Nucleon Excited States-Theoretical Issues

- Overview: why study nucleon and meson excited states?
- Four QCD-based models of hadron structure
- How experiments can help resolve theoretical issues: salient examples
- Urgently needed theoretical developments

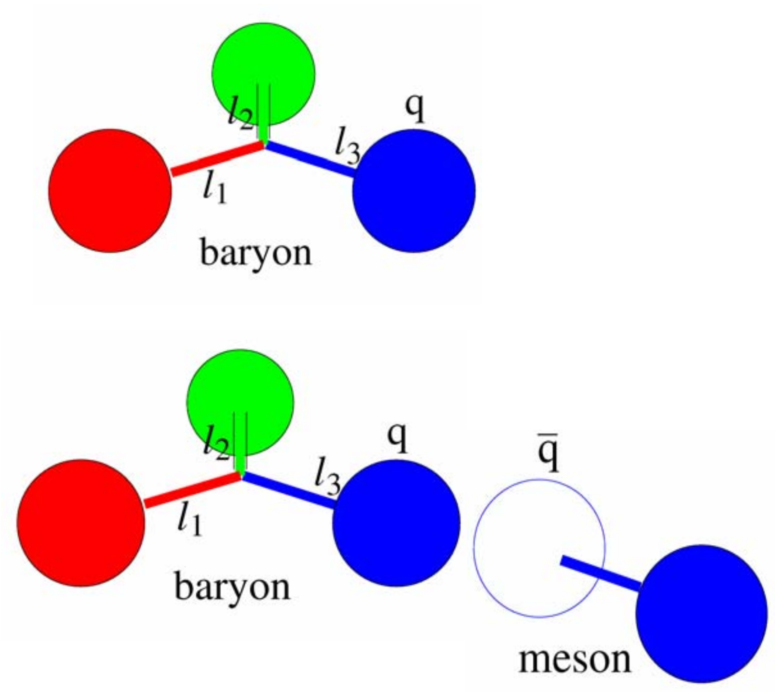
Why study nucleon and meson excited states?

1. Uniqueness: bound states of strongly-interacting, relativistic confined systems
2. Identification of important effective degrees of freedom in low-energy QCD
3. Potential discovery of entirely new forms of matter: glueballs, hybrids

Uniqueness

- Unique?
- Nucleons interact strongly in nuclei…
  - Can isolate relevant low-energy d.f. (nucleons)
  - Can directly probe two-body potential in experiment
  - Few body systems 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…

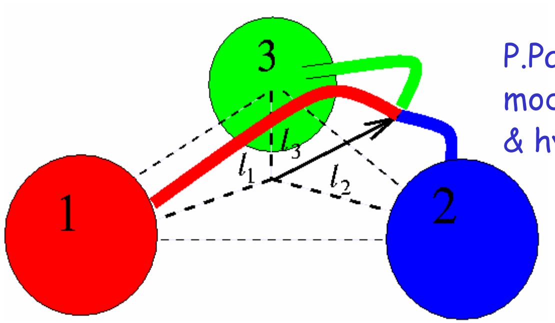


- Elementary d.f. are confined
  - Can only indirectly infer low-energy interaction
- Only qqq, $q\bar{q}$, $(qqqq\bar{q}')$ exist as bound states
- Not non-relativistic systems (unless **all** quarks heavy)

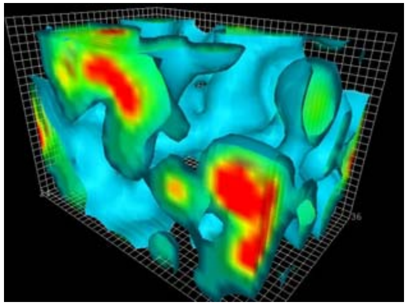
Effective degrees of freedom

Low-energy QCD:

- Constituent quarks (CQs), confined by flux tubes?
- Confined CQs, elementary meson fields?
- Confined CQs, gas of instantons?



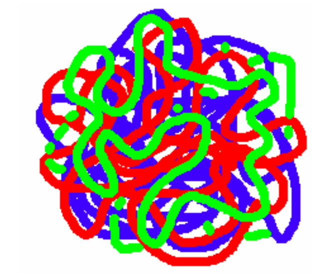
P.Page, S.C. Flux-tube model of baryons & hybrids

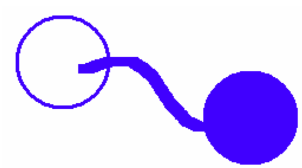


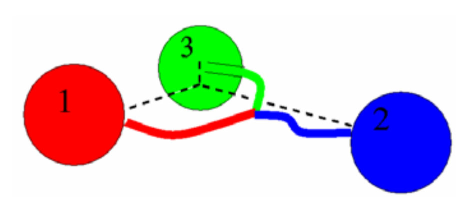
D. Leinweber et al. QCD vacuum action density

Entirely new forms of matter

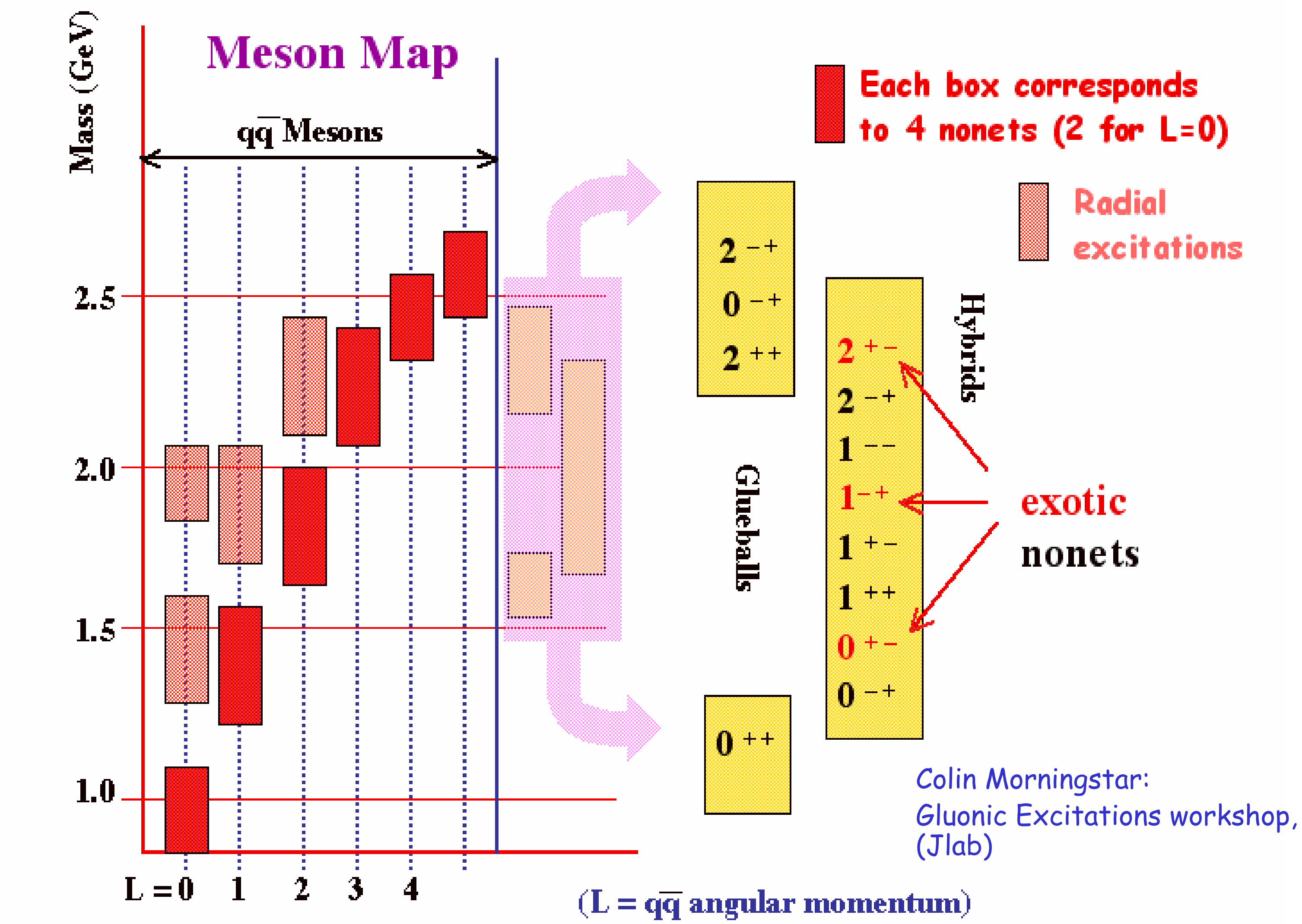
- Gauge-field configurations provide confining potential
  - States of pure glue exist
    - Exotic states not light
    - Others mix with $q\bar{q}$
  - Glue may not be in ground state
    - Hybrid mesons: exotic quantum numbers
    - Hybrid baryons: no exotics, mix with qqq







Glueballs and hybrid mesons



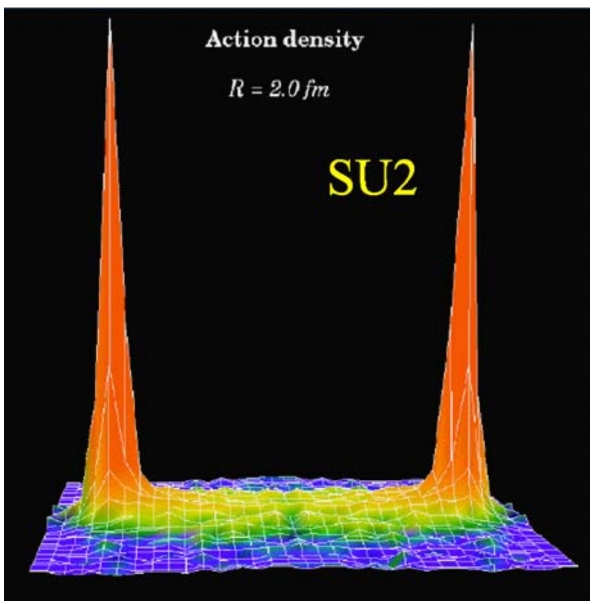
Colin Morningstar:
Gluonic Excitations workshop, 2003 (Jlab)

QCD-based models of hadron structure

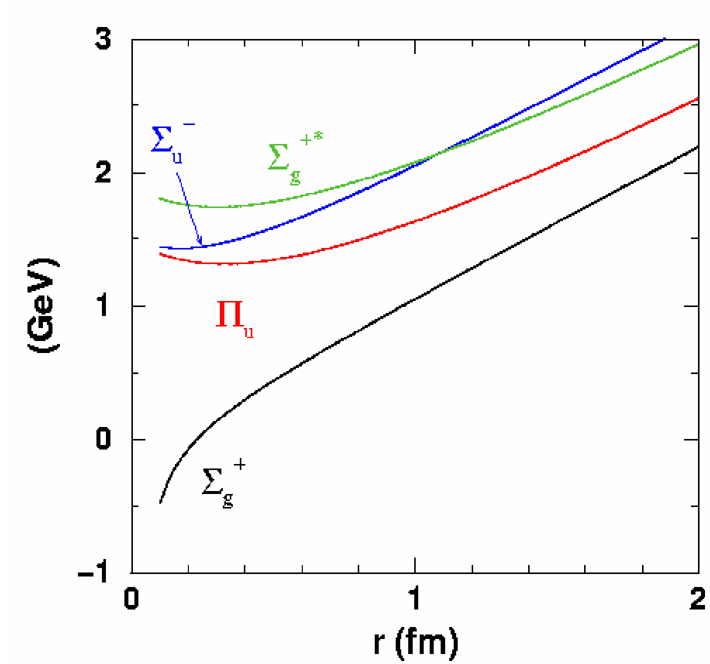
- Why do we need models?
- Can solve for certain quantities in QCD using lattice gauge theory
  - Masses of lightest few states with given quantum numbers (especially pure glue)
  - Hadronic matrix elements of electro-weak operators
    - Especially heavy-quark hadrons: f_B, f_D, ...
  - Heavy-quark potentials

Why do we need models?

- Heavy quark potentials in mesons
  - Action density has flux-tube at large r
  - Potentials deviate from flux-tube expectations at small r



Bali et al.

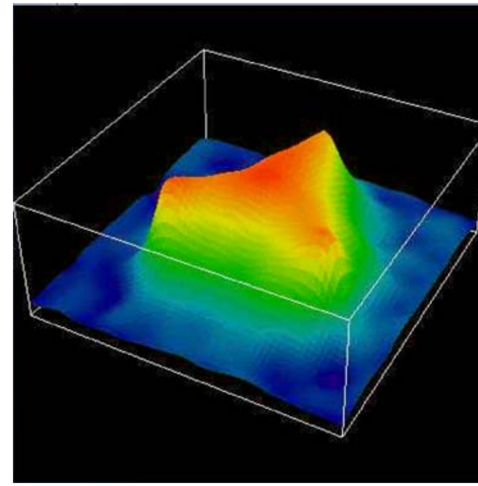


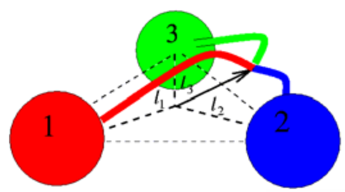
Juge, Kuti, & Morningstar

Heavy quark potentials in baryons

- Abelian action distribution of gluons and light quarks nr. QQQ

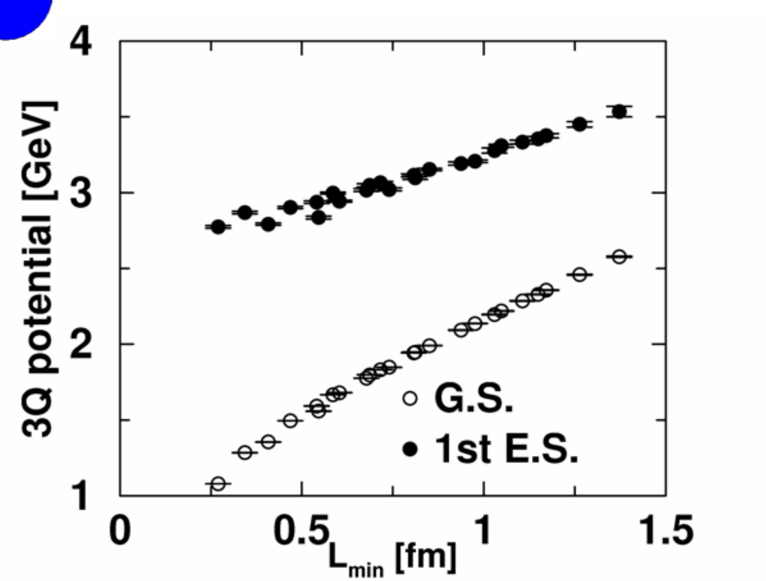
  Ichie, Bornyakov, Struer & Schierholz





Takahashi &Suganuma:

- Calculate $L_{min}=l_1+l_2+l_3$
- plot ground and first excited state energies of glue (V_B and V_{H1}) vs. L_{min}



Why do we need models…?

- Description of full spectrum requires models based on QCD
  - Quarks are confined
    - pair-wise linear confinement
    - string potential L_{min}, scale set by meson string tension
  - Spin and flavor-dependent "hyperfine" interactions are present between quarks
    - Models differ in mechanism for short-distance, spin-dependent interactions
    - Different pictures of the important physics!

Gluon-exchange models

- Emphasize:
  - Connection to heavy-quark limit
  - Universality of meson and baryon physics
- Quarks exchange gluons at short distance
  - color-magnetic hyperfine interactions
  - e.g. DeRujula, Georgi, Glashow (ground states)

$$M = \sum_{i=1}^{3} m_i + \frac{2\alpha_s}{3} \frac{8\pi}{3} \langle \delta^3(\mathbf{r}) \rangle \sum_{i<j=1}^{3} \frac{\mathbf{S}_i \cdot \mathbf{S}_j}{m_i m_j}$$

Gluon-exchange models…

- Predict presence of additional tensor interactions

$$H^{ij}_{\rm hyp} = \frac{2\alpha_s}{3m_i m_j}\left\{\frac{8\pi}{3}\mathbf{S}_i\cdot\mathbf{S}_j\delta^3(\mathbf{r}_{ij}) + \frac{1}{r^3_{ij}}\left[\frac{3(\mathbf{S}_i\cdot\mathbf{r}_{ij})(\mathbf{S}_j\cdot\mathbf{r}_{ij})}{r^2_{ij}} - \mathbf{S}_i\cdot\mathbf{S}_j\right]\right\}$$

  - Tensor
    - mixes states split by contact interaction
    - D-waves in the nucleon and Δ
  - Where are spin-orbit interactions?

One-boson exchange models

- Emphasize:
  - aspects of QCD at low momenta imposed by chiral symmetry
  - Goldstone-boson nature of π, K, η,… fields
- Bosons exchanged between quarks

$$H_\chi \sim -\sum_{i<j} \frac{V(\mathbf{r}_{ij})}{m_i m_j} \boldsymbol{\lambda}_i^{\mathrm{F}} \cdot \boldsymbol{\lambda}_j^{\mathrm{F}} \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j$$

  - No spin-orbit from OBE (confinement?)

Instanton-based model

- Another flavor-dependent possibility: instanton-induced interactions
- Present if qq in S-wave, I=0, S=0 state

$$\langle q^2; S, L, T | W | q^2; S, L, T \rangle = -4g\, \delta_{S,0}\, \delta_{L,0}\, \delta_{T,0} \mathcal{W}$$

- W is a contact interaction (has range λ)
  - causes no shifts in Δ^* masses
  - No tensor interaction, or spin-orbit forces
- Applied to excited states
  - Blask, Bohn, Huber, Metsch & Petry
  - solve Bethe-Salpeter equation

Instanton-induced interactions

- Quarks confined by linear q-q potential

$$V(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3) = A_3 + B_3 \sum_{i<j} |\mathbf{r}_i - \mathbf{r}_j|$$

- Relativistic treatment, so need to choose Dirac structure of potential

$$A_3 = a\,\frac{3}{4}\left[\mathbb{I}\otimes\mathbb{I}\otimes\mathbb{I} + \gamma^0\otimes\gamma^0\otimes\mathbb{I} + \gamma^0\otimes\mathbb{I}\otimes\gamma^0 + \mathbb{I}\otimes\gamma^0\otimes\gamma^0\right]$$

$$B_3 = b\,\frac{1}{2}\left[-\mathbb{I}\otimes\mathbb{I}\otimes\mathbb{I} + \gamma^0\otimes\gamma^0\otimes\mathbb{I} + \gamma^0\otimes\mathbb{I}\otimes\gamma^0 + \mathbb{I}\otimes\gamma^0\otimes\gamma^0\right]$$

  - Form chosen to reduce spin-orbit effects
  - Reproduces correct “Regge trajectories”

Dynamical approaches

- Are **all** (or many) excited baryon states dynamically generated?
  - States are poles in scattering matrix
  - Potentials chosen to reproduce low-energy scattering data (chiral dynamics)
  - Generate poles by iterating interaction based on potentials, coupled channels
    - E. Oset et al., M. Lutz, S. Krewald et al.

Important required developments

- Experiment + theoretical analysis:
  - Will ultimately sort out (or synthesize) these pictures
  - Steer lattice groups toward important quantities to calculate

Important required developments

1. Better determination of properties of states known to exist (say PDG 4*, 3*)
2. Verification/removal of poorly determined states, discovery of "missing" resonances
3. Evidence of overpopulation of states in some partial waves, decay signatures?
   - Hybrids
   - Possible N, Σ partners of S=+1 pentaquarks
4. Development of coupled-channel analysis (required for 1.-3.)

1. Properties of existing states

- E.g.: some models predict (tensor) mixing between S_{11} and D_{13} ($N^*1/2^-$,$N^*3/2^-$) states
  - Mixing angles differ in different approaches (no mixing at all with instantons)
- Theory: calculate mixing angles, effects on decays to:
  - $N\pi$, $N\eta$, ΛK, $N\pi\pi$ ($N\rho$, $\Delta\pi$,...)
- Experiment + analysis: find accurate partial widths

Mixing angles

- Physical states are admixtures of two possible L,S combinations

$$N(1535)1/2^- = \cos(\theta_S)\, N^2P1/2^- - \sin(\theta_S)\, N^4P1/2^-$$

$$N(1650)1/2^- = \sin(\theta_S)\, N^2P1/2^- + \cos(\theta_S)\, N^4P1/2^-$$

$$N(1520)3/2^- = \cos(\theta_D)\, N^2P3/2^- - \sin(\theta_D)\, N^4P3/2^-$$

$$N(1700)3/2^- = \sin(\theta_D)\, N^2P3/2^- + \cos(\theta_D)\, N^4P3/2^-$$

- Lattice QCD should also be able to determine θ_S and θ_D
  - enough time (CPU and elapsed!)
  - clever choice of correlators…

Properties of existing states…

- E.g. is the Roper resonance:
  - A qqq (radial) excitation?
  - Dynamically-generated bound state?
    - S. Krewald et al., iterated Nσ interaction
    - no elementary excitation needed to fit data!
  - Hybrid? Pentaquark?
    - Bag/flux-tube models: lightest hybrids include P_{11} ($N1/2^+$) states at 1500/1900 MeV
    - Chiral-soliton picture anti-decuplet N(1647)
  - More than one of the above?

Roper resonance

- Photo-couplings incompatible with (OGE) qqq interpretation
  - Accurate determinations of photo-couplings (in coupled-channel analysis) required
- EM form factor from $e^{-}N$
  - Should fall off rapidly if state is predominantly a baryon-meson effect
- Focus on P_{11} partial wave (also other states)
- Lattice:
  - Roper heavy in quenched calculations, lighter (threshold?) as pion mass is lowered: more development needed!

2. Missing and 1*, 2* states

- Why bother finding new states or confirming/removing old ones?
  - E.g.: current debate about chiral-symmetry restoration in spectrum
    - Prediction of pairing of +ve/-ve parity states with same J higher in spectrum
  - 1* states $N1/2^{+}(2100)$ & $N1/2^{-}(2090)$ identified as doublet (Cohen and Glozman)

    PDG: S11(2090) "any structure above 1800 MeV"

    1. 1885 +/- 30 MeV vs. 1928 +/- 59 (43 MeV)
    2. 2125 +/- 75 vs. 2180 +/- 80 (55 MeV)
    3. 2050 +/- 20 vs. 1880 +/- 20 (-165 MeV)

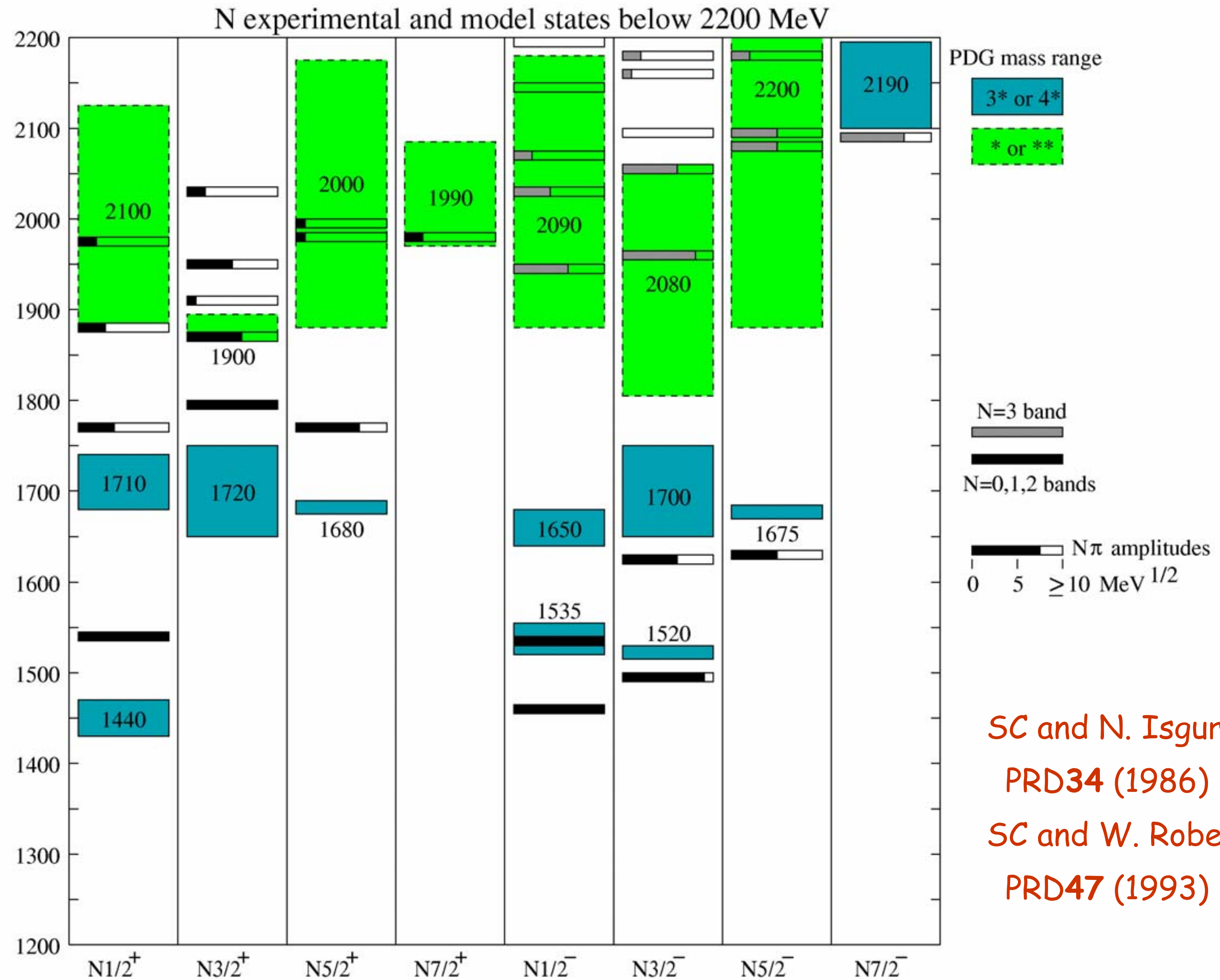
Missing resonances

- Symmetric (qqq) potential models:
  - Agree on **number** of excited states of a given character
  - Disagree on their **place** in spectrum, especially at higher energy
  - many positive (and doubly-excited negative) parity states not seen in analyses of data: "missing" resonances
- Largest differences in predictions for (formation &) decay-channel couplings
  - Model proponents **must** calculate baryon-meson (all open channels) and photo- couplings

Missing resonances

- Finding several missing (+ve parity) resonances:
  - Would verify symmetric qqq correct picture
- PDG states established in analyses of $N\pi$ elastic scattering
  - States which couple weakly to $N\pi$ will be "missing"
  - **Evidence** for them should show up in other ($N\pi\pi$, ΛK,…) final states, excited with EM probes from nucleon targets (make N^* or Δ^*)
  - Their existence will be **established** in multi-channel analyses of several final states

Nucleon model states and Nπ couplings



SC and N. Isgur,
PRD**34** (1986) 2809;
SC and W. Roberts,
PRD**47** (1993) 2004

3. Unconventional states

- All baryon J^P quantum numbers possible with qqq: no exotic hybrids
  - Light hybrid baryon states (flux-tube):
    - S_{qqq}=1/2 states: N1/2$^+$, N3/2$^+$ at ~1870 +/- 100 MeV
    - S_{qqq}=3/2 states: D1/2$^+$, D3/2$^+$, D5/2$^+$ approx. 2075 +/- 100 MeV
  - Theory needs to examine decays
    - Easily identified decay signatures?
    - Electromagnetic couplings? (Burkert and Li)

Unconventional states…

- Partners N, Σ of Θ^+ with $J^P=1/2^+$
  - will mix with conventional states
  - May have significant hidden strangeness: decays?
- Because of mixing, discovery may require overpopulation of states
  - Another important reason to carefully study P_{11} (P_{13}, P_{31}, P_{33}, F_{35}) partial wave!

4. Development of coupled-channel analysis

- Grand challenge for hadron structure physics:
  - Extraction of model-independent information about overlapping, broad resonances from EM-production and hadron scattering data

Analysis of N* (and meson) data

Masses, widths, decay branches, photocouplings, EM form factors

from

Partial wave data in many (all open) channels; multipoles in γN

from

Scattering data

Analysis of N* (and meson) data…

- Necessary ingredients?
- Coupled-channel unitarity
  - E.g. K-matrix approach: (D.M. Manley, KSU)

$$T = \frac{1+iK}{1-iK}, \;\; K = K^\dagger$$

    - K contains resonance information, background terms
  - CMB (Cutkosky; Vrana, Dytman and Lee) model:
    - all channels re-scatter into all others via loops
  - Effective Lagrangians: T. Sato and T.-S. H. Lee; GWU group: C. Bennhold, H. Haberzettl; Mainz group: L. Tiator, D. Drechsel,…

Analysis of N* (and meson) data…

- Fitting ambiguities can be lessened by imposing necessary analytic structure of amplitudes
  - Resonances appear as poles
  - Thresholds cause branch cuts, amplitudes on various sheets related
  - Analytic structure can be made compatible with unitarity (CMB model)

Analysis of N* (and meson) data…

- Theory must provide:
  - Strong form factors: e.g. N(1535) to Nη as a function of decay momentum (for loops)

$$\pi N \to N(1535) \to N(-k)\eta(k) \to N(1535) \to \pi N$$

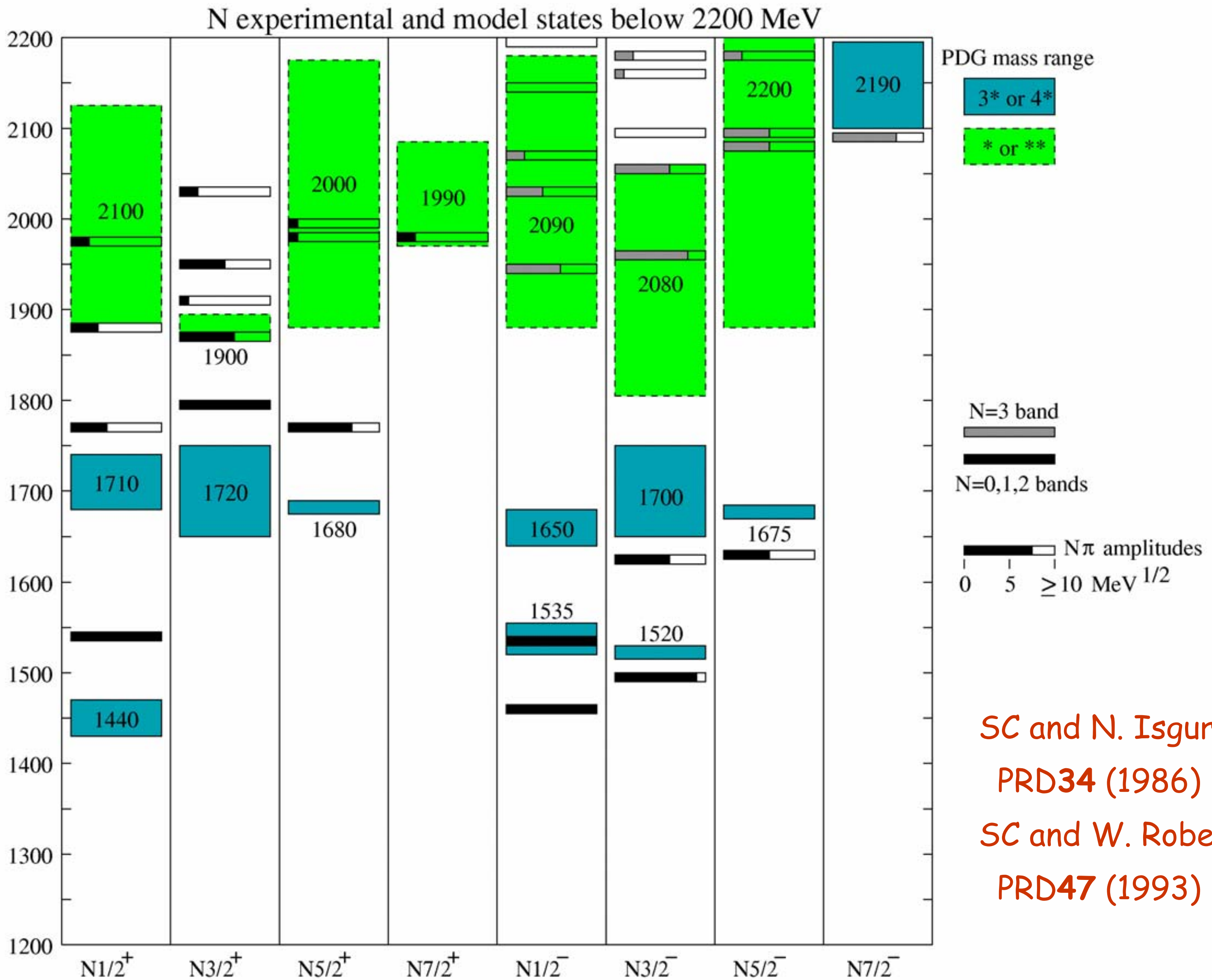
  - Open threshold causes cusp in Nπ elastic scattering amplitude
    - Amplitude is integral, involves form factor: not an observable!

Theoretical ingredients…

- Theory must provide:
  - Technique for constraining background amplitudes
    - Based on physics of competing processes

      e.g. t-channel (meson) exchange
    - Consistent with unitarity, analyticity, gauge invariance

Nucleon model states and Nπ couplings



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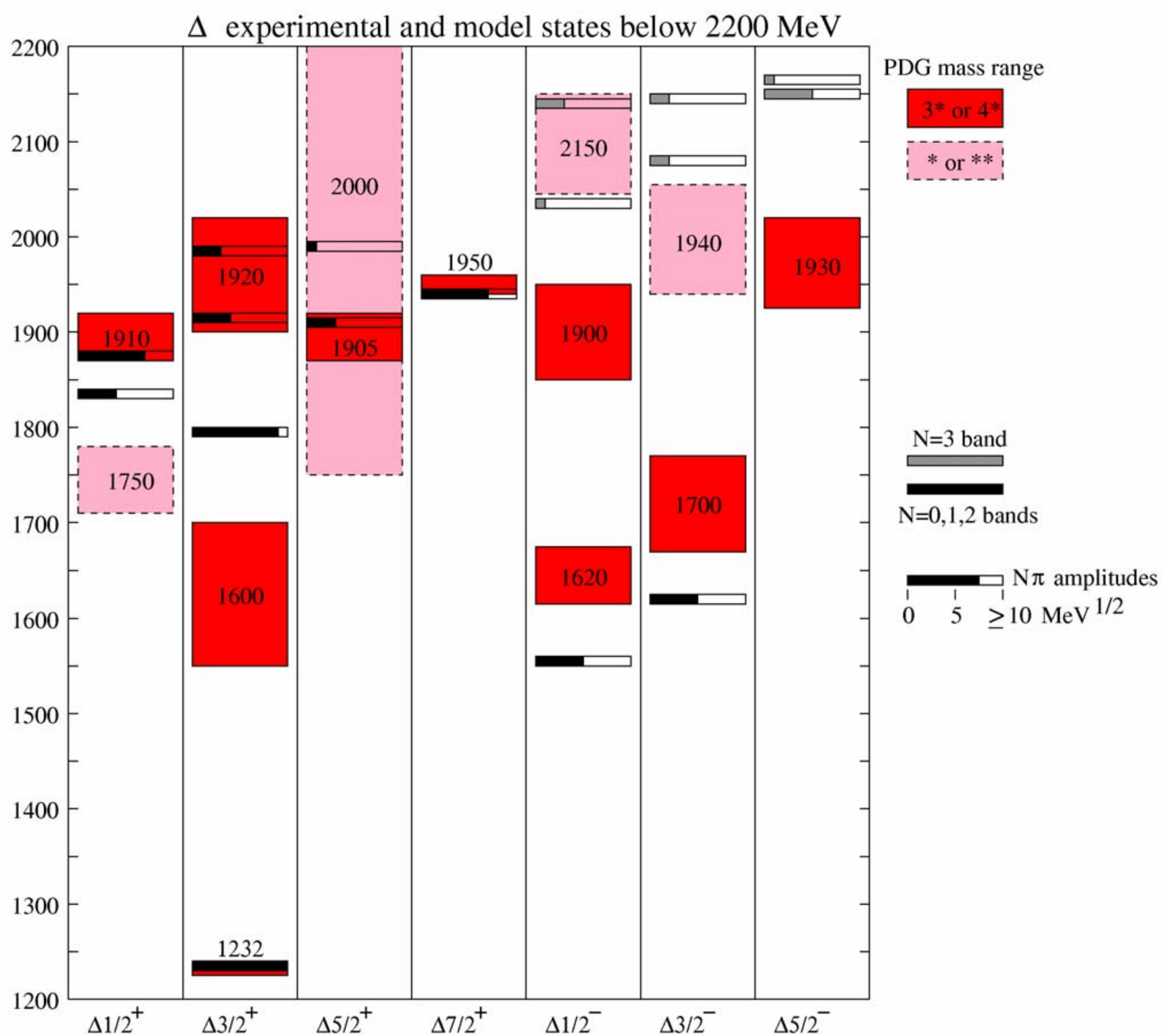
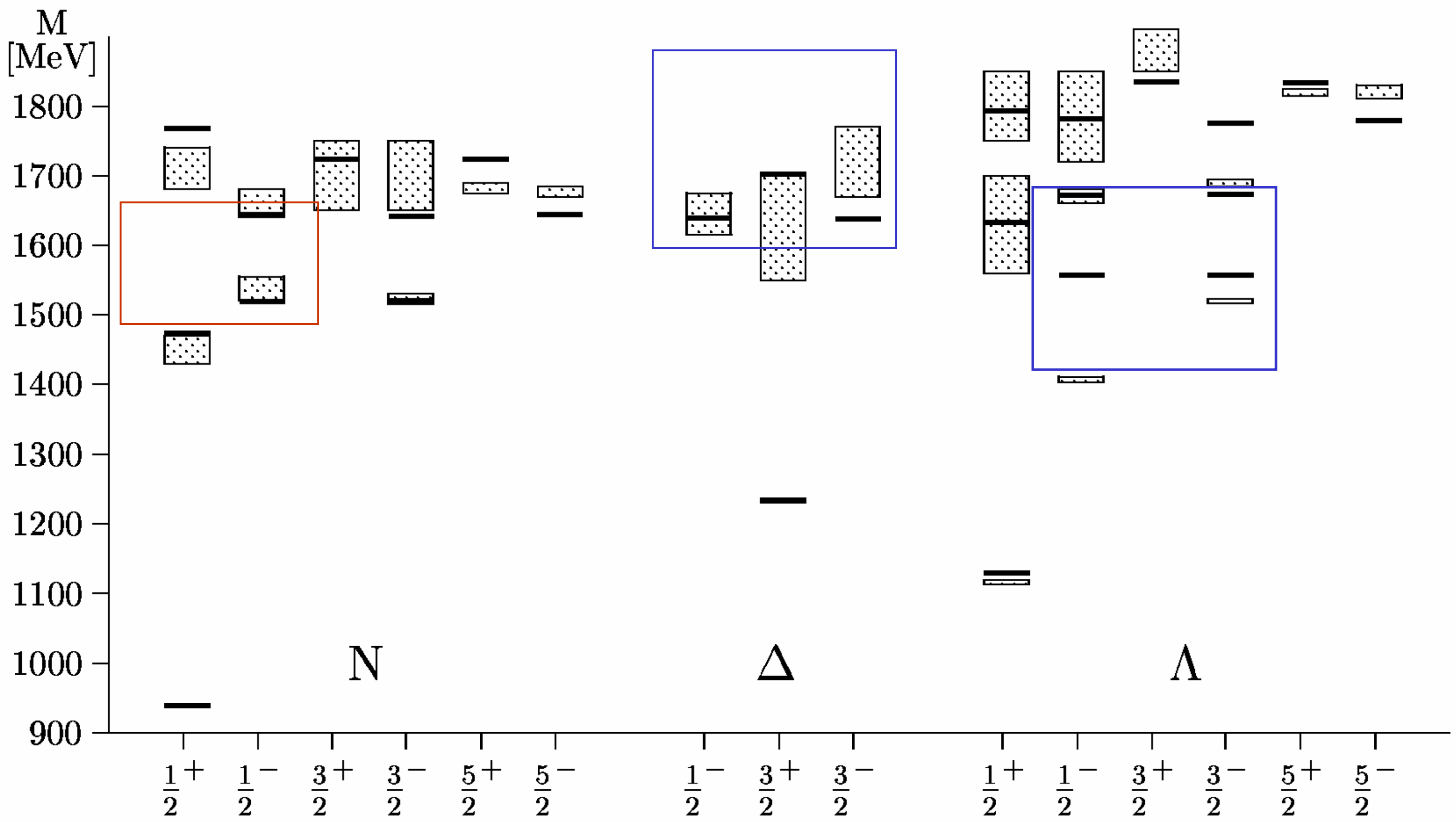
Δ model states and Nπ couplings



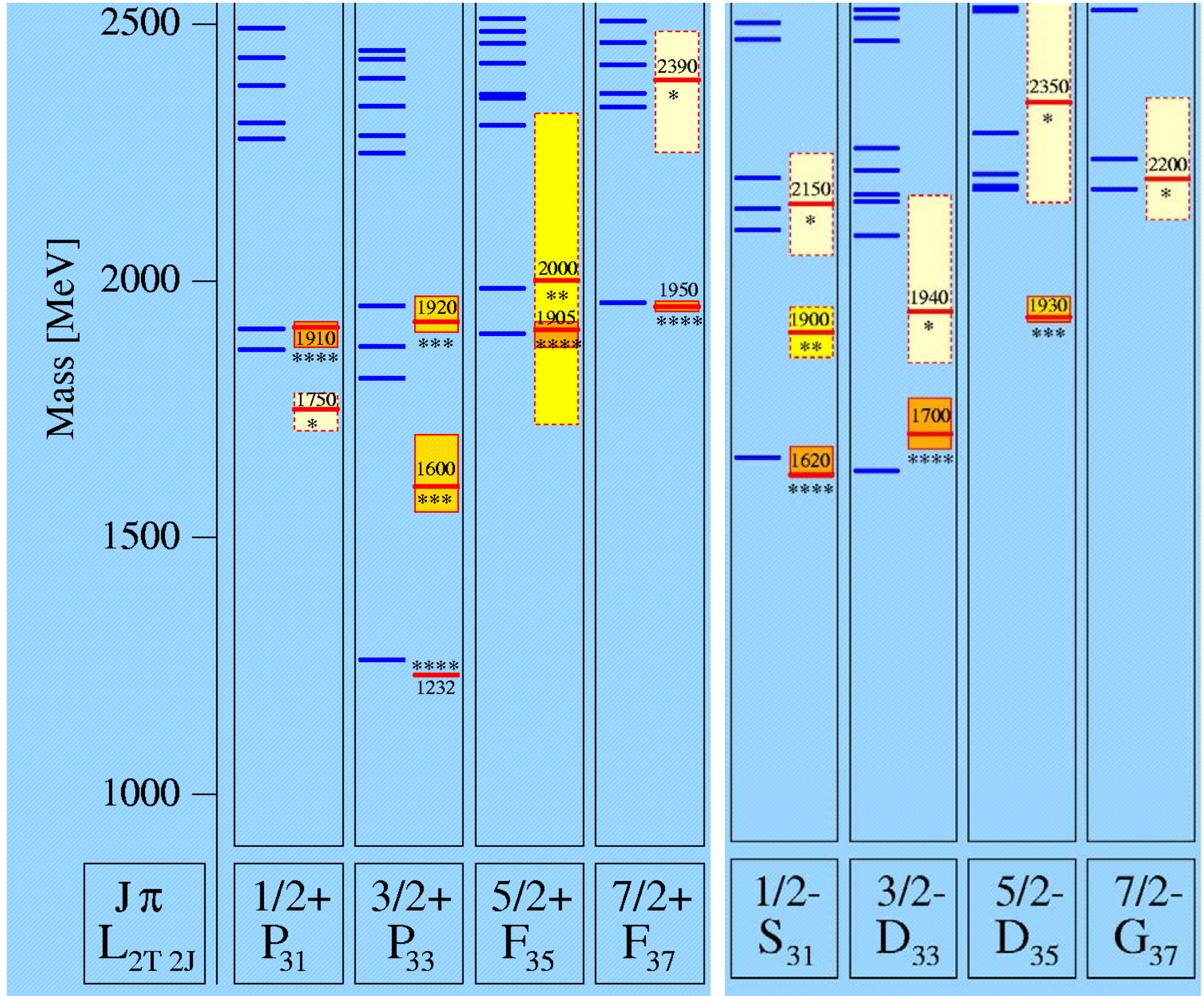
OBE spectrum…

- 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