Coupled-channels analysis of meson-production data and identification of nucleon resonances

Satoshi Nakamura

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Quark-gluon dynamics (QCD) in non-perturbative regime

What to do to understand it ?

Quark-gluon dynamics (QCD) in non-perturbative regime

is, e.g., encoded in nucleon structure

Nucleon structure can show up as :

* spectrum
* decay pattern

of excited states (nucleon resonances)

Nucleon structure can show up as :

$*$ spectrum

$*$ decay pattern

of excited states (nucleon resonances)

$\Longrightarrow$ Analysis of meson production reaction data

Partial wave amplitude analysis (PWA)

PWA and resonance

Pole of amplitude on complex energy plane is identified with a resonance

Pole position : $M_R \quad \Longrightarrow \quad$ Mass : $\mathrm{Re}[M_R]$

Width : $\mathrm{Im}[M_R] \times (-2)$

Residue of pole $\quad \Longrightarrow \quad$ Coupling strength to decay channel

PWA and resonance

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Width : $\mathrm{Im}[M_R] \times (-2)$

Residue of pole $\Longrightarrow$ Coupling strength to decay channel

$\Leftarrow$ M_R is eigenvalue of Hamiltonian for outgoing wave boundary condition

$\Leftarrow$ Pole is generated by unstable state that is formed and decays during collision

PWA and resonance

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Pole position : M_R $\Longrightarrow$ Mass : $\mathrm{Re}[M_R]$

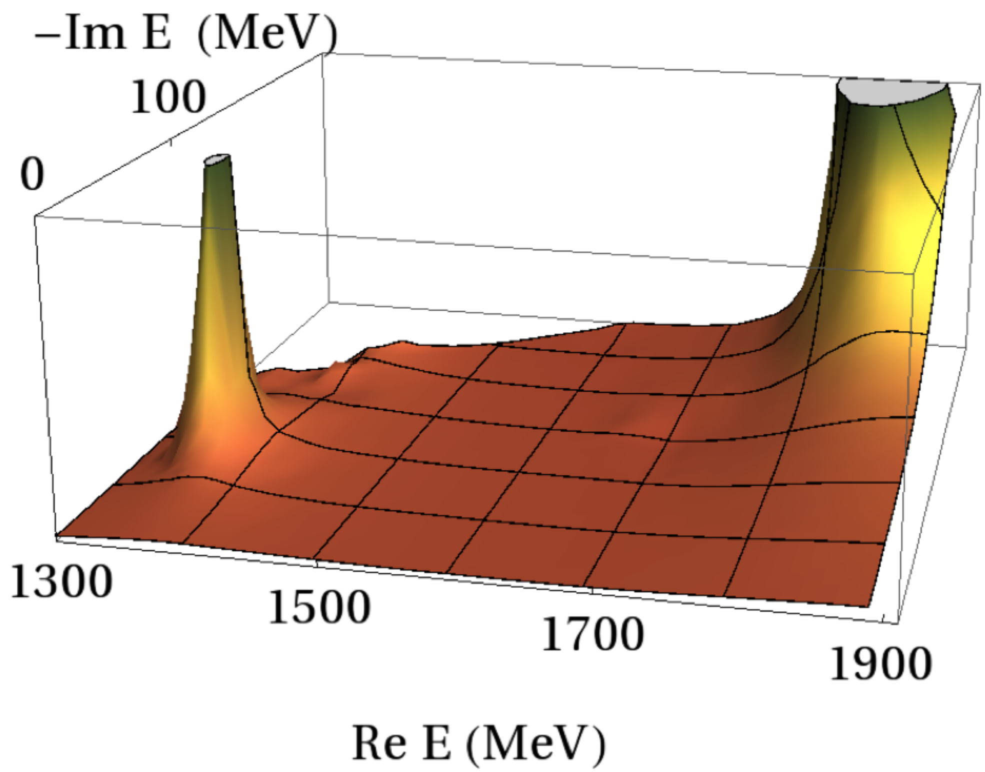
Width : $\mathrm{Im}[M_R] \times (-2)$

Residue of pole $\Longrightarrow$ Coupling strength to decay channel

cf. Breit-Wigner mass and width

When pole exists at $E = M_R$:

$$T(E \to M_R) \sim \frac{1}{E - M_R} = \frac{1}{E - \mathrm{Re}[M_R] - i\,\mathrm{Im}[M_R]}$$



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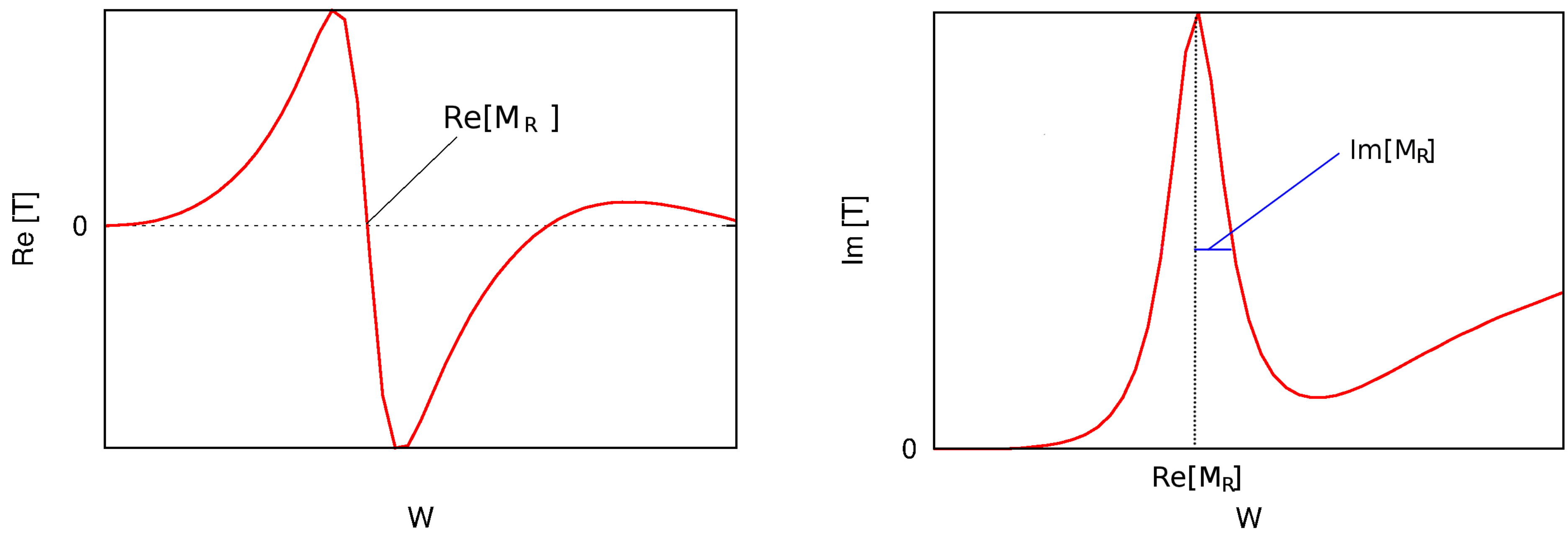
If M_R is close to real (physical energy) axis W, and no branch cut is around



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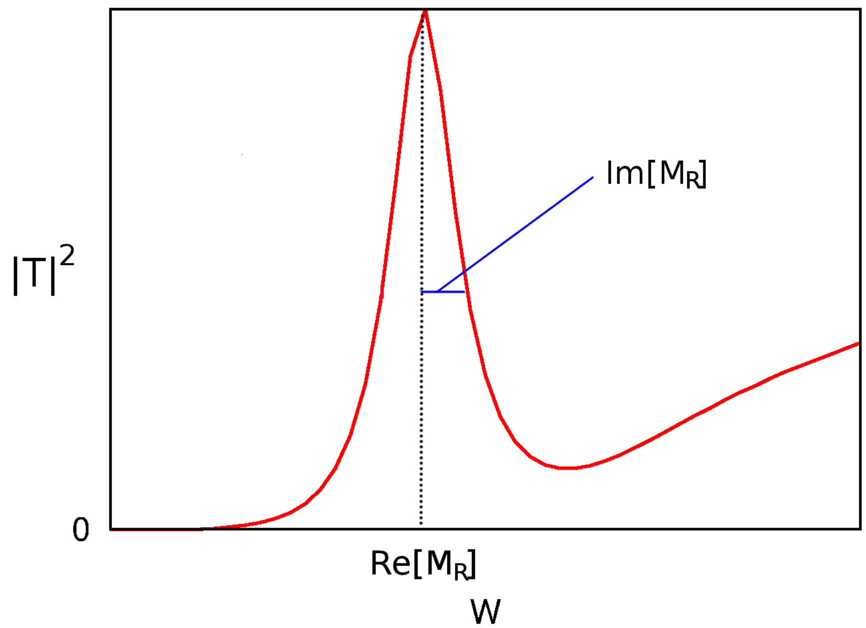


Resonance shows up as a sharp peak in spectrum

But in general, resonances do NOT necessarily show up as a sharp peak in spectrum

* Overlapping resonances can destructively interfere
* Branch cut prevents a resonance from clearly showing up in spectrum

PWA needs to be done to pin down the existence of resonances

How PWA works

Ideal situation : precise and complete data are available

$\Rightarrow$ Partial wave amplitudes on physical energy axis, $T^{\text{exp}}(W)$,

are umambiguously determined

$\Rightarrow$ Fit $T^{\text{exp}}(W)$ with any analytic function, $T(E)$, on $E = W$ axis

$\Rightarrow$ Search for a pole in $T(E)$ on complex energy plane E

pole position does not depend on the chosen $T(E)$

How PWA works

~~Ideal~~ situation : ~~precise~~ and ~~complete~~ data are available

Actual error incomplete

$\Rightarrow$ Partial wave amplitudes on physical energy axis, $T^{\mathrm{exp}}(W)$,

are ~~umambiguously~~ determined

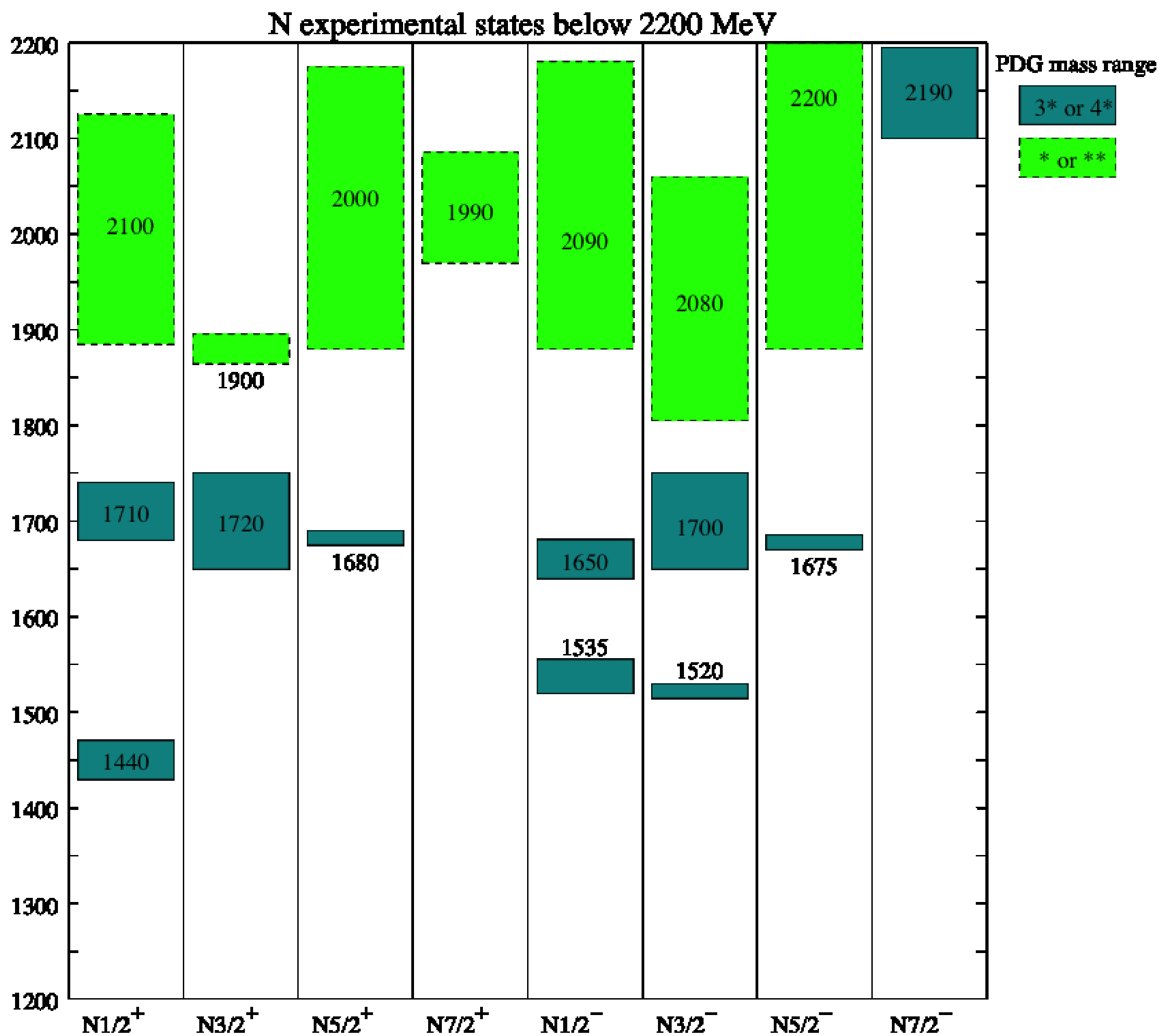
$\Rightarrow$ Fit $T^{\mathrm{exp}}(W)$ with ~~any~~ analytic function, $T(E)$, on $E = W$ axis

theoretically constrained

$\Rightarrow$ Search for a pole in $T(E)$ on complex energy plane E

pole position ~~does not~~ depend on the chosen $T(E)$

Nucleon resonance (N^*) Spectrum in PDG



Theoretically sound analytic function $T(E)$?

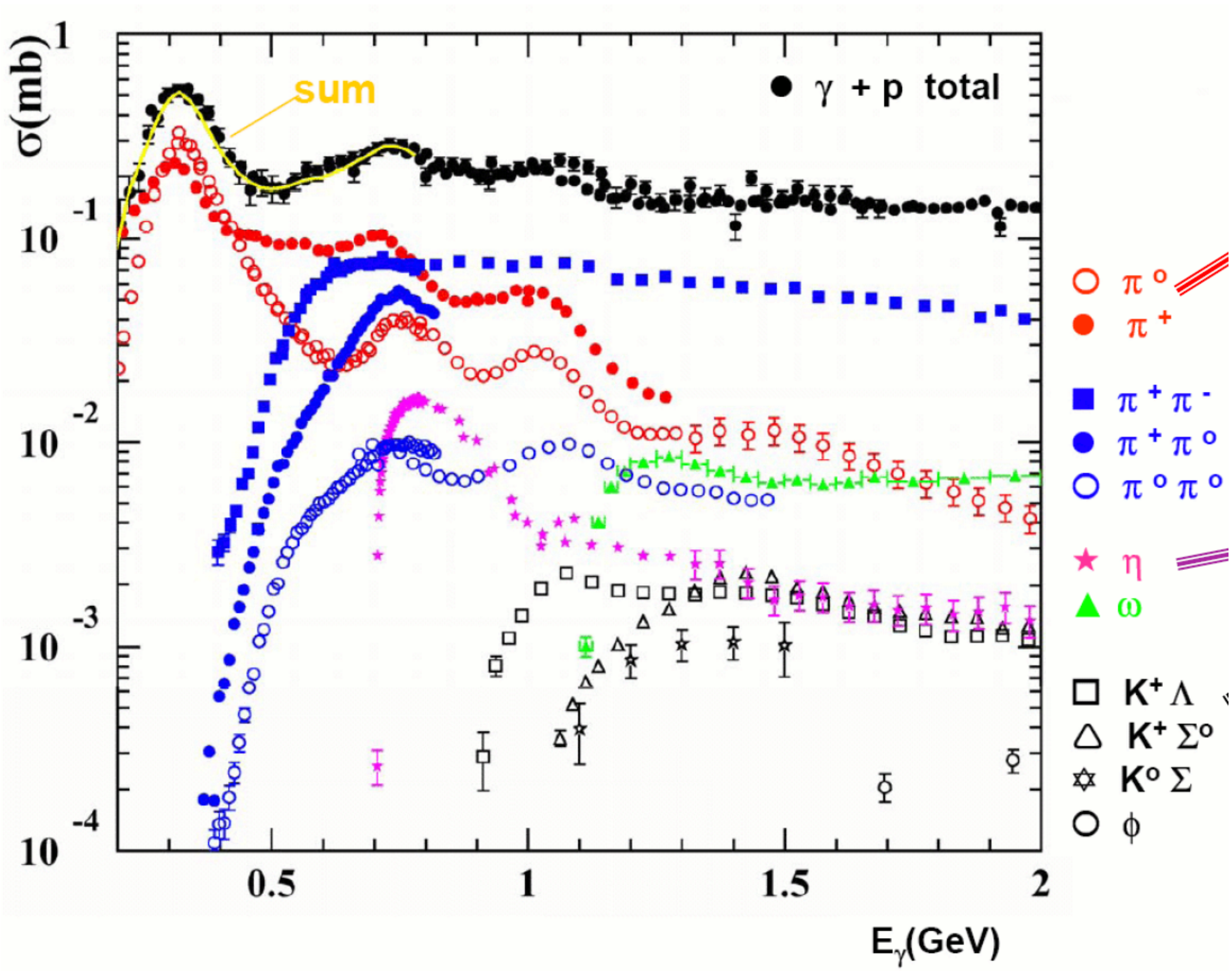
Guiding principle : unitarity

$$T_{ab} - T^*_{ab} \propto \sum_c T_{ac} \, T^*_{bc}$$

$$a, b, c = \gamma N \, , \; \pi N \, , \; \eta N \, , \; \pi\pi N \, ...$$

Unitarity requires coupled-channels

Meson photo-productions



Coupled-channels : $\gamma N\ ,\ \ \pi N\ ,\ \ \eta N\ ,\ \ \pi\pi N\ ,\ \ K\Lambda\ ,\ \ K\Sigma\ ,\ \ \omega N$

Theoretically sound analytic function $T(E)$?

$*$ Parametrization with K-matrix (GWU/VPI , Bonn-Gachina ...)

$$K = (\text{polynomial}) + (\text{Breit}-\text{Wigner})$$

$$T(E) = \frac{K}{1 - i\rho K} + (\text{tree}-\text{diagrams})$$

+ constraint from dispersion relation

$*$ Dynamical coupled-channels model (Our group , Jülich , Dubna-Mainz-Taipei ...)

Start with meson-baryon Lagrangian

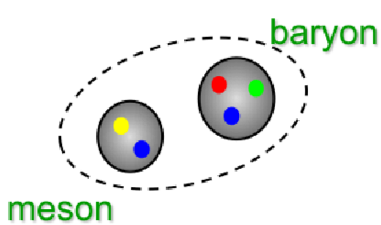
Solve Schrödinger equation with meson-exchange potential

Dynamical coupled-channels model of collaboration@EBAC

$*$ Well-established meson-exchange mechanisms for meson-baryon interactions

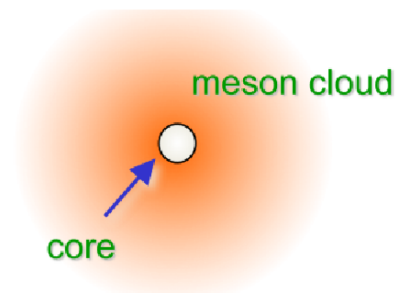
$*$ Description of nucleon resonance (N^*) as

meson-baryon molecule



$|N^*\rangle = |MB\rangle$

quark core + meson cloud



$|N^*\rangle = |qqq\rangle + |\text{m.c.}\rangle$

$\Rightarrow$ Interpretation of N^* (dynamical origin, content)

DCC (Dynamical Coupled-Channel) model

Matsuyama et al., Phys. Rep. **439**, 193 (2007)

Coupled-channel Lippmann-Schwinger equation

$$T_{ab} \quad = \quad V_{ab} + \sum_{c} V_{ac}\, G_c\, T_{cb}$$

$$\{a, b, c\} \quad = \quad \gamma N,\ \pi N,\ \eta N,\ \pi\pi N\,(\pi\Delta, \sigma N, \rho N),\ K\Lambda,\ K\Sigma$$

$T_{ab} \ \Rightarrow$ Observables of meson-baryon reactions

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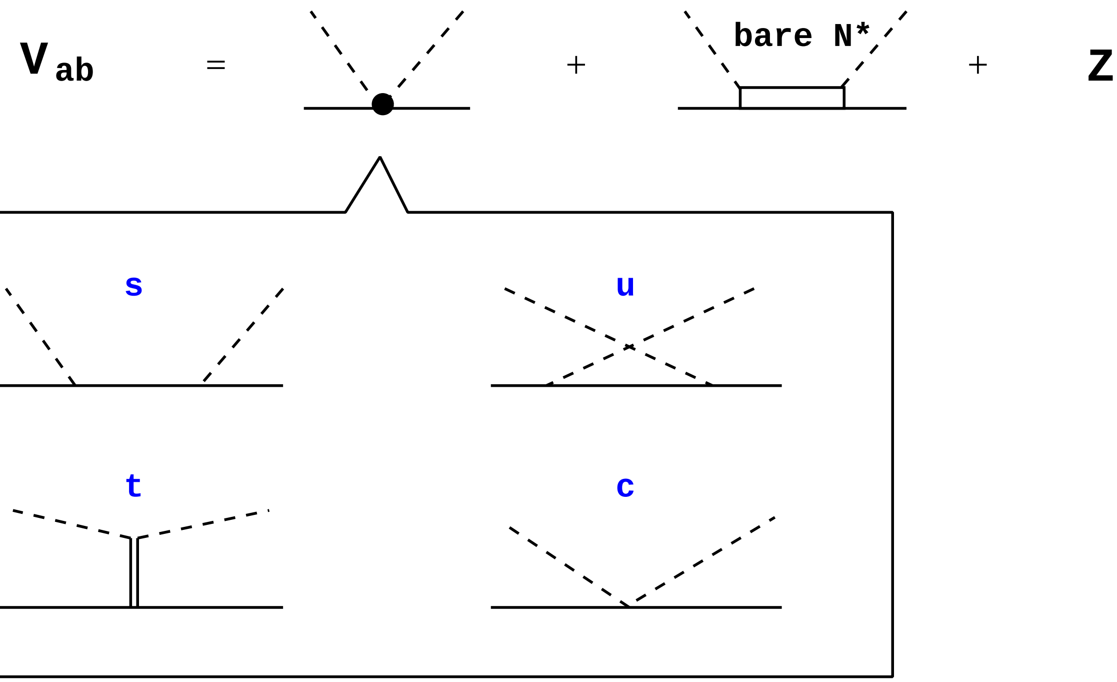

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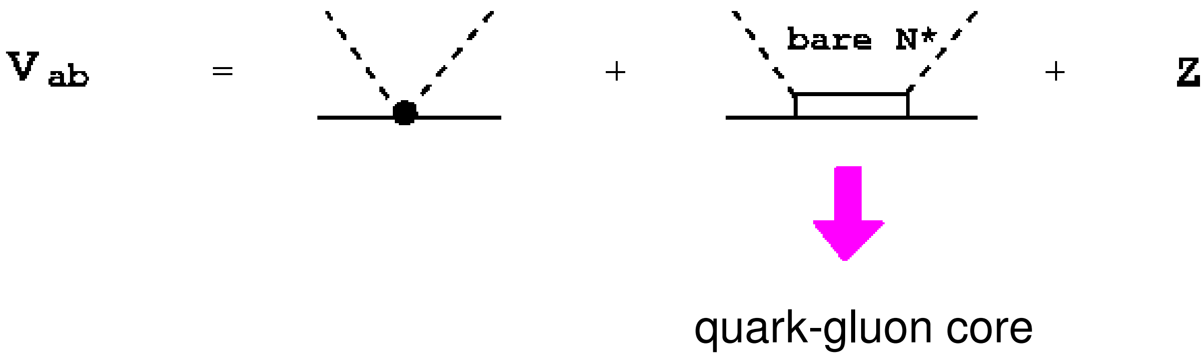

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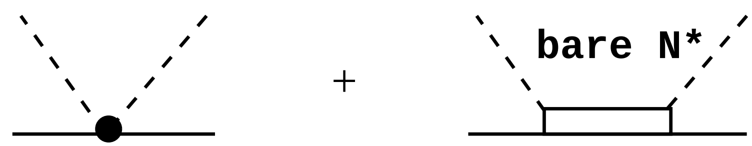
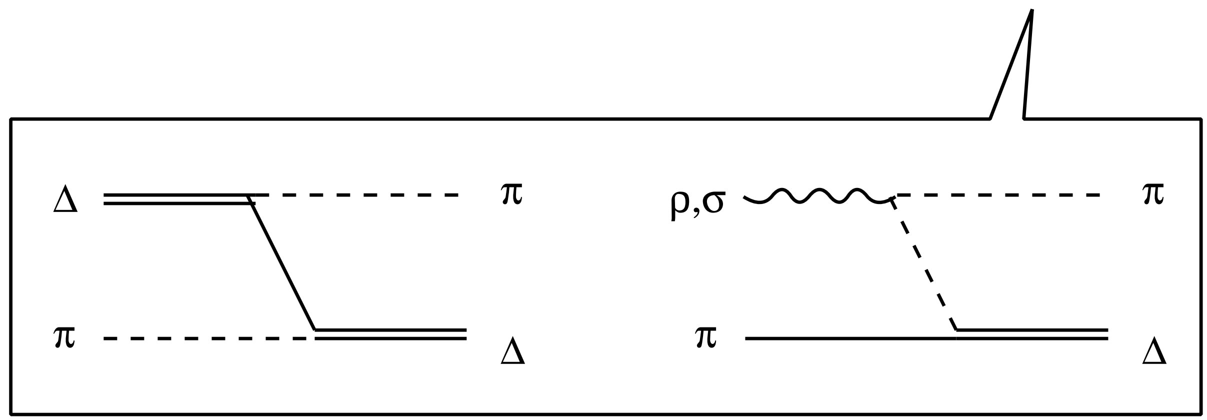
V **ab** =



\+ **Z**

essential for three-body unitarity



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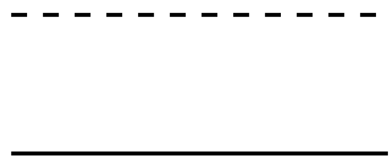
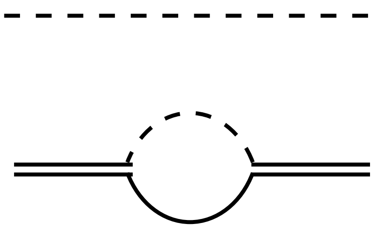
$G\,c$ =



for stable channels



for unstable channels

8ch-DCC Analysis 2010-2012

Kamano, Nakamura, Lee, Sato

DCC Analyses of collaboration@EBAC

	6ch	**8ch**
	2006 – 2009	**2010 – 2012** (Kamano, Nakamura, Lee, Sato)
coupled-channels	$(\gamma N, \pi N, \eta N, \pi\Delta, \sigma N, \rho N)$	$(\gamma N, \pi N, \eta N, \pi\Delta, \sigma N, \rho N, K\Lambda, K\Sigma)$
$* \; \pi N \to \pi N$	$<$ 2 GeV	$<$ 2 GeV
$* \; \gamma N \to \pi N$	$<$ 1.6 GeV	$<$ 2 GeV
$* \; \pi N \to \eta N$	$<$ 2 GeV	$<$ 2 GeV
$* \; \gamma N \to \eta N$	–	$<$ 2 GeV
$* \; \pi N \to K\Lambda, K\Sigma$	–	$<$ 2.1 GeV
$* \; \gamma N \to K\Lambda, K\Sigma$	–	$<$ 2.1 GeV

$\Downarrow$

Fully-combined analysis of $\pi N, \gamma N \to \pi N, \eta N, K\Lambda, K\Sigma$!

Analysis Database ~ 28,000 data points

SAID

	Waves	# of data	Waves	# of data
$\pi N \to \pi N$ PWA	S_{11}	56×2	D_{13}	52×2
	S_{31}	56×2	D_{15}	52×2
	P_{11}	56×2	D_{33}	50×2
	P_{13}	52×2	D_{35}	31×2
	P_{31}	52×2	F_{15}	39×2
	P_{33}	56×2	F_{17}	23×2
			F_{35}	34×2
			F_{37}	35×2
			Sum	1288

	$d\sigma/d\Omega$	P	R	a	Sum
$\pi^- p \to \eta p$	294	-	-	-	294
$\pi^- p \to K^0 \Lambda$	544	262	-	-	806
$\pi^- p \to K^0 \Sigma^0$	215	70	-	-	285
$\pi^+ p \to K^+ \Sigma^+$	552	312	-	-	864
Sum	1605	644	-	-	2249

	$d\sigma/d\Omega$	Σ	T	P	G	H	E	F	$O_{x'}$	$O_{z'}$	$C_{x'}$	$C_{z'}$	$T_{x'}$	$T_{z'}$	$L_{x'}$	$L_{z'}$	sum
$\gamma p \to \pi^0 p$	8290	1680	353	557	28	24	-	-	-	-	-	-	-	-	-	-	10860
$\gamma p \to \pi^+ n$	5384	1014	661	221	75	123	-	-	-	-	-	-	-	-	-	-	7478
$\gamma p \to \eta p$	1076	197	50	-	-	-	-	-	-	-	-	-	-	-	-	-	1323
$\gamma p \to K^+ \Lambda$	611	118	69	410	-	-	-	-	66	66	89	89	-	-	-	-	1518
$\gamma p \to K^+ \Sigma^0$	2949	116	-	320	-	-	-	-	-	-	52	52	-	-	-	-	3489
Sum	18310	3043	1133	1508	103	147	-	-	66	66	141	141	-	-	-	-	24668

Parameters

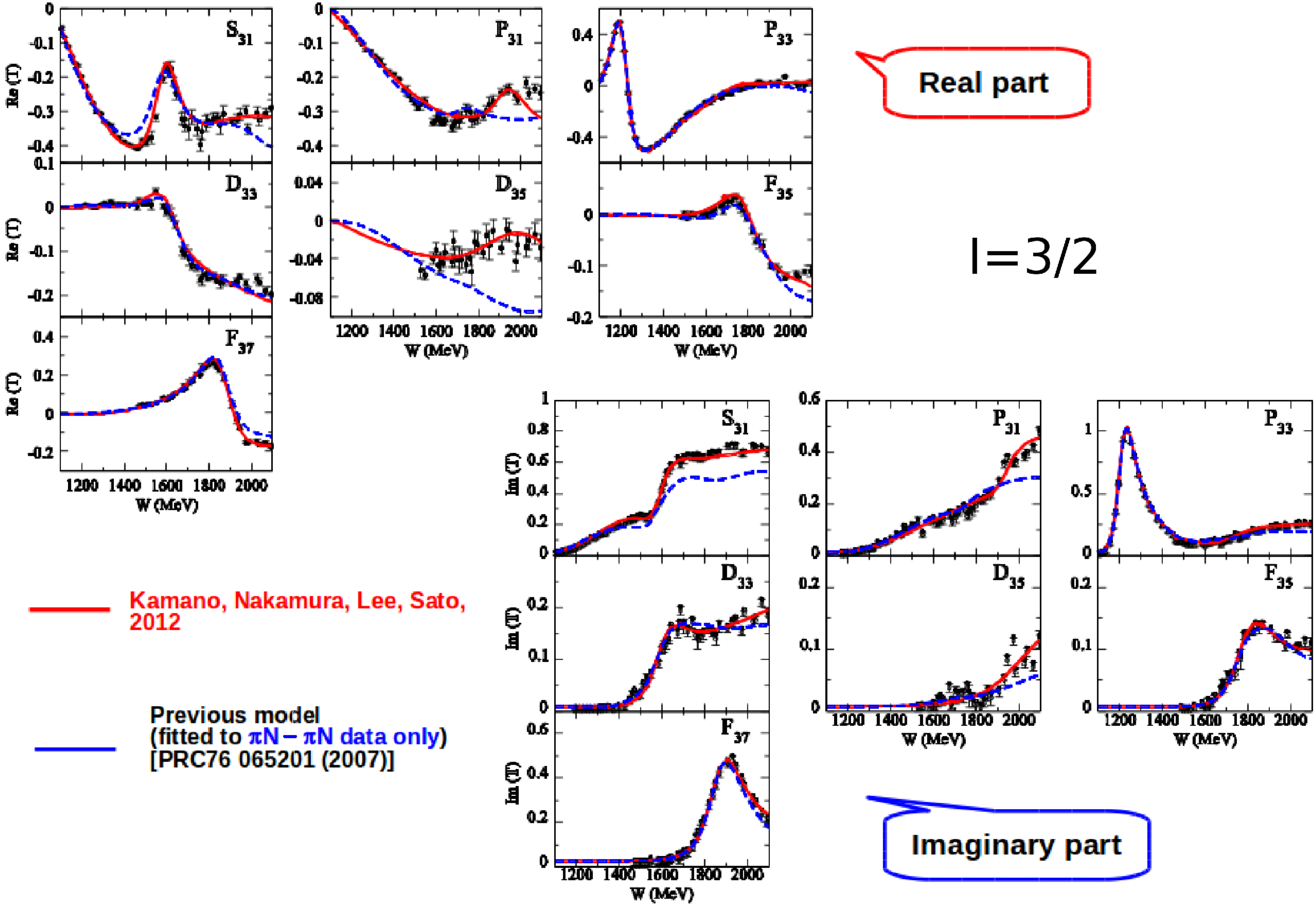
$*$ Bare mass ($M^0_{N^*}$)

$*$ Bare vertex for $N^* \to$ MB ($C_{N^*,MB}, \Lambda_{N^*,MB}$)

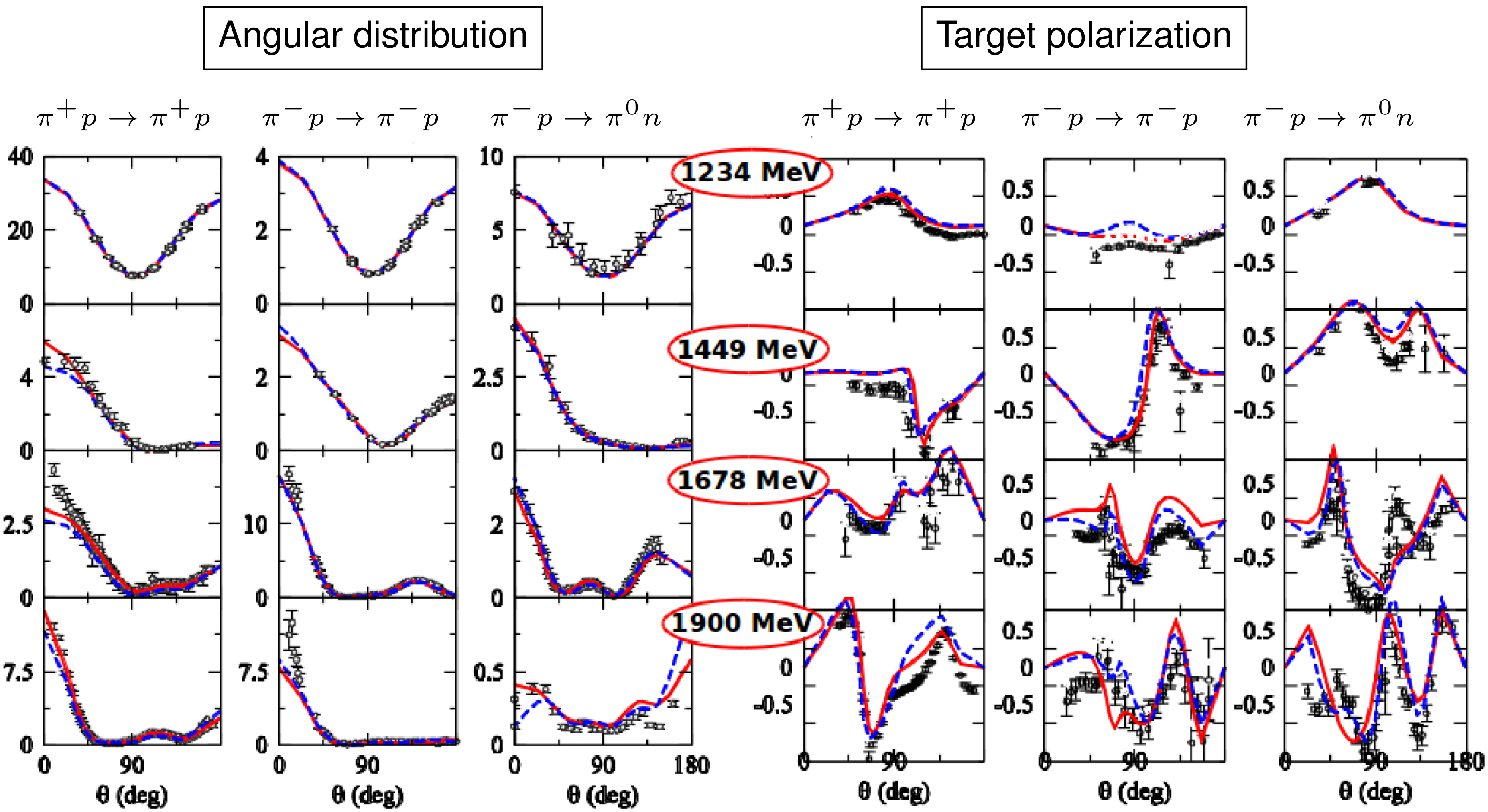
$$
\begin{aligned}
(\#\text{ of parameters}) &= n_{pw} \times n_{N^*} \times (1 + 2 \times n_{ch}) \\
&= 14 \times n_{N^*} \times (1 + 2 \times 8) \\
&\sim 200
\end{aligned}
$$

χ^2-fit to $\sim$ 28,000 data points

Partial wave amplitudes of pi N scattering



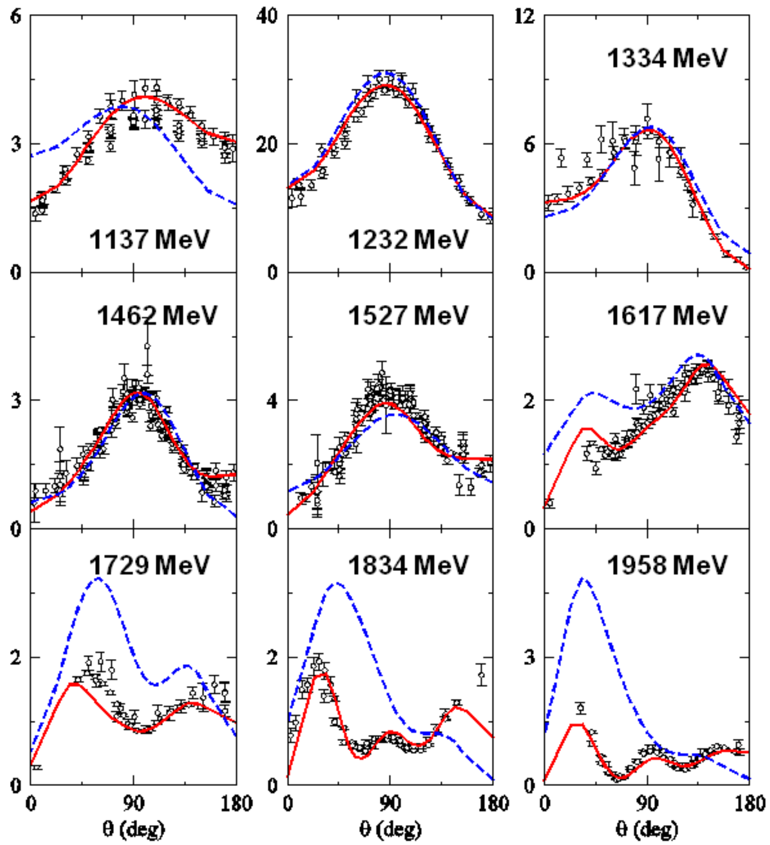
$\pi N \to \pi N$



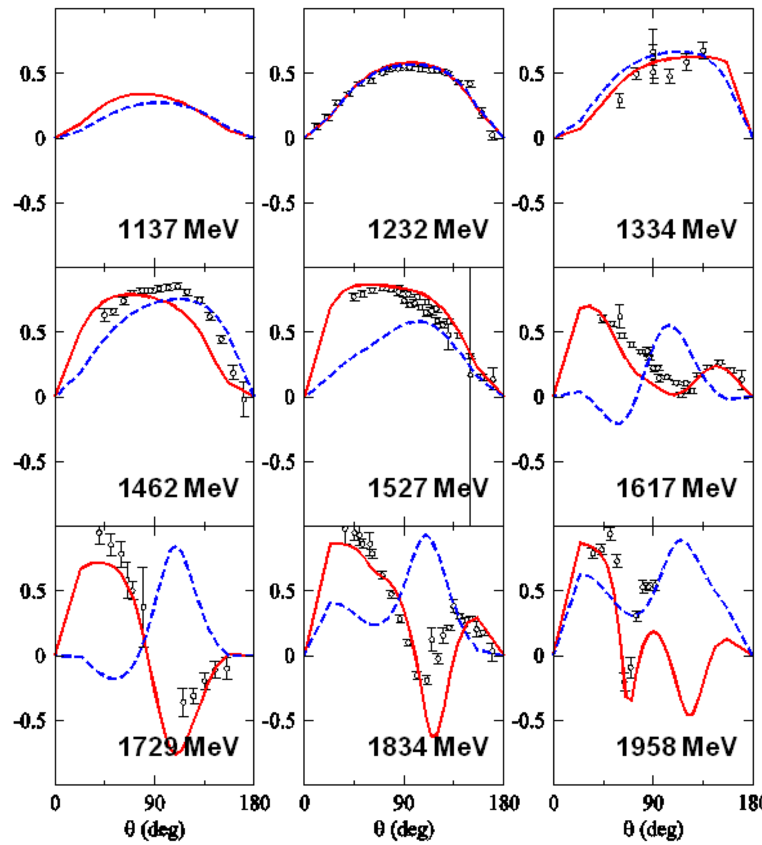
Kamano, Nakamura, Lee, Sato, 2012

$\gamma p \to \pi^0 p$

Angular distribution $d\sigma/d\Omega$ (μb/sr)

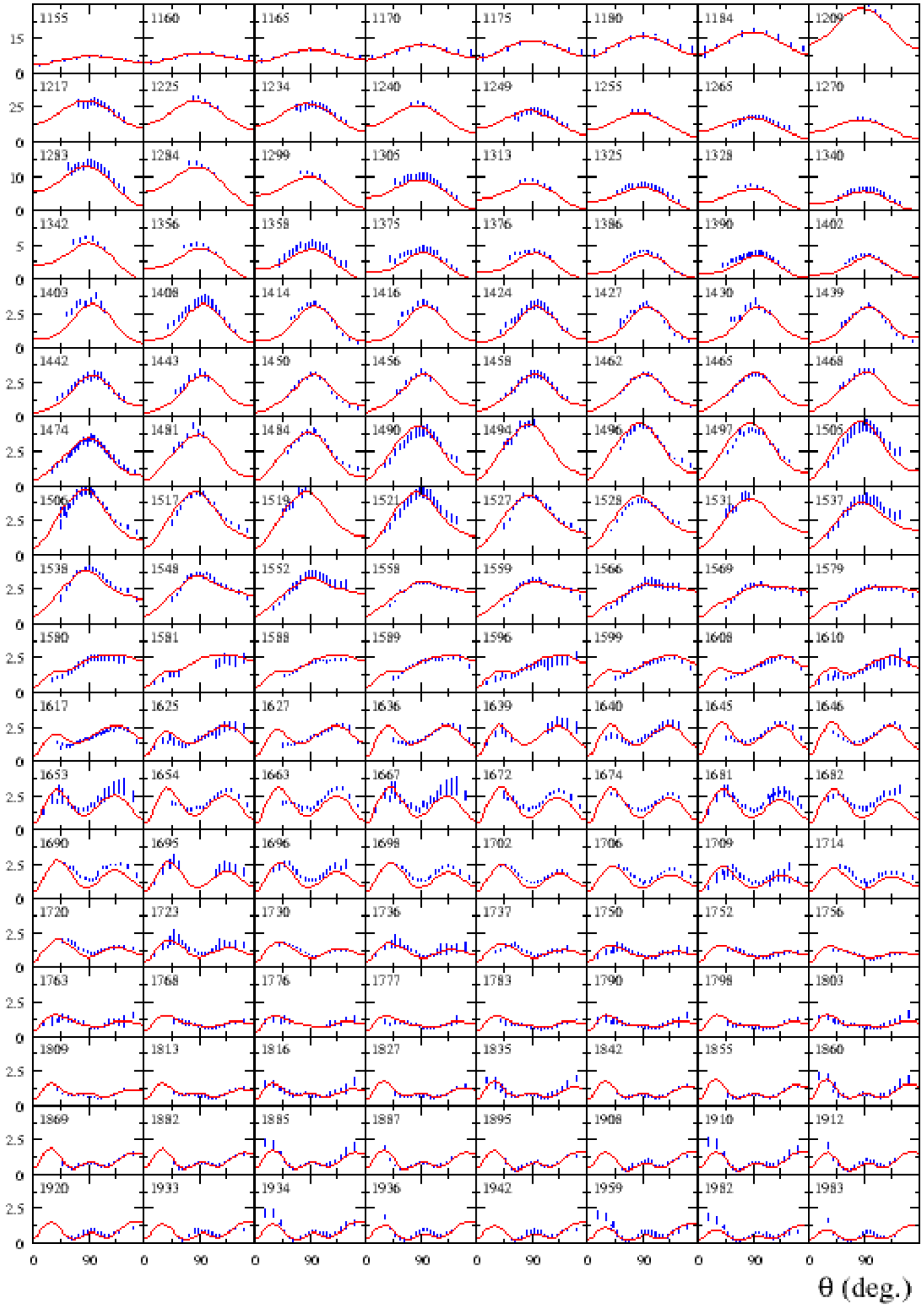


Photon asymmetry Σ



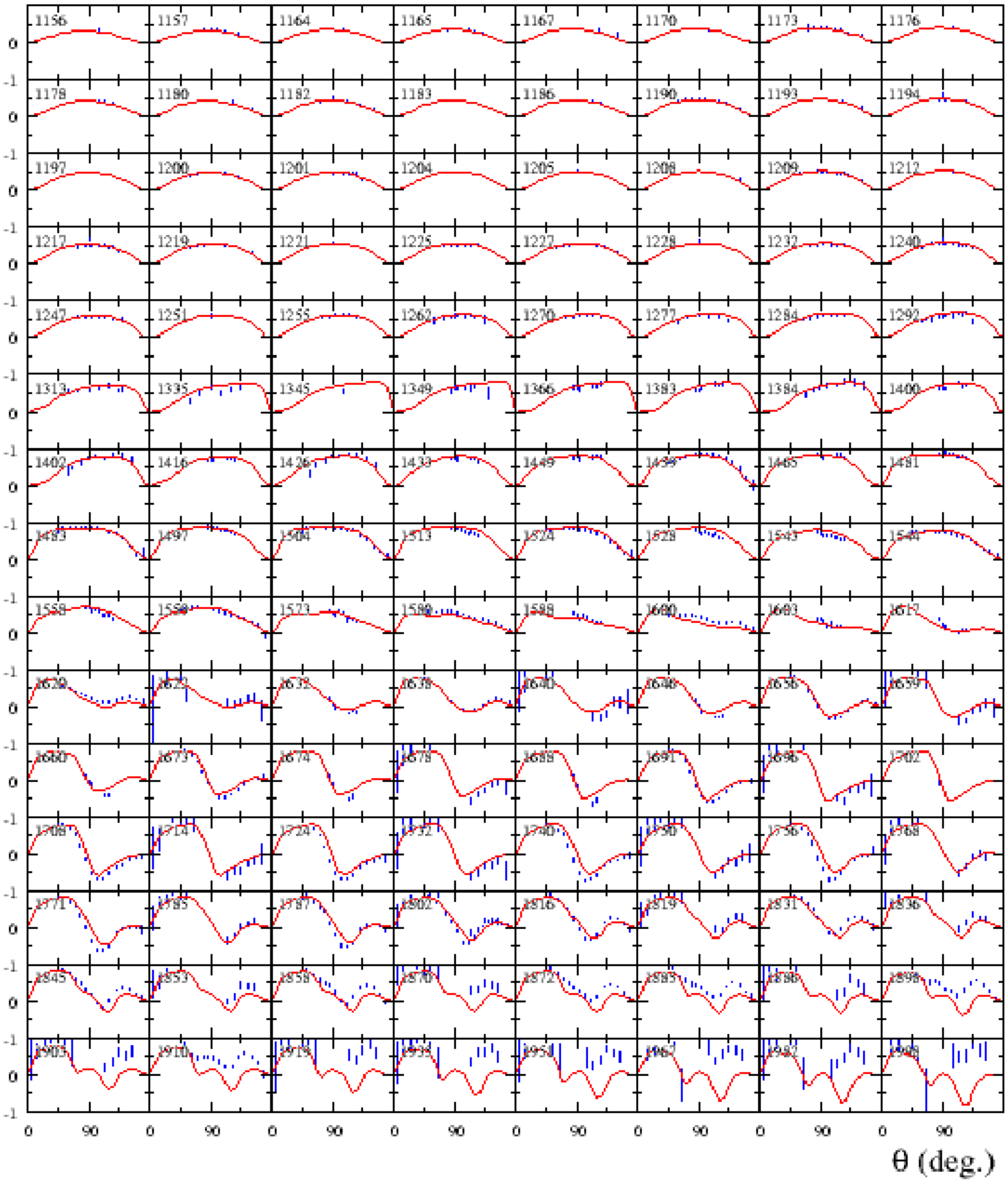
Kamano, Nakamura, Lee, Sato, 2012

$d\sigma/d\Omega \quad \gamma p \to \pi^0 p$



Kamano, Nakamura, Lee, Sato, 2012

$\Sigma \quad \gamma p \to \pi^0 p$

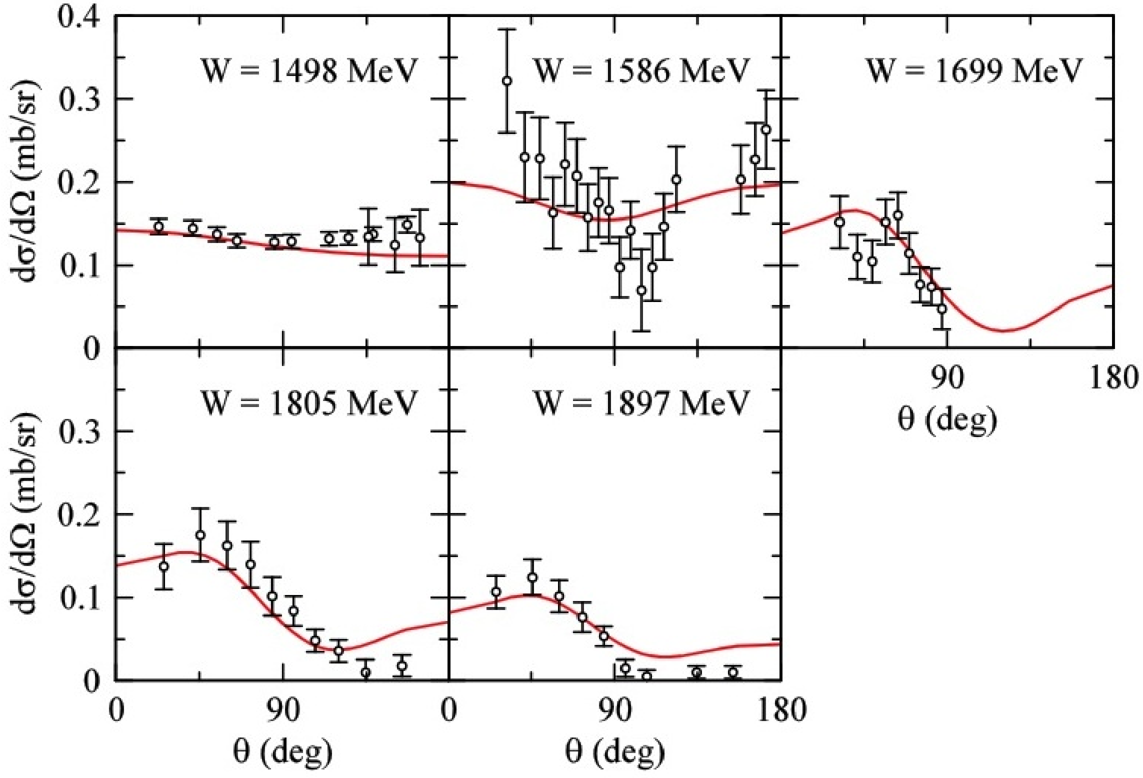


Kamano, Nakamura, Lee, Sato, 2012

η productions

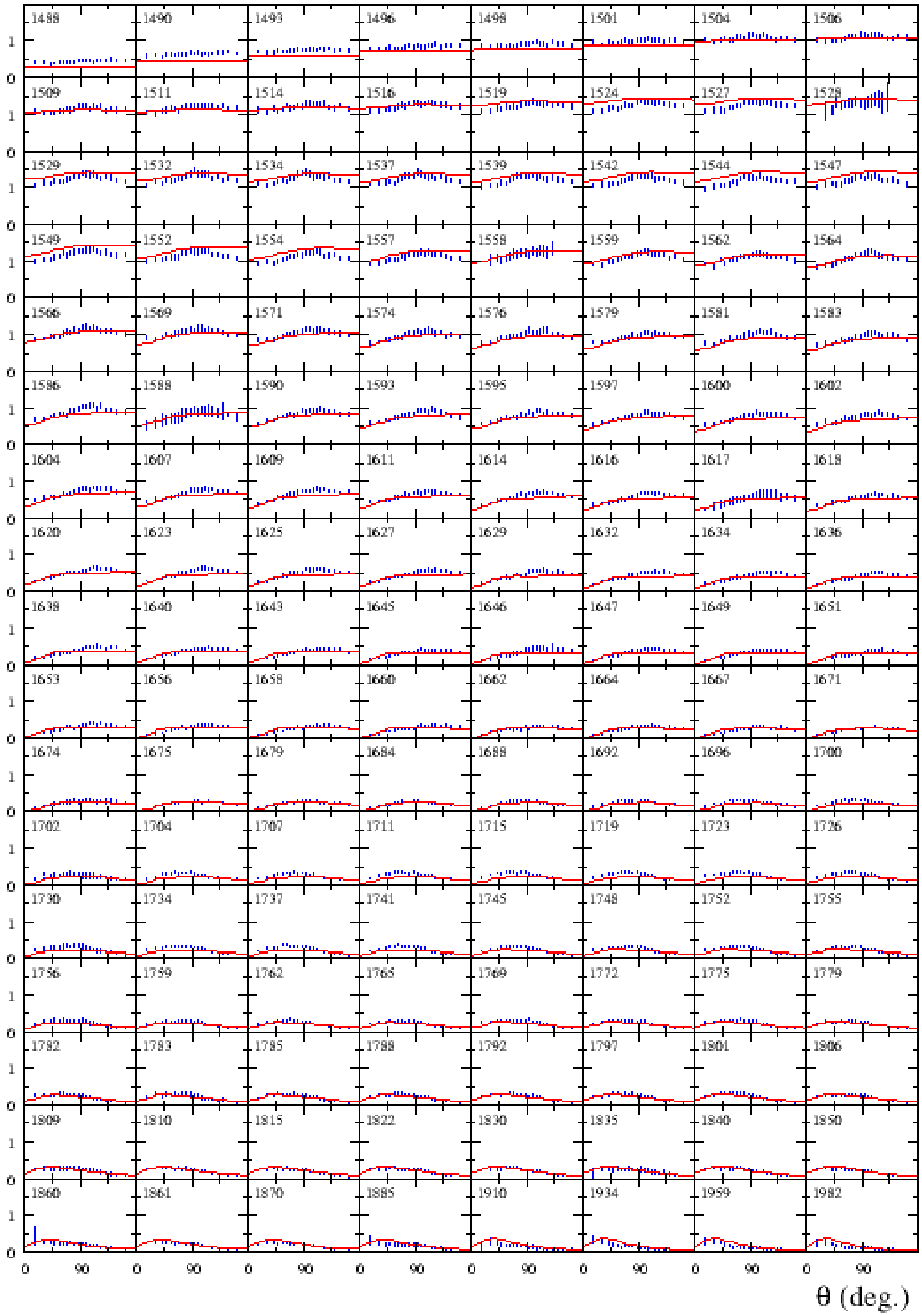
$$\pi^- p \to \eta n$$

$d\sigma/d\Omega$ (mb/sr)



Data are selected following Durand et al. PRC78 025204

$d\sigma/d\Omega \quad \gamma\, p \to \eta\, p$



Kamano, Nakamura, Lee, Sato, 2012

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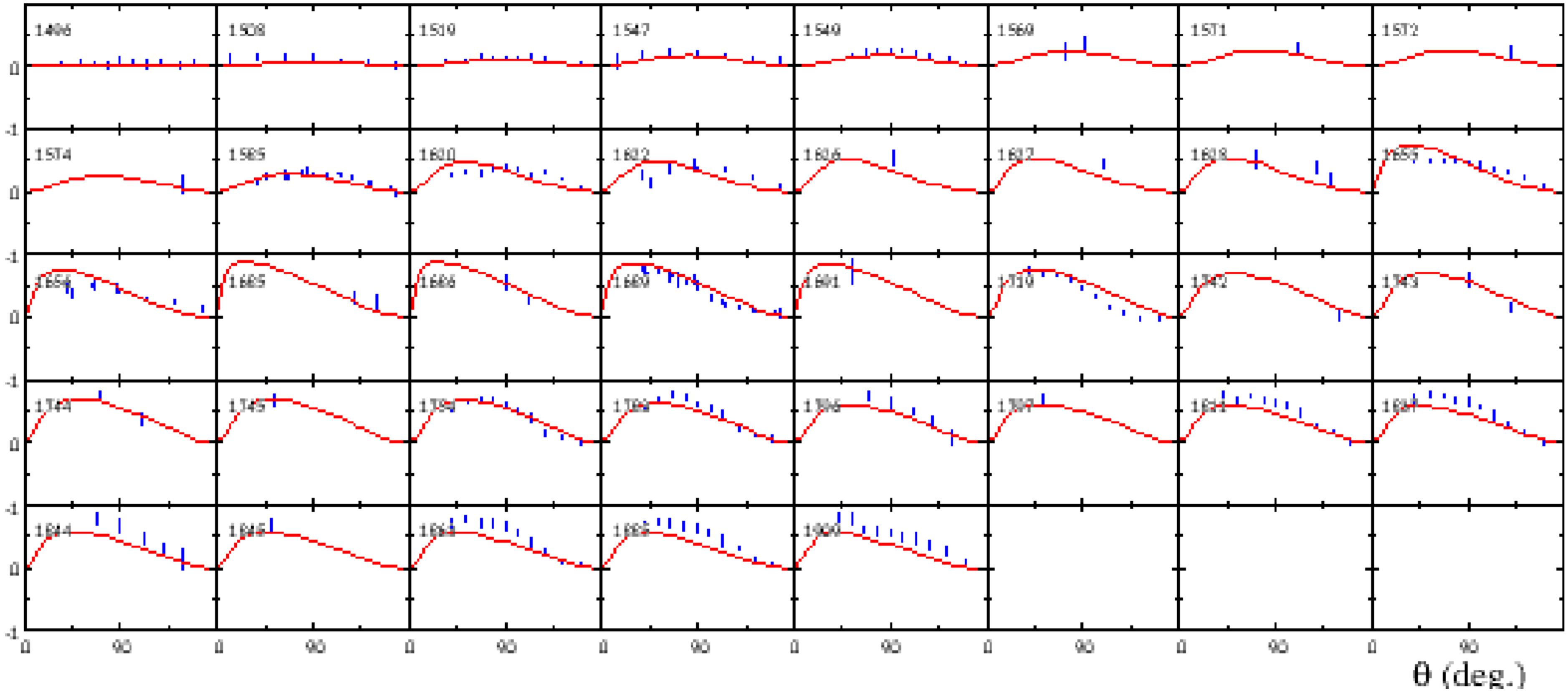
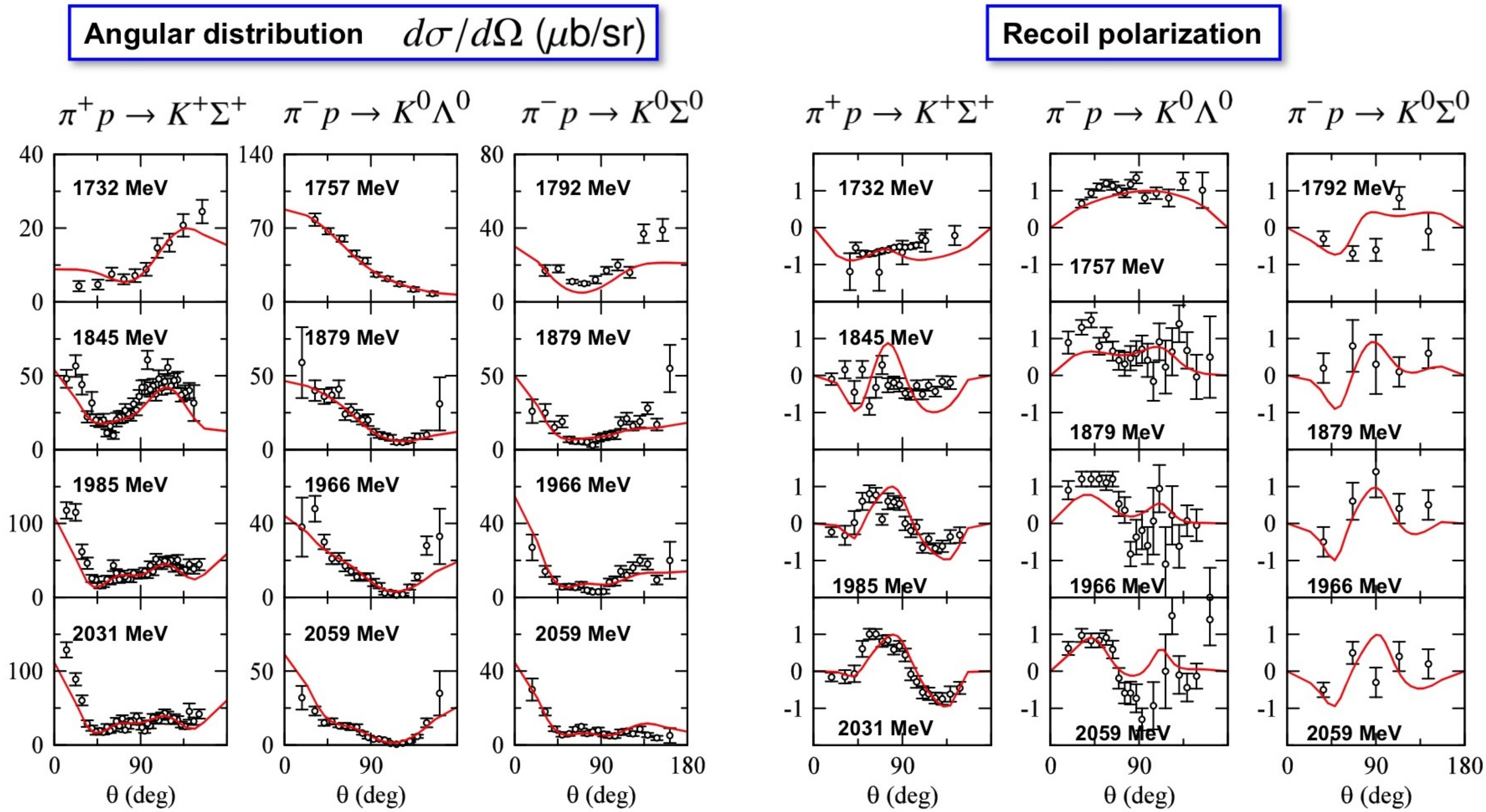


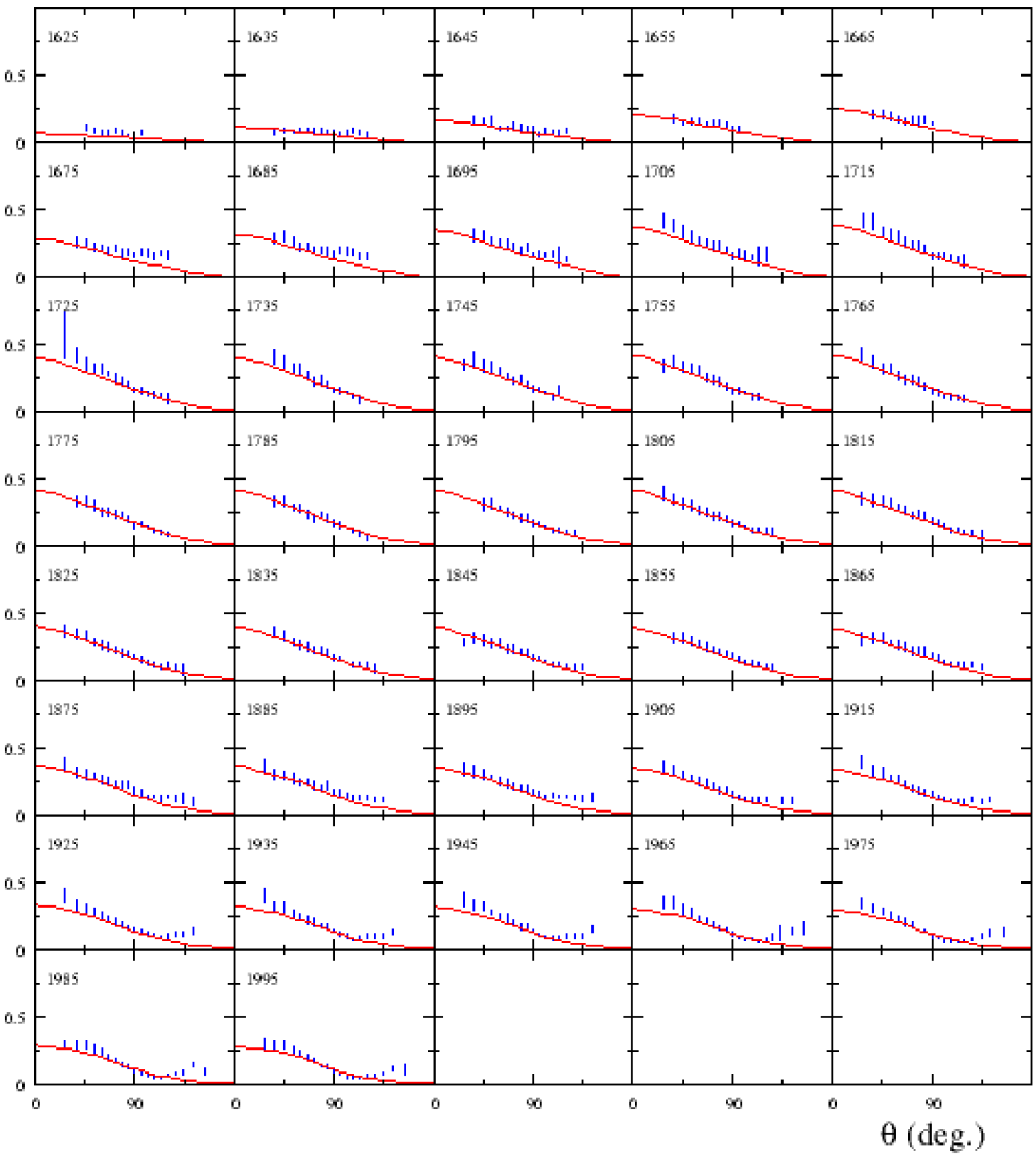
Kamano, Nakamura, Lee, Sato, 2012

$\pi N \to KY$



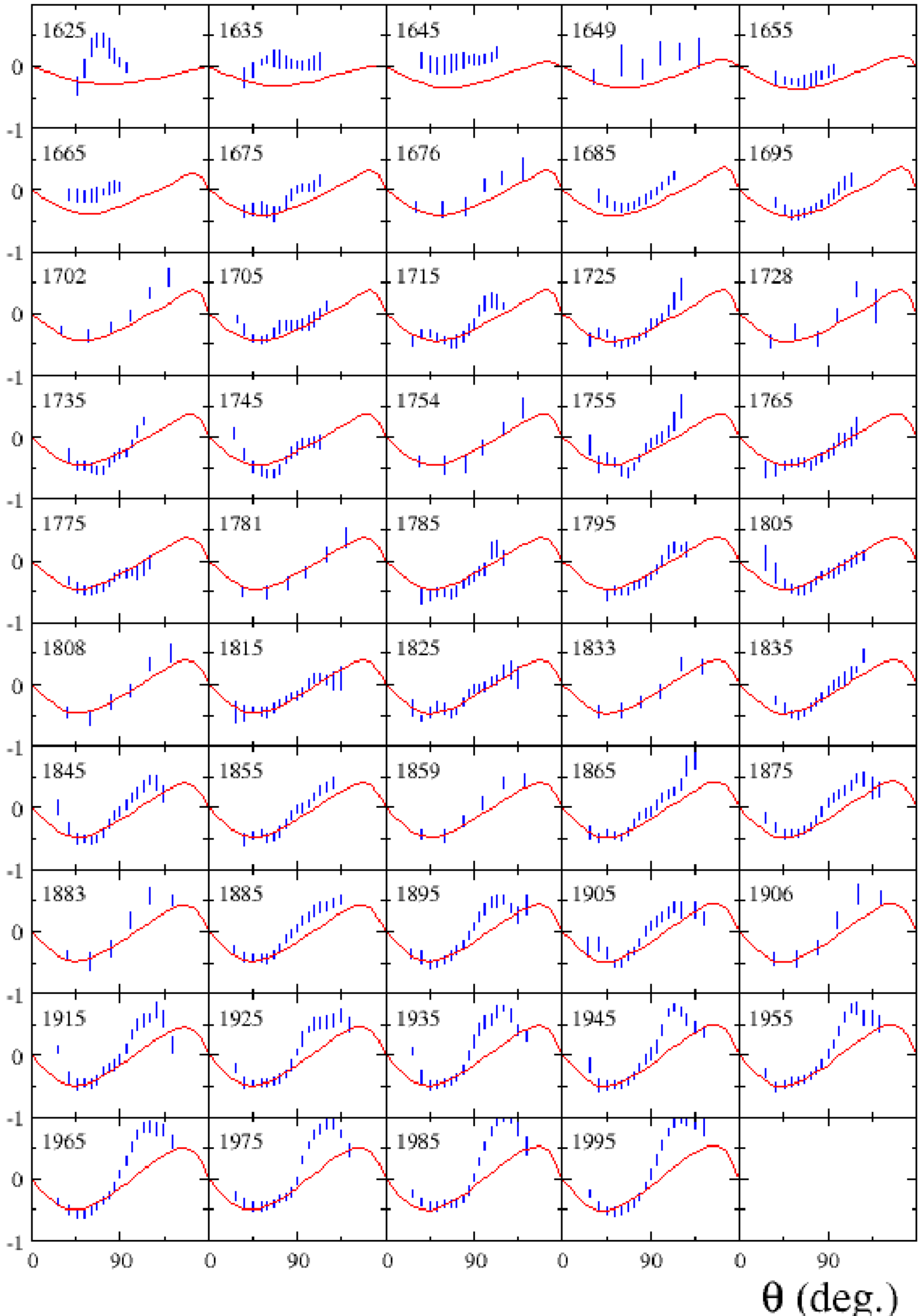
Kamano, Nakamura, Lee, Sato, 2012

$d\sigma/d\Omega \quad \gamma\, p \to K^+\, \Lambda$



Kamano, Nakamura, Lee, Sato, 2012

$P \quad \gamma\, p \to K^+\, \Lambda$



Kamano, Nakamura, Lee, Sato, 2012

Extraction of N^* information

Scattering amplitude near a pole ($E \sim M_R$)

$$T(E) \sim \frac{\bar{\Gamma}\,(M_R)\,\bar{\Gamma}\,(M_R)}{E - M_R} + (\text{regular terms})$$

Parameters characterizing Resonance

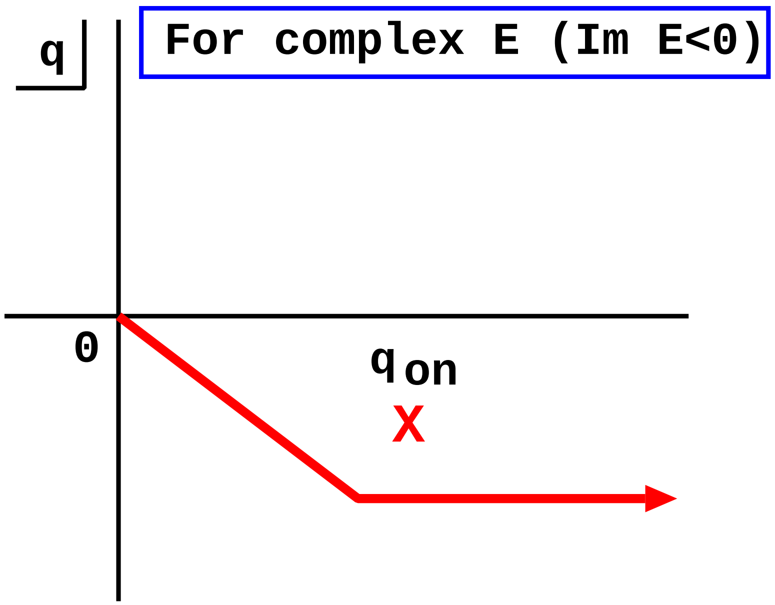
- Pole position of amplitude : M_R
- $N^* \to MB$ decay vertex : $\bar{\Gamma}\,(M_R)$

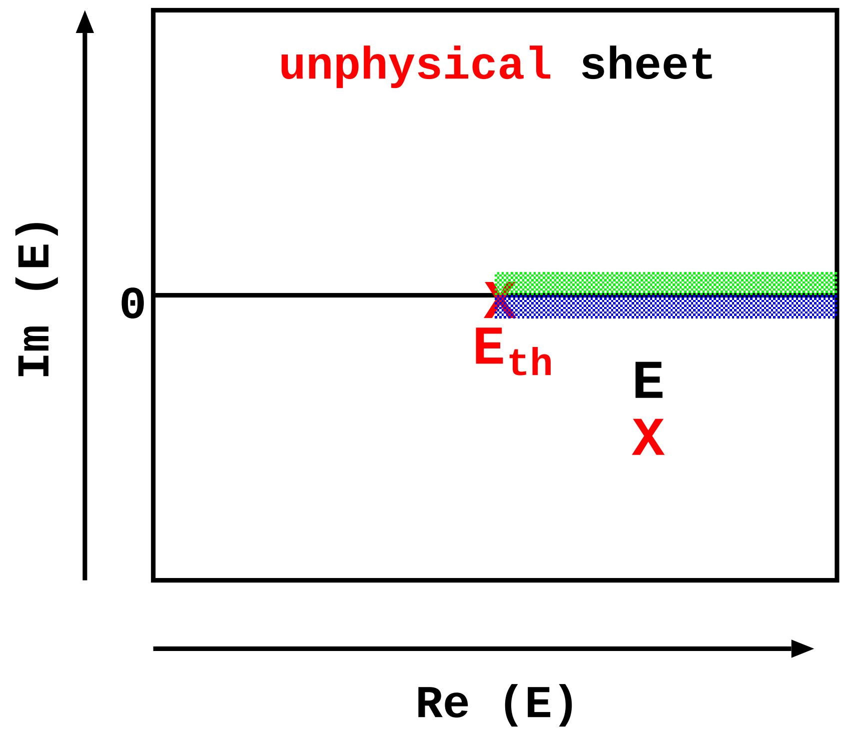
Suzuki, Sato, Lee, PRC **79**, 025205 (2009)

PRC **82**, 045206 (2010)

$$T_{ab}(p', p; E) = v_{ab}(p', p) + \sum_c \int_0^\infty dq\, q^2\, v_{ac}(p', q)\, G_c(q; E)\, T_{cb}(q, p; E)$$

$$\Downarrow$$

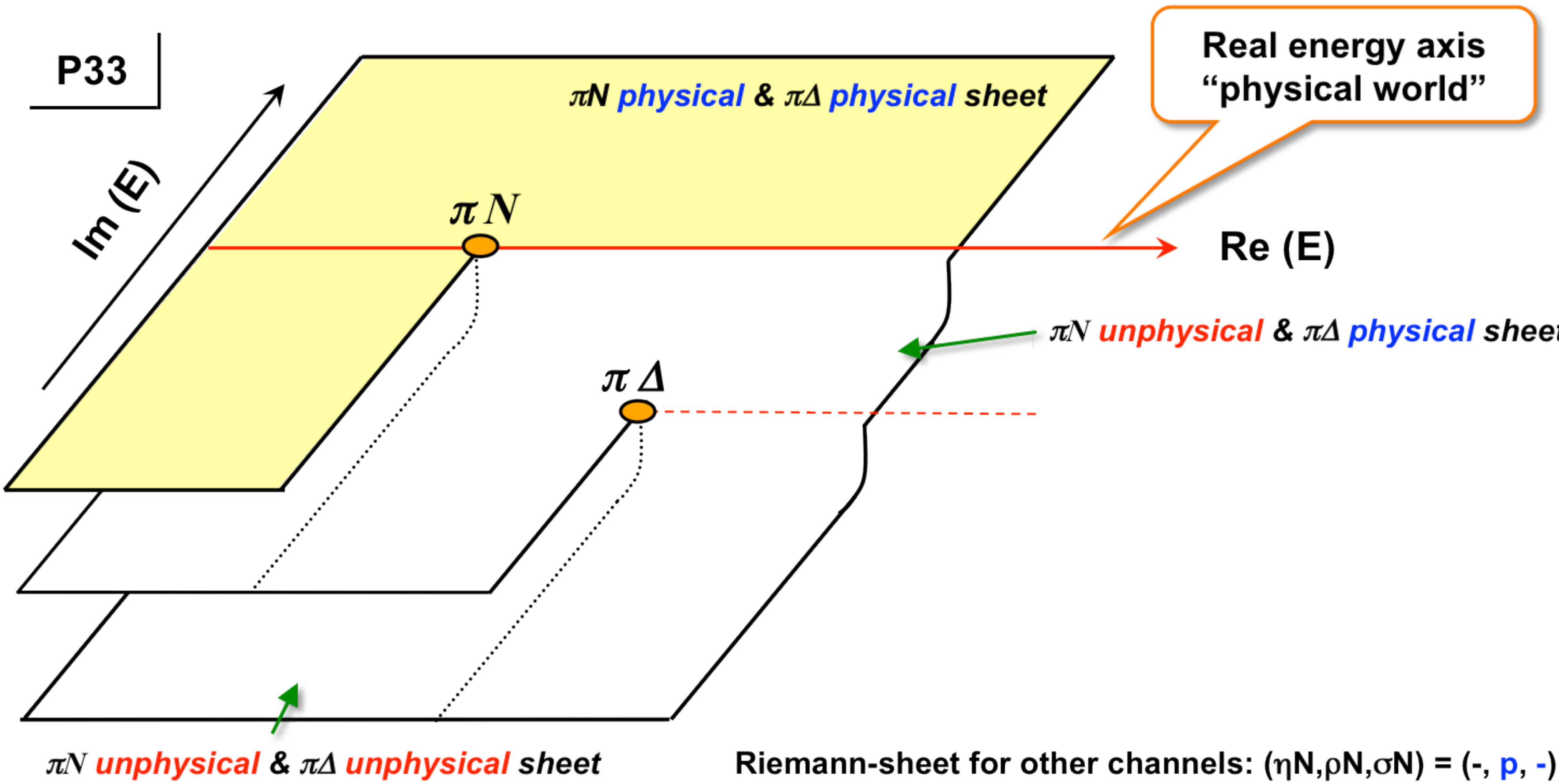




Delta(1232) : The 1st P33 resonance

Suzuki, Julia-Diaz, Kamano, Lee, Matsuyama, Sato, PRL104 042302 (2010)

Complex E-plane



Riemann-sheet for other channels: (ηN,ρN,σN) = (-, p, -)

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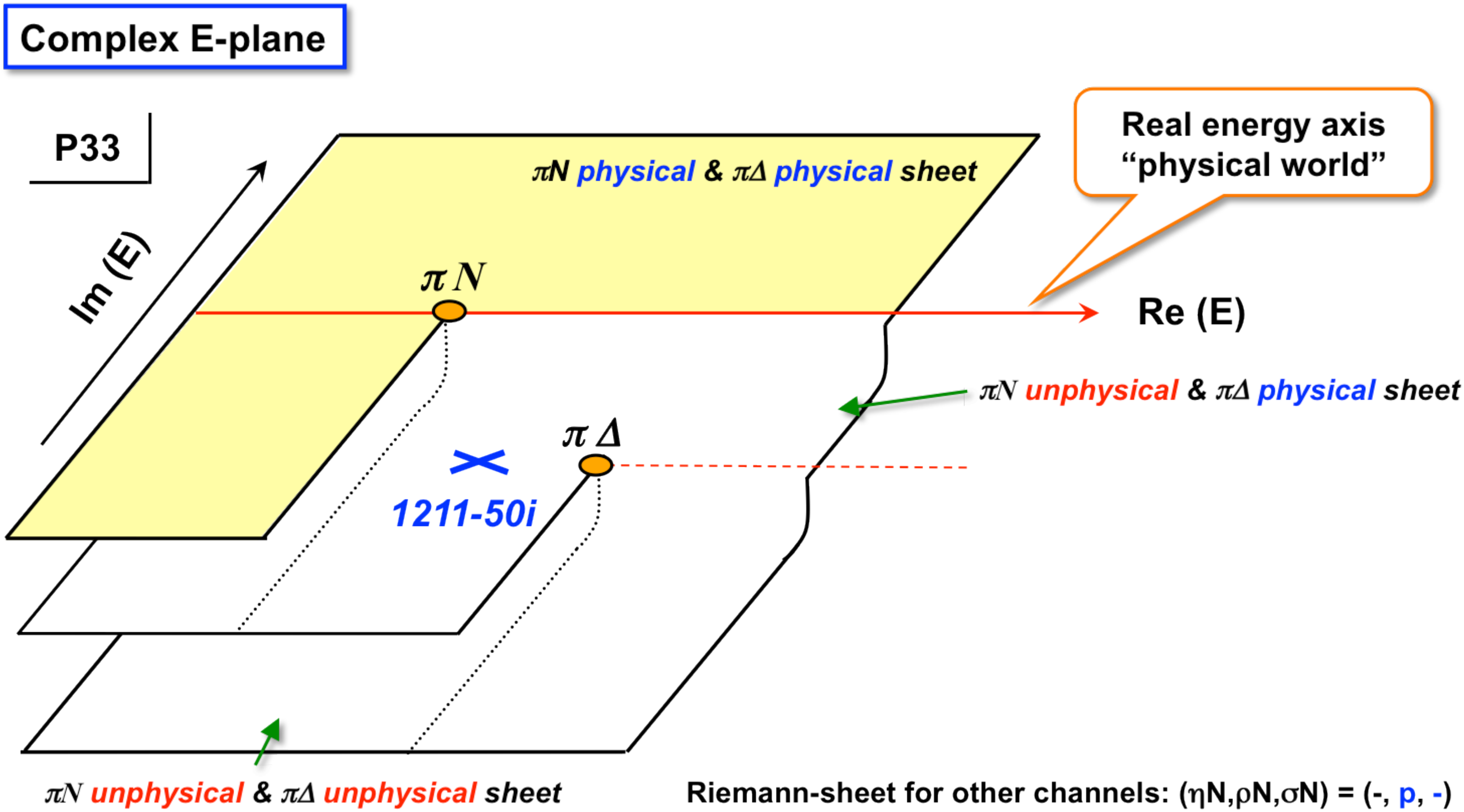

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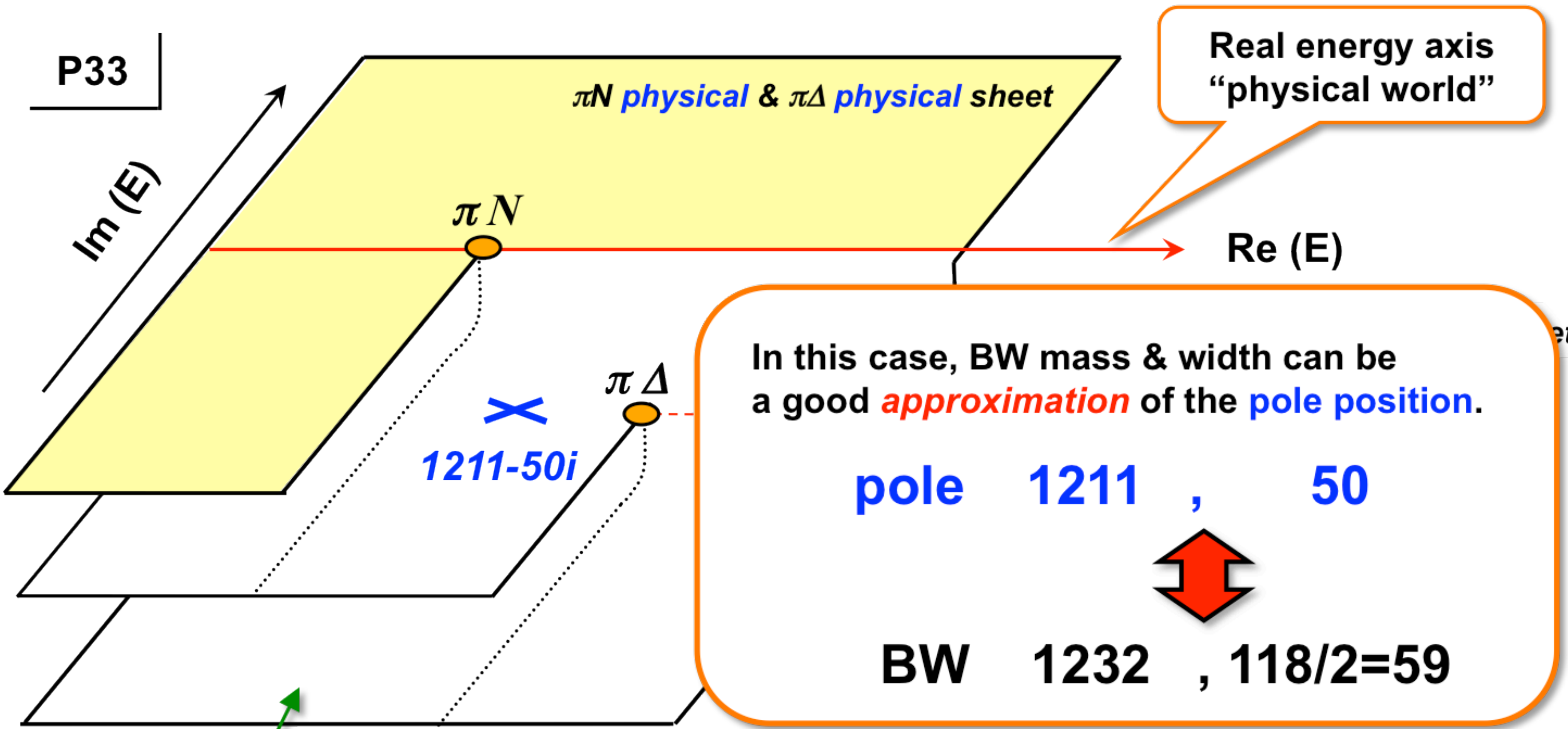


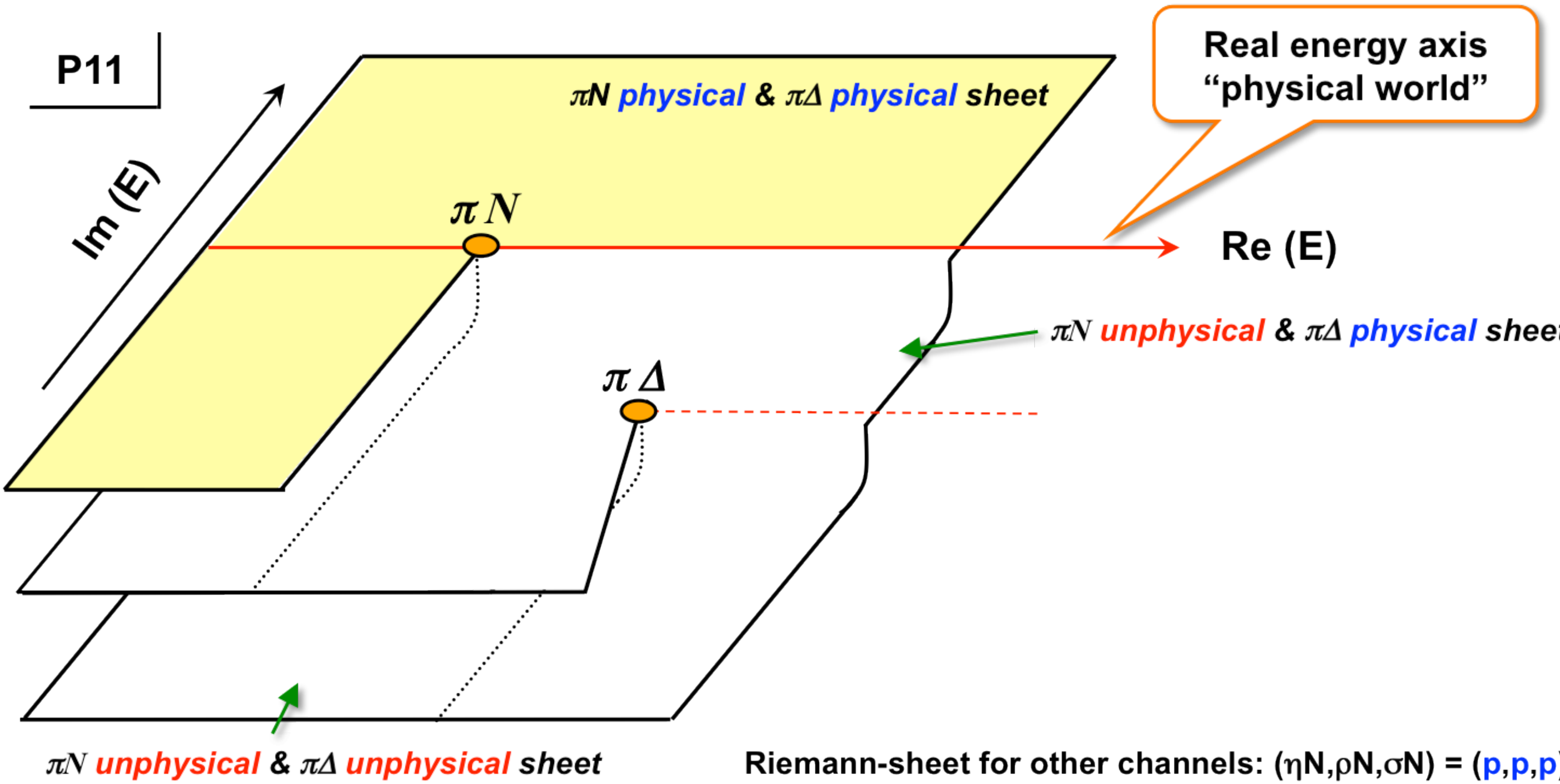
πN unphysical & πΔ unphysical sheet

Riemann-sheet for other channels: (ηN,ρN,σN) = (-, p, -)

Two-pole structure of the Roper P11(1440)

Suzuki, Julia-Diaz, Kamano, Lee, Matsuyama, Sato, PRL104 042302 (2010)

Complex E-plane



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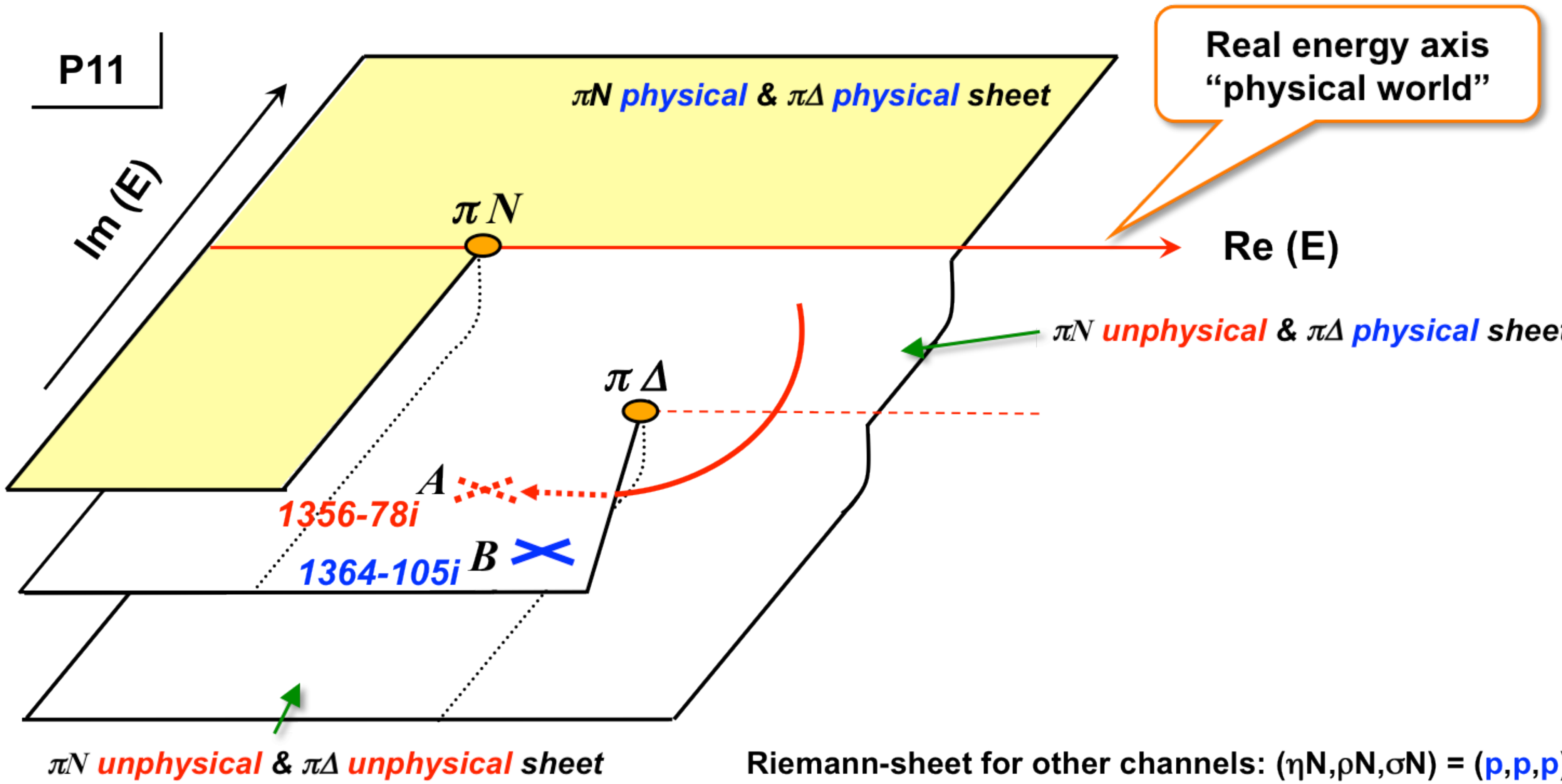

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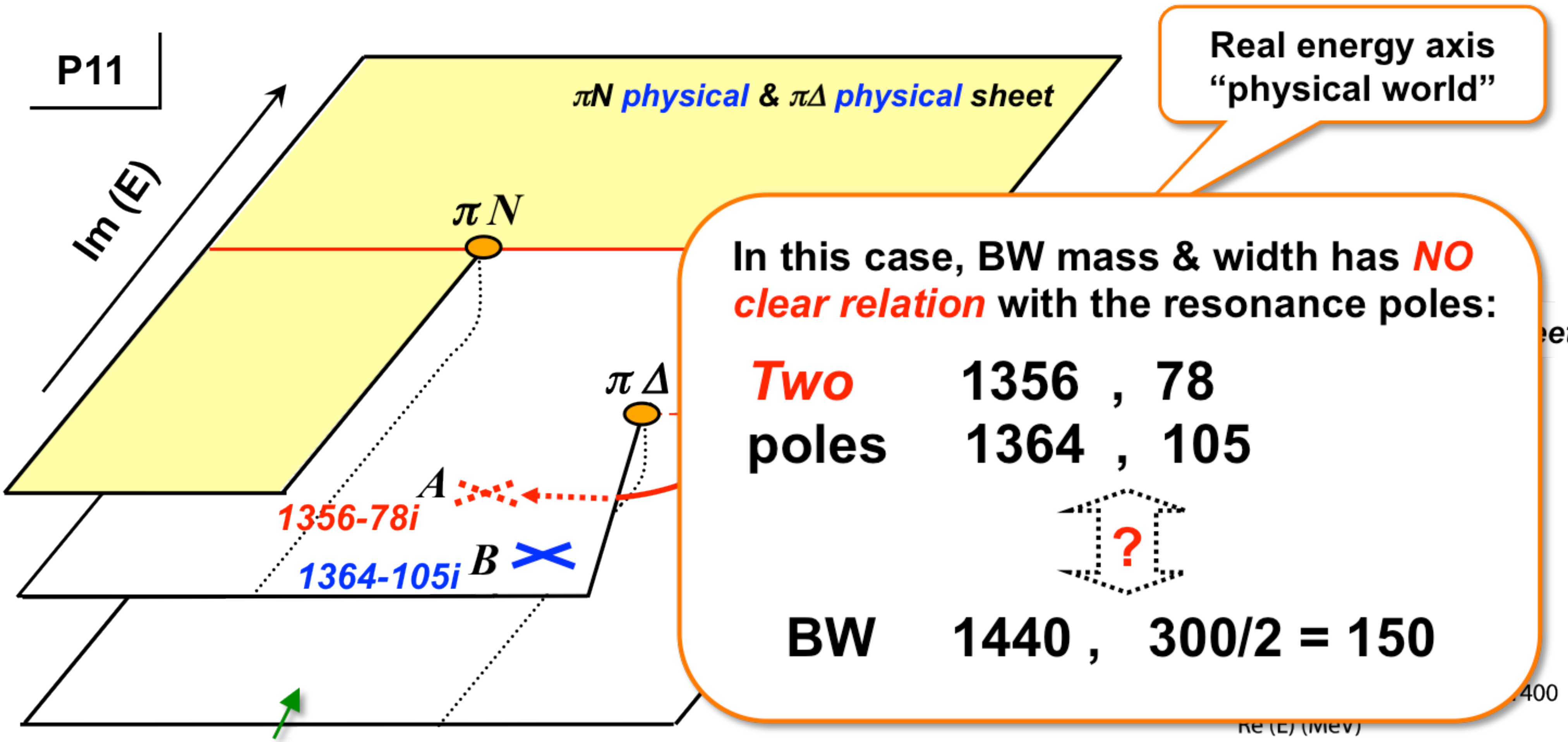
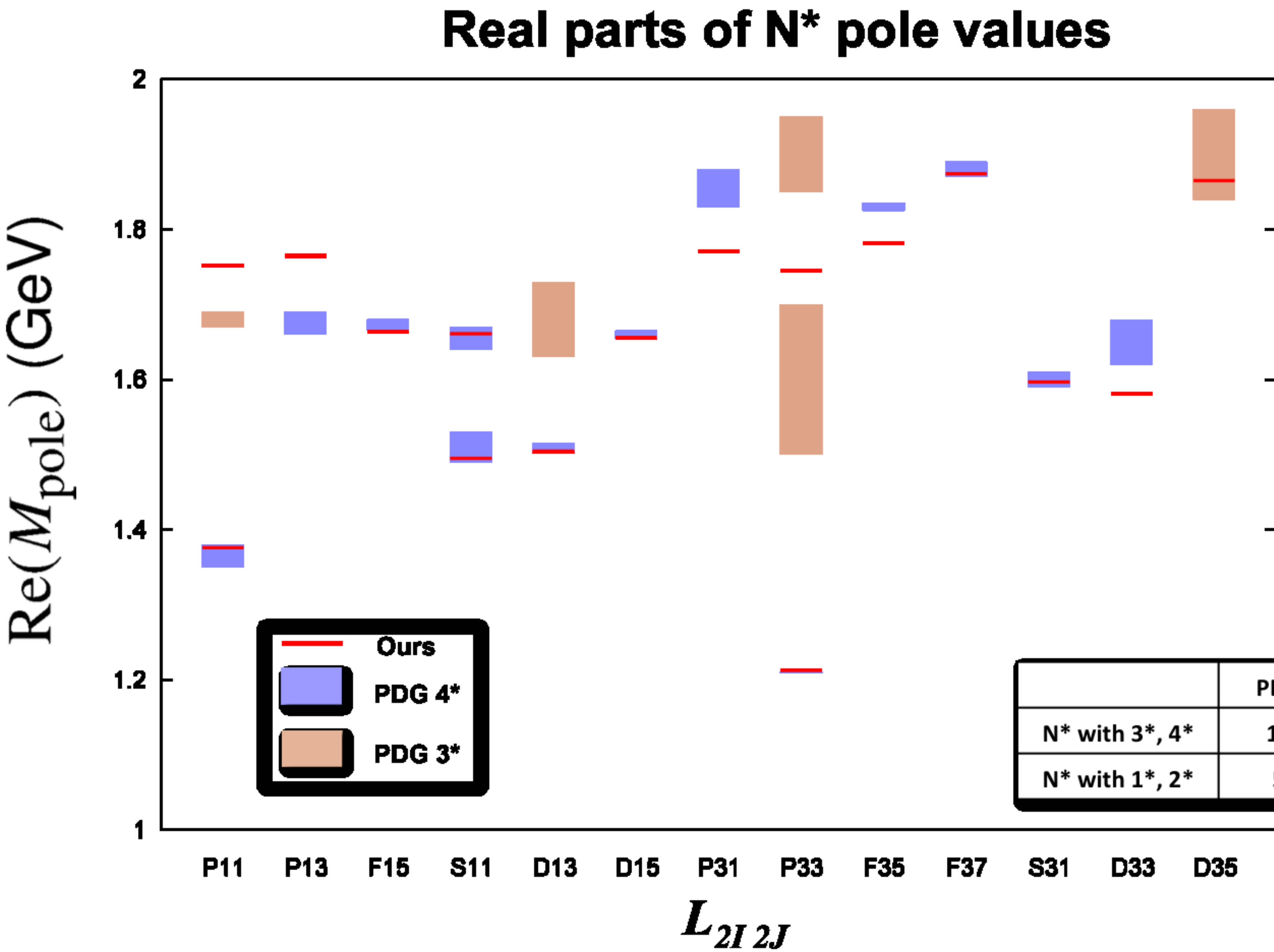


Riemann-sheet for other channels: (ηN,ρN,σN) = (p,p,p)

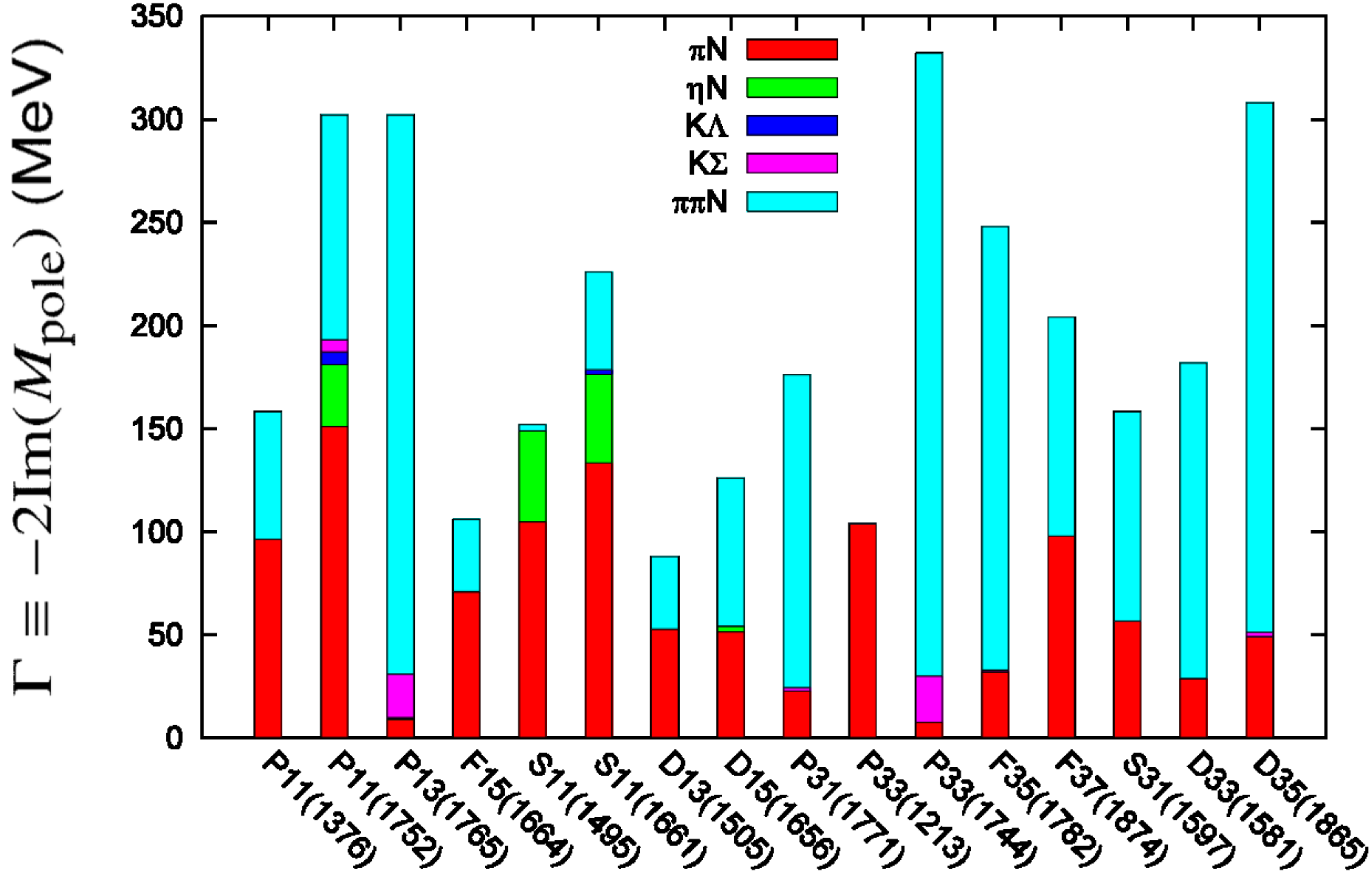
Spectrum of N* resonances

Kamano, Nakamura, Lee, Sato ,2012



	PDG	Ours
N* with 3*, 4*	18	16
N* with 1*, 2*	5	

Width of N* resonances

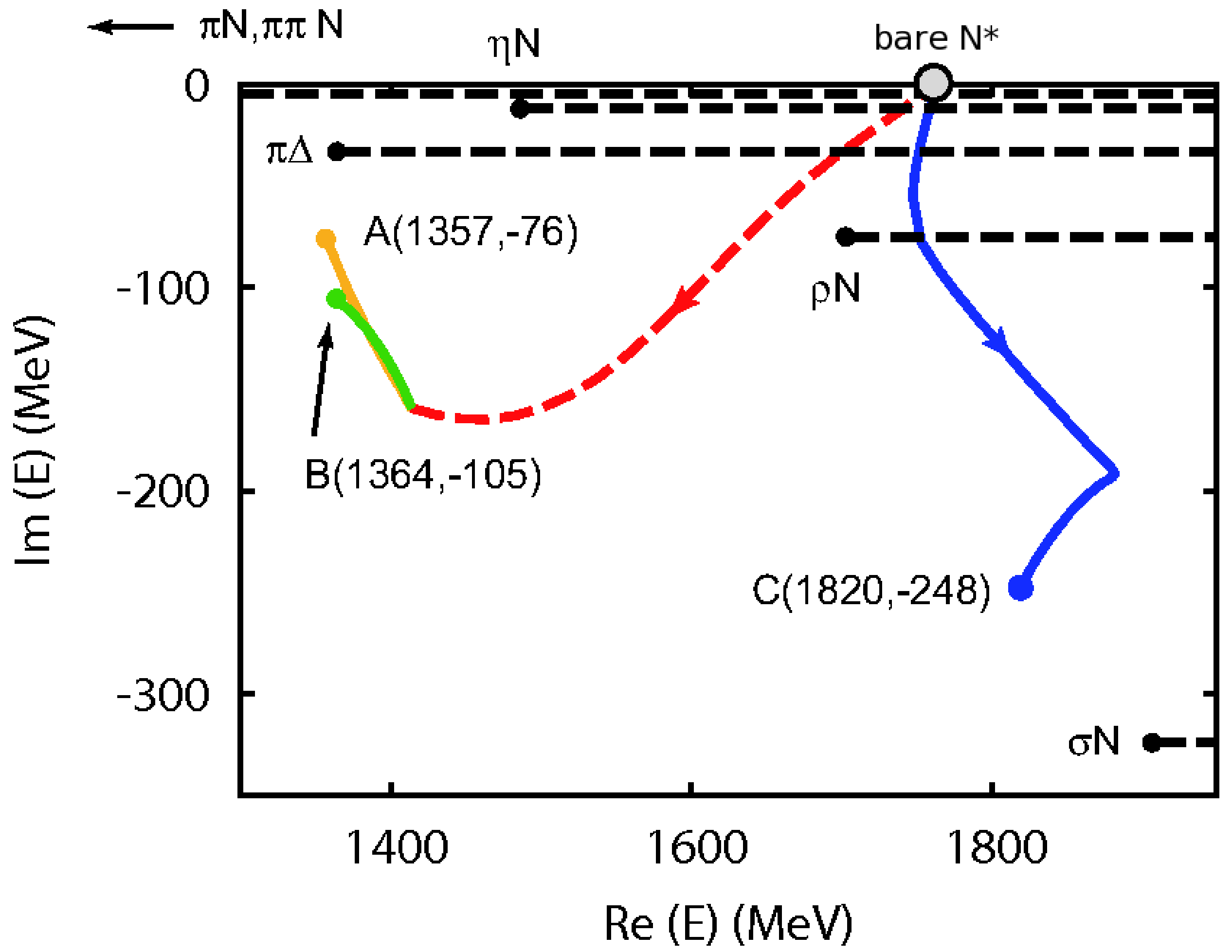


Kamano, Nakamura, Lee, Sato 2012

Dynamical coupled-channel effect on N^* pole

P_{11} resonance pole positions and its origin

Suzuki et al., PRL **104**, 042302 (2010)



SUMMARY

	6ch	**8ch**
	2006 – 2009	**2010 – 2012** (Kamano, Nakamura, Lee, Sato)
coupled-channels	$(\gamma N, \pi N, \eta N, \pi\Delta, \sigma N, \rho N)$	$(\gamma N, \pi N, \eta N, \pi\Delta, \sigma N, \rho N, K\Lambda, K\Sigma)$
$* \pi N \to \pi N$	$<$ 2 GeV	$<$ 2 GeV
$* \gamma N \to \pi N$	$<$ 1.6 GeV	$<$ 2 GeV
$* \pi N \to \eta N$	$<$ 2 GeV	$<$ 2 GeV
$* \gamma N \to \eta N$	–	$<$ 2 GeV
$* \pi N \to K\Lambda, K\Sigma$	–	$<$ 2.1 GeV
$* \gamma N \to K\Lambda, K\Sigma$	–	$<$ 2.1 GeV

$\Downarrow$

Fully-combined analysis of $\pi N, \gamma N \to \pi N, \eta N, K\Lambda, K\Sigma$!

N^* spectra in $W \leq 2$ GeV extracted

Plan

8ch model analysis

$*$ $N(e, e'\pi)$ data analysis

$\Rightarrow$ $\gamma N \rightarrow N^*$ form factor in $W \leq 2$ GeV

$*$ 2 π production data

$\Rightarrow$ $N^* \rightarrow \pi\Delta, \rho N, \sigma N$

$*$ $\gamma p \rightarrow K\Lambda$ data from complete experiment

$\Rightarrow$ New N^* ?

Collaborators@EBAC

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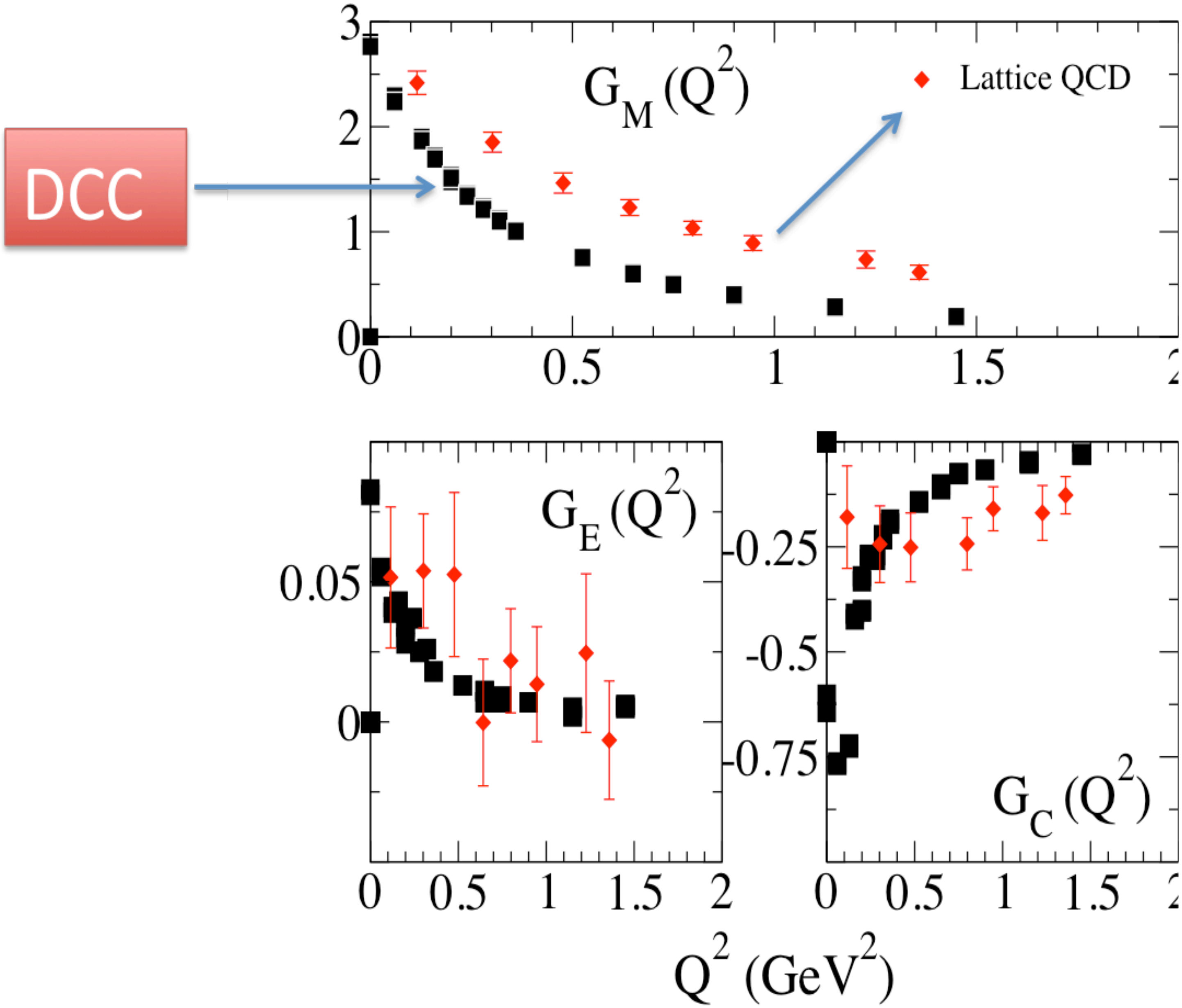
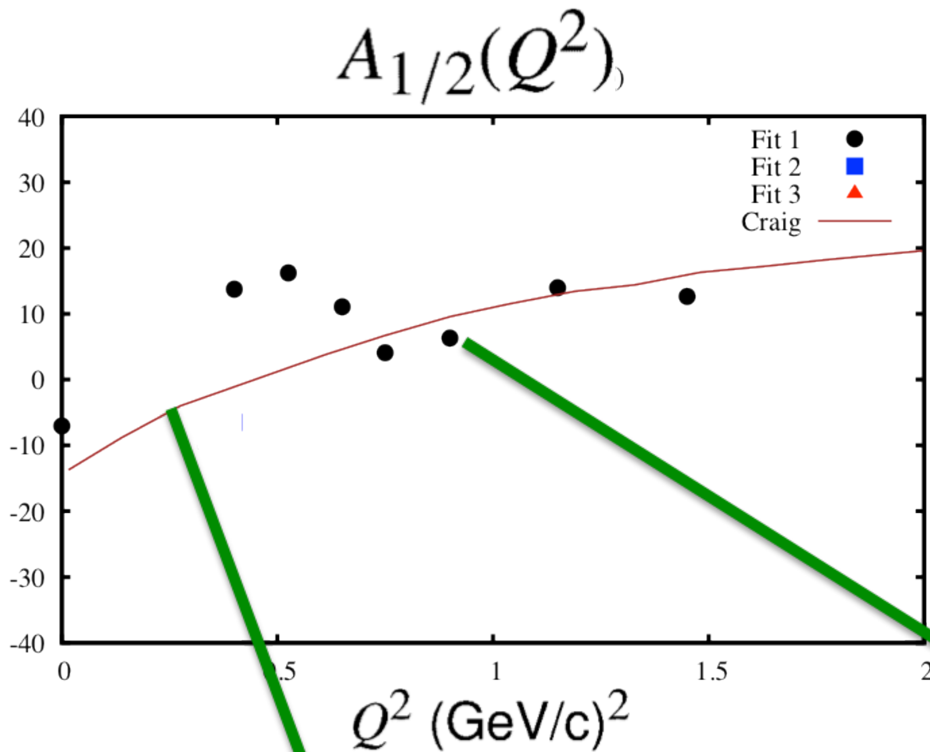
N. Suzuki	(Osaka)
K. Tsushima	(JLab)

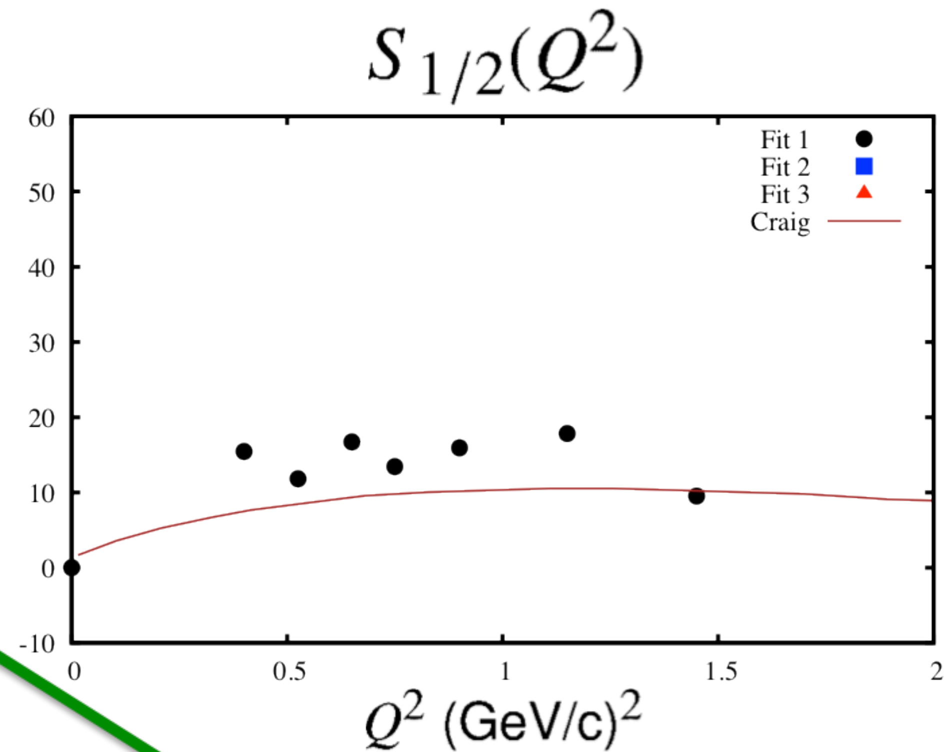
BACKUPS

γ N → Δ(1232) form factors compared with Lattice QCD data (2006)



γ p → Roper e.m. transition

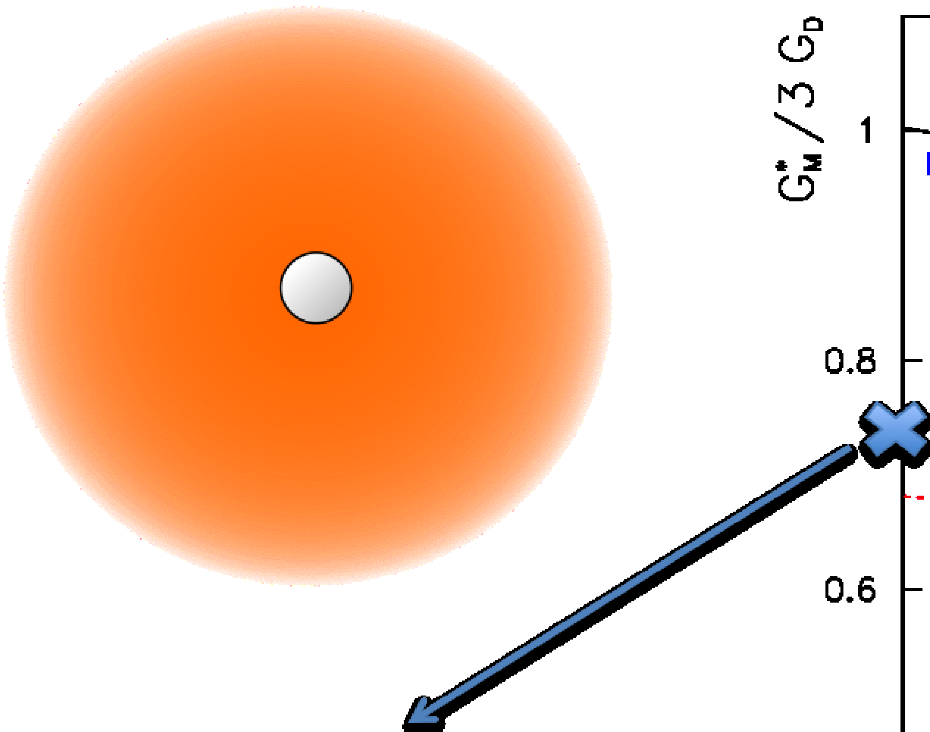


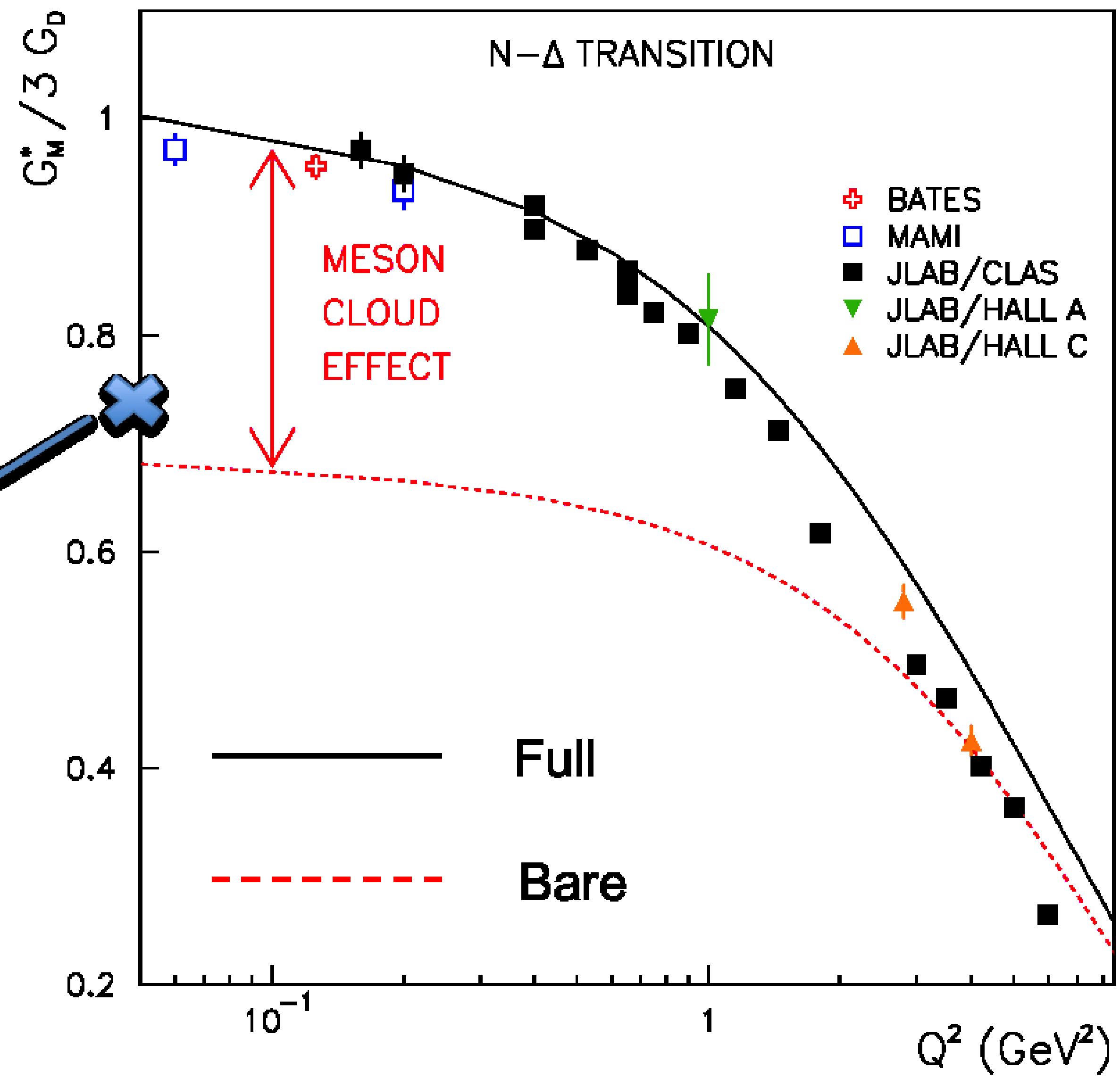


"Static" form factor from DSE-model calculation. (C. Roberts et al, 2011)

"Bare" form factor determined from our DCC analysis (2010).

$G_M(Q^2)$ for γ N → Δ (1232) transition



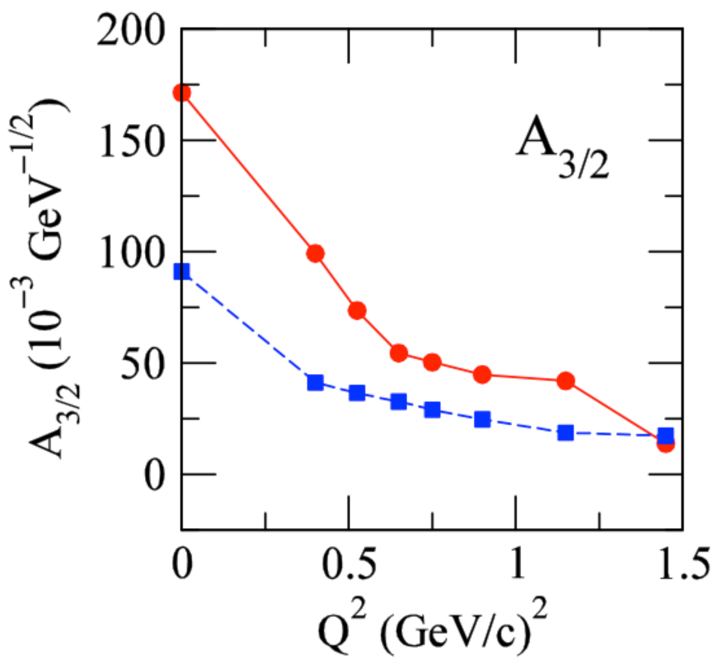


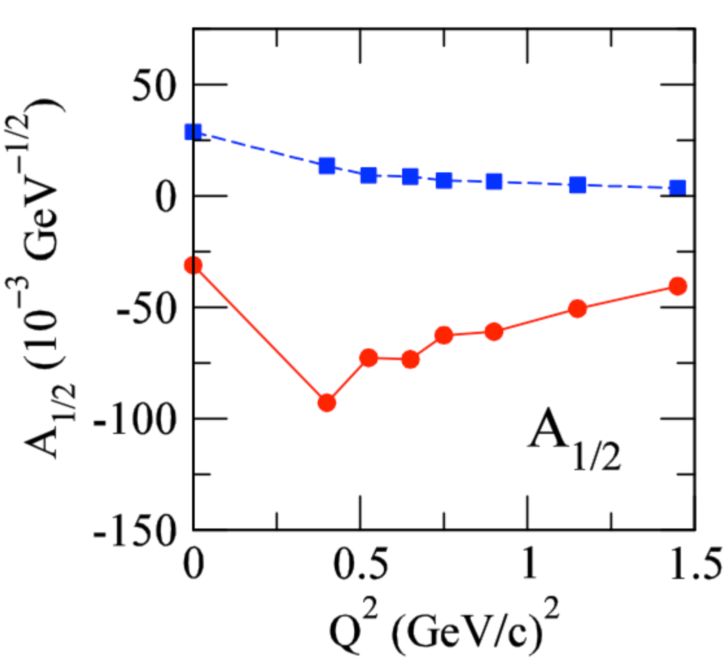
Note:
Most of the available static hadron models give $G_M(Q^2)$ close to "Bare" form factor.

Dynamical coupled-channel effect on N^* form factor

Nucleon-$N(1520)D_{13}$ e.m. transition form factor

Suzuki, Sato, Lee, PRC **82**, 045206 (2010)





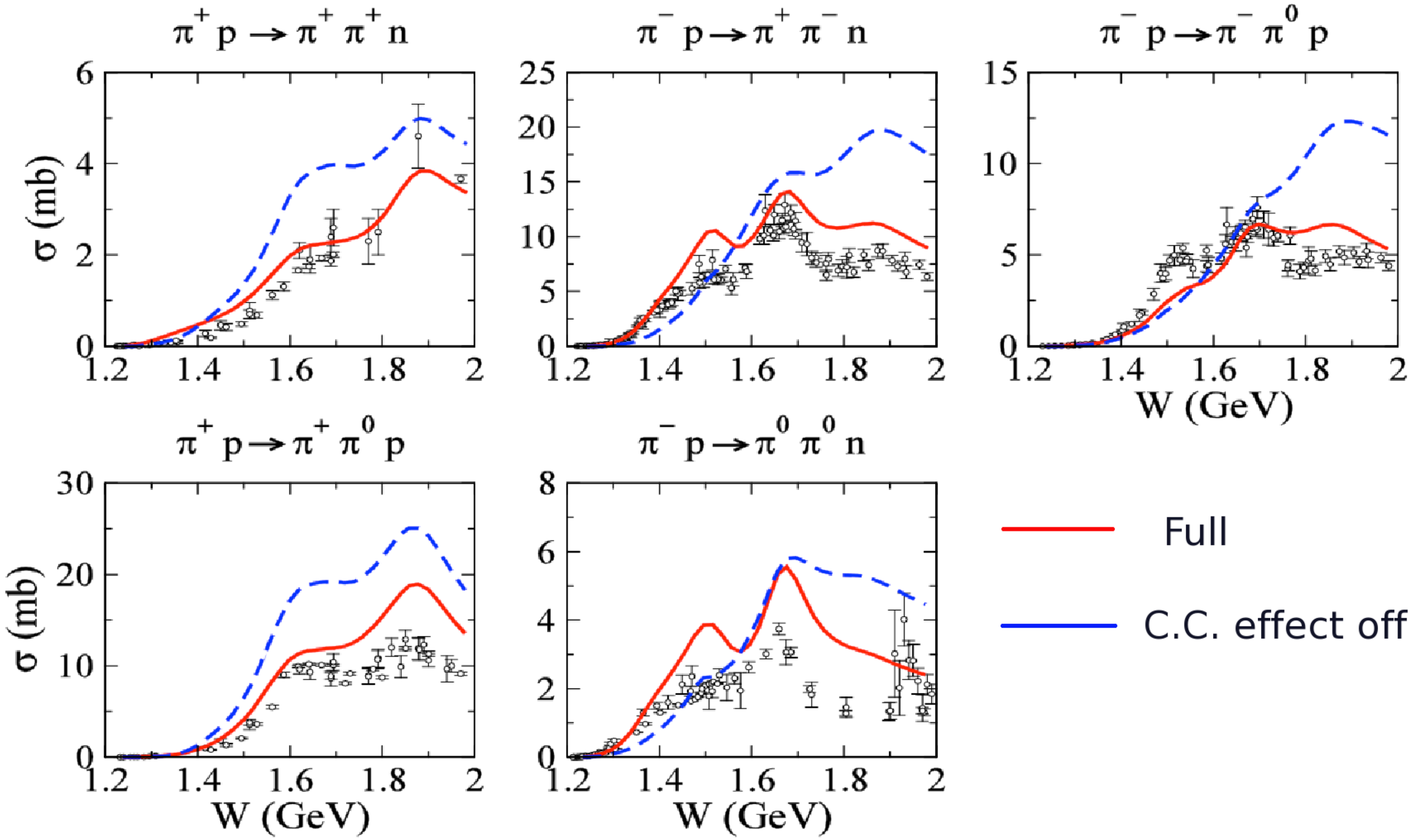
Complex $\Leftarrow$ Meson cloud effect on the N^* structure

Analytic continuation

$\pi N \to \pi\pi N$

(parameters had been fitted to $\pi N \to \pi N$)

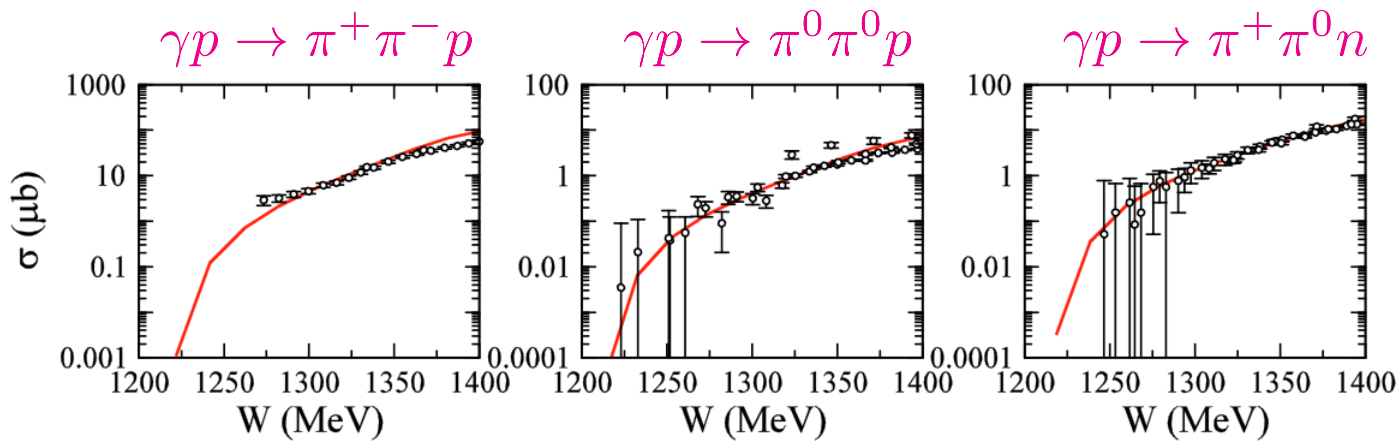
Kamano, Julia-Diaz, Lee, Matsuyama, Sato, PRC79 025206 (2009)

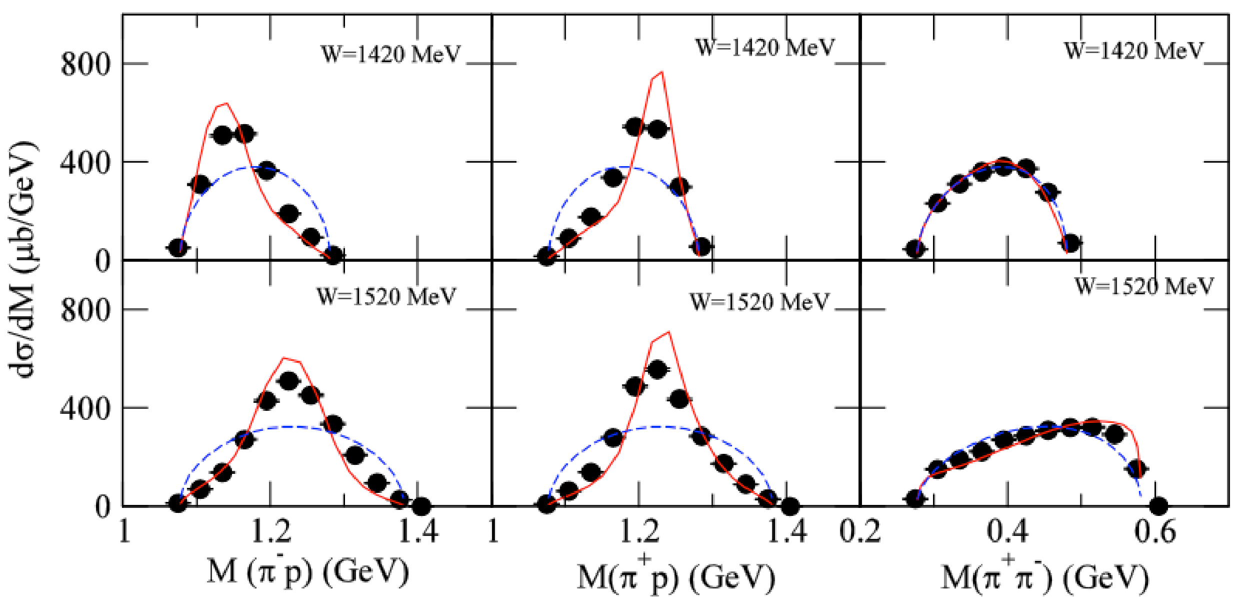


$\gamma N \to \pi\pi N$

(parameters had been fitted to $\pi N, \gamma N \to \pi N$)

Kamano, Julia-Diaz, Lee, Matsuyama, Sato, PRC80 065203 (2009)

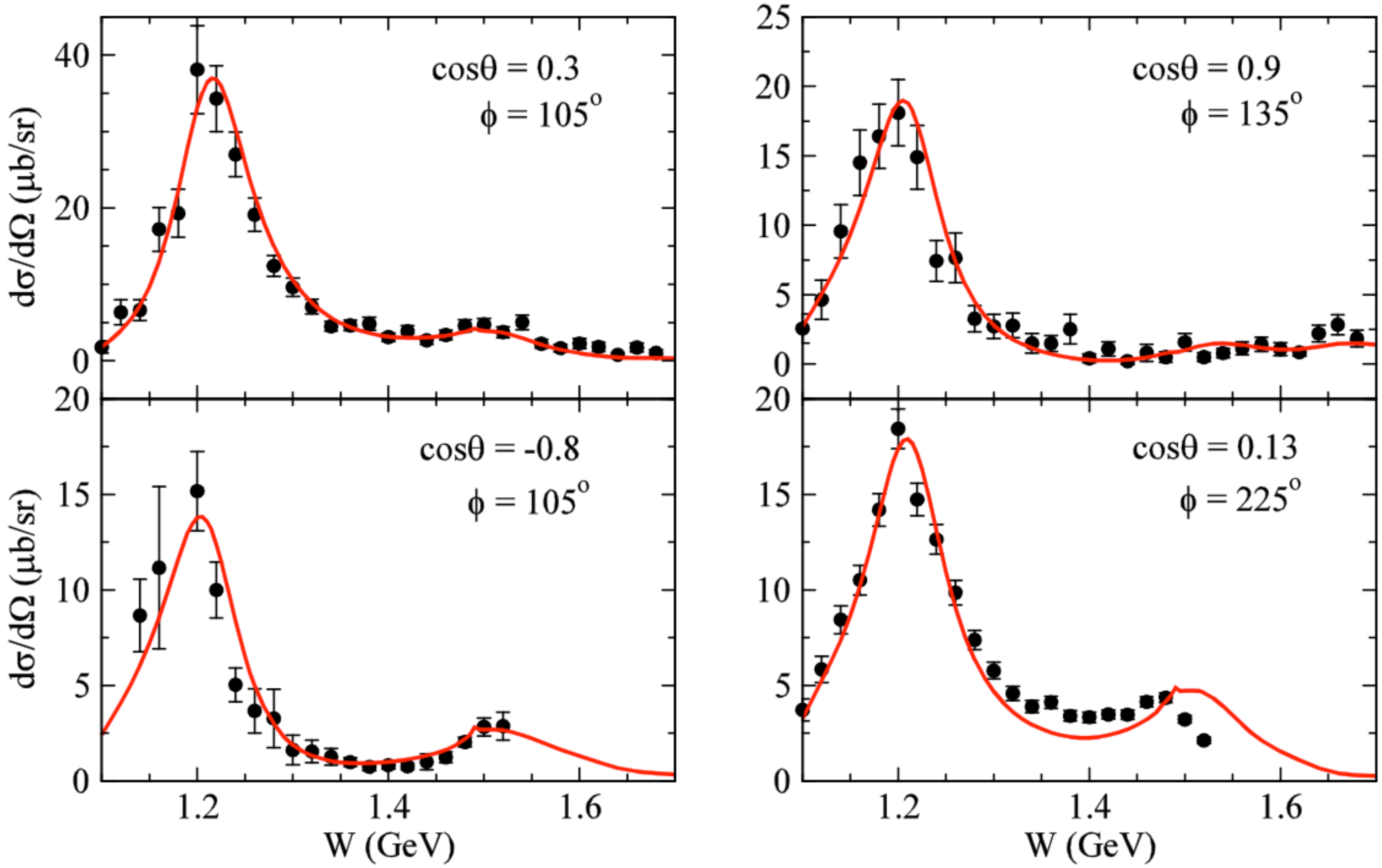




* Good description near threshold
* Good shape of invariant mass distribution
* Total cross sections overestimate data for $W \geq 1.5$ GeV

Single π electro-production

Julia-Diaz, Kamano, Lee, Matsuyama, Sato, Suzuki, PRC80 025207 (2009)



$p(e, e'\pi^0)p$

$p(e, e'\pi^+)n$