

Phenomenology of Charmed mesons in a Chiral Symmetric Model

Walaa I. Eshraim

in collaboration with

Francesco Giacosa and Dirk H. Rischke

- Quantum Chromodynamics: QCD
- Symmetries of the QCD Lagrangian.
if all quark massless then we have chiral $U(4)_r \times U(4)_l$ symmetry

$$U(N_f)_r \times U(N_f)_l = SU(N_f)_r \times SU(N_f)_l \times U(1)_V \times U(1)_A$$

- Spontaneous breaking of chiral symmetry by quark condensates
- Explicit breaking of a global chiral symmetry by quark masses and chiral anomaly
- Effective chiral models of QCD.
- Charm quark???

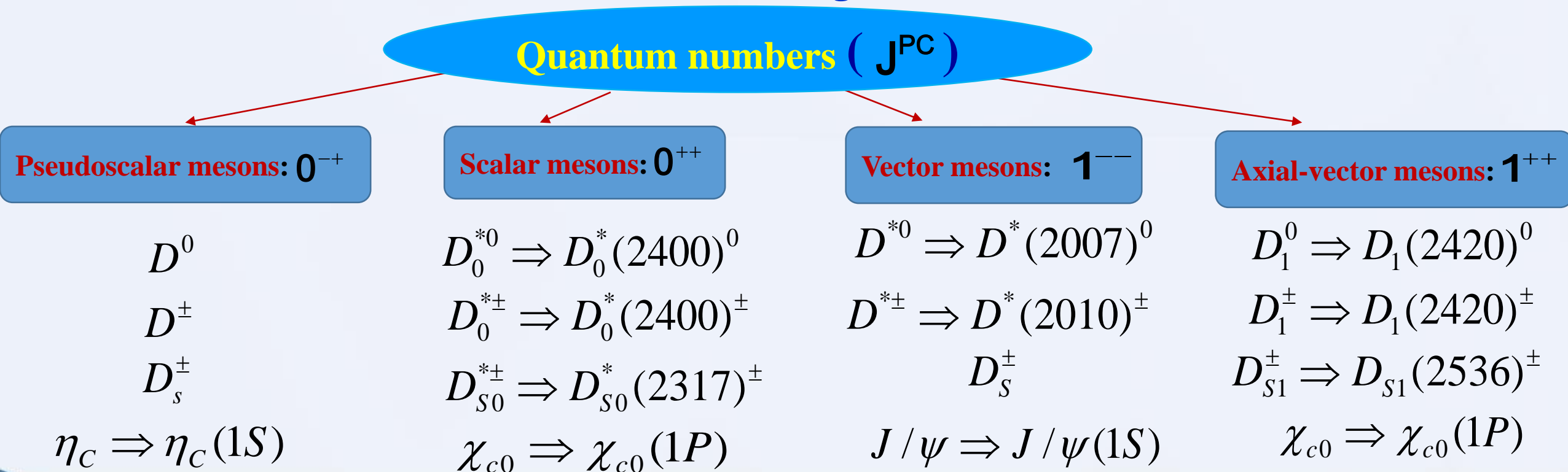
- Linear sigma model with vector and axial vector degrees of freedom.
- Inclusion of the charmed mesons into the linear sigma model (extended Linear Sigma Model - eLSM).
- Extension from low-energy to high-energy mesons.
- Study of the model for $T = \mu = 0$ (spectroscopy in vacuum).

Fields in the model

- Mesons: quark-antiquark states ($q \bar{q}$)

$$4N_f^2 + 2 \text{ fields}$$

- For $N_f = 4$ there are 66 mesons: 64 quark-antiquark fields + one pseudoscalar glueball \tilde{G} + one scalar glueball G



Including charm degree of freedom

1) Pseudoscalar fields:

$$P = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{1}{\sqrt{2}}(\eta_N + \pi^0) & \pi^+ & K^+ & D^0 \\ \pi^- & \frac{1}{\sqrt{2}}(\eta_N - \pi^0) & K^0 & D^- \\ K^- & \bar{K}^0 & \eta_S & D_S^- \\ \bar{D}^0 & D^+ & D_S^+ & \eta_c \end{pmatrix}$$

$$\eta = \eta_N \cos \phi + \eta_S \sin \phi \quad \text{and} \quad \eta' = -\eta_N \sin \phi + \eta_S \cos \phi$$

with mixing angle $\phi = -44.6^\circ$

[W. I. Eshraim; S. Janowski; F. Giacosa; D. H. Rischke. Phys.Rev. D87 (2013) 054036
[arXiv: 1208.6474 [hep-ph]].

2) Scalar fields:

$$S = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{1}{\sqrt{2}}(\sigma_N + a_0^0) & a_0^+ & K_0^{*+} & D_0^{*0} \\ a_0^- & \frac{1}{\sqrt{2}}(\sigma_N - a_0^0) & K_0^{*0} & D_0^{*-} \\ K_0^{*-} & \bar{K}_0^{*0} & \sigma_S & D_{S0}^{*-} \\ \bar{D}_0^{*0} & D_0^{*+} & D_{S0}^{*+} & \chi_{c0} \end{pmatrix}$$

$\bar{n}n \propto \bar{u}u + \bar{d}d$

$\bar{s}s$

$\bar{c}c$

The multiplet of the scalar and pseudoscalar quark-antiquark states: $\Phi = S + iP$

3) Vector fields:

$$V^\mu = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{1}{\sqrt{2}}(\omega_N + \rho^0) & \rho^+ & K^*(892)^+ & D^{*0} \\ \rho^- & \frac{1}{\sqrt{2}}(\omega_N - \rho^0) & K^*(892)^0 & D^{*-} \\ K^*(892)^- & \bar{K}^*(892)^0 & \omega_S & D_S^{*-} \\ \bar{D}^{*0} & D^{*+} & D_S^{*+} & J/\psi \end{pmatrix}^\mu$$

4) Axial vector fields:

$$A^\mu = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{1}{\sqrt{2}}(f_{1,N} + a_1^0) & a_1^+ & K_1^+ & D_1^0 \\ a_1^- & \frac{1}{\sqrt{2}}(f_{1,N} - a_1^0) & K_1^0 & D_1^- \\ K_1^- & \bar{K}_1^0 & f_{1,S} & D_{S1}^- \\ \bar{D}_1^0 & D_1^+ & D_{S1}^+ & \chi_{c,1} \end{pmatrix}^\mu$$

The left-handed matrix: $L^\mu = V^\mu + A^\mu$ and the right-handed matrix: $L^\mu = V^\mu - A^\mu$

W. I. Eshraim, PoS QCD -TNT-III (2014) 049 [arXiv:1401.3260 [hep-ph]]; W. I. Eshraim; F Giacosa; and D. H. Rischke; [arXiv:1405.5861 [hep-ph]]

Linear Sigma Model Lagrangian with (axial-)vector mesons

$$\begin{aligned}
 \mathcal{L} = & \mathcal{L}_{dil} + \text{Tr}[(D^\mu \Phi)^\dagger (D^\mu \Phi)] - m_0^2 \left(\frac{G}{G_0} \right)^2 \text{Tr}(\Phi^\dagger \Phi) - \lambda_1 [\text{Tr}(\Phi^\dagger \Phi)]^2 - \lambda_2 \text{Tr}(\Phi^\dagger \Phi)^2 \\
 & + \text{Tr} \left\{ \left[\left(\frac{G}{G_0} \right)^2 \frac{m_1^2}{2} + \Delta \right] [(L^\mu)^2 + (R^\mu)^2] \right\} + \text{Tr}[H(\Phi + \Phi^\dagger)] - 2 \text{Tr}[\varepsilon \Phi^\dagger \Phi] \\
 & - \frac{1}{4} \text{Tr}[(L^{\mu\nu})^2 + (R^{\mu\nu})^2] + c(\det \Phi - \det \Phi^\dagger)^2 + i\tilde{c} \tilde{G} (\det \Phi - \det \Phi^\dagger) + i\frac{g_2}{2} \{ \text{Tr}(L_{\mu\nu} [L^\mu, L^\nu]) \\
 & + \frac{h_1}{2} \text{Tr}(\Phi^\dagger \Phi) \text{Tr}[(L^\mu)^2 + (R^\mu)^2] + h_2 \text{Tr}[(\Phi R^\mu)^2 + (L^\mu \Phi)^2] + 2h_3 \text{Tr}(\Phi R_\mu \Phi^\dagger L^\mu) + \text{Tr}(R_{\mu\nu} [R^\mu, R^\nu]) \} + \dots,
 \end{aligned}$$

where \mathcal{L}_{dil} is the dilaton Lagrangian,

$$\mathcal{L}_{dil} = \frac{1}{2} (\partial_\mu G)^2 - \frac{1}{4} \frac{m_G^2}{\Lambda^2} \left(G^4 \ln \frac{G^2}{\Lambda^2} - \frac{G^4}{4} \right)$$

D.Parganlija, P.Kovacs, G.Wolf, F.Giacosa, and D.H. Rischke, Phys. Rev. D 87 (2013) 014011 [arXiv:1208.0585 [hep-ph]];

W. I. Eshraim, PoS QCD -TNT-III (2014) 049 [arXiv:1401.3260 [hep-ph]].

W. I. Eshraim

Spontaneous Symmetry Breaking (SSB)

Shifting the fields

$$G \rightarrow G + G_0, \quad \sigma_N \rightarrow \sigma_N + \phi_N, \quad \sigma_S \rightarrow \sigma_S + \phi_S$$

where,

$$\phi_N = Z_\pi f_\pi$$

$$\phi_S = \frac{2Z_k f_k - \phi_N}{\sqrt{2}}$$

D. Parganlija, P. Kovacs, G. Wolf, F. Giacosa, and D. H. Rischke, Phys. Rev. D 87 (2013) 014011 [arXiv:1208.0585 [hep-ph]].

For $N_f = 4$ new shift

$$\chi_{C0} \rightarrow \chi_{C0} + \phi_C$$

where

$$\phi_C = \frac{2Z_D f_D - \phi_N}{\sqrt{2}} = \sqrt{2}Z_{D_s} f_{D_s} - \phi_S = \frac{Z_{\eta_C} f_{\eta_C}}{\sqrt{2}}$$

W. I. Eshraim, PoS QCD -TNT-III (2014) 049 [arXiv:1401.3260 [hep-ph]]; W. I. Eshraim, F. Giacosa, and D. H. Rischke, , arXiv:1405.5861 [hep-ph]].

There are 29 eqs. of square masses of mesons with 15 unknown parameters.

Parameters

The values of the $N_f = 3$ parameters :

Parameter	Value	Parameter	Value
m_1^2	$0.413 \times 10^6 \text{ MeV}^2$	m_0^2	$-0.918 \times 10^6 \text{ MeV}^2$
$\phi_C^2 c/2$	$450 \cdot 10^{-6} \text{ MeV}^{-2}$	δ_S	$0.151 \times 10^6 \text{ MeV}^2$
g_1	5.84	h_1	0
h_2	9.88	h_3	3.87
ϕ_N	164.6 MeV	ϕ_S	126.2 MeV
λ_1	0	λ_2	68.3

[D. Parganlija, P. Kovacs, G. Wolf, F. Giacosa and D. H. Rischke, Phys. Rev. D 87 (2013) 014011 [arXiv:1208.0585 [hep-ph]].

→ $\chi^2/d.o.f = 1.23$

The new three parameters for $N_f = 4$ are $\phi_C, \delta_C, \varepsilon_C$.

By fit with $\chi^2/d.o.f = 1$:

$$\phi_C = (176 \pm 28) \text{ MeV}, \quad \delta_C = (3.91 \pm 0.36) \times 10^6 \text{ MeV}^2, \quad \varepsilon_C = (2.23 \pm 0.71) \times 10^6 \text{ MeV}^2 .$$

[W. I. Eshraim, F. Giacosa, and D. H. Rischke, , arXiv:1405.5861 [hep-ph]].

Results

Masses of light mesons:

Observable	our Value [MeV]	Experimental Value [MeV]
$m_{f_{1N}}$	1186	1281.8 ± 0.6
m_{a_1}	1185	1230 ± 40
$m_{f_{1S}}$	1372	1426.4 ± 0.9
m_{K^*}	885	891.66 ± 0.26
m_{K_1}	1281	1272 ± 7
m_{σ_1}	1362	$(1200-1500)-i(150-250)$
m_{a_0}	1363	1474 ± 19
m_{σ_2}	1531	1720 ± 60
m_{w_N}	783	782.65 ± 0.12
m_{w_S}	975	1019.46 ± 0.020
m_ρ	783	775.5 ± 38.8
m_η	509	547.853 ± 0.024
m_π	141	139.57018 ± 0.00035
$m_{\eta'}$	962	957.78 ± 0.06
$m_{K_0^*}$	1449	1425 ± 50
m_K	485	493.677 ± 0.016

D. Parganlija, P. Kovacs, G. Wolf, F. Giacosa and D. H. Rischke, Phys. Rev. D 87 (2013) 014011 [arXiv:1208.0585 [hep-ph];
W. I. Eshraim, PoS QCD -TNT-III (2014) 049 [arXiv:1401.3260 [hep-ph].

Masses of (open and hidden) charmed mesons:

Resonance	Quark content	J^P	Our Value [MeV]	Experimental Value [MeV]
D^0	$u\bar{c}, \bar{u}c$	0^-	1981 ± 73	1864.86 ± 0.13
D_S^\pm	$s\bar{c}, \bar{s}c$	0^-	2004 ± 74	1968.50 ± 0.32
$\eta_c(1S)$	$c\bar{c}$	0^-	2673 ± 118	2983.7 ± 0.7
$D_0^*(2400)^0$	$u\bar{c}, \bar{u}c$	0^+	2414 ± 77	2318 ± 29
$D_{S0}^*(2317)^\pm$	$s\bar{c}, \bar{s}c$	0^+	2467 ± 76	2317.8 ± 0.6
$\chi_{c0}(1P)$	$c\bar{c}$	0^+	3144 ± 128	3414.75 ± 0.31
$D^*(2007)^0$	$u\bar{c}, \bar{u}c$	1^-	2168 ± 70	2006.99 ± 0.15
D_s^*	$s\bar{c}, \bar{s}c$	1^-	2203 ± 69	2112.3 ± 0.5
$J/\psi(1S)$	$c\bar{c}$	1^-	2947 ± 109	3096.916 ± 0.011
$D_1(2420)^0$	$u\bar{c}, \bar{u}c$	1^+	2429 ± 63	2421.4 ± 0.6
$D_{S1}(2536)^\pm$	$s\bar{c}, \bar{s}c$	1^+	2480 ± 63	2535.12 ± 0.13
$\chi_{c1}(1P)$	$c\bar{c}$	1^+	3239 ± 101	3510.66 ± 0.07

W. I. Eshraim, F. Giacosa, and D. H. Rischke, [arXiv:1405.5861 [hep-ph]];

W. I. Eshraim, PoS QCD -TNT-III (2014) 049 [arXiv:1401.3260 [hep-ph]];

Mass difference and decay constants

The mass difference of the squared charmed (axial-)vector mesons:

mass difference	theoretical value MeV^2	experimental value MeV^2
$m_{D_1}^2 - m_{D^*}^2$	$(1.2 \pm 0.6) \times 10^6$	1.82×10^6
$m_{\chi_{C1}}^2 - m_{J/\psi}^2$	$(1.8 \pm 1.3) \times 10^6$	2.73×10^6
$m_{D_{S1}}^2 - m_{D_S^*}^2$	$(1.2 \pm 0.6) \times 10^6$	1.97×10^6

Weak decay constant of D , D_s , and f_{η_C} .

$$f_D = (254 \pm 17) \text{ MeV} , f_{D_S} = (261 \pm 17) \text{ MeV} , f_{\eta_C} = (222 \pm 28) \text{ MeV}$$



$$[\text{Exp. value} = 206.7 \pm 8.9] \text{ MeV}, [\text{Exp. value} = 260.5 \pm 5.4] \text{ MeV}, [\text{Exp. value} = 335 \pm 75] \text{ MeV}$$

W. I. Eshraim, F. Giacosa, and D. H. Rischke, arXiv:1405.5861 [hep-ph].

Decay widths of open charmed mesons:

Decay Channel	Theoretical result [MeV]	Experimental result [MeV]
$D_0^*(2400)^0 \rightarrow D\pi = D^+\pi^- + D^0\pi^0$	139^{+243}_{-114}	$D^+\pi^-$ seen; full width $\Gamma = 267 \pm 40$
$D_0^*(2400)^+ \rightarrow D\pi = D^+\pi^0 + D^0\pi^+$	51^{+182}_{-51}	$D^+\pi^0$ seen; full width: $\Gamma = 283 \pm 24 \pm 34$
$D^*(2007)^0 \rightarrow D^0\pi^0$	0.025 ± 0.003	seen; < 1.3
$D^*(2007)^0 \rightarrow D^+\pi^-$	0	not seen
$D^*(2010)^+ \rightarrow D^+\pi^0$	$0.018^{+0.002}_{-0.003}$	0.029 ± 0.008
$D^*(2010)^+ \rightarrow D^0\pi^+$	$0.038^{+0.005}_{-0.004}$	0.065 ± 0.017
$D_1(2420)^0 \rightarrow D^*\pi = D^{*+}\pi^- + D^{*0}\pi^0$	65^{+51}_{-37}	$D^{*+}\pi^-$ seen; full width: $\Gamma = 27.4 \pm 2.5$
$D_1(2420)^0 \rightarrow D^0\pi\pi = D^0\pi^+\pi^- + D^0\pi^0\pi^0$	0.59 ± 0.02	seen
$D_1(2420)^0 \rightarrow D^+\pi^-\pi^0$	$0.21^{+0.01}_{-0.015}$	seen
$D_1(2420)^0 \rightarrow D^+\pi^-$	0	not seen; $\Gamma(D^+\pi^-)/\Gamma(D^{*+}\pi^-) < 0.24$
$D_1(2420)^+ \rightarrow D^*\pi = D^{*+}\pi^0 + D^{*0}\pi^+$	65^{+51}_{-36}	$D^{*0}\pi^+$ seen; full width: $\Gamma = 25 \pm 6$
$D_1(2420)^+ \rightarrow D^+\pi\pi = D^+\pi^+\pi^- + D^+\pi^0\pi^0$	0.56 ± 0.02	seen
$D_1(2420)^+ \rightarrow D^0\pi^0\pi^+$	0.22 ± 0.01	seen
$D_1(2420)^+ \rightarrow D^0\pi^+$	0	not seen; $\Gamma(D^0\pi^+)/\Gamma(D^{*0}\pi^+) < 0.18$
$D_{S1}(2536)^+ \rightarrow D^*K = D^{*0}K^+ + D^{*+}K^0$	25^{+22}_{-15}	seen; full width $\Gamma = 0.92 \pm 0.03 \pm 0.04$
$D_{S1}(2536)^+ \rightarrow D^+K^0$	0	not seen
$D_{S1}(2536)^+ \rightarrow +D^0K^+$	0	not seen

W. I. Eshraim, F. Giacosa, and D. H. Rischke, arXiv:1405.5861 [hep-ph].

W. I. Eshraim

Mixing matrix of the three scalar fields (σ_N , σ_S , G)

$$\begin{pmatrix} f_0(1370) \\ f_0(1500) \\ f_0(1710) \end{pmatrix} = \begin{pmatrix} 0.94 & -0.17 & 0.29 \\ 0.21 & 0.97 & -0.12 \\ -0.26 & 0.18 & 0.95 \end{pmatrix} \begin{pmatrix} \sigma_N \equiv (\bar{u}u + \bar{d}d)/\sqrt{2} \\ \sigma_S \equiv \bar{s}s \\ G \equiv gg \end{pmatrix}$$

where G is a scalar glueball.

S. Janowski, F. Giacosa, and D. H. Rischke, in preparation.

- The decay widths of charmonium state depend on the parameters λ_I and h_I .

Using fit including the decay widths of charmonium state χ_{C0} , we obtain

$$\lambda_I = -0.16 \quad \text{and} \quad h_I = 0.046 \quad \text{by fit with } \chi^2/d.o.f = 0.7$$

W. I. Eshraim, F. Giacosa, and D. H. Rischke, in preparation, preliminary!

Decay widths of hidden charmed mesons:

1) Decay widths of (axial-)vector charmonium states:

$$\Gamma_{J/\psi} = 0 \quad \text{and} \quad \Gamma_{\chi_{c1}} = 0$$

2) Decay widths of scalar charmonium state (η_c):

W. I. Eshraim, F. Giacosa, and D. H. Rischke,
in preparation preliminary!

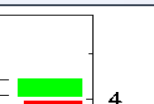
Decay Channel	theoretical result [MeV]	Experimental result [MeV]
$\Gamma_{\eta_c \rightarrow \bar{K}_0^* K}$	0.01	-
$\Gamma_{\eta_c \rightarrow a_0 \pi}$	0.01	-
$\Gamma_{\eta_c \rightarrow f_0(1370) \eta}$	0.00018	-
$\Gamma_{\eta_c \rightarrow f_0(1500) \eta}$	0.006	-
$\Gamma_{\eta_c \rightarrow f_0(1710) \eta}$	0.000032	-
$\Gamma_{\eta_c \rightarrow f_0(1370) \eta'}$	0.027	-
$\Gamma_{\eta_c \rightarrow f_0(1500) \eta'}$	0.024	-
$\Gamma_{\eta_c \rightarrow f_0(1710) \eta'}$	0.0006	-
$\Gamma_{\eta_c \rightarrow \eta \eta \eta}$	0.052	-
$\Gamma_{\eta_c \rightarrow \eta' \eta' \eta'}$	0.0023	-
$\Gamma_{\eta_c \rightarrow \eta' \eta \eta}$	0.44	-
$\Gamma_{\eta_c \rightarrow \eta' \eta' \eta}$	0.0034	-
$\Gamma_{\eta_c \rightarrow \eta K \bar{K}}$	0.15	0.32 ± 0.17
$\Gamma_{\eta_c \rightarrow \eta' K K}$	0.41	-
$\Gamma_{\eta_c \rightarrow \eta \pi \pi}$	0.12	0.54 ± 0.18
$\Gamma_{\eta_c \rightarrow \eta' \pi \pi}$	0.08	1.3 ± 0.6
$\Gamma_{\eta_c \rightarrow K K \pi}$	0.095	-

BESIII: $m_{\tilde{G}} = 2370 \text{ MeV}$

$\Gamma_{\eta_C \rightarrow \tilde{G} \pi \pi} =$

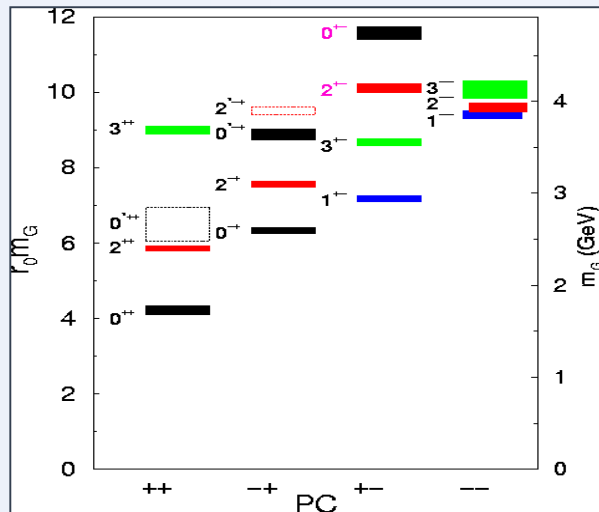
- $= 0.16 \text{ MeV}$
- $= 0.124 \text{ MeV}$

Calculations:



$$m_{\tilde{G}} = 2600 \text{ MeV}$$

W. I. Eshraim, F. Giacosa, and D. H. Rischke, in preparation preliminary!



Decay width of χ_{c0}

3) Decay widths of pseudoscalar charmonium state (χ_{c0}):

Decay Channel	theoretical result [MeV]	Experimental result [MeV]
$\Gamma_{\chi_{c0} \rightarrow a_0 a_0}$	0.004	-
$\Gamma_{\chi_{c0} \rightarrow k_1 \bar{K}_1}$	0.005	-
$\Gamma_{\chi_{c0} \rightarrow \eta \eta}$	0.022	0.031 ± 0.0039
$\Gamma_{\chi_{c0} \rightarrow \eta' \eta'}$	0.02	0.02 ± 0.0035
$\Gamma_{\chi_{c0} \rightarrow \eta \eta'}$	0.004	< 0.0024
$\Gamma_{\chi_{c0} \rightarrow K^* K_0^*}$	0.00007	-
$\Gamma_{\chi_{c0} \rightarrow \rho \rho}$	0.01	-
$\Gamma_{\chi_{c0} \rightarrow f_0(1370) f_0(1370)}$	0.005	< 0.003
$\Gamma_{\chi_{c0} \rightarrow f_0(1500) f_0(1500)}$	0.004	< 0.0005
$\Gamma_{\chi_{c0} \rightarrow f_0(1370) f_0(1500)}$	0.000004	< 0.001
$\Gamma_{\chi_{c0} \rightarrow f_0(1370) f_0(1710)}$	0.0003	0.0069 ± 0.004
$\Gamma_{\chi_{c0} \rightarrow f_0(1500) f_0(1710)}$	0.00004	< 0.0007
$\Gamma_{\chi_{c0} \rightarrow K_0^* K \eta}$	0.008	-
$\Gamma_{\chi_{c0} \rightarrow K_0^* K \eta'}$	0.004	-
$\Gamma_{\chi_{c0} \rightarrow f_0(1370) \eta \eta}$	0.0004	-
$\Gamma_{\chi_{c0} \rightarrow f_0(1500) \eta \eta}$	0.003	-
$\Gamma_{\chi_{c0} \rightarrow f_0(1370) \eta' \eta'}$	0.0027	-
$\Gamma_{\chi_{c0} \rightarrow f_0(1370) \eta \eta'}$	0.000089	-
$\Gamma_{\chi_{c0} \rightarrow f_0(1500) \eta \eta'}$	0.011	-
$\Gamma_{\chi_{c0} \rightarrow f_0(1710) \eta \eta}$	0.00008	-
$\Gamma_{\chi_{c0} \rightarrow f_0(1710) \eta \eta'}$	0.00003	-

Decay Channel	theoretical result [MeV]	Experimental result [MeV]
$\Gamma_{\chi_{c0} \rightarrow \bar{K}_0^{*0} K_0^{*0}}$	0.01	0.01 ± 0.0047
$\Gamma_{\chi_{c0} \rightarrow K^- K^+}$	0.059	0.061 ± 0.007
$\Gamma_{\chi_{c0} \rightarrow \pi \pi}$	0.089	0.088 ± 0.0092
$\Gamma_{\chi_{c0} \rightarrow \bar{K}^{*0} K^{*0}}$	0.0175	0.017 ± 0.0072
$\Gamma_{\chi_{c0} \rightarrow w w}$	0.01	0.0099 ± 0.0017
$\Gamma_{\chi_{c0} \rightarrow \phi \phi}$	0.004	0.0081 ± 0.0013
$\Gamma_{\chi_{c0} \rightarrow k_1^+ K^-}$	0.005	0.063 ± 0.0233

W. I. Eshraim, F. Giacosa, and D. H. Rischke, in preparation, preliminary!



Conclusions and Outlook

1. Linear sigma model with $N_f = 4$ and vector and axial-vector mesons.
 2. Masses of (open and hidden) charmed mesons.
 3. Charm-anticharm condensate and decay constants.
 4. Decay widths of (open and hidden) charmed mesons.
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- I. Light tetraquark nonet and its extension to $N_f = 4$ (on going).
 - II. Mixing of axial- and pseudo-vectors charmed mesons.
 - III. Inclusion of isospin breaking.
 - IV. Extension to non-zero temperature and density.