Baryon resonance physics & EBAC

- Why study excited states of the nucleon (N*s)?
- What do we really know about N* states, what are the open issues?
- Goals of the N* program
- Required developments (expt/theory)
- The role of EBAC

Why study N* states?

- The nucleon is a confined system
  - Confinement is poorly understood
  - Highly-excited states are sensitive to details of how quarks are confined
    - Is the confining interaction screened by quark pair creation?
    - Do such states decay strongly by string breaking?
    - Can we see evidence of excitation of the glue?

Why study N* states?

- Nuclei are strongly interacting bound states
  - Can isolate relevant low-energy d.f. (nucleons)
  - Can directly probe two-body potential in experiments
  - Few body bound states of most A exist to test model N-N, N-N-N,… potentials
  - Can systematically expand around non-relativistic limit
    - Heavy effective degrees of freedom
    - Relatively large states
- Hadrons (N*) are unique:
  - Elementary d.f. are confined
  - Can only indirectly infer low-energy interaction
  - Only $qqq,\ q\overline{q}$ are known to exist as bound states
  - Not non-relativistic systems (unless **all** quarks heavy)

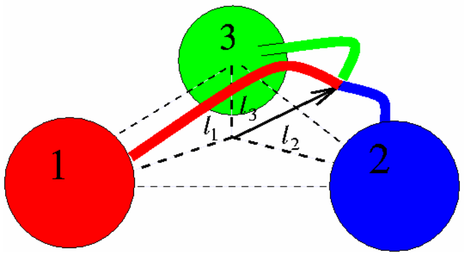
Why study N* states?

- Spectrum and properties of N* states are sensitive to the nature of the important effective degrees of freedom in low-energy QCD
  - High-energy and Q^2 (hard) scattering probes QCD at short-distance
    - With care can apply perturbative QCD
  - QCD becomes complex and interesting in the soft (non-perturbative) regime
    - Can we identify effective degrees of freedom and their interactions?
    - Can we see the soft to hard transition?

Effective degrees of freedom

Low-energy QCD:

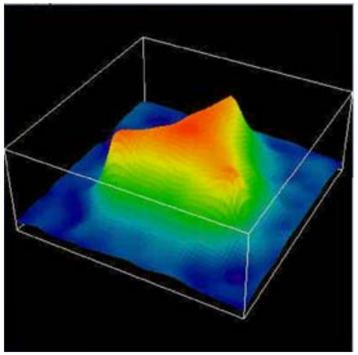
- Constituent quarks (CQs), confined by flux tubes?
- Confined CQs, elementary meson fields?
- Confined CQs, gas of instantons?
- Baryons and mesons interacting via chiral potentials?

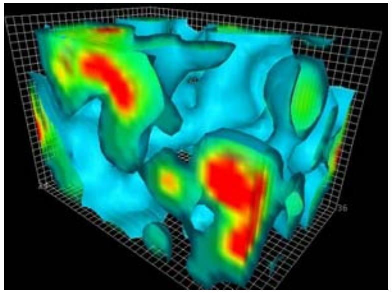


P.Page, S.C. Flux-tube model of baryons & hybrids

Ichie, Bornyakov, Struer & Schierholz

QQQ action density





D. Leinweber et al. QCD vacuum action density

What do we know about N* states?

- PDG lists many excited N and Δ states discovered in πN elastic scattering
  - Notation is $L_{2I,2J}$
    - L is (π,N) relative angular momentum
    - I = total isospin (N=1/2, Δ=3/2), J is total spin

p	P_{11}	****	$\Delta(1232)$	P_{33}	****
n	P_{11}	****	$\Delta(1600)$	P_{33}	***
$N(1440)$	P_{11}	****	$\Delta(1620)$	S_{31}	****
$N(1520)$	D_{13}	****	$\Delta(1700)$	D_{33}	****
$N(1535)$	S_{11}	****	$\Delta(1750)$	P_{31}	*
$N(1650)$	S_{11}	****	$\Delta(1900)$	S_{31}	**
$N(1675)$	D_{15}	****	$\Delta(1905)$	F_{35}	****
$N(1680)$	F_{15}	****	$\Delta(1910)$	P_{31}	****
$N(1700)$	D_{13}	***	$\Delta(1920)$	P_{33}	***
$N(1710)$	P_{11}	***	$\Delta(1930)$	D_{35}	***
$N(1720)$	P_{13}	****	$\Delta(1940)$	D_{33}	*
$N(1900)$	P_{13}	**	$\Delta(1950)$	F_{37}	****
$N(1990)$	F_{17}	**	$\Delta(2000)$	F_{35}	**
$N(2000)$	F_{15}	**	$\Delta(2150)$	S_{31}	*
$N(2080)$	D_{13}	**	$\Delta(2200)$	G_{37}	*
$N(2090)$	S_{11}	*	$\Delta(2300)$	H_{39}	**
$N(2100)$	P_{11}	*	$\Delta(2350)$	D_{35}	*
$N(2190)$	G_{17}	****	$\Delta(2390)$	F_{37}	*
$N(2200)$	D_{15}	**	$\Delta(2400)$	G_{39}	**
$N(2220)$	H_{19}	****	$\Delta(2420)$	$H_{3,11}$	****
$N(2250)$	G_{19}	****	$\Delta(2750)$	$I_{3,13}$	**
$N(2600)$	$I_{1,11}$	***	$\Delta(2950)$	$K_{3,15}$	**
$N(2700)$	$K_{1,13}$	**			

N* states…

- **If** we were able to classify resonances into $SU(6)_{fs} \otimes O(3)$ multiplets
  - Complicated by strong configuration mixing
- Good evidence for **all** negative parity N* (Δ*) predicted in lowest (N=1) band $[SU(6)_{fs}, L^P] = [70, 1^-]$
  - Also $\Delta(1930)D_{35}$ & $\Delta(1950)F_{37}$ in N=3 band

What do we really know?

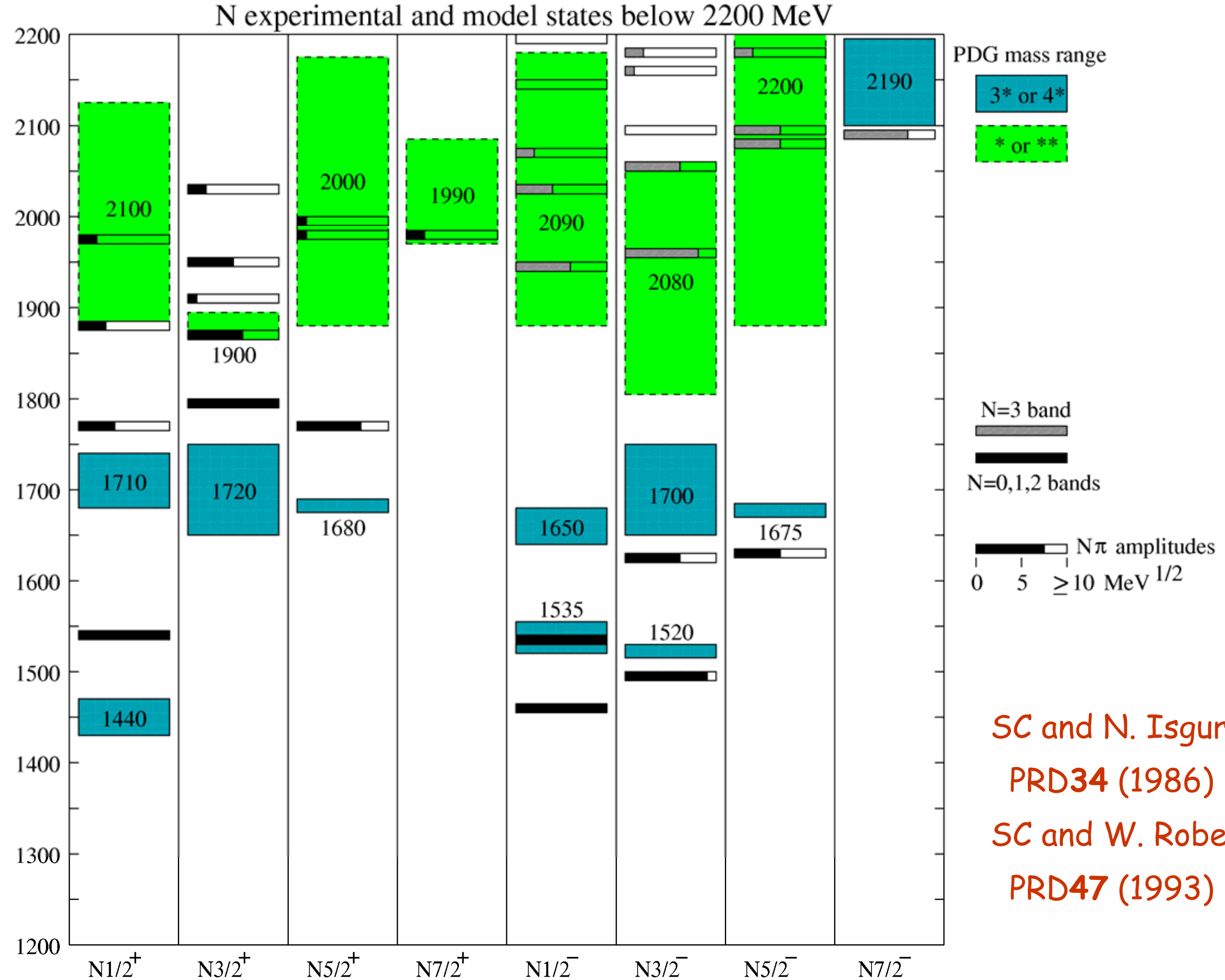
Table 1. The status of the N and Δ resonances. Only those with an overall status of *** or **** are included in the main Baryon Summary Table.

Particle	$L_{2I \cdot 2J}$	Overall status	$N\pi$	$N\eta$	ΛK	ΣK	$\Delta\pi$	$N\rho$	$N\gamma$
			Status as seen in —						
$N(939)$	P_{11}	****							
$N(1440)$	P_{11}	****	****	*			***	*	***
$N(1520)$	D_{13}	****	****	*			****	****	****
$N(1535)$	S_{11}	****	****	****			*	**	***
$N(1650)$	S_{11}	****	****	*	***	**	***	**	***
$N(1675)$	D_{15}	****	****	*	*		****	*	****
$N(1680)$	F_{15}	****	****				****	****	****
$N(1700)$	D_{13}	***	***	*	**	*	**	*	**
$N(1710)$	P_{11}	***	***	**	**	*	**	*	***
$N(1720)$	P_{13}	****	****	*	**	*	*	**	**
$N(1900)$	P_{13}	**	**					*	
$N(1990)$	F_{17}	**	**	*	*	*			*
$N(2000)$	F_{15}	**	**	*	*	*	*	**	
$N(2080)$	D_{13}	**	**	*	*				*
$N(2090)$	S_{11}	*	*						
$N(2100)$	P_{11}	*	*	*					
$N(2190)$	G_{17}	****	****	*	*	*		*	*
$N(2200)$	D_{15}	**	**	*	*				
$N(2220)$	H_{19}	****	****	*					
$N(2250)$	G_{19}	****	****	*					
$N(2600)$	$I_{1\,11}$	***	***						
$N(2700)$	$K_{1\,13}$	**	**						

Particle	$L_{2I \cdot 2J}$	Overall status	$N\pi$	$N\eta$	ΛK	ΣK	$\Delta\pi$	$N\rho$	$N\gamma$
			Status as seen in —						
$\Delta(1232)$	P_{33}	****	****	F					****
$\Delta(1600)$	P_{33}	***	***	o			***	*	**
$\Delta(1620)$	S_{31}	****	****	r			****	****	***
$\Delta(1700)$	D_{33}	****	****	b		*	***	**	***
$\Delta(1750)$	P_{31}	*	*	i					
$\Delta(1900)$	S_{31}	**	**	d		*	*	**	*
$\Delta(1905)$	F_{35}	****	****	d		*	**	**	***
$\Delta(1910)$	P_{31}	****	****	e		*	*	*	*
$\Delta(1920)$	P_{33}	***	***	n		*	**		*
$\Delta(1930)$	D_{35}	***	***			*			**
$\Delta(1940)$	D_{33}	*	*	F					
$\Delta(1950)$	F_{37}	****	****	o		*	****	*	****
$\Delta(2000)$	F_{35}	**		r				**	
$\Delta(2150)$	S_{31}	*	*	b					
$\Delta(2200)$	G_{37}	*	*	i					
$\Delta(2300)$	H_{39}	**	**	d					
$\Delta(2350)$	D_{35}	*	*	d					
$\Delta(2390)$	F_{37}	*	*	e					
$\Delta(2400)$	G_{39}	**	**	n					
$\Delta(2420)$	$H_{3\,11}$	****	****						*
$\Delta(2750)$	$I_{3\,13}$	**	**						
$\Delta(2950)$	$K_{3\,15}$	**	**						

**** Existence is certain, and properties are at least fairly well explored.
*** Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, *etc.* are not well determined.
** Evidence of existence is only fair.
* Evidence of existence is poor.

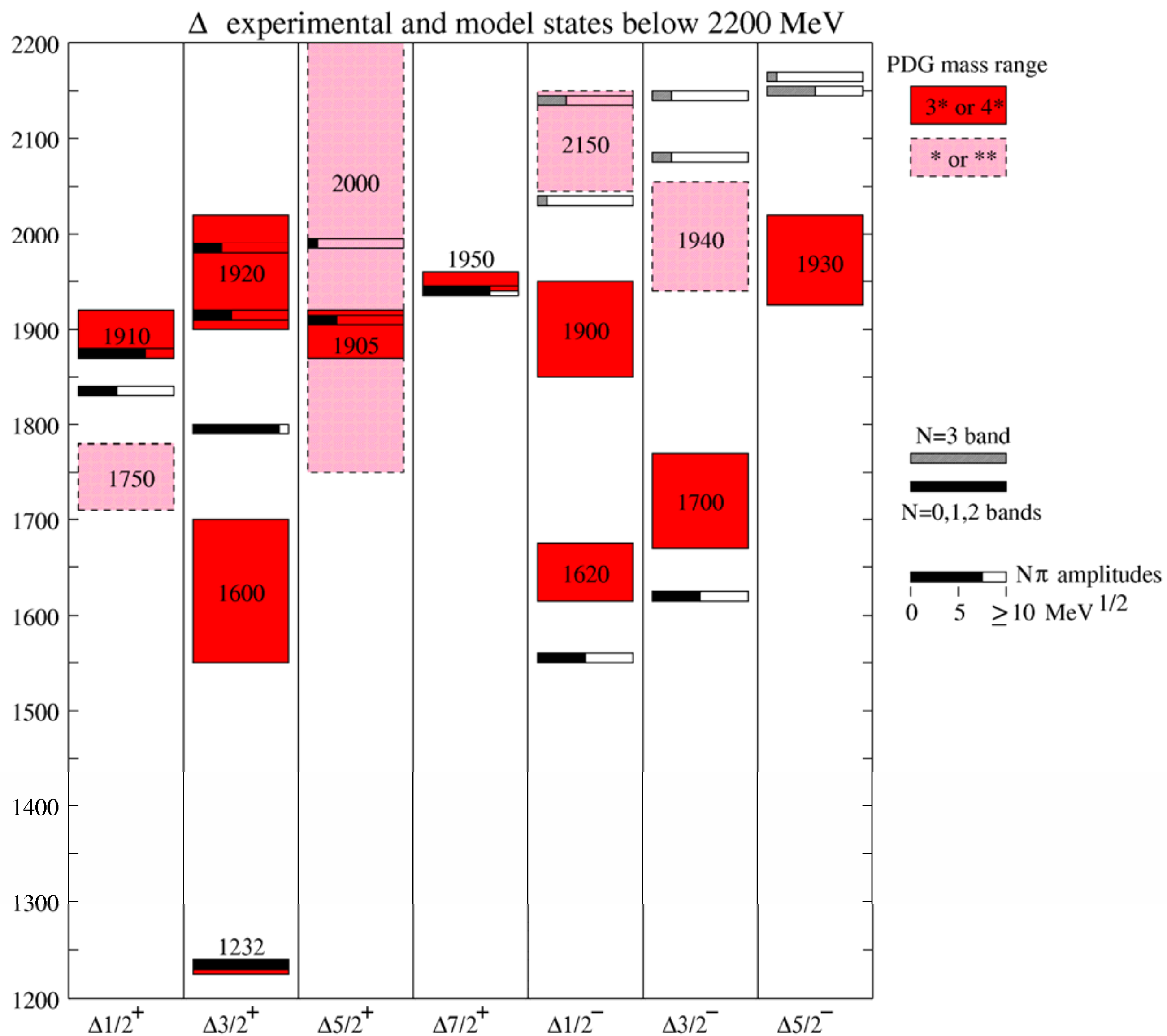
Nucleon model states and Nπ couplings



SC and N. Isgur, PRD**34** (1986) 2809;

SC and W. Roberts, PRD**47** (1993) 2004

Δ model states and Nπ couplings



N* states…

- Don't have enough states to fill out the positive-parity (N=2) multiplets
  - Not enough information to rule out a quark-diquark picture
  - Not enough information to establish or refute parity doubling higher in the spectrum

Isgur & Karl
Koniuk & Isgur
Cohen & Glozman

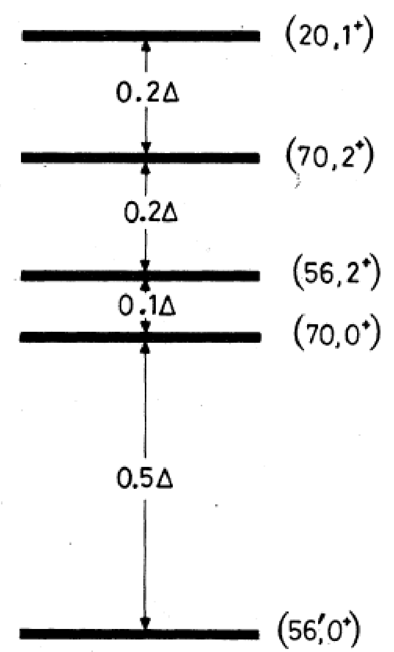


FIG. 1. The zeroth-order pattern of $N=2$ supermultiplets.

What do we know about N* states?

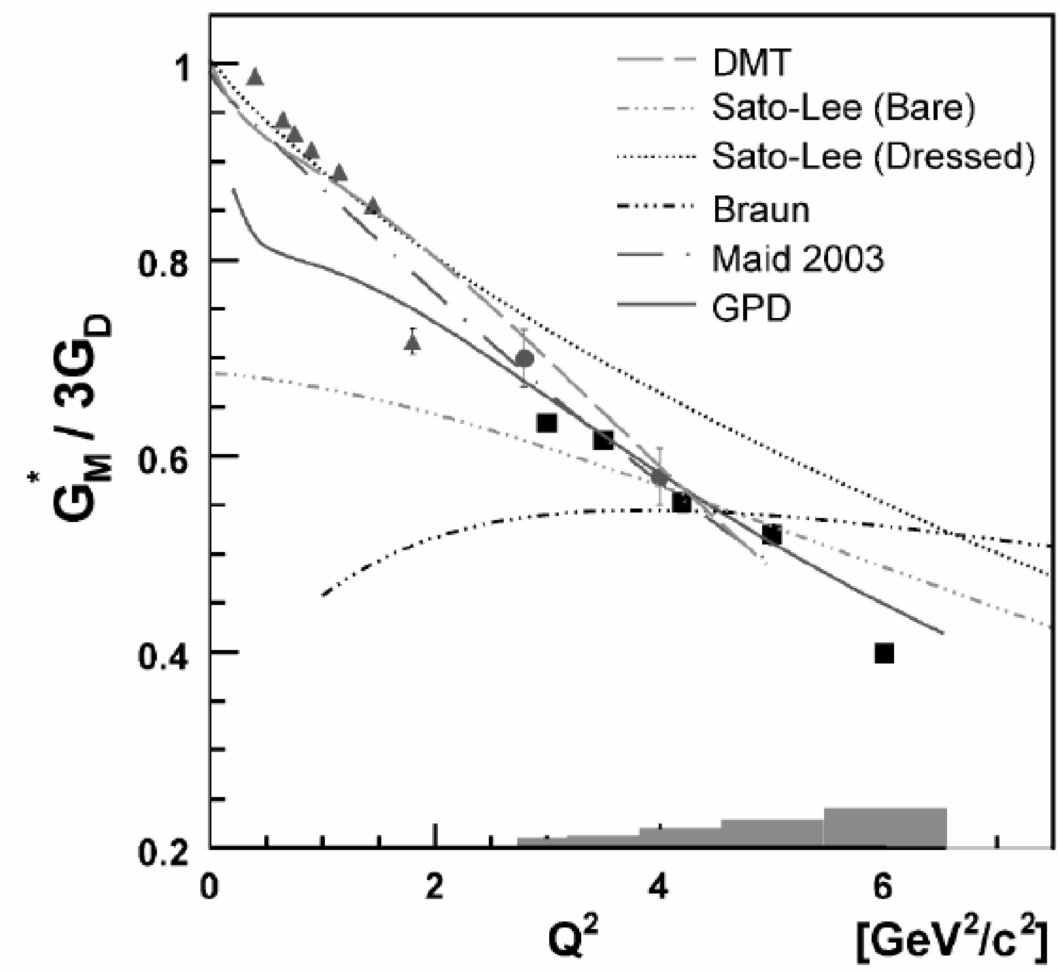
- EM transition amplitudes
  - Photo-couplings to proton and neutron
    - Helicity amplitudes $A^{p,n}_{1/2}$ and $A^{p,n}_{3/2}$ (photon spin ∥ or anti-∥ nucleon spin)
    - From $\gamma N \to \pi N$, $\gamma N \to \eta N$ [$S_{11}(1535)$]
- EM transition form factors
  - Single-π electro-production form factors
    - **$e^- N \to e^- N^* \to e^- \pi N$**
  - Sensitive to structure of nucleon and N*
    - *Also to reaction mechanism !*
  - Can probe evolution from soft to hard physics

Δ(1232) EM transition form factors

CLAS (2002)

Hall C (1999)

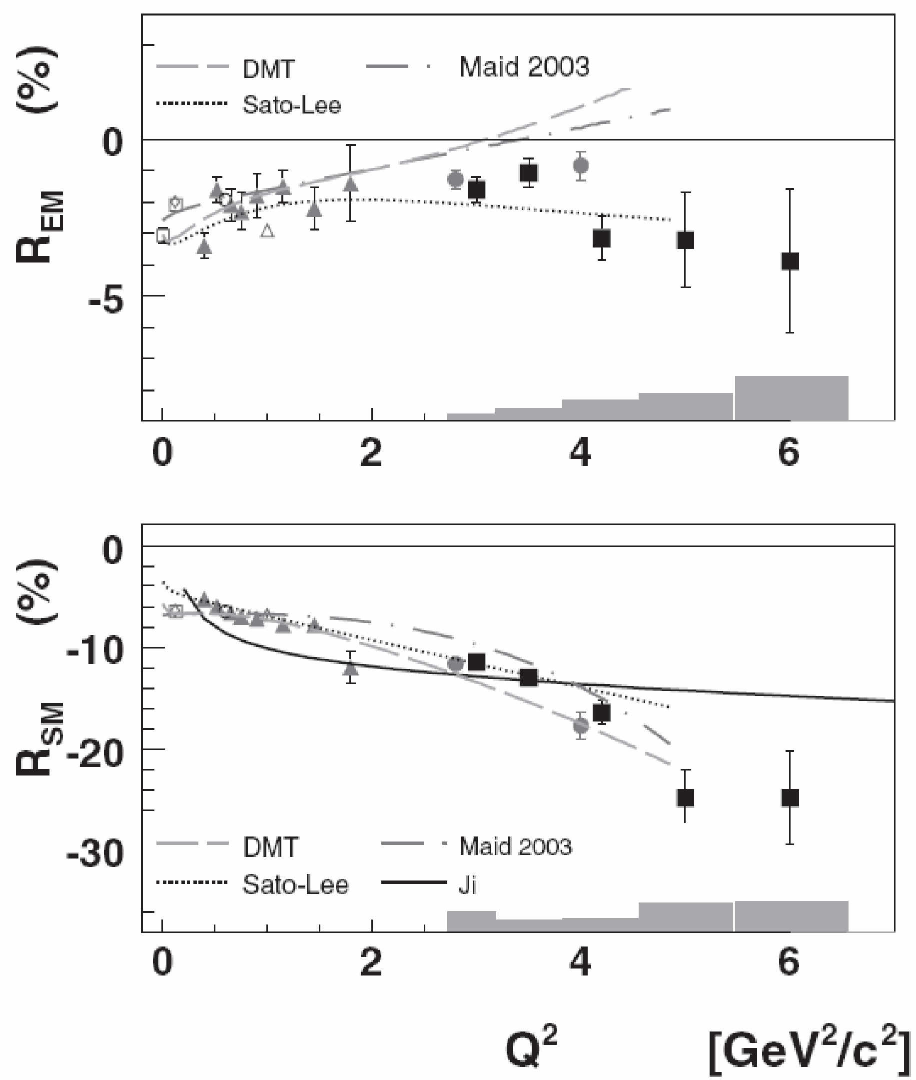
CLAS (2006)



Burkert & Lee
Int.J.Mod.Phys. E13, 1035(2004)

Δ(1232) EM transition form factors

Ratios of small E1+,S1+ amplitudes to dominant M1+ amplitude



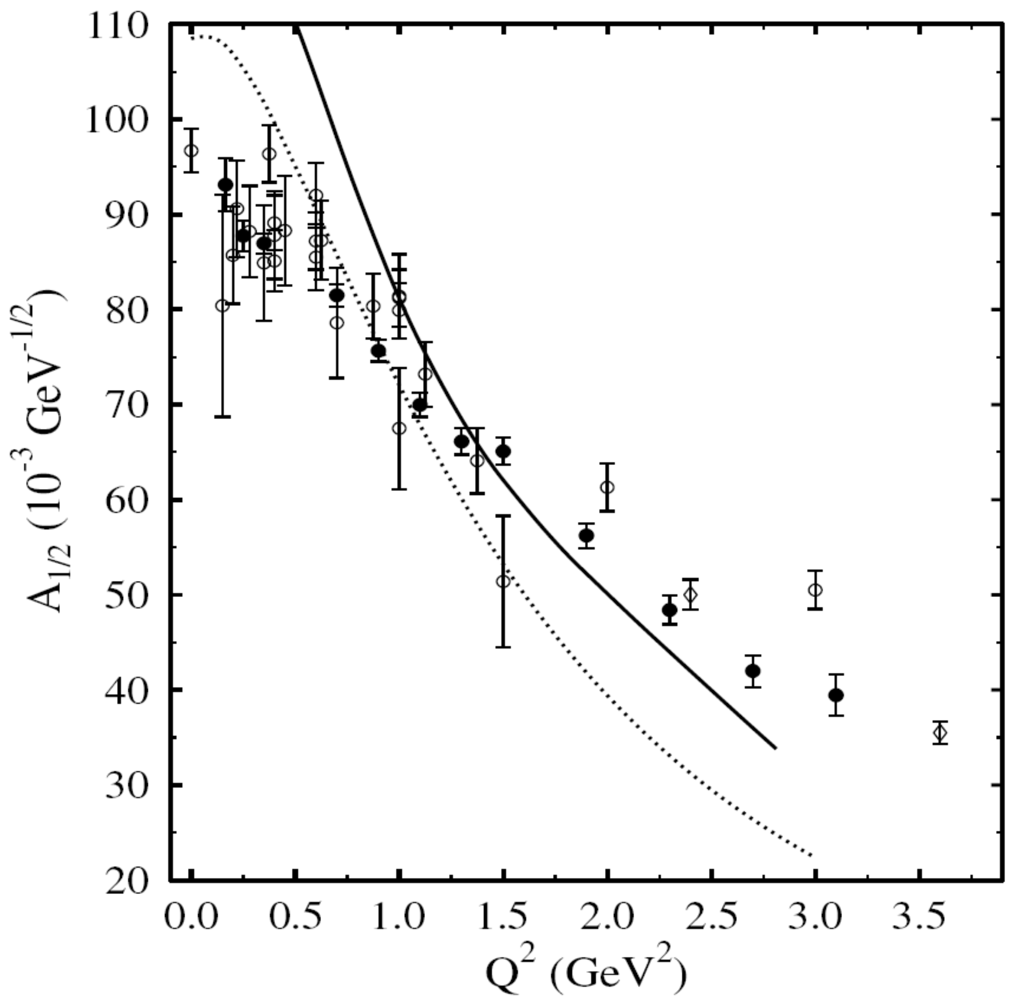
S_{11}(1535) EM transition form factor

data:

Previous expts.

Jefferson Lab:
Hall C

CLAS



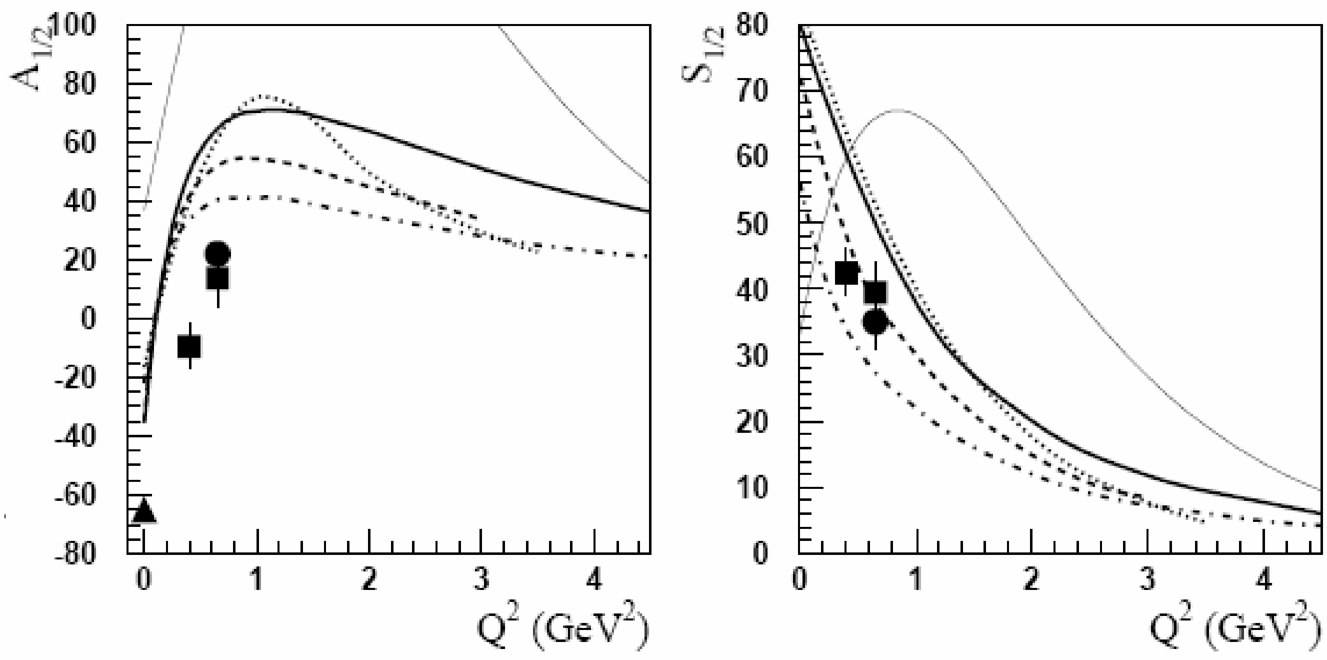
$P_{11}(1440)$ Roper

From preprint by Inna Aznauryan:

PDG at $Q^2=0$

Hall B analysis of single-pion electroproduction data by Aznauryan, Burkert, Egiyan et al.

Relativistic models see sign change in $A_{1/2}$



What are the goals of the N* program?

- Firmly establish the existence of several positive-parity baryons (esp. N* above 1800 MeV)
  - New states, or needing confirmation
  - Evidence for same state (mass, total width) in at least two channels
  - Extract photo-couplings and strong decay amplitudes into each channel
- Find convincing evidence for additional highly-excited (N=3 band) negative-parity baryons

Goals of the N* program…

- Measure EM transition form factors
  - Of new resonances
    - Second resonance in a given partial wave
    - Significant differences in structure?
  - Go to higher Q^2
    - Can we see transition to pQCD ?

Developments required to meet our goals

- Experiment
  - Photo- and electro-production:
    - Polarization measurements (target, beam, recoil) currently underway and planned
    - Extraction of amplitudes for production off neutron
  - Hadronic beams!
    - E.g. a few hours of running with modern detection systems would replace world data set on $\pi N \rightarrow \pi\pi N$

Required developments…

- Theory…
  - Develop ab-initio and model approaches to the spectrum and properties of N*s
    - Lattice QCD effort underway
    - Chiral models based on hadronic d.f., constituent quark models
  - Predict EM and strong transition form factors (models and lattice QCD)
    - Direct comparison to extracted values
    - Required input for calculation of re-scattering in dynamical models

Baryon spectrum from lattice QCD

- Lattice Hadron Physics Collaboration (LHPC): S. Basak, J.J. Dudek, R. G. Edwards, H.R. Fiebig, G.T. Fleming, U.M. Heller, K.J. Juge, A. Lichtl, N. Mathur, C. Morningstar, D. G. Richards, I. Sato, A.W. Thomas and S. J. Wallace
  - Recent work: quenched calculations of light-quark baryon spectrum (with m_π=490 MeV)
    - Operators constructed with use of Clebsch-Gordan coefficients of the octahedral group
    - Transform irreducibly under group rotations
    - See signals for 28 excited N and Δ states up to $J^p=5/2^\pm$

Required developments…

- Theory
  - Maintain and extend database and PWA for hadronic and EM production
  - Develop unitary, coupled-channel models of strong and EM transitions to multi-particle final states

Scattering data analysis

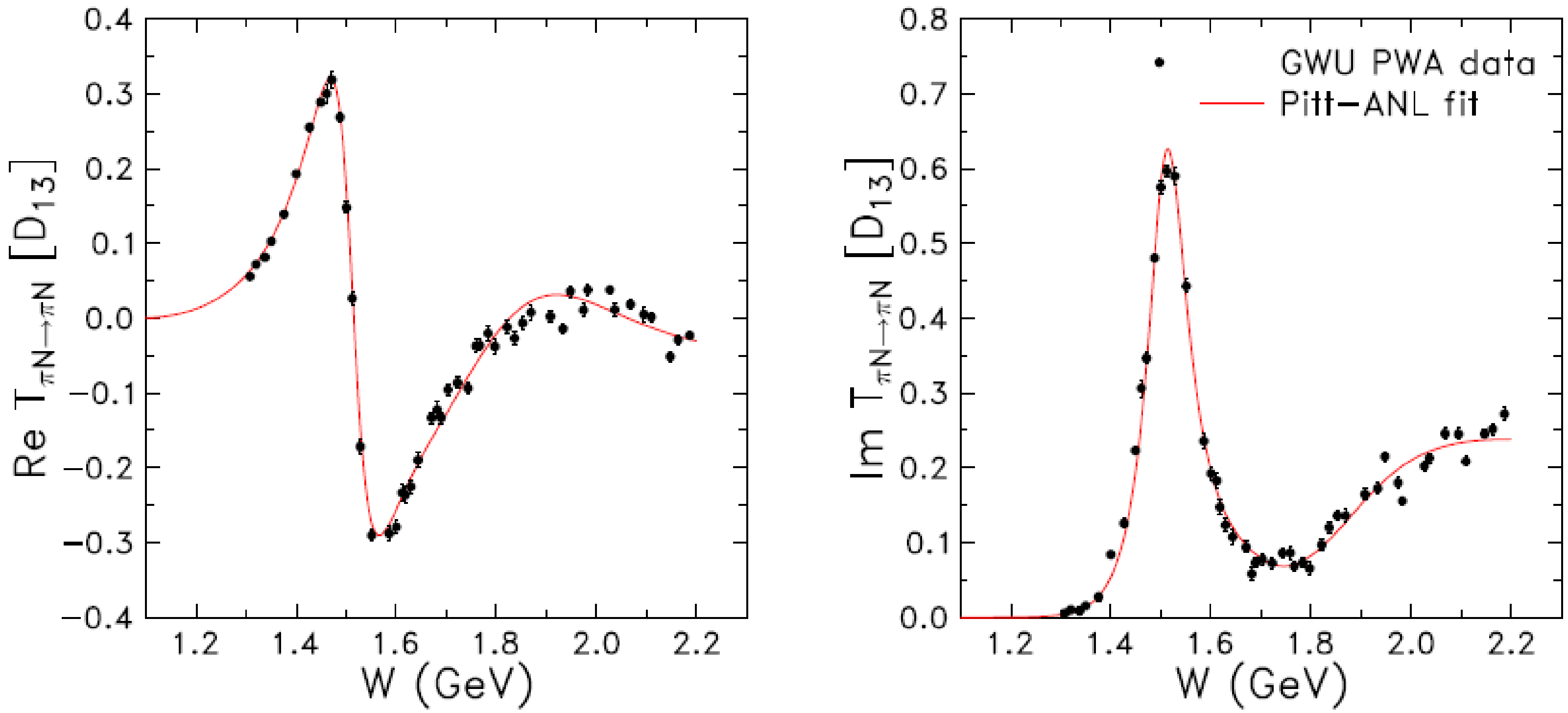
- How do we extract baryon resonance parameters from data?
- Data is πN and $\gamma N \to \pi N$, $\pi\pi$ N (ρN, $\Delta\pi$,...), $\pi\pi\pi N$ (ωN, $\rho\Delta$...), ηN, $K\Lambda$, $K\pi\Lambda$ ($K\Sigma$),...
  - For $\pi N \to \pi N$ have nearly complete data (missing some polarization observables); some inconsistencies
  - EM scattering labs (JLab, Mainz, Bonn,...) are rapidly improving γN data in various final states, with beam and recently target polarization

Scattering data analysis…

- Find the mass, total width, final state channel couplings $\gamma_{B'M}$ of each resonance B with a given J^P
  - Recently done in two steps:
    - Partial-wave analysis (PWA) of scattering observables
    - Resonance parameters are extracted from fitting a model of scattering T matrix to PW amplitudes

GWU PWA / Pitt-ANL fit to $\pi N \rightarrow \pi N$

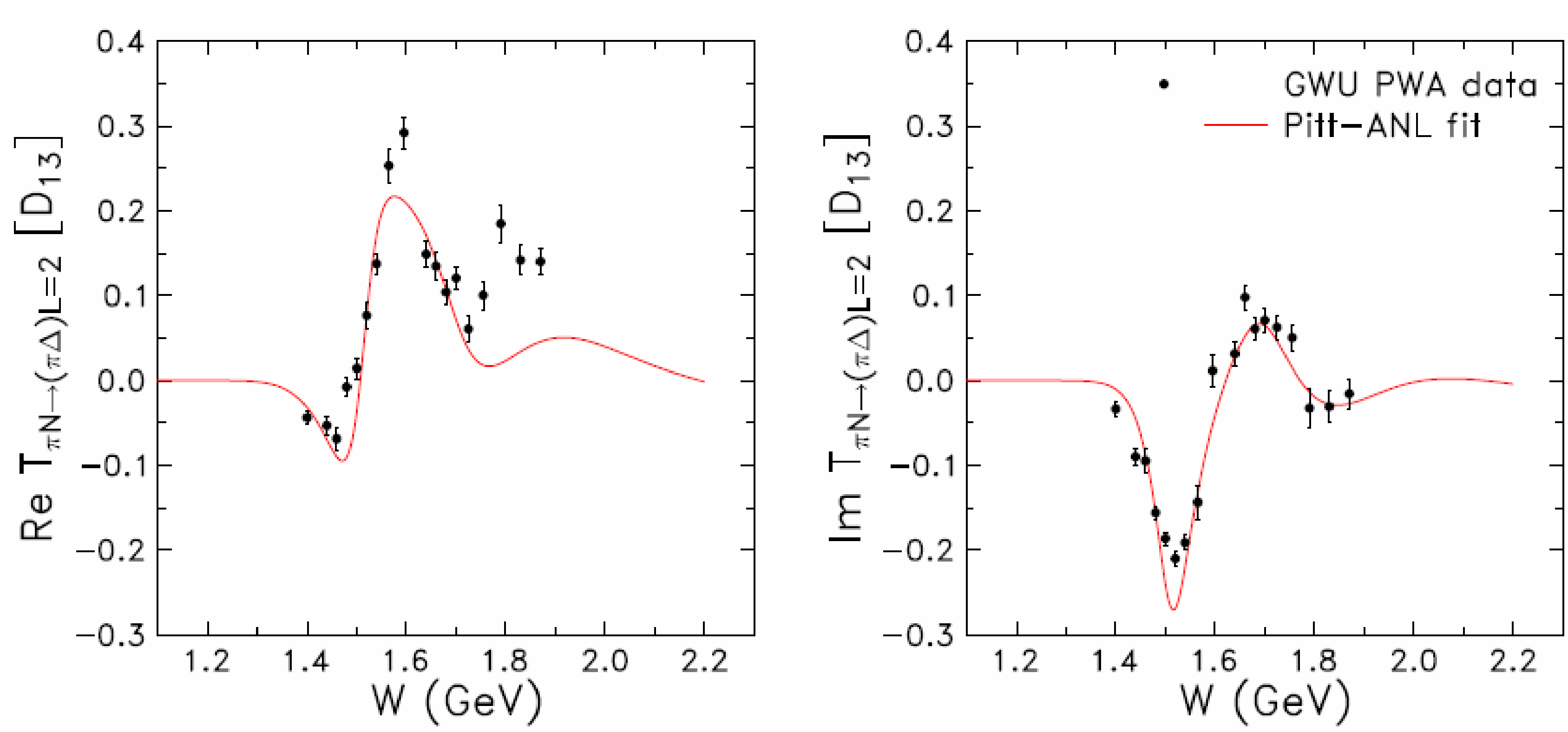
- Focus on $J^P = 3/2^-$ (D_{13} in πN), where PDG lists N(1520)****, N(1700)***, N(2080)**



- No solid evidence for N(1700) in $\pi N \rightarrow \pi N$

KSU isobar / Pitt-ANL fit, $\pi N \to (\pi\Delta)_D$

- Masses, widths and couplings of states consistent between πN elastic and $\pi N \to \pi\Delta$



- D_{13}(1700) weakly present in $\pi\Delta$ and also $K\Lambda$, with π and γ beams

Excited Baryon Analysis Center

- T.S. Harry Lee will give a full report on EBAC activities/program July 23
  - DOE's Science and Technology review of JLab
- Much more information available on web site

ebac-theory.jlab.org

Excited Baryon Analysis Center

Leading Investigator: T.-S. Harry Lee (Jointly with Argonne National Laboratory)

Members: Alexander Sibirtsev (Jointly with U. Bonn & FZ Juelich)
Mark Paris (Research Associate)

Participants: Inna Aznauryan (CLAS, Jefferson Laboratory)
Simon Capstick (Florida State University)
Johan Durand (Graduate Student, CEA/Saclay)
Bruno Julia-Diaz (University of Barcelona)
H. Haberzettl (George W. University)
Johann Haidenbauer (FZ Juelich)
C. Hanhart (FZ Juelich)
J. He (CEA/Saclay)
Alvin Kiswandhi (Graduate Student, Florida State University)
S. Krewald (FZ Juelich)
Akihiko Matsuyama (Shizuoka University)
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Viktor Mokeev (CLAS, Jefferson Laboratory)
Kanzo Nakayama (University of Georgia)
Winston Roberts (Florida State University)
Bijan Saghai (Saclay)
Toru Sato (Osaka University)
Cole Smith (CLAS, University of Virginia)
N. Suzuki (Graduate student, Osaka University)
Kazuo Tsushima (University of Salamanca)

EBAC

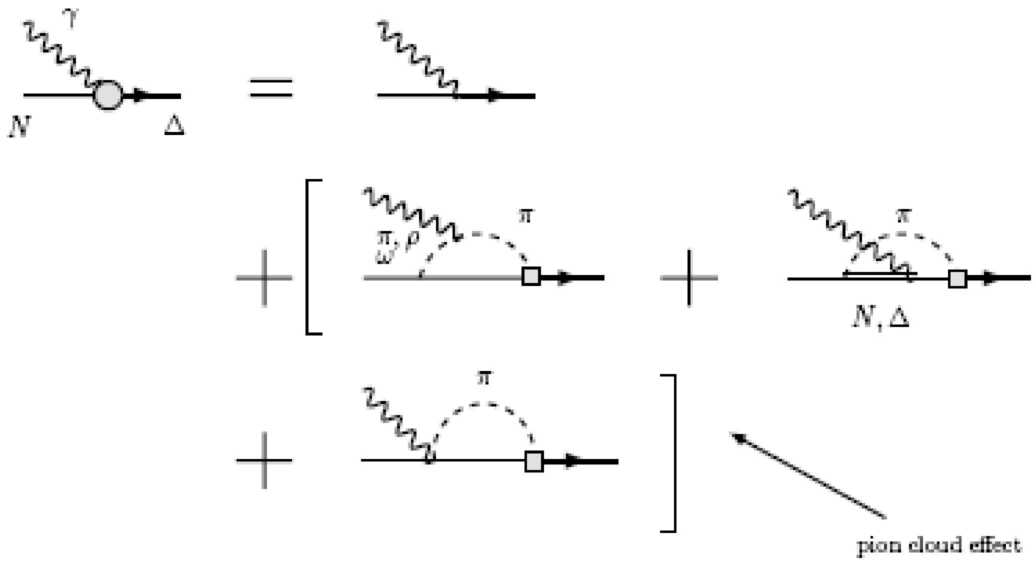
- Matsuyama, Sato and Lee (Phys. Rept. '07)
- Developed rescattering formalism in dynamical coupled-channels model for (γ,π) N $\leftrightarrow$ MB, $\pi\pi$N
  - MB = γN, πN, ηN, $\pi\Delta$, ρN, σN
  - Vertex interactions Γ_V for $N^* \leftrightarrow$ MB, $\pi\pi$N and $(\rho,\sigma) \leftrightarrow \pi\pi$
  - Non-resonant interactions:
    - $V_{MB\rightarrow M'B'}$ and $V_{\pi\pi\rightarrow\pi\pi}$
    - $V_{MB\rightarrow \pi\pi N}$
    - $V_{\pi\pi N\rightarrow \pi\pi N}$

EBAC…

- Matsuyama, Sato and Lee:
  - Scattering amplitude sum of non-resonant and resonant amplitudes
  - Meson-cloud effects explicitly included
  - Satisfies two-body (MB states considered), and three-body ($\pi\pi N$) unitarity conditions
    - Unitarity cut from $\pi\pi N$ has important effects on $\pi\Delta$, ρN, σ N unstable particle channel amplitudes
    - Large effects on two-pion production cross sections

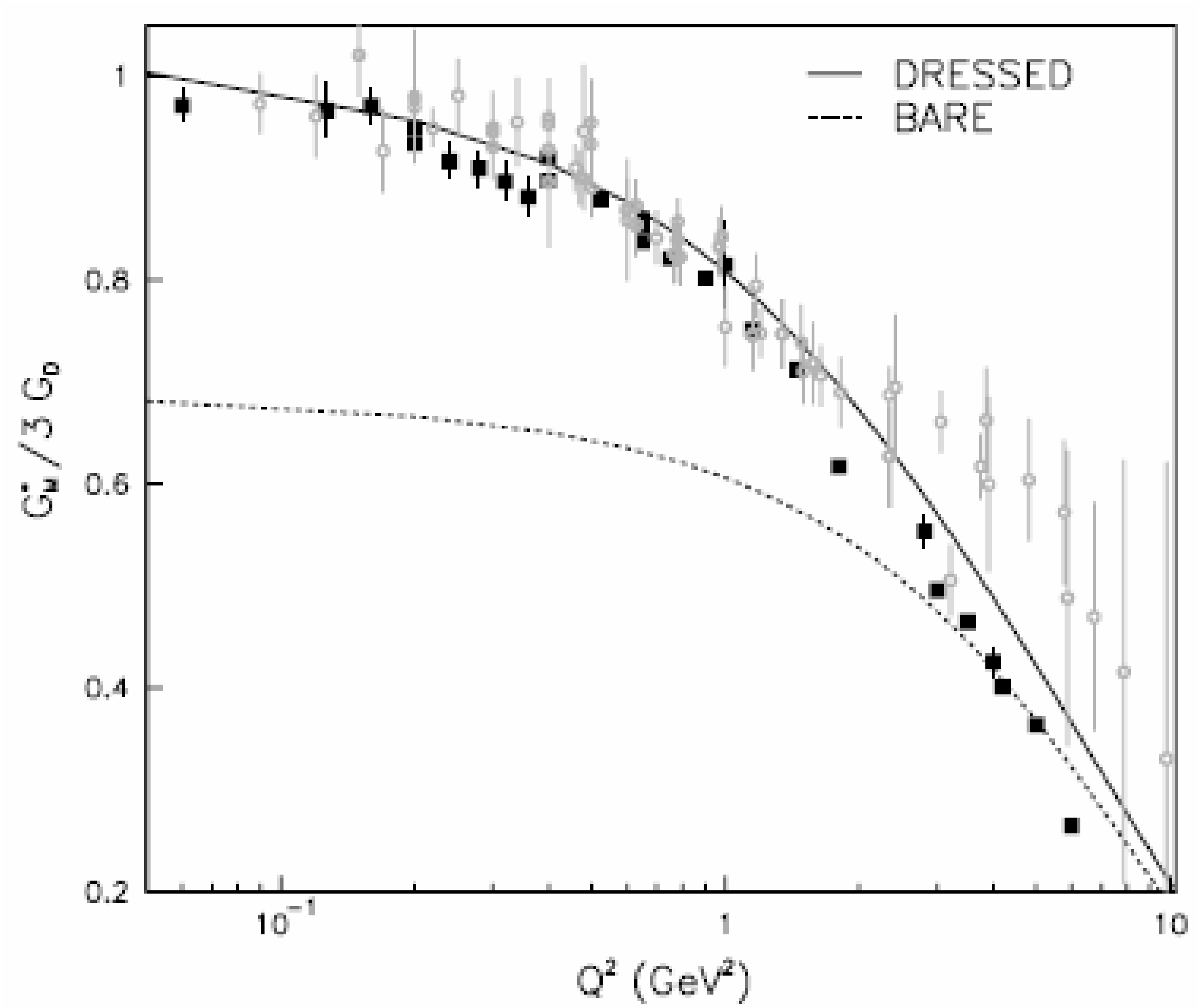
EBAC…

- B. Julia-Diaz, T.S.-H Lee, T. Sato & L.C. Smith
  - Analysis of $\gamma^* N \rightarrow \Delta$ using this dynamical model



EBAC...

- Data from DESY and SLAC
- Bates MAMI, JLab



EBAC…

- Julia-Diaz, Lee, Matsuyama & Sato, nucl-th/0704.1615
  - Analyse $\pi N \rightarrow \pi N$ using their dynamical coupled-channel model
    - Good fit to SAID (GWU/RPI) partial-wave amplitudes and $\pi N \rightarrow \pi N$, ηN total cross sections up to 2 GeV
    - Include πN, ηN, $\pi\pi N$ with $\pi\Delta$, ρN and σN resonant components
  - Identifies resonances and their strong-interaction couplings: crucial 1st step!

EBAC…

- Working on (highlights):
  - (Single) pion and η photo and electro-production
  - Analysing $\pi N \to \pi\pi N$
    - Must understand strong interactions before going to $(\gamma,\gamma^*)N \to \pi\pi N$
  - Extending formalism to KY, ωN, $\eta\pi N$ and KKN
    - Advantage of isospin selectivity (ωN, ΛK)

How am I involved?

- Working on unitary, coupled-channel model of $\gamma N \to \eta\pi N$ (new data from expt., Bonn)
  - With (excellent!) graduate student Alvin Kiswandhi
  - Warming up with model $\gamma N \to \pi\pi N$
    - Write down tree-level diagrams
    - Fit data by varying masses, partial widths of intermediate N* into various baryon-meson final states
    - Include MB→M'B' re-scattering to all orders by solving scattering equation
      - loop corrections to propagators and vertices (finite)

How am I involved?

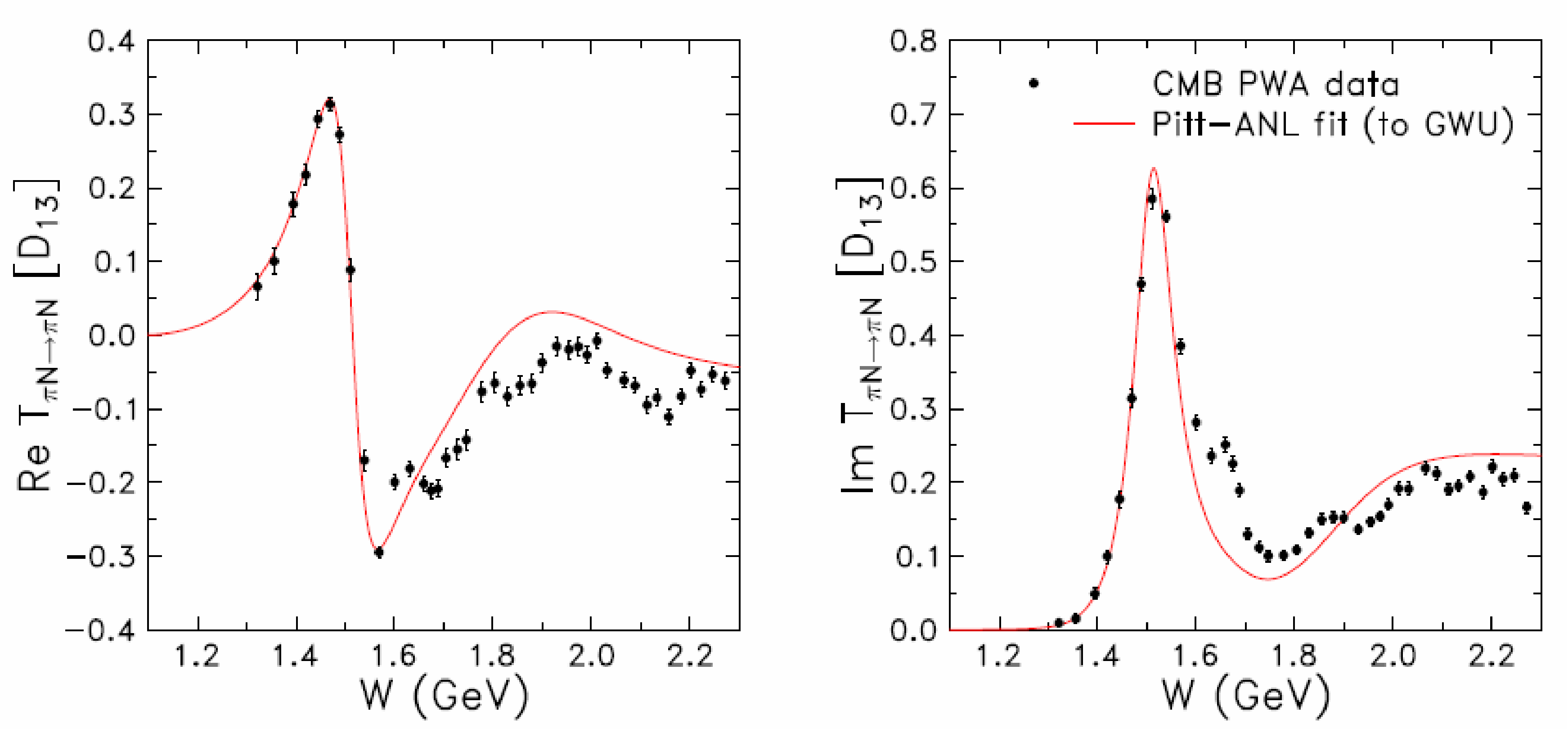
- Calculation of EM transition form factors for N to N*, with B. Keister
  - Relativistic light-front formalism
- Calculation of strong form factors for N* to baryon-meson final states, with D. Morel
  - Required input for models of reactions involving hadrons, loop effects
    - Loops rendered finite by form factors

Conclusions

- An exciting time for N* physics
  - New data coming out of JLab and other EM production labs have unprecented precision and scope
  - Reliable unitary, coupled-channels models are being used to extract resonance parameters from all data, simultaneously
- Bound to improve our understanding of QCD in the soft regime

CMB energy-dependent PWA

- Points are CMU-LBL PWA of **same** $\pi N \to \pi N$ elastic data, curves are Pitt-ANL fit to GWU PWA



KH80 energy-dependent PWA

- Points are KH80 energy-dependent PWA of **same** $\pi N \rightarrow \pi N$ elastic data, curves are Pitt-ANL fit to GWU PWA