The f_0(500) meson: its role at nonzero temperature and at nonzero density

Francesco Giacosa

in collaboration with:
Wojciech Broniowski (UJK-Kielce + IFJ-PAN-Krakow) Viktor Begun (UJK-Kielce)
Achim Heinz (Goethe Uni), Dirk H. Rischke (Goethe Uni) Susanna Gallas (Goethe Uni)
Giuseppe Pagliara (INFN & Ferrara Uni)

FAIRNESS 2016

14 - 19/2/2016, Garmisch-Partenkirchen

Outline

$f_0(500)$: a bit of history. Nature of it and other light scalars.

Nonzero temperature: negligible role.

Nonzero density: important role.

Summary

Existence and pole position of f0(500)

Complicated PDG history. Existence through the position of the pole.
Now: established.

Citation: K.A. Olive *et al.* (Particle Data Group), Chin. Phys. C, **38**, 090001 (2014) and 2015 update

$f_0(500)$ or σ [g]
was $f_0(600)$

$I^G(J^{PC}) = 0^+(0^{++})$

Mass $m = (400–550)$ MeV
Full width $\Gamma = (400–700)$ MeV

$f_0(500)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\pi\pi$	dominant	–
$\gamma\gamma$	seen	–

Citation: K.A. Olive *et al.* (Particle Data Group), Chin. Phys. C, **38**, 090001 (2014) and 2015 update

$f_0(500)$ or σ
was $f_0(600)$

$I^G(J^{PC}) = 0^+(0^{++})$

A REVIEW GOES HERE – Check our WWW List of Reviews

$f_0(500)$ T-MATRIX POLE $\sqrt{s}$

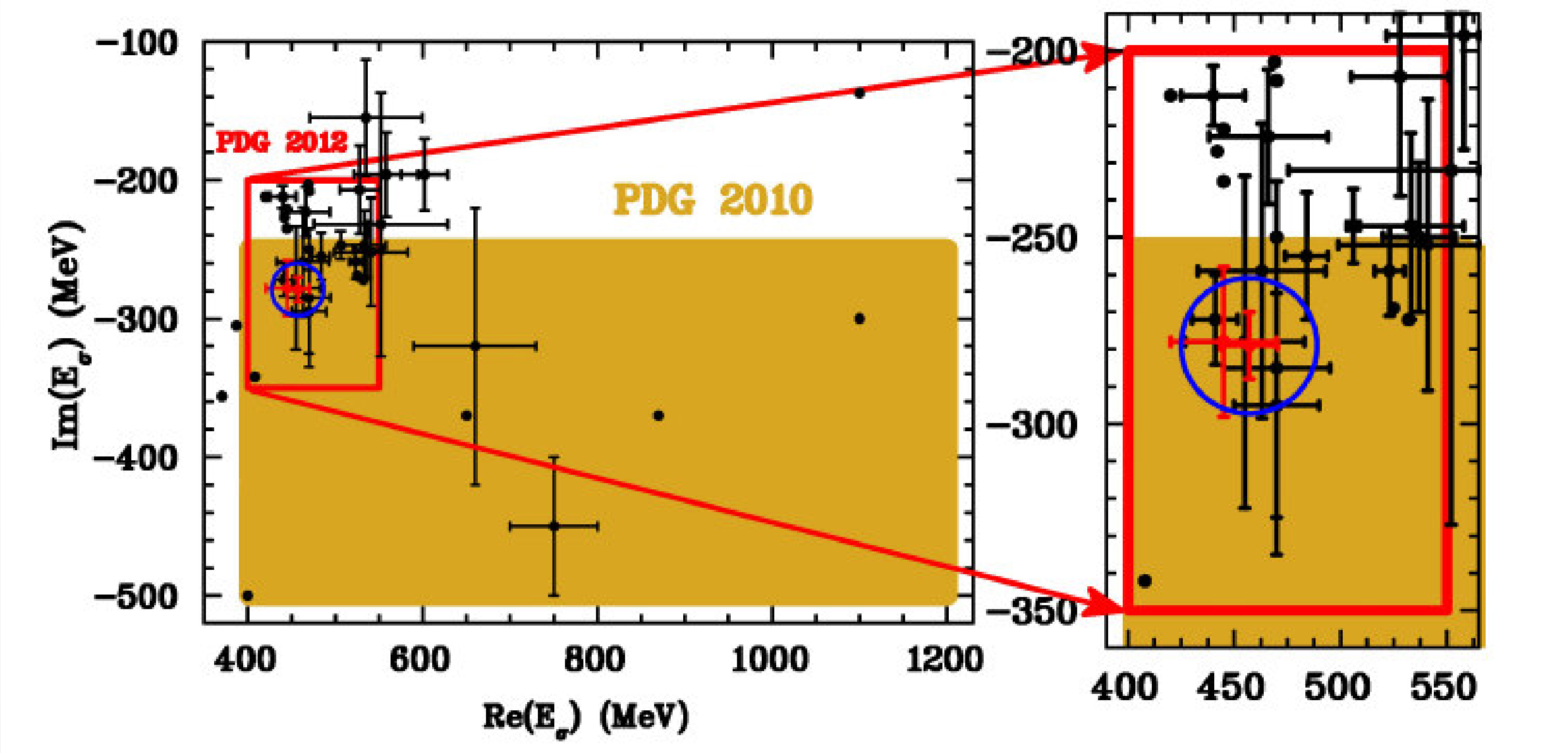
Note that $\Gamma \approx 2\ \text{Im}(\sqrt{s_{\text{pole}}})$.

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
(400–550)$-i$(200–350) OUR ESTIMATE			

$$\sqrt{s_{pole}} = M - i\frac{\Gamma}{2}$$

Existence and pole position of f0(500)

From 2010 to 2012: update…



See the review of J.R. Pelaez (Madrid U.), e-Print: **arXiv:1510.00653**
A review on the status of the non-ordinary f0(500) **resonance**

Madrid-Krakow and Bern results for the poles

precise determination of the pole, its couplings to the $\pi\pi$ channel and amplitude

$$g^2 = -16\pi \lim_{s \to s_{pole}} (s - s_{pole})\, t_\ell(s)\, (2\ell + 1)/(2p)^{2\ell}$$

	$\sqrt{s_{\rm pole}}$ (MeV)	$\lvert g \rvert$
$f_0(500)^{\rm GKPY}$	$(457^{+14}_{-13}) - i(279^{+11}_{-7})$	$3.59^{+0.11}_{-0.13}$ GeV
$f_0(500)^{\rm Roy}$	$(445 \pm 25) - i(278^{+22}_{-18})$	3.4 ± 0.5 GeV

$$\sqrt{s_{pole}} = M - i\frac{\Gamma}{2}$$

$$\Gamma \simeq 500 \text{ MeV}$$

$\rho(770)^{\rm GKPY}$	$(763.7^{+1.7}_{-1.5}) - i(73.2^{+1.0}_{-1.1})$	$6.01^{+0.04}_{-0.07}$
$\rho(770)^{\rm Roy}$	$(761^{+4}_{-3}) - i(71.7^{+1.9}_{-2.3})$	$5.95^{+0.12}_{-0.08}$

*S*0 scattering length

- ChPT + Roy eqs (Bern group): $0.220 \pm 0.005\, m_\pi^{-1}$
- GKPY: $0.220 \pm 0.008\, m_\pi^{-1}$

From R. Kaminski, EEF70, Coimbra (2014).

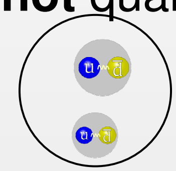
The light scalar mesons: what are they?

$$a_0(980) \quad k(800) \quad f_0(980) \quad f_0(500)$$

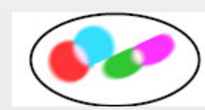
$$J^{PC} = 0^{++}$$

Various studies show that these states are **not** quark-antiquark states.

They can be meson-meson molecules

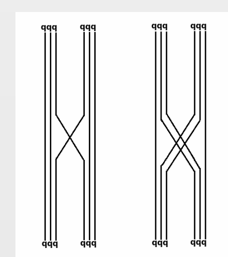


and/or diquark-antidiquark states.



In both cases we have **four-quark** objects.

f0(500) is the lighest scalar states: important in nuclear interaction and in studies of chiral symmetry restorations.



$f_0(500)$: its role at nonzero temperature

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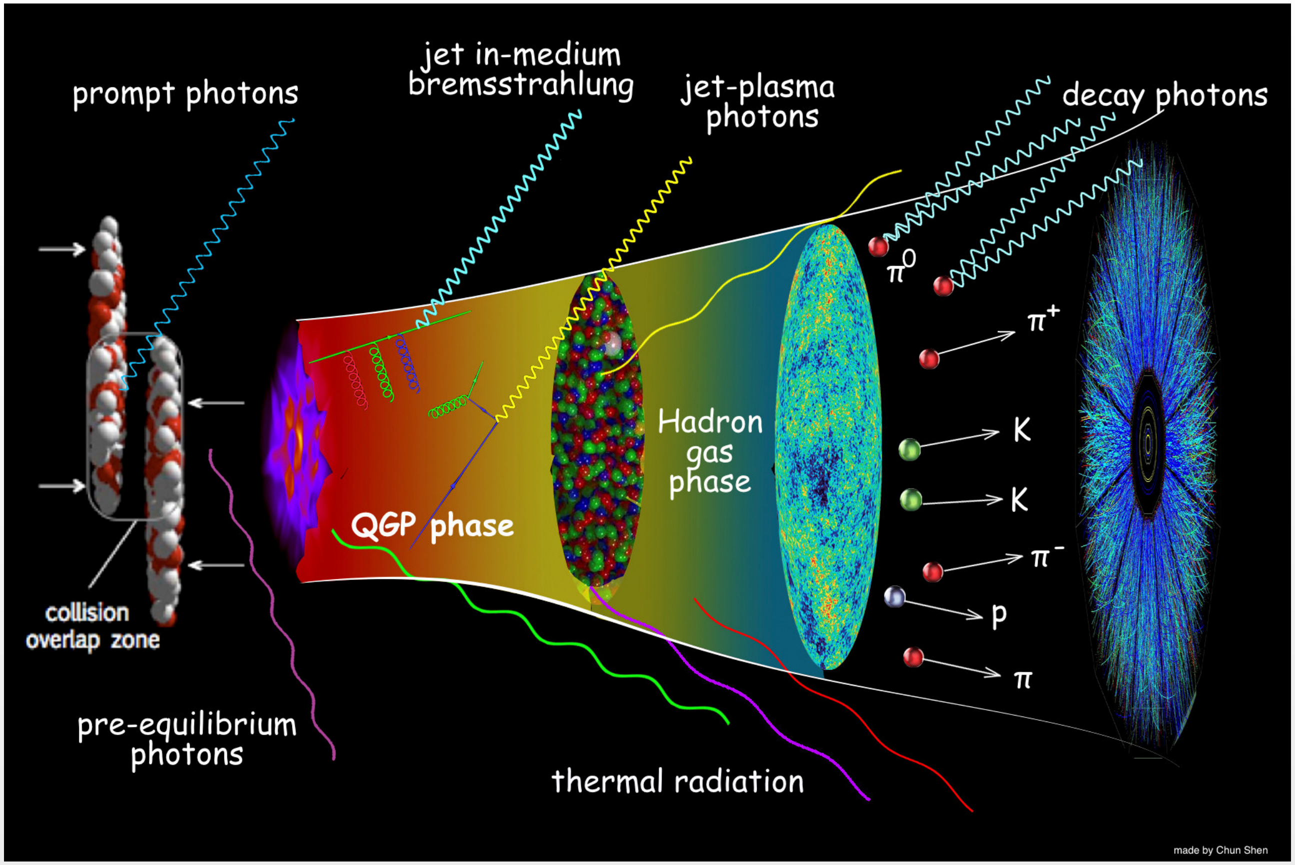
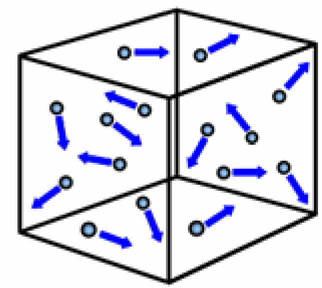
Heavy-ion collisions



At the freeze-out, the emission of hadrons is well described by thermal models.
Question: does the $f_0(500)$ (or σ) play a role? It is light and decays only to pions,
So at first sight yes!

Theoretical description of a thermal gas: stable particles

$$\ln Z = \sum_k \ln Z_k^{\text{stable}} + \sum_k \ln Z_k^{\text{res}}$$



$$\ln Z_k^{\text{stable,}} \quad = f_k V \int \frac{d^3p}{(2\pi)^3} \ln\left[1 \pm e^{-E_p/T}\right]^{\pm 1}$$

$$E_p = \sqrt{\vec{p}^2 + M_k^2}$$

Theoretical description of a thermal gas: unstable particles

$$\ln Z_k^{\mathrm{res}} = f_k V \int_0^\infty d_k(M)\, dM \int \frac{d^3p}{(2\pi)^3} \ln \left[1 - e^{-E_p/T}\right]^{-1}$$

The spectral function $d_k(m)$ can be interpreted as a mass probability density. Namely, a resonance does not have a definite mass but a mass distribution. If not too broad, $d_k(m)$ well described by a Breit-Wigner function. (This is not the case of $f_0(500)$.)

Thermal gas: connection to scattering data

R. Dashen, S.-K. Ma, and H. J. Bernstein, Phys.Rev. **187**, 345 (1969).
R. Dashen and R. Rajaraman, Phys.Rev. **D10**, 694 (1974).

W. Weinhold, B. Friman, and W. Noerenberg, Acta Phys.Polon. **B27**, 3249 (1996).
W. Weinhold, B. Friman, and W. Norenberg, Phys.Lett. **B433**, 236 (1998), arXiv:nucl-th/9710014 [nucl-th].

The spectral function can be directly extracted from two-body scattering data (phase shifts).

$$d_k(M) = \frac{d\delta_k(M)}{\pi dM}$$

Recall from scattering theory:

$$\frac{e^{2i\delta_k} - 1}{2i} = a_k = \frac{-\sqrt{s}\Gamma(\sqrt{s})}{s - m^2 + i\sqrt{s}\Gamma(\sqrt{s})}$$

This is a model-independent way of taking the resonances into account.

Indeed, it is a justification of the validity of thermal gas models.

But it is even more, since it allows also to include repulsions in some channels.

Theoretical description of a thermal gas: QCD

$$\ln Z = \ln Z_\pi + f_{IJ} \int_0^\infty dM \frac{d\delta_{IJ}}{\pi dM} \int \frac{d^3p}{(2\pi)^3} \ln \left[1 - e^{-E_p/T}\right]^{-1}$$

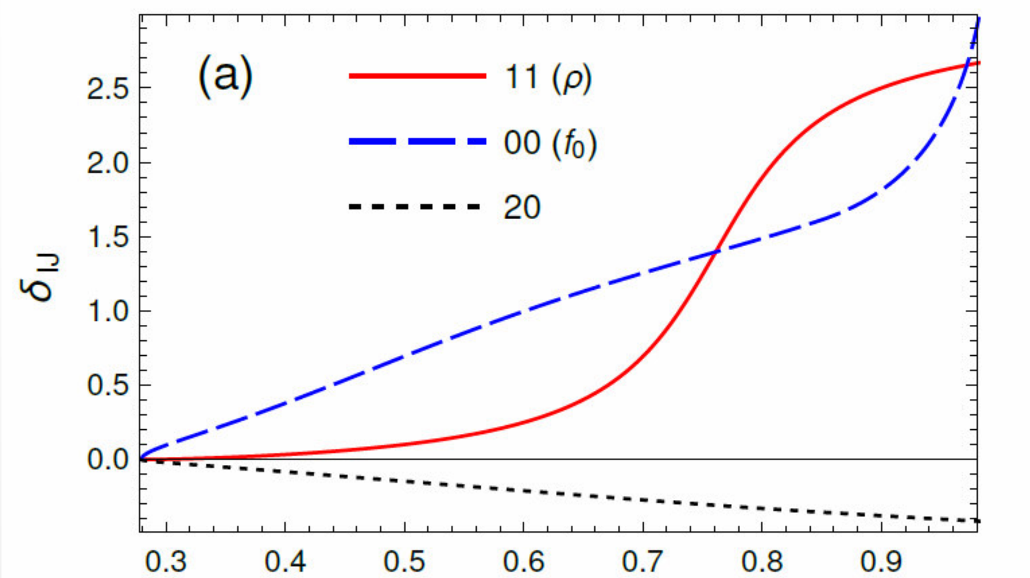
I = isopsin, J = total spin. Sum over I and J understood.

$$f_{IJ} = (2I+1)(2J+1)$$

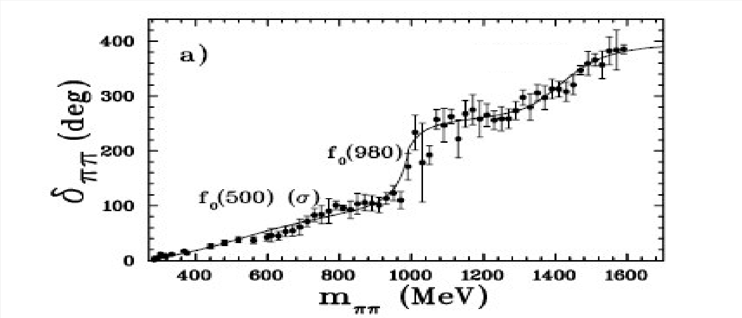
Also in QCD, for many resonances the Breit-Wigner approximation is valid

However, this approximation does not hold for $f_0(500)$. For that we use data.

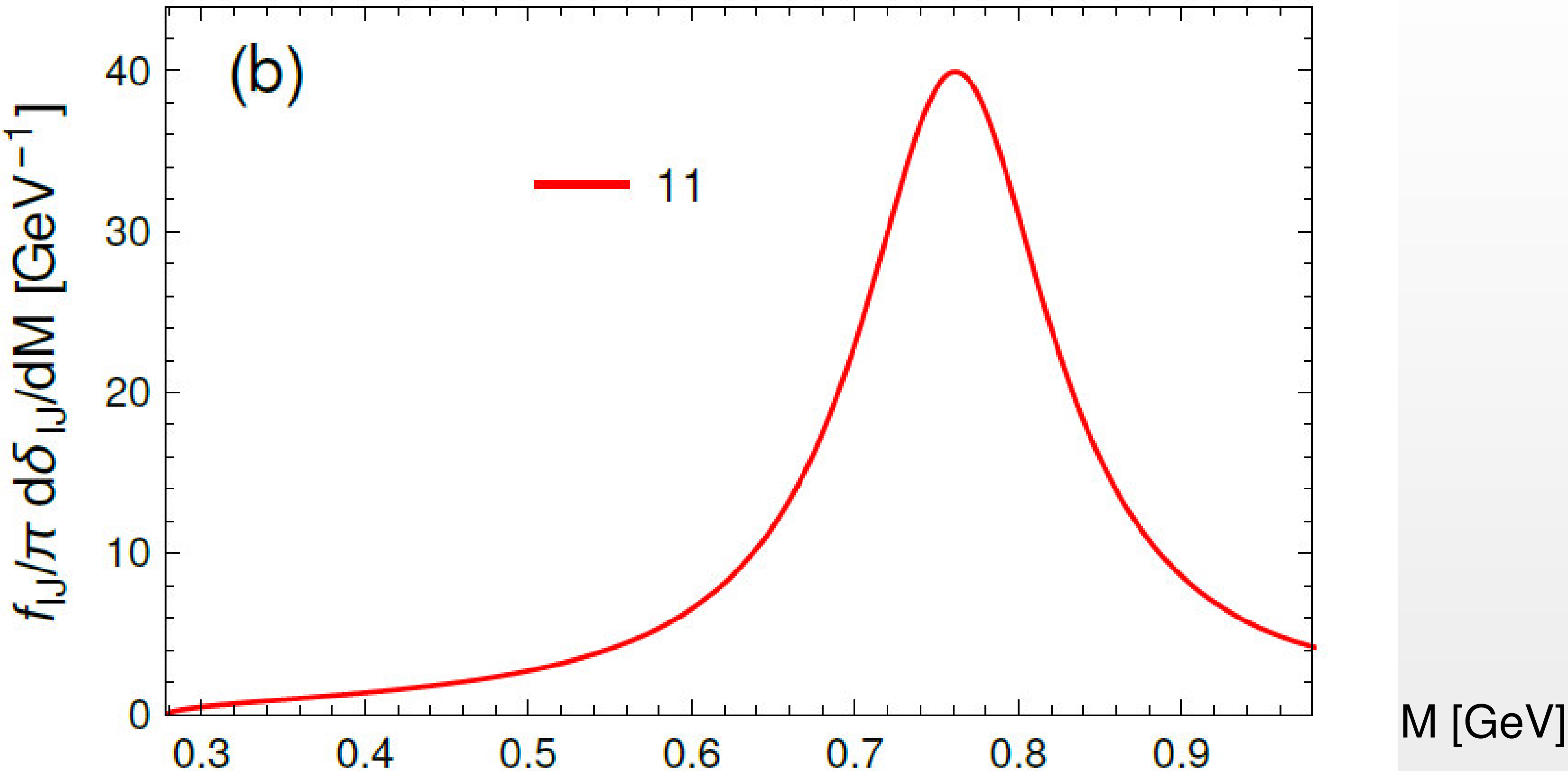
Phase shifts: pion-pion scattering **data!**
Not only I=J=0 but **also** I=2, J=0.



M [GeV]

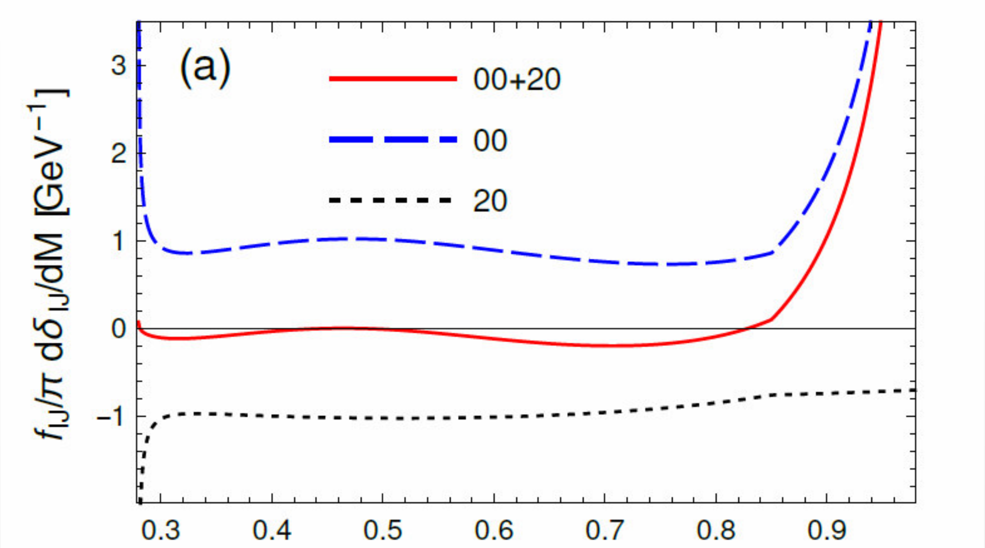


The ρ meson spectral function



$$\ln Z_{(1,1)} = 3 \cdot 3 \int_0^{1\ \mathrm{GeV}} dM \frac{1}{\pi} \frac{d\delta_{(1,1)}}{dM} \int \frac{d^3p}{(2\pi)^3} \ln\left[1 + e^{-\sqrt{p^2+M^2}/T}\right]^{-1}$$

The f0(500) spectral function **and** the isotensor repulsion



M [GeV]

The total contribution from J=0 is the red curve: almost zero!

$$\ln Z_{(0,0)} + \ln Z_{(2,0)} = \int_0^{0.8\ \mathrm{GeV}} dM \frac{1}{\pi}\left(\frac{d\delta_{(0,0)}}{dM} + 5\frac{d\delta_{(2,0)}}{dM}\right)\int \frac{d^3p}{(2\pi)^3} \ln\left[1 + e^{-\sqrt{p^2+M^2}/T}\right]^{-1} \simeq 0$$

lnZ(0,0) is the contribution of f0(500). It is indeed nonzero and even non-negligible, but it is almost exactly cancelled by the isotensor repulsion. Thermal models however usually neglect repulsions.

Either take into account both I=0 and I =2, or –simply- neglect both of them!

Details in: W. Broniowski, F.G., V. Begun, Phys.Rev. C 92 (2015) 3, 034905 arxiv: 1506.01260.

The scalar kaonic resonace $K_0^*(800)$

Citation: K.A. Olive *et al.* (Particle Data Group), Chin. Phys. C, **38**, 090001 (2014) and 2015 update

$K_0^*(800)$
or κ

$I(J^P) = \frac{1}{2}(0^+)$

OMITTED FROM SUMMARY TABLE

Needs confirmation. See the mini-review on scalar mesons under $f_0(500)$ (see the index for the page number).

$K_0^*(800)$ MASS

VALUE (MeV)		*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
682	**±29**	**OUR AVERAGE**	Error includes scale factor of 2.4. See the ideogram below.		

Talk of **M. Sołtysiak**, tomorrow at 11:35 (On the nature of K0*(800))

$f_0(500)$ at finite density

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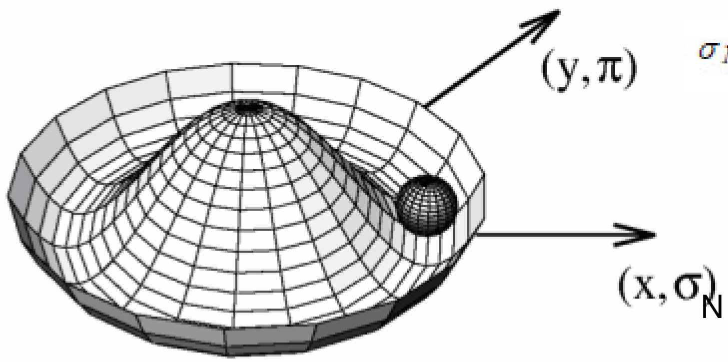
Chiral models based on Mexican-hat



$\sigma_N = \bar{u}u + \bar{d}d$ is a quark-antiquark state. It corresponds to $f_0(1370)$.

$\langle \sigma_N \rangle = \phi$ is the chiral condensate.

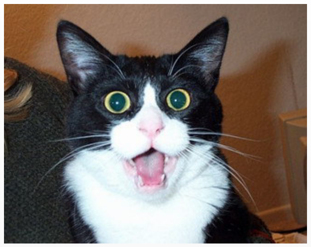
$\chi = \pi\pi$ and/or $[\bar{u}, d][u, d]$ is a four-quark state. It corresponds to $f_0(500)$.

$\langle \chi \rangle = \chi_0$ is the four-quark condensate.

We expect two condensates: a quark-antiquark and a four-quark condensate.

Need of a specific chiral model.
Extended Linear Sigma Model was developed in Ffm in the last years.

Model of QCD – eLSM – Mesons



$$
\begin{aligned}
\mathcal{L} \;=\; & \frac{1}{2}(\partial_\mu G)^2 - \frac{1}{4}\frac{m_G^2}{\Lambda^2}\left(G^4 \ln\left|\frac{G}{\Lambda}\right| - \frac{G^4}{4}\right) + \mathrm{Tr}\left[(D^\mu\Phi)^\dagger(D_\mu\Phi)\right] \\
& - m_0^2\left(\frac{G}{G_0}\right)^2 \mathrm{Tr}\left[\Phi^\dagger\Phi\right] - \lambda_1\left(\mathrm{Tr}\left[\Phi^\dagger\Phi\right]\right)^2 - \lambda_2 \mathrm{Tr}\left[(\Phi^\dagger\Phi)^2\right] \\
& + \left(\frac{G}{G_0}\right)^2 \mathrm{Tr}\left[\left(\frac{m_1^2}{2} + \Delta\right)\left((L^\mu)^2 + (R^\mu)^2\right)\right] \\
& - \frac{1}{4}\mathrm{Tr}\left[(L^{\mu\nu})^2 + (R^{\mu\nu})^2\right] + \mathrm{Tr}\left[H\left(\Phi^\dagger + \Phi\right)\right] \\
& + c_1[\det(\Phi) - \det(\Phi^\dagger)]^2 + \frac{h_1}{2}\mathrm{Tr}[\Phi^\dagger\Phi]\mathrm{Tr}[L_\mu L^\mu + R_\mu R^\mu] \\
& + h_2 \mathrm{Tr}[\Phi^\dagger L_\mu L^\mu \Phi + \Phi R_\mu R^\mu \Phi^\dagger] + 2h_3 \mathrm{Tr}[\Phi R_\mu \Phi^\dagger L^\mu]
\end{aligned}
$$

$$
\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix}
\frac{(\sigma_N + a_0^0) + i(\eta_N + \pi^0)}{\sqrt{2}} & a_0^+ + i\pi^+ & K_0^{\star +} + iK^+ \\
a_0^- + i\pi^- & \frac{(\sigma_N - a_0^0) + i(\eta_N - \pi^0)}{\sqrt{2}} & K_0^{\star 0} + iK^0 \\
K_0^{\star -} + iK^- & \bar{K}_0^{\star 0} + i\bar{K}^0 & \sigma_S + i\eta_S
\end{pmatrix}
$$

$$
L^\mu, R^\mu = \frac{1}{\sqrt{2}}\begin{pmatrix}
\frac{\omega_N \pm \rho^0}{\sqrt{2}} \pm \frac{f_{1N} \pm a_1^0}{\sqrt{2}} & \rho^+ \pm a_1^+ & K^{\star +} \pm K_1^+ \\
\rho^- \pm a_1^- & \frac{\omega_N \mp \rho^0}{\sqrt{2}} \pm \frac{f_{1N} \mp a_1^0}{\sqrt{2}} & K^{\star 0} \pm K_1^0 \\
K^{\star -} \pm K_1^- & \bar{K}^{\star 0} \pm i\bar{K}_1^0 & \omega_S \pm f_{1S}
\end{pmatrix}
$$

S. Janowski, D. Parganlija, F. Giacosa, D. H. Rischke, **Phys. Rev. D84, 054007 (2011**)
D. Parganlija, P. Kovacs, G. Wolf , F. Giacosa, D. H. Rischke, **Phys.Rev. D87 (2013) 014011**

Model of QCD – eLSM – Baryons

$$\mathcal{L}_{eLSM} = \bar{\Psi}_{1L} i\gamma_\mu D^\mu_{1L} \Psi_{1L} + \bar{\Psi}_{1R} i\gamma_\mu D^\mu_{1R} \Psi_{1R} + \bar{\Psi}_{2L} i\gamma_\mu D^\mu_{2R} \Psi_{2L} + \bar{\Psi}_{2R} i\gamma_\mu D^\mu_{2L} \Psi_{2R}$$
$$- \hat{g}_1 (\bar{\Psi}_{1L} \Phi \Psi_{1R} + \bar{\Psi}_{1R} \Phi^+ \Psi_{1L}) - \hat{g}_2 (\bar{\Psi}_{2L} \Phi^+ \Psi_{2R} + \bar{\Psi}_{2R} \Phi \Psi_{2L})$$
$$- a\chi (\bar{\Psi}_{1L} \Psi_{2R} - \bar{\Psi}_{1R} \Psi_{2L} - \bar{\Psi}_{2L} \Psi_{1R} + \bar{\Psi}_{2R} \Psi_{1L})$$

$$D^\mu_{1R} = \partial^\mu - ic_1 R^\mu \;,\; D^\mu_{1L} = \partial^\mu - ic_1 L^\mu$$

$$D^\mu_{2R} = \partial^\mu - ic_2 R^\mu, \; D^\mu_{2L} = \partial^\mu - ic_2 L^\mu$$

S. Gallas, F. G., D. H. Rischke, Phys. Rev. D. 82 (2010) 014004 ; arXiv: 0907.5084
S. Gallas, F. G., G. Pagliara, Nucl. Phys. A 872 (2011), arXiv: 1105.5003

Four-quark state χ=f0(500) coupled in chirally invariant way.

Talk of **L. Olbrich**, tomorrow at 18:25 (A three-flavor model)

Origin of the nucleon mass

$$m_N = m_N(\phi, \chi_0) = \sqrt{a^2\chi_0^2 + ((\hat{g}_1 + \hat{g}_2)\phi/4)^2 + ((\hat{g}_1 - \hat{g}_2)\phi/4)}$$

If $a\chi_0 = 0 \rightarrow m_N = \frac{1}{2}\hat{g}_1\phi$

old linear sigma models, but they do not work

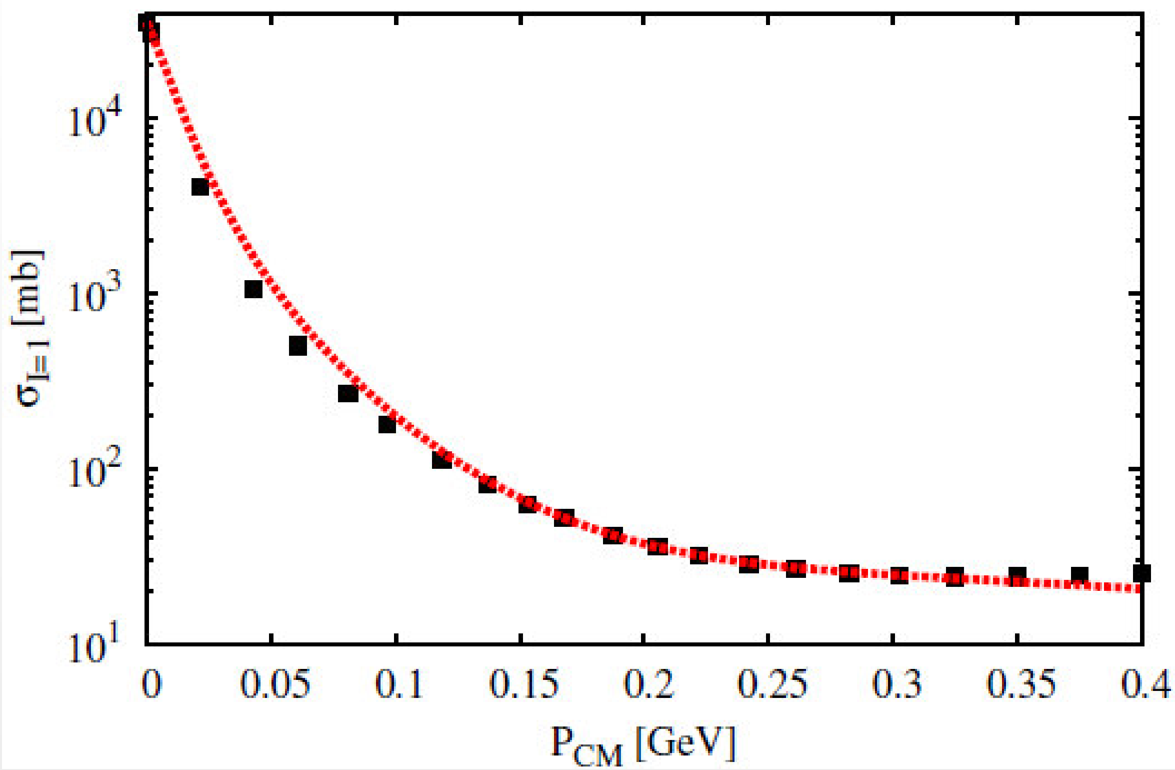
$$m_0 = a\chi_0 \simeq 500 \text{ MeV}$$

is the mass which contribution arising from the four-quark condensate

This is the mechanism generating to 95% of the visible Universe's visible mass.

It is not the Higgs!!! Higgs is only responsible for the remaining 5%.

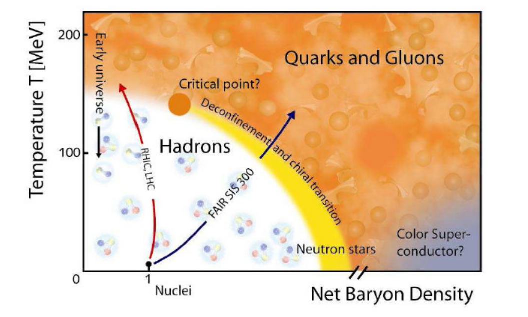
Neutron-Proton I=1 scattering: preliminary!



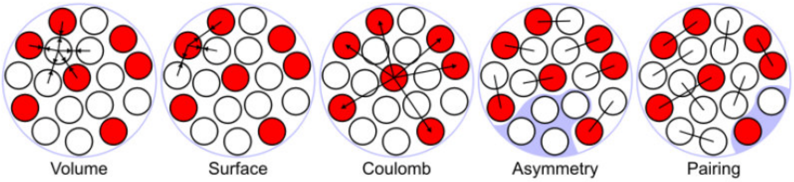
Role of f0(500) crucial above 200 MeV.
W. Deinet, K. Teilab, F.G., D. Rischke, in preparation.

SAID Data of the CNS data analysis center

Description of nuclear matter



Bethe-Weizsäcker formula:



$$E_B = a_V A - a_s A^{2/3} - a_C \frac{Z^2}{A^{1/3}} - a_A \frac{(A-2Z)^2}{A} + \delta(A, Z)$$

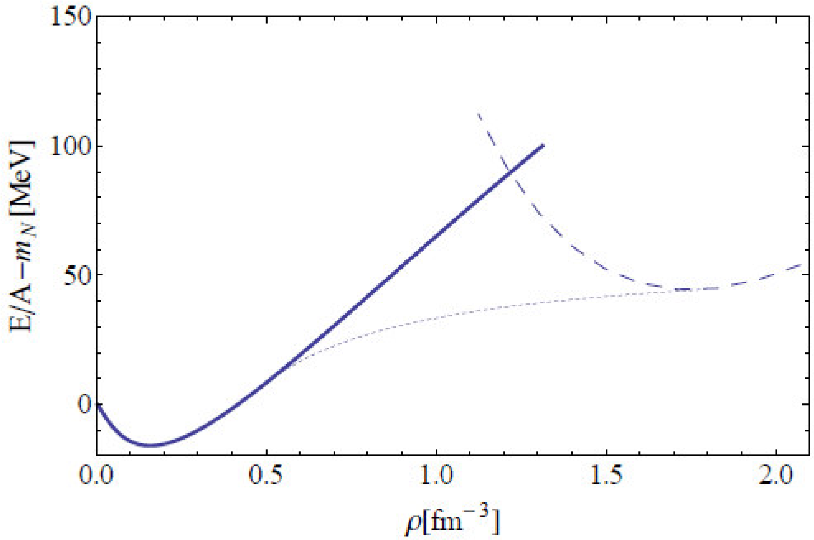
A: number of nucleons, Z: number of protons

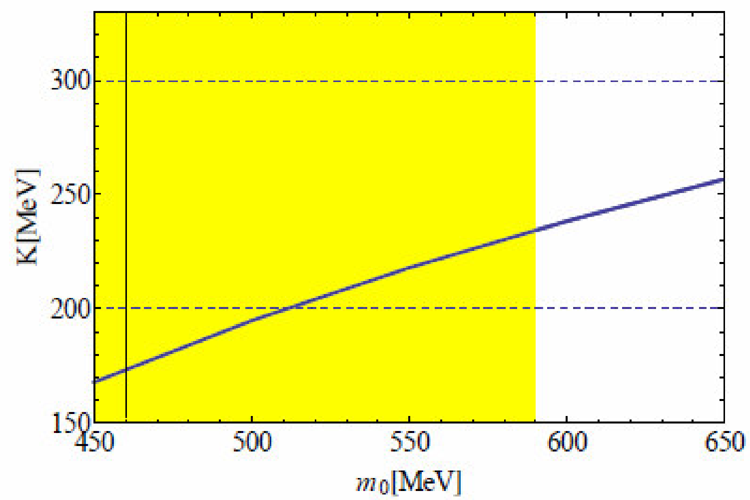
For large systems $A \to \infty$ and neglecting a_c:

$$E_B/A(\rho_0) = E/A(\rho_0) - m_N = -16 \text{ MeV}$$

with $\rho_0 = 0.16\ \text{fm}^{-3}$ and $m_N = 939$ MeV.

Nuclear matter saturation and compressibilty



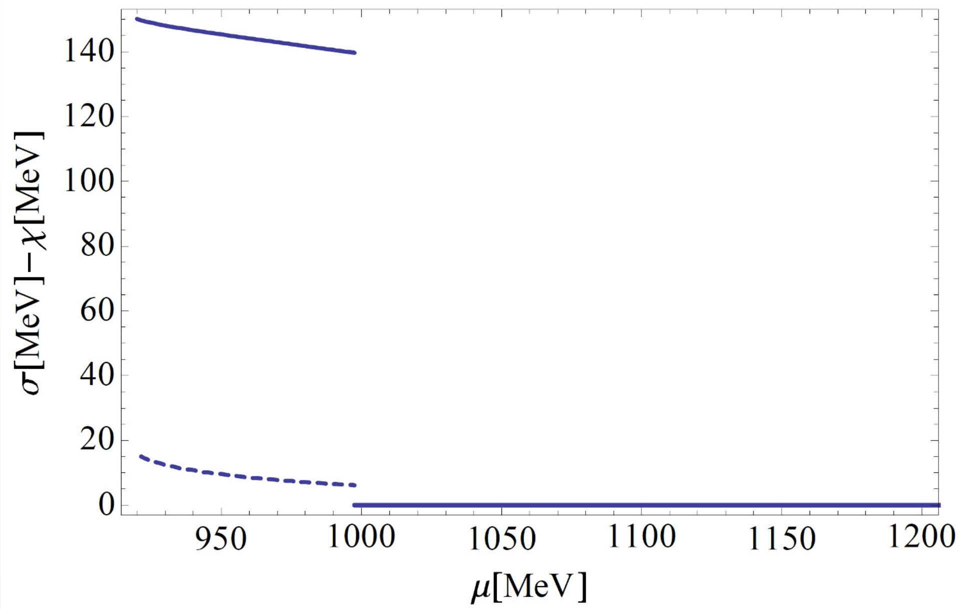


f_0(500) again important.

K=200-230 MeV in agreement with exp.

Details in: S. Gallas, F. G:, G. Pagliara, **Nucl.Phys. A872 (2011) 13-24 arXiv:1105.5003**

Chiral phase transition



arXiv:1105.5003

Critical density at the onset of chiral restoration (first order):

$$\rho_{crit} / \rho_0 \approx 2.5$$

(slightly dependent on m0)

Conclusions

The $f_0(500)$ is a well-established scalar-isoscalar meson which –however- is not relevant in isospin-averaged thermal observables.
This is due to the repulsion in the isotensor channel, which 'de facto' cancels the effect that $f_0(500)$.

Summary for thermal-models: neglect the the $f_0(500)$ and also the isotensor repulsion.

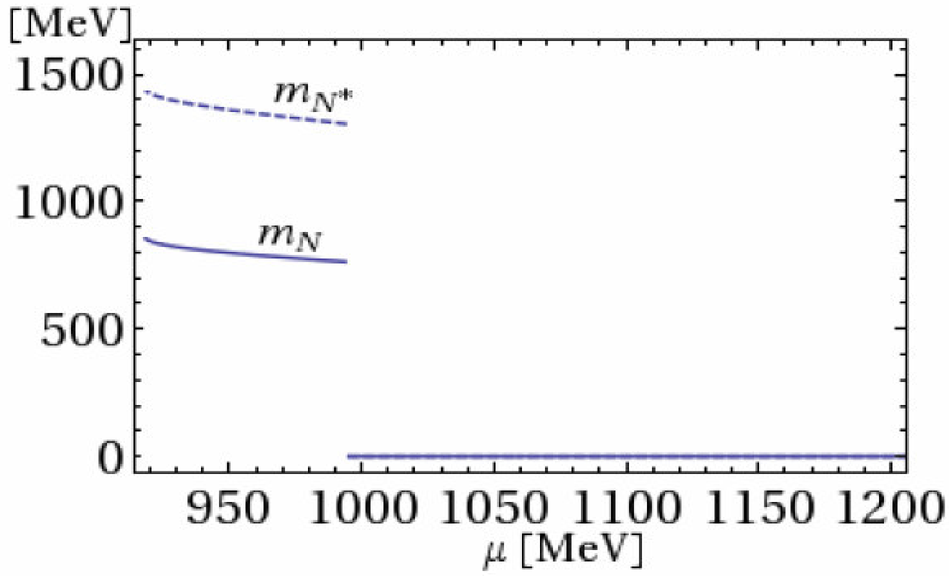
On the other hand: $f_0(500)$ is important for nucleon-nulceon interaction and for the binding of nuclei, and in the context of chiral restoration at finite density.

Summary for model-builders: include $f_0(500)$ since it is important.

Thank You

Chiral phase transition/2

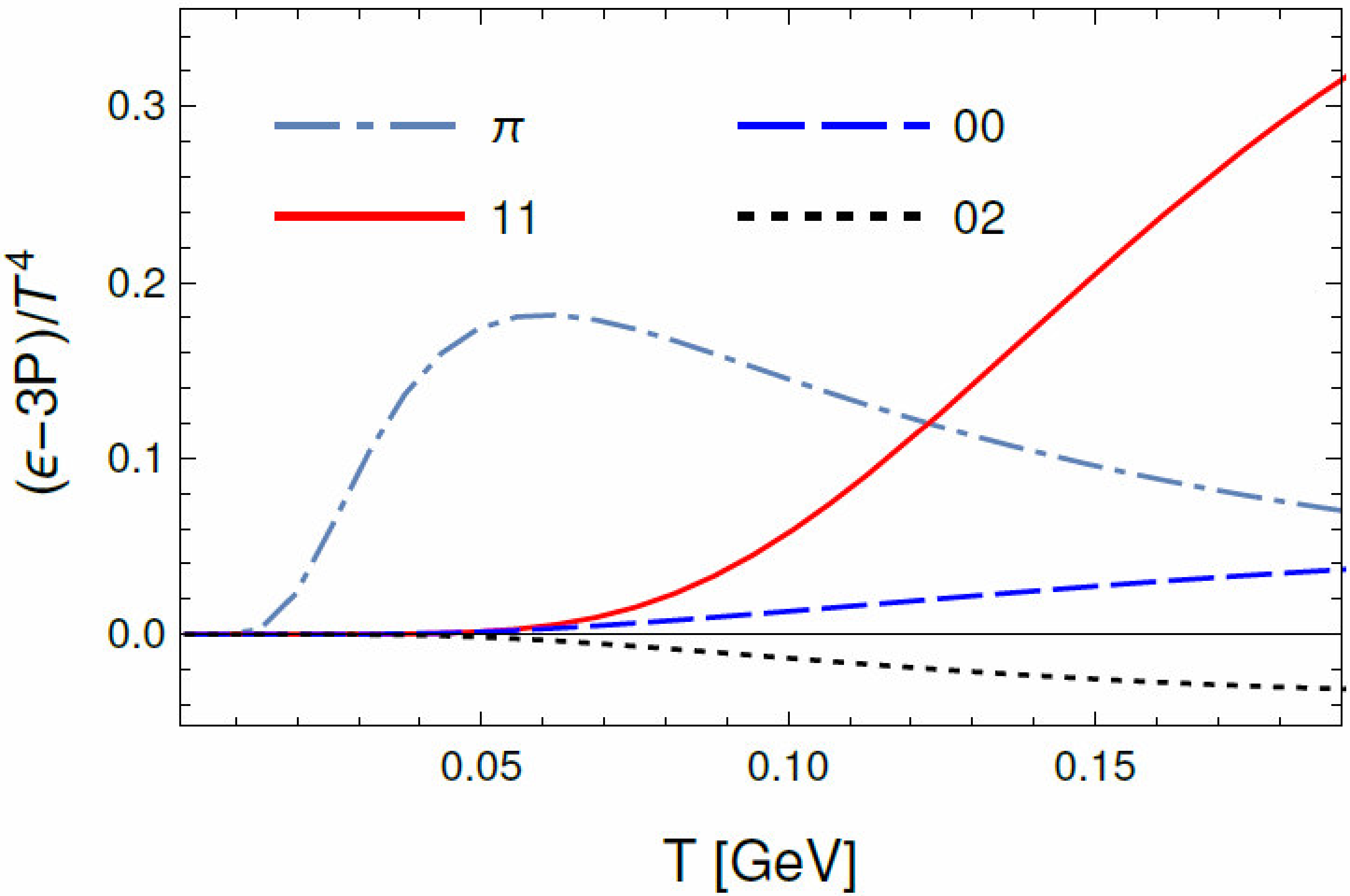
Masses



The masses drop almost to zero above the critical value of the chemical potential.

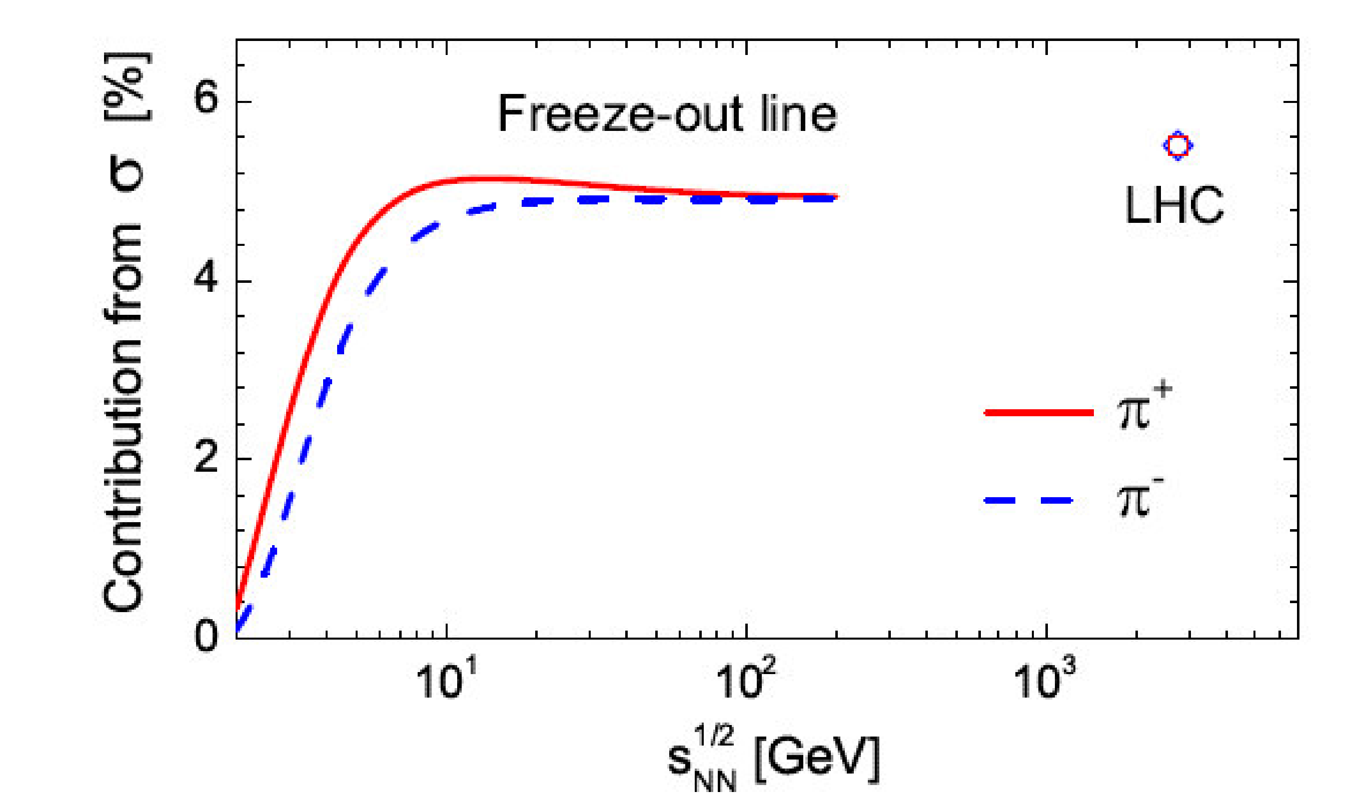
arXiv:1105.5003

Example 1: the trace anomaly



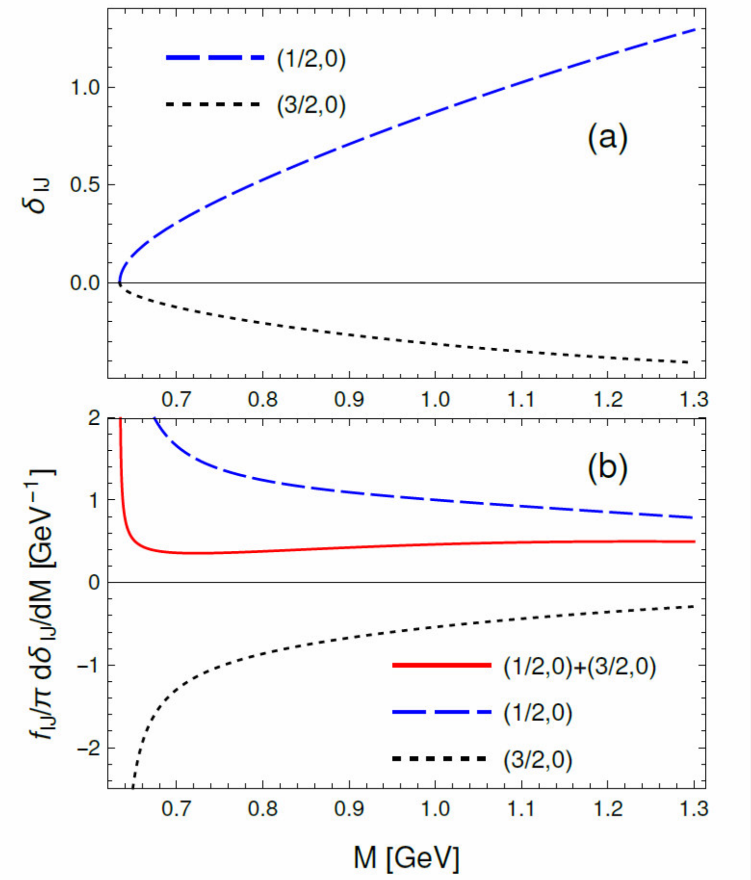
arxiv: 1506.01260

Example 2: the **would-be** contribution of pions from f0(500) in A-A collisions (using SHARE)



Breit-Wigner with mass 0.484 GeV and width 510 MeV was used.
The 'improper' treatment of f0(500) is roughly a 5% effect.

The scalar kaonic resonace $K_0^*(800)$: partial cancellation



Similar result: a cancellation is evident (even if not so precise as for $f_0(500)$)

Phase-shift and scattering

$$\frac{e^{2i\delta_k}-1}{2i}=a_k=\frac{-\sqrt{s}\Gamma(\sqrt{s})}{s-m^2+i\sqrt{s}\Gamma(\sqrt{s})}$$