N* transition form factors from the ANL-Osaka dynamical coupled-channels analysis of meson electroproductions

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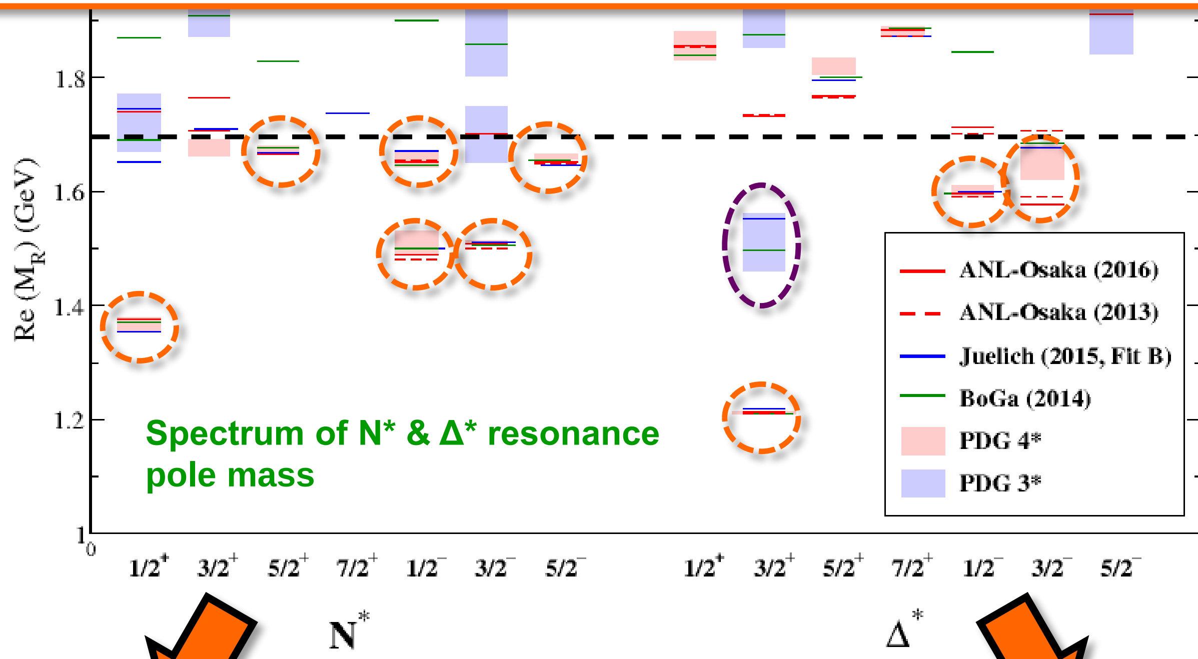
Current trends in N* spectroscopy

N* & Δ* resonances below Re(M_R) ~ 1.7 GeV have been established !!

[One exception: *Roper-like state of Δ* (Δ(1600)3/2⁺ in PDG notation)]



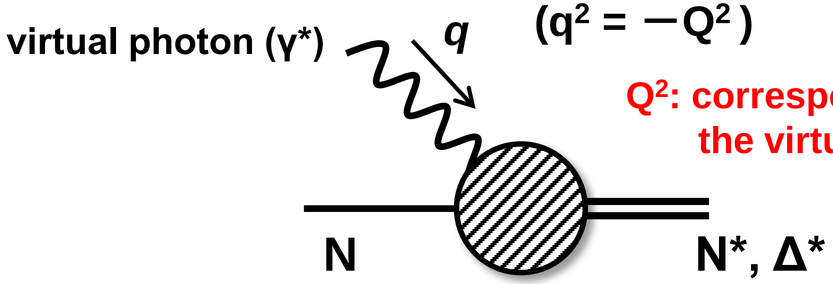
1) Establishing spectrum of high-mass N* & Δ* resonances [Re(M_R) > 1.7 GeV]

- ✓ "Complete" experiments for photoproduction reactions (ELSA, JLab, LEPS, MAMI,...)
- ✓ High-statistics measurements of pion-induced reactions: πN → ππN, KΛ, KΣ,... (GSI, J-PARC,...)

2) Clarifying substructure of well-established N* & Δ* resonances

- ✓ Electroproduction reactions (Q^2>0 region) (JLab,...)
- ✓ Lepton-pair/baryon-pair productions (Q^2<0 region) (Belle, BES, GSI,...)

Electromagnetic transition form factors:
Key element of N* & Δ* substructure studies



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

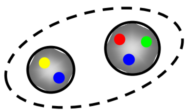
Q^2: corresponds to "resolution" of the virtual photon

e.m. N* transition form factor

e.g.) Roper resonance from DCC models (at long distance scales)

- **"core" + meson cloud**
  Suzuki et al., PRL104(2010)042302

- **meson-baryon molecule-like state**
  Ronchen et al., EPJA49(2013)44

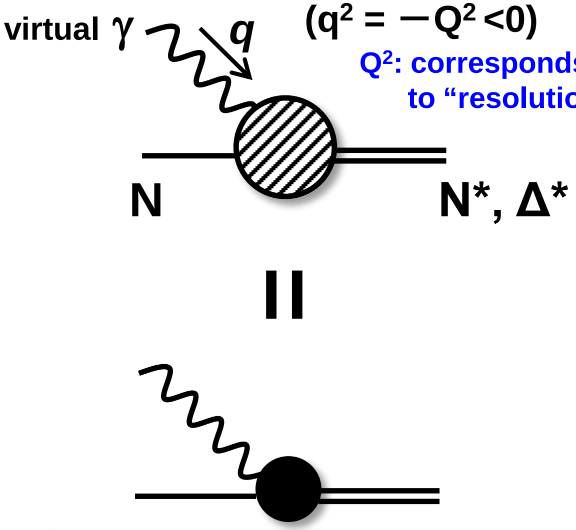


(NOTE: obtained with πN analyses)

Further constraints provided by the e.m. transition form factors could judge the substructure of the Roper resonance !!
[e.g., Segovia et al, PRL115(2015)171801]

Electromagnetic transition form factors:
Key element of N* & Δ* substructure studies

N-N* e.m. transition form factor

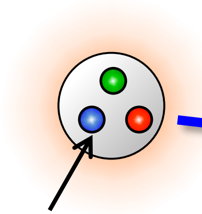


Q^2: corresponds to "resolution"

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)

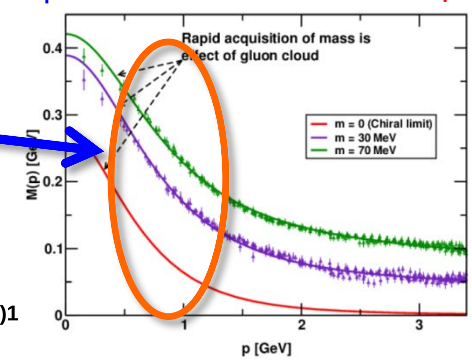
Running dressed quark mass

"constituent" quark ⟷ "current" quark

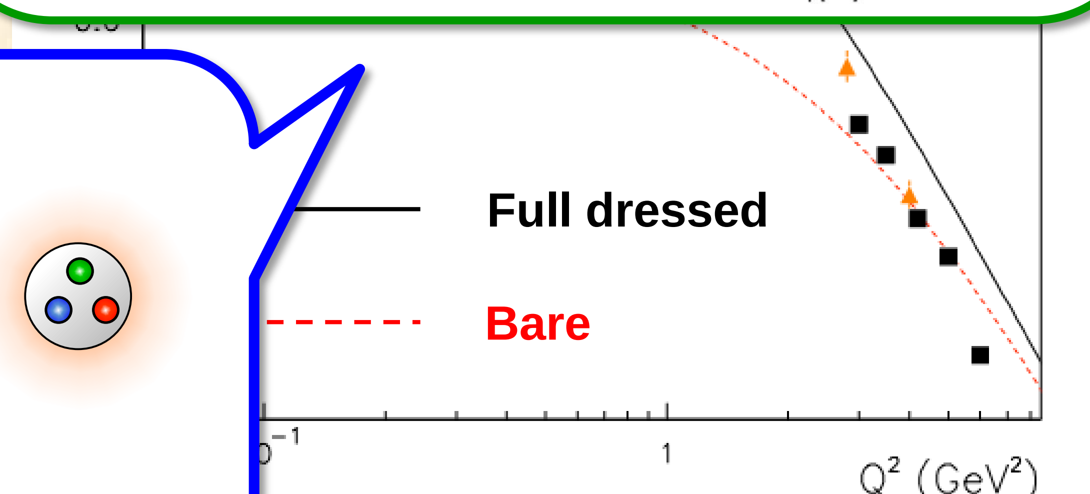


could be accessed with CLAS12 !!

"dressed"-quark with "running" mass

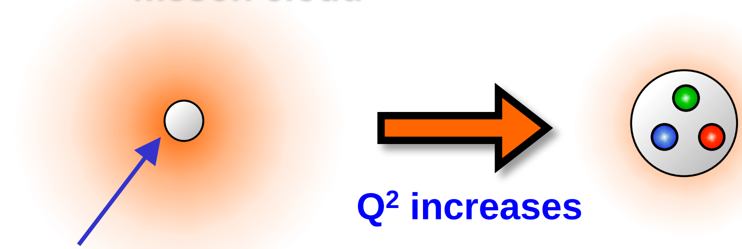


e.g.) Cloet, Roberts, Prog.Part.Nucl.Phys.77(2014)1



...ia-Diaz, Lee, Sato, Smith, PRC75 015205 (2007)

meson cloud



Q^2 increases

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

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

s-channel u-channel t-channel contact

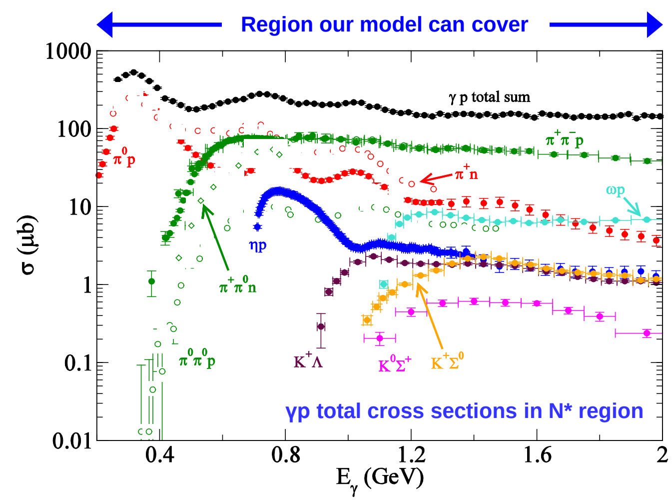
✓ **Construct a model by making χ^2-fit of the world data of π- & γ-induced meson production reactions.**

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

➔ **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.**



N N N Λ Δ

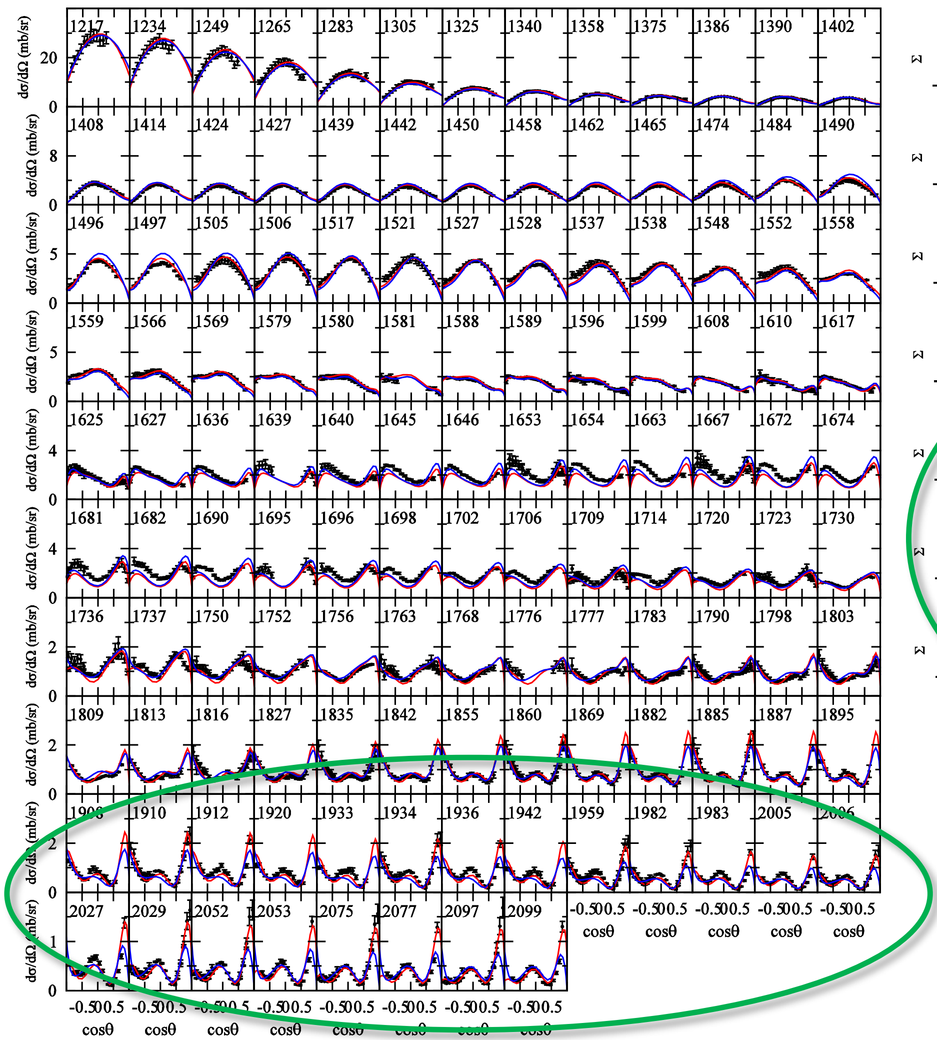
Exchange potentials Z-diagrams bare N* states

ANL-Osaka DCC approach to **N* and Δ***

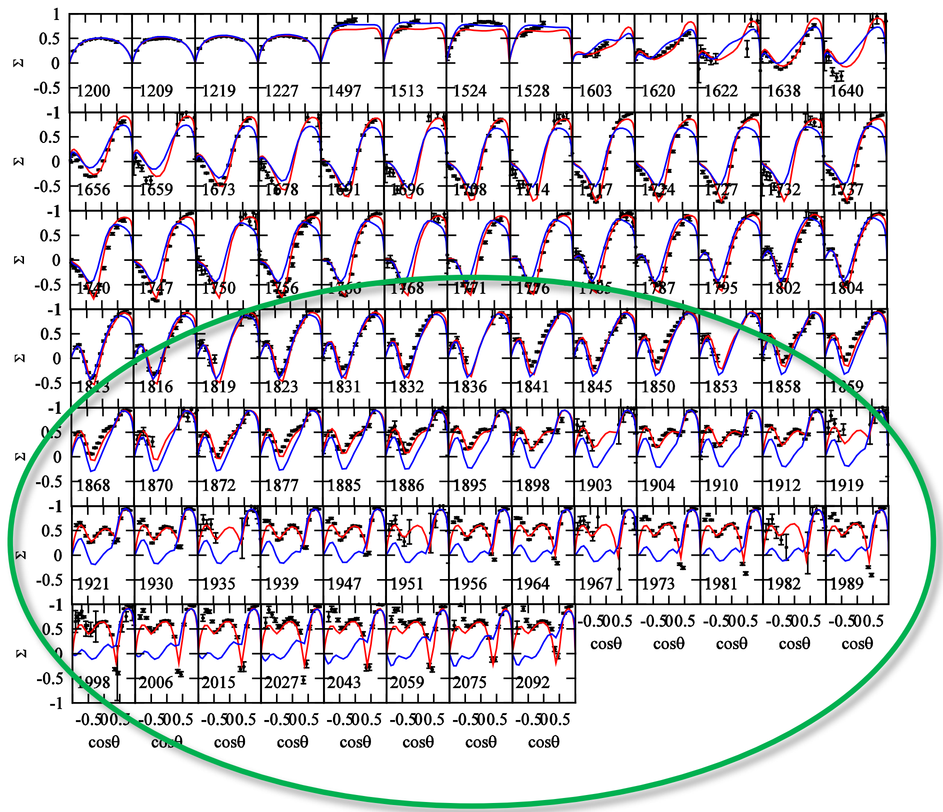
$\gamma p \rightarrow \pi^0 p$

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

dσ/dΩ for W < 2.1 GeV



Σ for W < 2.1 GeV

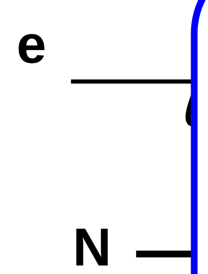


Red: Updated model [PRC94(2016)015201]

Blue: Original model [PRC88(2013)035209]

Analysis of electroproduction reactions to determine N-N* e.m. transition form factors

- **Meson electroproductions:**



✓ **Q^2-dependent (global) analysis:**

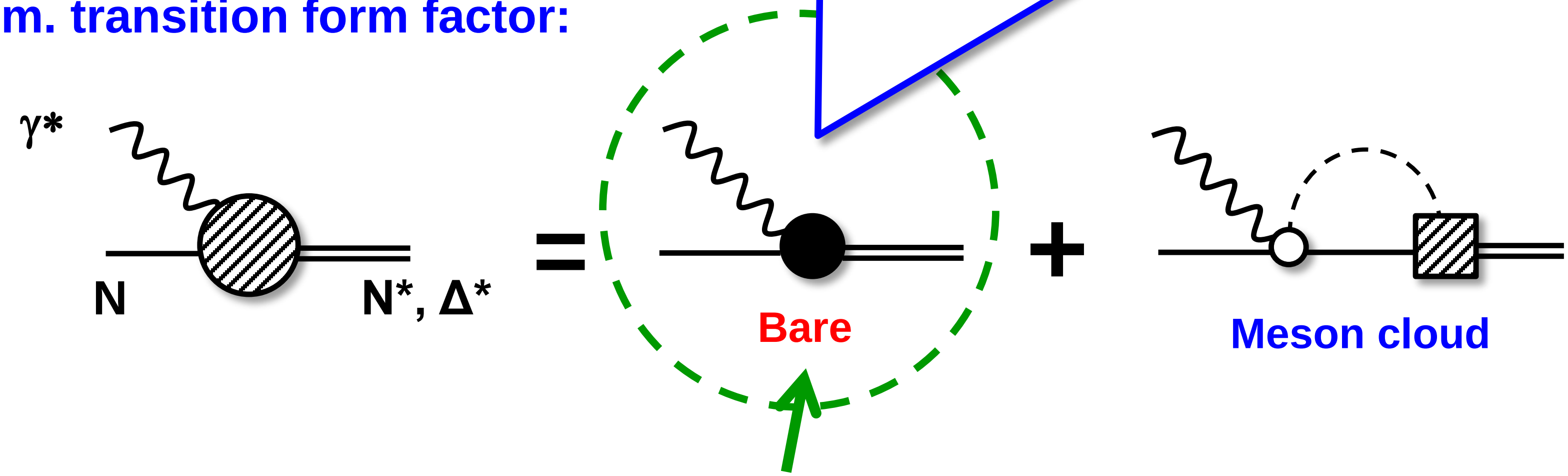
Parametrize "Bare" form factors as a function of Q^2
(Account for smooth Q^2 behavior):
[Sato, Lee, PRC63(2001)055201]

$$F(Q^2) = \left(\frac{1}{1+Q^2/(0.71\mathrm{GeV}^2)}\right) \times (\underline{f_0} + \underline{f_1} Q^2 + \underline{f_2} Q^4 + \cdots) \times \exp(-\underline{f_{\mathrm{exp}}} Q^2)$$

parameters

$$(F = A_{3/2},\ A_{1/2},\ S_{1/2})$$

e.m. transition form factor:



Parameters included only in the "bare" transition form factors are varied.

(Other parameters have been fixed via the combined πN & γN analysis.)

Analysis of single-pion electroproduction reactions

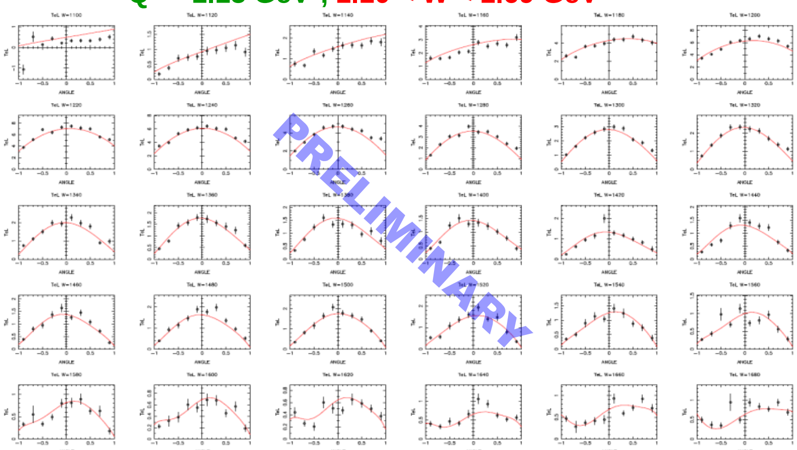
$$\frac{d\sigma^5}{dE_{e'}d\Omega_{e'}d\Omega^*_\pi} = \Gamma_\gamma\left[\sigma_T + \epsilon\sigma_L + \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}\cos\phi^*_\pi + \epsilon\sigma_{TT}\cos 2\phi^*_\pi + h_e\sqrt{2\epsilon(1-\epsilon)}\sigma_{LT'}\sin\phi^*_\pi\right].$$

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

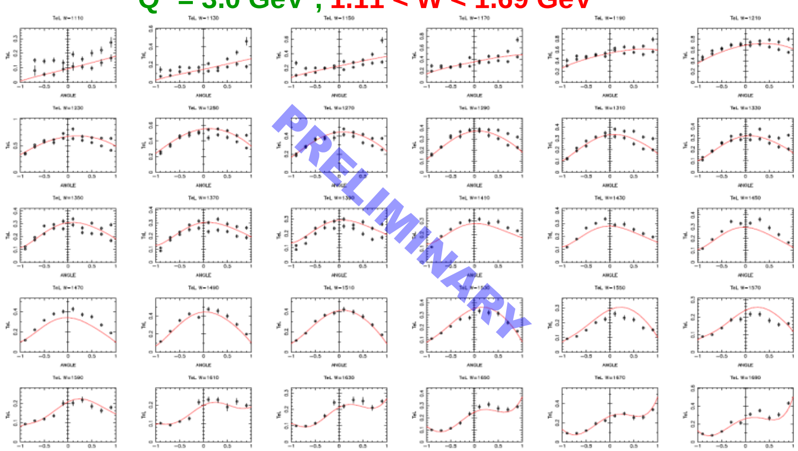
$\sigma_T + \epsilon\sigma_L$ for $ep \rightarrow e'\pi^0 p$

Data for structure functions are provided by K. Joo and L. C. Smith

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

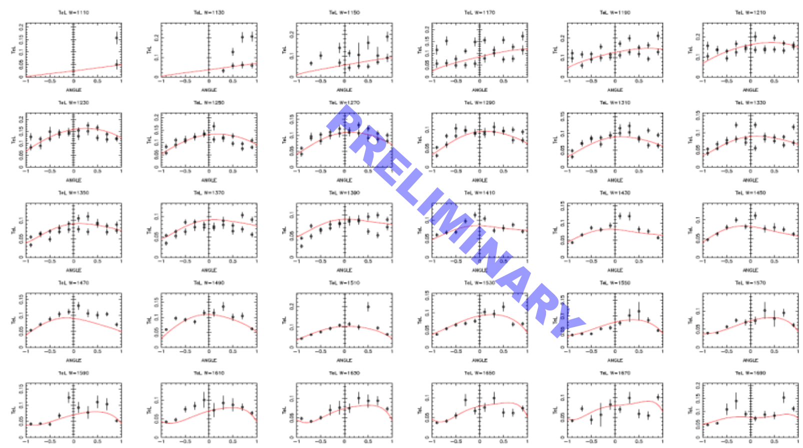


$Q^2 = 3.0$ GeV^2, $1.11 < W < 1.69$ GeV

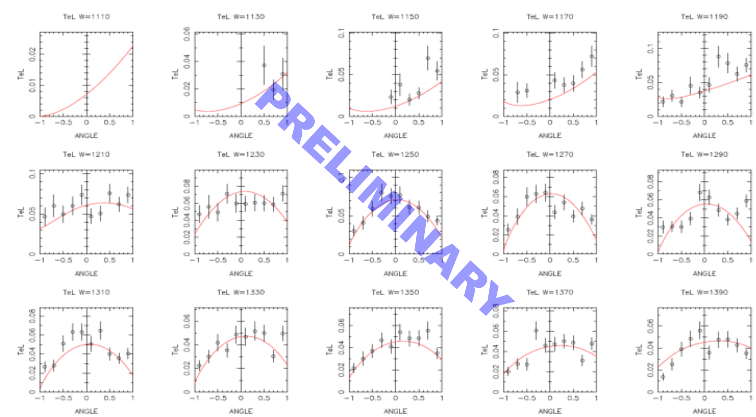


cosθ

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



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



cosθ

Resonance parameters defined by 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 multi-particle states** ➔ **~ Residues$^{1/2}$ at the pole**

Residue at the pole

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* solved under the Purely Outgoing Boundary Condition (POBC)."

Energy eigenvalue = pole energy

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

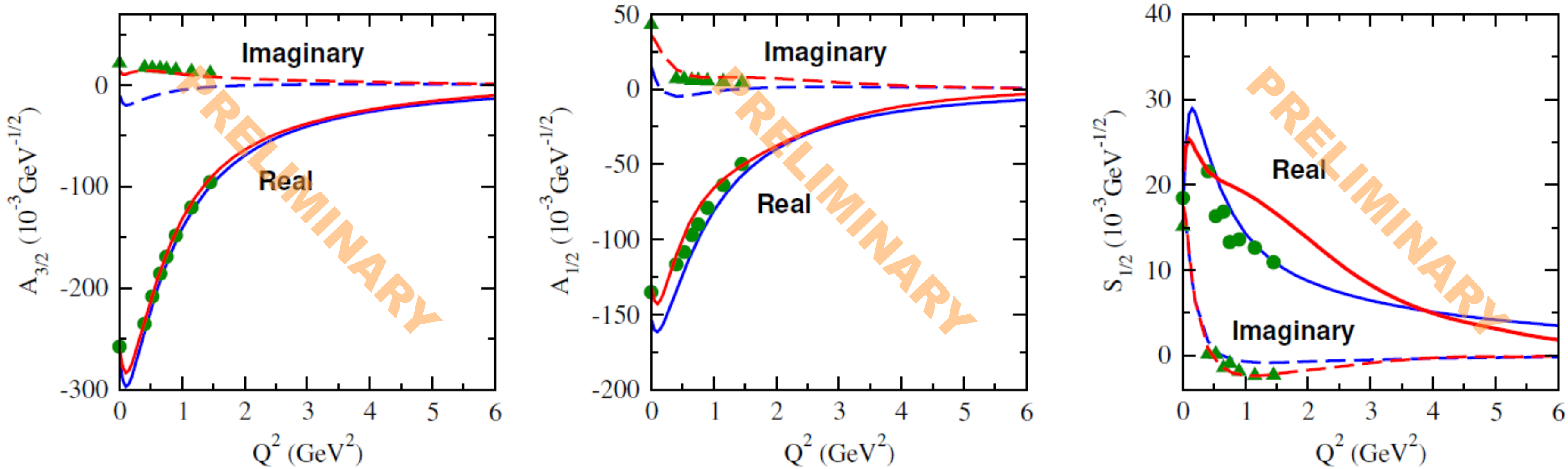
See, e.g., R. de la Madrid, NPA812(2008)13;962(2017)24;arXiv:quant-ph/0201091

Electromagnetic transition form factors evaluated at resonance pole

1st P_{33} resonance [$\Delta(1232)3/2^+$]

Previous: PRC80(2009)025207; 82(2010)045206
Sato-Lee: PRC63(2001)055201; 75(2007)015205

	Current	Previous	Sato-Lee
Re part	red solid line	●	blue solid line
Im part	red dashed line	▲	blue dashed line

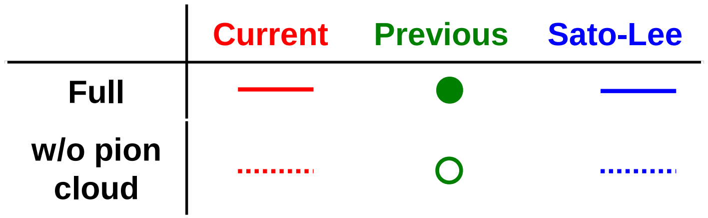


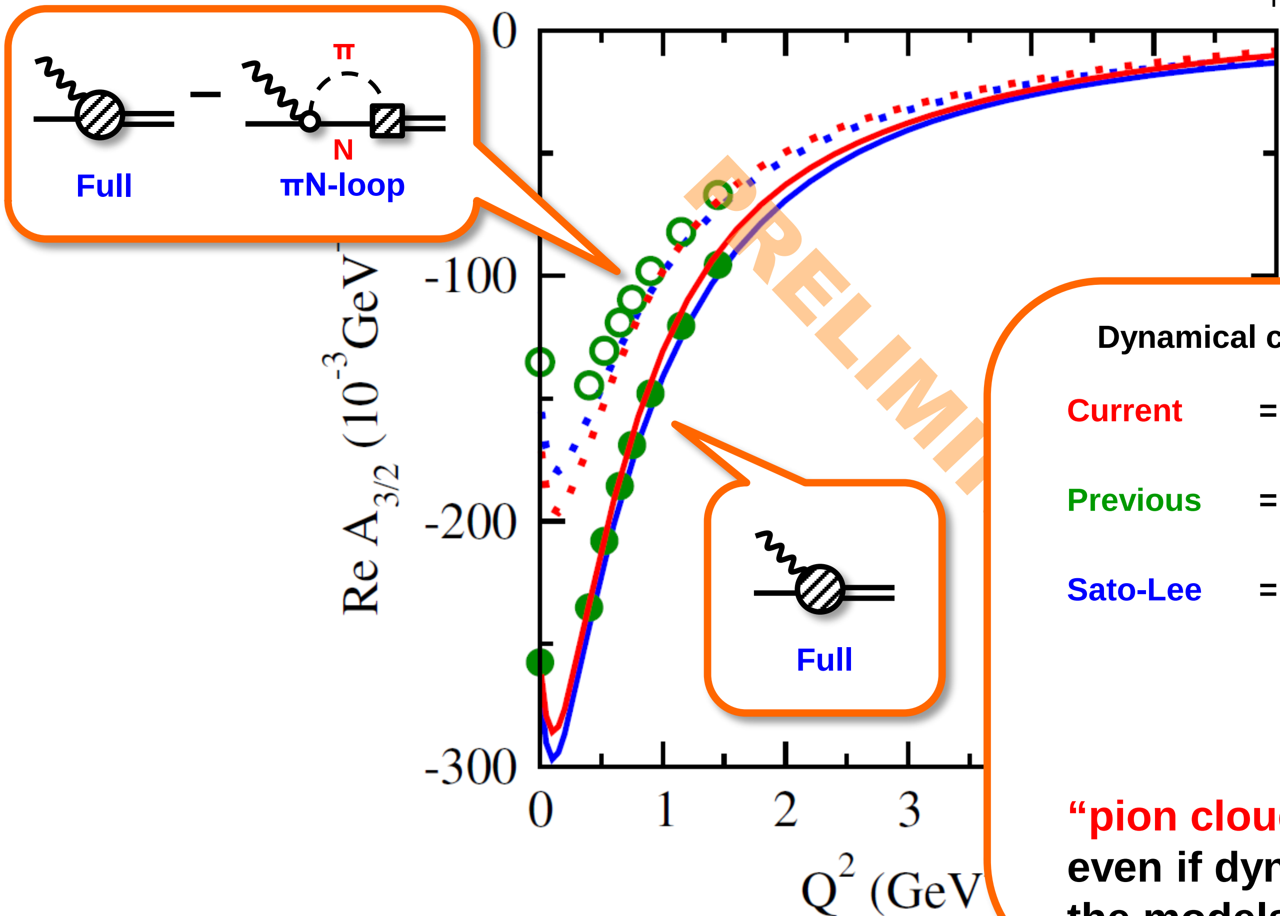
✓ **Evaluated at resonance pole position.**
➔ **Form factors inevitably become complex (fundamental nature of decaying particles).**

✓ **All three dynamical model analyses show a rather convergent results.**
➔ **$\Delta(1232)3/2^+$ e.m. transition form factors (pole definition) seem well established.**

"Pion cloud" contribution

$Re(A_{3/2})$ for $\Delta(1232)3/2^+$





Dynamical contents of the three models

Current = coupled πN, ππN, ηN, KΛ, KΣ
2 bare states in P33

Previous = coupled πN, ππN, ηN
2 bare states in P33

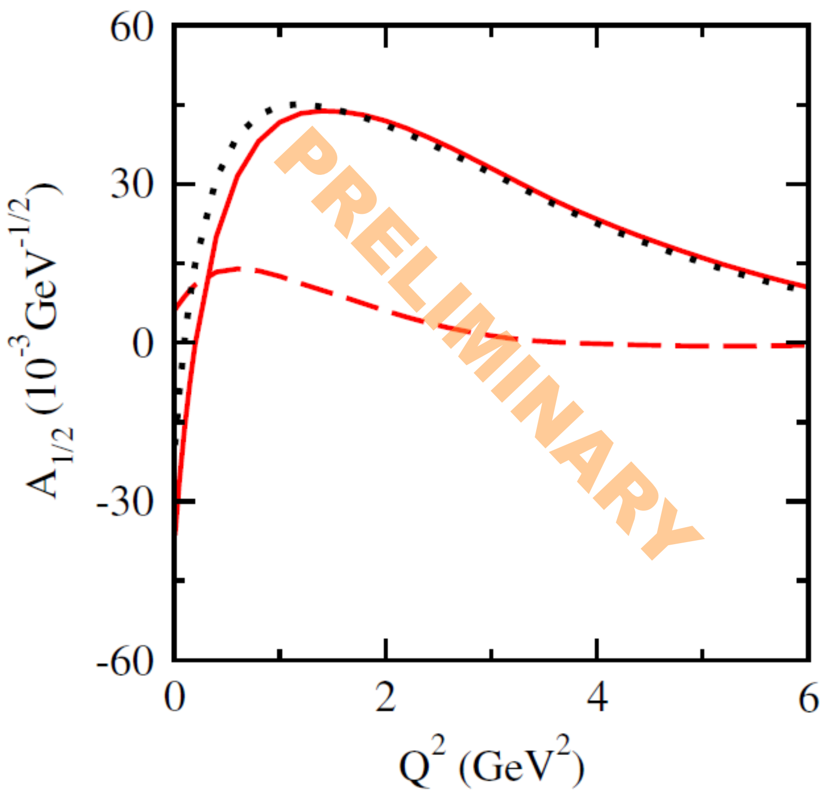
Sato-Lee = single πN
1 bare state in P33

"pion cloud" might also be stable even if dynamical contents of the models are quite different !!

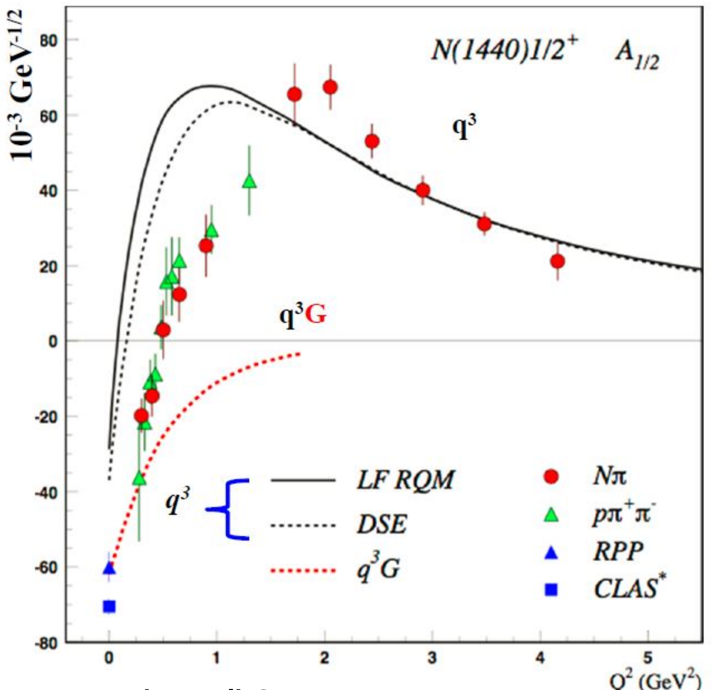
Electromagnetic transition form factors evaluated at resonance pole

Roper resonance [N(1440)1/2⁺]

- ✓ **Imaginary part is small.**
  ➔ **Real part & BW results show similar behavior.**
- ✓ **"w/o pion cloud" shows similar behavior to LFRQM and DSE.**



Full result (real part)
Full result (imaginary part)
w/o "pion cloud" (real part)



R. Gothe's talk@MENU2016

NOTE:
Form factors are REAL within Breit-Wigner (BW) analyses & static hadron models.

Summary

✓ Presented current status for **1π electroproduction analysis** based on **ANL-Osaka DCC approach** in the kinematical region of **$Q^2 < 6$ GeV^2 & $W <\sim 2$ GeV**.

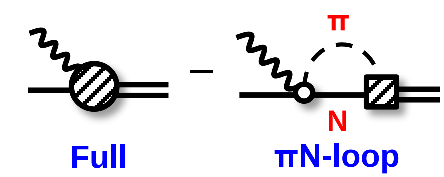
✓ Presented preliminary results of **Δ(1232)3/2$^+$ & N(1440)1/2$^+$** electromagnetic transition form factors **defined by poles**.

Form factors become **complex** !!

- **Δ(1232)3/2$^+$ form factors:**

  - Results from different dynamical models agree very well (particularly for A3/2 & A1/2)
    ➔ seems **well established up to $Q^2 = 6$ GeV^2**.

  - **"pion cloud"** contributions seem also quite similar *regardless of* dynamical models employed



- **N(1440)1/2$^+$ form factors:**

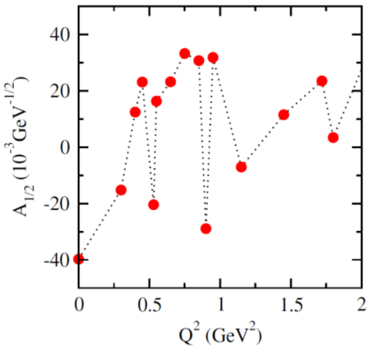
  - **$A_{1/2}$ amplitude w/o "pion cloud"** shows a qualitatively similar behavior to 3-quark model and DSE calculation.

Back up

Strategy for electroproduction analysis

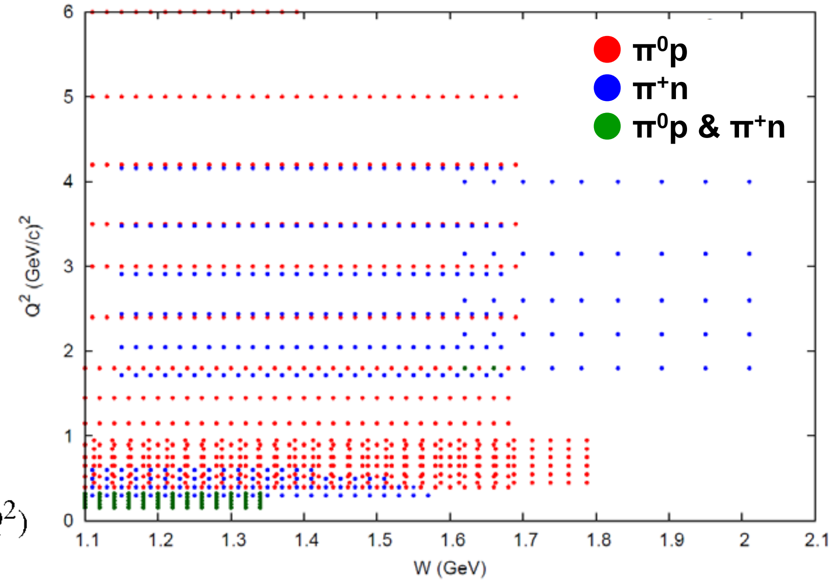
✓ **Q^2 independent analysis:**

Treat "bare" form factors as real parameters; determine them by fitting to each Q^2 independently.



Solution fluctuates a lot!!

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



✓ **Q^2 dependent (global) analysis:**

Parametrize "Bare" form factors as a function of Q^2:
[Sato, Lee, PRC63(2001)055201]

$$F(Q^2) = \left(\frac{1}{1 + Q^2/(0.71\mathrm{GeV}^2)}\right) \times (\underline{f_0} + \underline{f_1} Q^2 + \underline{f_2} Q^4 + \cdots) \times \exp(-\underline{f_{\mathrm{exp}}} Q^2)$$

parameters

$$(F = A_{3/2},\ A_{1/2},\ S_{1/2})$$

Once a global solution is obtained, return to the Q^2 independent analysis using the solution as starting value.

➔ **Similar to the procedure practically applied in the energy independent analyses of πN & γN reactions.**

Analysis of single-pion electroproduction reactions

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

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

$ep \rightarrow e'\pi^0 p$ @ $Q^2 = 0.4$ GeV^2, $1.10 < W < 1.68$ GeV

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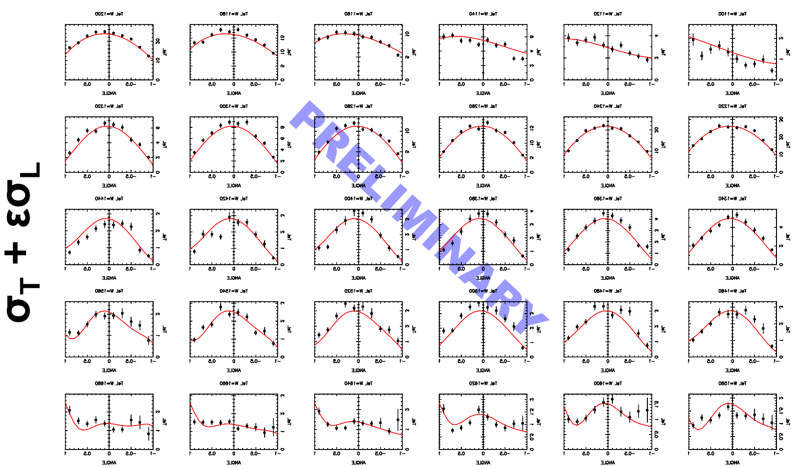

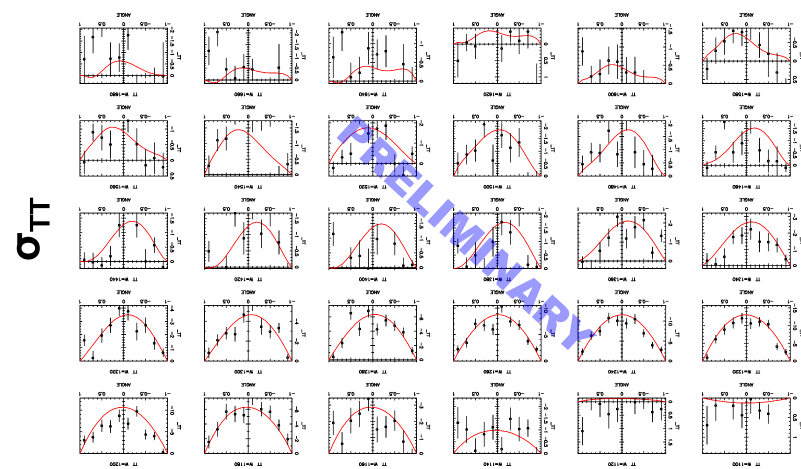

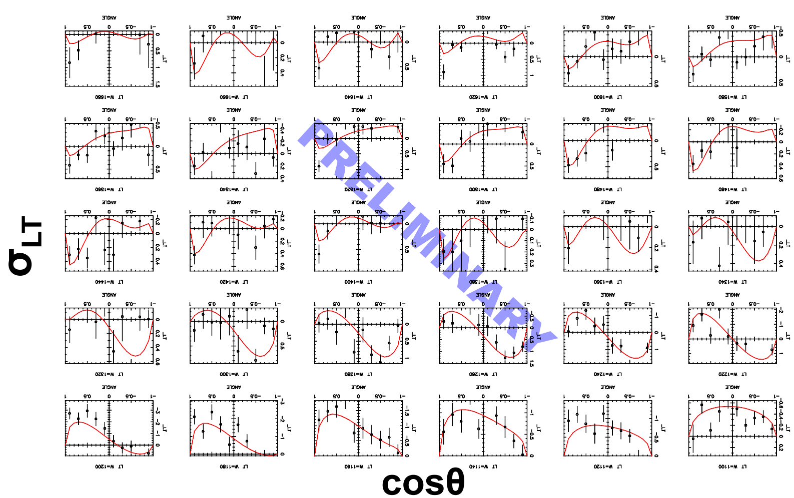

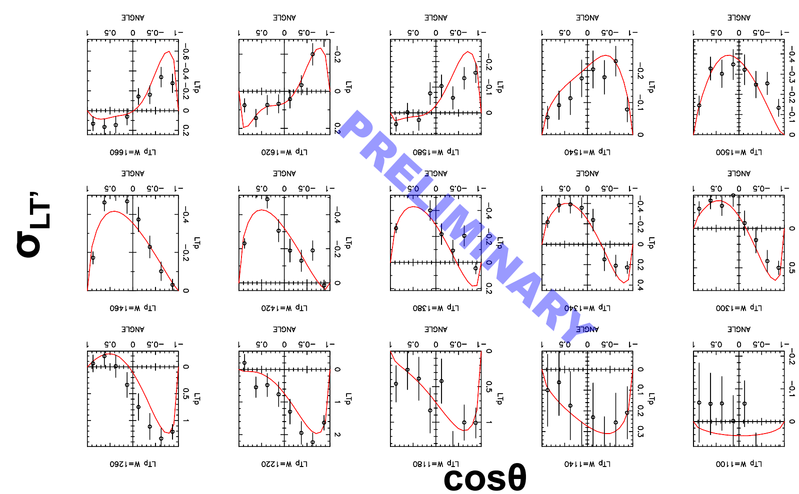

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$$\sigma_\alpha = \sigma_\alpha(W, Q^2, \cos\theta^*_\pi)$$

$ep \rightarrow e'\pi^+ n$ @ $Q^2 = 0.4$ GeV^2, $1.10 < W < 1.53$ GeV

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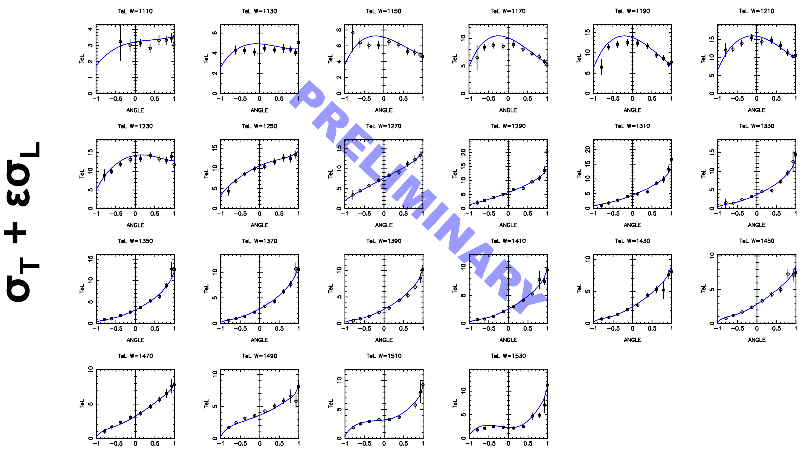
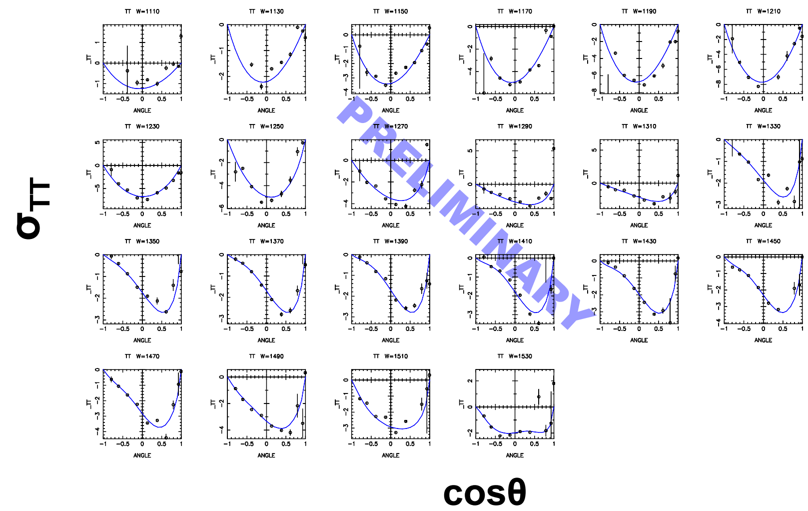
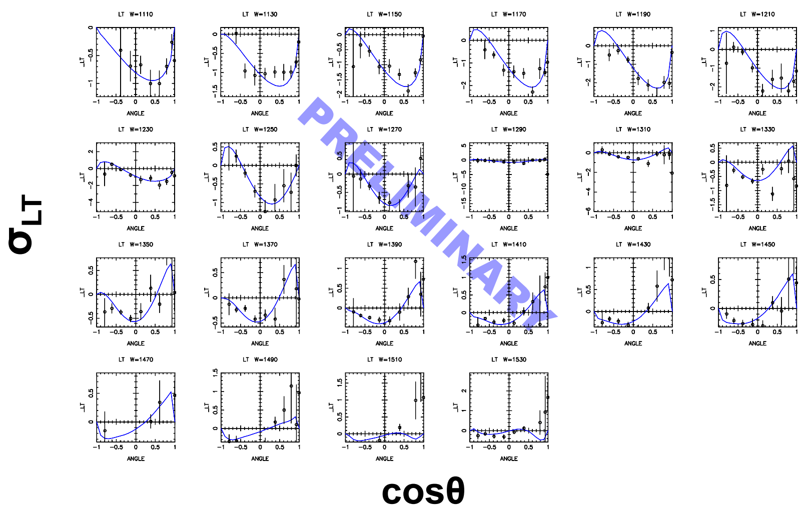


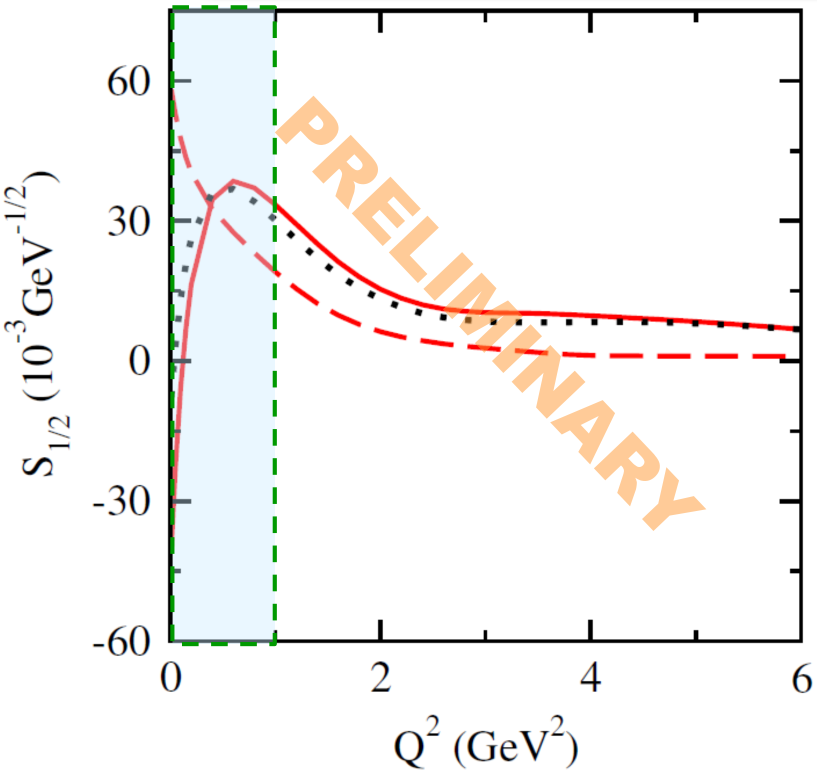




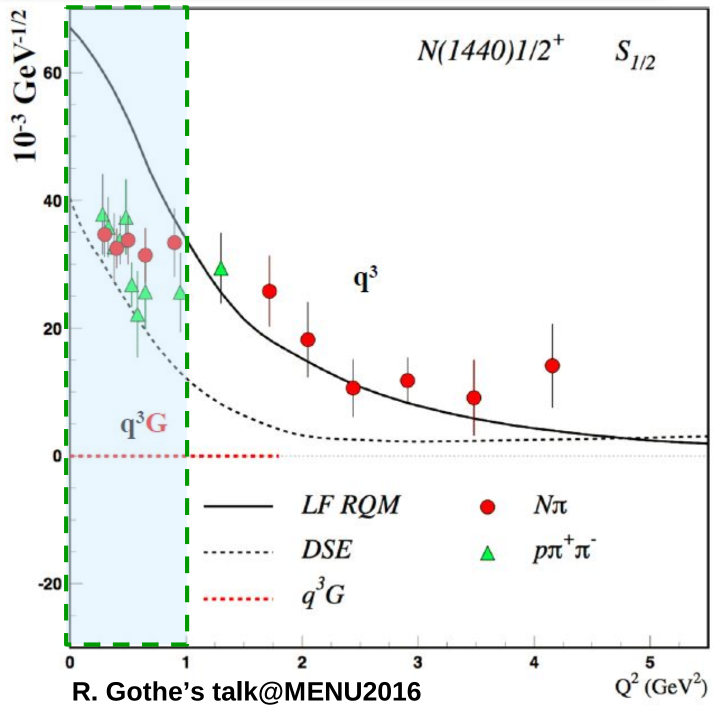
Electromagnetic transition form factors evaluated at resonance pole

Rop

- ✓ **$Q^2 > 1$ GeV^2: Conclusion similar to $A_{1/2}$ is obtained.**
- ✓ **$Q^2 < 1$ GeV^2: Imaginary part is comparable to or larger than real part.**
  ➔ Seems *NO* clear/simple similarity to BW results.



Full result (real part)
Full result (imaginary part)
w/o "pion cloud" (real part)



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