φ meson polarization in pA collisions
- expectations from theory -

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 ExHIC 2022,
APCTP, Pohang, South Korea/online,
September 30, 2022

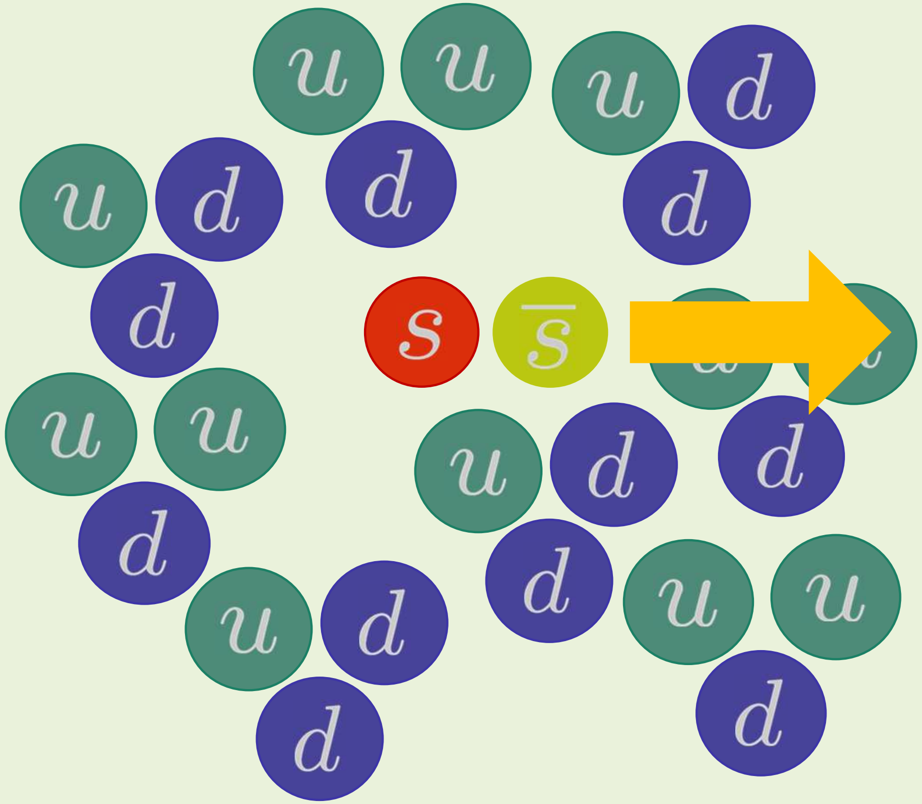
Work done in collaboration with
HyungJoo Kim (Yonsei U.)
InWoo Park (Yonsei U.)
Hiroyuki Sako (JAEA)
Kazuya Aoki (KEK)
Su Houng Lee (Yonsei U.)

Interest

ϕ meson

$m_\phi = 1019$ MeV

$\Gamma_\phi = 4.3$ MeV

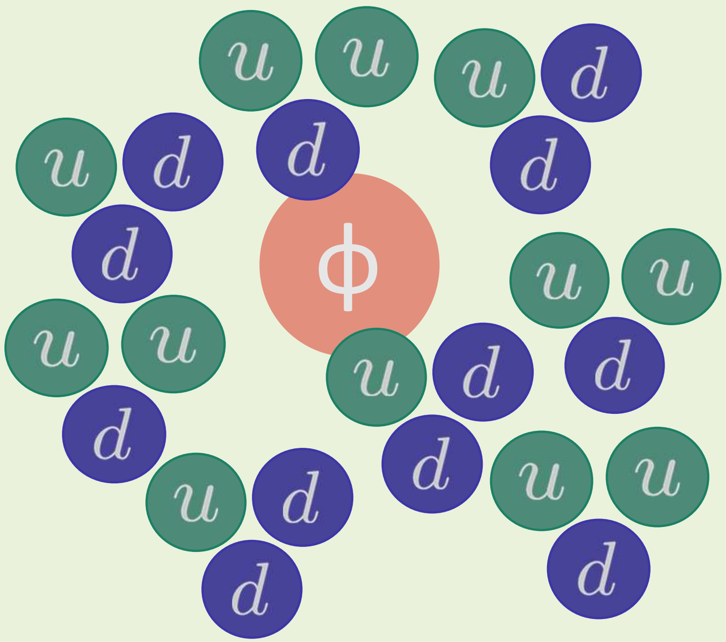


Case 1: φ meson **at rest** in nuclear matter

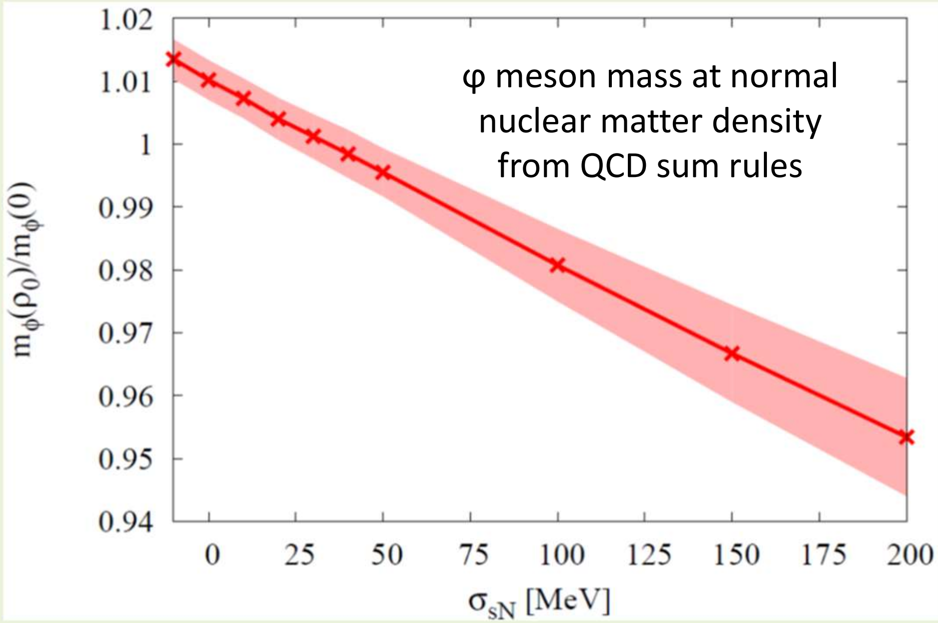
The φ meson mass in nuclear matter probes the strange quark condensate at finite density!

$|\langle\bar{s}s\rangle_\rho|$ ↘

m_ϕ ↘ ?



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



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

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

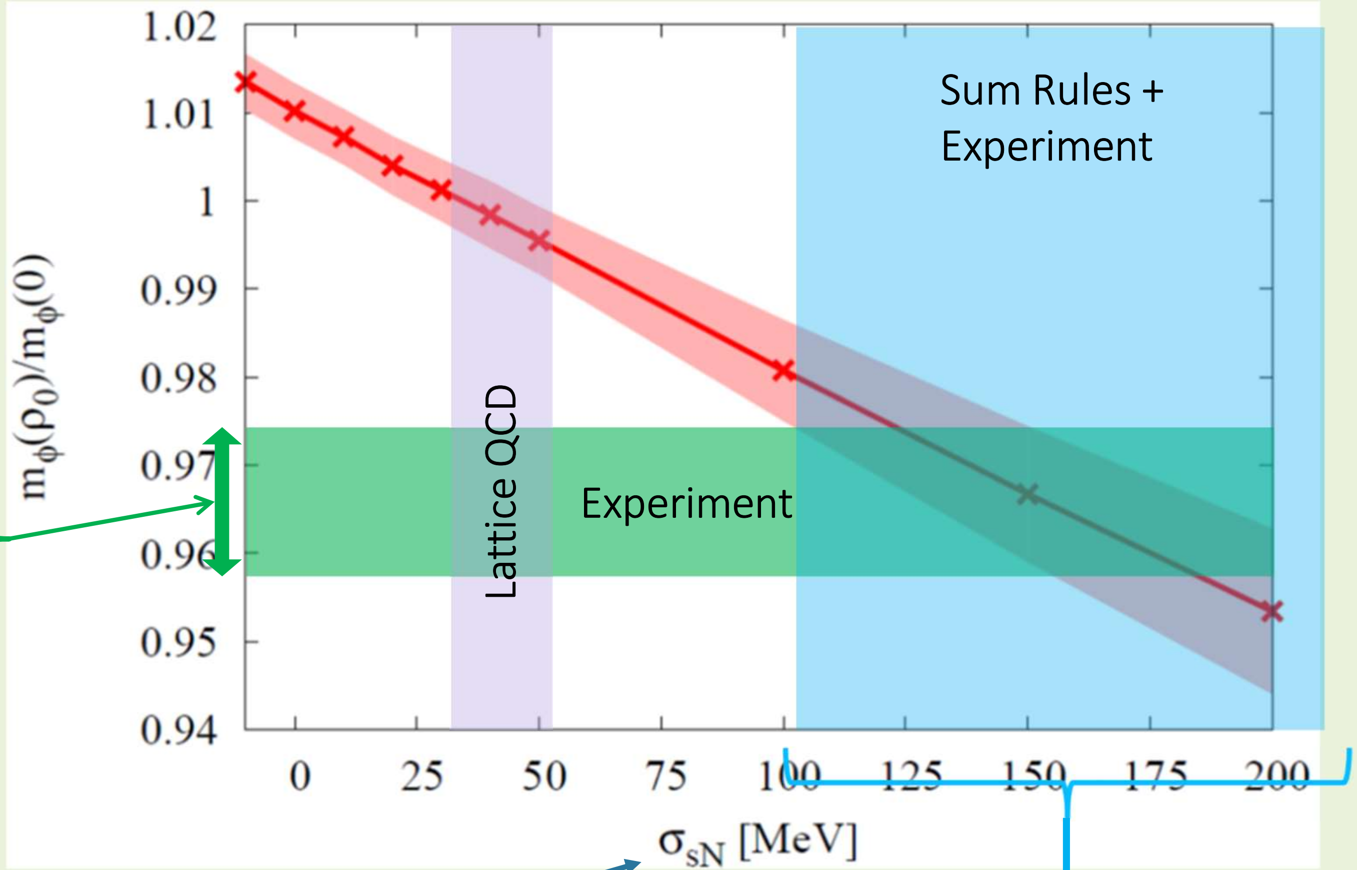
The φ meson mass in nuclear matter probes the strange quark condensate at finite density!

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!)

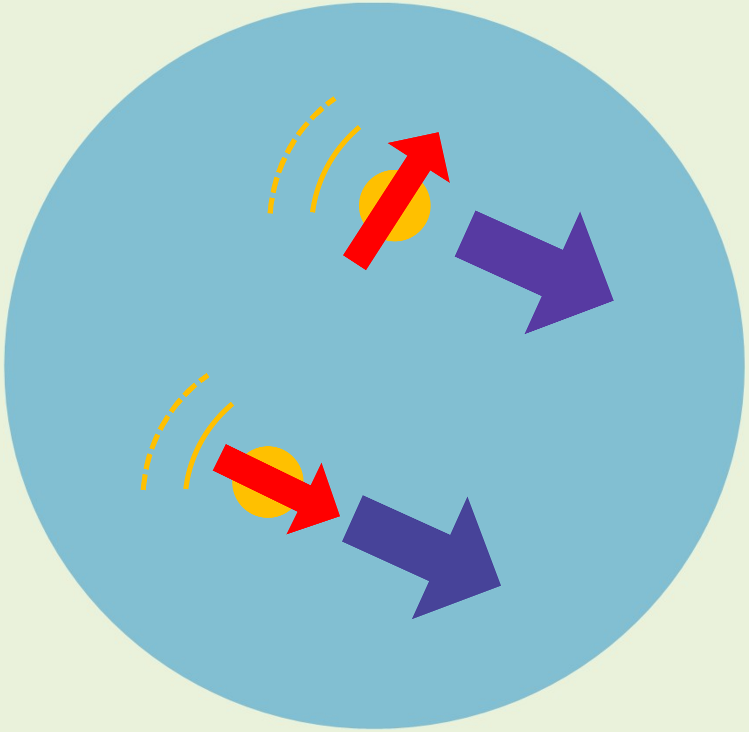
$$\frac{m_\phi(\rho)}{m_\phi(0)} = 0.966 \pm 0.007$$



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

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

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

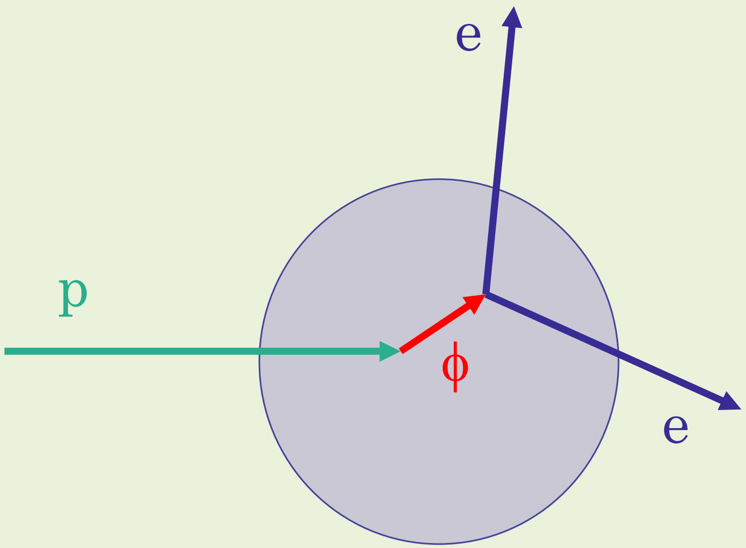


φ meson properties depend on the spin polarization (longitudinal or transverse)

↓ Broken Lorentz symmetry

Non-trivial polarization dependent dispersion relations

Motivation for considering **moving** φ meson



E325 (KEK)
E16 (J-PARC)

In an actual experiment, the ϕ is (almost) always moving with non-zero velocity

Non-negligible effect on the spectral function?

On mass?

On width?

Possible measurement of the non-trivial dispersion relation at the J-PARC E16 experiment

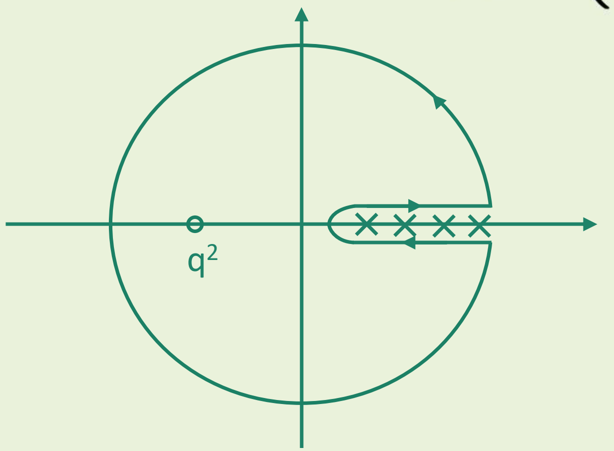
M.A. Shifman, A.I. Vainshtein and V.I. Zakharov,
Nucl. Phys. B147, 385 (1979); B147, 448 (1979).

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

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

$$\left.\begin{array}{l}\langle\overline{s}s\rangle_\rho,\\ \langle G^a_{\mu\nu}G^{a\mu\nu}\rangle_\rho,\\ \langle\overline{s}\sigma_{\mu\nu}\frac{\lambda^a}{2}G^{a\mu\nu}s\rangle_\rho,\\ \langle\overline{s}s\overline{s}s\rangle_\rho,\end{array}\right\}$$

scalar condensates:
trivial dispersion relation

$$\left.\begin{array}{l}\langle\mathcal{ST}\overline{s}\gamma^\alpha iD^\beta s\rangle_\rho,\\ \langle\mathcal{ST}G^{a\alpha}_{\mu}G^{a\mu\beta}\rangle_\rho,\\ \langle\mathcal{ST}\overline{s}\gamma^\alpha iD^\beta iD^\gamma iD^\delta s\rangle_\rho\end{array}\right\}$$

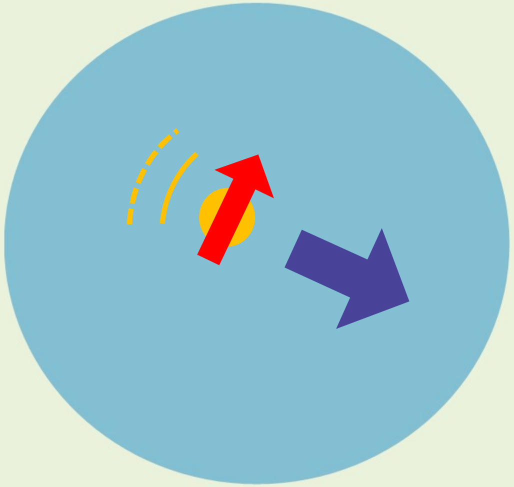
non-scalar condensates:
non-trivial dispersion relation

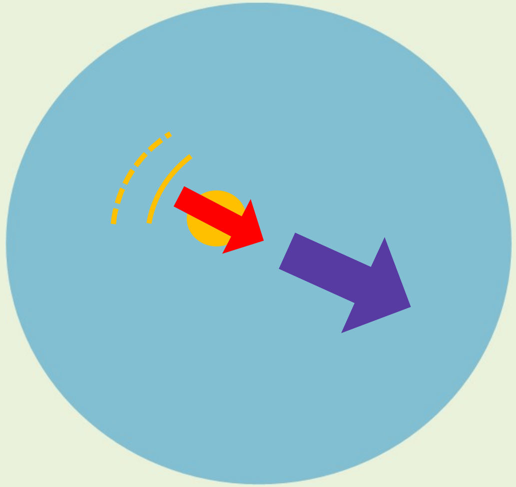
The non-zero momentum case: Disentangling longitudinal and transverse components

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

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

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





The ϕ meson with non-zero momentum

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

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

longitudinal part

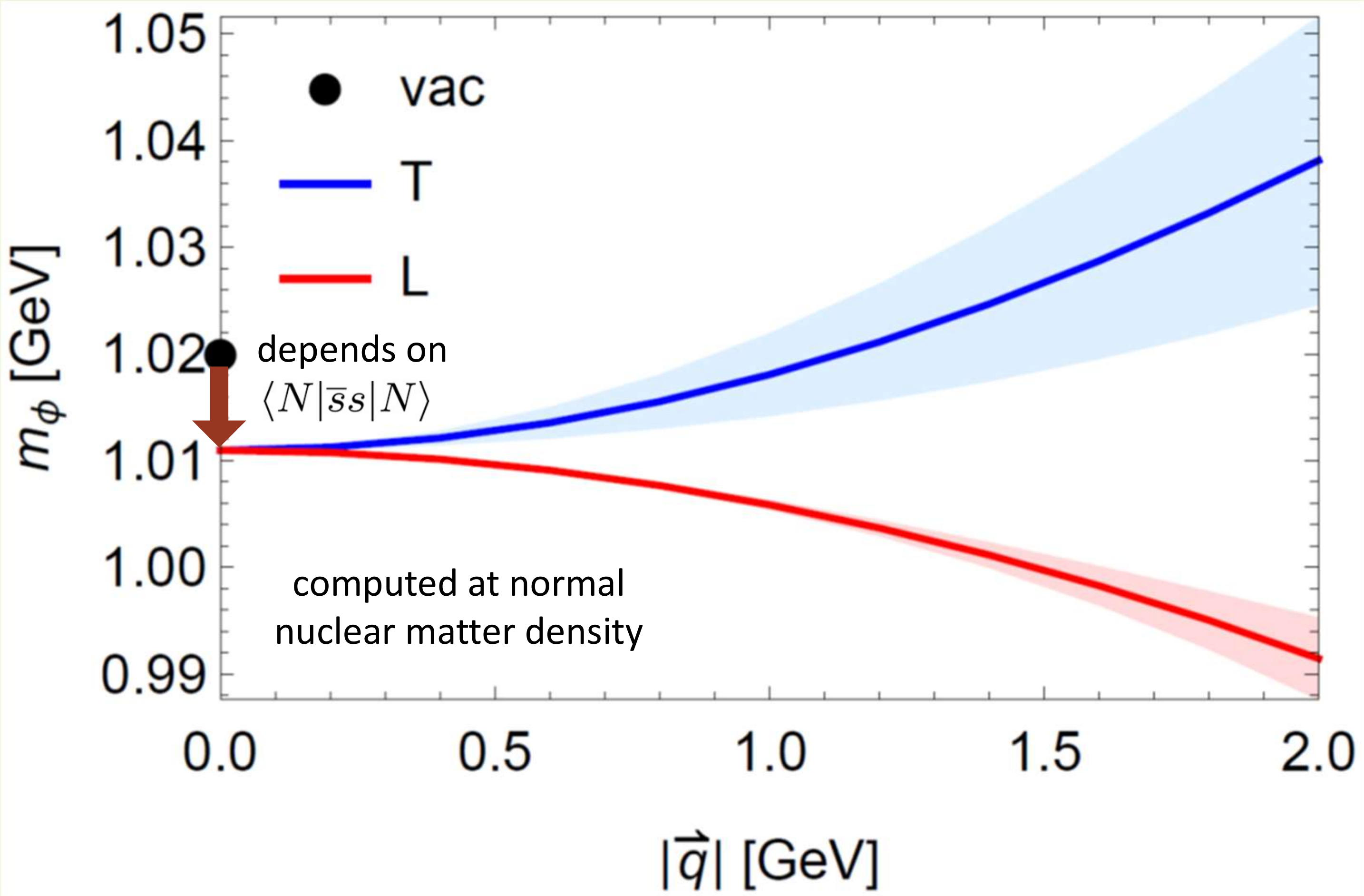
$$\frac{1}{\omega^2 - \vec{q}^{\,2} - m_{\phi,T}^2(\vec{q}^{\,2})}$$

transverse part

zero momentum

non-zero momentum $\vec{q}$

Results for the ϕ meson mass with non-zero momentum



caused by

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

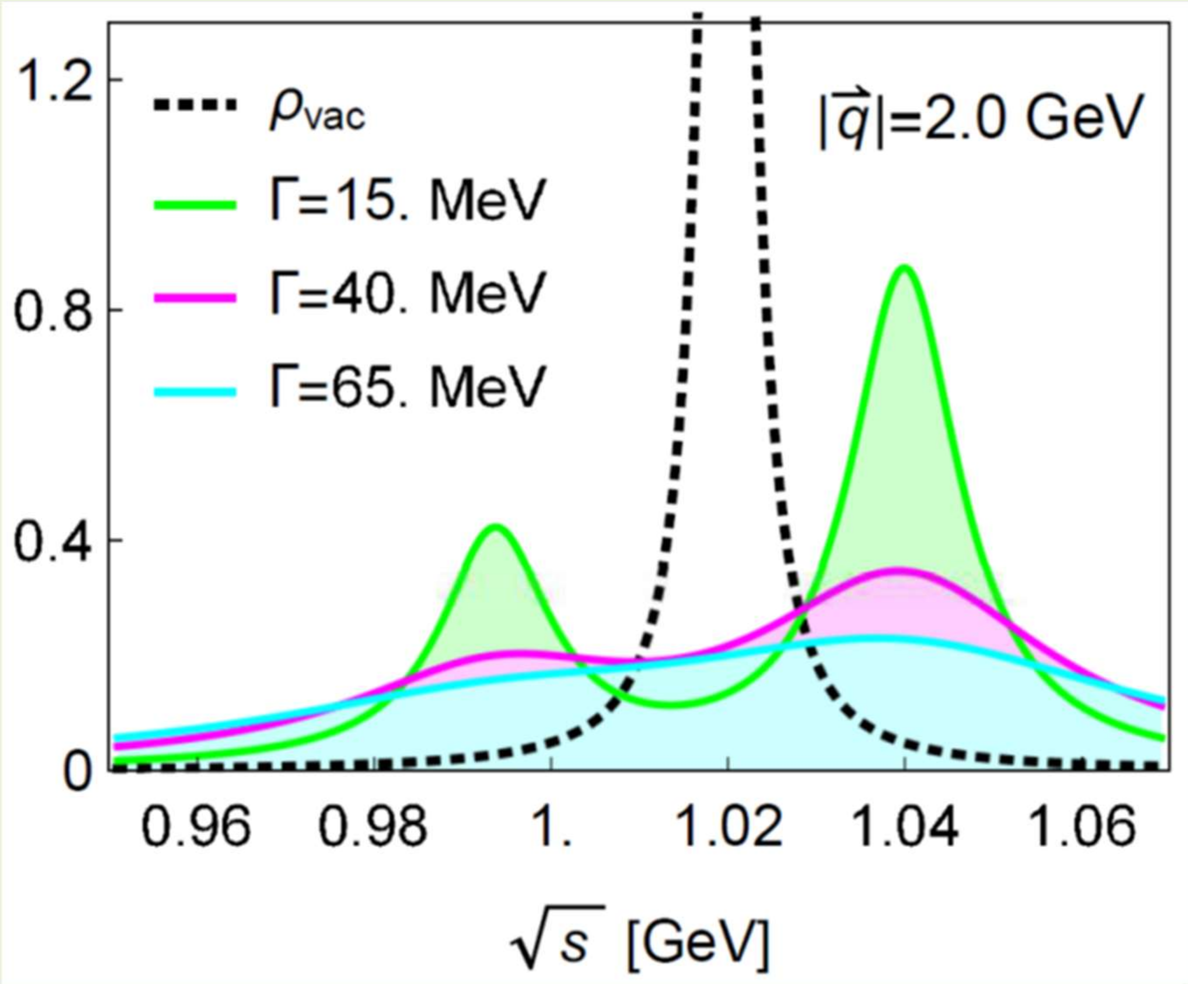
caused by

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

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

The angle-averaged di-lepton spectrum

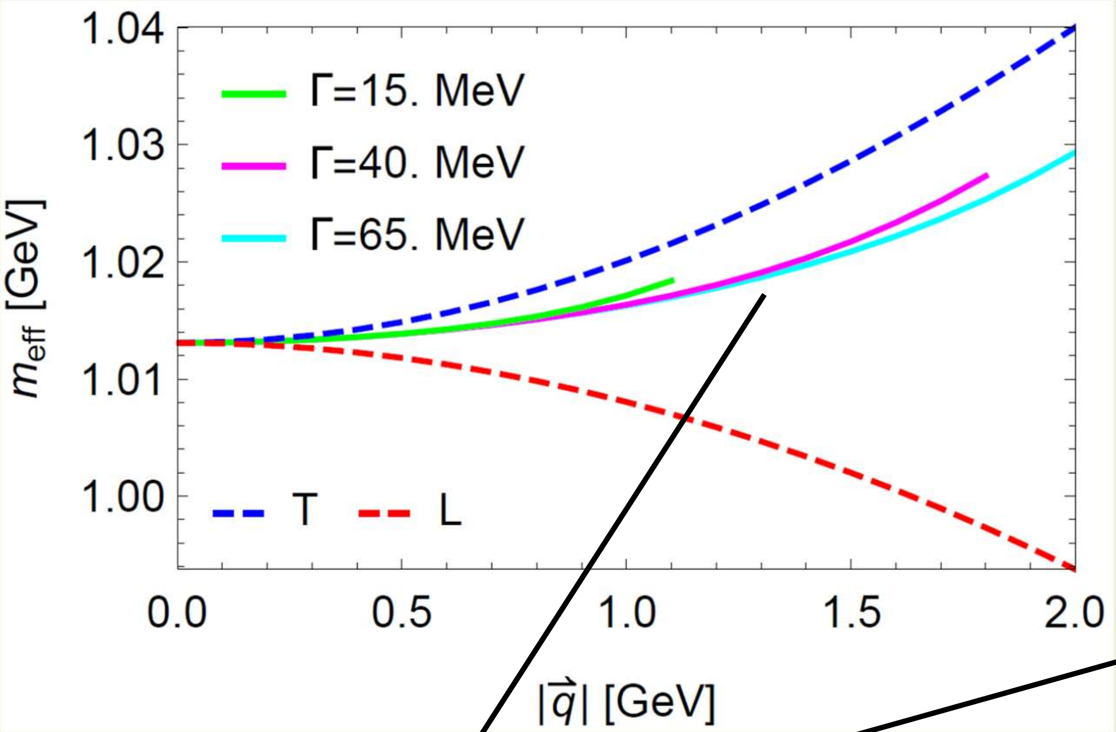
A double peak?

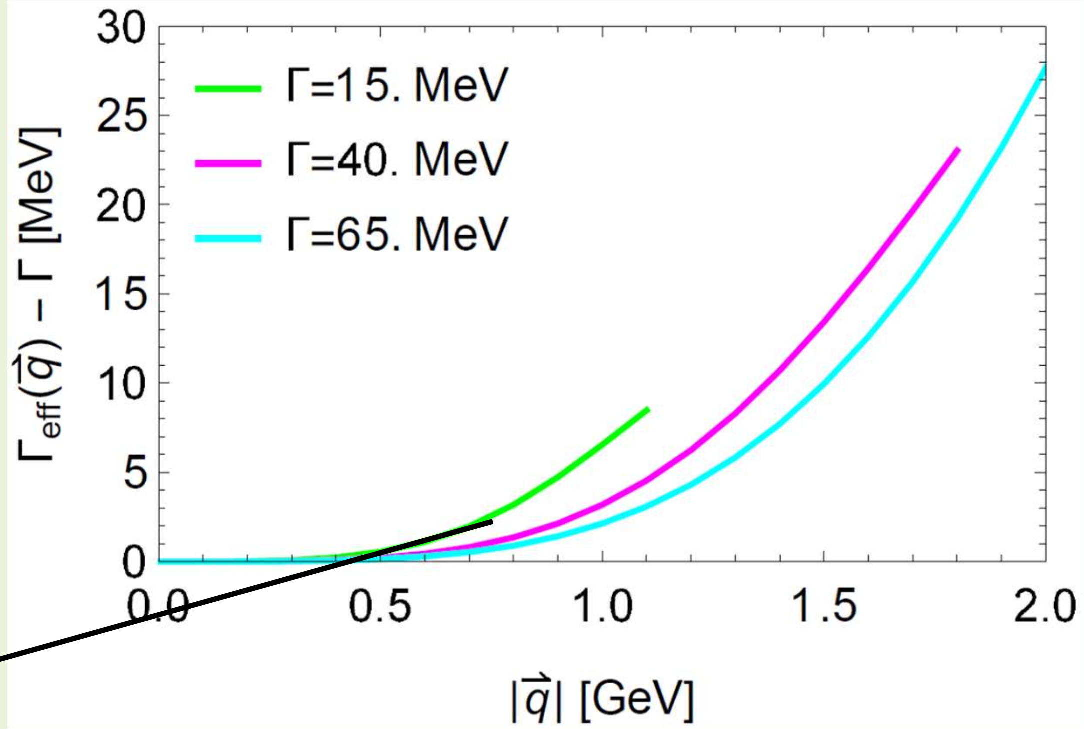


H.J. Kim and P. Gubler, Phys. Lett. B **805**, 135412 (2020).

The angle-averaged di-lepton spectrum

Even without a double peak, momentum effects can be observed



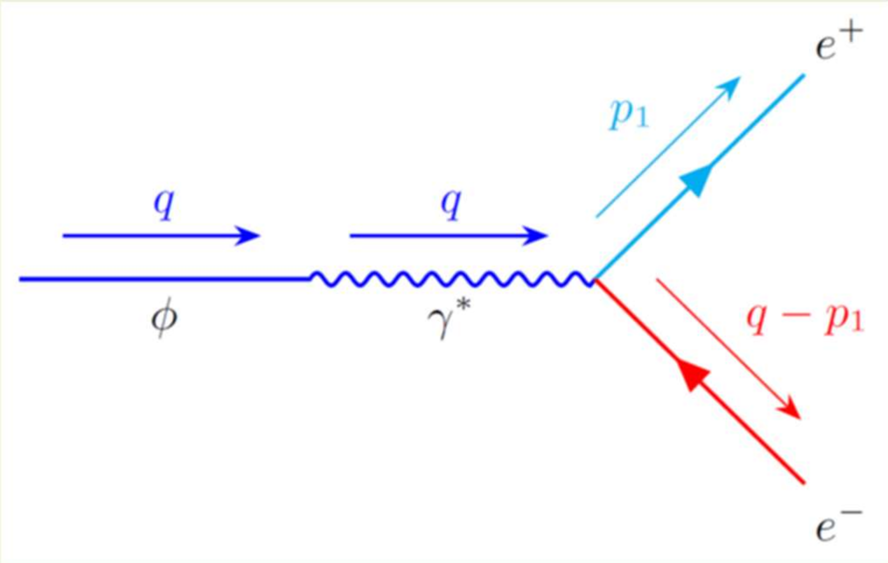


Results of one-peak fits

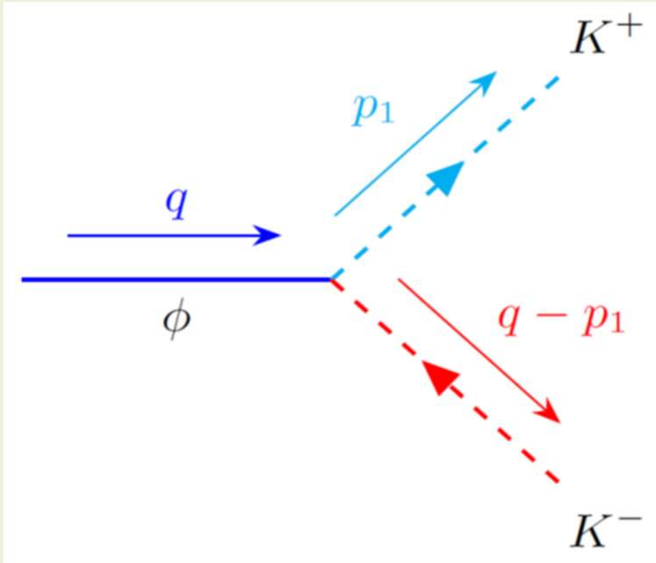
H.J. Kim and P. Gubler, Phys. Lett. B **805**, 135412 (2020).

Can the two polarizations be disentangled?

Look at the angular distributions of various decay channels



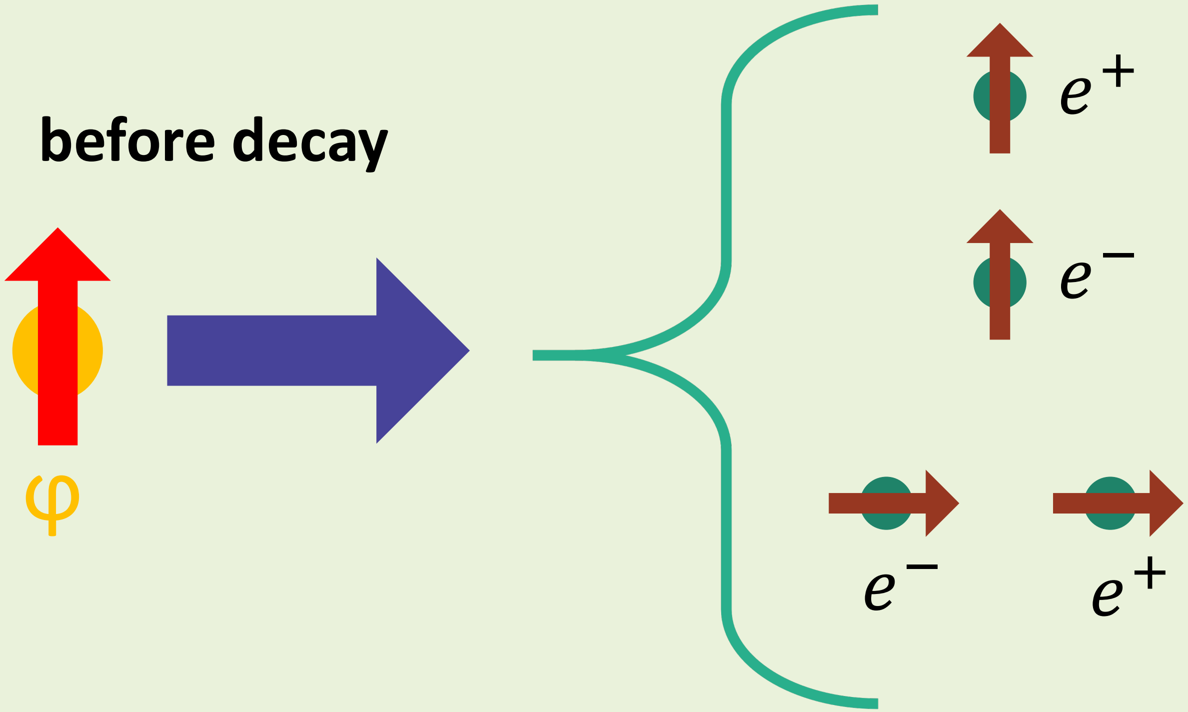
To be measured soon at
the J-PARC E16 experiment



New proposal P88
submitted to J-PARC PAC

A simple example of dilepton decay of a longitudinally polarized φ

after decay

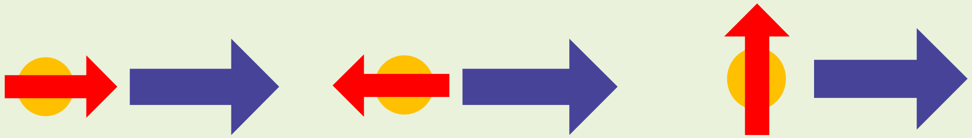


decay <u>perpendicular</u> to the φ meson momentum: **allowed**

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

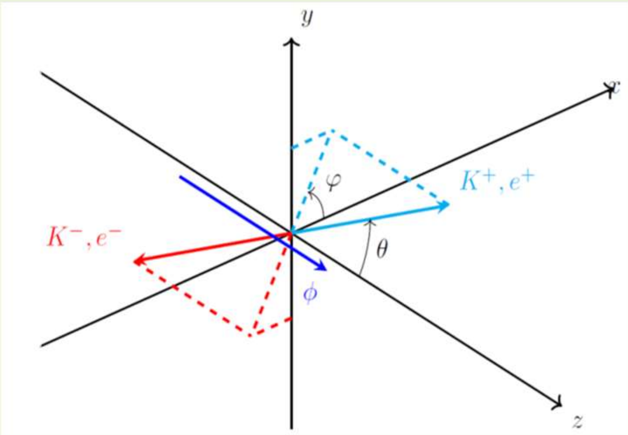
measurement in this direction can be used to observe purely transverse mode

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

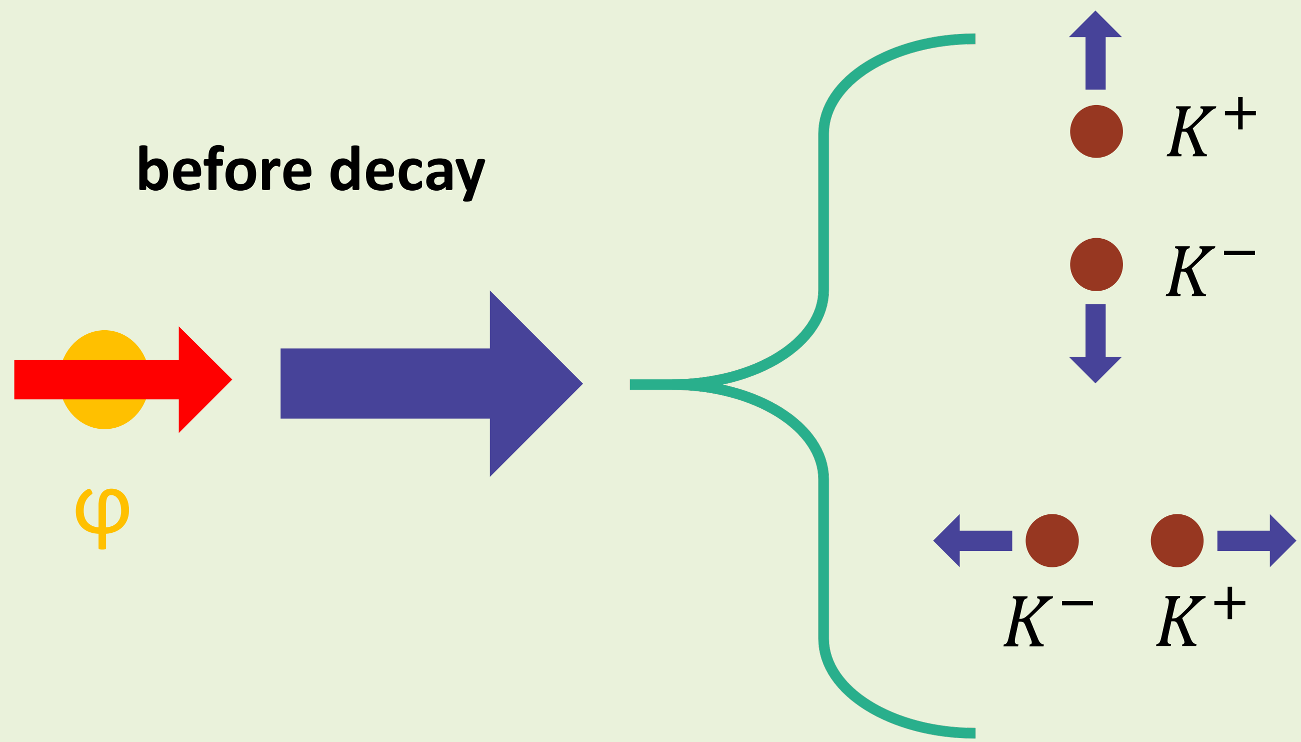
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\Omega} = \frac{3}{16\pi}\Big[(|a_{+1}|^2 + |a_{-1}|^2)(1+\cos^2\theta) + 2|a_0|^2(1-\cos^2\theta)$$
$$+2\mathrm{Re}(a_{+1}a_{-1}^*)\sin^2\theta\cos 2\phi + \ldots\Big]$$

other ϕ-dependent terms

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

after decay

before decay

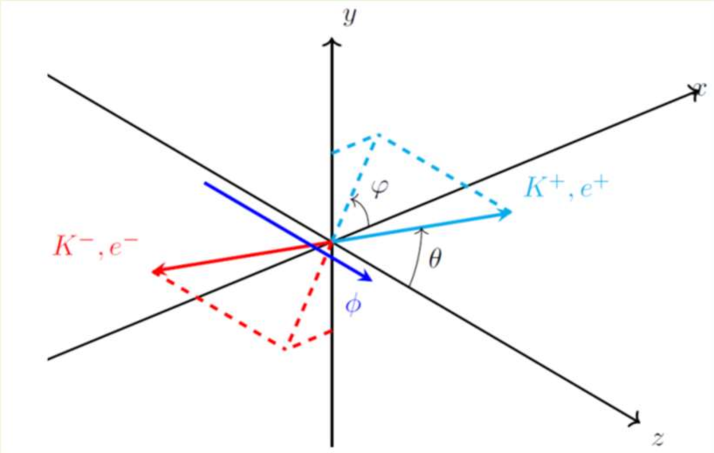


decay <u>perpendicular</u> to the φ meson momentum: **allowed**

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

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

Full angular distribution of K^+K^- decay



θ: polar angle
ϕ: azimuthal angle

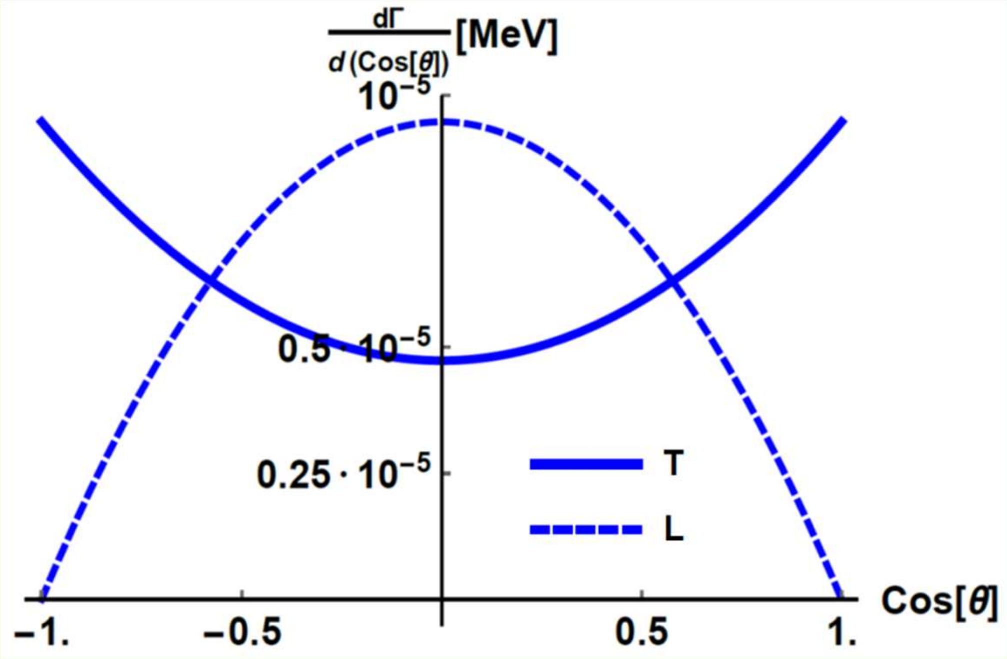
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\Omega} = \frac{3}{16\pi}\Big[\overbrace{(|a_{+1}|^2 + |a_{-1}|^2)}^{\text{Transverse modes}}\sin^2\theta + 2|a_0|^2\cos^2\theta$$
$$-2\mathrm{Re}(a_{+1}a^*_{-1})\sin^2\theta\cos 2\phi + \ldots\Big]$$

Longitudinal mode

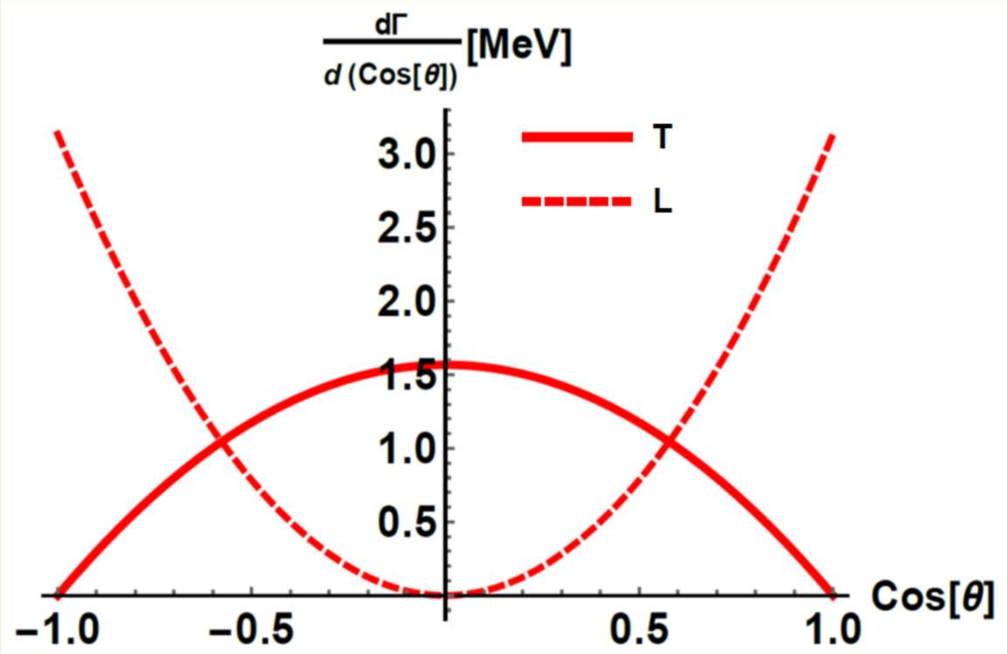
other ϕ-dependent terms

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

Dilepton decay angular distribution



K^+K^- decay angular distribution

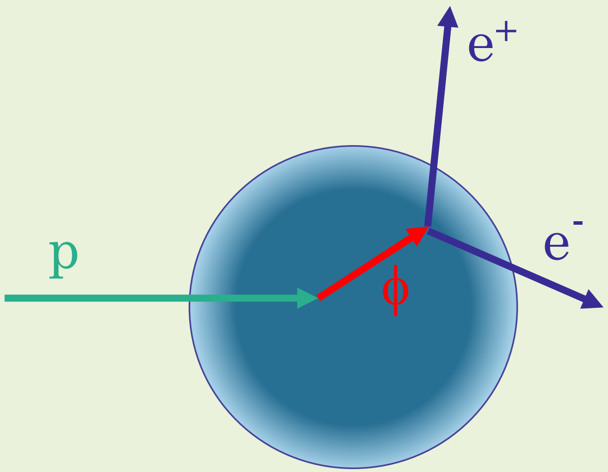


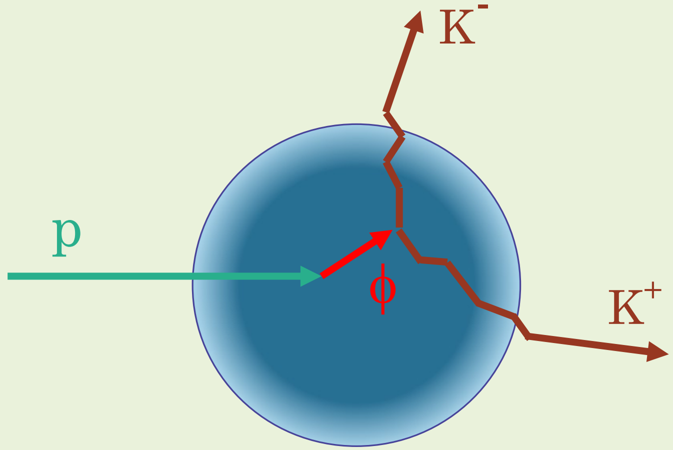
Discussions with J-PARC E16 members on how to distinguish the transverse and longitudinal modes are ongoing.

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

A further task 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

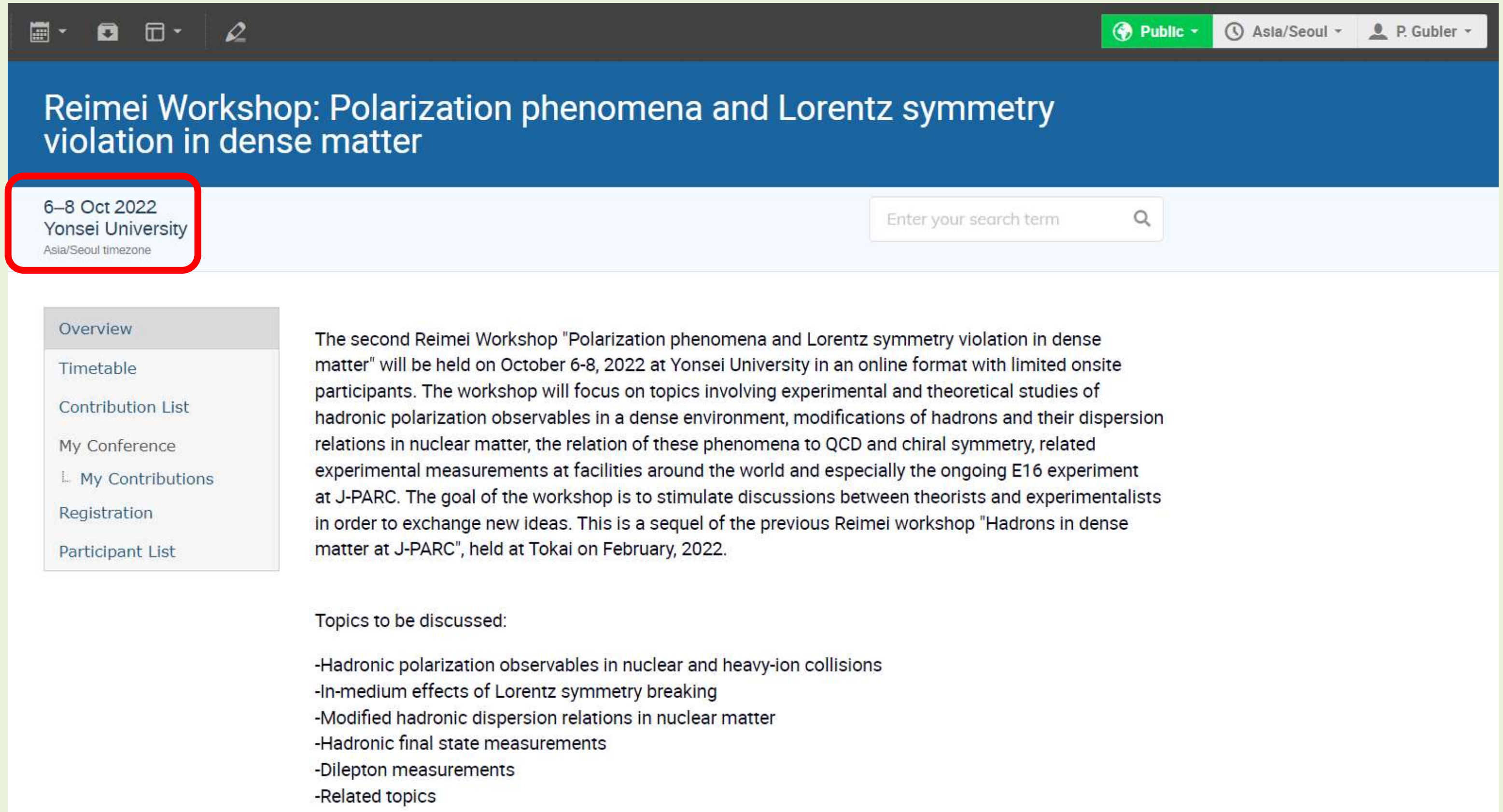
★ Dispersion relations of hadrons can be non-trivially modified in nuclear matter.

★ 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**

Announcement/Advertisement



Public Asia/Seoul P. Gubler

Reimei Workshop: Polarization phenomena and Lorentz symmetry violation in dense matter

6–8 Oct 2022
Yonsei University
Asia/Seoul timezone

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The second Reimei Workshop "Polarization phenomena and Lorentz symmetry violation in dense matter" will be held on October 6-8, 2022 at Yonsei University in an online format with limited onsite participants. The workshop will focus on topics involving experimental and theoretical studies of hadronic polarization observables in a dense environment, modifications of hadrons and their dispersion relations in nuclear matter, the relation of these phenomena to QCD and chiral symmetry, related experimental measurements at facilities around the world and especially the ongoing E16 experiment at J-PARC. The goal of the workshop is to stimulate discussions between theorists and experimentalists in order to exchange new ideas. This is a sequel of the previous Reimei workshop "Hadrons in dense matter at J-PARC", held at Tokai on February, 2022.

Topics to be discussed:

-Hadronic polarization observables in nuclear and heavy-ion collisions
-In-medium effects of Lorentz symmetry breaking
-Modified hadronic dispersion relations in nuclear matter
-Hadronic final state measurements
-Dilepton measurements
-Related topics

More information can be found here:
https://indico.knu.ac.kr/event/594/

Backup slides

Experimental results

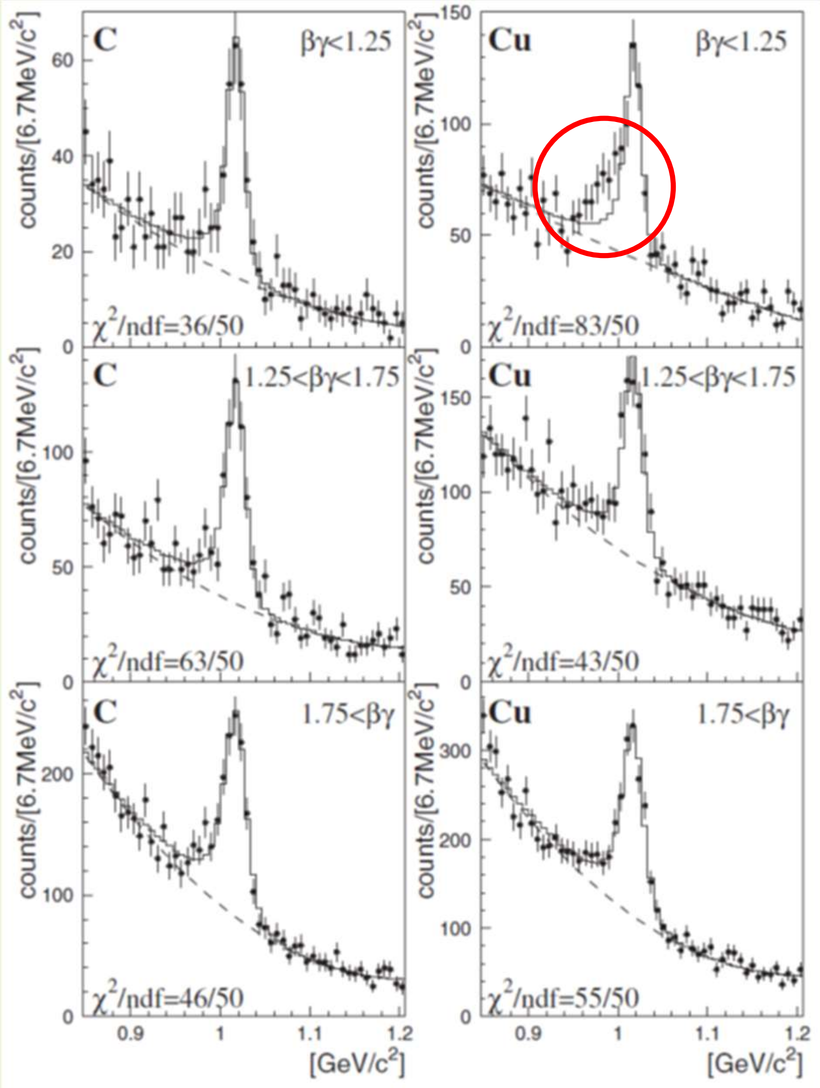
(E325, KEK)

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

k_1: 0.034 ± 0.007

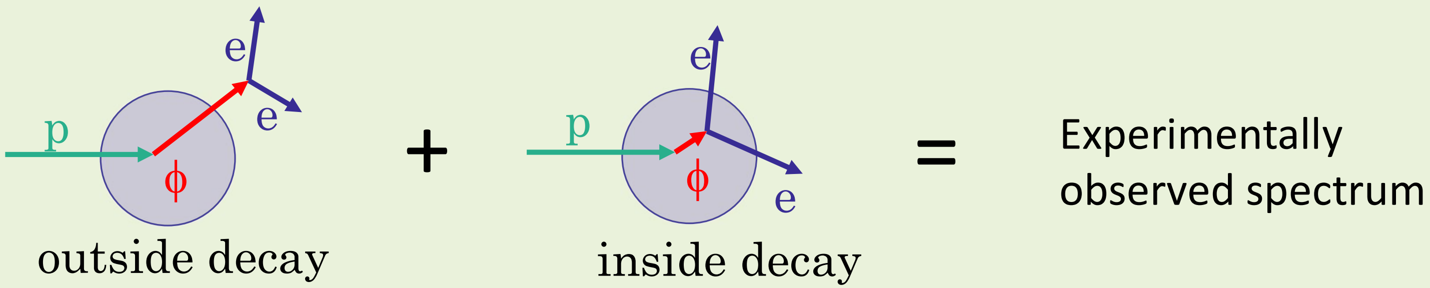
Pole width: $$\frac{\Gamma_\phi(\rho)}{\Gamma_\phi(0)} = 1 + k_2 \frac{\rho}{\rho_0}$$

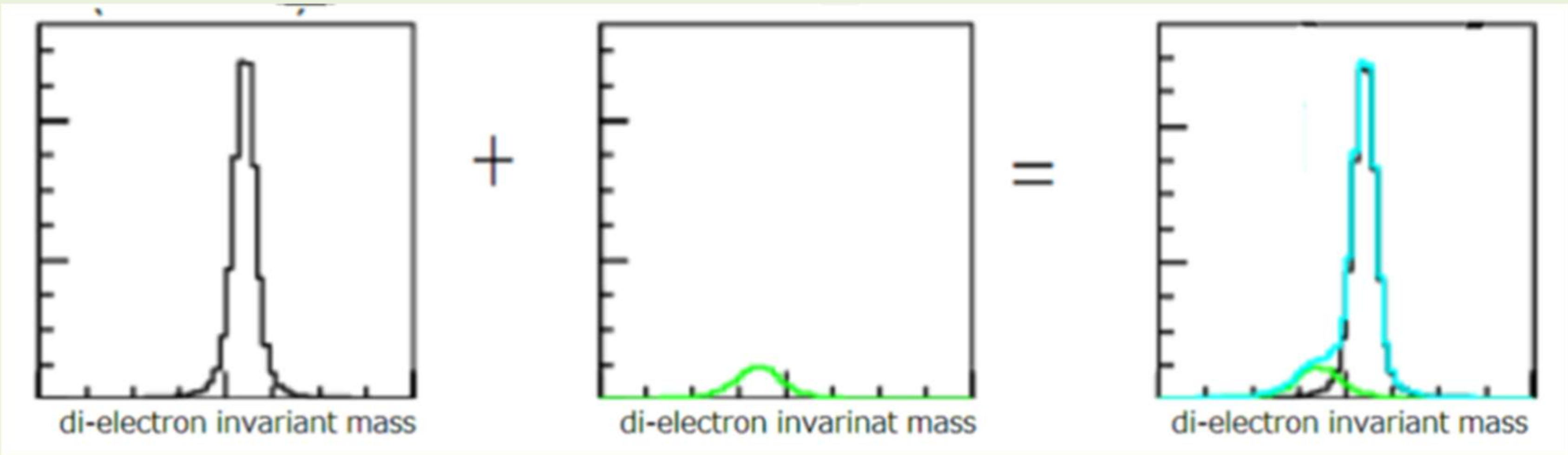
k_2: 2.6 ± 1.5



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

Experimental di-lepton spectrum





Our tool: transport simulation HSD (Hadron String Dynamics)

E.L. Bratkovskaya and W. Cassing, Nucl. Phys. A **807**, 214 (2008).
W. Cassing and E.L. Bratkovskaya, Phys. Rev. C **78**, 034919 (2008).

Off-shell dynamics of vector mesons and kaons is included (dynamical modification of the mesonic spectral function during the simulated reaction)

off-shell terms

Testparticle approach:

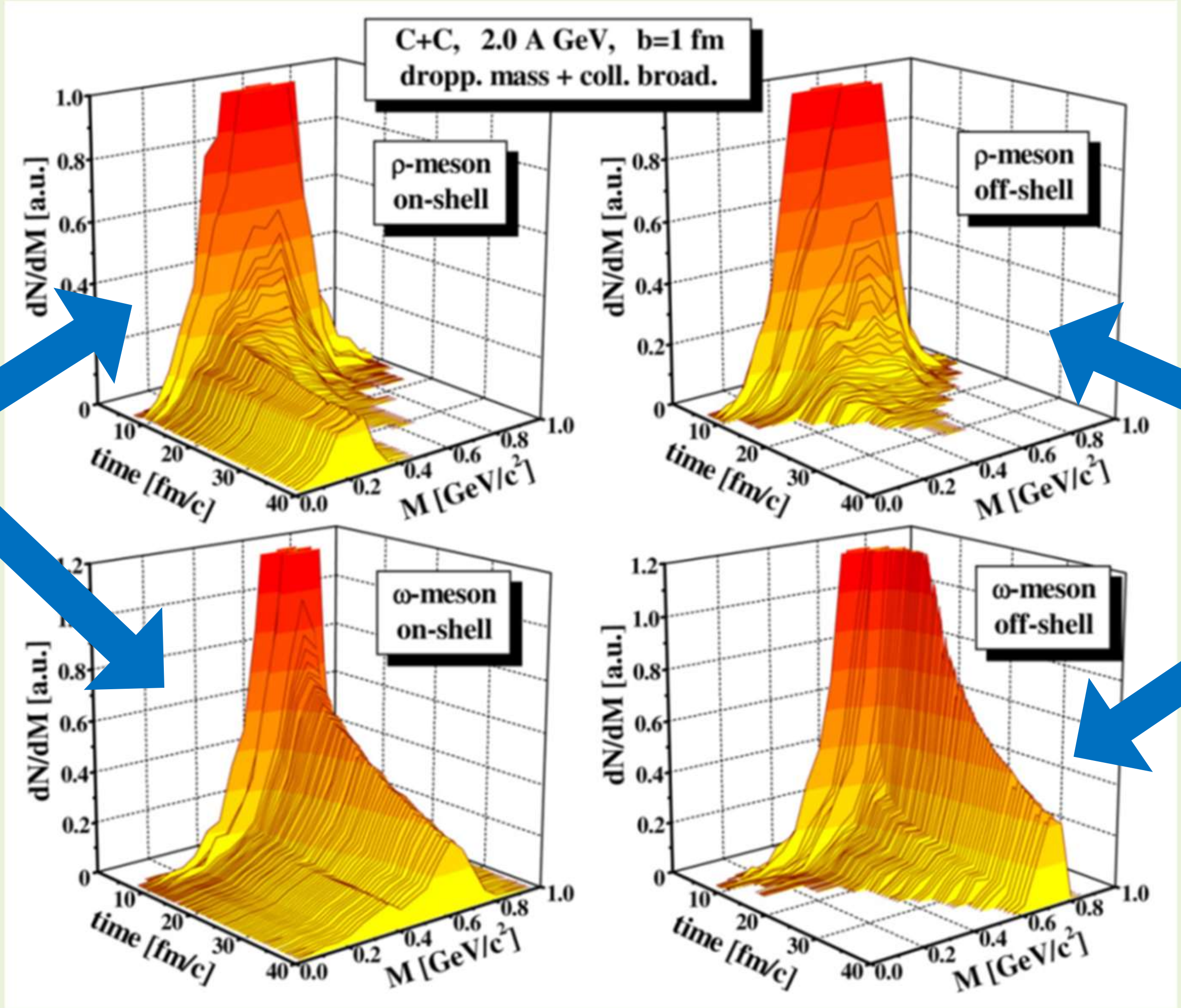
$$\frac{d\vec{X}_i}{dt} = \frac{1}{1-C_{(i)}} \frac{1}{2\varepsilon_i} \left[2\vec{P}_i + \vec{\nabla}_{P_i} \mathrm{Re}\,\Sigma^{\mathrm{ret}}_{(i)} + \frac{\varepsilon_i^2 - \vec{P}_i^2 - M_0^2 - \mathrm{Re}\,\Sigma^{\mathrm{ret}}_{(i)}}{\tilde{\Gamma}_{(i)}} \vec{\nabla}_{P_i} \tilde{\Gamma}_{(i)} \right],$$

$$\frac{d\vec{P}_i}{dt} = -\frac{1}{1-C_{(i)}} \frac{1}{2\varepsilon_i} \left[\vec{\nabla}_{X_i} \mathrm{Re}\,\Sigma^{\mathrm{ret}}_{i} + \frac{\varepsilon_i^2 - \vec{P}_i^2 - M_0^2 - \mathrm{Re}\,\Sigma^{\mathrm{ret}}_{(i)}}{\tilde{\Gamma}_{(i)}} \vec{\nabla}_{X_i} \tilde{\Gamma}_{(i)} \right],$$

$$\frac{d\varepsilon_i}{dt} = \frac{1}{1-C_{(i)}} \frac{1}{2\varepsilon_i} \left[\frac{\partial\, \mathrm{Re}\,\Sigma^{\mathrm{ret}}_{(i)}}{\partial t} + \frac{\varepsilon_i^2 - \vec{P}_i^2 - M_0^2 - \mathrm{Re}\,\Sigma^{\mathrm{ret}}_{(i)}}{\tilde{\Gamma}_{(i)}} \frac{\partial \tilde{\Gamma}_{(i)}}{\partial t} \right],$$

The importance of off-shell contributions

Only on-shell contributions: Vacuum spectral function are not recovered at late time of the reaction



Off-shell contributions included: correct behavior

Taken from: E.L. Bratkovskaya and W. Cassing, Nucl. Phys. A **807**, 214 (2008).

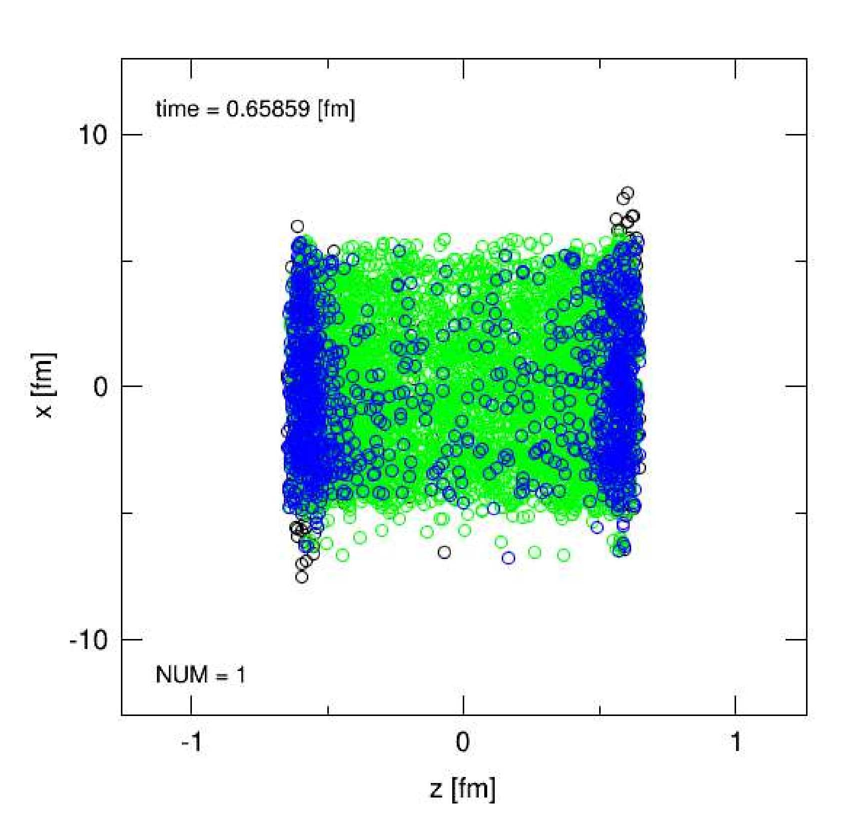
Our tool: a transport code
PHSD (Parton Hadron String Dynamics)

W. Cassing and E. Bratkovskaya, Phys. Rev. C **78**, 034919 (2008).

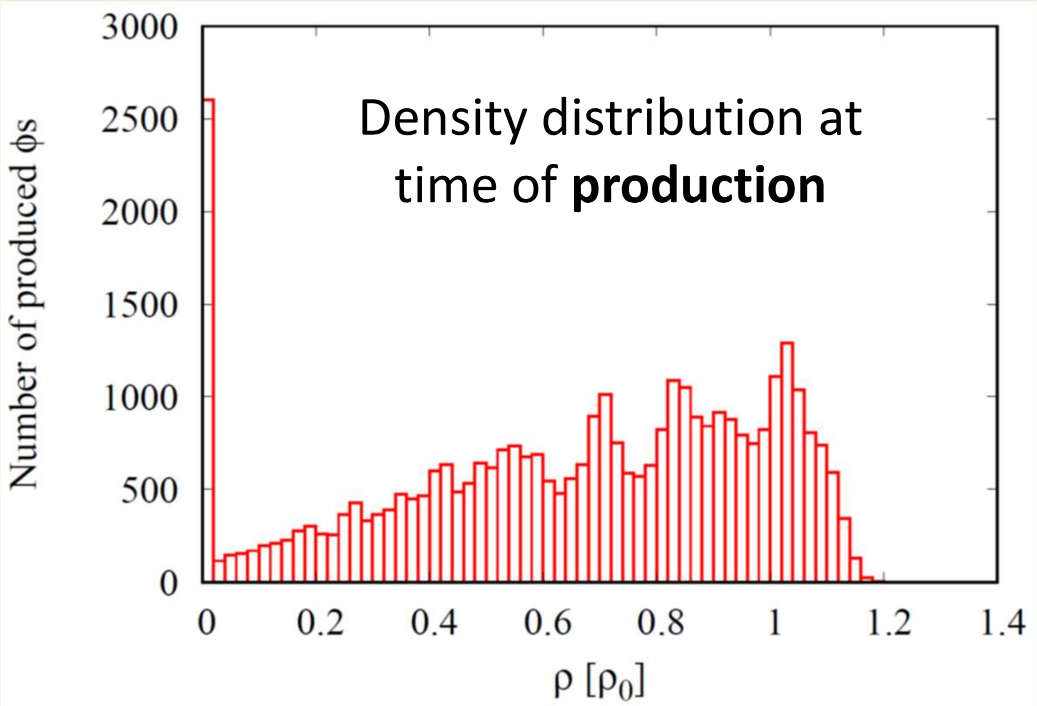
Example:

Au+Au collision at 200 GeV
b = 2 fm

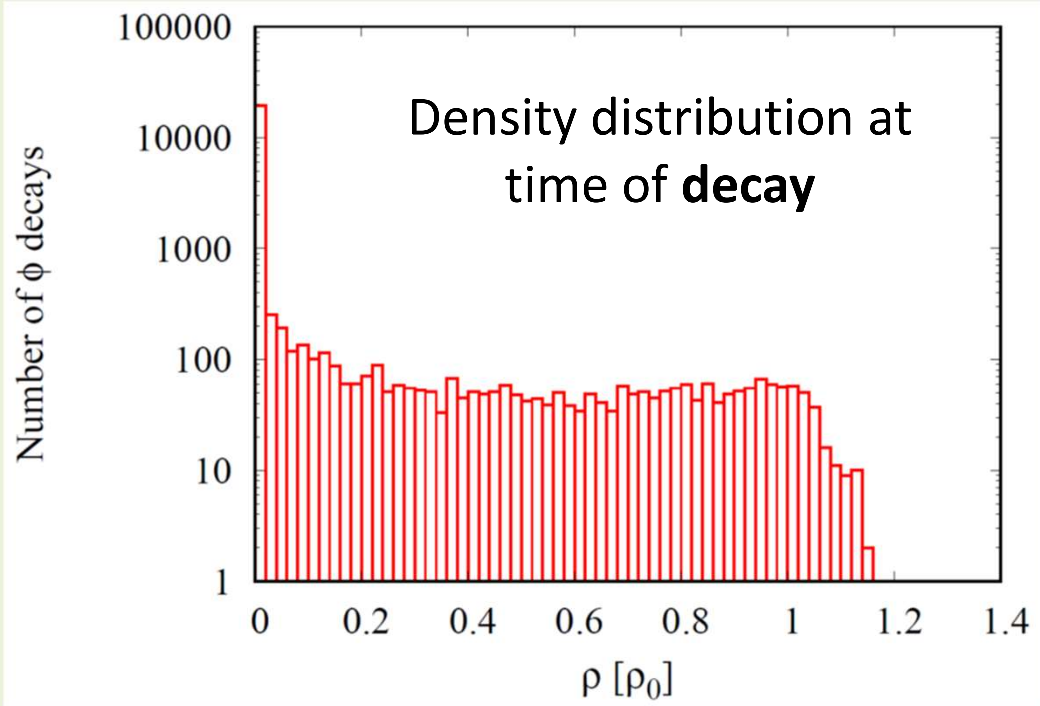
nucleons
quarks
gluons



What density does the φ feel in the reaction (p+Cu at 12 GeV)?

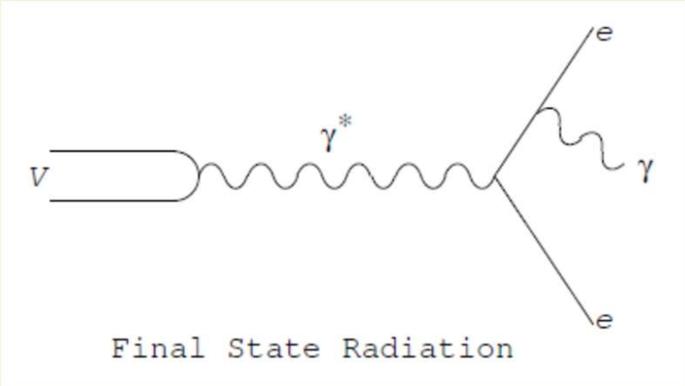


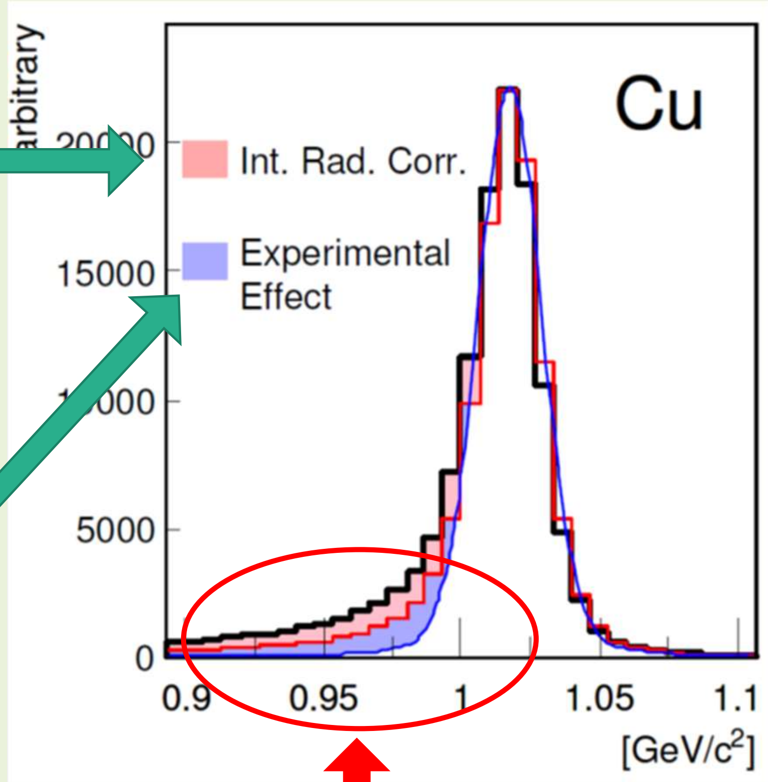
Majority of φ mesons are produced at densities around ρ_0



Majority of φ mesons decay in free space (note the log-scale!)

How do experimental rescattering and QED effects modify the dilepton spectrum?





PhD Thesis of R. Muto,
Kyoto U., 2007

Rescattering effect

(multiple scattering,
energy loss)

Similar to the shape expected
for a negative mass shift