Pentaquarks in dense matter

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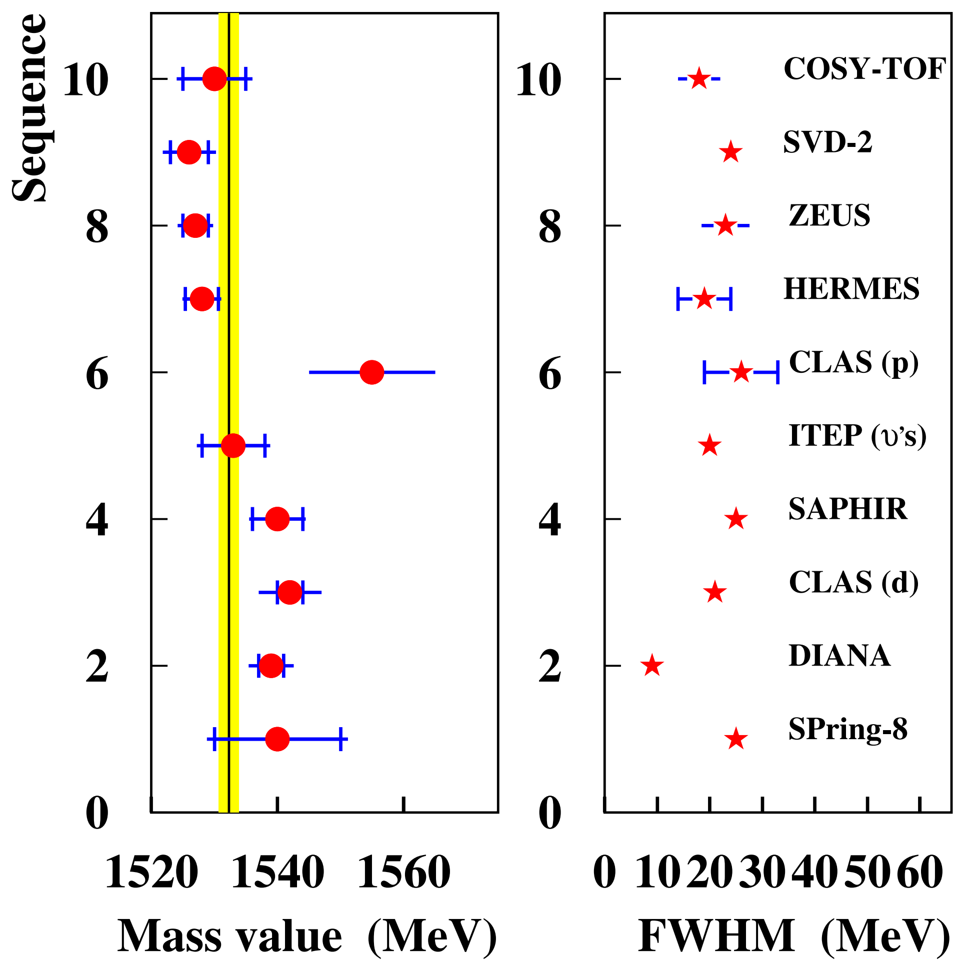
What do we know?

experiments with evidence for Θ^+



high-energy experiments $\left\{ \begin{array}{l} \text{BES} \\ \text{HERA-B} \\ \text{SPHINX} \\ \text{PHENIX} \end{array} \right.$

See no evidence for Θ^+

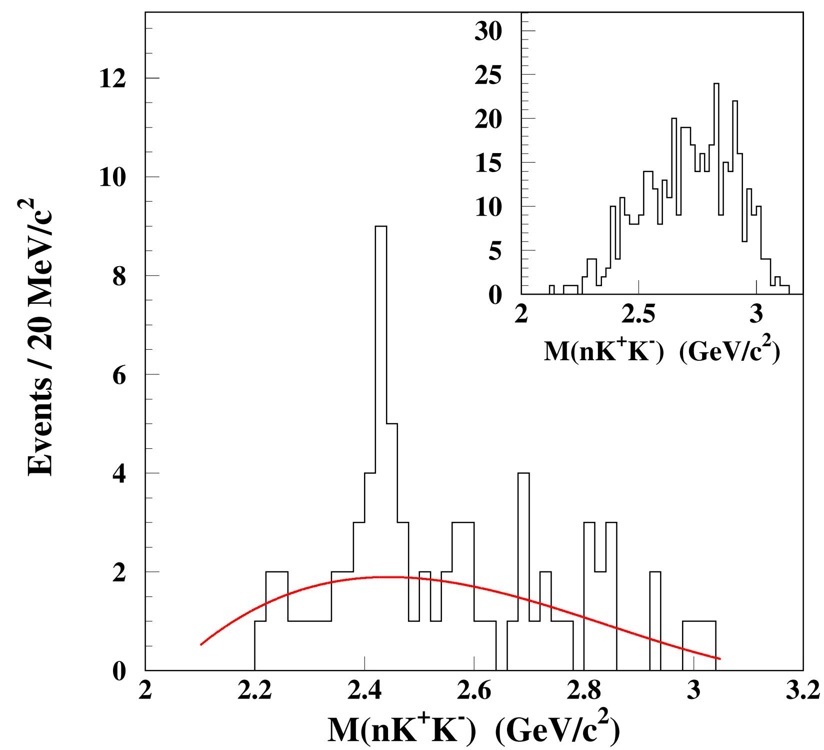
apparent contradiction

$\Downarrow$

Production Mechanism

$$\gamma + p \longrightarrow \pi^+ + N^*(2400)$$
$$\pi^- + p \longrightarrow N^*(2400)$$
$$N^*(2400) \longrightarrow \Theta^+ + K^-$$

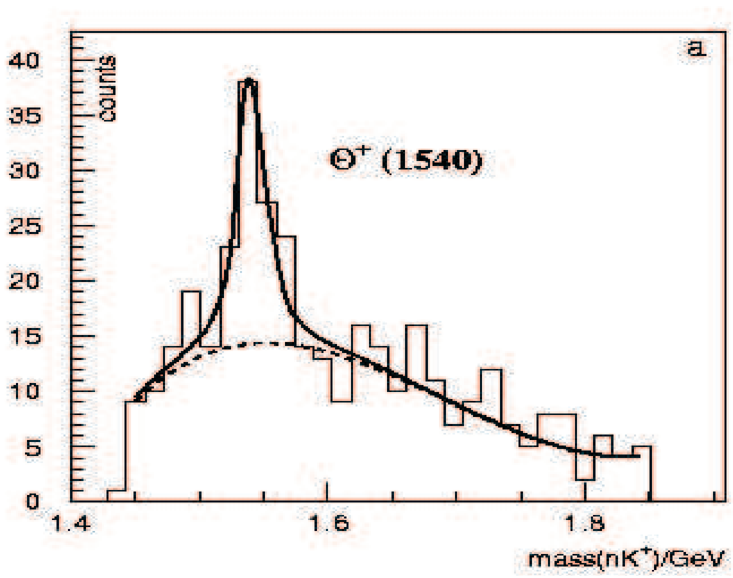
CLAS Coll. hep-ex/032001



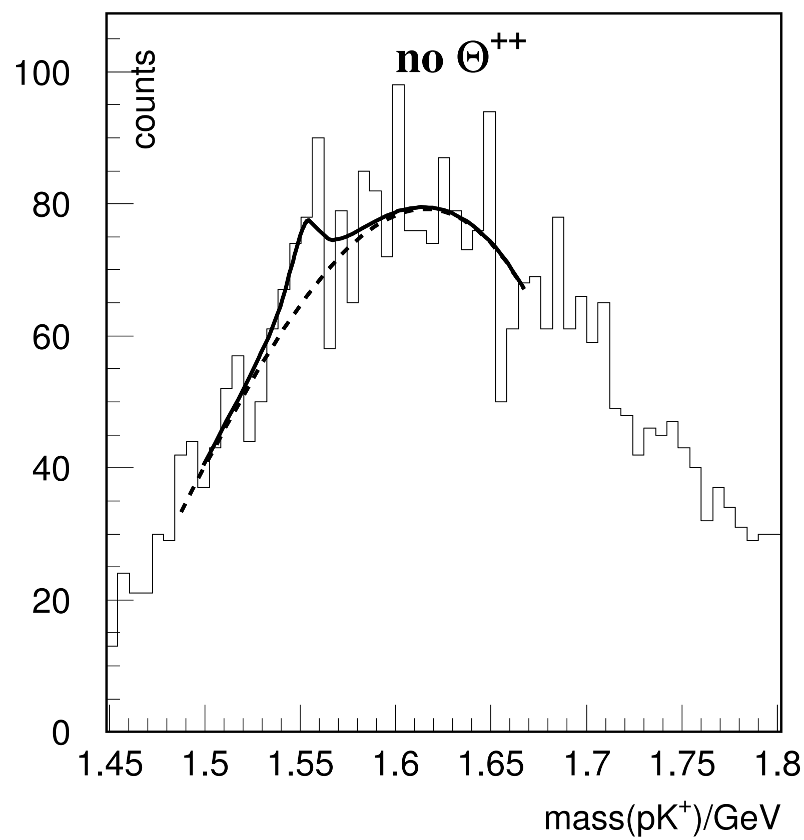
Isospin

$$I = 0 \rightarrow udud\bar{s}$$

$$I = 1 \begin{cases} uuud\bar{s} \\ udud\bar{s} \\ dddu\bar{s} \end{cases}$$



SAPHIR Coll. hep-ex/0307083

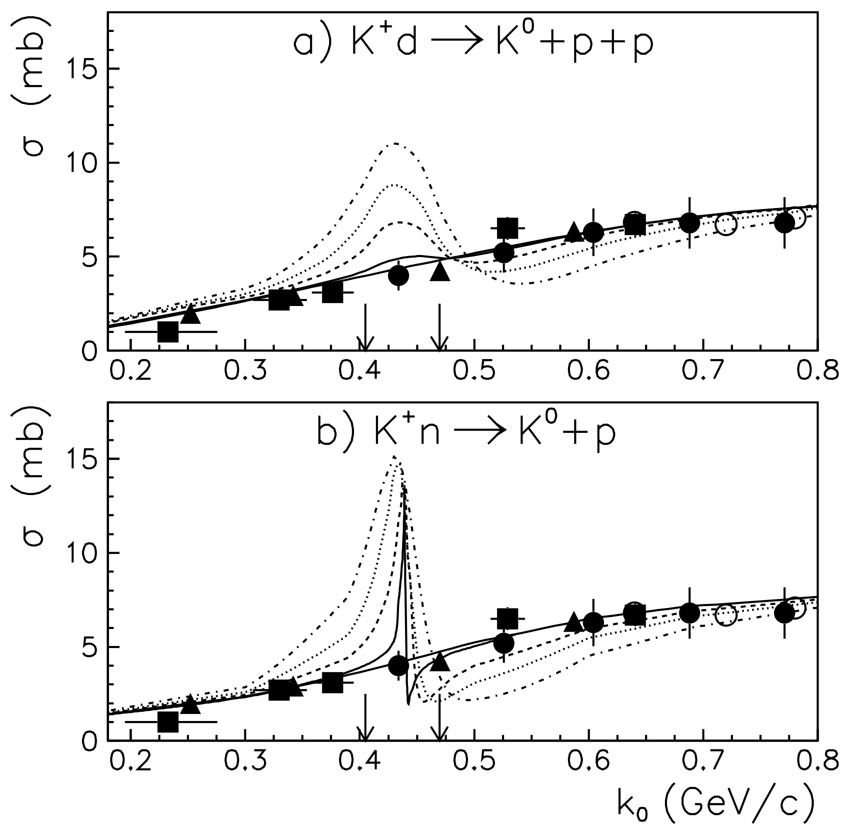


$\boxed{\Theta^+ \text{ isospin} = 0}$

Width

Experimental information $\Rightarrow$ upper limits

old data from NK scattering (Sibirtsev et al. hep-ph/0405099)



$\Gamma_\Theta = 1$ MeV
$\Gamma_\Theta = 5$ MeV
$\Gamma_\Theta = 10$ MeV
$\Gamma_\Theta = 20$ MeV

Parity

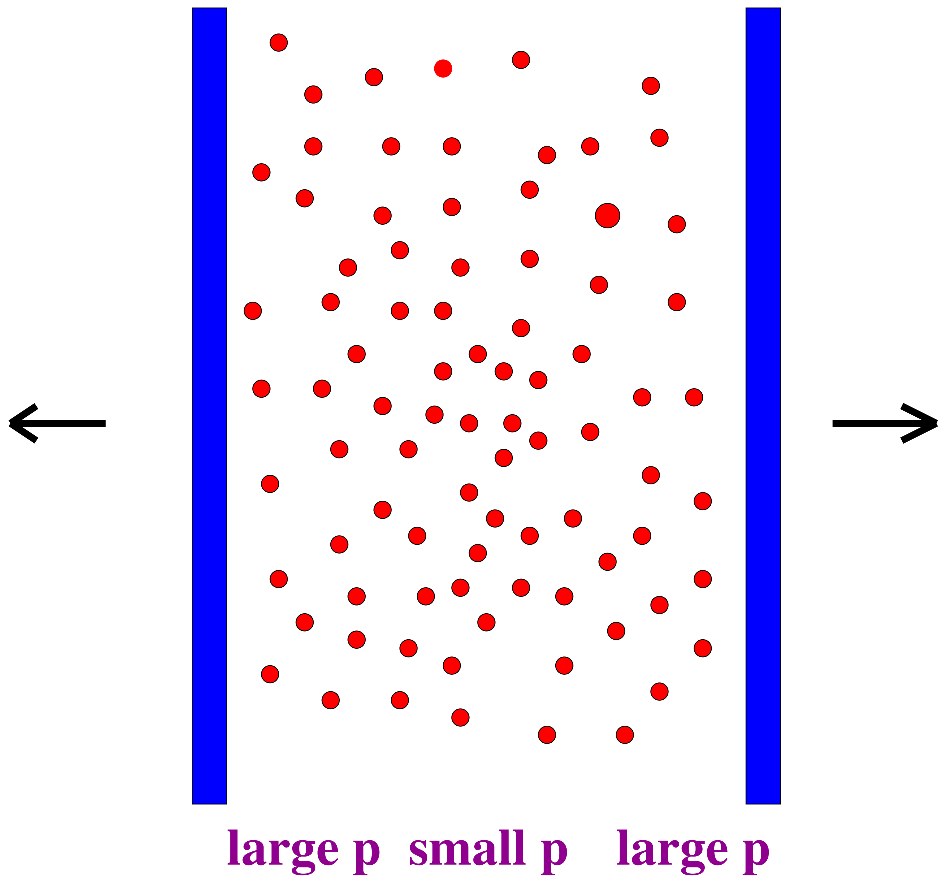
Naive quark models $\begin{cases} q^4(1^+) + \bar{q}(1/2^-) \\ P = - \end{cases}$

Diquark pictures $\begin{cases} q^2\ (L=1)\ q^2 + \bar{q}(1/2^-) \\ P = + \end{cases}$

Lattice QCD $\begin{cases} \text{Csikor et al. (hep-ph/0309090)} \Rightarrow P = - \\ \text{Mattur et al. (hep-ph/0406196) see no } \Theta^+ \end{cases}$

QCD sum rules $\begin{cases} \text{Sugiyama et al. (hep-ph/030927)} \Rightarrow P = - \\ \text{Ioffe et al. (hep-ph/0408152)} \Rightarrow P = + \end{cases}$

Heavy Ion Collisions



many $p\pi^-$ collisions

$$N^*(2400) \longrightarrow \Theta^+ + K^-$$

$$\Downarrow$$

Θ^+ should be seen

$\boxed{\Theta^+ \textbf{ in a nuclear medium}}$

in-medium QCD sum rules for Θ^+

$$\Pi(q) \equiv i \int d^4x\, e^{iq\cdot x} \langle \Psi_0 | T\eta(x)\overline{\eta}(0) | \Psi_0 \rangle \ ,$$

$|\Psi_0\rangle$: nuclear matter ground state $[\rho,\ u_\mu = (1,0)]$

$$\eta(x) = \epsilon_{abc}\epsilon_{def}\epsilon_{cfg}[u_a^T(x)Cd_b(x)][u_d^T(x)C\gamma_5 d_e(x)]C\bar{s}_g^T(x),$$

diquark-diquark-antiquark

$$\eta \nearrow I = 0, \qquad \eta \searrow P = - \text{ for } \Theta^+$$

Sugiyama et al. (hep-ph/030927)

$$\Pi(q) \equiv \Pi_s(q_0, |\vec{q}|) + \Pi_q(q_0, |\vec{q}|)\not{q} + \Pi_u(q_0, |\vec{q}|)\not{u}$$

QCD Sum Rule

Fundamental Assumption: Principle of Duality

Theoretical side	Phenomenological side
↓	↓
quark level quark and gluon degrees of freedom	hadron level hadron parameters (masses, couplings, form-factors,...)
↓	↓
Wilson OPE	dispersion relation

To improve the matching $\Rightarrow$ Borel transform

Phenomenological side

$$\Pi_i(q_0, |\vec{q}|) = \frac{1}{2\pi i} \int_{-\infty}^{\infty} d\omega \frac{\Delta\Pi_i(\omega, |\vec{q}|)}{\omega - q_0} ,$$

$\Delta\Pi_i(\omega, |\vec{q}|) \longrightarrow$ spectral information on quasiparticle, quasihole and higher-energy states

in vacuum $\nearrow$ particle, $\searrow$ hole — related by charge symmetry

finite density $\Rightarrow$ states no longer related by charge conjugation

poles
- $\nearrow$ positive energy: $E_q = \Sigma_v + E_q^*$
- $\searrow$ negative energy: $\bar{E}_q = \Sigma_v - E_q^*$

$$E_q^* = \sqrt{{m_\Theta^*}^2 + |\vec{q}|^2}, \qquad m_\Theta^* = m_\Theta + \Sigma_s$$

Discontinuities

$$\Delta\Pi_s(\omega, |\vec{q}|) = -2\pi i \frac{m^*_\Theta {\lambda^*_\Theta}^2}{2E^*_q}\left[\delta(\omega - E_q) - \delta(\omega - \bar{E}_q)\right] + \cdots$$

$$\Delta\Pi_q(\omega, |\vec{q}|) = -2\pi i \frac{{\lambda^*_\Theta}^2}{2E^*_q}\left[\delta(\omega - E_q) - \delta(\omega - \bar{E}_q)\right] + \cdots$$

$$\Delta\Pi_u(\omega, |\vec{q}|) = 2\pi i \frac{\Sigma_u {\lambda^*_\Theta}^2}{2E^*_q}\left[\delta(\omega - E_q) - \delta(\omega - \bar{E}_q)\right] + \cdots$$

$\cdots\cdots \longrightarrow$ higher-energy states (s_0)

${\lambda^*_\Theta}^2 \longrightarrow$ Θ^+-current coupling

Theoretical side

$$\langle \hat{O}_n \rangle_{\rho_N} = \langle \Psi_0 | \hat{O}_n | \Psi_0 \rangle$$

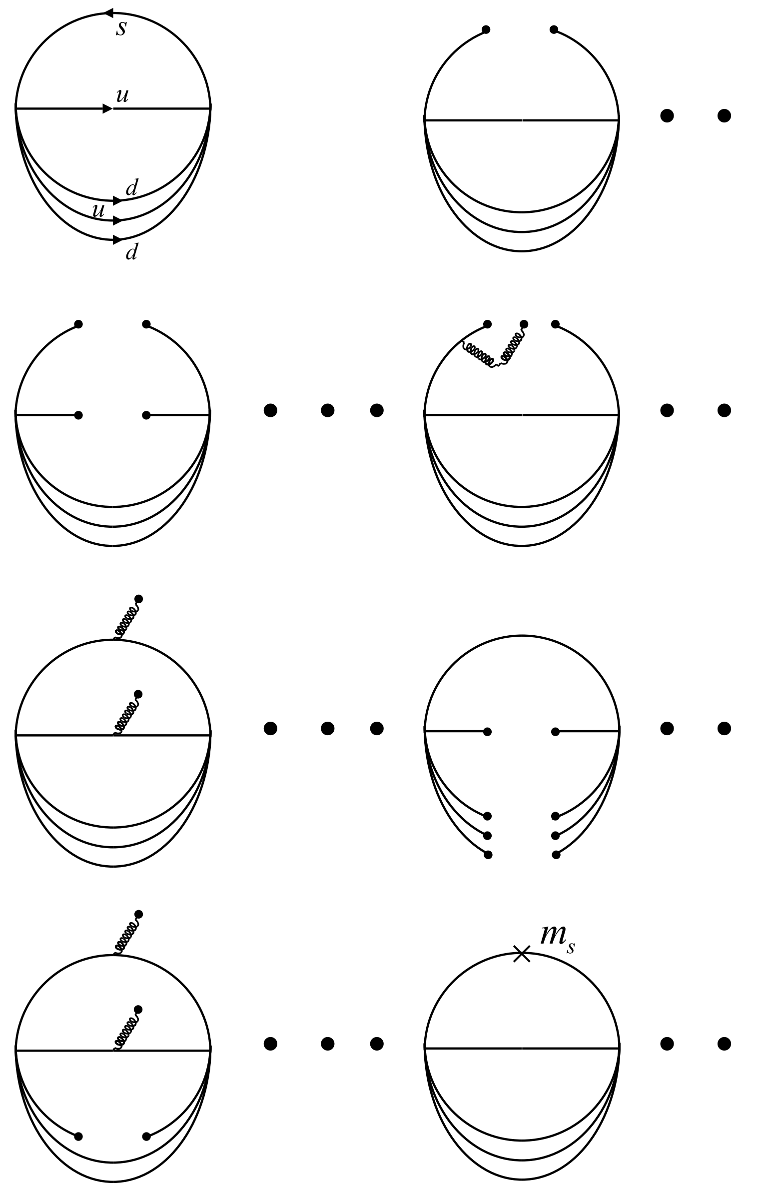
$$\langle \hat{O} \rangle_{\rho_N} \sim \langle \hat{O} \rangle + (\langle \hat{O} \rangle_N) \rho_N$$

$\langle \hat{O} \rangle_N = \langle N | \hat{O} | N \rangle$: spin-averaged nucleon matrix element

$\langle q^\dagger q \rangle_{\rho_N} = \frac{3}{2} \rho_N$
$\langle s^\dagger s \rangle_{\rho_N} = 0$
$\langle \overline{q} q \rangle_{\rho_N} = \langle \overline{q} q \rangle + \frac{\sigma_N}{m_u + m_d} \rho_N$
$\langle \bar{s} s \rangle_{\rho_N} = \langle \bar{s} s \rangle + y \frac{\sigma_N}{m_u + m_d} \rho_N$

$$y = \langle \bar{s} s \rangle_N / \langle \overline{q} q \rangle_N$$

$$0 \leq y \leq 0.5$$



Sum Rules

$$\Pi_q$$

$$\lambda_\Theta^{*\,2} e^{-(E_q^2-\vec{q}^2)/M^2} = \frac{M^{12}E_5}{2^{10}\pi^8 5!7} + \frac{m_s\langle\bar{s}s\rangle_{\rho_N}}{2^8\pi^6 5!} M^8 E_3 + \cdots$$

$$\Pi_s$$

$$\pm\lambda_\Theta^{*\,2} m_\Theta^* e^{-(E_q^2-\vec{q}^2)/M^2} = \frac{m_s M^{12}E_5}{2^{10}\pi^8 5!} - \frac{\langle\bar{s}s\rangle_{\rho_N}}{2^7\pi^6 5!} M^{10} E_4 + \cdots$$

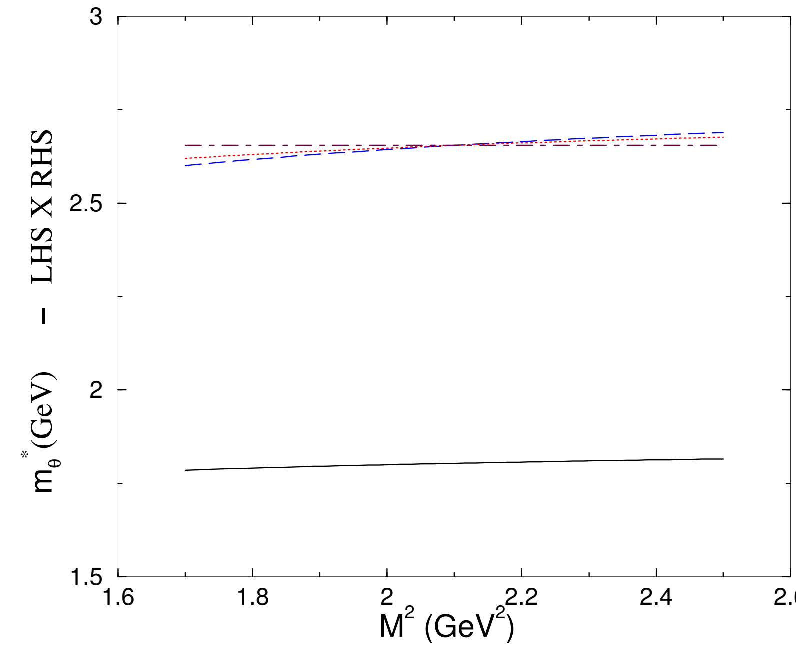
$$\Pi_v$$

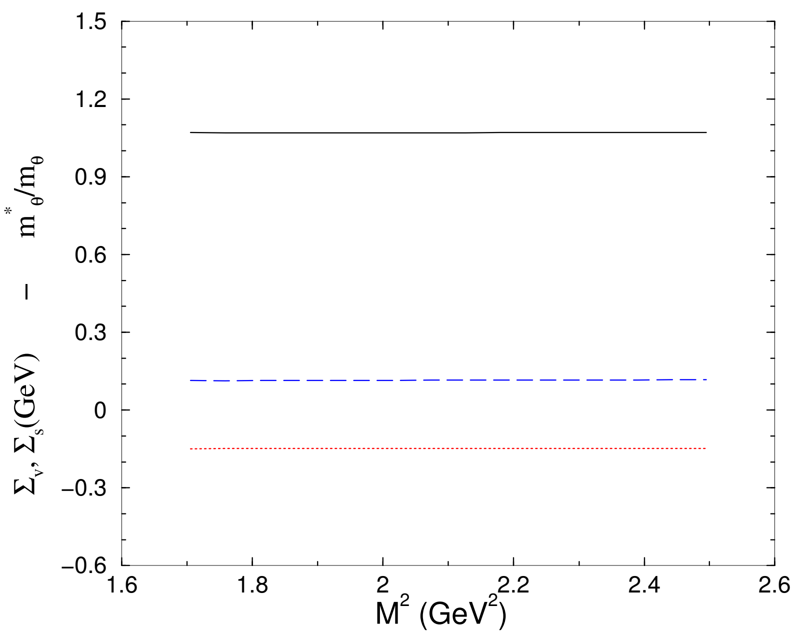
$$\lambda_\Theta^{*\,2} \Sigma_v e^{-(E_q^2-\vec{q}^2)/M^2} = -\frac{M^{10}E_4}{2^7\pi^6 5!3}\left(\langle q^\dagger q\rangle_{\rho_N} + 3\langle s^\dagger s\rangle_{\rho_N}\right) + \cdots$$

Self Energies

LHS $\longrightarrow E_q^2$
RHS1 $\longrightarrow \cancel{q}$
RHS2 $\longrightarrow \cancel{u}$

LHS
RHS1
RHS2





m^*_Θ / m_Θ
$\Sigma_s > 0$
$\Sigma_v < 0$

$(y = 0.3, \ |\vec{q}| = 270\mathrm{MeV})$

$\langle g_s^2 G^2 \rangle = \mathbf{0.47}$ GeV^4 (Sugiyama et al. hep-ph/0309271)

y	Σ_s (MeV)	Σ_v (MeV)	$\Sigma_s + \Sigma_v$ (Mev)	E_q (GeV)
0	50	-90	-40	1.60
0.3	110	-150	-40	1.60
0.5	150	-190	-40	1.60

$\langle g_s^2 G^2 \rangle = \mathbf{0.24}$ GeV^4 (Ioffe & Oganesian hep-ph/0408152)

y	Σ_s (MeV)	Σ_v (MeV)	$\Sigma_s + \Sigma_v$ (Mev)	E_q (GeV)
0	20	-110	-90	1.60
0.3	90	-180	-90	1.60
0.5	130	-220	-90	1.60

Relativistic mean field app.
Zhong et al. nucl-th/0408046

$$\left\{ \begin{array}{l} \Theta - \sigma,\ \Theta - \omega \text{ couplings} \\ -90MeV \leq U \leq -45MeV \end{array} \right.$$

$$N,\ \Lambda,\ \Sigma \nearrow \langle \overline{q}q\overline{q}q \rangle_{\rho_N} = f \langle \overline{q}q \rangle^2_{\rho_N} + (1-f) \langle \overline{q}q \rangle^2$$

$$\searrow \Sigma_v \text{ “stable”},\ \Sigma_s \leftrightarrow f$$

$\boxed{\text{small } f}$

$$N:\ \Sigma_v^N \sim 250 \text{ MeV},\quad \Sigma_s^N + \Sigma_v^N \sim -50 \text{ MeV}$$

$$\Lambda:\ \Sigma_v^\Lambda \sim 90 \text{ MeV},\quad \Sigma_s^\Lambda + \Sigma_v^\Lambda \sim -30 \text{ MeV}$$

$$\Sigma:\ \Sigma_v^\Sigma \sim 240 \text{ MeV},\quad \Sigma_s^\Lambda + \Sigma_v^\Lambda \sim -30 \text{ MeV}$$

$$\frac{\Sigma_v^{\Lambda}}{\Sigma_v^{N}} \simeq 0.3 - 0.4, \quad \frac{\Sigma_v^{\Sigma}}{\Sigma_v^{N}} \simeq 0.8 - 1.1, \quad \left|\frac{\Sigma_v^{\Theta}}{\Sigma_v^{N}}\right| \simeq 0.3 - 0.5$$

$\boxed{B - \omega \text{ coupling constant}}$

weak for $\Theta^+, \ \Lambda$ "strong" for $N, \ \Sigma$

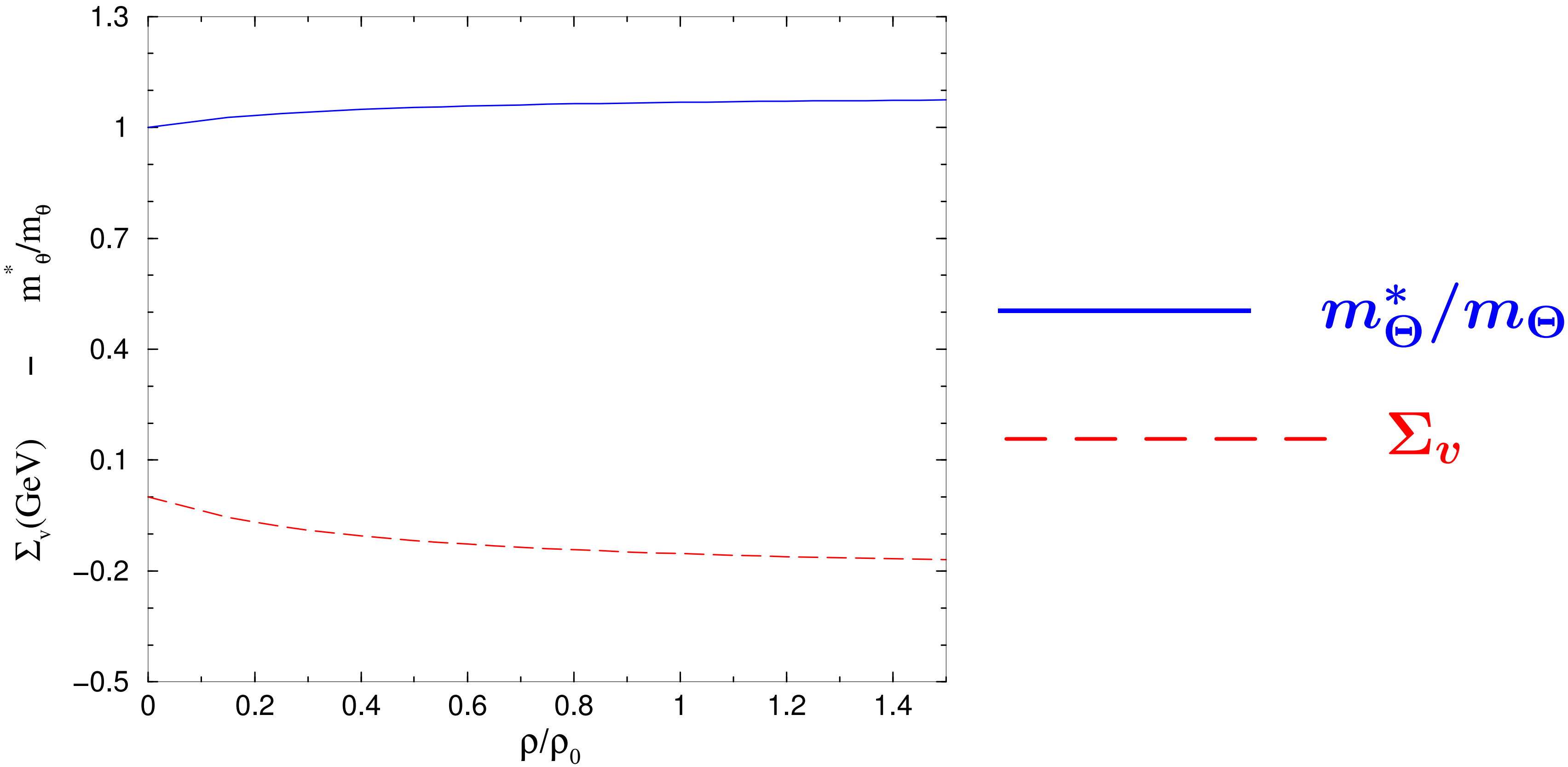
$$N \to ([ud]_{I,S=0})q, \quad \Sigma \to ([qs]_{S=0})q,$$

$$\Lambda \to ([ud]_{I,S=0})s, \quad \Theta^+ \to ([ud]_{I,S=0}[ud]_{I,S=0})\bar{s}$$

ω → no strange content

ω → no coupling with Λ and Θ^+

Density dependence



$$\langle\hat{O}\rangle_{\rho_N} \sim \langle\hat{O}\rangle + (\langle\hat{O}\rangle_N)\rho_N$$

Conclusions

- We have evaluated the self energies of the Θ^+ in a nuclear medium
- For tradicional values of the condensates and supposing a small strange content in the nucleon ($y = 0.3$) we got:

$$\Sigma_s \simeq 110 \text{ MeV, and } \Sigma_v \simeq -150 \text{ MeV}$$

with opposite signals to what as obtained for the nucleon and the hyperons Λ and Σ

- Σ_s and Σ_v change with y but their sum remains very stable:

$$\Sigma_s + \Sigma_v \simeq -40 \text{ MeV}$$

- Results compatible with relativistic mean field calculation