Summary Talk – Theory

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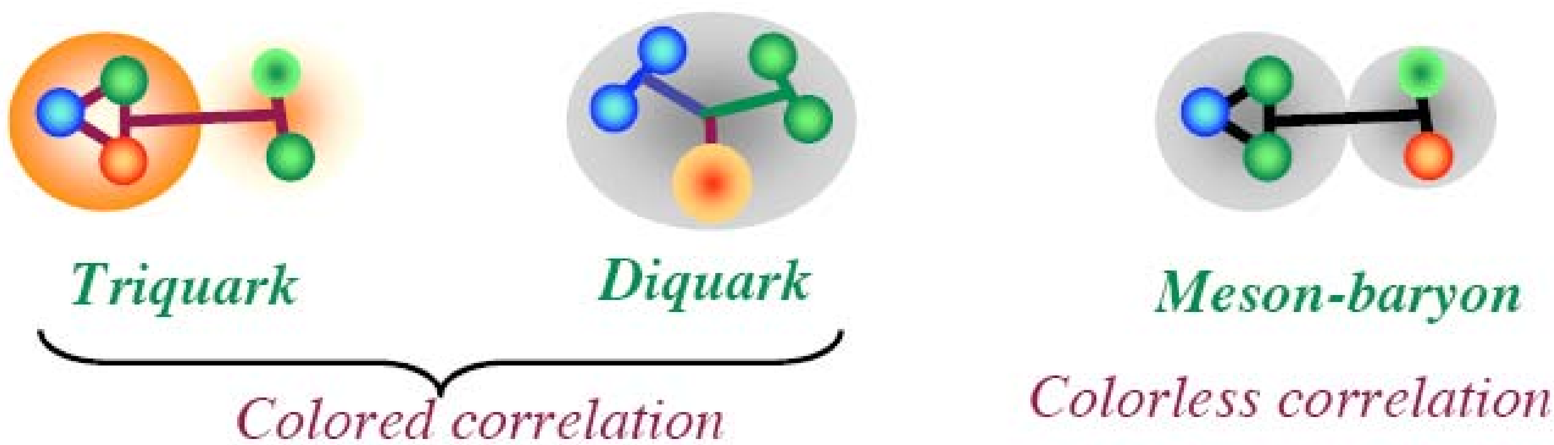
Narrow Nucleon Resonances Workshop, Edinburgh, June 2009

exotic hadron resonances

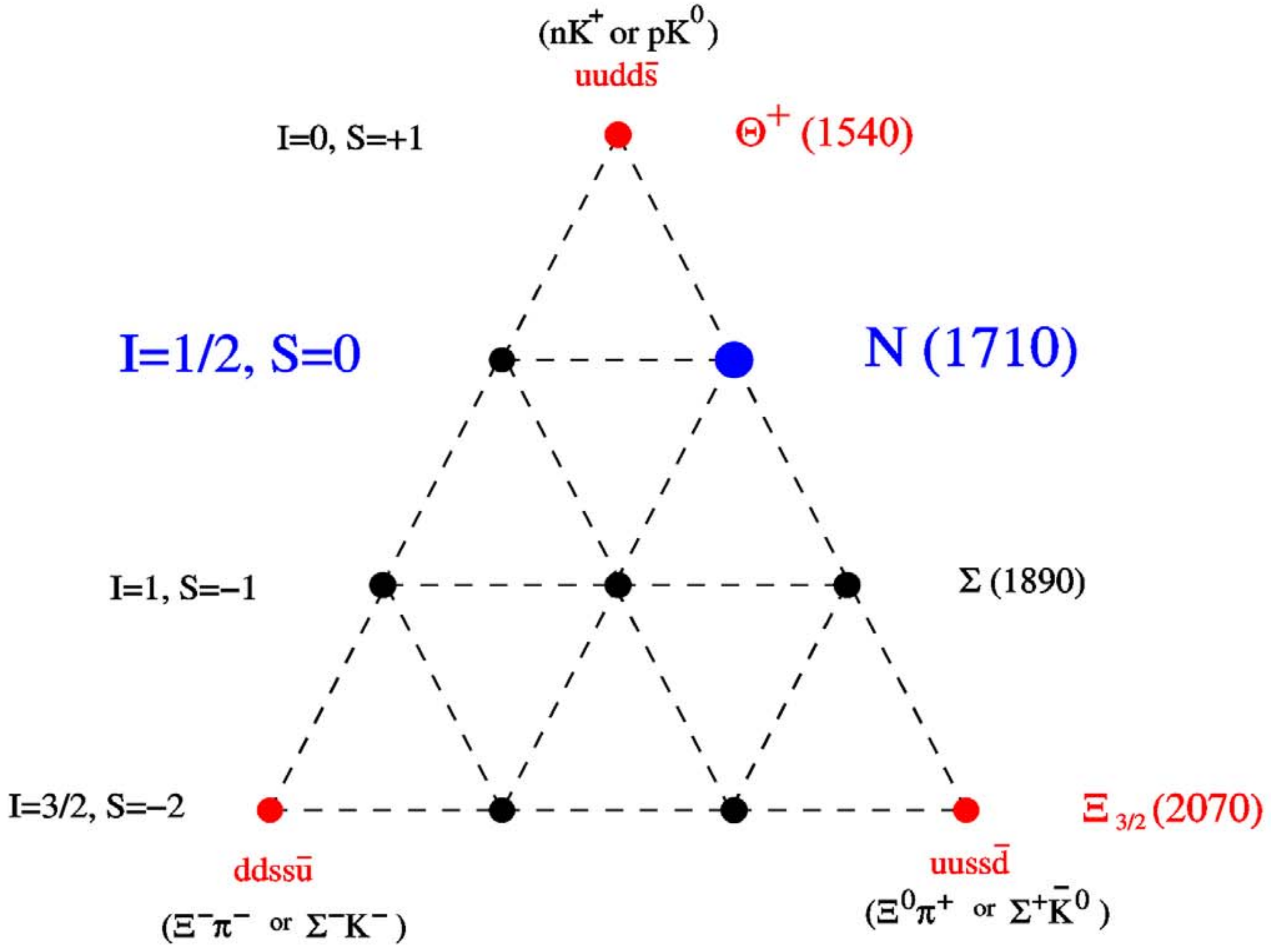
Non-standard structure:



(Hosaka)

Pentaquark States

anti-decuplet in the chiral soliton model by Diakonov, Petrov and Polyakov (1997)



Azimov: Why a Narrow N*(1680)?

- PWA mathematically ill-defined, so need extra assumptions: usually assume smooth energy dependence
- → no narrow resonances, $\Gamma > 20\text{-}25$ MeV
- Modified PWA: insert narrow resonance, check if $\chi 2$ improved
- Example: $\Theta+$ is possible, but with $\Gamma < 1$ MeV

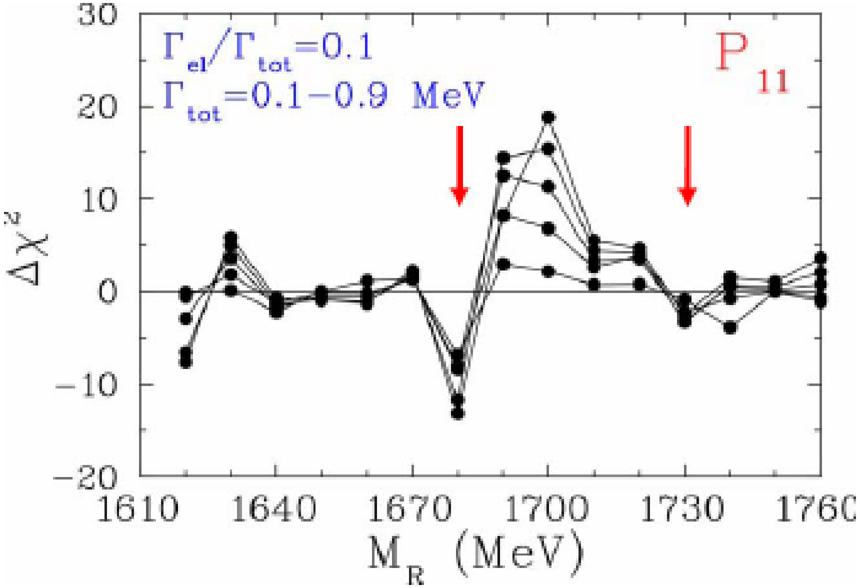
Modified πN PWA

[R.Arndt, Ya.A., M.V.Polyakov, I.Strakovsky, R.Workman,
PR **C69**, 035208 (2004)]

- $\Delta\chi^2$ due to insertion of a Resonance into P_{11} ($J^P = 1/2^+$)

- At $|M_R - W| \gg \Gamma_R$, Resonance contributes $\sim \Gamma_{el}/(M_R - W)$

- The procedure is less sensitive to Γ_{tot} than to Γ_{el}



- Two candidates: M_R = 1680 MeV 1730 MeV
  $\Gamma_{\pi N}$ < 0.5 MeV < 0.3 MeV

Current status

N*(1680)

- For observations,
  see experimental talks at the present Workshop.
  Interpretation of the signals is still an open question.

- Small ratio of photoyields (off p/off n)
  agrees with 10* members
  (would completely vanish for exact $SU(3)_F$).

- If there is the narrow N*(1680) ,
  the transition magnetic moment is very small:

  $$\mu(n^* \to n) = (0.13 - 0.37)\ \mu_N$$

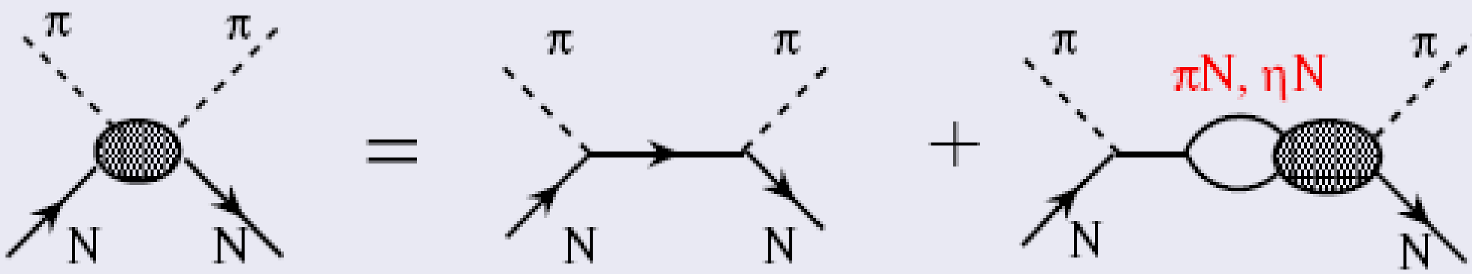
  [Ya.A., V.Kuznetsov, M.V.Polyakov, I.Strakovsky, EPJ **A25**, 325 (2005)] ;

  agrees with expectations of χQSA,
  but is much smaller than familiar values (*e.g.*, $\mu(\Delta \to N) \sim 3\ \mu_N$).

Shklar: η production in a coupled-channel Lagrangian model

take rescattering in the πN and ηN channels into account

The interaction potentials $V_{\pi N \to \eta N}$ and $V_{\pi N \to \pi N}$ enter to



Coupled-channel problem for $\pi N \to \pi N$ scattering:

- K-matrix approximation to the BSE provide a simple and powerful tool to analyze experimental data on pion- and photon induced reactions.
- combined description of the reaction
  $\gamma N \to \gamma N, \pi N, \eta N, \omega N, K\Lambda, K\Sigma$
  $\pi N \to \pi N, 2\pi N, \eta N, \omega N, K\Lambda, K\Sigma$
- Old $\pi N \to \eta N$ data shows a promising structure around 1.7 GeV Unfortunately the data is pure.
- $\gamma n \to \eta n$: the resonance like structure seen in the TAPS data can be explained the excitations of $S_{11}(1650)$ and $P_{11}(1710)$ states. Interference effects might be crucial - further analyses is needed.
- more detailed description of the 2π channel is necessary to understand the reaction mechanism

Tiator: η photoproduction in presence of narrow P11(1680)

MAID

the Mainz-Dubna Unitary Isobar Model

$$t^{\alpha}_{\gamma,\pi} = v^{\alpha}_{\gamma,\pi}(Born + \omega, \rho)\,(1 + i t^{\alpha}_{\pi,\pi})$$

ETA-MAID

uses a simpler approach without unitarization

$$t_{\gamma,\eta} = v_{\gamma,\eta}(Born + \omega, \rho) + t_{\gamma,\eta}(Resonances)$$

what is missing:
influence of other coupled channels
possibly: $K\Lambda$, $K\Sigma$, ...

η - M A I D

- **EtaMaid 2001**
  W.-T Chiang
  C. Bennhold
  D. Drechsel
  L.T.

  Born terms in s- and u-channel
  ρ,ω pole terms in t-channel
  N* resonances:
  D13(1520), S11(1535), S11(1650), D15(1675)
  F15(1680), D13(1700), P11(1710), P13(1720)

- **ReggeMaid 2003**
  W.-T. Chiang
  M. Vanderhaeghen
  L.T.

  Born terms
  ρ,ω Regge trajectories
  N* resonances:
  D13(1520), S11(1535), S11(1650), D15(1675)

- **EtaMaid 2006**
  A. Fix
  M. Polyakov
  L.T.

  Regge isobar model as ReggeMaid2003
  with additional narrow P11(1675) resonance

Summary on η production

- The old EtaMaid 2001 describes new data > 2002 very well
- D_{15} resonance needs a very large ηN branching ratio,
  to describe the photon asymmetry on the proton
  this leads to the peak in $\sigma(n)/\sigma(p)$
  ds/dW is described very well, but it fails for S
- a non-strange narrow pentaquark state $P_{11}(1675)$
  Fermi averaged in the deuteron would also produce such a peak
  with 1670 MeV < M* < 1685 MeV
- other observables which could show strong signals
  from narrow P11 resonances are: T, P, F, H, Cz

Nakayama: how to determine parity of narrow resonances

Establishing parity crucial for comparison with theory, especially for exotic baryons.

Chiral soliton models predict that antidecuplet has the same parity as nucleon. An S-wave pentaquark has opposite parity, so this immediately implies a P-wave.

Bohr's theorem: a general result for spin-parity relation (Bohr, NPA'59, Satchler, Direct Nuclear Reactions, '83)

reflection symmetry in the scattering plane

product of all intrinsic parities

sum of the spin-projections onto the axis ⊥ to the reaction plane

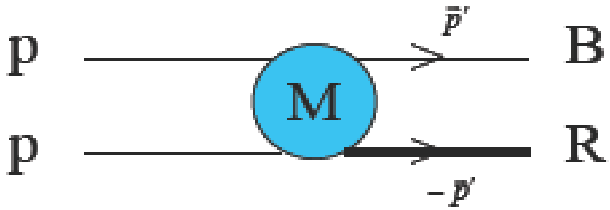
$$\pi_{if} = (-)^{M_i - M_f}$$

- allows for an unambiguous determination of the parity.

[see: Nakayama&Love, PRC70, 012201(R)(2004)]

- drawback: requires the measurement of the polarization of all the particles in the initial and final states.

Conclusion :

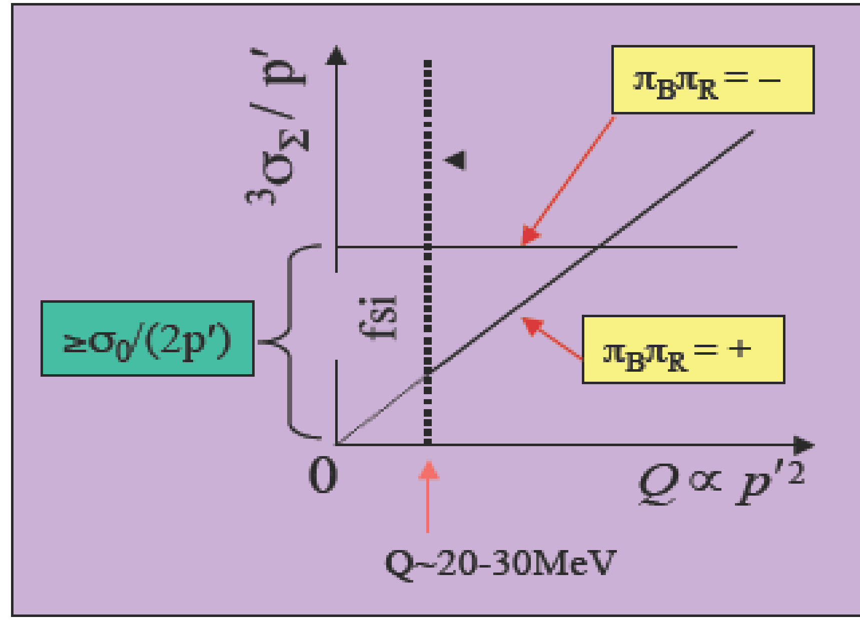


$$^{3}\sigma_{\Sigma} = \frac{\sigma_0}{4}\left(2 + A_{xx} + A_{yy}\right)$$

$^{3}\sigma_{\Sigma}(Q)$ and/or $d(^{3}\sigma_{\Sigma})/d\Omega$ in proton-proton collisions offers a possibility to determine the parity of a narrow baryon resonance with an arbitrary spin and isospin in a model independent way.

[Feasible at COSY !!!]

essential features near threshold:



only P-waves

$$\frac{1}{p'}\frac{d(^{3}\sigma_{\Sigma})}{d\Omega} = \tilde{\alpha}_0 + \tilde{\alpha}_1 \cos^2(\theta)$$

$\pi_B\pi_R = +$

may be 0

$$\frac{1}{p'}\frac{d(^{3}\sigma_{\Sigma})}{d\Omega} = \tilde{\alpha}'_0$$

$\pi_B\pi_R = -$

only S-waves

Bing-Song Zou: Evidence for a new Σ*

An outstanding problem for the classical 3q model

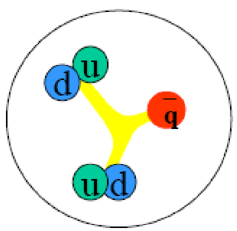
- **Mass order reverse problem for the lowest excited baryons**

uud (L=1) ½ - ~ N*(1535) **should be the lowest**

uud (n=1) ½ + ~ N*(1440)

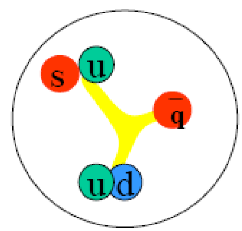
uds (L=1) ½ - ~ Λ*(1405)

A new scheme for the $1/2^-$ baryon nonet



$\bar{q}$ ½+

$\left.\begin{matrix}[ud]\\ [ud]\end{matrix}\right\}$ L=1



$\bar{q}$ ½ -

$\left.\begin{matrix}[ud]\\ [us]\end{matrix}\right\}$ L=0

N*(1535) ~ uud (L=1) + ε [ud][us] $\bar{s}$ + …

N*(1440) ~ uud (n=1) + ξ [ud][ud] $\bar{d}$ + …

Λ*(1405) ~ uds (L=1) + ε [ud][su] $\bar{u}$ + …

N*(1535): [ud][us] $\bar{s}$ → larger coupling to Nη, Nη', Nϕ & KΛ, weaker to Nπ & KΣ, and heavier !

Strange properties of N*(1535)

Evidence for large $g_{N^*K\Lambda}$

From relative branching ratios of
$J/\psi \rightarrow p\ \bar{N}^* \rightarrow p\ (K^-\ \bar{\Lambda})\ /\ p\ (\bar{p}\eta)$

$g_{N^*K\Lambda} / g_{N^*p\eta} / g_{N^*N\pi} \sim 2 : 2 : 1$

Phenomenology : Large $g_{N^*K\Lambda}$ → large $s\bar{s}$ in N*(1535)

$\bar{s}$[su][ud] or $K\Lambda$-$K\Sigma$ state

Evidence for large $g_{N^*K\Lambda}$ from $pp \rightarrow p K^+ \Lambda$

Evidence for small $g_{N^*K\Sigma}$ from $pp \rightarrow p K^+\Lambda / pp \rightarrow p K^+\Sigma^0$

Evidence for large $g_{N^*N\phi}$ from $\pi^- p \rightarrow n\phi$, $pp \rightarrow pp\phi$, $pn \rightarrow d\phi$

Evasion of OZI rule by N*(1535) !

Evidence for large $g_{N^*N\eta'}$ from $\gamma p \rightarrow p\eta'$, $pp \rightarrow pp\eta'$

The new picture for the $1/2^-$ nonet predicts:

Λ^* $[us][ds]\,\bar{s}$ ~ 1575 MeV

Σ^* $[us][du]\,\bar{d}$ ~ 1360 MeV

Ξ^* $[us][ds]\,\bar{u}$ ~ 1520 MeV

Important to look for the $\Sigma^*(1/2^-)$ around 1380 MeV !

It is very important to check whether under the $\Sigma(1385)$ and $\Xi(1520)$ peaks there are $1/2^-$ components ?

Quenched quark models and unquenched models give very distinctive predictions for $\Sigma^*(1/2^-)$;

Possible existence of a $\Sigma^*(1/2^-)$ around 1380 MeV cannot be excluded although its evidence is not strong ;

It should be checked by forthcoming experiments :

$K^- p \rightarrow \pi\, \Sigma^*(1360),\ \Sigma^*(1360) \rightarrow \Lambda\, \pi$

$\gamma N \rightarrow K^+\, \Sigma^*(1360),\ \Sigma^*(1360) \rightarrow \Lambda\, \pi$

$J/\psi \rightarrow \bar{\Sigma}\, \Sigma^*(1360),\ \Sigma^*(1360) \rightarrow \Lambda\, \pi$

Lipkin: Exotics are one possibility

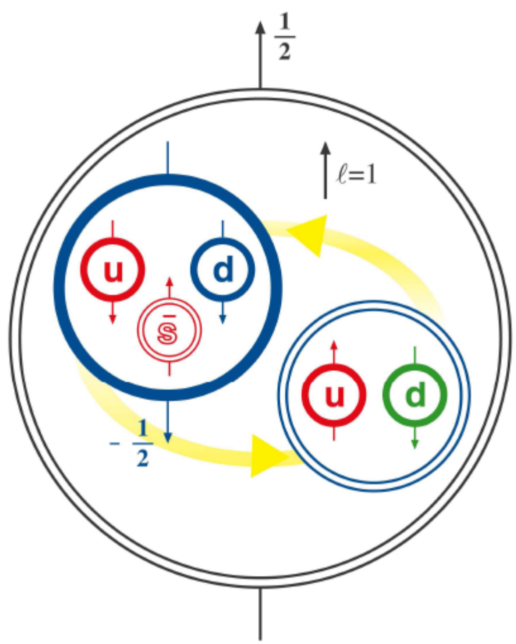
A Posible Nonstrange Cousin of the Θ^+ pentaquark

Narrow πN resonance (width $\approx$ 25 MeV) at 1680 MeV suggests nonstrange pentaquark

In same SU(3) multiplet as the strange Θ^+ pentaquark with mass 1540 MeV.

We consider extension of diquark-triquark model for Θ^+ to a nonstrange pentaquark

Novel kind of pentaquark with unusual color structure



diquark – triquark configuration of the *uudd*$\bar{s}$ pentaquark

Extension of diquark-triquark model for strange pentaquark to nonstrange pentaquark

us diquark instead of the ud diquark in Θ^+ and the same $ud\bar{s}$ triquark

System divided into two color non-singlet clusters separating pairs of identical flavor.

In relative P-wave separated by distance larger than range of color-magnetic force

Clusters kept together by color electric force; hyperfine interaction only within each cluster

General pentaquark has two allowed $SU(3)_f$ couplings $\mathbf{\bar{10}}$ and $\mathbf{8}$ of $SU(3)_f$.

Only $\mathbf{\bar{10}}$ antidecuplet allowed for Θ^+; no positive strangeness state in octet.

Nonstrange pentaquarks mix octet and antidecuplet like singlet-octet ($\omega - \phi$ mixing.

Mixing determined by dominant symmetry-breaking; $m_s - m_d$

$\boxed{\text{Diquark-triquark model mixes nonstrange octet and antidecuplet states,}}$

The mass of πN pentaquark is predicted to be higher than Θ^+ mass by $M(\Lambda) - M(N)$

$M(\pi N)_{pred} = M(\Theta^+) + M(\Lambda) - M(N) = 1540 + 180 = 1720$; $\quad M(\pi N)_{exp} = 1680$

Not bad for such a crude calculation

Flavor antisymmetry suggests that the commonly used bag or single-cluster models

May be correct to treat normal hadrons not adequate for multiquark systems.

These models have identical pair correlations for all pairs in the system,

They miss the flavor anisymmetry which requires different pair correlations for pairs with the same flavor and for pairs with different flavors.

8 – 10bar mixing has dramatic EXP consequences:

γn → N* allowed and γp → N* forbidden
only if N is a pure 10bar
If confirmed,
need to understand why no 8-10bar mixing

MK & Lipkin, hep-ph/0506084 :

$\gamma \rightarrow K^+K^- >> \gamma \rightarrow K^0 \bar{K}^0$

Prediction:

$\gamma p \rightarrow \Lambda(1520) >> \gamma n \rightarrow \Lambda(1520)$

Recently beautifully confirmed by LEPS, arXiv:0904.2034 (accepted by PRL)

$\rightarrow$Immediate implication for Θ^+ production in γN:

$\gamma n \rightarrow \Theta^+ K^- >> \gamma p \rightarrow \Theta^+ K^0$!

Cohen: soliton models of exotics have a shaky TH foundation

Early analysis predicting the θ^+ used collective quantization for almost all calculations

Collective quantization treats the soliton as rigid rotor
Makes sense if rotational energy much smaller than vibrational modes, otherwise soliton is deformed

√ OK for non-exotic baryons, formally justified by 1/N_c

X But not for exotic baryons, because rot. splitting from nucleon ~ N_c^0 , so get mixing with vibrational excitations

Approximation becomes uncontrollable and model-dep.

→ *Predictive power is lost*

(MK): for non-exotic baryons chiral soliton models work much better than expected from such formal considerations

This indicates suppression of potentially dangerous corrections,
→ cancellations or numerically small

But then model-dependent?!

Width also model-dependent

The results for exotics depend sensitively on details of the model in this case in terms of the *ad hoc* rules by which one calculates *1/Nc* corrections.

Thus the models in the exotic sector do not simply encode some underlying general features of QCD requiring exotics with rather particular properties.

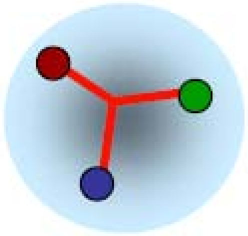
Qiang Zhao: Properties of 1/2- states

Baryons in SU(6)⊗O(3) symmetric quark model

Basic assumptions:

i) Chiral symmetry spantaneous breaking leads to the presence of massive constituent quarks as effective degrees of freedom inside hadrons;

ii) Hadrons can be viewed as quark systems in which the gluon fields generate effective potentials that depend on the spins and positions of the massive quarks.



- Moorhouse selection rule (Moorhouse, PRL16, 771 (1966))

$$\gamma + p(|\mathbf{56}, {}^2\mathbf{8}; 0, 0, 1/2\rangle) \not\leftrightarrow \quad N^*(|\mathbf{70}, {}^4\mathbf{8}\rangle)$$

$$\gamma + n(|\mathbf{56}, {}^2\mathbf{8}; 0, 0, 1/2\rangle) \leftrightarrow N^*(|\mathbf{70}, {}^4\mathbf{8}\rangle)$$

etc.

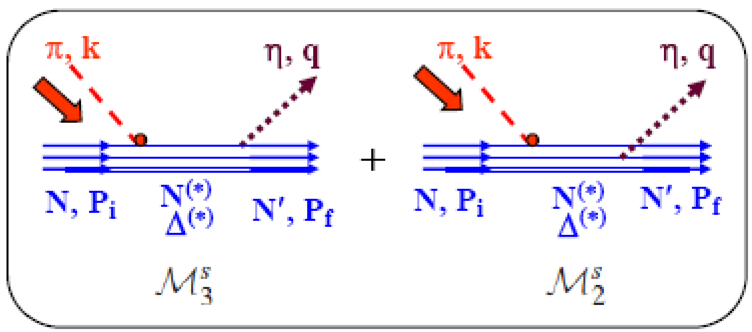
Spin-dependent potential from one-gluon-exchange

SU(6)⊗O(3) symmetry breaking

Moorhouse selection rule must be violated

- ❑ **S-channel resonance excitations in hadronic productions**

s-channel



$$\mathcal{M}_s = \sum_j \langle N_f|H_\eta|N_j\rangle\langle N_j|\sum_n \frac{1}{\omega_\pi^{n+1}}(\hat{H} - E_i)^n H_\pi|N_i\rangle$$

The mixing between the quark model representations can explain the large S11 couplings to ηN, πN, $K\Lambda$. But not as large as that proposed for 5-quark scenario by Zou and Riska.

The S11(1535) and S11(1650) appear to have destructive interferences in photo and hadronic productions of which the relative sign can be given by the quark model. This seems to be consistent with the coupled-channel results by Shklyar et al.

In the real photon limit, the transverse helicity amplitudes seem to be consistent with the mixings determined in hadronic decays. But the magnitude at large Q^2 region is much lower than the data just as been found in many other studies.

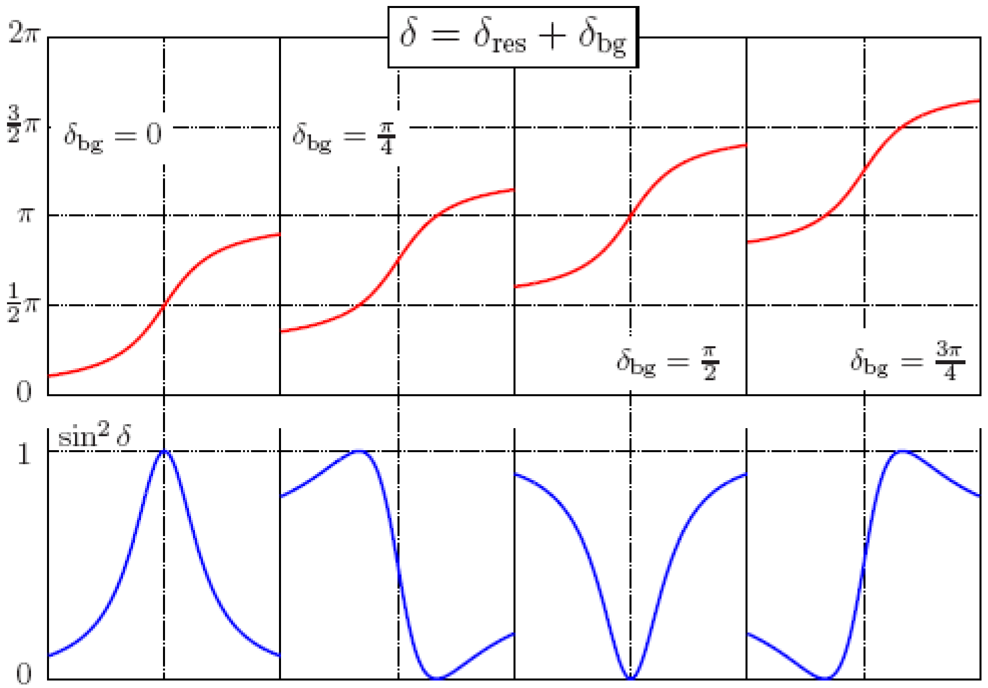
The longitudinal one has a reversed sign which is impossible to be explained by the leading EM operator in 3q framework and/or the mixing due to Moorhouse selection rule.

→ Some mechanisms seem indeed to have been missed by the NRCQM

Haberzettl: Resonances – scattering theory meets real world

Resonance Basics — Wide Resonance

Resonant phase shifts with various constant background contributions



Each tile 300 MeV wide; width $\Gamma = 100$ MeV

Assume

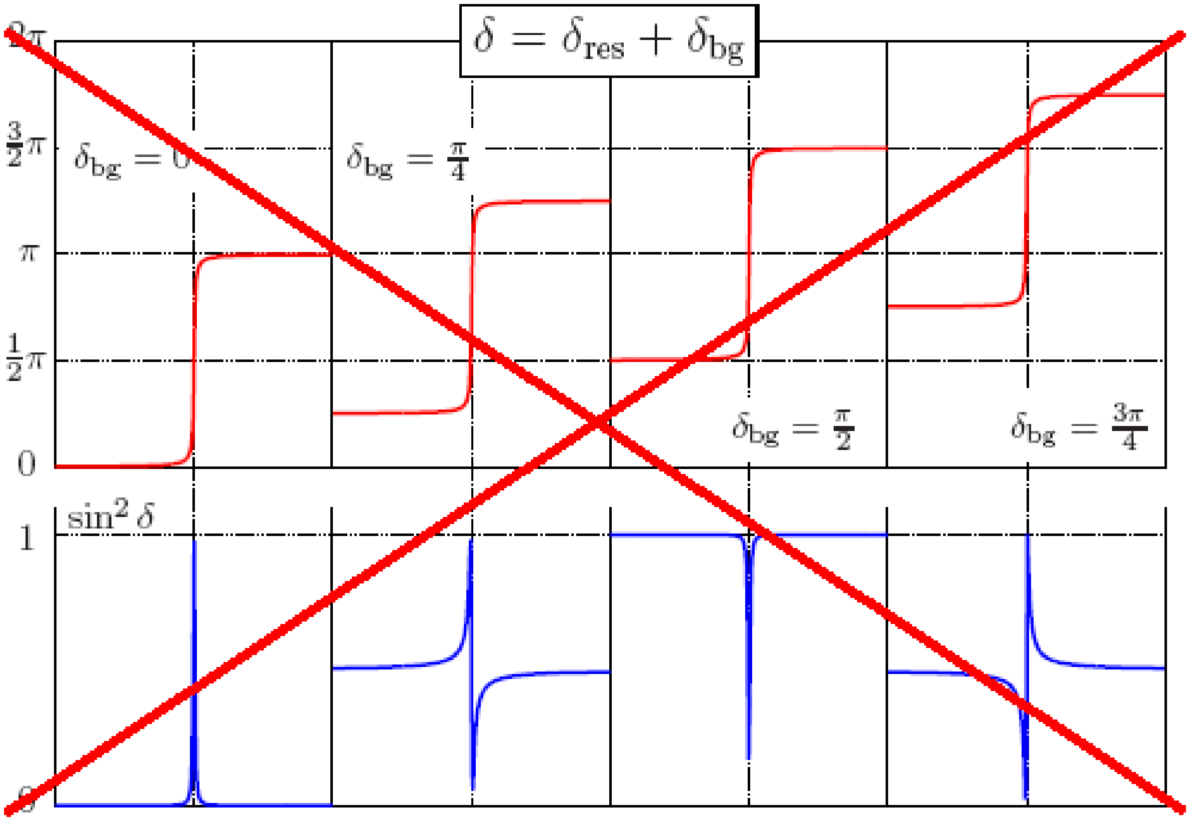
$$\Delta E \ll \Gamma$$

Then

$$\frac{d\sigma}{d\Omega} = |T|^2$$

Resonance Basics — Narrow Resonance

Resonant phase shifts with various constant background contributions



Each tile 300 MeV wide; width $\Gamma = 2$ MeV

If

$$\Delta E \gtrsim \Gamma$$

Then

$$\frac{d\sigma}{d\Omega} \neq |T|^2$$

Time-dependent scattering:

$$\Psi^{(+)}(\mathbf{r},t) \quad \xrightarrow{r\to\infty} \quad \int d^3p\,\phi(\mathbf{p})\,\mathrm{e}^{-iE_pt}\left[\mathrm{e}^{i\mathbf{p}\cdot\mathbf{r}} + T\,\frac{\mathrm{e}^{ipr}}{r}\right] = \Psi_{\mathsf{in}}(\mathbf{r},t) + \Psi_{\mathsf{sc}}(\mathbf{r},t)$$

$\phi(\mathbf{p})$: experimental momentum distribution peaked at $\mathbf{p}_0$

IF T varies rapidly across the width of $\phi(\mathbf{p})$, then

$$\Psi_{\mathsf{sc}}(\mathbf{r},t) \neq \frac{T}{r}\int d^3p\,\phi(\mathbf{p})\,\mathrm{e}^{i(pr-E_pt)} \qquad \text{and} \qquad \frac{d\sigma}{d\Omega} \neq |T|^2$$

- Usual scattering-theoretical relations do not apply.
- **Needed: Correct theoretical description of narrow structures.**

- There are many structures — dynamical or otherwise — that produce signatures usually attributed to resonant behavior.
- For a truly resonant state one should establish that there is a (positive) time delay, i.e., that the reacting particles spend an enhanced period of time in the interaction region.
- For narrow structures with $\Delta E \gtrsim \Gamma$, the basics of scattering theory need to be revisited.
- Model builders need to be more critical of their own models when assessing the physical consequences of their findings.
- Whether poles of T- or S-matrices are elementary or dynamic in origin cannot be unambiguously decided at the phenomenological level.
- Bare input for hadron-dynamical models cannot be directly related to quark constituent models. (At least not without a *lot* of work.)

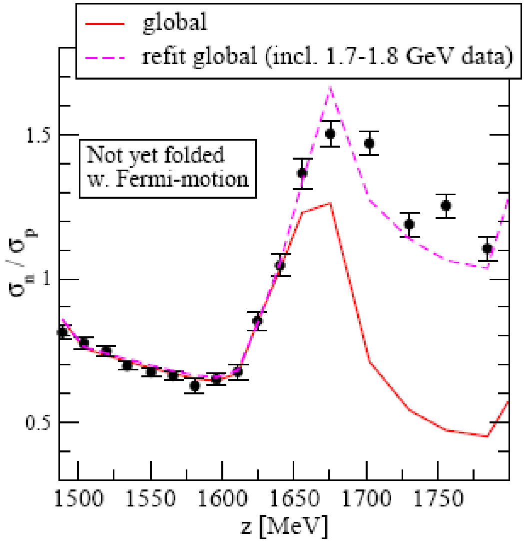
Doering:

S_{11} resonances in meson baryon production

Dynamically generated resonances: N*(1535)

No pole term in the potential for Roper, still a pole in the complex plane

The ratio $\dfrac{\sigma(\gamma n \to \eta n)}{\sigma(\gamma p \to \eta p)}$ Fermi motion not yet included.



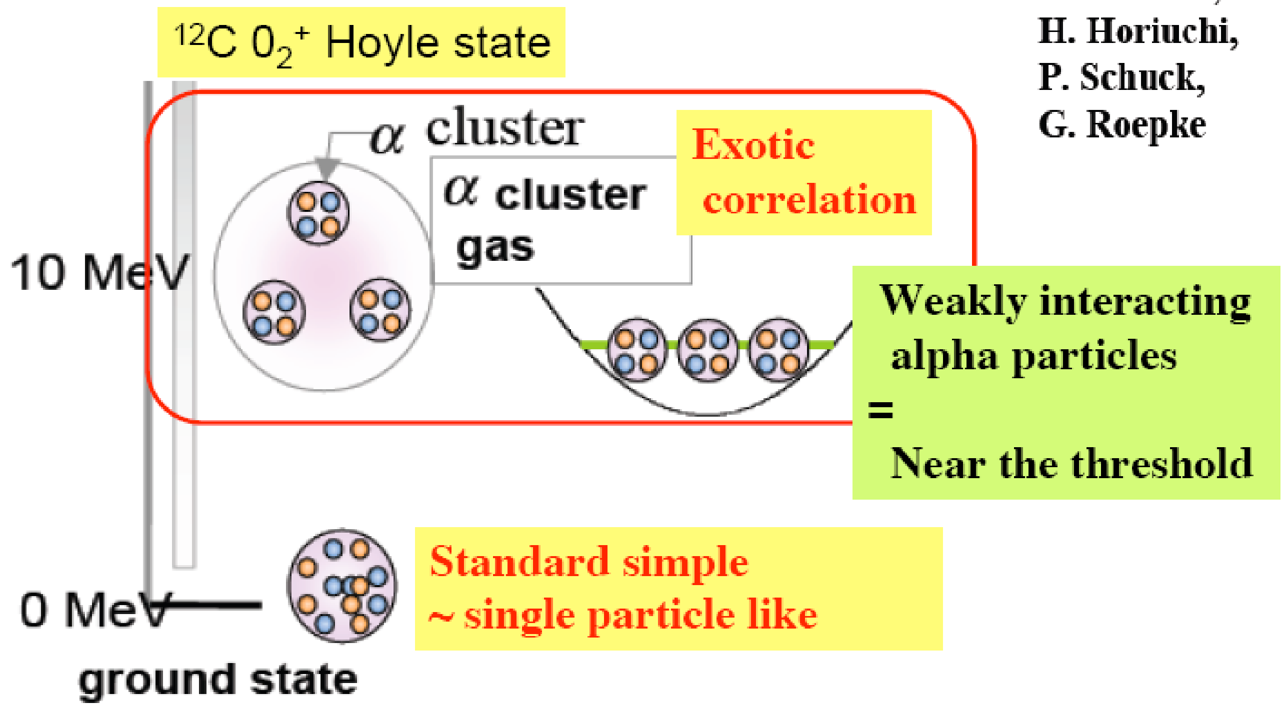
Properties of the present solution

- Combined analysis of reactions in S_{11} and S_{31}, for
  - πN and γN initial state.
  - πN, ηN, $K\Lambda$, $K\Sigma$ final state.
- Features of the solution (decided by the fit):
  - Dynamically generated $N^*(1535)$.
  - Genuine pole term for the $N^*(1650)$ (resonance interferenc with $N^*(1535)$).
  - Second genuine pole far in complex plane produces small background instead of replacing the $N^*(1535)$. Mostly needed for missing t channel meson exchange with anomalous photon couplings.
  - Dynamical generation of virtual state close to threshold. May be genuine or "mock up" of subthreshold cuts.
  - Some need for higher chiral interactions at low energies is seen (too much strengths below the ηN threshold); $\pi\pi N$ channel could be included.
- Simultaneous description of different ηN cusps (forms, strengths) and $N^*(1535)$ phases in $S_{11}(\pi N \to \pi N)$, $E_{0+}(\gamma p)$, $E_{0+}(\gamma n)$.
- Photon coupling to intermediate πN, $K\Lambda$, $K\Sigma$ can explain σ_n/σ_p in $\gamma N \to \eta N$.

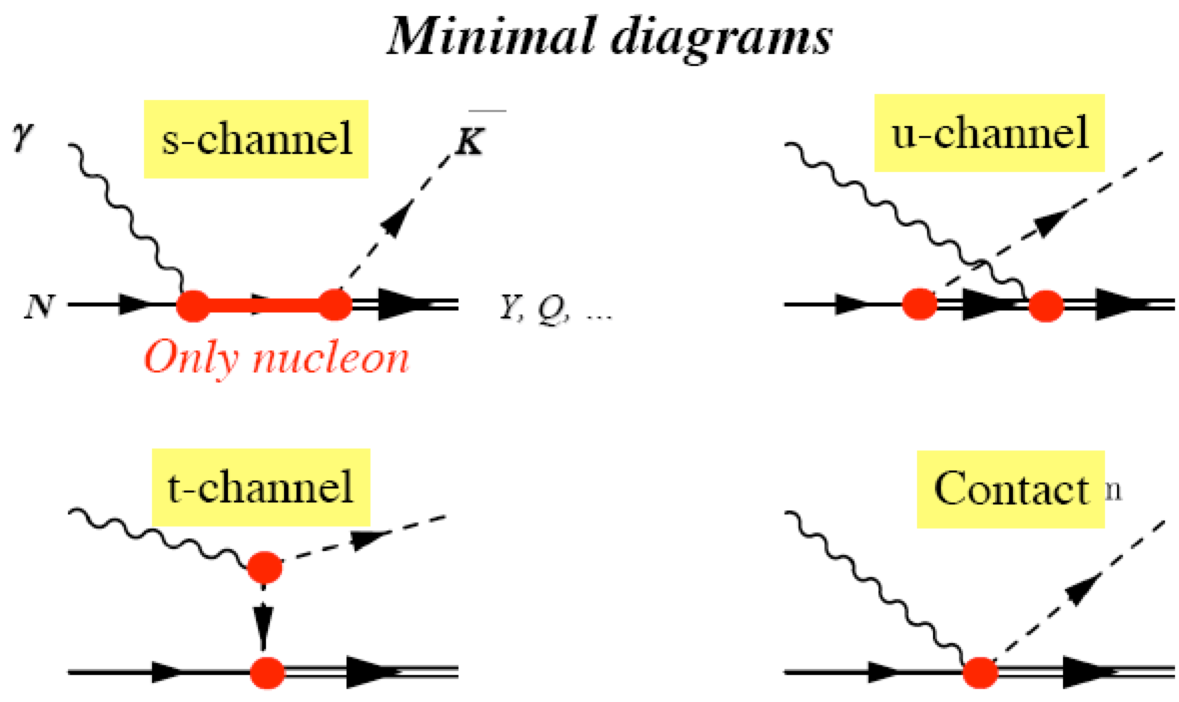
Hosaka: Reaction dynamics in effective Lagrangian approach

Quark clustering essential for exotics
Example from Nuclear Physics

Y. Funaki,
A. Tohsaki,
H. Horiuchi,
P. Schuck,
G. Roepke



Effective Lagrangian method



$\Lambda(1520)$

$\gamma p \to K^+ \Lambda(1520)$ and $\gamma n \to K^0 \Lambda(1520)$

Nam, Hosaka, Kim, PRD71, 114012 (2005)
e-Print: **hep-ph/0503149**
Also Karliner & Lipkin: e-Print: **hep-ph/0506084**

- Exotics may have *correlations*

  $q\bar{q}$, qq, qqq

  Question; how are they realized and observed

- $\Lambda(1520)$ can be explained by standard react. mechanism

  Structure information is in various coupling constants
- Importance of the virtual meson clouds in $K\Lambda$ prod.
- $\Lambda(1405)$ seems very unusual
- Possible explanation of ϕ production: $N^* \sim 2200$ MeV

Experimental wishlist

Need (better) data, esp. around 1680 MeV:

- $d\sigma/d\Omega$ for $\gamma N \to \eta N$
- polarization, to improve PWA
- $K\Lambda$ final state in γN, etc., compare with ηN
- $\pi\Delta$ final state, potentially largest decay channel of $N^*(1680)$
- K+ n golden-plated experiment
- "neighborhood watch": exotic mesons $\leftrightarrow$ tetraquarks

Theoretical wishlist

- exotic baryons require quark clustering → need better tools for understanding dynamics of color recoupling, esp. spin-dependent forces, i.e. color hyperfine interaction

- exotics from lattice QCD

- for ordinary baryons naïve quark model + color HF works much better than it should. Need to understand why, to see if and how can be applied to exotic baryons

- chiral soliton models: what predictions can be trusted

"But don't you see, Gershon - if the particle is too small and too short-lived to detect, we can't just take it on faith that you've discovered it."