Measuring the ϕ meson polarization modes from dilepton and kaon decays

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 the Reimei Workshop "Polarization phenomena and
Lorentz symmetry violation in dense matter",
Yonsei University, Seoul, South Korea/online,
October 6, 2022

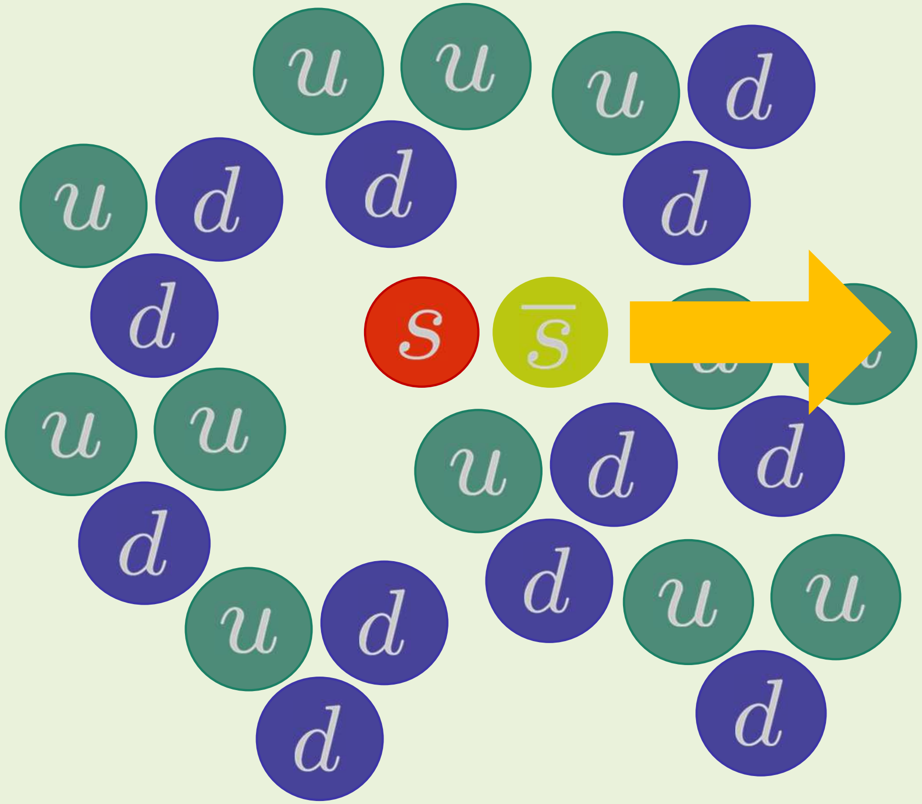
Work done in collaboration with
HyungJoo Kim (Yonsei U.)
InWoo Park (Yonsei U.)
Hiroyuki Sako (JAEA)
Kazuya Aoki (KEK)
Su Houng Lee (Yonsei U.)

Interest

ϕ meson

m_ϕ = 1019 MeV

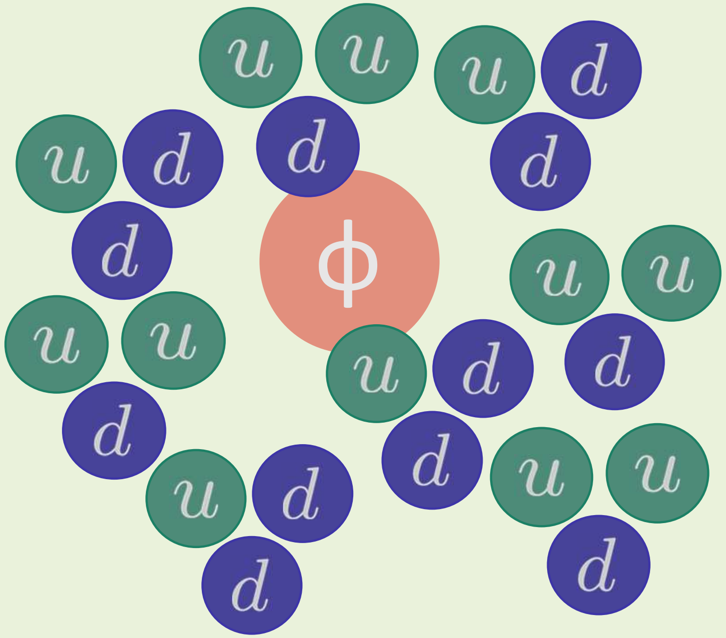
Γ_ϕ = 4.3 MeV



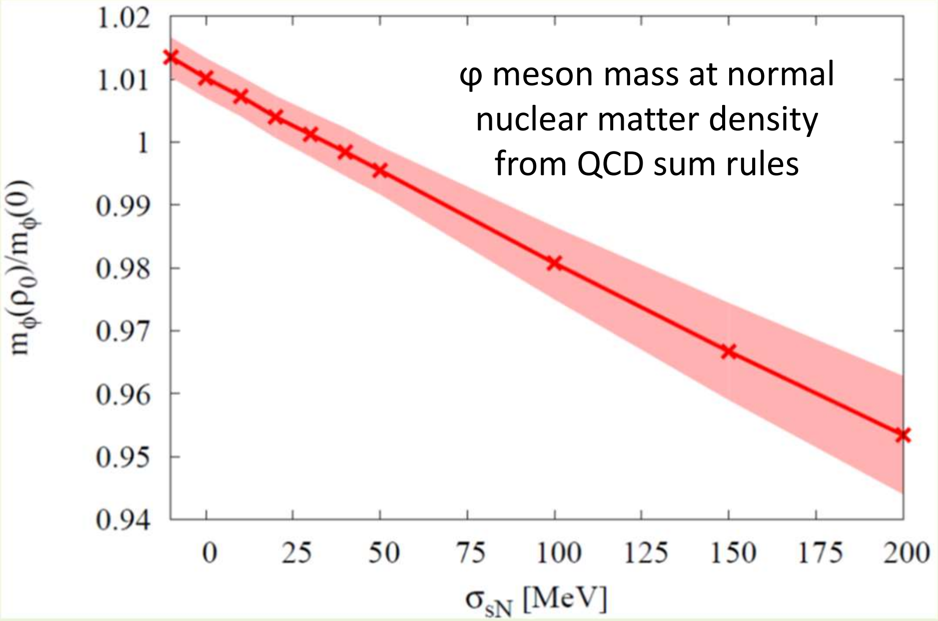
Case 1: φ meson **at rest** in nuclear matter

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).

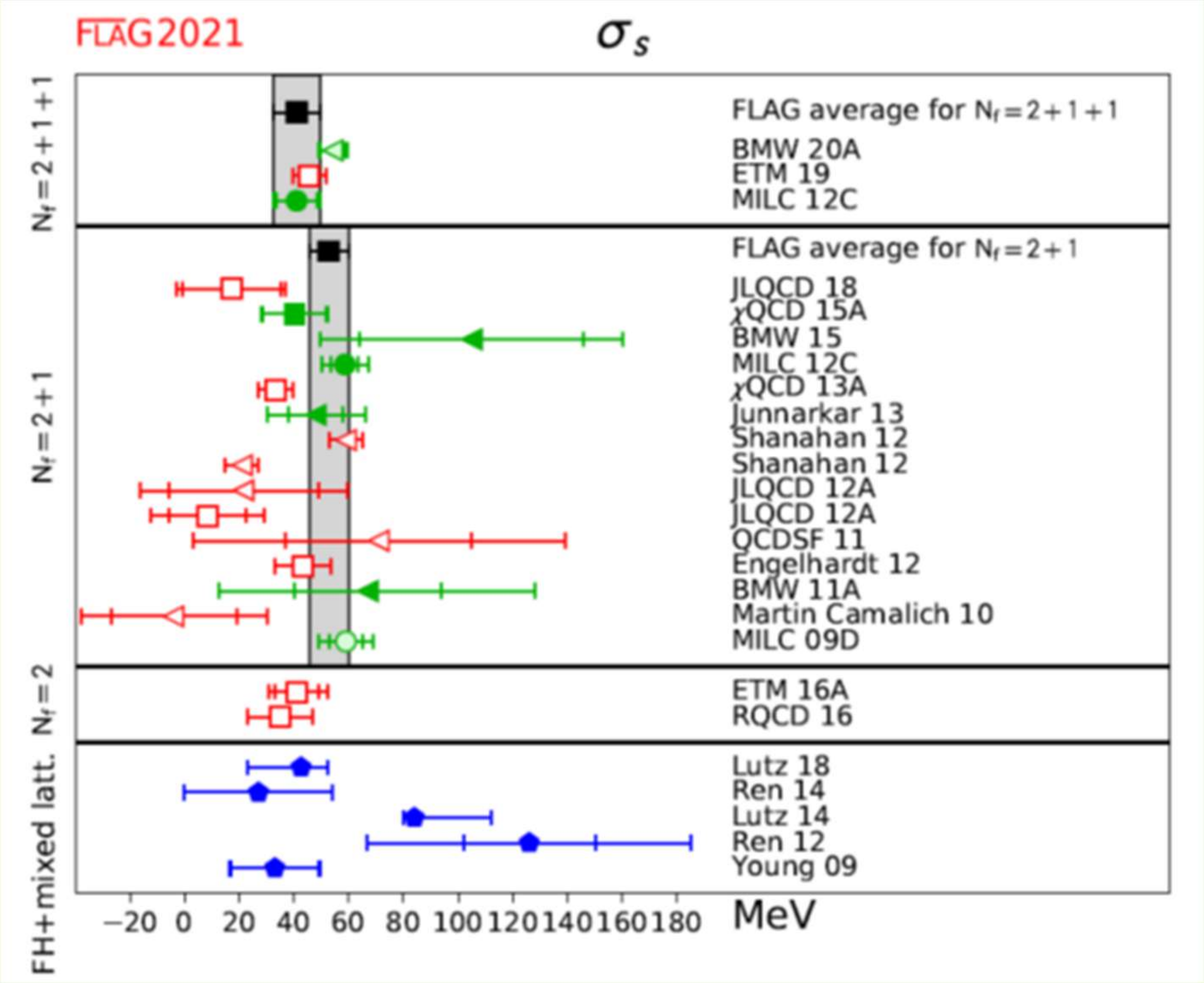


φ meson mass at normal nuclear matter density from QCD sum rules

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

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 results

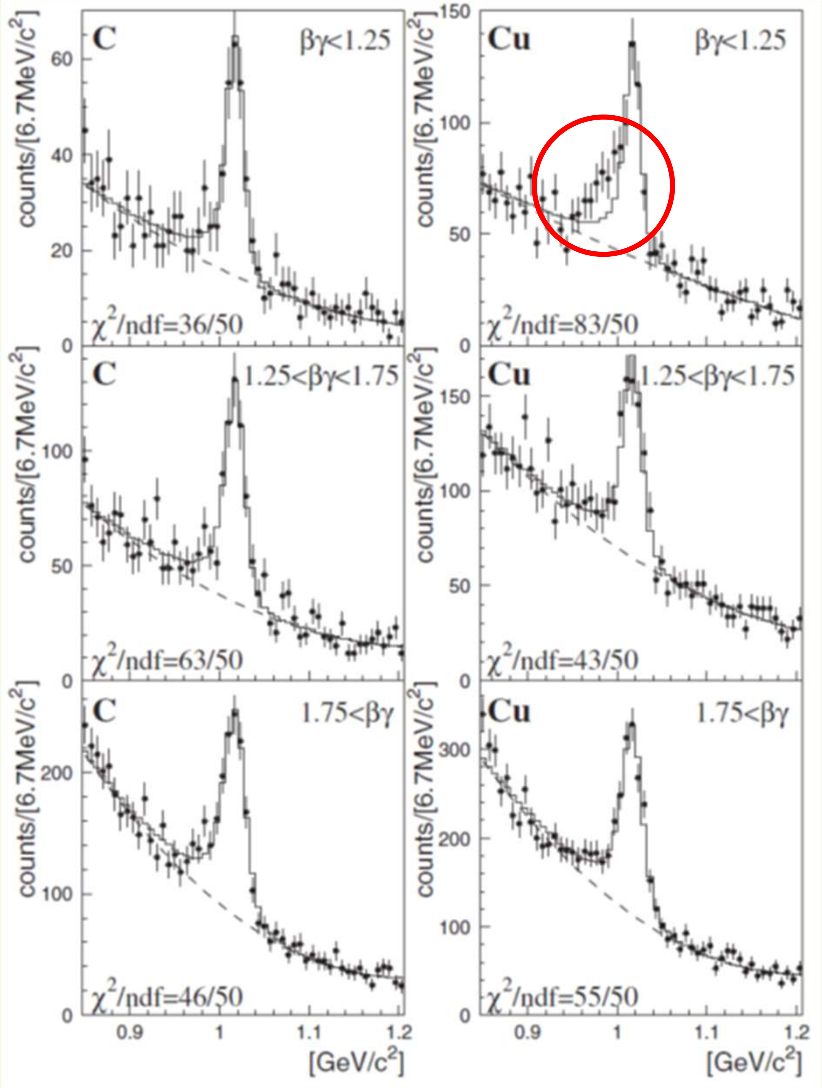
(E325, KEK)

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



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

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

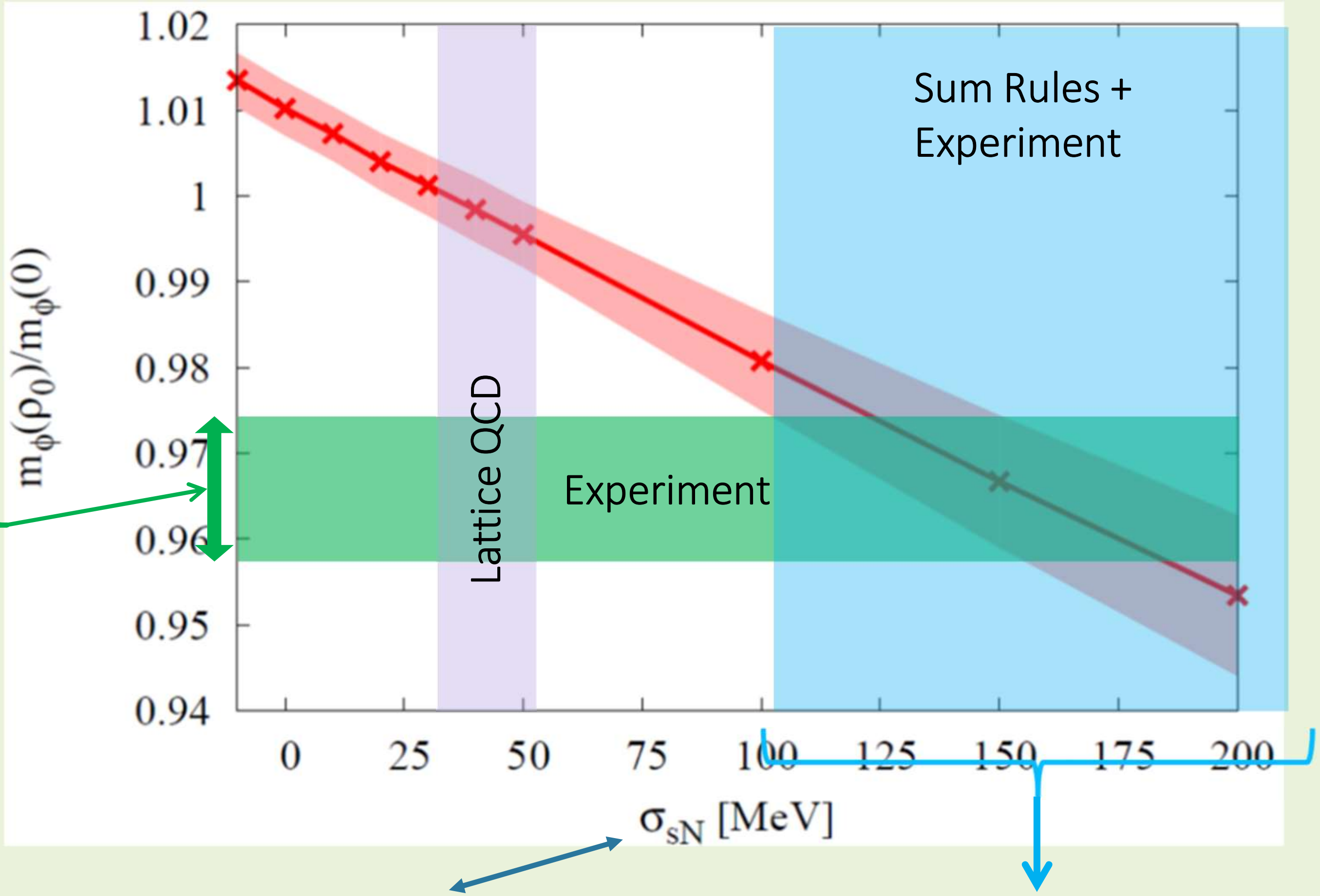
The φ meson mass in nuclear matter probes the strange quark condensate at finite density!

Not consistent?

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

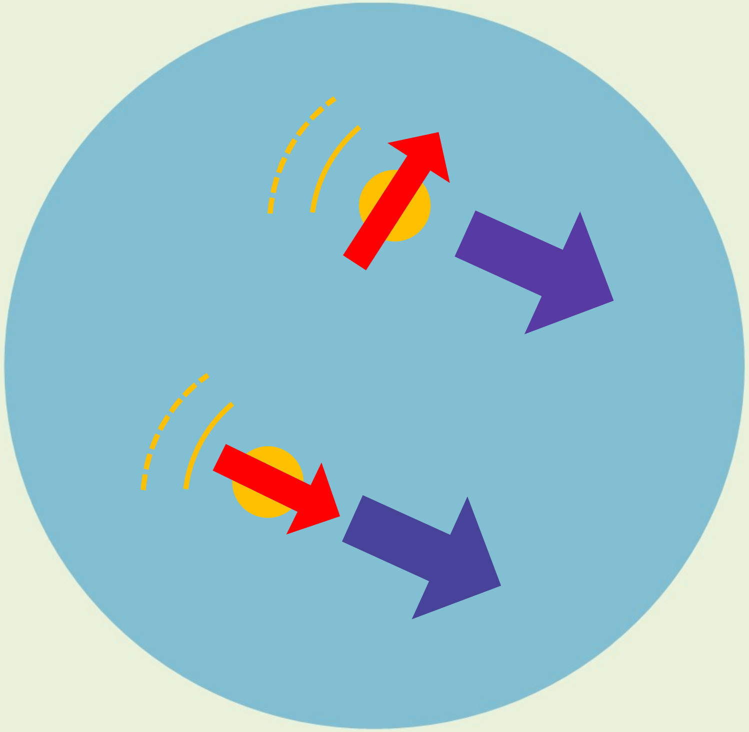
Measurement will be
repeated at the
J-PARC E16 experiment
(with 100 times
increased statistics!)

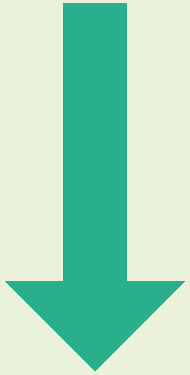
$$\frac{m_\phi(\rho)}{m_\phi(0)} = 0.966 \pm 0.007$$



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

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



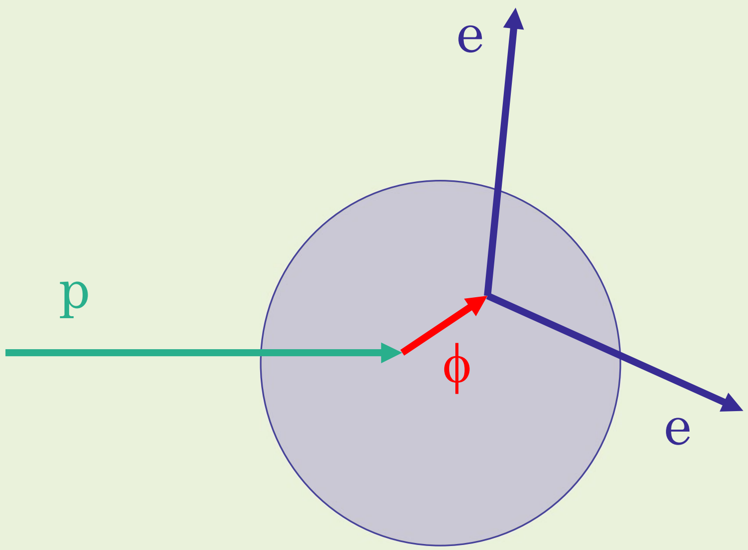


φ meson properties depend on the spin polarization (longitudinal or transverse)

Broken
Lorentz symmetry

Non-trivial polarization dependent dispersion relations

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

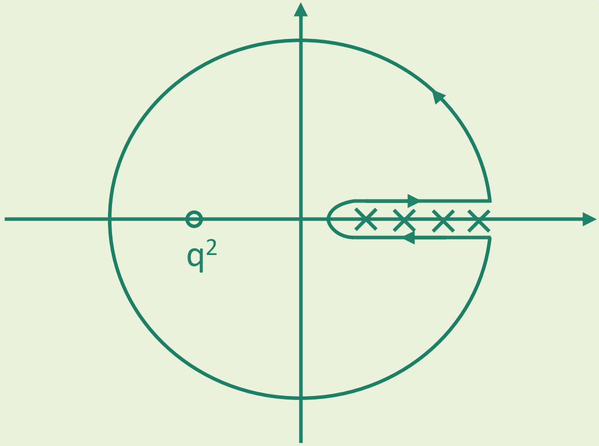
M.A. Shifman, A.I. Vainshtein and V.I. Zakharov,
Nucl. Phys. B147, 385 (1979); B147, 448 (1979).

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

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

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

scalar condensates:
trivial dispersion relation

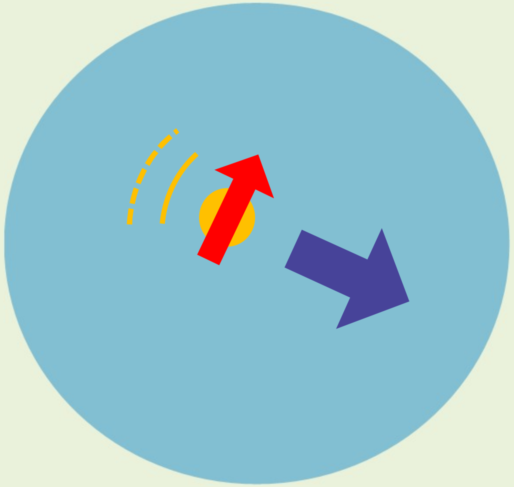
$\langle\mathcal{ST}\overline{s}\gamma^\alpha iD^\beta s\rangle_\rho$,
$\langle\mathcal{ST}G^{a\alpha}_\mu G^{a\mu\beta}\rangle_\rho$,
$\langle\mathcal{ST}\overline{s}\gamma^\alpha iD^\beta iD^\gamma iD^\delta s\rangle_\rho$

non-scalar condensates:
non-trivial dispersion relation

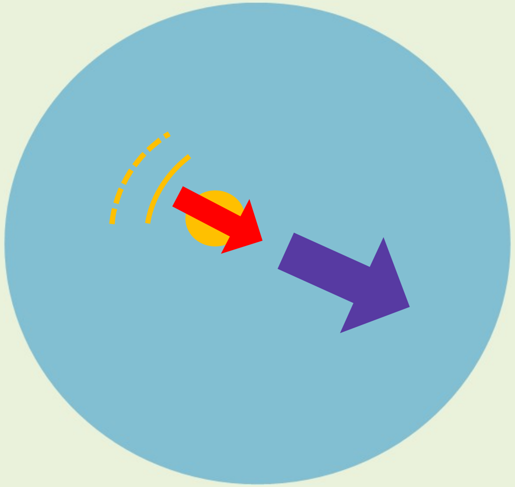
The non-zero momentum case: Disentangling longitudinal and transverse components

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

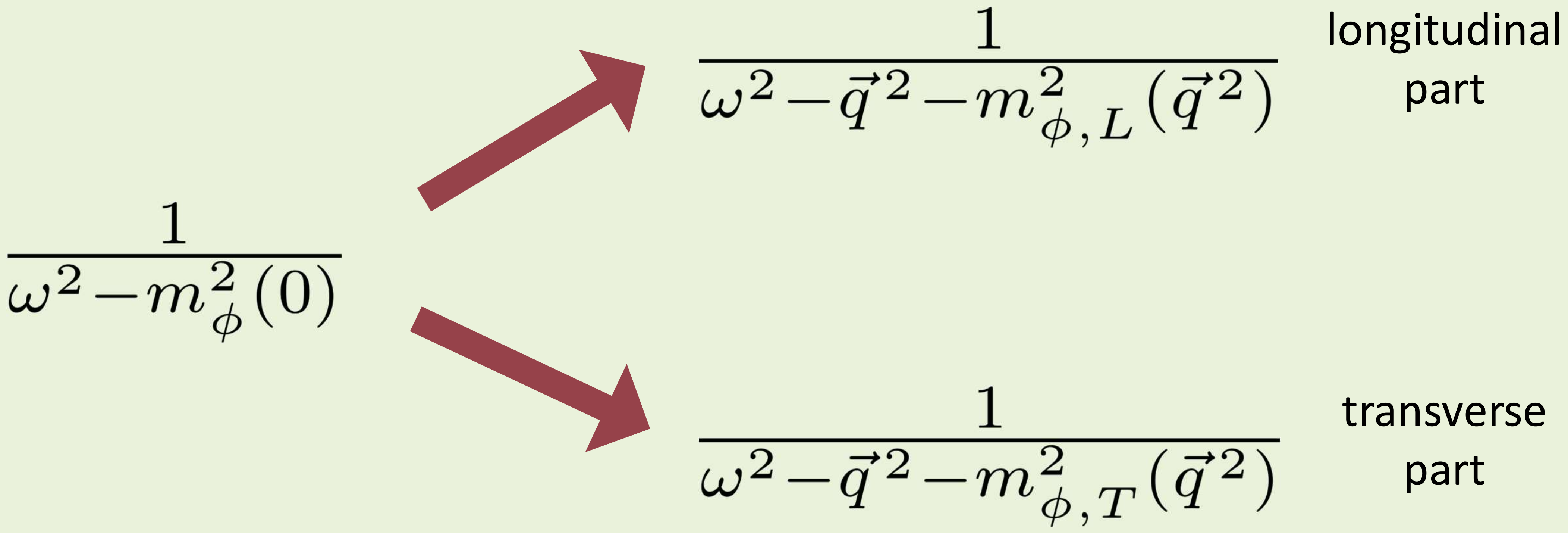
$$\Pi_L(\omega^2, \vec{q}^{\,2}) = \tfrac{1}{\vec{q}^{\,2}}\Pi_{00}$$



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



The ϕ meson with non-zero momentum



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

longitudinal
part

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

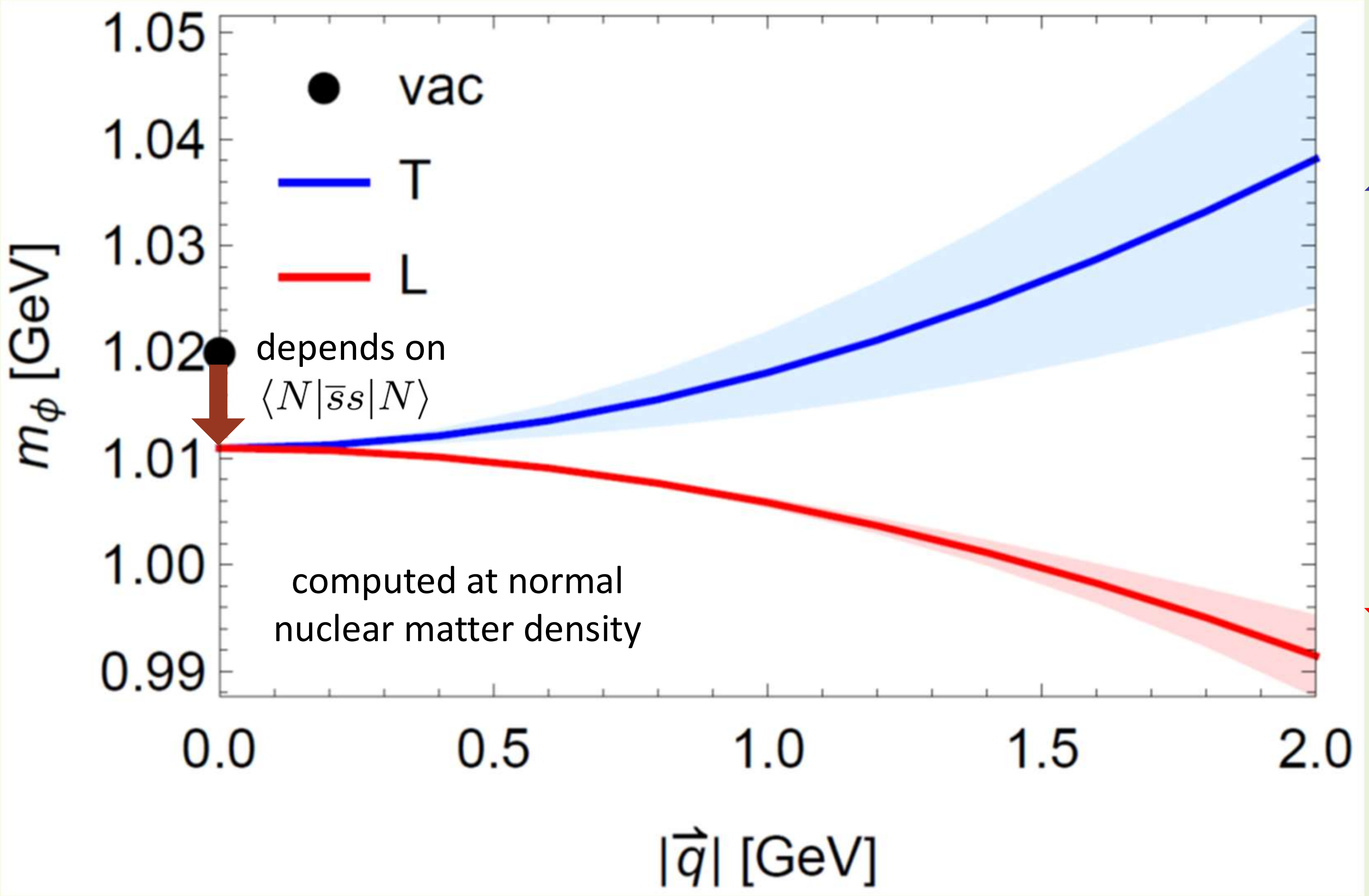
$$\frac{1}{\omega^2 - \vec{q}^{\,2} - m^2_{\phi,T}(\vec{q}^{\,2})}$$

transverse
part

zero momentum

non-zero momentum $\vec{q}$

Results for the ϕ meson mass with non-zero momentum



depends on $\langle N|\bar{s}s|N\rangle$

computed at normal nuclear matter density

caused by

$$\langle N|\mathcal{S}\mathcal{T}\bar{s}\gamma^{\alpha}iD^{\beta}s|N\rangle$$

$$+$$

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

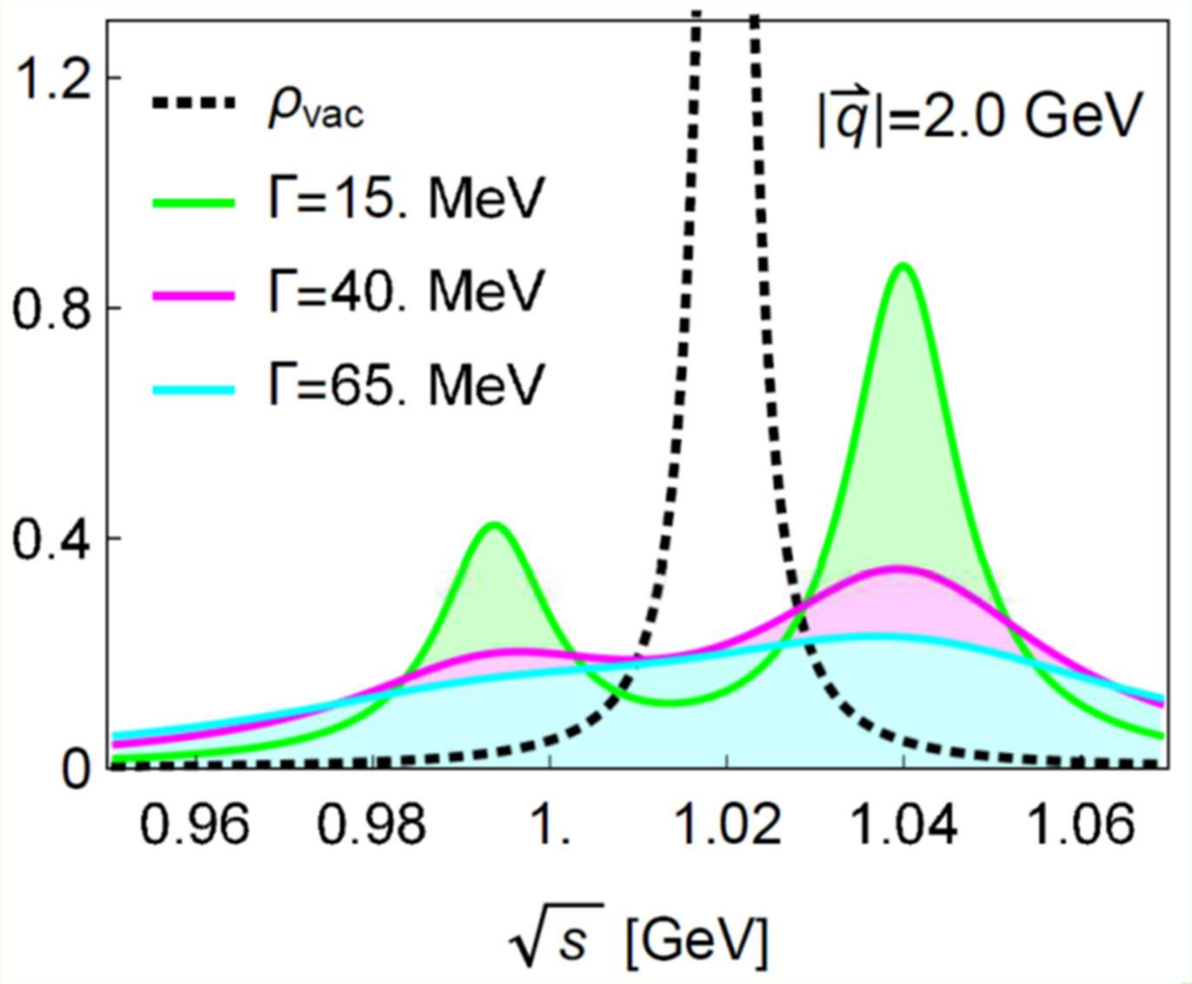
caused by

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

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

The angle-averaged di-lepton spectrum

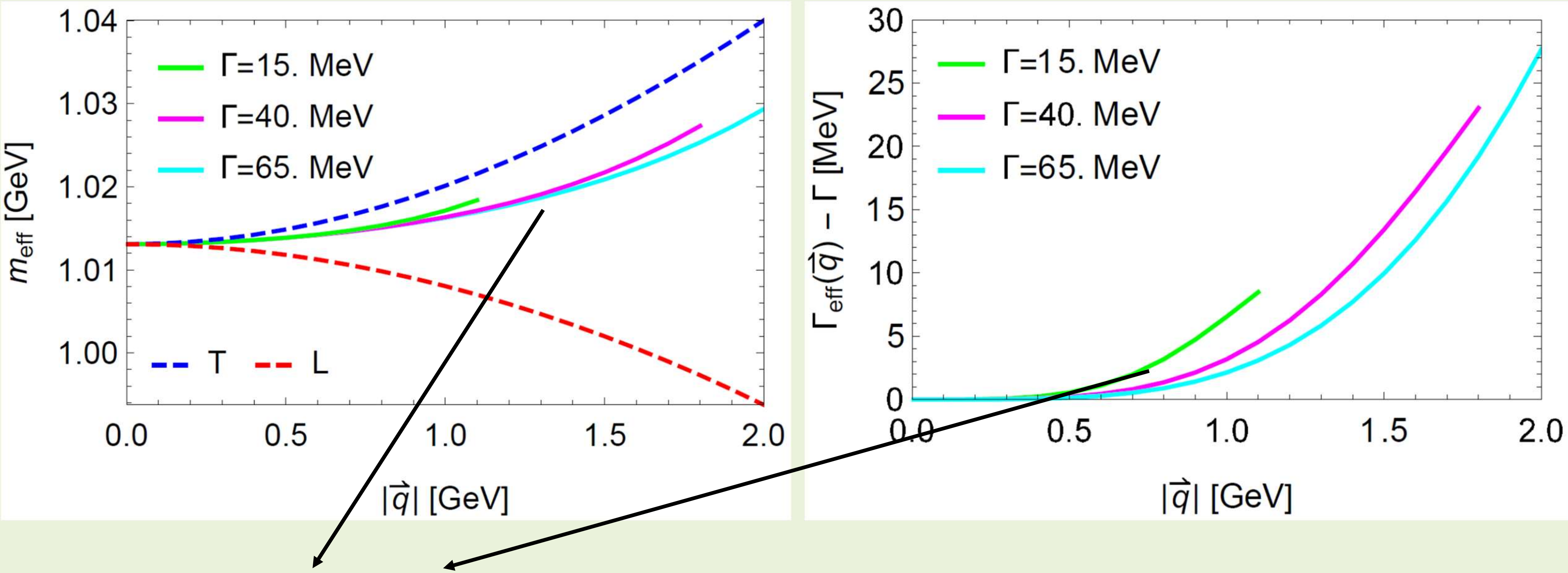
A double peak?



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

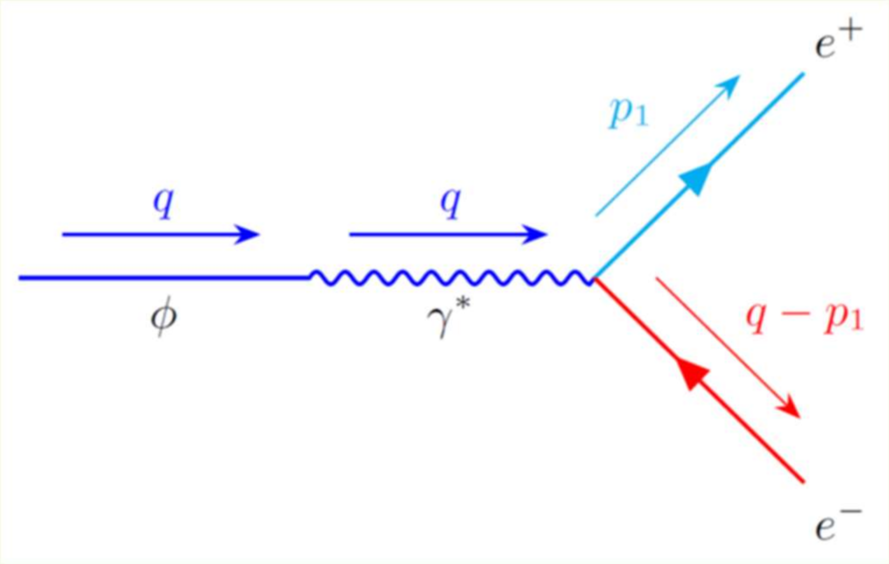


Results of one-peak fits

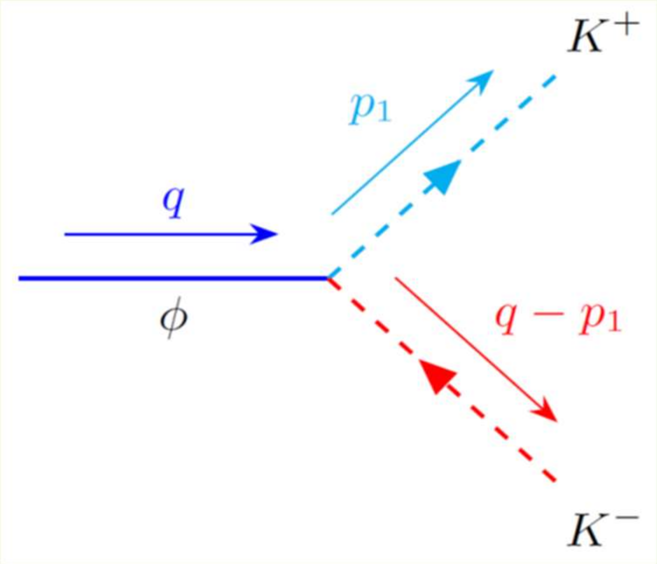
H.J. Kim and P. Gubler, Phys. Lett. B **805**, 135412 (2020).

Can the two polarizations be disentangled?

→ Look at the angular distributions of various decay channels

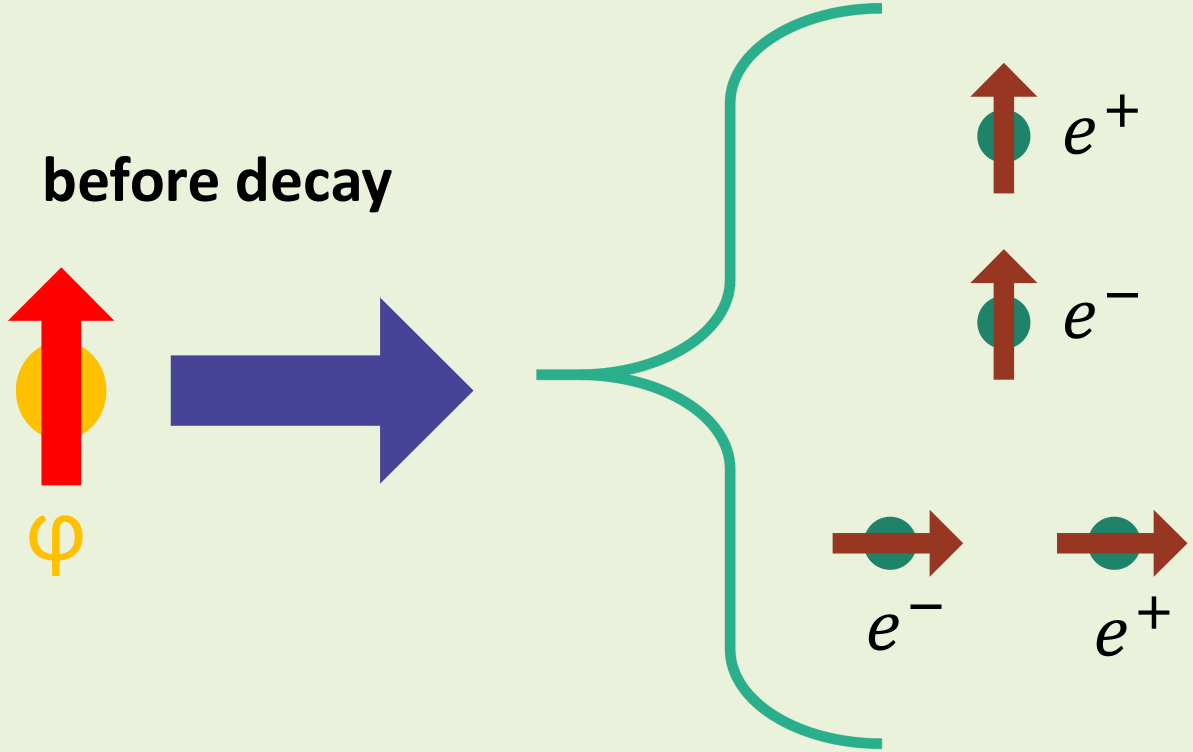


To be measured soon at
the J-PARC E16 experiment



New proposal P88
submitted to J-PARC PAC

A simple example of dilepton decay of a longitudinally polarized φ



before decay

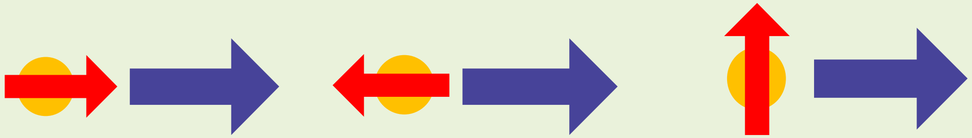
after decay

decay perpendicular to the φ meson momentum:
allowed

decay parallel to the φ meson momentum:
not allowed

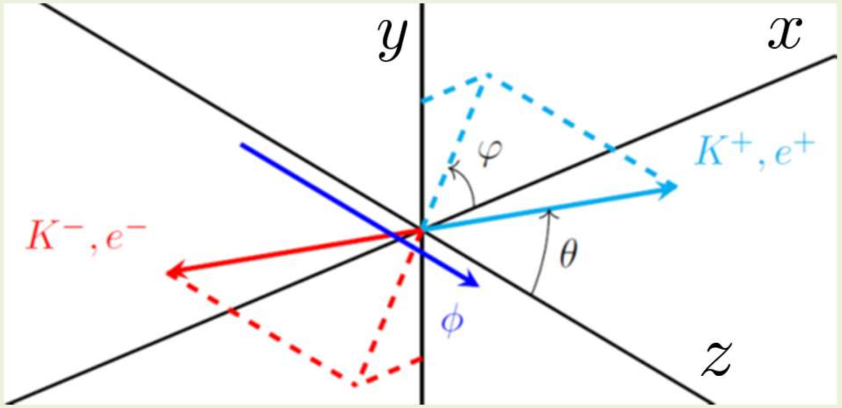
measurement in this direction can be used to observe purely transverse mode

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



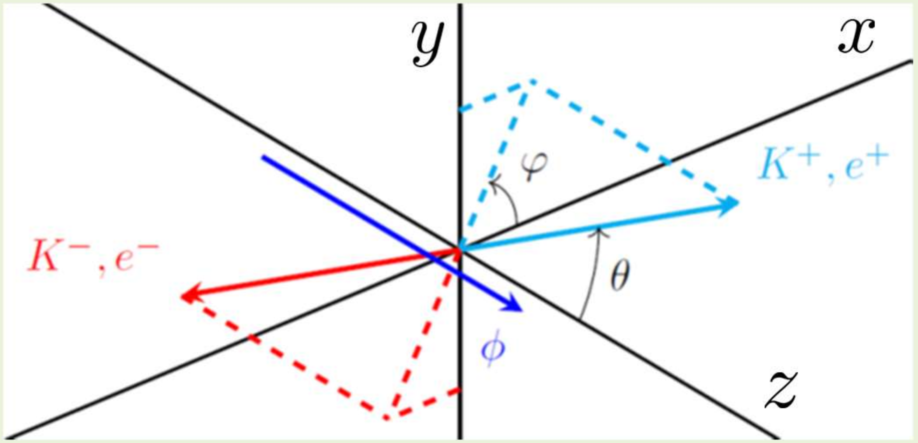
θ: polar angle

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

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

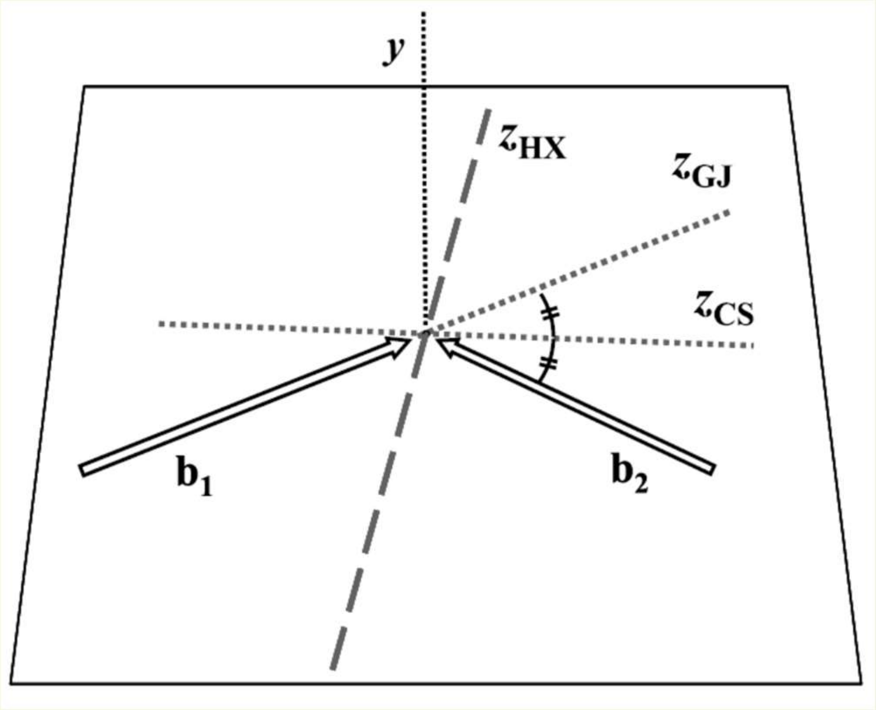
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\Omega} = \frac{3}{16\pi}\left[1 + \cos^2\theta + \rho_{00}(1 - 3\cos^2\theta) + \ldots\right]$$

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

Unpolarized case: vanishing θ-dependence

ϕ-dependent terms

Choice of the reference frame (polarization axis)



P. Faccioli *et al.*, Eur. Phys. J. C **69**, 657 (2010).

Three different choices for the polarization/z axis are frequently used in the literature:

★ Collins-Soper (CS) frame

★ Gottfried-Jackson (GJ) frame

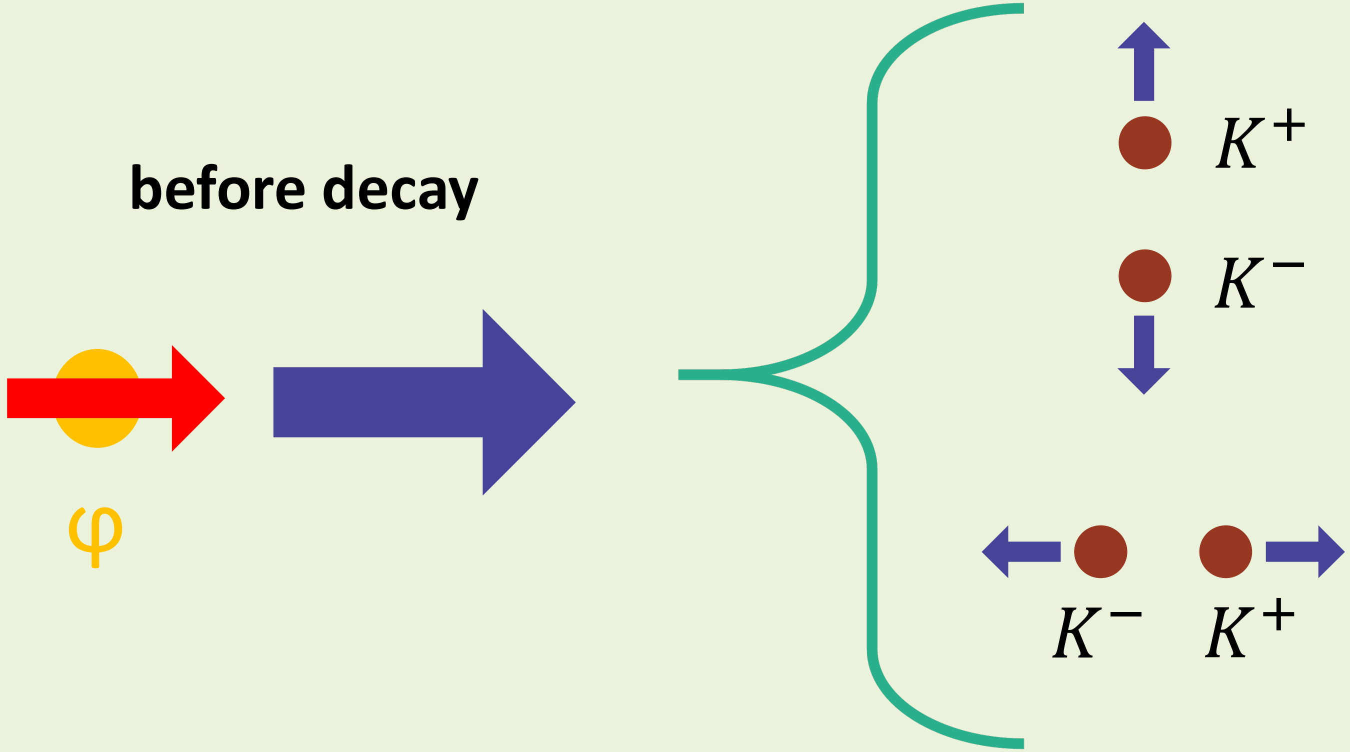
★ Helicity (HX) frame

↑

Only the HX frame should be used to properly disentangle the independent dispersion relations of the longitudinal and transverse modes!

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

before decay



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

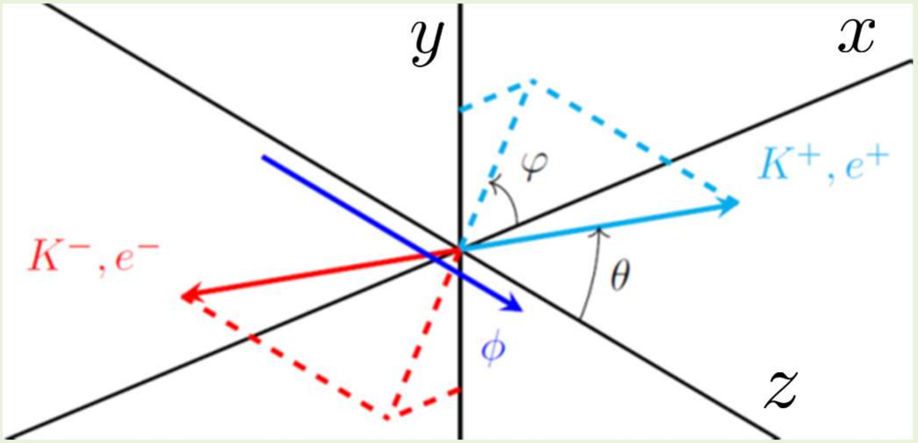
after decay

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 K$^+$K$^-$ decay



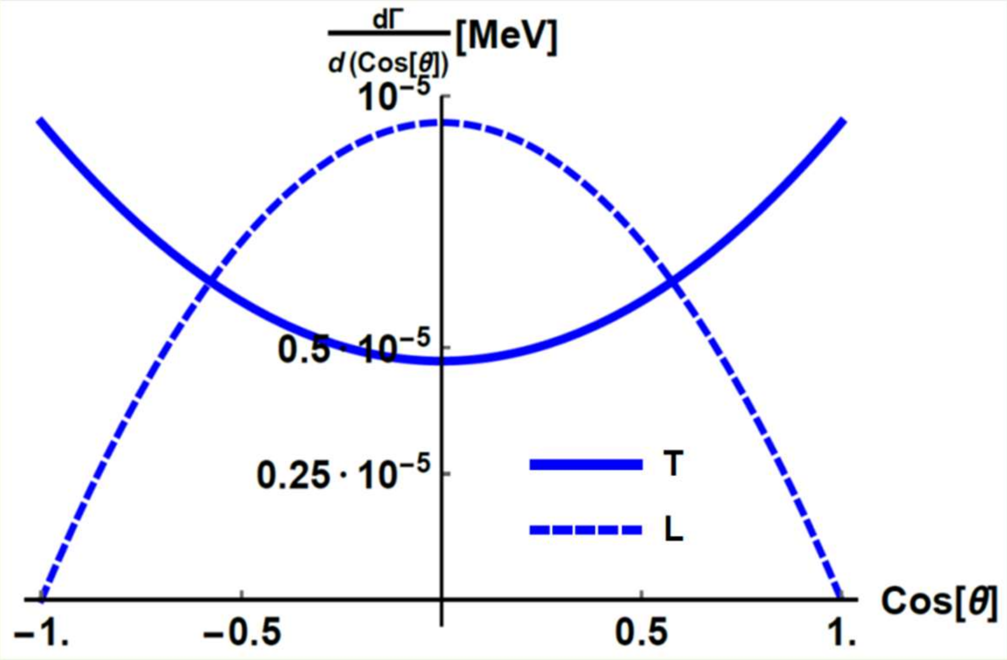
θ: polar angle
ϕ: azimuthal angle

$$\begin{aligned}\frac{1}{\Gamma}\frac{d\Gamma}{d\Omega} &= \frac{3}{16\pi}\Big[\overbrace{(|a_{+1}|^2+|a_{-1}|^2)}^{\text{Transverse modes}}\sin^2\theta + \overset{\text{Longitudinal mode}}{2|a_0|^2\cos^2\theta} \\ &\qquad -2\mathrm{Re}(a_{+1}a^*_{-1})\sin^2\theta\cos 2\phi + \dots\Big] \\ &= \frac{3}{16\pi}\Big[1-\cos^2\theta-\rho_{00}(1-3\cos^2\theta)+\dots\Big]\end{aligned}$$

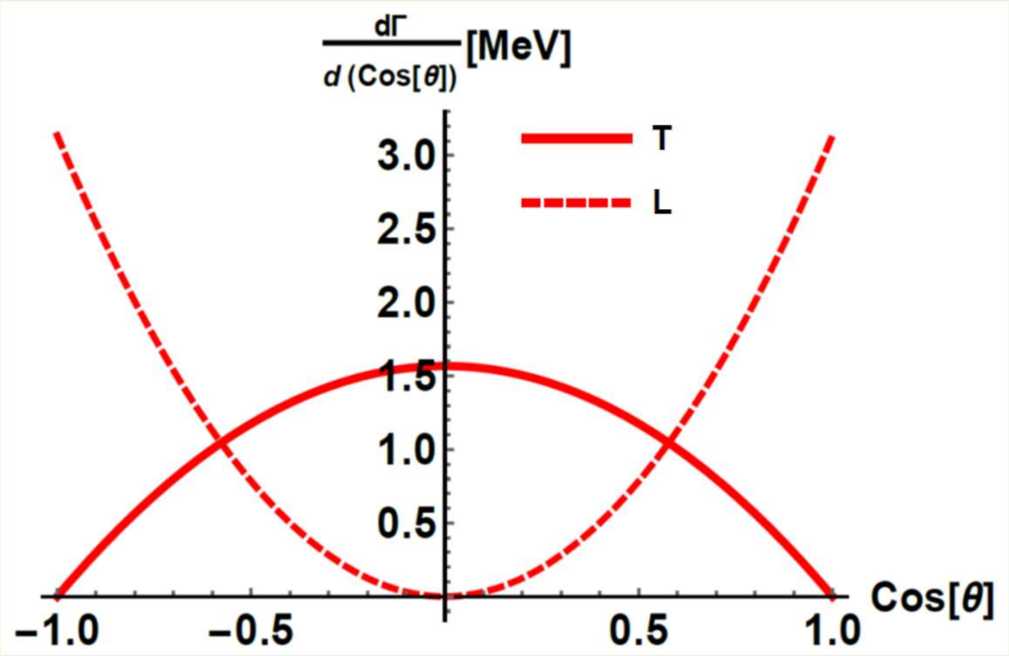
ϕ-dependent terms

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

Dilepton decay angular distribution



K^+K^- decay angular distribution

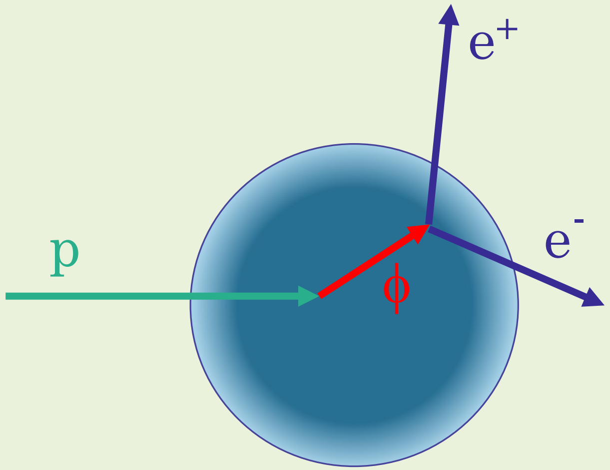


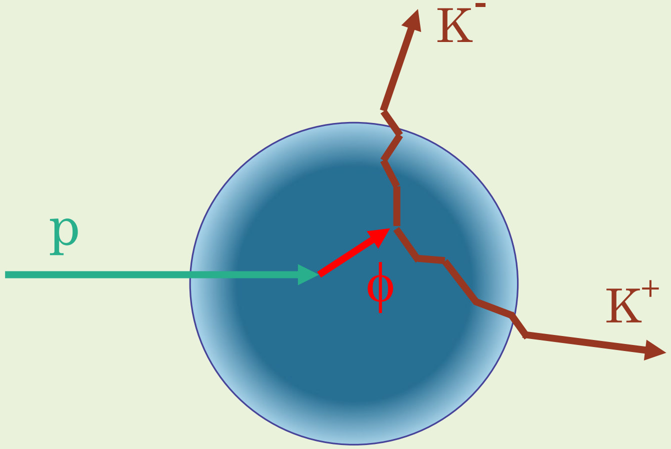
Discussions with J-PARC E16 members on how to distinguish the transverse and longitudinal modes are ongoing.

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^-)?

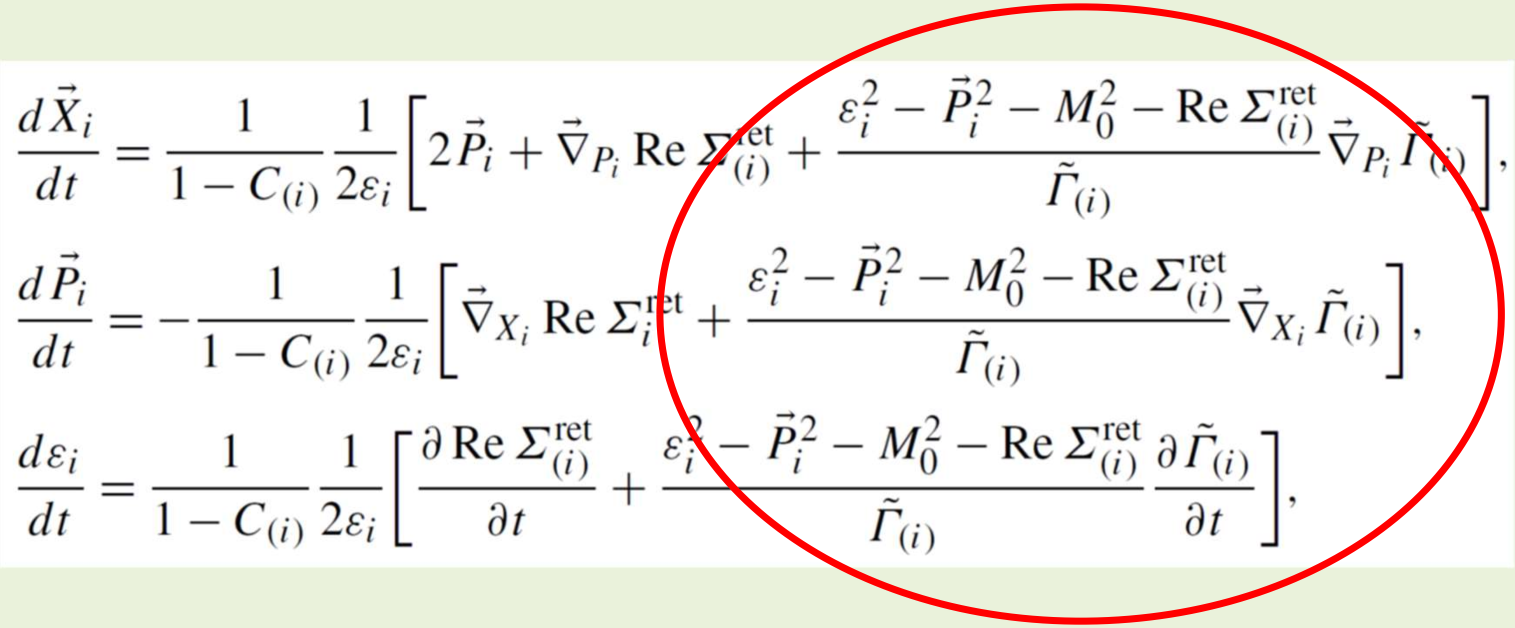
➡ Realistic transport simulations using a transport approach (calculations using the PHSD code are ongoing)

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)

Testparticle approach:



off-shell terms

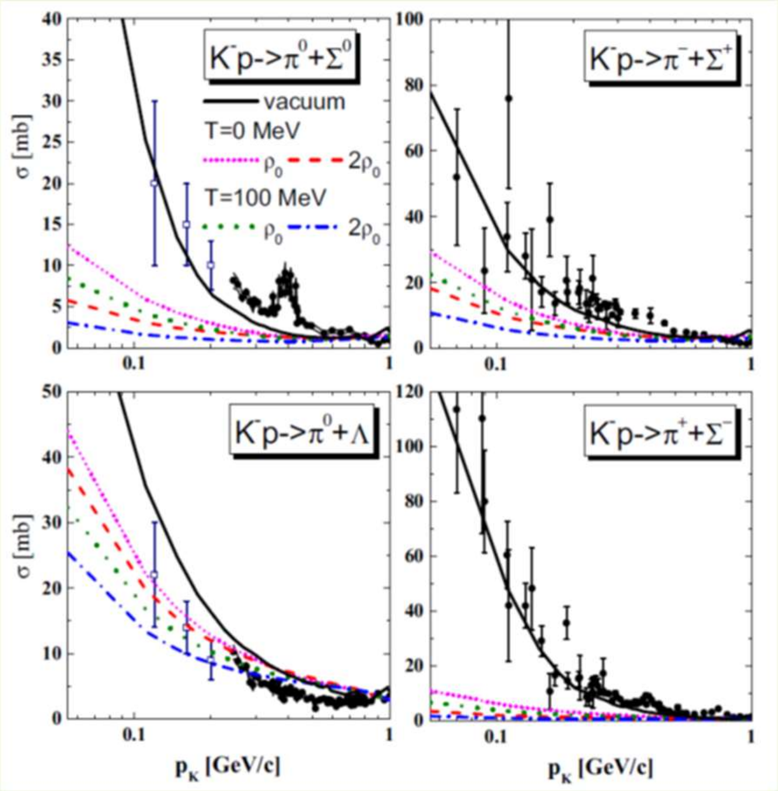
$$\frac{d\vec{X}_i}{dt} = \frac{1}{1-C_{(i)}}\frac{1}{2\varepsilon_i}\left[2\vec{P}_i + \vec{\nabla}_{P_i}\mathrm{Re}\,\Sigma^{\mathrm{ret}}_{(i)} + \frac{\varepsilon_i^2 - \vec{P}_i^2 - M_0^2 - \mathrm{Re}\,\Sigma^{\mathrm{ret}}_{(i)}}{\tilde{\Gamma}_{(i)}}\vec{\nabla}_{P_i}\tilde{\Gamma}_{(i)}\right],$$

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

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

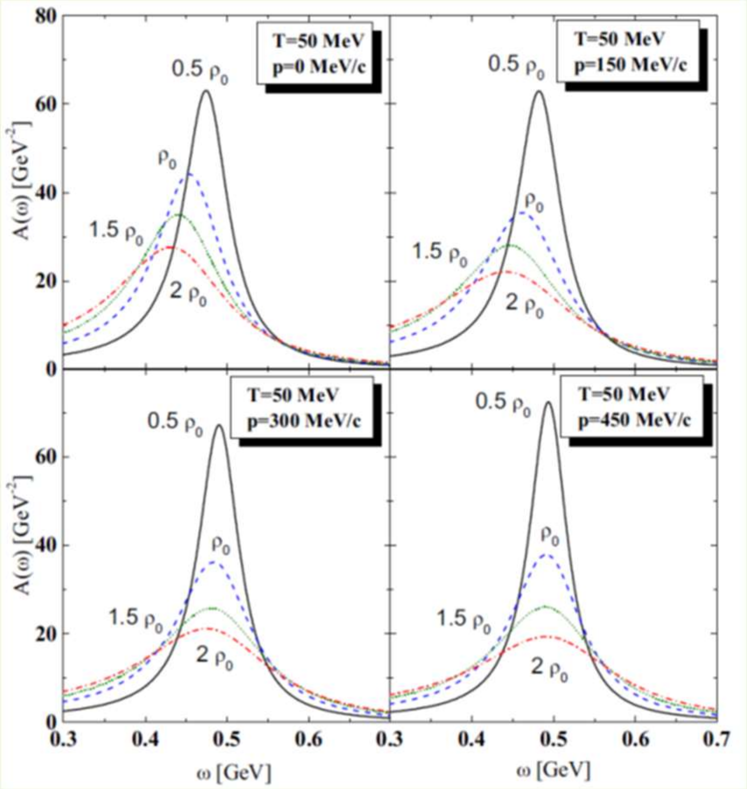
Treatment of KN-interactions

Density dependent cross sections based on the chiral unitary model
(including coupled channels and s-/p-wave of $\bar{K}N$ interactions)



Vacuum and density dependent $\bar{K}N$ cross sections

Density dependent $\bar{K}$ spectral functions

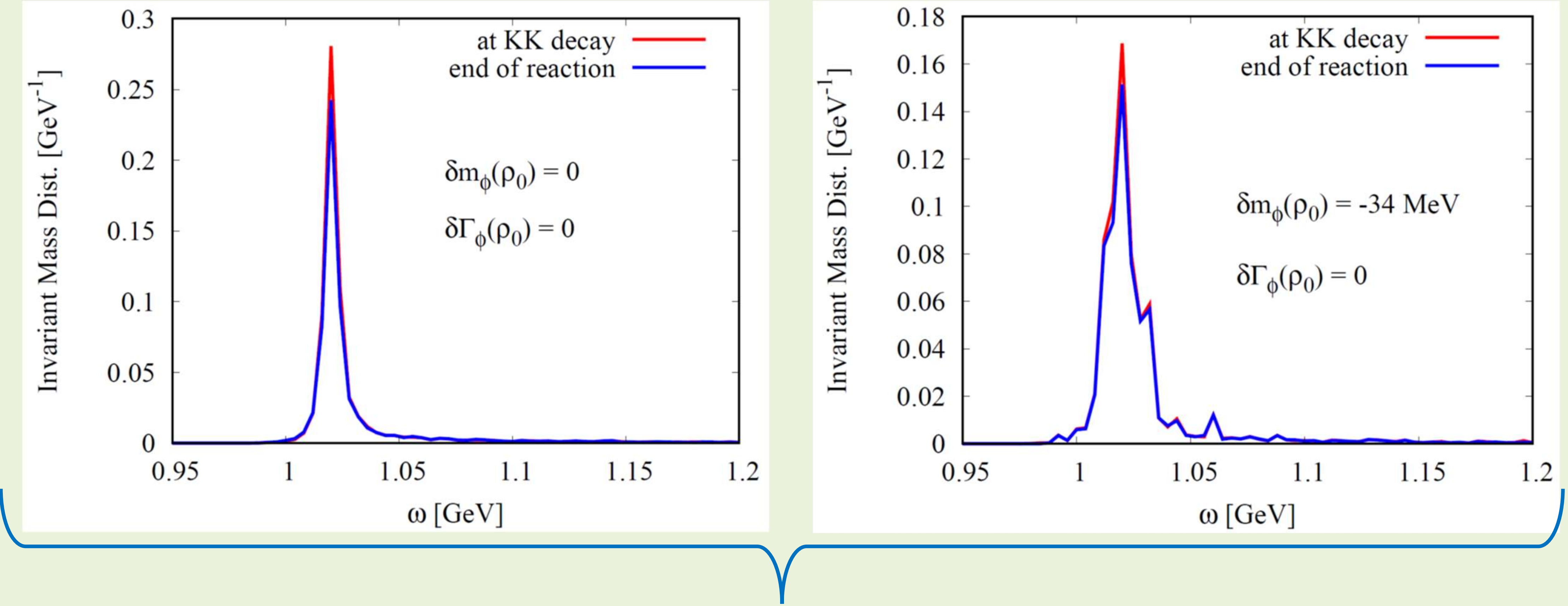


T. Song et al., Phys. Rev. C **103**, 044901 (2021).

Preliminary

Distortion of the in-medium φ meson signal in the K^+K^- channel

(p + Cu at 30 GeV)



Small distortion effect from the strong KN interaction !?

Summary and conclusions

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

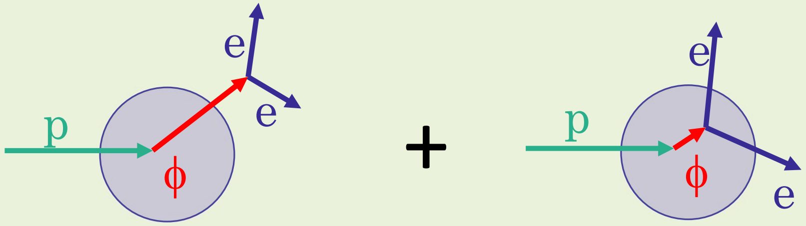
★ For the φ meson, the longitudinal and transverse modes are shifted in opposite directions with increasing momentum.

➡ 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

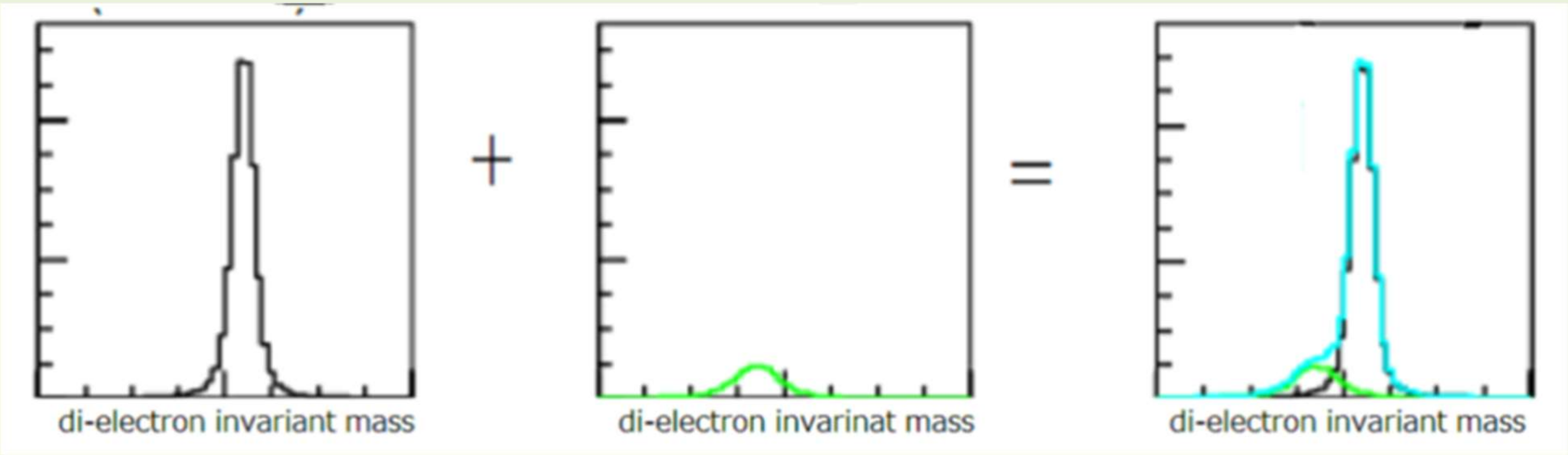
➡ Making use of the angular dependences of the dilepton and K^+K^- decay channels, it is possible to **disentangle the longitudinal and transverse polarization modes**

Backup slides

Experimental di-lepton spectrum



outside decay + inside decay = Experimentally observed spectrum



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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)

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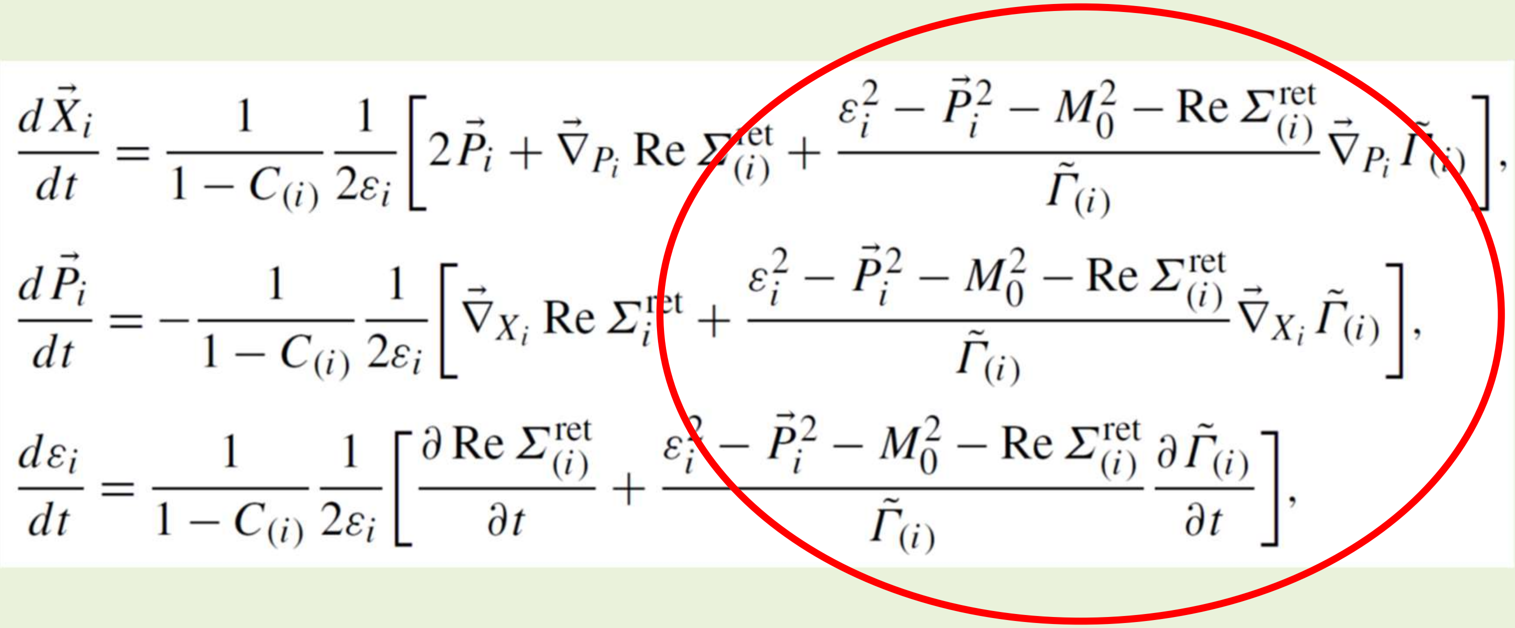


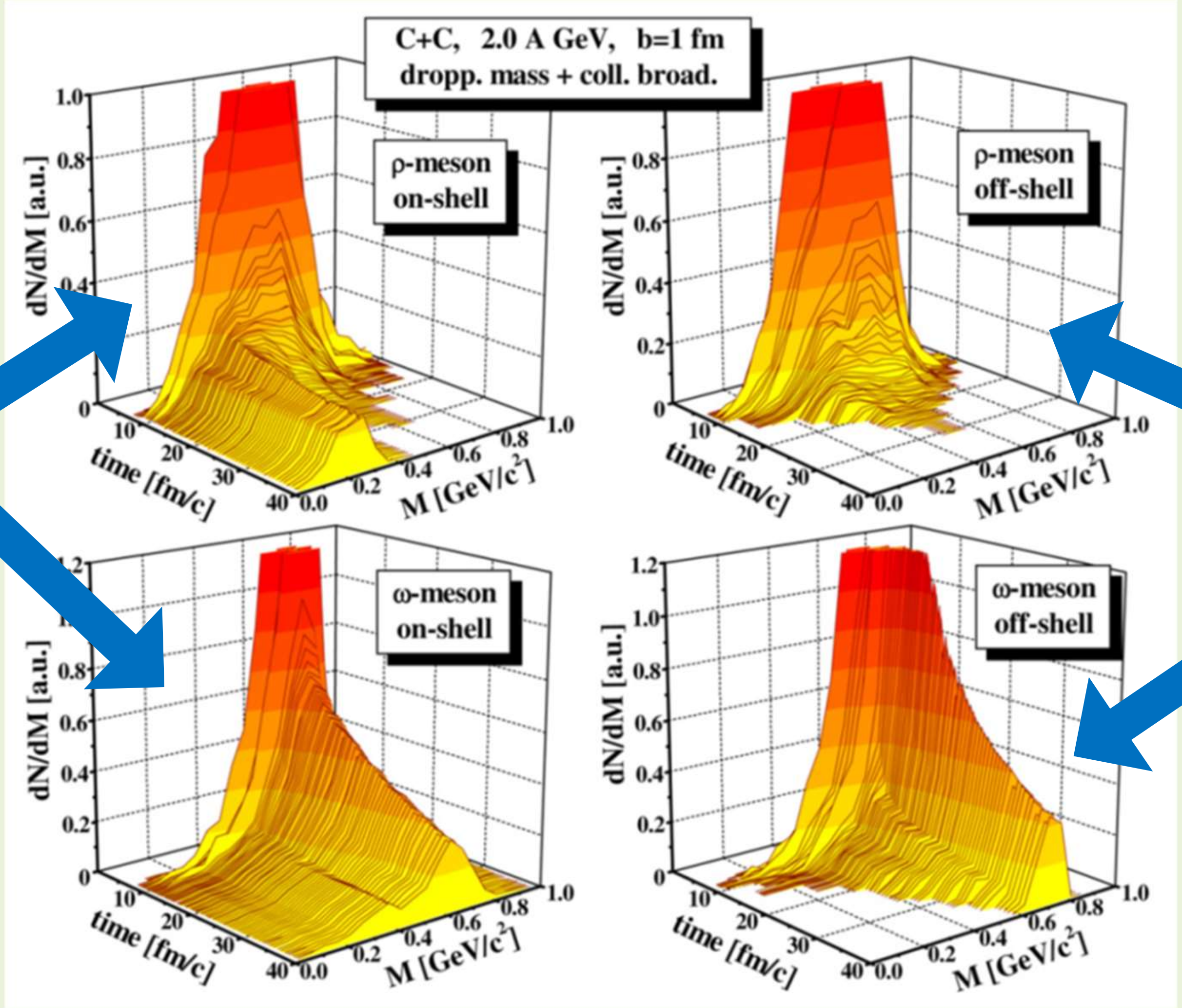
off-shell terms

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

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

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

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).

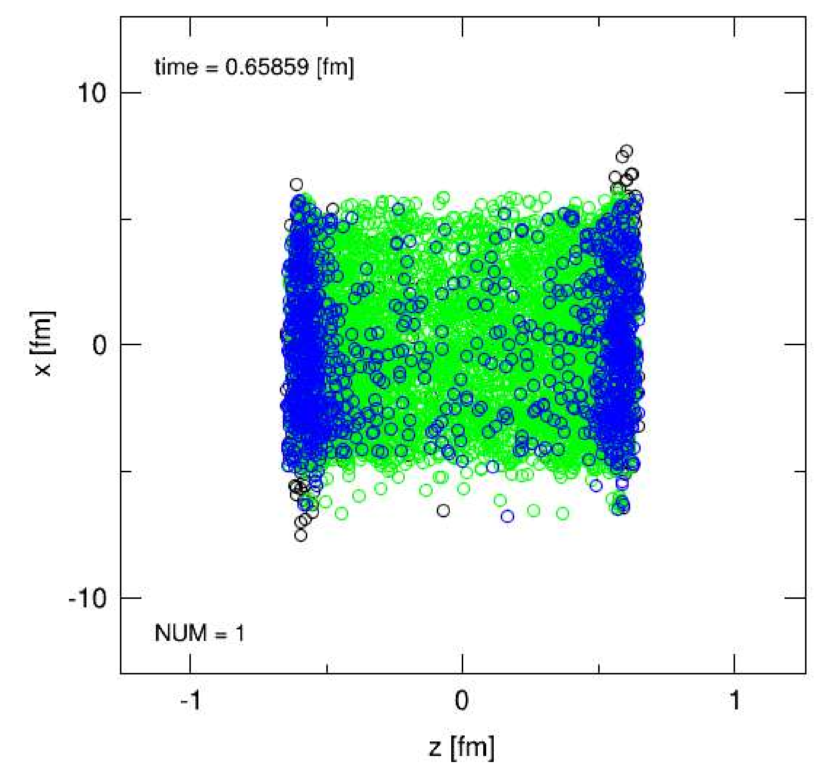
Our tool: a transport code
PHSD (Parton Hadron String Dynamics)

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

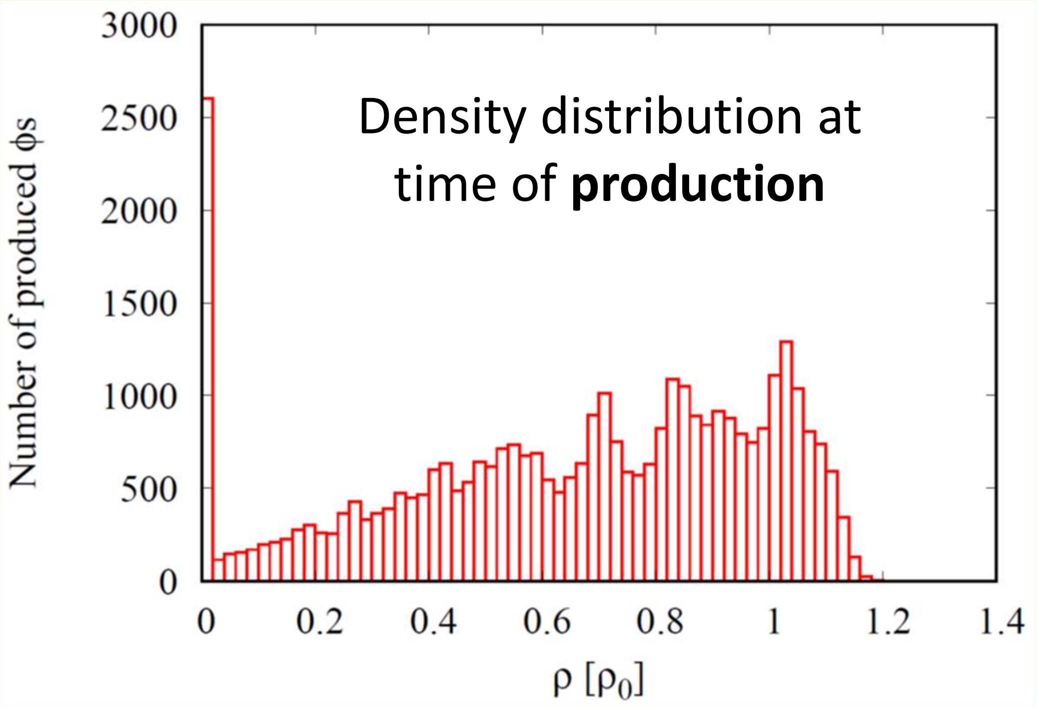
Example:

Au+Au collision at 200 GeV
b = 2 fm

nucleons
quarks
gluons

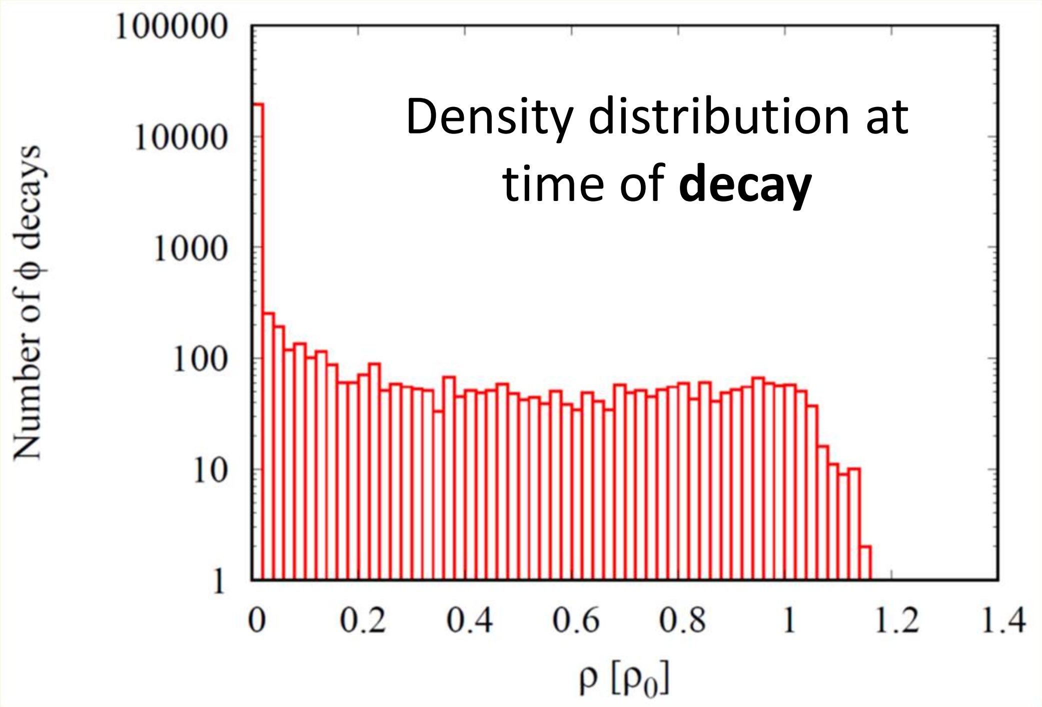


What density does the φ feel in the reaction (p+Cu at 12 GeV)?



Density distribution at time of **production**

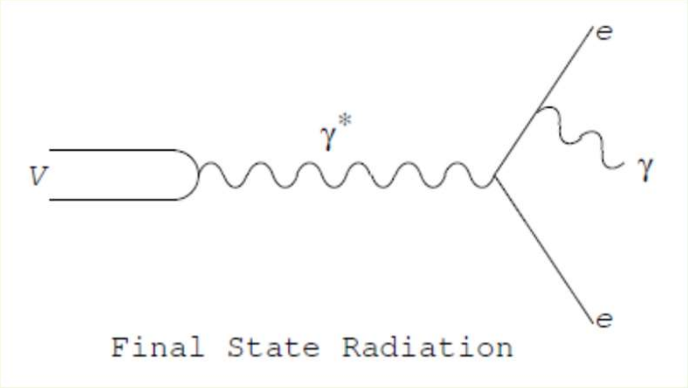
Majority of φ mesons are produced at densities around ρ_0

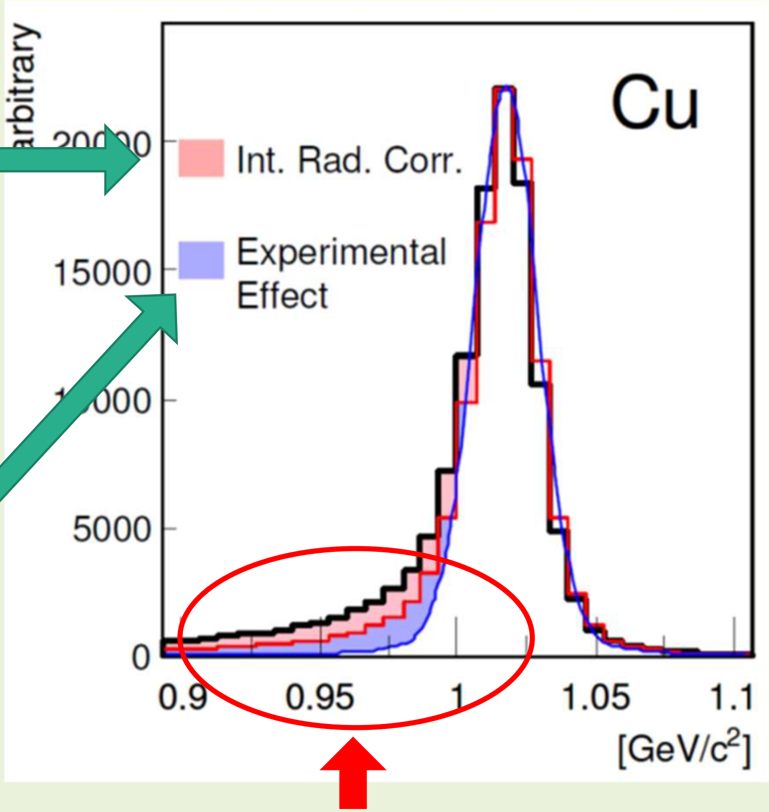


Density distribution at time of **decay**

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

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





Rescattering effect

(multiple scattering, energy loss)

Similar to the shape expected for a negative mass shift

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