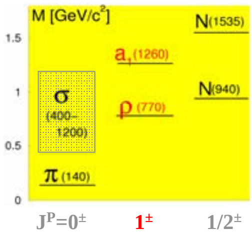
4.8

Spontaneous chiral symmetry breaking



Exact chiral symmetry:

all hadrons should exist in 2 degenerate parity states!

Parity operator P = γ^0:

$$P_R = \tfrac{1}{2}(1+\gamma^5)$$
$$P_L = \tfrac{1}{2}(1-\gamma^5)$$

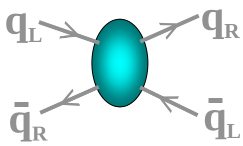
$$P \mid q_R > = \mid q_L >$$
$$P \mid q_L > = \mid q_R >$$

Construct: $$\mid \psi_{\pm} > = \frac{1}{\sqrt{2}}\left(\mid q_R > \pm \mid q_L >\right)$$

$$P \mid \psi_+ > = + \mid \psi_+ >$$
$$P \mid \psi_- > = - \mid \psi_- >$$

These 2 states should have the same energy / mass.
This feature is not observed in nature,
Mass difference between chiral partners much larger than current quark mass difference

⇒chiral symmetry is spontaneously broken.



Chiral condensate fills QCD vacuum:

$$\langle \bar{q}q \rangle = \langle \bar{q}_L q_R + \bar{q}_R q_L \rangle \neq 0$$

4.8

Symmetry breaking

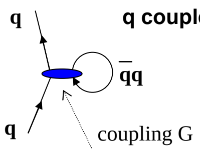
- **spontaneous breaking of electro-weak symmetry (Higgs mechanism)**
  ⇒ **current mass of quark**

for	**u & d quarks**	**$m^o_u \sim m^o_d \sim 5$ MeV**
	s quark	**$m^o_s \sim 175$ MeV**

  explicitly breaking of chiral symmetry

- **spontaneous breaking of chiral symmetry**
  ⇒ **constituent mass of quarks**

q couples to $\bar{q}q$ vacuum



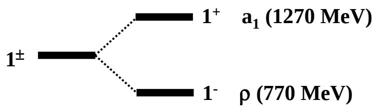
$$m_q = m_q^0 - G\langle \bar{q}q \rangle$$

for	**u & d quarks**	**$m_u \sim m_d \sim 300$ MeV (~1/3 m_{proton})**
s quark	**$m^o_s \sim 500$ MeV**

4.8

Consequences of Spontaneous Chiral Symmetry Breaking

1) All hadrons have well defined parity, chiral J^P doublets not observed.



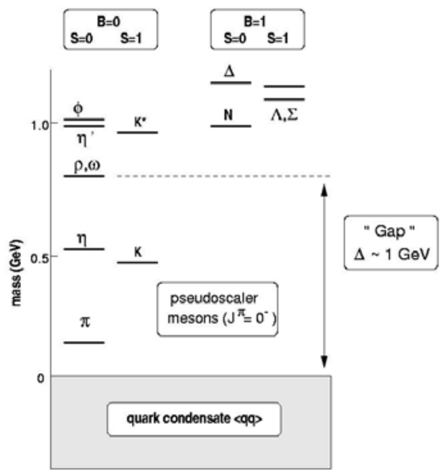
2) Chiral symmetry spontaneously broken, vacuum is filled with qq – condensate.

3) Goldstone theorem:
Any spontaneously broken contious symmetry generates a massless boson (→ Goldstone bosons).

4) Characteristic mass scale of hadrons

1 GeV mass gap to quark condensate

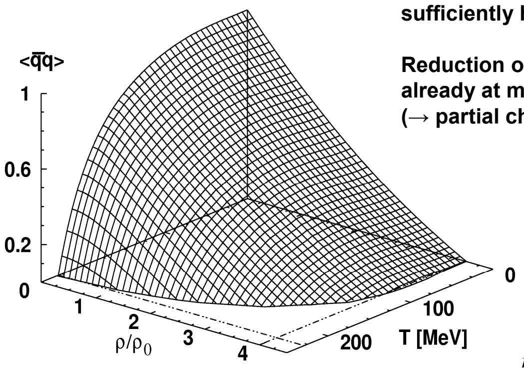
except pseudoscalar mesons that are the Goldstone bosons:
π, η, and K



4.8

Chiral symmetry restoration of QCD

Chiral Condensate



W.Weise, Prog. Theor. Phys. Suppl. 149 (2003) 1
initially: S.Klimt et al.., PLB 249, 386 (1990)

Chiral symmetry should be restored at sufficiently high temperatures and baryon densities.

Reduction of vacuum value should be visible already at moderate densities
(→ partial chiral symmetry restoration)

Symmetry breaking pattern of Chiral Symmetry of QCD

Gell-Mann-Oaks-Renner Relation:

$$m_\pi^2 f_\pi^2 = -\frac{1}{2}(m_u + m_d)\langle \bar{u}u + \bar{d}d\rangle + O(m_u^2)$$

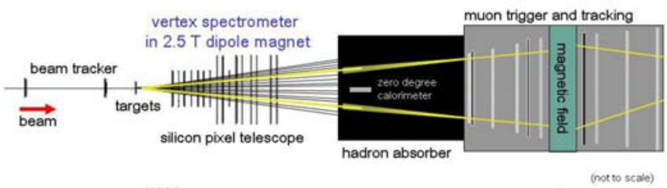
$$m_K^2 f_K^2 = -\frac{1}{2}(m_u + m_s)\langle \bar{u}u + \bar{s}s\rangle + O(m_s^2)$$

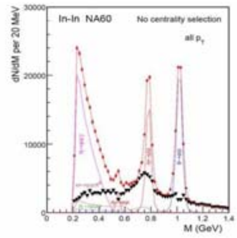
spontaneous symmetry breaking

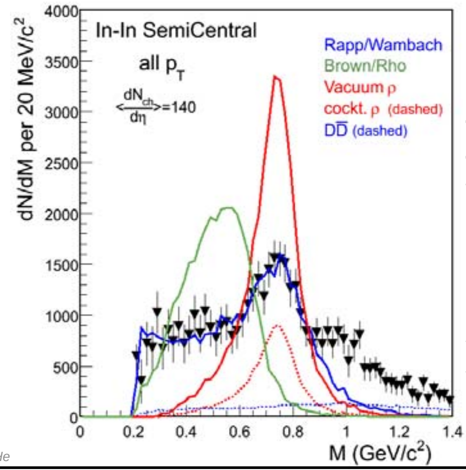
explicit symmetry breaking

4.8

Dilepton production: NA60 results







R. Arnaldi, et al. [NA60], Phys. Rev. Lett. 96, 162302 (2006)

In-medium spectral function,

ρ – meson appears broadened.

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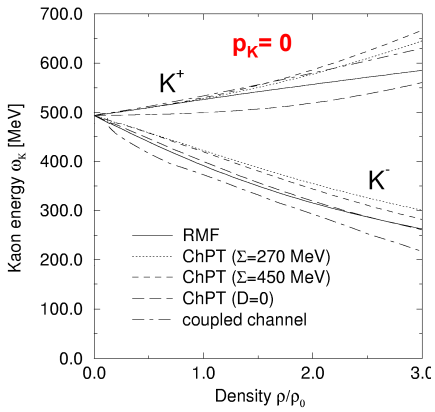
4.8

Kaon in-medium energy



D.B. Kaplan, A.E. Nelson, Phys. Lett. B 175 (1986) 57

G.E Brown, C.H. Lee, M. Rho, V. Thorsson, Nucl. Phys. A 567 (1994) 937

T. Waas, N. Kaiser, W. Weise, Phys. Lett. B 379 (1996) 34

J. Schaffner-Bielich, J. Bondorf, I. Mishustin , Nucl. Phys. A 625 (1997) 325

G.Mao et al., Phys.Rev. C59 (1999) 3381

Note: In – medium energy at vanishing momentum is an effective mass.
Effective meson masses modified due to the presence of the baryonic medium.

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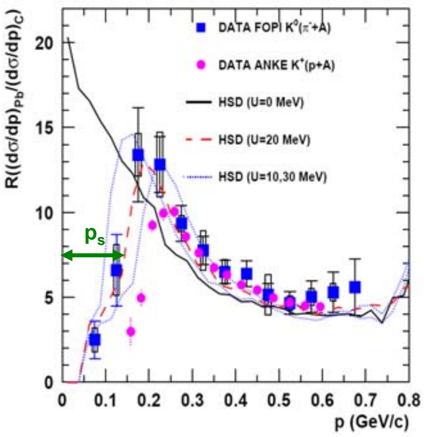
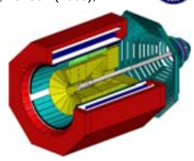
K^0 production in π^- + A reactions at 1.15 GeV/c

M.L. Benabderramahne et al., PRL 102, 182501 (2009), arXiv:0807.3361

Ratio of momentum distributions:





Anke data @ COSY

M. Büscher et al., *EPJ*, A22, 301 (2004)

p + p → K^+ + X at 2.5 GeV

Model interpretation with RBUU
U(K^+) = + 20 MeV

Model independent analysis:

$$U_K = \frac{p_s^2}{2m_K} = \frac{(140\mathrm{MeV})^2}{2\cdot 498\mathrm{MeV}} = 20\mathrm{MeV}$$

Potential depth: U(K^0) = + 20 (+/- 5) MeV consistent with heavy-ion data on K^+,
Accuracy (only) statistics limited,

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5.

Weak interactions

Characteristica of weak processes:

- long lifetimes, e.g. $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$ with $\tau = 2.8\cdot 10^{-8} s$
- neutrinos
- parity violation
- violation of flavor conservation: $\Lambda \rightarrow \pi^- + p$ $(\Delta S = 1)$ with $\tau = 2.6\cdot 10^{-10} s$

Observation of weak interaction only possible,
if strong and electromagnetic interactions are forbidden.
(or via interference of effects: γ/Z – interference, e.g. atomic parity violation)

Summary of conservation laws

	strong	e.m.	weak
Flavor (strangeness,charm,beauty,top)	yes	yes	no
(strong) isospin I_3	yes	yes	no
Lepton number: L_e, L_μ, L_τ	-	yes	(yes)
Baryon number	yes	yes	yes

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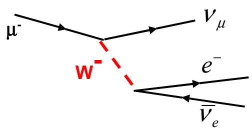
5.1

Phenomenology

Leptonic decays

$$\mu^- \to \nu_\mu + e^- + \bar{\nu}_e$$
$$\text{with } \tau = 2.6 \cdot 10^{-6} s$$



Hadronic decays:

dominant modes

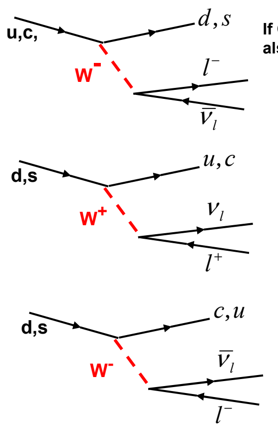
$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix}$$

$$u \to d + l^+ + \nu_l \qquad c \to s + l^+ + \nu_l$$
$$d \to u + l^- + \bar{\nu}_l \qquad s \to c + l^- + \bar{\nu}_l$$

suspressed modes

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix}$$

$$u \to s + l^+ + \nu_l \qquad c \to d + l^+ + \nu_l$$
$$d \to c + l^- + \bar{\nu}_l \qquad s \to u + l^- + \bar{\nu}_l$$



If Q^2 large enough, also:

d $\bar{u}$

u $\bar{d}$

$\sim\cos^2\theta_C$ ~ 0.95

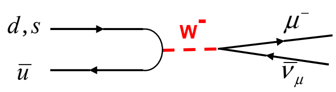
d $\bar{u}$

$\sim\sin^2\theta_C$ ~ 0.05

5.1

Phase space estimate for pseudoscalar decays

Compare π^- to K^- decays



$$\Gamma_{\mu^-\bar{\nu}_\mu}(\pi^-) = \frac{1}{\tau} = 3.8 \cdot 10^8 s^{-1}$$

$$\Gamma_{\mu^-\bar{\nu}_\mu}(K^-) = BR_i \cdot \Gamma = BR_i \cdot \frac{1}{\tau} = 5.3 \cdot 10^7 s^{-1}$$

Decay width of kaon smaller than pion despite larger mass.

Phase space (from chapter 1.3):

$$\Gamma_{fi} = \frac{1}{32\pi^2 m_i} \int |M_{fi}|^2 \left. \frac{E_1 E_2}{|\vec{p}_1|(E_1+E_2)} \frac{|\vec{p}_1|^2}{E_1 E_2} \right|_{p_1 = p^*} d\Omega$$

$$= \frac{|\vec{p}^*|}{32\pi^2 m_i^2} \int |M_{fi}|^2 d\Omega$$

Phase space ratio:

$$\frac{|\vec{p}^*|}{m_i}(\pi^-) = \frac{30}{140} = 0.21$$

$$\frac{|\vec{p}^*|}{m_i}(K^-) = \frac{236}{494} = 0.48$$

$$R_{\text{phase space}}\left(\frac{\pi^-}{K^-}\right) = 0.44$$

$$R_{\text{exp}}\left(\frac{\Gamma(\pi^-)}{\Gamma(K^-)}\right) = 7.2 > R_{\text{phase space}}\left(\frac{\pi^-}{K^-}\right) = 0.44$$

$\Rightarrow$ **K - decay suppressed**