Establishing S=-1 hyperon resonances using kaon-induced meson productions within dynamical coupled-channels approach

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(RCNP, Osaka U.)

"Physics with Neutral Kaon Beam at JLab" Workshop (KL2016)
Jefferson Lab, VA, USA, February 1th-3th, 2016

Outline

- ✓ **Overview of Y* (= Λ*, Σ*) spectroscopy via dynamical coupled-channels (DCC) analysis of K^- p reactions**

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

- ✓ **Application to $\bar{K}$ d reactions (ongoing)**

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.**
  - ➢ ***ONLY 6* out of 26 Σ*s are rated as 4* by PDG**
  - ➢ **Even low-lying states are still uncertain.**
- ✓ **Spin-parity has not been determined for a number of Y* resonances.**
- ✓ **Before 2012, PDG listed only Breit-Wigner (BW) mass and width [except Σ(1385)3/2⁺, Λ(1520)3/2⁻]**
  - ➢ **N* & Δ* case:**
    Resonances defined by poles of scattering amplitudes are extensively studied;
    PDG lists BOTH pole and BW parameters.

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+	***
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Σ(1750)	1/2−	***
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Σ(3170)		*

PDG listing

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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:

[HK, Nakamura, Lee, Sato, PRC88(2013)035209; PRC90(2014)065204]

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

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 $\pi\pi\Lambda$ & $\pi\bar{K}N$

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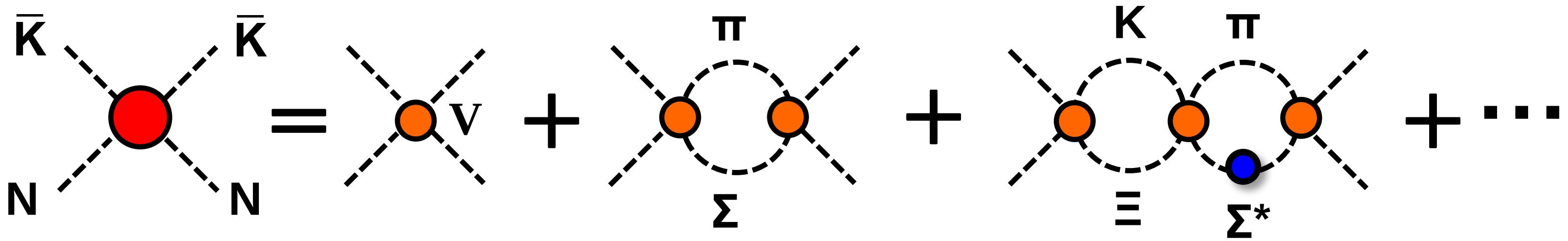
quasi two-body channels of three-body ππΛ & πK̄N

- ✓ **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]

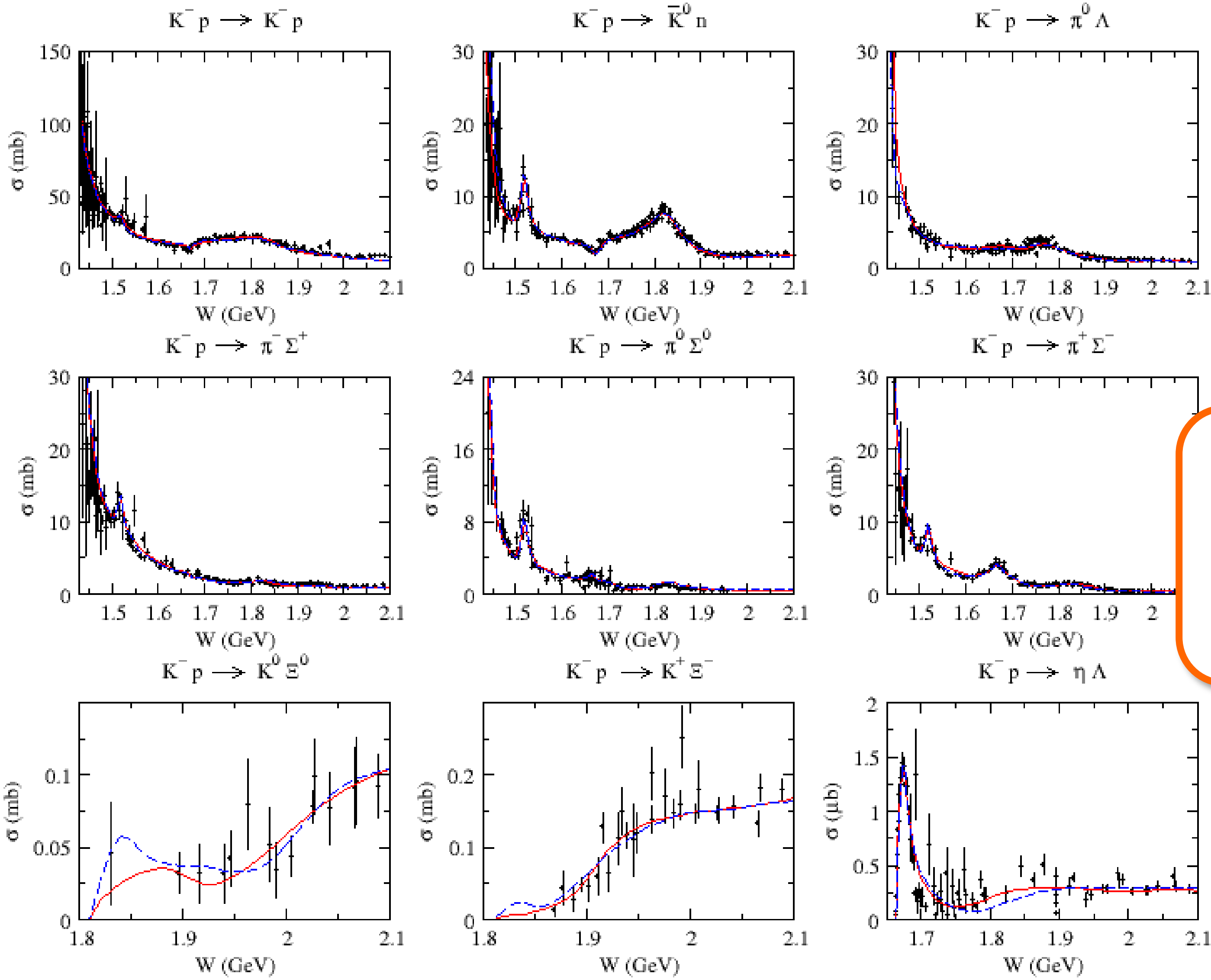
- ✓ **Determination of threshold parameters (scattering lengths, effective ranges,…); the partial-wave amplitudes of $\bar{K}N \rightarrow \bar{K}N, \pi\Sigma, \pi\Lambda, \eta\Lambda, K\Xi$ for S, P, D, and F waves.**
  [HK, Nakamura, Lee, Sato, PRC90(2014)065204]

- ✓ **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 → MB total cross sections

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



Red: Model A

Blue: Model B

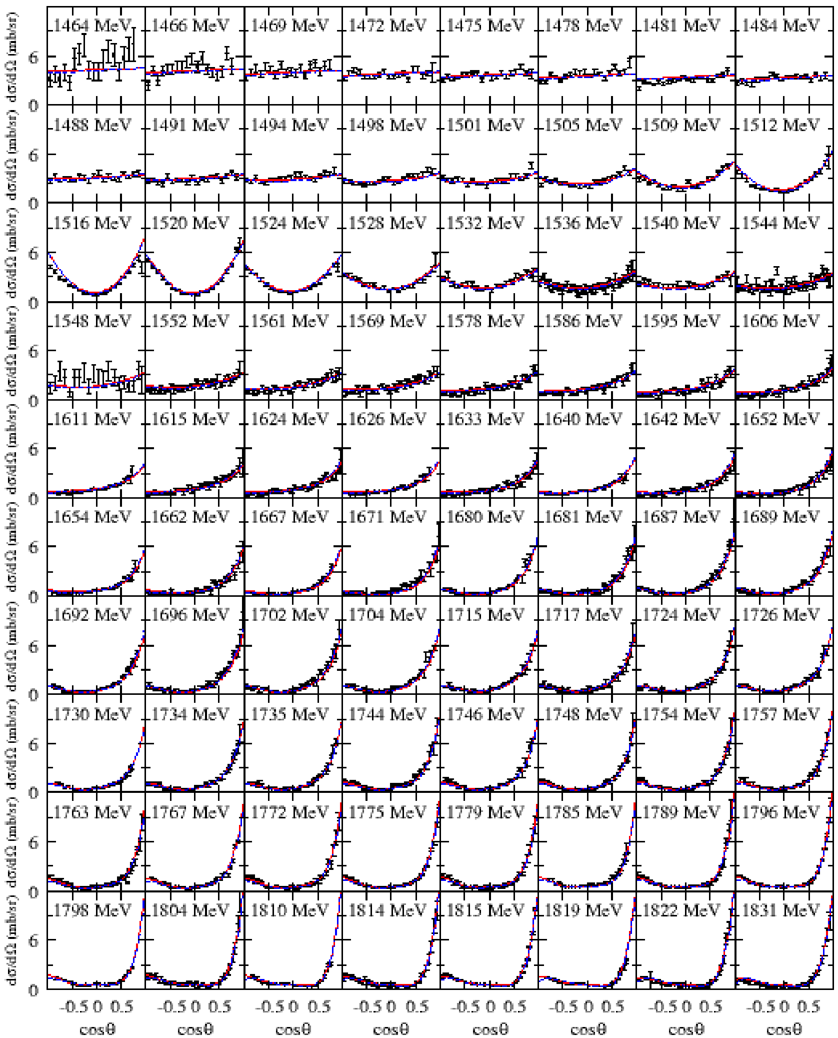
"Incompleteness" of the current database allows us to have two parameter sets that give similar quality of the fit.

Results of the fits

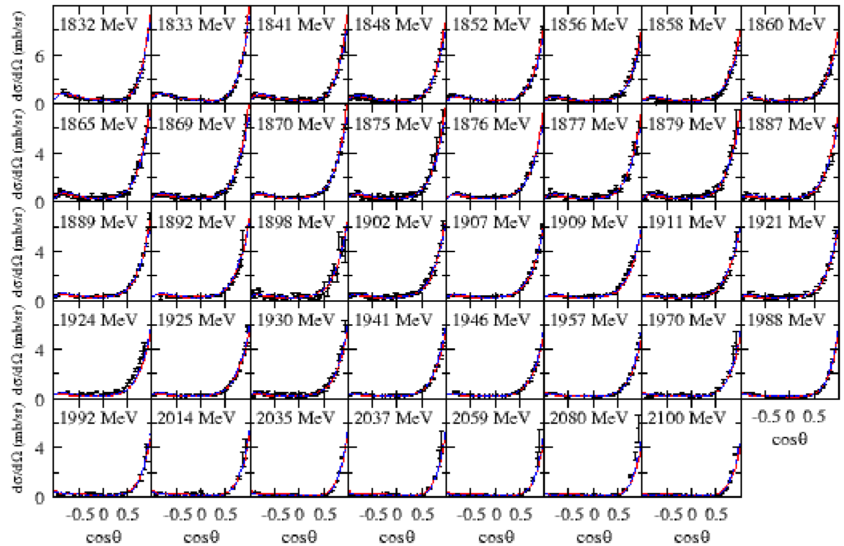
K⁻ p → K⁻ p scattering

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

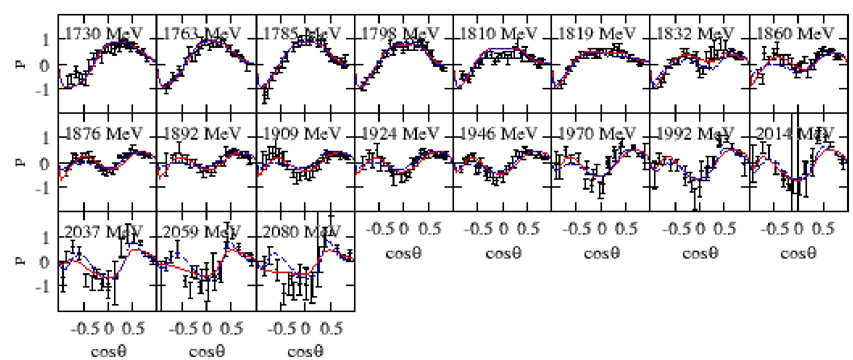
dσ/dΩ (1464 < W < 1831 MeV)



dσ/dΩ (1832 < W < 2100 MeV)



P (1730 < W < 2080 MeV)



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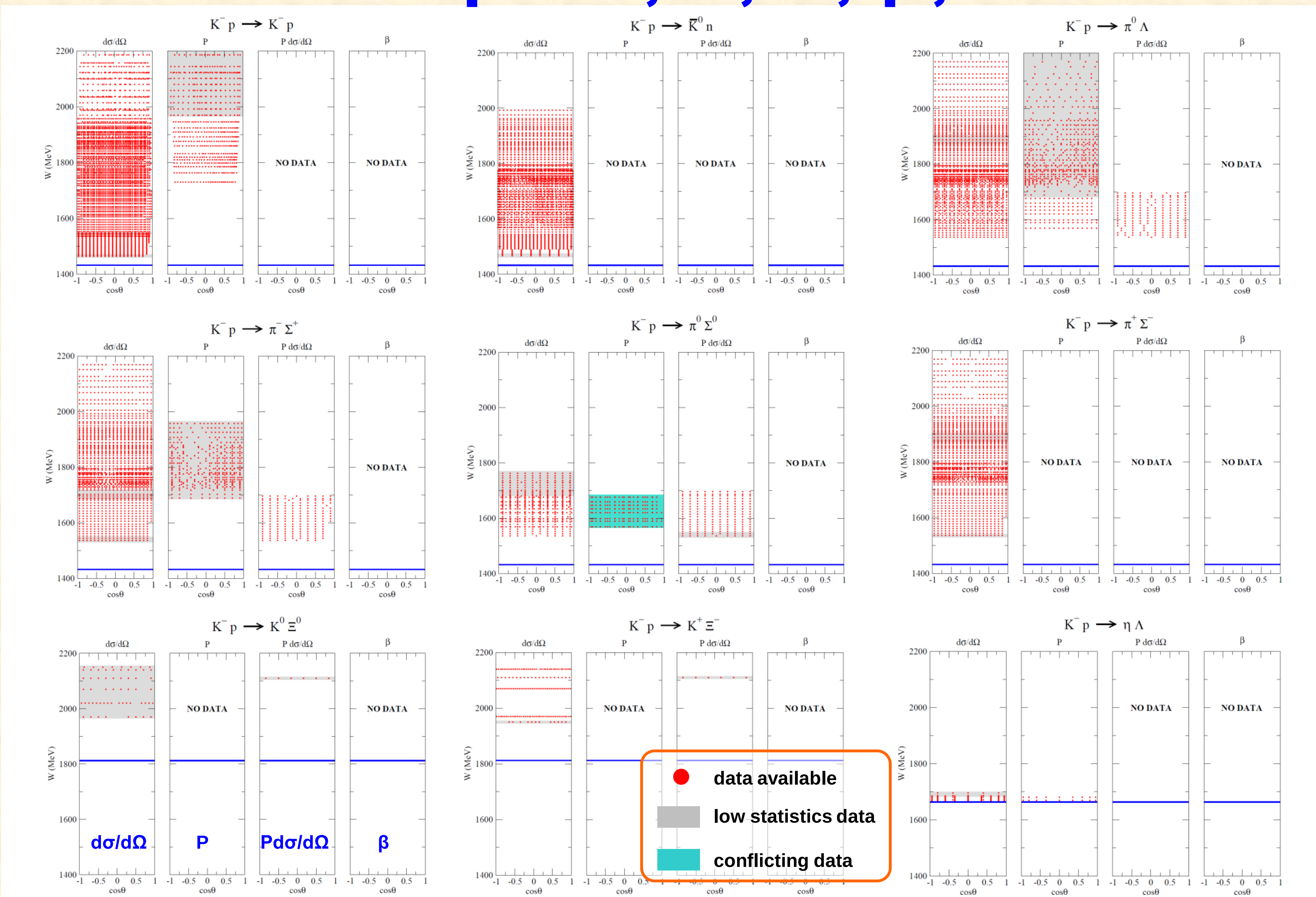
Kinematical (W, cosθ) coverage of available $K^- p \rightarrow \bar{K}N$, $\pi\Sigma$, $\pi\Lambda$, $\eta\Lambda$, $K\Xi$ data



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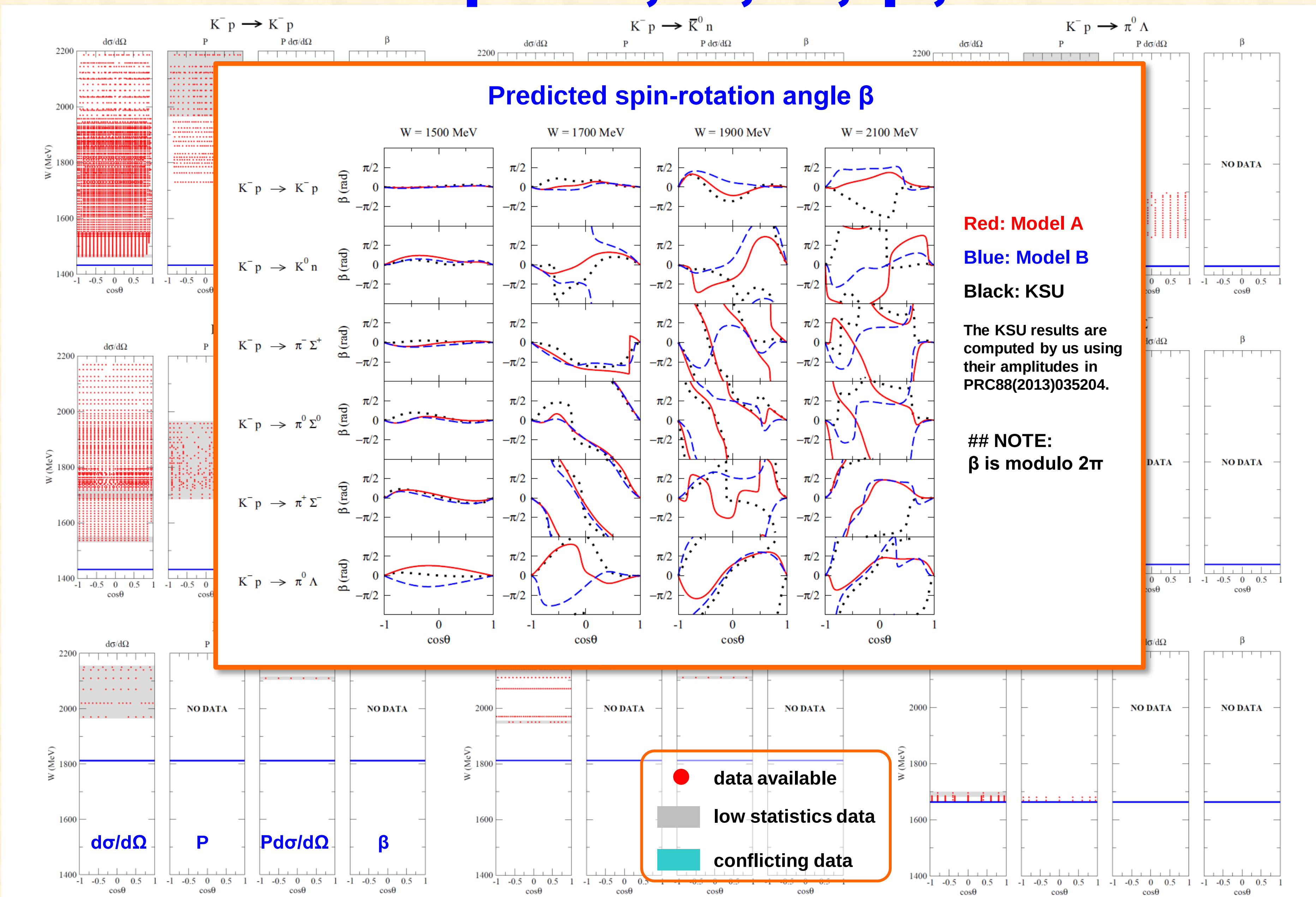
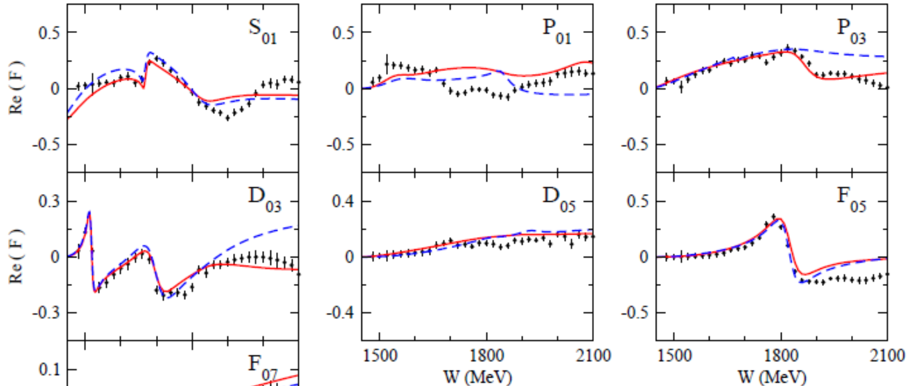
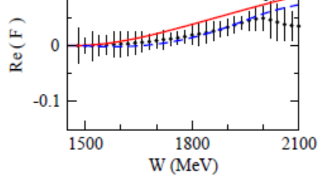
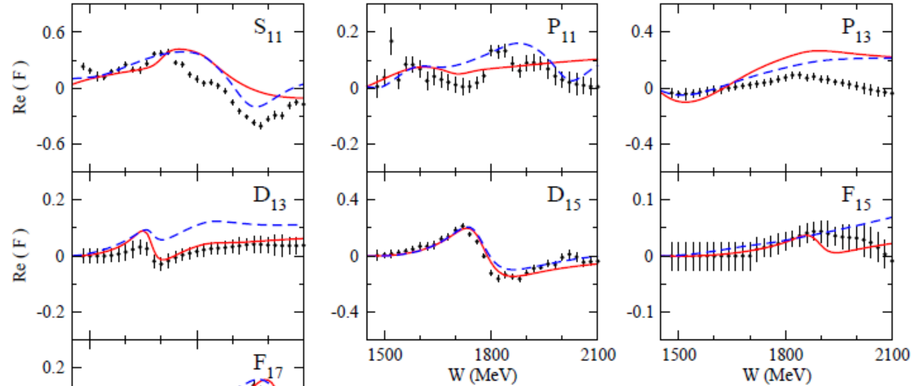
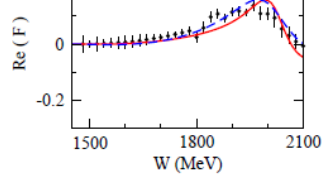


Comparison of extracted partial-wave amplitudes

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

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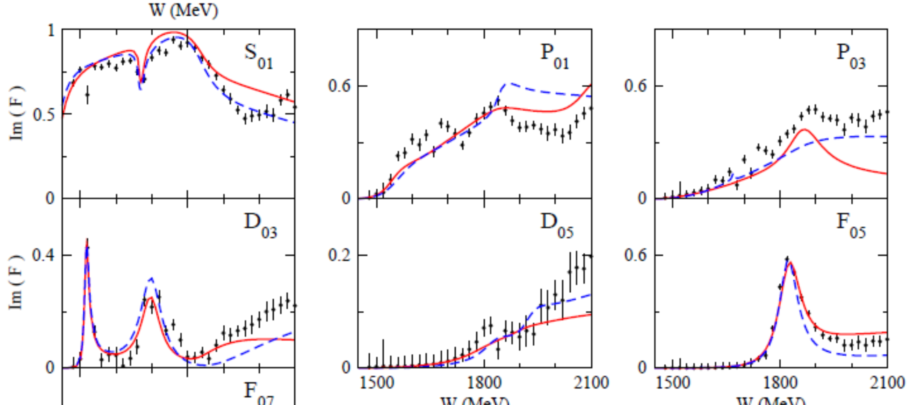
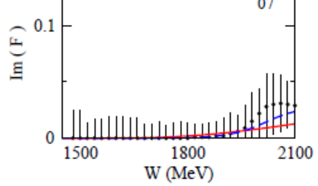
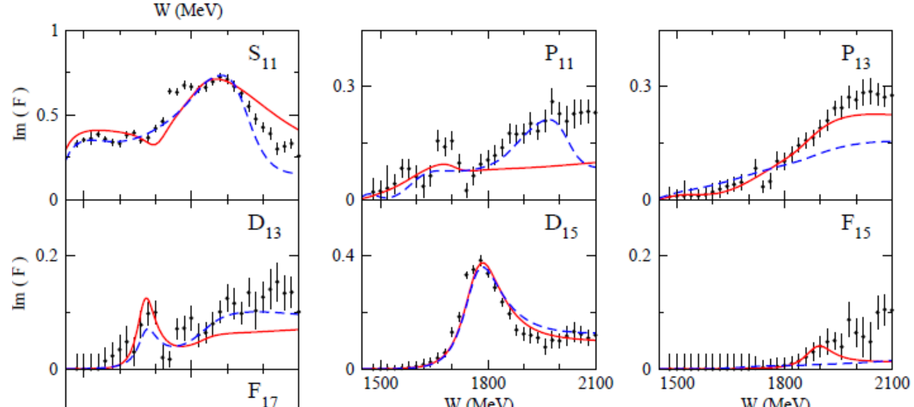
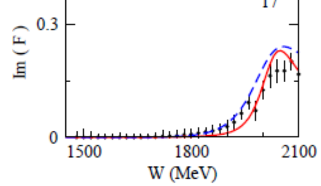

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Circles: KSU single-energy solution [PRC88(2013)035204]

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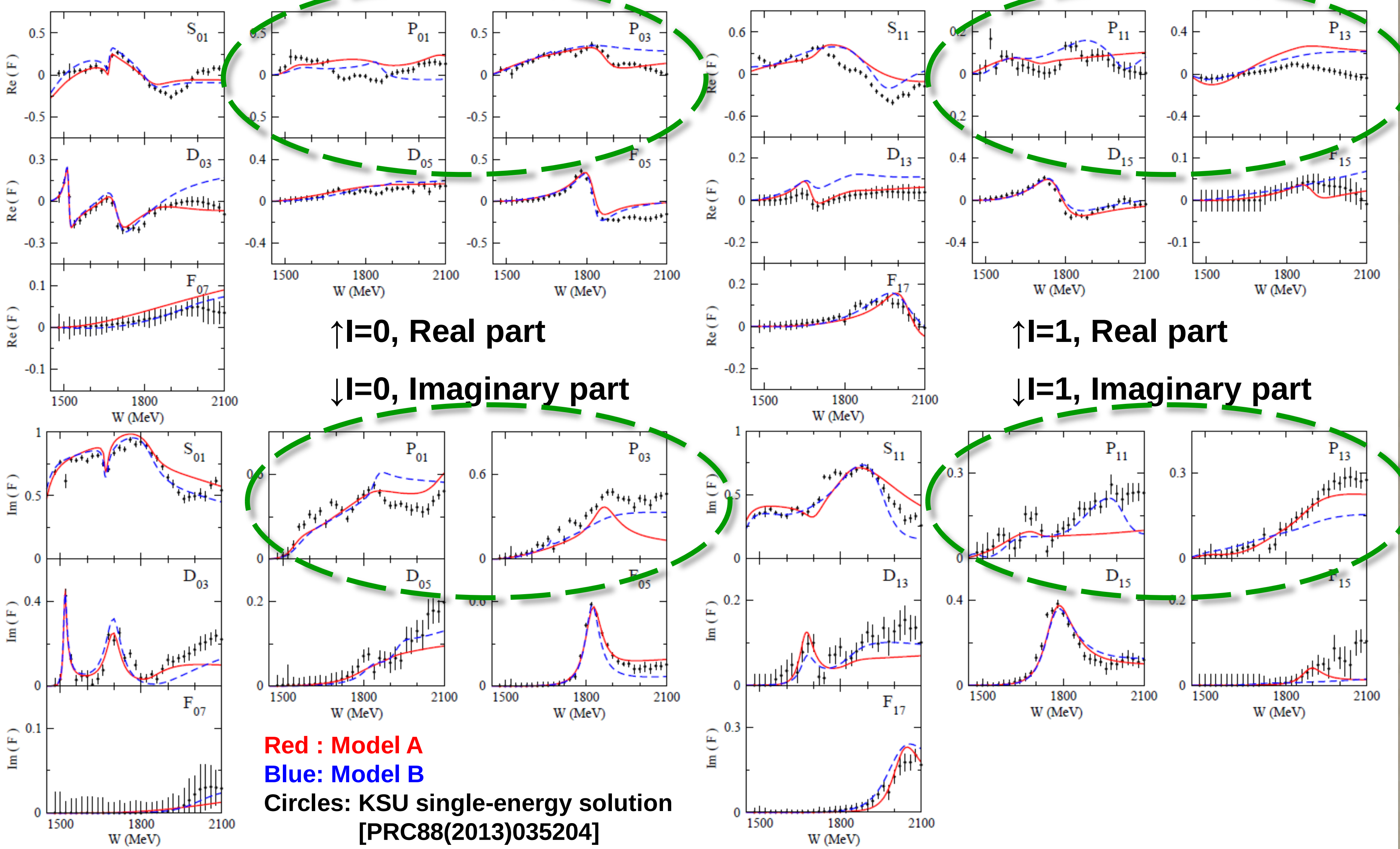

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Extracted Λ* and Σ* mass spectrum

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

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

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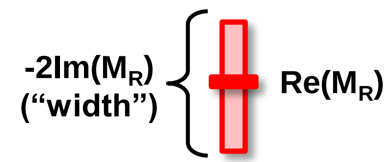
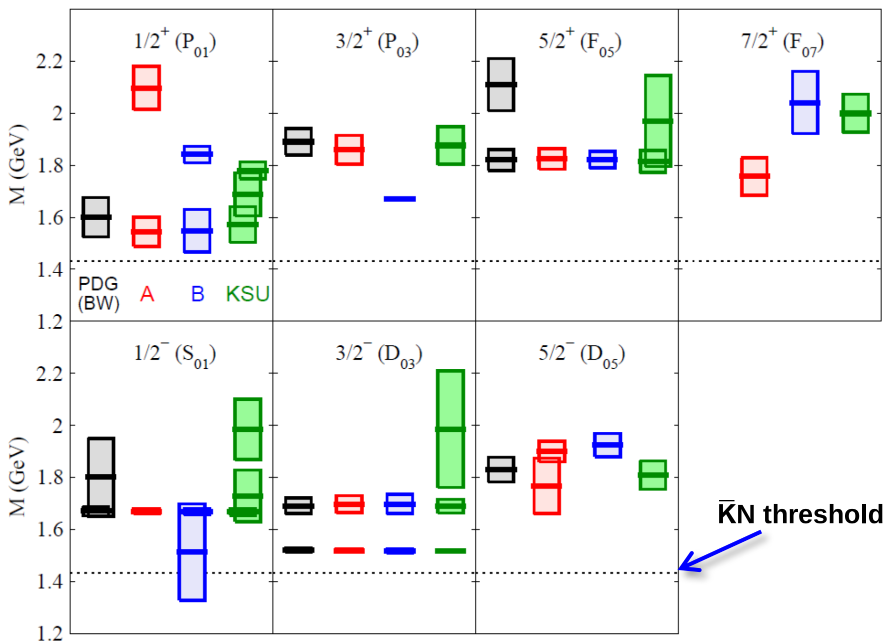
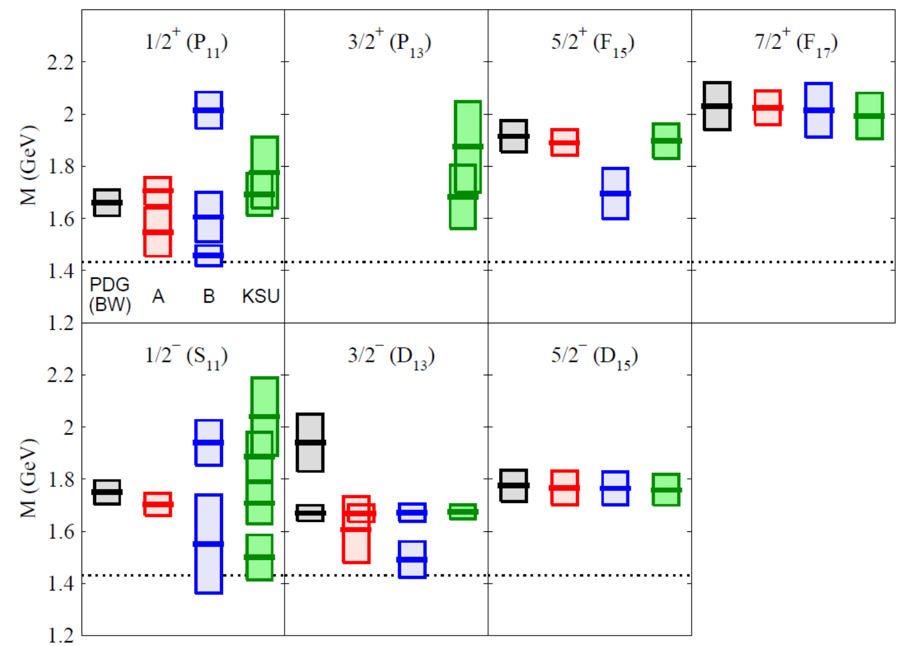
Black: PDG (only 4- & 3-star Y*; Breit-Wigner)



$J^P(L_{I\,2J})$ "Λ" resonance (I=0)



$J^P(L_{I\,2J})$ "Σ" resonance (I=1)



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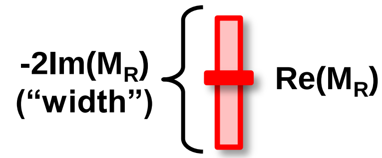

M_R : Resonance pole mass (complex)

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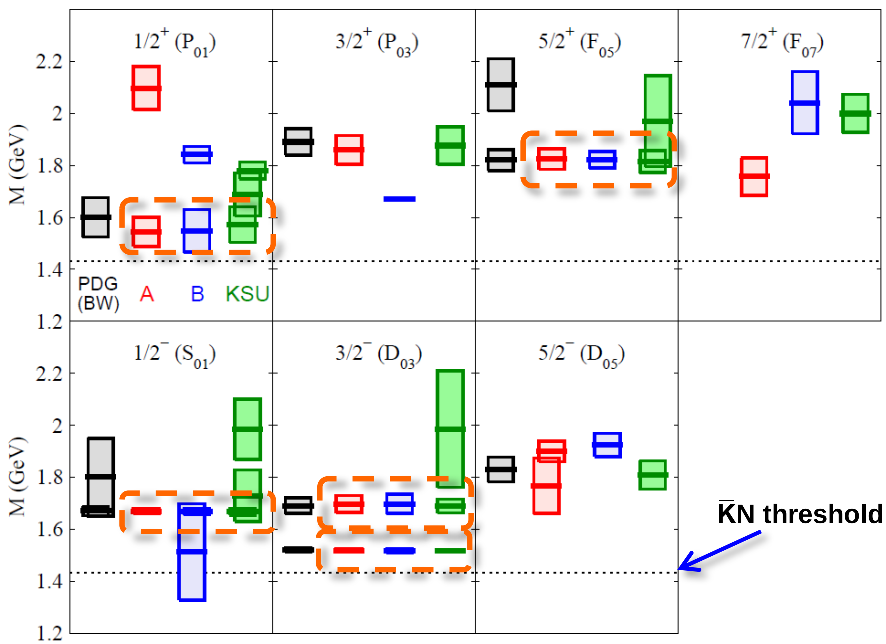

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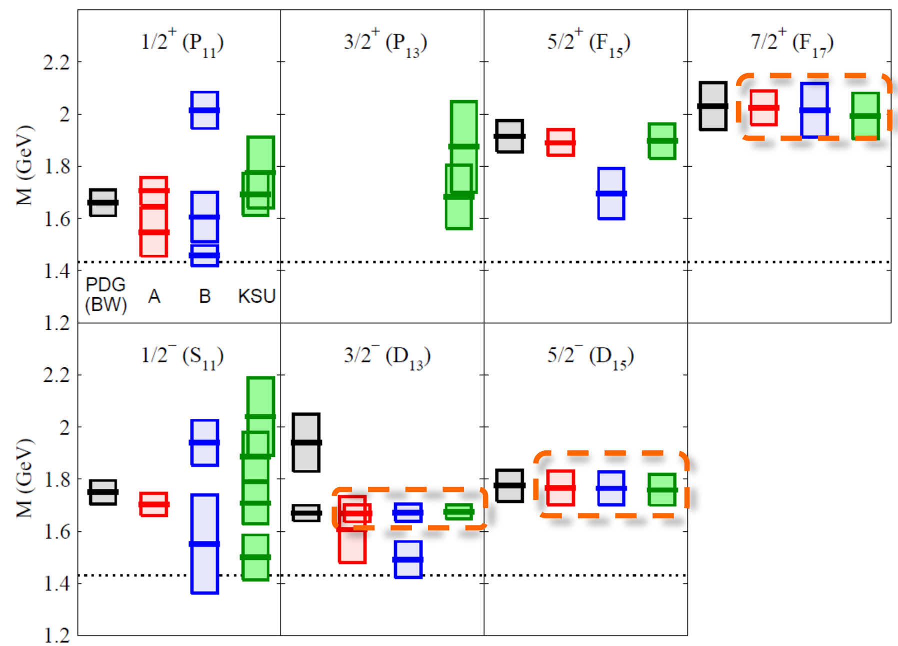

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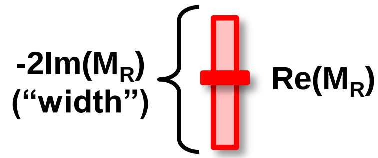
New narrow $3/2^+$ resonance
M = 1671 – 5i MeV
near the $\eta\Lambda$ threshold !!



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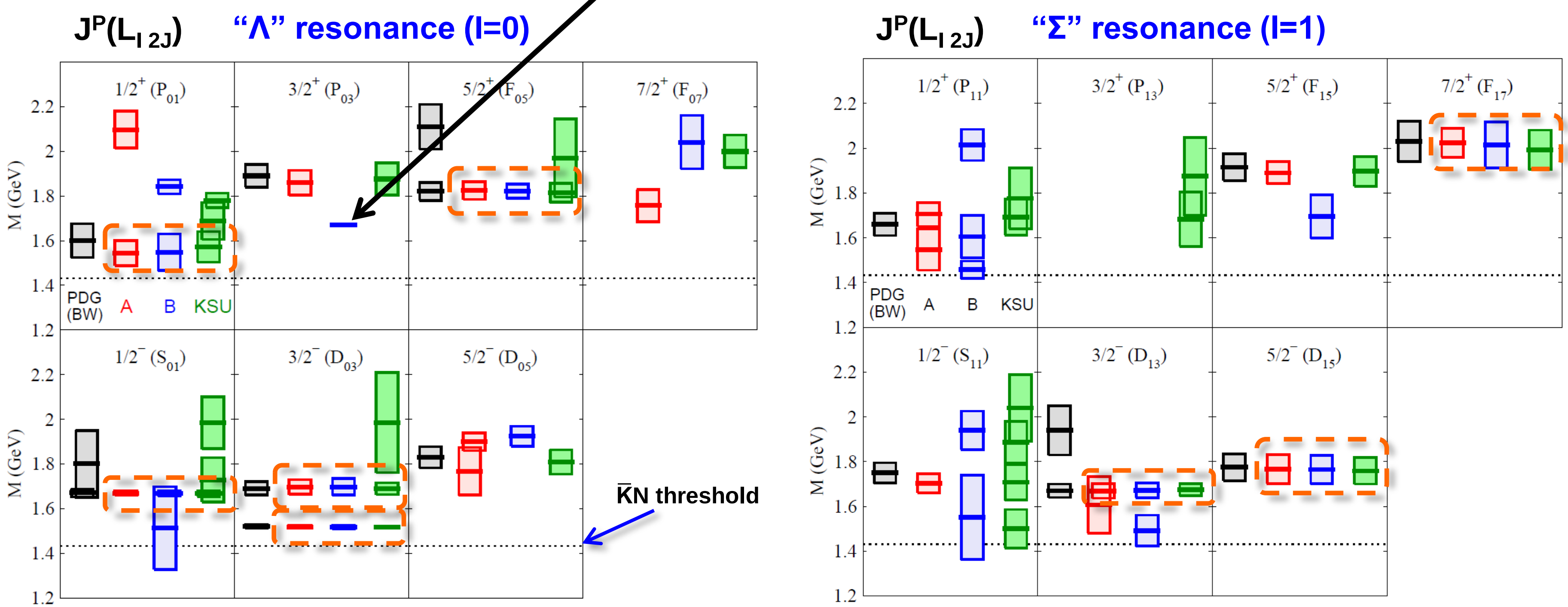

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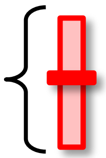
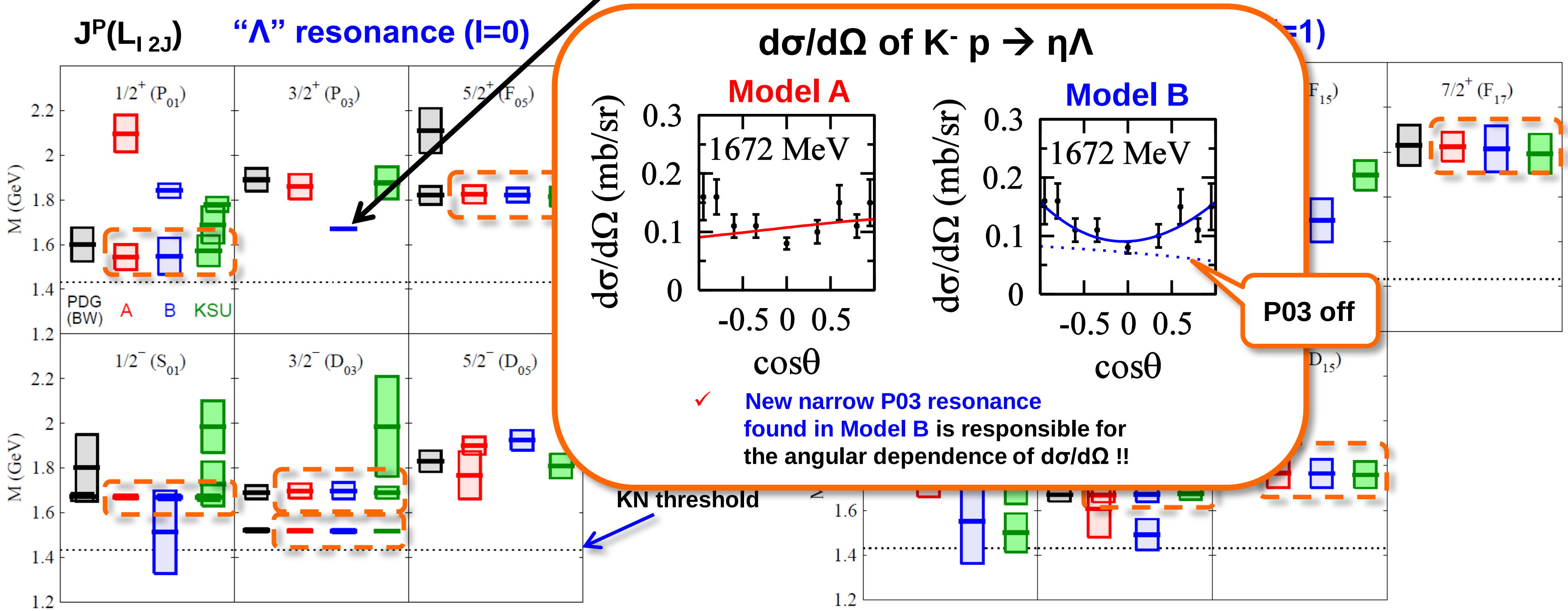
M = 1671 – 5i MeV
near the ηΛ threshold !!



M_R : Resonance pole mass (complex)

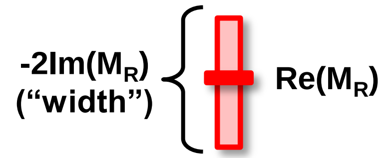


Extracted Λ* and Σ* mass spectrum

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



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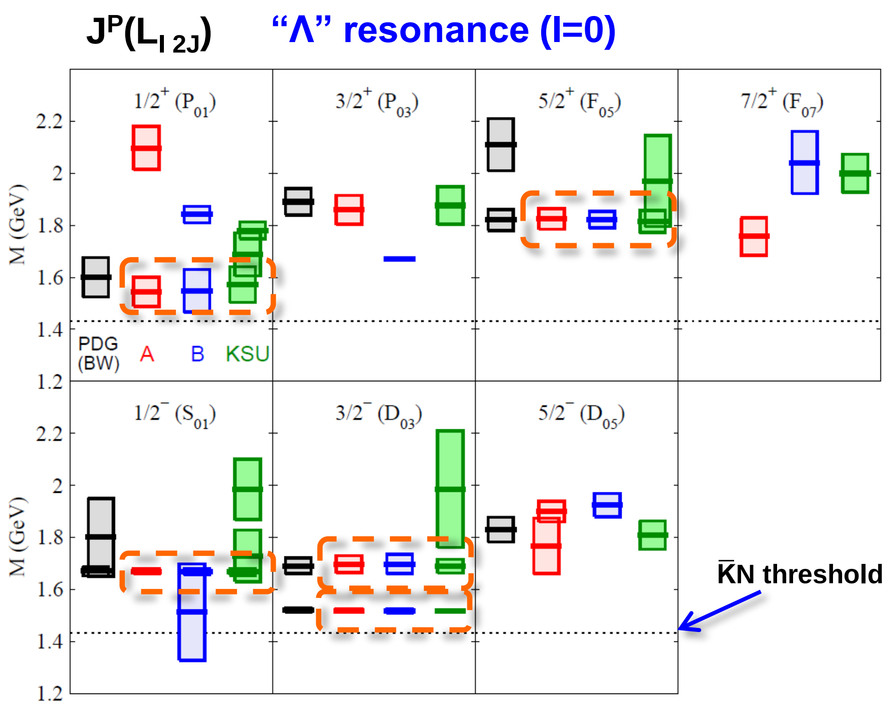
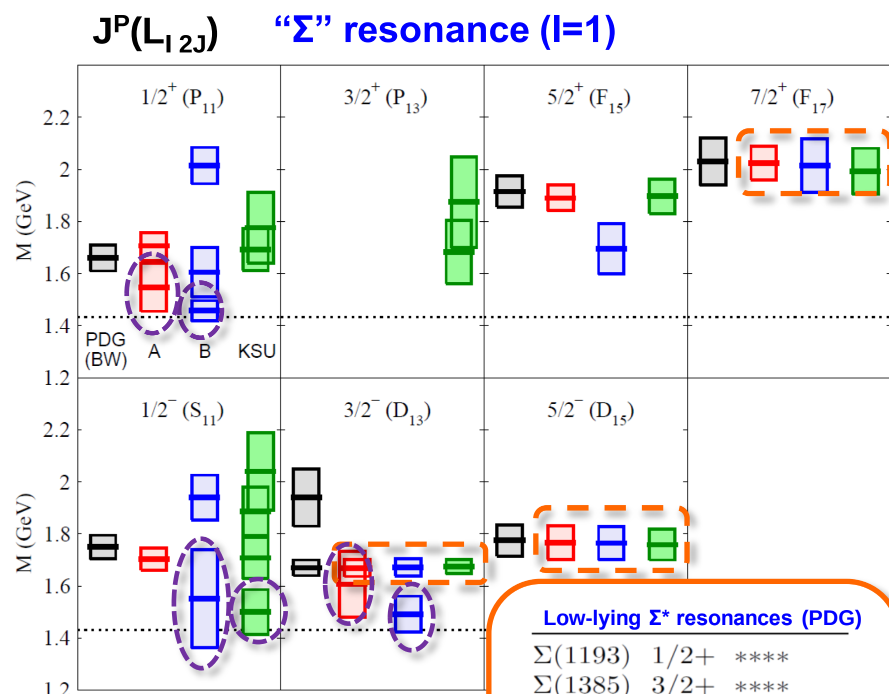




Low-lying Σ* resonances (PDG)

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−	****

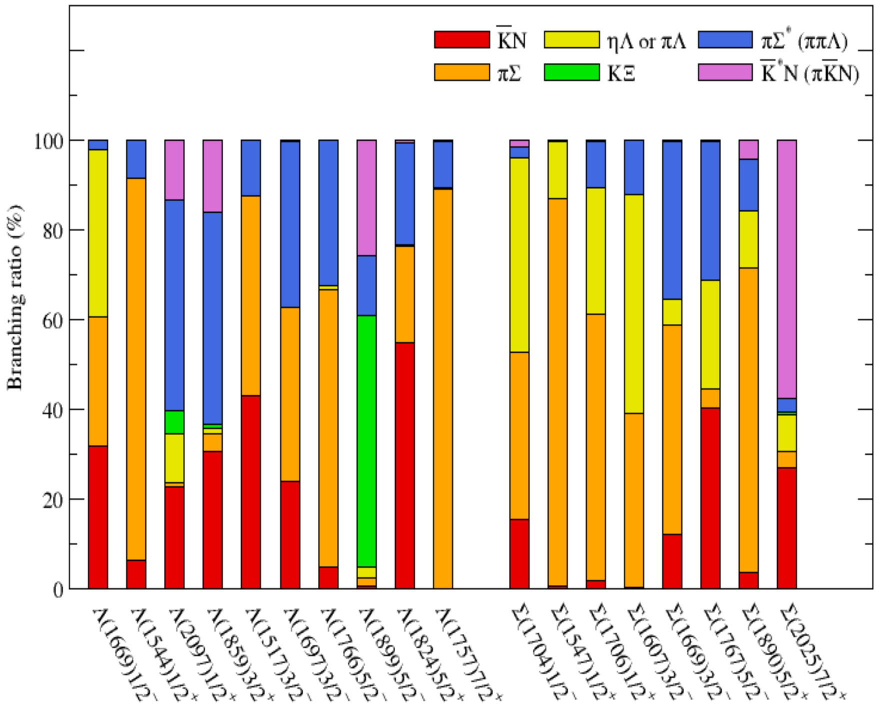
?

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

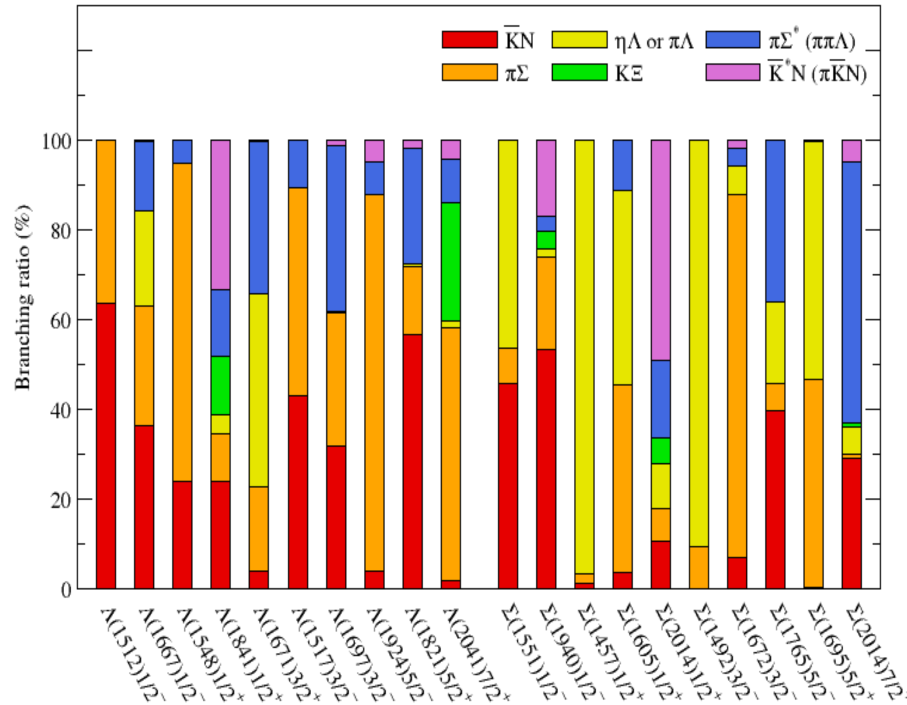
✓ **High-mass Y* have large branching ratio to πΣ* (ππΛ) & $\bar{K}$*N (π$\bar{K}$N)**

- **K⁻ p → ππΛ, π$\bar{K}$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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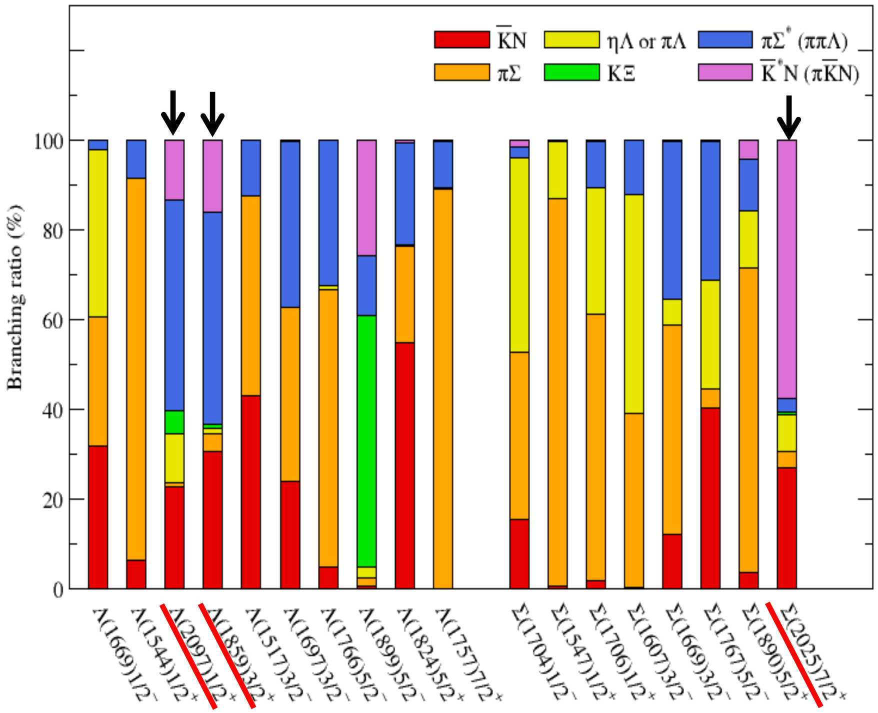
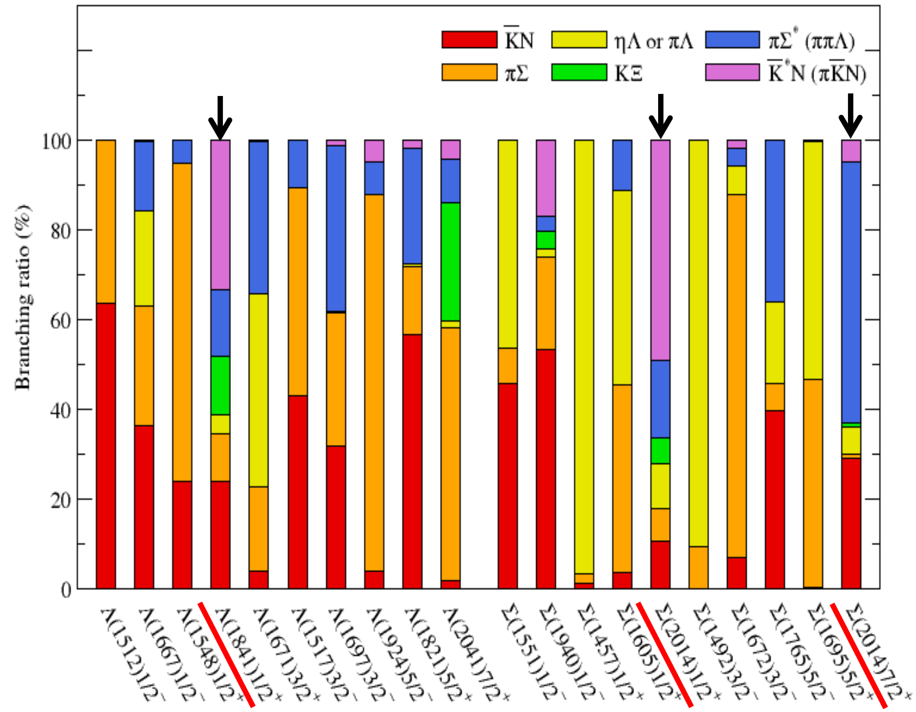


Model B



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

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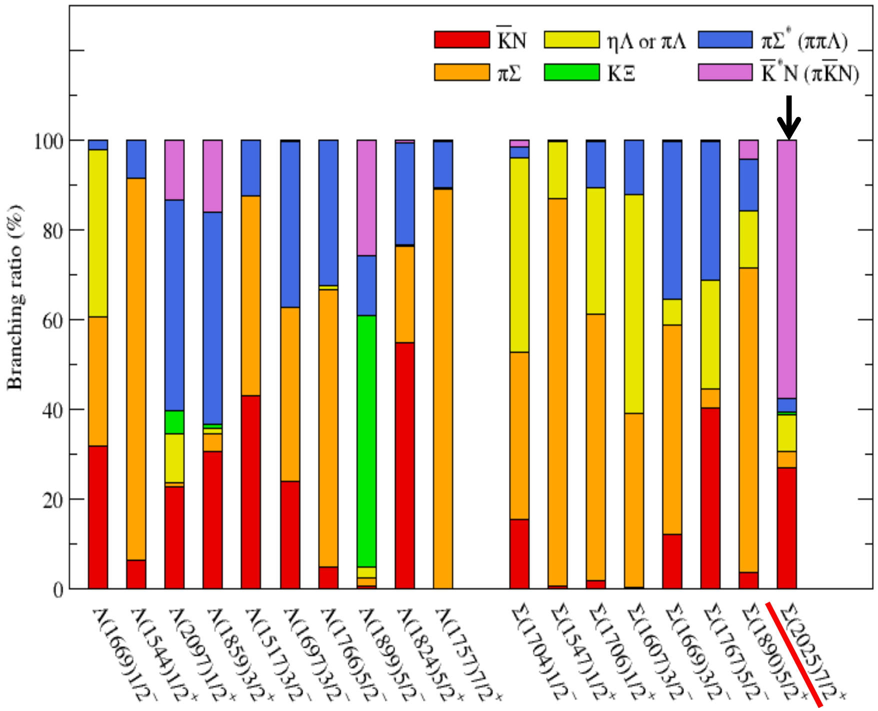
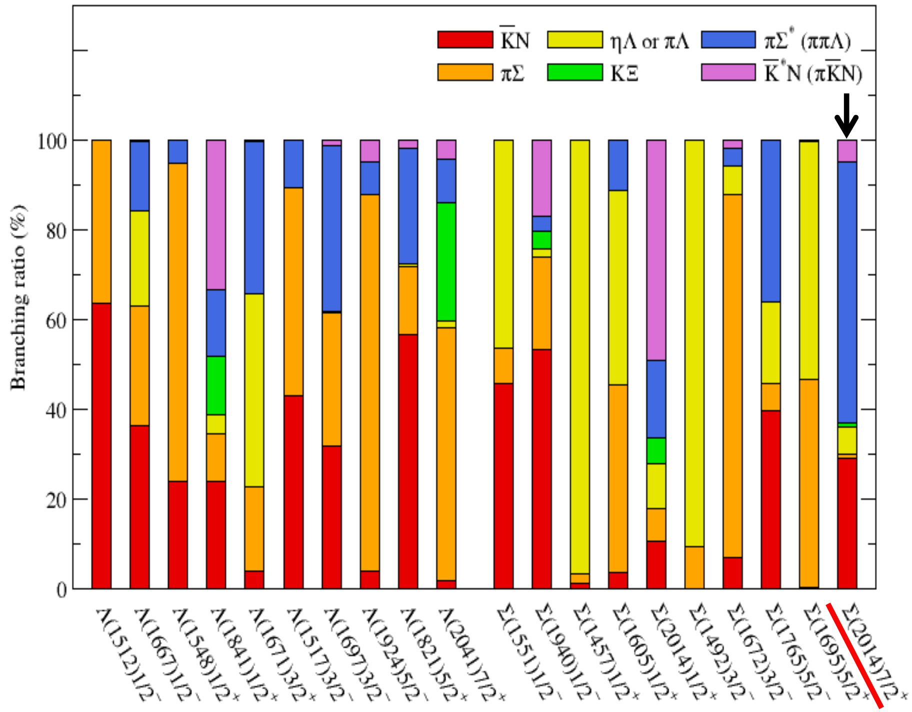
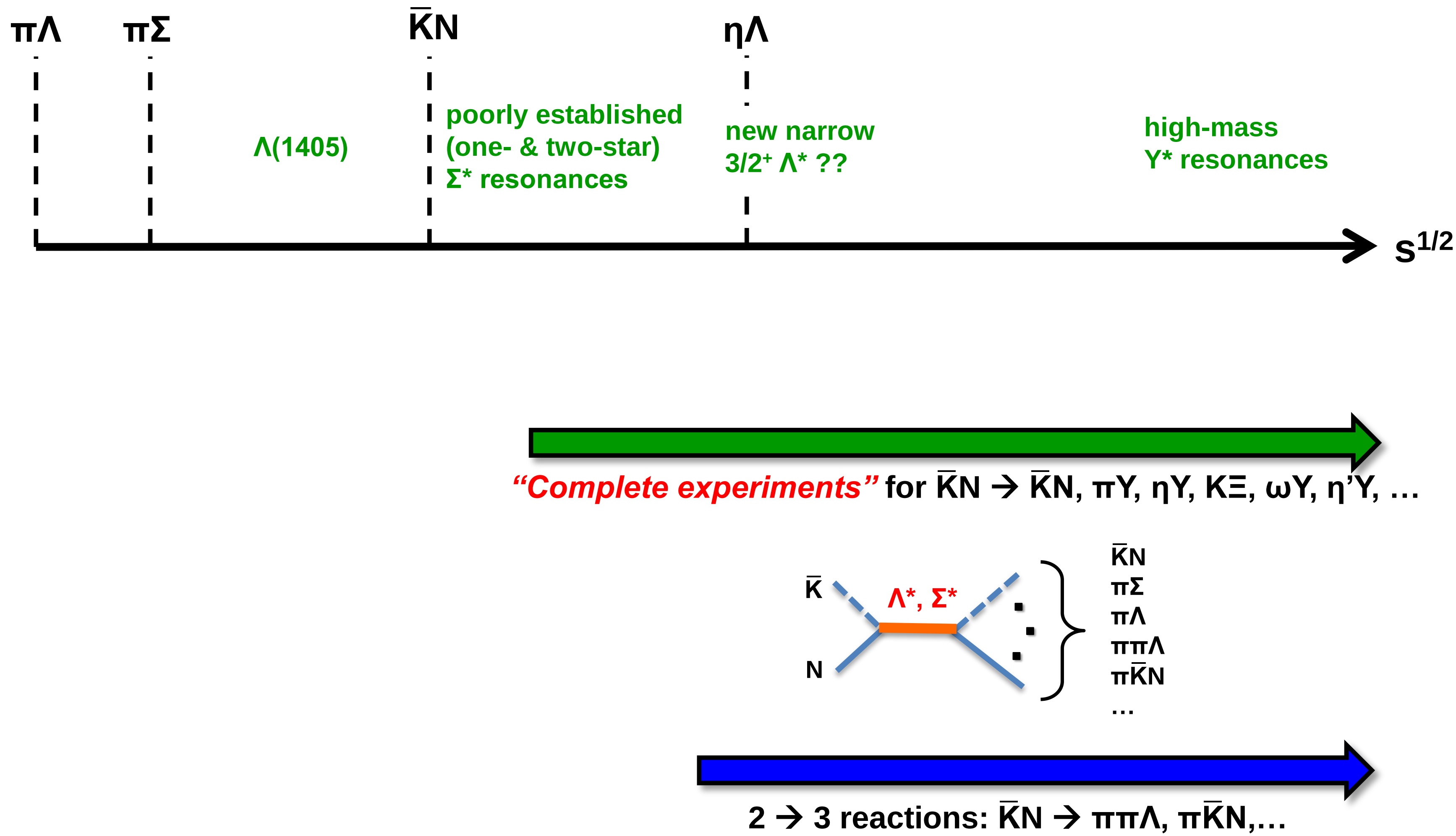


Model B



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

Strategy for establishing Y* resonances using antikaon-induced reactions



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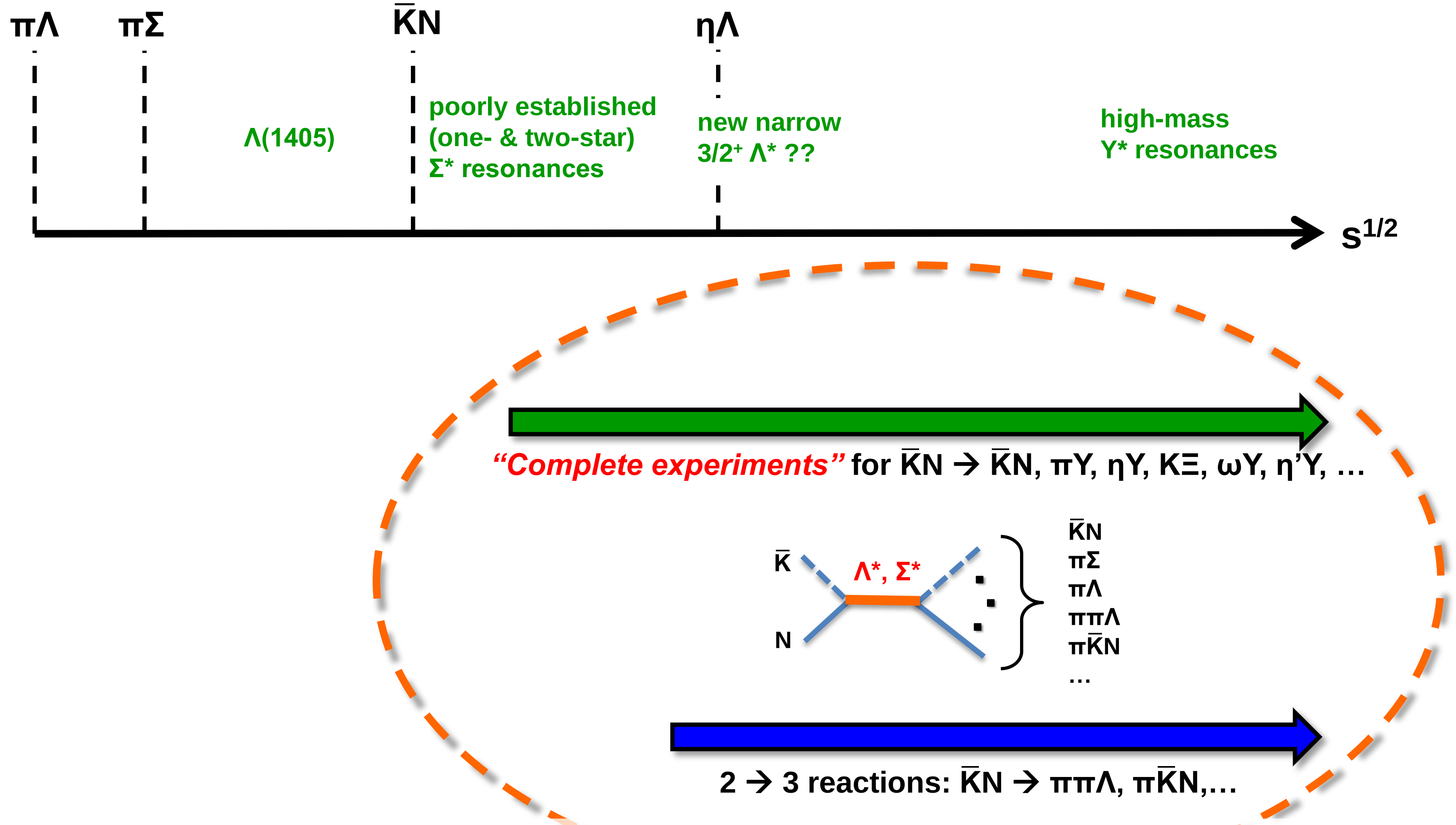

New measurements using HypTPC@J-PARC ??

[discussions ongoing with J-PARC E45 members (H. Sako, K. Hicks et al.)]

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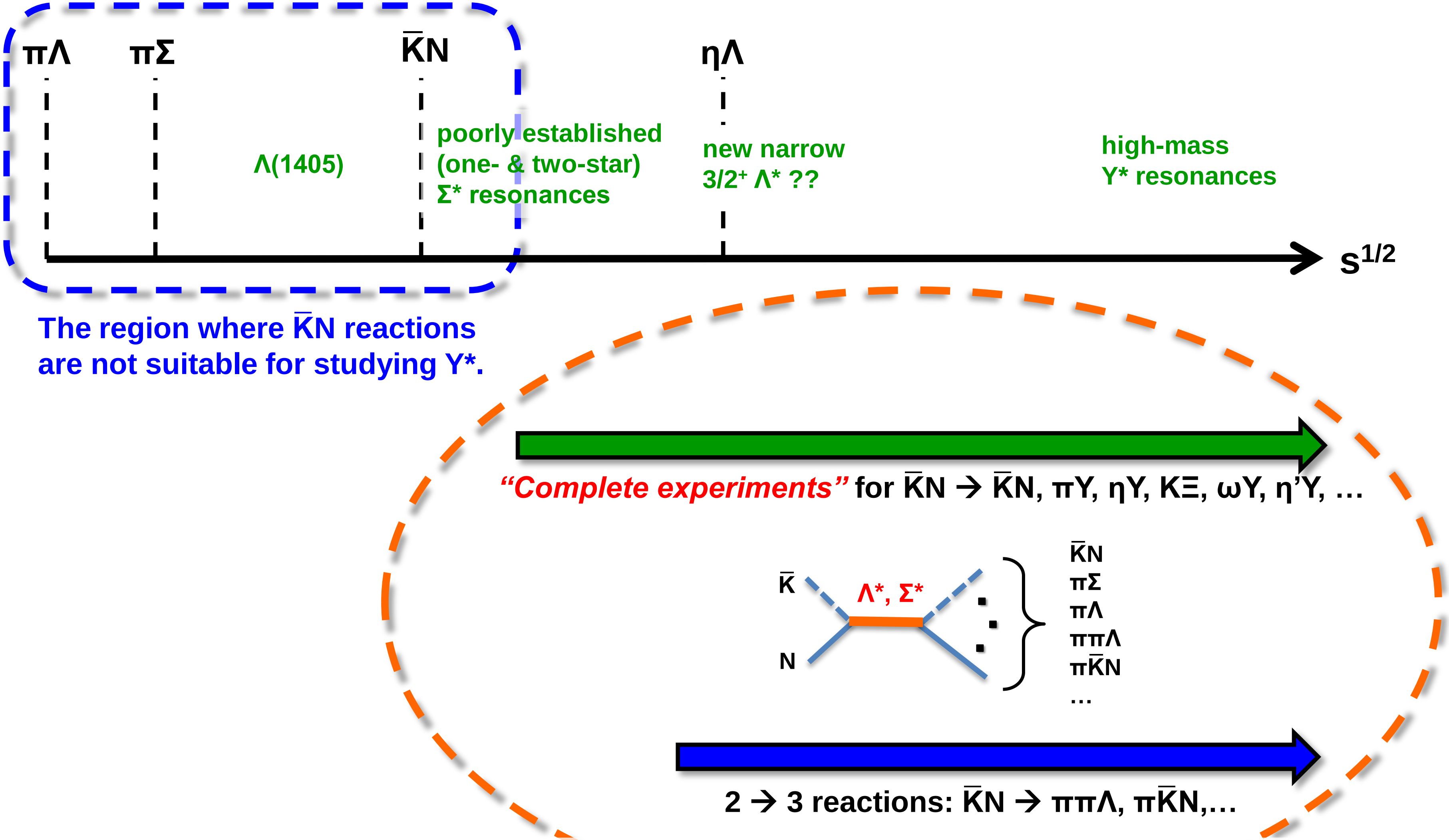

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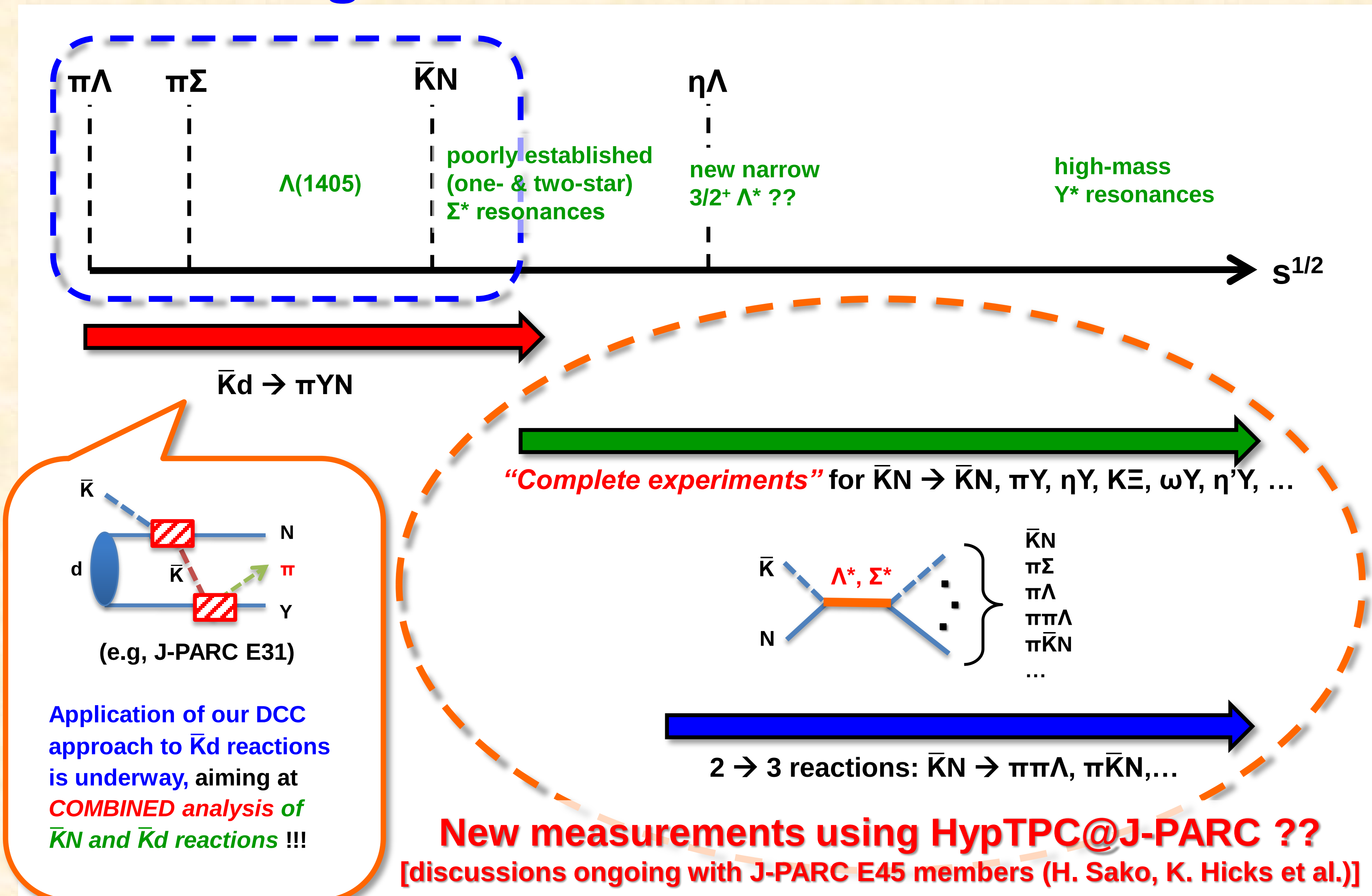
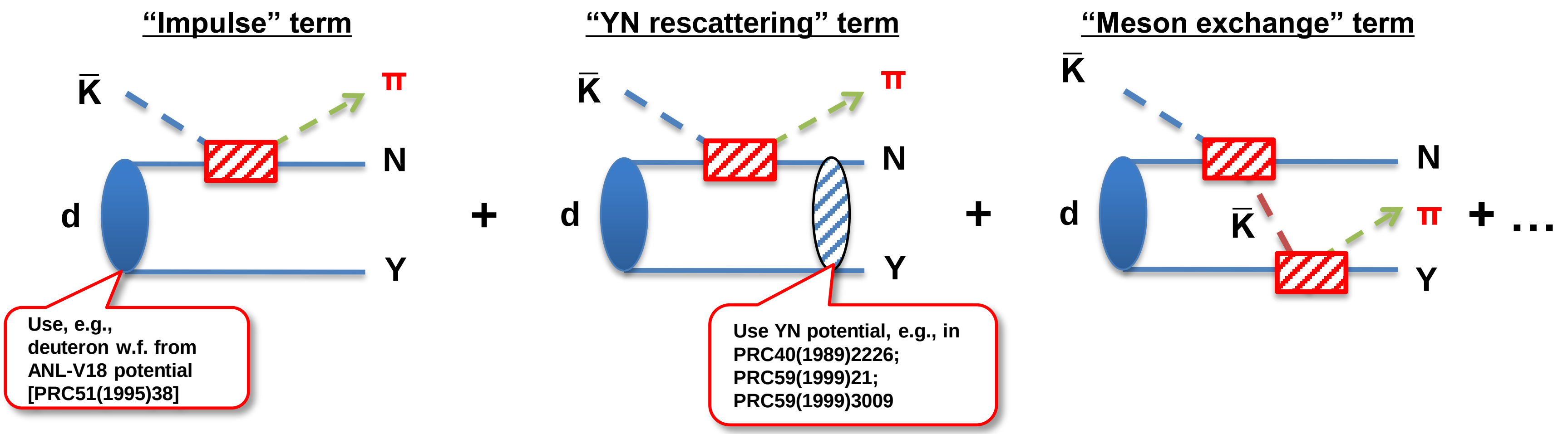


Model for deuteron-target reactions

- ✓ 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



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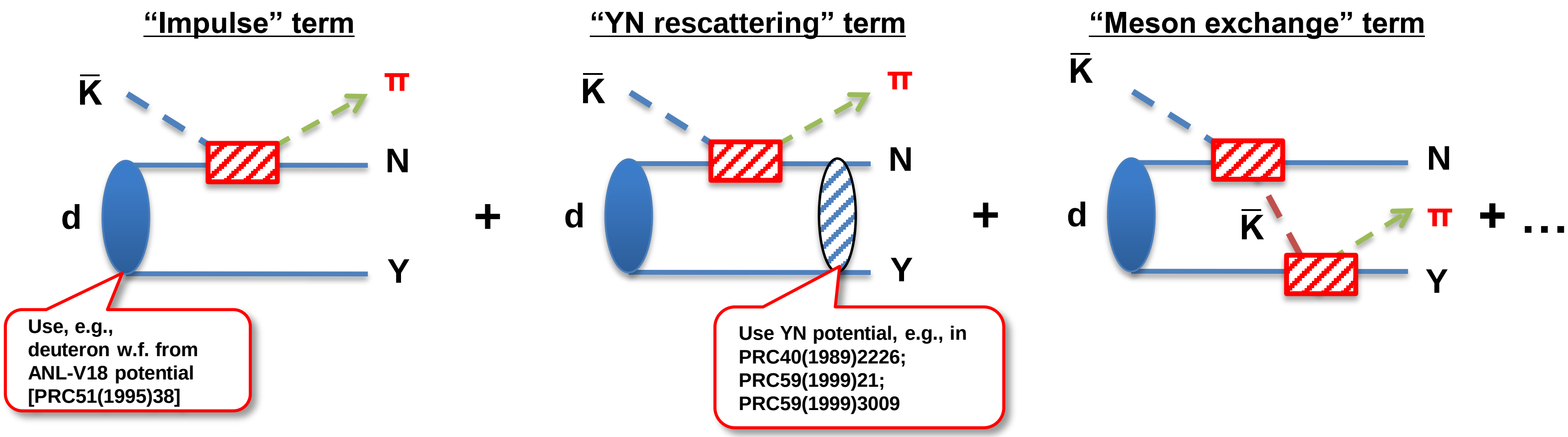

Unique feature of our work:

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

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

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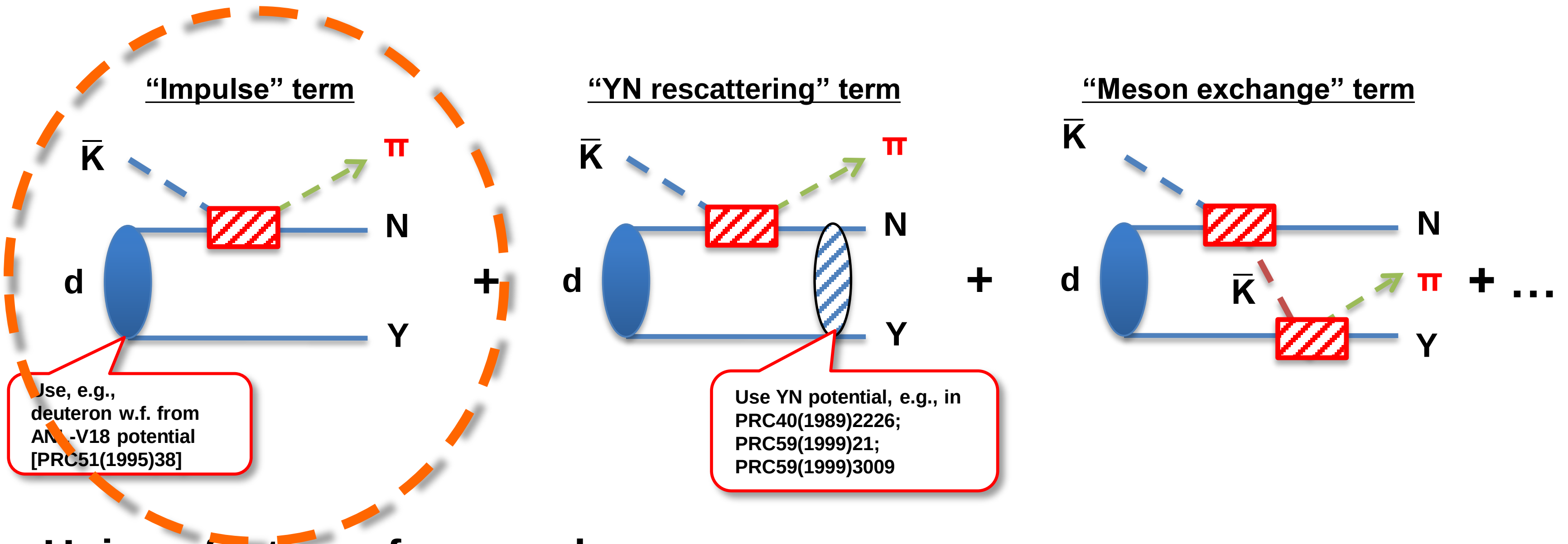

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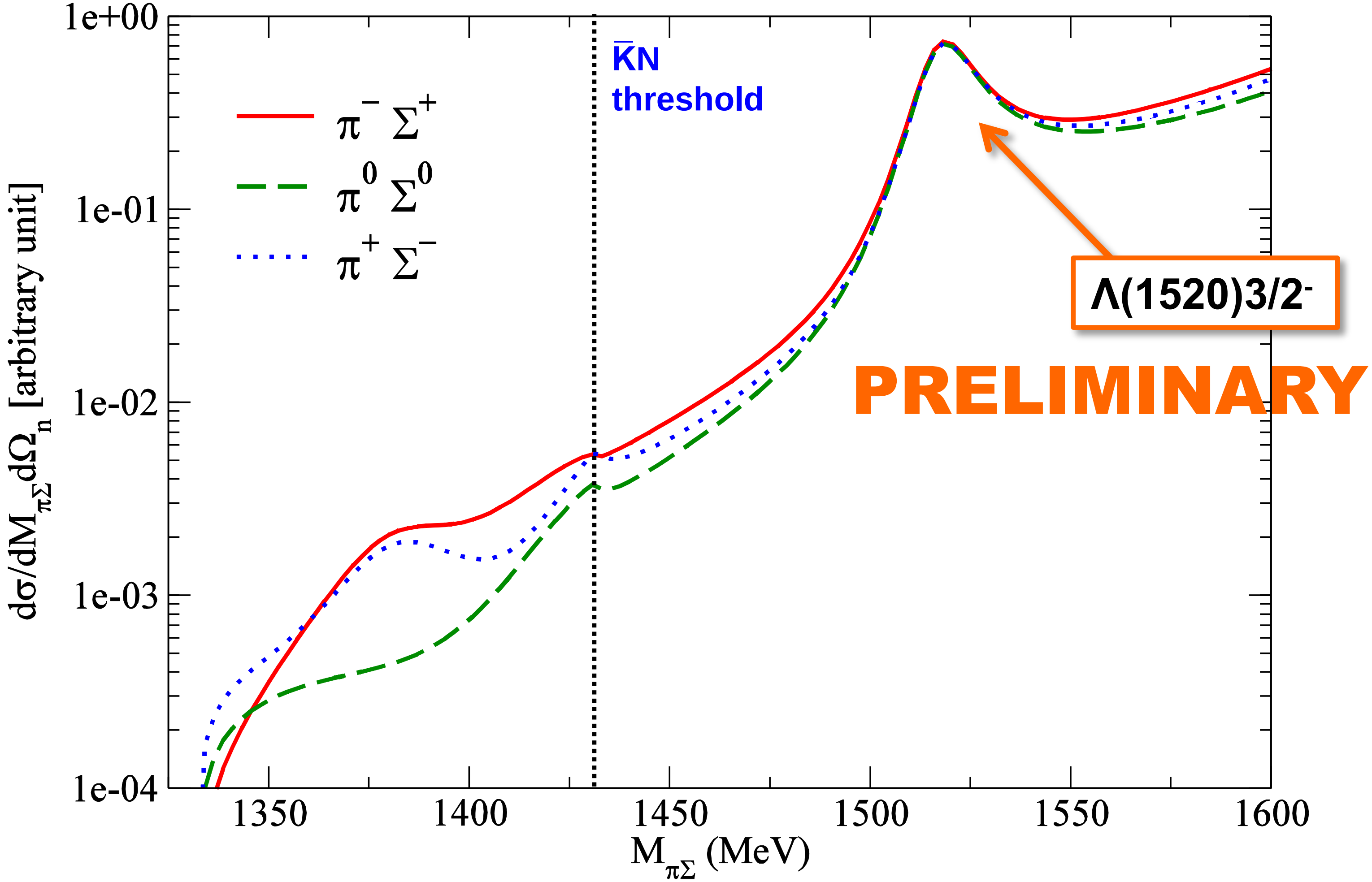
Results (IMPULSE TERM ONLY !!)

$d\sigma/dM_{\pi\Sigma}d\Omega_n$ for $K^- d \rightarrow (\pi\Sigma)_0\, n$
(P_{K^-} = 1 GeV, θ_n = 0 deg.)

Same kinematics as J-PARC E31



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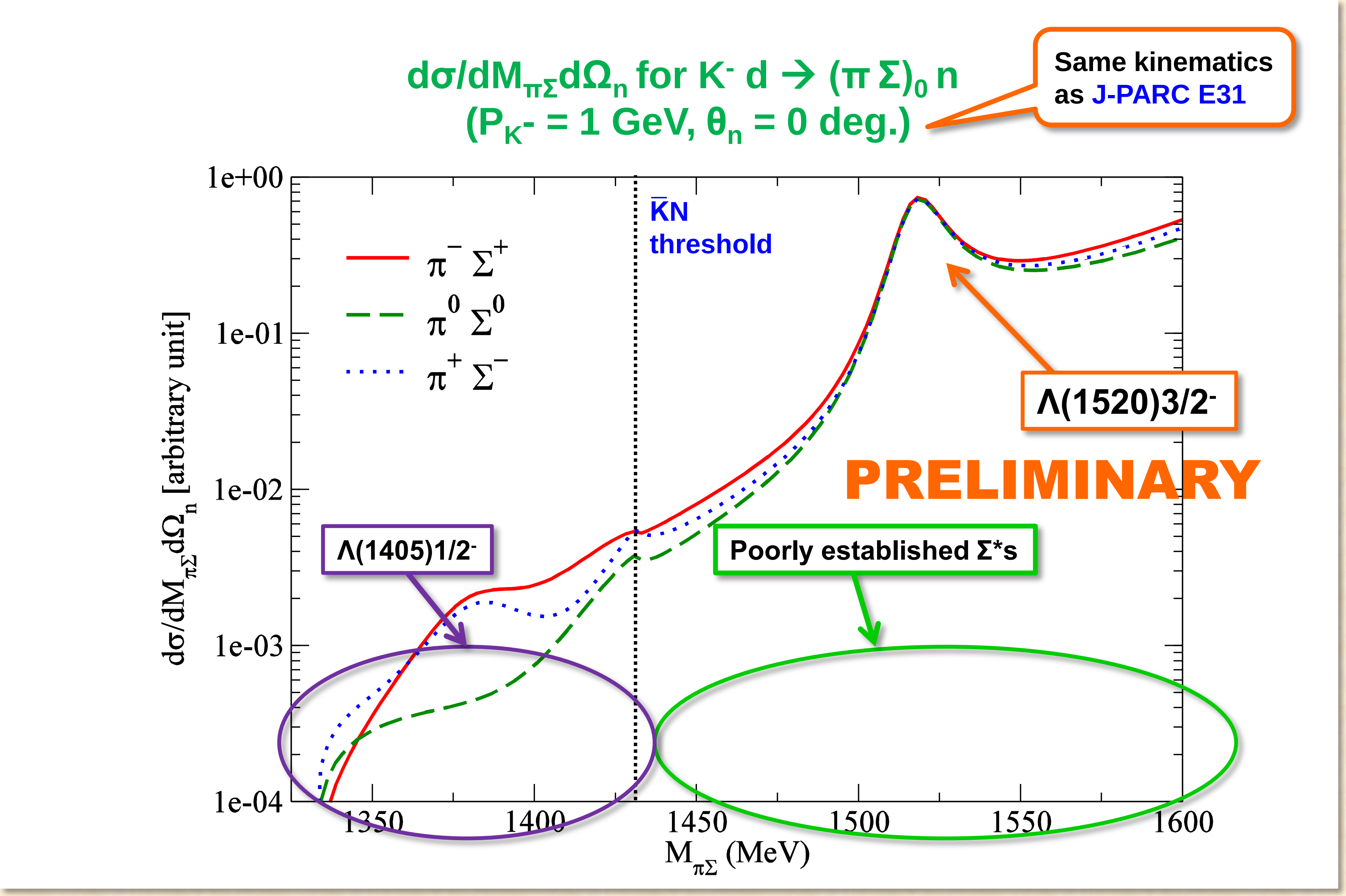

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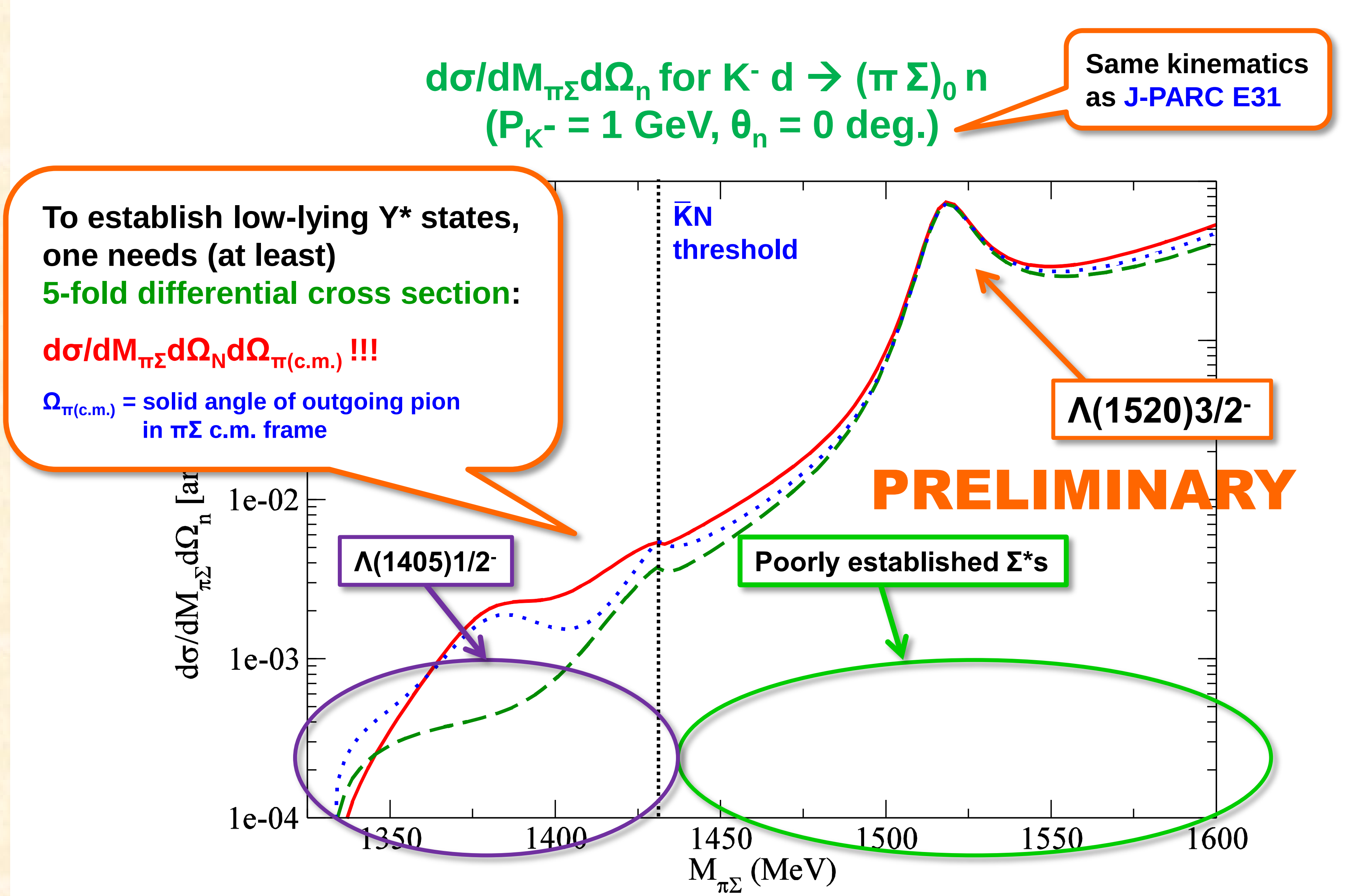

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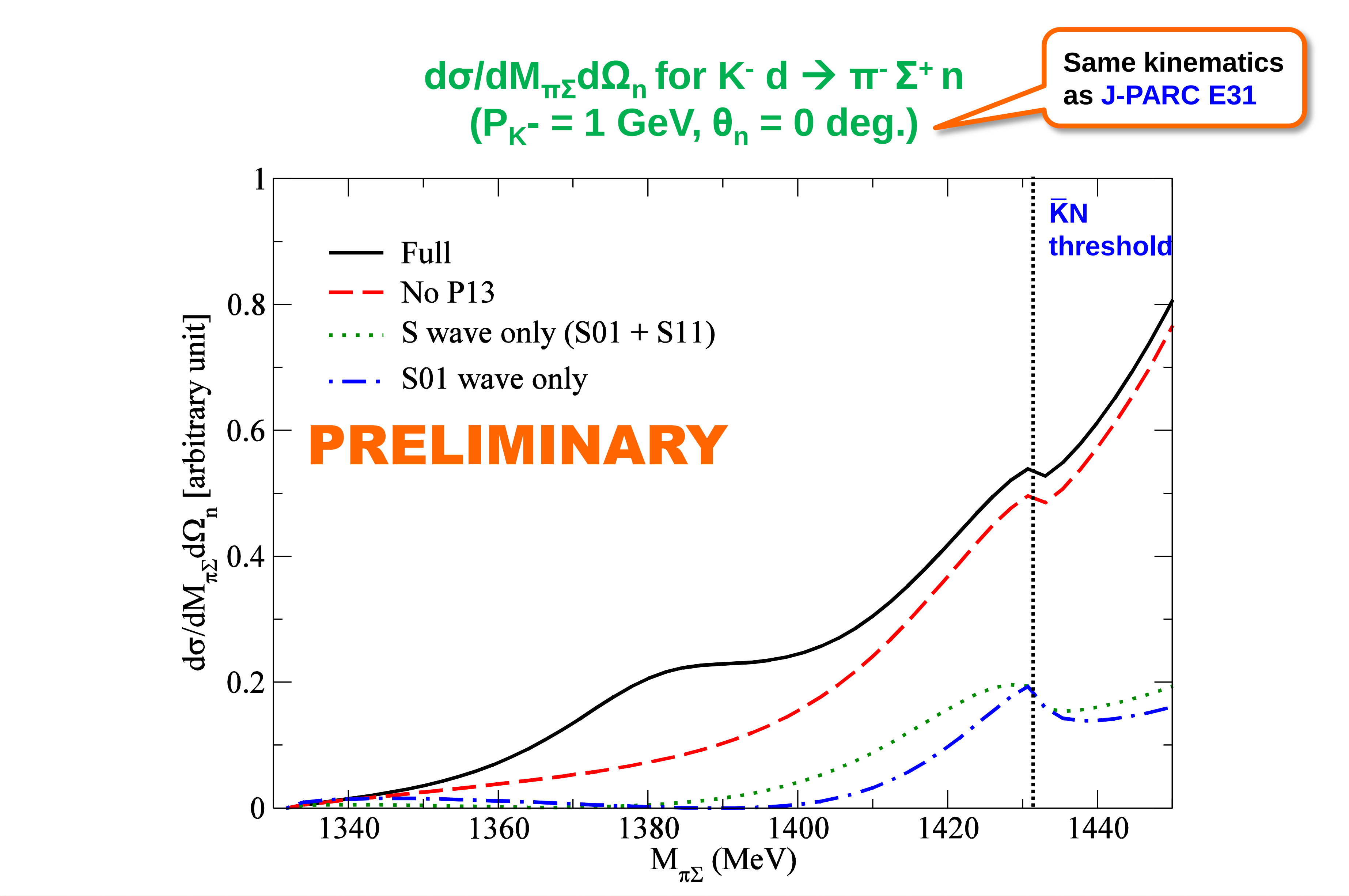

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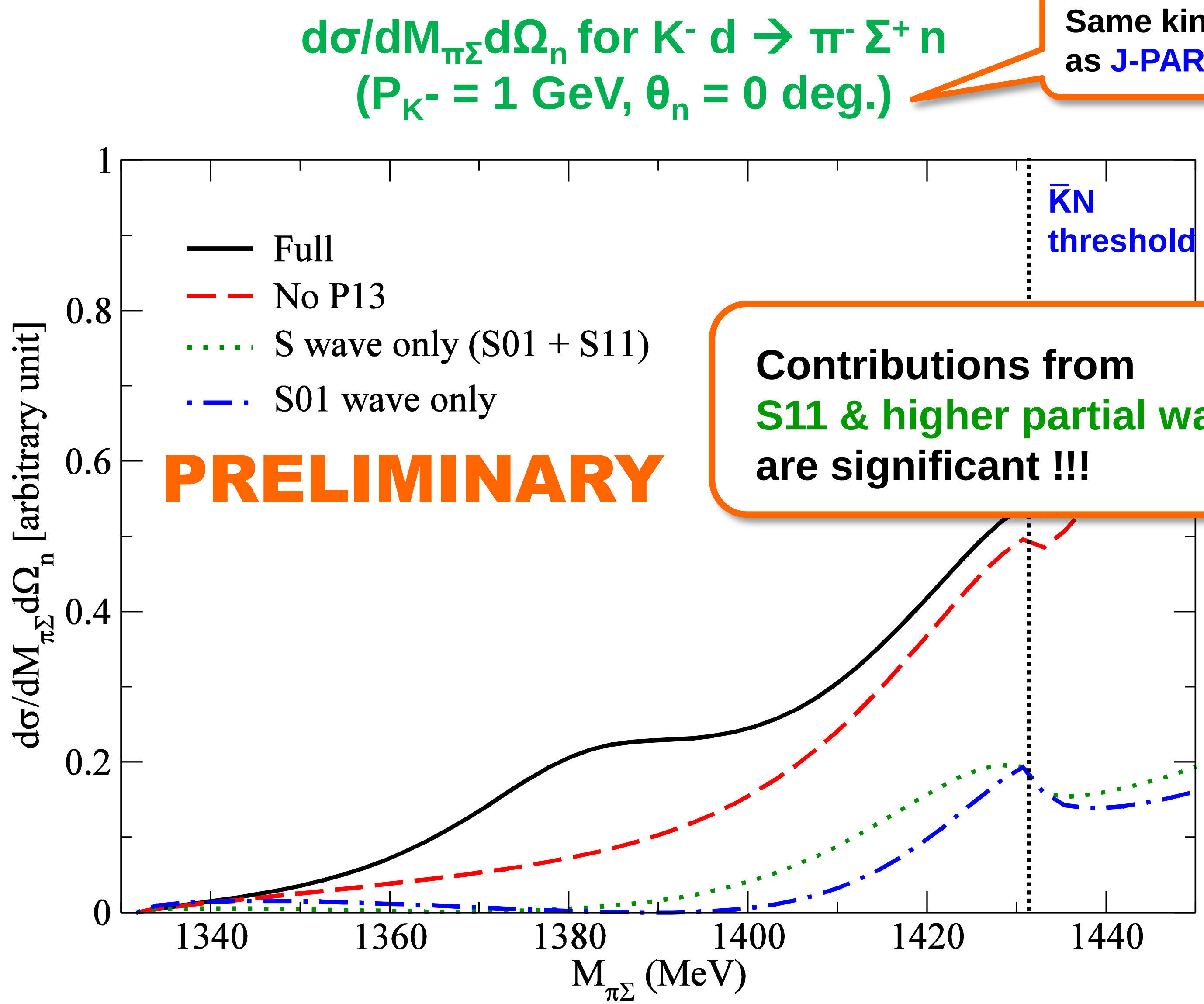
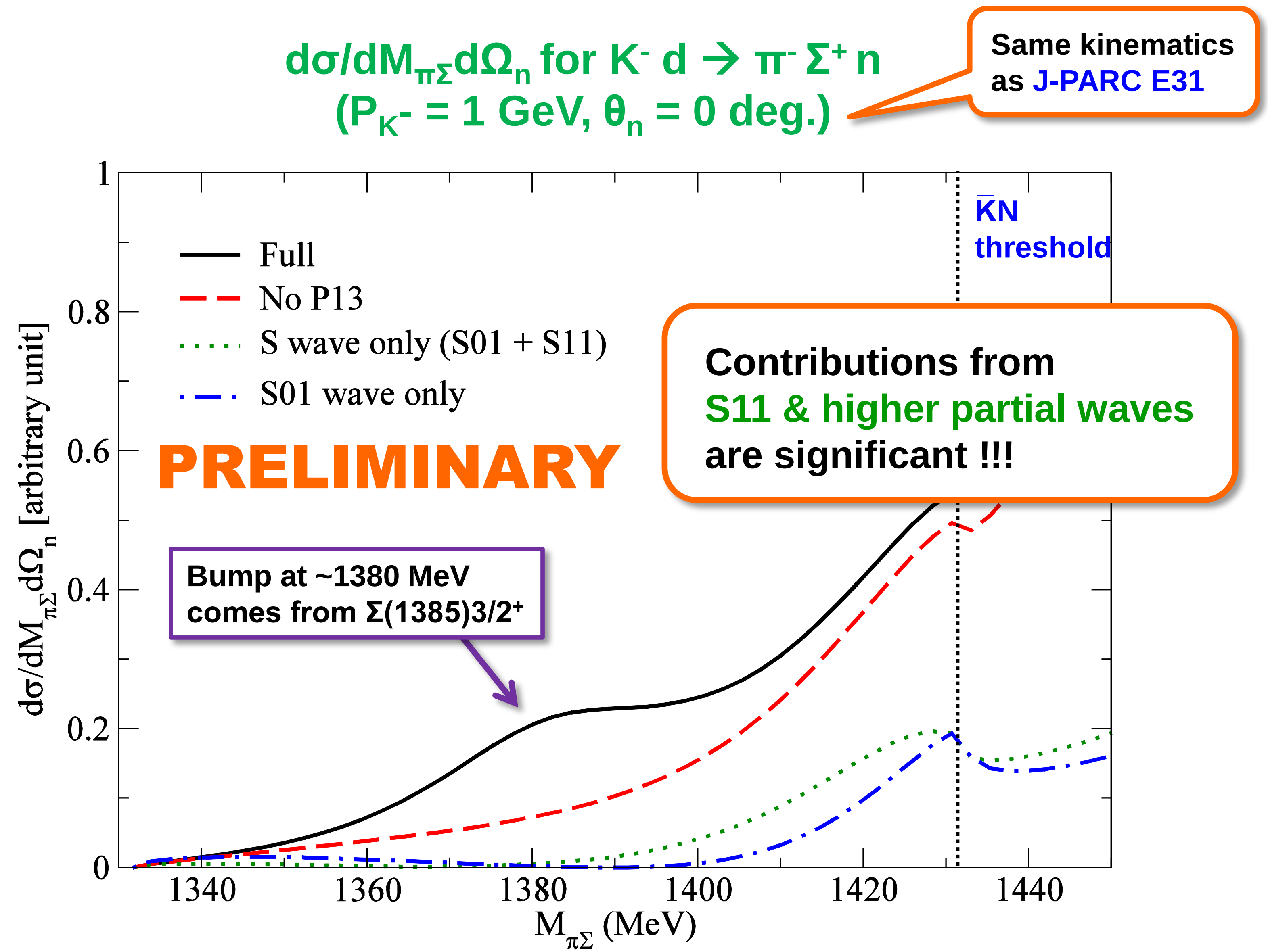


Contributions from S11 & higher partial waves are significant !!!

Results (IMPULSE TERM ONLY !!)



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 within a dynamical coupled-channels approach.

- ✓ Successfully extracted partial-wave amplitudes (up to F wave) and Y* resonance parameters defined by poles of amplitudes.
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✓ Presented preliminary results for $\bar{K}d$ reaction model.

✓ New accurate data for both $\bar{K}N$ and $\bar{K}d$ reactions are much appreciated !!!

- "Complete experiments" for 2 → 2 reaction ($\bar{K}N \to \bar{K}N$, πΣ, πΛ, ηΛ, KΞ, ηΣ, η'Y, ωY, ΦY,…)
- 2 → 3 reaction ($\bar{K}N \to \pi\pi Y, \pi\bar{K}N$,…) to determine high-mass Y*
- Deuteron-target reaction ($\bar{K}d \to \pi YN$, …) to determine low-lying Y*

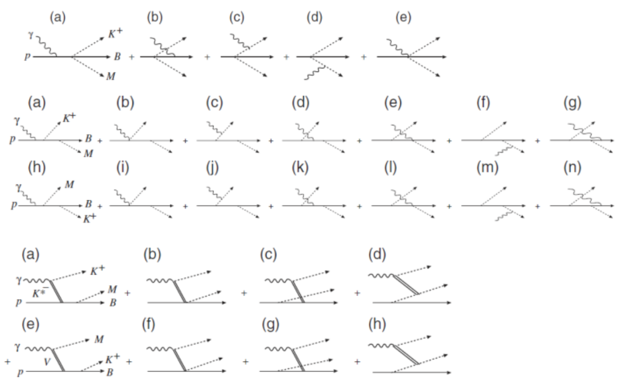
" $K_L^0 p \to$ (final states with S=-1) " reactions exclusively produce I = 1 Σ* resonances in direct s-channel processes due to the isospin filter !!

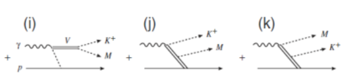
Back up

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

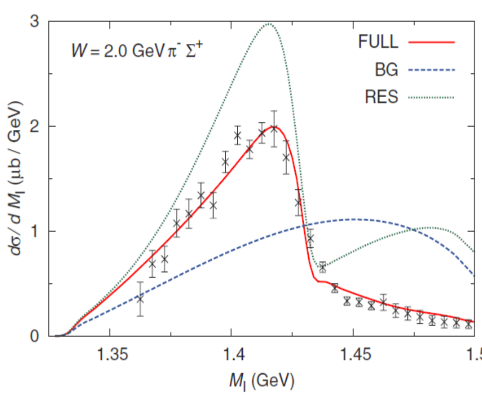
γp → $K^+\pi\Sigma$ @CLAS

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





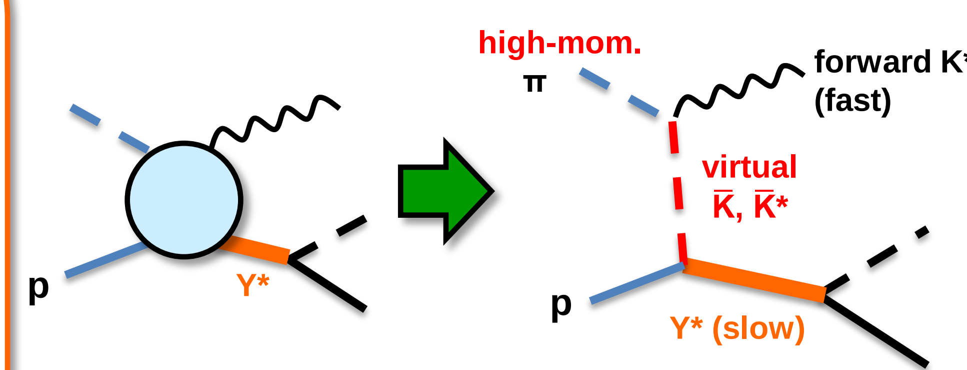
Nakamura, Jido, PTEP(2014)023D01



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 $\bar{K}N$→ MB and $\bar{K}$*N → 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−	****

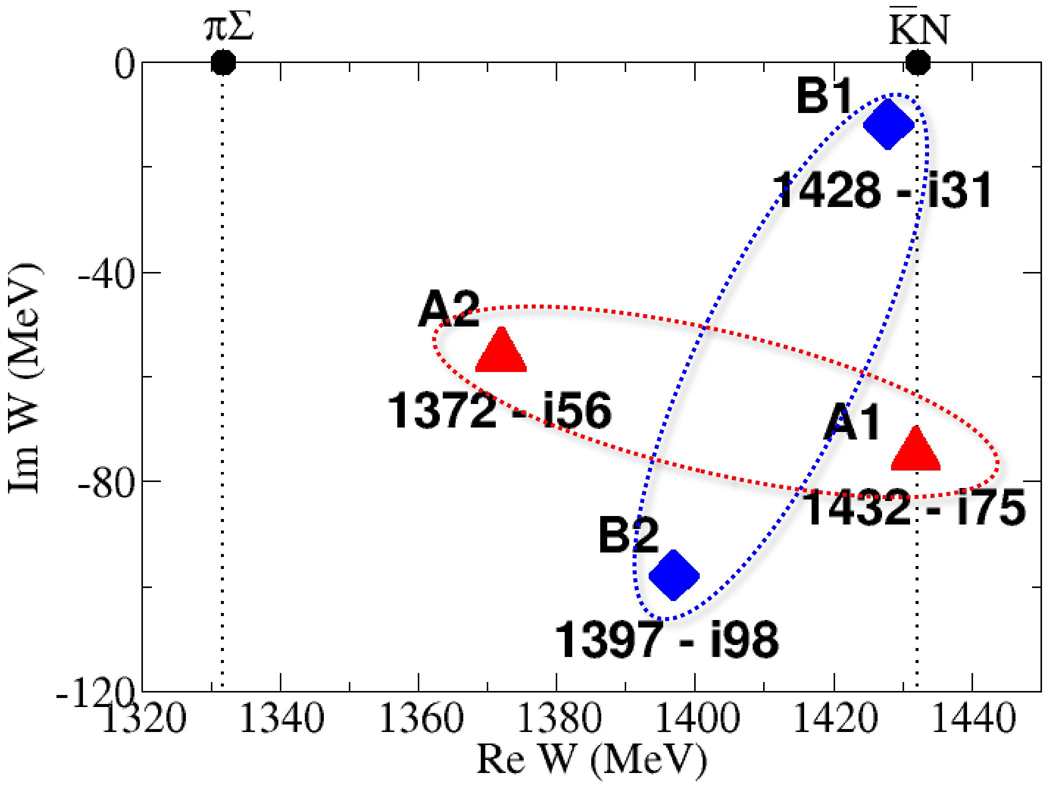
? (Σ(1480)–Σ(1620))

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



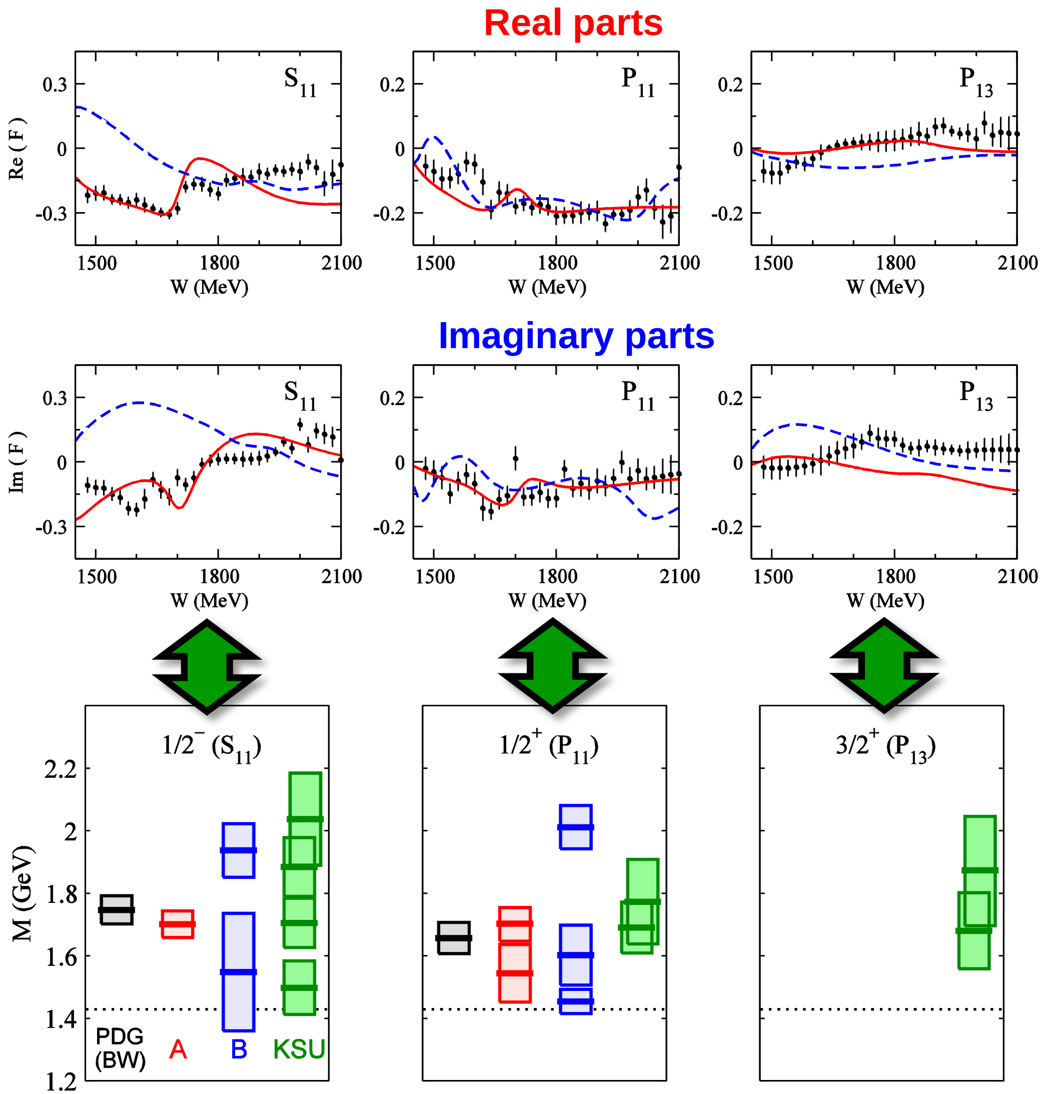
- ✓ Two resonance poles are found in both Models A and B.
  - ➢ A1 & B1 seem correspond to Λ(1405)
  - ➢ Another Λ resonance with mass 30-60 MeV lower than Λ(1405) (A2 & B2) is also found to exist.

Red triangles: Model A
Blue diamonds: Model B

New data can eliminate analysis dependence ??

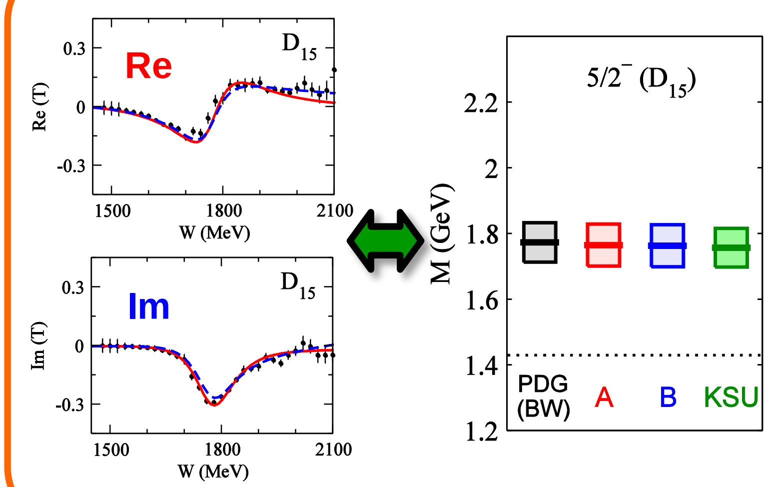
Extracted $\bar{K}N \rightarrow \pi\Lambda$ amplitudes

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



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

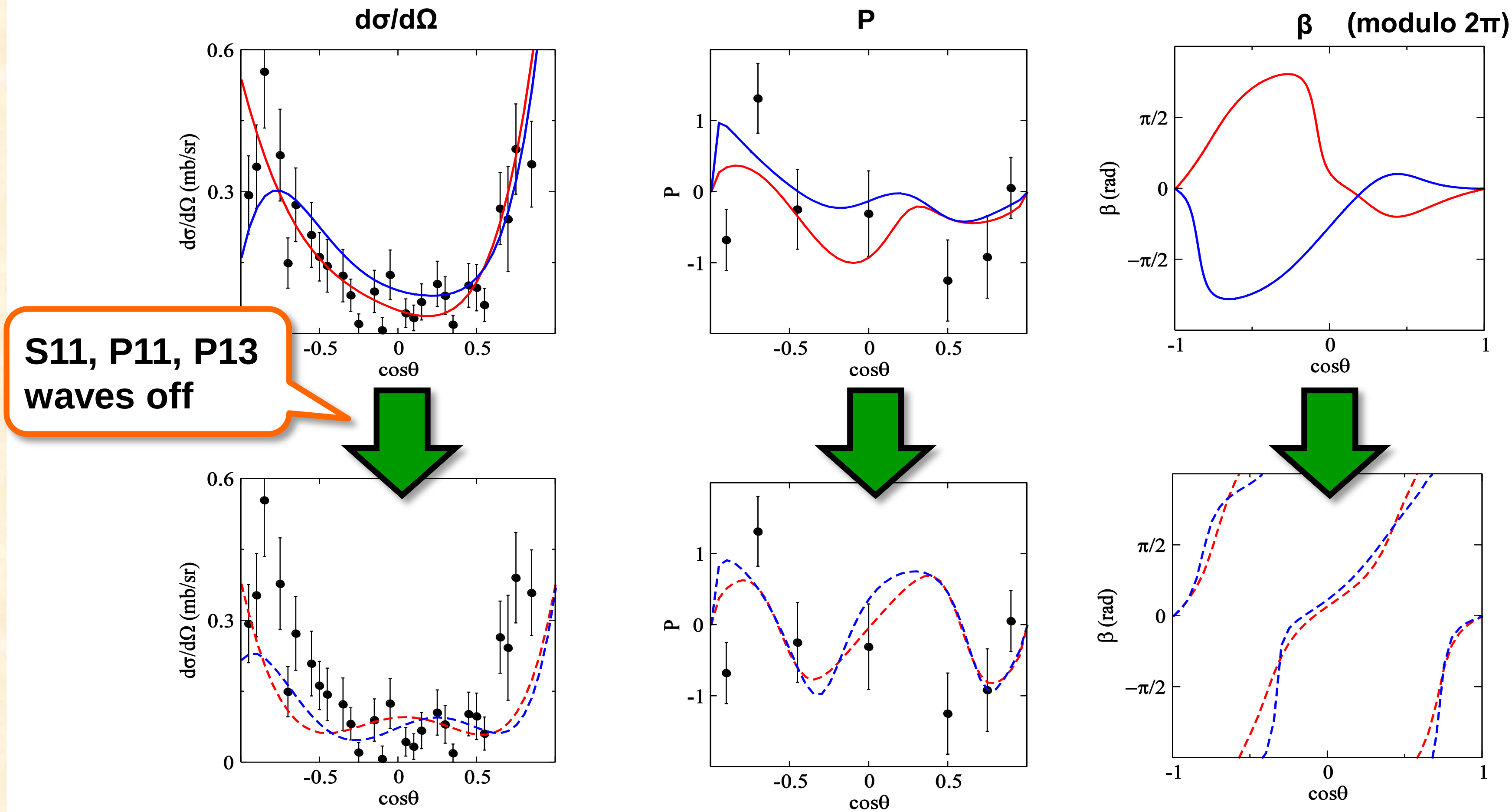
Red : Model A
Blue: Model B
Circles: KSU single-energy solution [PRC88(2013)035204]



New data can eliminate analysis dependence ??

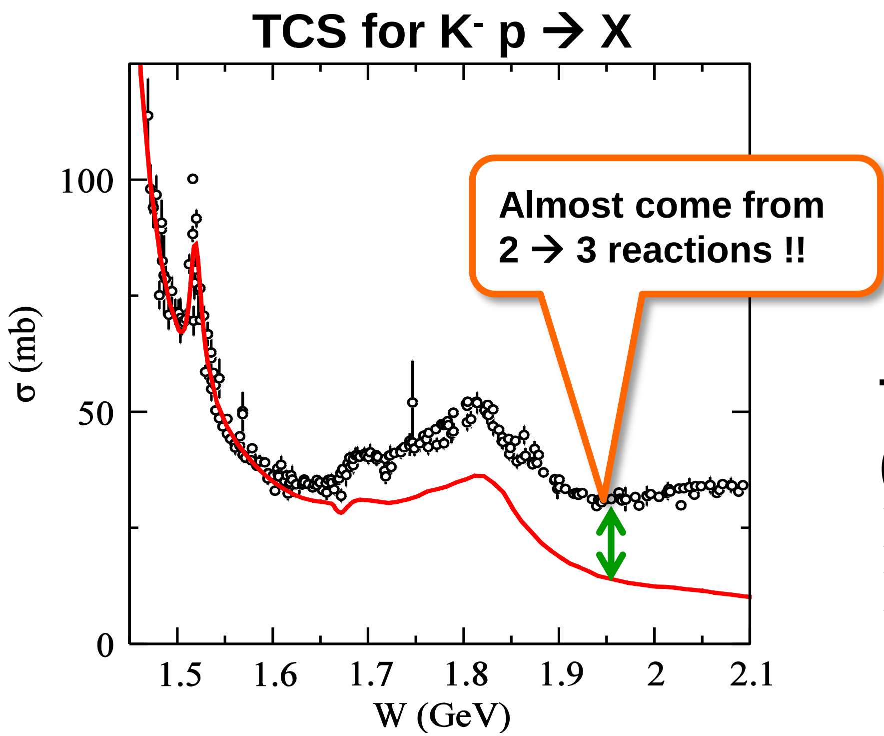
$K^- p \rightarrow \pi^0 \Lambda$ observables @ W = 1700 MeV

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



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 ($K^- p \to \pi\pi\Lambda, \pi\bar{K}N, \ldots$):

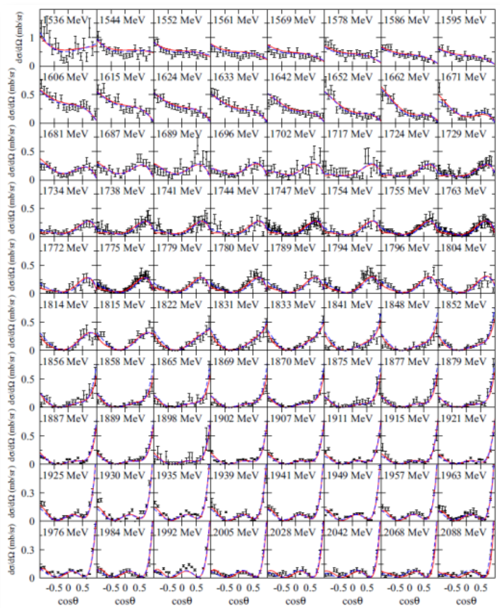
- significant above W ~ 1.7 GeV.
- even larger than the 2 → 2 TCS above W ~ 1.9 GeV !!

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 !!

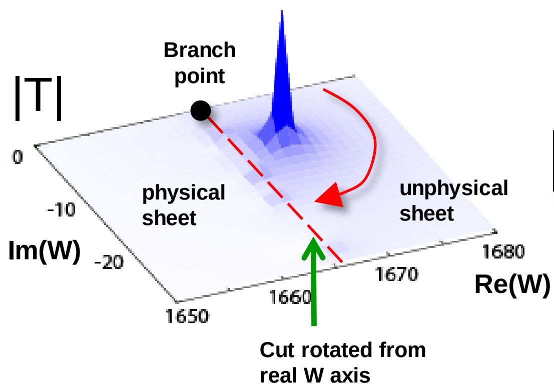
Our strategy for light-quark baryon spectroscopy

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:**

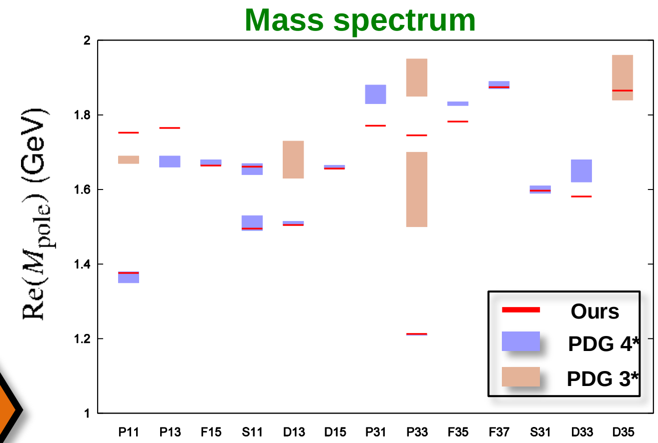
2) Search *poles* of determined scattering amplitudes by making analytic continuation to a complex energy plane.

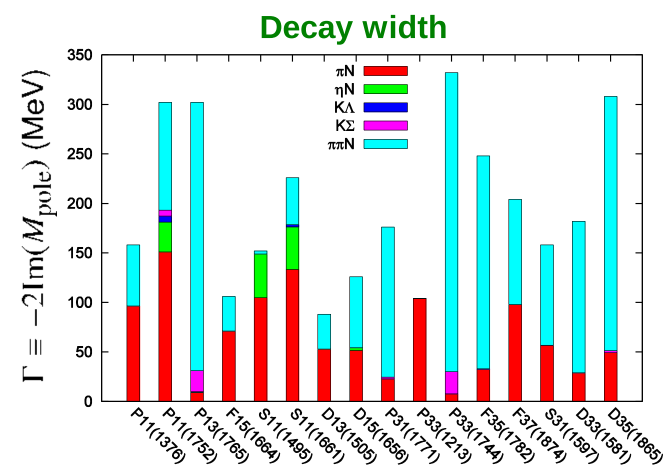


Pole position → (complex) resonance mass

Residues → coupling strengths between Y* and MB

3) Extract resonance parameters defined by poles.





Extracted scattering lengths and effective ranges

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

Scattering length and effective range

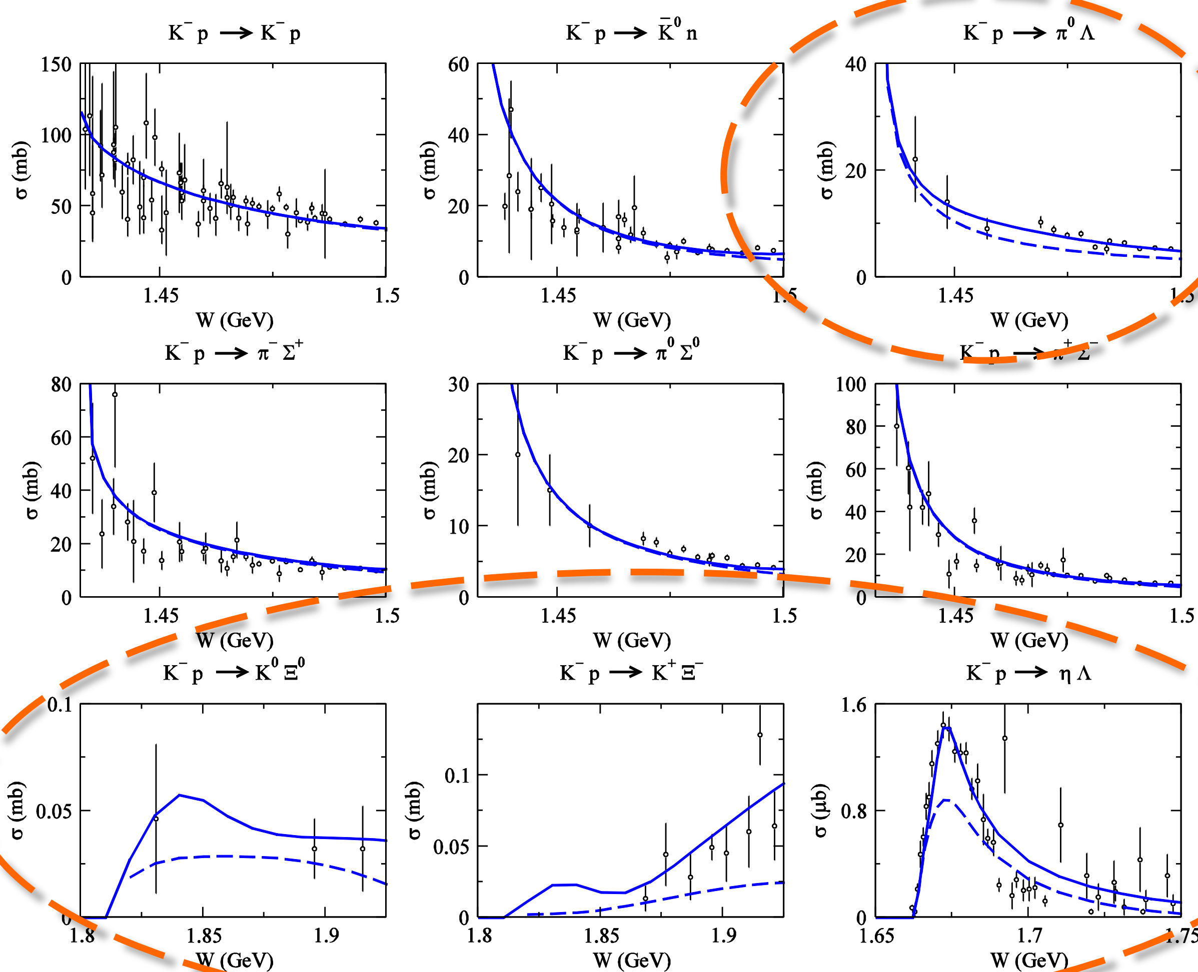
	Model A		Model B	
	$I=0$	$I=1$	$I=0$	$I=1$
$a_{\bar{K}N}$ (fm)	$-1.37+i0.67$	$0.07+i0.81$	$-1.62+i1.02$	$0.33+i0.49$
$a_{\eta\Lambda}$ (fm)	$1.35+i0.36$	-	$0.97+i0.51$	-
$a_{K\Xi}$ (fm)	$-0.81+i0.14$	$-0.68+i0.09$	$-0.89+i0.13$	$-0.83+i0.03$
$r_{\bar{K}N}$ (fm)	$0.67-i0.25$	$1.01-i0.20$	$0.74-i0.25$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

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 !!

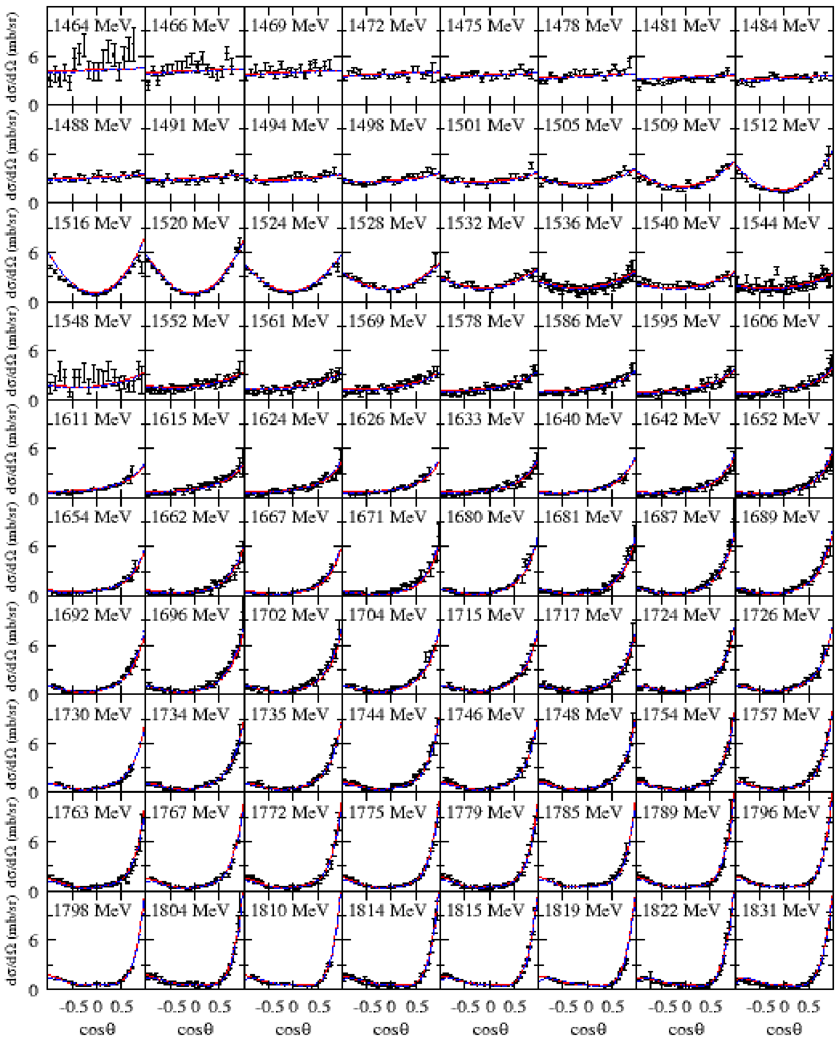
HK, Nakamura, Lee, Sato, PRC90(2014)065204

Results of the fits

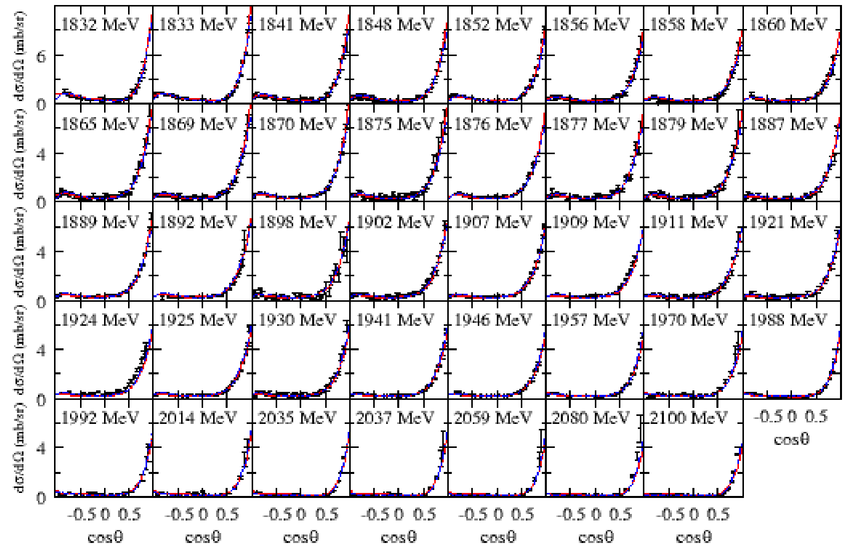
K⁻ p → K⁻ p scattering

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

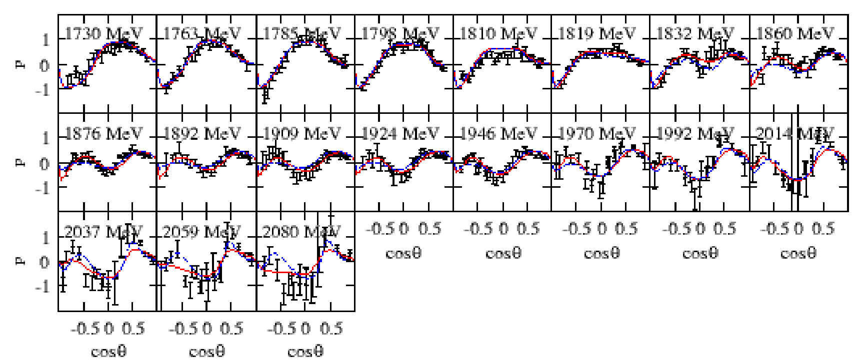
dσ/dΩ (1464 < W < 1831 MeV)



dσ/dΩ (1832 < W < 2100 MeV)



P



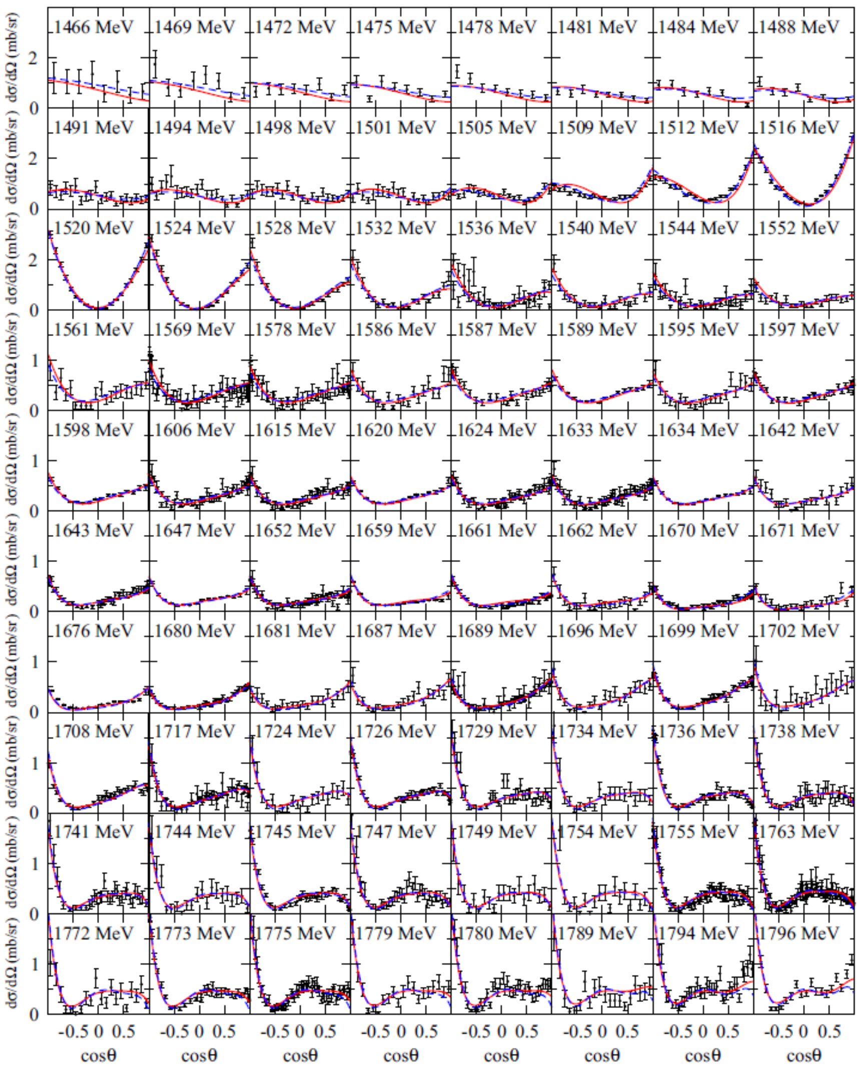
Red: Model A Blue: Model B

Results of the fits

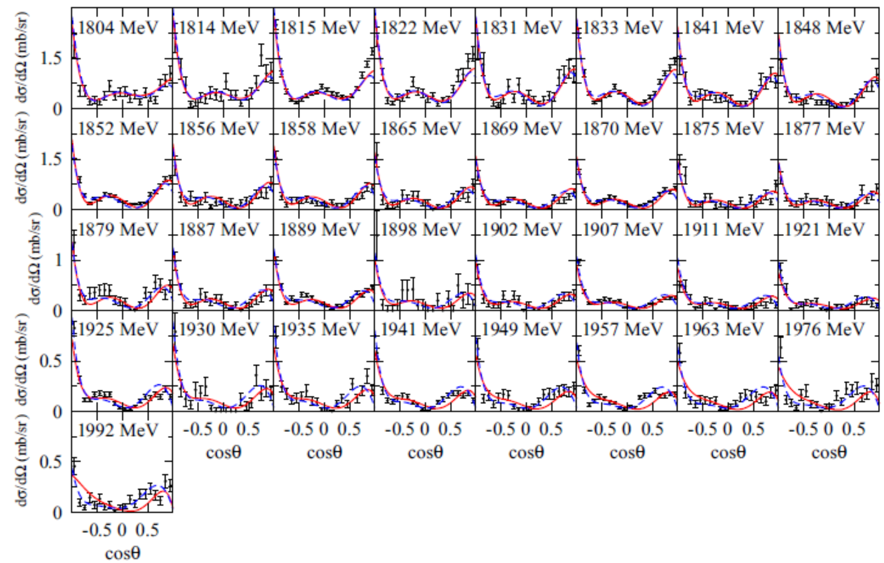
$K^- p \rightarrow K^0 n$ reaction

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

dσ/dΩ (1466 < W < 1796 MeV)



dσ/dΩ (1804 < W < 1992 MeV)



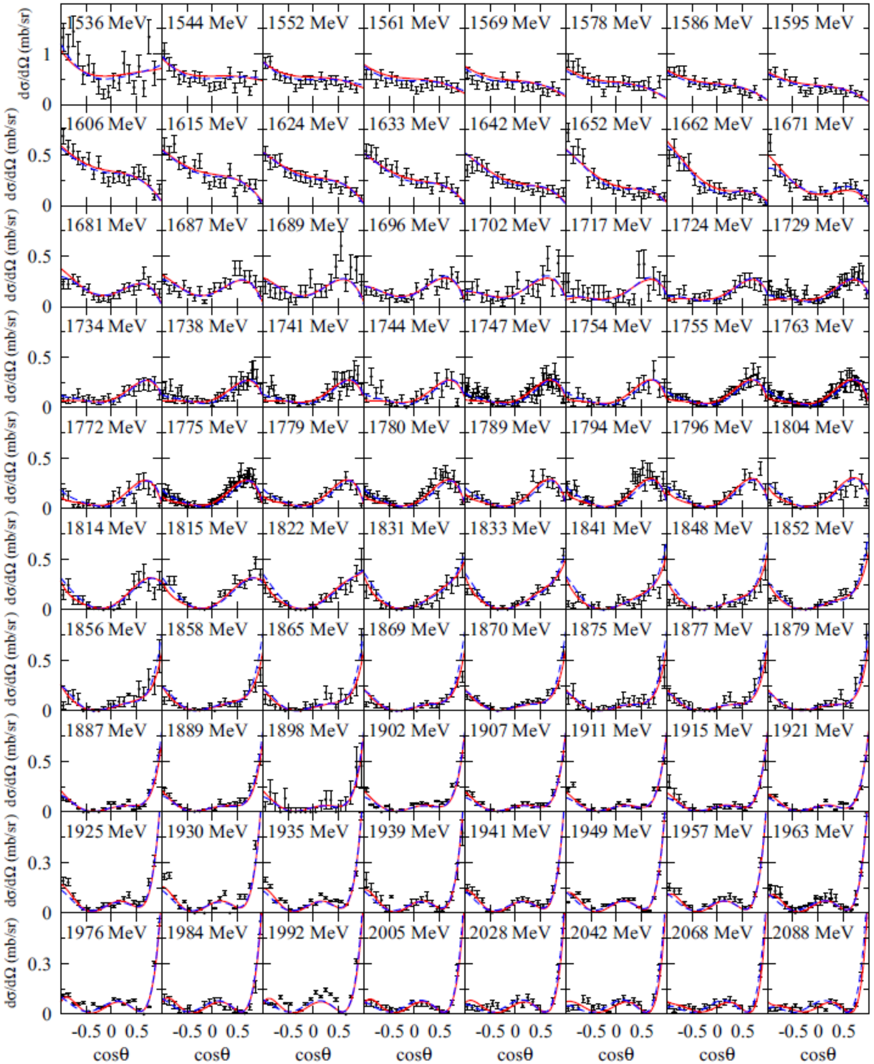
Red: Model A Blue: Model B

Results of the fits

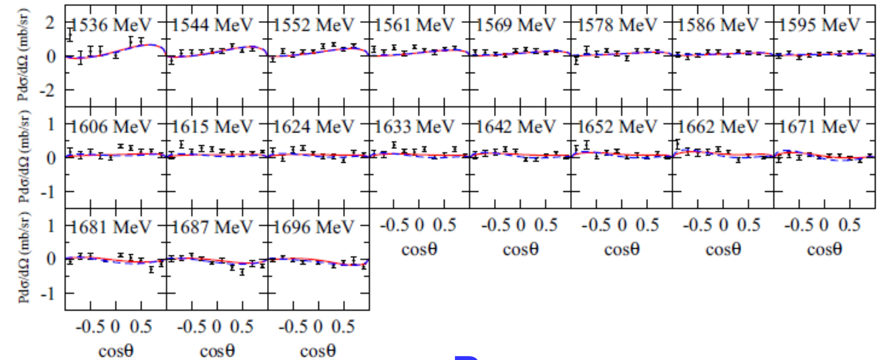
K⁻ p → π⁻ Σ⁺ reaction

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

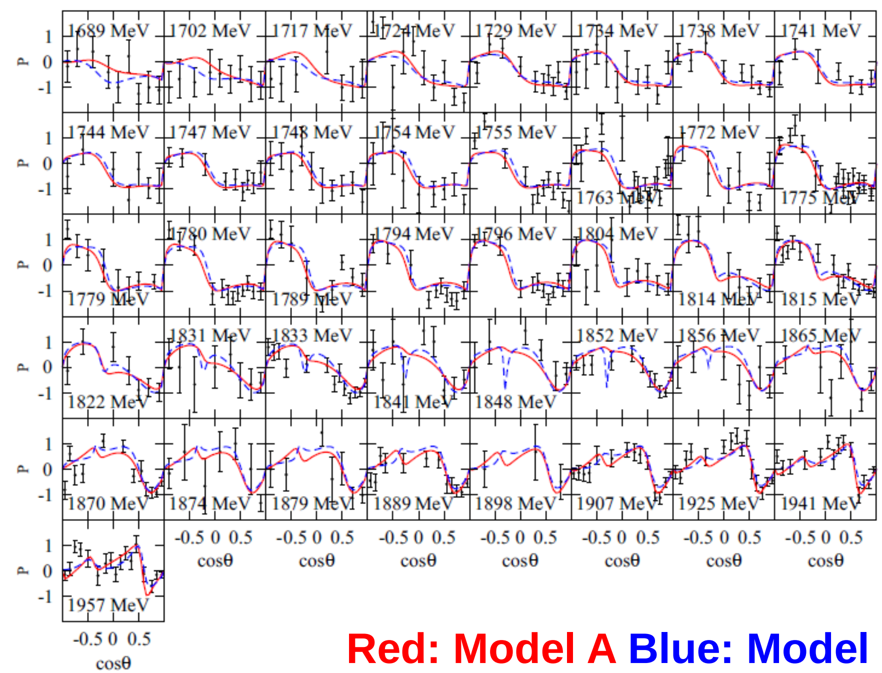
dσ/dΩ



P x dσ/dΩ



P



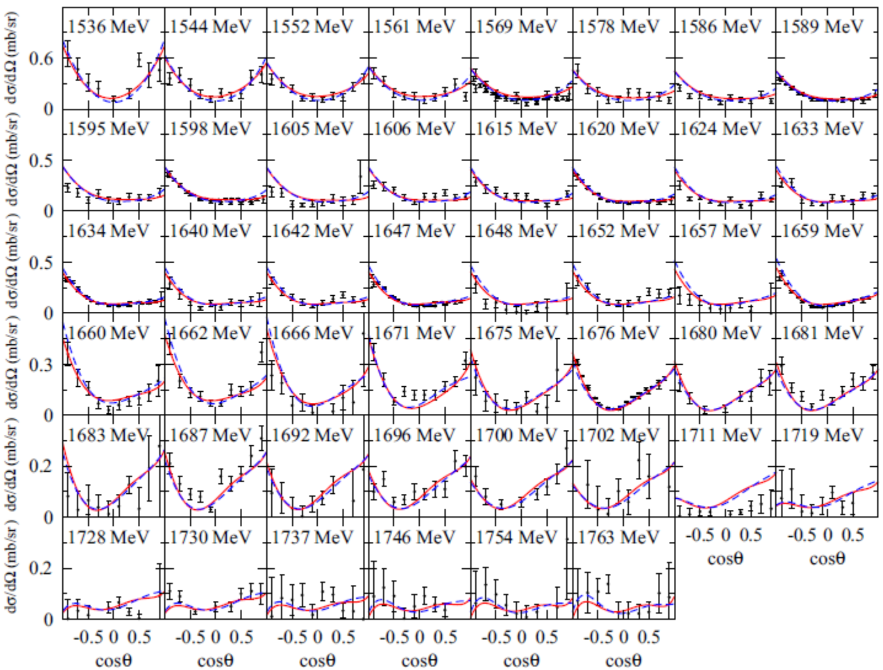
Red: Model A Blue: Model B

Results of the fits

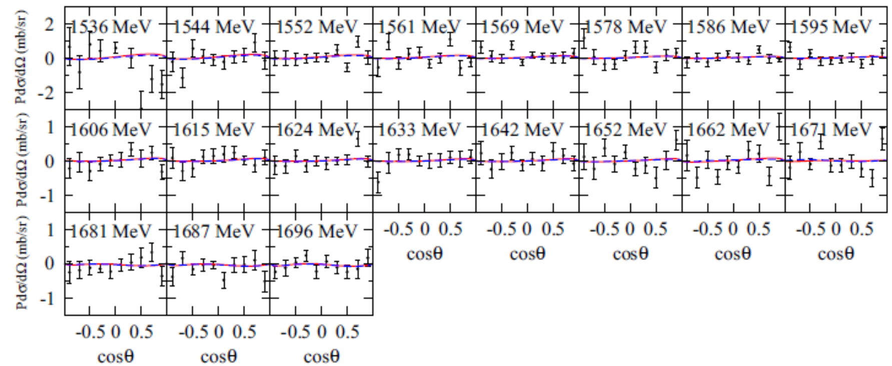
K⁻ p → π^0 Σ^0 reaction

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

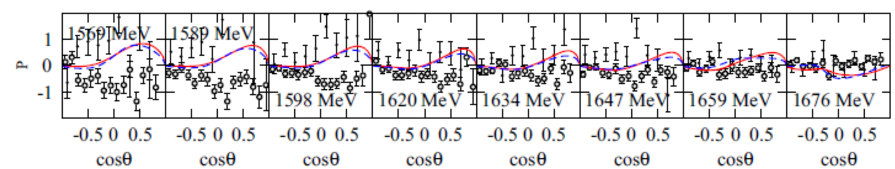
dσ/dΩ



P x dσ/dΩ



P



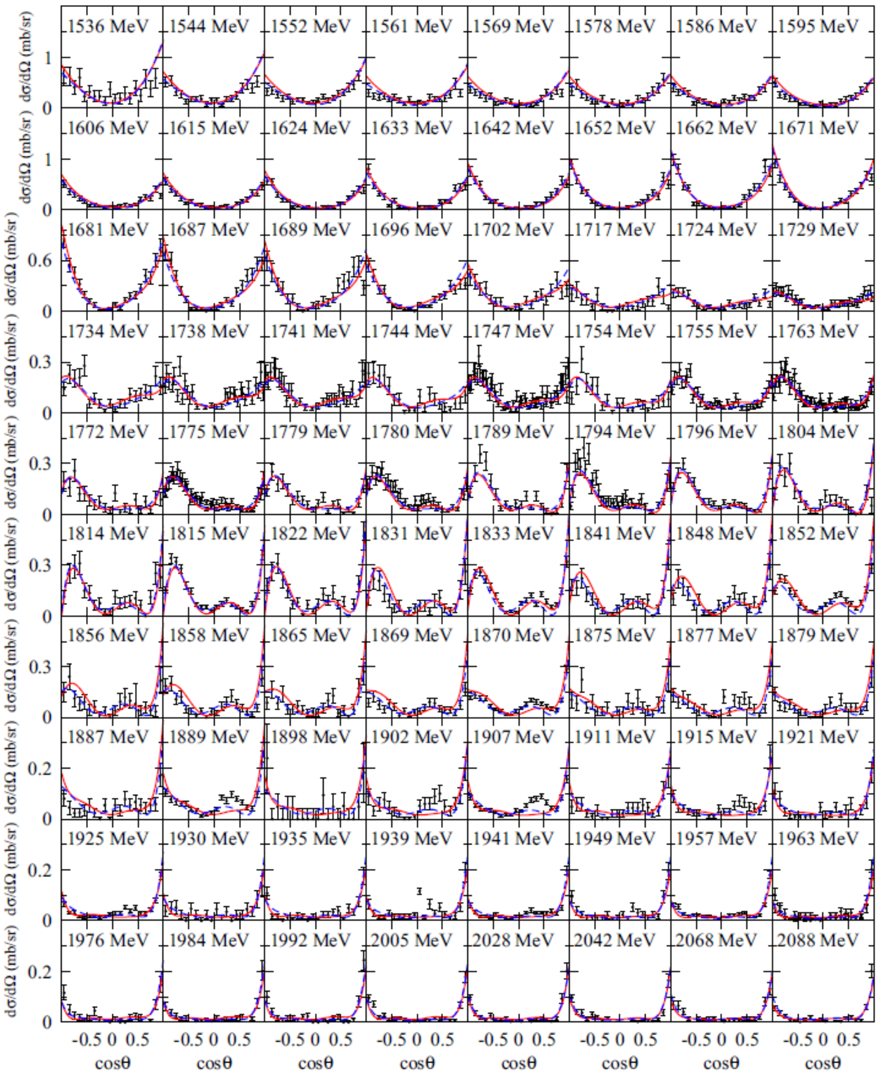
Red: Model A Blue: Model B

Results of the fits

$K^- p \rightarrow \pi^+ \Sigma^-$ reaction

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

dσ/dΩ



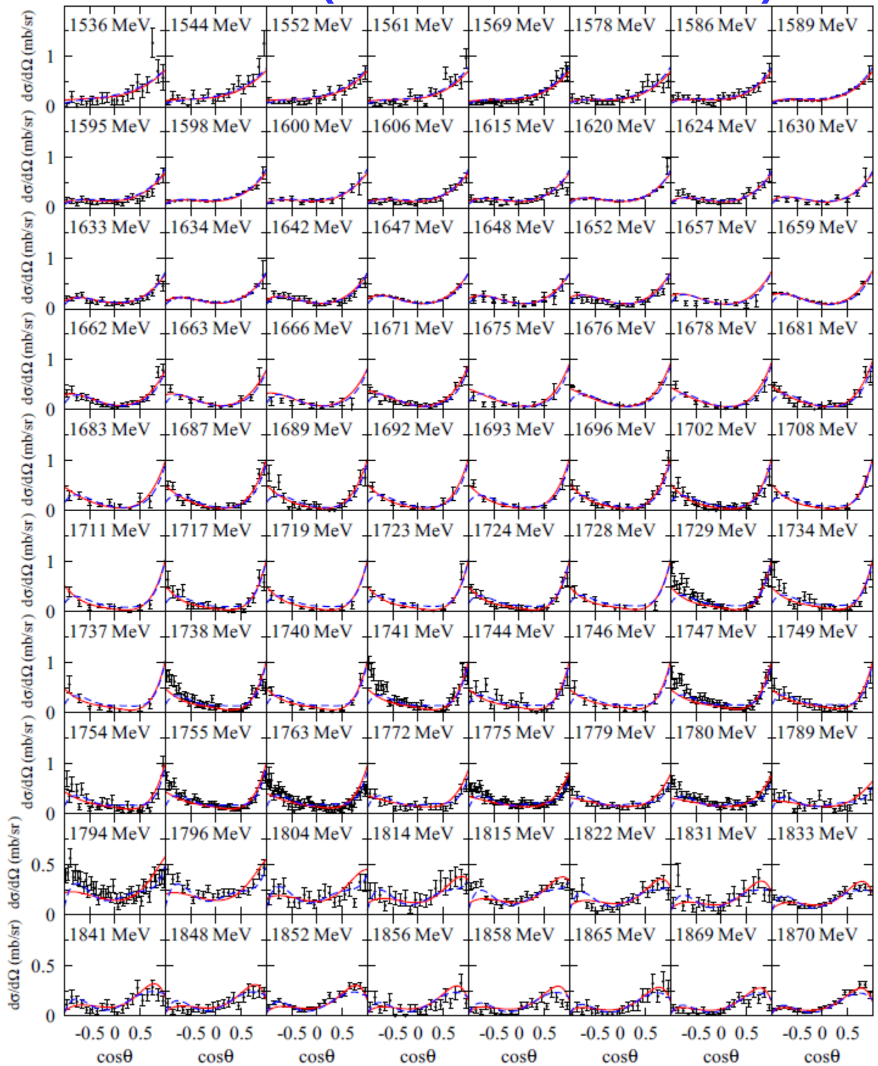
Red: Model A Blue: Model B

Results of the fits

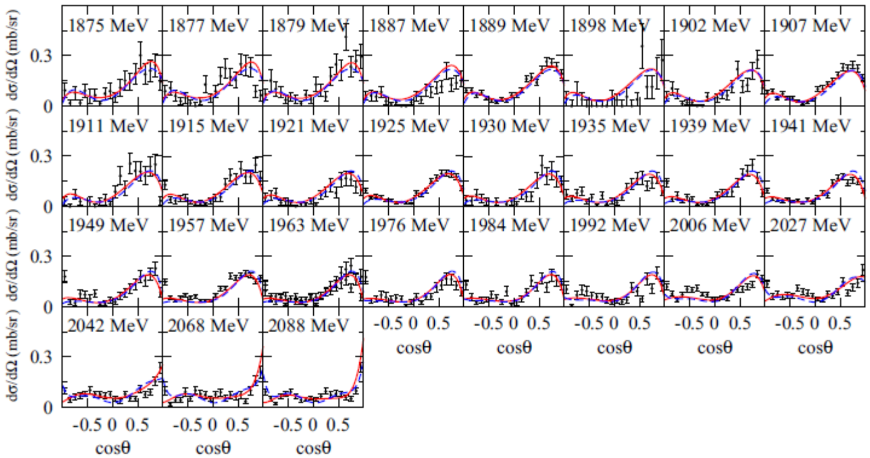
$K^- p \rightarrow \pi^0 \Lambda$ reaction

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

dσ/dΩ (1536 < W < 1870 MeV)



dσ/dΩ (1875 < W < 2088 MeV)



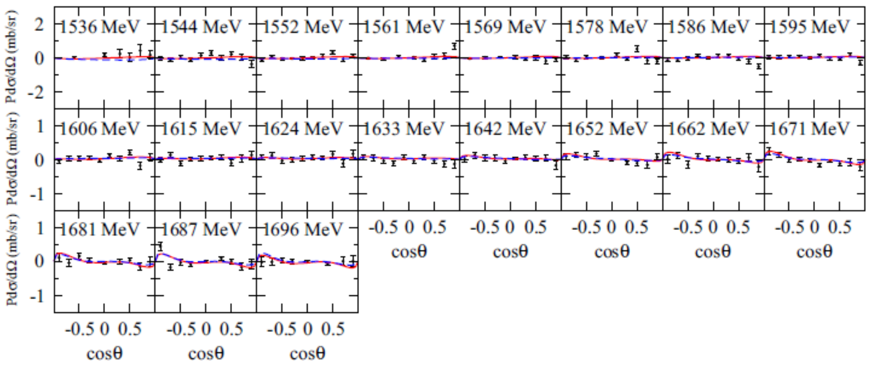
Red: Model A Blue: Model B

Results of the fits

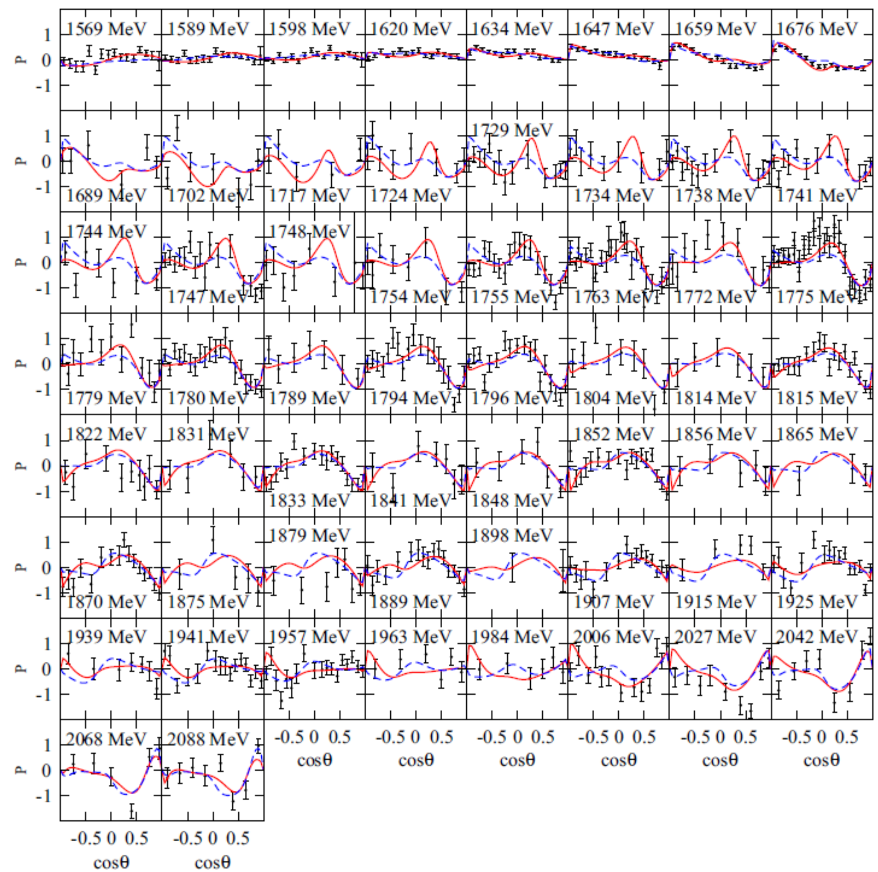
HK, Nakamura, Lee, Sato, PRC90(2014)065204

$K^- p \rightarrow \pi^0 \Lambda$ reaction (cont'd)

P x dσ/dΩ



P



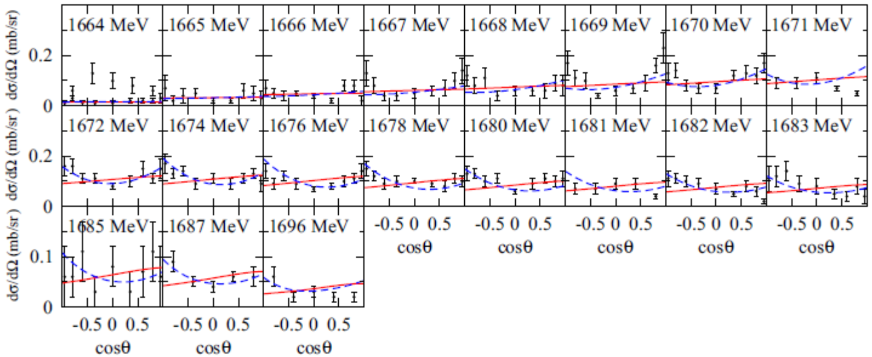
Red: Model A Blue: Model B

Results of the fits

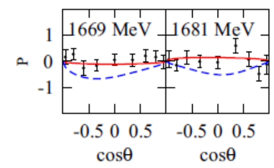
HK, Nakamura, Lee, Sato, PRC90(2014)065204

K$^-$ p → ηΛ reaction

dσ/dΩ

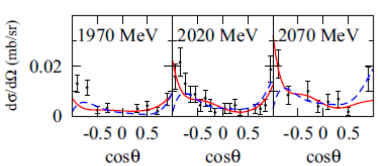


P



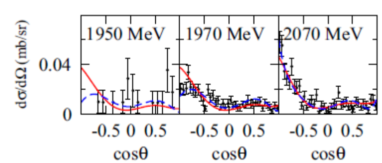
K$^-$ p → K^{0}Ξ^0 reaction

dσ/dΩ



K$^-$ p → K$^+$Ξ$^-$ reaction

dσ/dΩ

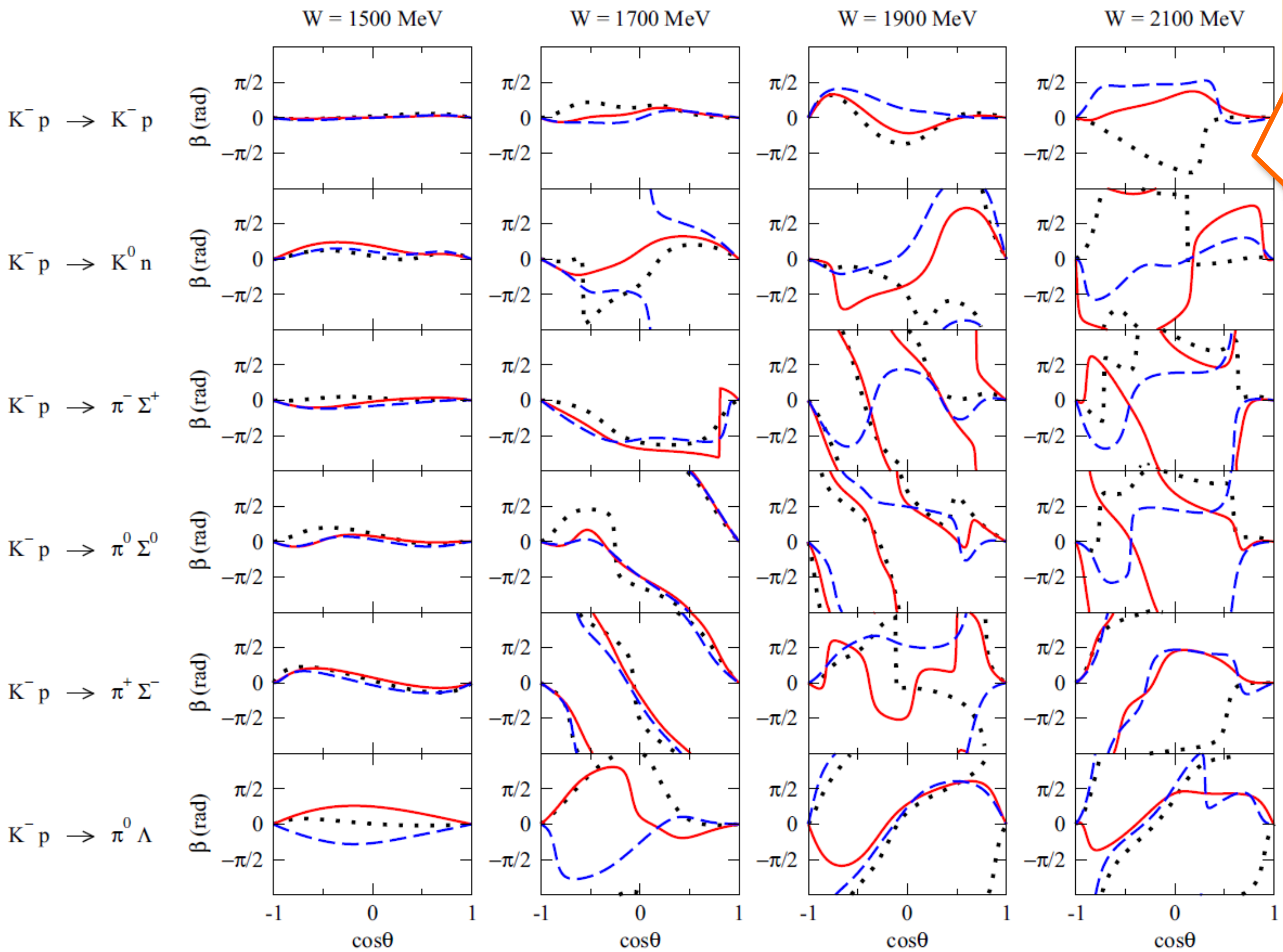


Red: Model A Blue: Model B

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.

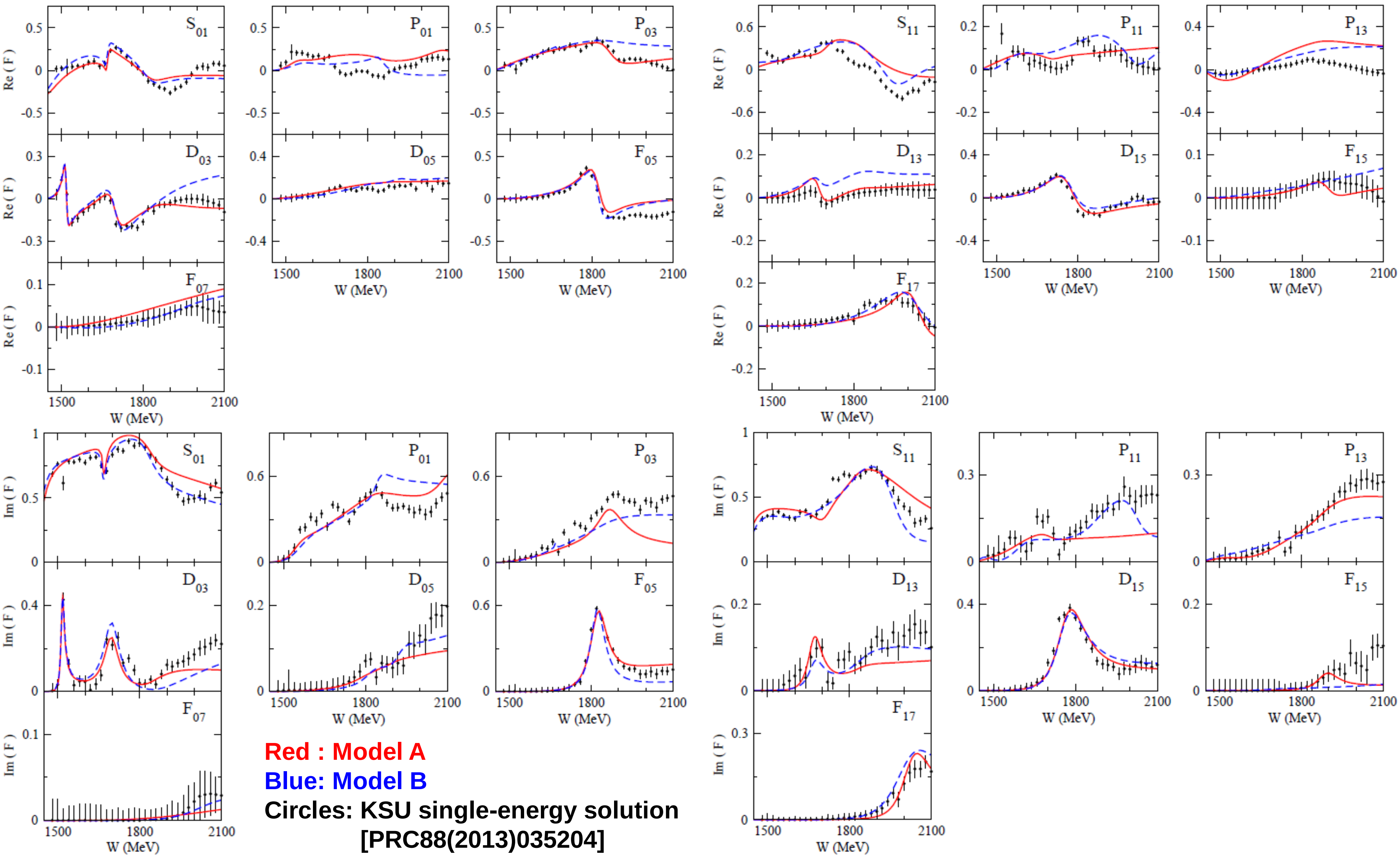
NOTE:
β is modulo 2π

Comparison of extracted partial-wave amplitudes

Extracted K̄N 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

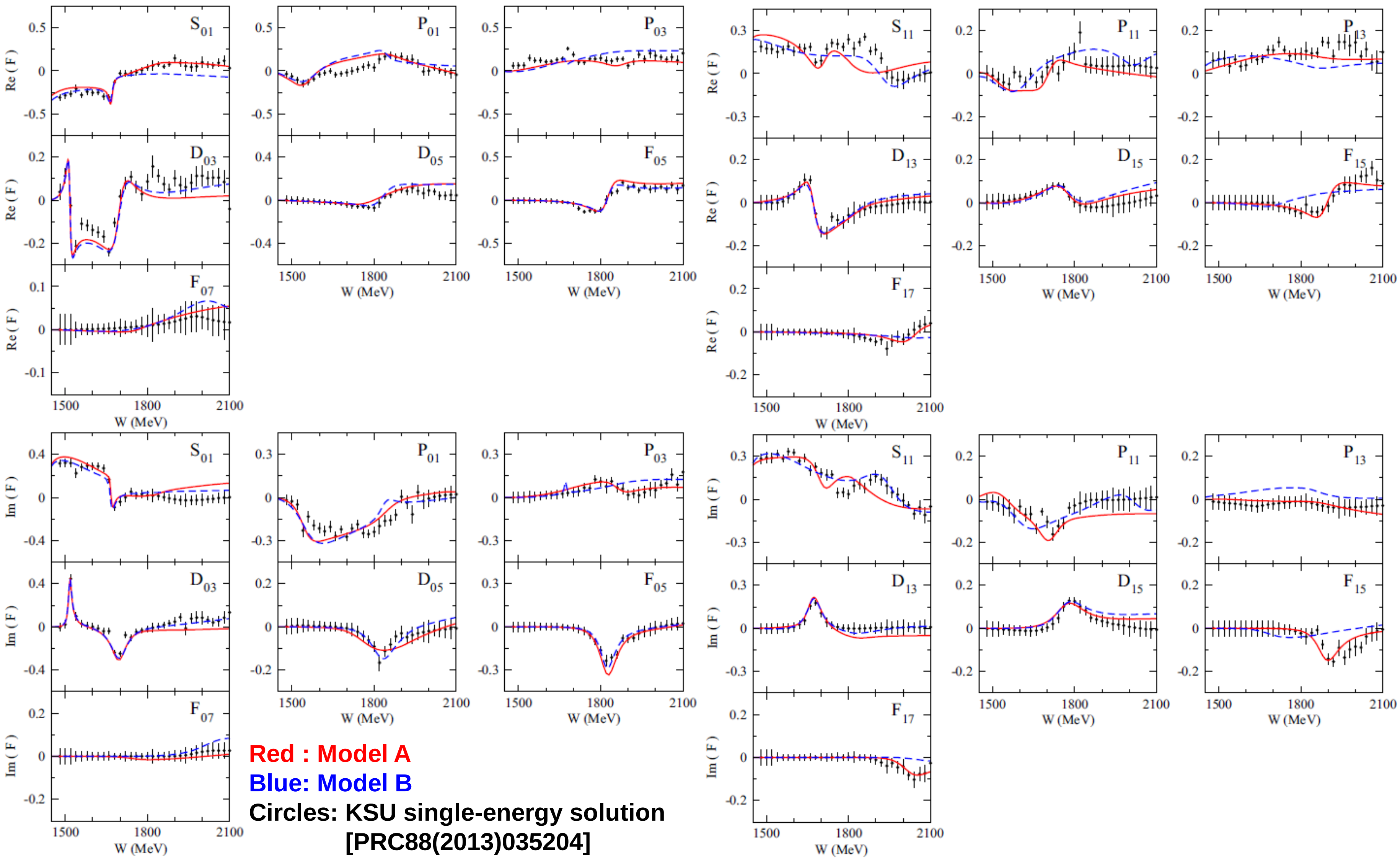
Circles: KSU single-energy solution [PRC88(2013)035204]

Comparison of extracted partial-wave amplitudes

Extracted $\bar{K}N \rightarrow \pi\Sigma$ amplitudes

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

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



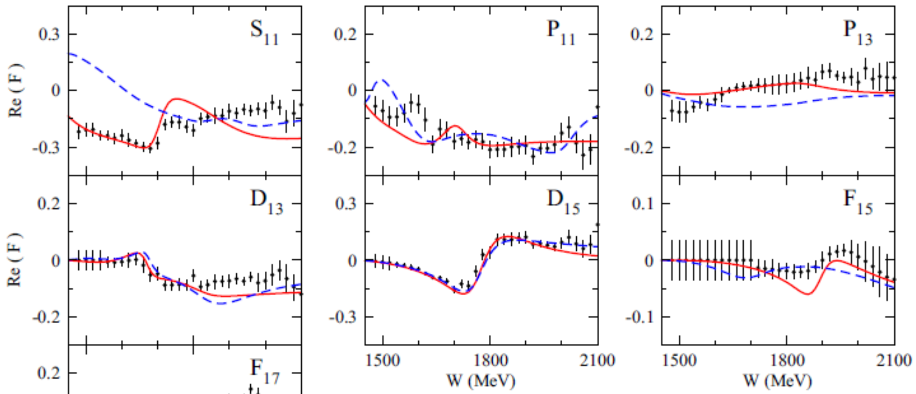
Red : Model A

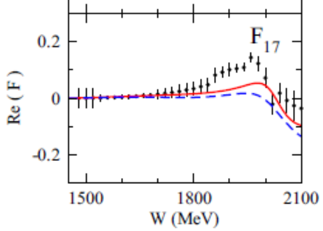
Blue: Model B

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

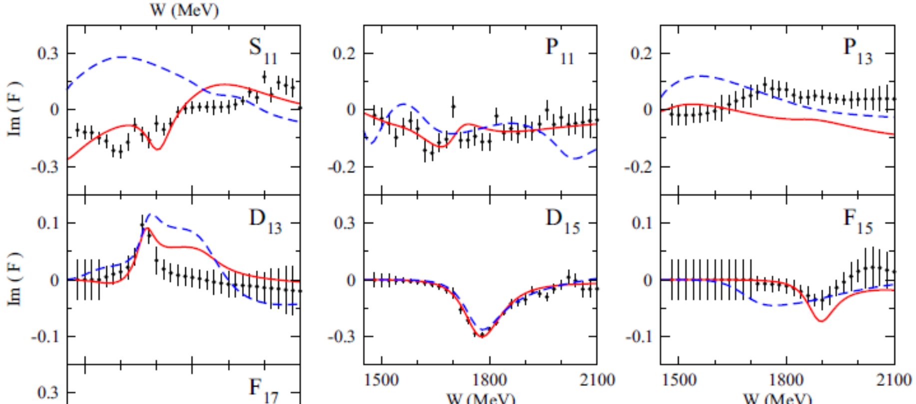
Comparison of extracted partial-wave amplitudes

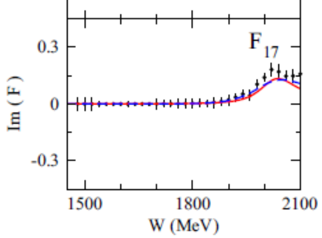
Extracted $\bar{K}N \rightarrow \pi\Lambda$ amplitudes





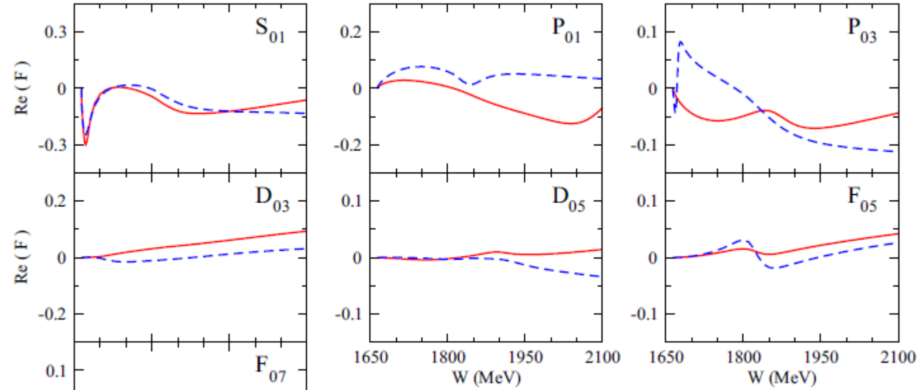
$L_{I\ 2J}$: L = S,P,.. ; I = isospin;
J = Total angular mom.

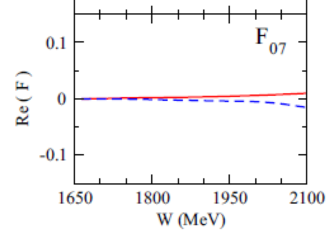


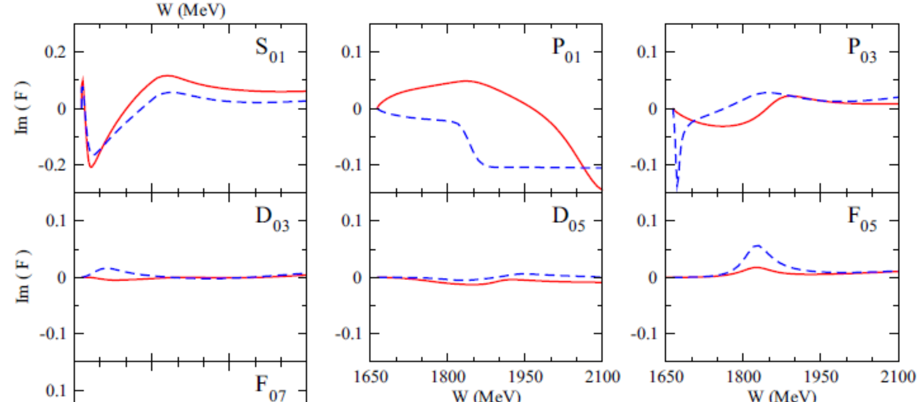


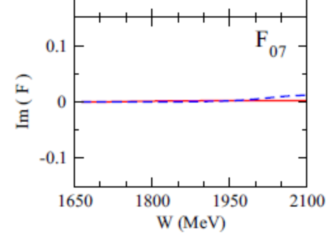
HK, Nakamura, Lee, Sato,
PRC90(2014)065204

Extracted $\bar{K}N \rightarrow \eta\Lambda$ amplitudes









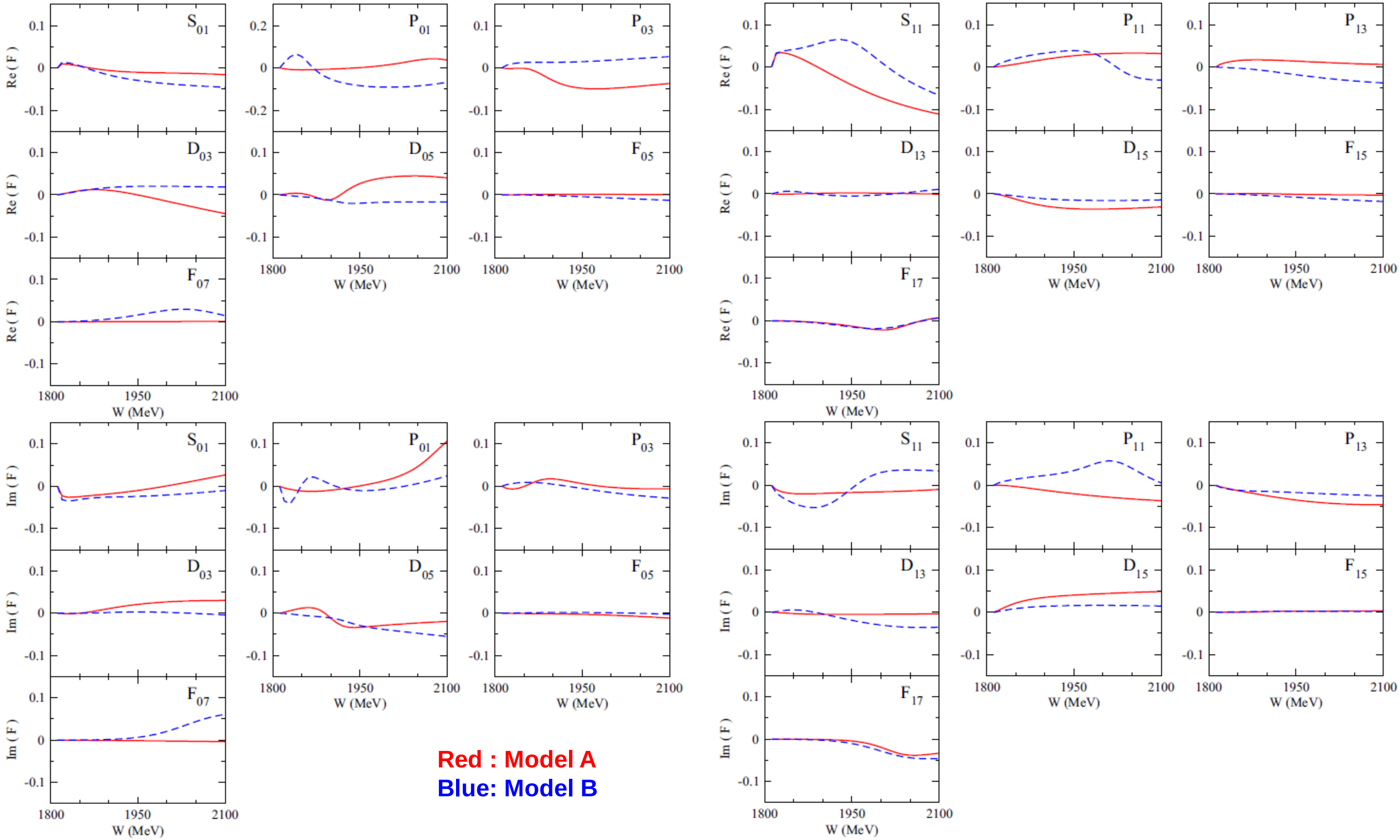
Red : Model A
Blue: Model B
Circles: KSU single-energy solution
[PRC88(2013)035204]

Comparison of extracted partial-wave amplitudes

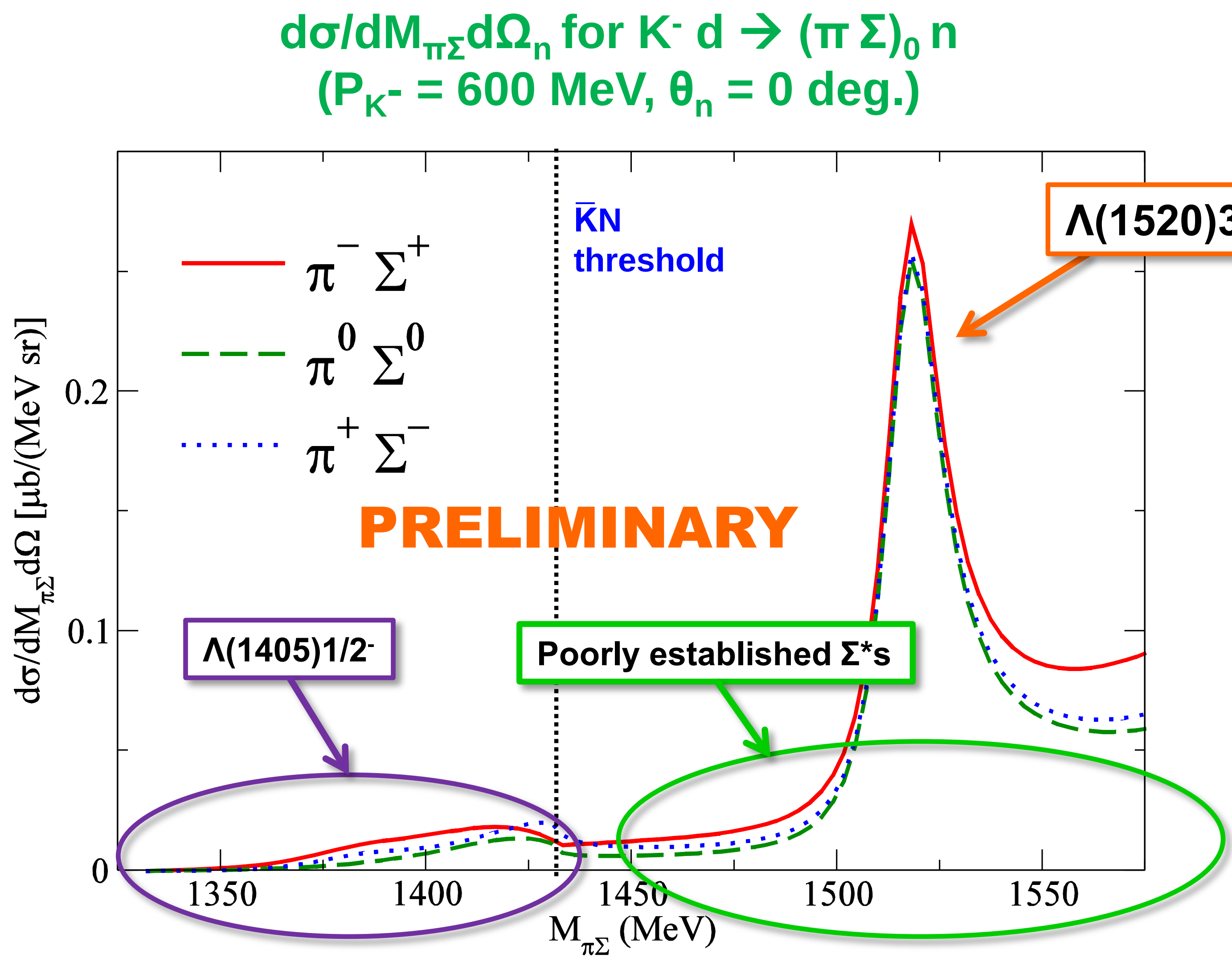
Extracted $\bar{K}N \rightarrow K\Xi$ amplitudes

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

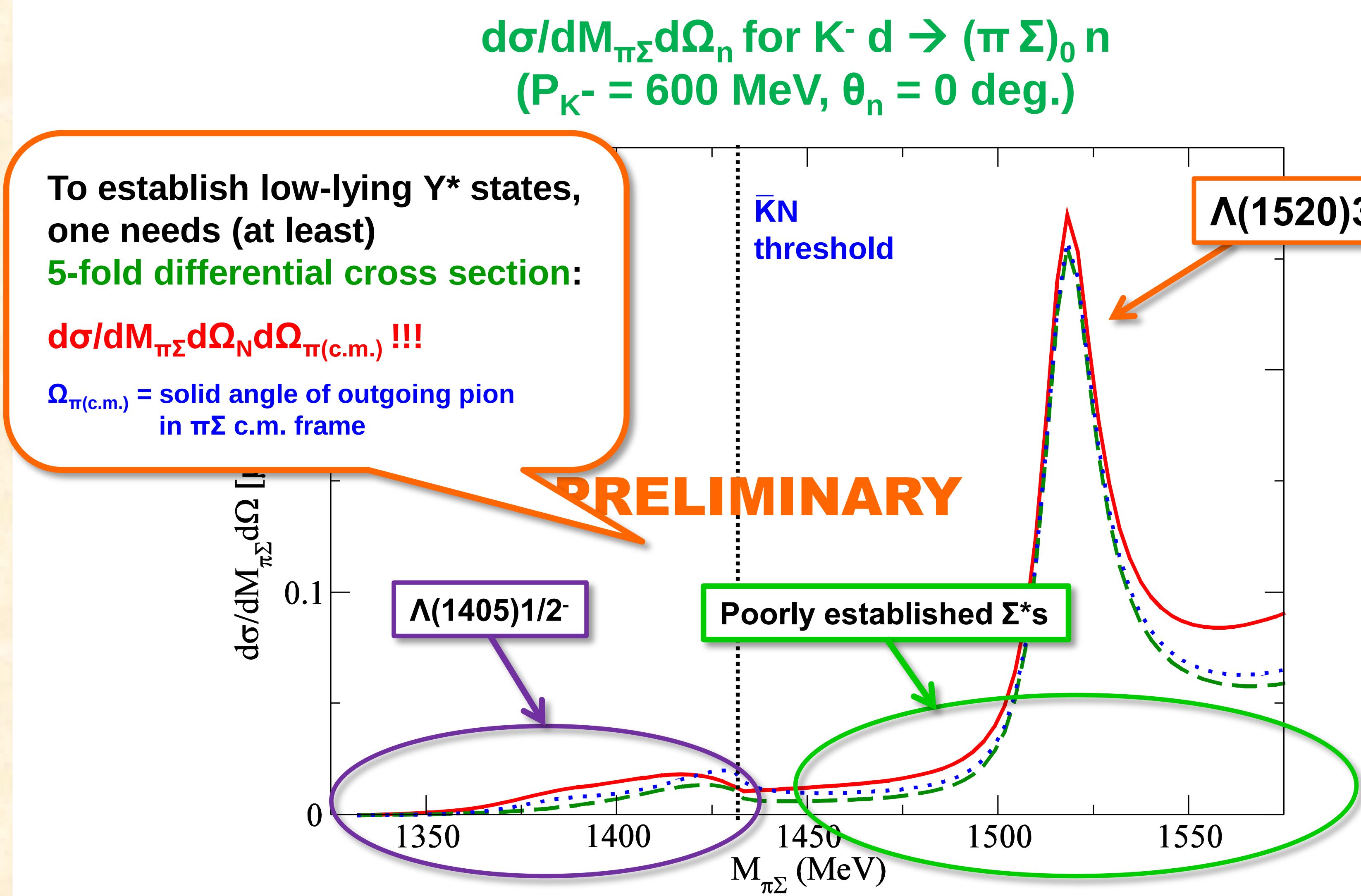
$L_{I\,2J}$: L = S,P,.. ; I = isospin; J = Total angular mom.



Results (IMPULSE TERM ONLY !!)

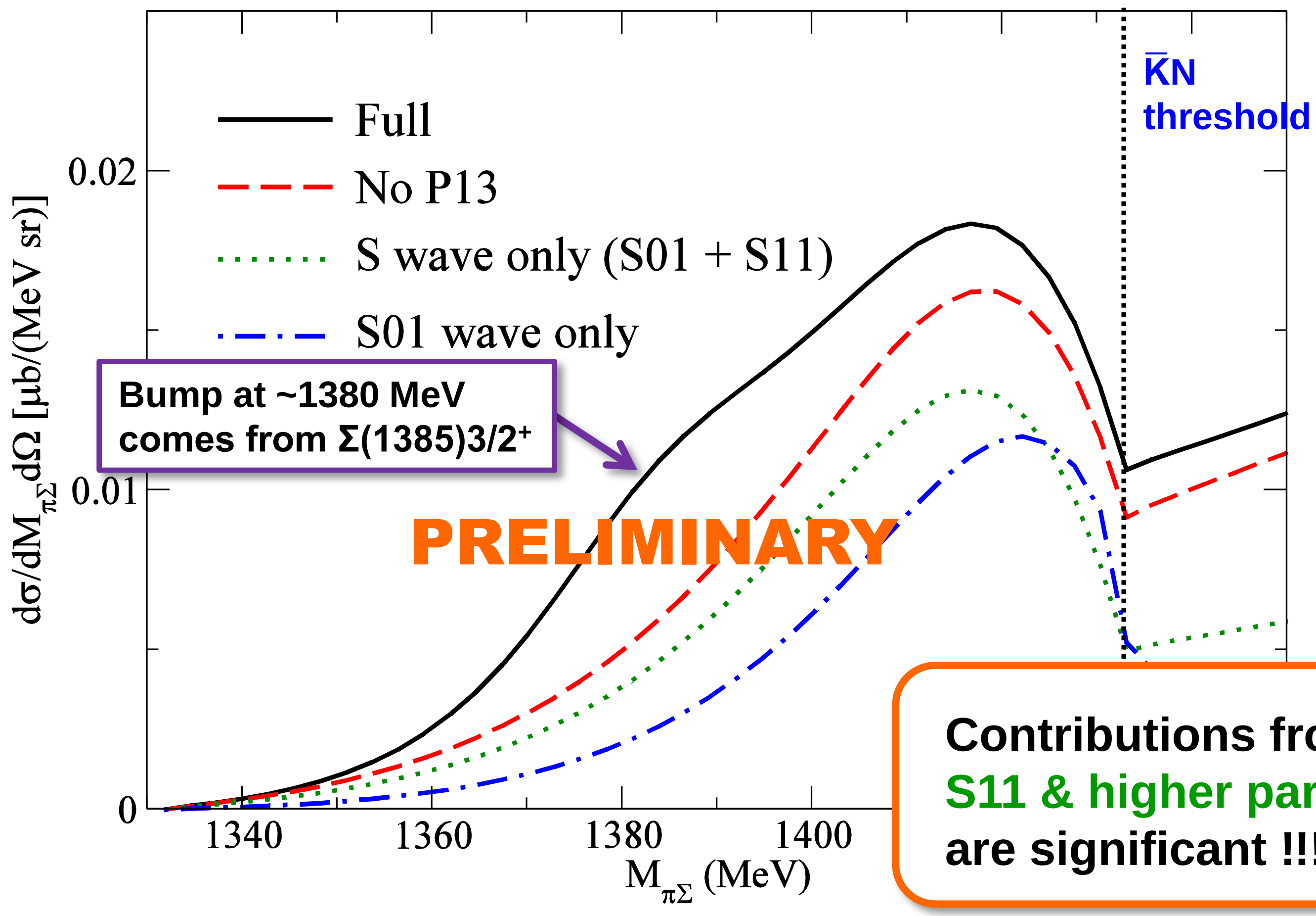


Results (IMPULSE TERM ONLY !!)



Results (IMPULSE TERM ONLY !!)

$d\sigma/dM_{\pi\Sigma}d\Omega_N$ for $K^- d \rightarrow \pi^- \Sigma^+ n$
(P_{K^-} = 600 MeV, θ_n = 0 deg.)



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