The status of the scalar channel in chiral dynamics

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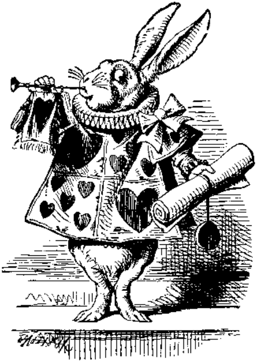
or

A chiralist's adventures in Scalarland



Contents

Scalars : simple, elusive . . .

Conceptually, scalars are very simple objects

- Simplest under space-time transformations
- Quantum numbers of the vacuum

But the light scalars do not seem to behave very nicely

- No scalar source provided by nature ($\neq$ vector, axial)
- Mixture of broad and narrow resonances, $\sigma(\sim 600)$, $f_0(980)\ldots$
- Hard to "interpret" : $q\bar{q}, q\bar{q}q\bar{q}, K\bar{K}$ molecule, glueballs. . .

. . . and hard to put together again

Scalar "multiplet" completely baffling

$$I = 0 \quad : \quad \sigma(\sim 600), f_0(980), f_0(1370), f_0(1500)\ldots$$

$$I = 1 \quad : \quad a_0(980), a_0(1450)\ldots \qquad I = 1/2 : \kappa(\sim 800), K_0^*(1430)\ldots$$

Mass splittings ? Gell-Mann-Okubo formula ? Ideal mixing ?

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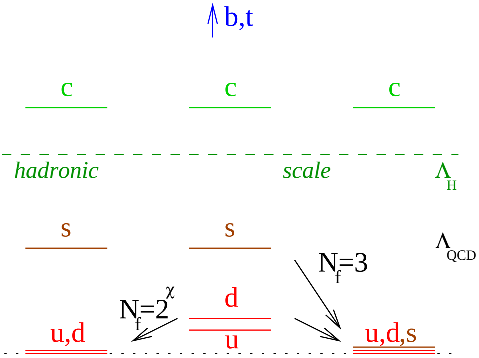
Mass splittings ? Gell-Mann-Okubo formula ? Ideal mixing ?

Humpty Dumpty sat on a wall
Humpty Dumpty had a great fall
All the king's horses and all the king's men
Couldn't put Humpty together again

Scalar channel has the quantum numbers of the vacuum

Nonperturbative properties of QCD vacuum
related to all this scalar nonsense ?

Three chiral limits of interest



$m_u, m_d \longrightarrow 0$

$N_f = 3$	:	$m_s \longrightarrow 0$
$N_f = 2^\chi$	:	m_s physical
$N_f = 2^{\mathrm{lat}}$	:	no dynamical s

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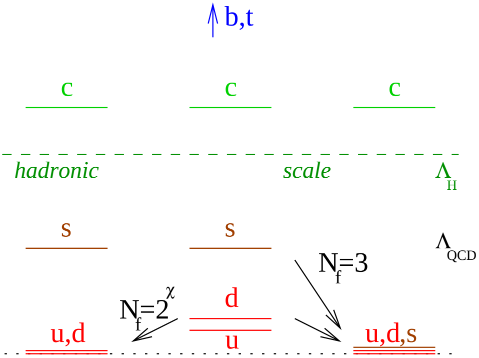

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Two versions of χPT	$N_f = 2^\chi$:	π only d.o.f	(few param. & processes)
	$N_f = 3$:	π, K, η d.o.f	(more param. & processes)

From 2 to 3 massless flavours

$$\Sigma(2; m_s) = \lim_{m_u, m_d \to 0} -\langle 0|\bar{u}u|0\rangle$$

$$\begin{cases} \Sigma(3) & = & \Sigma(2; 0) \\ \Sigma(2^{\chi}) & = & \Sigma(2; m_s^{\rm phys}) \\ \Sigma(2^{\rm lat}) & = & \Sigma(2; \infty) \end{cases}$$

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$$\Sigma(2; m_s) = \Sigma(2; 0) + m_s \frac{\partial \Sigma(2; m_s)}{\partial m_s} + O(m_s^2)$$

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$$\Sigma(2^\chi) = \Sigma(3) + m_s^{\mathrm{phys}} \lim_{m_u, m_d \to 0} i \int d^4x \, \langle 0|\bar{u}u(x)\, \bar{s}s(0)|0\rangle + O(m_s^2)$$

From 2 to 3 massless flavours

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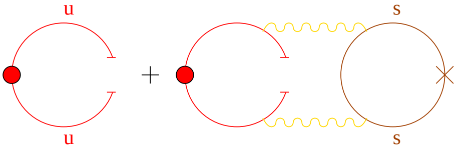
$\Sigma(2^\chi)$ contains

- A "genuine" condensate $\Sigma(3)$
- An "induced" condensate $m_s \times$ (scalar N_c-suppressed) *[effect from sea $s\bar{s}$-pairs]*



$\Sigma(2^\chi)$

In the isospin limit $m = m_u = m_d$

$$\begin{aligned} SU(2^\chi) : F_\pi^2 M_\pi^2 &= 2m\Sigma(2^\chi) + O(m^2) \\ SU(3) : F_\pi^2 M_\pi^2 &= 2m\Sigma(3) + O(m_s^2, mm_s, m^2) \end{aligned}$$

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\end{aligned}
$$

$\pi\pi$ scattering data from K_{e4}^+ decay — E865 Brookhaven (2001)

$+$ analyticity, unitarity, crossing — B.Ananthanarayan et al.

$$\frac{2m\Sigma(2^\chi)}{F_\pi^2 M_\pi^2} = 0.81 \pm 0.08$$ SDG et al.

...even larger — G.Colangelo et al.

$\Longrightarrow N_f = 2^\chi$ χPT framework experimentally confirmed

$\Sigma(2^\chi) - \Sigma(3)$

$$\Sigma(2^\chi) - \Sigma(3) \propto \Pi(0) \qquad \Pi(k^2) = \lim_{m_{u,d}\to 0} \int d^4x\, e^{-ik\cdot x} \langle \bar{u}u(x)\; \bar{s}s(0)\rangle_c$$

$\Pi(0)$ from superconvergent sum rule

B. Moussallam

$$\mathrm{Im}\,\Pi(s) \propto \sum_\sigma \sqrt{\frac{s - M_\sigma^2}{s}}\,\theta(s - M_\sigma^2)\langle 0|\bar{u}u|\sigma\rangle\langle\sigma|\bar{s}s|0\rangle \quad \sigma = (\pi\pi, K\bar{K}, \ldots)^{\ell=0}_{I=0}$$

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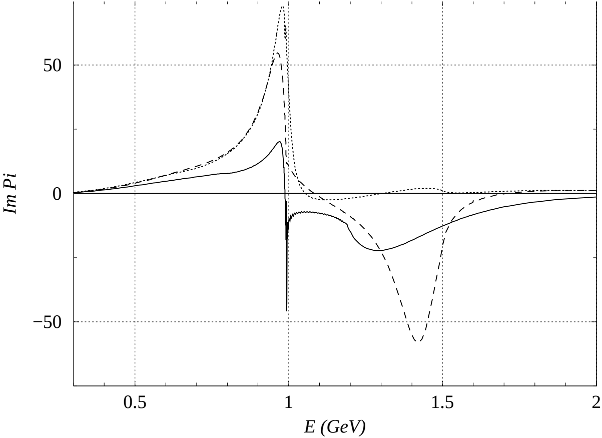
- Requires π and K scalar form factors. . .
- . . . in some cases, out of the physical region

$\Longrightarrow$ Models for the interactions in $\pi\pi$ and $K\bar{K}$ channels



Various models for the scalar spectral function Im Π suggest

- $f_0(980)$ strongly coupled to nonstrange and strange scalar densities
- $\langle(\bar{u}u)(\bar{s}s)\rangle$ large and positive
- $\Sigma(3)$ could be as small as $\Sigma(2^{\chi})/2$ B. Moussallam,SDG

$\Sigma(3)$:

$$\underbrace{\langle \bar{u}u \rangle|_{m_u=m_d=0, m_s \text{ phys}}}_{\text{sizeable } \Sigma(2^\chi)} = \underbrace{\langle \bar{u}u \rangle|_{m_u=m_d=m_s=0}}_{\Sigma(3)} + m_s \langle (\bar{u}u)(\bar{s}s) \rangle + \ldots$$

$\Sigma(3)$: a fat cat,

$$\underbrace{\langle \bar{u}u \rangle|_{m_u=m_d=0,m_s \text{ phys}}}_{\text{sizeable } \Sigma(2^\chi)} = \underbrace{\langle \bar{u}u \rangle|_{m_u=m_d=m_s=0}}_{\Sigma(3)} + m_s \langle (\bar{u}u)(\bar{s}s) \rangle + \dots$$

$\Sigma(3) \simeq \Sigma(2^\chi)$

$\langle (\bar{u}u)(\bar{s}s) \rangle$ small

Large-N_c picture

$\Sigma(3)$: a fat cat, or just a grin ?

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$\Sigma(3) \simeq \Sigma(2^\chi)$
$\langle(\bar{u}u)(\bar{s}s)\rangle$ small
Large-N_c picture

$\Sigma(3) < \Sigma(2^\chi)$
$\langle(\bar{u}u)(\bar{s}s)\rangle$ large
Big Zweig-rule violation

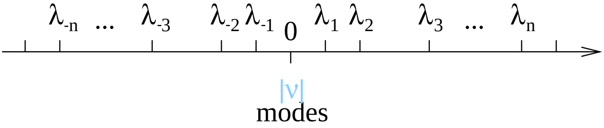
Well, I understand large-N_c pretty well...

But how could the other alternative occur ?

The Dirac operator

In Euclidean QCD on a torus L^4, the Dirac operator can be diagonalised

$$H[G] \equiv \not{D} = \gamma_\mu(\partial_\mu + iG_\mu) \qquad H\phi_n = \lambda_n[G]\phi_n$$



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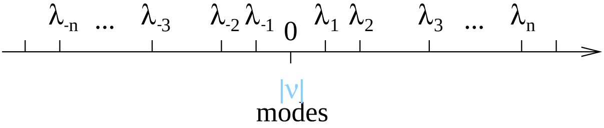

A correlation function expressed as a statistical average over G

$$\ll\Gamma\gg \propto \int dG \; e^{-S_{YM}[G]} \prod_j \Delta(m_j|G) \; \Gamma$$

with the fermionic determinant $\qquad \Delta(m_j|G) \propto m^{|\nu[G]|} \prod_{n>0} (m_j^2 + \lambda_n{}^2)$

Order parameters and IR Dirac spectrum

Scalar density $\bar{q}q$	Eigenvalue density $\rho(\lambda) = \sum_n \delta(\lambda - \lambda_n[G])$
$\Sigma(N_f)$	Average e.v. density around 0
$\langle(\bar{u}u)(\bar{s}s)\rangle$	Fluctuation of e.v. density around 0

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For order parameters dominated by lowest Dirac e.v. like $\Sigma(N_f)$

- Dependence on m_s through fermionic determinant $\Delta(m_s|G)$
- IR end of fermionic determinant increasing function of m_s

$$\Delta_{IR}(m_s|G) \propto m_s^{|\nu[G]|} \prod_{n>0}^{K} (m_s^2 + \lambda_n{}^2)$$

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$\Sigma(2,0) < \Sigma(2,m_s)$

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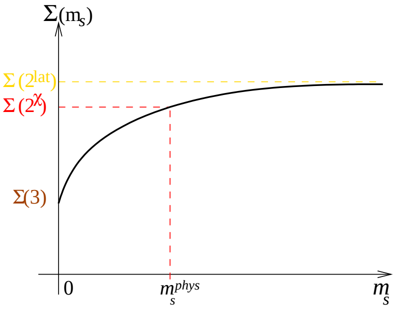
$\Sigma(3) < \Sigma(2^\chi)$ — Decrease of Σ due to sea $s\bar{s}$-pairs (similar effect for $F^2 = \lim_{N_f} F_\pi^2$)

Vacuum fluctuations of $s\bar{s}$ pairs



$$\textcolor{red}{\Sigma(2^\chi)} \sim \Sigma(3) \quad + \quad \langle \bar{u}u\ \bar{s}s \rangle$$

Mean & Fluctuations

of the density of Dirac eigenvalues

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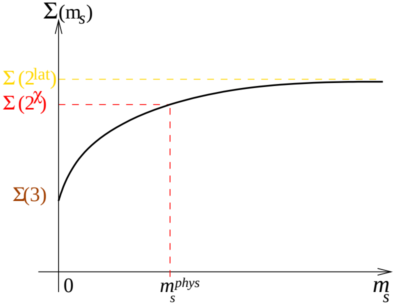

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Mean-field

- Large average, small fluct.
- Zweig rule not violated in 0^+
- No impact of strange sea quarks

$$\Sigma(3) \simeq \Sigma(2^\chi)$$

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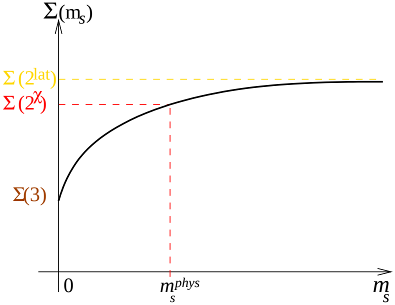

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$$\Sigma(3) \simeq \Sigma(2^{\chi})$$

Near a critical point

- Small average, large fluct.
- Large violation of Zweig rule
- Strange sea quarks important

$$\Sigma(3) < \Sigma(2^{\chi})$$

$\Sigma(3)$ might be smaller than usually assumed...

So what ?

Convergence and instabilities

$$F_\pi^2 M_\pi^2 = 2m\Sigma(3) + 64m(m_s + 2m)B_0^2 \Delta L_6 + 64m^2 B_0^2 \Delta L_8 + O(m_q^2)$$

- $B_0 = -\lim_{m_u,m_d,m_s \to 0} \langle \bar{u}u \rangle / F_\pi^2$
- $\Delta L_8 = L_8(M_\rho) + 0.20 \cdot 10^{-3} = O(p^4)\ \mathrm{LEC} + \chi \log$
- $\Delta L_6 = L_6(M_\rho) + 0.26 \cdot 10^{-3} = O(p^4)\ \mathrm{LEC} + \chi \log$

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L_6 is the awesome guy here

- Enhanced by m_s, related to $\langle(\bar{u}u)(\bar{s}s)\rangle\ldots$
- ...and "guestimated" assuming Zweig rule in scalar sector

Numerical competition between $O(p^2)$ and $O(p^4)$?
Source of instability in chiral series ?

A usual (and dangerous) treatment of $N_f = 3$ series

$$X(3) \equiv \frac{2m\Sigma(3)}{F_\pi^2 M_\pi^2} = \frac{2m\Sigma(3)}{2m\Sigma(3) + \Delta L_{6,8} + O(p^6)}$$

$$\to 1 - 16\frac{2M_K^2 + M_\pi^2}{F_\pi^2}\Delta L_6 - \frac{M_\pi^2}{F_\pi^2}\Delta L_8 + \ldots$$

using $1/(1+x) = 1 - x + \ldots$ and reexpressing mB_0 and $m_s B_0$

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For $r = 25,\ L_6(M_\rho) = 0.4 \cdot 10^{-3},\ L_8(M_\rho) = 0.9 \cdot 10^{-3}$

$$X(3) = 1 - 0.62 + 0.04 + O(p^6)$$

- No fluctuations : $\Delta L_6 = L_6(M_\rho) + 0.23 \cdot 10^{-3}$ very close to 0
- If (m_s-enhanced) fluctuations, $N_f = 3$ series require extra care

Alternatives

There may be large fluctuations of $s\bar{s}$ pairs with a dramatic impact on the convergence of $SU(3)$ chiral expansion

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- Determine $\Sigma(3)$ and fluctuations from experiment

  SDG,L.Girlanda,N.Fuchs,J.Stern
  - Assume overall convergence for a subset of observables
  - Leave open a numerical competition between LO and NLO
  - Do not reexpress perturbatively ratios of observables $1/(1+x) \neq 1-x$
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  $\pi\pi$ scattering $\Longrightarrow 2m_s/(m_u+m_d) \geq 14$ @ 95 % CL

Lattice connections

In case of large fluctuations with LO and NLO comparable $\gg$ NNLO

- Not all observables have good convergence properties
- Trading chiral couplings for observables delicate $2mB_0 \to M_\pi^2$
- Chiral extrapolations modified : $\Sigma(3)/F(3)^2 \times \log$

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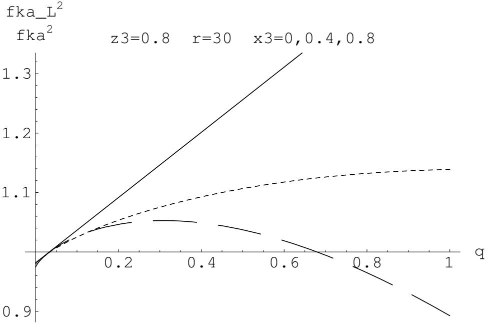

(2+1) simulation
$(m_{\rm lat}, m_{\rm lat}, m_s)$

$$\frac{F_K^2\big|_{\rm lat}}{F_K^2} = F\left(q \equiv \frac{m_{\rm lat}}{m_s}\right)$$

for some choice of $F(3)$ and m_s/m

Typical sea-quark/unquenched effect

Be careful when you use $N_f = 3$ χPT for chiral extrapolations...

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It might prove a tool more difficult to use than expected !

Conclusions

- Scalar sector exhibit very unusual features
  ...related to nonperturbative properties of QCD vacuum ?

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- Two chiral limits
  $N_f = 3 : m_u, m_d, m_s \to 0$
  $N_f = 2^\chi : m_u, m_d \to 0, m_s$ physical

$$\Sigma(2^\chi) = \Sigma(3) + m_s \langle (\bar{u}u)(\bar{s}s) \rangle + O(m_s^2)$$

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  ↔ Zweig rule violation in scalar sector

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- N_f-dependence of order parameters $\leftrightarrow$ Role of sea $s\bar{s}$-pairs
  $\leftrightarrow$ Zweig rule violation in scalar sector

- In terms of the spectrum of the Dirac operator $\Sigma(2^\chi) \geq \Sigma(3)$
  $\Sigma(3)$ average density, $\langle(\bar{u}u)(\bar{s}s)\rangle$ fluctuations } of eigenvalues around 0

  $\Longrightarrow$ Possibility of small $\Sigma(3)$ and large fluctuations

Conclusions (2)

- In $N_f = 3$ $O(p^4)$ χPT, fluctuations mirrored by L_4 and L_6
  L_6 (L_4) related to N_f-dependence of Σ (F^2)

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  L_6 (L_4) related to N_f-dependence of Σ (F^2)
- Due to m_s-enhancement, $L_{4,6}(M_\rho)$ a few 10^{-3} larger than

$$L_6^{\text{no fluc}}(M_\rho) = -0.23 \cdot 10^{-3} \qquad L_4^{\text{no fluc}} = -0.51 \cdot 10^{-3}$$

  means large fluctuations ...

Conclusions (2)

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We must assess experimentally
how large the vacuum fluctuations of $s\bar{s}$-pairs are !

The scalar channel is definitely very talkative. . .

but its shouting is sometimes hard to understand !