CHIRAL SYMMETRY AND STRINGS

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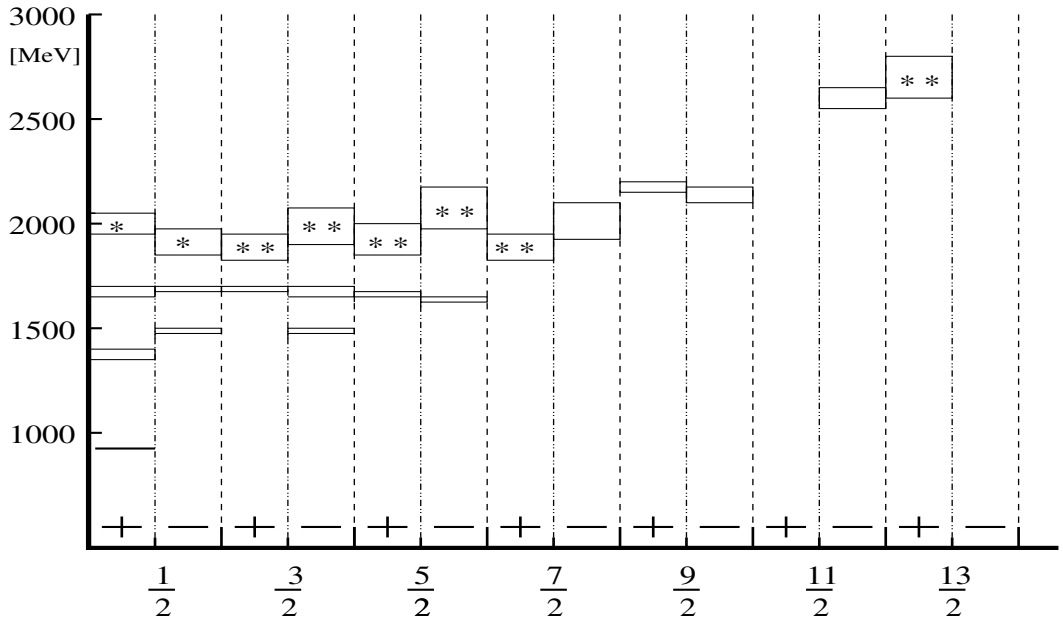
Contents of the Talk

- Chiral symmetry restoration in excited hadrons.
- Generalized NJL (’t Hooft) Model.
- Chiral symmetry restoration and the string picture.
- Summary.

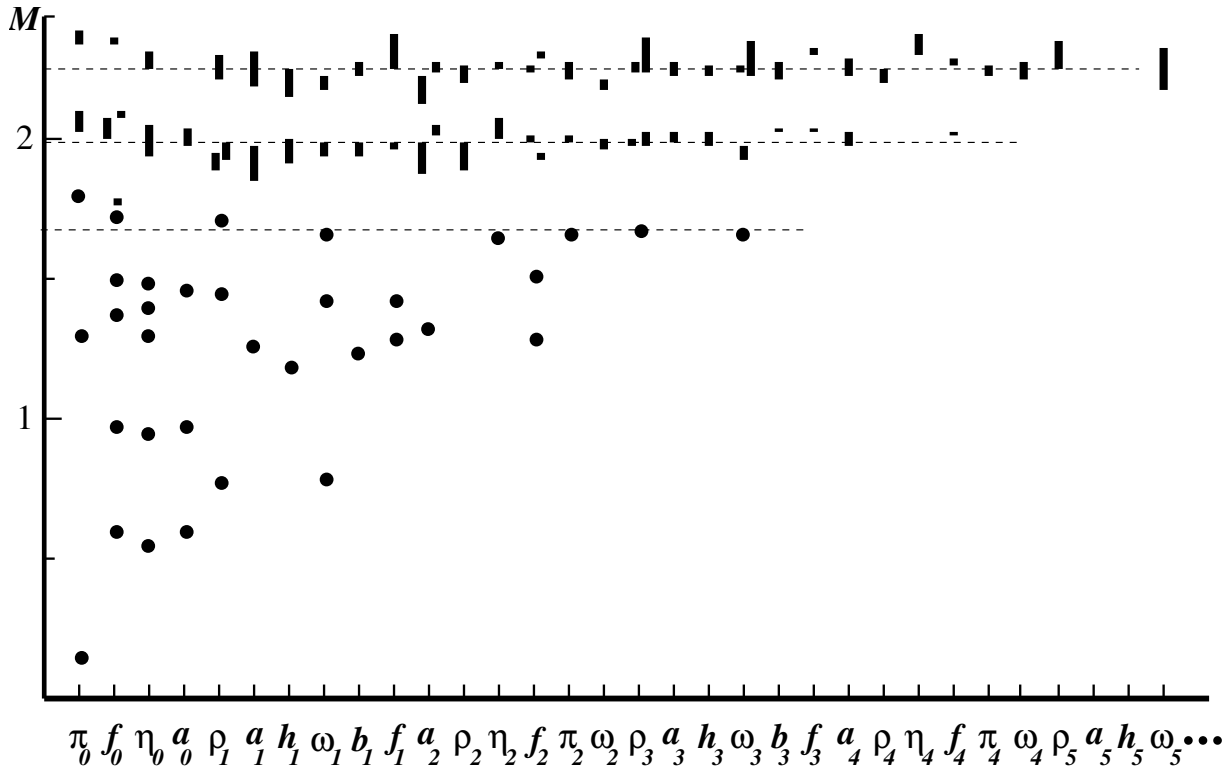
Low and high lying baryon spectra.



Low-lying spectrum: spontaneous breaking of chiral symmetry dominates physics.

High-lying spectrum: parity doubling indicates the onset of the new physical regime - EFFECTIVE chiral symmetry restoration.

Low and high lying meson spectra.



The high-lying mesons are from LEAR. They must be confirmed. Still missing states must be found.

Large symmetry: $N = n + J$ plus chiral symmetry.

An alternative: $N = n + L$ without chiral symmetry is not consistent with the Lorentz symmetry and unitarity.

Low and high lying hadron spectra.

THE MASS GENERATION MECHANISMS IN THE LOW- AND HIGH-LYING HADRONS ARE ESSENTIALLY DIFFERENT !

Alternative evidence for chiral restoration. PRL,2007

There is no chiral partner to the nucleon. Hence its mass is entirely from the quark condensate. The chiral-invariant $NN\pi$ vertex is then

$$\sim \bar{N} e^{i\gamma_5 \frac{\vec{\pi}\cdot\vec{\tau}}{f_\pi}} N; \qquad N \to \exp\left(\imath\gamma_5 \frac{\theta_A^a \tau^a}{2}\right) N. \tag{1}$$

The Goldberger-Treiman relation, $g_{NN\pi} = \frac{g_A M_N}{f_\pi}$, translates the nucleon mass into the $NN\pi$ coupling constant. Hence the large $NN\pi$ coupling constant is a natural unit for strong chiral symmetry breaking in a baryon.

Assume that we have a free $I = 1/2$ chiral doublet B in $(0, 1/2) + (1/2, 0)$.

$$B = \begin{pmatrix} B_+ \\ B_- \end{pmatrix}, \qquad B \to \exp\left(\imath \frac{\theta_A^a \tau^a}{2} \sigma_1\right) B, \qquad \mathcal{L}_0 = i\bar{B}\gamma^\mu \partial_\mu B - m_0 \bar{B} B \tag{2}$$

Then $g_+^A = g_-^A = 0$, while the off-diagonal axial charge is 1, $|g_{+-}^A| = |g_{-+}^A| = 1$. The $\pi B_\pm B_\pm$coupling is 0.

The chiral-invariant vertex $B_\pm N\pi$ is impossible!

Alternative evidence for chiral restoration. PRL,2007

Predictions of the chiral symmetry restoration scenario: If a state is a member of an approximate chiral multiplet, then its decay into $N\pi$ must be strongly suppressed, $(f_{BN\pi}/f_{NN\pi})^2 \ll 1$. If, on the contrary, this excited hadron has no chiral partner and hence its mass is due to chiral symmetry breaking in the vacuum, then it should strongly decay into $N\pi$ and hence $(f_{BN\pi}/f_{NN\pi})^2 \sim 1$.

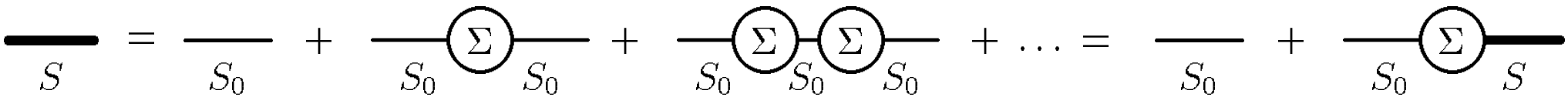
Spin	Chiral multiplet	Representation	$(f_{B_+N\pi}/f_{NN\pi})^2 - (f_{B_-N\pi}/f_{NN}$
1/2	$N_+(1440) - N_-(1535)$	$(1/2,0)\oplus(0,1/2)$	0.15 - 0.026
1/2	$N_+(1710) - N_-(1650)$	$(1/2,0)\oplus(0,1/2)$	0.0030 - 0.026
3/2	$N_+(1720) - N_-(1700)$	$(1/2,0)\oplus(0,1/2)$	0.023 - 0.13
5/2	$N_+(1680) - N_-(1675)$	$(1/2,0)\oplus(0,1/2)$	0.18 - 0.012
7/2	$N_+(?) - N_-(2190)$	?	? - 0.00053
9/2	$N_+(2220) - N_-(2250)$	?	0.000022 - 0.0000020
11/2	$N_+(?) - N_-(2600)$	?	? - 0.000000064
3/2	$N_-(1520)$	no chiral partner	2.5

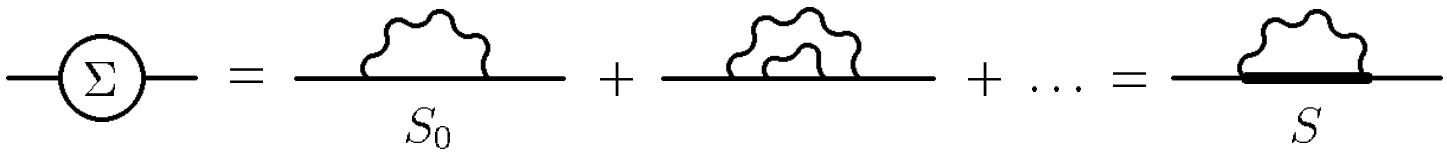
Generalized NJL ('t Hooft) model.

In 1+1 't Hooft model the only interaction is the Coulomb (linear) potential.
Le Yaouanc, Oliver, Pene and Raunal, 1983 : Postulate the confining instantaneous Lorentz-vector potential in 3+1 dim. Proof of chiral symmetry breaking.

Chiral symmetry breaking is via the Schwinger-Dyson (gap) equation:

$$S = S_0 + S_0 \Sigma S$$





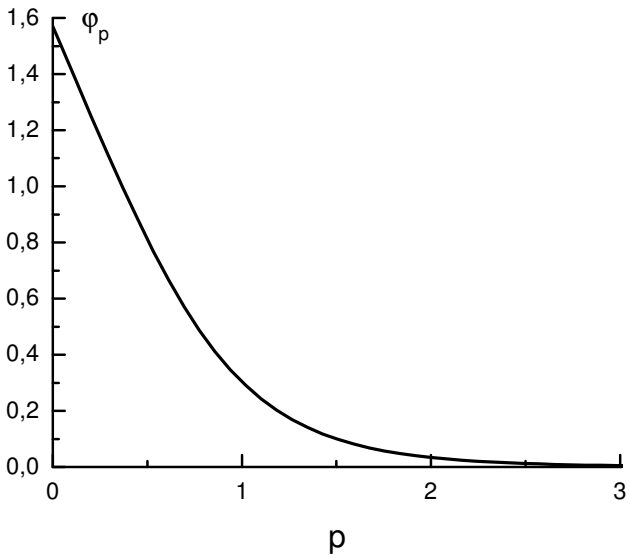
Generalized NJL ('t Hooft) model

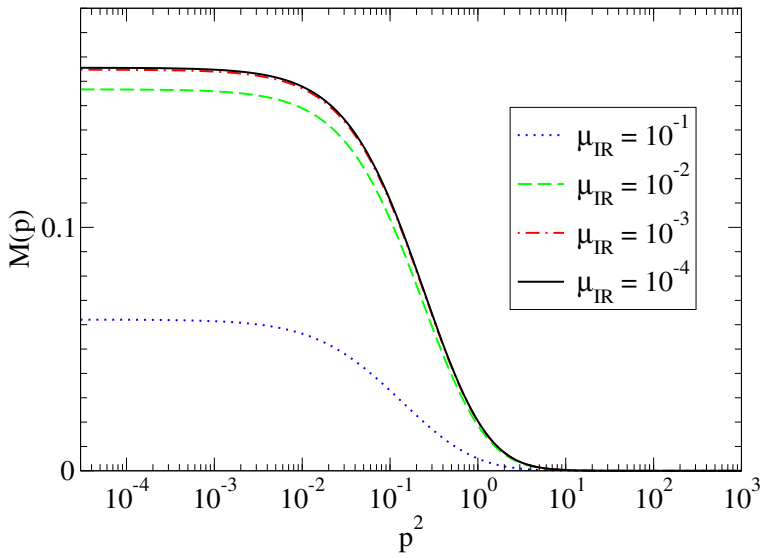
The gap equation:

$$i\Sigma(\vec{p}) = \hbar \int \frac{d^4k}{(2\pi)^4} V_{CONF}(\vec{p}-\vec{k})\gamma_0 \frac{1}{S_0^{-1}(k_0,\vec{k}) - \Sigma(\vec{k})}\gamma_0.$$

The self-energy consists of the scalar (chiral symmetry breaking) $M(\vec{p}) \equiv A_p$ part and vector B_p (chiral symmetric) parts: $\Sigma(\vec{p}) = [A_p - m] + (\vec{\gamma}\hat{\vec{p}})[B_p - p]$.
They come entirely from quantum fluctuations - loops!

Then the dispersive law is: $E_p = A_p \sin\phi_p + B_p \cos\phi_p;$ $\tan\phi_p = \frac{A_p}{B_p}$





Given the dressed quark Green function, solve the Bethe-Salpeter eq.

Generalized NJL ('t Hooft) model

What should one expect if the chiral symmetry restoration does take place? The multiplets of $SU(2)_L \times SU(2)_R$.

$$J = 0$$

$$\begin{aligned} (1/2,1/2)_a &: \quad 1, 0^{-+} \longleftrightarrow 0, 0^{++} \\ (1/2,1/2)_b &: \quad 1, 0^{++} \longleftrightarrow 0, 0^{-+}, \end{aligned}$$

Even $J > 0$

$$\begin{aligned} (0,0) &: \quad 0, J^{--} \longleftrightarrow 0, J^{++} \\ (1/2,1/2)_a &: \quad 1, J^{-+} \longleftrightarrow 0, J^{++} \\ (1/2,1/2)_b &: \quad 1, J^{++} \longleftrightarrow 0, J^{-+} \\ (0,1) \oplus (1,0) &: \quad 1, J^{++} \longleftrightarrow 1, J^{--} \end{aligned}$$

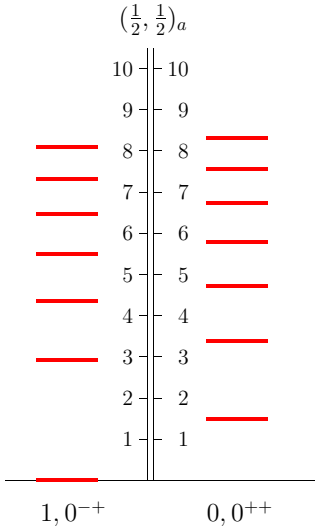
Odd $J > 0$

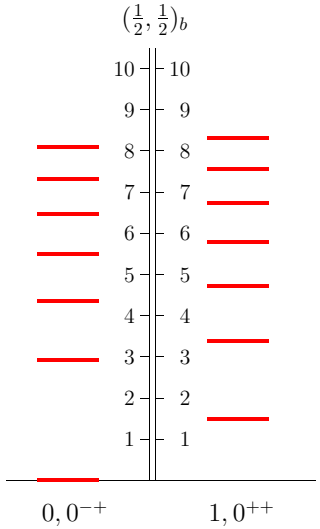
$$\begin{aligned} (0,0) &: \quad 0, J^{++} \longleftrightarrow 0, J^{--} \\ (1/2,1/2)_a &: \quad 1, J^{+-} \longleftrightarrow 0, J^{--} \\ (1/2,1/2)_b &: \quad 1, J^{--} \longleftrightarrow 0, J^{+-} \\ (0,1) \oplus (1,0) &: \quad 1, J^{--} \longleftrightarrow 1, J^{++} \end{aligned}$$

The $U(1)_A$ multiplets: the opposite spatial parity states with the same isospin from the distinct $(1/2,1/2)_a$ and $(1/2,1/2)_b$ multiplets of $SU(2)_L \times SU(2)_R$.

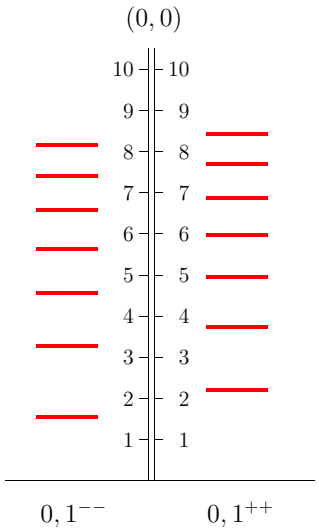
Spectra and wave functions: R. Wagenbrunn, L.Ya.G.

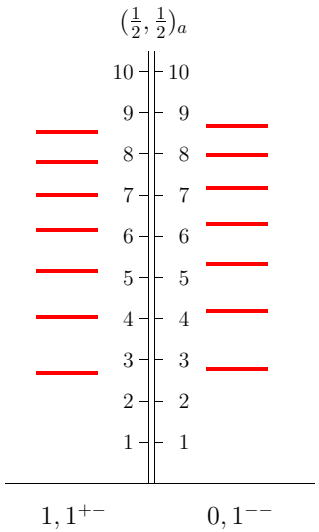
$J = 0$

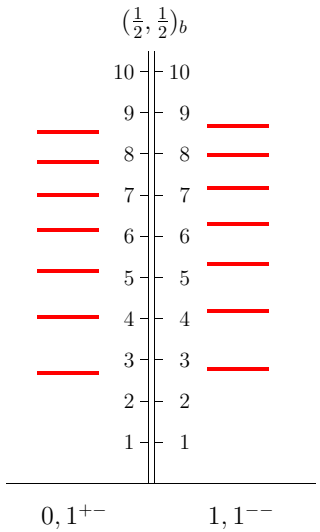


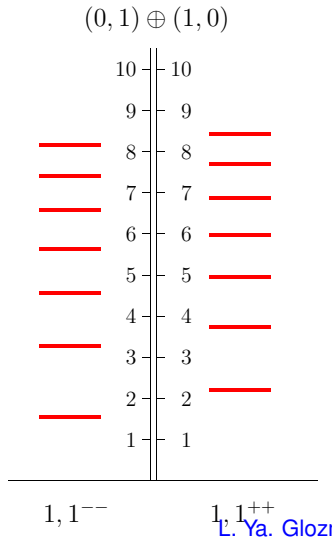


$J = 1$



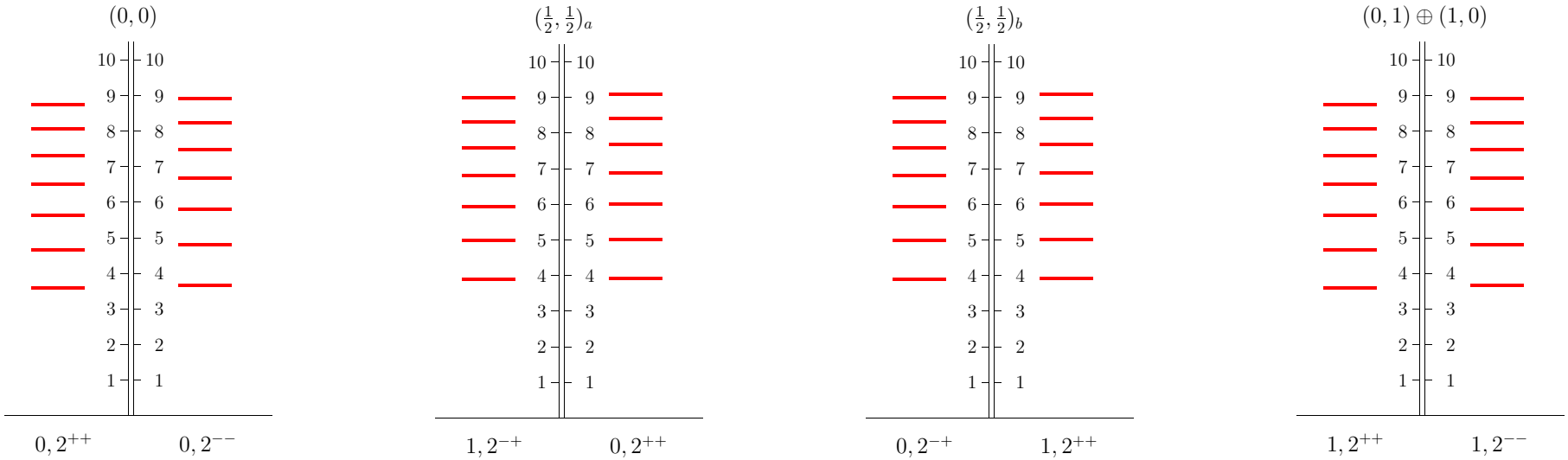




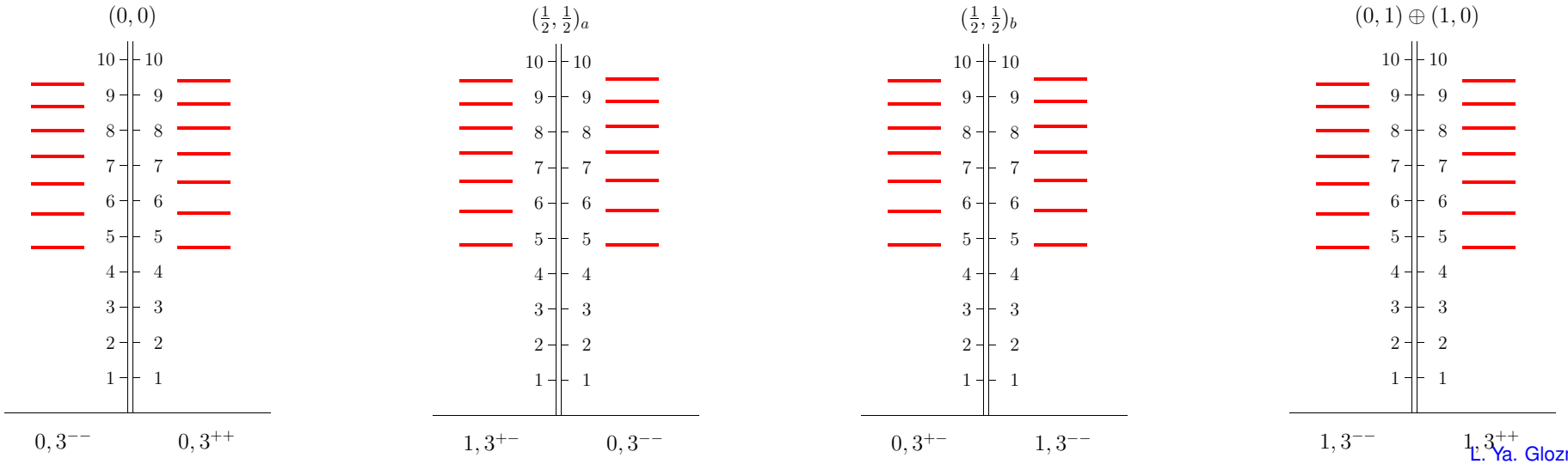


Spectra and wave functions R. Wagenbrunn, L.Ya.G.

$J = 2$

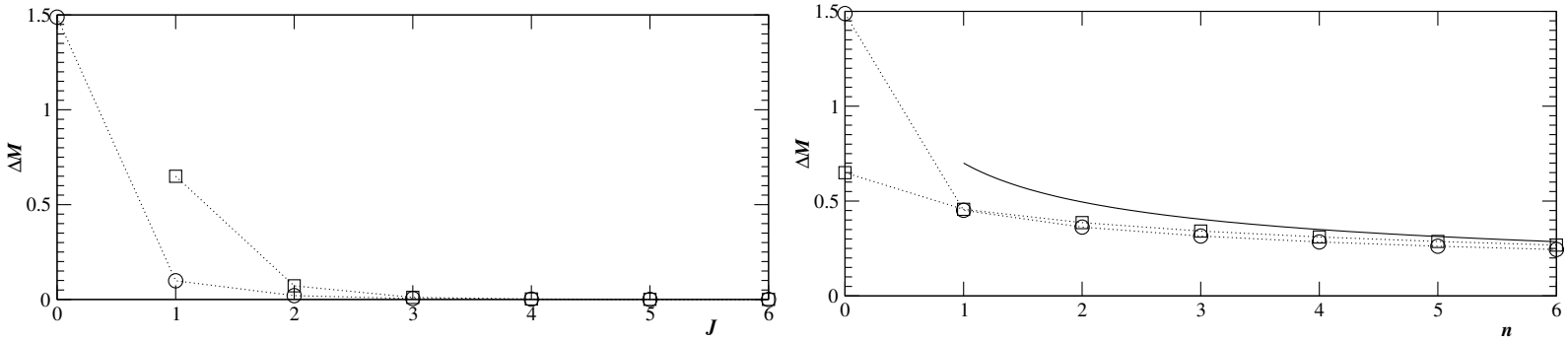


$J = 3$

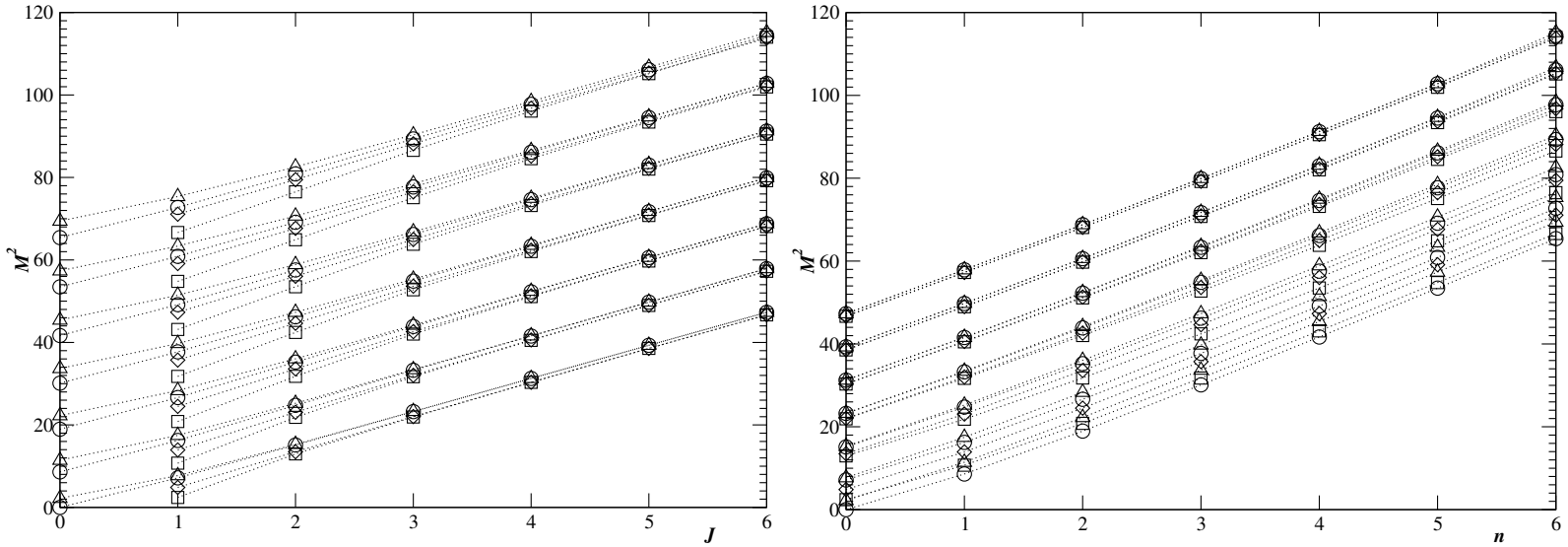


Spectra and wave functions. R. Wagenbrunn, L. Ya. G.

Rates of the symmetry restoration:



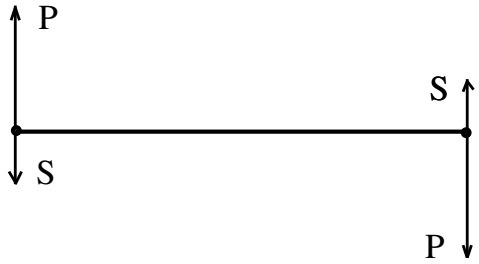
Regge trajectories:



At $n \to \infty$ and/or $J \to \infty$ one observes a complete degeneracy of all multiplets, i.e. the states fall into $[(0,1/2) \oplus (1/2,0)] \times [(0,1/2) \oplus (1/2,0)]$. The loop effects disappear completely and the system becomes classical.

Chiral restoration and the string picture.

What is the ASYMPTOTIC picture for excited hadrons? :



(i) the field in the string is of pure color-electric origin

(ii)the valence quarks have a definite chirality

Then:

(i) The hadrons that belong to the same intrinsic quantum state of the string with quarks falling into the same parity-chiral multiplet must be degenerate.

(ii) The total parity of the hadron is a product of parity of the string and the parity of the specific parity-chiral configuration of the quarks at the ends.

(iii) The spin-orbit interaction of quarks with the fixed chirality is absent

(iv) The tensor interaction is absent ($\vec{\sigma}(i)\cdot\vec{r}(i)=0;\ \ \vec{\sigma}(i)\cdot\vec{r}(j)=0$)

Symmetry: $SU(2)_L \times SU(2)_R \times U(1)_A \times\ dynamical symmetry$

Dynamical symmetry of the open string: $N = N_{rot} + N_{rad} + N_{tr}$

Hybrids: $N_{tr} > 0$

Is Nambu-Goto string consistent with chiral symmetry?

Nambu-Goto string: energy is stored in the rotating string (color-electric flux tube) and is prescribed by L and n . Output - linear orbital and radial Regge trajectories.

No quarks at the ends, no chiral symmetry.

Consider string with chiral quarks at the ends. Then we can construct a unitary transformation from a given chiral representation R to the $\{I;{}^{2S+1}L_J\}$ basis.

$$|R;IJ^{PC}\rangle=\sum_{LS}\sum_{\lambda_q\lambda_{\bar q}}\chi^{RPI}_{\lambda_q\lambda_{\bar q}}\times\sqrt{\frac{2L+1}{2J+1}}C^{S\Lambda}_{\frac12\lambda_q\frac12-\lambda_{\bar q}}C^{J\Lambda}_{L0S\Lambda}|I;{}^{2S+1}L_J\rangle.$$

Fixed L : $a_1:\ |(0,1)+(1,0);1\ 1^{++}\rangle=|1;{}^3P_1\rangle,\quad h_1:\ |(1/2,1/2)_b;0\ 1^{+-}\rangle=|0;{}^1P_1\rangle.$

However, there are two kinds of ρ-mesons, fixed L is impossible!

$$\begin{aligned}|(0,1)+(1,0);1\ 1^{--}\rangle &= \sqrt{\frac23}|1;{}^3S_1\rangle+\sqrt{\frac13}|1;{}^3D_1\rangle,\\ |(1/2,1/2)_b;1\ 1^{--}\rangle &= \sqrt{\frac13}|1;{}^3S_1\rangle-\sqrt{\frac23}|1;{}^3D_1\rangle.\end{aligned}$$

Energy cannot be prescribed by L !

Summary.

1. Physics of the lowest-lying and excited hadrons is very different. The low-lying hadrons are strongly affected by the spontaneous breaking of chiral and $U(1)_A$ symmetries. Their mass is due to quark condensate of the vacuum. In the high-lying states these chiral symmetry breakings become irrelevant. Most of the mass is manifestly chirally symmetric, i.e. it comes NOT from the quark condensate.

2. A fundamental origin of this phenomenon is that effects of quantum fluctuations (loops) of the quark fields vanish at large n and J.

3. There appears higher degree of degeneracy that includes chiral $U(2)_L \times U(2)_R$ as a subgroup. An origin of this larger symmetry is unknown!

4. If it is a kind of string, then it is an unusual string. The Nambu-Goto string (electric flux tube) is not compatible with restored chiral symmetry, at least in the known forms.