Chiral effective theory for h and γ^* production in NN & AA collisions

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$$
\begin{aligned}
\mathcal{L} &= \mathcal{L}_{\text{meson}} + \mathcal{L}_{\text{baryon}} + \mathcal{L}_{\text{weak}} \\
\mathcal{L}_{\text{meson}} &= \mathrm{Tr}[(D_\mu\Phi)^\dagger(D^\mu\Phi)] - m_0^2\,\mathrm{Tr}(\Phi^\dagger\Phi) - \lambda_1[\mathrm{Tr}(\Phi^\dagger\Phi)]^2 - \lambda_2\,\mathrm{Tr}(\Phi^\dagger\Phi)^2 \\
&\quad + c_1(\det\Phi - \det\Phi^\dagger)^2 + \mathrm{Tr}[H(\Phi+\Phi^\dagger)] - \tfrac{1}{4}\mathrm{Tr}(L_{\mu\nu}^2 + R_{\mu\nu}^2) \\
&\quad + \mathrm{Tr}\left[\left(\tfrac{m_1^2}{2} + \Delta\right)(L_\mu^2 + R_\mu^2)\right] + i\tfrac{g_2}{2}(\mathrm{Tr}\{L_{\mu\nu}[L^\mu, L^\nu]\} + \mathrm{Tr}\{R_{\mu\nu}[R^\mu, R^\nu]\}) \\
&\quad + \tfrac{h_1}{2}\mathrm{Tr}(\Phi^\dagger\Phi)\,\mathrm{Tr}(L_\mu^2 + R_\mu^2) + h_2\,\mathrm{Tr}[(L_\mu\Phi)^2 + (\Phi R_\mu)^2] + 2h_3\,\mathrm{Tr}(L_\mu\Phi R^\mu\Phi^\dagger) \\
&\quad + \text{chirally invariant vector and axialvector four-point interaction vertices} \\
\mathcal{L}_{\text{baryon}} &= \bar\Psi_{1L} i\gamma_\mu D_{1L}^\mu \Psi_{1L} + \bar\Psi_{1R} i\gamma_\mu D_{1R}^\mu \Psi_{1R} + \bar\Psi_{2L} i\gamma_\mu D_{2R}^\mu \Psi_{2L} + \bar\Psi_{2R} i\gamma_\mu D_{2L}^\mu \Psi_{2R} \\
&\quad - \hat g_1(\bar\Psi_{1L}\Phi\Psi_{1R} + \bar\Psi_{1R}\Phi\Psi_{1L}) - \hat g_2(\bar\Psi_{2L}\Phi^\dagger\Psi_{2R} + \bar\Psi_{2R}\Phi^\dagger\Psi_{2L}) \\
&\quad - M(\bar\Psi_{1L}\Psi_{2R} - \bar\Psi_{1R}\Psi_{2L} - \bar\Psi_{2L}\Psi_{1R} - \bar\Psi_{2R}\Psi_L) \\
\mathcal{L}_{\text{weak}} &= \delta\,\tfrac{g\cos\theta_C}{2}\mathrm{Tr}[W_{\mu\nu}L^{\mu\nu}] + \bar\delta\,\tfrac{e}{2}\mathrm{Tr}[B_{\mu\nu}R^{\mu\nu}] + \tfrac{1}{4}\mathrm{Tr}[(W^{\mu\nu})^2 + (B^{\mu\nu})^2]
\end{aligned}
$$

$N_F = 2$ and $N_F = 3$ meson multiplets:

$$
\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} \frac{(\sigma_N+a_0^0)}{\sqrt{2}} + \frac{i(\eta_N+\pi^0)}{\sqrt{2}} & a_0^+ + i\pi^+ & K_0^{\star+} + iK^+ \\ a_0^- + i\pi^- & \frac{(\sigma_N-a_0^0)}{\sqrt{2}} + \frac{i(\eta_N-\pi^0)}{\sqrt{2}} & K_0^{\star0} + iK^0 \\ K_0^{\star-} + iK^- & \bar K_0^{\star0} + i\bar K^0 & \sigma_S + i\eta_S \end{pmatrix}
$$

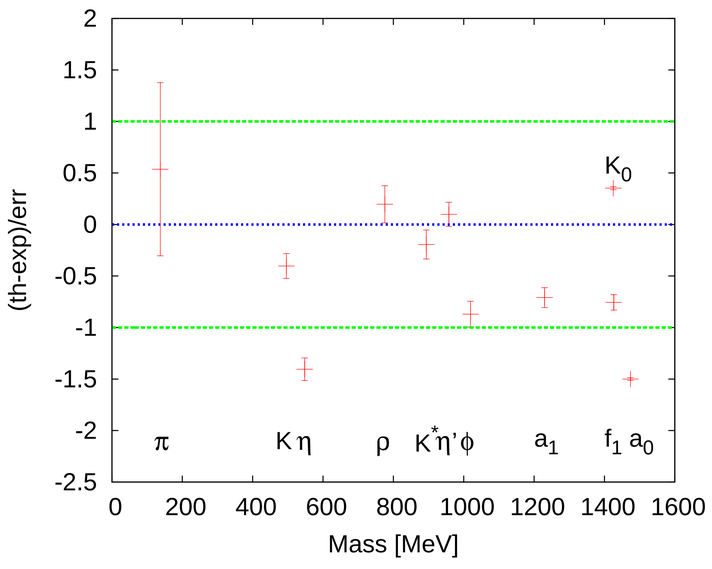
$$
L^\mu = \frac{1}{\sqrt{2}}\begin{pmatrix} \frac{\omega_N+\rho^0}{\sqrt{2}} + \frac{f_{1N}+a_1^0}{\sqrt{2}} & \rho^+ + a_1^+ & K^{\star+} + K_1^+ \\ \rho^- + a_1^- & \frac{\omega_N-\rho^0}{\sqrt{2}} + \frac{f_{1N}-a_1^0}{\sqrt{2}} & K^{\star0} + K_1^0 \\ K^{\star-} + K_1^- & \bar K^{\star0} + \bar K_1^0 & \omega_S + f_{1S} \end{pmatrix}^\mu
$$

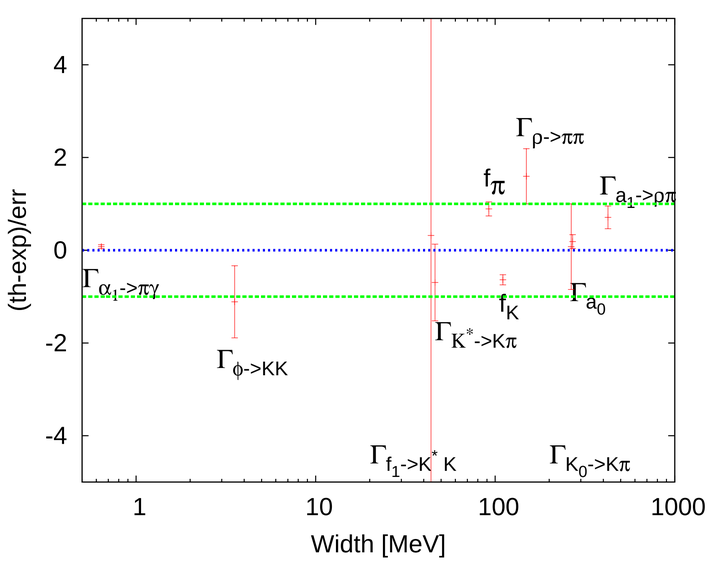
$$
R^\mu = \frac{1}{\sqrt{2}}\begin{pmatrix} \frac{\omega_N+\rho^0}{\sqrt{2}} - \frac{f_{1N}+a_1^0}{\sqrt{2}} & \rho^+ - a_1^+ & K^{\star+} - K_1^+ \\ \rho^- - a_1^- & \frac{\omega_N-\rho^0}{\sqrt{2}} - \frac{f_{1N}-a_1^0}{\sqrt{2}} & K^{\star0} - K_1^0 \\ K^{\star-} - K_1^- & \bar K^{\star0} - \bar K_1^0 & \omega_S - f_{1S} \end{pmatrix}^\mu
$$

$$
\begin{aligned}
&D^\mu\Phi \equiv \partial^\mu\Phi - ig_1(L^\mu\Phi - \Phi R^\mu) - ie[A^\mu,\Phi] - ig\cos\theta_C(W_1^\mu t_1 + W_2^\mu t_2)\Phi - ig\cos\theta_W(Z^\mu\Phi + \tan^2\theta_W\Phi Z^\mu)\,, \\
&L^{\mu\nu} \equiv \partial^\mu L^\nu - ie[A^\mu, L^\nu] - ig[W_1^\mu t_1 + W_2^\mu t_2, L^\nu] - \{\partial^\nu L^\mu - ie[A^\nu, L^\mu] - ig[W_1^\nu t_1 + W_2^\nu t_2, L^\mu]\} \quad \text{(and similar for } R^{\mu\nu})
\end{aligned}
$$

- Global chiral $U(3)_L \times U(3)_R = U(1)_V \times U(1)_A \times SU(3)_V \times SU(3)_A$ symmetry, spontaneously broken by VEV ϕ of σ field ($m_0^2 < 0$)
- Chiral symmetry explicitly broken to $U(1)_V$ by $U(1)_A$ anomaly and quark masses
- Mass difference of chiral partners generated by VEV ϕ of σ, e.g.: $m_{a_1}^2 - m_\rho^2 = (g_1\phi)^2 - \frac{h_3}{2}\phi^2$
- Mirror assignment for baryons N and their chiral partners N^*: new, chirally invariant mass term $\sim M$
- Inclusion of electroweak interactions

Meson sector for $N_F = 3$: D. Parganlija, P. Kovács, Gy. Wolf, F. Giacosa, D.H. Rischke, arXiv:1208.0585 [hep-ph]





- Fit of 11 parameters to 21 hadron vacuum properties: reproduction within one standard deviation!
- Scalar isoscalar quarkonia (chiral partners of the pseudoscalar isovector mesons) lie above 1 GeV!
- Axial-vector mesons (chiral partners of the vector mesons) are quarkonia!

Scalar isoscalar meson – glueball mixing for $N_F = 2$:

S. Janowski, D. Parganlija, F. Giacosa, D.H. Rischke, PRD84 (2011) 054007

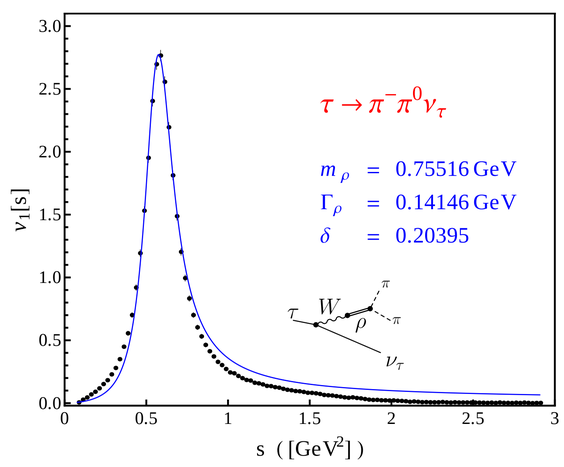
Quantity	eLSM [MeV]	Exp. [MeV]
$M_{\sigma'}$	1191 ± 26	$1200 - 1500$
$M_{G'}$	1505 ± 6	1505 ± 6
$G' \to \pi\pi$	38 ± 5	38.04 ± 4.95
$G' \to \eta\eta$	5.3 ± 1.3	5.56 ± 1.34
$G' \to K\bar K$	9.3 ± 1.7	9.37 ± 1.69

Quantity	eLSM [MeV]	Exp. [MeV]
$G' \xrightarrow{2\rho} 4\pi$	30	54 ± 7.1
$G' \to \eta\eta'$	0.6	2.1 ± 1.0
$\sigma' \to \pi\pi$	284 ± 43	325
$\sigma' \to \eta\eta$	72 ± 6	61.8 ± 22.8

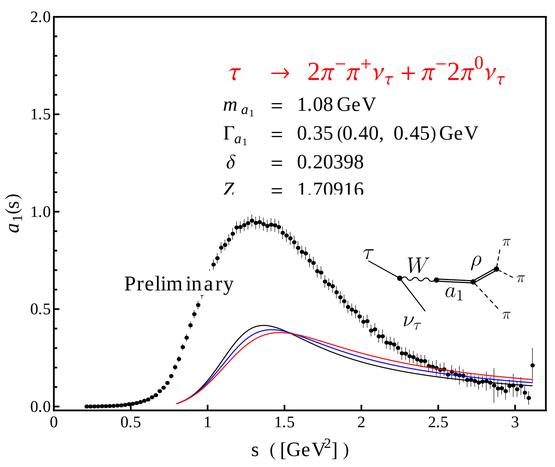
- Upper table: quantities used in fit of parameters
- Lower table: predictions for other quantities
- σ' associated with $f_0(1370)$ and G' with $f_0(1500)$
- mixing angle $\theta = (29.7 \pm 3.6)^\circ$ and therefore $f_0(1500)$ is 75% glueball

Calculation of τ (axial-)vector spectral functions:

A. Habersetzer, diploma thesis



Vector channel reproduced with one(!) free parameter δ



No(!) free parameter; but so far only contribution from $W \to a_1 \to \rho\pi$

Chiral partner of the nucleon: $N(1535)$ or $N(1650)$?

S. Gallas, F. Giacosa, D.H. Rischke, PRD82 (2010) 014004

- Parameters fitted to $M_N, M_{N^*}, g_A, g_{A^*}$ and $\Gamma(N^* \to N\pi)$
- Two scenarios: $\boldsymbol{N^* = N(1535)}$ or $\boldsymbol{N^* = N(1650)}$
- πN scattering lengths reasonably well reproduced for both assignments, but:

Scenario	$\Gamma^{theor}(N^* \to N\eta)$ [MeV]	$\Gamma^{exp}(N^* \to N\eta)$ [MeV]
$N^* = N(1535)$	10.9 ± 3.8	78.7 ± 24.3
$N^* = N(1650)$	18.3 ± 8.5	10.7 ± 6.7

- $\boldsymbol{N^* = N(1650)}$ favored as chiral partner of $N(940)$!
- But then what is chiral partner of $\boldsymbol{N(1535)}$? (Could it be $\boldsymbol{N(1440)}$?)

Outlook:

- Isoscalar-glueball mixing for $\boldsymbol{N_F = 3}$ (S. Janowski)
- Mixing of axial- and pseudo-vectors
- Extension to charm $\boldsymbol{N_F = 4}$ (W. Eshraim)
- Inclusion of isoscalars below 1 GeV, $M = a\chi + bG$
- four-baryon mixing between $N(940)$, $N(1440)$, $N(1535)$, $N(1650)$
- NN scattering (W. Deinet)
- Exclusive h production in NN collisions (K. Teilab)
- Dilepton rate in NN collisions (A. Habersetzer)
- Nonzero temperature and density: in-medium properties

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