Finding Missing and Exotic Baryon Resonances

Hadronic versus Electromagnetic Reactions

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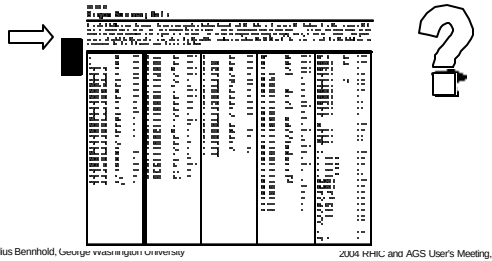
- **Why?**
  - **to test strong QCD!**
- **How?**
  - **Coupled-channels approach constrained by theory:**
    - ✓Lorentz invariance, gauge invariance
    - ✓Chiral symmetry, large N_C limit
  - **…and experiment:**
    - ✓Electromagnetic reactions
    - ✓Hadronic reactions

What do we want?

Quantum Chromodynamics (QCD)

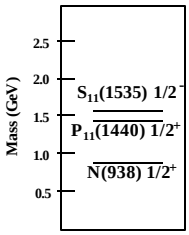
--- the fundamental theory of the strong interaction (in terms of quarks and gluons)

$$L_{QCD} = \tfrac{1}{2}\mathrm{Tr}F_{\mu\nu}F^{\mu\nu} + \bar{q}(\gamma^{\mu}D_{\mu} + m_q)q$$



Comparison with lattice results

What is the nature of the Roper ($P_{11}(1440)\ 1/2^+$) resonance?

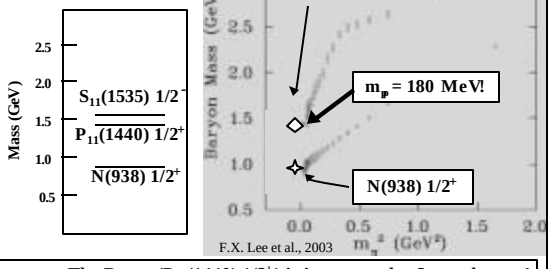


Naïve quark model gives the wrong ordering

- N(1440) 1/2+
- h ω
- N(1535) 1/2-
- h ω
- N(938)1/2+

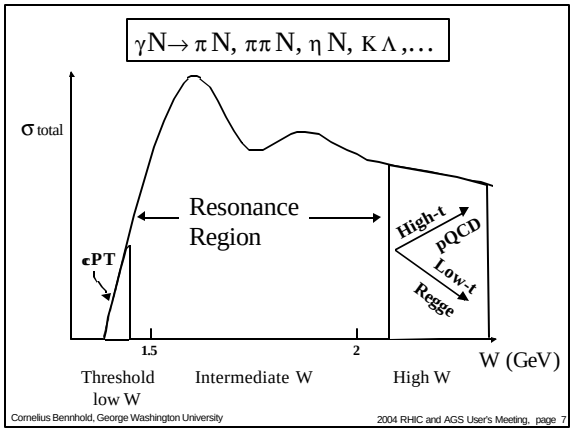
- **Hybrid state ($qqqg$)?**
- **Dynamical meson-baryon state?**

What is the nature of the Roper (**$P_{11}(1440)\ 1/2^+$**) resonance?



Answer: The Roper ($P_{11}(1440)\ 1/2^+$) is just a regular 3-quark state!

How do we find the resonances?


γN→ πN, ππN, ηN, KΛ,…
σ total
Resonance Region
ChPT
High-t pQCD
Low-t Regge
1.5
2
W (GeV)
Threshold low W
Intermediate W
High W
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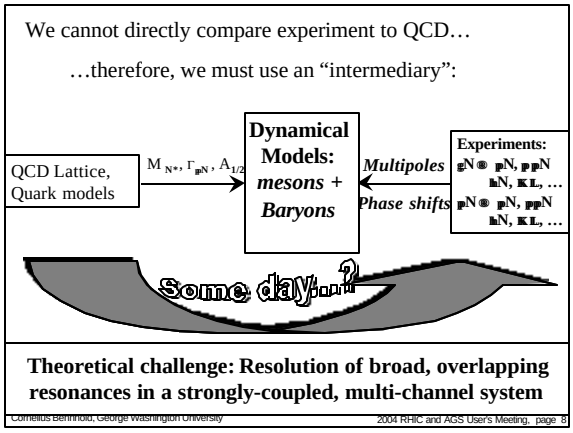
We cannot directly compare experiment to QCD…
…therefore, we must use an "intermediary":
QCD Lattice, Quark models
Dynamical Models: mesons + Baryons
Multipoles
Phase shifts
Experiments:
Some day…?
Theoretical challenge: Resolution of broad, overlapping resonances in a strongly-coupled, multi-channel system
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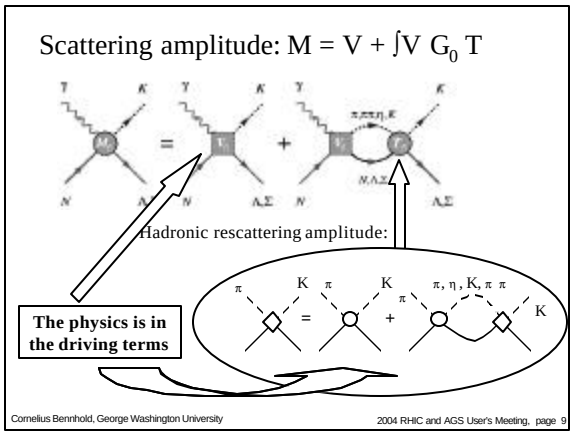
Scattering amplitude: M = V + ∫V G0 T
Hadronic rescattering amplitude:
The physics is in the driving terms
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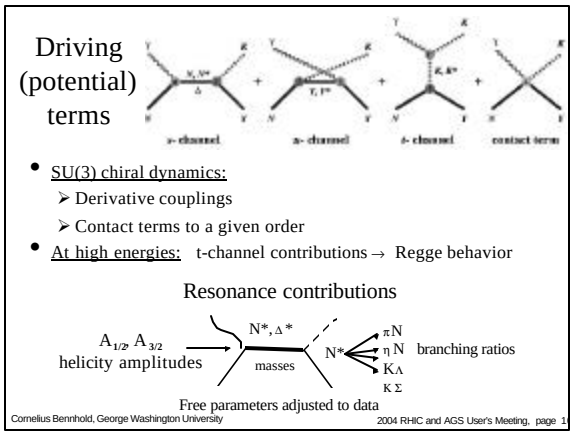
Driving (potential) terms
SU(3) chiral dynamics:
Derivative couplings
Contact terms to a given order
At high energies: t-channel contributions → Regge behavior
Resonance contributions
A1/2, A3/2 helicity amplitudes
N*, Δ* masses
πN
ηN
KΛ
KΣ
branching ratios
Free parameters adjusted to data
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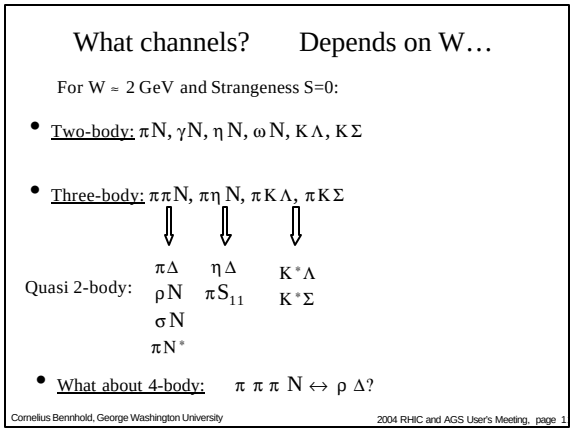
What channels? Depends on W…
For W ≈ 2 GeV and Strangeness S=0:
Two-body: πN, γN, ηN, ωN, KΛ, KΣ
Three-body: ππN, πηN, πKΛ, πKΣ
Quasi 2-body:
πΔ
ρN
σN
πN*
ηΔ
πS11
K*Λ
K*Σ
What about 4-body: π π π N ↔ ρ Δ?
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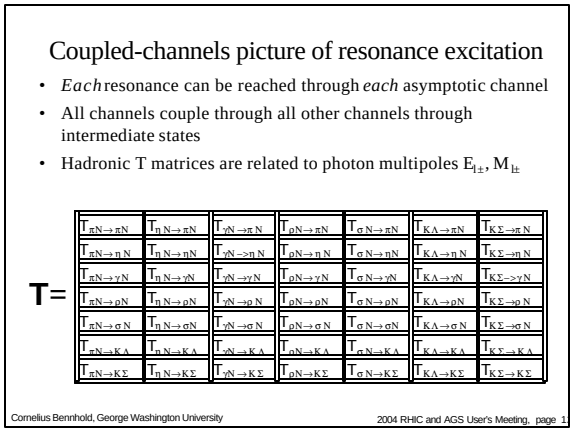
Coupled-channels picture of resonance excitation
Each resonance can be reached through each asymptotic channel
All channels couple through all other channels through intermediate states
Hadronic T matrices are related to photon multipoles El±, Ml±
T=
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Why bother with coupled channels?
Unitarity!

- Missing N*:

gN → N* → pN, pD, rN, hN, KL

Find the *same* N* in *different* reaction channels!

Example: the P_{33} partial wave

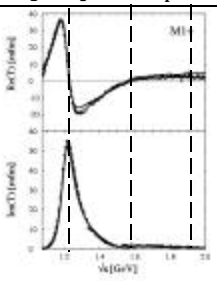
P_{33}(1232):
Mass: 1232 MeV
Width: 110 MeV
$A_{1/2}$= -140 ± 10
$A_{3/2}$= -255 ± 12

P_{33}(1600):
Mass: 1670 - 1695 MeV
Width: 350 - 560 MeV
$A_{1/2}$= - 81 … +2
$A_{3/2}$= -104 … + 27

P_{33}(1920):
Mass: 1870 - 2000 MeV?
Width: 300 - 600 MeV?

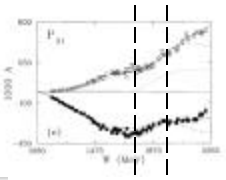
Existence controversial!

gN → pN multipole

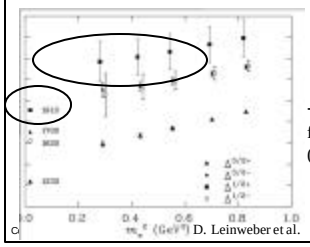


Exception: P_{31}

- Where is the ground state?
- 1910 MeV? 1750 MeV?



1750? 1910?



D. Leinweber et al.

- Recalculate with overlapping fermion action close to chiral limit (in progress)

How many N* do we have?

State-of-the-art multi-channel analyses find, *for a given partial wave:*

- Ground states (1st tier): $P_{33}(1232)$, $D_{13}(1520)$,…
  - Clear resonance signal, Mass known to within a few %.
  - $A_{1/2}$, Γ_{total}, partial widths fairly well known
  - Exceptions: $S_{31}(1620)$,…
- 2nd tier states: $P_{33}(1600)$, $D_{13}(1700)$, …
  - Existence confirmed, but poorly understood
- 3rd tier states: $P_{33}(1920)$, $D_{13}(2080)$, …
  - Existence controversial. *Where is everybody?*

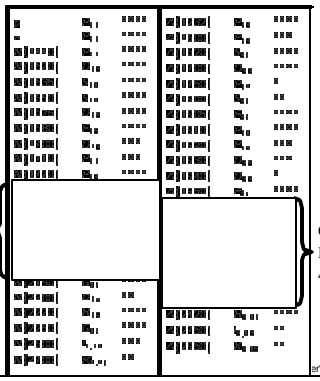
How many N* do we need?

"Missing" and "Exotic" Resonances?

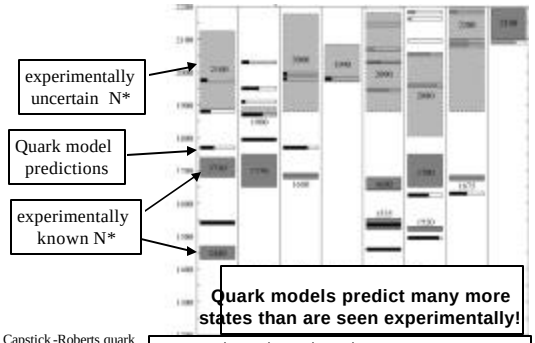
Current spectrum of *baryon resonances*:

Gap of ≈450 MeV between 4-star N*

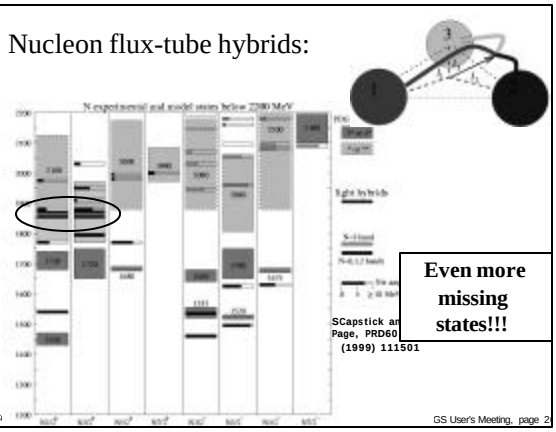
Gap of ≈ 450 MeV between 4-star Δ*



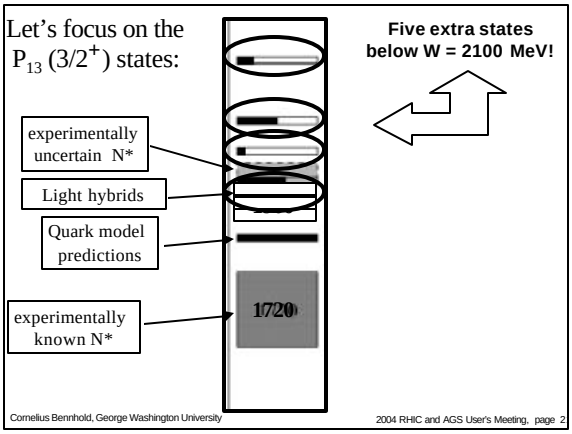
Compare experimental N* and quark model states



Nucleon flux-tube hybrids:



Let's focus on the P_{13} $(3/2^+)$ states:



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How many N* do we need?

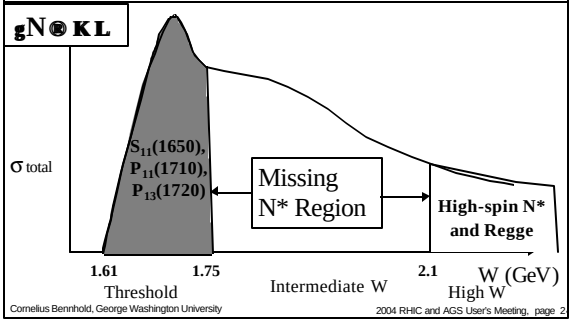
Possibly 4-5 N* for selected partial waves!

…looking in Strange places: gN ⊗ KL(S)

New Topic

Divide energy region into three parts:

- **Threshold region (1.61 – 1.75 GeV):** $S_{11}(1650)$, $P_{11}(1710)$, $P_{13}(1720)$
- **Missing N* region (1.75 – 2.1 GeV):** $D_{13}(1900)$,…
- **High-spin N* region (2.1 – 2.4 GeV):** $G_{17}(2190)$?

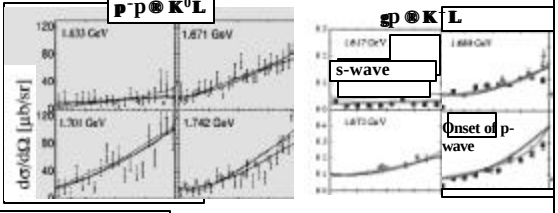


Threshold Region: $S_{11}(1650)$, $P_{11}(1710)$, $P_{13}(1720)$

What does the quark model predict? (Capstick, Roberts)

Result of coupled-channels analysis for:

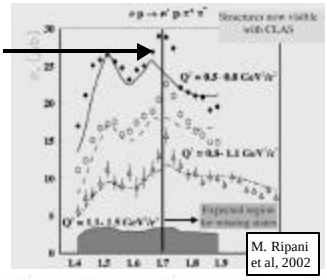
$\gamma p \to K^+\Lambda$ and $\pi^- p \to K^0\Lambda$



New result (prelim.):

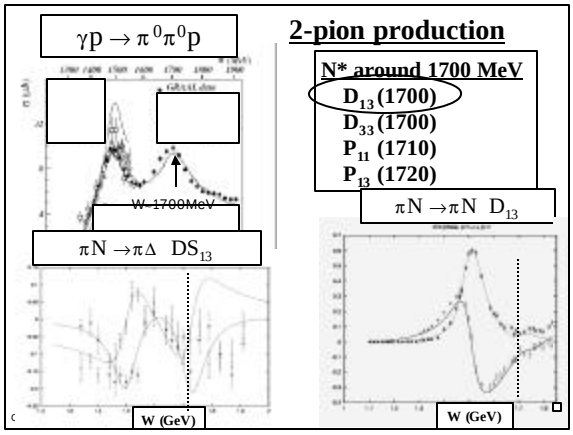
$S_{11}(1650)$	1610 – 1650 MeV
$P_{11}(1710)$	1650 or 1730 MeV ▶ possibly 2 different N*?
$P_{13}(1720)$	1660 – 1720 ▶ *but* total width is 40-70 MeV!

Another signal for a new P_{13} around 1700?



M. Ripani et al, 2002

	Mass (MeV)	Γ (MeV)	B(Δπ) (%)	B(Nη) (%)
our fit of PDG P_{13}	1725 ± 20	114 ± 25 ± 29	65 ± 12 ± 17	19 ± 9 ± 14
PDG values	1650 - 1750	100 - 200	absent	70 - 85
new P_{13}	1720 ± 20	88 ± 17 ± 25	41 ± 13 ± 20	17 ± 10 ± 17



2-pion production

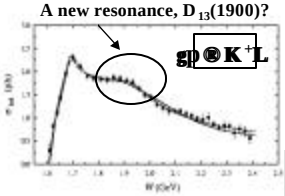
N* around 1700 MeV

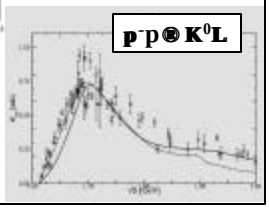
- $D_{13}(1700)$
- $D_{33}(1700)$
- $P_{11}(1710)$
- $P_{13}(1720)$

$\pi N \to \pi N$ D_{13}

Missing N* region

A new resonance, $D_{13}(1900)$?





New resonances in $\gamma N \to K\Lambda$ in the region $1.75 < W < 2.1$ GeV (preliminary)

N* State	Mass range (MeV)	Particle Data Group
P_{13}	1880 – 1930	P_{13} (1900)**?
D_{13}	1820 – 1880	D_{13} ---
D_{13}	2000 – 2080	D_{13} (2080)**?
D_{15}	1970 – 2030	D_{15} ---
F_{17}	1890 – 1950	F_{17} (1900)**?

Conclusions

- New resonancesmay appear in photoreactions like $\gamma p \to K^+\Lambda$

Are missing N* finally appearing?

- For confirmation we need:
  - New data for $\pi^- p \to K^0\Lambda$, $\pi^- p \to \eta n$
  - New data for $\pi N \to \pi\pi N$ – *redo partial-wave analysis!*
  - Partial-wave analysis for $\gamma N \to \pi\pi N$