The role of the σ-meson in thermal models

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Outline

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

Inclusion in a thermal model? Why one should **not**.

The similar case $K_0^*(800)$.

Summary

Existence and pole position of $f_0(500)$

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 $m = (400\text{–}550)$ MeV
Full width $\Gamma = (400\text{–}700)$ 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 $f_0(600)$

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

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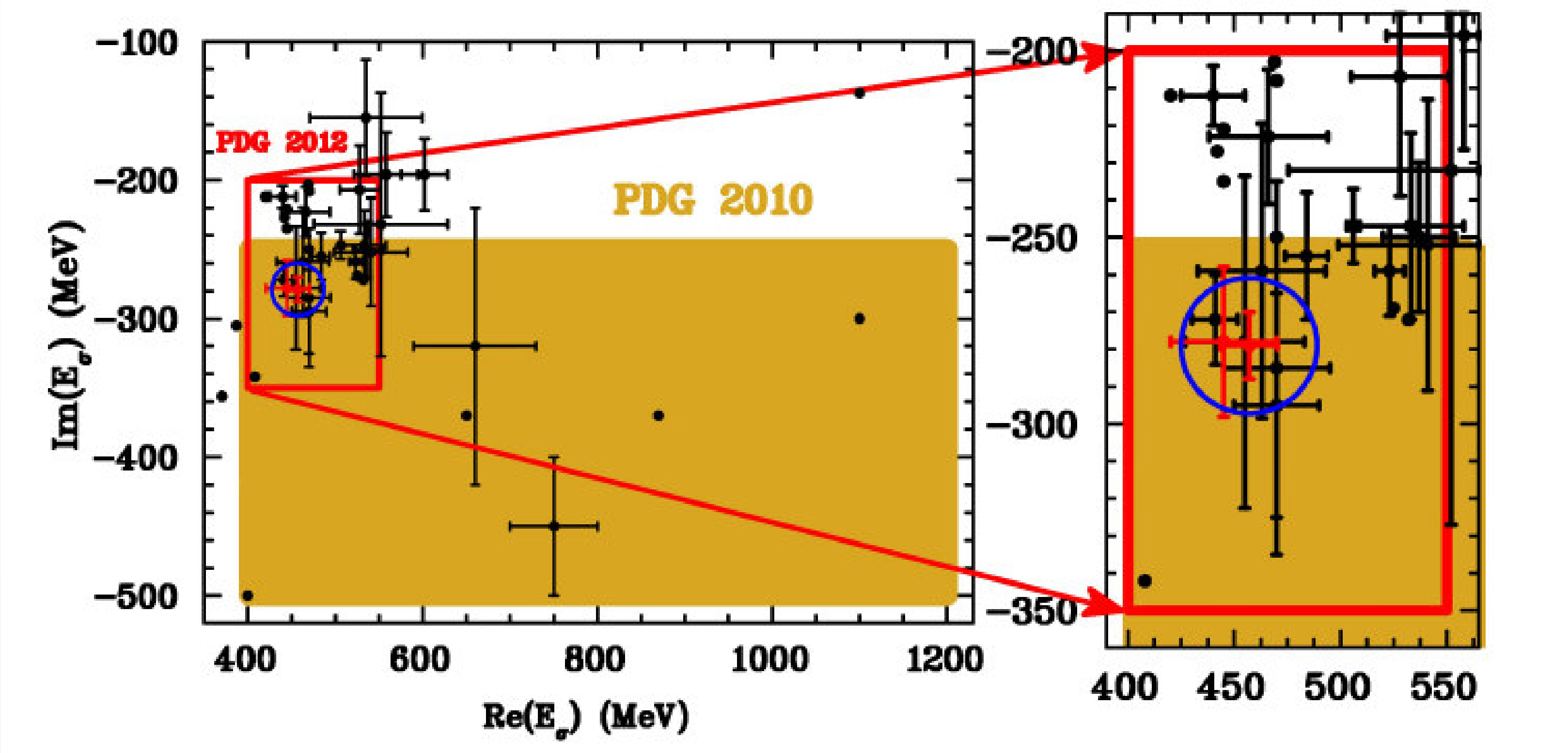
$f_0(500)$ T-MATRIX POLE $\sqrt{s}$

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

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

Existence and pole position of f0(500)

From 2010 to 2012: update…



J.R. Pelaez (Madrid U.). e-Print: **arXiv:1510.00653**
From controversy to precision on the sigma meson:
a review on the status of the non-ordinary f0(500) **resonance**

Madrid-Krakow and Bern results for the poles

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

	$\sqrt{s_{\rm pole}}$ (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
$f_0(980)^{\rm GKPY}$	$(996 \pm 7) - i(25^{+10}_{-6})$	2.3 ± 0.2 GeV
$f_0(980)^{\rm Roy}$	$(1003^{+5}_{-27}) - i(21^{+10}_{-8})$	$2.5^{+0.2}_{-0.6}$ GeV
$\rho(770)^{\rm GKPY}$	$(763.7^{+1.7}_{-1.5}) - i(73.2^{+1.0}_{-1.1})$	$6.01^{+0.04}_{-0.07}$
$\rho(770)^{\rm Roy}$	$(761^{+4}_{-3}) - i(71.7^{+1.9}_{-2.3})$	$5.95^{+0.12}_{-0.08}$

*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).

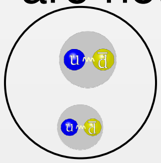
The light scalar mesons: what are they?

$$a_0(980) \quad k(800) \quad \mathrm{f}_0(980) \quad \mathrm{f}_0(500)$$

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

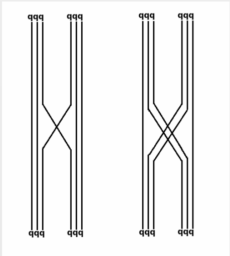
Various studies show that these states they are not quark-antiquark states.

They can be meson-meson molecules



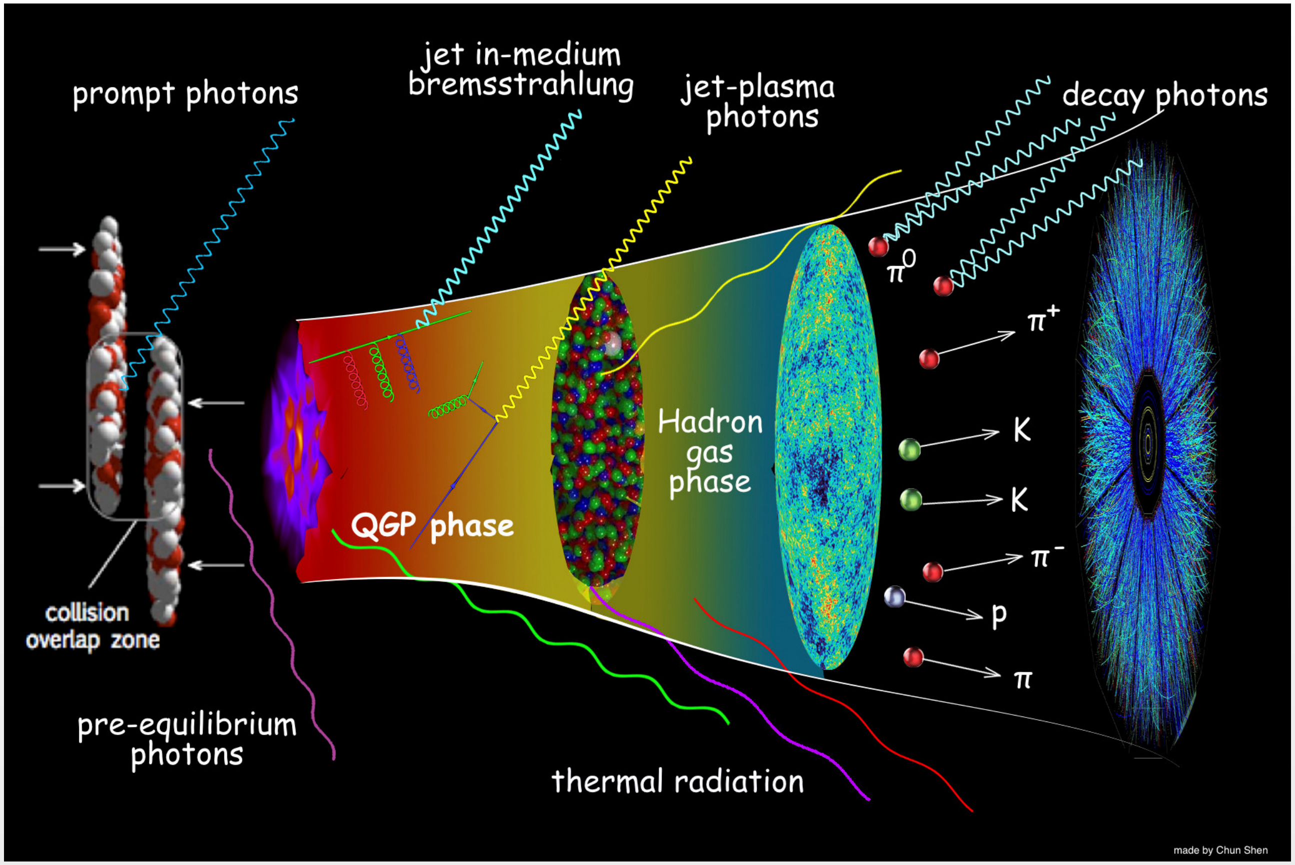
and/or diquark-antidiquark states.

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



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

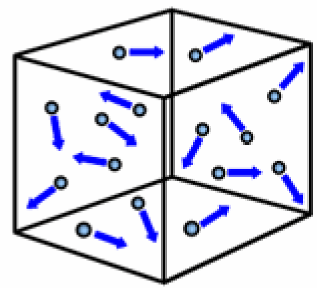
Heavy-ion collisions



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/1

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



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

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

Theoretical description of a thermal gas/2

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

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 it is not too broad, $d_k(m)$ can be approximated by a Breit-Wigner function. (This is not the case of $f_0(500)$.)

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

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

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].

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

Theoretical description of a thermal gas: QCD

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

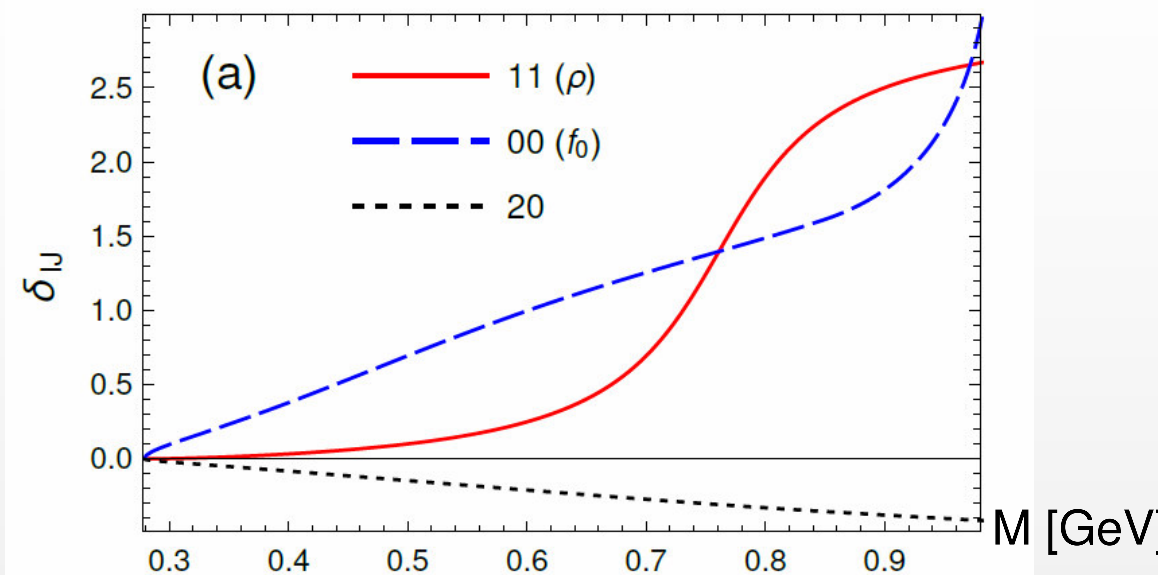
I = isopsin, J = total spin. $f_{IJ} = (2I+1)(2J+1)$

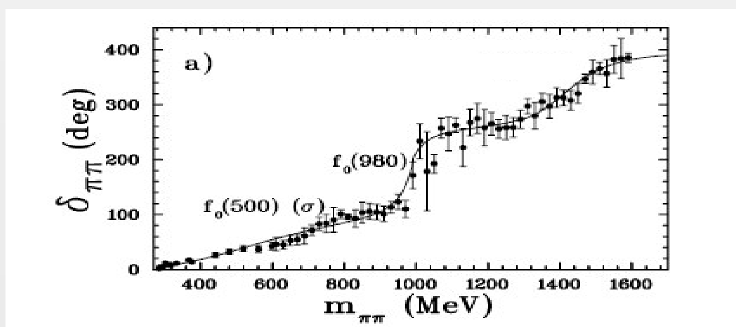
Also in QCD, for many resonances the Breit-Wigner approximation is valid

$$\frac{d\delta_{IJ}}{\pi dM} \simeq \sum_k \frac{\Gamma_{IJ,k}}{2\pi} \left[(M - M_{IJ,k})^2 + \frac{\Gamma_{IJ,k}^2}{4}\right]^{-1}$$

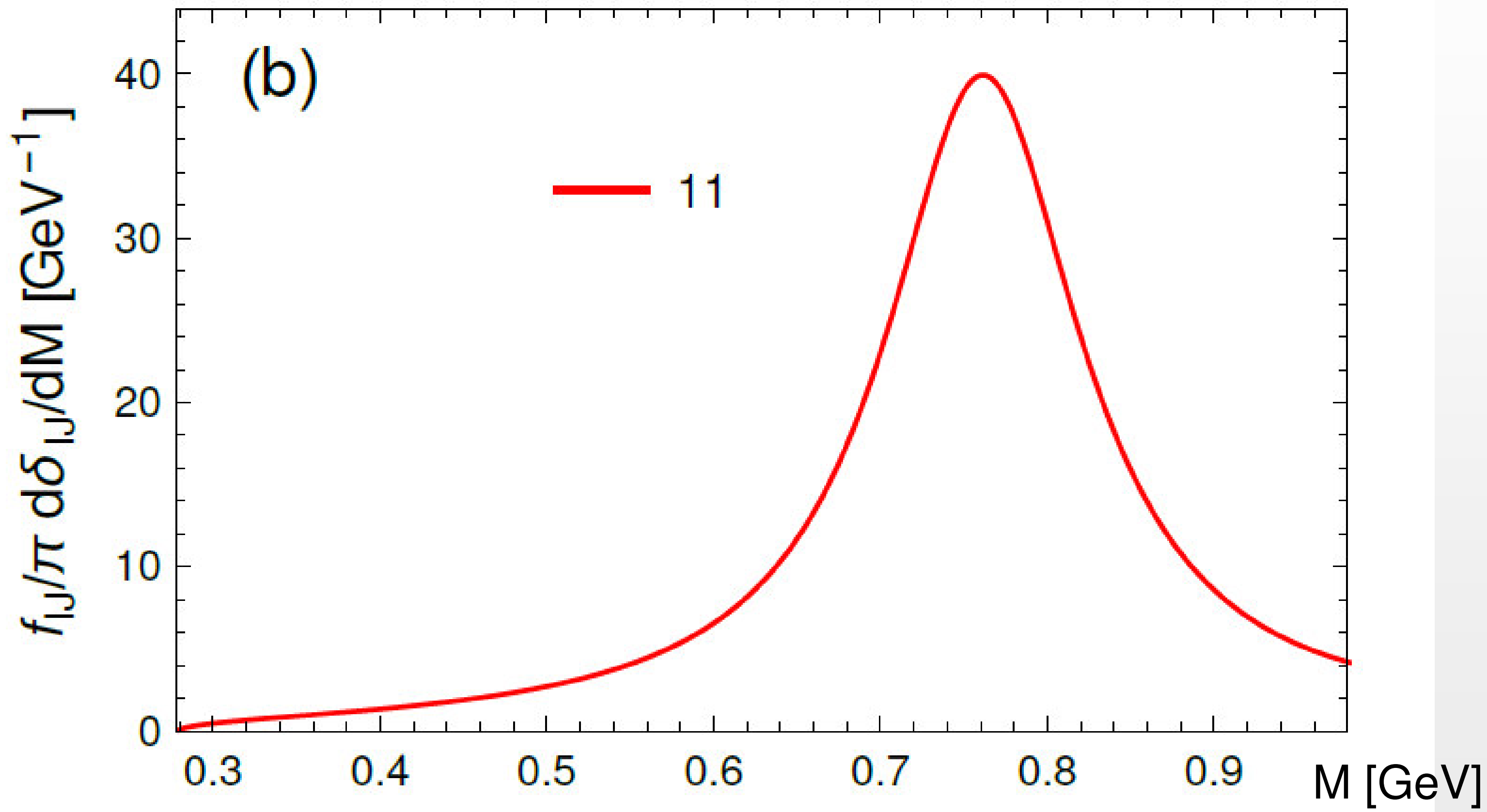
However, this approximation does not hold for $f_0(500)$.

Phase shifts: pion-pion scattering **data!**

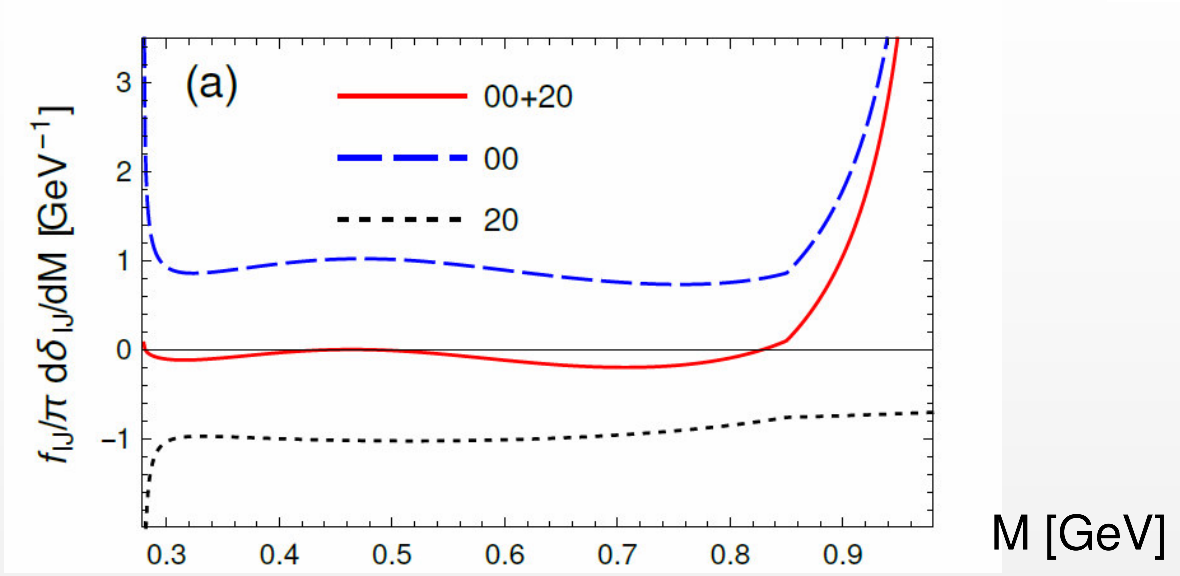




The ρ meson spectral function



The $f_0(500)$ spectral function **and** the isotensor repulsion



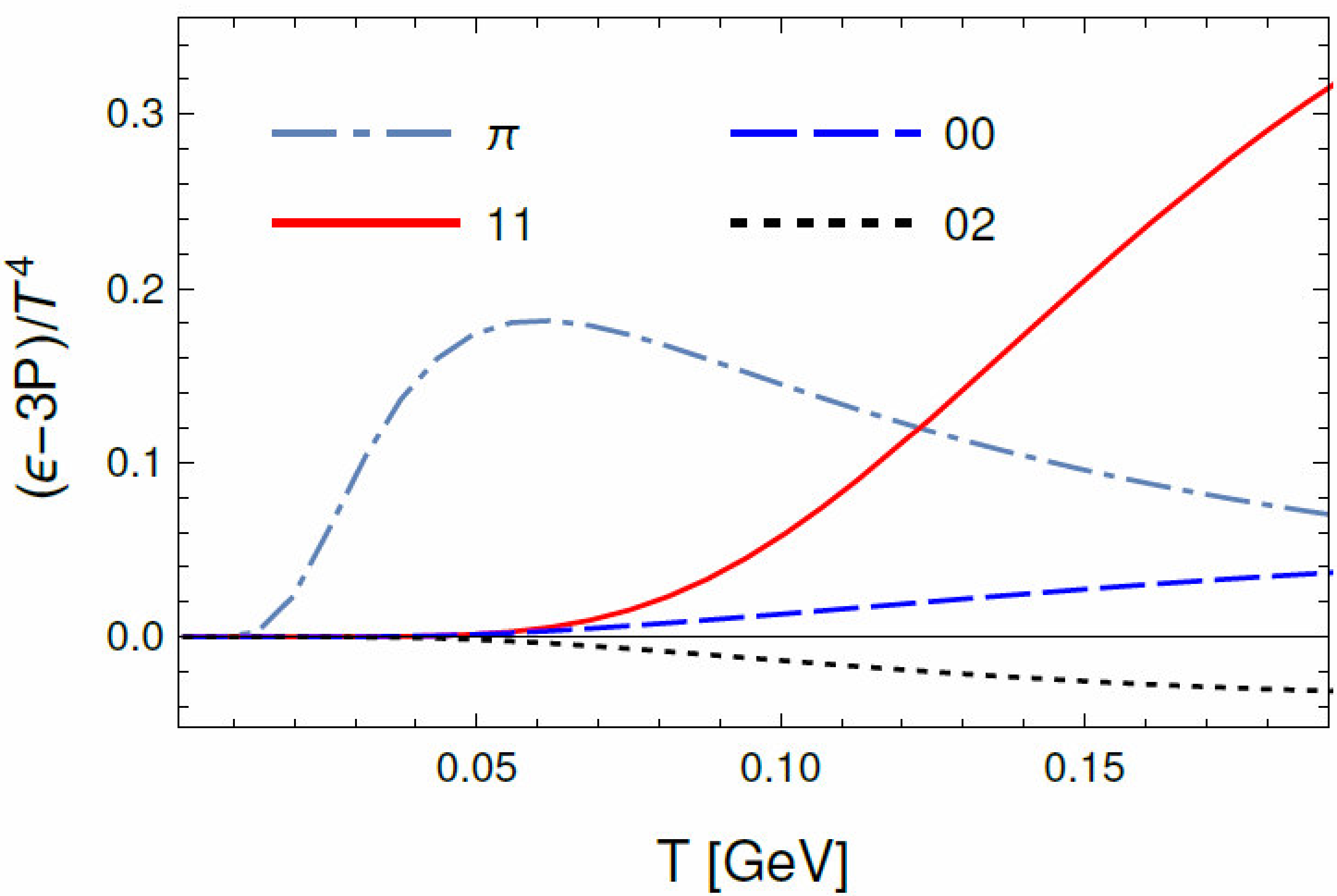
arxiv: 1506.01260

The total contribution from J=0 is the red curve: $\ln Z_{(0,0)} + \ln Z_{(2,0)}$

$\ln Z_{(0,0)}$ is the contribution of $f_0(500)$. It is indeed nonzero and even non-negligible, but it is almost exactly cancelled by the isotensor repulsion. Thermal models however usually neglect repulsions.

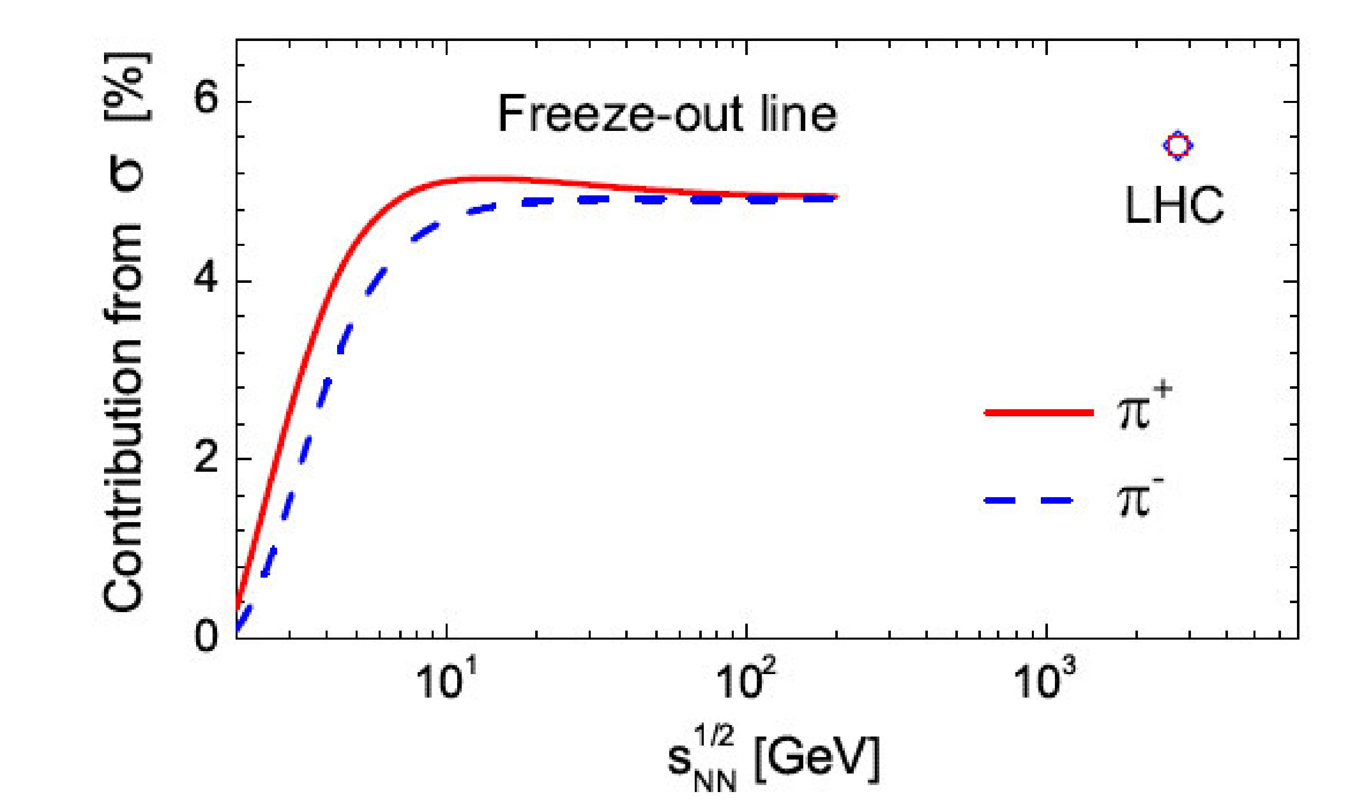
Either you take into account both I=0 and I =2, or –simply- you neglect both of them

Example 1: the trace anomaly



arxiv: 1506.01260

Example 2: the **would-be** contribution of pions from $f_0(500)$ in A-A collisions (using SHARE)



Breit-Wigner with mass 0.484 GeV and width 510 MeV was used.
The ‘improper’ treatment of $f_0(500)$ is roughly a 5% effect.

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

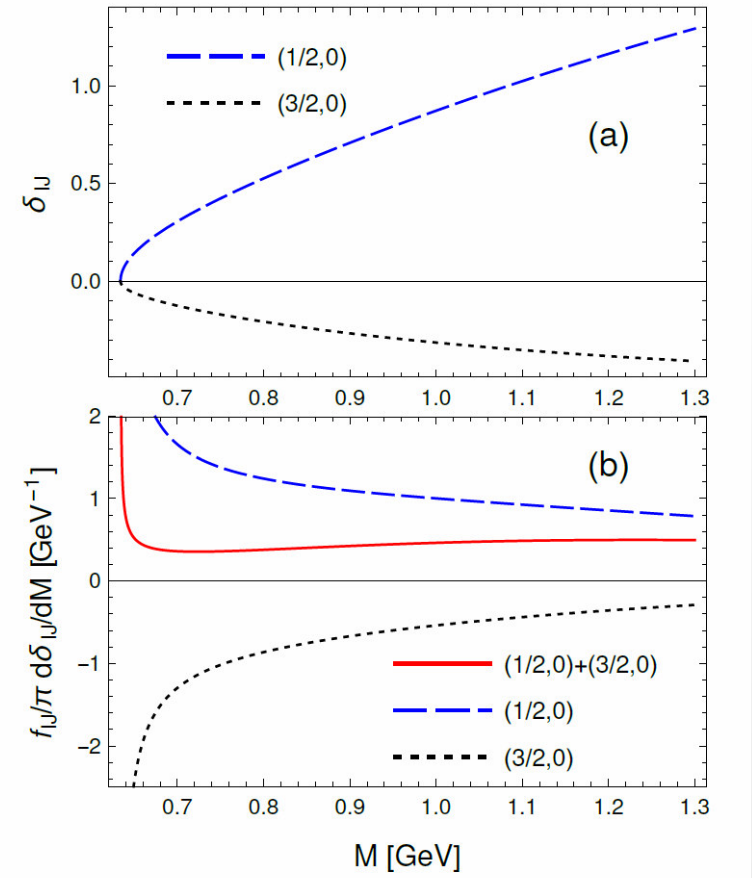
Needs confirmation. See the mini-review on scalar mesons under $f_0(500)$ (see the index for the page number).

$K_0^*(800)$ 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 10:15 (K0*(800) as a companion pole of K0*(1450))

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



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

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 $f_0(500)$ (or σ) and also the isotensor repulsion.

Similar conclusion for $K_0^*(800)$.

However: when studying correlated $\pi^+\pi^-$ pair production, the cancellation does not occur and an effect of the $f_0(500)$ is still present.

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

Thank You