The phi meson in-medium polarization modes from theory and experiment

Philipp Gubler (JAEA)

H.J. Kim, P. Gubler and S.H. Lee, Phys. Lett. B **772**, 194 (2017).

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, Phys. Rev. D **107**, 074033 (2023).

Talk at QCD Theory Seminars,
online,
October 19, 2023

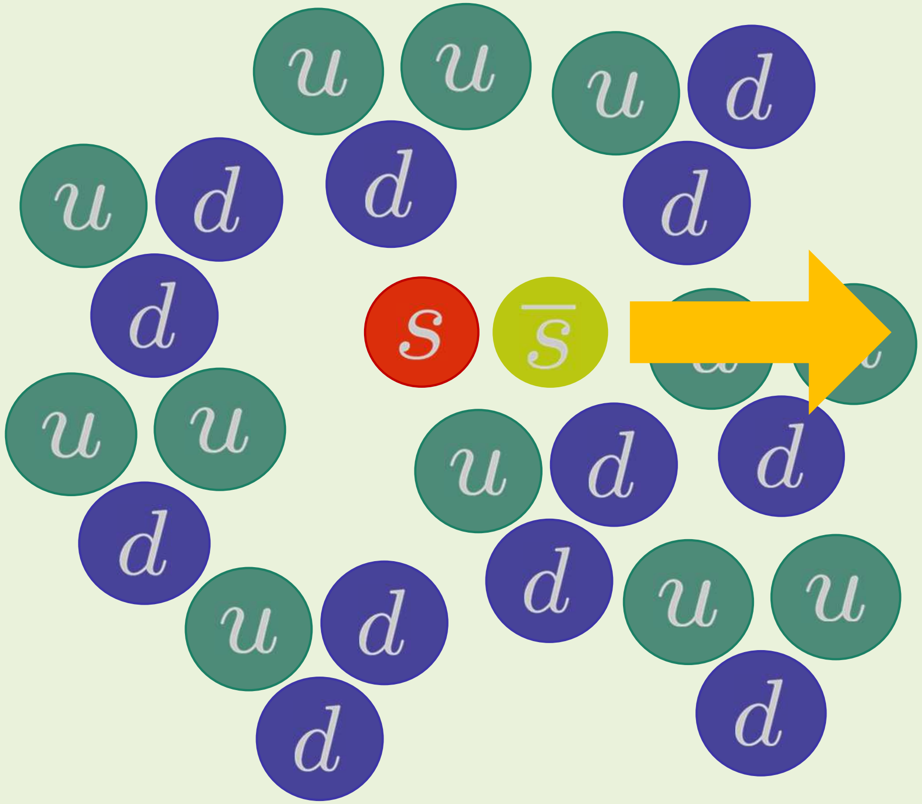
Work done in collaboration with
HyungJoo Kim (Yonsei U.)
InWoo Park (Yonsei U.)
Hiroyuki Sako (JAEA)
Kazuya Aoki (KEK)
Su Houng Lee (Yonsei U.)

Interest

ϕ meson

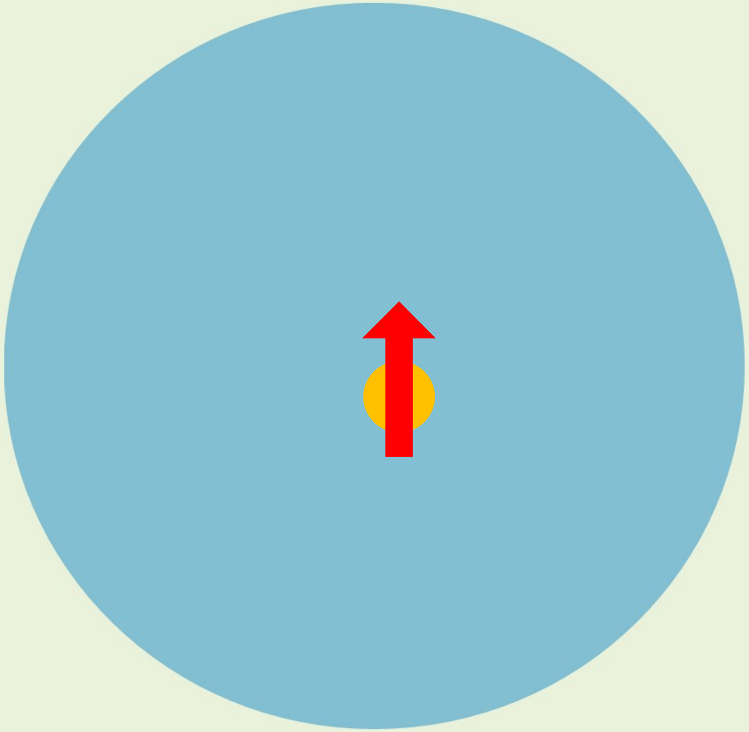
$m_\phi = 1019$ MeV

$\Gamma_\phi = 4.3$ MeV

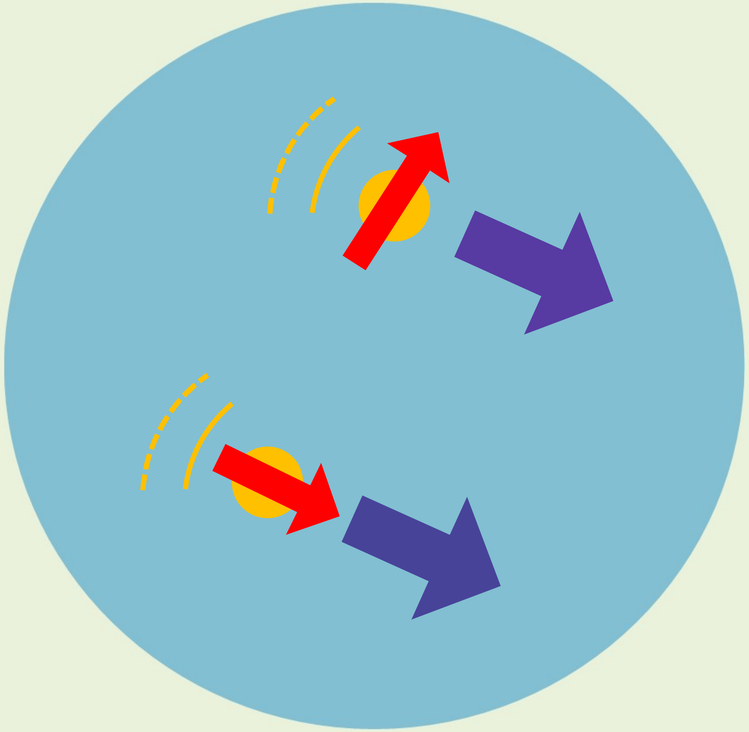


Role of spin

meson at rest in nuclear matter



meson moving in nuclear matter

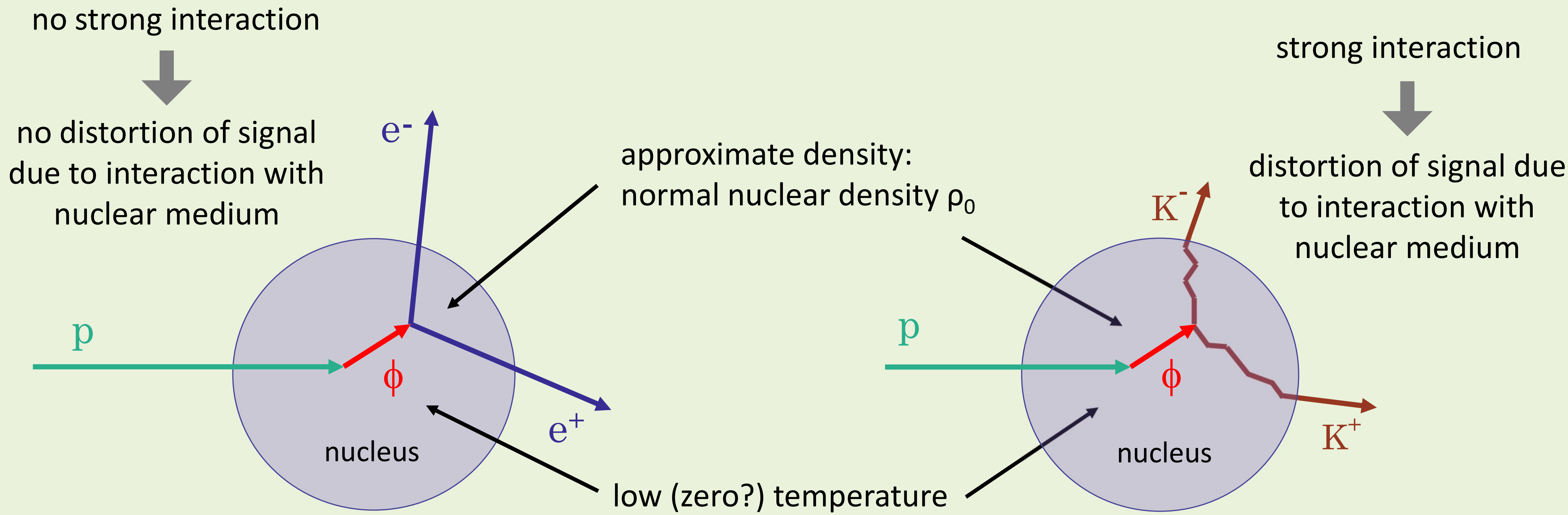


→ spin direction does not change physics
(rotational symmetry)

→ spin direction changes physics
(broken rotational symmetry)

The φ meson in pA collisions

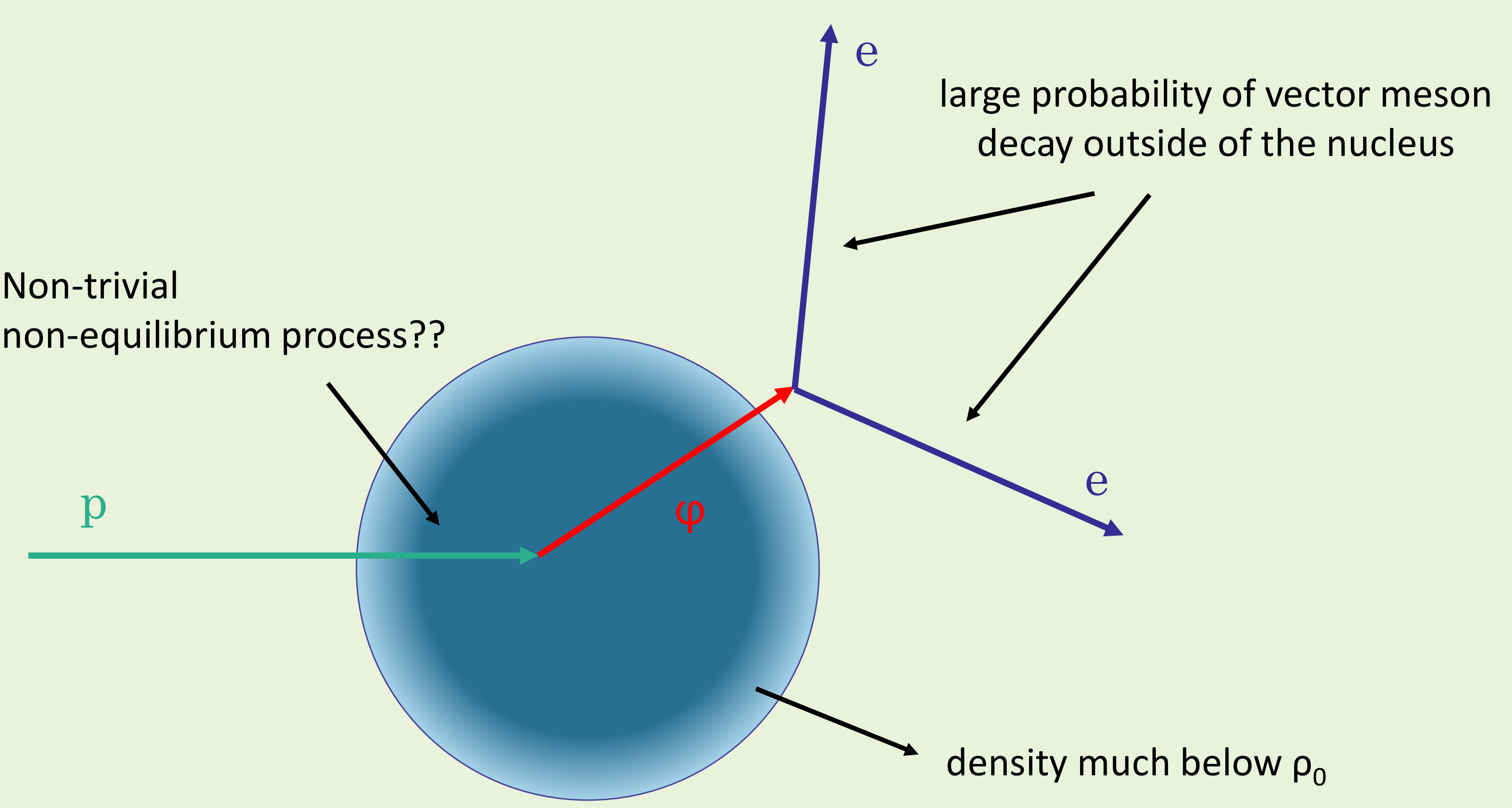
Experiments to be discussed in this talk



E325 (KEK)
E16 (J-PARC)

pion beam (HADES)
E88 (J-PARC)

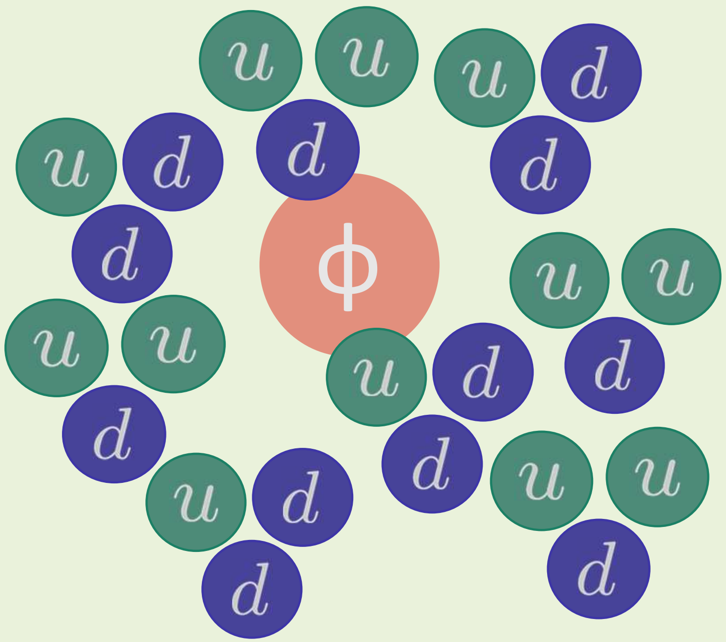
Complications of the experimental measurement



Baseline: φ meson **at rest** in nuclear matter

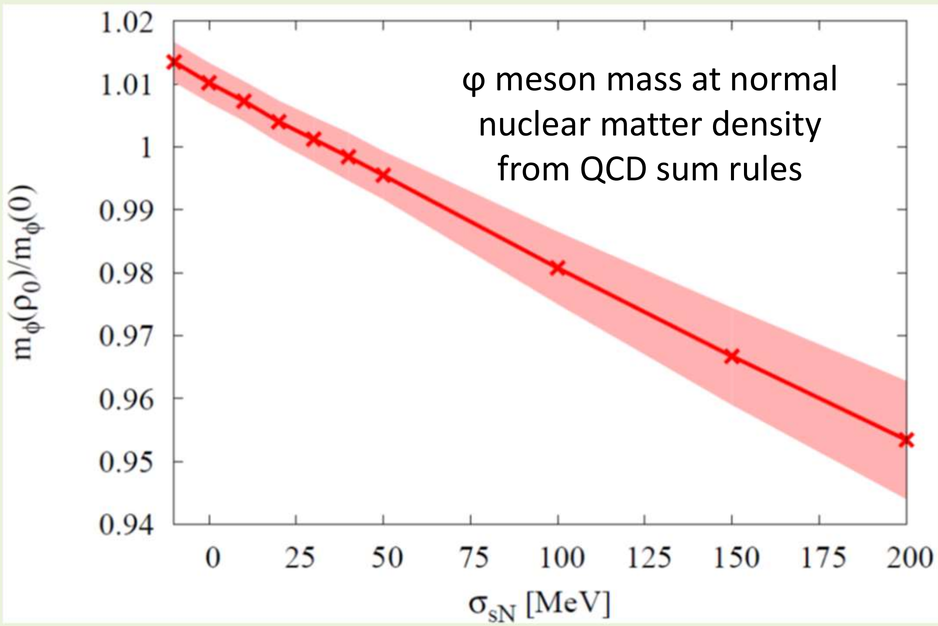
The φ meson mass in nuclear matter probes the strange quark condensate at finite density

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



T. Hatsuda and S.H. Lee, Phys. Rev. C **46**, R34 (1992).

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



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

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

QCD sum rules

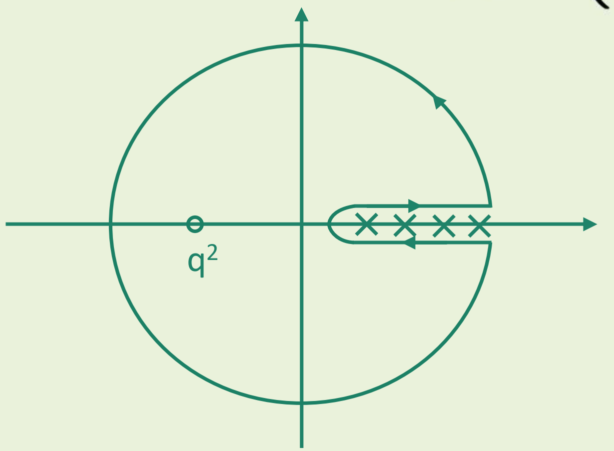
Makes use of the analytic properties of the correlation function:

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

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

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:
same for longitudinal and transverse modes

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

non-scalar condensates:
cause difference between longitudinal and transverse modes

Structure of QCD sum rules for the φ meson channel

(after application of the Borel transform)

$$\chi(x) = \overline{s}(x)\gamma_\mu s(x)$$

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

In Vacuum

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

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

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

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

Structure of QCD sum rules for the φ meson

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

At finite density

(within the linear density approximation)

$$\boxed{\langle \overline{s}s\rangle_\rho = \langle 0|\overline{s}s|0\rangle + \langle N|\overline{s}s|N\rangle\rho + \dots}$$

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

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

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

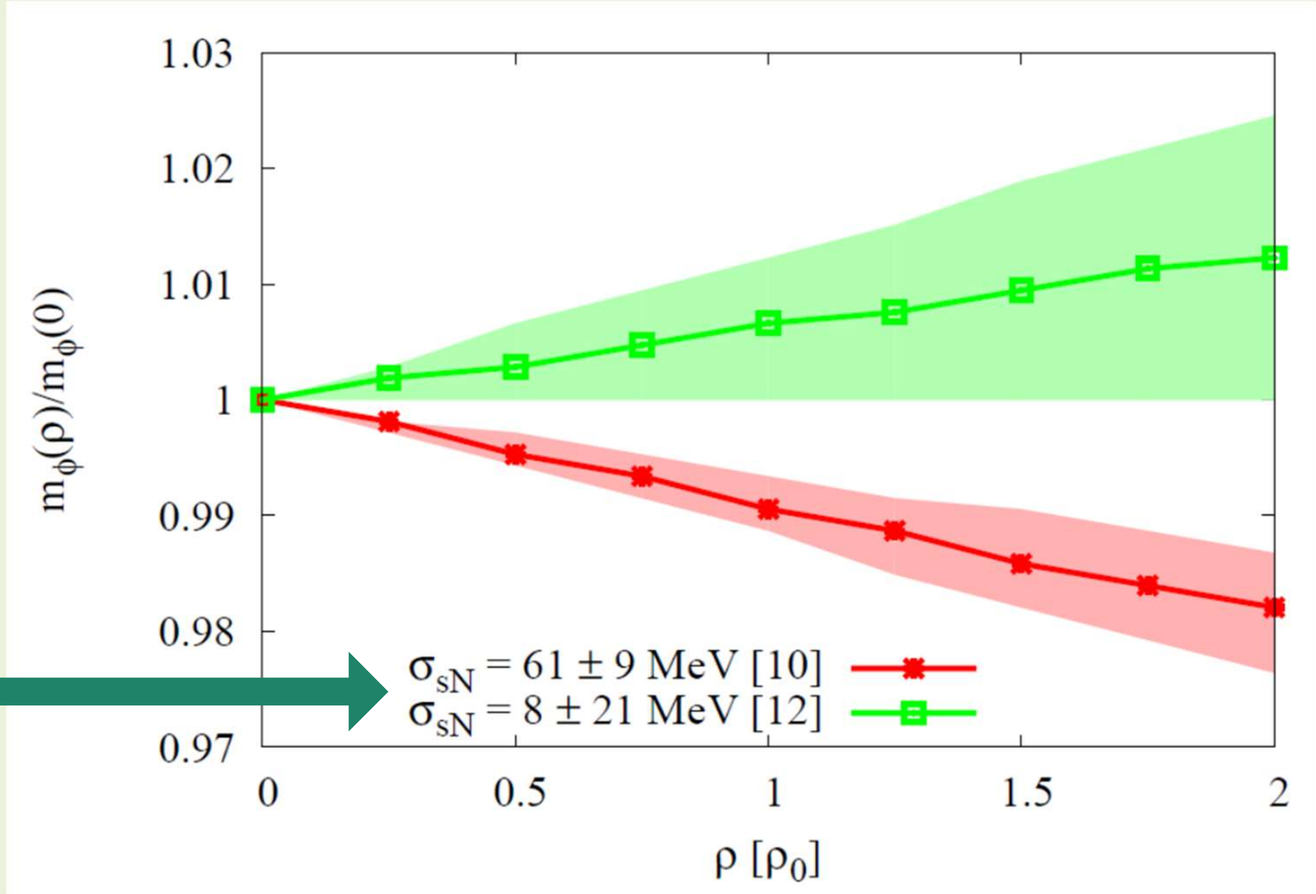
Dim. 6: $c_6(\rho) = c_6(0) + \rho[-\frac{896}{81}\kappa_N \pi^3 \alpha_s \langle \overline{s}s\rangle\langle N|\overline{s}s|N\rangle - \frac{5}{6}A_4^s M_N^3]$

Results for the ϕ meson mass at rest

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

Strangeness content of the nucleon

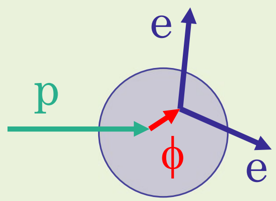
$$\sigma_{sN} = m_s \langle N | \bar{s}s | N \rangle$$



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

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

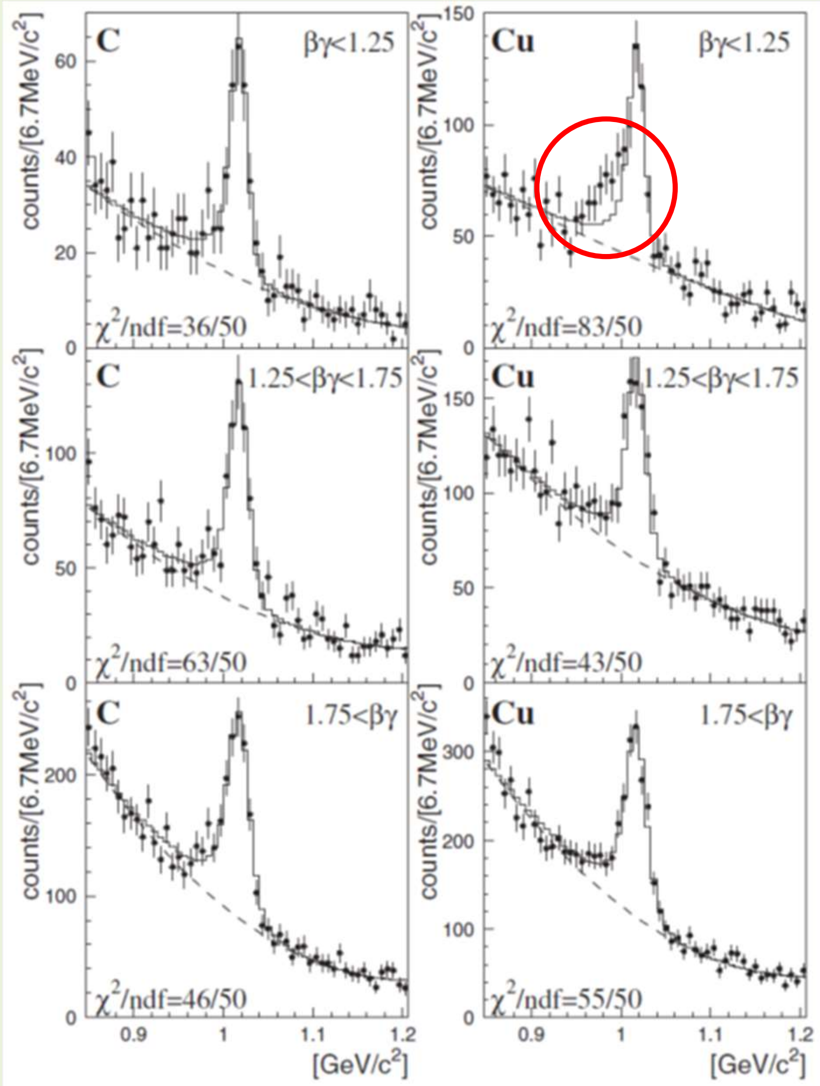
2.6 ± 1.5

slow φs

intermediate φs

fast φs

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

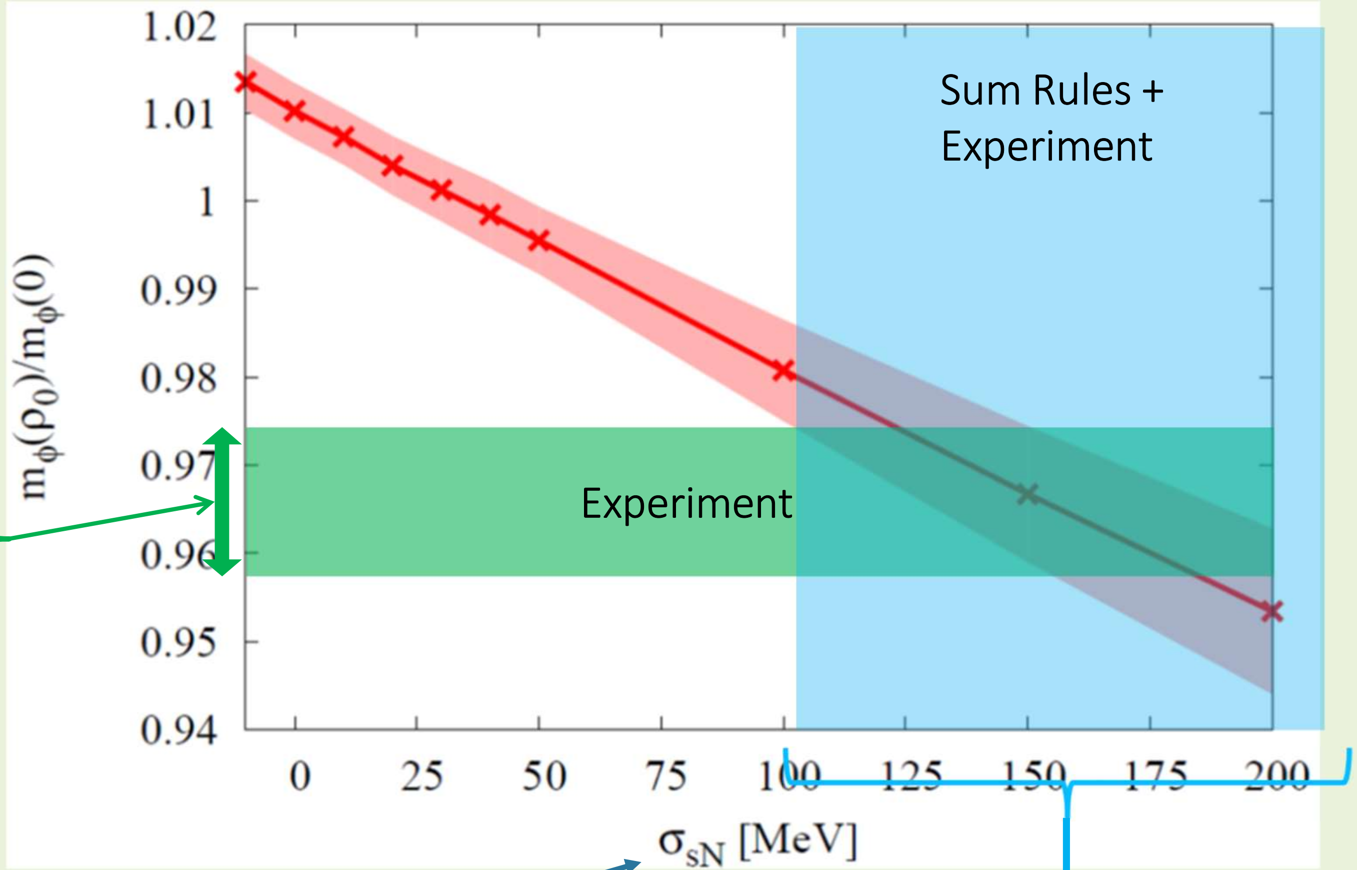


R. Muto et al. (E325 Collaboration), Phys. Rev. Lett. **98**, 042501 (2007).

Comparison between theory and experiment

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

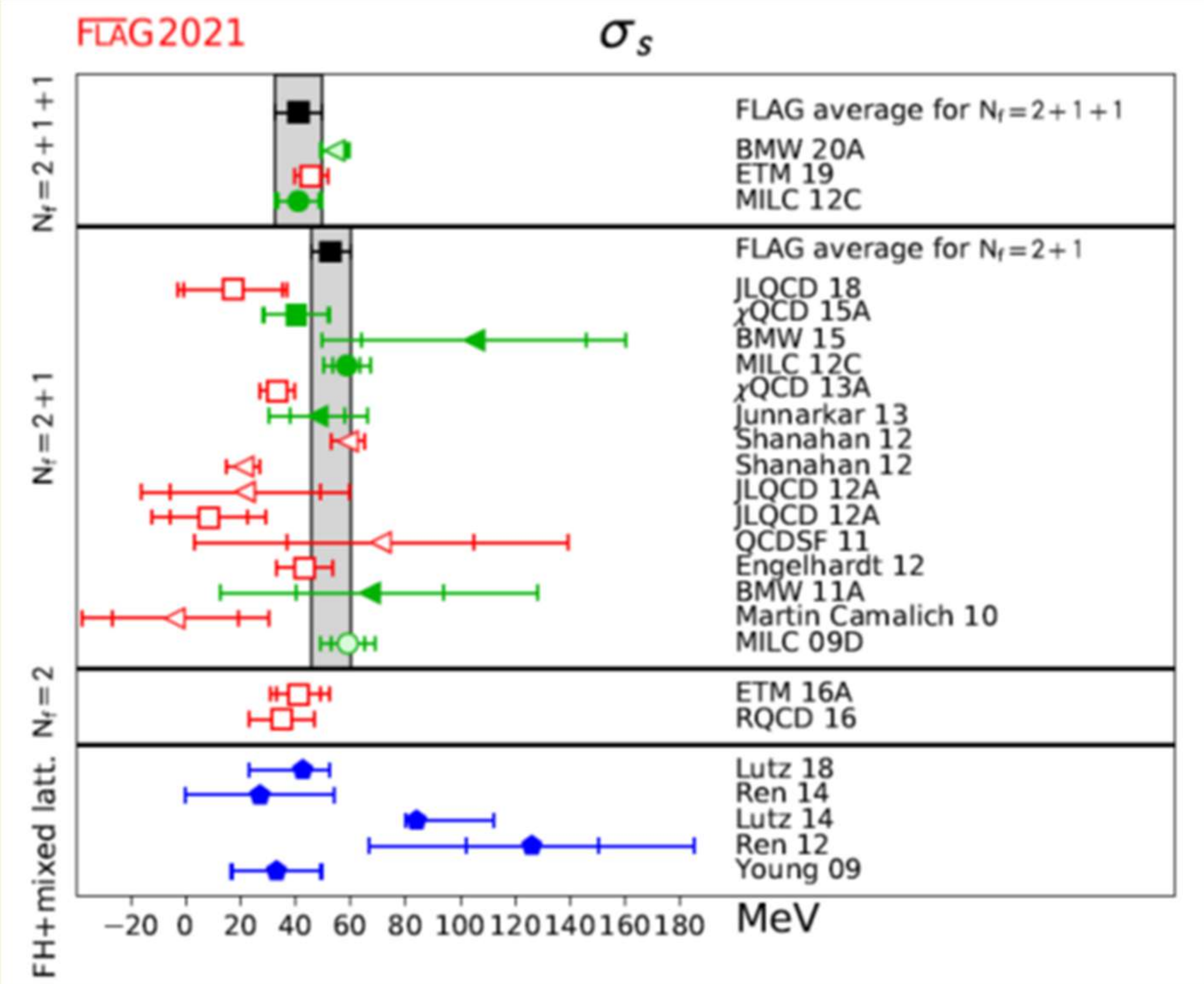
$$\frac{m_\phi(\rho)}{m_\phi(0)} = 0.966 \pm 0.007$$



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

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/

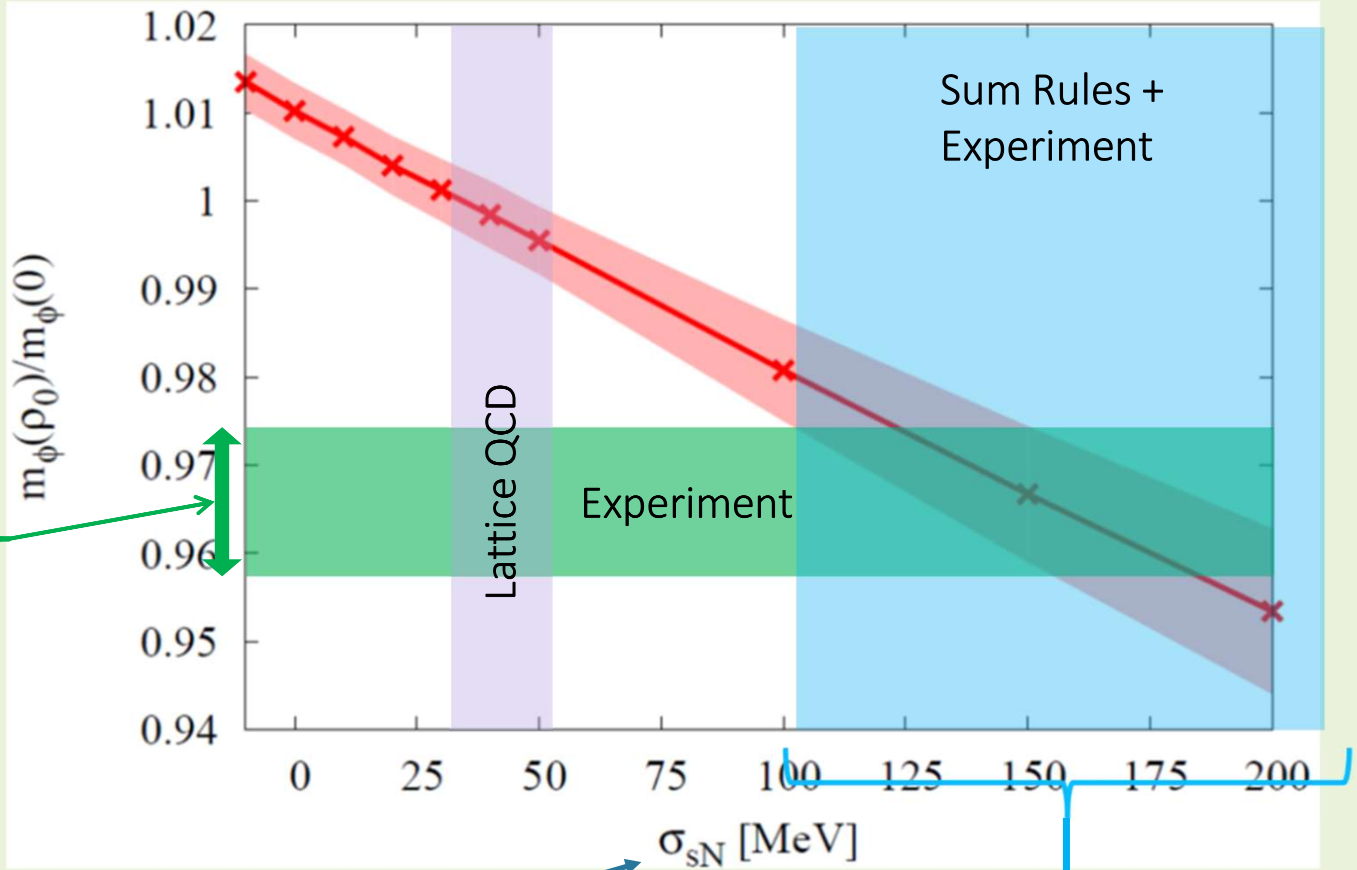
Comparison between theory and experiment

Not consistent?

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

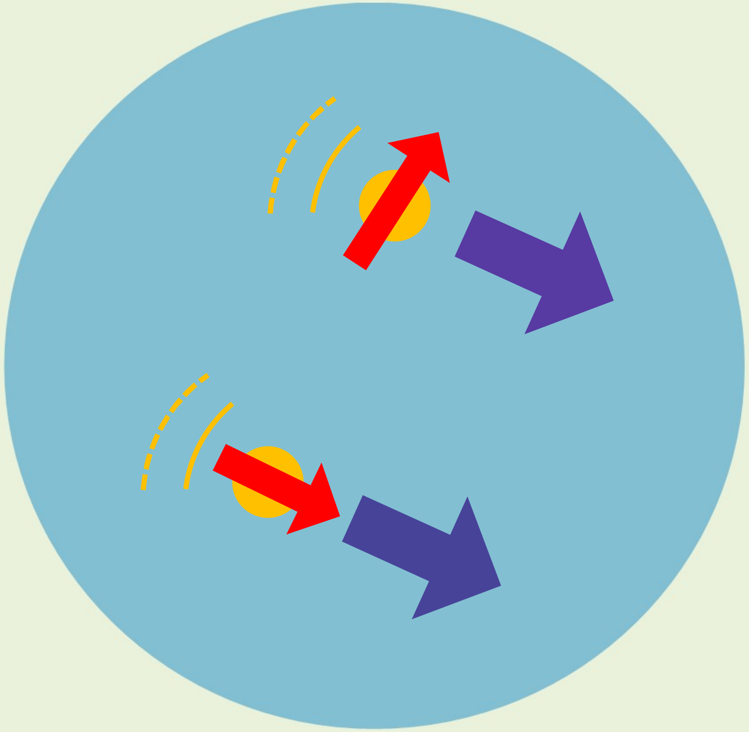
Measurement will be repeated at the J-PARC E16 experiment (with 100 times increased statistics!)

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

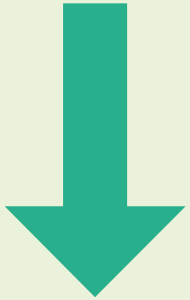


$$\sigma_{sN} = m_s \langle N | \bar{s}s | N \rangle \qquad \sigma_{sN} \sim 160 \pm 50 \text{ MeV}$$

φ meson **moving** in nuclear matter



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



Broken
Lorentz symmetry

★ Potential effect on mass shift measurement?

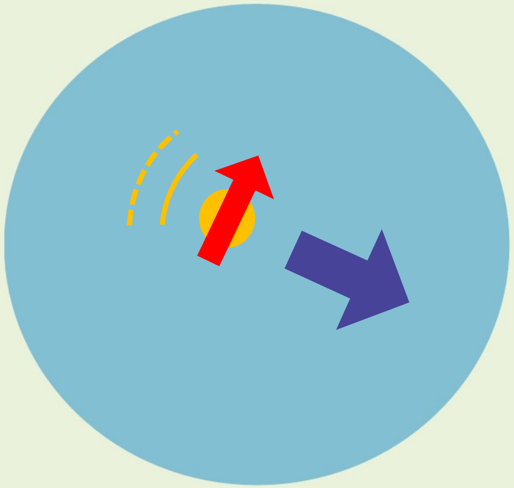
★ Splitting between different polarization modes?

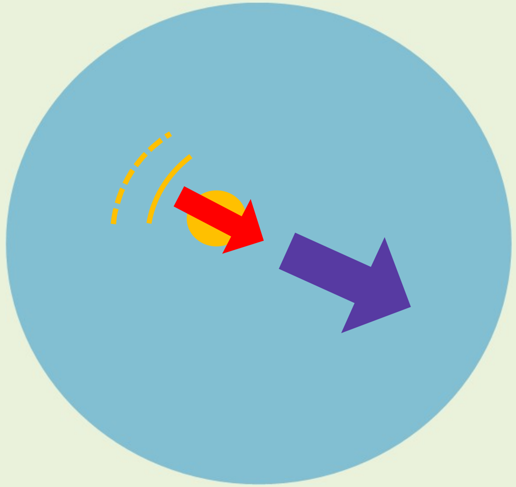
The non-zero momentum case: Disentangling longitudinal and transverse components

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

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

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





The ϕ meson with non-zero momentum

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

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

longitudinal part

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

transverse part

zero momentum

non-zero momentum $\vec{q}$

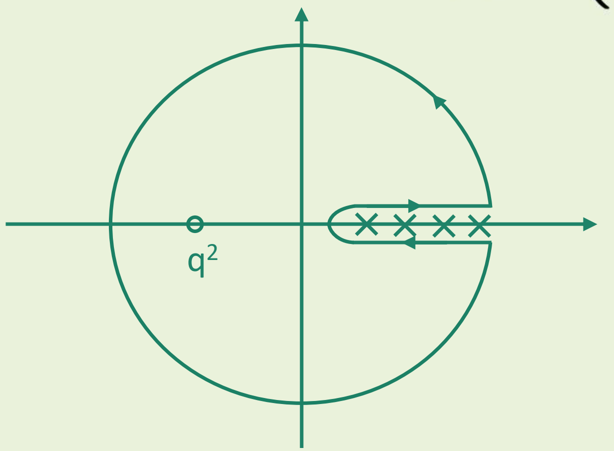
M.A. Shifman, A.I. Vainshtein and V.I. Zakharov, Nucl. Phys. B147, 385 (1979); B147, 448 (1979).

QCD sum rules

Makes use of the analytic properties of the correlation function:

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

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



spectral function

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

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

scalar condensates: **same for longitudinal and transverse modes**

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

non-scalar condensates: **cause difference between longitudinal and transverse modes**

Condensates that appear in the vector channel

Quark condensates

scalar:

$$\langle \bar{q} j q \rangle \equiv \langle g \bar{q} \gamma_\mu (D_\nu G_{\mu\nu}) q \rangle,$$
$$\langle j_5 j_5 \rangle \equiv \langle g^2 \bar{q} t^a \gamma_5 \gamma_\mu q \bar{q} t^a \gamma_5 \gamma_\mu q \rangle,$$

non-scalar:

$$A_{\alpha\beta} \equiv \langle g \bar{q} (D_\mu G_{\alpha\mu}) \gamma_\beta q | ST \rangle,$$
$$B_{\alpha\beta} \equiv \langle g \bar{q} \{ i D_\alpha, \tilde{G}_{\beta\mu} \} \gamma_5 \gamma_\mu q | ST \rangle,$$
$$C_{\alpha\beta} \equiv \langle m \bar{q} D_\alpha D_\beta q | ST \rangle,$$
$$F_{\alpha\beta} \equiv \langle \bar{q} \gamma_\alpha i D_\beta q | ST \rangle,$$
$$H_{\alpha\beta} \equiv \langle g^2 \bar{q} t^a \gamma_5 \gamma_\alpha q \bar{q} t^a \gamma_5 \gamma_\beta q \rangle,$$
$$K_{\alpha\beta\gamma\delta} \equiv \langle \bar{q} \gamma_\alpha D_\beta D_\gamma D_\delta q | ST \rangle$$

Gluon condensates

scalar:

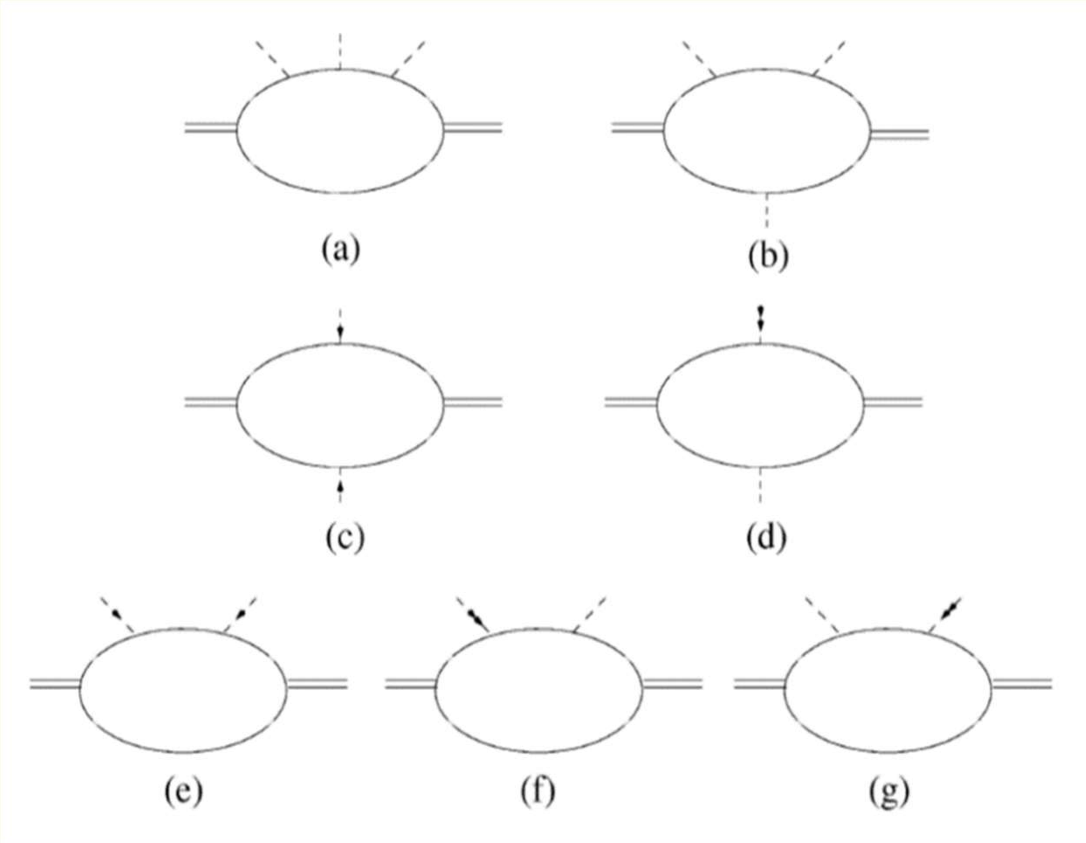
$$\langle G^2 \rangle \equiv \langle g^2 G^a_{\mu\nu} G^a_{\mu\nu} \rangle,$$
$$\langle G^3 \rangle \equiv \langle g^3 f^{abc} G^a_{\mu\nu} G^b_{\nu\lambda} G^c_{\lambda\mu} \rangle,$$
$$\langle j^2 \rangle \equiv \langle g^2 (D_\mu G^a_{\alpha\mu})(D_\nu G^a_{\alpha\nu}) \rangle,$$

non-scalar:

$$G_{2\alpha\beta} \equiv \langle g^2 G^a_{\alpha\mu} G^a_{\beta\mu} | ST \rangle,$$
$$X_{\alpha\beta} \equiv \langle g^2 G^a_{\mu\nu} D_\beta D_\alpha G^a_{\mu\nu} | ST \rangle,$$
$$Y_{\alpha\beta} \equiv \langle g^2 G^a_{\alpha\mu} D_\mu D_\nu G^a_{\beta\nu} | ST \rangle,$$
$$Z_{\alpha\beta} \equiv \langle g^2 G^a_{\alpha\mu} D_\beta D_\nu G^a_{\mu\nu} | ST \rangle,$$
$$G_{4\alpha\beta\gamma\delta} \equiv \langle g^2 G^a_{\alpha\mu} D_\delta D_\gamma G^a_{\beta\mu} | ST \rangle$$

Wilson coefficients were not yet available until recently

OPE calculation



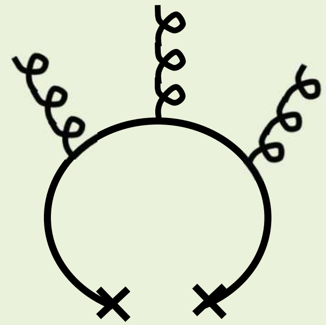
S. Kim and S.H. Lee, Nucl. Phys. **679**, 517 (2001).

H.J. Kim, P. Gubler and S.H. Lee, Phys. Lett. B **772**, 194 (2017).

Mass singularities in chiral limit!

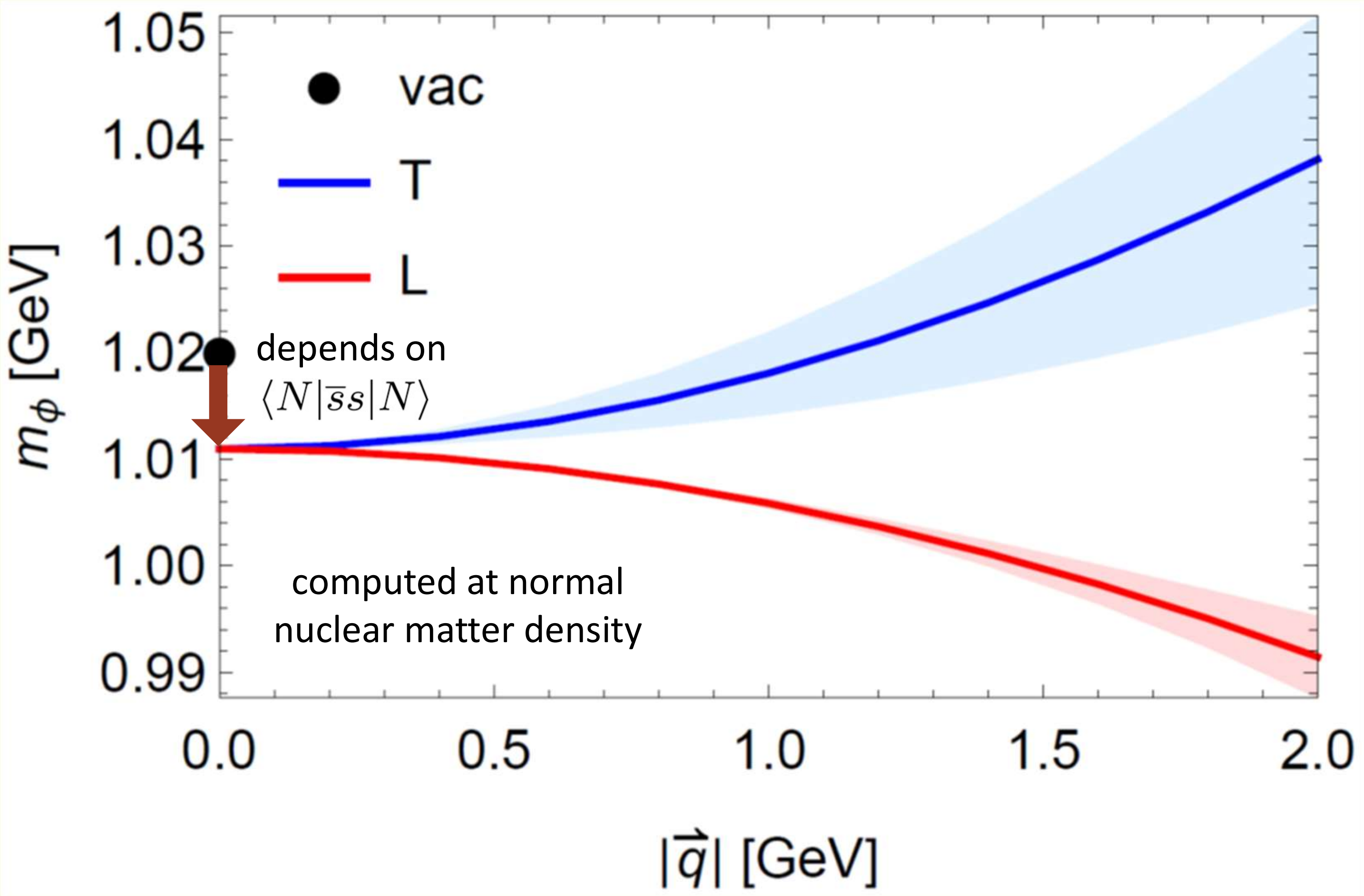
$$\frac{1}{m^2},\ \log\left(\frac{\mu^2}{m^2}\right),\ \dots$$

Subtract corresponding quark condensate contribution



$\langle \bar{q}\,\Gamma(D,G)q\rangle$

Results for the ϕ meson mass with non-zero momentum



caused by

$$\langle N|\mathcal{ST}\bar{s}\gamma^\alpha iD^\beta s|N\rangle$$
$$+$$
$$\langle N|\mathcal{ST}G^{a\alpha}_\mu G^{a\mu\beta}|N\rangle$$

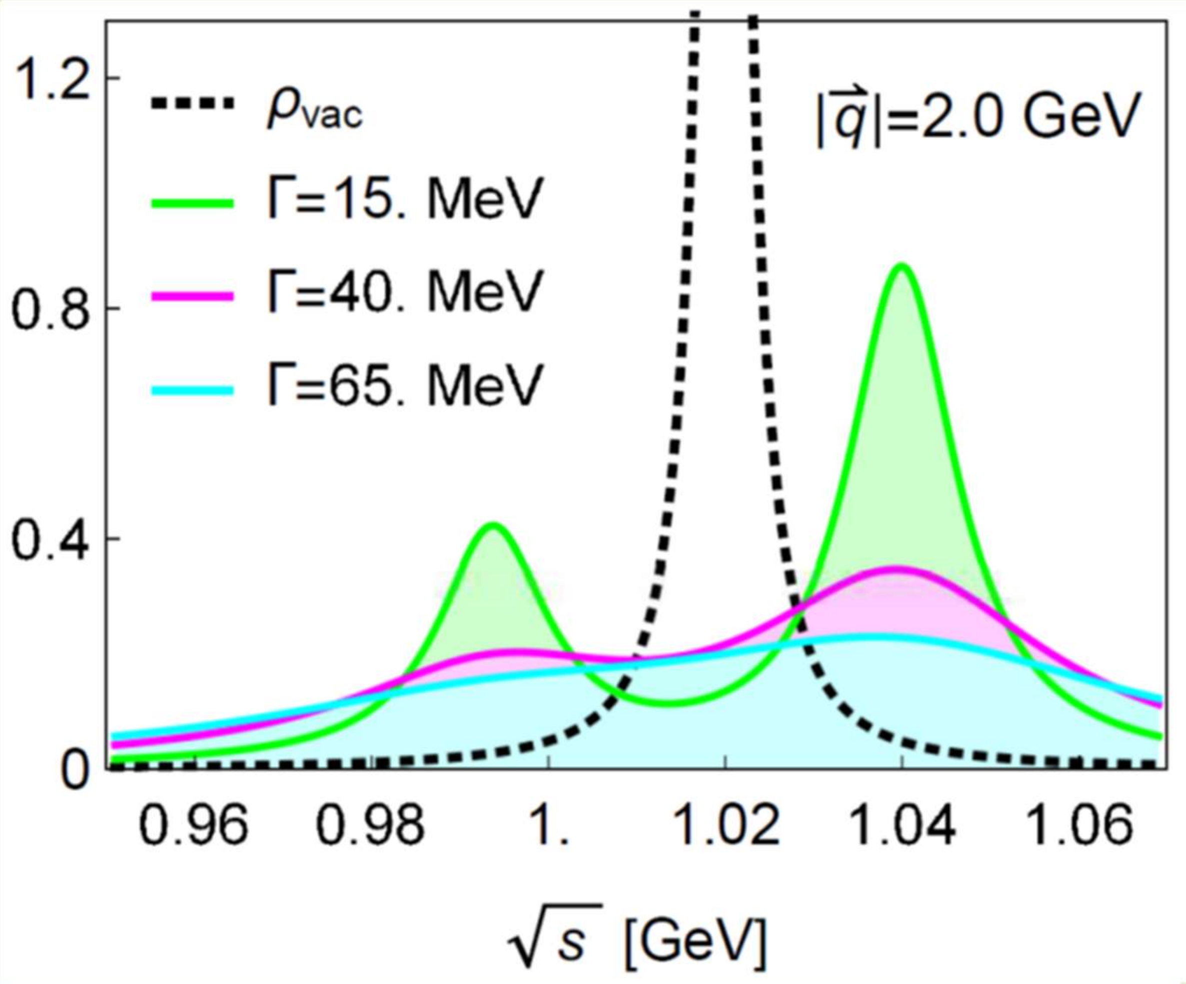
caused by

$$\langle N|\mathcal{ST}G^{a\alpha}_\mu G^{a\mu\beta}|N\rangle$$

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

The angle-averaged di-lepton spectrum

A double peak?

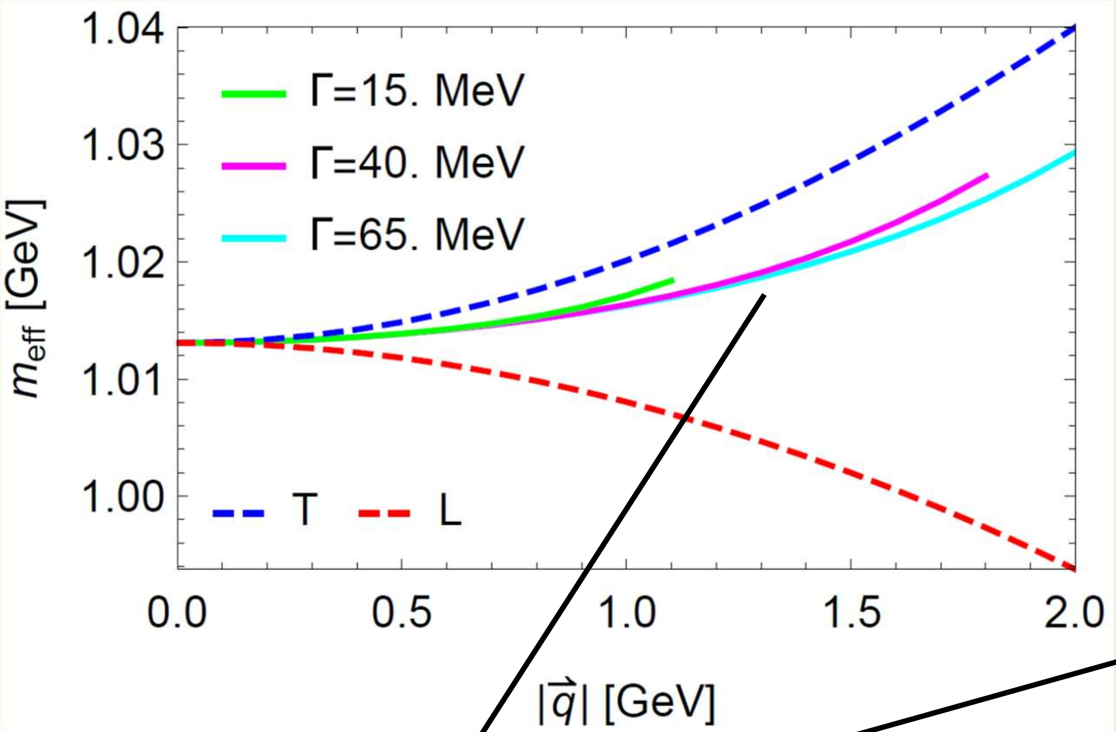


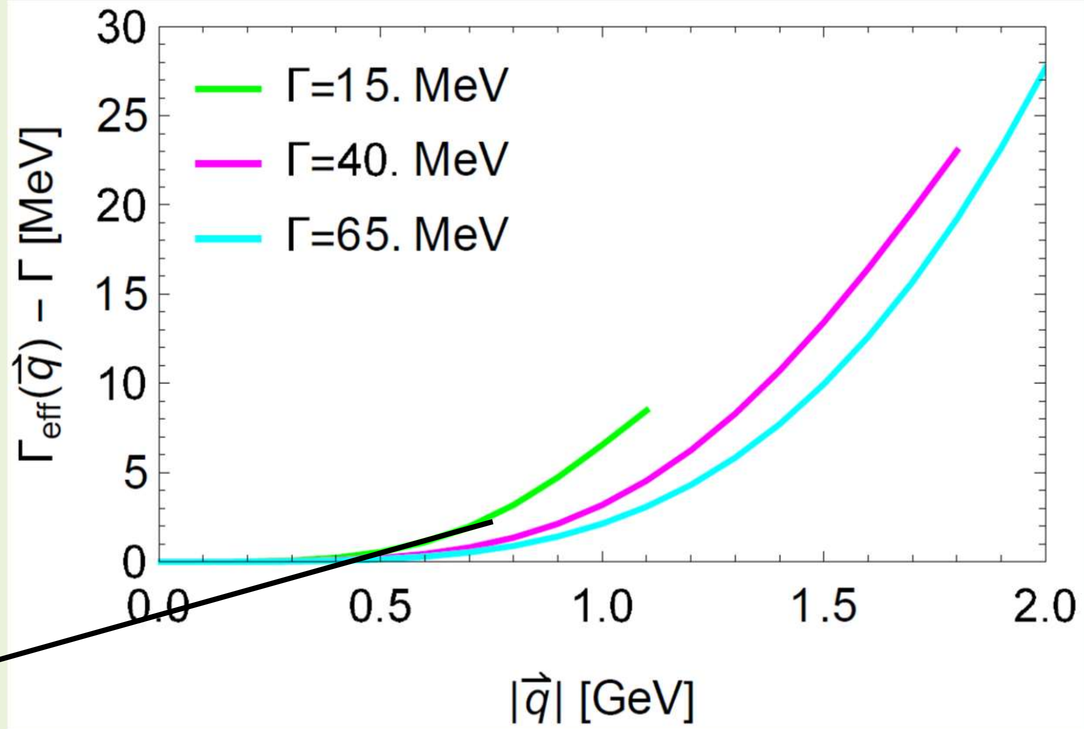
Computed at normal nuclear matter density

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



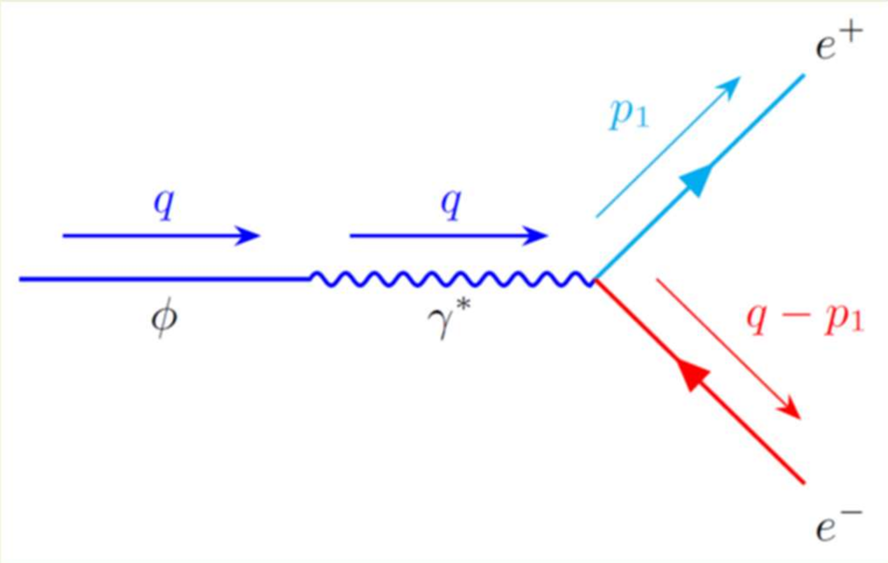


Results of one-peak fits

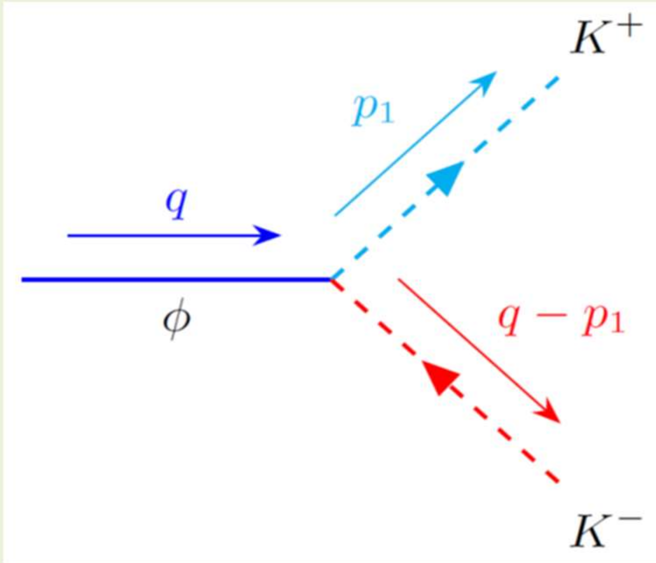
H.J. Kim and P. Gubler, Phys. Lett. B **805**, 135412 (2020).

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

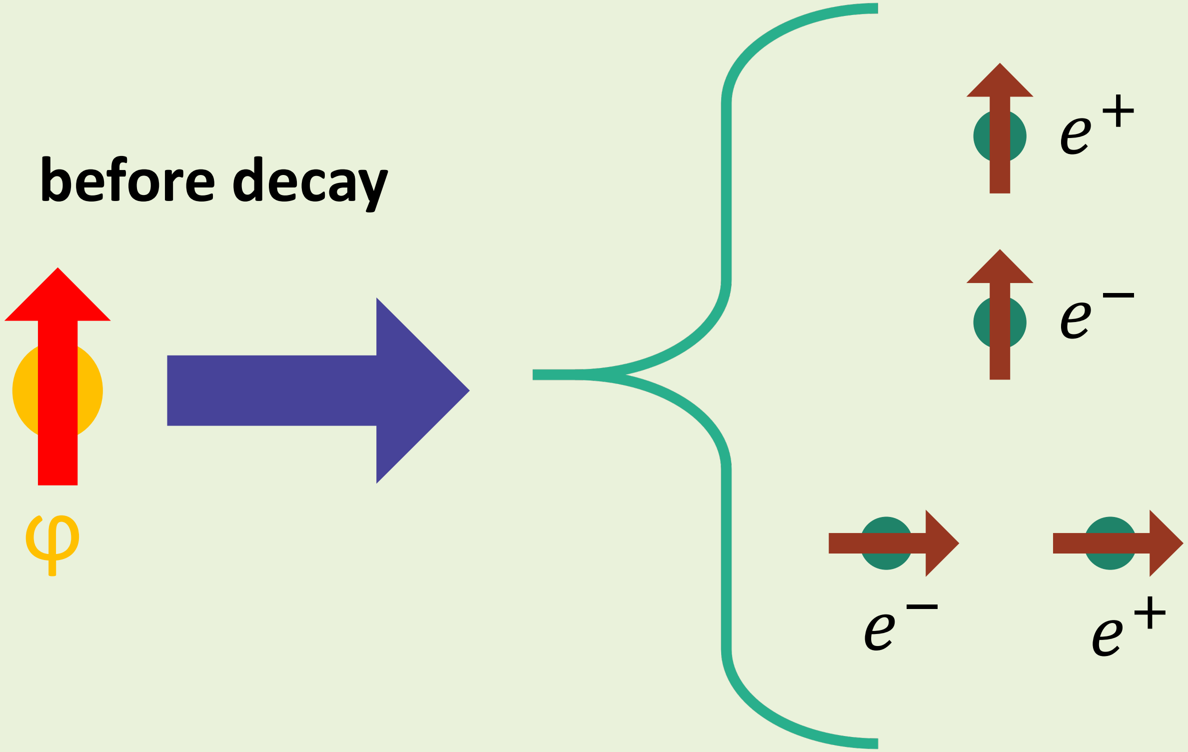


New E88 experiment
at J-PARC (in a few years)

A simple example of dilepton decay of a longitudinally polarized φ

before decay

after decay



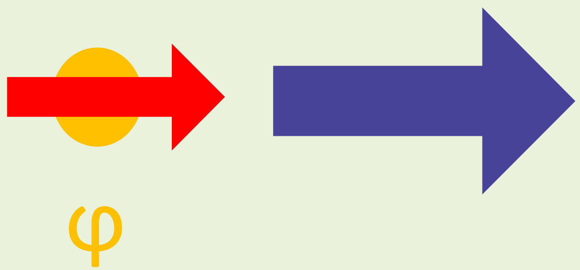
decay <u>perpendicular</u> to
the φ meson momentum:
allowed

decay <u>parallel</u> to the
φ meson momentum:
not allowed

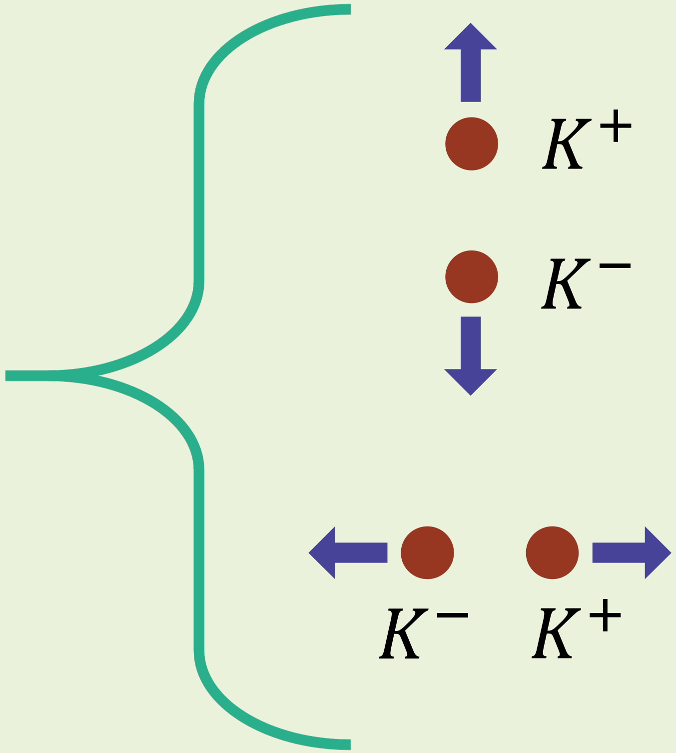
measurement in this direction
can be used to observe purely
transverse mode

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

before decay



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



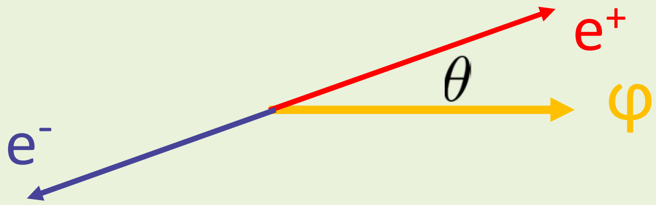
after decay

decay <u>perpendicular</u> to the φ meson momentum: **allowed**

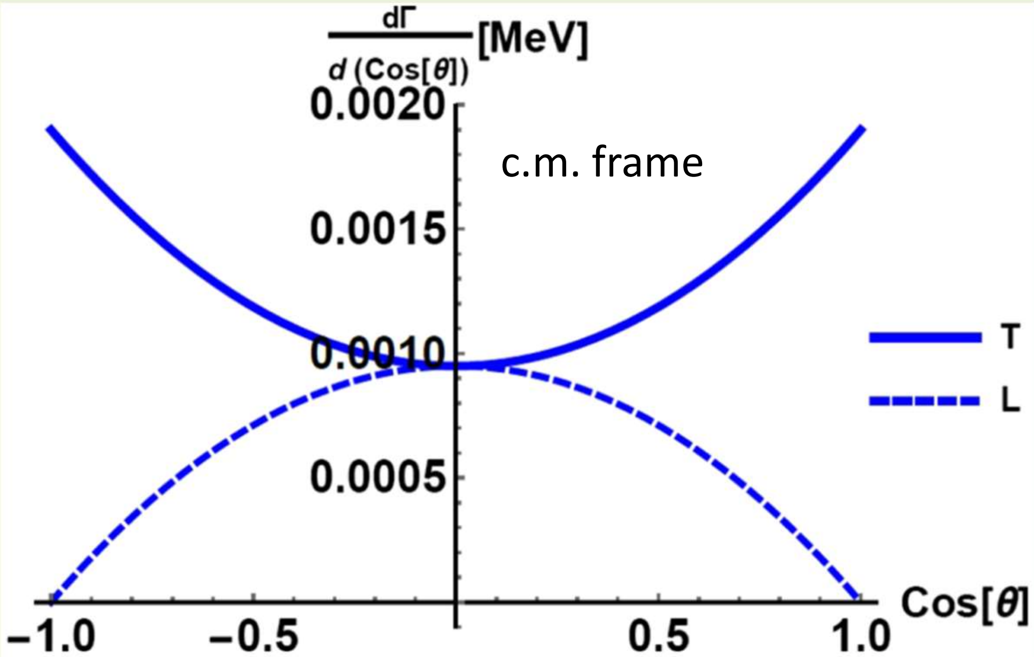
decay <u>parallel</u> to the φ meson momentum: **not allowed**

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

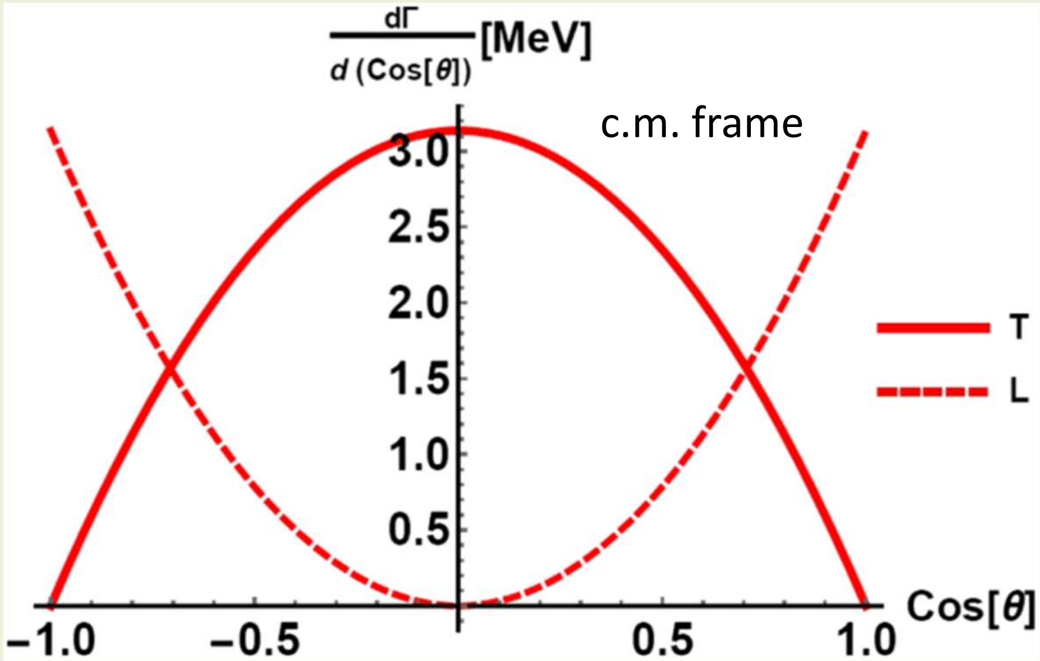
Summary of φ meson dilepton and K⁺K⁻ decays



Dilepton decay angular distribution



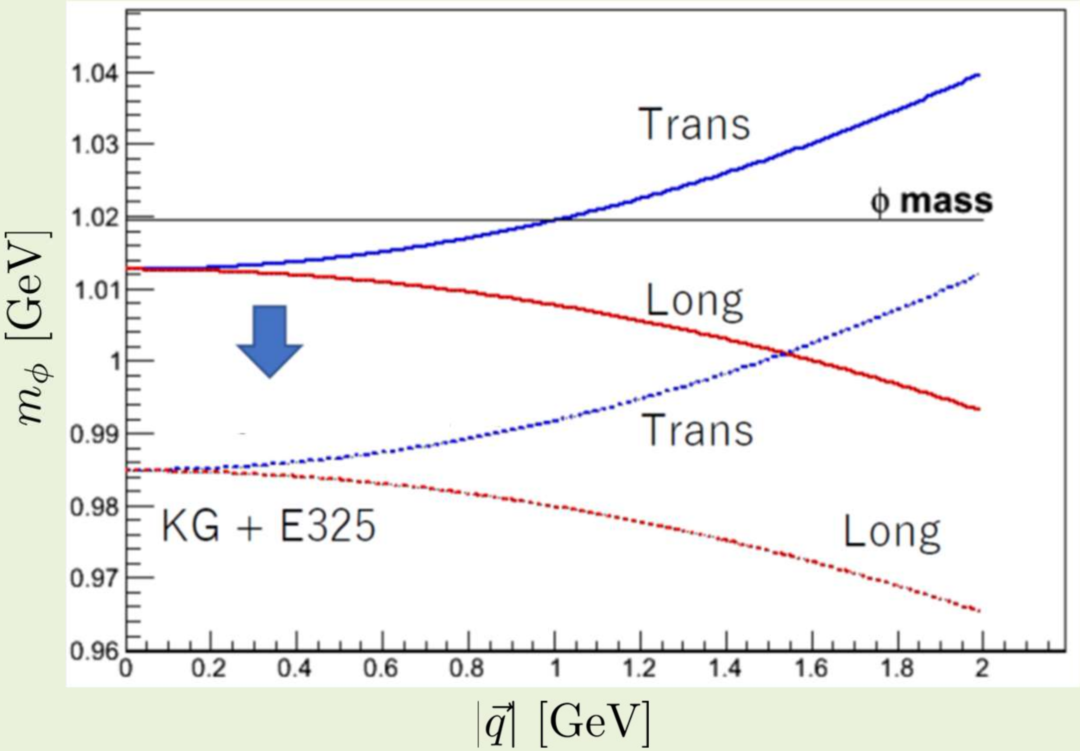
K⁺K⁻ decay angular distribution



I.W. Park, H. Sako, K. Aoki, P. Gubler and S.H. Lee, Phys. Rev. D **107**, 074033 (2023).

Is it possible to disentangle the two polarization modes?

Model setup:



$$\frac{m_\phi^{L/T}(\vec{q})}{m_\phi^{\mathrm{vac}}} = 1 + \left[a + b^{L/T}\vec{q}^{\,2}\right]\frac{\rho_N}{\rho_0}$$

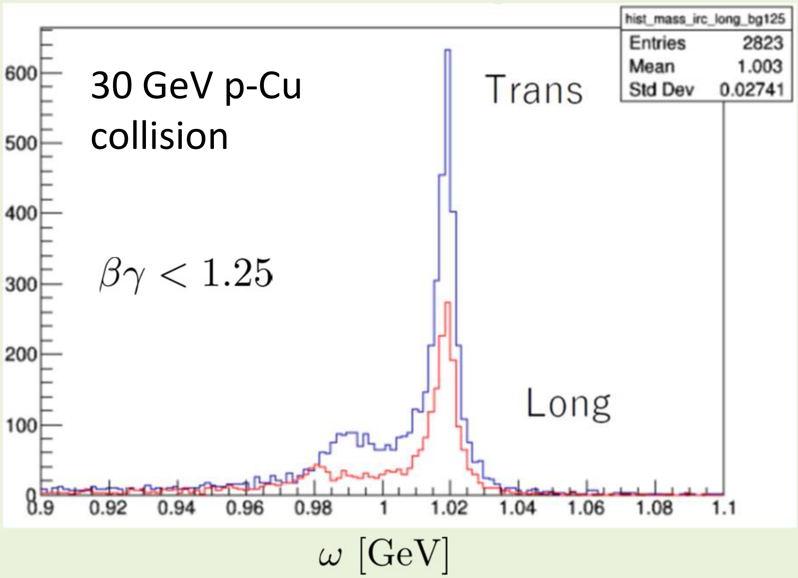
adjusted to the mass shift
observed by the E325 experiment:
a = -0.034
[R. Muto et al.,
Phys. Rev. Lett. **98**, 042501 (2007).]

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

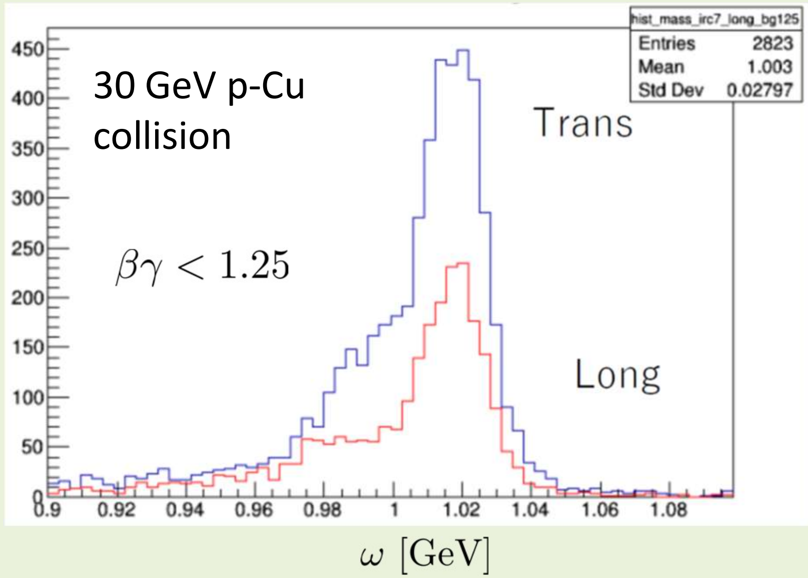
Analysis done by Kazuya Aoki (KEK)

A simple Monte Carlo simulations under realistic experimental conditions

- ★ Momentum distribution from JAM (nuclear cascade code)
- ★ Breit-Wigner spectral function with density dependent mass
- ★ Radiative corrections (photon emission) of final state dileptons included
- ★ Target density: assumed to have a Woods-Saxon shape
- ★ φ production: assumed to be proportional to density

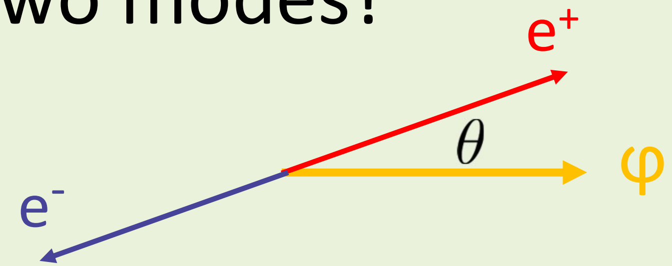


smeared by the expected mass resolution (7 MeV)



How to disentangle the two modes?

$$x = \cos(\theta)$$



$$G(\omega, x) = g_T(\omega) f_T(x) + g_L(\omega) f_L(x)$$

measured

to be extracted

known $\propto 1 + x^2$

to be extracted

known $\propto 1 - x^2$

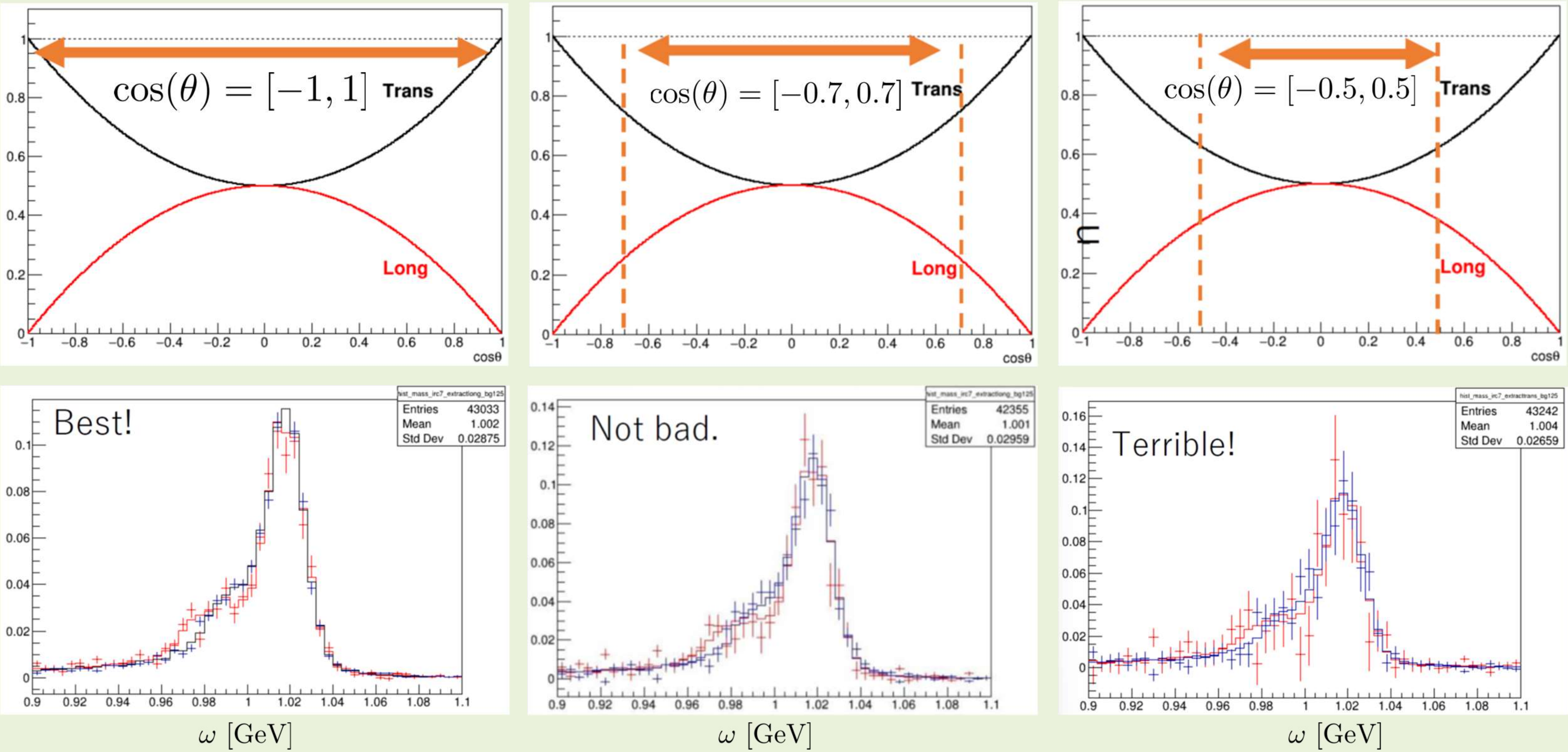
Find functions $h_{T/L}(x)$ such that:

depend on acceptance of the experiment

$$\int_a^b dx\, h_T(x) f_L(x) = 0$$

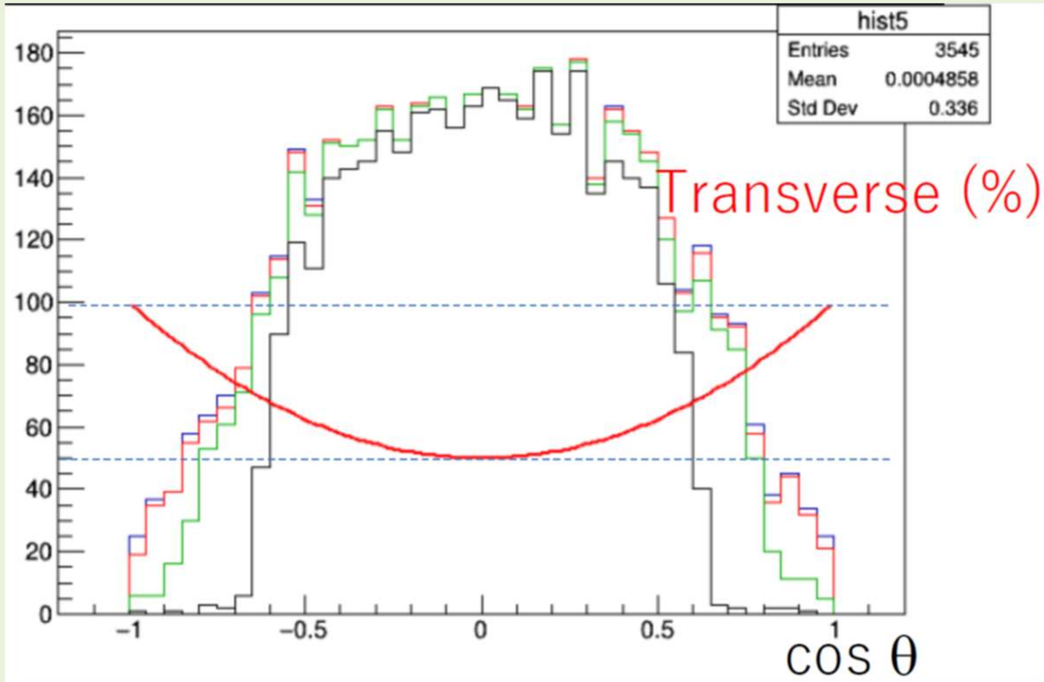
$$\int_a^b dx\, h_L(x) f_T(x) = 0$$

Results depend on the angular acceptance!



What will the angular acceptance look like at the J-PARC E16 experiment

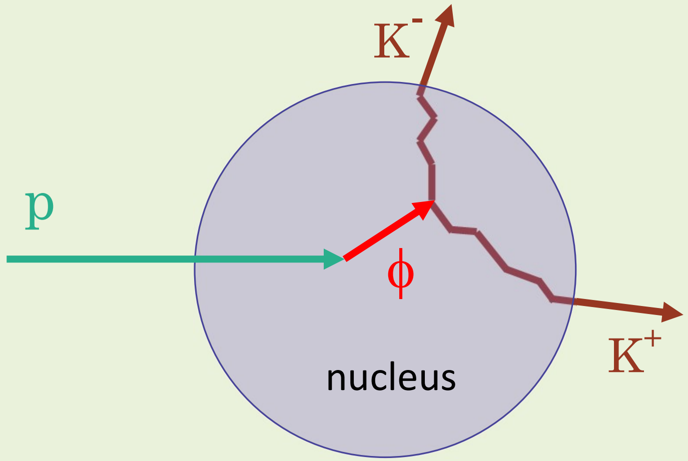
Acceptance corr. + βγ < 1.25 + low momentum cuts



Different low momentum cuts

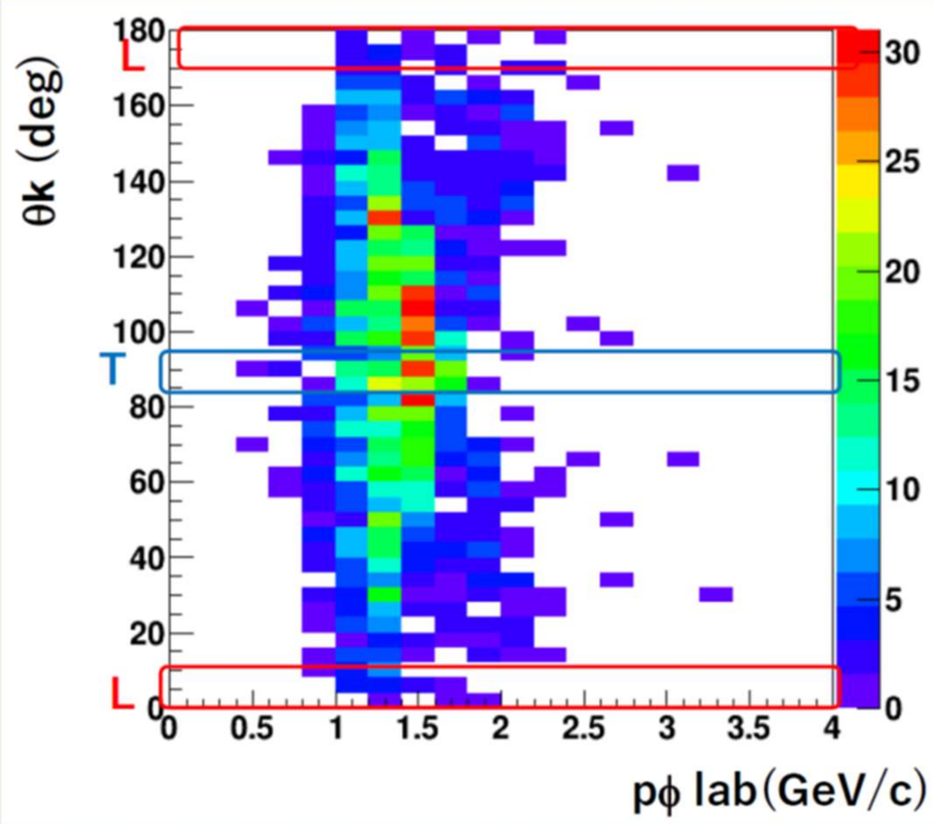
$\cos(\theta) = [-0.7, 0.7]$ seems realistic

The situation could be better for J-PARC E88 (K^+K^- decay)



Remaining issue:
How large are the final state interactions?

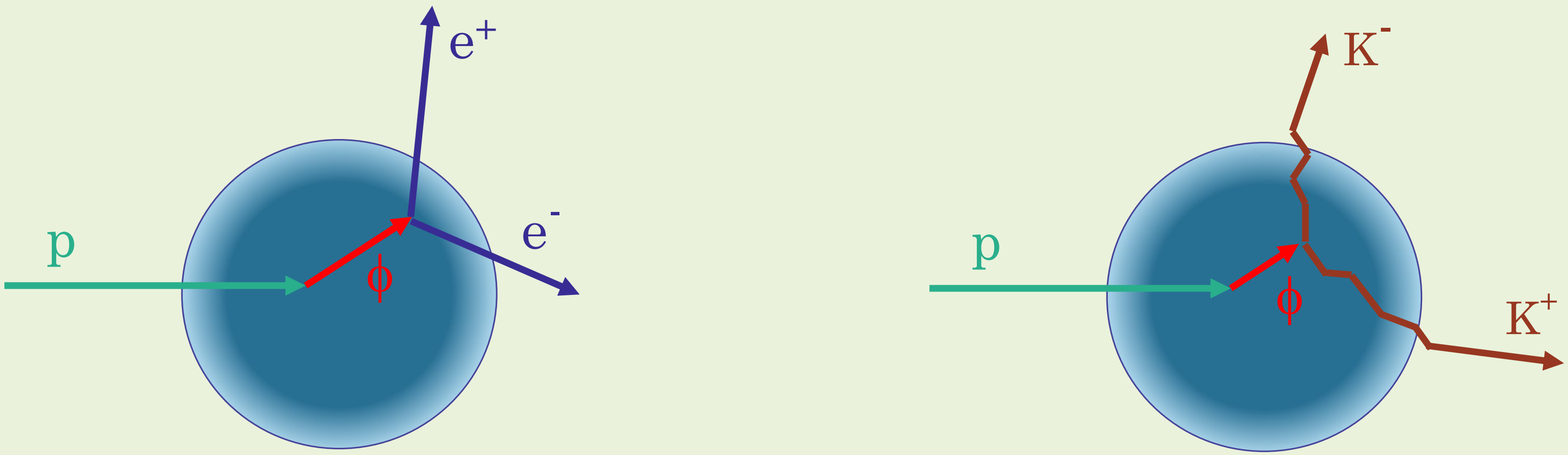
experimental acceptance of K^+K^- decay for E88



Analysis done by H. Sako (JAEA)

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.

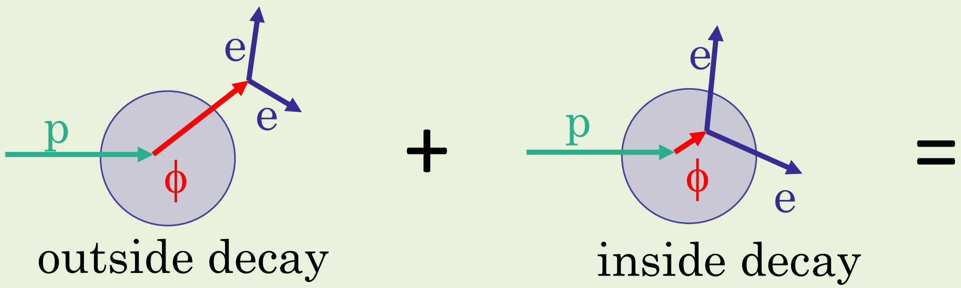
★ For the φ meson, the longitudinal and transverse modes are shifted in opposite directions with increasing momentum.

→ May be observed as a small **positive mass shift + width increase** at the E16 experiment at J-PARC

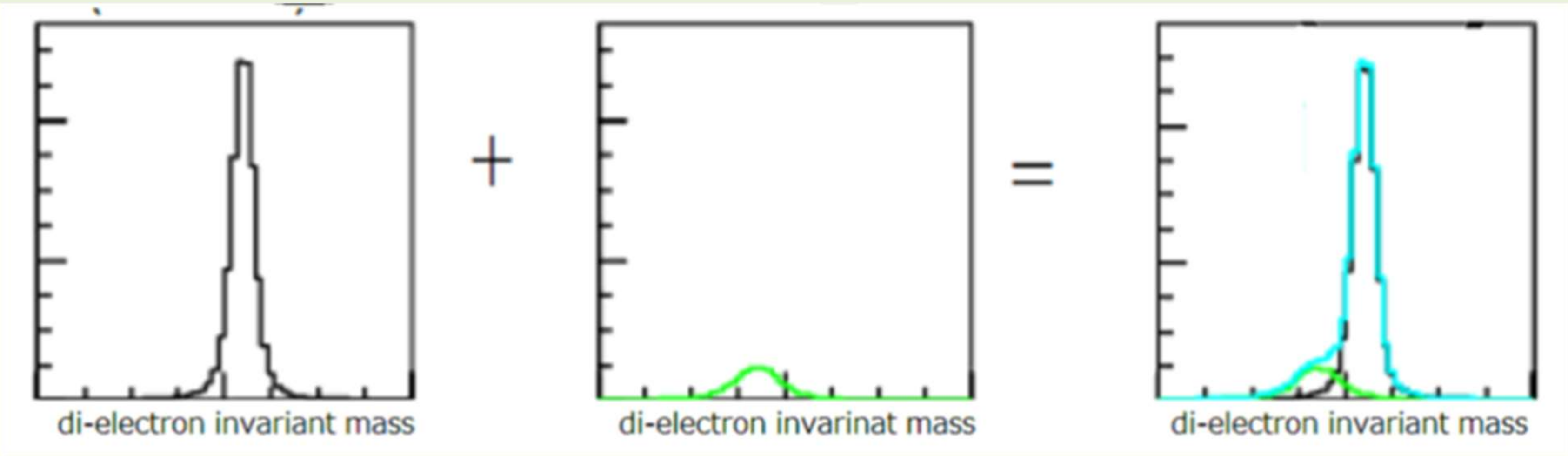
→ Making use of the angular dependences of the dilepton and K^+K^- decay channels, it is possible to **disentangle the longitudinal and transverse polarization modes**

Backup slides

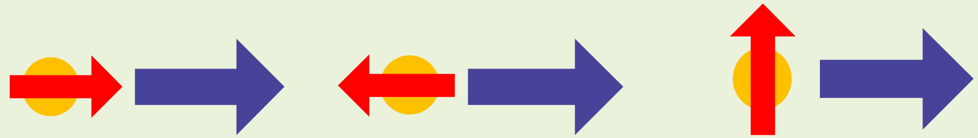
Experimental di-lepton spectrum



Experimentally observed spectrum

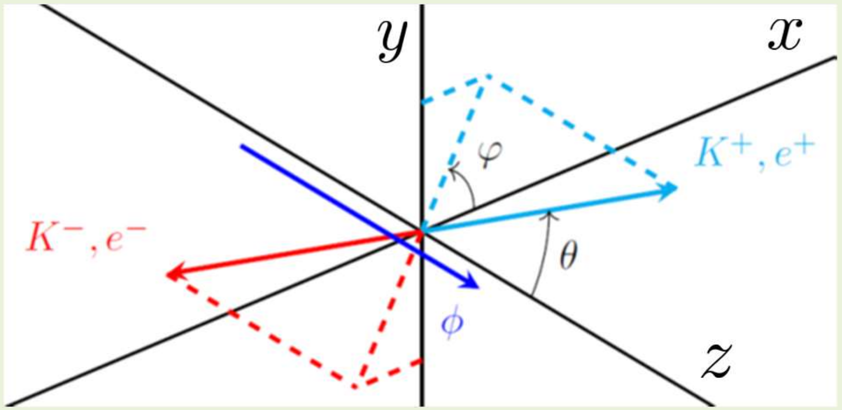


Full angular distribution of dilepton decay



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

Longitudinal polarization



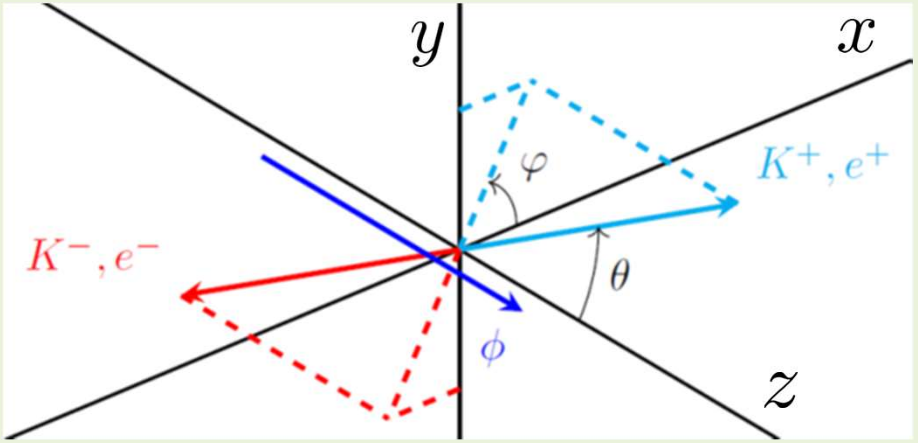
θ: polar angle

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

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

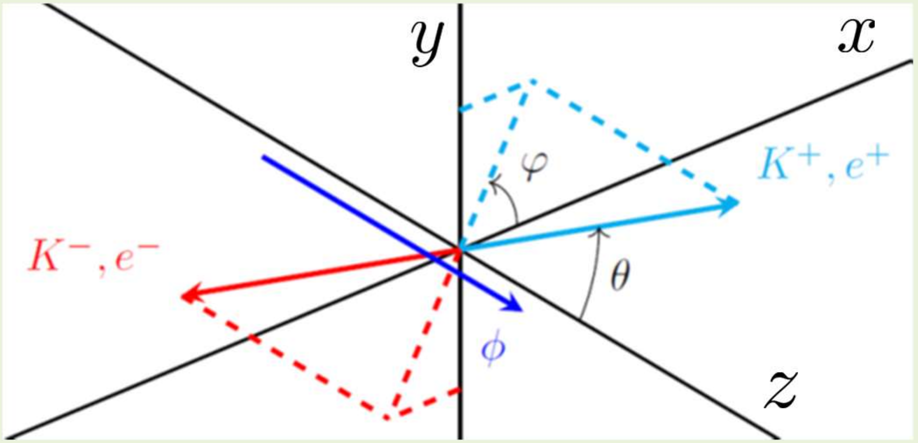
00-component of spin-density matrix

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

$\rho_{00} = \frac{1}{3}$ Unpolarized case: vanishing θ-dependence

ϕ-dependent terms

Full angular distribution of K$^+$K$^-$ decay



θ: polar angle
ϕ: azimuthal angle

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\Omega} = \frac{3}{16\pi}\Big[\underbrace{\left(|a_{+1}|^2 + |a_{-1}|^2\right)}_{\text{Transverse modes}}\sin^2\theta + 2|a_0|^2\cos^2\theta$$
$$-2\mathrm{Re}(a_{+1}a_{-1}^*)\sin^2\theta\cos 2\phi + \ldots\Big]$$
$$= \frac{3}{16\pi}\left[1 - \cos^2\theta - \rho_{00}(1 - 3\cos^2\theta) + \ldots\right]$$

Longitudinal mode

ϕ-dependent terms