Overview of N* Physics

- Why study excited states of the nucleon?
- What do we know about N* states?
- What are the goals of the N* program?
- What developments are required to reach these goals?
  - Experimental and theoretical

Why study N* states?

- What are their relevance to nuclear and strong-interaction physics?
  - The nucleus is a composite system
    - How much would we know about nuclei if we only studied their ground states?
  - The nucleon is a composite system
    - A full understanding of the nucleon requires knowledge of the spectrum and properties of its excited states

Why study N* states?

- What are their relevance to nuclear and strong-interaction physics?
  - 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?

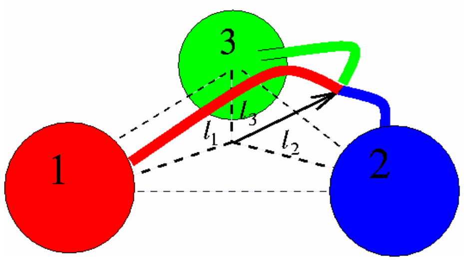
Why study N* states?

- What is 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?
- The spectrum and properties of N* states are sensitive to their nature

Effective degrees of freedom

Low-energy QCD:

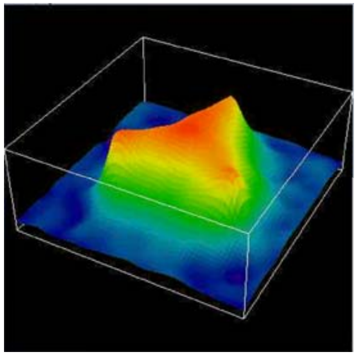
- Constituent quarks (CQs), confined by flux tubes?
- Confined CQs, elementary meson fields?
- Confined CQs, gas of instantons?
- Baryons and mesons interacting via chiral potentials?

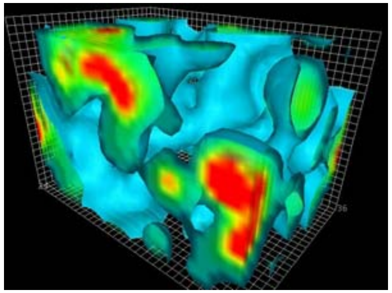


P.Page, S.C. Flux-tube model of baryons & hybrids

Ichie, Bornyakov, Struer & Schierholz

QQQ action density



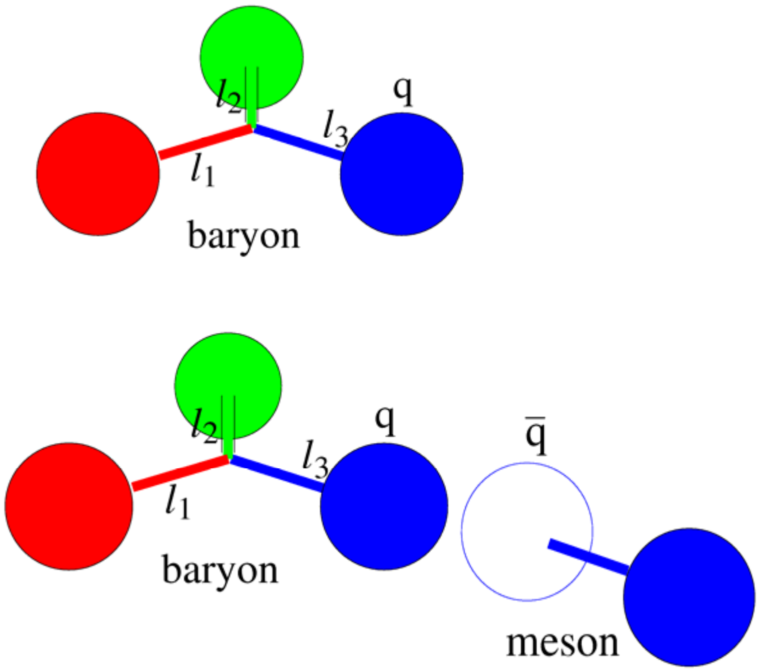


D. Leinweber et al. QCD vacuum action density

Why study N* states?

- The N*s (hadrons) are unique: bound states of strongly-interacting, relativistic confined constituents
- Nucleons interact strongly in nuclei, but:
  - Can isolate relevant low-energy d.f. (nucleons)
  - Can directly probe two-body potential in experiment
  - 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

Uniqueness…



- Elementary d.f. are confined
  - Can only indirectly infer low-energy interaction
- Only qqq, $q\bar{q}$ exist as bound states
- Not non-relativistic systems (unless **all** quarks heavy)

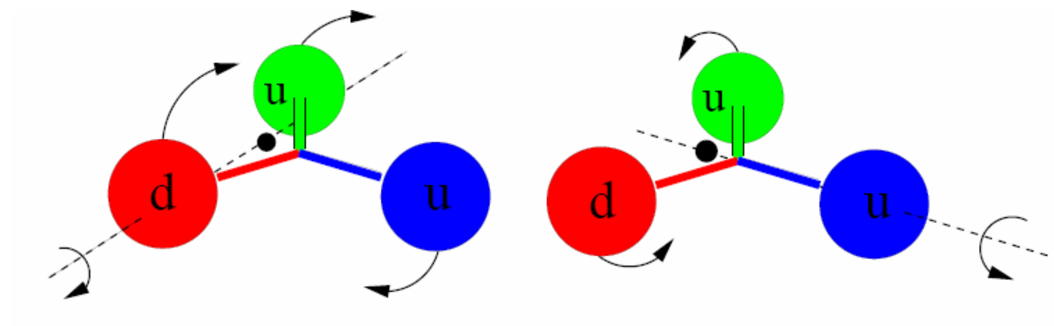
N and Δ excited states

- 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

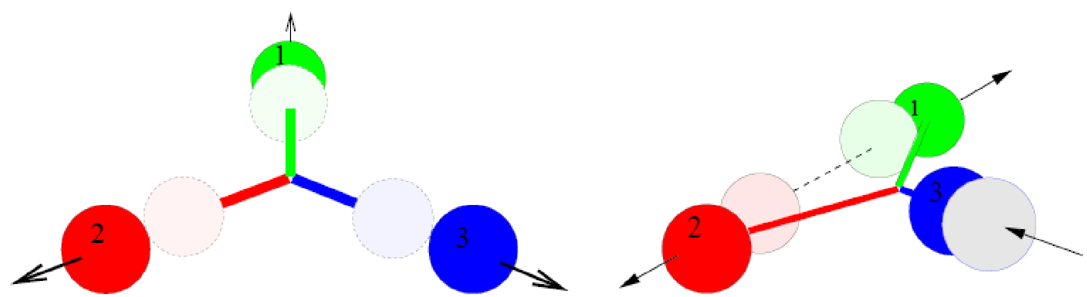
p	P_{11}	****	Δ(1232)	P_{33}	****
n	P_{11}	****	Δ(1600)	P_{33}	***
N(1440)	P_{11}	****	Δ(1620)	S_{31}	****
N(1520)	D_{13}	****	Δ(1700)	D_{33}	****
N(1535)	S_{11}	****	Δ(1750)	P_{31}	*
N(1650)	S_{11}	****	Δ(1900)	S_{31}	**
N(1675)	D_{15}	****	Δ(1905)	F_{35}	****
N(1680)	F_{15}	****	Δ(1910)	P_{31}	****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

N and Δ excited states…

- Orbital excitations (two distinct kinds)



- Radial excitations (also two kinds)



“Missing” resonances

- **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*) resonances 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

“Missing” resonances

- 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 and Isgur

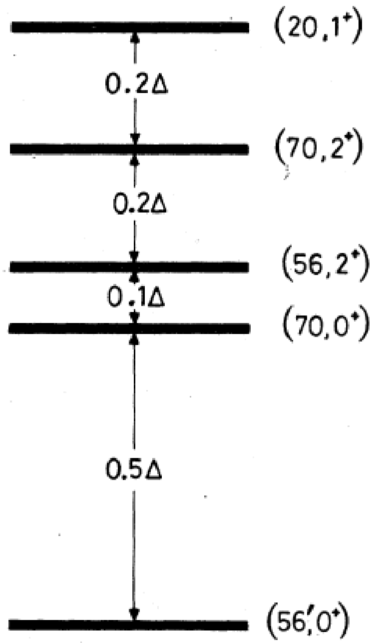


FIG. 1. The zeroth-order pattern of $N=2$ supermultiplets.

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	Status as seen in — $N\pi$	$N\eta$	ΛK	ΣK	$\Delta\pi$	$N\rho$	$N\gamma$
$N(939)$	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	Status as seen in — $N\pi$	$N\eta$	ΛK	ΣK	$\Delta\pi$	$N\rho$	$N\gamma$
$\Delta(1232)$	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.

A paragraph of caution

- From the PDG note on N and Δ resonances written by G. Hohler and R. Workman (GWU) in 2002:

  "In the search for 'missing' quark-model states, indications of new structures occasionally are found. Often these are associated (if possible) with the one- and two-star states listed in Table 1. We caution against this: The status of the one- and two-star states found in the Karlsruhe-Helsinki (KH80) and Carnegie-Mellon/Berkeley (CMB80) fits is now doubtful."

More caution

"I can make no objective statement that any of the states S_{11}(2090) [3rd N1/2^{-}], P_{11}(2100) [3rd N*1/2^{+}], and D_{13}(2080) [3rd N3/2^{-}] exist."

"1* states are a dream, 2* states are a fantasy."

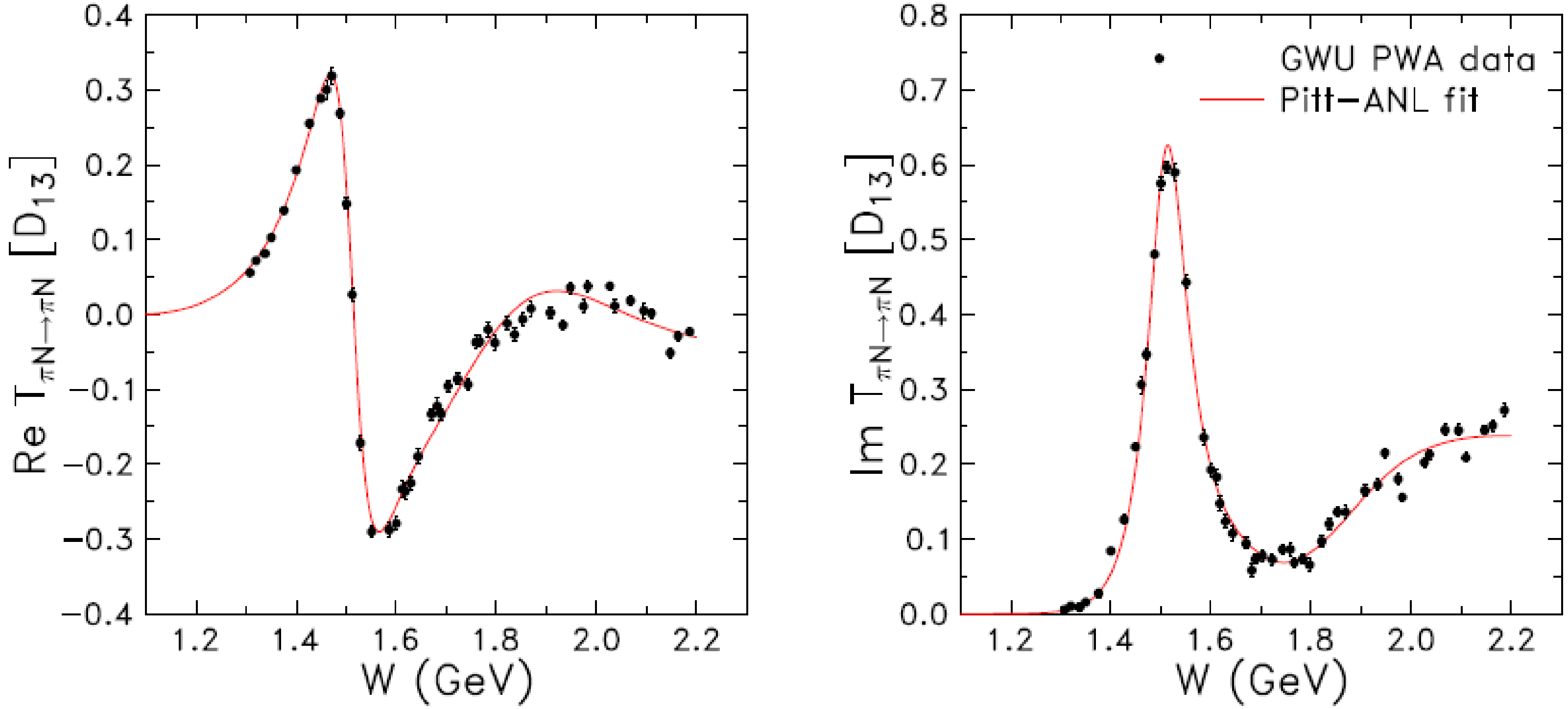
Steve Dytman, 2005

Scattering data analysis

- How do we extract baryon resonance parameters from data?
- Data is πN and $\gamma N \rightarrow \pi N$, $\pi\pi$ N (ρN, $\Delta\pi$,…), $\pi\pi\pi N$ (ωN, $\rho\Delta$…), ηN, $K\Lambda$, $K\pi\Lambda$ ($K\Sigma$),…
  - For $\pi N \rightarrow \pi N$ 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
- 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 $\pi N \rightarrow \pi N$

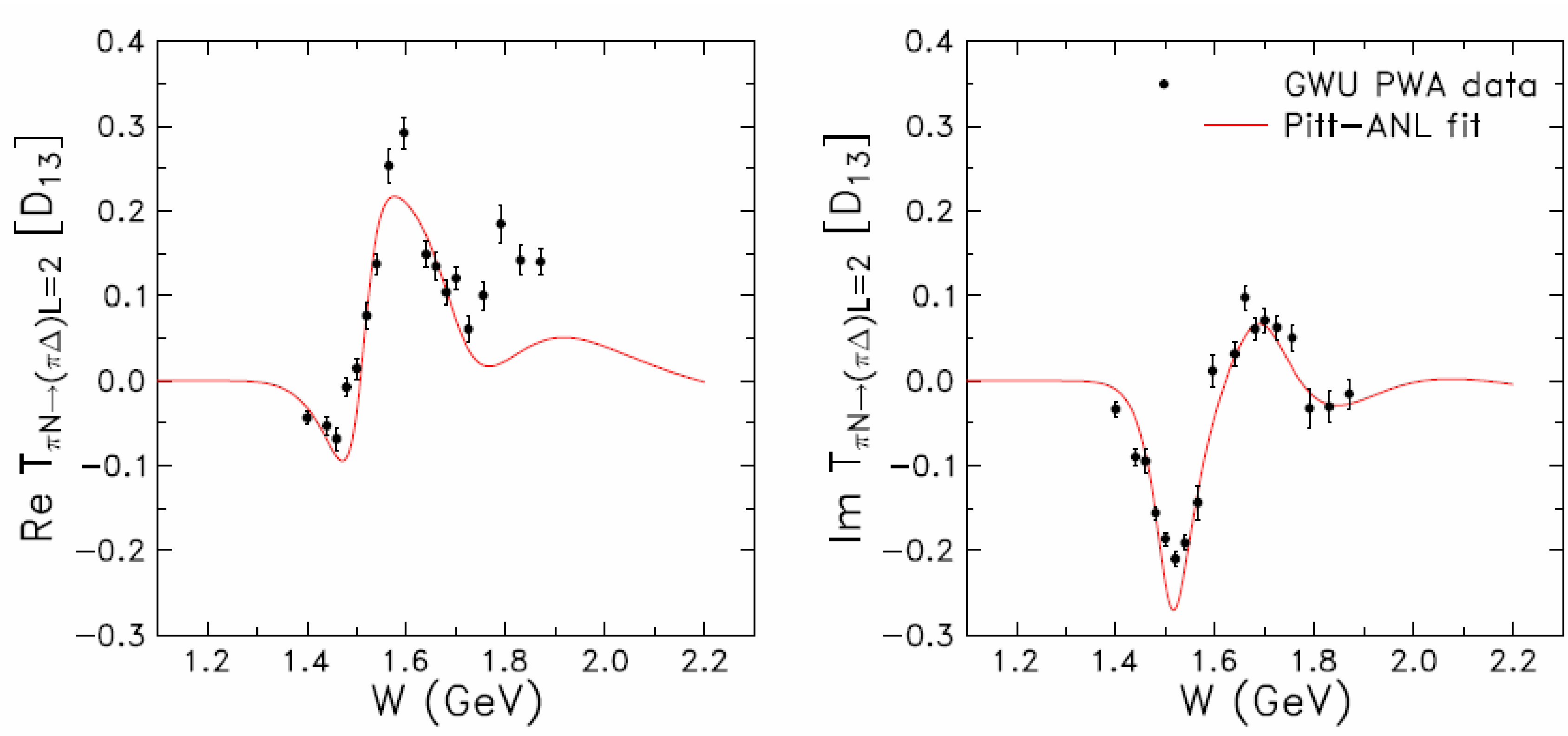
- Focus on $J^P = 3/2^-$ (D_{13} in πN), where PDG lists N(1520)****, N(1700)***, N(2080)**



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

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

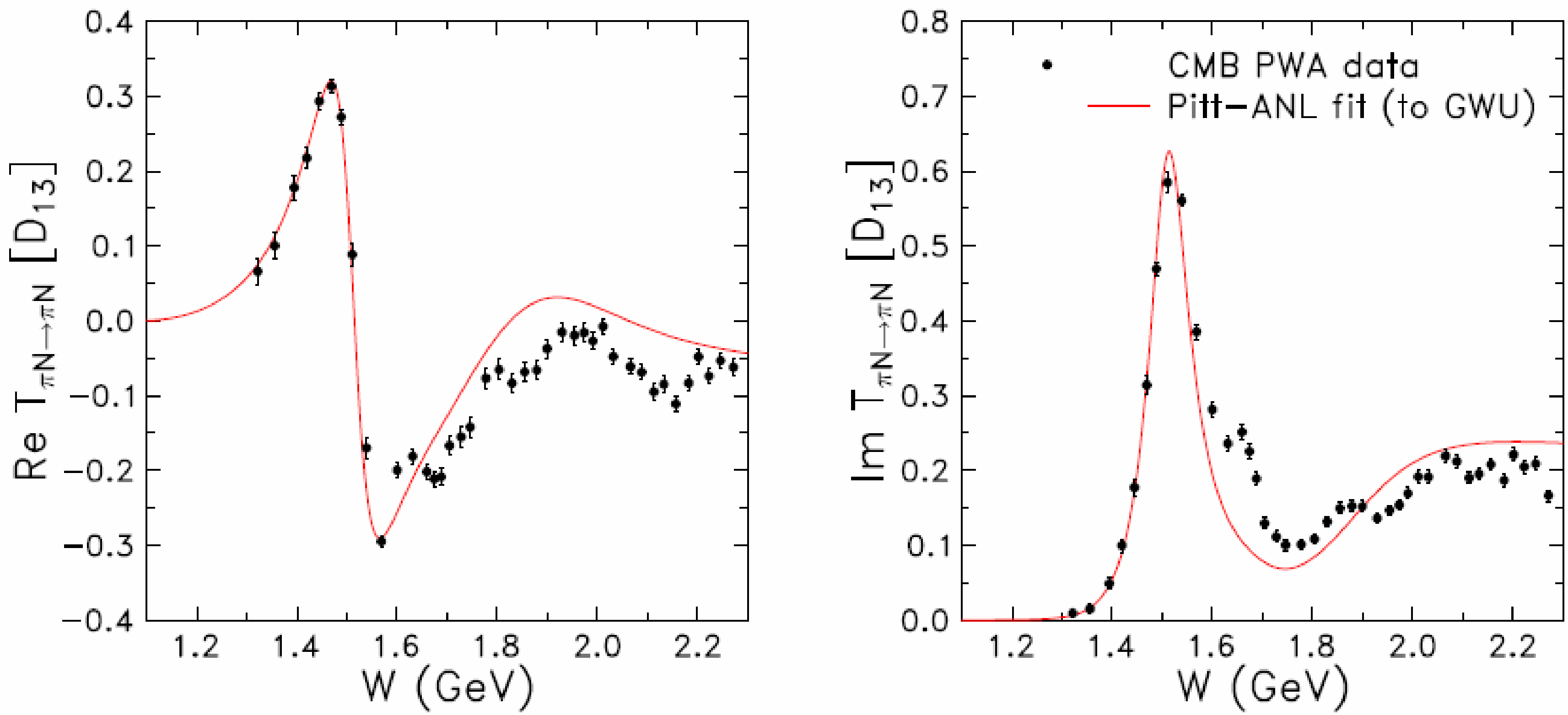
- Masses, widths and couplings of states consistent between πN elastic and $\pi N \rightarrow \pi\Delta$



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

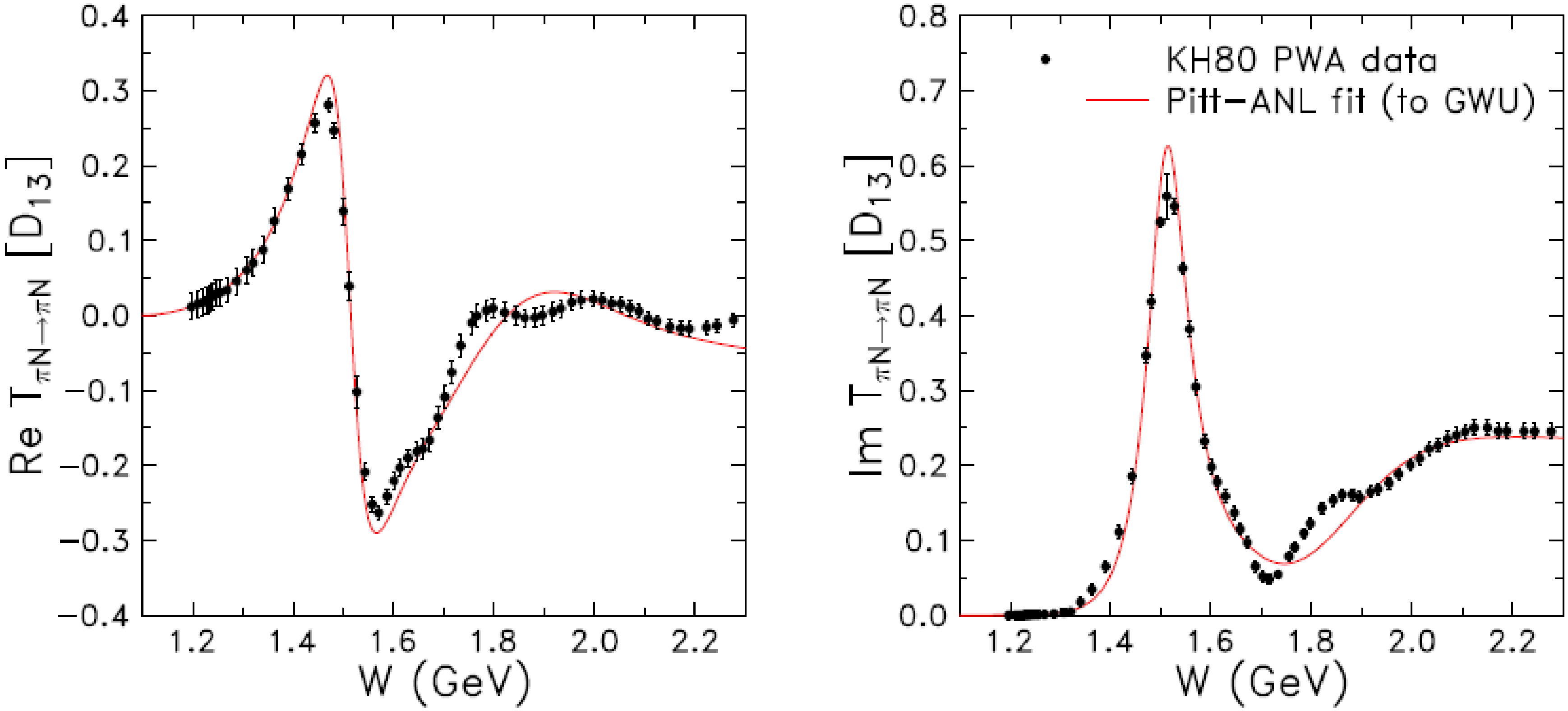
CMB energy-dependent PWA

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

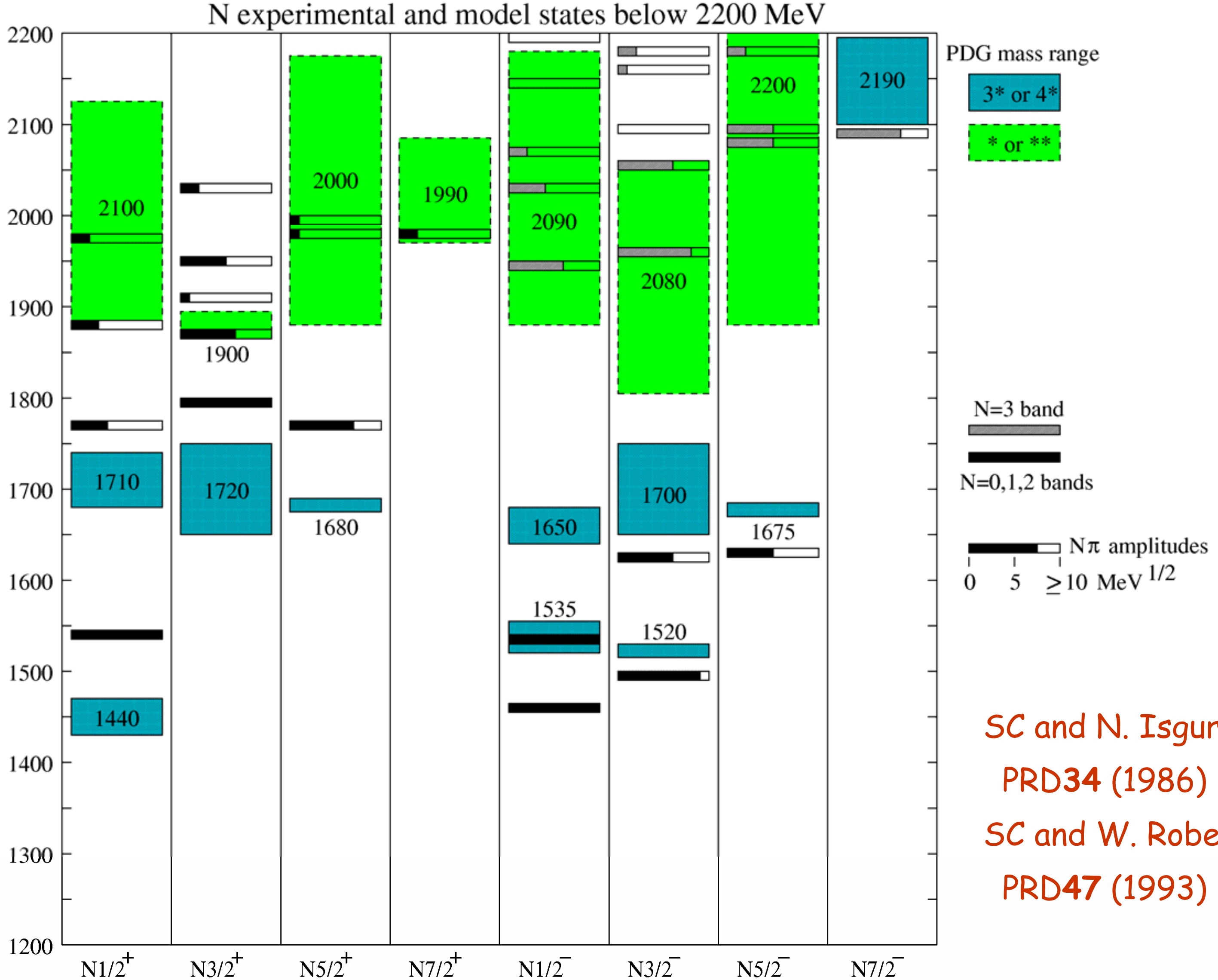


KH80 energy-dependent PWA

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



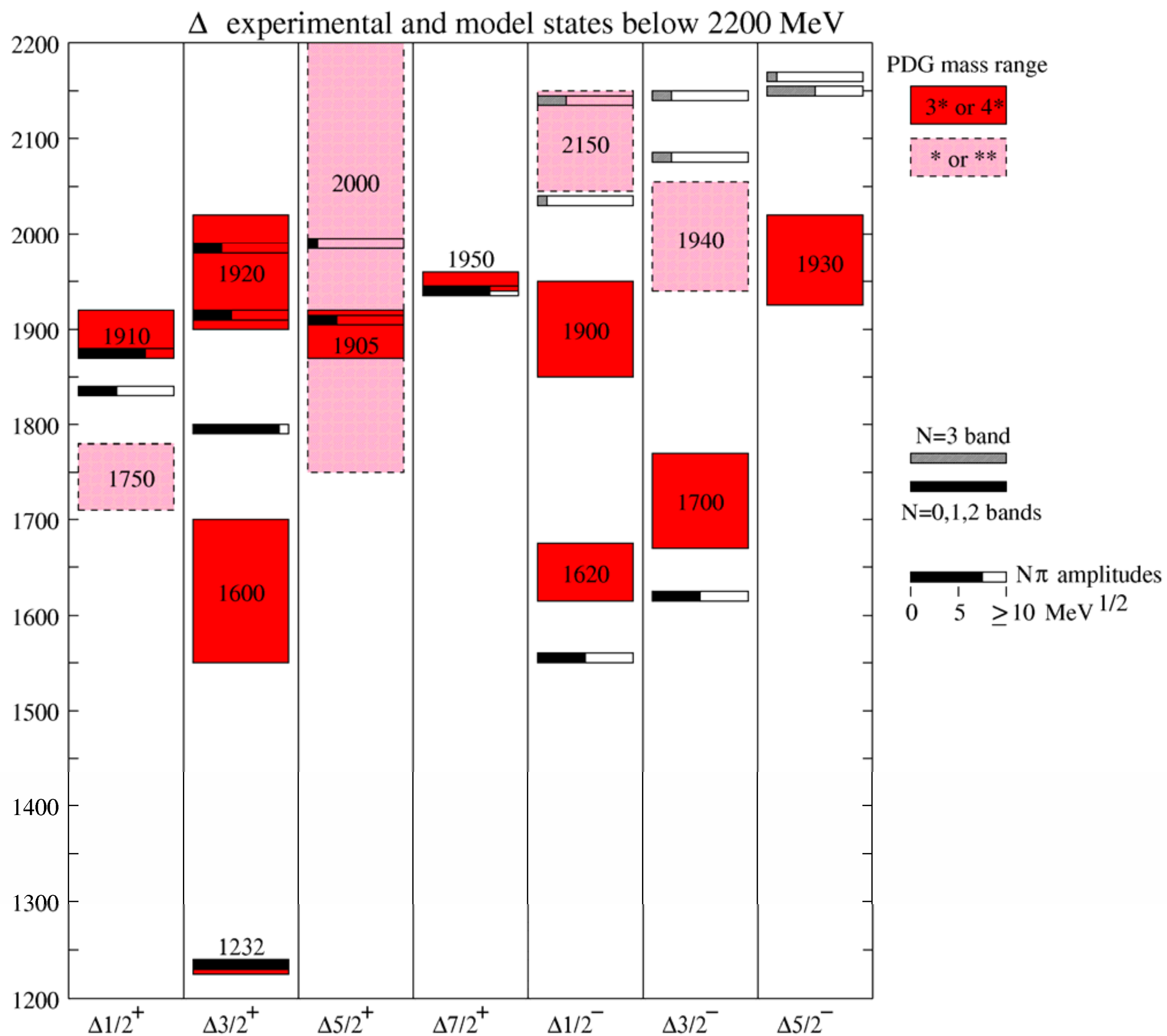
Nucleon model states and Nπ couplings



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

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

Δ model states and Nπ couplings



What do we know about N* states?

- EM transition amplitudes
  - Photo-couplings to proton and neutron
    - Allow calculation of partial widths $N^* \to \gamma N$
    - Resolved into helicity amplitudes $A^{p,n}_{1/2}$ and $A^{p,n}_{3/2}$ (photon spin $\|$ or anti-$\|$ nucleon spin)
      - Include the relative signs of $\gamma N \to N^* \to \pi N$
    - Largely from $\gamma N \to \pi N$
      - also $\gamma N \to \eta N$ [$S_{11}(1535)$]
      - This yields different photo-coupling $A^p_{1/2}$!

What do we know about N* states?

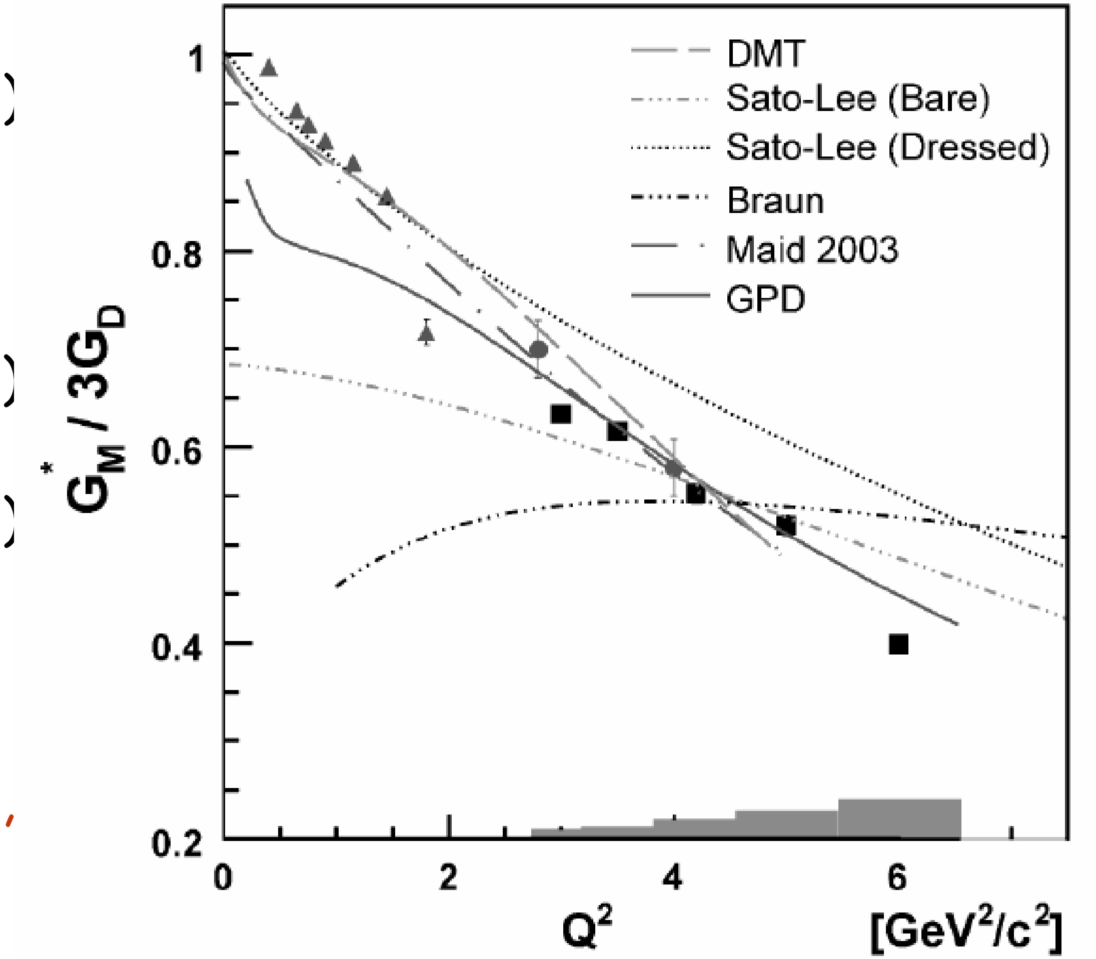
- EM transition form factors
  - Single-π electro-production form factors
    - $e^- N \to e^- N^* \to e^- \pi N$
  - High-precision amplitudes published for $\Delta(1232)$ up to 6 GeV^2
  - Amplitudes published at low and intermediate Q^2 for $N(1440)P_{11}$, $N(1535)S_{11}$, $N(1520)D_{13}$
    - Analysis near completion for higher Q^2 values, and for $N(1680)F_{15}$
- 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)

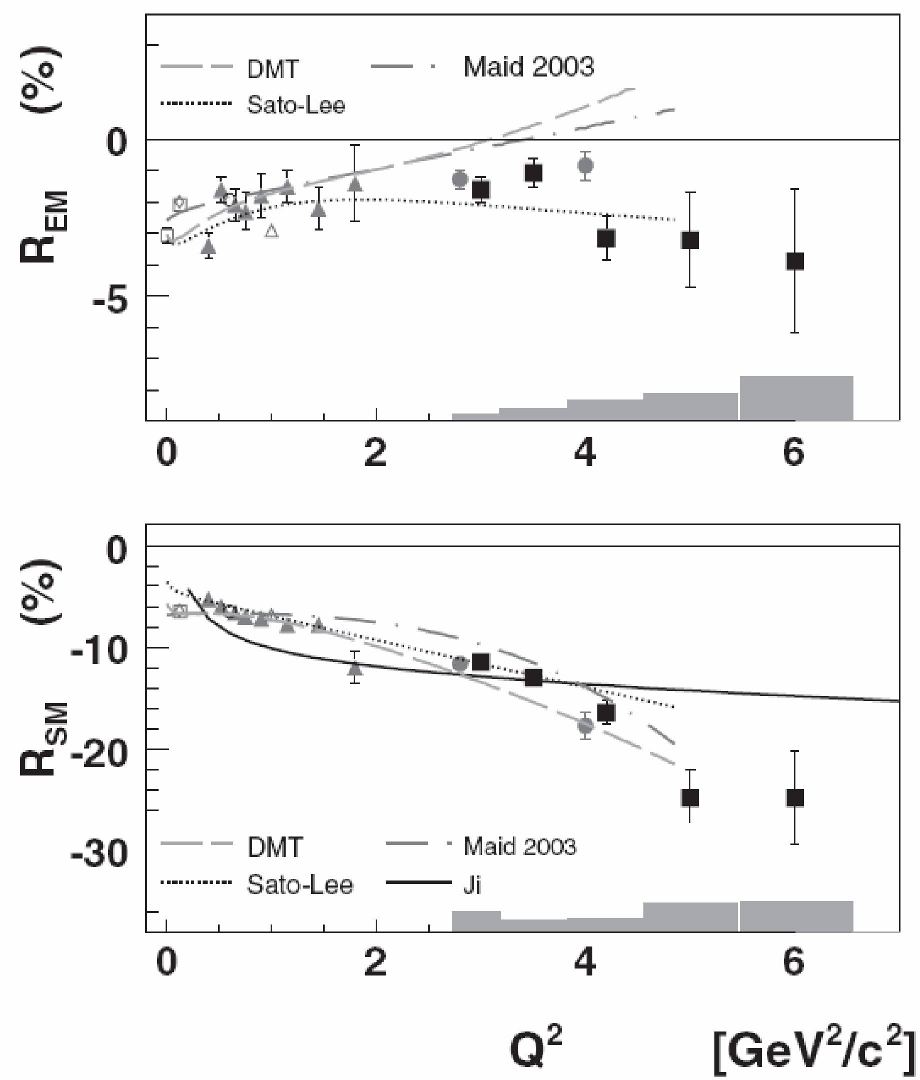
CLAS (2006)



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



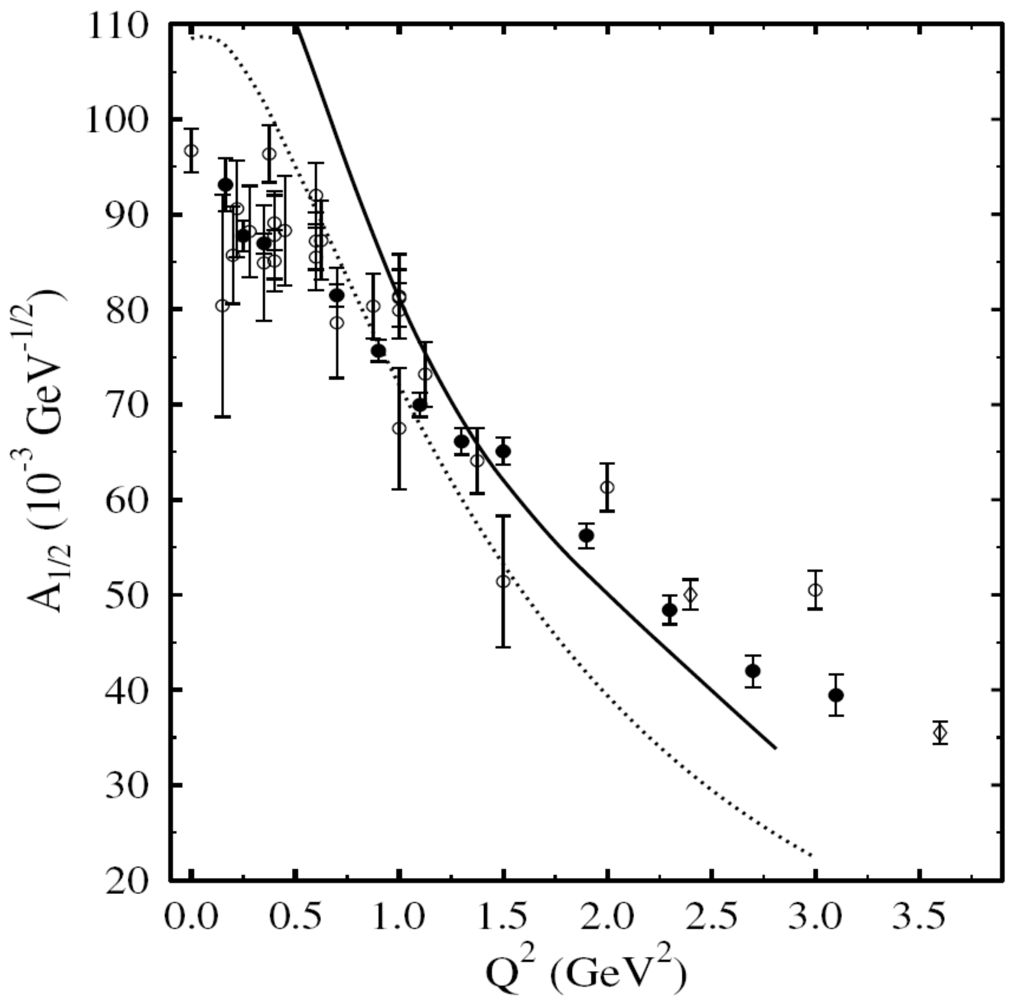
$S_{11}(1535)$ EM transition form factor

Previous expts.

Hall C

CLAS

- Nη bound state?



What are the goals of the N* program?

- Firmly establish the existence of several positive-parity baryons (esp. N* above 1800 MeV) that are currently missing 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

What are the goals of the N* program?

- Find convincing evidence for additional highly-excited (N=3 band) negative-parity baryons
- Extend measurements of EM transition form factors
  - Higher Q^2
  - Second resonance in a given partial wave
    - Significant differences in structure?

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
      - Talks in next session (1)
- Hadronic beams
    - E.g. a few hours of running with modern detection systems would replace world data set on $\pi N \to \pi\pi N$
      - See Winston Roberts' talk

Required developments…

- Theory
  - Maintain and extend database and PWA for hadronic and EM production
  - Develop unitary, couple-channel models of EM and strong transitions to multi-particle final states
    - Strong focus of this afternoon's second session and tomorrow morning's session

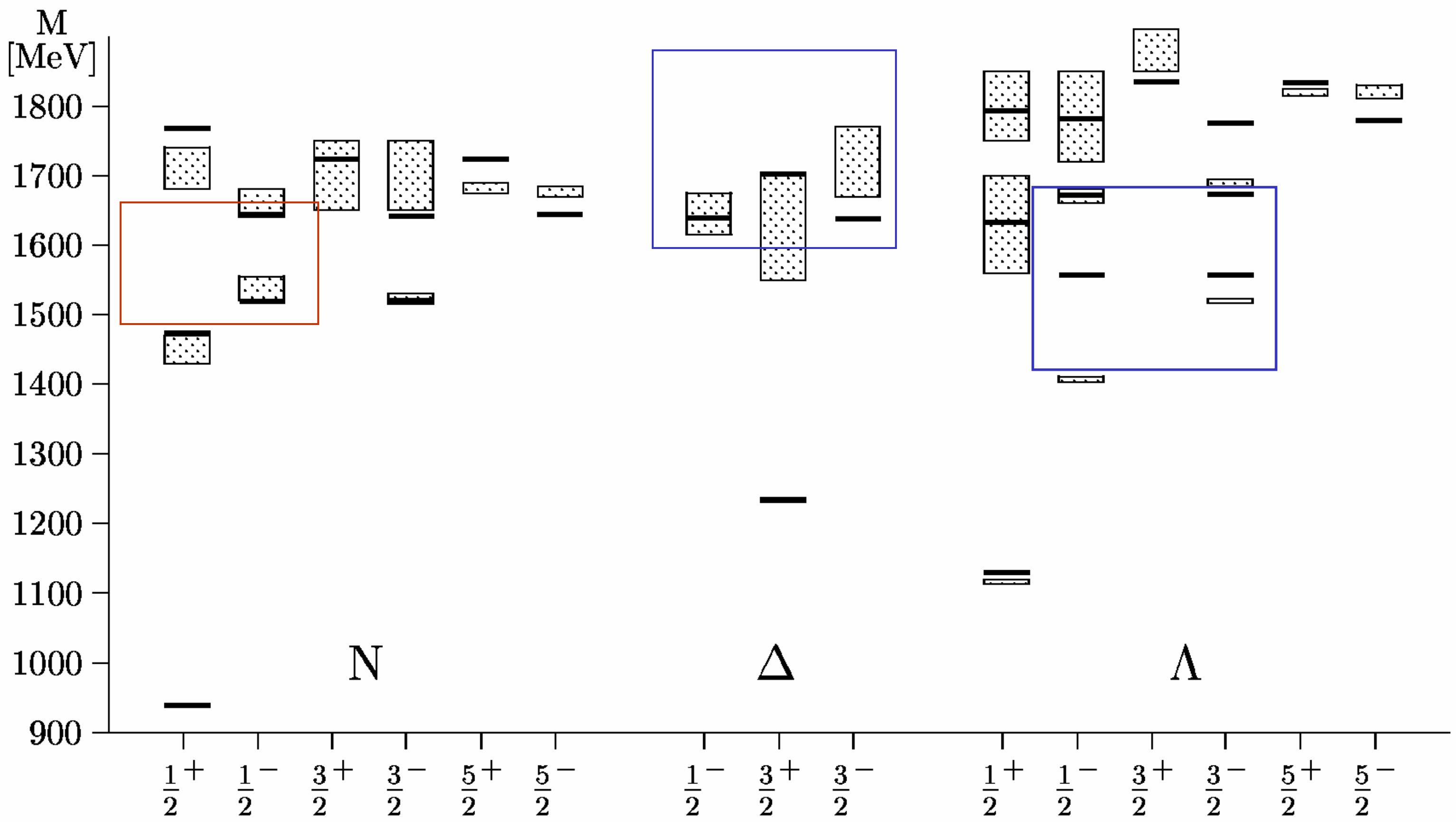
Required developments…

- Theory…
  - Develop ab-initio and model approaches to the spectrum and properties of N*s
    - Lattice QCD
    - 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

Backup slides…

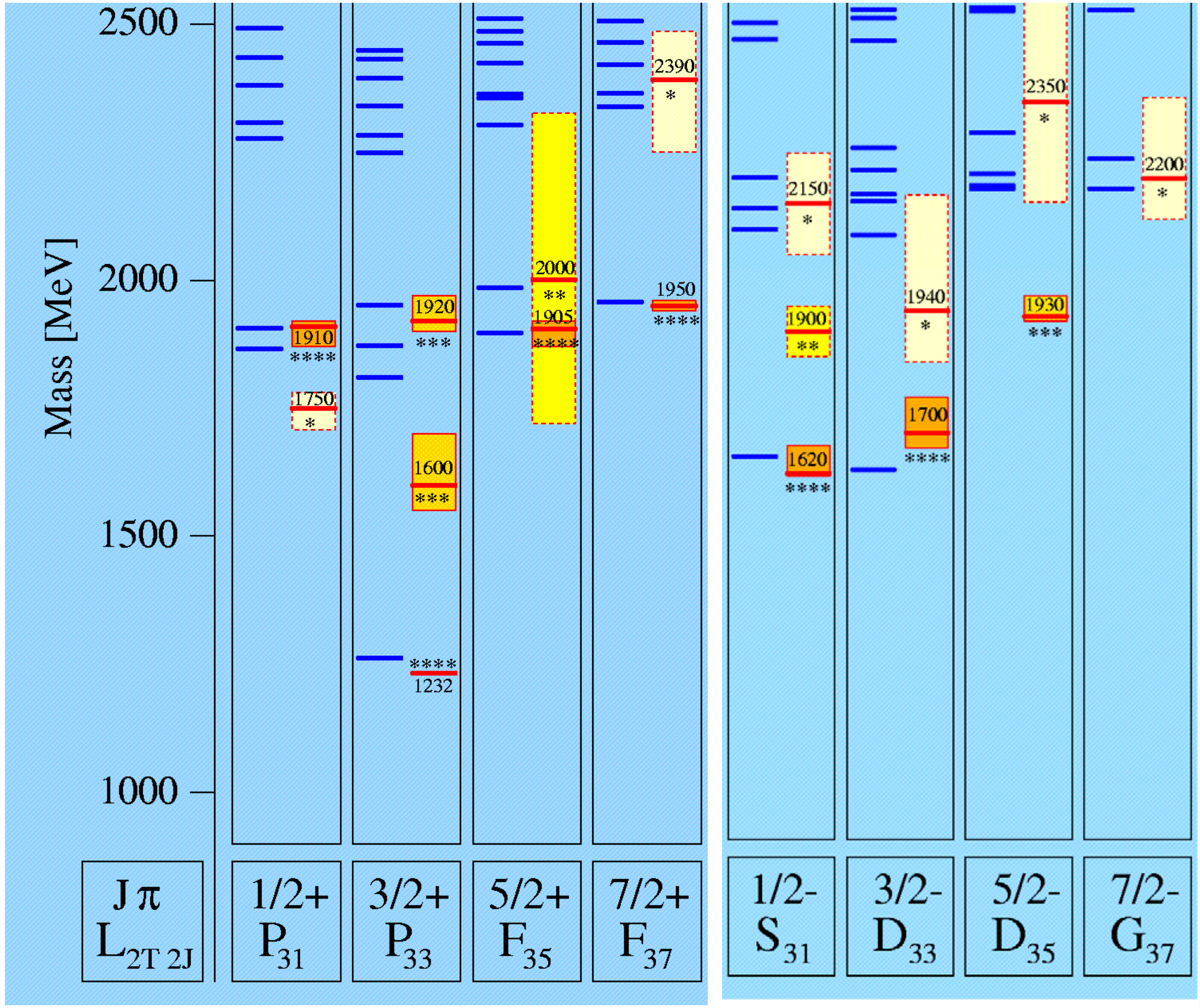
OBE spectrum…

- OBE Results for spectrum: Glozman, Plessas, Theussl, Wagenbrunn, & Varga



Instanton-induced interactions…

- spectrum of Δ* only from confining potential
- Blask, Bohn, Huber, Metsch & Petry



N* spectrum from 't Hooft's force