The phi meson in nuclear matter recent results from QCD sum rules and effective theories

P. Gubler and K. Ohtani, Phys. Rev. D **90**, 094002.

P. Gubler and W. Weise, arXiv:1507.03769 [hep-ph].

Talk at the ACHT 2015 workshop,

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Introduction

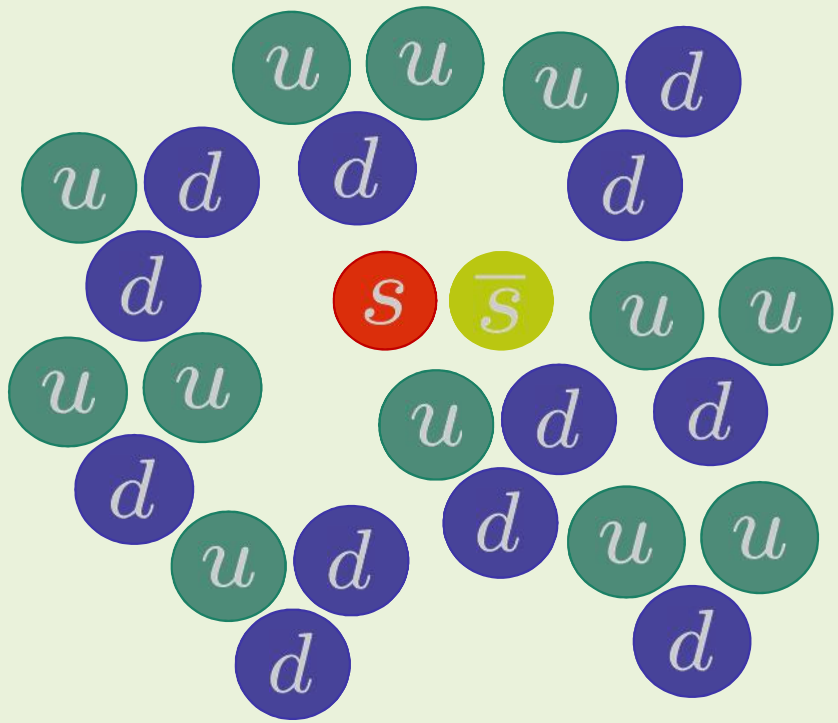
Object of study:

ϕ meson

$m_\phi = 1019$ MeV

$\Gamma_\phi = 4.3$ MeV

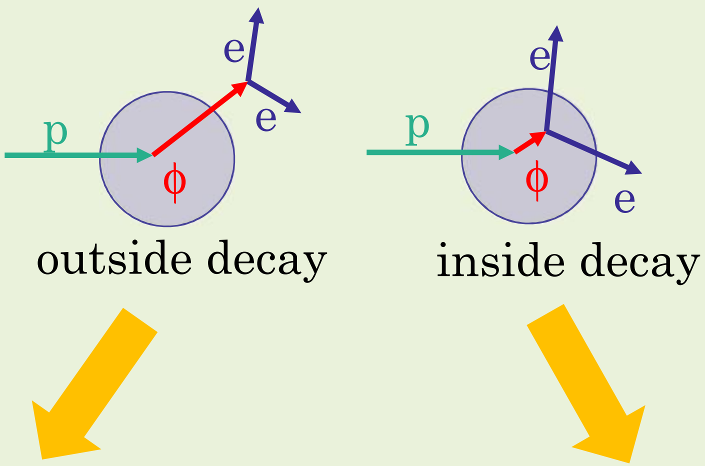
Interest:



Experimental developments

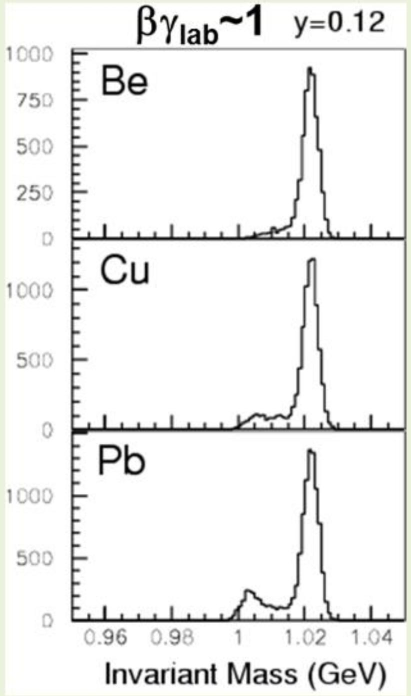
The E325 Experiment (KEK)

Slowly moving ϕ mesons are produced in 12 GeV *p+A* reactions and are measured through di-leptons.



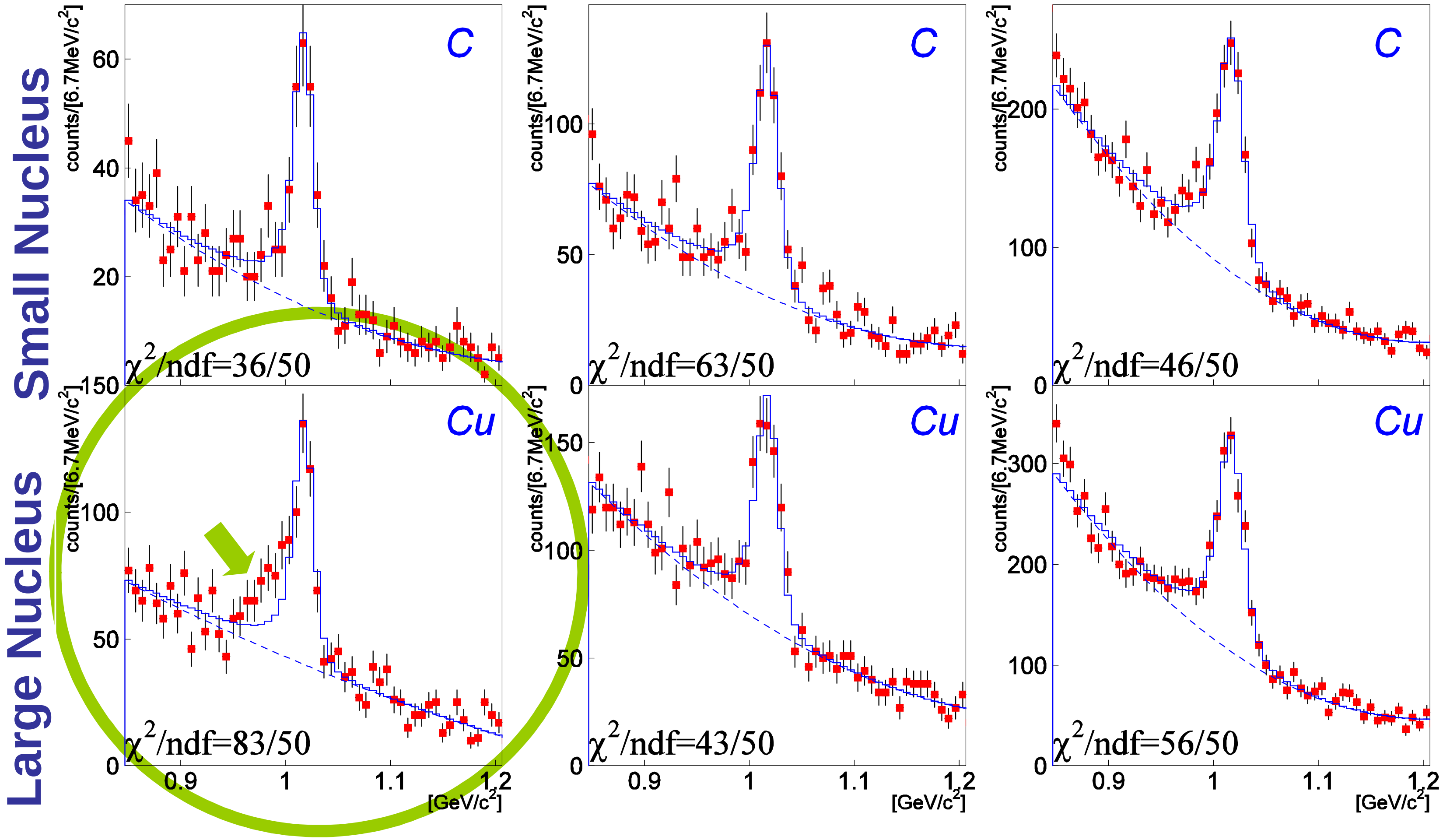
No effect
(only vacuum)

Di-lepton spectrum
reflects the modified
ϕ-meson



Fitting Results

b g≤1.25 (Slow) | 1.25<b g≤1.75 | 1.75<b g (Fast)



Experimental Conclusions

R. Muto et al, Phys. Rev. Lett. **98**, 042501 (2007).

Pole mass:

$$\frac{m_\phi(\rho)}{m_\phi(0)} = 1 - \underbrace{k_1}_{0.034 \pm 0.007} \frac{\rho}{\rho_0}$$

35 MeV negative mass shift at normal nuclear matter density

Pole width:

$$\frac{\Gamma_\phi(\rho)}{\Gamma_\phi(0)} = 1 + \underbrace{k_2}_{2.6 \pm 1.5} \frac{\rho}{\rho_0}$$

Increased width to 15 MeV at normal nuclear matter density

Caution!

Fit to experimental data is performed with a simple Breit-Wigner parametrization

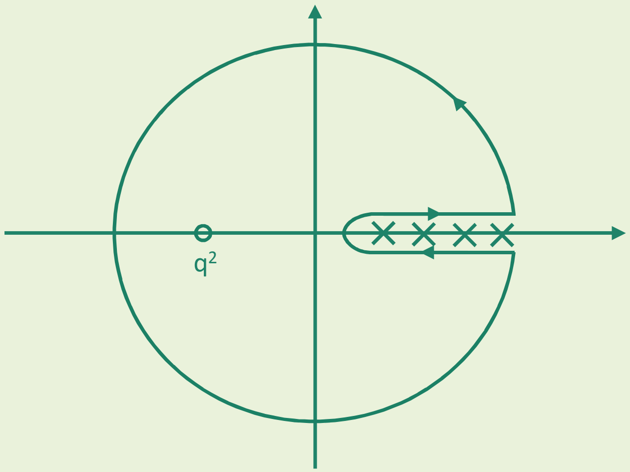
Too simple??

M.A. Shifman, A.I. Vainshtein and V.I. Zakharov,
Nucl. Phys. B147, 385 (1979); B147, 448 (1979).

QCD sum rules

In this method the properties of the two point correlation function is fully exploited:

$$\Pi(q^2) = i \int d^4x e^{iqx} \langle 0 | T\{\chi(x)\overline{\chi}(0)\} | 0 \rangle$$



$$\rightarrow \Pi(q^2) = \frac{1}{\pi} \int_0^\infty ds \frac{\mathrm{Im}\Pi(s)}{s - q^2 - i\epsilon}$$

is calculated "perturbatively", using OPE

spectral function of the operator χ

After the Borel transformation:

$$G_{OPE}(M) = \frac{1}{\pi} \int_0^\infty ds \frac{1}{M^2} e^{-\frac{s}{M^2}} \mathrm{Im}\Pi(s)$$

More on the OPE in matter

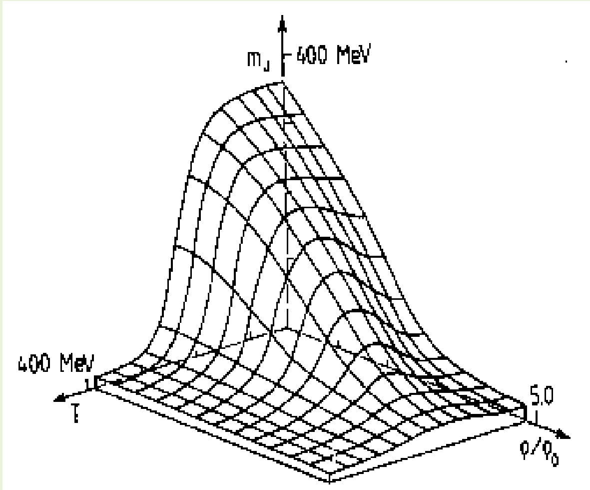
perturbative Wilson coefficients

non-perturbative condensates

$$i\int d^4x e^{iqx}\langle 0|T\{\chi(x)\overline{\chi}(0)\}|0\rangle = C_I(q^2)I+\sum_n C_n(q^2)\langle 0|O_n|0\rangle$$

$$\begin{aligned}\langle 0|O_n|0\rangle = &\langle 0|\overline{q}q|0\rangle,\\ &\langle 0|G^a_{\mu\nu}G^{a\mu\nu}|0\rangle,\\ &\langle 0|\overline{q}\sigma_{\mu\nu}\frac{\lambda^a}{2}G^{a\mu\nu}q|0\rangle,\\ &\langle 0|\overline{q}q\overline{q}q|0\rangle,\dots\end{aligned}$$

Change in hot or dense matter!



Structure of QCD sum rules for the phi meson

$$\frac{1}{M^2}\int_0^\infty ds e^{-\frac{s}{M^2}} A(s) = c_0(\rho) + \frac{c_2(\rho)}{M^2} + \frac{c_4(\rho)}{M^4} + \frac{c_6(\rho)}{M^6} + \dots$$

<u>In Vacuum</u>

Dim. 0: $c_0(0) = 1 + \frac{\alpha_s}{\pi}$

Dim. 2: $c_2(0) = -6m_s^2$

Dim. 4: $c_4(0) = \frac{\pi^2}{3}\langle\frac{\alpha_s}{\pi}G^2\rangle + 8\pi^2 m_s \langle\bar{s}s\rangle$

Dim. 6: $c_6(0) = -\frac{448}{81}\kappa\pi^3\alpha_s\langle\bar{s}s\rangle^2$

Structure of QCD sum rules for the phi meson

$$\frac{1}{M^2}\int_0^\infty ds e^{-\frac{s}{M^2}} A(s) = c_0(\rho) + \frac{c_2(\rho)}{M^2} + \frac{c_4(\rho)}{M^4} + \frac{c_6(\rho)}{M^6} + \dots$$

<u>In Nuclear Matter</u>

$$\boxed{\langle \overline{s}s\rangle_\rho = \langle \overline{s}s\rangle_0 + \langle N|\overline{s}s|N\rangle\rho + \dots}$$

Dim. 0: $c_0(\rho) = c_0(0)$

Dim. 2: $c_2(\rho) = c_2(0)$

Dim. 4:
$$c_4(\rho) = c_4(0) + \rho[-\frac{2}{27}M_N + \frac{56}{27}m_s\langle N|\overline{s}s|N\rangle + \frac{4}{27}m_q\langle N|\overline{q}q|N\rangle + A_2^s M_N - \frac{7}{12}\frac{\alpha_s}{\pi}A_2^g M_N]$$

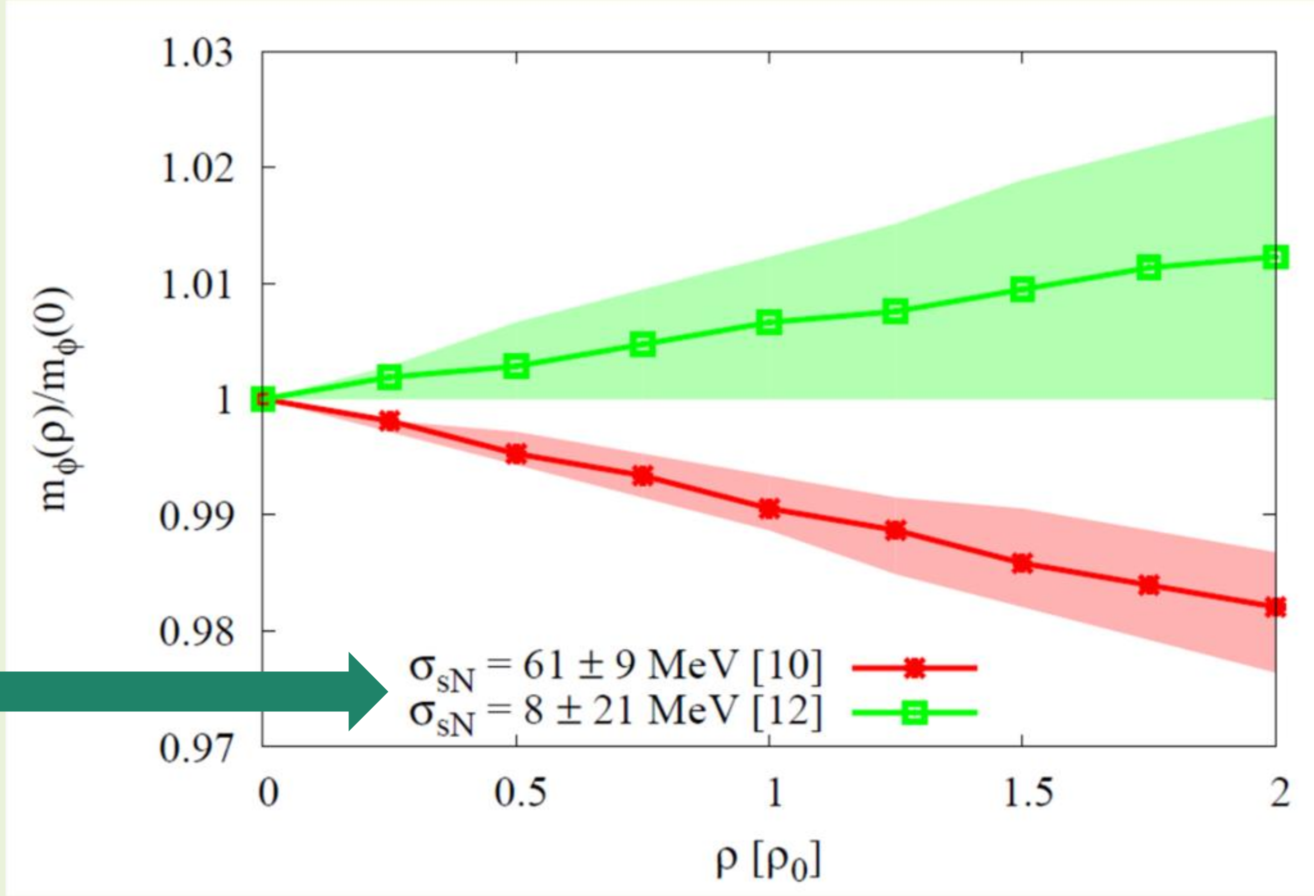
Dim. 6:
$$c_6(\rho) = c_6(0) + \rho[-\frac{896}{81}\kappa_N \pi^3 \alpha_s \langle \overline{s}s\rangle\langle N|\overline{s}s|N\rangle - \frac{5}{6}A_4^s M_N^3]$$

Results for the ϕ meson mass

Most important parameter, that determines the behavior of the ϕ meson mass at finite density:

Strangeness content of the nucleon

$$\sigma_{sN} = m_s \langle N | \bar{s}s | N \rangle$$



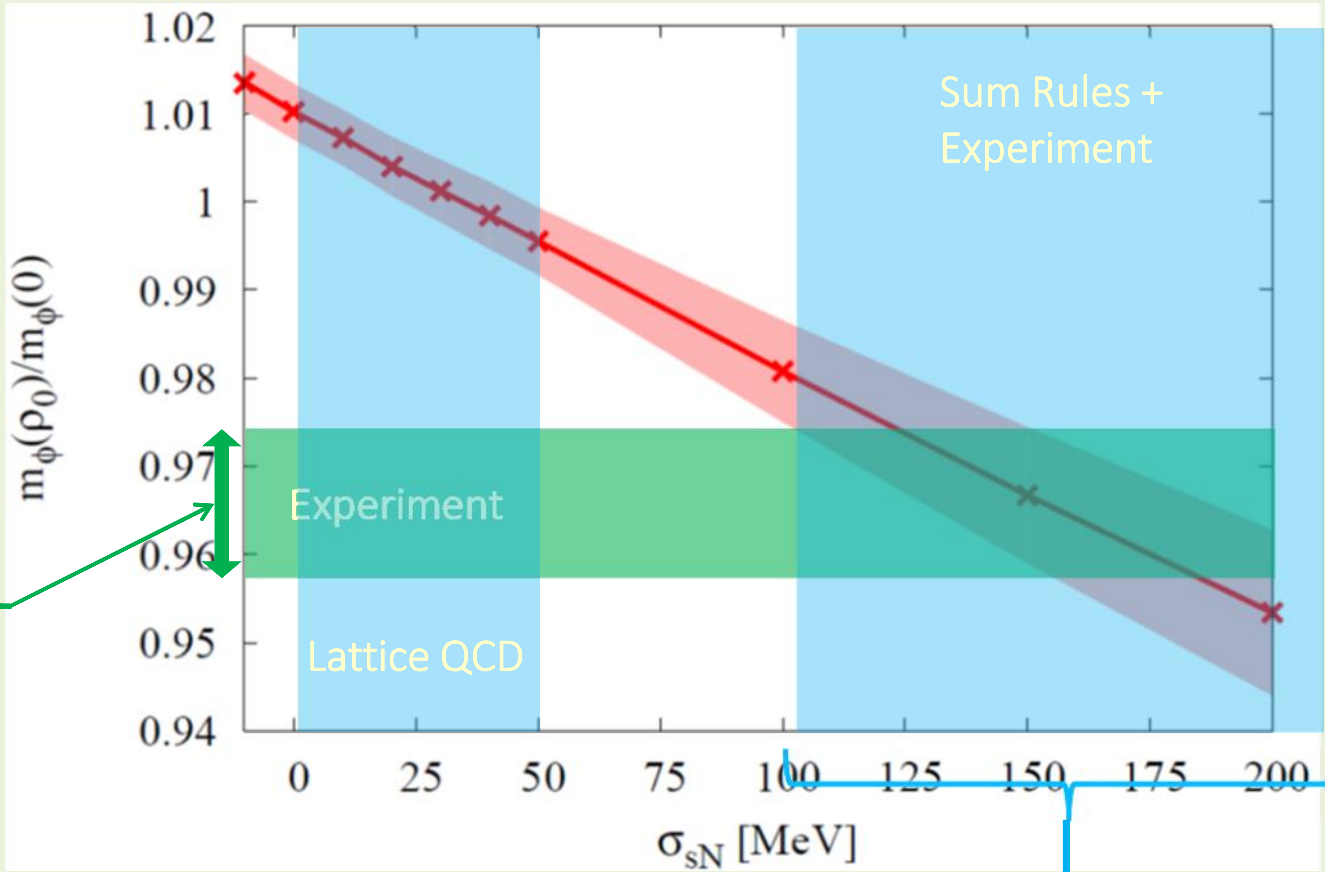
P. Gubler and K. Ohtani, Phys. Rev. D **90**, 094002 (2014).

Compare sum rule results with experiment and lattice QCD

Not consistent?

Looking forward to new E-16 experiment at J-PARC!

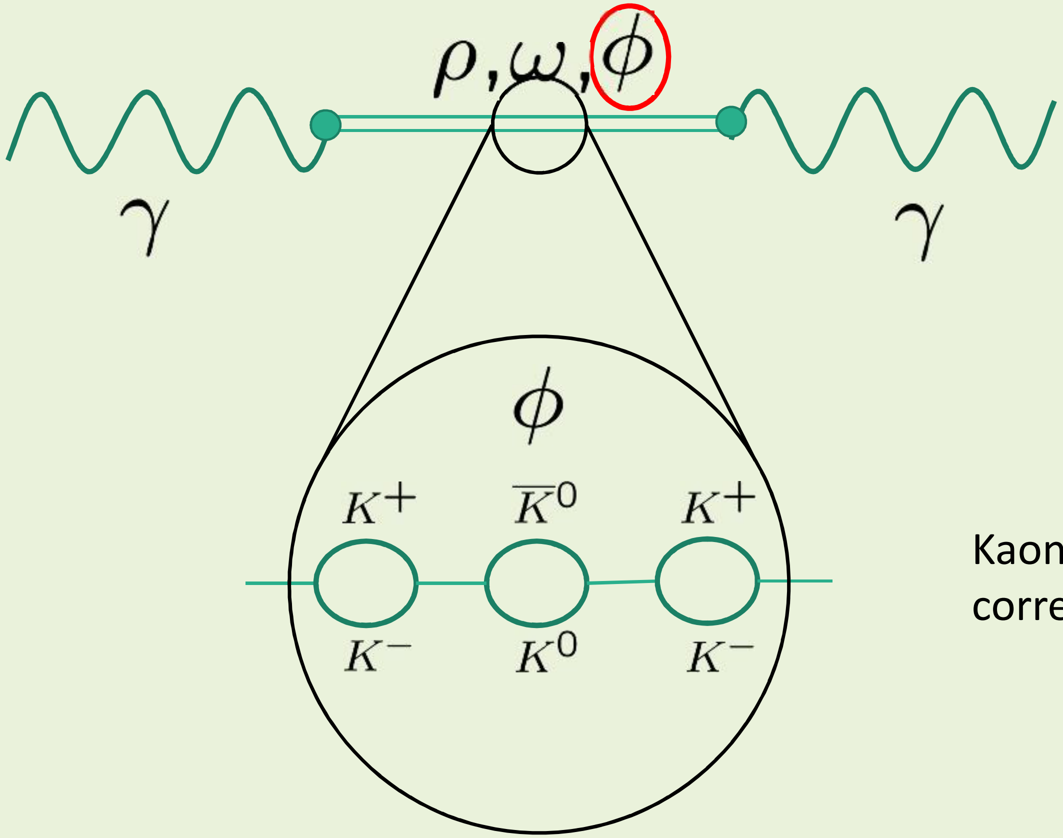
$$\frac{m_\phi(\rho)}{m_\phi(0)} = 0.966 \pm 0.007$$



$$\sigma_{sN} \sim 160 \pm 50 \text{ MeV}$$

Another Method: Use effective theory

Vector meson dominance model:



Kaon-loops introduce self-energy corrections to the ϕ-meson propagator

Starting point:

$$\Pi_{\mu\nu}(q) = i \int d^4x e^{iqx} \langle T[j_\mu(x) j_\nu(0)] \rangle_\rho$$

$$j_\mu(x) = \tfrac{1}{3}\bar{s}(x)\gamma_\mu s(x)$$

$$\Pi(q^2) = \tfrac{1}{3q^2}\Pi^\mu_\mu(q)$$

Rewrite using hadronic degrees of freedom

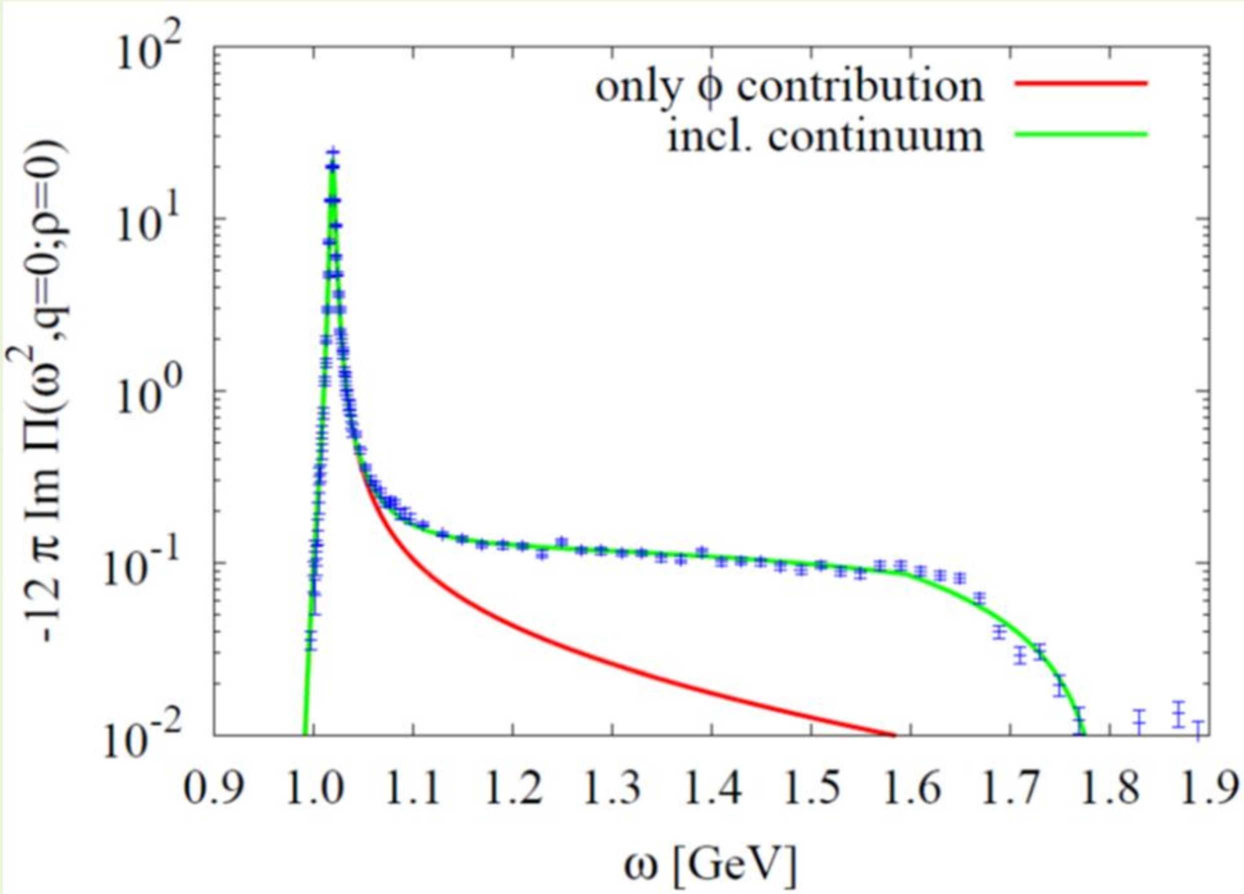
$$\mathrm{Im}\Pi(q^2) = \frac{\mathrm{Im}\Pi_\phi(q^2)}{q^2 g_\phi^2}\left|\frac{(1-a_\phi)q^2-\mathring{m}_\phi^2}{q^2-\mathring{m}_\phi^2-\Pi_\phi(q^2)}\right|^2$$

Kaon loops

Spectral function in vacuum

$$\frac{\sigma(e^+e^-\to K^+K^-)}{\sigma(e^+e^-\to\mu^+\mu^-)}$$

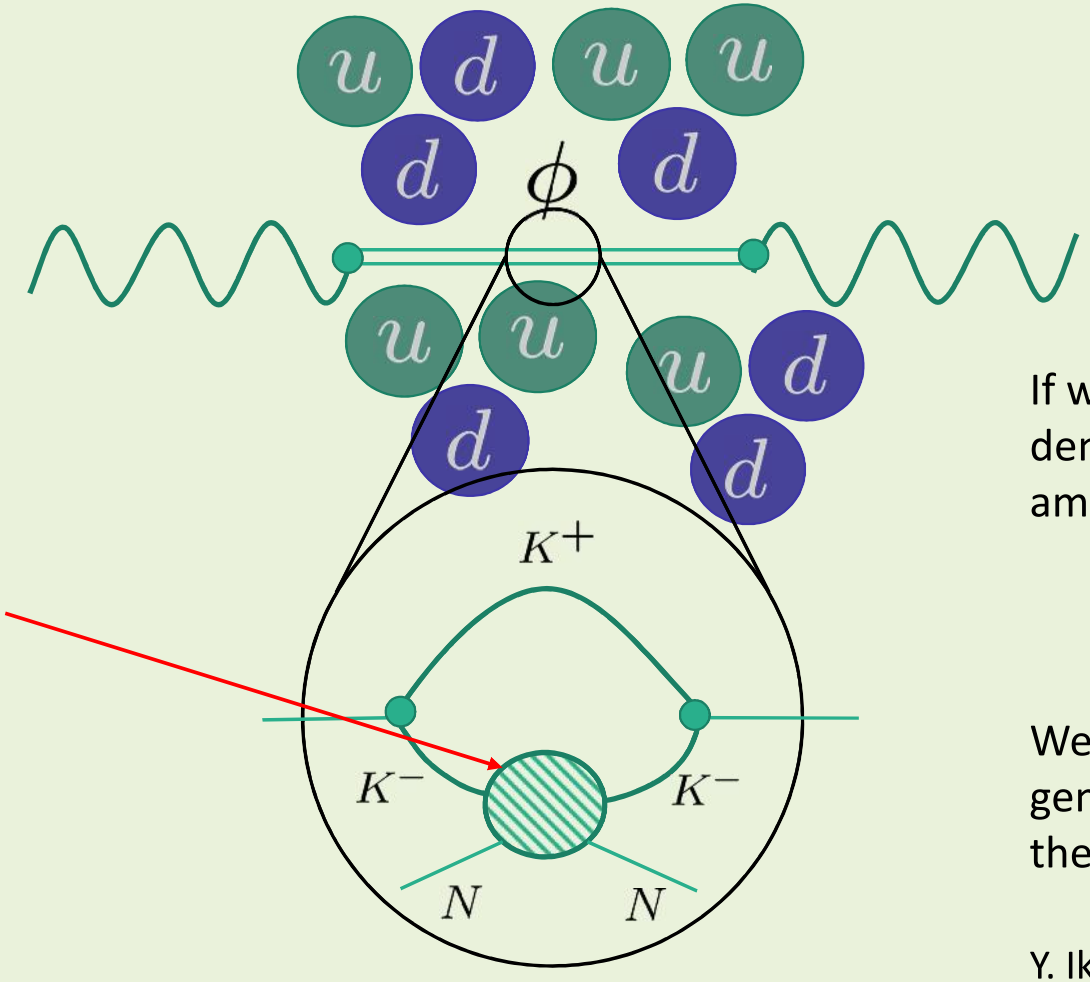
(Vacuum)



How is this spectrum modified in nuclear matter?

Data from
J.P. Lees et al. (BABAR Collaboration), Phys. Rev. D **88**, 032013 (2013).

What happens in nuclear matter?



Forward $\bar{K}$N (or KN) scattering amplitude

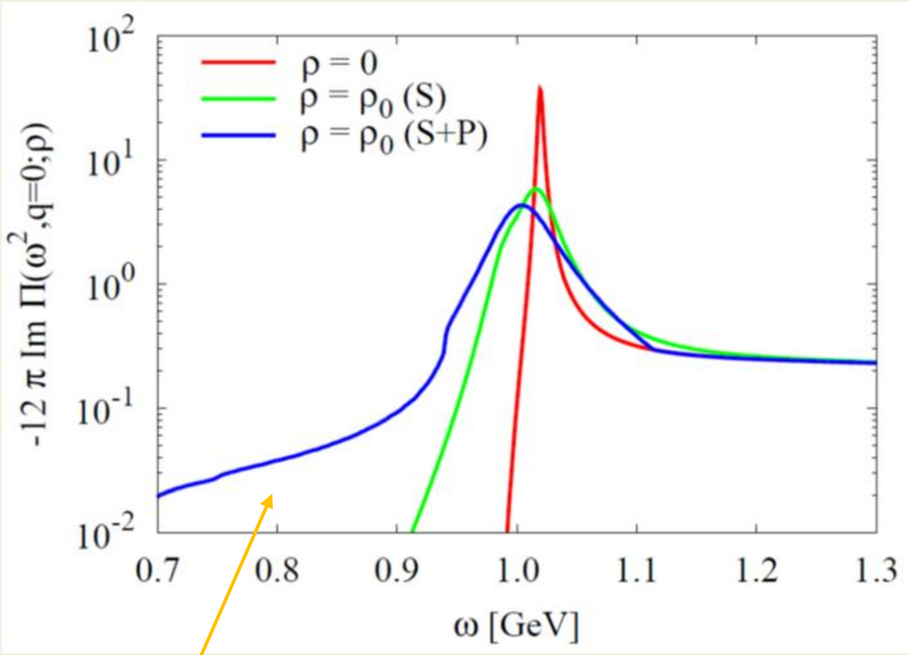
If working at linear order in density, the free scattering amplitudes can be used

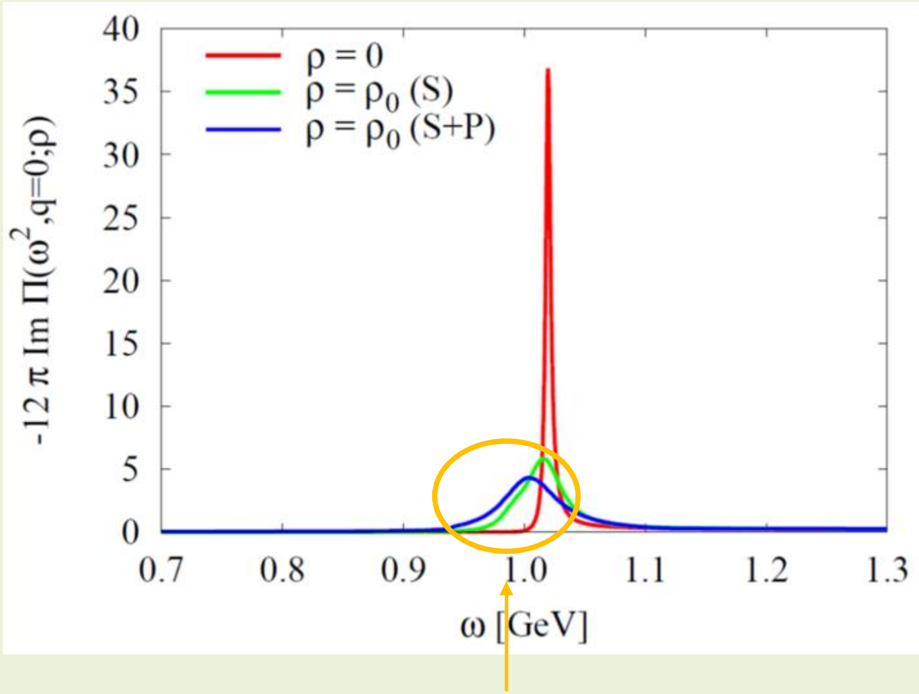
We use the amplitudes generated with the help of the chiral unitary approach.

Y. Ikeda, T. Hyodo and W. Weise, Nucl. Phys. A **881**, 98 (2012).

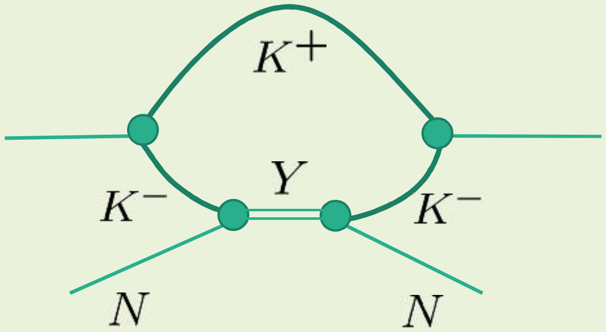
Results (Spectral Density)

P. Gubler and W. Weise, arXiv:1507.03769 [hep-ph].





Takes into account further $\bar{K}N$-interactions with intermediate hyperons, such as:



Asymmetric modification of the spectrum.
→ Not necessarily parametrizable by a simple Breit-Wigner peak!
→ Important message for future E16 experiment at J-PARC

Summary and Conclusions

The ϕ-meson mass shift in nuclear matter constrains the strangeness content of the nucleon:

Most recent lattice calculations give a small σ_{sN}-value

→ increasing ϕ-meson mass in nuclear matter??

The E325 experiment at KEK measured a negative mass shift of -35 MeV at normal nuclear matter density

→ a σ_{sN}-value of > 100 MeV??

We have computed the ϕ meson spectral density in vacuum and nuclear matter based on an effective vector dominance model:

→ non-symmetric behavior of peak in nuclear matter

Backup slides

Moment analysis of obtained spectral functions

Starting point: Borel-type QCD sum rules

$$\frac{1}{M^2}\int_0^\infty ds e^{-\frac{s}{M^2}} R(s) = c_0(\rho) + \frac{c_2(\rho)}{M^2} + \frac{c_4(\rho)}{M^4} + \frac{c_6(\rho)}{M^6} + \dots$$

$$c_0 = \frac{1}{4\pi^2}\left(1+\frac{\alpha_s}{\pi}\right) \qquad c_4 = -\frac{1}{12}\left\langle \frac{\alpha_s}{\pi} G^2 \right\rangle_\rho + 2m_s\langle \bar{s}s\rangle_\rho$$

$$c_2 = -\frac{3m_s^2}{2\pi^2} \qquad c_6 = -2\pi\alpha_s\Big[\langle(\bar{s}\gamma_\mu\gamma_5\lambda^a s)^2\rangle_\rho + \frac{2}{9}\langle(\bar{s}\gamma_\mu\lambda^a s)\sum_{q=u,d,s}(\bar{q}\gamma_\mu\lambda^a q)\rangle_\rho\Big]$$

$$R(s) = R_\phi(s)\Theta(s_0 - s) + c_0\Theta(s - s_0)$$

Large M limit

$$\int_0^{s_0} ds R_\phi(s) = c_0 s_0 + c_2$$

$$\int_0^{s_0} ds s R_\phi(s) = \frac{c_0}{2}s_0^2 - c_4$$

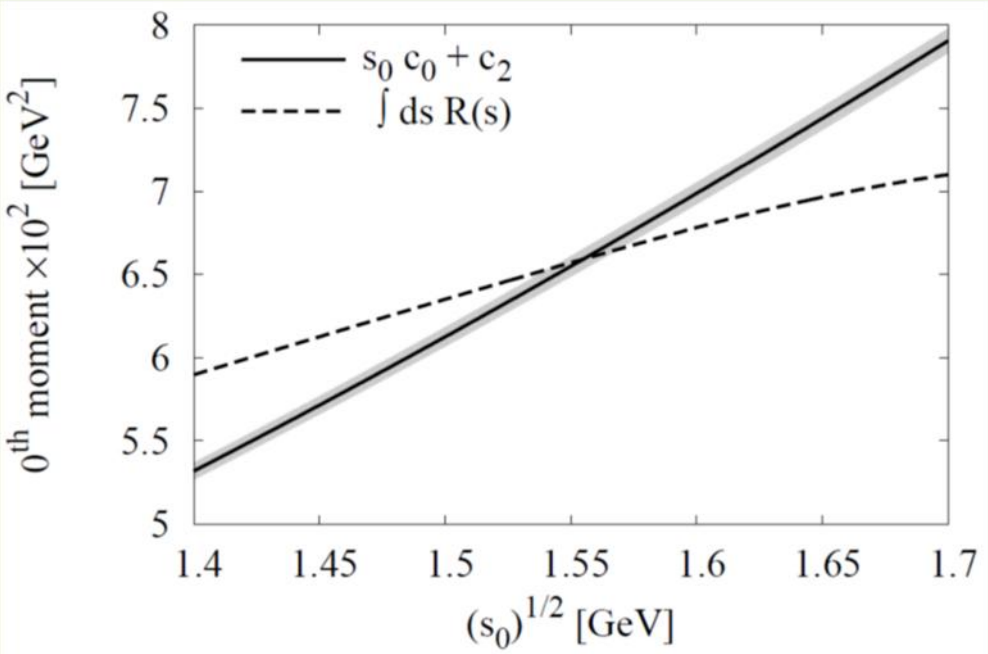
$$\int_0^{s_0} ds s^2 R_\phi(s) = \frac{c_0}{3}s_0^3 + c_6$$

Finite-energy sum rules

Consistency check
(Vacuum)

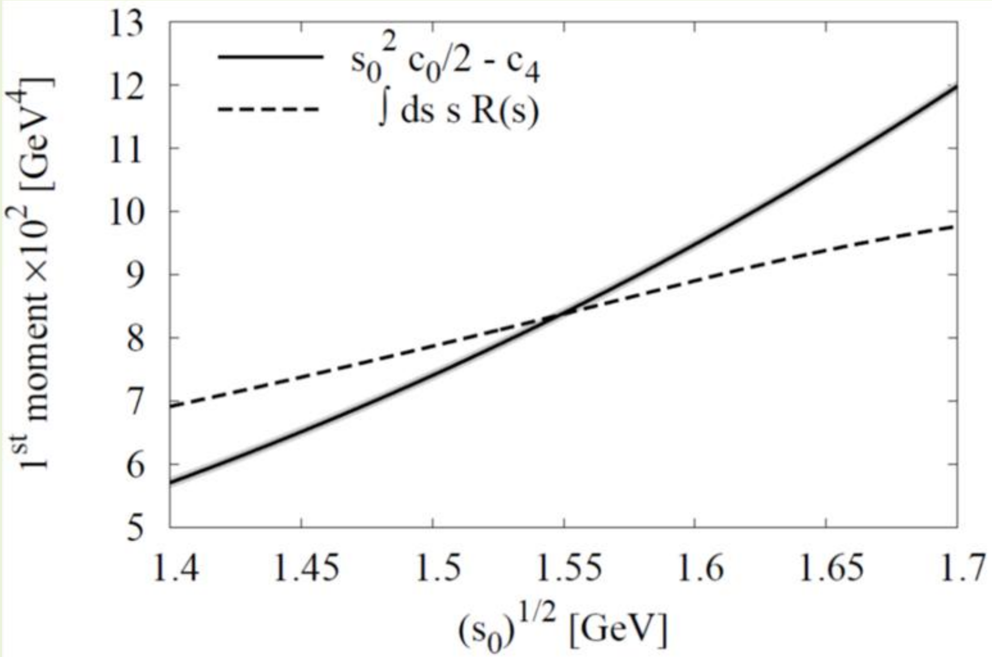
Are the zeroth and first momentum sum rules consistent with our phenomenological spectral density?

Zeroth Moment



$$\sqrt{s_0} = (1.55 \pm 0.02)\ \text{GeV}$$

First Moment



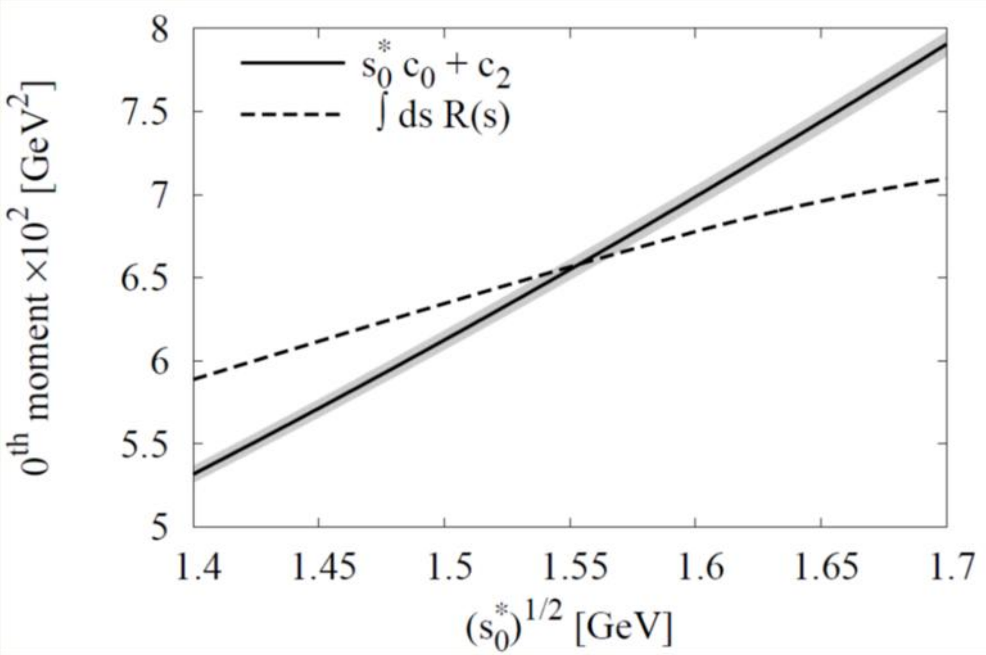
$$\sqrt{s_0} = (1.55 \pm 0.01)\ \text{GeV}$$

Consistent!

Consistency check
(Nuclear matter)

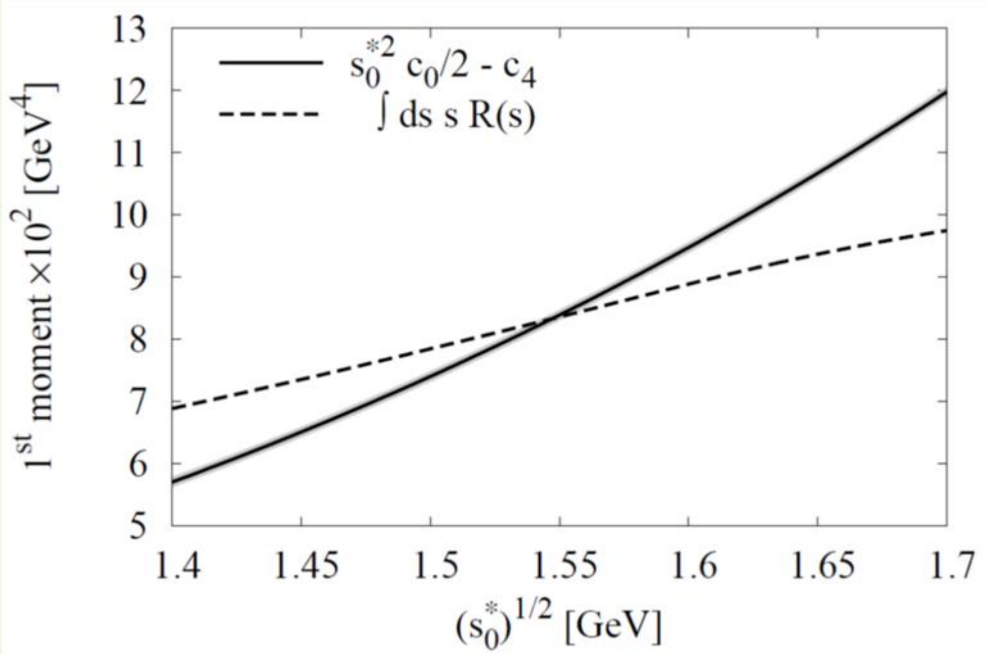
Are the zeroth and first momentum sum rules consistent with our phenomenological spectral density?

Zeroth Moment



$$\sqrt{s_0^*} = (1.55 \pm 0.02)\ \text{GeV}$$

First Moment



$$\sqrt{s_0^*} = (1.55 \pm 0.01)\ \text{GeV}$$

Consistent!