Theory predictions for the J-PARC E16 experiment

Philipp Gubler (JAEA)

H.J. Kim and P. Gubler, Phys. Lett. B **805**, 135412 (2020).

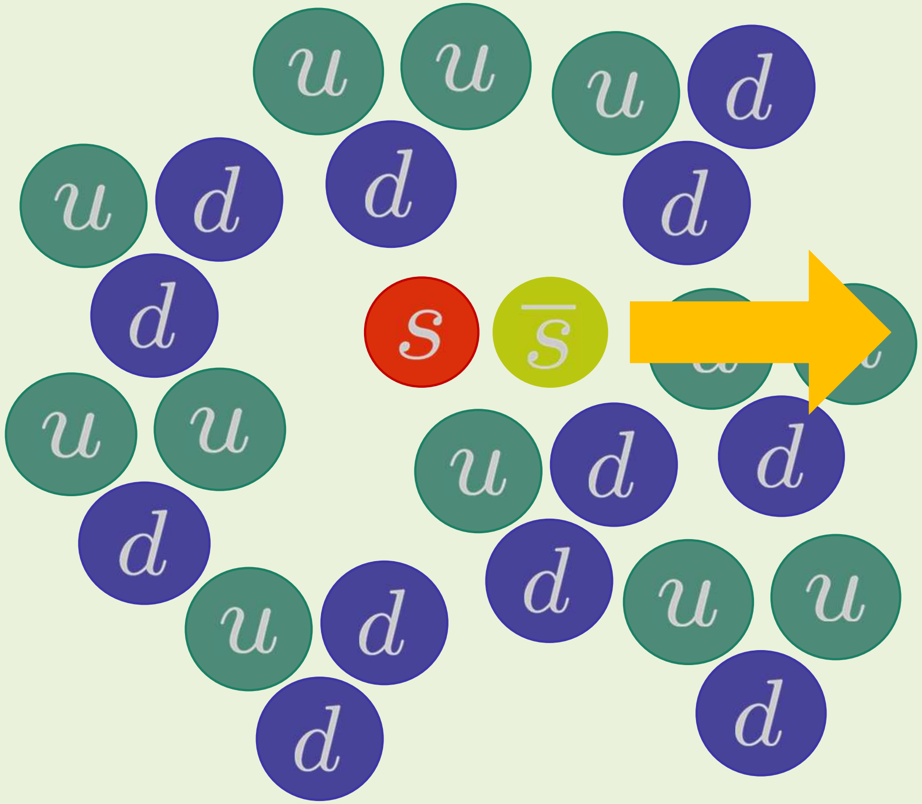
I.W. Park, H. Sako, K. Aoki, P. Gubler and S.H. Lee, in preparation.

Talk at Baryons 2022,
Sevilla, Spain/online,
November 8, 2022

Work done in collaboration with
HyungJoo Kim (Yonsei U.)
InWoo Park (Yonsei U.)
Hiroyuki Sako (JAEA)
Kazuya Aoki (KEK)
Su Houng Lee (Yonsei U.)

Interest

ϕ meson



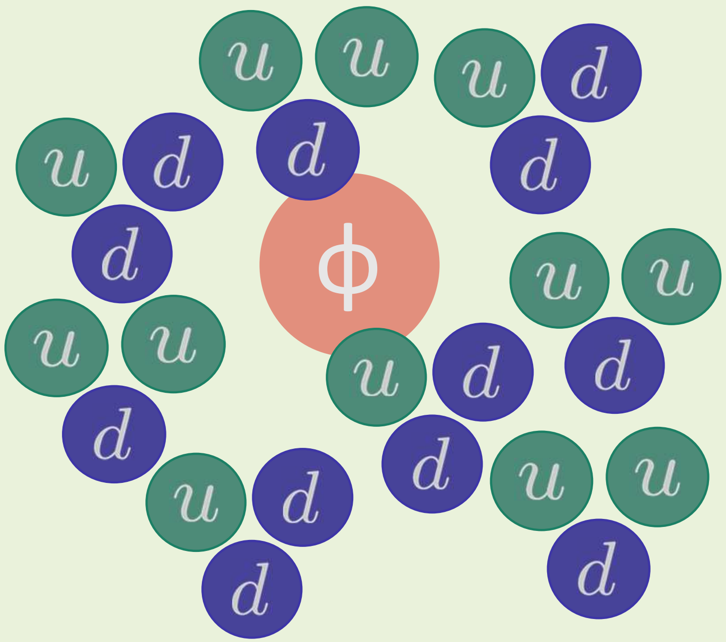
$m_\phi = 1019$ MeV

$\Gamma_\phi = 4.3$ MeV

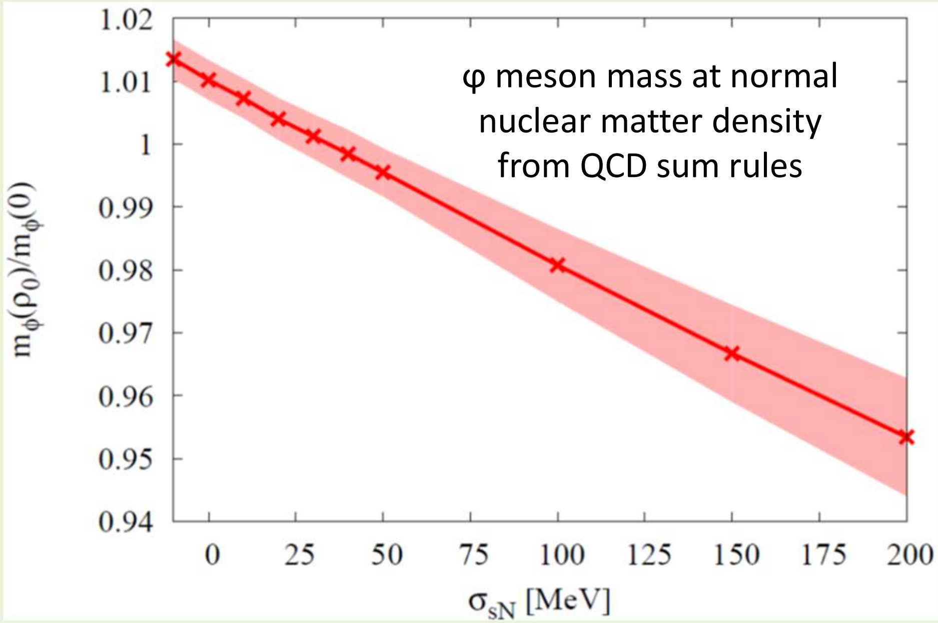
Case 1: φ meson **at rest** in nuclear matter

The φ meson mass in nuclear matter probes the strange quark condensate at finite density!

$|\langle \bar{s}s \rangle_\rho| \searrow$ $\quad\Rightarrow\quad$ $m_\phi \searrow$?



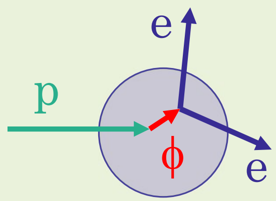
P. Gubler and K. Ohtani, Phys. Rev. D **90**, 094002 (2014).



$$|\langle \bar{s}s \rangle_\rho| = |\langle \bar{s}s \rangle_0| - \frac{\rho}{m_s}\sigma_{sN} + \dots$$

Experimental results

(E325, KEK)



12 GeV
pA-reaction

Pole mass: $$\frac{m_\phi(\rho)}{m_\phi(0)} = 1 - k_1 \frac{\rho}{\rho_0}$$

0.034 ± 0.007

Pole width: $$\frac{\Gamma_\phi(\rho)}{\Gamma_\phi(0)} = 1 + k_2 \frac{\rho}{\rho_0}$$

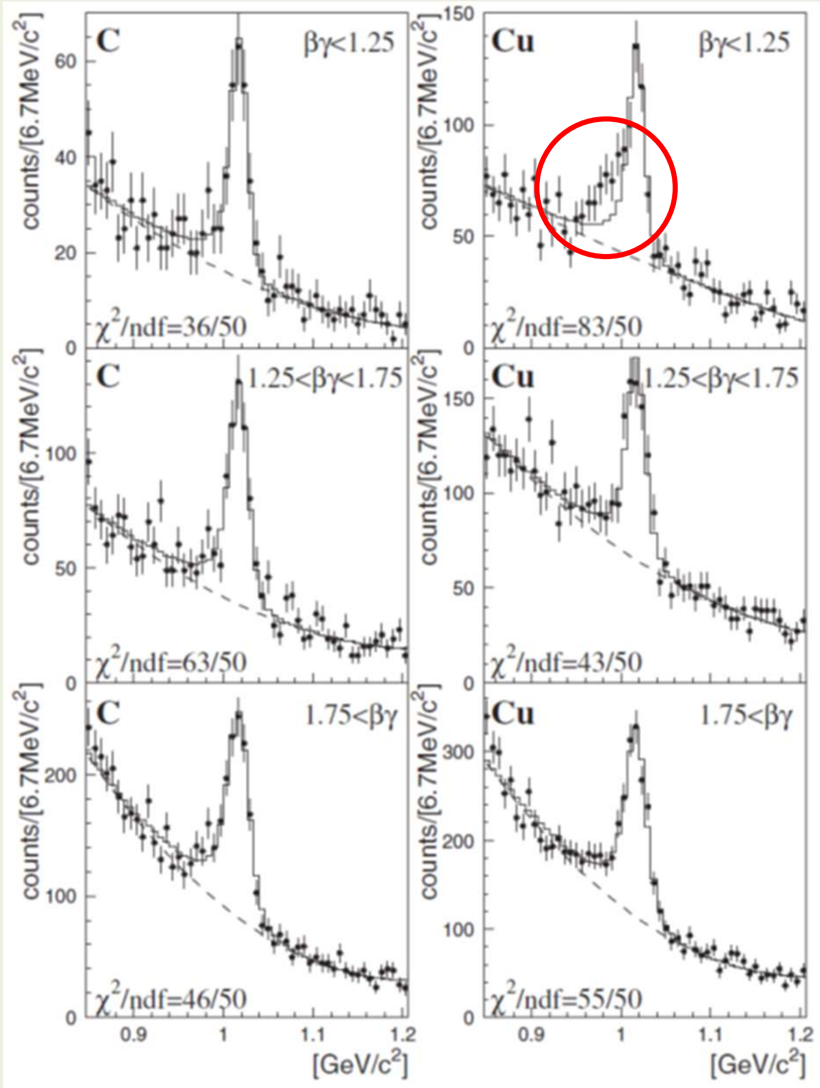
2.6 ± 1.5

slow φs

intermediate φs

fast φs

$\beta\gamma = \frac{|\vec{p}|}{m_\phi}$



R. Muto et al. (E325 Collaboration), Phys. Rev. Lett. **98**, 042501 (2007).

Case 1: φ meson **at rest** in nuclear matter

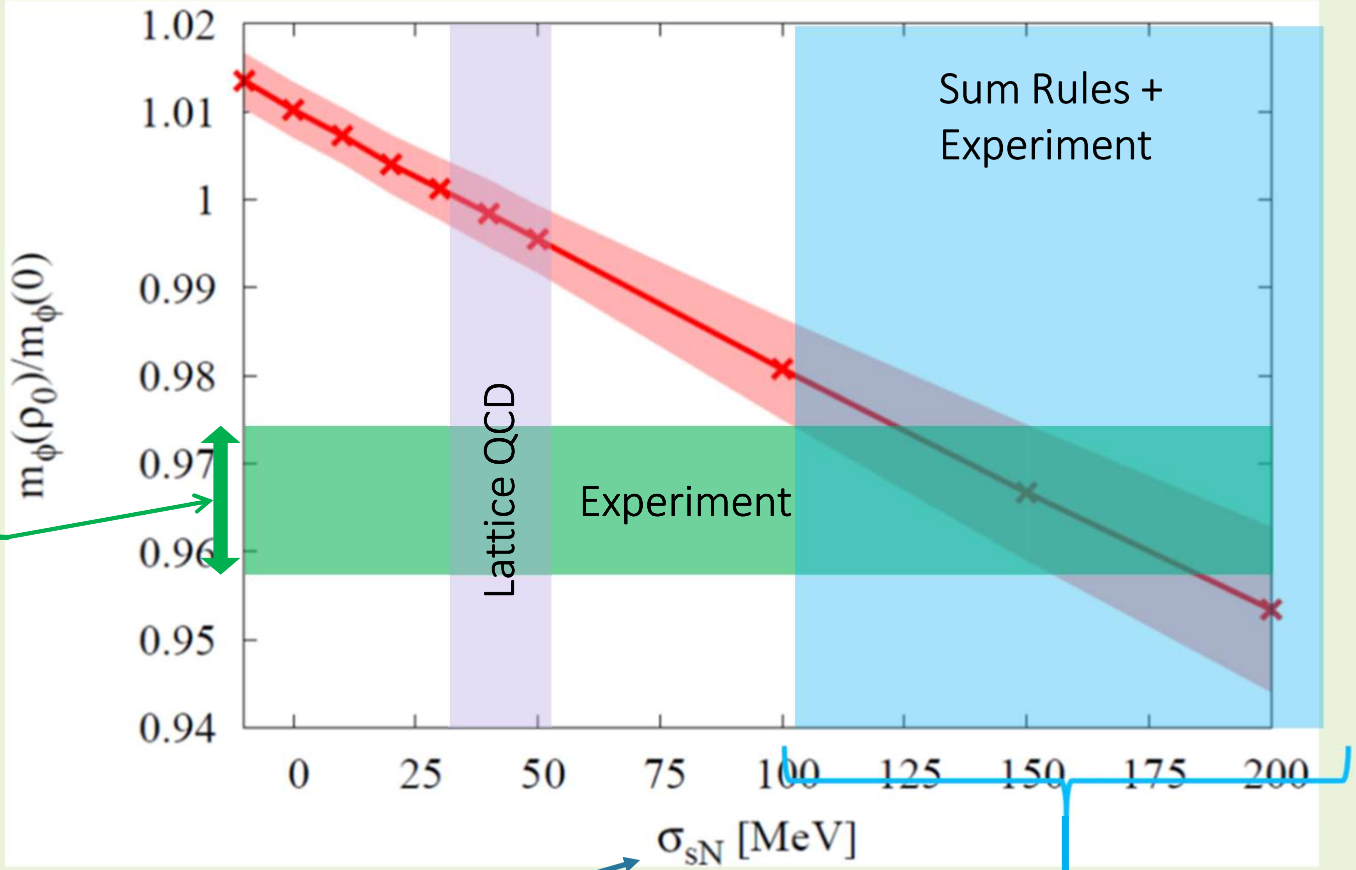
The φ meson mass in nuclear matter probes the strange quark condensate at finite density!

Not consistent?

R. Muto et al.
(KEK, E325 Collaboration),
Phys. Rev. Lett. **98**,
042501 (2007).

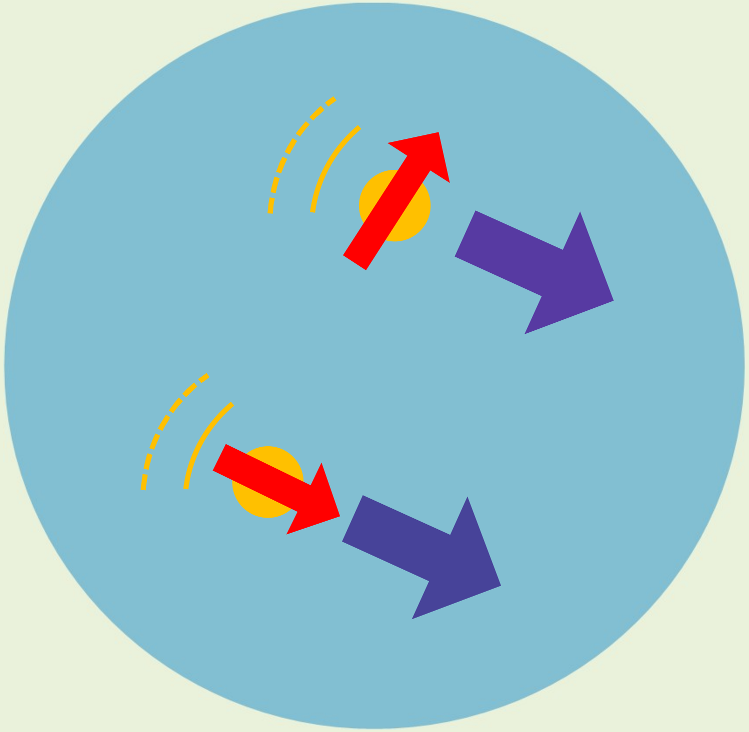
Measurement will be repeated at the J-PARC E16 experiment (with 100 times increased statistics!)

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

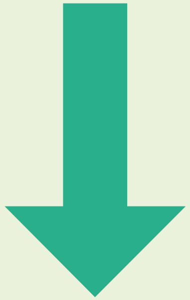


$$\sigma_{sN} = m_s \langle N|\bar{s}s|N\rangle \qquad \sigma_{sN} \sim 160 \pm 50 \text{ MeV}$$

Case 2: φ meson **moving** in nuclear matter



φ meson properties depend on the spin polarization (longitudinal or transverse)



Broken
Lorentz symmetry

- ★ Non-trivial, polarization dependent dispersion relations
- ★ Potential effect on mass shift measurement?

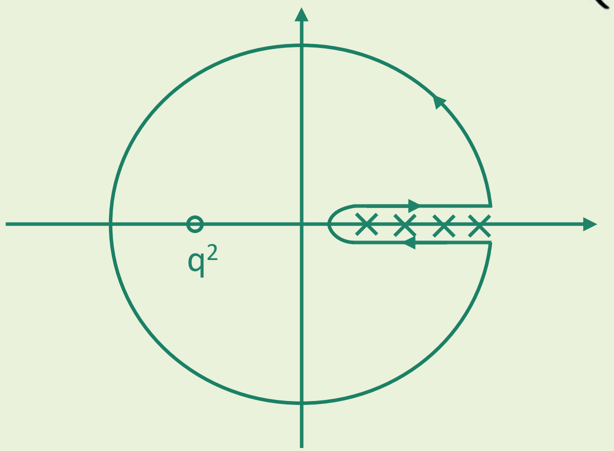
M.A. Shifman, A.I. Vainshtein and V.I. Zakharov, Nucl. Phys. B147, 385 (1979); B147, 448 (1979).

QCD sum rules

Makes use of the analytic properties of the correlation function:

$$j^\mu(x) = \overline{s}(x)\gamma^\mu s(x)$$

$$\Pi^{\mu\nu}(q^2) = i\int d^4x e^{iqx}\langle T[j^\mu(x)j^\nu(0)]\rangle_\rho$$



spectral function

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

$\langle\overline{s}s\rangle_\rho$,
$\langle G^a_{\mu\nu}G^{a\mu\nu}\rangle_\rho$,
$\langle\overline{s}\sigma_{\mu\nu}\frac{\lambda^a}{2}G^{a\mu\nu}s\rangle_\rho$,
$\langle\overline{s}s\overline{s}s\rangle_\rho$,

scalar condensates: trivial dispersion relation

$\langle\mathcal{ST}\overline{s}\gamma^\alpha iD^\beta s\rangle_\rho$,
$\langle\mathcal{ST}G^{a\alpha}_\mu G^{a\mu\beta}\rangle_\rho$,
$\langle\mathcal{ST}\overline{s}\gamma^\alpha iD^\beta iD^\gamma iD^\delta s\rangle_\rho$

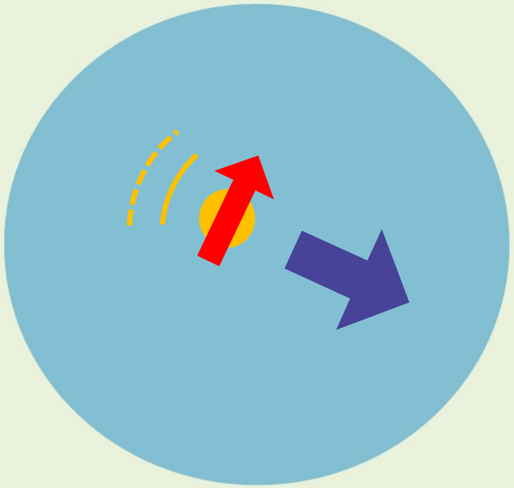
non-scalar condensates: non-trivial dispersion relation

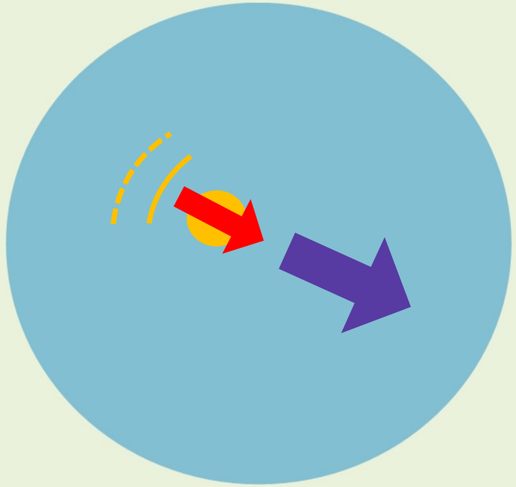
The non-zero momentum case: Disentangling longitudinal and transverse components

$$\Pi^{\mu\nu}(\omega^2, \vec{q}^{\,2})$$

$$\Pi_L(\omega^2, \vec{q}^{\,2}) = \tfrac{1}{\vec{q}^{\,2}}\Pi_{00}$$

$$\Pi_T(\omega^2, \vec{q}^{\,2}) = -\tfrac{1}{2}\left(\tfrac{1}{\vec{q}^{\,2}}\Pi_{00} + \tfrac{1}{q^2}\Pi^{\mu}_{\mu}\right)$$





The φ meson with non-zero momentum

$$\frac{1}{\omega^2 - \vec{q}^{\,2} - m^2_{\phi,L}(\vec{q}^{\,2})}$$

longitudinal part

$$\frac{1}{\omega^2 - m^2_\phi(0)}$$

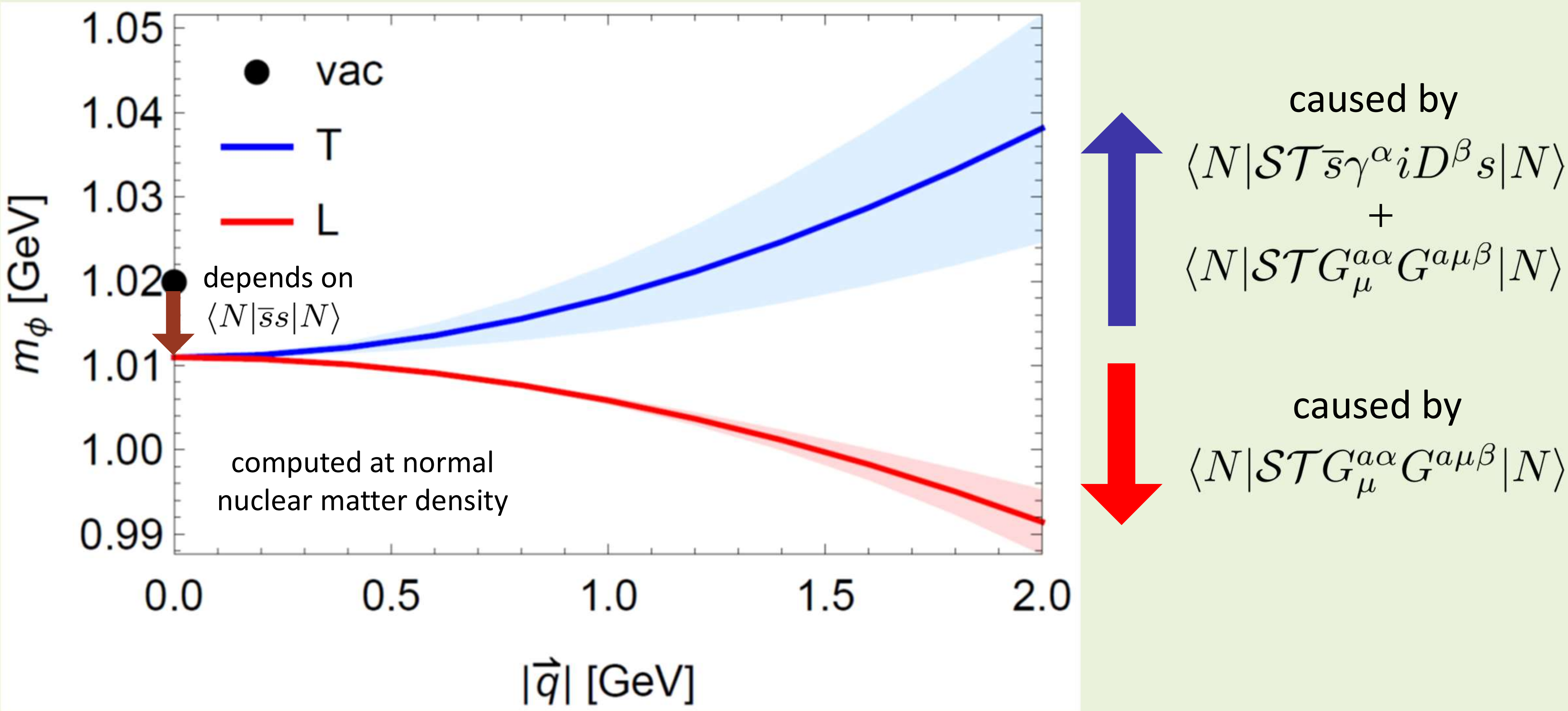
$$\frac{1}{\omega^2 - \vec{q}^{\,2} - m^2_{\phi,T}(\vec{q}^{\,2})}$$

transverse part

zero momentum

non-zero momentum $\vec{q}$

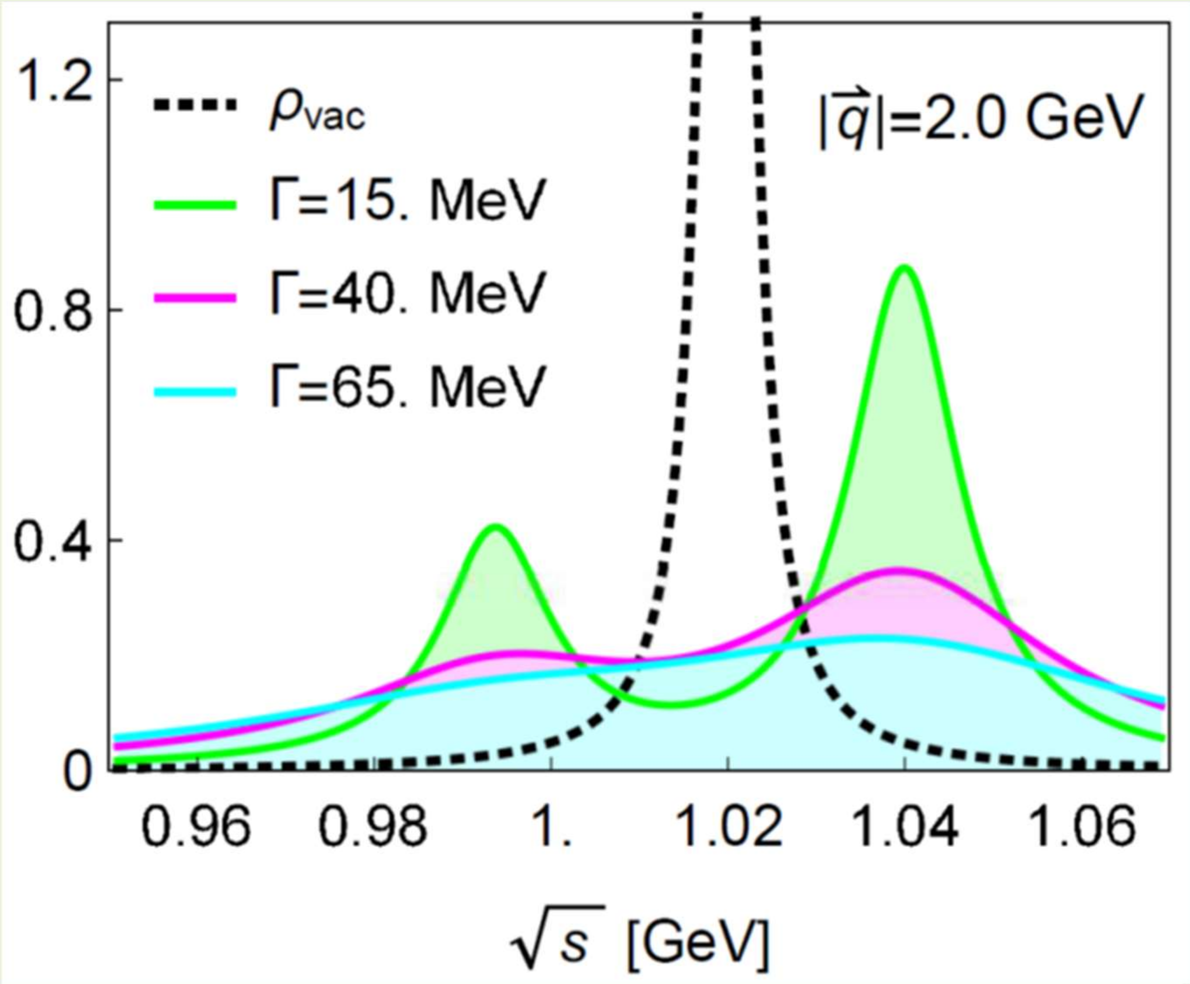
Results for the ϕ meson mass with non-zero momentum



H.J. Kim and P. Gubler, Phys. Lett. B **805**, 135412 (2020).

The angle-averaged di-lepton spectrum

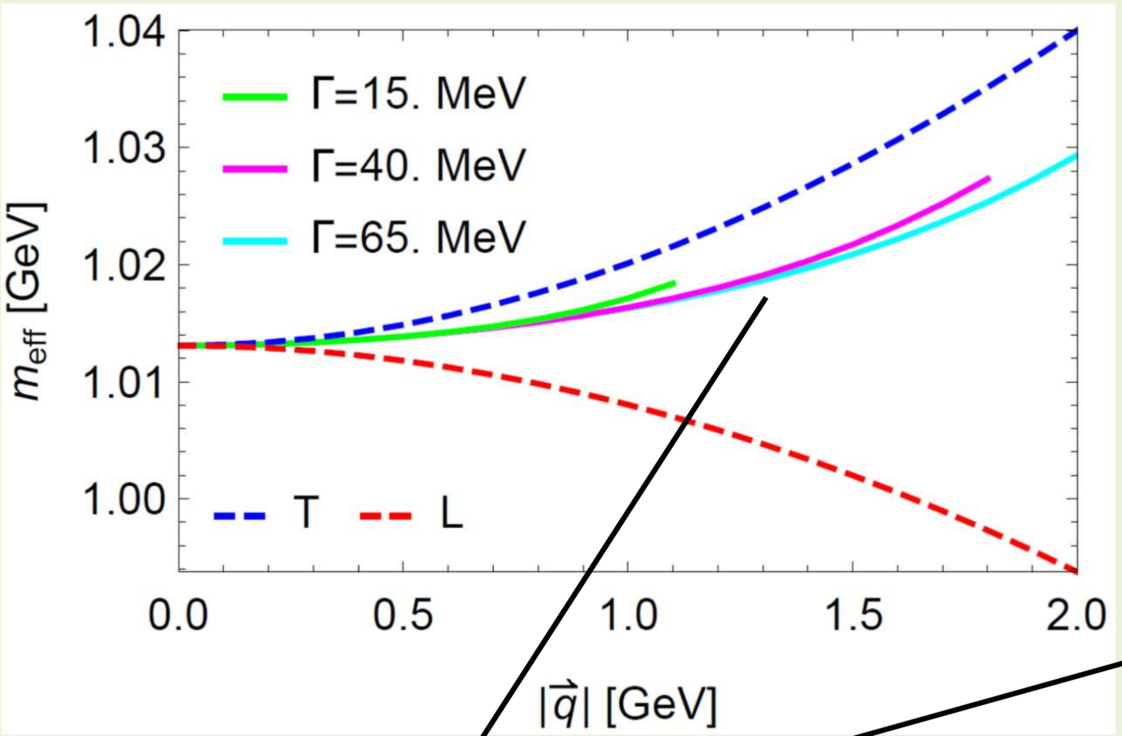
A double peak?



H.J. Kim and P. Gubler, Phys. Lett. B **805**, 135412 (2020).

The angle-averaged di-lepton spectrum

Even without a double peak, momentum effects can be observed

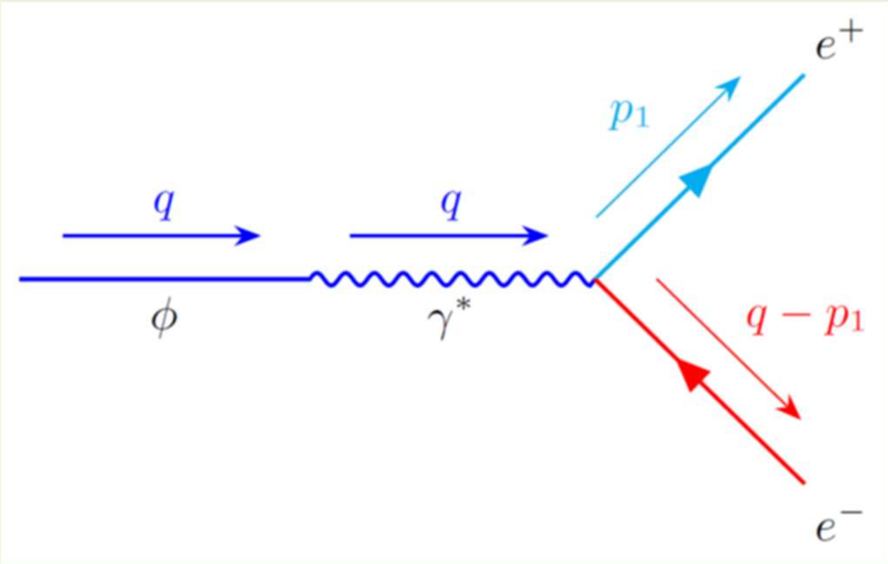


Results of one-peak fits

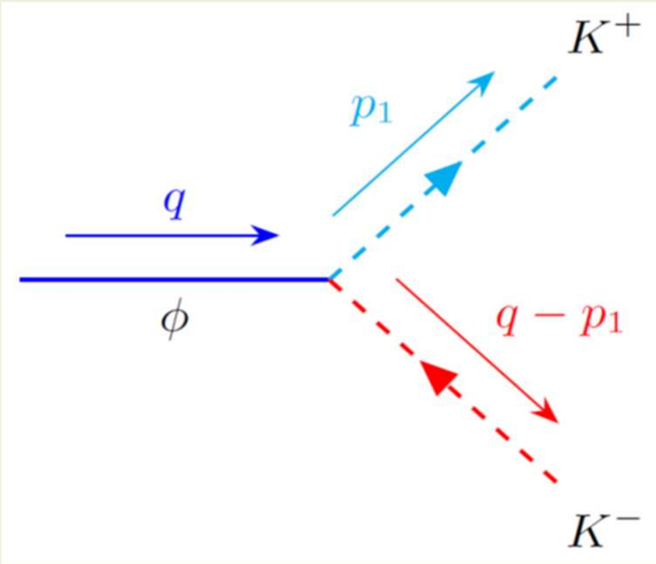
H.J. Kim and P. Gubler, Phys. Lett. B **805**, 135412 (2020).

Can the two polarizations be disentangled?

Look at the angular distributions of various decay channels



To be measured soon at
the J-PARC E16 experiment

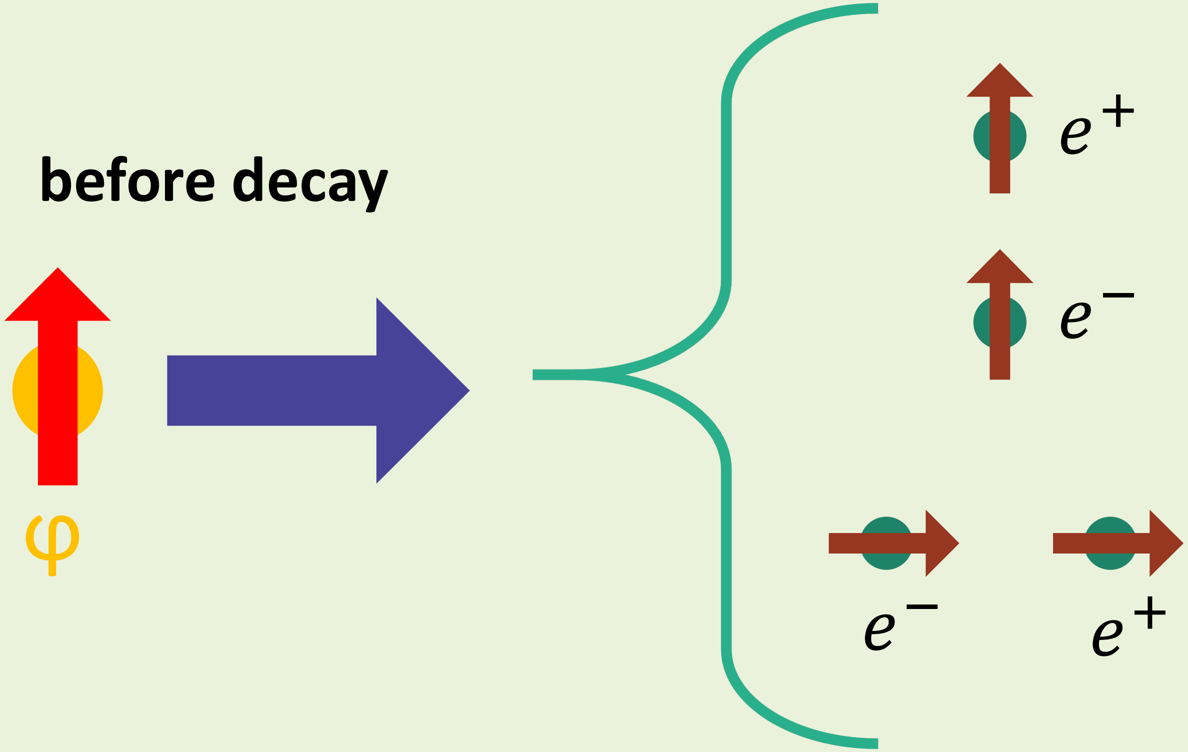


New proposal P88
submitted to J-PARC PAC

A simple example of dilepton decay of a longitudinally polarized φ

after decay

before decay



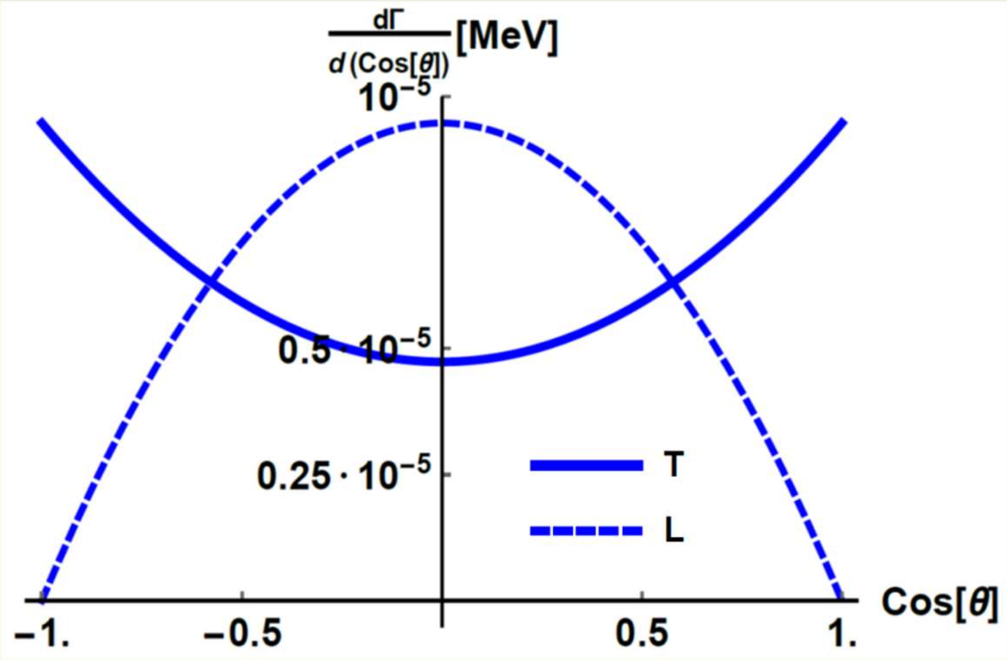
decay perpendicular to the φ meson momentum: **allowed**

decay parallel to the φ meson momentum: **not allowed**

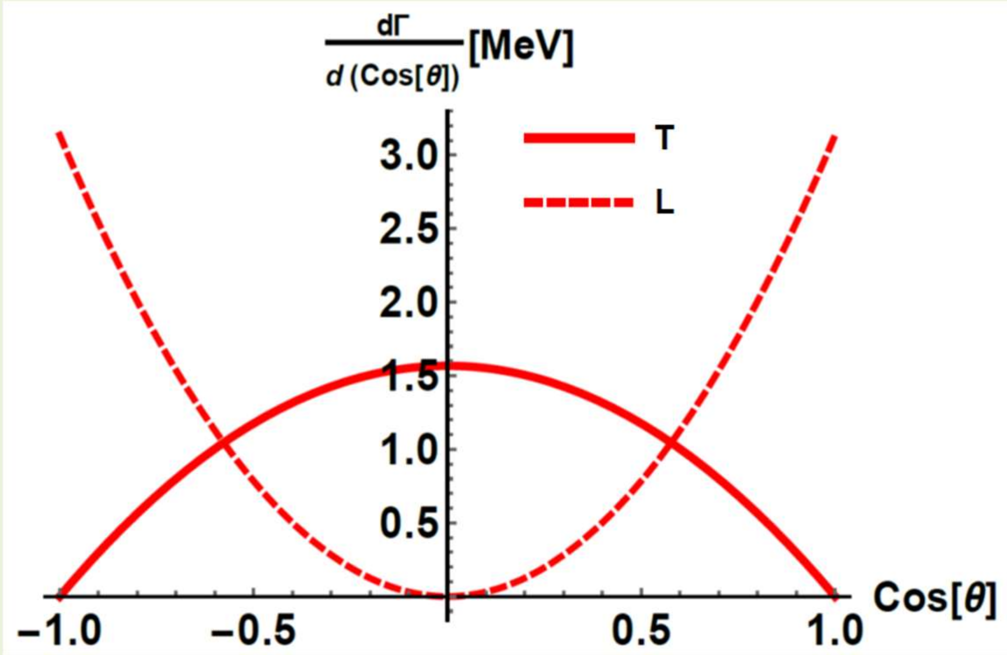
measurement in this direction can be used to observe purely transverse mode

Summary of φ meson dilepton and K^+K^- decays

Dilepton decay angular distribution



K^+K^- decay angular distribution

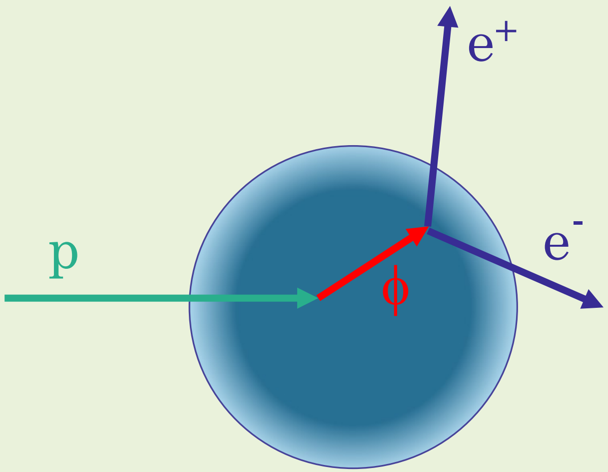


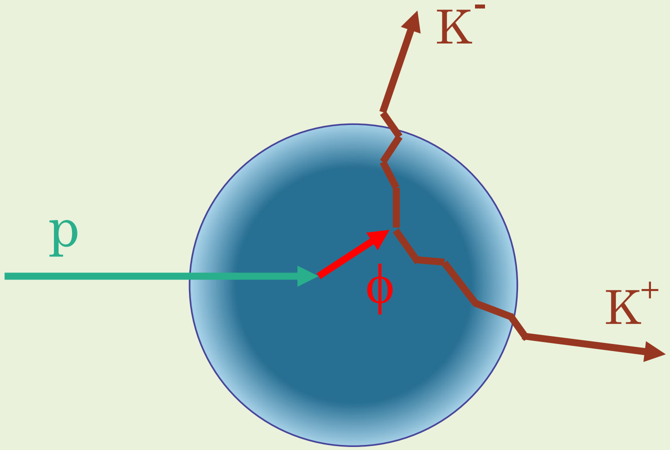
Discussions with J-PARC E16 members on how to distinguish the transverse and longitudinal modes are ongoing.

I.W. Park, H. Sako, K. Aoki, P. Gubler and S.H. Lee, in preparation.

Further tasks for theory

Have a good understanding of the production mechanisms of the φ mesons in nuclei from pA reactions.





★ Where (and at what densities) is the φ meson produced and where does it decay?

★ How do the final state interactions of the decay particles influence the decay spectrum (especially for K^+K^-)?

➡ Realistic transport simulations using a transport approach (calculations using the PHSD code are ongoing)

Summary and conclusions

★ Dispersion relations of hadrons can be non-trivially modified in nuclear matter.

★ For the φ meson, the longitudinal and transverse modes are shifted in opposite directions with increasing momentum.

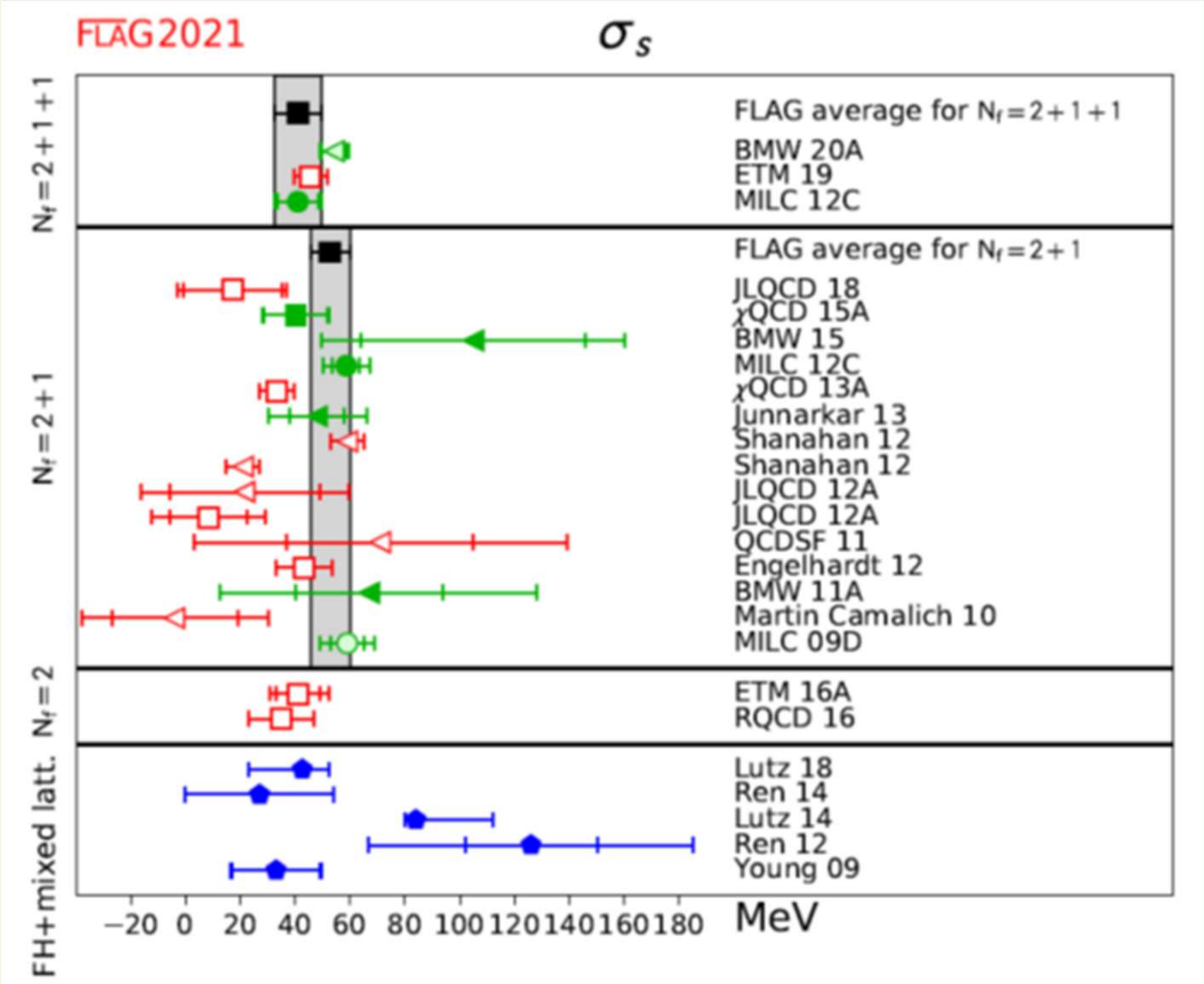
→ May be observed as a **double peak** in the angle averaged di-lepton spectrum or a small **positive mass shift + width increase** at the E16 experiment at J-PARC

→ Making use of the angular dependences of the dilepton and K^+K^- decay channels, it is possible to **disentangle the longitudinal and transverse polarization modes**

Backup slides

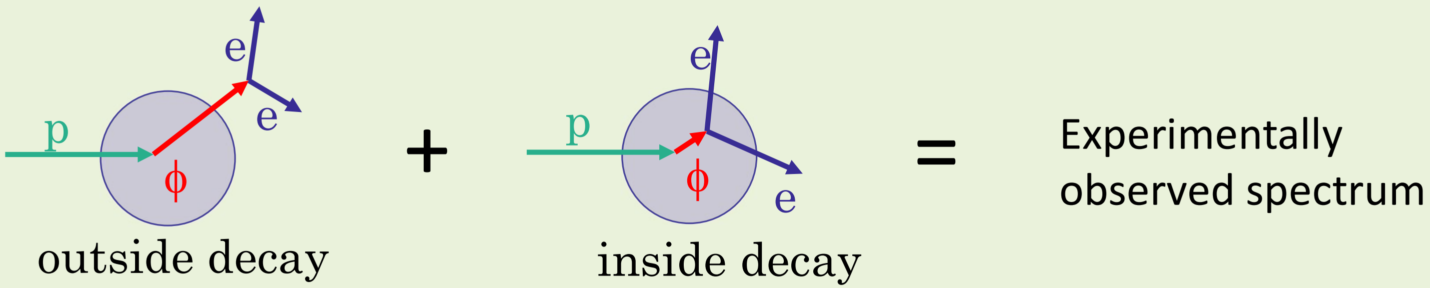
What does lattice QCD say about the strange sigma term?

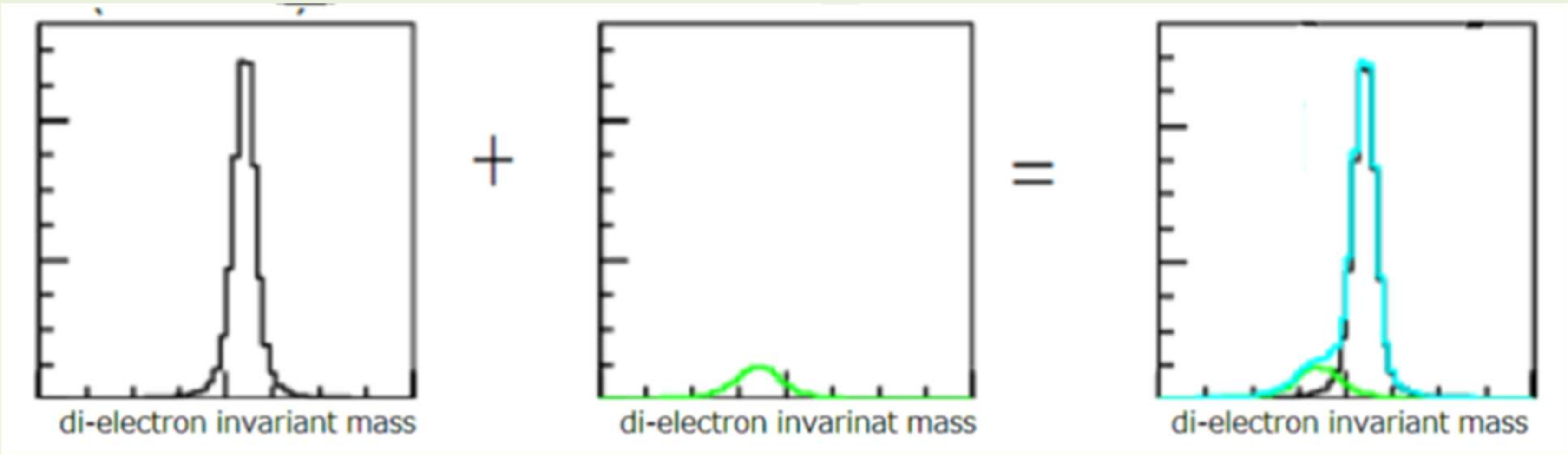
$$\sigma_{sN} = m_s \langle N|\bar{s}s|N\rangle$$



http://flag.unibe.ch/2021/

Experimental di-lepton spectrum



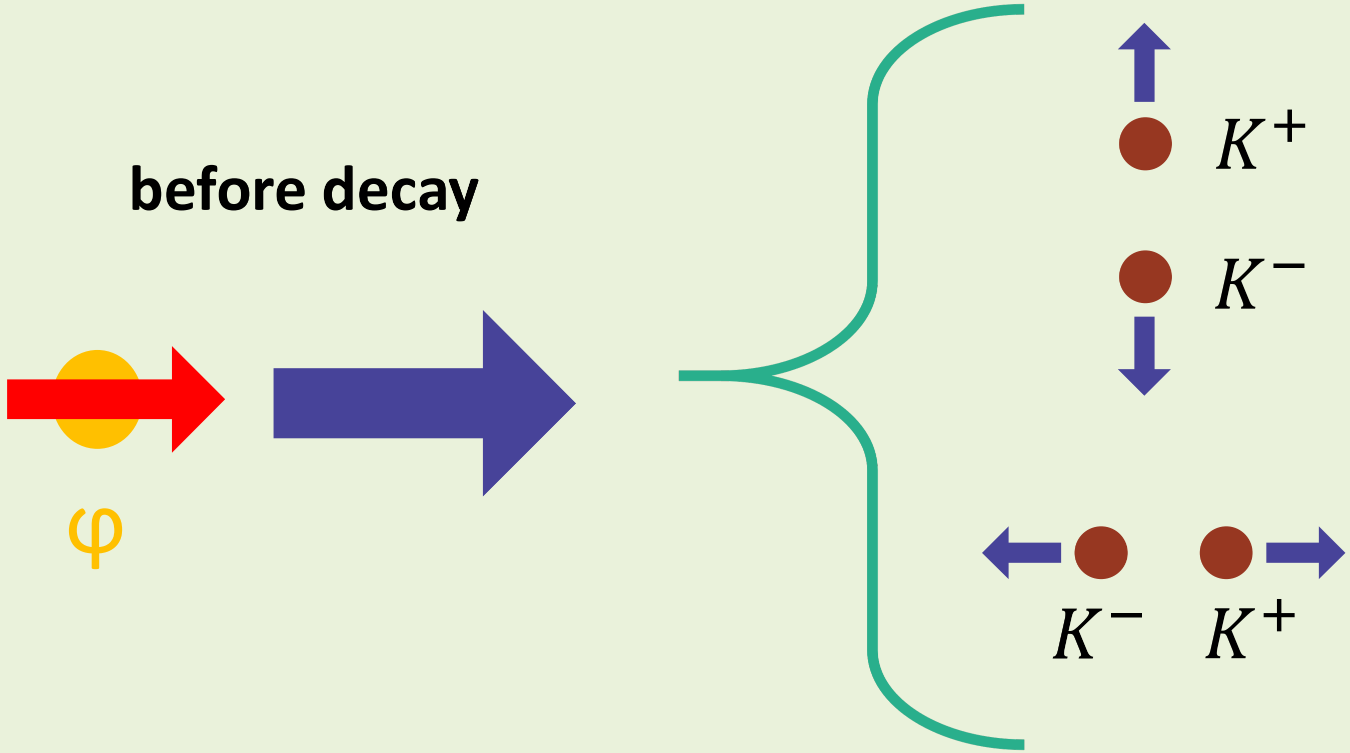


A simple example of K^+K^- decay of a transeversely polarized φ

$$|Y_1^1(\theta,\phi)|^2 \sim \sin^2\theta$$

before decay

after decay

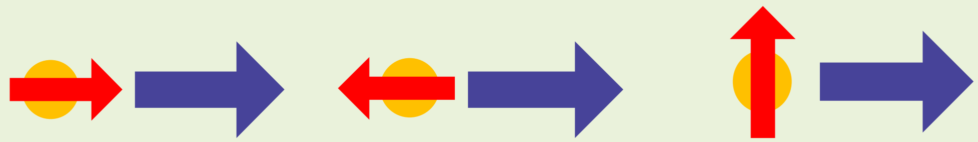


decay perpendicular to the φ meson momentum: **allowed**

decay parallel to the φ meson momentum: **not allowed**

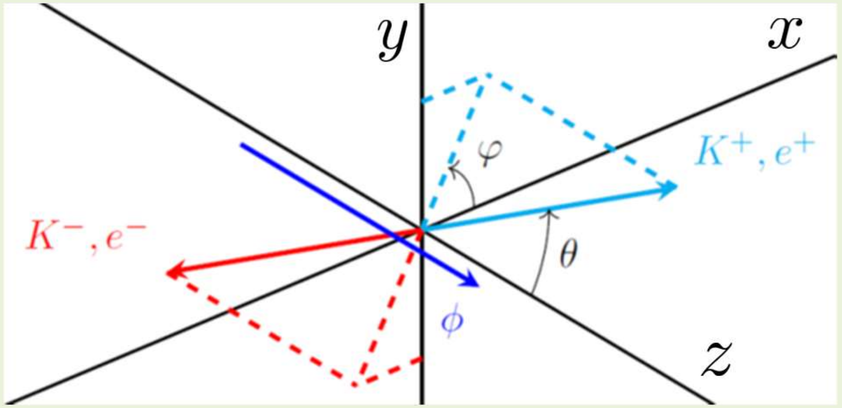
measurement in this direction can be used to observe purely longitudinal mode

Full angular distribution of dilepton decay



Initial polarization: $$|V\rangle = \underbrace{a_{+1}|+1\rangle + a_{-1}|-1\rangle}_{\text{Transverse polarization}} + a_0|0\rangle$$

Longitudinal polarization



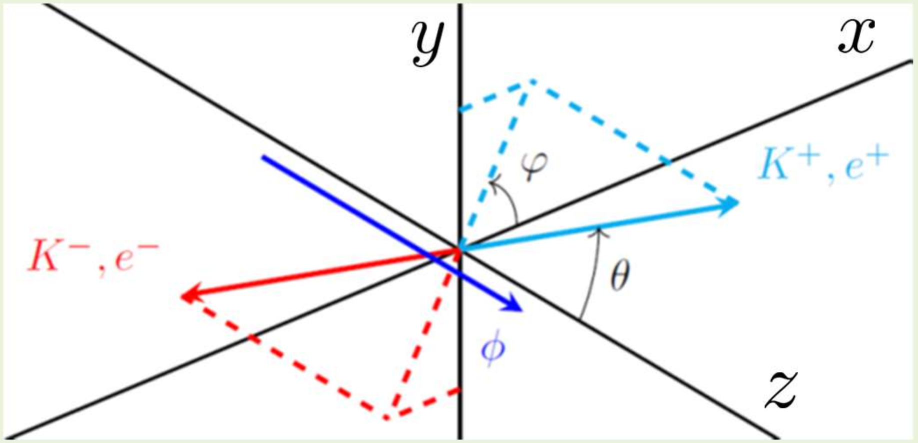
θ: polar angle

ϕ: azimuthal angle

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\Omega} = \frac{3}{16\pi}\Big[(|a_{+1}|^2 + |a_{-1}|^2)(1+\cos^2\theta) + 2|a_0|^2(1-\cos^2\theta)$$
$$+2\mathrm{Re}(a_{+1}a_{-1}^*)\sin^2\theta\cos 2\phi + \ldots\Big]$$

other ϕ-dependent terms

Full angular distribution of dilepton decay



θ: polar angle
ϕ: azimuthal angle

With

00-component of spin-density matrix

$$|a_{+1}|^2 + |a_{-1}|^2 + |a_0|^2 = 1, \;\; |a_0|^2 = \rho_{00}$$

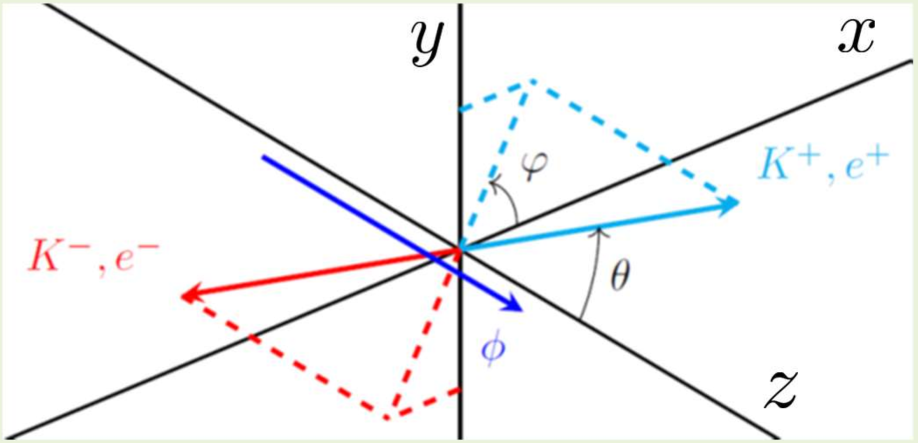
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\Omega} = \frac{3}{16\pi}\left[1 + \cos^2\theta + \rho_{00}(1 - 3\cos^2\theta) + \ldots\right]$$

$$\rho_{00} = \frac{1}{3}$$

Unpolarized case: vanishing θ-dependence

ϕ-dependent terms

Full angular distribution of K⁺K⁻ decay



θ: polar angle
ϕ: azimuthal angle

Longitudinal mode

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\Omega} = \frac{3}{16\pi}\Big[\overbrace{\left(|a_{+1}|^2 + |a_{-1}|^2\right)}^{\text{Transverse modes}}\sin^2\theta + 2|a_0|^2\cos^2\theta$$

$$-2\mathrm{Re}(a_{+1}a_{-1}^*)\sin^2\theta\cos 2\phi + \ldots\Big]$$

$$= \frac{3}{16\pi}\left[1 - \cos^2\theta - \rho_{00}(1 - 3\cos^2\theta) + \ldots\right]$$

ϕ-dependent terms