The ANL-Osaka dynamical coupled-channels (DCC) approach for baryon spectroscopy

Hiroyuki Kamano
(KEK)

Collaborators:
T.-S. Harry Lee (Argonne Natl. Lab.)
Satoshi Nakamura (Cruzeiro do Sul U.)
Toru Sato (Osaka U.)

ECT* workshop on "Space-like and time-like electromagnetic baryonic transitions"
ECT*, Trento, Italy, May 7-12, 2017

ANL-Osaka DCC approach to N* & Δ*

Dynamical coupled-channels model [Matsuyama, Sato, Lee, Phys. Rep. 439(2007)193]

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

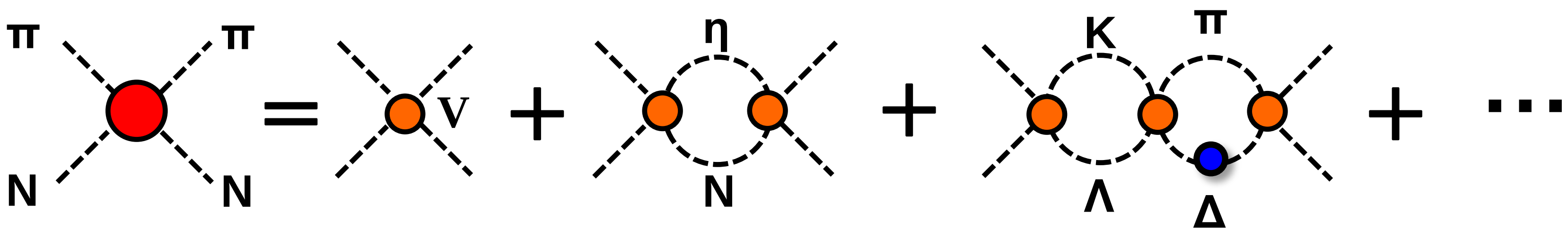
CC effect

off-shell effect

$$a,b,c = (\,\gamma^{(*)}N,\ \pi N,\ \eta N,\ \underbrace{\pi\Delta,\ \sigma N,\ \rho N}_{\pi\pi N},\ K\Lambda,\ K\Sigma,\cdots)$$

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

e.g.) πN scattering



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

ANL-Osaka DCC approach to N* & Δ*

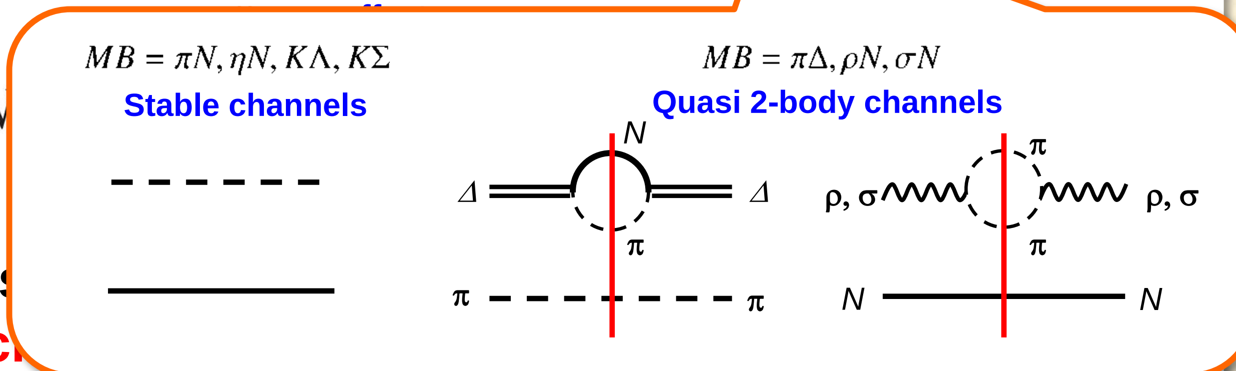
Dynamical coupled-channels model [Matsuyama, Sato, Lee, Phys. Rep. 439(2007)193]

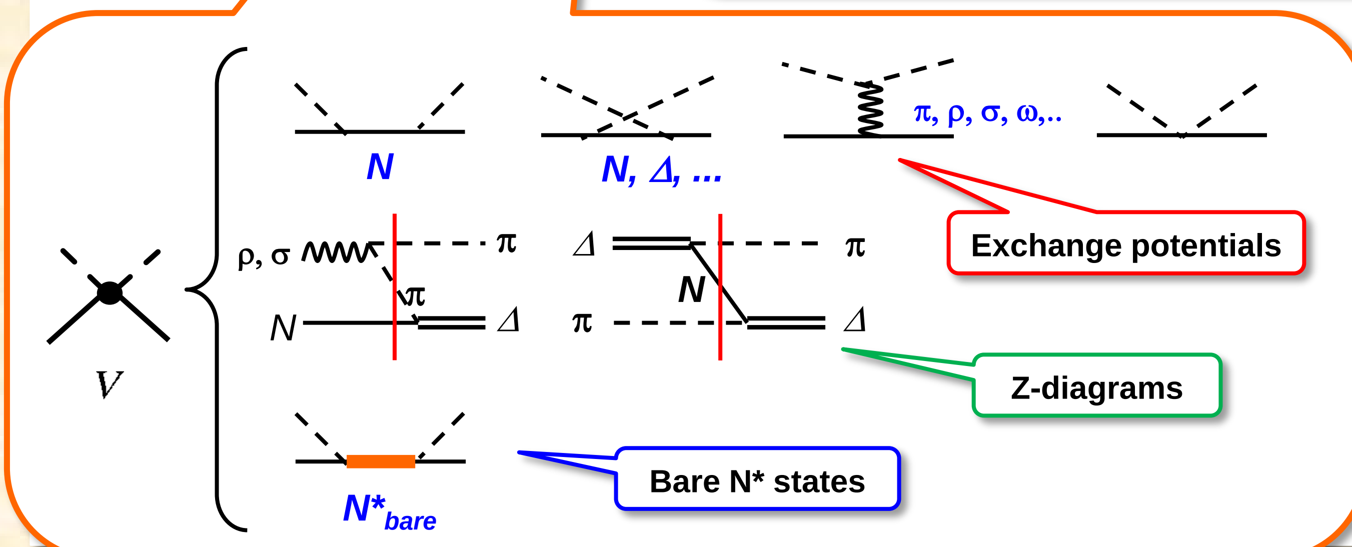
$$T^{(LS\,J)}_{a,b}(p_a,p_b;E) = V^{(LS\,J)}_{a,b}(p_a,p_b;E) + \sum_c \int_0^\infty q^2 dq V^{(LS\,J)}_{a,c}(p_a,q;E) G_c(q;E) T^{(LS\,J)}_{c,b}(q,p_b;E)$$

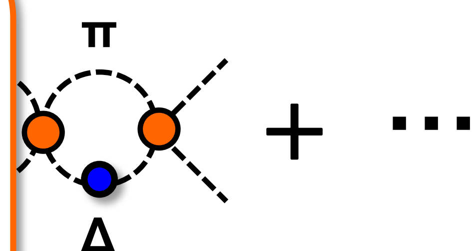
CC off-shell

$a,b,c =$ ... $^{)}N$

✓ **Summi... oss...**
(➔ ... ltic...







...escattering effects

ANL-Osaka DCC approach to N* & Δ*

Dynamical coupled-channels model [Matsuyama, Sato, Lee, Phys. Rep. 439(2007)193]

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

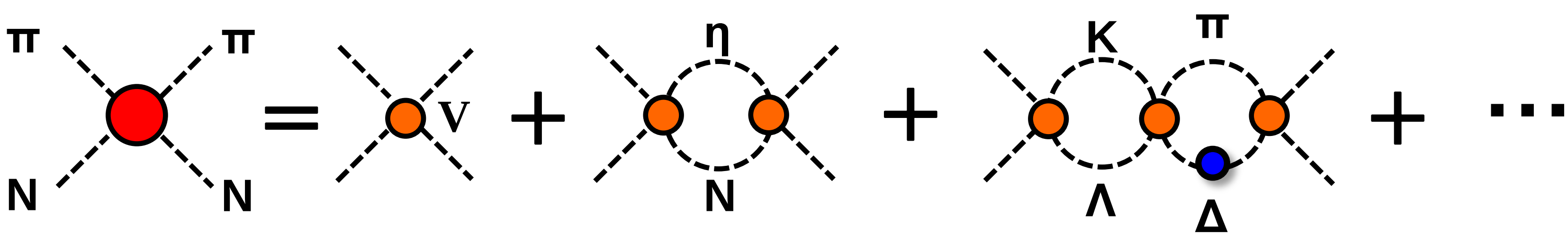
CC effect

off-shell effect

$$a,b,c \;=\; (\,\gamma^{(*)}N,\ \pi N,\ \eta N,\ \underbrace{\pi\Delta,\ \sigma N,\ \rho N}_{\pi\pi N},\ K\Lambda,\ K\Sigma,\cdots)$$

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

e.g.) πN scattering



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

ANL-Osaka DCC approach to N* & Δ*

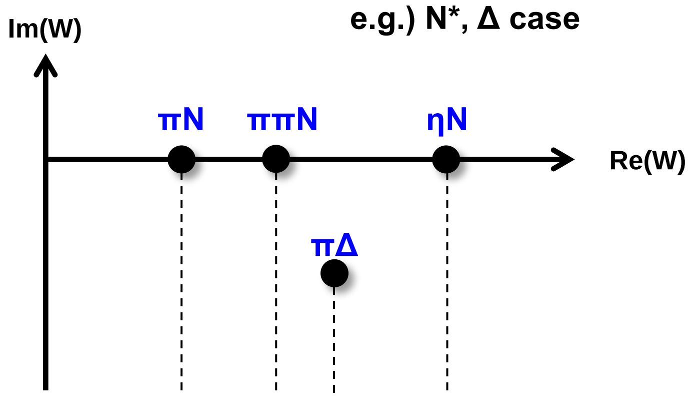
Dynamical coupled-channels model [Matsuyama, Sato, Lee, Phys. Rep. 439(2007)193]

Why DCC approach ??

✓ **It defines proper analytic structure (branch points, cuts,…) of scattering amplitudes in the complex energy plane, as required by scattering theory**

- **Crucial for extracting resonances "correctly", and avoiding *WRONG* resonance signals !! [e.g., Ceci et al, PRC84(2011)015205]**

e.g.) N*, Δ case

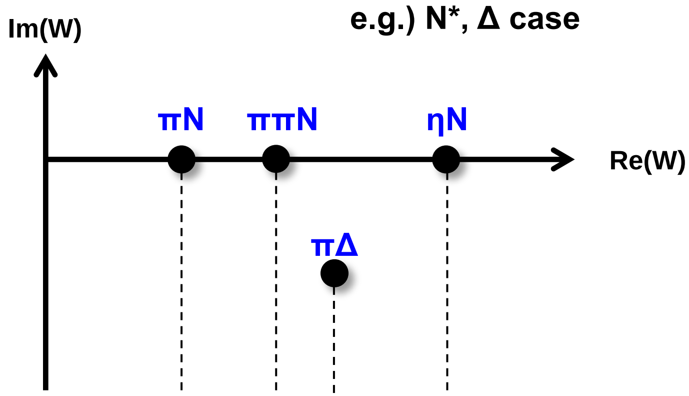


ANL-Osaka DCC approach to N* & Δ*

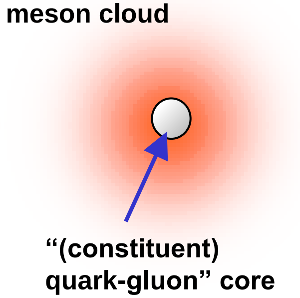
Dynamical coupled-channels model [Matsuyama, Sato, Lee, Phys. Rep. 439(2007)193]

Why DCC approach ??

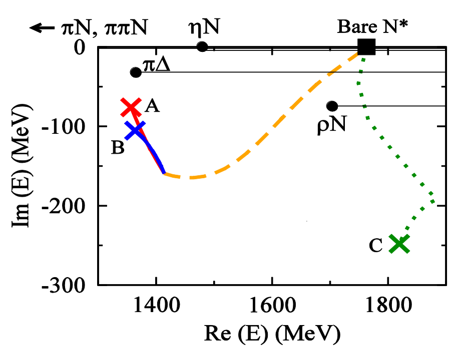
- ✓ It defines proper analytic structure (branch points, cuts,…) of scattering amplitudes in the complex energy plane, as required by scattering theory
  - ➢ Crucial for extracting resonances "correctly", and avoiding *WRONG* resonance signals !! [e.g., Ceci et al, PRC84(2011)015205]



- ✓ Interested in clarifying the physics of reaction dynamics behind formation, substructure, etc. of baryon resonances.



dynamical origin of P11 N*



Modeling reaction processes appropriately with a model Hamiltonian & solving proper quantum scattering equation (LS eq.) is crucial !!

ANL-Osaka DCC approach to N* & Δ*

Dynamical coupled-channels model [Matsuyama, Sato, Lee, Phys. Rep. 439(2007)193]

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

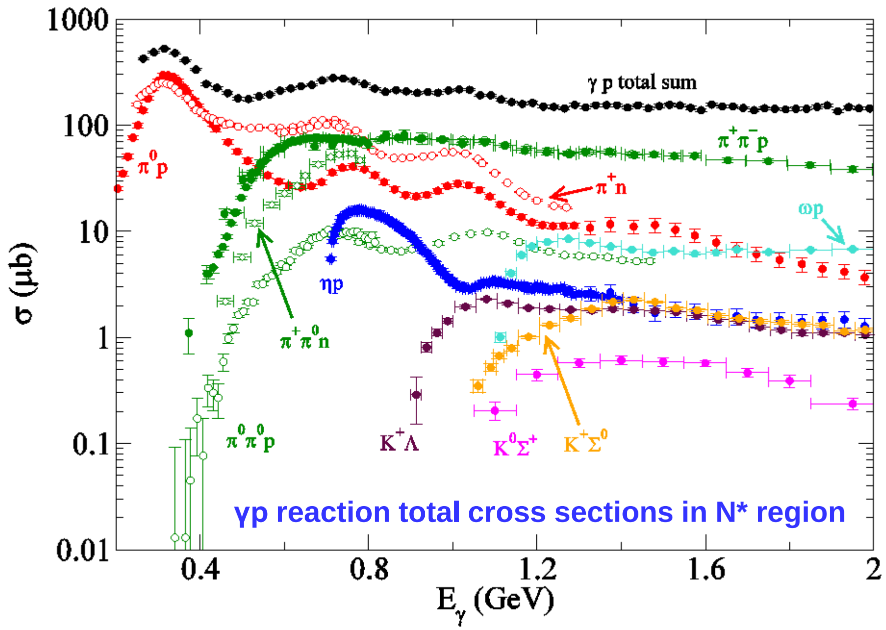
CC effect

off-shell effect

$$a,b,c = (\gamma^{(*)}N,\ \pi N,\ \eta N,\ \underbrace{\pi\Delta,\ \sigma N,\ \rho N}_{\pi\pi N},\ K\Lambda,\ K\Sigma,\cdots)$$

$\pi\pi N$

Region our model can cover



Latest published model:

HK, Nakamura, Lee, Sato, PRC94(2016)015201
[updated version of PRC88(2013)035209]

Constructed by simultaneous analysis of

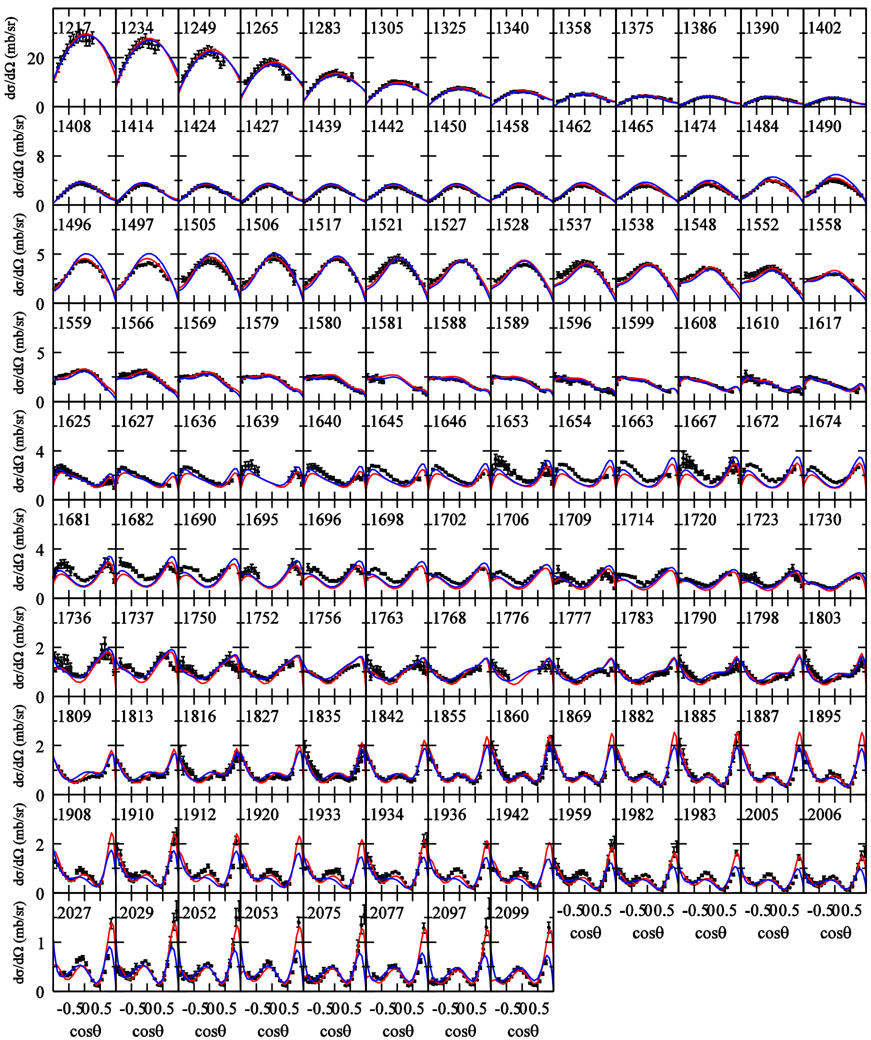
- πN SAID PW amps. (W < 2.3 GeV)
- πp → ηN, KΛ, KΣ (W < 2.1 GeV)
- γp → πN, ηN, KΛ, KΣ (W < 2.1 GeV)
- γ'n' → πN (W < 2 GeV)

ANL-Osaka DCC approach to N* & Δ*

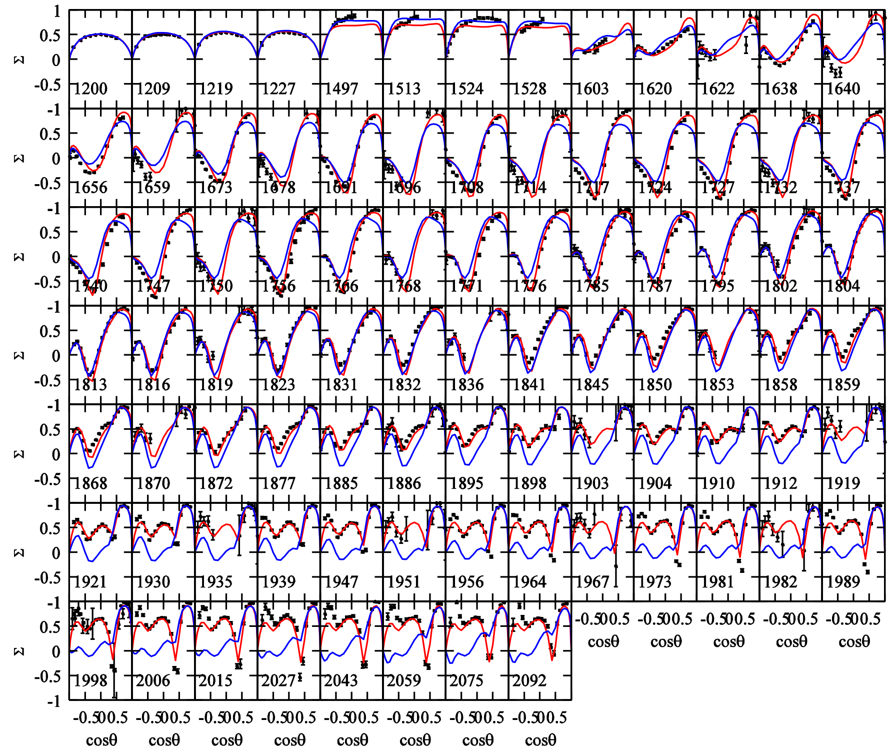
HK, Nakamura, Lee, Sato, PRC88(2013)035209; 94(2016)015201

$\gamma p \rightarrow \pi^0 p$

dσ/dΩ for W < 2.1 GeV



Σ for W < 2.1 GeV



Red: Updated model [PRC94(2016)015201]

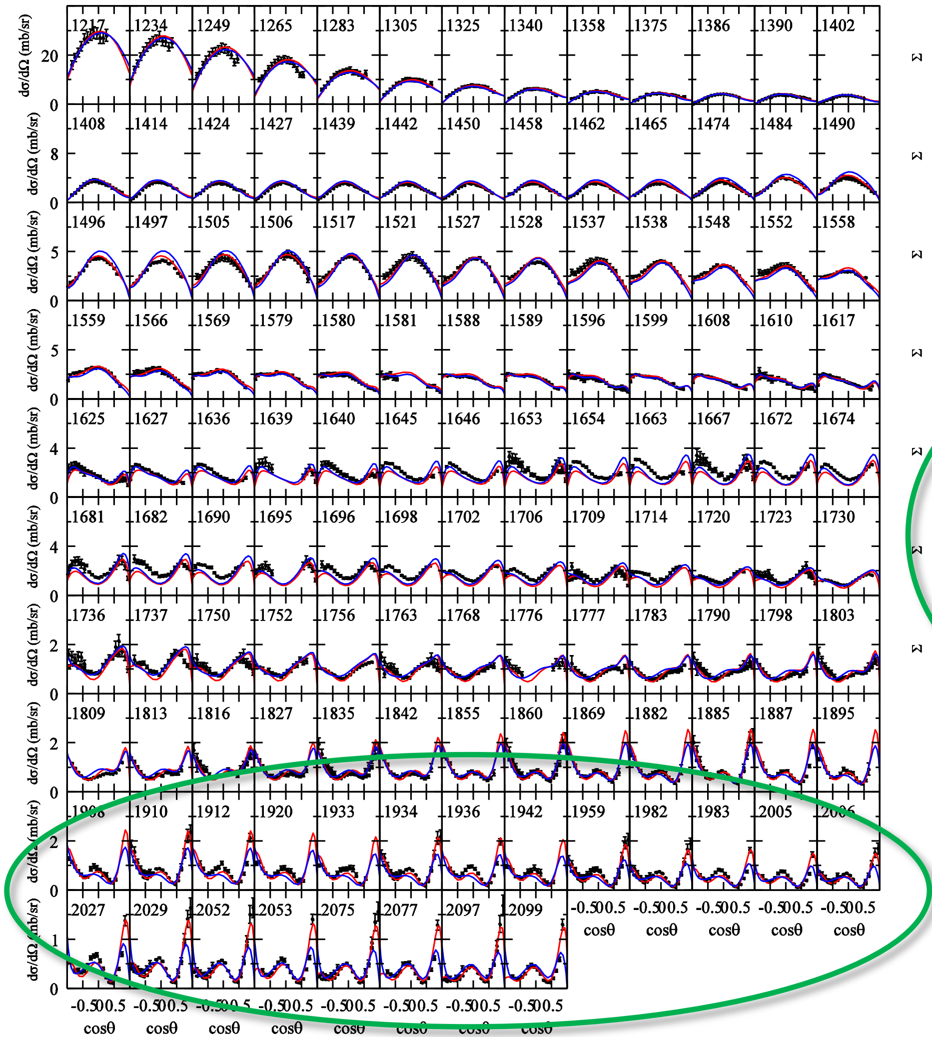
Blue: Original model [PRC88(2013)035209]

ANL-Osaka DCC approach to N* & Δ*

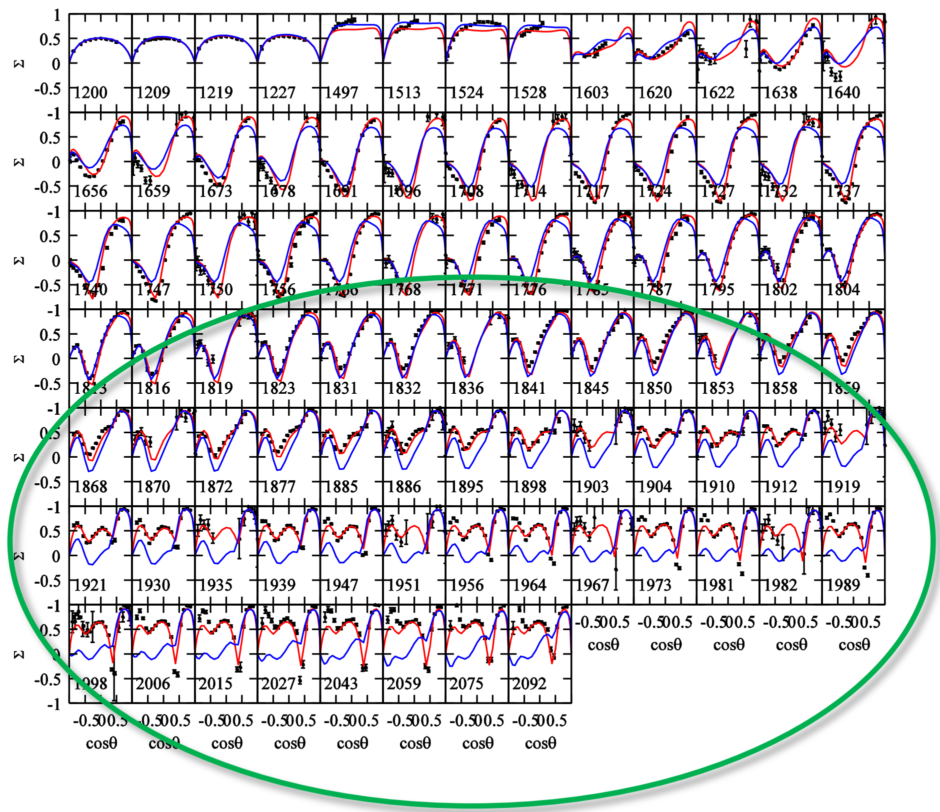
HK, Nakamura, Lee, Sato, PRC88(2013)035209; 94(2016)015201

$\gamma p \rightarrow \pi^0 p$

dσ/dΩ for W < 2.1 GeV



Σ for W < 2.1 GeV

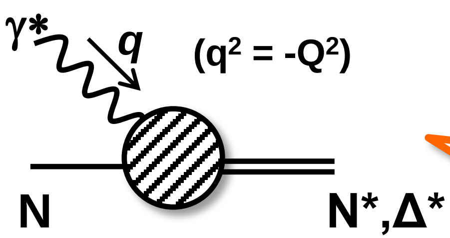


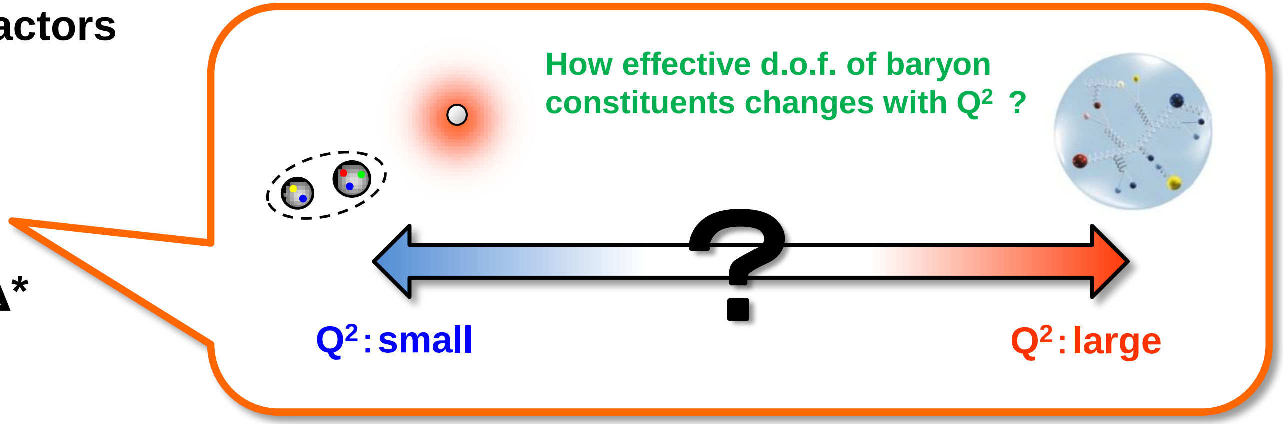
Red: Updated model [PRC94(2016)015201]

Blue: Original model [PRC88(2013)035209]

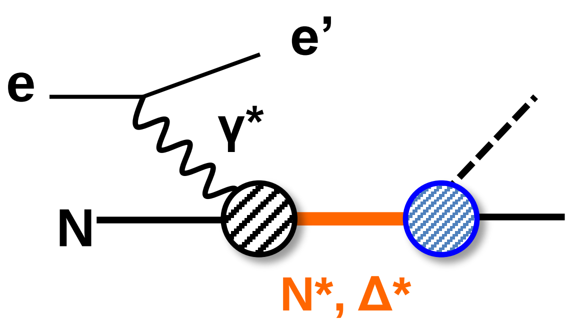
Analysis of electroproduction reactions: Determining N-N*, N-Δ* e.m. transition form factors

N-N* e.m. transition form factors

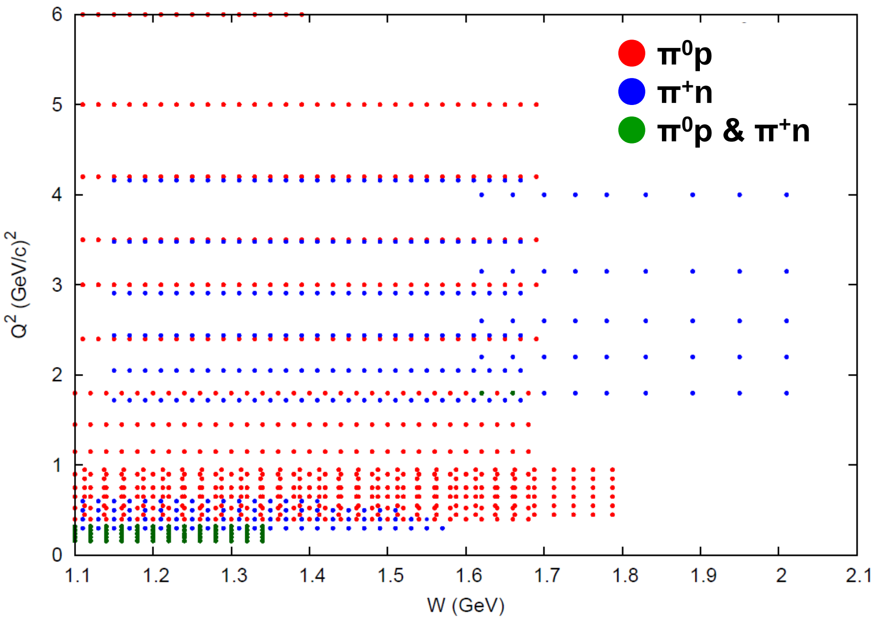




Meson electroproductions:



CLAS database for 1π electroproductions
(Q² < 6 GeV²)



Analysis of electroproduction reactions: Determining N-N*, N-Δ* e.m. transition form factors

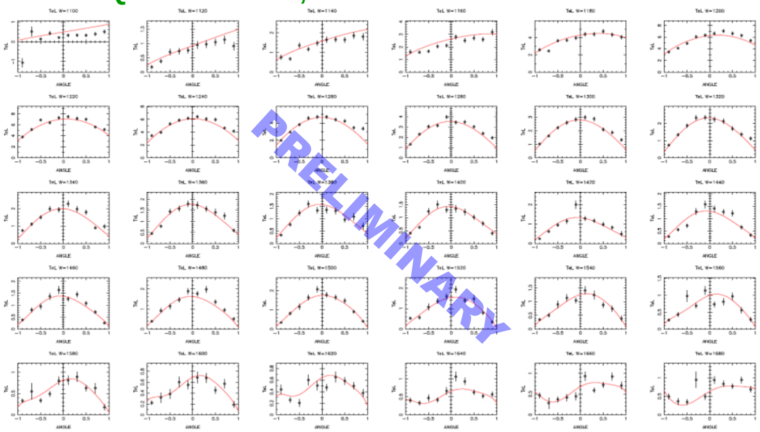
$$\frac{d\sigma^5}{dE_{e'}d\Omega_{e'}d\Omega^*_\pi} = \Gamma_\gamma\left[\sigma_T + \epsilon\sigma_L + \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}\cos\phi^*_\pi + \epsilon\sigma_{TT}\cos 2\phi^*_\pi + h_e\sqrt{2\epsilon(1-\epsilon)}\sigma_{LT'}\sin\phi^*_\pi\right].$$

$$\sigma_\alpha = \sigma_\alpha(W, Q^2, \cos\theta^*_\pi)$$

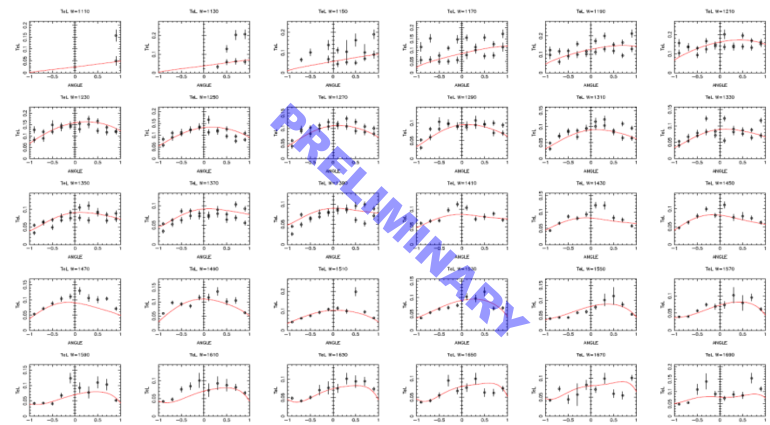
$\sigma_T+\epsilon\sigma_L$ for ep → eπ^0p

Data for structure functions are obtained with the help of K. Joo and L. C. Smith.

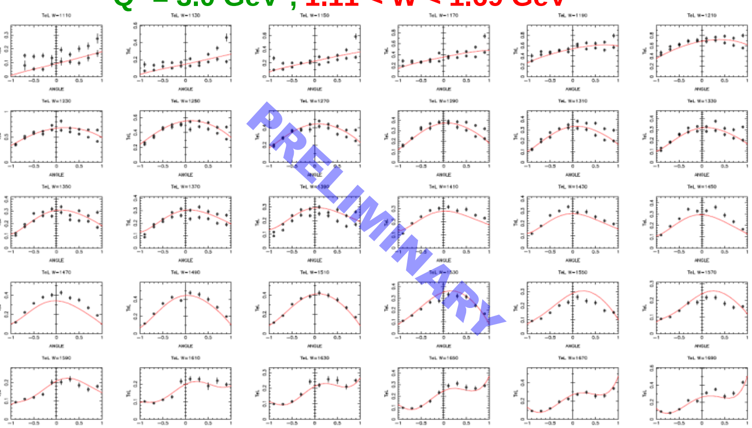
Q^2 = 1.15 GeV^2, 1.10 < W < 1.69 GeV



Q^2 = 5.0 GeV^2, 1.11 < W < 1.69 GeV

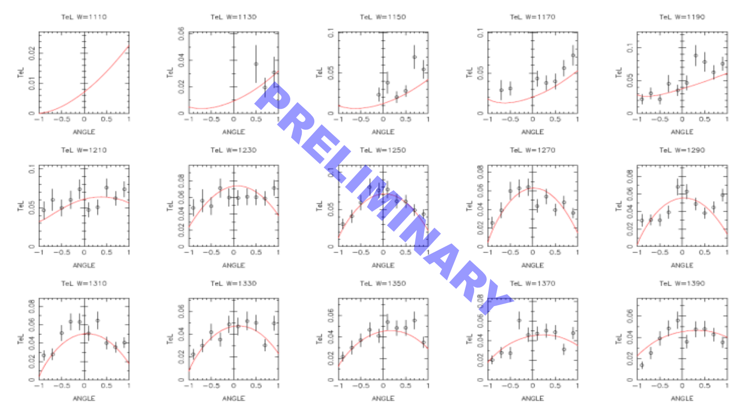


Q^2 = 3.0 GeV^2, 1.11 < W < 1.69 GeV



cosθ

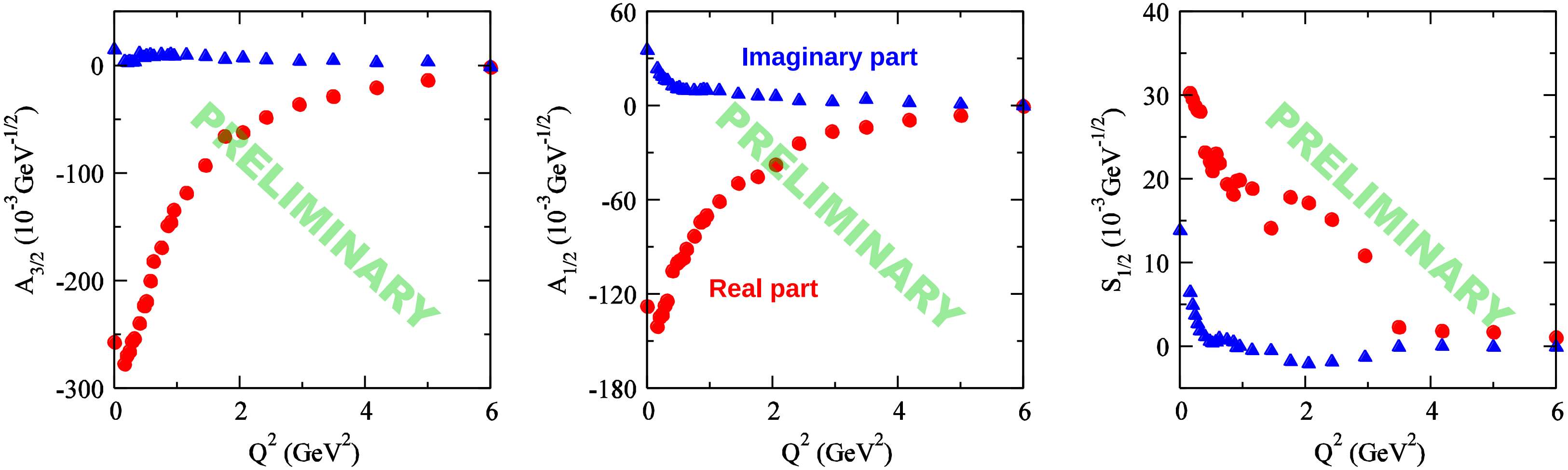
Q^2 = 6.0 GeV^2, 1.11 < W < 1.39 GeV



cosθ

Extracted γ(*) p → N*, Δ* transition form factors at finite Q² (evaluated at resonance poles)

$\gamma^{(*)}$ p → Δ(1232)3/2⁺



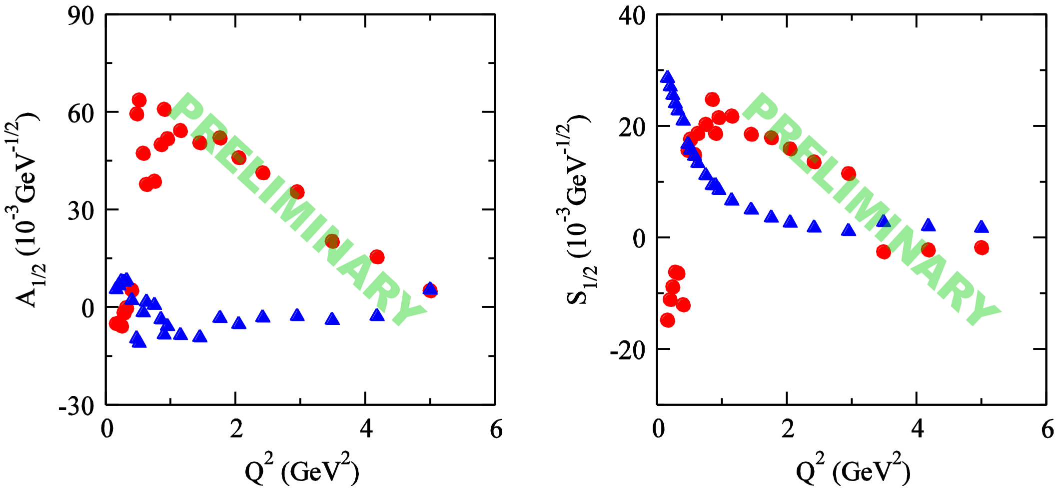
$\gamma^{(*)}$ p → N(1440)1/2⁺

Definition of $A_{1/2}$, $A_{3/2}$, $S_{1/2}$:

$$A_{3/2}(Q^2) \equiv \langle R|\, J^{\mu}_{\rm e.m.}(Q^2)\, \varepsilon_\mu^{(\lambda_\gamma=+1)}\, |N(\lambda_N=-1/2)\rangle$$

$$A_{1/2}(Q^2) \equiv \langle R|\, J^{\mu}_{\rm e.m.}(Q^2)\, \varepsilon_\mu^{(\lambda_\gamma=+1)}\, |N(\lambda_N=+1/2)\rangle$$

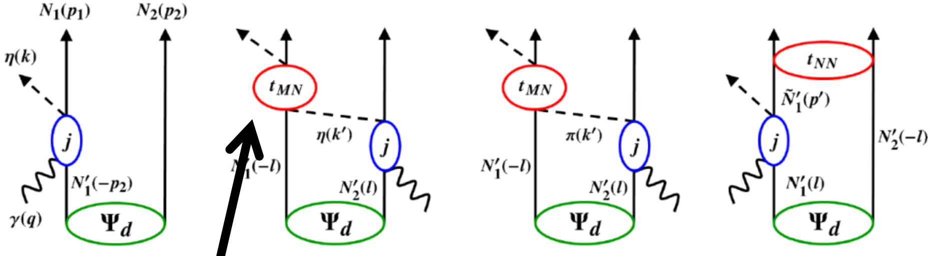
$$S_{1/2}(Q^2) \equiv \langle R|\, J^{\mu}_{\rm e.m.}(Q^2)\, \varepsilon_\mu^{(\lambda_\gamma=\ 0)}\, |N(\lambda_N=-1/2)\rangle$$



γd→ηpn reaction: Study of ηN scattering parameters

Nakamura, HK, Ishikawa, arXiv:1704.07029

At E_γ = 940 MeV & θ_p = 0 deg. :

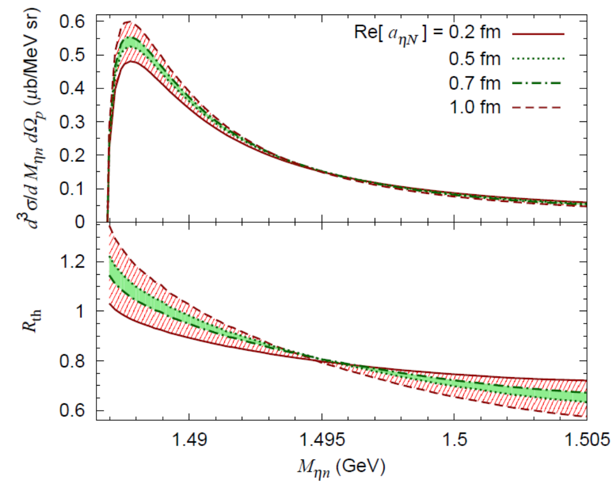


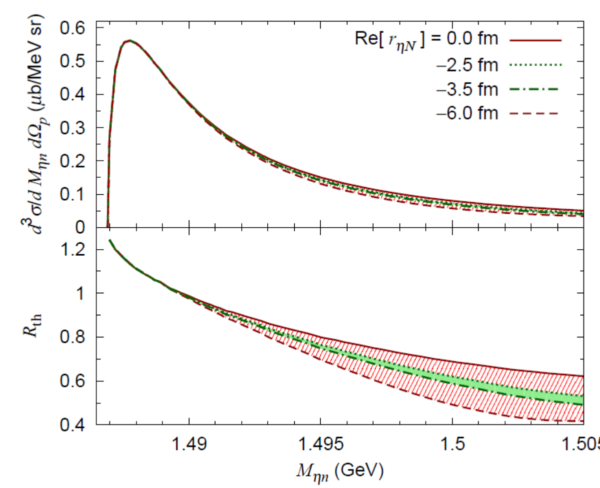
(a) Impulse (b) η exchange (c) π exchange (d) NN rescattering

ηn →ηn rescattering

highly suppressed !!

$$R = \frac{d^3\sigma_{\rm full}/dM_{\eta n}d\Omega_p|_{\theta_p=0^\circ}}{d^3\sigma_{\rm imp}/dM_{\eta n}d\Omega_p|_{\theta_p=0^\circ}}$$

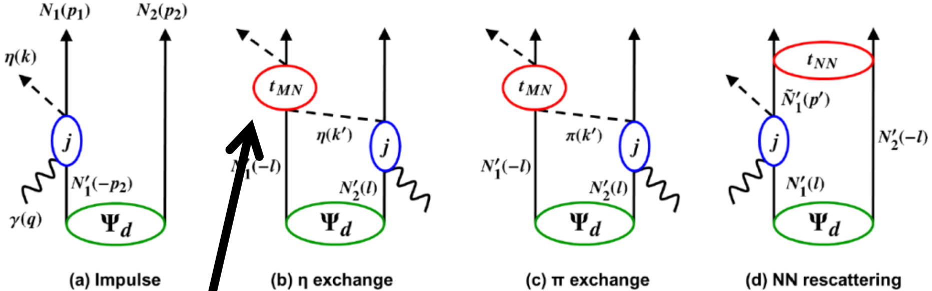




γd→ηpn reaction:
Study of ηN scattering parameters

Nakamura, HK, Ishikawa, arXiv:1704.07029

At E_γ = 940 MeV & θ_p = 0 deg. :



ηn →ηn rescattering

highly suppressed !!

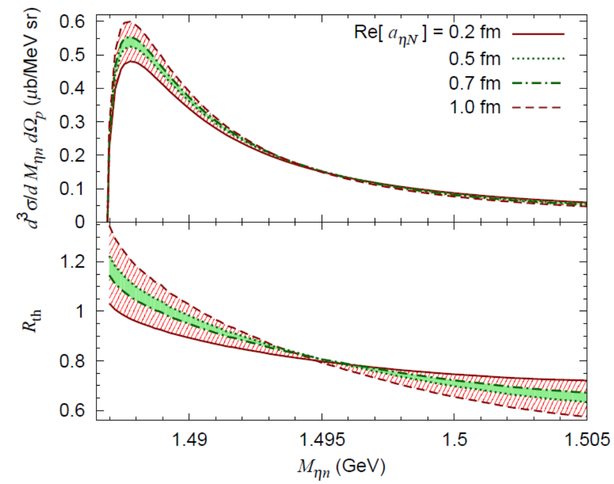
$$R = \frac{d^3\sigma_{\mathrm{full}}/dM_{\eta n}d\Omega_p|_{\theta_p=0^\circ}}{d^3\sigma_{\mathrm{imp}}/dM_{\eta n}d\Omega_p|_{\theta_p=0^\circ}}$$

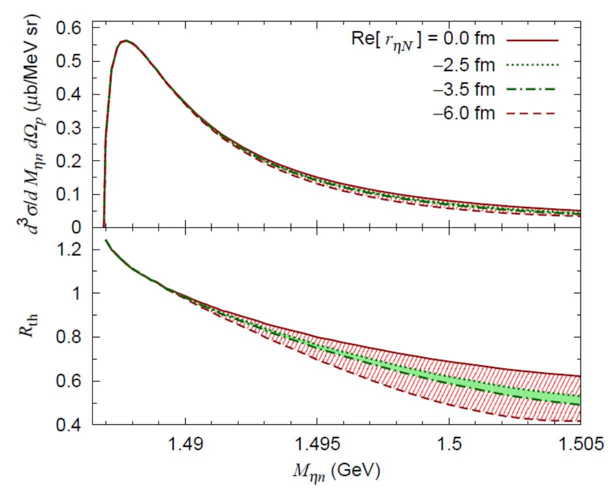
With 5% accuracy of R (accessible with forthcoming experiment at ELPH@Tohoku U.), uncertainties in real parts of $a_{\eta n}$, $r_{\eta n}$ can be drastically reduced:

$\mathrm{Re}[a_{\eta n}]$ = 0.45fm +/- 0.5fm ➔ ... +/- 0.1fm

$\mathrm{Re}[r_{\eta n}]$ = -2.5fm +/- 3.5fm ➔ ... +/- 0.5fm

Range from previous estimations

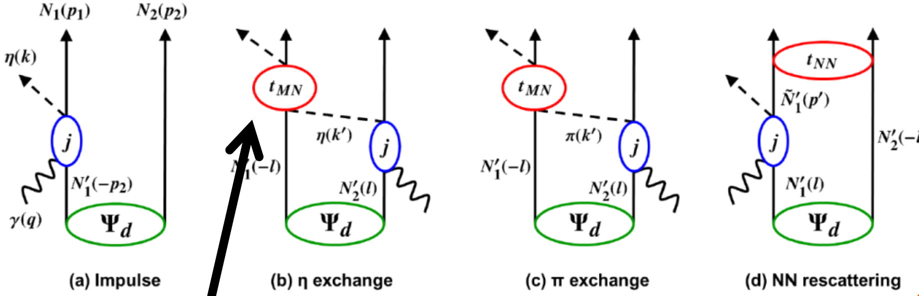




γd→ηpn reaction:
Study of ηN scattering parameters

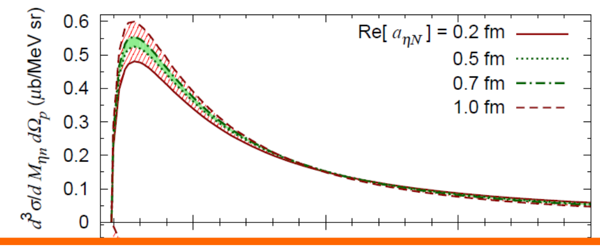
Nakamura, HK, Ishikawa, arXiv:1704.07029

At E_γ = 940 MeV & θ_p = 0 deg. :

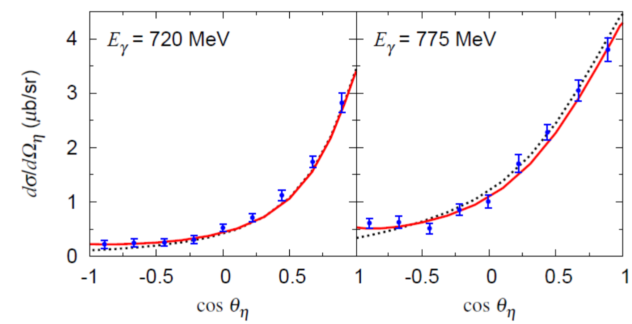


ηn →ηn rescattering

highly suppressed !



Reliable model that **all the relevant subprocesses are under control** is very important to have this conclusion !!



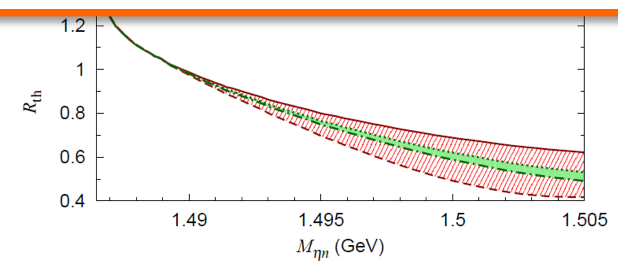
$$R = \frac{d^3\sigma_{\rm full}/dM_{\eta n}d\Omega_p|_{\theta_p=0^\circ}}{d^3\sigma_{\rm imp}/dM_{\eta n}d\Omega_p|_{\theta_p=0^\circ}}$$

With 5% accuracy of R (accessible with forthcoming experiment at ELPH@Tohoku U.), uncertainties in real parts of $a_{\eta n}$, $r_{\eta n}$ can be drastically reduced:

Re[$a_{\eta n}$] = 0.45fm +/- 0.5fm ➔ ... +/- 0.1fm

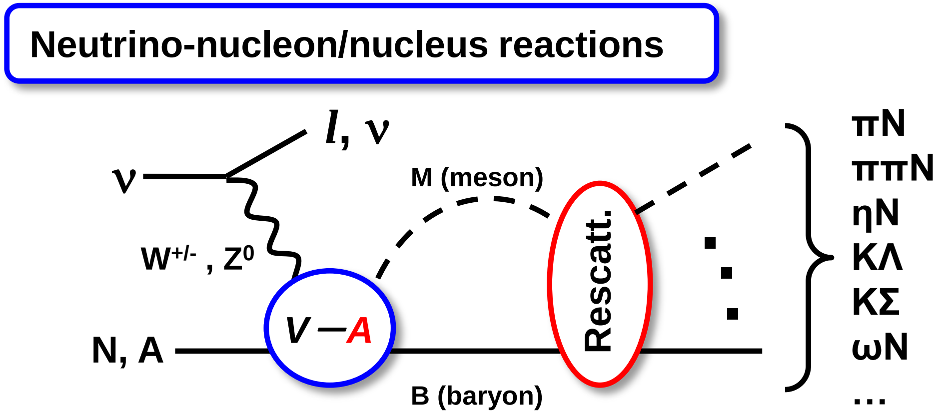
Re[$r_{\eta n}$] = -2.5fm +/- 3.5fm ➔ ... +/- 0.5fm

Range from previous estimations



Application to neutrino-induced reactions

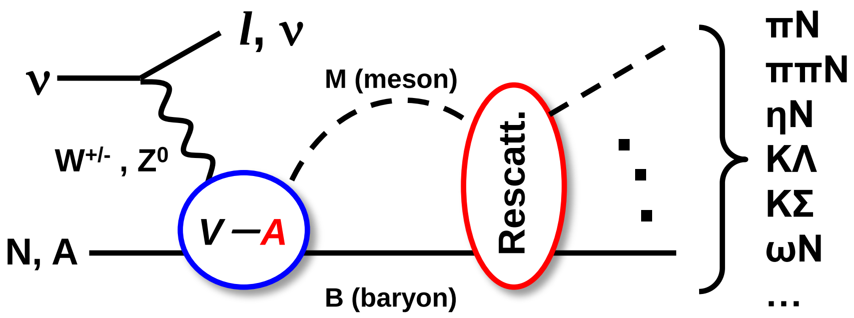
- ✓ **Reliable neutrino reaction model is necessary for *precise* determination of neutrino parameters from future neutrino-oscillation experiments (leptonic CP phase, neutrino mass hierarchy…)**



Application to neutrino-induced reactions

✓ **Reliable neutrino reaction model** is necessary for ***precise*** determination of neutrino parameters from **future neutrino-oscillation experiments** (leptonic CP phase, neutrino mass hierarchy…)

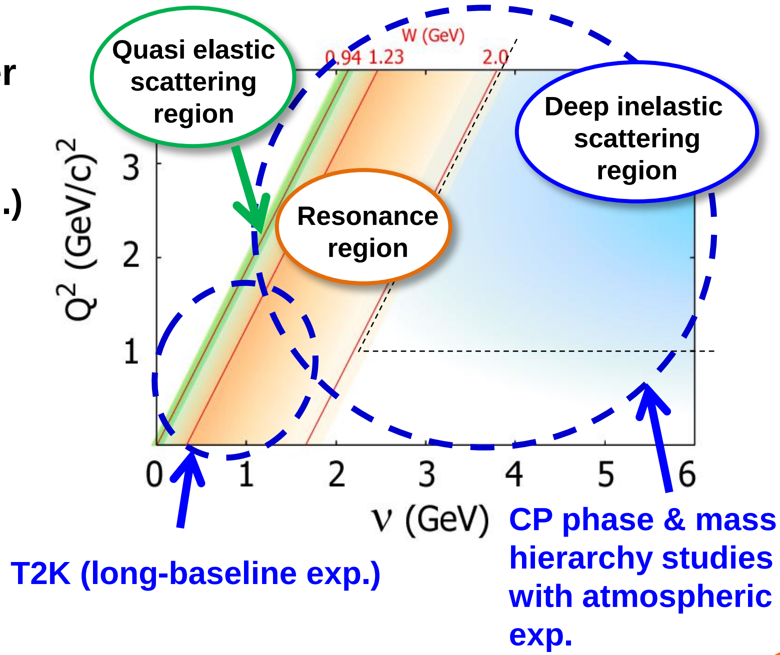
Neutrino-nucleon/nucleus reactions



Collaboration@J-PARC Branch of KEK Theory Center
[http://j-parc-th.kek.jp/html/English/e-index.html]

Y. Hayato (ICRR, U. of Tokyo), M. Hirai (Nippon Inst. Tech.)
H. Kamano (KEK), S. Kumano (KEK)
S. Nakamura (Cruzeiro do Sul U.),
K. Saito (Tokyo U. of Sci.) , M. Sakuda (Okayama U.),
T. Sato (Osaka U.)

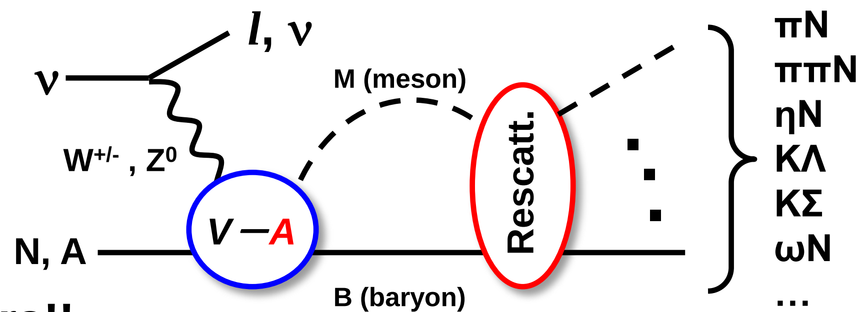
[➔ Rept. Prog. Phys. 80(2017)056301]



Application to neutrino-induced reactions

- ✓ **Reliable neutrino reaction model** is necessary for ***precise*** determination of neutrino parameters from **future neutrino-oscillation experiments** (leptonic CP phase, neutrino mass hierarchy…)

Neutrino-nucleon/nucleus reactions

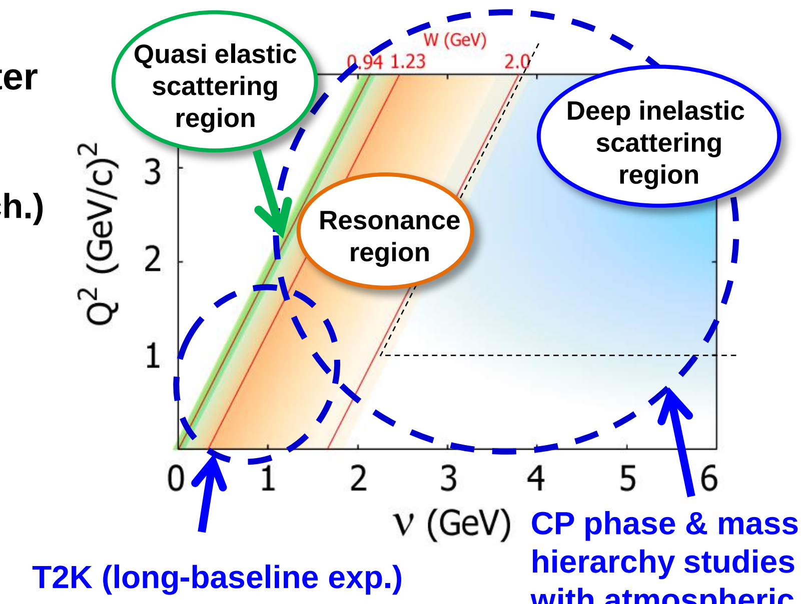


- ✓ **Can provide *axial* transition form factors!!**

Collaboration@J-PARC Branch of KEK Theory Center
[http://j-parc-th.kek.jp/html/English/e-index.html]

Y. Hayato (ICRR, U. of Tokyo), M. Hirai (Nippon Inst. Tech.)
H. Kamano (KEK), S. Kumano (KEK)
S. Nakamura (Cruzeiro do Sul U.),
K. Saito (Tokyo U. of Sci.) , M. Sakuda (Okayama U.),
T. Sato (Osaka U.)

[➔ Rept. Prog. Phys. 80(2017)056301]

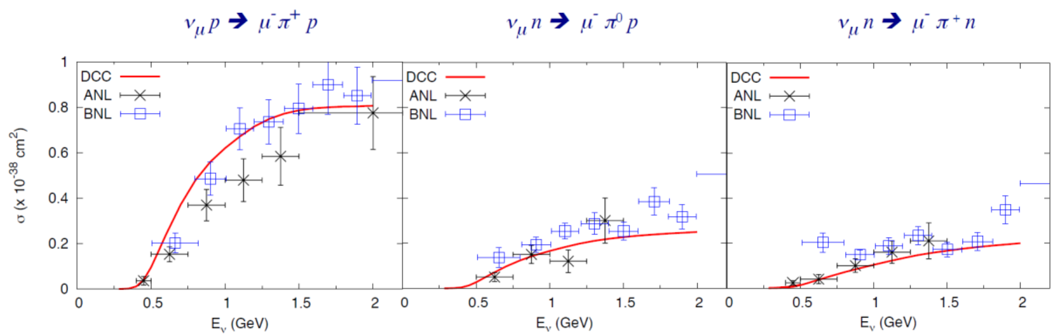


Application to neutrino-induced reactions

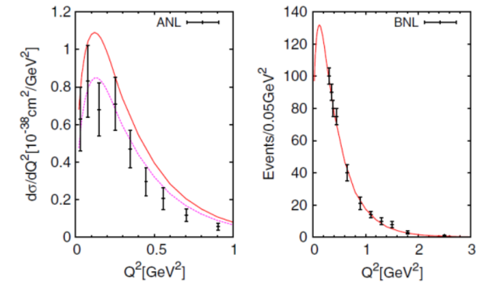
Nakamura, HK, Sato, PRD92(2015)074204

The first-time full coupled-channels calculation of ν-nucleon reactions beyond the Δ(1232) region !!

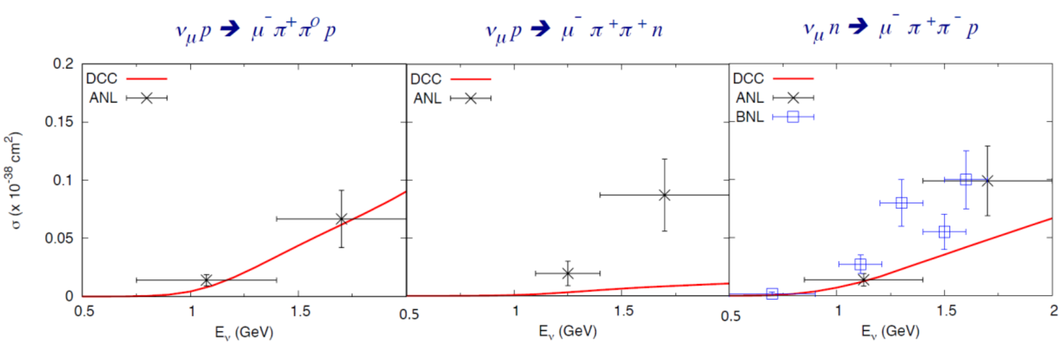
✓ **Single pion production:**



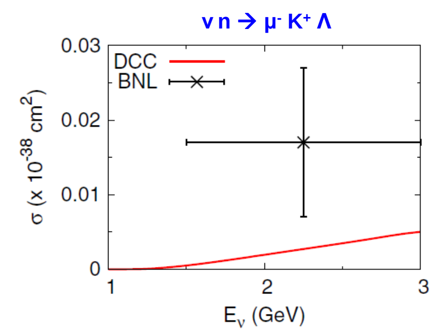
dσ/dQ² for ν p → μ⁻ π⁺ p (flux averaged for E_ν)



✓ **Double pion production:**



✓ **KΛ production:**



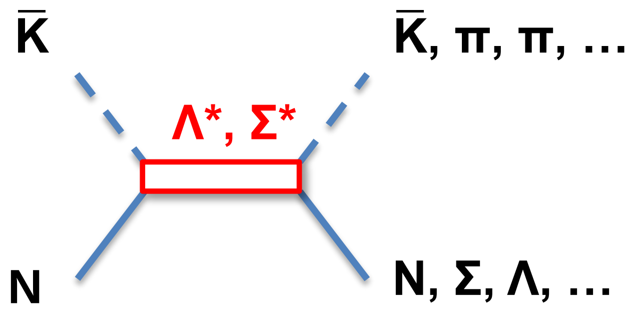
##NOTE: Q^2 dependence of all N-N* axial transition form factors are currently fixed with the nucleon dipole form factor.

ηN & KΣ productions can also be calculated.

DCC approach to Λ* & Σ* spectroscopy

Recently, our DCC approach has been applied to the analysis of K^-p reactions to establish the mass spectrum of Y* (=Λ*, Σ*) baryons with strangeness -1.

HK, Nakamura, Lee, Sato,
PRC90(2014)065204; PRC92(2015)025205



- ✓ Taking into account $\bar{K}N$, πΣ, πΛ, ηΛ, KΞ, πΣ*(ππΛ), $\bar{K}^*N(\pi\bar{K}N)$ channels.
- ✓ Comprehensive analysis of *ALL* available data (more than 17,000 data points) of $K^- p \to \bar{K}N$, πΣ, πΛ, ηΛ, KΞ up to W = 2.1 GeV.

⬇

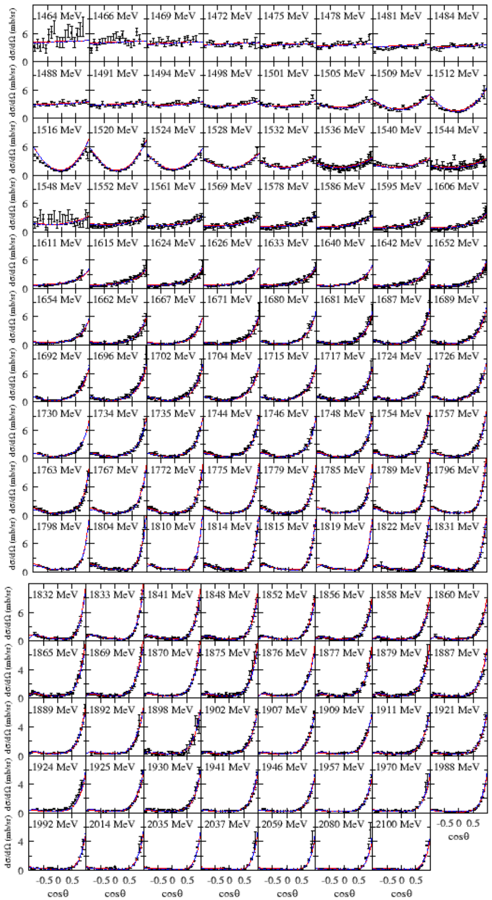
- ✓ Determination of threshold parameters (scattering lengths, effective ranges,…); the partial-wave amplitudes of $\bar{K}N \to \bar{K}N$, πΣ, πΛ, ηΛ, KΞ for S, P, D, and F waves.
- ✓ Extraction of Y* resonance parameters (mass, width, couplings, …) defined by poles of scattering amplitudes.

Selected results of the fits

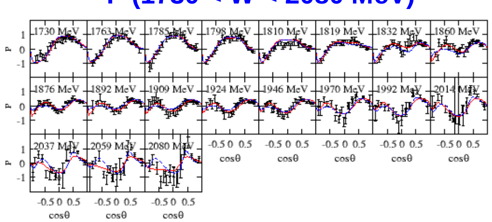
HK, Nakamura, Lee, Sato, PRC90(2014)065204

$K^- p \to K^- p$

dσ/dΩ (1464 < W < 2100 MeV)

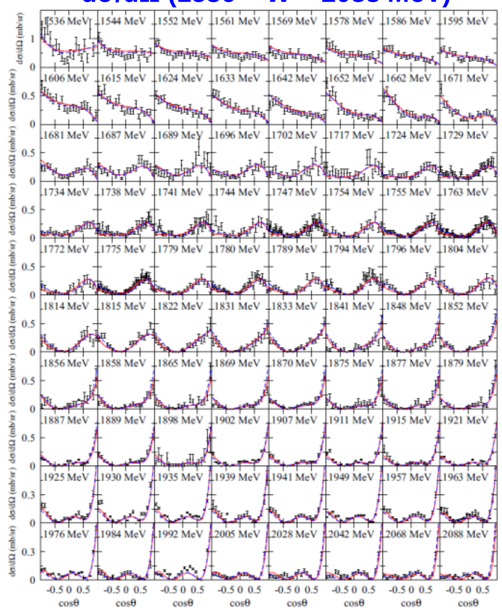


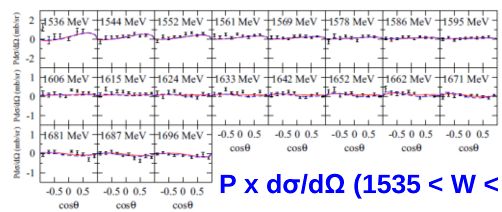
P (1730 < W < 2080 MeV)



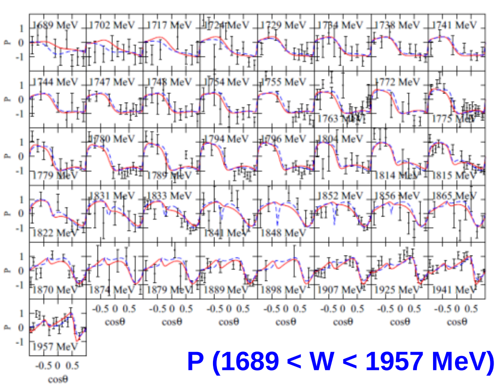
$K^- p \to \pi^- \Sigma^+$

dσ/dΩ (1536 < W < 2088 MeV)





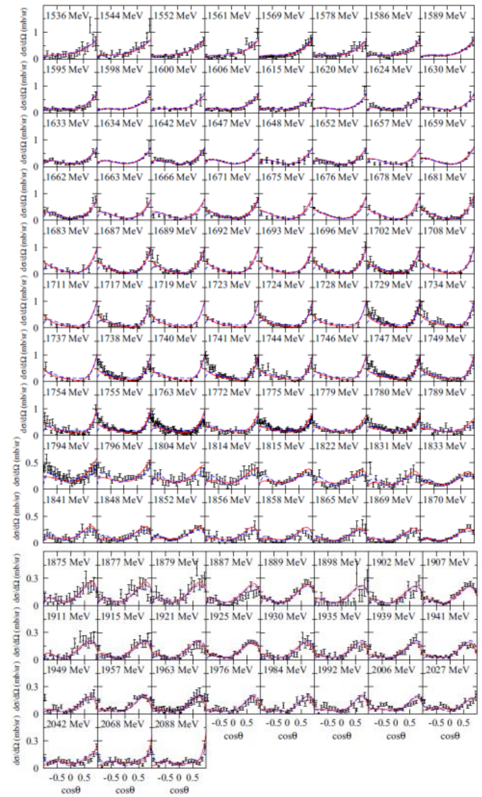
P x dσ/dΩ (1535 < W < 1696 MeV)



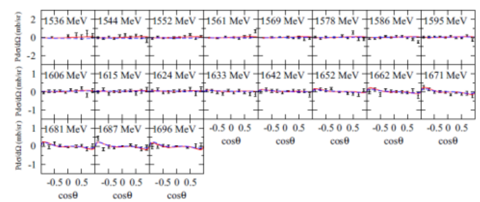
P (1689 < W < 1957 MeV)

$K^- p \to \pi^0 \Lambda$

dσ/dΩ (1536 < W < 2088 MeV)



P x dσ/dΩ (1536 < W < 1696 MeV)



Red curve: Model A

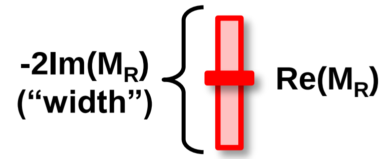
Blue curve: Model B

Λ* and Σ* mass spectrum extracted from the $K^{-}p$ reaction data

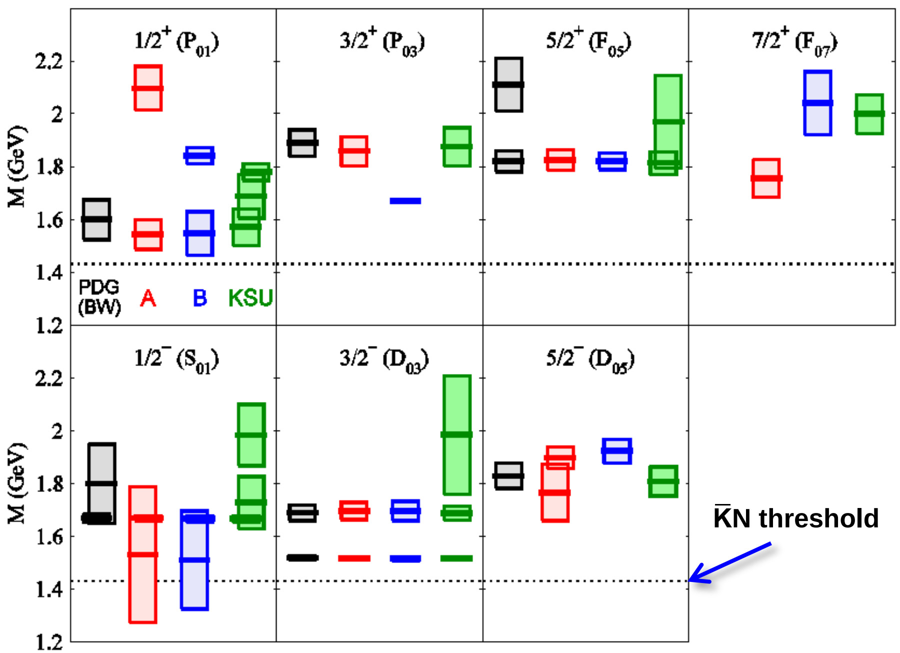
HK, Nakamura, Lee, Sato, PRC92(2015)025205

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

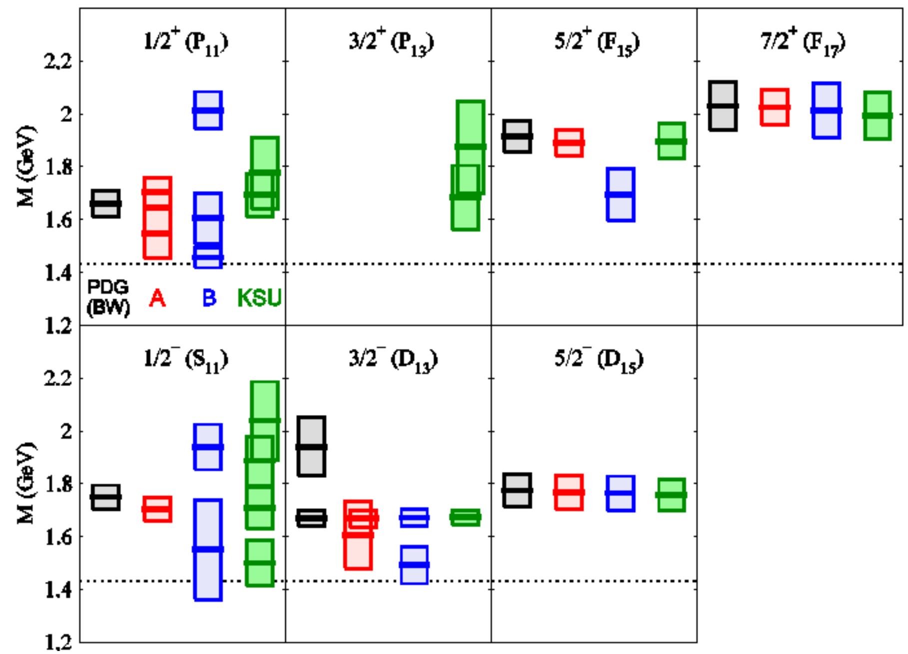
Red: Model A
Blue: Model B
Green: KSU[PRC88(2013)035205]
Black: PDG (only 4- & 3-star Y*; Breit-Wigner)



$J^P(L_{I\,2J})$ "Λ" resonance (I=0)



$J^P(L_{I\,2J})$ "Σ" resonance (I=1)

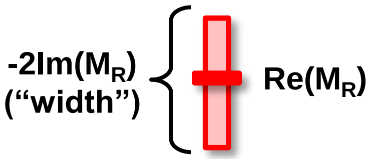


Λ* and Σ* mass spectrum extracted from the K⁻p reaction data

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

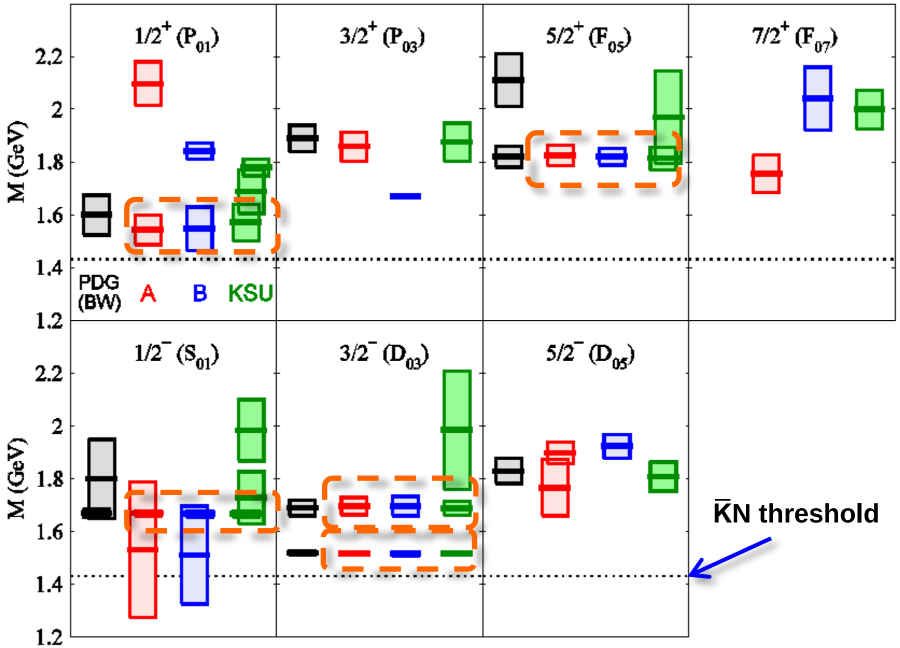
Spectrum for Y* resonances found above the K̄N threshold

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

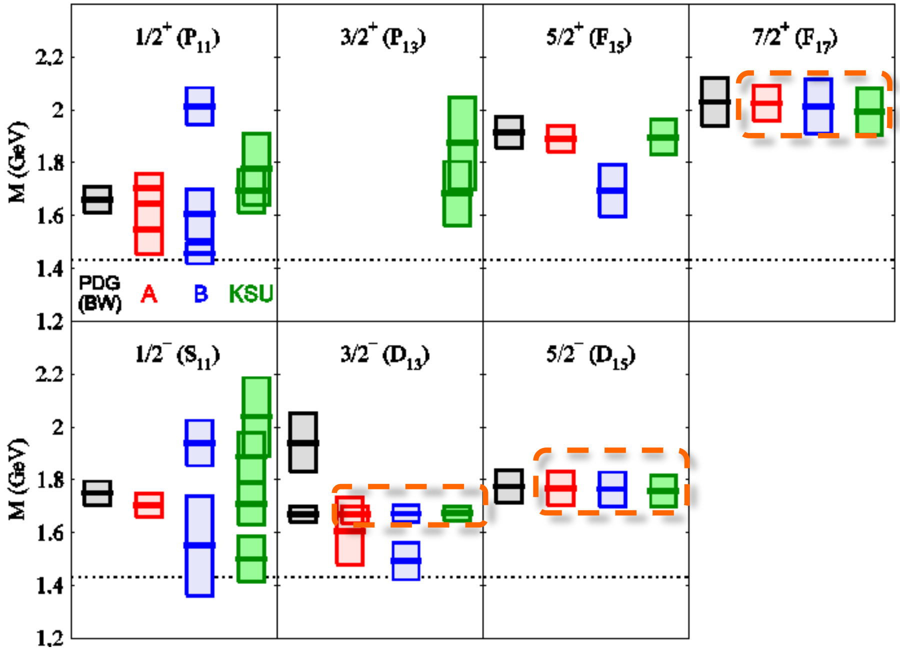


M_R : Resonance pole mass (complex)

$J^P(L_{I\ 2J})$ "Λ" resonance (I=0)



$J^P(L_{I\ 2J})$ "Σ" resonance (I=1)



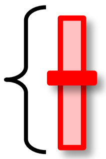
Λ* and Σ* mass spectrum extracted from the K^-p reaction data

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)

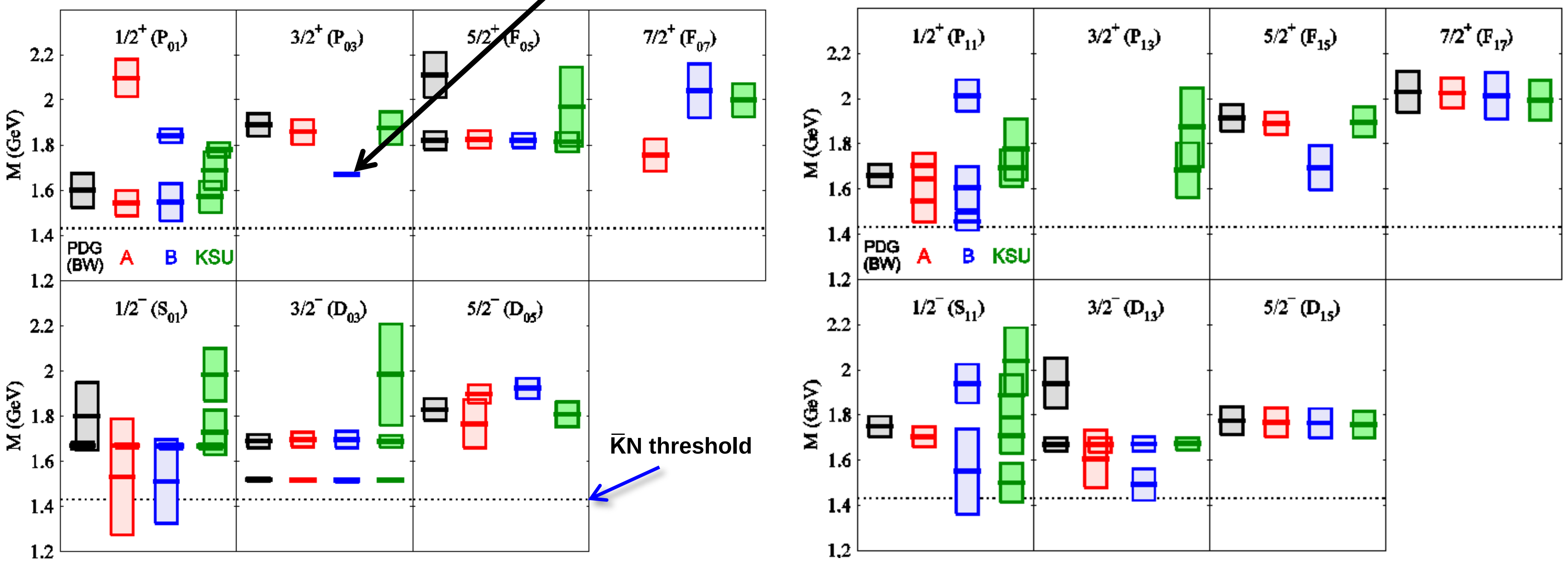
New narrow 3/2+ resonance
M = 1671 – 5i MeV
near the ηΛ threshold !!



M_R : Resonance pole mass (complex)

$J^P(L_{I\ 2J})$ "Λ" resonance (I=0)

$J^P(L_{I\ 2J})$ "Σ" resonance (I=1)



Λ* and Σ* mass spectrum extracted from the K⁻p reaction data

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

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

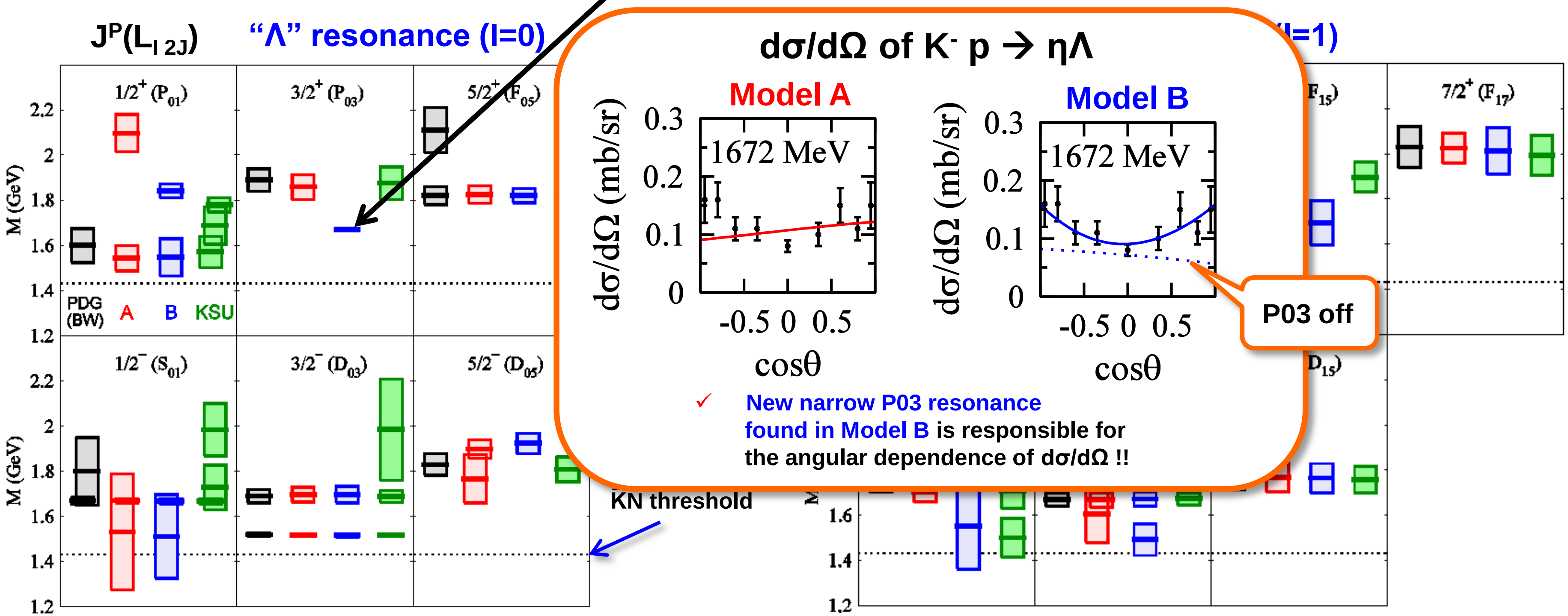
Red: Model A
Blue: Model B
Green: KSU[PRC88(2013)035205]
Black: PDG (only 4- & 3-star Y*; Breit-Wigner)

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)

$J^P(L_{I\,2J})$ "Λ" resonance (I=0) (I=1)

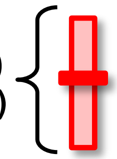


Λ^* and Σ^* mass spectrum extracted from the K^-p reaction data

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

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

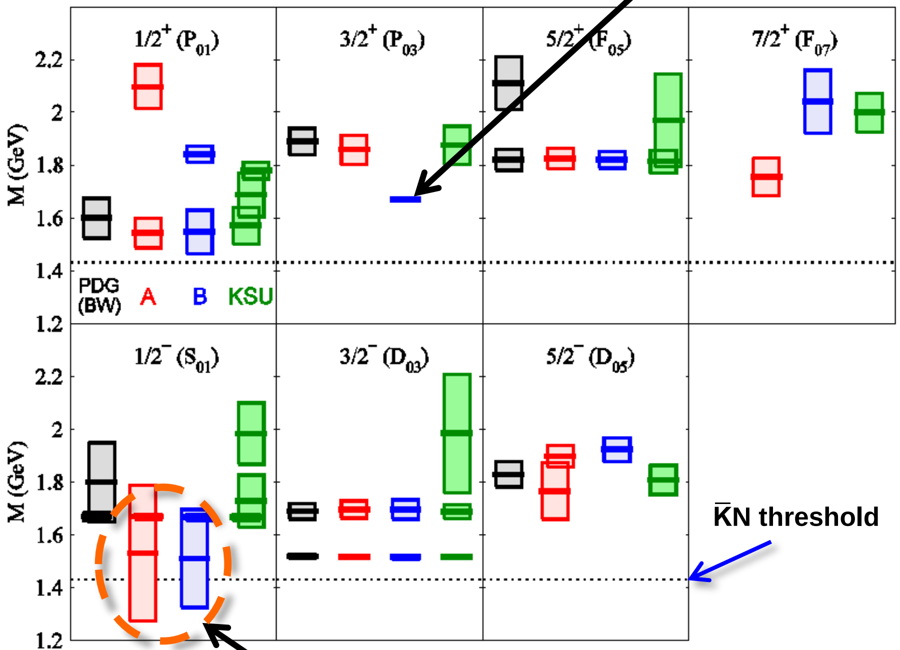
Red: Model A
Blue: Model B
Green: KSU[PRC88(2013)035205]
Black: PDG (only 4- & 3-star Y*; Breit-Wigner)



M_R : Resonance pole mass (complex)

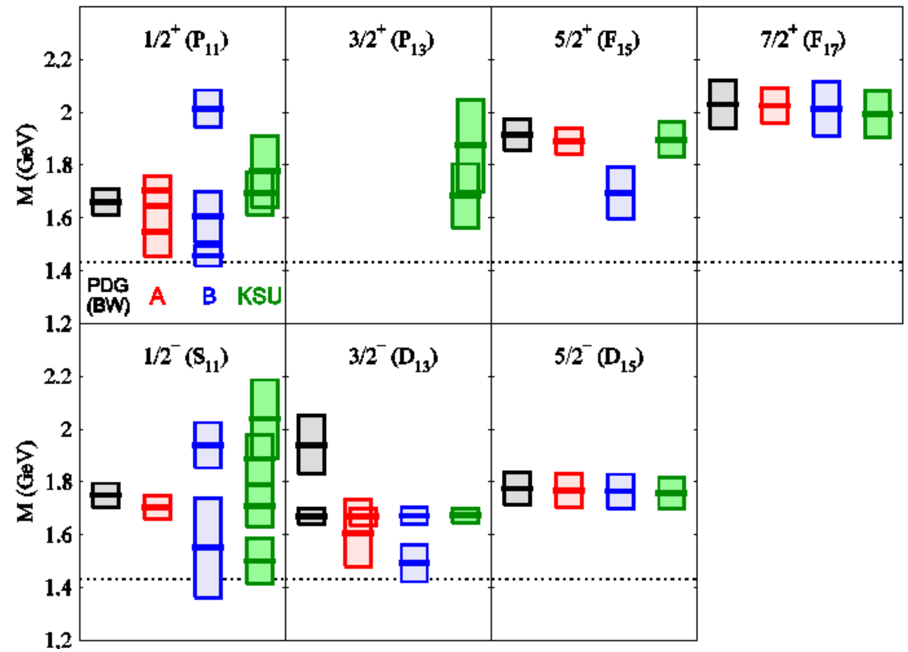
New narrow 3/2+ resonance
M = 1671 – 5i MeV
near the ηΛ threshold !!

$J^P(L_{I\,2J})$ "Λ" resonance (I=0)



Spin partner of Λ(1520)3/2- ??

$J^P(L_{I\,2J})$ "Σ" resonance (I=1)

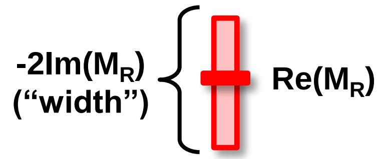


Λ* and Σ* mass spectrum extracted from the $K^{-}p$ reaction data

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

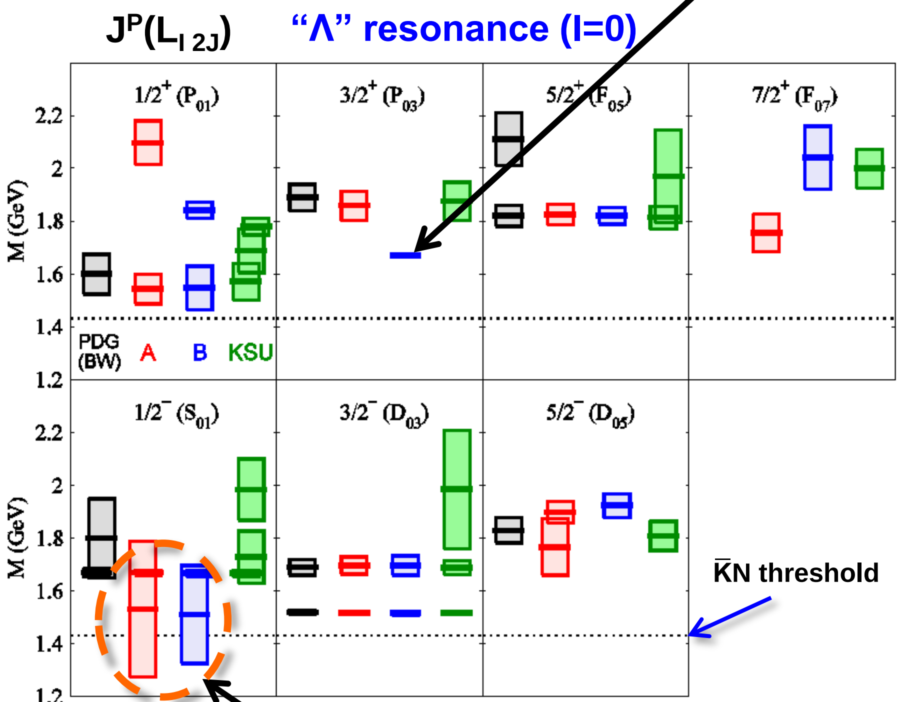
Spectrum for Y* resonances found above the $\bar{K}N$ threshold

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

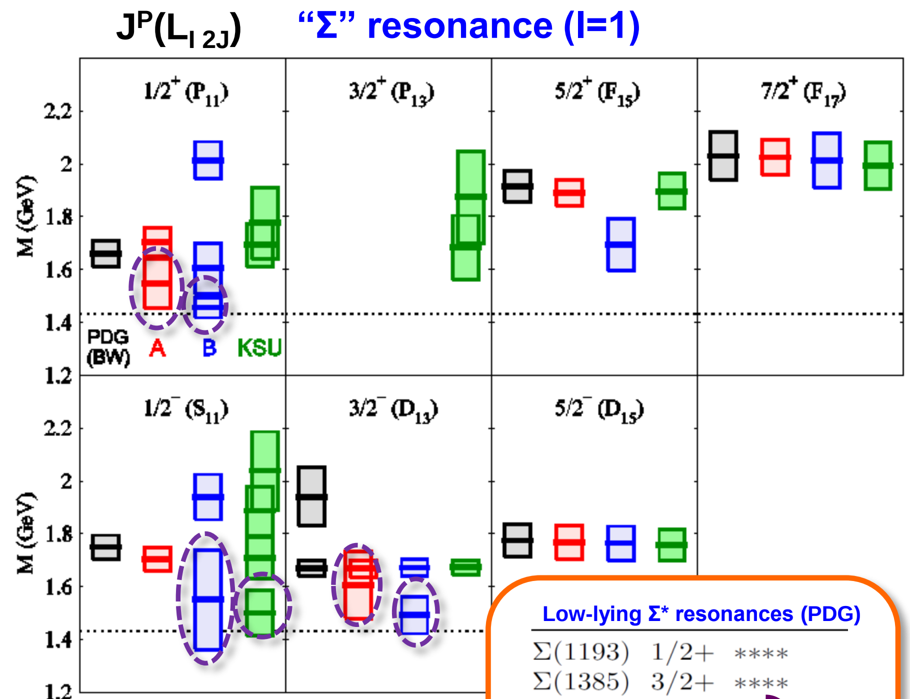


M_R : Resonance pole mass (complex)

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



Spin partner of Λ(1520)$3/2^{-}$??



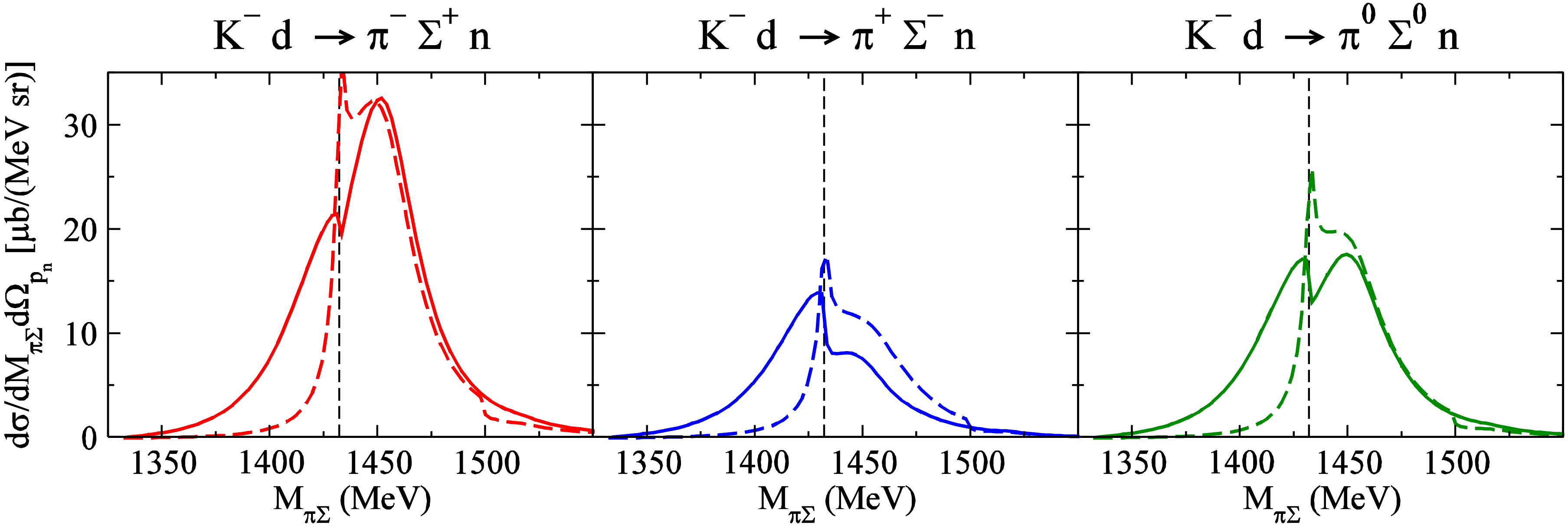
Low-lying Σ* resonances (PDG)

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−	****

$K^- d \to (\pi\Sigma)_0 n$ reaction: Study of $\Lambda(1405)$ & other low-lying Y^* resonances

HK, Lee, PRC94(2016)015201

p_{K^-} = 1 GeV, θ_n = 0 deg.



Full (Model B for $\bar{K}N$ processes)

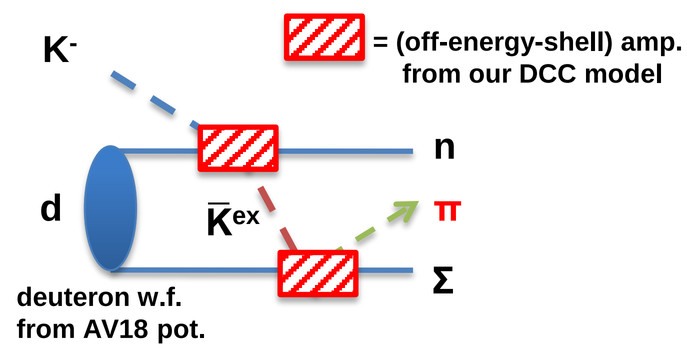
w/o $J^P=1/2^-$ Λ resonant amplitude in $\bar{K}^{ex}N \to \pi\Sigma$

Model B predicts two $J^P=1/2^-$ Λ resonances below $\bar{K}N$ threshold: [PRC92(2015)025205]

M_R = 1428 –i31 MeV ← corresponding to Λ(1405)

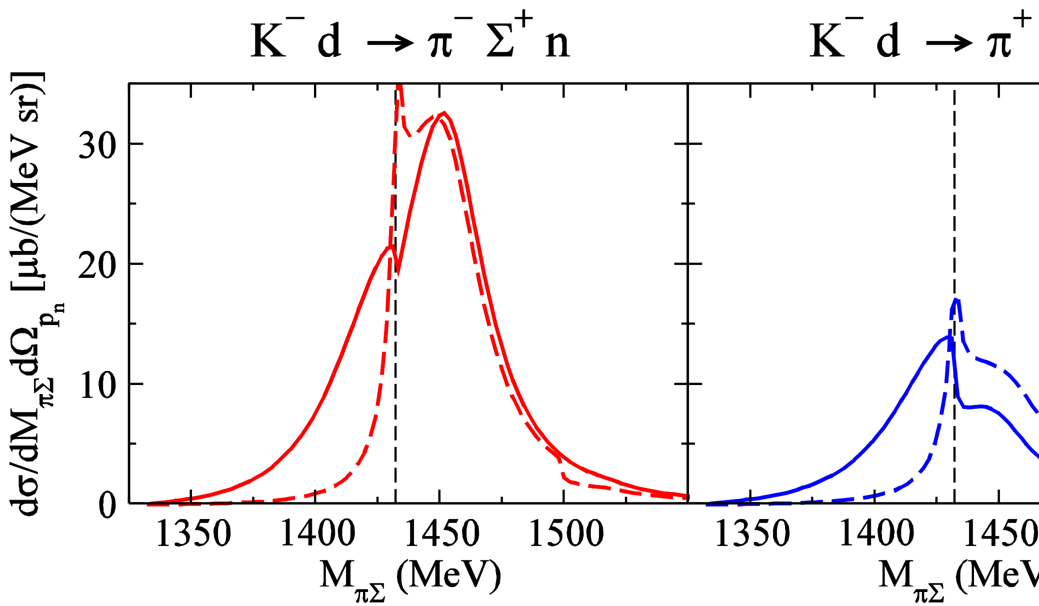
M_R = 1397 –i98 MeV

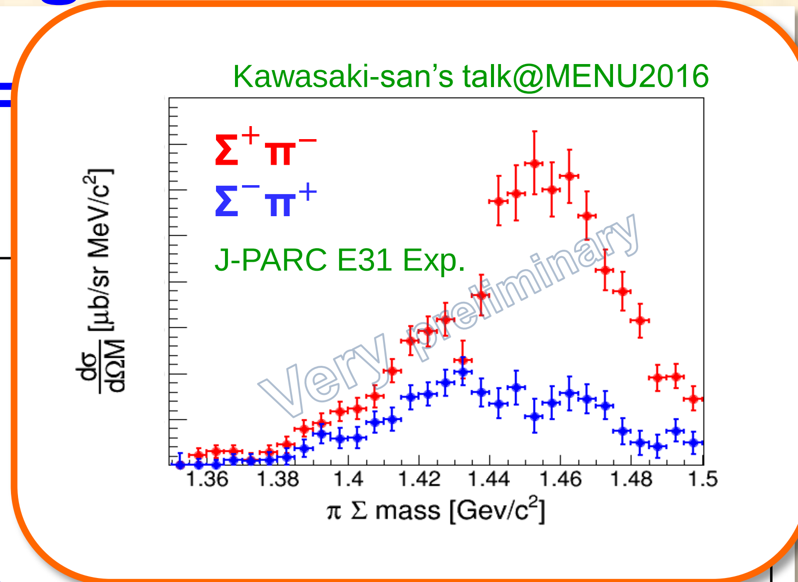
"$\bar{K}$-exchange" term



$K^- d \rightarrow (\pi\Sigma)_0 n$ reaction: Study of $\Lambda(1405)$ & other low-lying Y* resonances

p_{K^-} = 1 GeV, θ_n =





Full (Model B for $\bar{K}N$ processes)

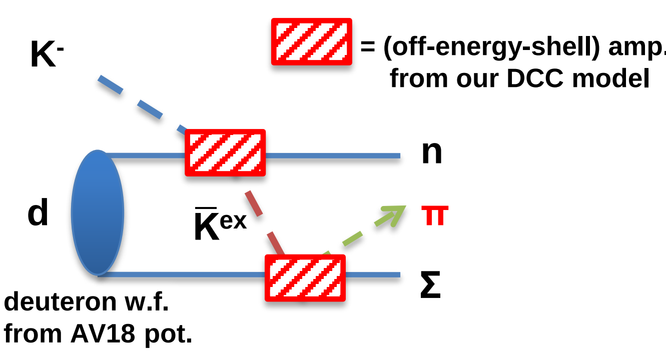
w/o $J^P=1/2^-$ Λ resonant amplitude in $\bar{K}^{ex}N \rightarrow \pi\Sigma$

Model B predicts two $J^P=1/2^-$ Λ resonances below $\bar{K}N$ threshold: [PRC92(2015)025205]

M_R = 1428 –i31 MeV ← corresponding to Λ(1405)

M_R = 1397 –i98 MeV

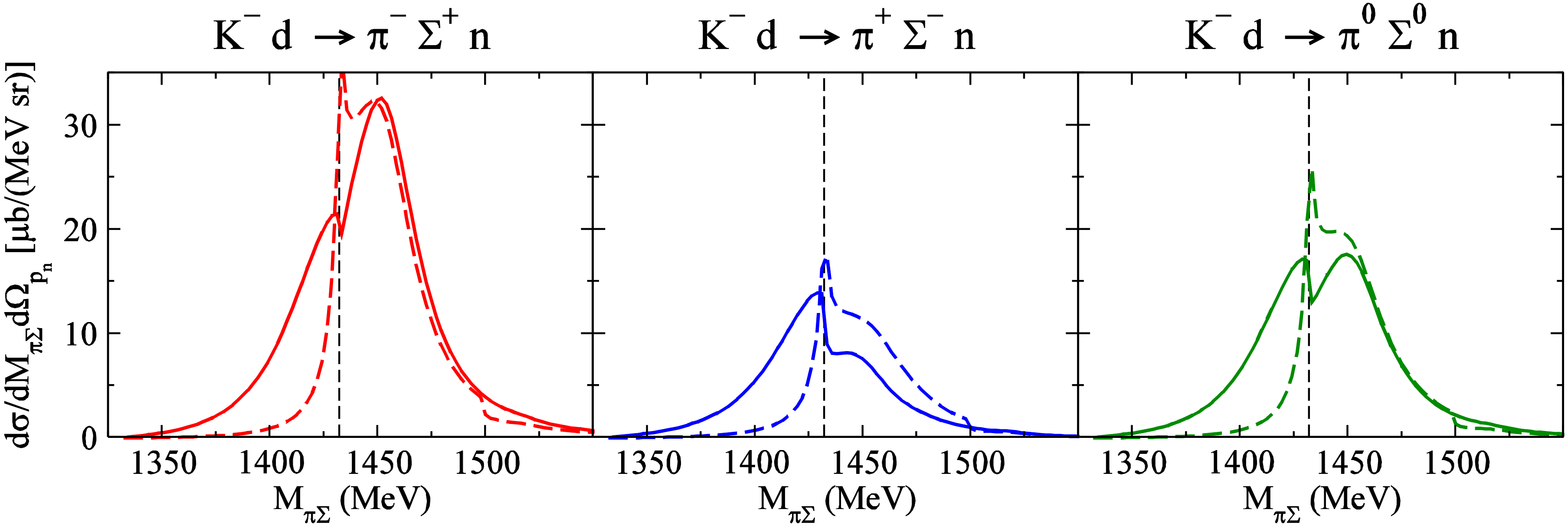
"$\bar{K}$-exchange" term



$K^- d \to (\pi\Sigma)_0 n$ reaction: Study of $\Lambda(1405)$ & other low-lying Y^* resonances

HK, Lee, PRC94(2016)015201

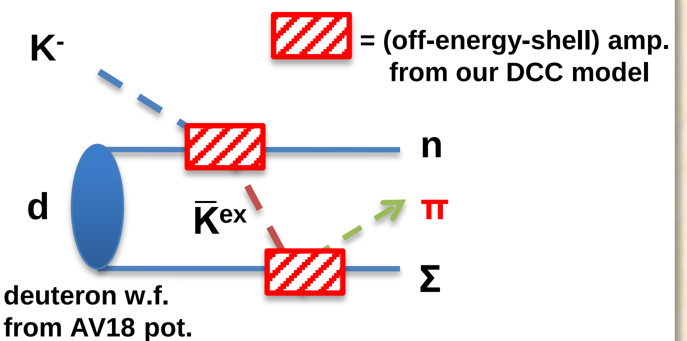
p_{K^-} = 1 GeV, θ_n = 0 deg.



Full (Model B for $\bar{K}N$ processes)

w/o $J^P=1/2^-$ Λ resonant amplitude in $\bar{K}^{ex}N \to \pi\Sigma$

"$\bar{K}$-exchange" term



Model B predicts two $J^P=1/2^-$ Λ resonances below $\bar{K}N$ threshold: [PRC92(2015)025205]

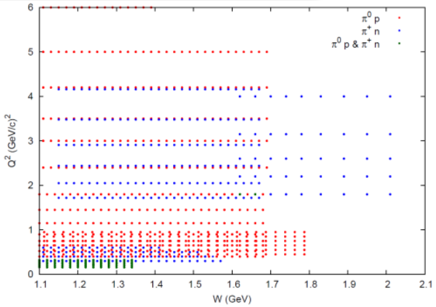
M_R = 1428 –i31 MeV ← corresponding to $\Lambda(1405)$

M_R = 1397 –i98 MeV

Prospects for studies of baryon transition form factors

N* & Δ* e.m. transition form factors ($Q^2 > 0$)

CLAS database for
1π electroproductions
($Q^2 < 6$ GeV^2, $W < 2$ GeV)
[ongoing]

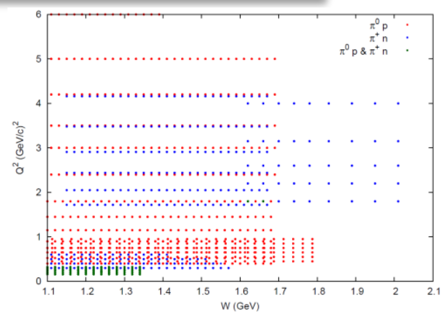


+ $K^+\Lambda$, $K^+\Sigma^0$ electroproduction data
(Q^2=0.65-2.55 GeV^2, W=1.65-2.25 Gev)

Prospects for studies of baryon transition form factors

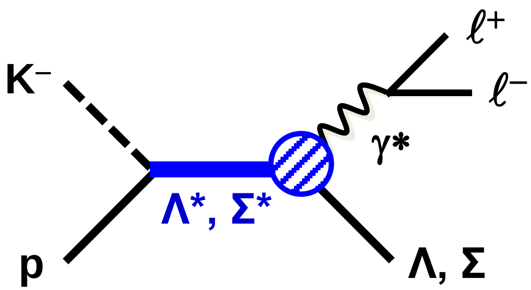
N* & Δ* e.m. transition form factors ($Q^2 > 0$)

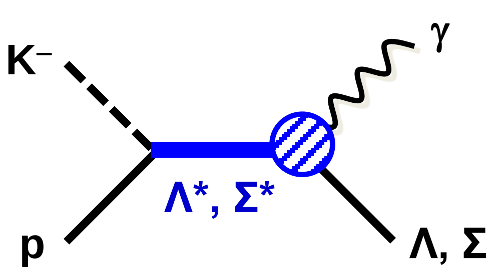
CLAS database for
1π electroproductions
($Q^2 < 6$ GeV², W < 2 GeV)
[ongoing]



+ *K⁺Λ, K⁺ Σ⁰ electroproduction data*
(Q^2=0.65-2.55 GeV², W=1.65-2.25 Gev)

Λ* & Σ* e.m. transition form factors ($Q^2 < 0$, $Q^2 = 0$)

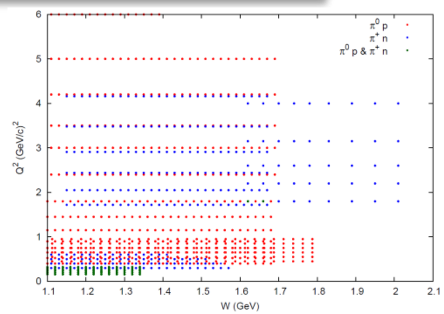




Prospects for studies of baryon transition form factors

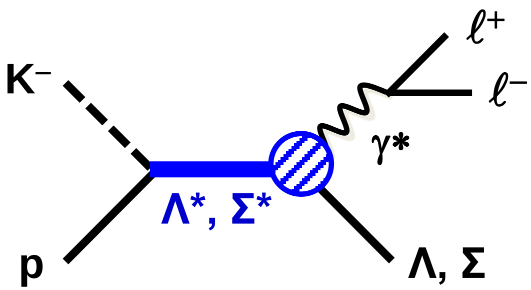
N* & Δ* e.m. transition form factors ($Q^2 > 0$)

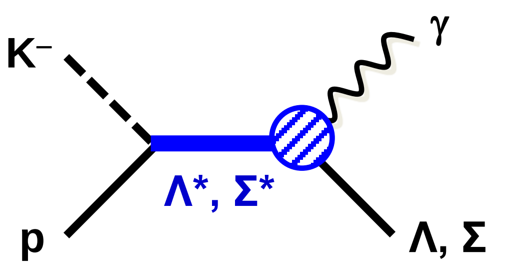
CLAS database for
1π electroproductions
($Q^2 < 6$ GeV^2, W < 2 GeV)
[ongoing]



+ *$K^+\Lambda$, $K^+\Sigma^0$ electroproduction data*
(Q^2=0.65-2.55 GeV^2, W=1.65-2.25 Gev)

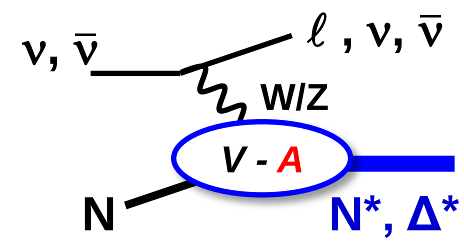
Λ* & Σ* e.m. transition form factors
($Q^2 < 0$, $Q^2 = 0$)



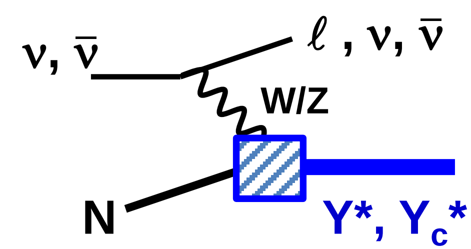


WEAK current transition form factors
($Q^2 < 0$)

✓ Axial transition form factors



✓ |ΔS|=1(u→s), |ΔC|=1(d→c) transition form factors



Thank you for your attention !!

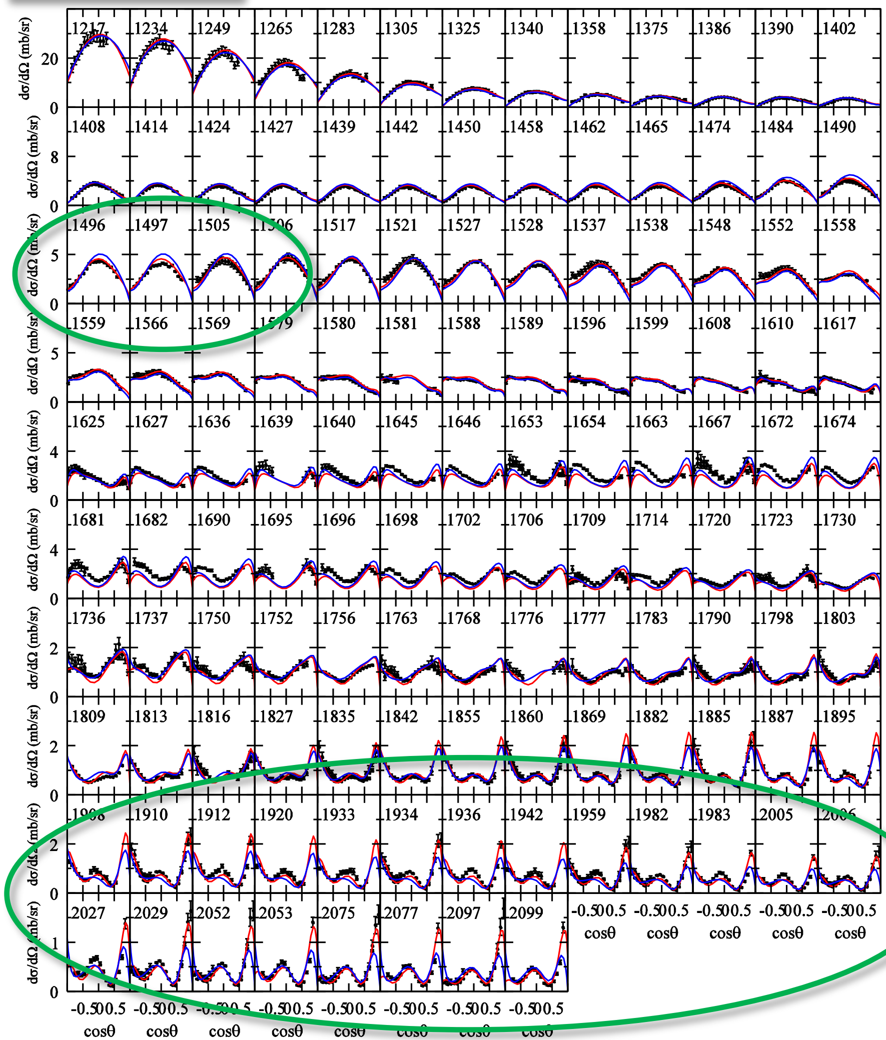
Back up

ANL-Osaka DCC approach to N* & Δ*

HK, Nakamura, Lee, Sato, PRC94(2016)015201; PRC88(2013)035209

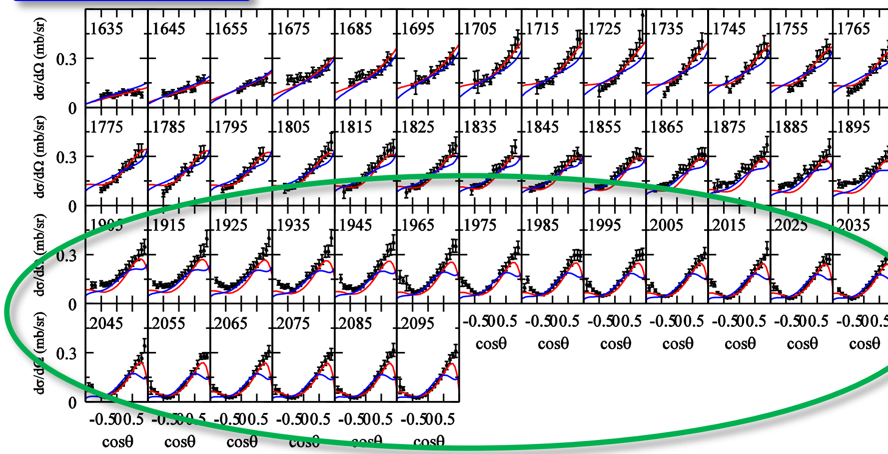
$\gamma p \rightarrow \pi^0 p$

dσ/dΩ for W < 2.1 GeV



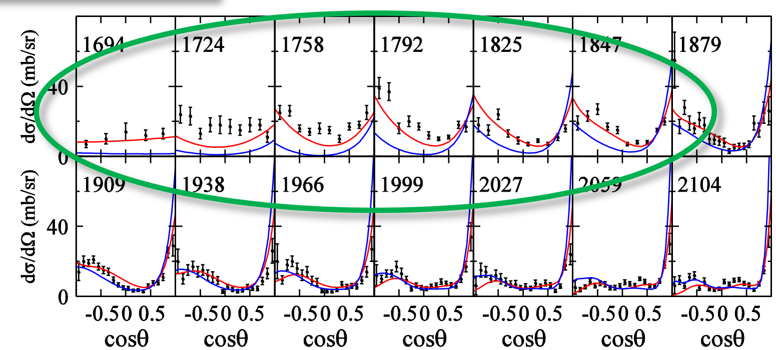
$\gamma p \rightarrow K^+ \Lambda$

dσ/dΩ for W < 2.1 GeV



$\pi^- p \rightarrow K^0 \Sigma^0$

dσ/dΩ for W < 2.1 GeV



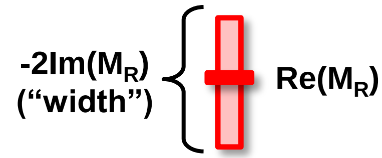
Red: PRC94(2016)015201 (updated ver.)

Blue: PRC88(2013)035209

Comparison of N* & Δ* spectrum between multichannel analyses

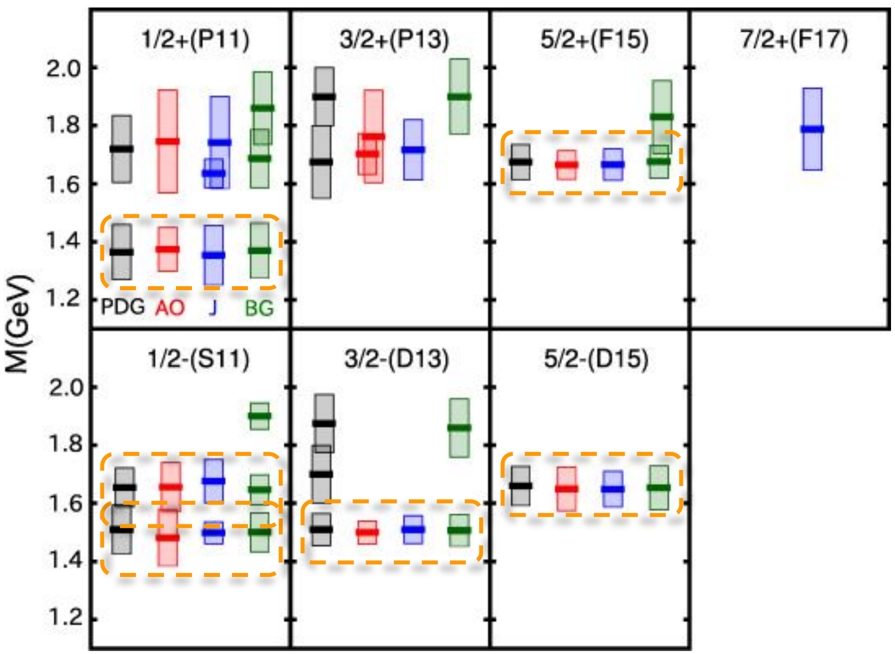
HK, Nakamura, Lee, Sato, PRC88 (2013) 035209

Spectrum for low-lying states with $\mathrm{Re}(M_R) < 1.6$ GeV is now well established !!
(One exception is 2nd P33, Roper-like state of Δ)

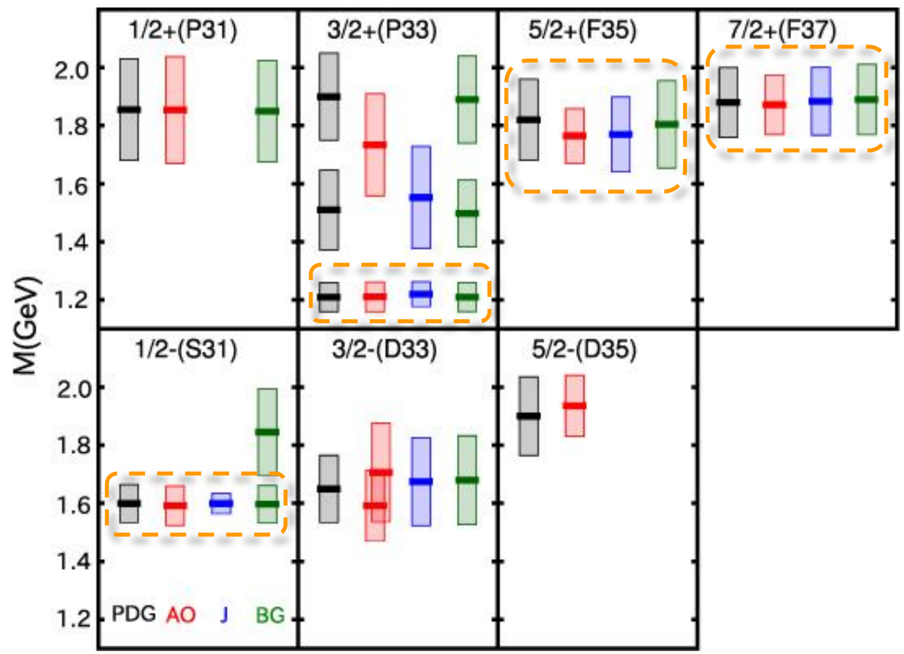


M_R : Resonance pole mass (complex)

$J^P(L_{2I\,2J})$ "N" resonance (I=1/2)



$J^P(L_{2I\,2J})$ "Δ" resonance (I=3/2)



PDG: 4* & 3* states assigned by PDG2012

AO : ANL-Osaka (DCC)

J : Juelich [DCC, EPJA49(2013)44]

BG : Bonn-Gatchina [on-shell K-matrix, EPJA48(2012)5]

Extracted scattering lengths and effective ranges

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

Scattering length and effective range

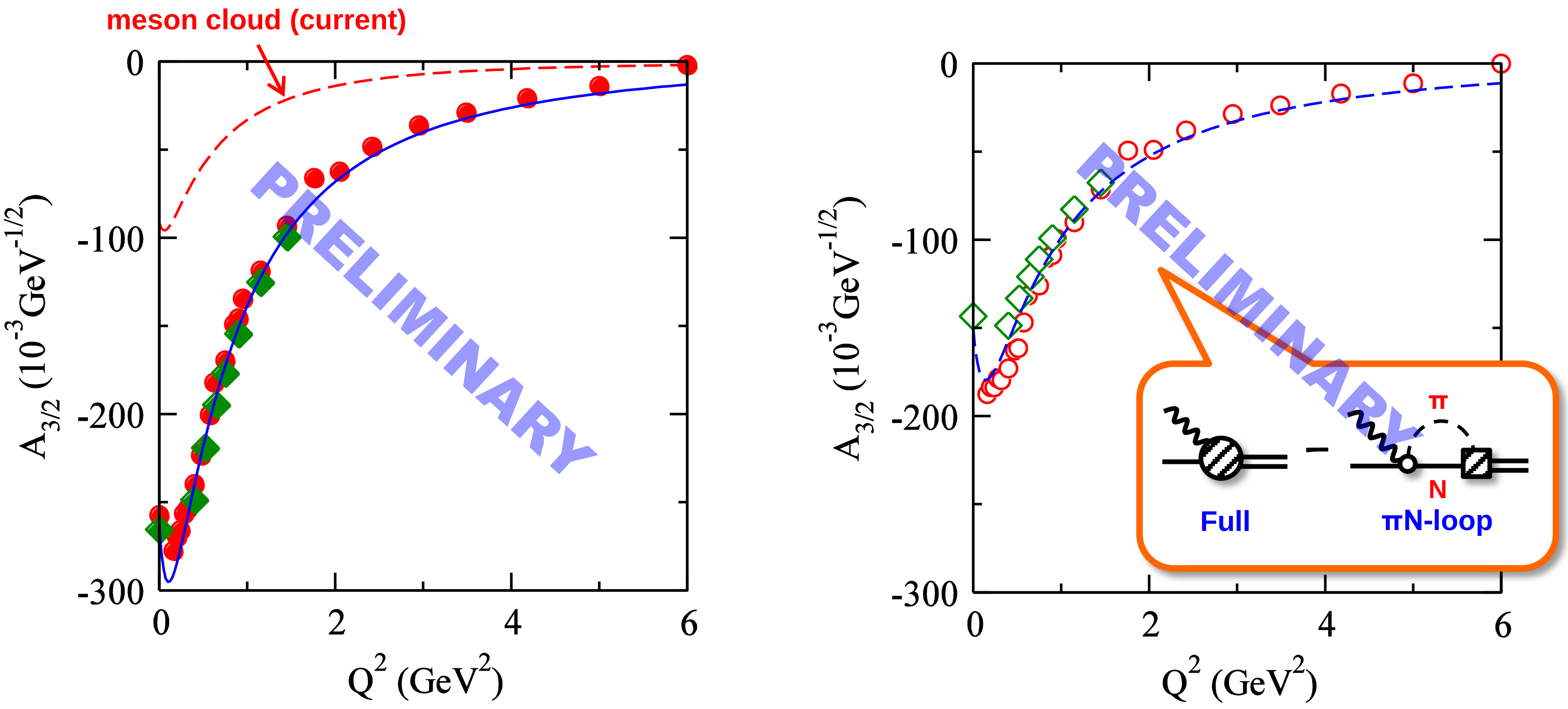
	Model A		Model B	
	$I=0$	$I=1$	$I=0$	$I=1$
$a_{\bar{K}N}$ (fm)	$-1.37+i0.67$	$0.07+i0.81$	$-1.62+i1.02$	$0.33+i0.49$
$a_{\eta\Lambda}$ (fm)	$1.35+i0.36$	-	$0.97+i0.51$	-
$a_{K\Xi}$ (fm)	$-0.81+i0.14$	$-0.68+i0.09$	$-0.89+i0.13$	$-0.83+i0.03$
$r_{\bar{K}N}$ (fm)	$0.67-i0.25$	$1.01-i0.20$	$0.74-i0.25$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

Extracted e.m. transition form factors

✓ **N → "1st P33($J^P=3/2^+$) Δ" transition form factor $A_{3/2}$**

[evaluated at Δ pole mass: M_R = 1210 –i 50 MeV]



Current	= πN, ππN, ηN, KΛ, KΣ; 2 bare states in P33
JLMS	= πN, ππN, ηN; 2 bare states in P33 [PRC80(2009)025207; 82(2010)045206]
Sato-Lee	= πN; 1 bare state in P33 [PRC63(2001)055201; 75(2007)015205]