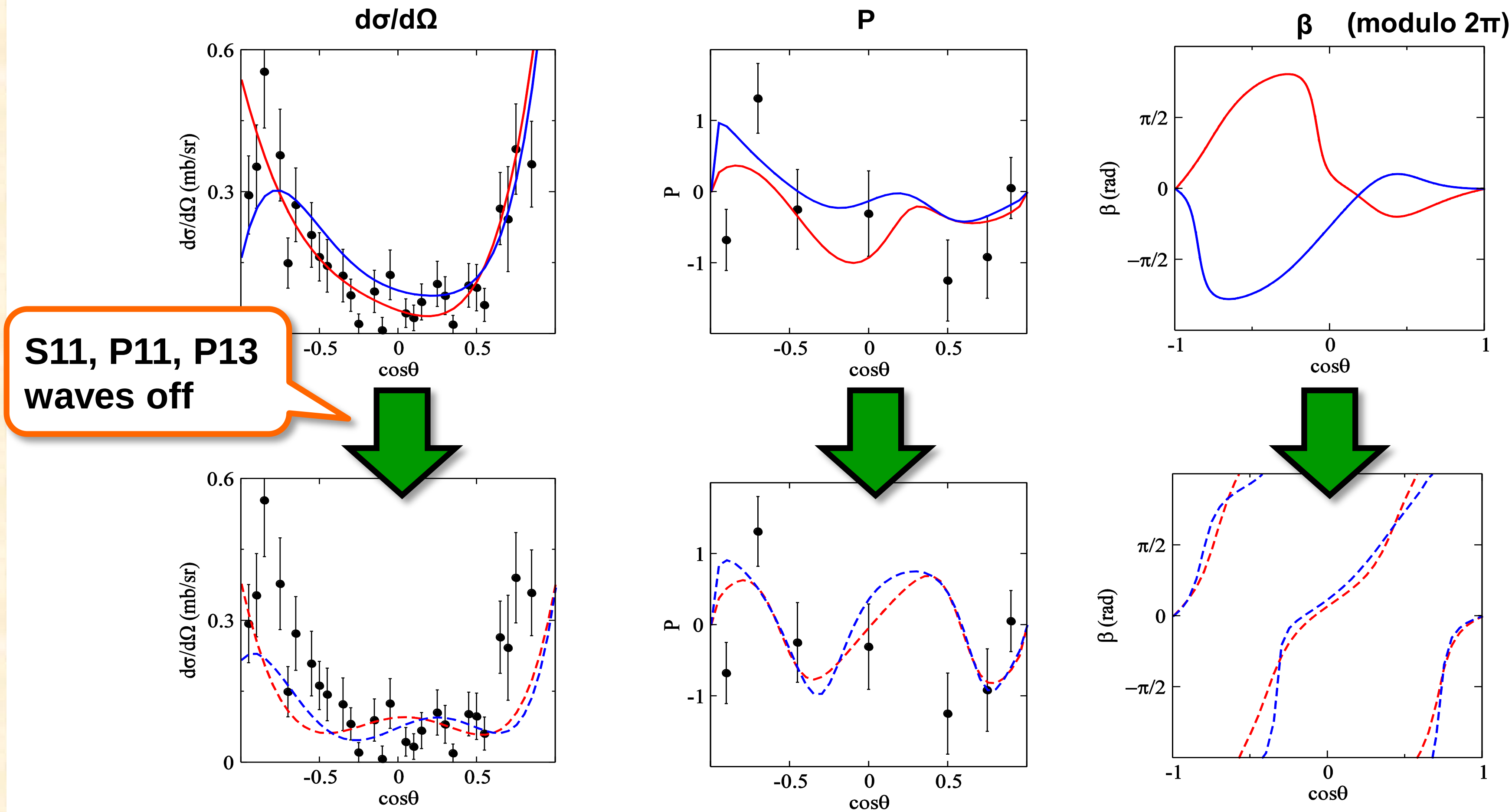




New data can eliminate analysis dependence ??

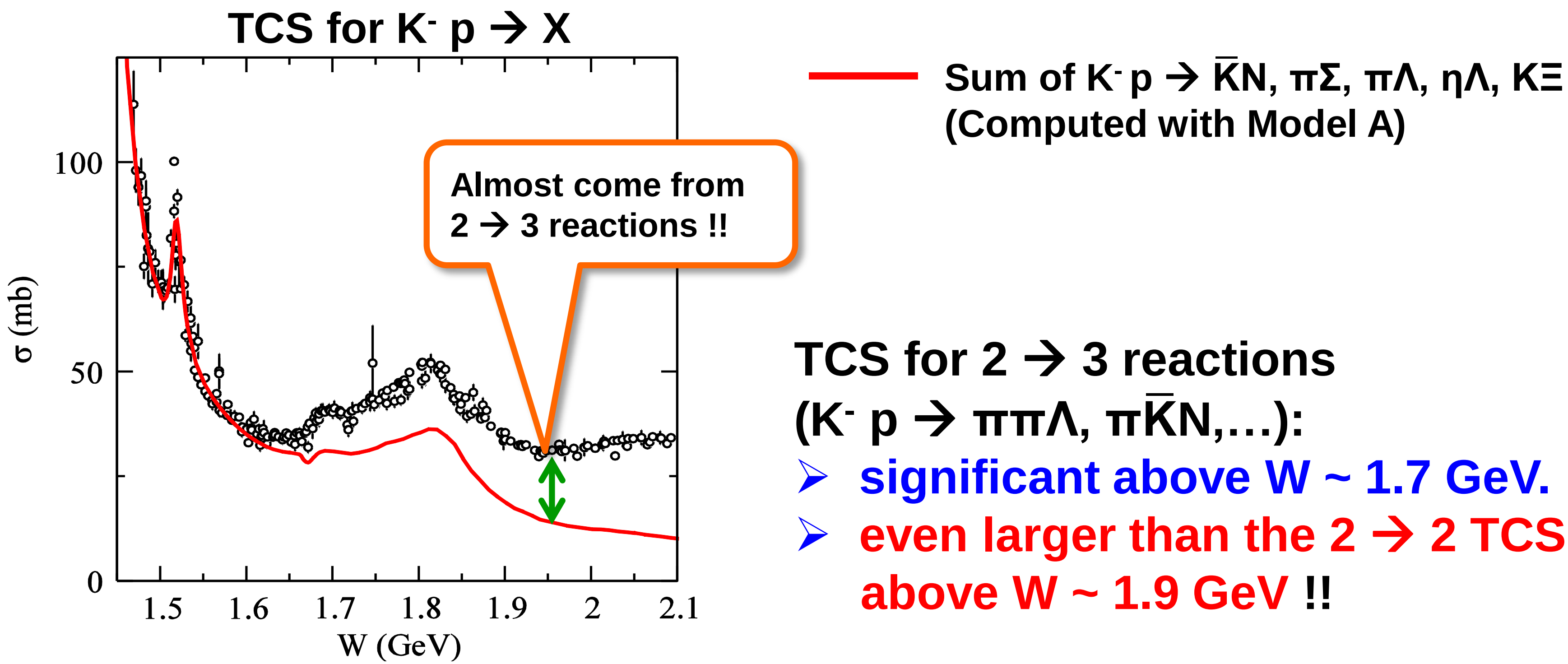
$K^-p \rightarrow \pi^0\Lambda$ observables @ W = 1700 MeV

Red: Model A
Blue: Model B



- At this energy, the difference between Models A & B mostly comes from S11, P11, P13 waves.
- High statistics data (of P and β in particular) will reduce significantly the analysis dependence !!!

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



TCS for 2 → 3 reactions
(K⁻ p → ππΛ, πK̄N,…):

- 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 !!

Extracted scattering lengths and effective ranges

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

Scattering length and effective range

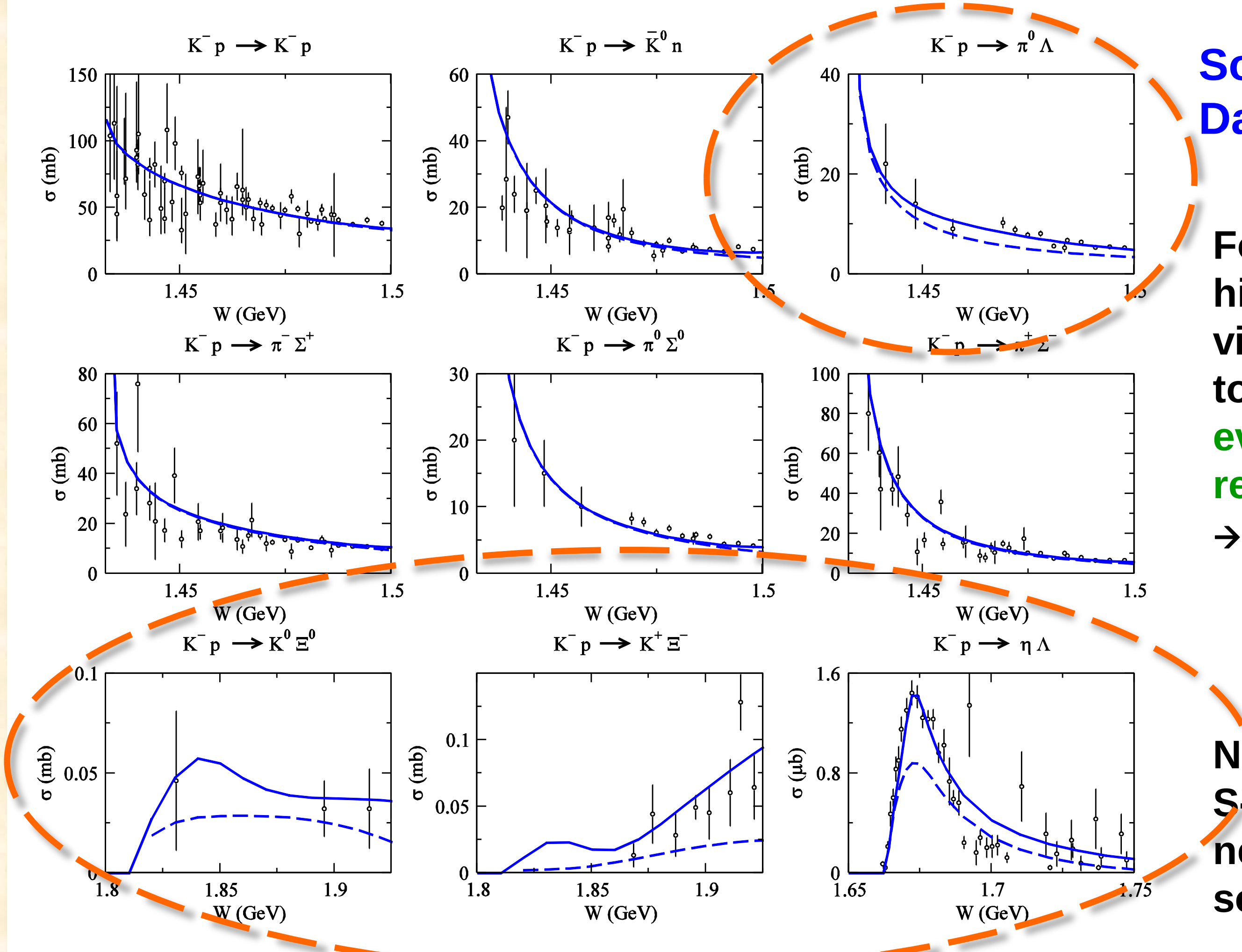
	Model A		Model B	
	$I=0$	$I=1$	$I=0$	$I=1$
$a_{\bar{K}N}$ (fm)	$-1.37+i0.67$	$0.07+i0.81$	$-1.62+i1.02$	$0.33+i0.49$
$a_{\eta\Lambda}$ (fm)	$1.35+i0.36$	-	$0.97+i0.51$	-
$a_{K\Xi}$ (fm)	$-0.81+i0.14$	$-0.68+i0.09$	$-0.89+i0.13$	$-0.83+i0.03$
$r_{\bar{K}N}$ (fm)	$0.67-i0.25$	$1.01-i0.20$	$0.74-i0.25$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

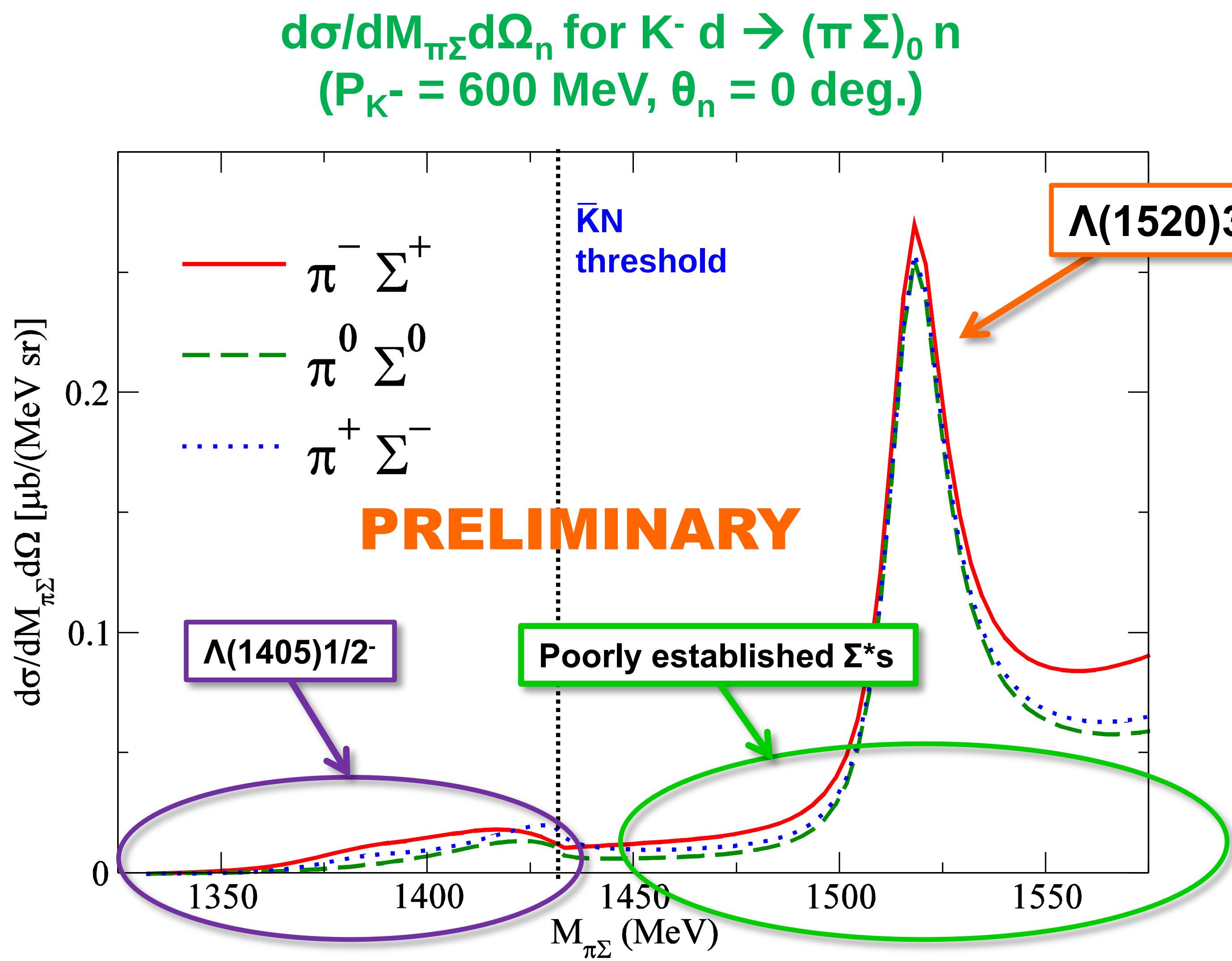
For K- p → πΛ, ηΛ, KΞ, higher partial waves visibly contribute to the cross sections even in the threshold region.

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

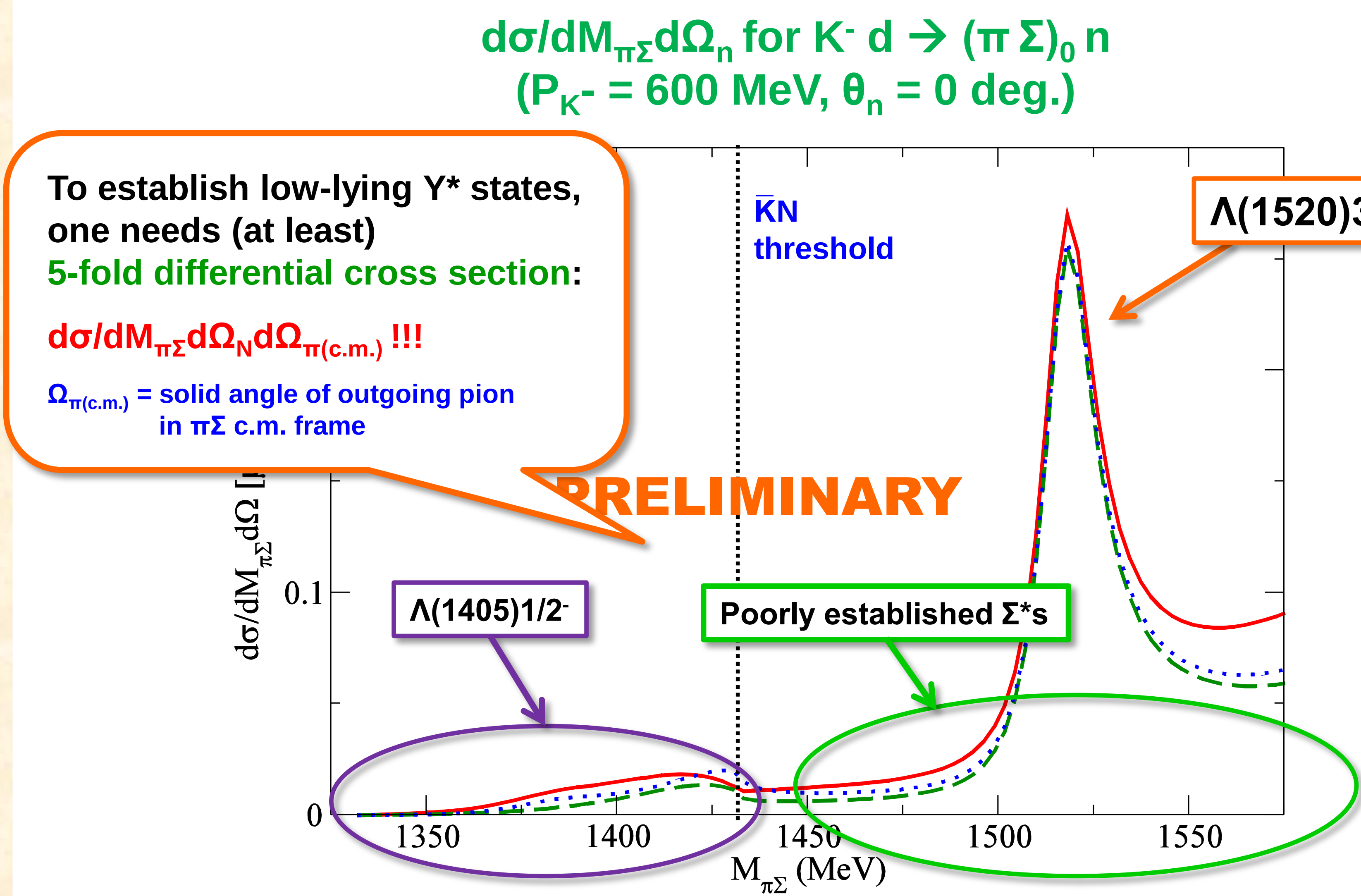
Naïve expectation for S-wave dominance near the threshold sometimes does not hold !!

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

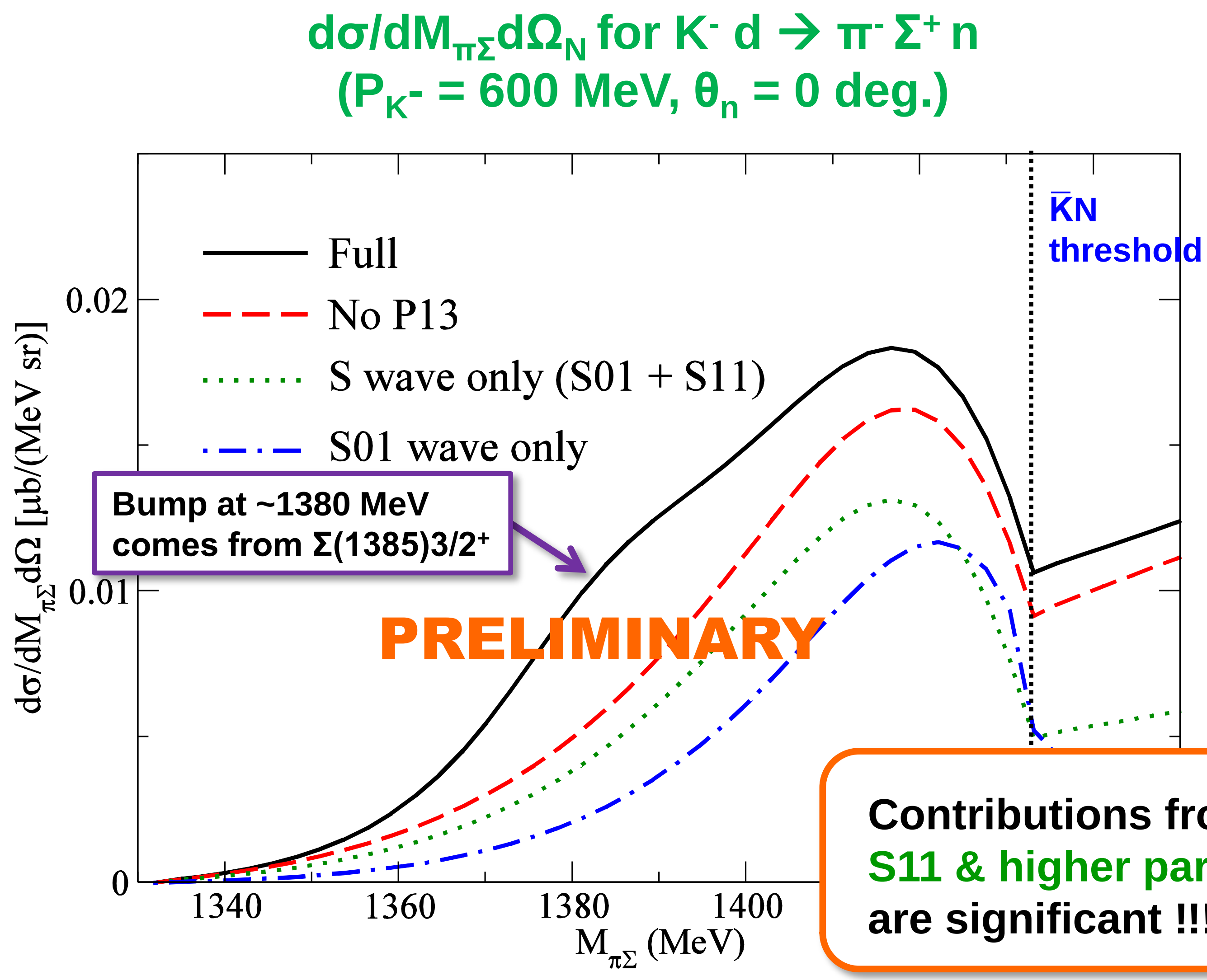
Results (IMPULSE TERM ONLY !!)



Results (IMPULSE TERM ONLY !!)



Results (IMPULSE TERM ONLY !!)



Contributions from
S11 & higher partial waves
are significant !!!