Construction and validation of a chiral effective model

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and

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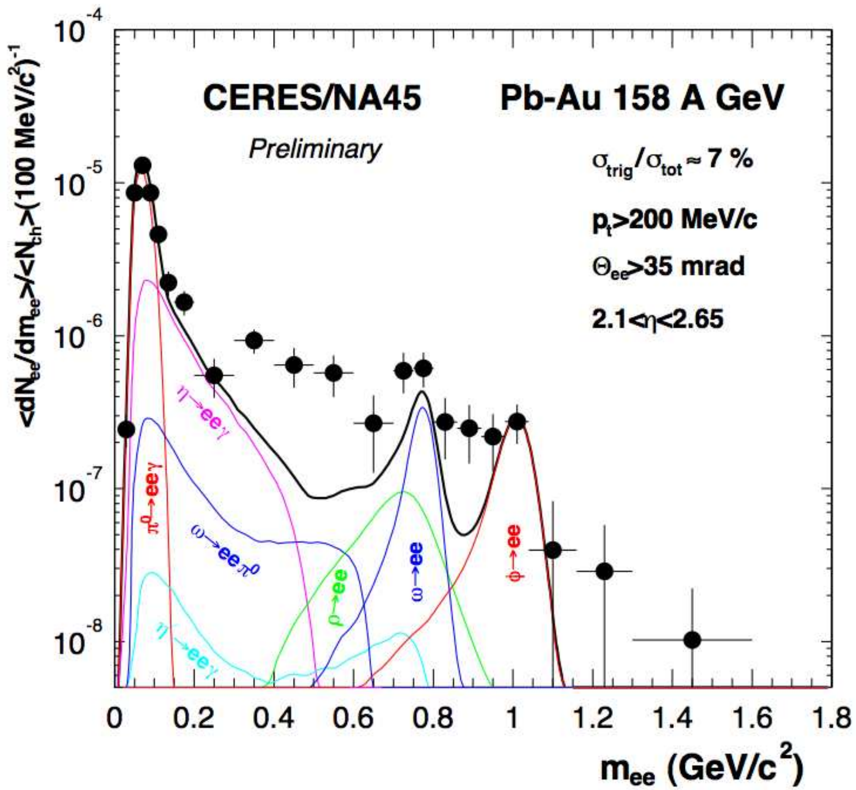
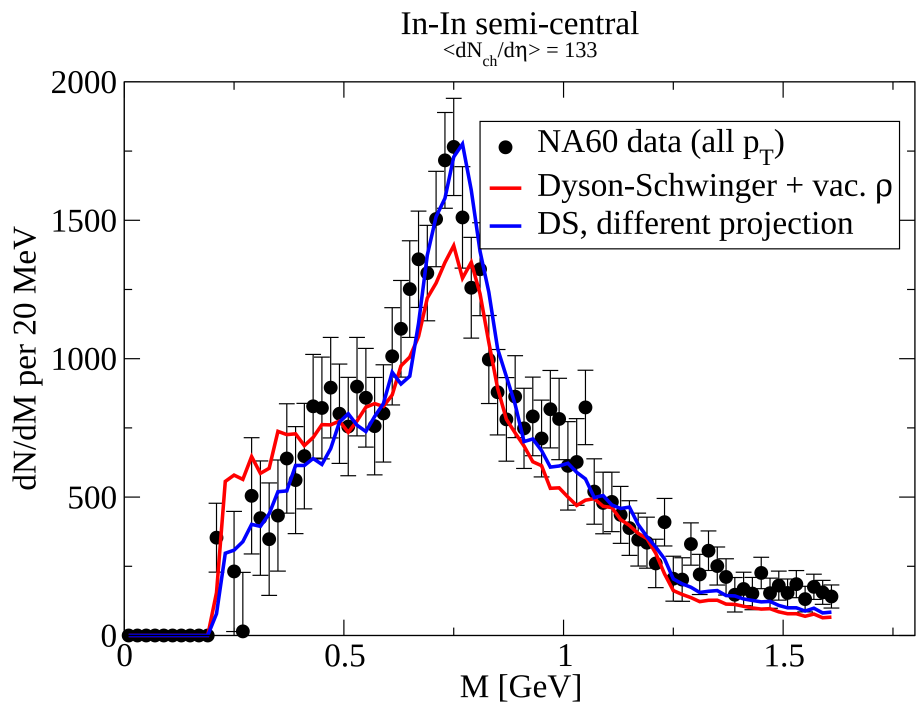
Motivation (I)

Dileptons carry information from hot and dense stages of heavy-ion collisions:



CERES/NA45 collaboration



NA60 collaboration

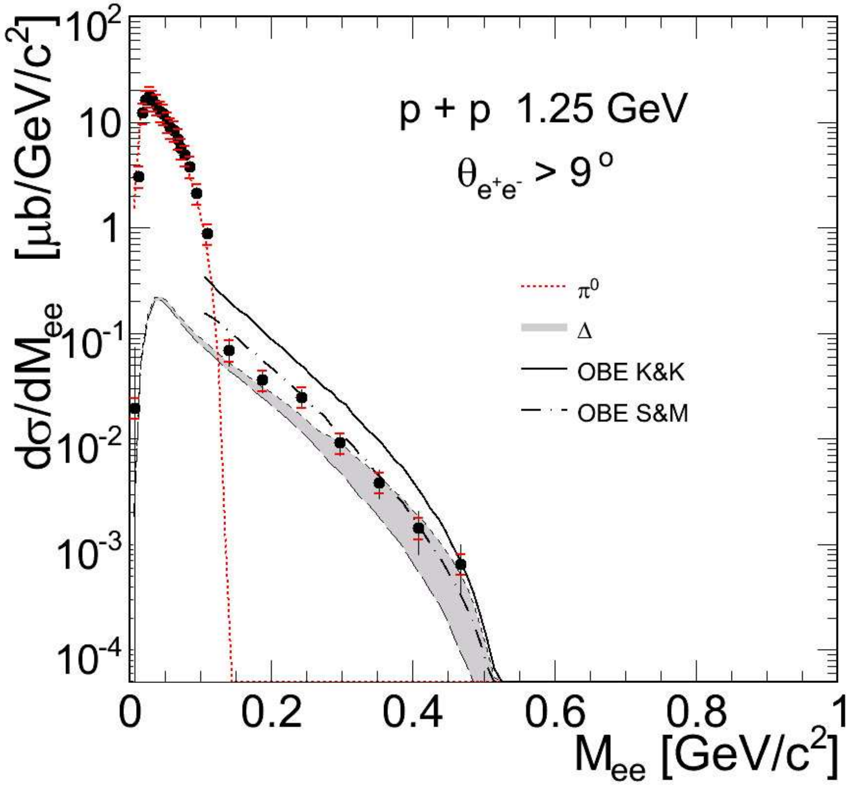
(fig. courtesy of Thorsten Renk)

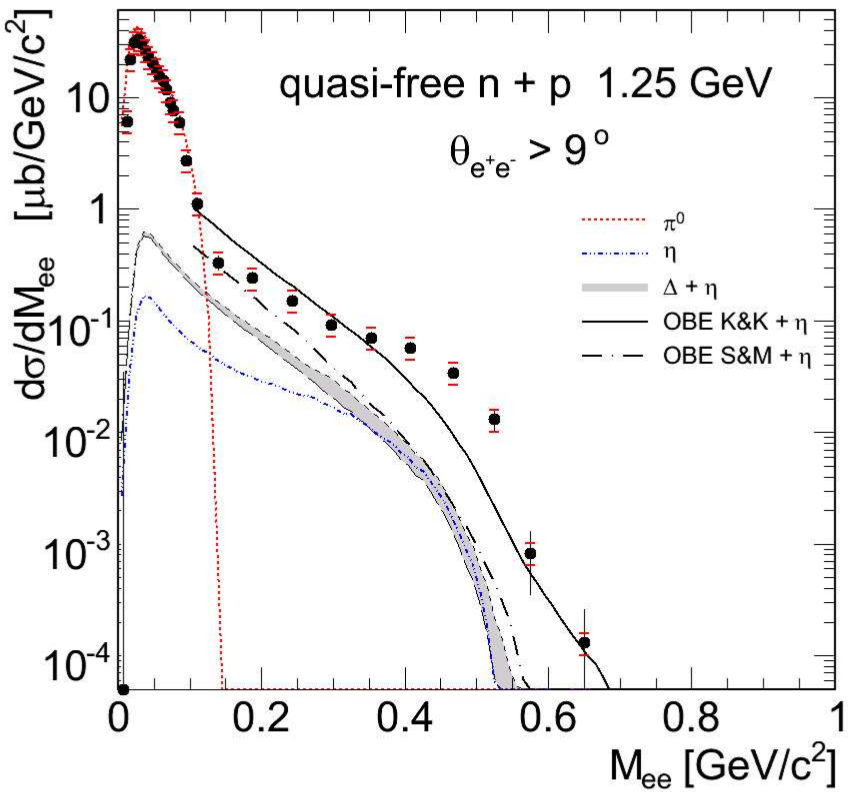
⟹ **learn about chiral symmetry restoration in hot and dense hadronic matter!**

see R. Rapp, J. Wambach, Adv. Nucl. Phys. 25 (2000) 1

Motivation (II)

Prior to describing AA: understand dilepton production in NN collisions!





HADES collaboration, Acta Phys.Polon. B41 (2010) 365

The chiral effective model

Chiral symmetry of QCD: global $U(N_f)_r \times U(N_f)_\ell$ symmetry (classically)

$\Longrightarrow$ spontaneously broken in vacuum by nonzero quark condensate $\langle \bar{q} q \rangle \neq 0$

$\Longrightarrow$ restored at nonzero temperature T and chemical potential μ

$\Longrightarrow$ degeneracy of hadronic chiral partners in the chirally restored phase

$\Longrightarrow$ for this application: chiral symmetry must be linearly realized

$\Longrightarrow$ Linear sigma model

Disclaimer: No attempt to fit precision data for hadron vacuum phenomenology!

(No attempt to compete with chiral perturbation theory)

Nevertheless: achieve reasonable description of hadron vacuum phenomenology!

Moreover: strong statement on the nature of the scalar mesons!

scalar-meson puzzle: too many scalar states to fit into a $q\bar{q}$ meson nonet

$$f_0(600),\ f_0(980),\ f_0(1370),\ f_0(1500),\ f_0(1710)$$

$\Longrightarrow$ Jaffe's conjecture: R.L. Jaffe, PRD 15 (1977) 267, 281

two scalar $[qq][\bar{q}\bar{q}]$ tetraquark states mix with two scalar $q\bar{q}$ meson states

$\Longrightarrow$ fifth scalar meson could be due to mixing with glueball

Scalar and pseudoscalar mesons

$$\mathcal{L}_S = \mathrm{Tr}\left(\partial_\mu \Phi^\dagger \partial^\mu \Phi - m^2\, \Phi^\dagger \Phi\right) - \lambda_1 \left[\mathrm{Tr}\left(\Phi^\dagger \Phi\right)\right]^2 - \lambda_2 \mathrm{Tr}\left(\Phi^\dagger \Phi\right)^2 + c\left(\det\Phi - \det\Phi^\dagger\right)^2 + \mathrm{Tr}\left[H\left(\Phi + \Phi^\dagger\right)\right]$$

$\Phi \in (N_f^*, N_f) \implies \Phi \equiv \phi_a T_a$, T_a generators of $U(N_f)$, $\phi_a \equiv \sigma_a + i\pi_a$, $H \equiv h_a T_a$

$h_a = c = 0$, $m^2 > 0$: $U(N_f)_r \times U(N_f)_\ell$ symmetry

$h_a = c = 0$, $m^2 < 0$: v.e.v. $\langle \Phi \rangle = \phi\, N_f\, T_0$, $\phi \equiv \langle \sigma_0 \rangle > 0$

Spontaneous symmetry breaking (SSB):

$U(N_f)_r \times U(N_f)_\ell \longrightarrow U(N_f)_V \quad (V \equiv \ell + r)$

$h_a = 0$, $c \neq 0$: $U(1)_A$ anomaly $(A \equiv \ell - r)$

Explicit symmetry breaking (ESB):

$U(N_f)_r \times U(N_f)_\ell \longrightarrow SU(N_f)_r \times SU(N_f)_\ell \times U(1)_V$

$m^2 < 0$: SSB: $SU(N_f)_r \times SU(N_f)_\ell \longrightarrow SU(N_f)_V$

$\dim[SU(N_f)_r \times SU(N_f)_\ell / SU(N_f)_V] = 2\,(N_f^2 - 1) - (N_f^2 - 1) = N_f^2 - 1$

$\implies N_f^2 - 1$ Goldstone bosons $\implies$ pseudoscalar mesons!

h_a, $c \neq 0$, $m^2 < 0$: ESB $\implies N_f^2 - 1$ pseudo - Goldstone bosons

Vector and axial-vector mesons

$$\begin{aligned}\mathcal{L}_V = &-\frac{1}{4}\,\mathrm{Tr}(\mathcal{L}^0_{\mu\nu}\mathcal{L}^{\mu\nu}_0 + \mathcal{R}^0_{\mu\nu}\mathcal{R}^{\mu\nu}_0) + \frac{1}{2}\,\mathrm{Tr}\left[\left(m_1^2 + 2\hat{\delta}\right)\,(\mathcal{L}_\mu\mathcal{L}^\mu + \mathcal{R}_\mu\mathcal{R}^\mu)\right]\\ &+ i\,\frac{g_2}{2}\,\mathrm{Tr}\left\{\mathcal{L}^0_{\mu\nu}[\mathcal{L}^\mu, \mathcal{L}^\nu] + \mathcal{R}^0_{\mu\nu}[\mathcal{R}^\mu, \mathcal{R}^\nu]\right\}\\ &+ g_3\,\mathrm{Tr}\,(\mathcal{L}^\mu\mathcal{L}^\nu\mathcal{L}_\mu\mathcal{L}_\nu + \mathcal{R}^\mu\mathcal{R}^\nu\mathcal{R}_\mu\mathcal{R}_\nu) - g_4\,\mathrm{Tr}\,(\mathcal{L}^\mu\mathcal{L}_\mu\mathcal{L}^\nu\mathcal{L}_\nu + \mathcal{R}^\mu\mathcal{R}_\mu\mathcal{R}^\nu\mathcal{R}_\nu)\\ &+ g_5\,\mathrm{Tr}\,(\mathcal{L}^\mu\mathcal{L}_\mu)\;\mathrm{Tr}\,(\mathcal{R}^\nu\mathcal{R}_\nu)\\ &+ g_6\,\left[\mathrm{Tr}\,(\mathcal{L}^\mu\mathcal{L}_\mu)\;\mathrm{Tr}\,(\mathcal{L}^\nu\mathcal{L}_\nu) + \mathrm{Tr}\,(\mathcal{R}^\mu\mathcal{R}_\mu)\;\mathrm{Tr}\,(\mathcal{R}^\nu\mathcal{R}_\nu)\right]\end{aligned}$$

$$\mathcal{L}^0_{\mu\nu} \equiv \partial_\mu\mathcal{L}_\nu - \partial_\nu\mathcal{L}_\mu,\;\; \mathcal{R}^0_{\mu\nu} \equiv \partial_\mu\mathcal{R}_\nu - \partial_\nu\mathcal{R}_\mu,\;\; \mathcal{L}_\mu \equiv L^a_\mu T_a,\;\; \mathcal{R}_\mu \equiv R^a_\mu T_a$$

vector mesons: $V^a_\mu \equiv \frac{1}{2}\left(L^\mu_a + R^a_\mu\right)$, **axial-vector mesons:** $A^a_\mu \equiv \frac{1}{2}\left(L^\mu_a - R^a_\mu\right)$

$\hat{\delta}$ **: matrix which accounts for difference in quark masses**

g_3, g_4, g_5, g_6: **not determined by global fit to masses and decay widths**

Scalar – vector interactions

$$\mathcal{L}_{SV} = i\, g_1 \,\mathrm{Tr}\left[\partial_\mu \Phi \left(\Phi^\dagger \mathcal{L}^\mu - \mathcal{R}^\mu \Phi^\dagger\right) - \partial_\mu \Phi^\dagger \left(\mathcal{L}^\mu \Phi - \Phi \mathcal{R}^\mu\right)\right]$$
$$+\frac{h_1}{2}\,\mathrm{Tr}\left(\Phi^\dagger \Phi\right) \mathrm{Tr}\left(\mathcal{L}_\mu \mathcal{L}^\mu + \mathcal{R}_\mu \mathcal{R}^\mu\right) + (g_1^2 + h_2)\,\mathrm{Tr}\left(\Phi^\dagger \Phi \mathcal{R}_\mu \mathcal{R}^\mu + \Phi \Phi^\dagger \mathcal{L}_\mu \mathcal{L}^\mu\right)$$
$$- 2(g_1^2 - h_3)\,\mathrm{Tr}\left(\Phi^\dagger \mathcal{L}_\mu \Phi \mathcal{R}^\mu\right)$$

SSB:

- induces mass splitting $m_A^2 - m_V^2 = (g_1^2 - h_3)\phi^2$
- induces bilinear term $\sim g_1 \phi\, A_a^\mu\, \partial_\mu \pi_a$:

$\Longrightarrow$ eliminate by shift $A_a^\mu \longrightarrow A_a^\mu + w(\phi)\, \partial^\mu \pi_a \;,\quad w(\phi) \equiv \dfrac{g_1 \phi}{m_A^2}$

$\Longrightarrow$ wave function renormalization of pseudoscalar fields

$\pi_a \longrightarrow Z\, \pi_a \;,\quad Z^2 \equiv \left(1 - \frac{g_1^2 \phi^2}{m_A^2}\right)^{-1}$ (KSFR : $Z \equiv \sqrt{2}$)

$\Longrightarrow$ v.e.v. $\phi \equiv Z\, f_\pi$

$\Longrightarrow$ complete meson Lagrangian $\boxed{\mathcal{L}_M = \mathcal{L}_S + \mathcal{L}_V + \mathcal{L}_{SV}}$

Vacuum phenomenology: Global fit for $N_f = 3$ (I)

$N_f = 3 \Longrightarrow$ two scalar-isoscalar mesons f_0^L , f_0^H (combinations of $\bar{q}q$ and $\bar{s}s$)
$\Longrightarrow$ all (pseudo-)scalar masses and decay widths except those of f_0^L , f_0^H determined by linear combination of m^2 , λ_1 and of m_1^2 , h_1

Since nature of scalar-isoscalar mesons (quarkonium, glueball, or tetraquark?) is unclear

$\Longrightarrow$ at first omit scalar-isoscalar mesons from the fit

$\Longrightarrow$ perform χ^2–fit of $m^2, \lambda_2 , c , h_0 , h_8 , m_1^2 , \delta , g_1 , g_2 , h_2 , h_3$ (11 parameters) to 21 experimental quantities

D. Parganlija, F. Giacosa, P. Kovacs, Gy. Wolf, DHR, PRD 87 (2013) 014011

Constraints: (i) no isospin violation

$\Longrightarrow$ experimental error $= \max(\text{PDG error}\,, 5\%)$

(ii) $m^2 < 0$ (SSB)

(iii) $\lambda_2 > 0\,,\ \lambda_1 > -\lambda_2/2$ (boundedness of potential)

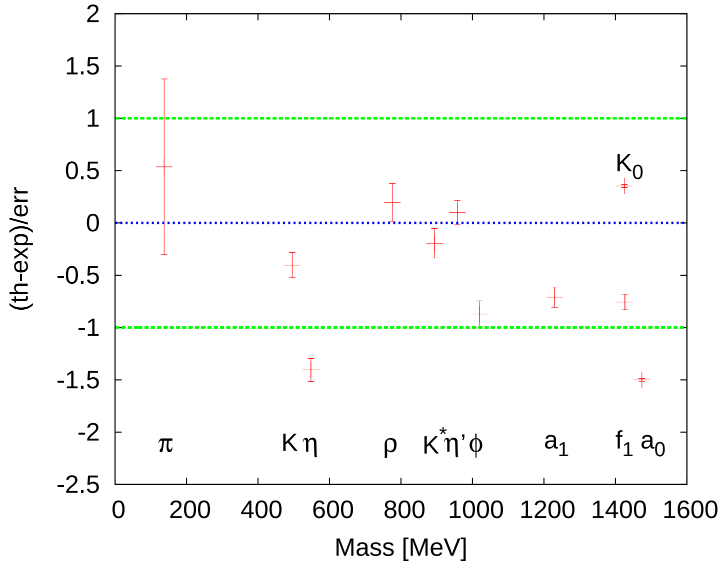
(iv) $m_1 \geq 0$ (boundedness of potential)

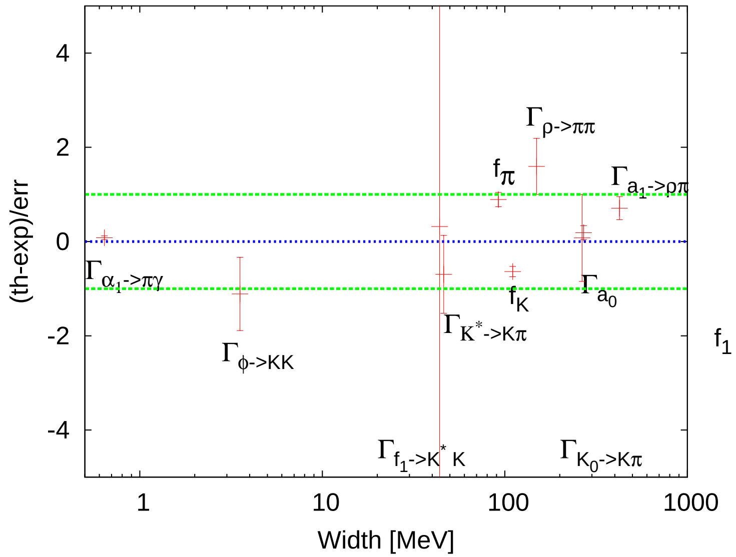
(v) $m_1 \leq m_\rho$ (SSB increases mass of vector mesons)

Vacuum phenomenology: Global fit for $N_f = 3$ (II)

Observable	Fit [MeV]	Experiment [MeV]
f_π	96.3 ± 0.7	92.2 ± 4.6
f_K	106.9 ± 0.6	110.4 ± 5.5
m_π	141.0 ± 5.8	137.3 ± 6.9
m_K	485.6 ± 3.0	495.6 ± 24.8
m_η	509.4 ± 3.0	547.9 ± 27.4
$m_{\eta'}$	962.5 ± 5.6	957.8 ± 47.9
m_ρ	783.1 ± 7.0	775.5 ± 38.8
$m_{K^\star}$	885.1 ± 6.3	893.8 ± 44.7
m_ϕ	975.1 ± 6.4	1019.5 ± 51.0
m_{a_1}	1186 ± 6	1230 ± 62
$m_{f_1(1420)}$	1372.5 ± 5.3	1426.4 ± 71.3
m_{a_0}	1363 ± 1	1474 ± 74
$m_{K_0^\star}$	1450 ± 1	1425 ± 71
$\Gamma_{\rho\to\pi\pi}$	160.9 ± 4.4	149.1 ± 7.4
$\Gamma_{K^\star\to K\pi}$	44.6 ± 1.9	46.2 ± 2.3
$\Gamma_{\phi\to\bar{K}K}$	3.34 ± 0.14	3.54 ± 0.18
$\Gamma_{a_1\to\rho\pi}$	549 ± 43	425 ± 175
$\Gamma_{a_1\to\pi\gamma}$	0.66 ± 0.01	0.64 ± 0.25
$\Gamma_{f_1(1420)\to K^\star K}$	44.6 ± 39.9	43.9 ± 2.2
Γ_{a_0}	266 ± 12	265 ± 13
$\Gamma_{K_0^\star\to K\pi}$	285 ± 12	270 ± 80

accuracy of fit: $\chi^2/\text{d.o.f.} \simeq 1.23$





Vacuum phenomenology: Global fit for $N_f = 3$ (III)

large–N_c suppressed parameters $\lambda_1 = h_1 \equiv 0$:

$\Longrightarrow$ prediction for the masses of the isoscalar-scalar states:
$m_{f_0^L} = 1362.7$ MeV, $m_{f_0^H} = 1531.7$ MeV

$\Longrightarrow$ masses are in the range of the heavy scalar states:
$m_{f_0(1370)} = (1350 \pm 150)$ MeV, $m_{f_0(1500)} = (1505 \pm 75)$ MeV,
$m_{f_0(1710)} = 1720 \pm 86$ MeV

$\Longrightarrow$ mass of f_0^L close to mass of $f_0(1370)$

$\Longrightarrow$ mass of f_0^H close to $f_0(1500)$, but decay pattern similar to that of $f_0(1710)$

$\Longrightarrow$ include mixing with glueball state

$\Longrightarrow$ (most likely) $f_0(1500)$ (predominantly) glueball

$\Longrightarrow$ $f_0(1370)$, $f_0(1710)$ appear to be (predominantly) $\bar{q}q$–states

$\Longrightarrow$ chiral partners of π, η'!

$\Longrightarrow$ light scalar states $f_0(600)$, $f_0(980)$ could be (predominantly) $[qq][\bar{q}\bar{q}]$–states
(see, however, W. Heupel, G. Eichmann, C.S. Fischer, PLB 718 (2012) 545
$\Longrightarrow$ light scalars have a dominant meson-molecule component!)

Incorporating the scalar glueball (I)

Another confirmation of the (predominantly) $q\bar{q}$ assignment for the heavy scalar mesons: $\Longrightarrow$ coupling to the glueball/dilaton field! (so far only $N_f = 2$)

S. Janowski, D. Parganlija, F. Giacosa, DHR, PRD 84 (2011) 054007

- dilatation symmetry $\Longrightarrow$ dynamical generation of tree-level meson mass parameters through glueball field G: $m^2 \rightarrow m^2 \left(\frac{G^2}{G_0^2}\right)$, $\quad m_1^2 \rightarrow m_1^2 \left(\frac{G^2}{G_0^2}\right)$
- add glueball Lagrangian: $$\mathcal{L}_G = \frac{1}{2}\,(\partial_\mu G)^2 - \frac{1}{4}\,\frac{m_G^2}{\Lambda^2}\,G^4 \left(\ln\left|\frac{G}{\Lambda}\right| - \frac{1}{4}\right)$$

$\Lambda \sim$ gluon condensate $\langle G^a_{\mu\nu} G_a^{\mu\nu} \rangle$

$\Longrightarrow \quad \mathcal{L}_M \longrightarrow \mathcal{L}_M + \mathcal{L}_G$

- shift σ and G by their v.e.v.'s, $\sigma \rightarrow \sigma + \phi$, $G \rightarrow G + G_0$

$\Longrightarrow$ v.e.v. G_0 given by $\quad -\frac{m^2}{m_G^2}\,\phi^2\,\Lambda^2 = G_0^4\,\ln\left|\frac{G_0}{\Lambda}\right|$

$\Longrightarrow$ glueball mass given by $\quad M_G^2 = m^2\,\frac{\phi^2}{G_0^2} + m_G^2\,\frac{G_0^2}{\Lambda^2}\left(1 + 3\ln\left|\frac{G_0}{\Lambda}\right|\right)$

$\Longrightarrow$ bilinear term $\sim \sigma G \quad \Longrightarrow$ eliminate by $O(2)$ transformation

$$\begin{pmatrix} \sigma' \\ G' \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \sigma \\ G \end{pmatrix}$$

Incorporating the scalar glueball (II)

$\Longrightarrow$ χ^2 fit of Λ, M_σ, m_G^2, m_1^2 to the following experimental quantities:

Quantity	Our Value [MeV]	Experiment [MeV]
$M_{\sigma'}$	1191 ± 26	1350 ± 150
$M_{G'}$	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

$\chi^2/\text{d.o.f.} = 0.29$

$\Longrightarrow$ $\theta = (29.7 \pm 3.6)^o$ $\Longrightarrow$ $f_0(1500)$ is 76% glueball!

$\Longrightarrow$ predict the following quantities:

Quantity	Our Value [MeV]	Experiment [MeV]
$G' \to \rho\rho \to 4\pi$	30	54.0 ± 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

$\Longrightarrow$ reasonable description of experimental data!

Note: demanding dilatation symmetry of full effective model

$\Longrightarrow$ analyticity prohibits operators with naive scaling dimension higher than 4 in Φ, V^μ, A^μ (would require inverse powers of dilaton field)

$\Longrightarrow$ effective model is complete!

Predictions for a pseudoscalar glueball

Consider decay of pseudoscalar glueball into scalar and pseudoscalar mesons

$$\mathcal{L}_{\tilde{G}\Phi} = i\, c_{\tilde{G}\Phi}\, \tilde{G}\, \left(\det\Phi - \det\Phi^{\dagger}\right)$$

$\Longrightarrow$ **predict branching ratios for decays into scalar and pseudoscalar mesons**

$\Longrightarrow$ **could be measured in PANDA!**

BR	$M_{\tilde{G}} = 2.6$ GeV	$M_{\tilde{G}} = 2.37$ GeV
$\Gamma_{\tilde{G}\to KK\eta}/\Gamma^{tot}_{\tilde{G}}$	0.049	0.042
$\Gamma_{\tilde{G}\to KK\eta'}/\Gamma^{tot}_{\tilde{G}}$	0.019	0.011
$\Gamma_{\tilde{G}\to\eta\eta\eta}/\Gamma^{tot}_{\tilde{G}}$	0.016	0.013
$\Gamma_{\tilde{G}\to\eta\eta\eta'}/\Gamma^{tot}_{\tilde{G}}$	0.0017	0.00080
$\Gamma_{\tilde{G}\to\eta\eta'\eta'}/\Gamma^{tot}_{\tilde{G}}$	0.00013	0
$\Gamma_{\tilde{G}\to KK\pi}/\Gamma^{tot}_{\tilde{G}}$	0.46	0.46
$\Gamma_{\tilde{G}\to\eta\pi\pi}/\Gamma^{tot}_{\tilde{G}}$	0.16	0.16
$\Gamma_{\tilde{G}\to\eta'\pi\pi}/\Gamma^{tot}_{\tilde{G}}$	0.094	0.088

BR	$M_{\tilde{G}} = 2.6$ GeV	$M_{\tilde{G}} = 2.37$ GeV
$\Gamma_{\tilde{G}\to KK_S}/\Gamma^{tot}_{\tilde{G}}$	0.059	0.069
$\Gamma_{\tilde{G}\to a_0\pi}/\Gamma^{tot}_{\tilde{G}}$	0.082	0.10
$\Gamma_{\tilde{G}\to\eta\sigma_N}/\Gamma^{tot}_{\tilde{G}}$	0.028	0.033
$\Gamma_{\tilde{G}\to\eta\sigma_S}/\Gamma^{tot}_{\tilde{G}}$	0.012	0.0093
$\Gamma_{\tilde{G}\to\eta'\sigma_N}/\Gamma^{tot}_{\tilde{G}}$	0.019	0.013

W.I. Eshraim, S. Janowski, F. Giacosa, DHR, PRD 87 (2013) 054036

Extension to $N_f = 4$

Fit of 3(!) additional parameters from the charm sector:

Observable	Our Value [MeV]	Exp. Value [MeV]
$m_{D_{s1}}$	2500.54	2535.12 ± 0.13
$m_{D_s^*}$	2188.33	2112.3 ±0.5
m_{D^*}	2154.58	2010.28 ± 0.13
$m_{D^{*0}}$	2154.58	2006.98 ± 0.15
m_{D_1}	2447.92	2421.3 ± 0.6
$m_{\chi_{c1}}$	3282.32	3510.66 ± 0.07
$m_{\chi_{c0}}$	3160.21	3414.75 ± 0.31
$m_{J/\psi}$	2911.3	3096.916 ± 0.011
m_{D_0}	1882.28	1864.86 ± 0.13
m_{η_c}	2490.55	2981 ± 1.1
$m_{D_0^*}$	2416.08	2403 ± 14 ± 35
m_D	1882.28	1869.62 ± 0.15
$m_{D_{s0}^*}$	2470.19	2317.8 ± 0.6
m_{D_s}	1900.39	1968.49 ± 0.32
$m_{D_0^{*0}}$	2416.08	2318 ± 29
$\Gamma_{D_1^0\to\overline{D}^{*0}\pi^0}$	8.889	-
$\Gamma_{D_1^0\to D^{*+}\pi^-}$	17.778	seen
$\Gamma_{D_1^+\to D^{*0}\pi^+}$	17.778	-
$\Gamma_{D_1^+\to D^{*+}\pi^0}$	8.88	-
$\Gamma_{D^{*0}\to D^0\pi^0}$	0.0295	<1.29
$\Gamma_{D^{*0}\to D\pi}$	0.09136	<2.1
$\Gamma_{D^{*0}\to D^+\pi^-}$	0.061	-
$\Gamma_{D^{*+}\to D^+\pi^0}$	28.1447	29.5 ± 8
$\Gamma_{D^{*+}\to D^0\pi^+}$	57.726	65 ± 17
$\Gamma_{D_0^{*+}\to D^0\pi^+}$	1.467	seen
$\Gamma_{D_0^{*+}\to D^+\pi^0}$	0.733	-
$\Gamma_{D_0^{*0}\to D^+\pi^-}$	4.159	seen
$\Gamma_{D_0^{*0}\to D^0\pi^0}$	2.079	-
$\Gamma_{D_1^0\to\overline{D}^0\pi^+\pi^-}$	0.399	seen
$\Gamma_{D_1\to D\pi\pi}$	0.608	-

Decay Channel	Our Value [MeV]	Exp. Value [MeV]
$\Gamma_{\chi_{c0}\to\overline{K}_0^* K_0^*}$	0.058	0.010
$\Gamma_{\chi_{c0}\to K^- K^+}$	0.001	0.063
$\Gamma_{\chi_{c0}\to\pi\pi}$	0.083	0.0884
$\Gamma_{\chi_{c0}\to a_0 a_0}$	0.080	-
$\Gamma_{\chi_{c0}\to k_1^0 K_1^0}$	0.003	-
$\Gamma_{\chi_{c0}\to\overline{K}^{*0} K^{*0}}$	0.0167	0.01768
$\Gamma_{\chi_{c0}\to\eta\eta}$	0.37	0.37
$\Gamma_{\chi_{c0}\to\eta'\eta'}$	14.09	0.021
$\Gamma_{\chi_{c0}\to\eta\eta'}$	4.839	<0.0025
$\Gamma_{\chi_{c0}\to ww}$	0.031	0.019
$\Gamma_{\chi_{c0}\to k_1^+ K^-}$	0.0669	0.066
$\Gamma_{\chi_{c0}\to K^* K_0^*}$	0.00006	-
$\Gamma_{\chi_{c0}\to\rho_0\rho_0}$	0.01606	-
$\Gamma_{\chi_{c0}\to\sigma_1\sigma_1}$	0.032	<0.0029
$\Gamma_{\chi_{c0}\to K_0^* K\eta}$	2.66	-
$\Gamma_{\chi_{c0}\to K_0^* K\eta'}$	6.47	-
$\Gamma_{\chi_{c0}\to\sigma_1\eta\eta}$	0.719	-
$\Gamma_{\chi_{c0}\to\sigma_2\eta\eta}$	0.693	-
$\Gamma_{\chi_{c0}\to\sigma_1\eta'\eta'}$	0.911	-
$\Gamma_{\chi_{c0}\to\sigma_1\eta\eta'}$	1.747	-
$\Gamma_{\chi_{c0}\to\sigma_2\eta\eta'}$	0.8116	-
$\Gamma_{\chi_{c0}\to\sigma_2\eta'\eta'}$	0.4148	-

$\chi^2/\mathrm{d.o.f.} \simeq 0.377$

W.I. Eshraim, F. Giacosa, DHR, in preparation

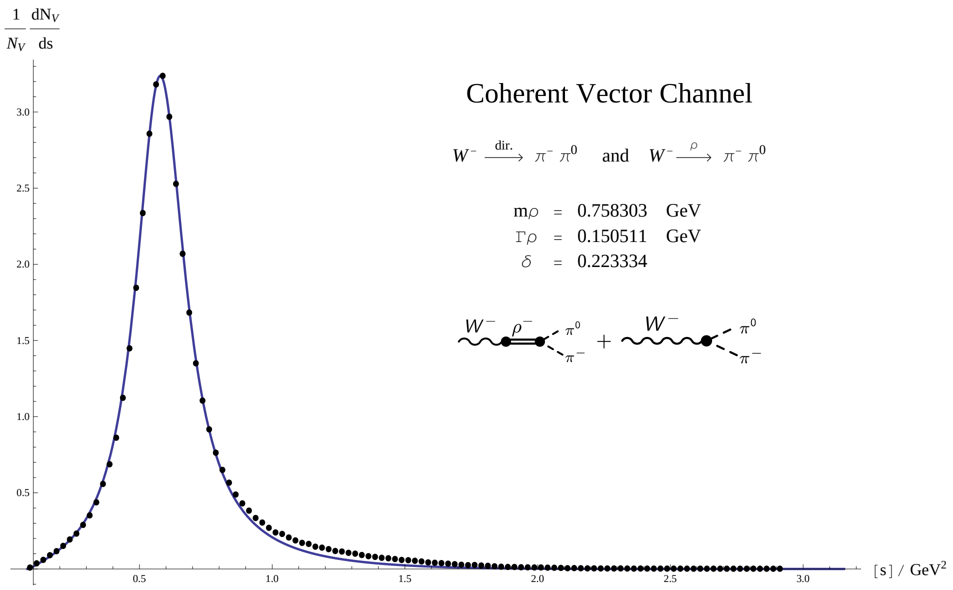
Electroweak interactions

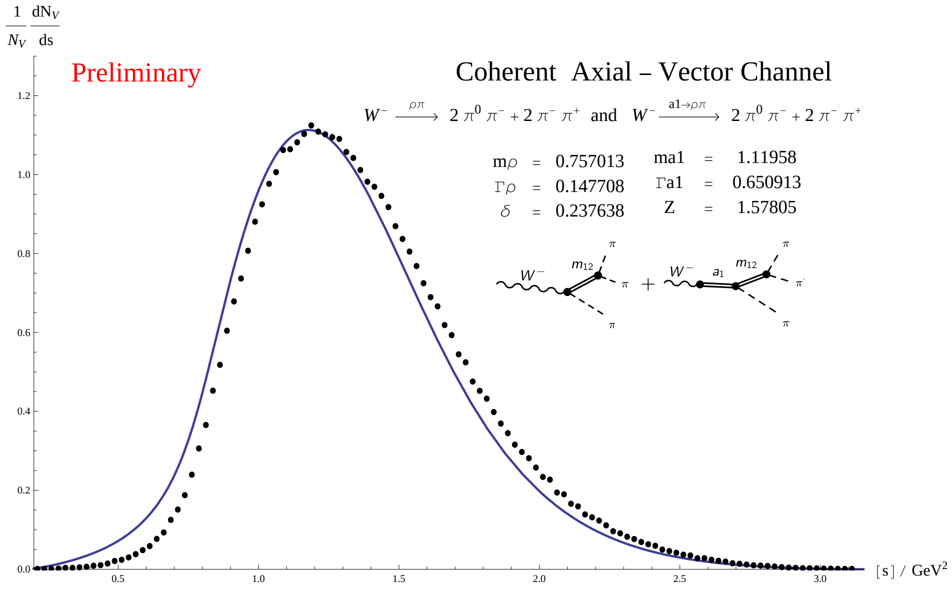
A. Habersetzer, F. Giacosa, DHR, in preparation

$$\partial^\mu \Phi \longrightarrow D^\mu \Phi \equiv \partial^\mu \Phi - i\, e\, A^\mu\, [T_3, \Phi] - i\, g \cos\theta_C\, (W_1^\mu T_1 + W_2^\mu T_2)\Phi$$
$$- i\, g \cos\theta_W\, (Z^\mu T_3 \Phi + \tan^2\theta_W\, \Phi T_3 Z^\mu)$$

$$\mathcal{L}_0^{\mu\nu} \longrightarrow \mathcal{L}^{\mu\nu} \equiv \partial^\mu \mathcal{L}^\nu - i\, e\, A^\mu [T_3, \mathcal{L}^\nu] - i\, g [W_1^\mu T_1 + W_2^\mu T_2, \mathcal{L}^\nu]$$
$$- \partial^\nu \mathcal{L}^\mu + i\, e\, A^\nu [T_3, \mathcal{L}^\mu] + i\, g [W_1^\nu T_1 + W_2^\nu T_2, \mathcal{L}^\mu] \quad \text{(similarly for } R_0^{\mu\nu}\text{)}$$

$$\mathcal{L}_M \longrightarrow \mathcal{L}_M + \frac{\delta}{2}\, g\, \cos\theta_C\, \mathrm{Tr}[W_{\mu\nu}\mathcal{L}^{\mu\nu}] + \frac{\bar{\delta}}{2}\, e\, \mathrm{Tr}[B_{\mu\nu}\mathcal{R}^{\mu\nu}] + \frac{1}{4}\, \mathrm{Tr}[(W^{\mu\nu})^2 + (B^{\mu\nu})^2]$$





cf. M. Urban, M. Buballa, J. Wambach, NPA 697 (2002) 338

Baryons and their chiral partners

Inclusion of baryons and their chiral partners:

⟹ **Mirror assignment:** C. DeTar and T. Kunihiro, PRD 39 (1989) 2805

$$\Psi_{1,r} \longrightarrow U_r\,\Psi_{1,r}\;,\quad \Psi_{1,\ell} \longrightarrow U_\ell\,\Psi_{1,\ell}\;,\quad \text{but: } \Psi_{2,r} \longrightarrow U_\ell\,\Psi_{2,r}\;,\quad \Psi_{2,\ell} \longrightarrow U_r\,\Psi_{2,\ell}$$

⟹ **new, chirally invariant mass term:**

$$\mathcal{L}_B = \bar{\Psi}_{1,\ell}\, i\partial\!\!\!/\, \Psi_{1,\ell} + \bar{\Psi}_{1,r}\, i\partial\!\!\!/\, \Psi_{1,r} + \bar{\Psi}_{2,\ell}\, i\partial\!\!\!/\, \Psi_{2,\ell} + \bar{\Psi}_{2,r}\, i\partial\!\!\!/\, \Psi_{2,r} + m_0 \left(\bar{\Psi}_{2,\ell}\,\Psi_{1,r} - \bar{\Psi}_{2,r}\,\Psi_{1,\ell} - \bar{\Psi}_{1,\ell}\,\Psi_{2,r} + \bar{\Psi}_{1,r}\,\Psi_{2,\ell} \right)$$

Note: chiral symmetry restoration:

chiral partners become degenerate, but not necessarily massless!

⟹ m_0 **models contribution from gluon condensate to baryon mass**

⟹ **allows for stable nuclear matter ground state! (see below)**

Vector – baryon interactions

$$\mathcal{L}_{VB} = c_1 \left(\bar{\Psi}_{1,\ell} \not{\mathcal{L}} \Psi_{1,\ell} + \bar{\Psi}_{1,r} \not{\mathcal{R}} \Psi_{1,r} \right) + c_2 \left(\bar{\Psi}_{2,\ell} \not{\mathcal{R}} \Psi_{2,\ell} + \bar{\Psi}_{2,r} \not{\mathcal{L}} \Psi_{2,r} \right)$$

Note: in general $c_1 \neq c_2$

$\Longrightarrow$ **allows to fit axial coupling constants (see below)!**

Scalar – baryon interactions

Yukawa interaction:

$$\mathcal{L}_{SB} = -\hat{g}_1 \left(\bar{\Psi}_{1,\ell}\, \Phi\, \Psi_{1,r} + \bar{\Psi}_{1,r}\, \Phi^\dagger\, \Psi_{1,\ell} \right) - \hat{g}_2 \left(\bar{\Psi}_{2,r}\, \Phi\, \Psi_{2,\ell} + \bar{\Psi}_{2,\ell}\, \Phi^\dagger\, \Psi_{2,r} \right)$$

$N_f = 2$ mass eigenstates:

$$\begin{pmatrix} N \\ N^* \end{pmatrix} \equiv \begin{pmatrix} N^+ \\ N^- \end{pmatrix} = \frac{1}{\sqrt{2\cosh\delta}} \begin{pmatrix} e^{\delta/2} & \gamma_5\, e^{-\delta/2} \\ \gamma_5\, e^{-\delta/2} & -e^{\delta/2} \end{pmatrix} \begin{pmatrix} \Psi_1 \\ \Psi_2 \end{pmatrix}, \quad \sinh\delta = \frac{\phi}{4\, m_0} (\hat{g}_1 + \hat{g}_2)$$

$$m_\pm = \sqrt{m_0^2 + \frac{\phi^2}{16} (\hat{g}_1 + \hat{g}_2)^2} \pm \frac{\phi}{4} (\hat{g}_1 - \hat{g}_2) \quad \longrightarrow \quad m_0 \qquad (\phi \to 0)$$

axial coupling constant:

$$g_A = +\tanh\delta \left[1 - \frac{c_1 + c_2}{2\, g_1} \left(1 - \frac{1}{Z^2} \right) \right] - \frac{c_1 - c_2}{2\, g_1} \left(1 - \frac{1}{Z^2} \right)$$

$$g_A^* = -\tanh\delta \left[1 - \frac{c_1 + c_2}{2\, g_1} \left(1 - \frac{1}{Z^2} \right) \right] - \frac{c_1 - c_2}{2\, g_1} \left(1 - \frac{1}{Z^2} \right) \neq -g_A\,!$$

$\Longrightarrow$ for $c_1 \neq c_2$ compatible with $g_A \simeq 1.26\,,\; g_A^* \simeq 0\,!$

T.T. Takahashi, T. Kunihiro, PRD 78 (2008) 011503

T. Maurer, T. Burch, L.Ya. Glozman, C.B. Lang, D. Mohler, A. Schäfer, arXiv:1202.2834[hep-lat]

Vacuum phenomenology: The chiral partner of the nucleon (I)

Baryon sector ($N_f = 2$): S. Gallas, F. Giacosa, DHR, PRD 82 (2010) 014004

Determine m_0, c_1, c_2, $\hat{g}_1$, $\hat{g}_2$ through χ^2 fit to

$$M_N\,,\ M_{N^*}\,,\ g_A = 1.267 \pm 0.004\,,\ g_A^*\,,\ \Gamma(N^* \to N\pi)$$

(i) Scenario A: $N = N(940),\ N^* = N(1535)$

$\Longrightarrow$ $g_A^* = 0.2 \pm 0.3$ T.T. Takahashi, T. Kunihiro, PRD 78 (2008) 011503

$\Gamma(N^* \to N\pi) = (67.5 \pm 23.6)$ MeV

(ii) Scenario B: $N = N(940),\ N^* = N(1650)$

$\Longrightarrow$ $g_A^* = 0.55 \pm 0.2$ T.T. Takahashi, T. Kunihiro, PRD 78 (2008) 011503

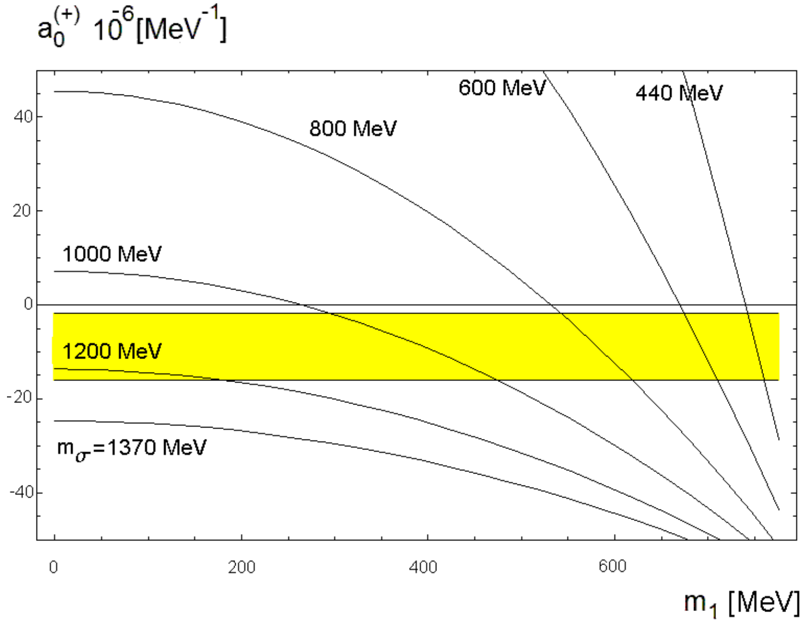
$\Gamma(N^* \to N\pi) = (128 \pm 44)$ MeV

Test validity of the two scenarios through comparison to:

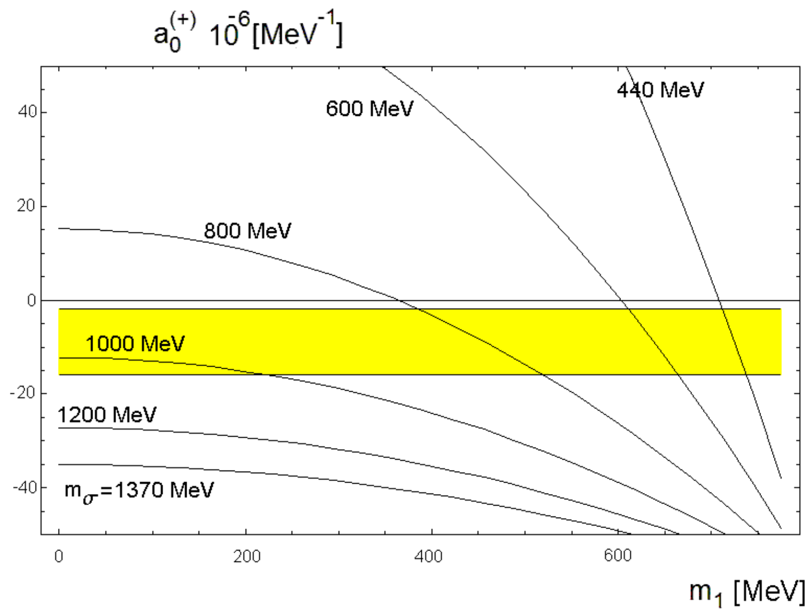
- πN scattering lengths
- decay width $\Gamma(N^* \to N\eta)$

Vacuum phenomenology: The chiral partner of the nucleon (II)

πN scattering lengths $a_0^{(\pm)}$:



m_{N^*} = 1535 MeV



m_{N^*} = 1655 MeV

$$a_0^{(-)} = (6.04 \pm 0.63) \cdot 10^{-4}\ \text{MeV}^{-1} \qquad\qquad a_0^{(-)} = (5.90 \pm 0.46) \cdot 10^{-4}\ \text{MeV}^{-1}$$

for comparison: $a_{0,\text{exp}}^{(-)} = (6.4 \pm 0.1) \cdot 10^{-4}\ \text{MeV}^{-1}$

However: $\Gamma(N^* \to N\eta) = (10.9 \pm 3.8)$ MeV $\qquad$ $\Gamma(N^* \to N\eta) = (18.3 \pm 8.5)$ MeV

$\Gamma_{\text{exp}}(N^* \to N\eta) = (78.7 \pm 24.3)$ MeV! $\qquad$ $\Gamma_{\text{exp}}(N^* \to N\eta) = (10.7 \pm 6.7)$ MeV

$\Longrightarrow$ **Scenario B seems to be favored!**

Vacuum phenomenology: The chiral partner of the nucleon (III)

⟹ But then: what is the chiral partner of $N(1535)$?

Remember L.Ya. Glozman, PRL 99 (2007) 191602:

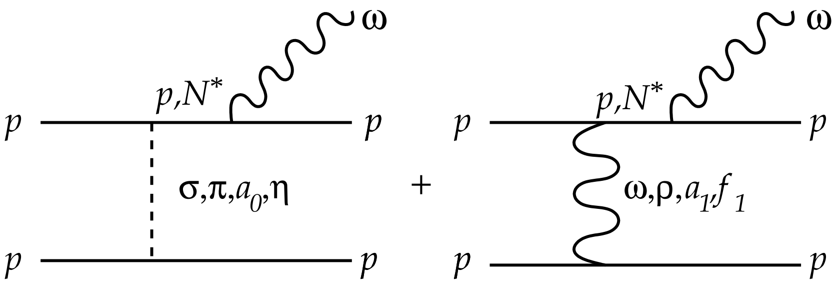
Heavy chiral partners are closer in mass than lighter ones

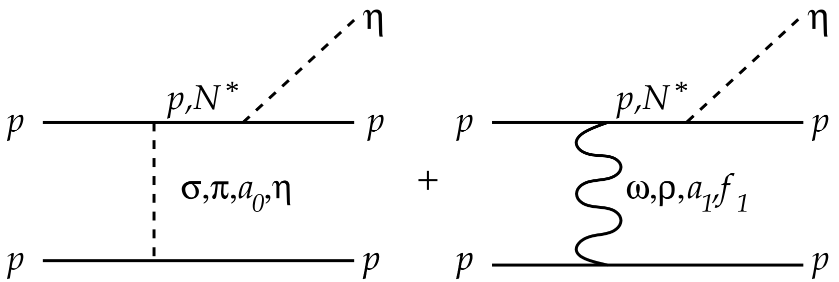
⟹ Signal of chiral symmetry restoration in the QCD mass spectrum

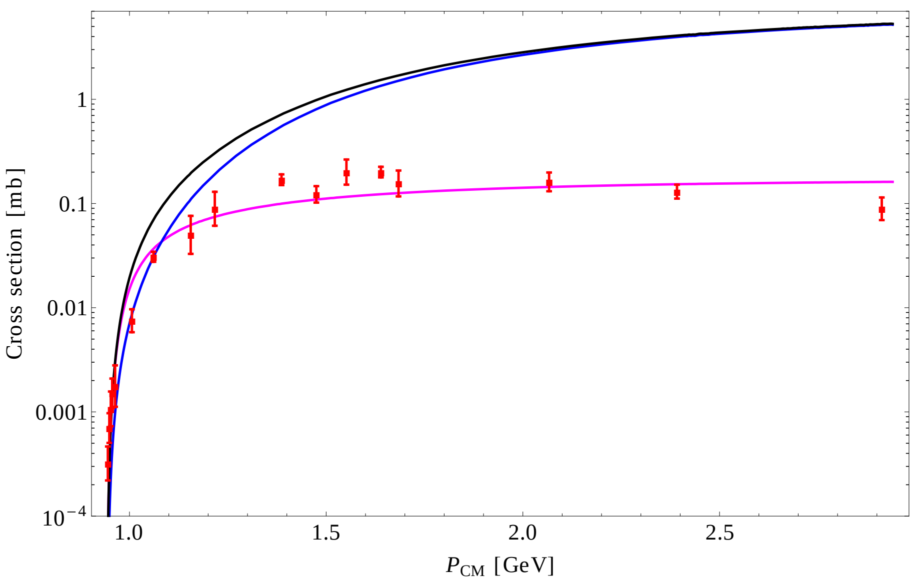
⟹ Could the partner of $N(1535)$ be $N(1440)$?

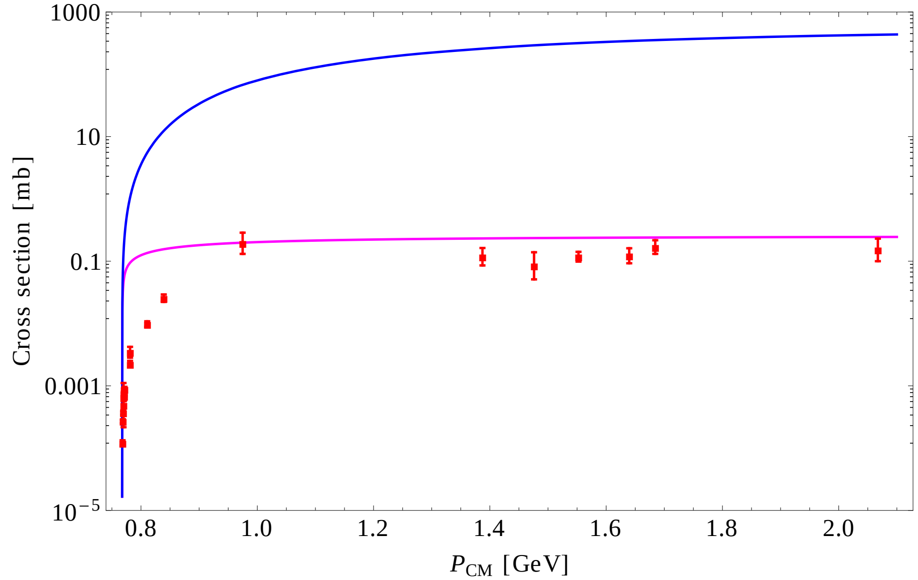
Exclusive hadro-production in pp

K. Teilab, F. Giacosa, D.H.R., in preparation **preliminary!**









Born: p only, **Born: incl. N*,** **K-matrix unitarized,**

data: SPES III, PINOT, COSY-TOF, COSY-11

Conclusions

I. Linear σ model with $U(N_f)_r \times U(N_f)_\ell$ symmetry with scalar, vector mesons, baryons and their chiral partners

II. Vacuum phenomenology:

1. Excellent fit of mesonic vacuum properties for $N_f = 3$
2. The scalar meson puzzle: evidence for tetraquark assignment for the light scalar mesons $f_0(600)$, $f_0(980)$, glueball is most likely (predominantly) $f_0(1500)$
3. The chiral partner of the nucleon: is it $N(1650)$ instead of $N(1535)$?

(III. Nonzero densities:

1. Nuclear matter ground state: correctly described by chiral effective model with mirror assignment for chiral partner of N)

Outlook: Further studies

1. Vacuum:
   (i) Extension to $N_f = 4$ W. Eshraim
   (ii) Full scalar mixing scenario including $q\bar{q}$, tetraquark, and glueball states
   S. Janowski
   cf. T. Mukherjee, M. Huang, Q.-S. Yan, PRD 86 (2012) 114022, arXiv:1209.1191[hep-ph]
   (iii) electroweak interactions, τ decay A. Habersetzer, F. Giacosa, DHR
   (iv) Δ resonance S. Gallas
   (v) NN scattering W. Deinet
   (vi) Exclusive hadron, dilepton production in elementary NN collisions
   K. Teilab
2. Nonzero T, μ:
   (i) $q\bar{q}$–tetraquark mixing
   A. Heinz, S. Strüber, F. Giacosa, DHR, PRD 79 (2009) 037502
   (ii) Inhomogeneous phases A. Heinz, M. Wagner
   (iii) Hadron properties, signals for chiral symmetry restoration

Nuclear matter saturation (I)

D. Zschiesche, L. Tolos, J. Schaffner-Bielich, R.D. Pisarski, PRC 75 (2007) 055202

studied cold nuclear matter within the mirror assignment

used effective potential in mean-field approximation:

$$\mathcal{V}_{\rm eff}(\sigma,\omega_0) = \sum_{i=\pm} \frac{d_i}{(2\pi)^3} \int_0^{k_{F,i}} \mathrm{d}^3\vec{k}\, \left[E_i^*(k) - \mu_i^*\right] + \frac{1}{2}\, m^2\, \sigma^2 + \frac{1}{4}\, \lambda\, \sigma^4 - h\sigma - \frac{1}{2}\, m_1^2\, \omega_0^2 - g_4\, \omega_0^4$$

d_i internal degrees of freedom of N, N^*

$k_{F,i} = \sqrt{\mu_i^{*\,2} - m_i^2}$ Fermi momentum

$E_i^*(k) = \sqrt{k^2 + m_i^2}$ single-particle energy

$\mu_i^* = \mu_i - g_\omega\, \omega_0$ effective chemical potential

$$m^2 = \frac{1}{2}\left(3m_\pi - m_\sigma^2\right)\,, \qquad \lambda = \frac{m_\sigma^2 - m_\pi^2}{2\sigma}\,, \qquad h = f_\pi\, m_\pi^2\,,$$

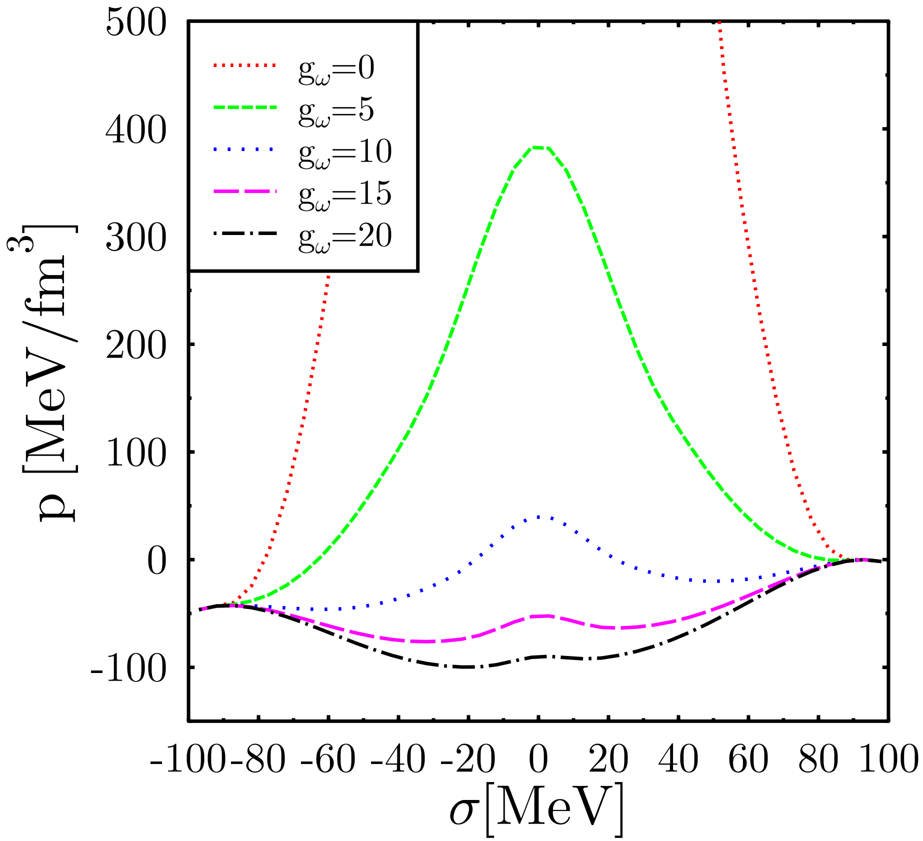
v.e.v.'s $\phi = \langle \sigma \rangle$, $\bar{\omega} = \langle \omega_0 \rangle$ determined by

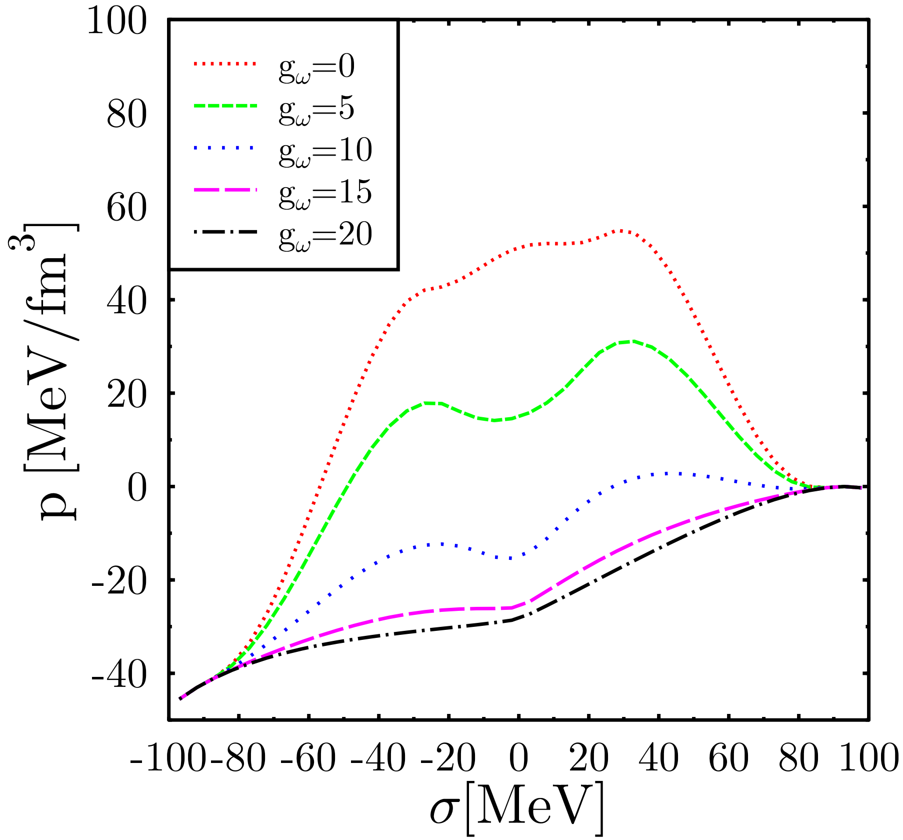
$$\left.\frac{\delta \mathcal{V}_{\rm eff}(\sigma,\omega_0)}{\delta\sigma}\right|_{\phi,\bar{\omega}} = \left.\frac{\delta \mathcal{V}_{\rm eff}(\sigma,\omega_0)}{\delta\omega_0}\right|_{\phi,\bar{\omega}} = 0$$

Nuclear matter saturation (II)

$m_0 = 0$: $\Longrightarrow$ $\nexists\, g_\omega$ for which nuclear matter saturates

$m_0 > 0$: $\Longrightarrow$ $\exists\, g_\omega$ for which nuclear matter saturates





$\Longrightarrow$ ground state is either vacuum or chirally restored phase

(both figs.: $\mu_B = 923$ MeV, $g_4 = 0$, $m_- = 1.5$ GeV
left: $m_\sigma = 1$ GeV, right: $m_\sigma = 400$ MeV)

Nuclear matter saturation (III)

$\exists$ nuclear matter ground state for:

m_- [GeV]	m_0 [MeV]	m_σ [MeV]	g_4	$m_+(n_0)/m_+$	$m_-(n_0)/m_-$	K [MeV]
1.5	790	370.63	0	0.84	0.73	510.57
1.5	790	346.59	3.8	0.83	0.72	440.51
1.2	790	318.56	0	0.86	0.79	436.41
1.2	790	302.01	3.8	0.86	0.78	374.75

$\Longrightarrow$ scalar meson too light, compressibility too large!

S. Gallas, F. Giacosa, G. Pagliara, NPA 872 (2011) 13

inclusion of tetraquark d.o.f. χ : m_0 dynamically generated, $m_0 = a\,\chi$

$\Longrightarrow$ $\mathcal{V}_{\text{eff}}(\sigma, \omega_0, \chi) = \mathcal{V}_{\text{eff}}(\sigma, \omega_0) - g\,\chi\,\sigma^2 + \frac{1}{2}\,m_\chi^2\,\chi^2$

v.e.v. $\bar{\chi} = \langle \chi \rangle$ determined by $\left.\dfrac{\delta \mathcal{V}_{\text{eff}}(\sigma, \omega_0, \chi)}{\delta \chi}\right|_{\phi,\bar{\omega},\bar{\chi}} = 0$

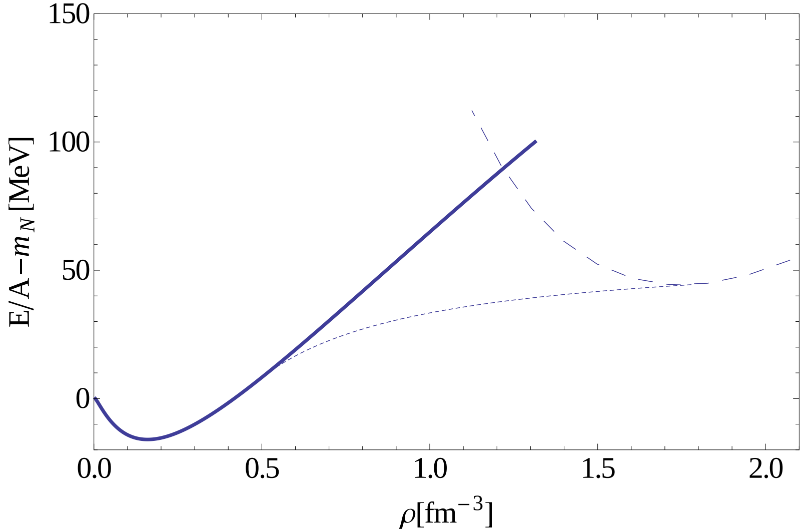
$\Longrightarrow$ nuclear matter ground state:

m_- [GeV]	m_0 [MeV]	m_σ [GeV]	g_4	m_χ [MeV]	K [MeV]
1.535	500	1.294	0	612	194

Note: fit to vacuum properties requires $m_0 = 460 \pm 130$ MeV

Nuclear matter at large densities

⟹ **1st order phase transition to chirally restored phase:**



S. Gallas, F. Giacosa, G. Pagliara, NPA 872 (2011) 13