Modern dynamical coupled-channels calculations for extracting and understanding the nucleon spectrum

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(KEK)

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(MENU2016)
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Outline

PART I:

Background & motivation for spectroscopic study of N* & Δ* resonances

PART II:

Recent results from ANL-Osaka Dynamical Coupled-Channels (DCC) analysis

PART I

Background & motivation for spectroscopic study of N* & Δ* resonances

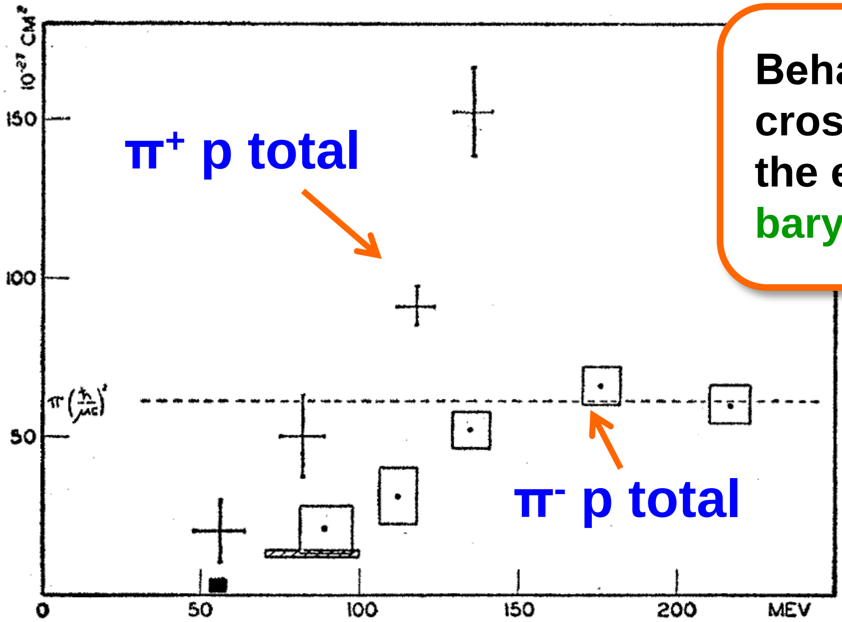
Introduction: N* & Δ* spectroscopy

Discovery of the Δ baryon (1952)

Total Cross Sections of Positive Pions in Hydrogen*

H. L. ANDERSON, E. FERMI, E. A. LONG,† AND D. E. NAGLE
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(Received January 21, 1952)



π^+ p total

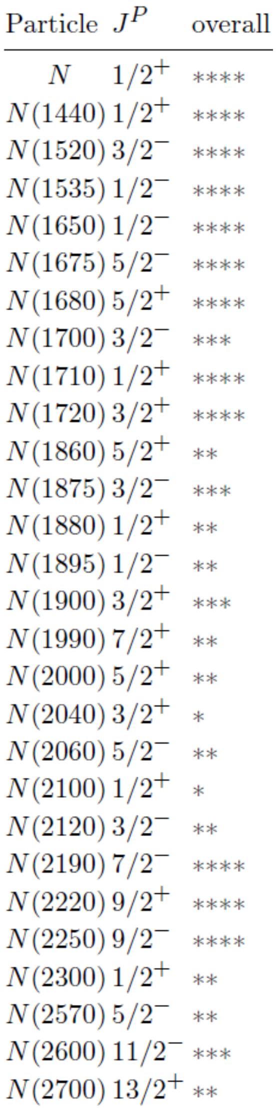
π^- p total

Behavior of the π^+ p & π^- p cross sections implies the existence of a new baryon with isospin 3/2 !!

FIG. 1. Total cross sections of negative pions in hydrogen (sides of the rectangle represent the error) and positive pions in hydrogen (arms of the cross represent the error). The cross-hatched rectangle is the Columbia result. The black square is the Brookhaven result and does not include the charge exchange contribution.

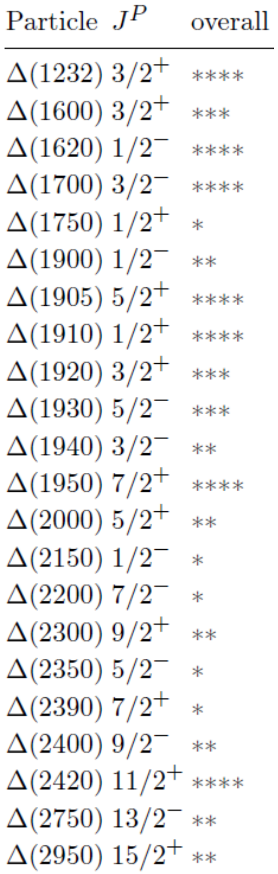
Introduction: N* & Δ* spectroscopy

N*



Particle	J^P	overall
N	$1/2^+$	****
$N(1440)$	$1/2^+$	****
$N(1520)$	$3/2^-$	****
$N(1535)$	$1/2^-$	****
$N(1650)$	$1/2^-$	****
$N(1675)$	$5/2^-$	****
$N(1680)$	$5/2^+$	****
$N(1700)$	$3/2^-$	***
$N(1710)$	$1/2^+$	****
$N(1720)$	$3/2^+$	****
$N(1860)$	$5/2^+$	**
$N(1875)$	$3/2^-$	***
$N(1880)$	$1/2^+$	**
$N(1895)$	$1/2^-$	**
$N(1900)$	$3/2^+$	***
$N(1990)$	$7/2^+$	**
$N(2000)$	$5/2^+$	**
$N(2040)$	$3/2^+$	*
$N(2060)$	$5/2^-$	**
$N(2100)$	$1/2^+$	*
$N(2120)$	$3/2^-$	**
$N(2190)$	$7/2^-$	****
$N(2220)$	$9/2^+$	****
$N(2250)$	$9/2^-$	****
$N(2300)$	$1/2^+$	**
$N(2570)$	$5/2^-$	**
$N(2600)$	$11/2^-$	***
$N(2700)$	$13/2^+$	**

Δ*



Particle	J^P	overall
$\Delta(1232)$	$3/2^+$	****
$\Delta(1600)$	$3/2^+$	***
$\Delta(1620)$	$1/2^-$	****
$\Delta(1700)$	$3/2^-$	****
$\Delta(1750)$	$1/2^+$	*
$\Delta(1900)$	$1/2^-$	**
$\Delta(1905)$	$5/2^+$	****
$\Delta(1910)$	$1/2^+$	****
$\Delta(1920)$	$3/2^+$	***
$\Delta(1930)$	$5/2^-$	***
$\Delta(1940)$	$3/2^-$	**
$\Delta(1950)$	$7/2^+$	****
$\Delta(2000)$	$5/2^+$	**
$\Delta(2150)$	$1/2^-$	*
$\Delta(2200)$	$7/2^-$	*
$\Delta(2300)$	$9/2^+$	**
$\Delta(2350)$	$5/2^-$	*
$\Delta(2390)$	$7/2^+$	*
$\Delta(2400)$	$9/2^-$	**
$\Delta(2420)$	$11/2^+$	****
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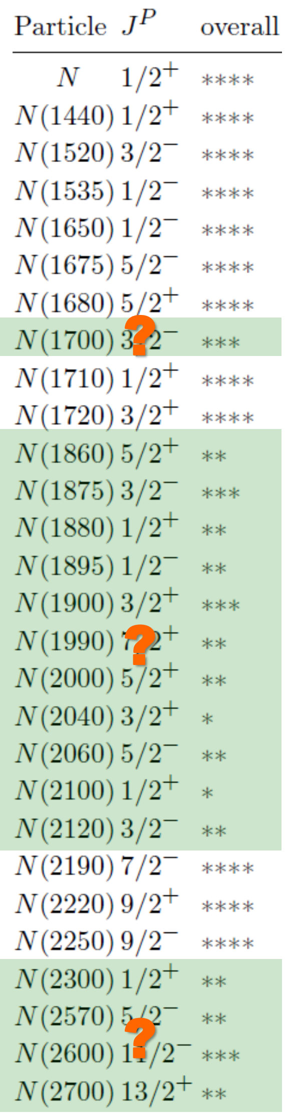
PDG(2015):
http://pdg.lbl.gov

Introduction: N* & Δ* spectroscopy

N*



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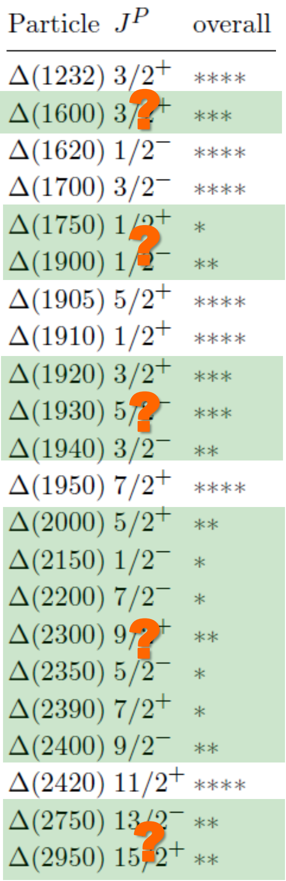

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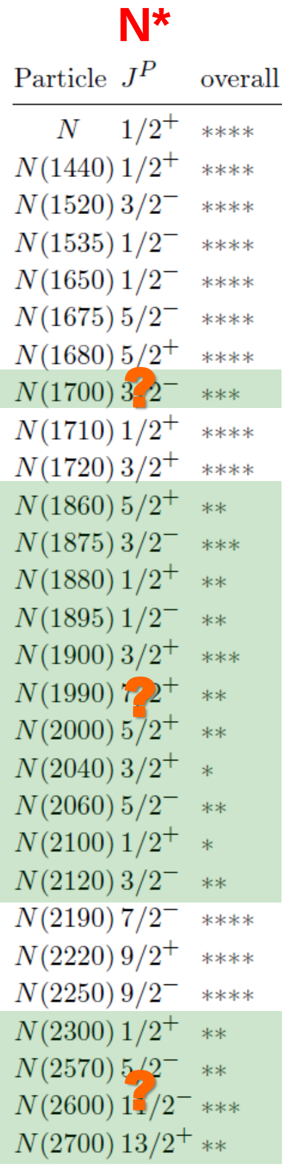
> —— **Arndt, Briscoe, Strakovsky, Workman PRC74(2006)045205**

Introduction: N* & Δ* spectroscopy



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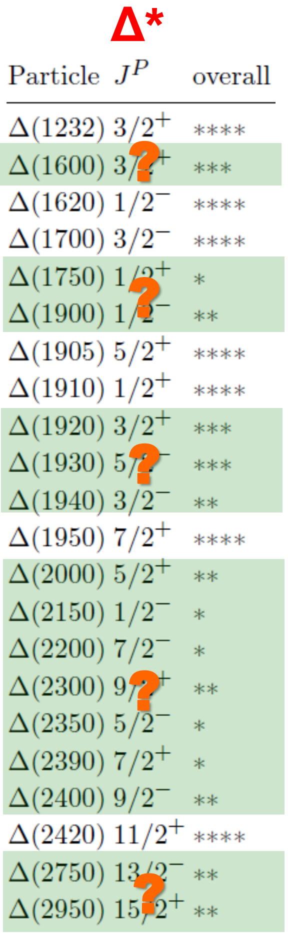

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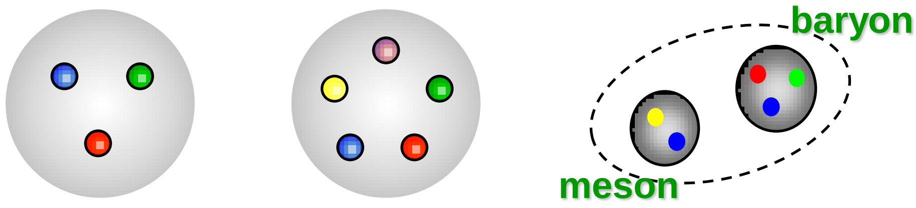
N* & Δ* spectroscopy remains as central issue in the hadron physics !!

- Mass, width, spin, parity …?
- quark-gluon structure (form factors)?
- How produced in reaction processes?

…

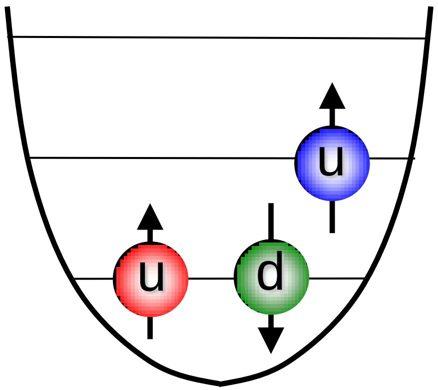


3-quark state multiquark state "molecule-like" state

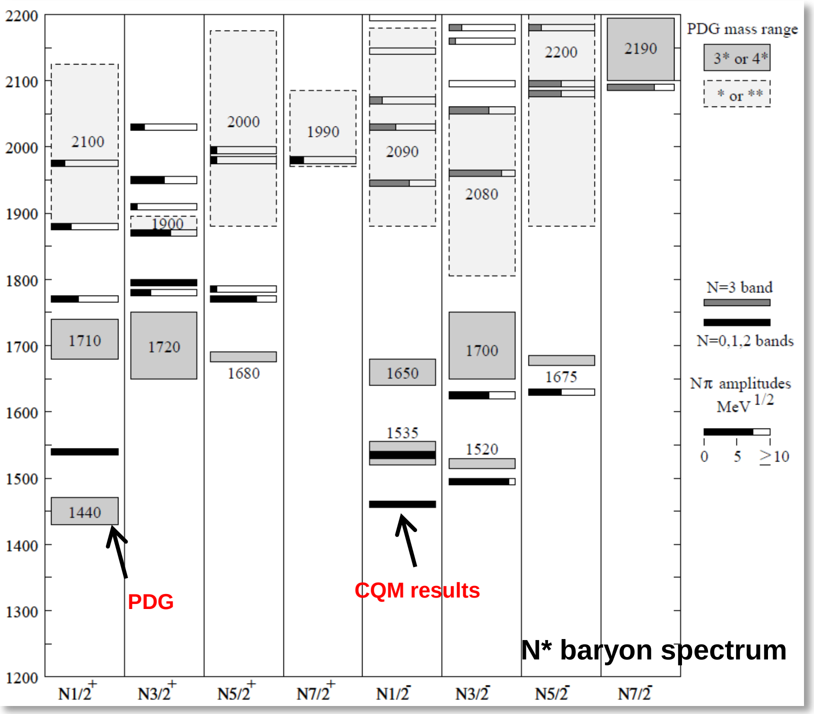
Static hadron models and reaction dynamics

✓ Various *static* hadron models have been proposed to calculate hadron spectrum and form factors.

- ➢ Constituent quark models, soliton models, Dyson-Schwinger Eq. approaches,...
- ➢ Excited hadrons are treated as stable particles.



Constituent quark model



Capstick, Roberts, Prog. Part. Nucl. Phys 45(2000)S241

Static hadron models and reaction dynamics

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  - ➢ **Constituent quark models, soliton models, Dyson-Schwinger Eq. approaches,...**
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- ✓ **In reality, excited hadrons are “unstable” and can exist only as resonance states in hadron reactions.**

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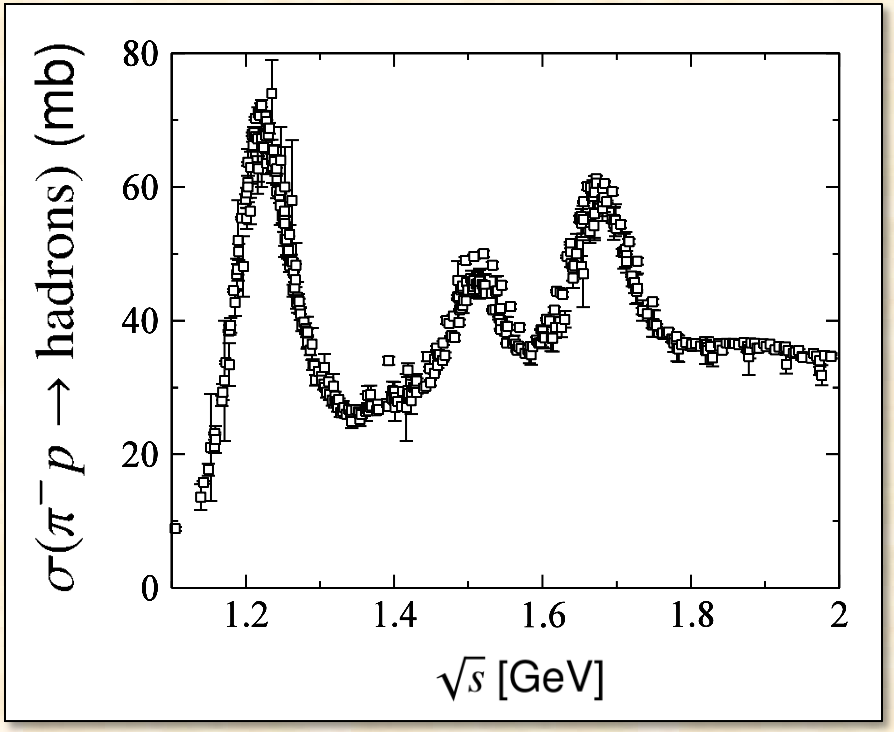
✓ In reality, excited hadrons are “unstable” and can exist only as resonance states in hadron reactions.

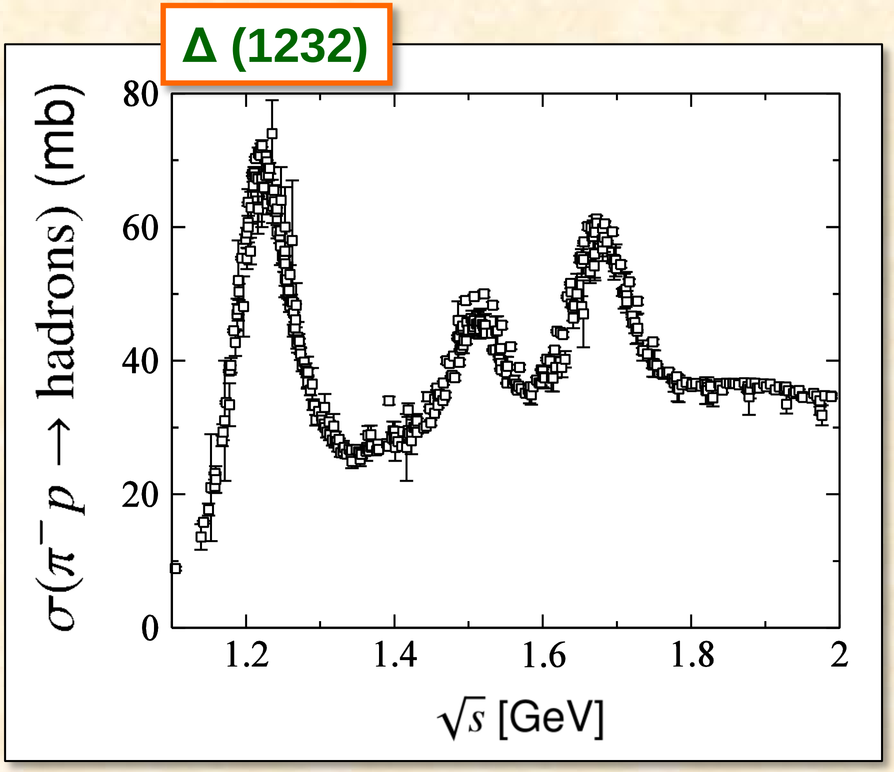
What is the role of reaction dynamics in interpreting the hadron spectrum, structures, and dynamical origins ??

Light-quark hadron spectroscopy : Physics of broad & overlapping resonances



- ✓ **Width:** **a few hundred MeV.**
- ✓ **Resonances are highly overlapping in energy except $\Delta(1232)$.**

Light-quark hadron spectroscopy : Physics of broad & overlapping resonances



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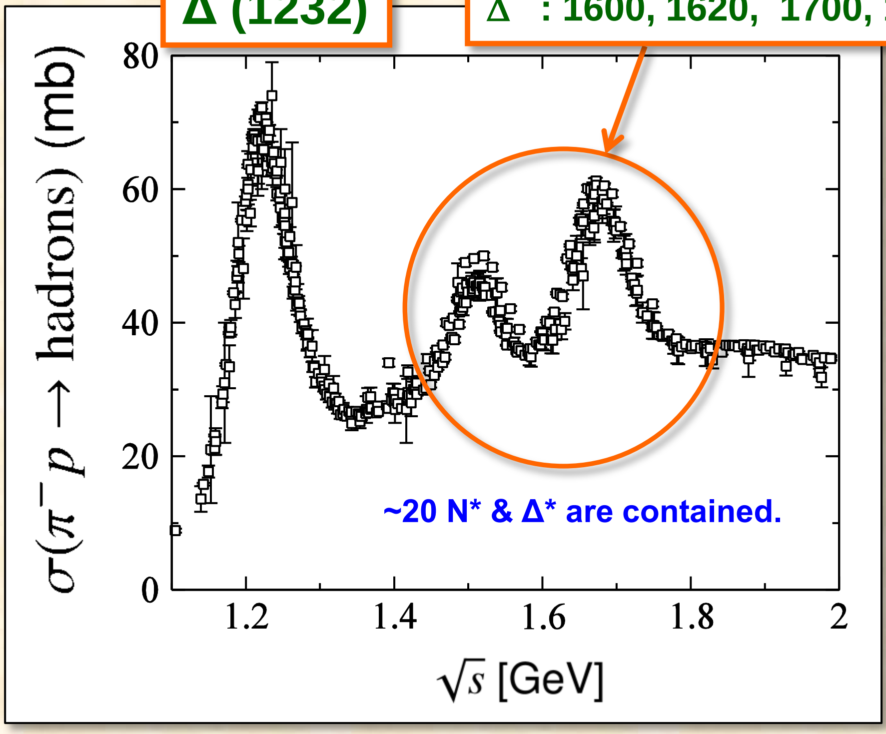

Δ (1232)

N* : 1440, 1520, 1535, 1650, 1675, 1680, ...

Δ : 1600, 1620, 1700, 1750, 1900, …

~20 N* & Δ* are contained.

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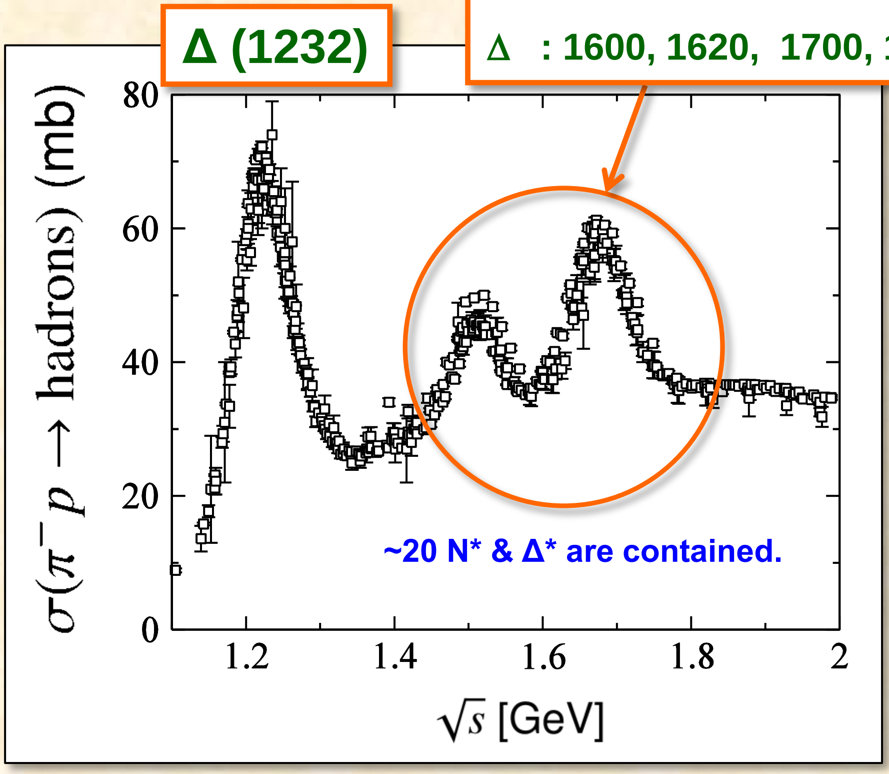

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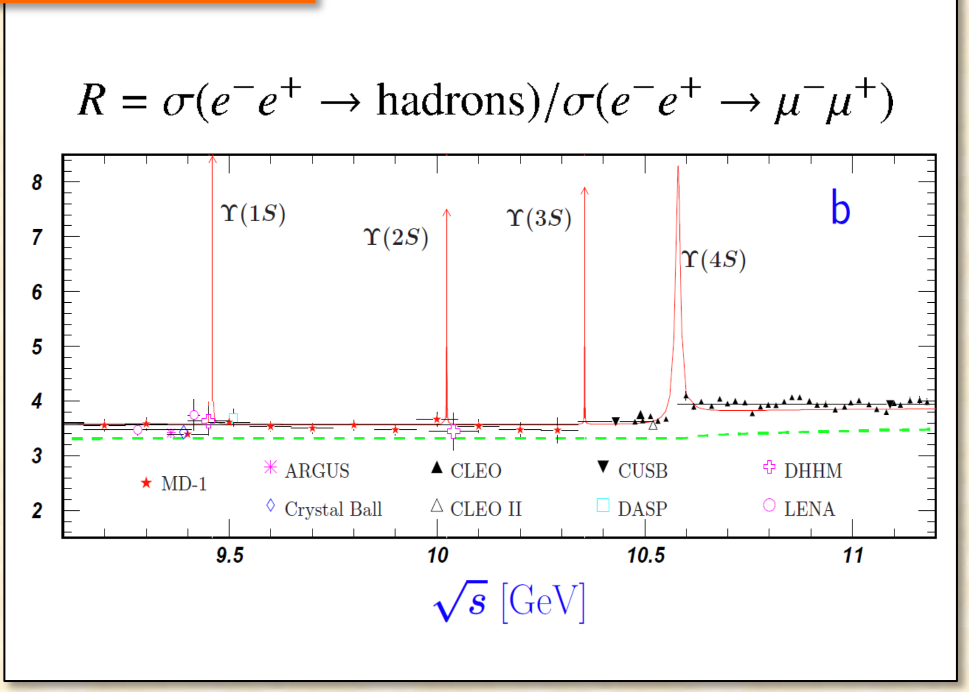
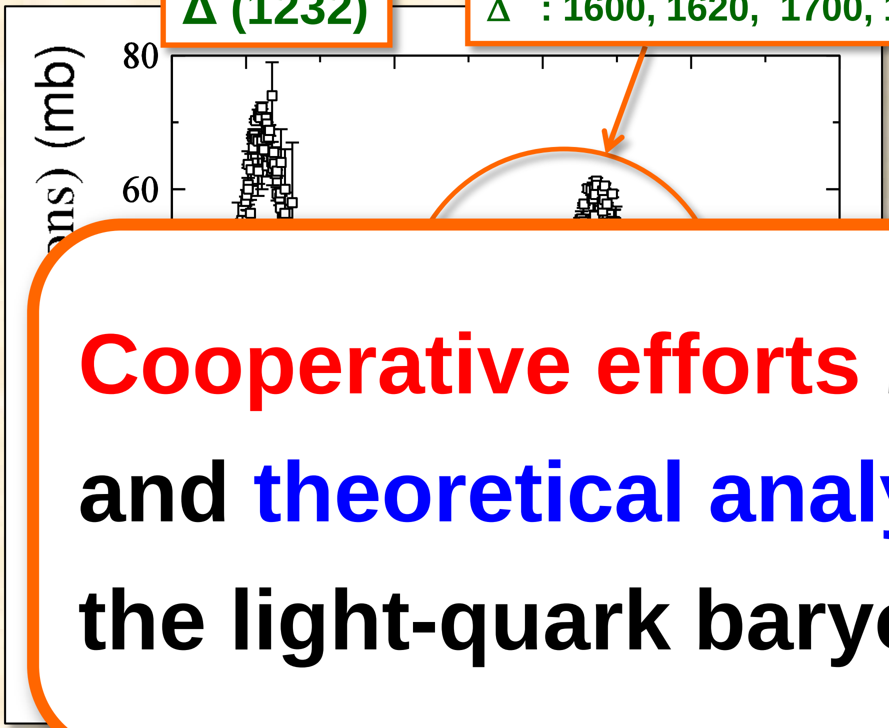


$R = \sigma(e^- e^+ \to \text{hadrons})/\sigma(e^- e^+ \to \mu^- \mu^+)$

- ✓ **Width: a few hundred MeV.**
- ✓ **Resonances are highly overlapping in energy except Δ(1232).**

- ✓ **Width: ~10 keV to tens of MeV**
- ✓ **Each resonance peak is clearly separated.**

Light-quark hadron spectroscopy : Physics of broad & overlapping resonances



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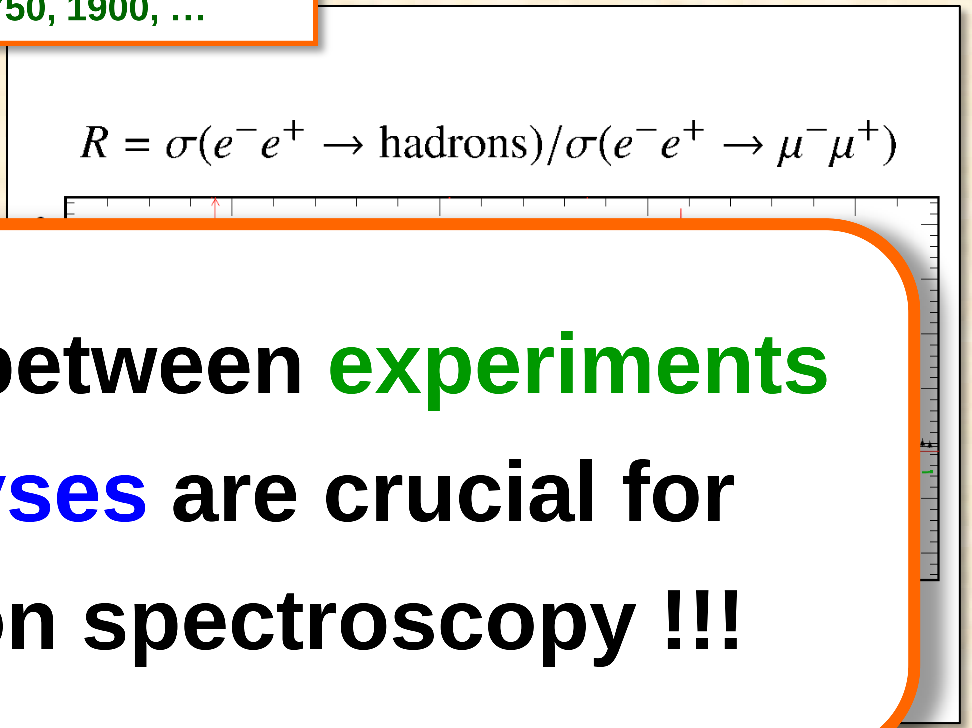

Cooperative efforts between experiments and theoretical analyses are crucial for the light-quark baryon spectroscopy !!!

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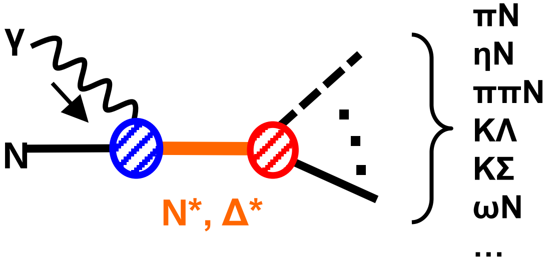
Cooperative efforts between experiments and theoretical analyses

Experiments

Since late 90s

- e.g.) Meson photoproductions



ELSA, ELPH, GRAAL, JLab, MAMI, SPring-8, ...

Theoretical analyses

with coupled-channels framework

ANL-Osaka
Argonne-Pittsburgh
Bonn-Gatchina
Carnegie-Mellon-Berkeley
Dubna-Mainz-Taipei
EBAC
Giessen
GWU/VPI
Juelich-Bonn
Karlsruhe-Helsinki
KSU
Zagreb
…

✓ Multichannel unitary condition:

$$T_{ab}(E) - T^{\dagger}_{ab}(E) = -2\pi i \sum_{c} T^{\dagger}_{ac}\delta(E - E_c)T_{cb}(E)$$

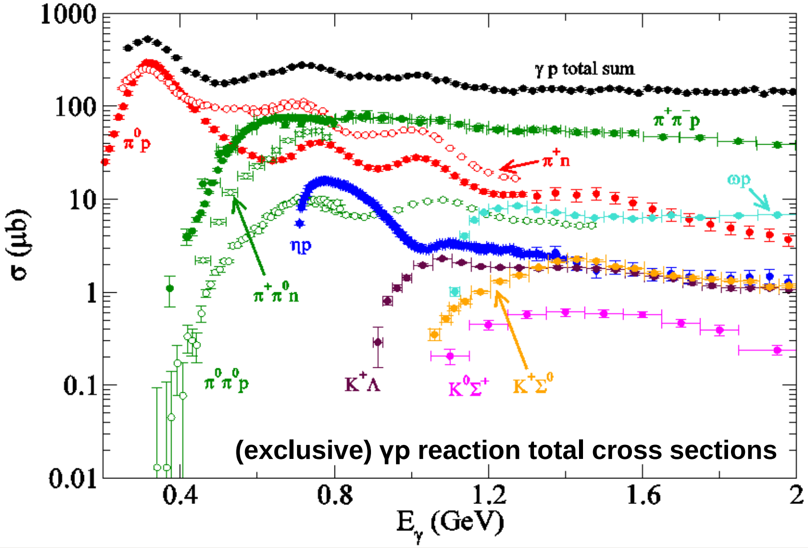
Why multichannel unitarity is so important ??

$$T_{ab}(E) - T^{\dagger}_{ab}(E) = -2\pi i \sum_{c} T^{\dagger}_{ac}\delta(E - E_c)T_{cb}(E)$$

1) Ensures **conservation of probabilities** in multichannel reaction processes

Key essential to

- **simultaneous analysis** of various inelastic reactions.
- increasing **predictivity** of constructed reaction models



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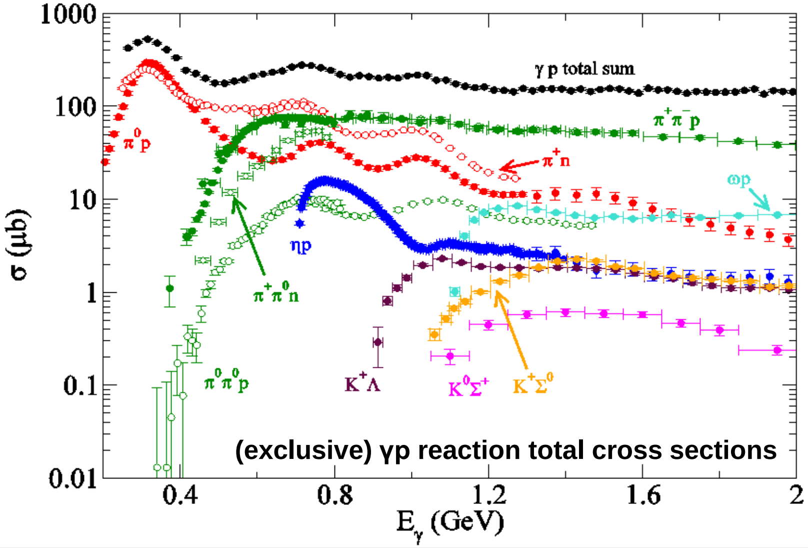
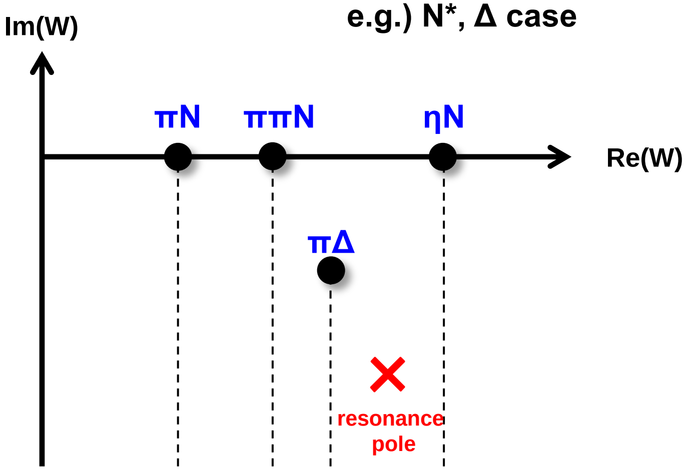

(exclusive) γp reaction total cross sections

2) 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]**



Approaches for coupled-channels analysis

- ✓ **Multichannel unitary condition:**

$$T_{ab}(E) - T^{\dagger}_{ab}(E) = -2\pi i \sum_{c} T^{\dagger}_{ac}\delta(E - E_c)T_{cb}(E)$$

- ✓ **Heitler equation:**

K-matrix: **must be hermitian for real E.**

$$T_{ab}(E) = K_{ab}(E) + \sum_{c} K_{ac}(E)\left[-i\pi\delta(E - E_c)\right] T_{cb}(E)$$

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- **(on-shell) K-matrix approach:**

$$K_{ab}(E) \equiv (\text{Polynomials of } E) + (\text{Pole terms})$$

✓ **Heitler equation can be solved algebraically.**

Argonne-Pittsburgh, Bonn-Gatchina, Carnegie Mellon-Berkely, GWU/VPI, Karlsruhe-Helsinki, KSU, ...

- **Dynamical-model approach:**

✓ **Heitler equation becomes identical to Lippmann-Schwinger integral equation.**

✓ **Potential *V* is derived from a model Hamiltonian.**

$$K_{ab}(E) \equiv K_{ab}(\vec{p}_a, \vec{p}_b; E) = V_{ab}(\vec{p}_a, \vec{p}_b; E) + \underline{\sum_{c} \mathcal{P} \int d\vec{q}\, V_{ac}(\vec{p}_a, \vec{q}; E) \frac{1}{E - H^0_c + i\varepsilon} K_{cb}(\vec{q}, \vec{p}_b; E)}$$

off-shell rescattering effect

ANL-Osaka, Dubna-Mainz-Taipei, Juelich-Bonn,...

Why dynamical coupled-channels approach??

	(on-shell) K-matrix	**Dynamical model**
Numerical cost	Cheap ☺ - solve on-shell algebraic eq. (Analysis can be done quickly on PC.)	(Very) Expensive ☹ - solve off-shell integral eq. (Supercomputers are needed.)
Data fitting	Efficient ☺ - K(E) can be parametrized as one likes	Not so efficient ☹ - Form of *V* is severely constrained by theoretical input (model Hamiltonian)

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To understand the physics of reaction dynamics behind formation, structure, etc. of hadron resonances, one needs:

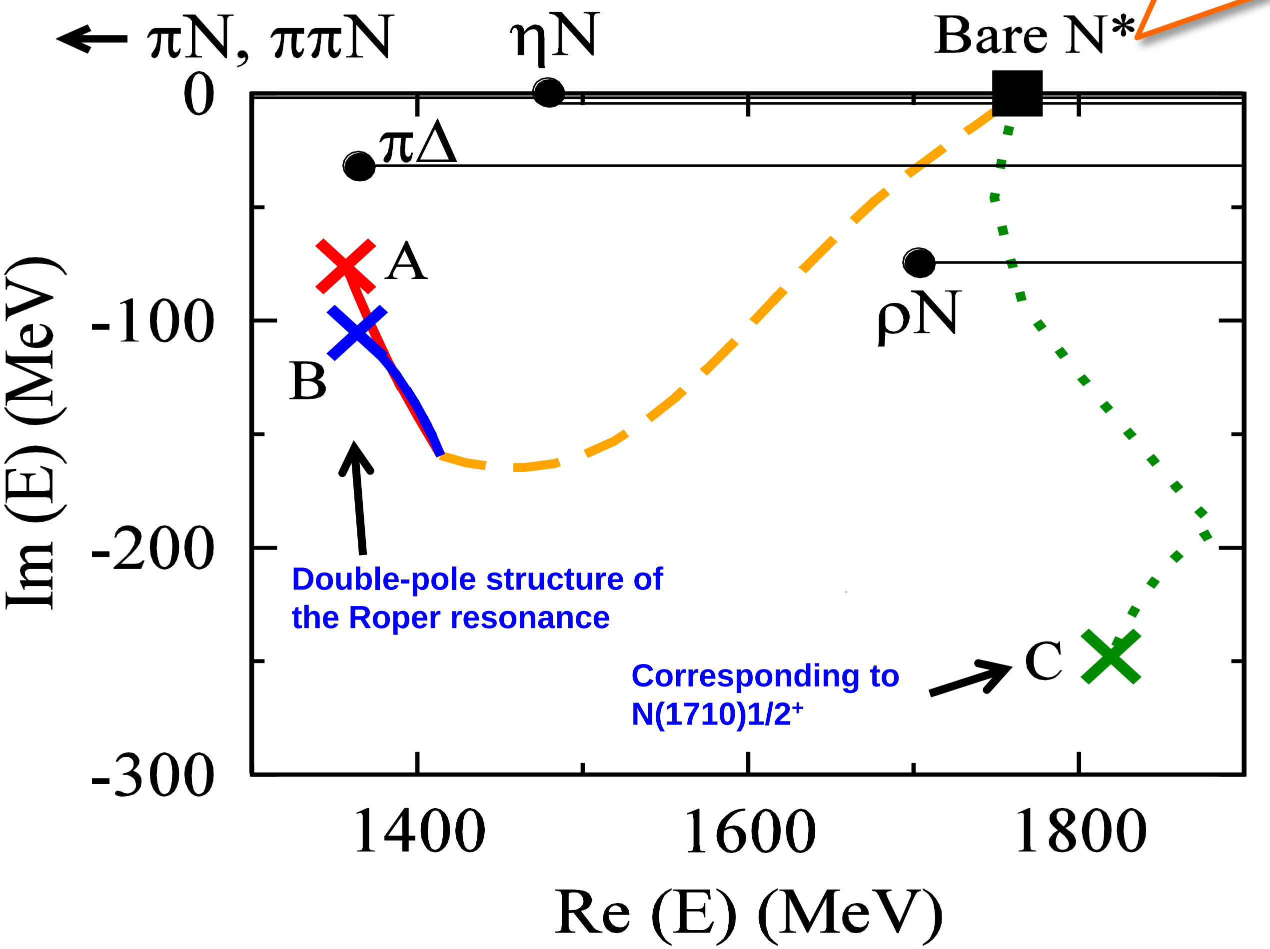
- **Modeling reaction processes appropriately with a model Hamiltonian.**
  (➔ not a simple “pole + polynomial” parametrization, etc.)

- **Solving proper quantum scattering equation (LS eq.) in which off-shell rescattering effects are also appropriately contained.**

This can be achieved only by using the dynamical-model approach !!

Dynamical origin of P_{11} N* resonances

(nontrivial feature of multichannel reaction dynamics)



Would be related to a baryon state in static hadron models excluding meson-baryon continuums

Double-pole structure of the Roper resonance

Corresponding to N(1710)1/2$^+$

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

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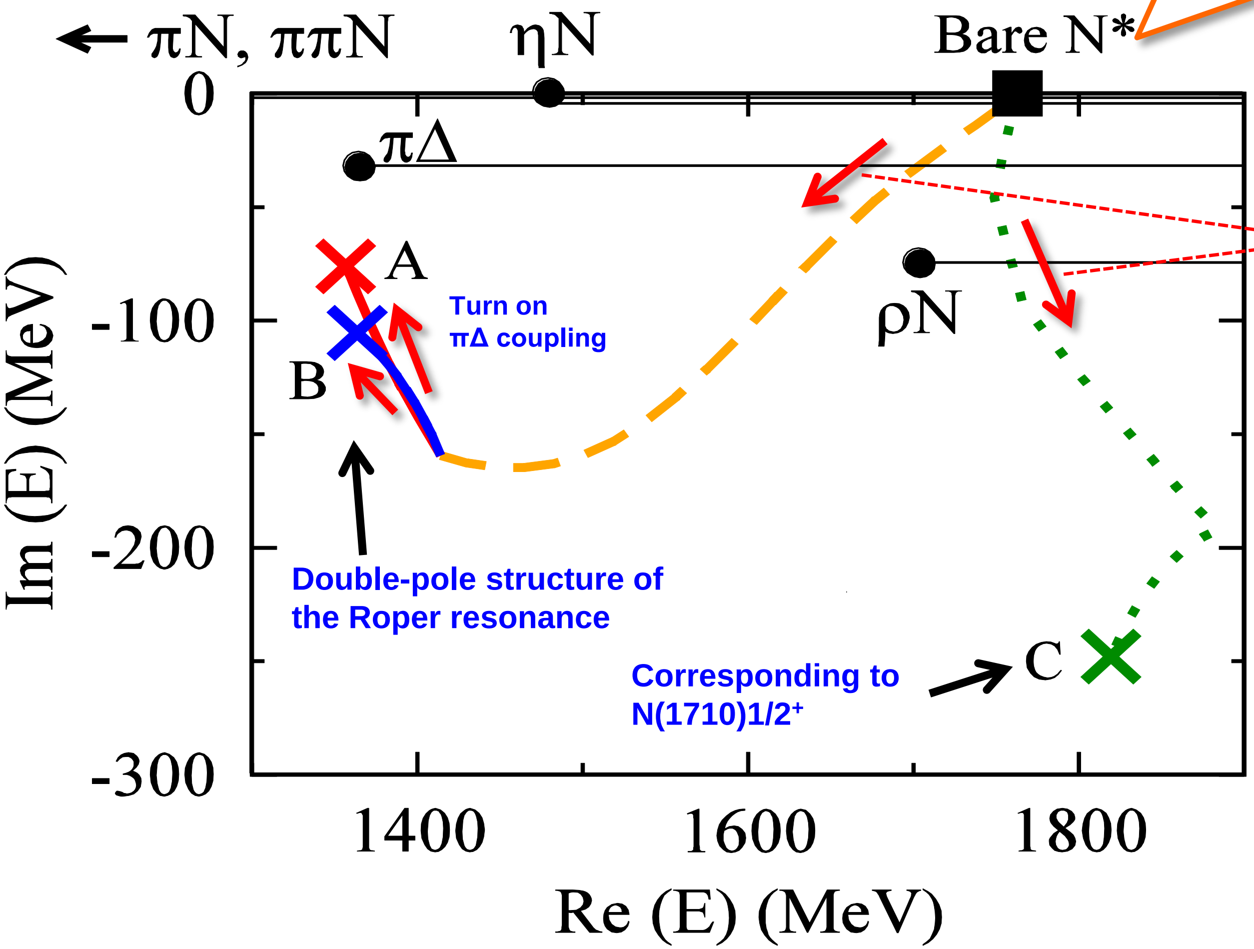

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Move of poles by “gradually” strengthening channel couplings

Turn on πΔ coupling

Double-pole structure of the Roper resonance

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PART II

Recent results from ANL-Osaka DCC analysis

Dynamical coupled-channels (DCC) model for meson production reactions

For details see Matsuyama, Sato, Lee, Phys. Rep. 439(2007)193
HK, Nakamura, Lee, Sato, PRC(2013)035209

- ✓ **Partial-wave (LSJ) amplitudes of a → b reaction:**

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

- ✓ **Reaction channels:**

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

- ✓ **Transition Potentials:**

$$V_{a,b} = \underbrace{v_{a,b}}_{\boxed{\text{Exchange potentials}}} + \underbrace{Z_{a,b}}_{\boxed{\text{Z-diagrams}}} + \underbrace{\sum_{N^*} \frac{\Gamma^\dagger_{N^*,a}\Gamma_{N^*,b}}{E - M_{N^*}}}_{\boxed{\text{bare N* states}}}$$

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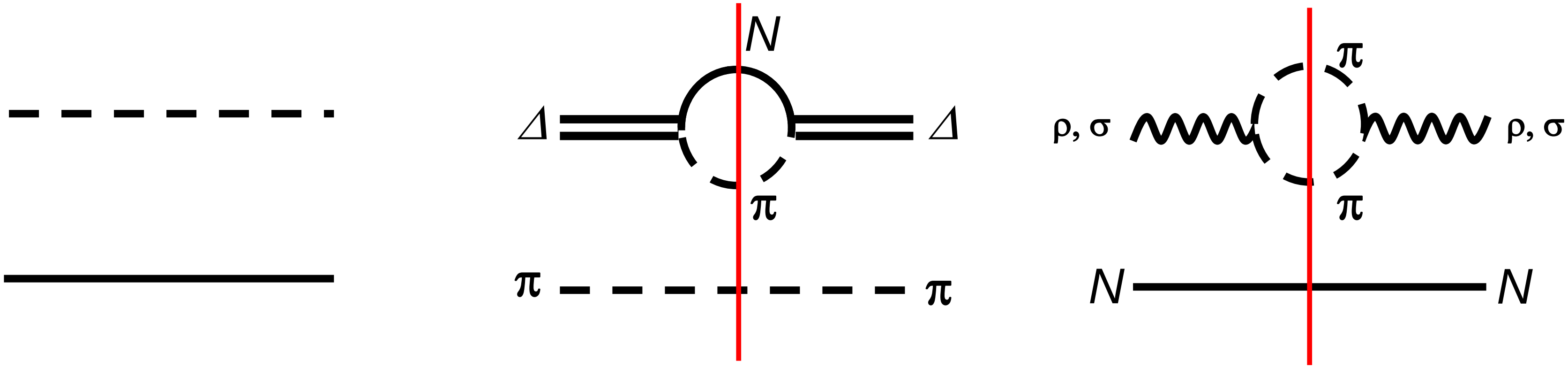
✓ **Meson-Baryon Green functions** G_{MB}

$MB = \pi N, \eta N, K\Lambda, K\Sigma, \omega N$

Stable channels

$MB = \pi\Delta, \rho N, \sigma N$

Quasi 2-body channels



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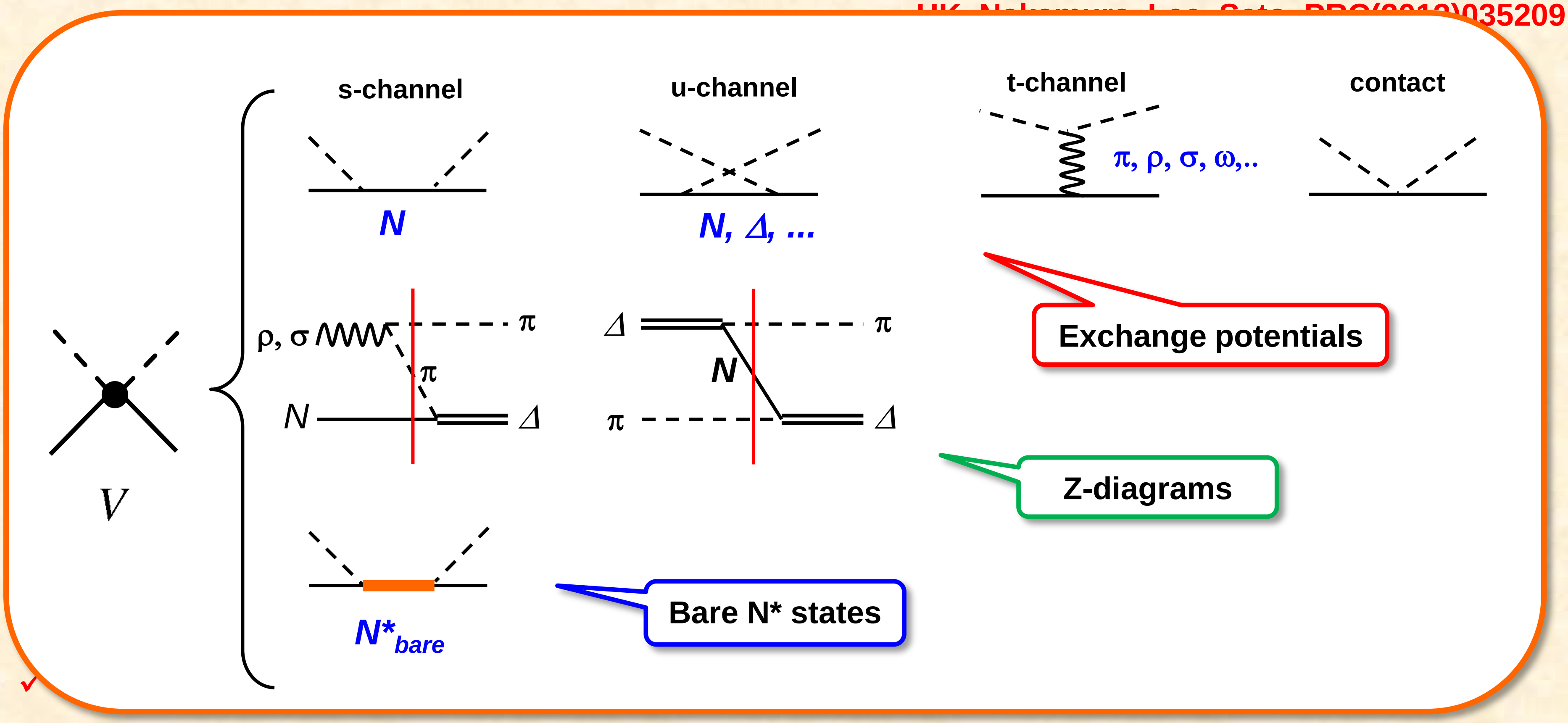

Exchange potentials

Z-diagrams

Bare N* states

$$V_{a,b} \quad = \quad v_{a,b} \quad + \quad Z_{a,b} \quad + \quad \sum_{N^*} \frac{\Gamma^{\dagger}_{N^*,a}\Gamma_{N^*,b}}{E - M_{N^*}}$$

Exchange potentials | Z-diagrams | bare N* states

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- ✓ **Reaction channels:**

$$a,b,c \;=\; (\,\gamma^{(*)}N$$

Would be related with hadron states of the static hadron models (quark models, DSE, etc.) excluding meson-baryon continuums.

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Strategy for N* and Δ* spectroscopy

1) Construct a model by making χ^2-fit of the world data of meson production reactions.

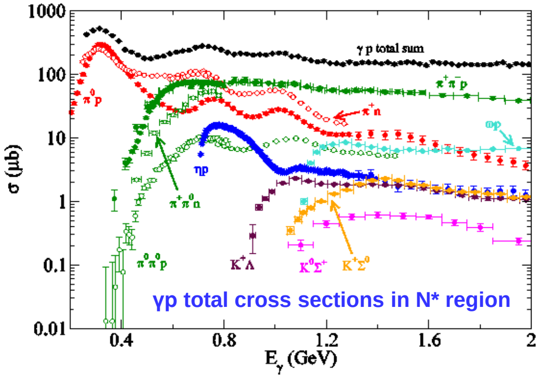
✓ Latest published model (8-channel):
HK, Nakamura, Lee, Sato, PRC88(2013)035209
[updated in PRC94(2016)015201]

Made simultaneous analysis of

- πN → πN(SAID amp) (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)

→~27,000 data points of both
dσ/dΩ & spin-pol. obs.

← Region our model can cover →



γp total cross sections in N* region

➢ Use supercomputers to accomplish coupled-channels analyses:

NERSC

Argonne NATIONAL LABORATORY

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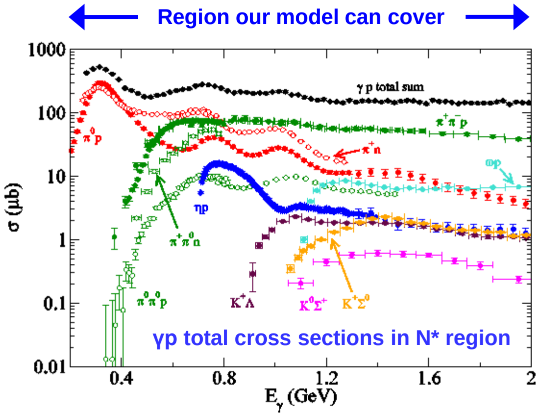
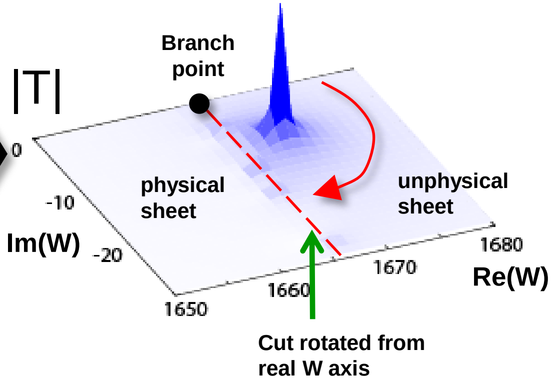


- Use supercomputers to accomplish coupled-channels analyses:

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



Pole position → (complex) resonance mass

Residues → coupling strengths between resonance and meson-baryon channel

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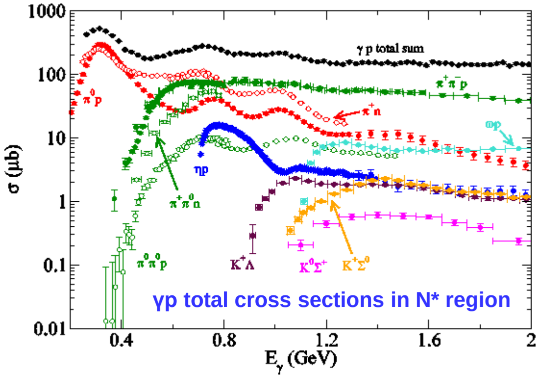

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NERSC Argonne NATIONAL LABORATORY

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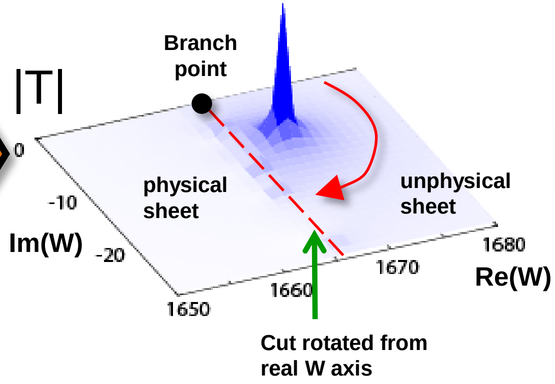


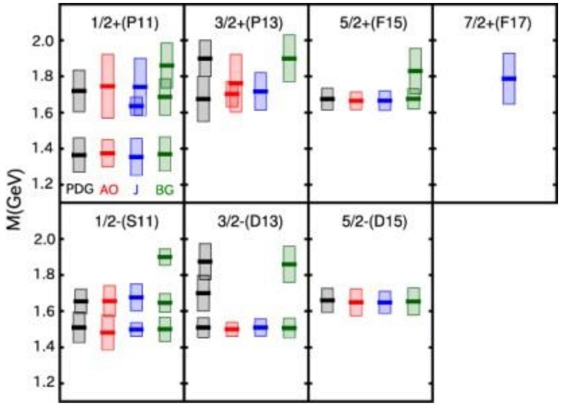
Cut rotated from real W axis

Pole position → (complex) resonance mass

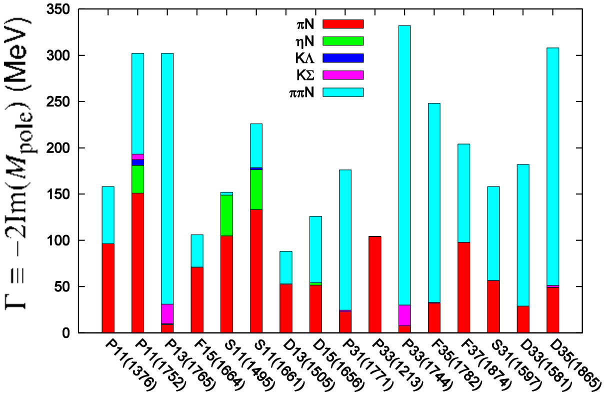
Residues → coupling strengths between resonance and meson-baryon channel

3) Extract resonance parameters defined by poles.

Mass spectrum



Partial decay widths

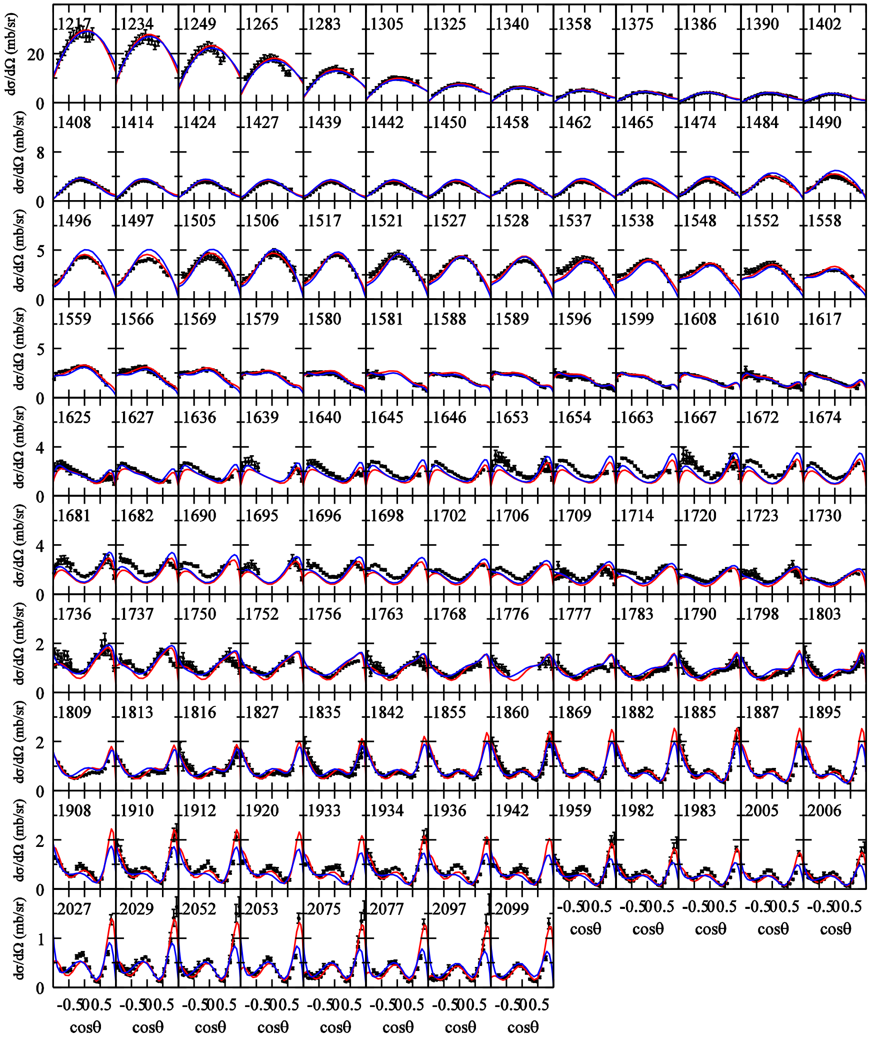


ANL-Osaka DCC analysis

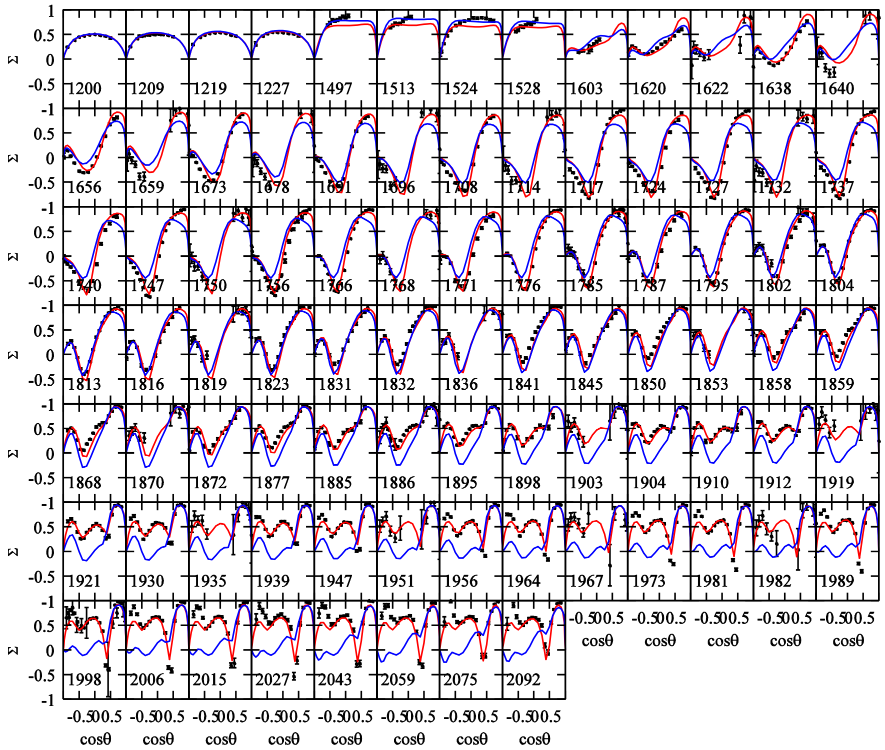
$\gamma p \rightarrow \pi^0 p$

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

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]

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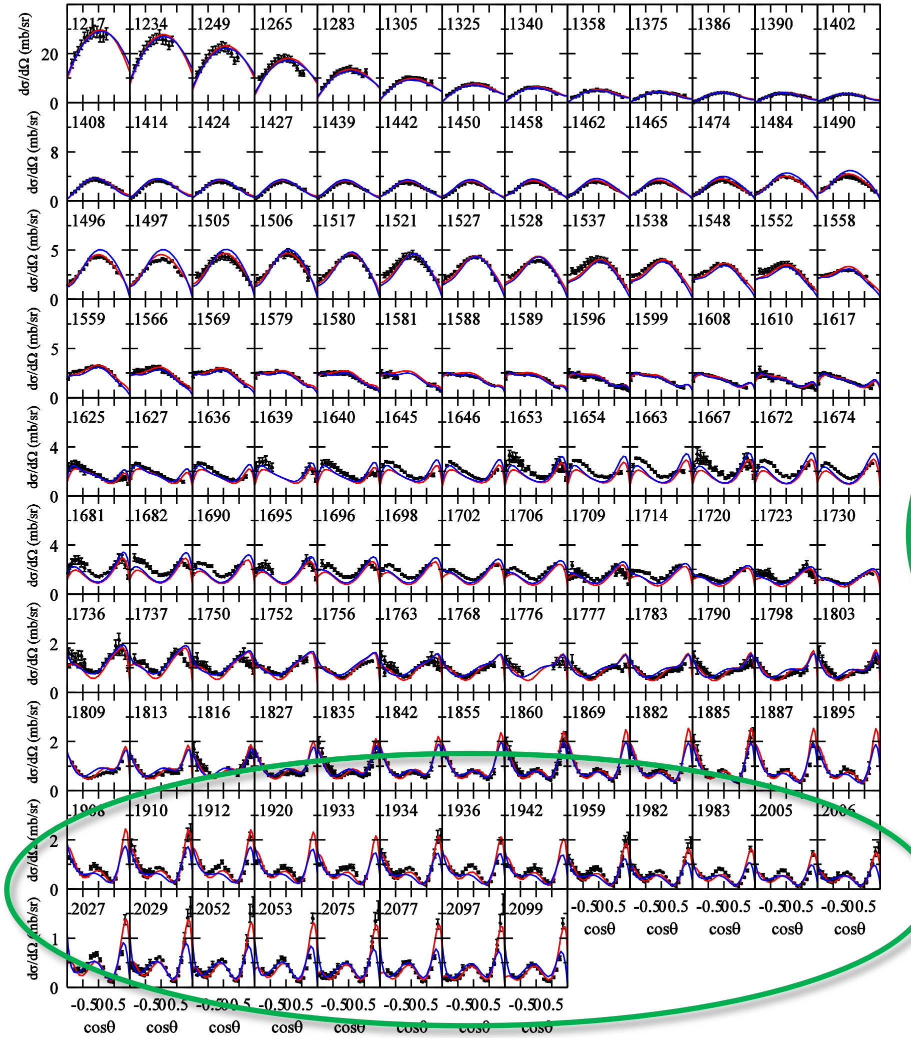

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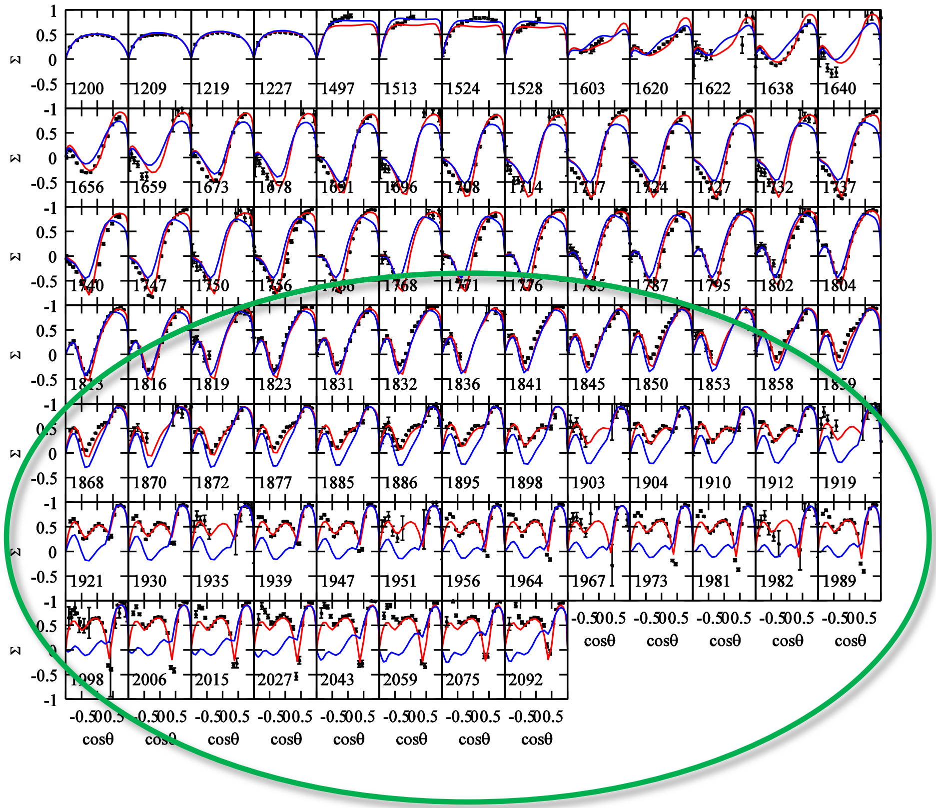

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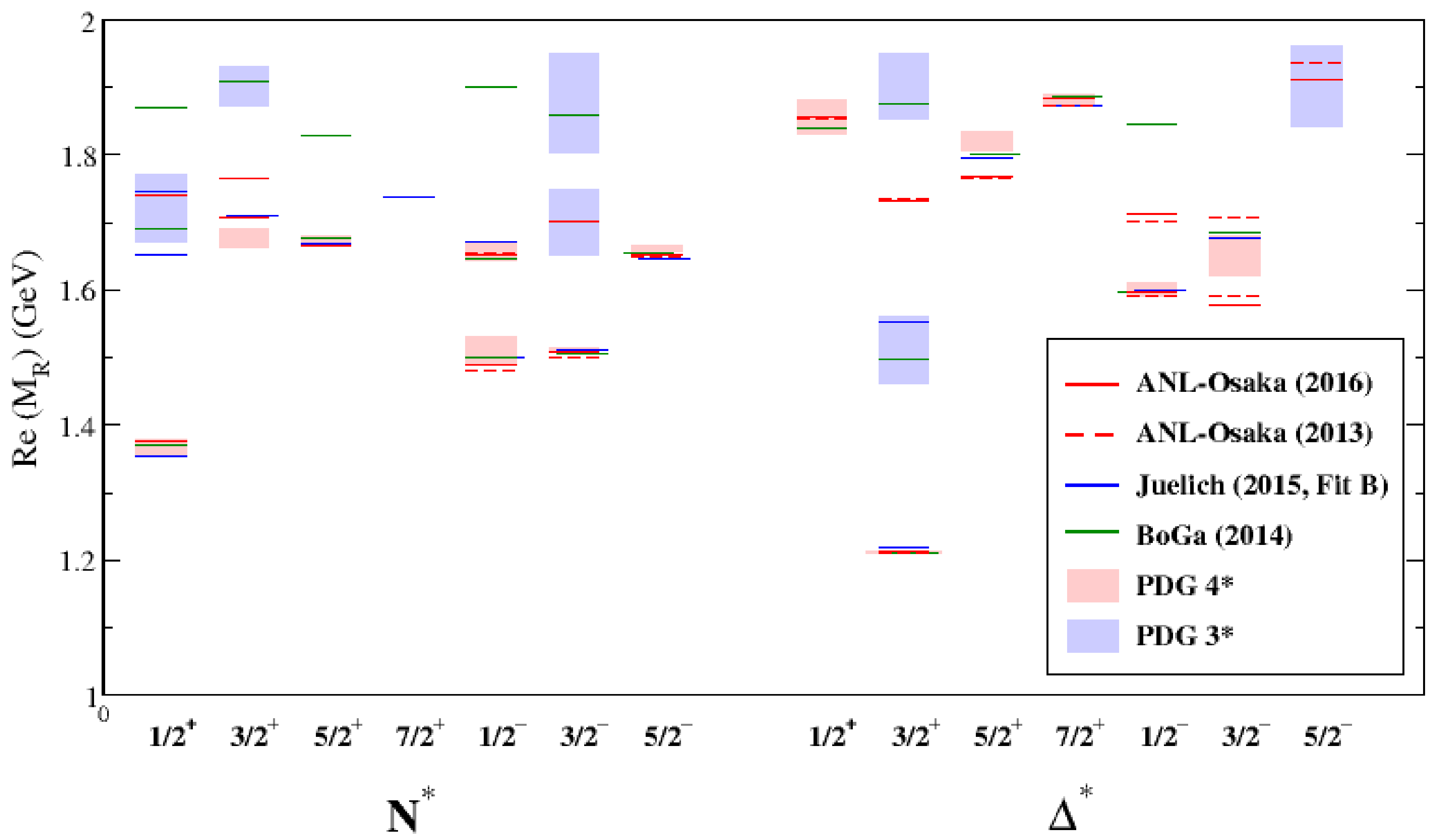
Extracted N* & Δ* mass spectrum (pole mass M_R)



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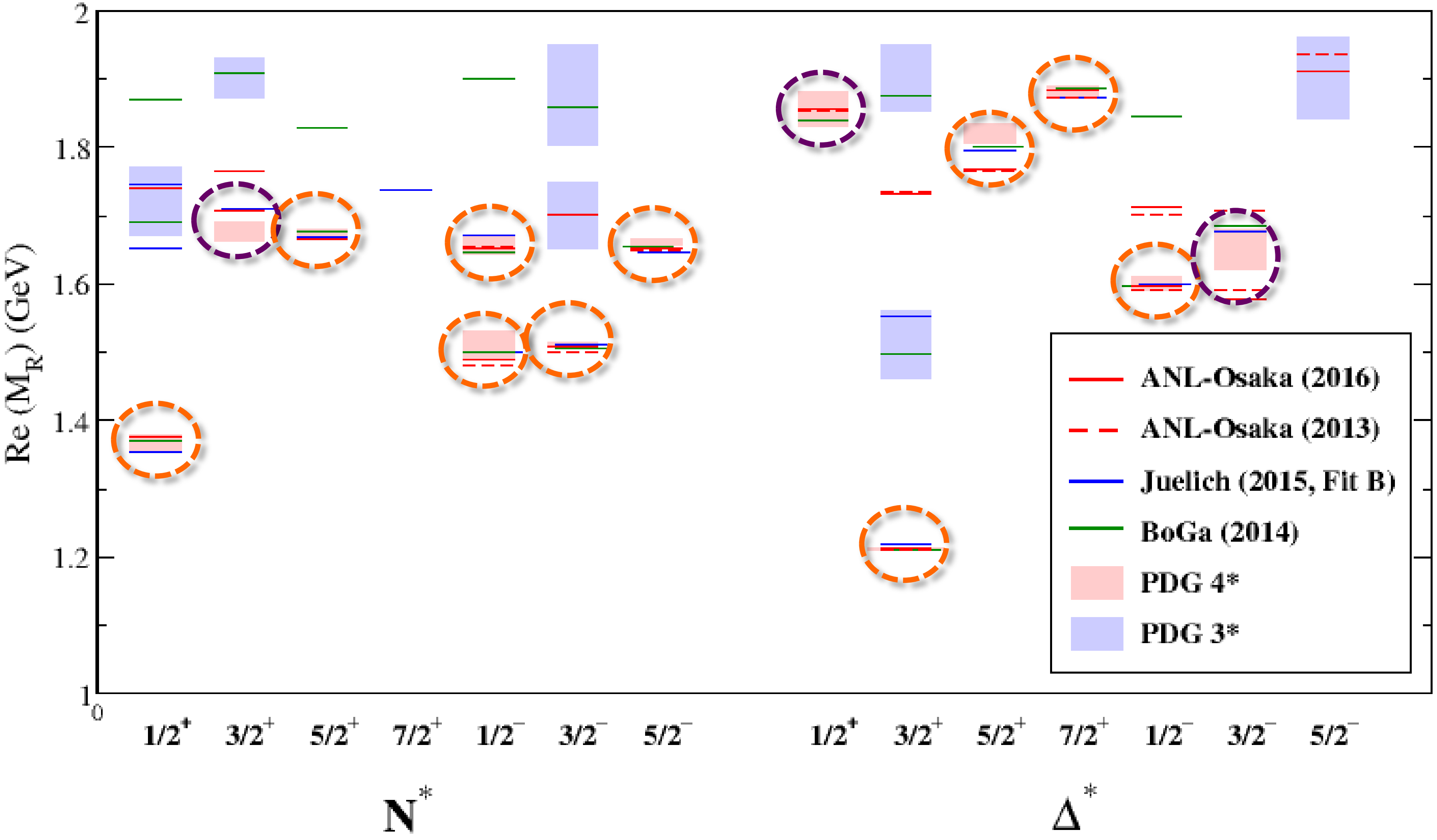

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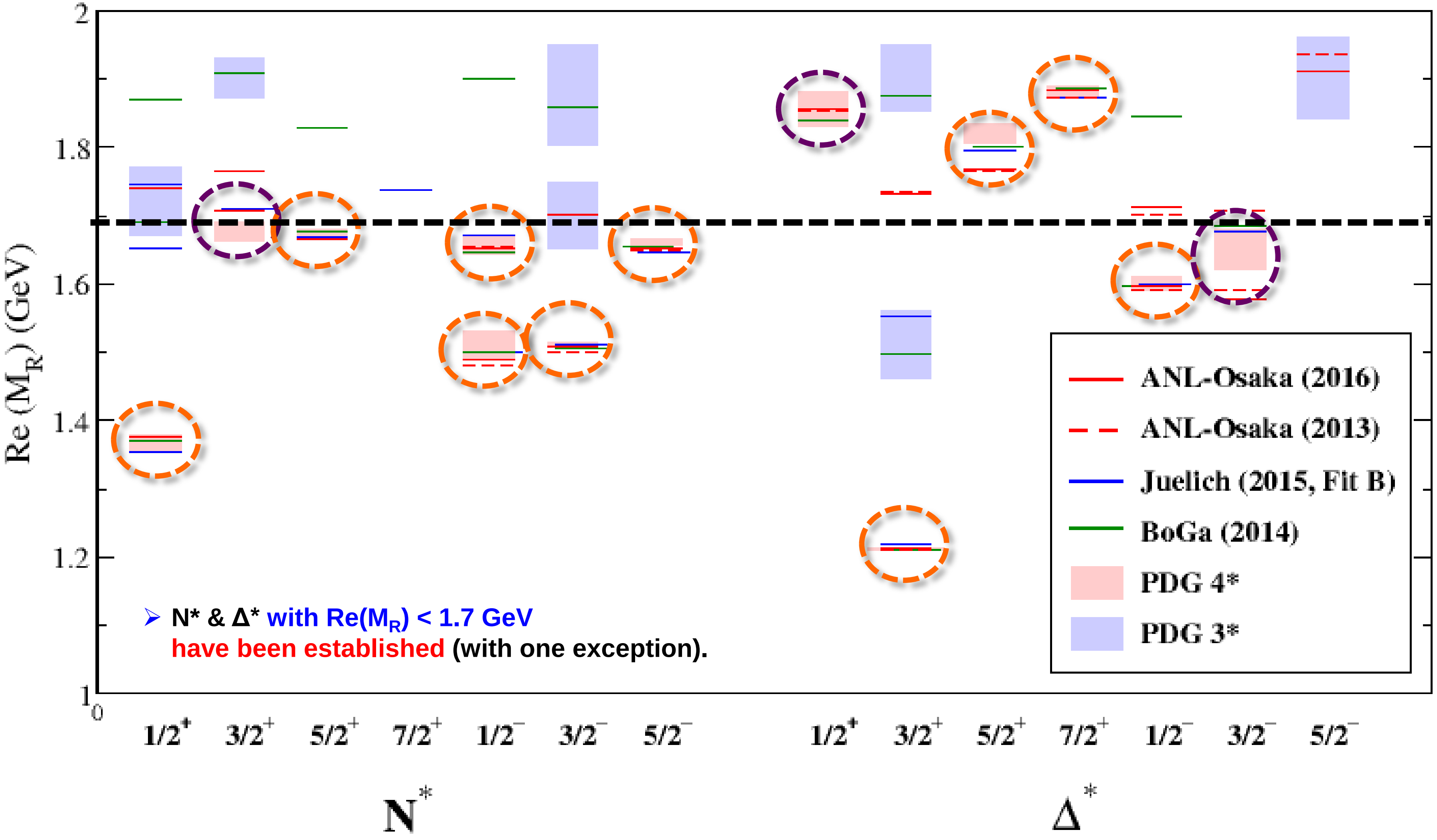
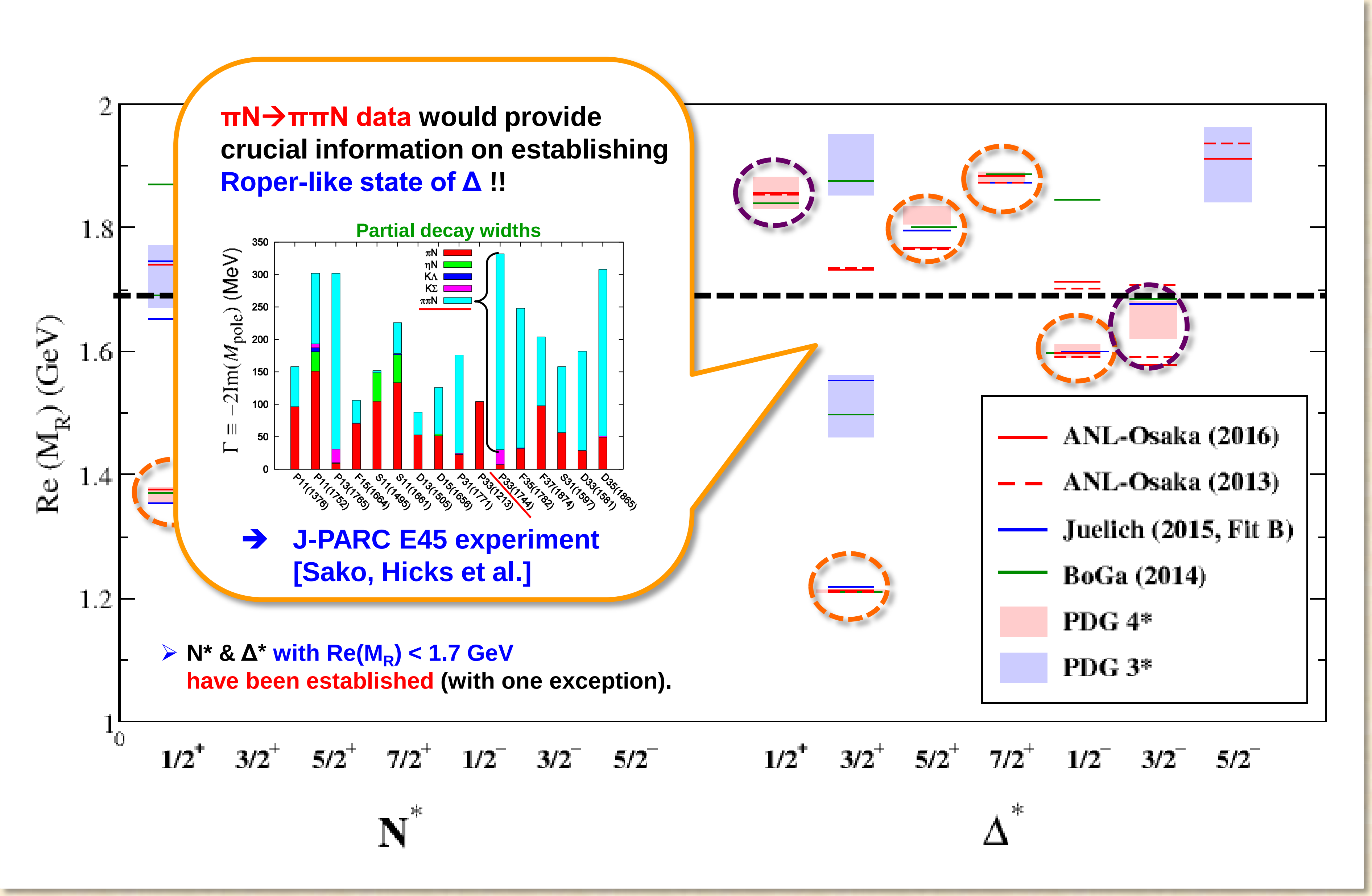


- N* & Δ* with Re(M_R) < 1.7 GeV have been established (with one exception).

Extracted N* & Δ* mass spectrum (pole mass M_R)

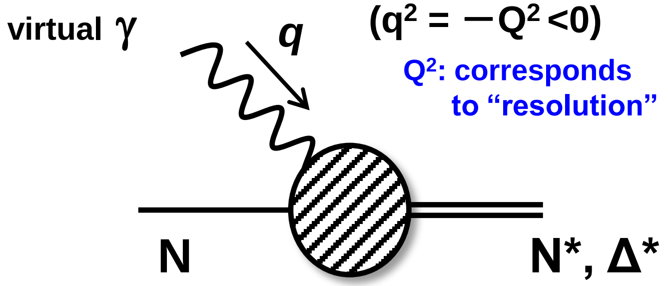


πN→ππN data would provide crucial information on establishing **Roper-like state of Δ !!**

→ **J-PARC E45 experiment [Sako, Hicks et al.]**

- N* & Δ* with Re(M_R) < 1.7 GeV **have been established** (with one exception).

Electromagnetic transition form factors: quantitative understanding of N* & Δ* structure

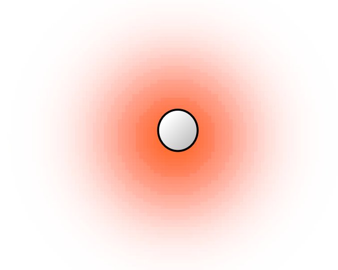


($q^2 = -Q^2 < 0$)

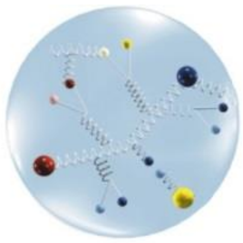
Q^2: corresponds
to “resolution”

N-N* e.m. transition form factor

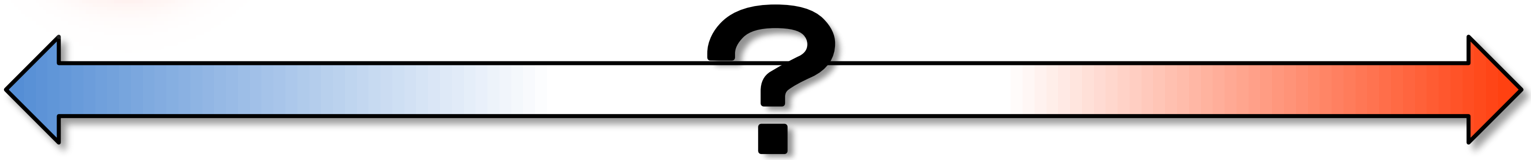
“dressed”-quark core
obscured by dense meson clouds



“Partons”



How effective d.o.f.s of baryon constituents change with Q^2 ??

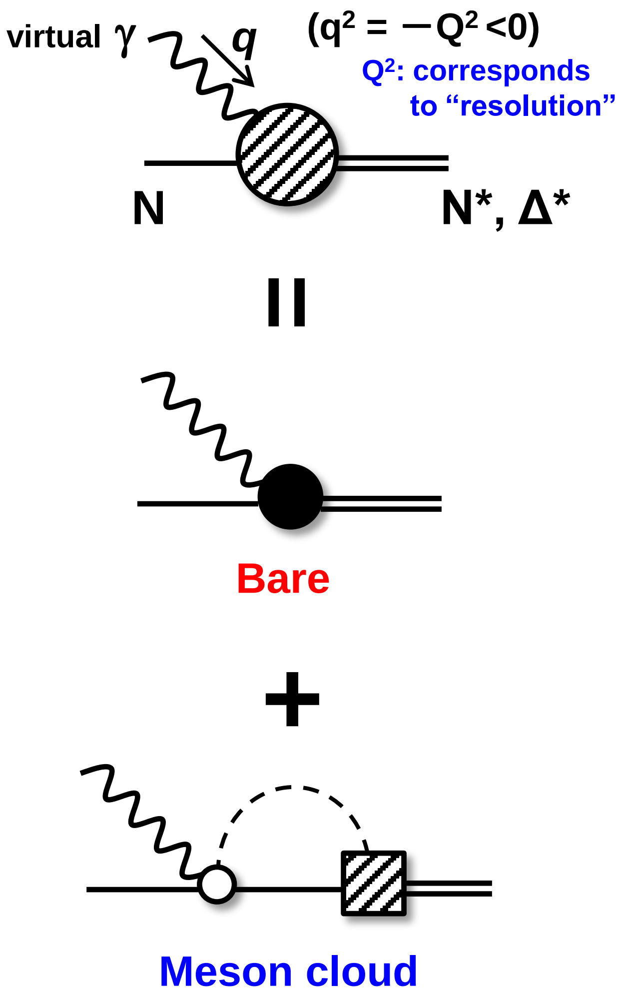


Q^2 : small
(low “resolution”)

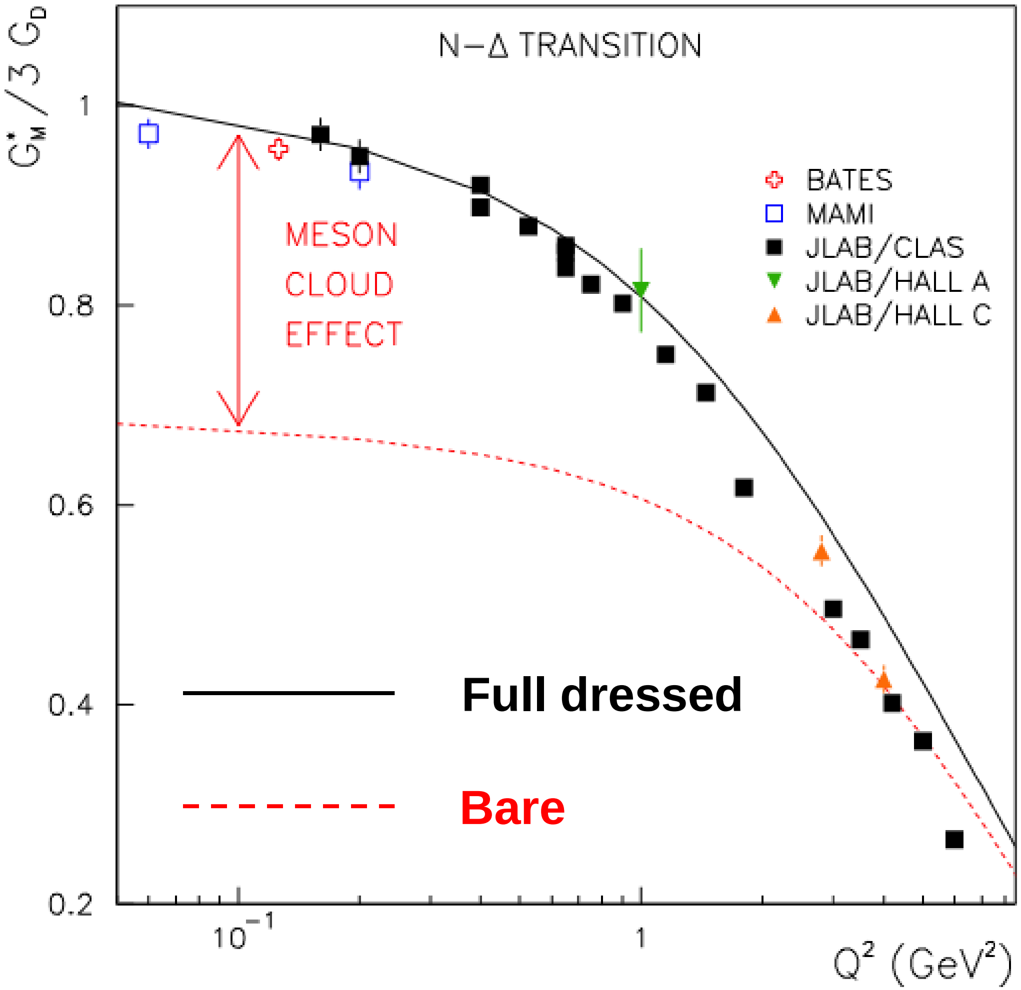
Q^2 : large
(high “resolution”)

Role of reaction dynamics in form factors: Meson-cloud effect

N-N* e.m. transition form factor



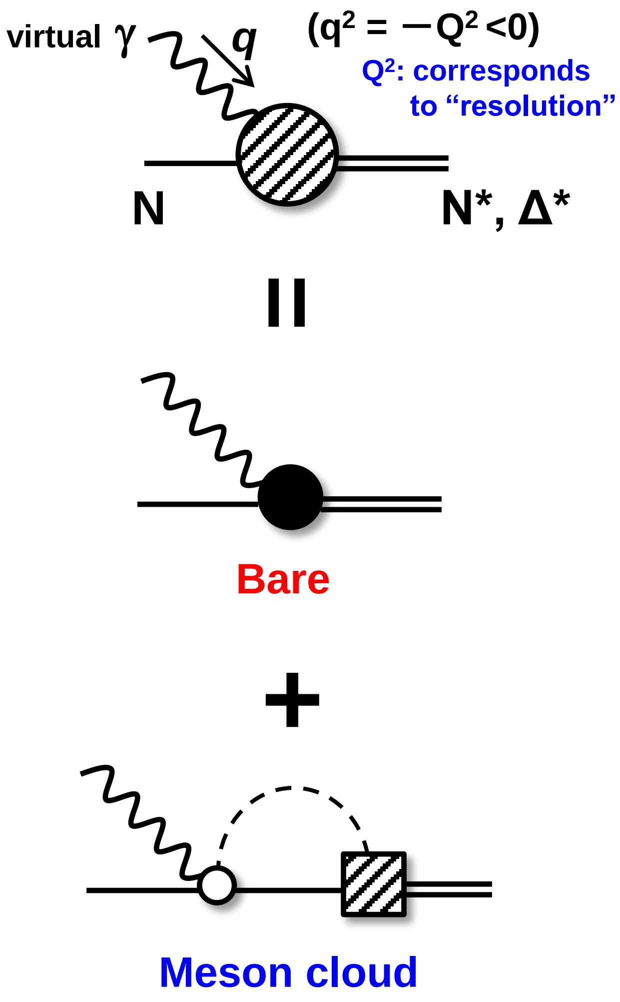
Re[$G_M(Q^2)$] for γ N → Δ (1232) M1 transition

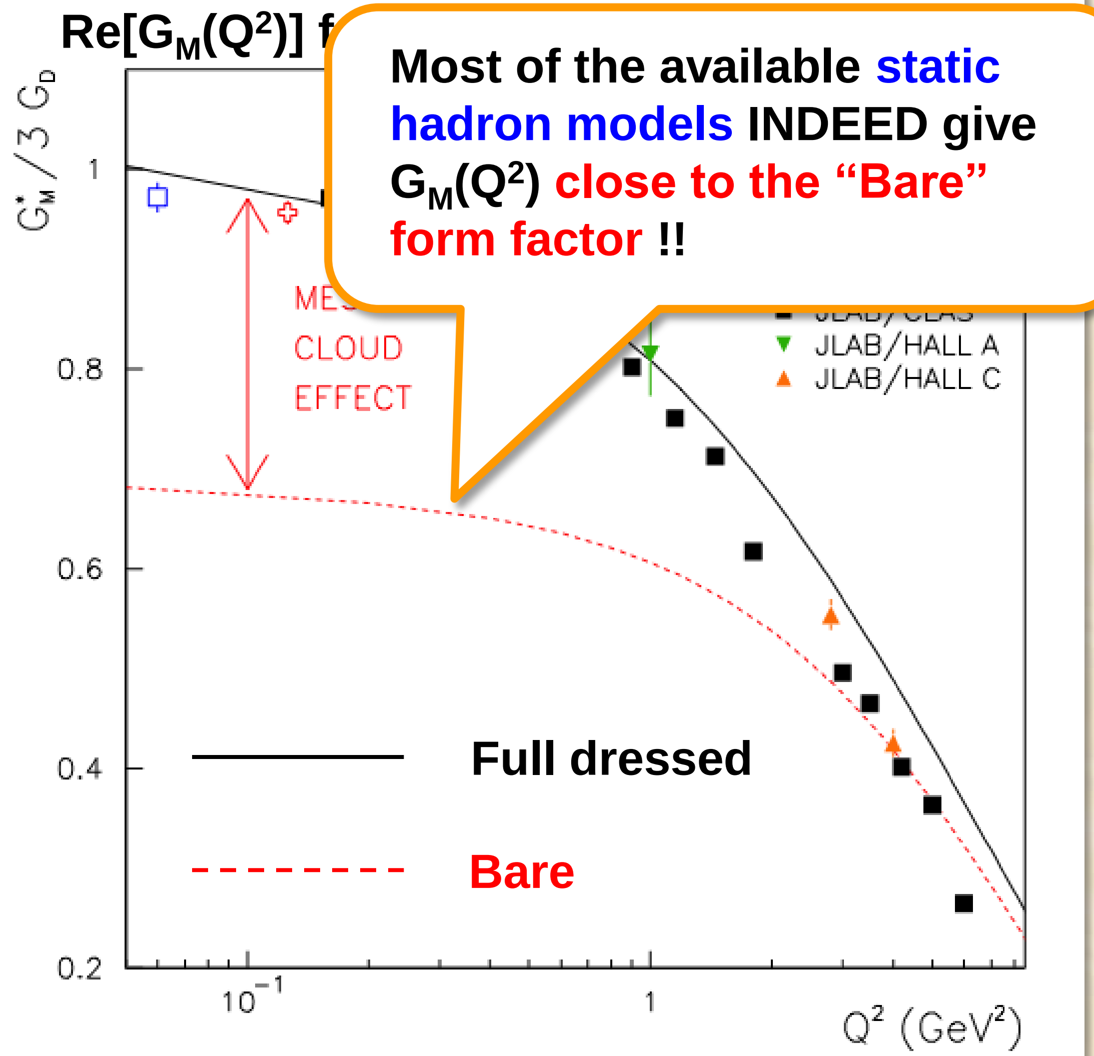


Julia-Diaz, et al., PRC75 015205 (2007)

Role of reaction dynamics in form factors: Meson-cloud effect

N-N* e.m. transition form factor



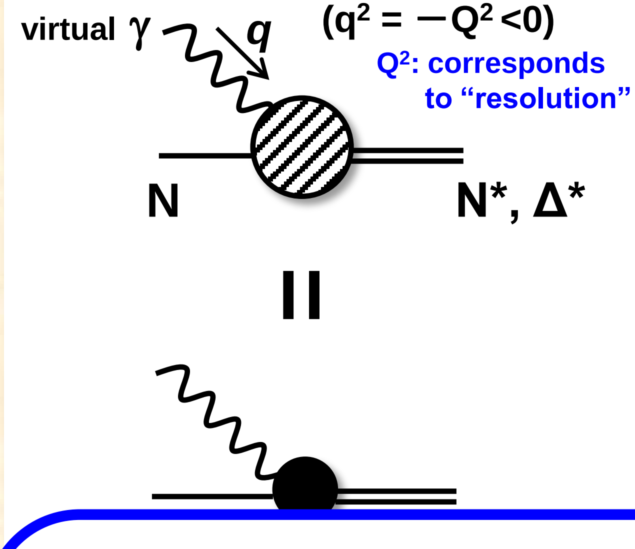


Most of the available **static hadron models** INDEED give $G_M(Q^2)$ **close to the "Bare" form factor !!**

Julia-Diaz, et al., PRC75 015205 (2007)

Role of reaction dynamics in form factors: Meson-cloud effect

N-N* e.m. transition form factor



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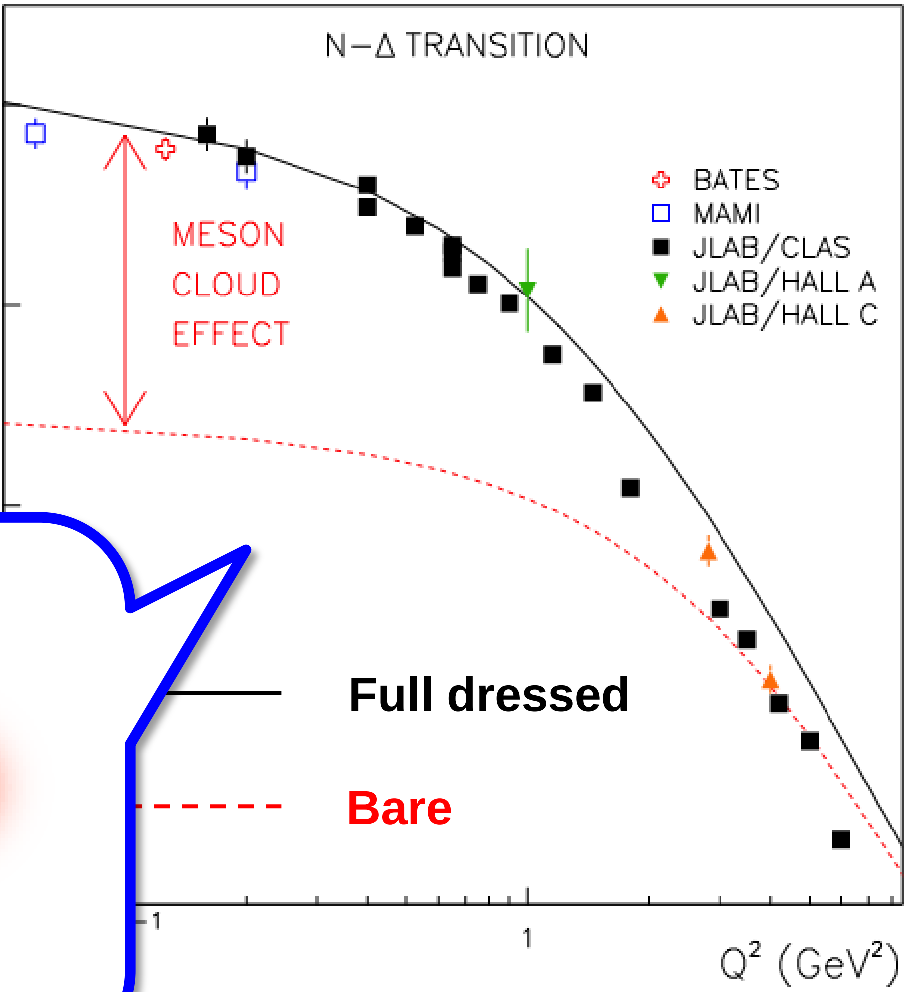
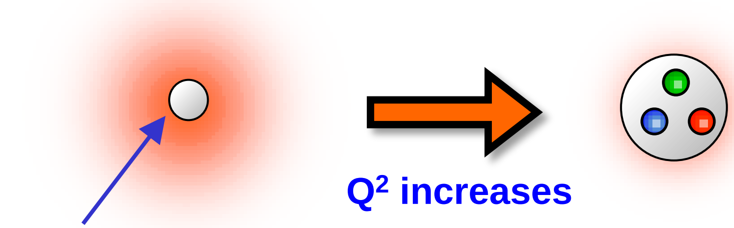


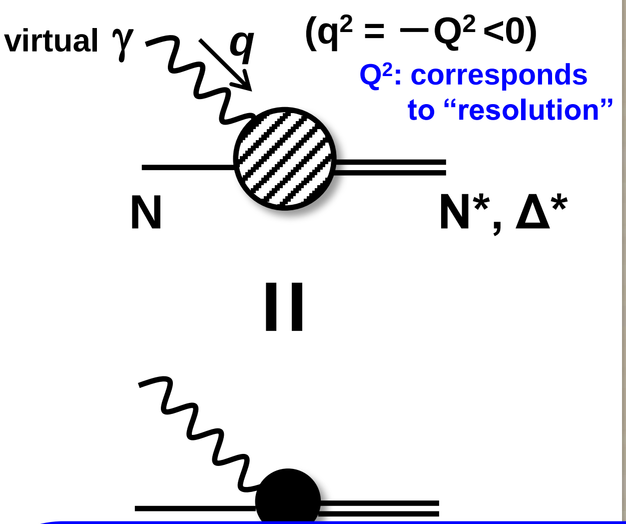
a-Diaz, et al., PRC75 015205 (2007)



"bare" state
(core composed of
"dressed" quarks)

Role of reaction dynamics in form factors: Meson-cloud effect

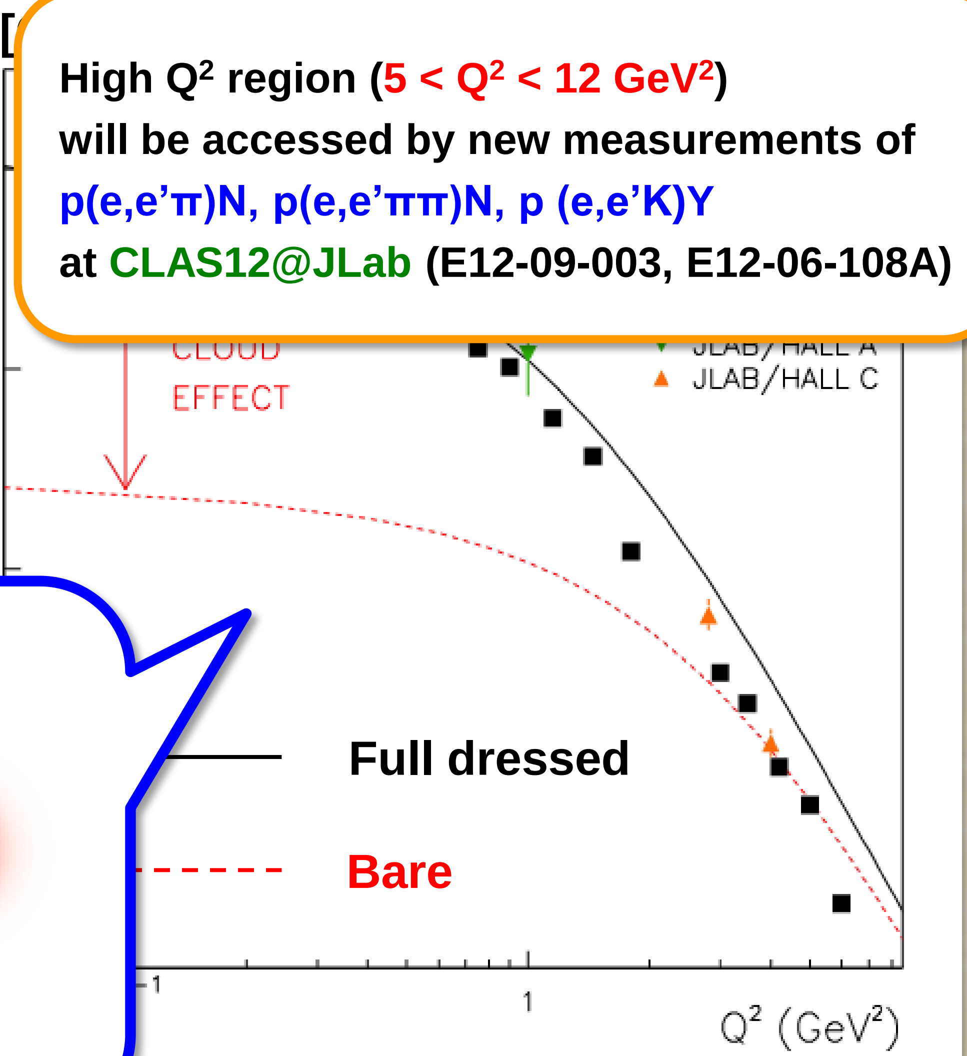
N-N* e.m. transition form factor



(q^2 = −Q^2 <0)

Q^2: corresponds to “resolution”

High Q^2 region (5 < Q^2 < 12 GeV^2)
will be accessed by new measurements of
p(e,e’π)N, p(e,e’ππ)N, p (e,e’K)Y
at CLAS12@JLab (E12-09-003, E12-06-108A)



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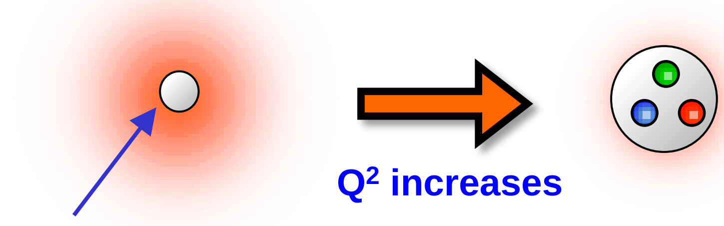
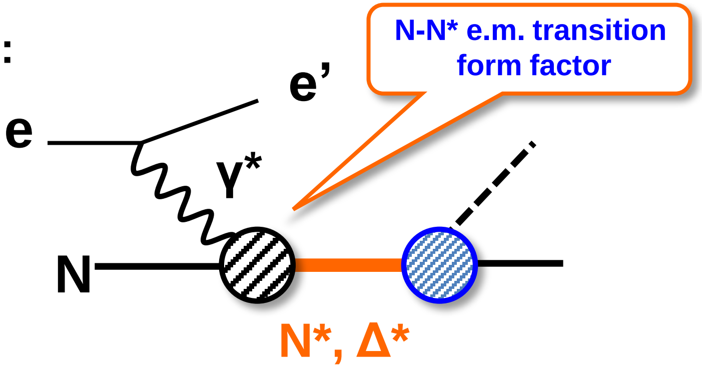


Q^2 increases

“bare” state
(core composed of
“dressed” quarks)

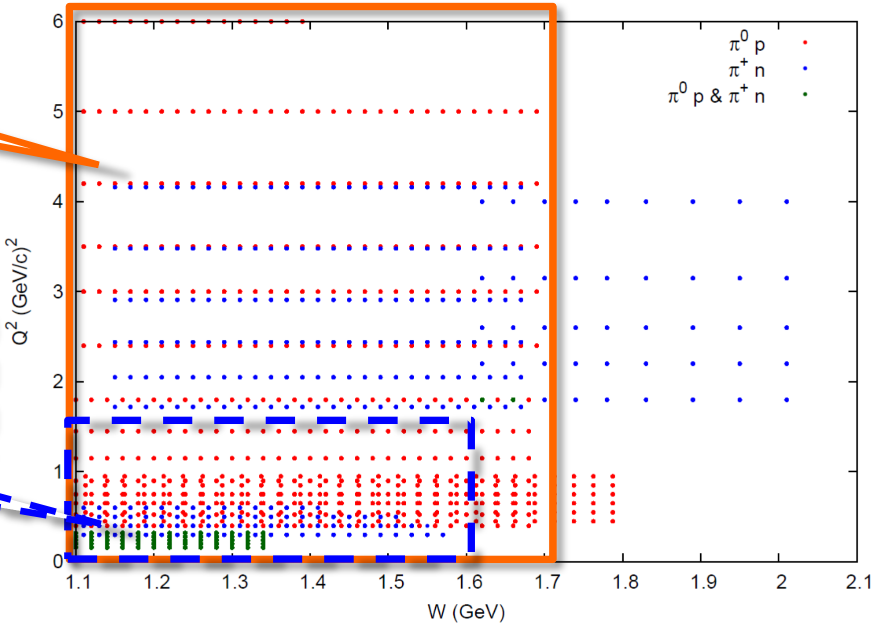
Analysis of electroproduction reactions: Determining N-N* e.m. transition form factors

- Meson **electro**productions:



N-N* e.m. transition form factor

Database for 1π electroproduction@CLAS6 ($Q^2 < 6$ GeV^2)



(W,Q^2) region in the current analysis ($Q^2 < 6$ GeV^2, $W < 1.7$ GeV)

(W,Q^2) region in the early analysis:
Julia-Diaz, HK, Lee, Matsuyama, Sato, Suzuki, PRC80(2009)025207

+ $K^+\Lambda$, $K^+ \Sigma^0$, $\pi\pi N$ *electro-production data*

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

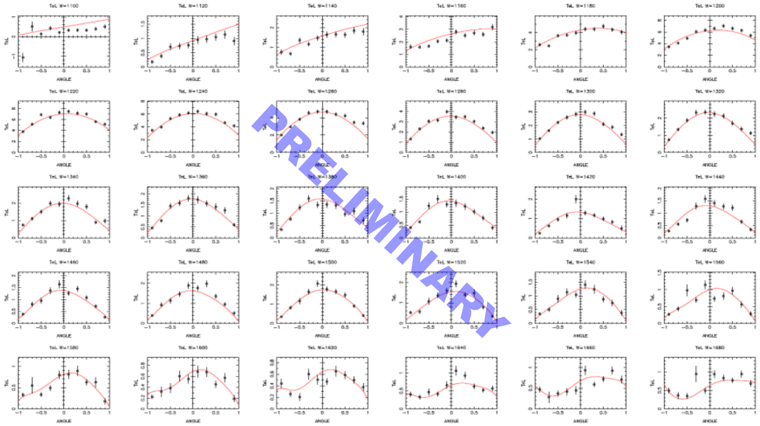
$$\frac{d\sigma^5}{dE_{e'}d\Omega_{e'}d\Omega^*_\pi} = \Gamma_\gamma\left[\sigma_T + \epsilon\sigma_L + \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}\cos\phi^*_\pi + \epsilon\sigma_{TT}\cos 2\phi^*_\pi + h_e\sqrt{2\epsilon(1-\epsilon)}\sigma_{LT'}\sin\phi^*_\pi\right].$$

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

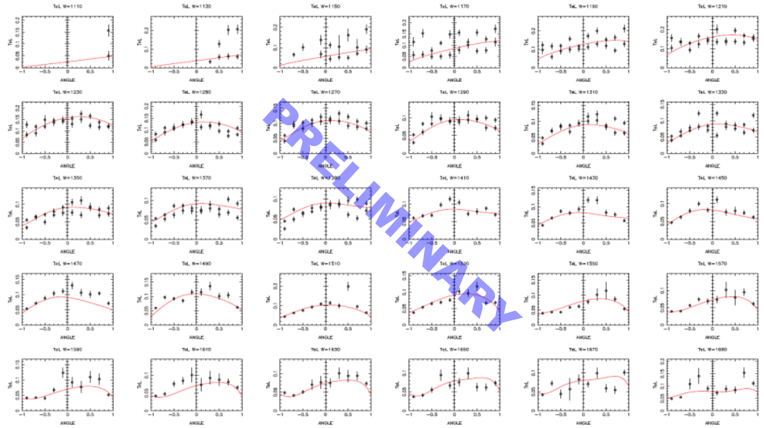
$\sigma_T+\varepsilon\sigma_L$ for $ep \rightarrow e\pi^0 p$

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

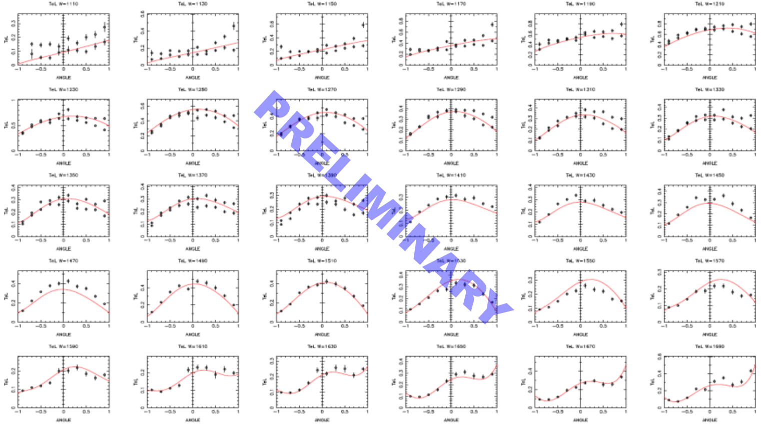
Q^2 = 1.15 GeV^2, 1.10 < W < 1.69 GeV



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

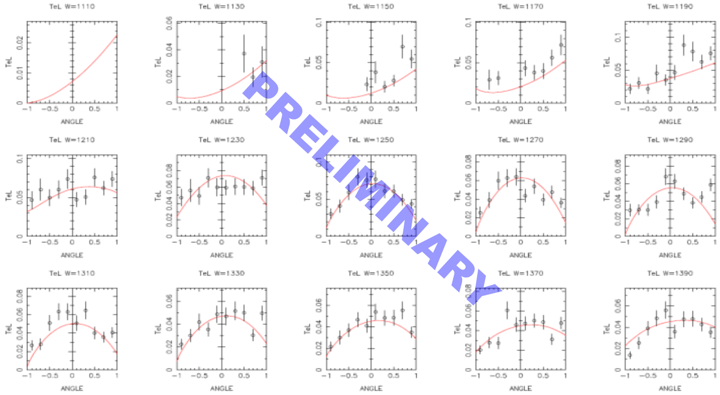


Q^2 = 3.0 GeV^2, 1.11 < W < 1.69 GeV



cosθ

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

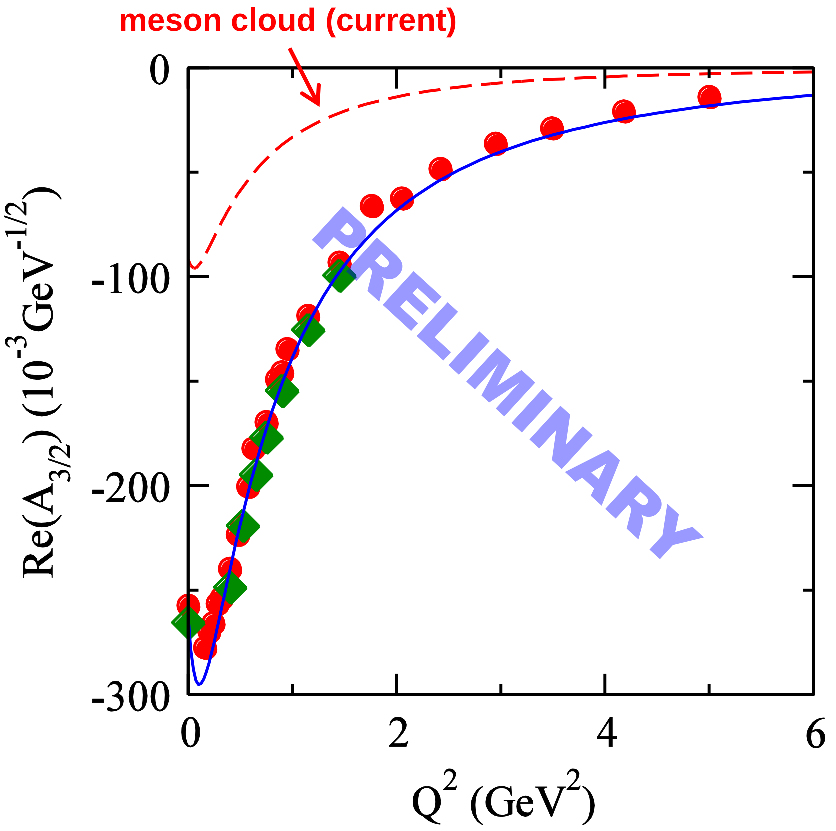


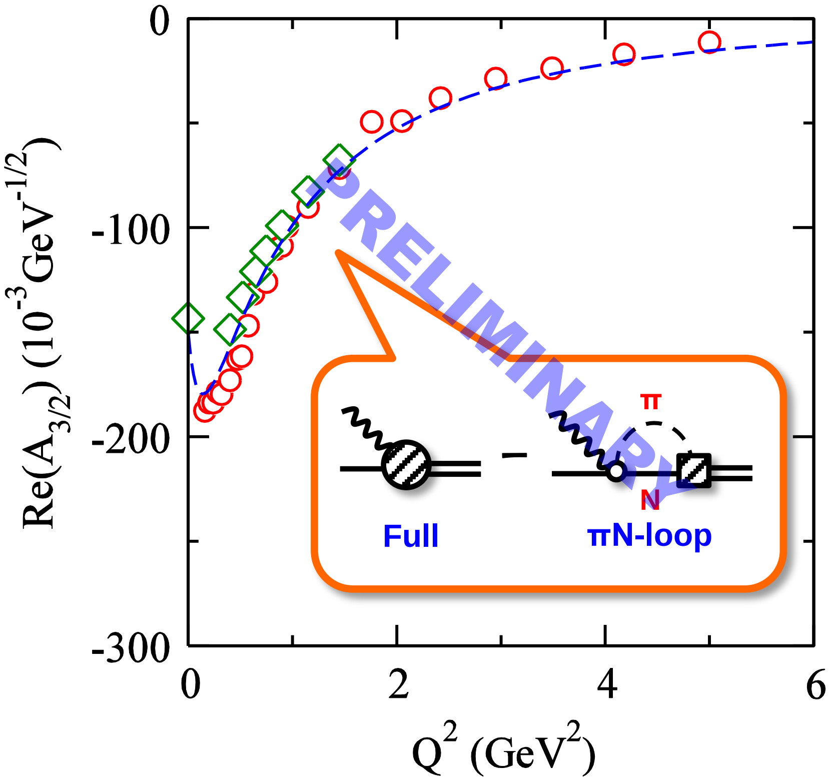
cosθ

Extracted 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]

Summary

✓ **N* & Δ* spectroscopy as physics of broad & overlapping resonances**

- **Cooperative efforts between experiments and theoretical analyses with coupled-channels framework are indispensable to establishing the spectrum.**
- **Reaction dynamics is a crucial part of understanding the spectrum, dynamical origin, and structure, ... of N* & Δ*.**
- **Dynamical coupled-channels approach is a suitable one to study the role of reaction dynamics.**
  - → **Multichannel reaction dynamics in the origin of P_{11} N* resonances.**
  - → **Meson-cloud effect on the transition form factors.**

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- Establishing high-mass N* & Δ* resonances [$\mathrm{Re}(M_R) > 1.7$ GeV]
  - ➔ "(over-)complete" experiments for photoproduction reactions (CLAS6, ELSA, MAMI,...)

- Determining Q^2 dependence of electromagnetic transition form factors for well-established low-lying N* & Δ* resonances.
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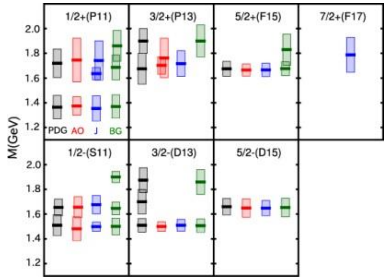
Electroproduction analysis & extension of our DCC model are underway !!

Back up

Applications of ANL-DCC approach

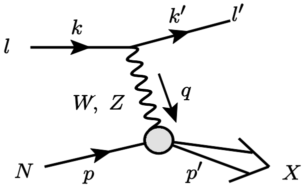
N* & Δ* spectroscopy

- **Early analyses of πN & γN reactions**:
  PRC76(2007)065201; 77(2008)045205; 78(2008)025204
  PRC79(2009)025206; 80(2009)065203; 81(2010)065207
  PRL104(2010)042302
- **Latest analysis of πN & γN reactions**:
  PRC88(2013)035209; 88(2013)045203; 94(2016)015201
- **Electroproduction analysis & Form factor extraction**:
  PRC80(2009)025207; 82(2010)045206

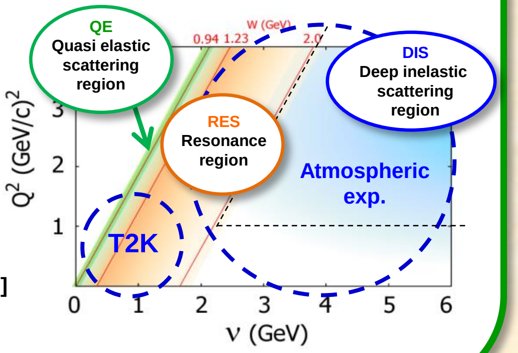


Neutrino reactions

- **Calculation in $Q^2 = 0$ limit**:
  PRD86(2012)097503
- **Full DCC-model calculation up to W = 2 GeV, $Q^2 = 3$ GeV^2**:
  PRD92(2015)074024



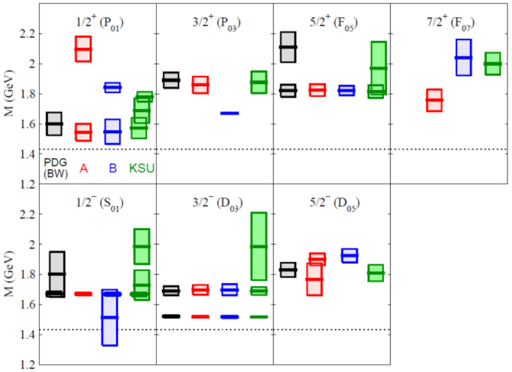
Collaboration@J-PARC Branch,
KEK Theory Center [arXiv:1303.6032]
http://j-parc-th.kek.jp/html/English/e-index.html



ANL-Osaka
DCC approach

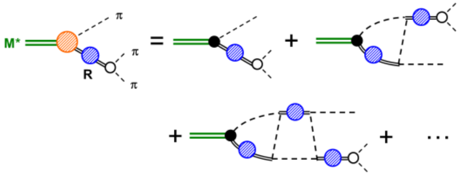
Λ* & Σ* spectroscopy

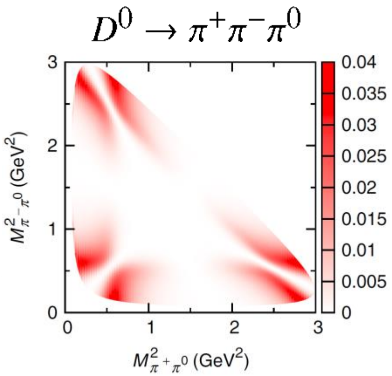
- **Λ*, Σ* resonance extractions via analysis of K⁻p reactions**:
  PRC90(2014)065204; 92(2015)025205



Meson spectroscopy

- **Formulation of 3-body unitary model for decays of mesons**:
  PRD84(2011)114019
- **Application to γp → M*N → (3π)N**:
  PRD86(2012)114012





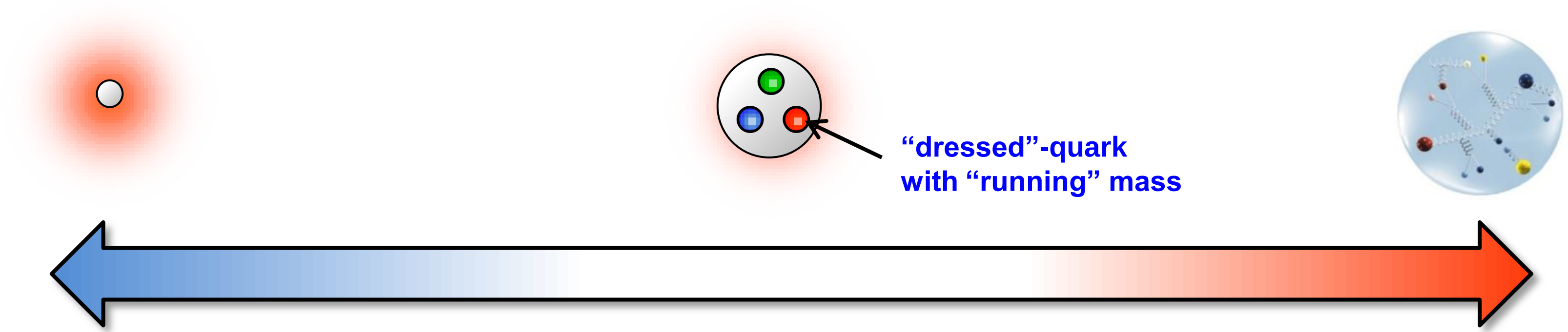
Substructure of N* & Δ*

See, e.g., ECT* workshop "Nucleon Resonances: From Photoproduction to High Photon Virtualities", Oct. 2015
http://www.ectstar.eu/node/1227

"dressed"-quark core
obscured by dense meson clouds

Meson clouds become small;
"dressed"-quark core dominates

"Partons"



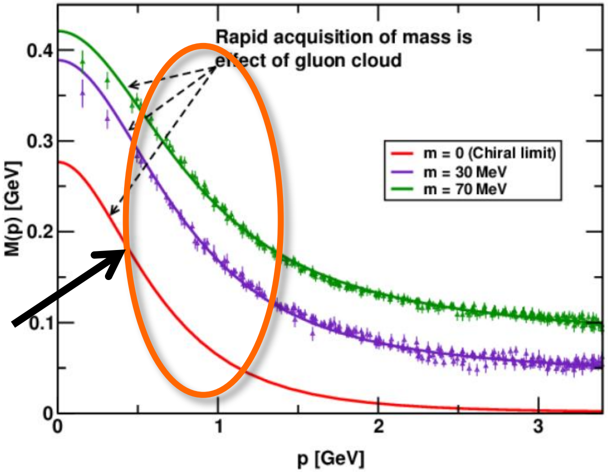
"dressed"-quark
with "running" mass

Q^2: small
(low "resolution")

Q^2: large
(high "resolution")

Running dressed quark mass

"constituent" quark ⟷ "current" quark



Will be accessed by
CLAS12@JLab
(E12-09-003, E12-06-108A)

Curves: a model based on
Dyson-Schwinger
equations (Landau gauge)

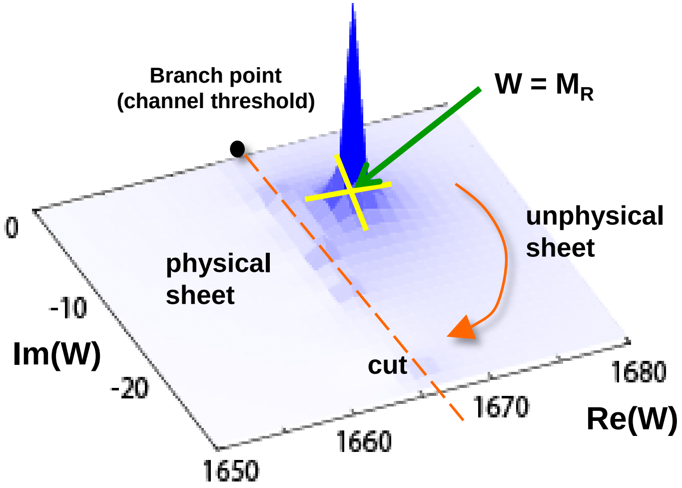
Points: Lattice QCD

e.g.) Cloet, Roberts,
Prog.Part.Nucl.Phys.77(2014)1

Baryon resonances as poles of scattering amplitudes

PROPER definition of

- ✓ **Hadron resonance masses (complex)** ➔ **Pole positions of scattering amplitudes in the lower-half of complex-W plane**
- ✓ **Transition amplitudes between resonance and scattering states** ➔ **~ Residues$^{1/2}$ at the pole**



Residue at the pole
~ $\langle p_b|V|R\rangle \times \langle R|V|p_a\rangle$

$$\langle p_b|\hat{T}(E)|p_a\rangle\Big|_{E\to M_R} \rightarrow \frac{R_{b,a}}{E-M_R} + (\text{regular terms})$$

Resonance pole position
(Im(M$_R$) < 0)

Extracting poles of amplitudes from analyzing reaction data is nothing but obtaining *"exact"* energy eigenvalues of QCD !!!

Baryon resonances as poles of scattering amplitudes

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

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

Energy eigenvalue = pole energy

Transition matrix elements between resonance and scattering states ~ Residues$^{1/2}$ at the pole

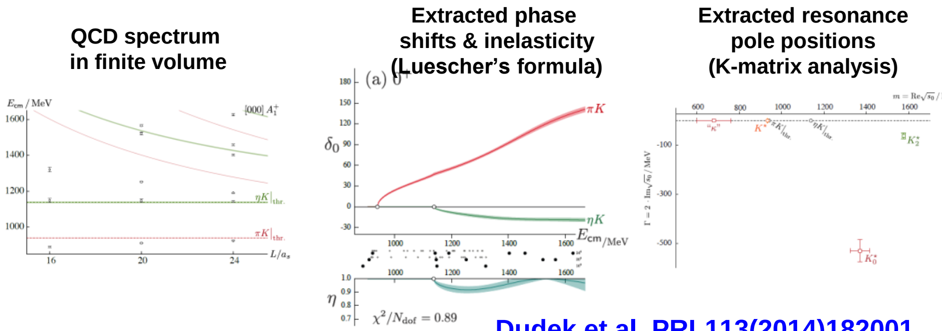
Extracting poles of amplitudes from analyzing reaction data is nothing but obtaining *"exact"* energy eigenvalues of QCD !!!

Baryon resonances as poles of scattering amplitudes

PROPER definition of

- ✓ Hadron resonance masses (comple
- ✓ Transition amplitudes between resonance and scattering states

There are attempts to link real energy spectrum of QCD in the finite volume to resonance pole masses.


QCD spectrum in finite volume

Extracted phase shifts & inelasticity (Luescher's formula)

Extracted resonance pole positions (K-matrix analysis)

Dudek et al, PRL113(2014)182001

Resonance theory based o

[G. Gamow (1928), R. E. Peierls

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Purely Outgoing Boundary Conditio

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