Phi meson properties in nuclear matter in a transport approach

Philipp Gubler (JAEA)

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

P. Gubler, E. Bratkovskaya and T. Song, in progress.

Talk at NeD-2022,
Krabi, Thailand,
December 1, 2022

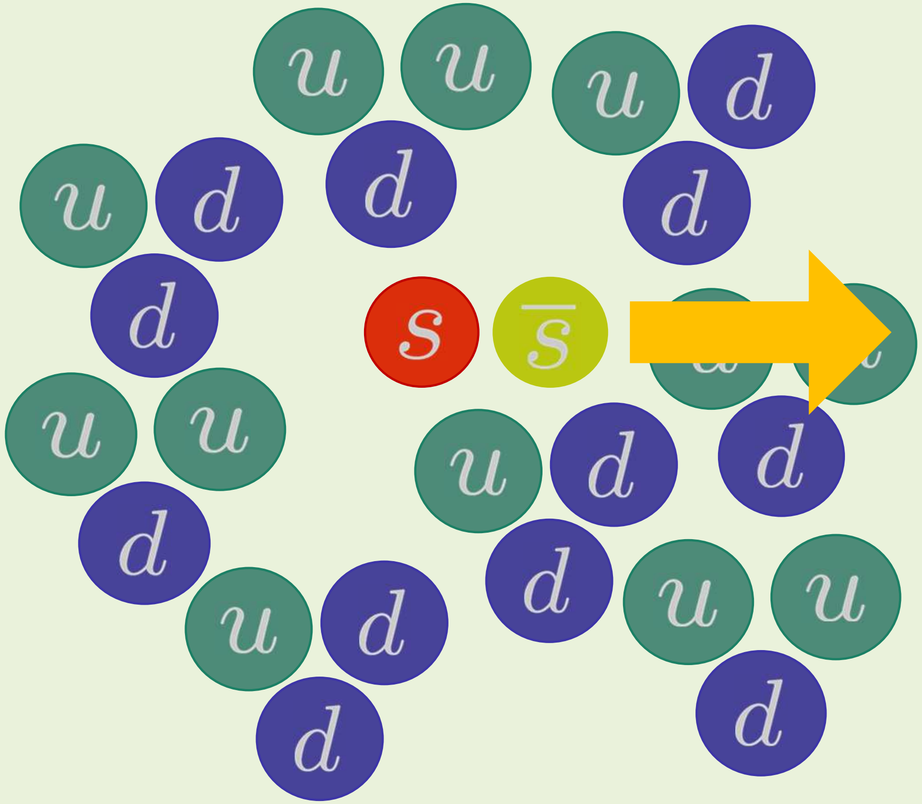
Work done in collaboration with:
HyungJoo Kim (Yonsei U.)
Elena Bratkovskaya (Frankfurt/GSI)
Taesoo Song (GSI)

Interest

ϕ meson

m_ϕ = 1019 MeV

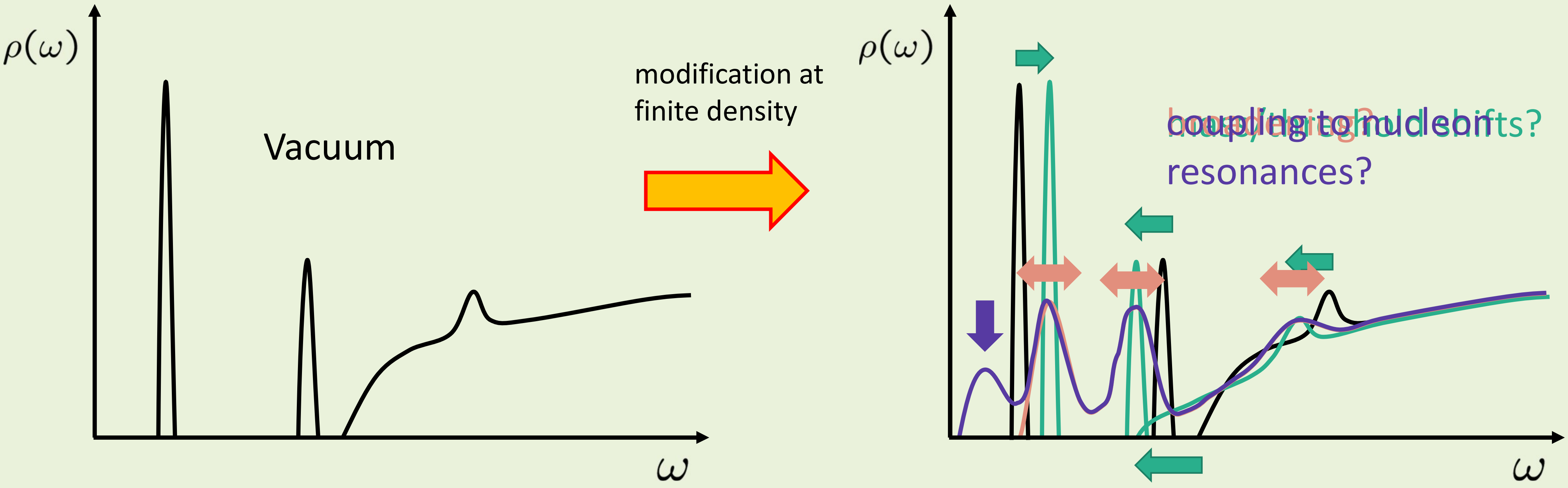
Γ_ϕ = 4.3 MeV



Hadrons as components of spectral functions

Spectral functions at finite density

How is this complicated behavior related to the change of QCD condensates?



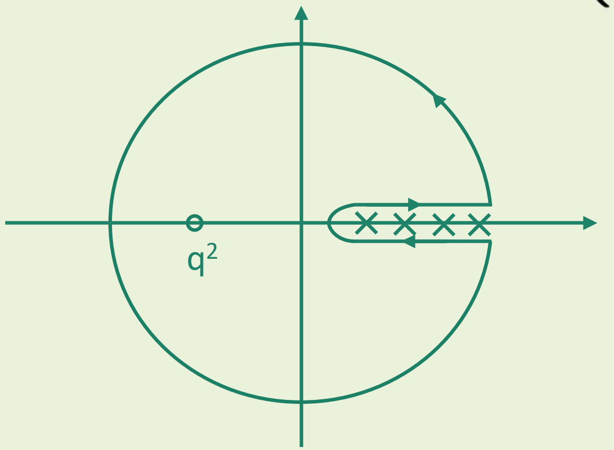
M.A. Shifman, A.I. Vainshtein and V.I. Zakharov,
Nucl. Phys. B147, 385 (1979); B147, 448 (1979).

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:
trivial dispersion relation

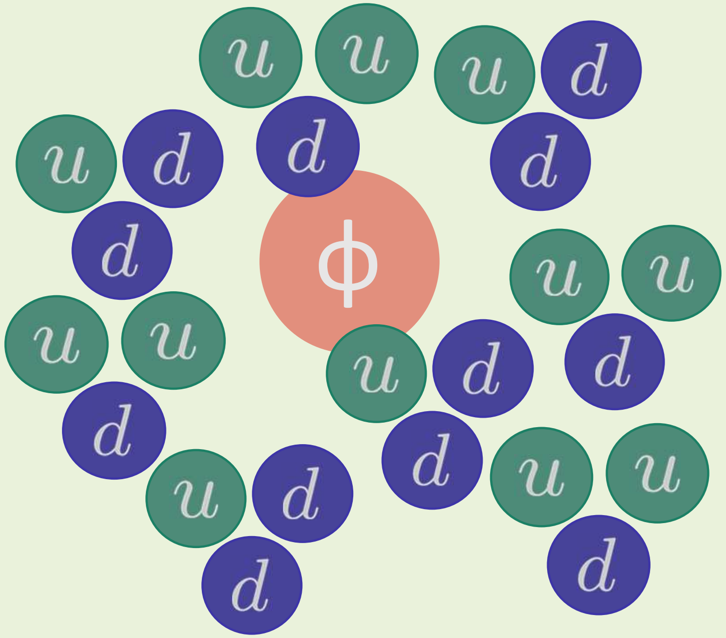
$\langle \mathcal{ST}\bar{s}\gamma^\alpha iD^\beta s\rangle_\rho,$
$\langle \mathcal{ST}G^{a\alpha}_{\mu}G^{a\mu\beta}\rangle_\rho,$
$\langle \mathcal{ST}\bar{s}\gamma^\alpha iD^\beta iD^\gamma iD^\delta s\rangle_\rho$

non-scalar condensates:
non-trivial dispersion relation

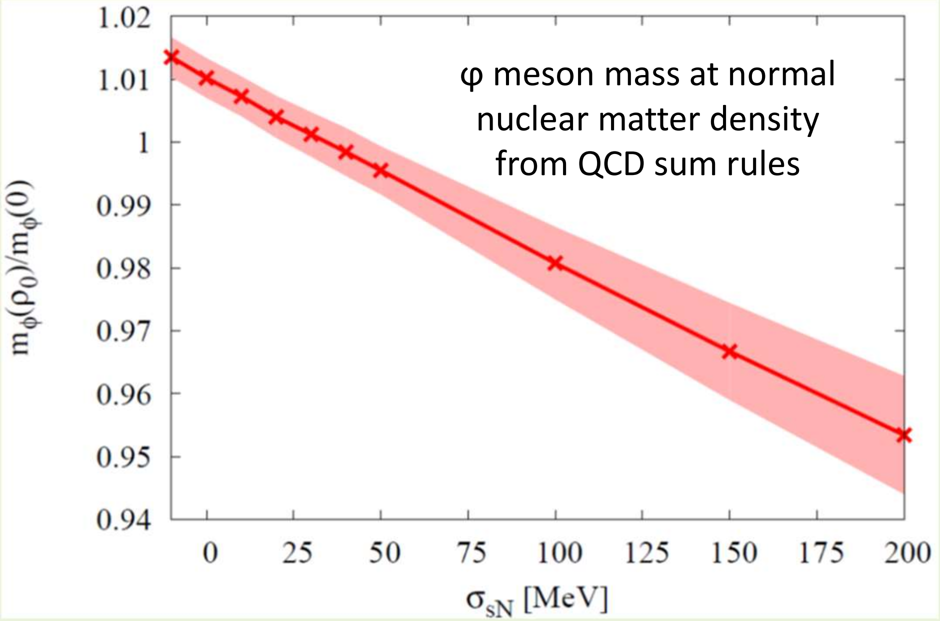
φ meson **at rest** in nuclear matter

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

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



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

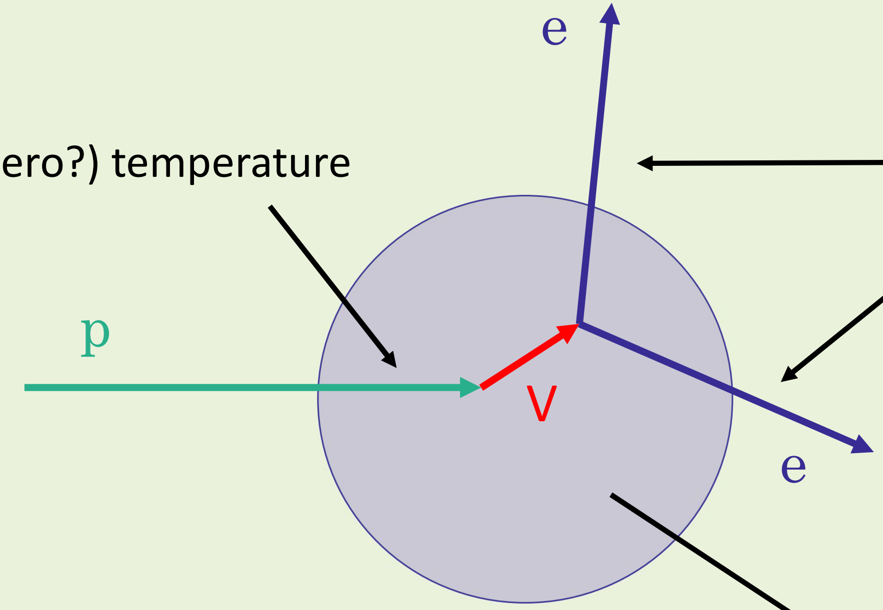


φ meson mass at normal nuclear matter density from QCD sum rules

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

A typically used reaction

Proton induced generation of vector mesons in nuclei



low (zero?) temperature

no strong interaction

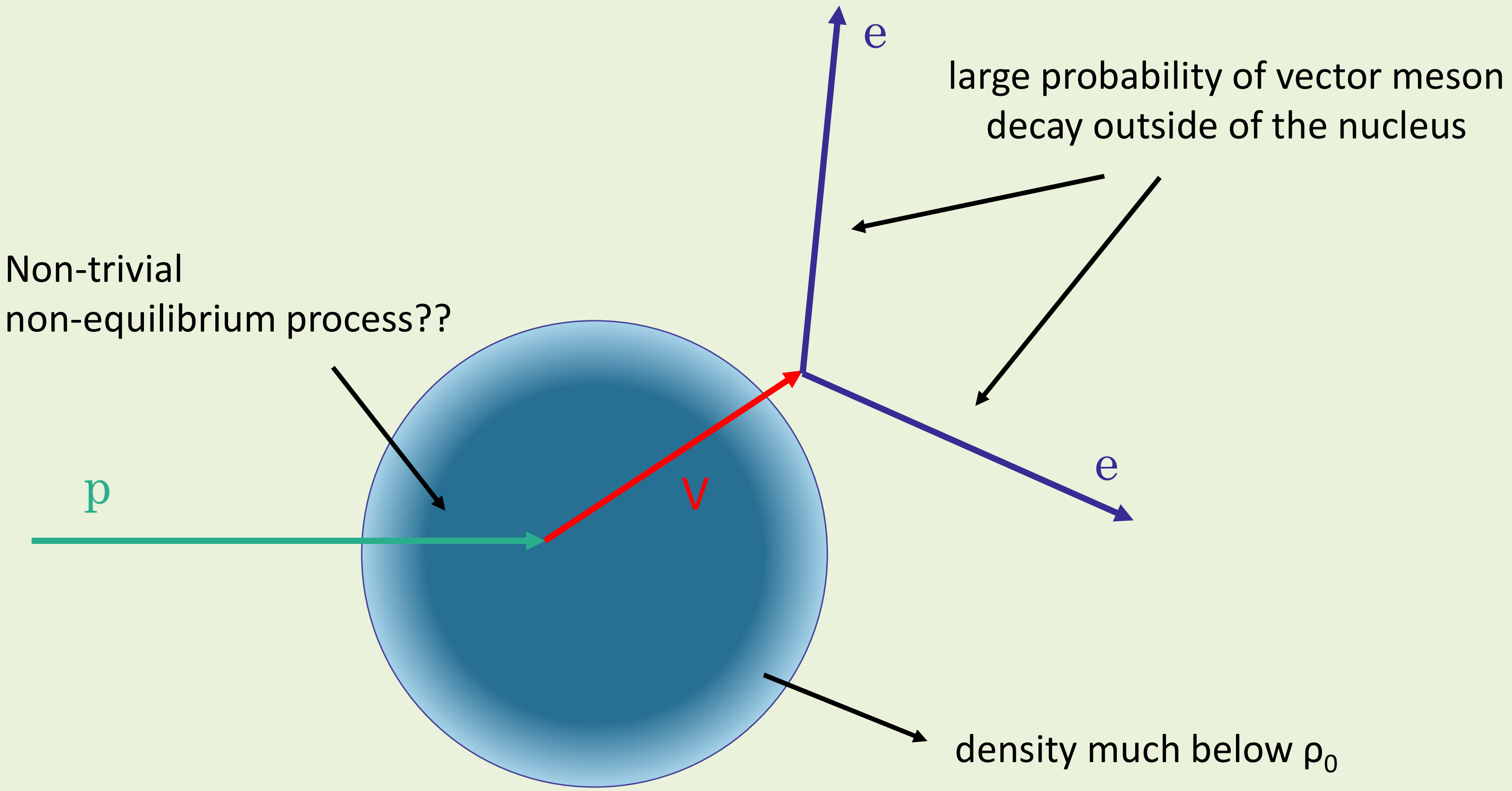
no distortion of signal due to interaction with nuclear medium

approximate density:
normal nuclear density ρ_0

E325 (KEK)
E16 (J-PARC)

However, things are not so simple…

Proton induced generation of vector mesons in nuclei



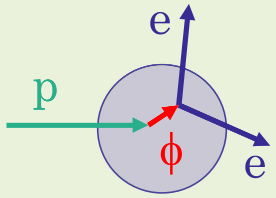
large probability of vector meson decay outside of the nucleus

Non-trivial
non-equilibrium process??

density much below ρ_0

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

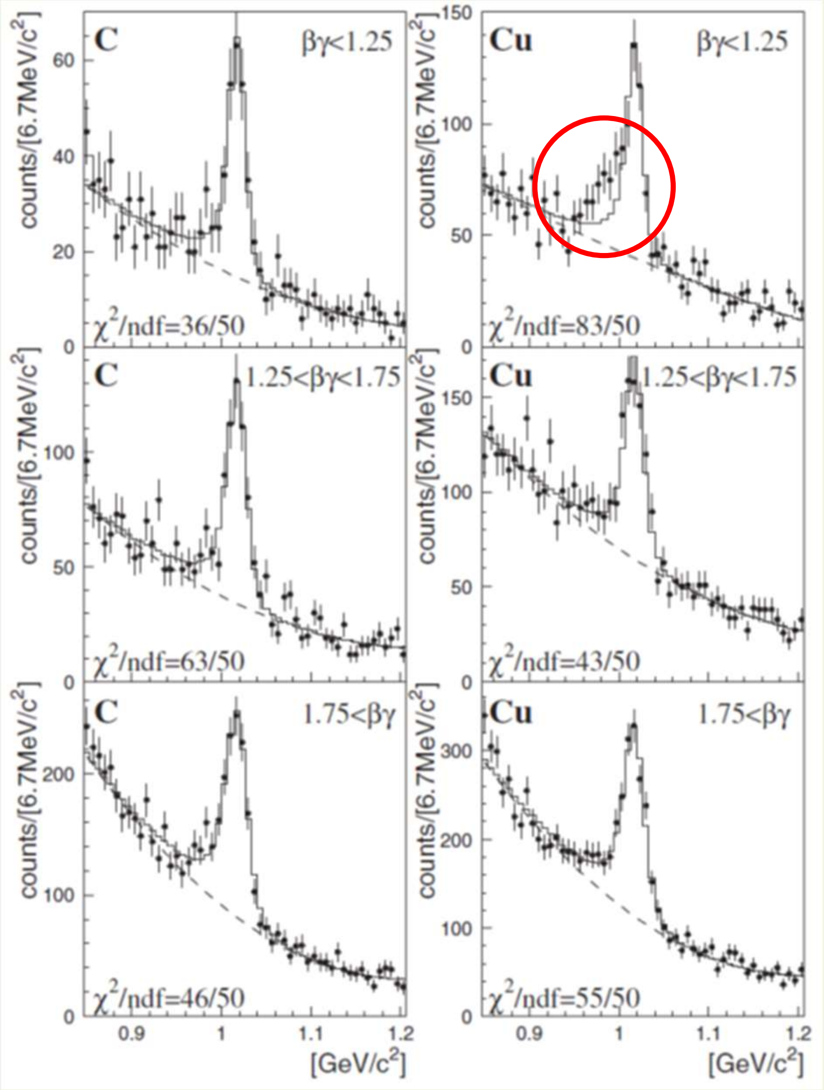
2.6 ± 1.5

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

slow φs

intermediate φs

fast φs

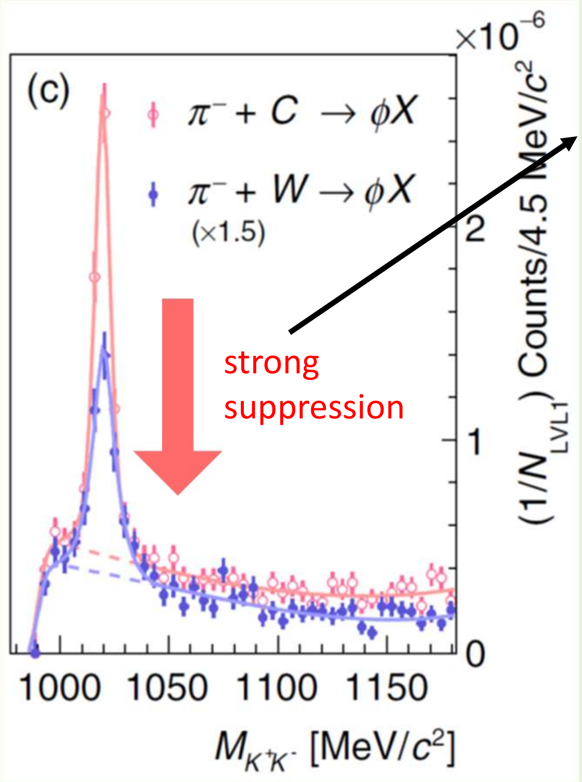


R. Muto et al. (E325 Collaboration), Phys. Rev. Lett. **98**, 042501 (2007).

More recent results

HADES: 1.7 GeV π^-A-reaction

K^+K^- - invariant mass spectrum



J. Adamczewski-Musch et al. (HADES Coll.),
Phys. Rev. Lett. **123**, 022002 (2019).

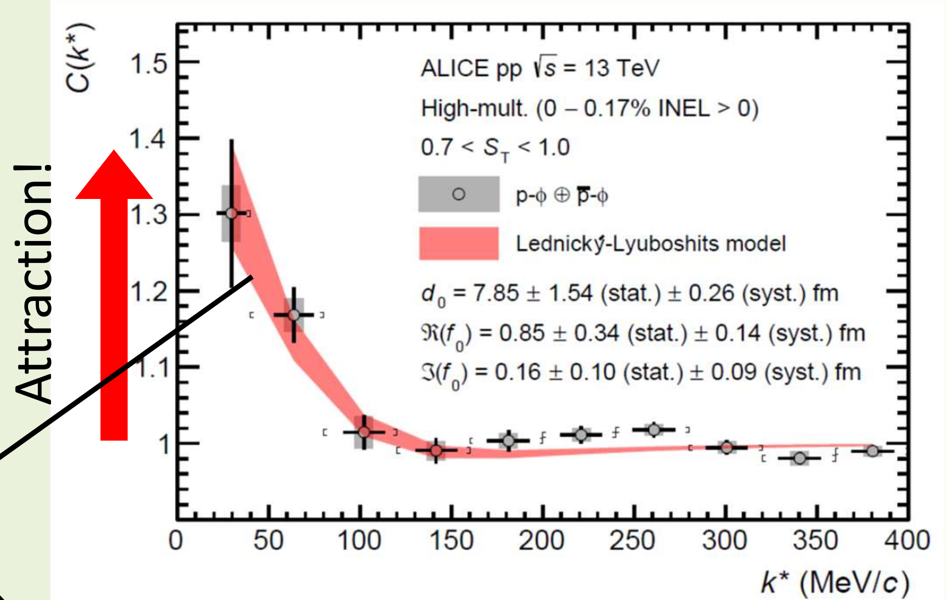
★ Broadening?

★ Consistent with attractive potential?

Negative mass shift ?

ALICE: pp

Measurement of φN correlation



S. Acharya et al. (ALICE Coll.),
Phys. Rev. Lett. **127**, 172301 (2021).

See also: Y. Lyu et al. (Lattice QCD, HAL QCD Collaboration),
Phys. Rev. D **106**, 074507 (2022).

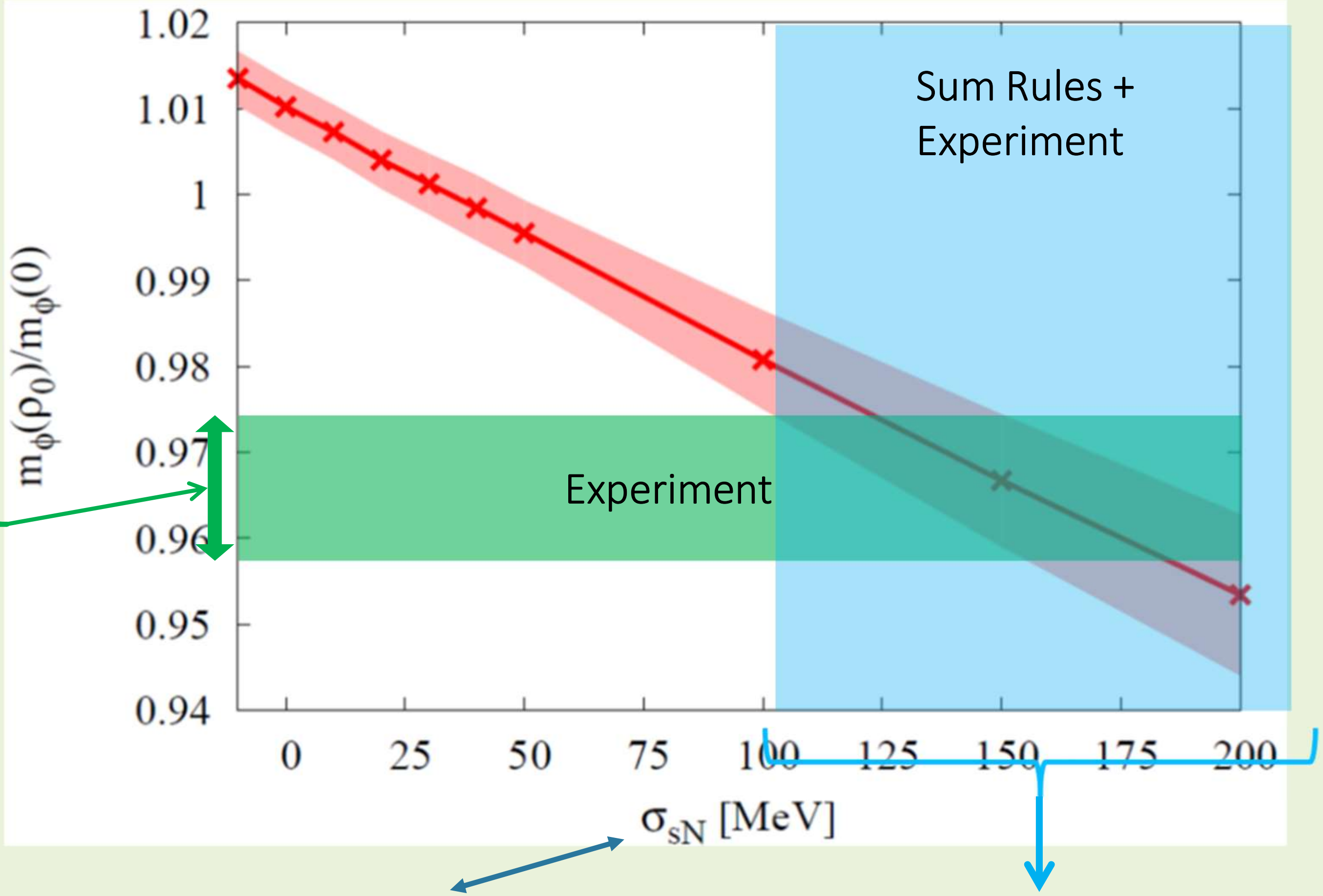
→ $a_0^{3/2} = 1.43(23)_{\text{stat.}}\left(^{+36}_{-06}\right)_{\text{syst.}}$ fm

φ meson **at rest** in nuclear matter

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

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

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

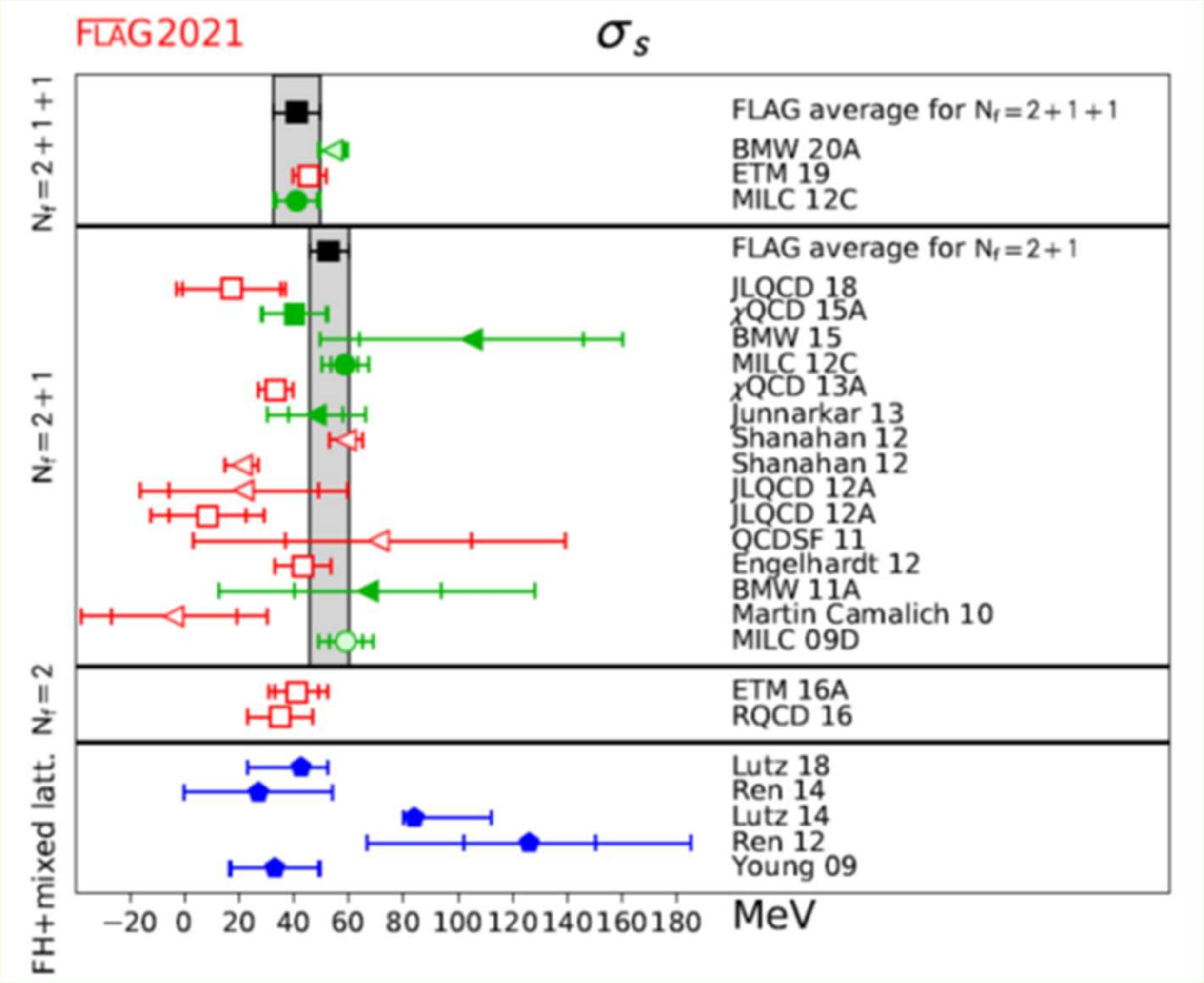


$$\sigma_{sN} = m_s \langle N | \bar{s}s | N \rangle$$

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

What does lattice QCD say about the strange sigma term?

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

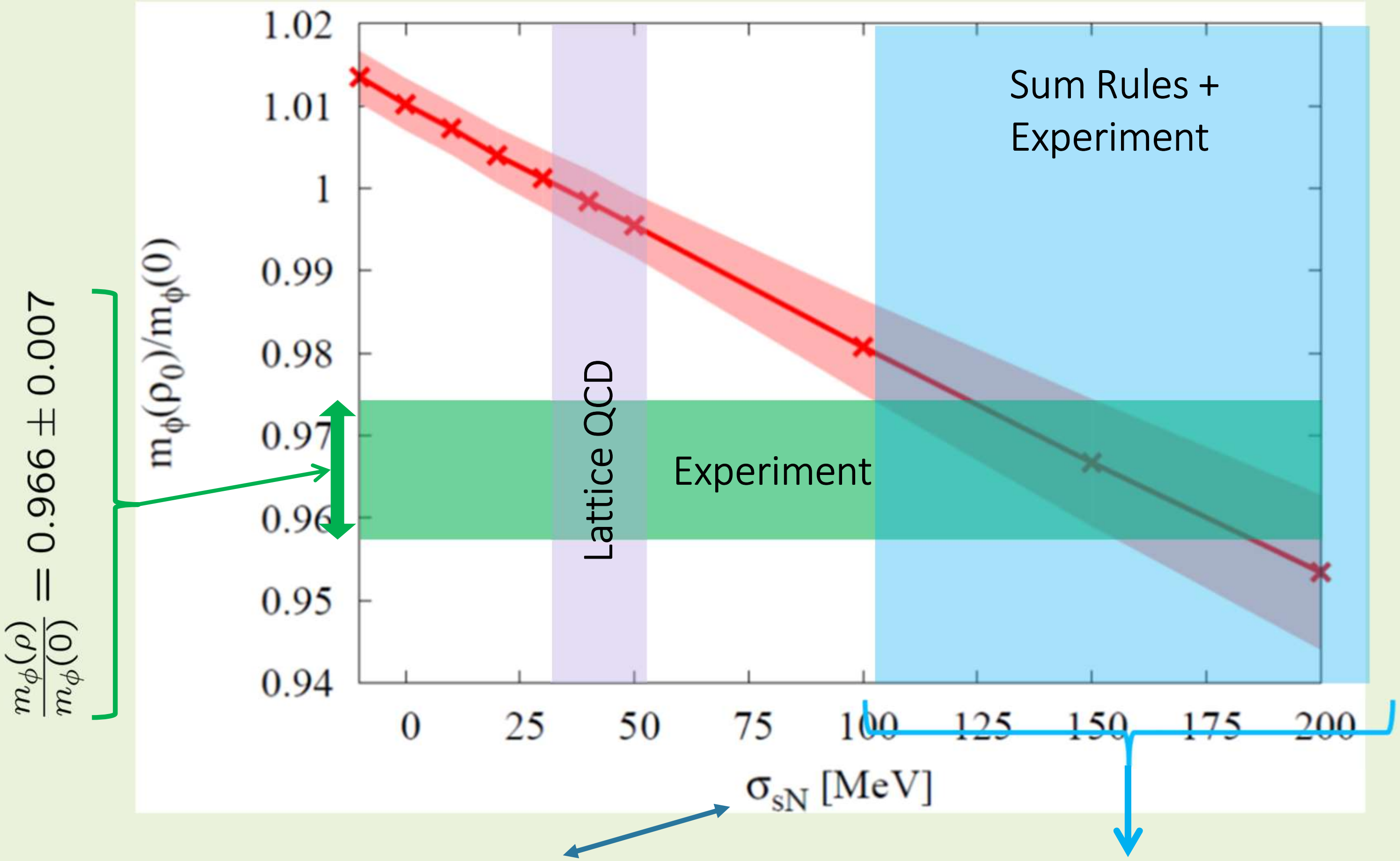


http://flag.unibe.ch/2021/

φ meson **at rest** in nuclear matter

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

Not consistent?



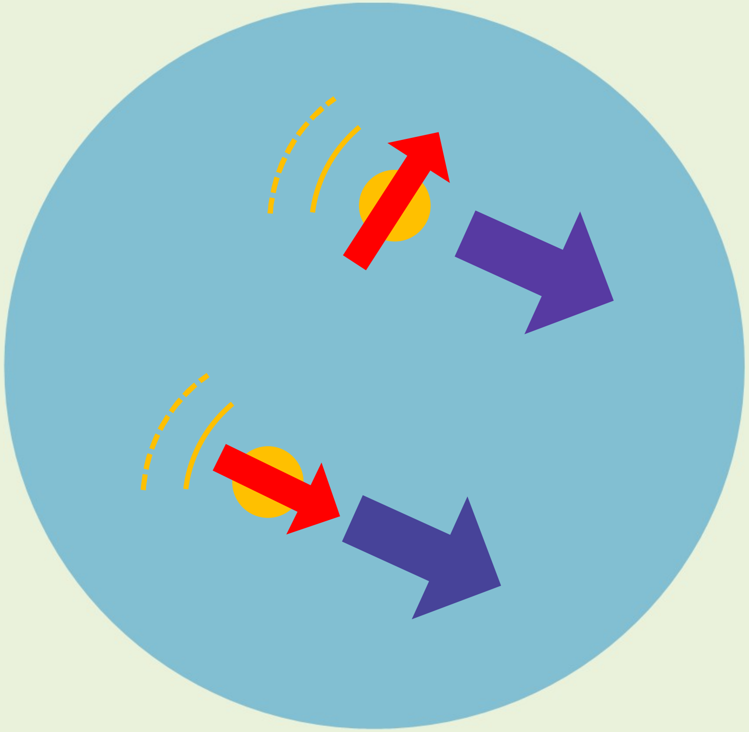
$$\frac{m_\phi(\rho)}{m_\phi(0)} = 0.966 \pm 0.007$$

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

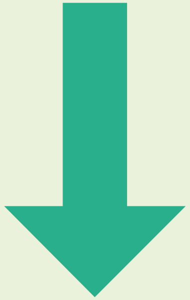
Measurement will be
repeated at the
J-PARC E16 experiment
(with 100 times
increased statistics!)

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

φ meson **moving** in nuclear matter



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



Broken
Lorentz symmetry

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

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

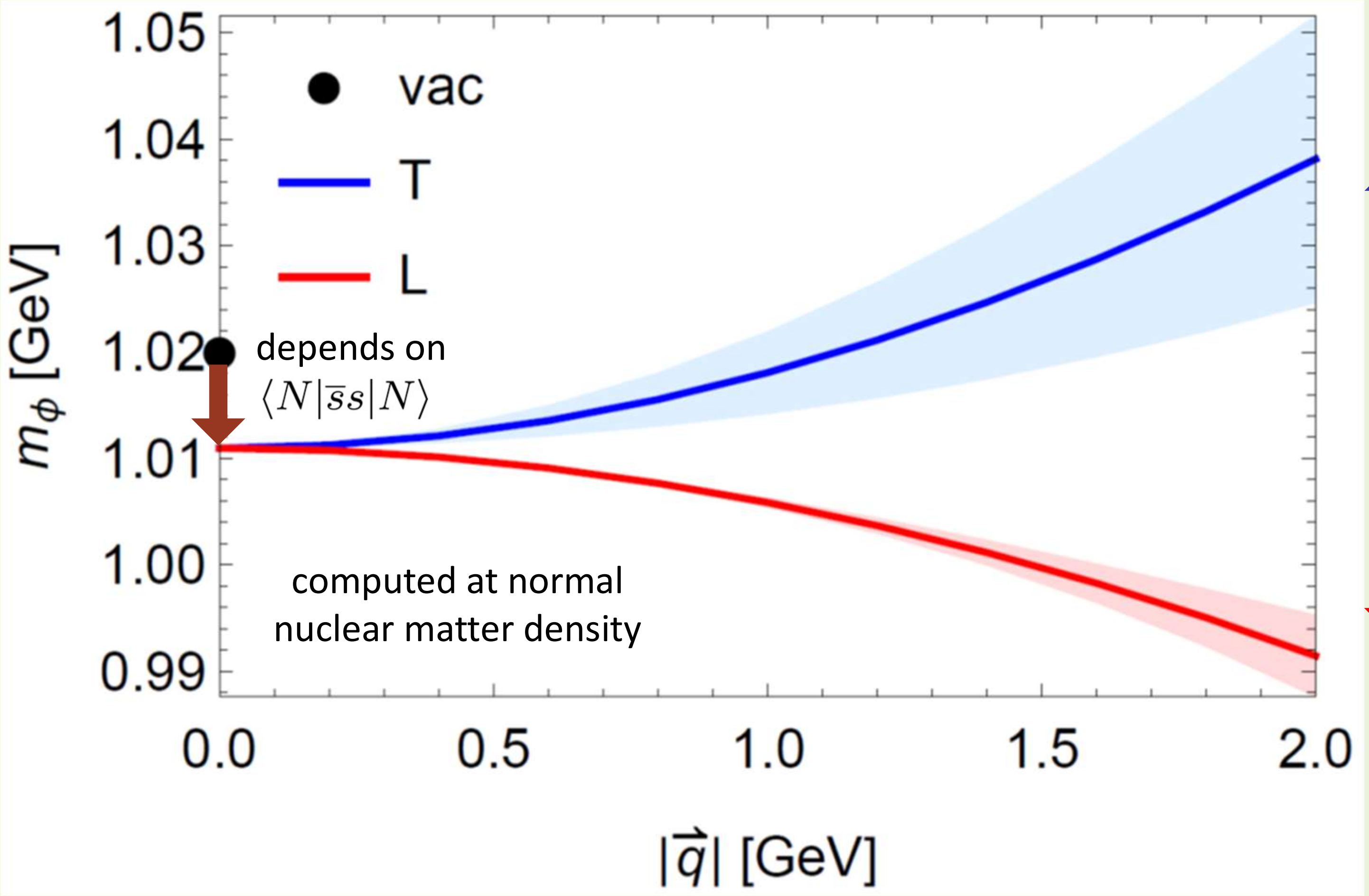
$$\frac{1}{\omega^2 - \vec{q}^{\,2} - m_{\phi,T}^2(\vec{q}^{\,2})}$$

transverse part

zero momentum

non-zero momentum $\vec{q}$

Results for the ϕ meson mass with non-zero momentum



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

computed at normal nuclear matter density

caused by

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

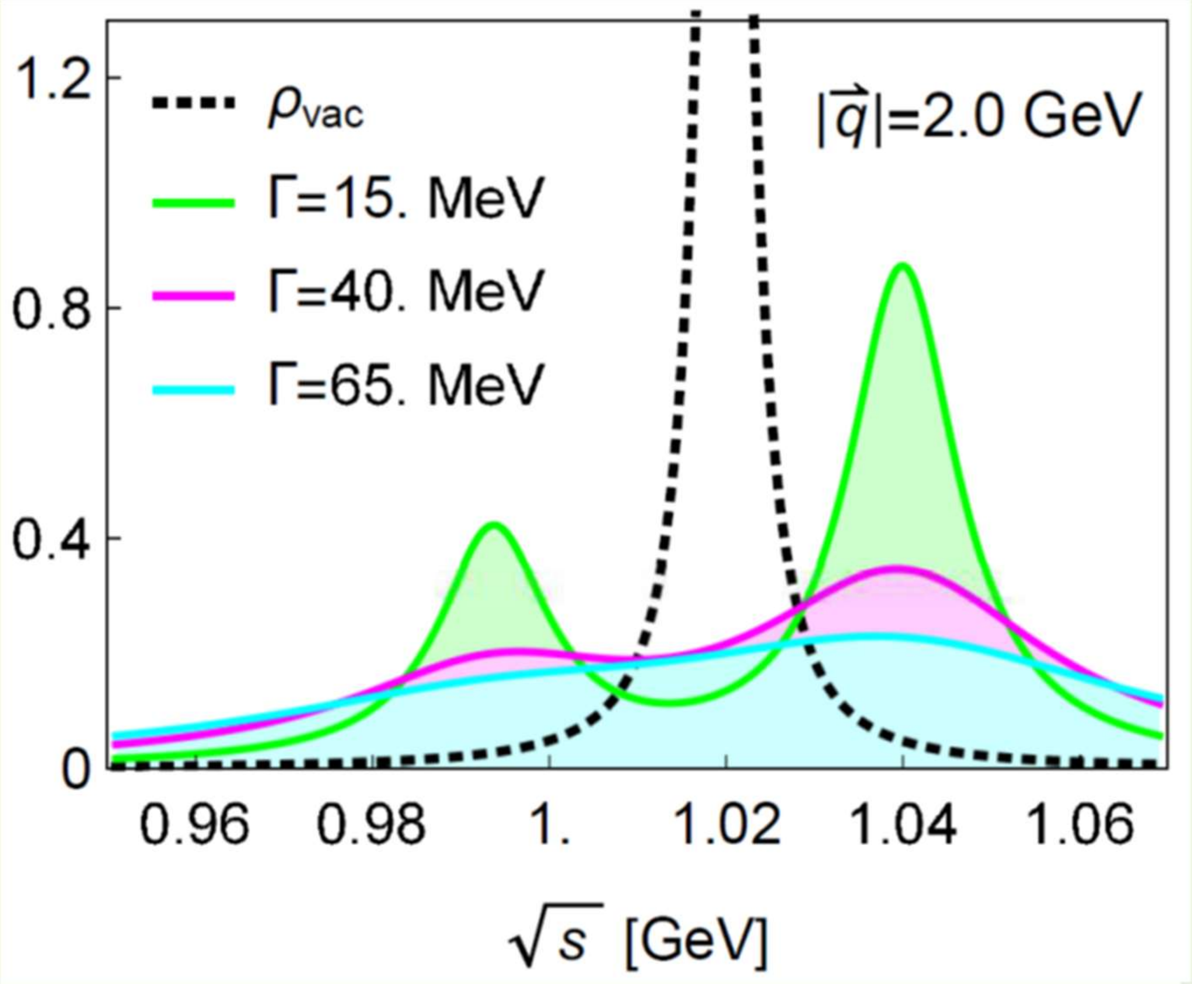
caused by

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

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

The angle-averaged di-lepton spectrum

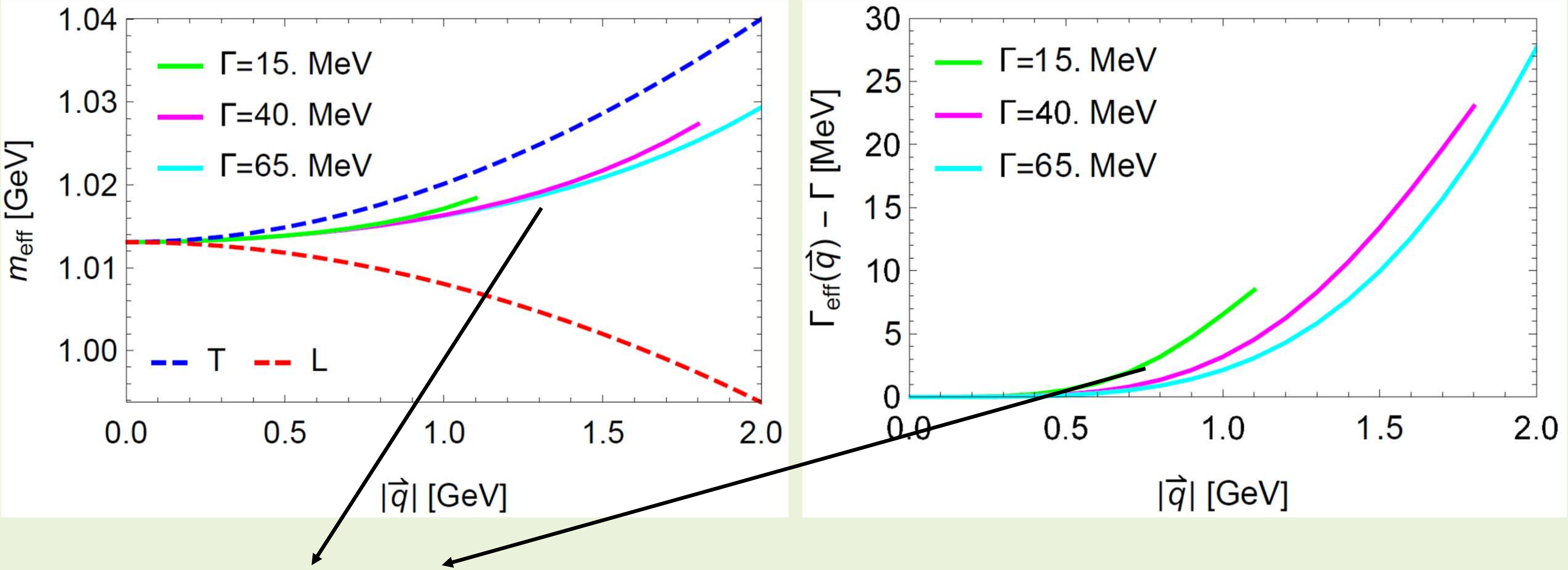
A double peak?



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

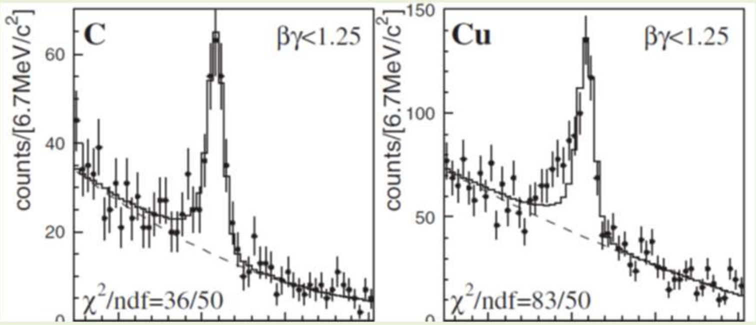
H.J. Kim and P. Gubler, Phys. Lett. B **805**, 135412 (2020).

How compare theory with experiment?

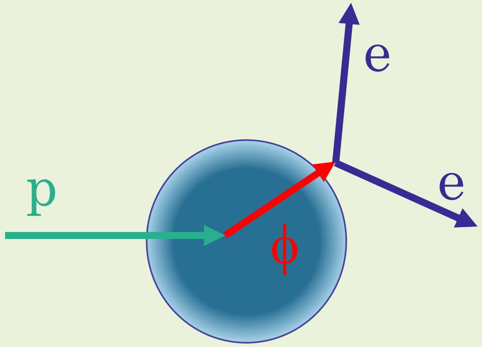
Information useful for theory

- Spectral function as a function of density
- Mass at normal nuclear matter density
- Decay width at normal nuclear matter density

Experimental data



Realistic simulation of pA reaction is needed!

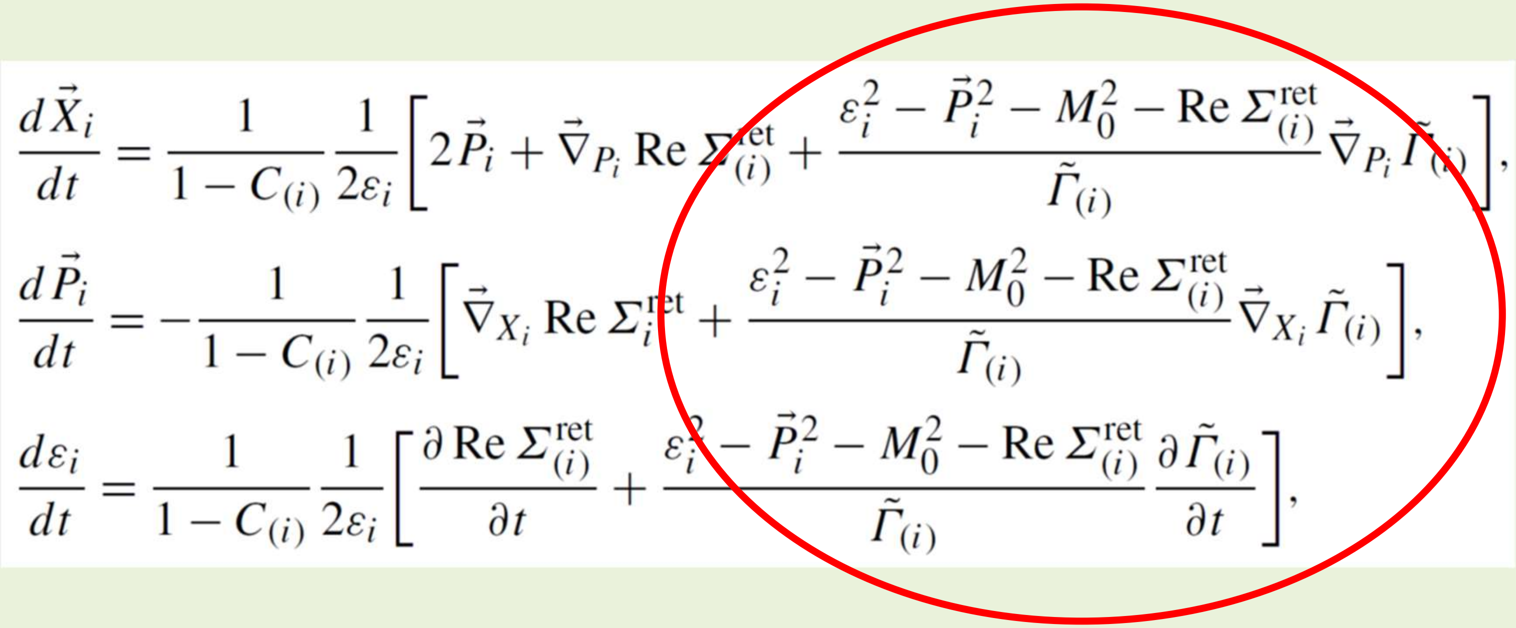


Our tool: a transport approach
PHSD (Parton Hadron String Dynamics)

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

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

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

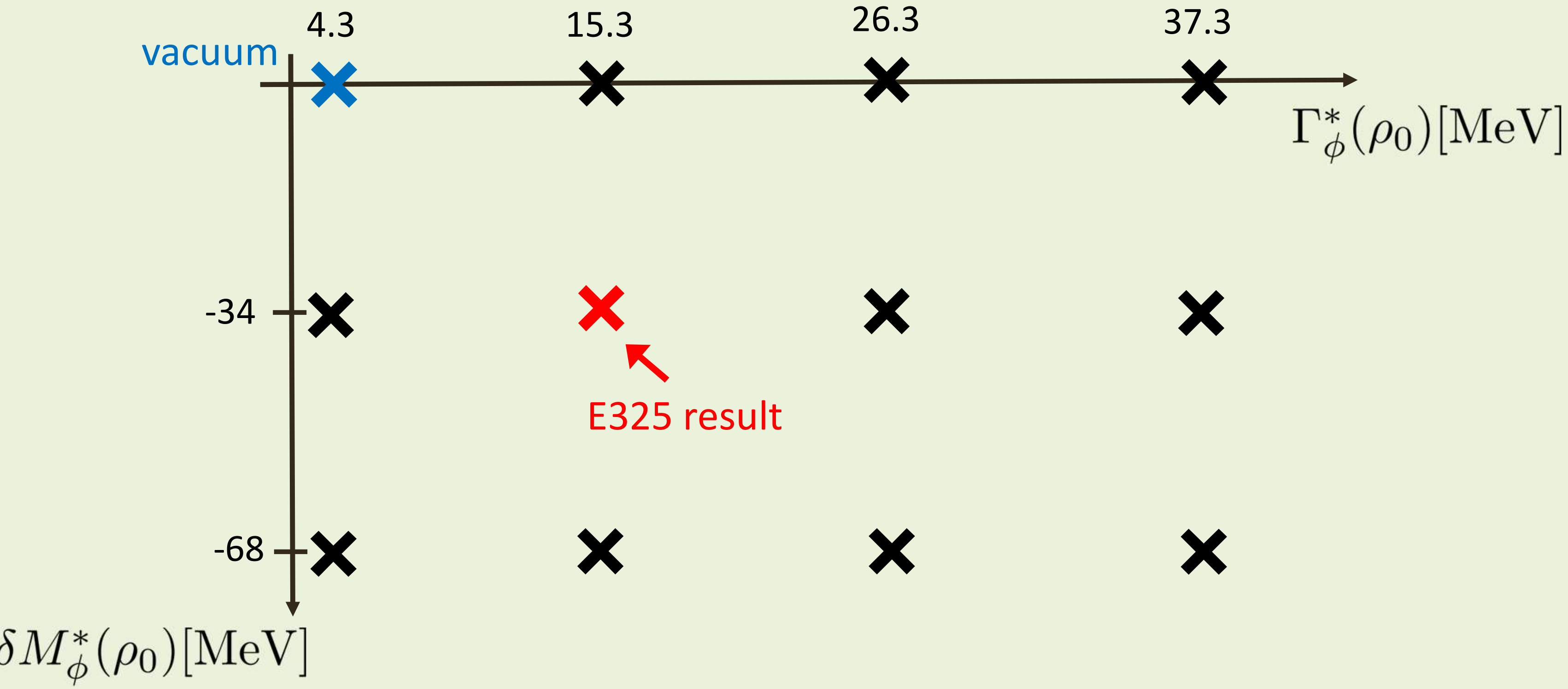
$$\frac{d\varepsilon_i}{dt} = \frac{1}{1-C_{(i)}}\frac{1}{2\varepsilon_i}\left[\frac{\partial\,\mathrm{Re}\,\Sigma^{\mathrm{ret}}_{(i)}}{\partial t} + \frac{\varepsilon_i^2 - \vec{P}_i^2 - M_0^2 - \mathrm{Re}\,\Sigma^{\mathrm{ret}}_{(i)}}{\tilde{\Gamma}_{(i)}}\frac{\partial\tilde{\Gamma}_{(i)}}{\partial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

Advantage: vector meson spectra can be chosen freely

Our choice: a Breit-Wigner with density dependent mass and width

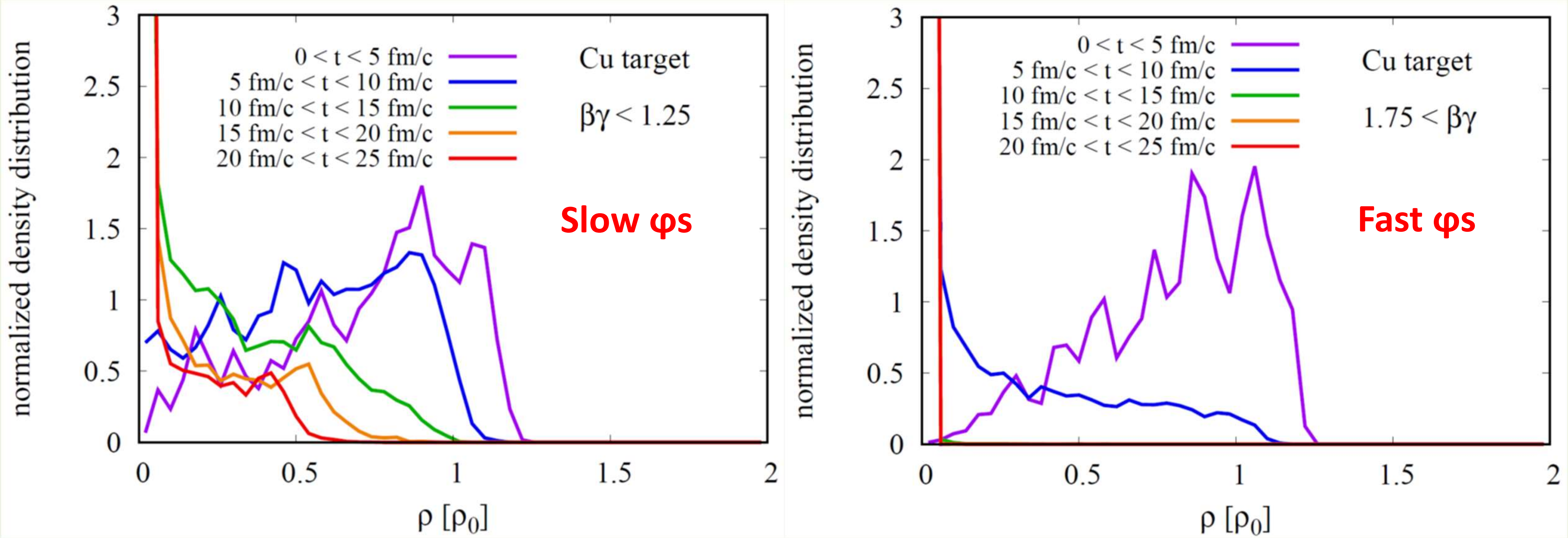
$$A_\phi(M,\rho) = C\,\frac{2}{\pi}\,\frac{M^2\Gamma^*_\phi(M,\rho)}{[M^2-M^{*2}_\phi(\rho)]^2+M^2\Gamma^{*2}_\phi(M,\rho)} \quad \text{with} \quad \begin{cases} M^*_\phi(\rho) = M^{\text{vac}}_\phi\left(1-\alpha^\phi\frac{\rho}{\rho_0}\right), \\ \Gamma^*_\phi(M,\rho) = \Gamma^{\text{vac}}_\phi + \alpha^\phi_{\text{coll}}\frac{\rho}{\rho_0} \end{cases}$$

Simulated scenarios:



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

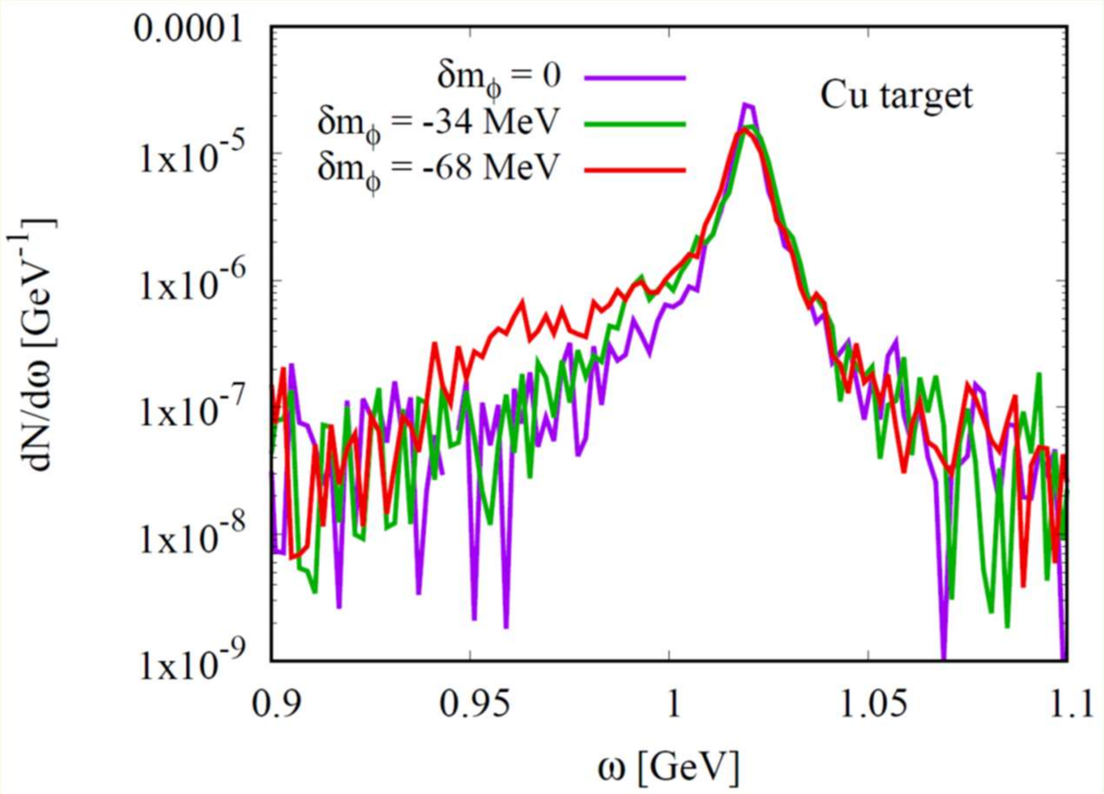
Preliminary



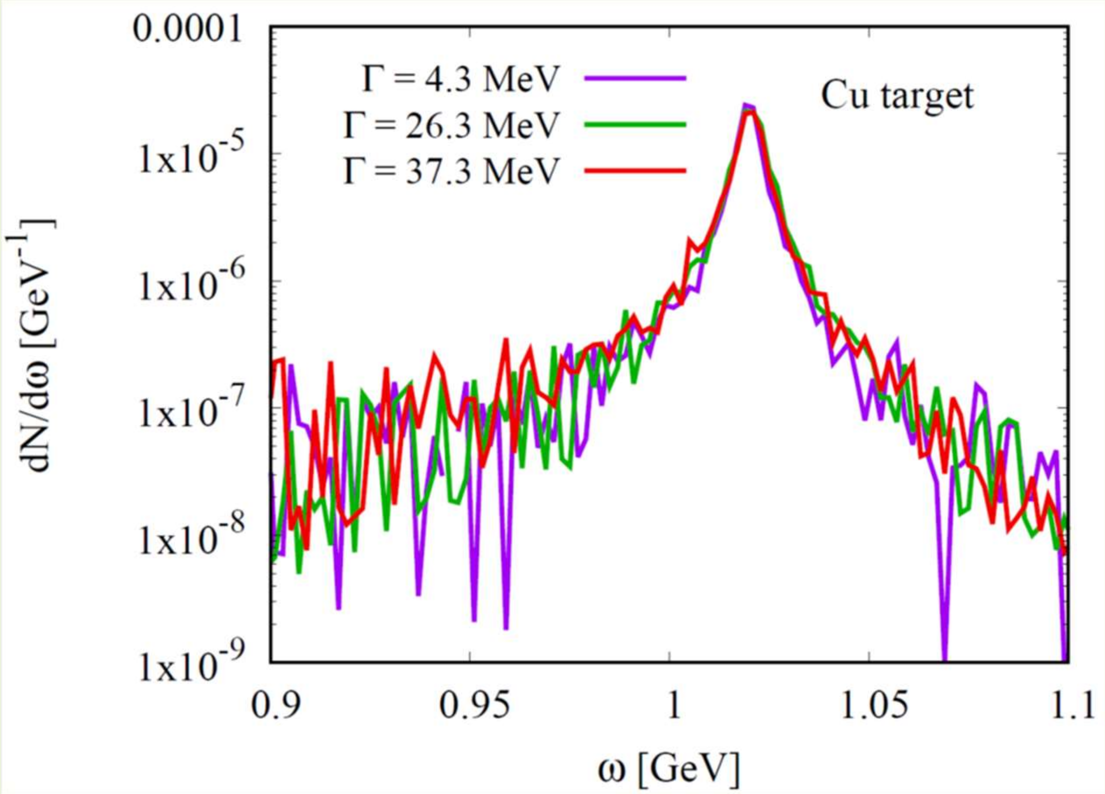
Dilepton spectrum generated by φ mesons

Preliminary

Increasing mass shifts



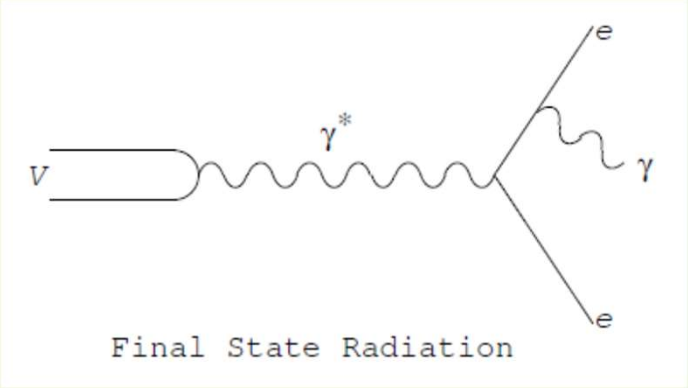
Increasing broadening

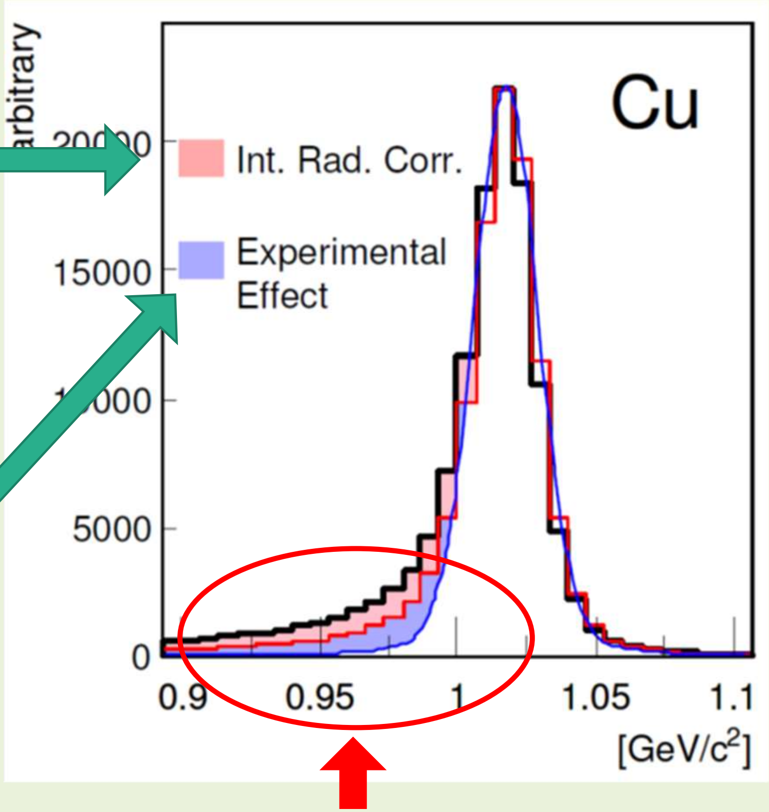


→ large sensitivity on mass shift!

→ low sensitivity on broadening!

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





Rescattering effects

(multiple scattering, energy loss)

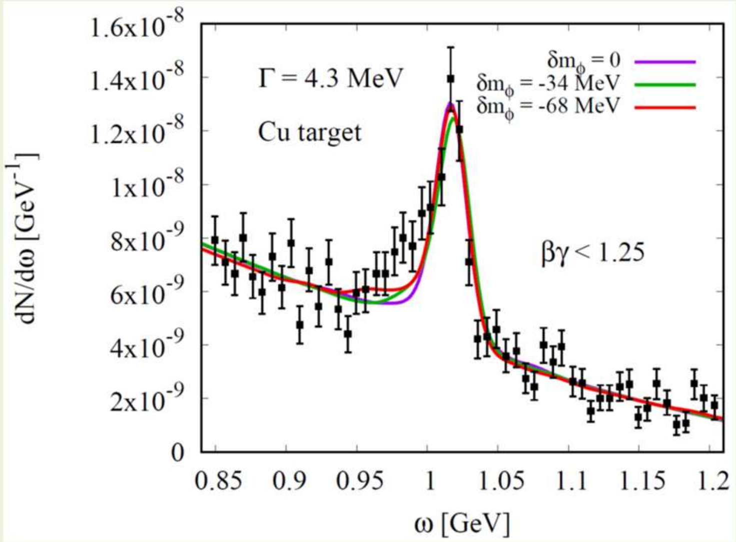
Similar to the shape expected for a negative mass shift

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

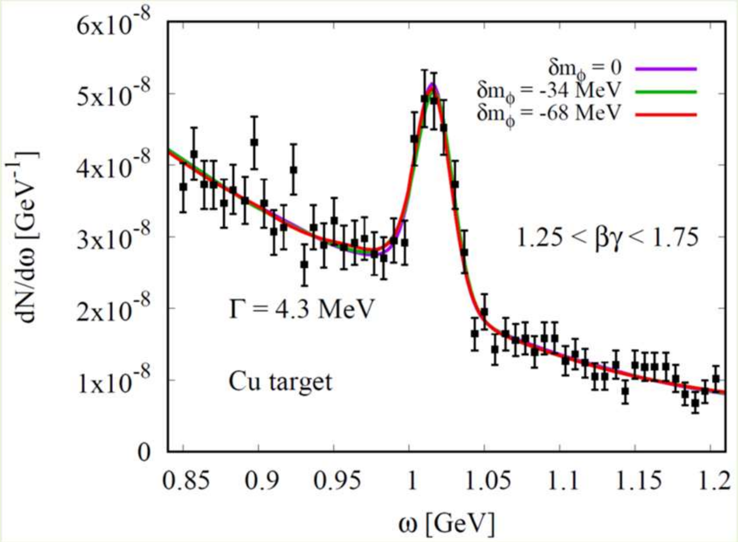
Fit to experimental Copper target data (E325)

(including elemag. and rescattering effects)

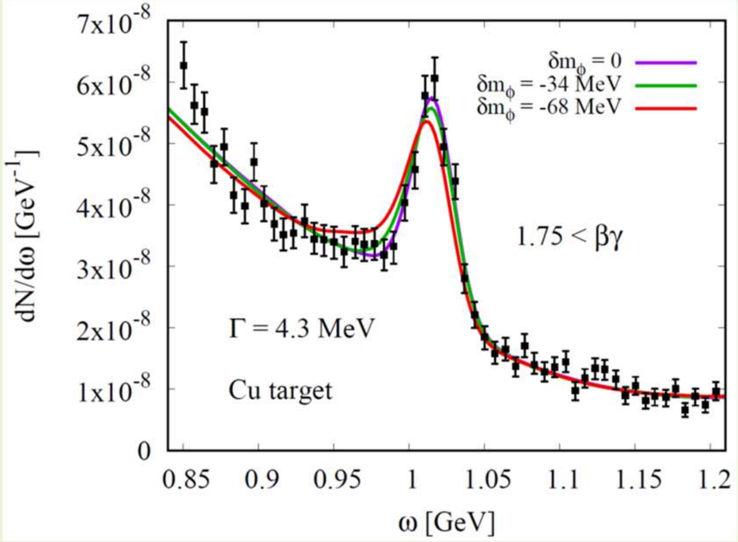
Preliminary



slow φs



intermediate φs



fast φs

Favors negative mass shift

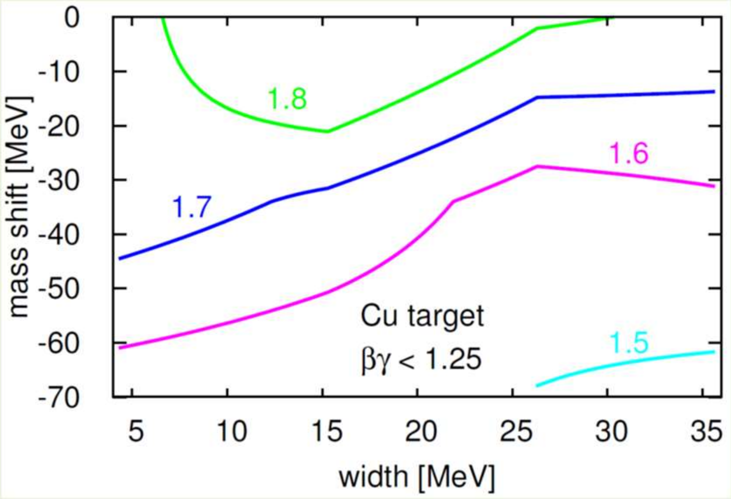
Favors no mass shift

Need momentum dependent mass shift??

Fit to experimental Copper target data (E325)

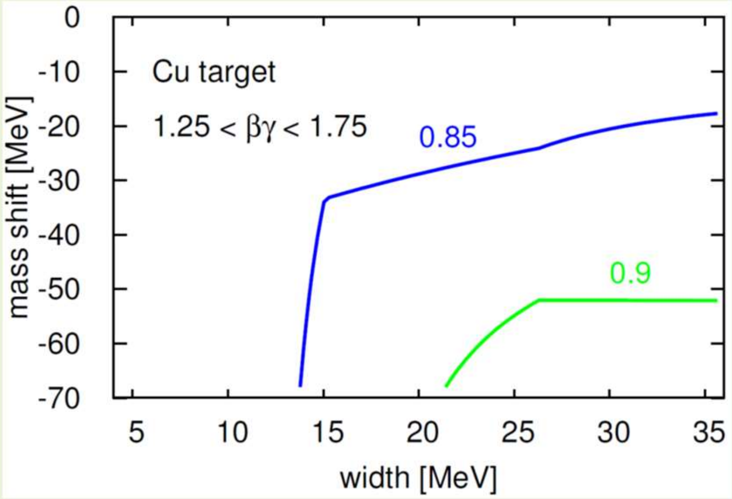
$(\chi^2/\mathrm{d.o.f.}$ values)

Preliminary

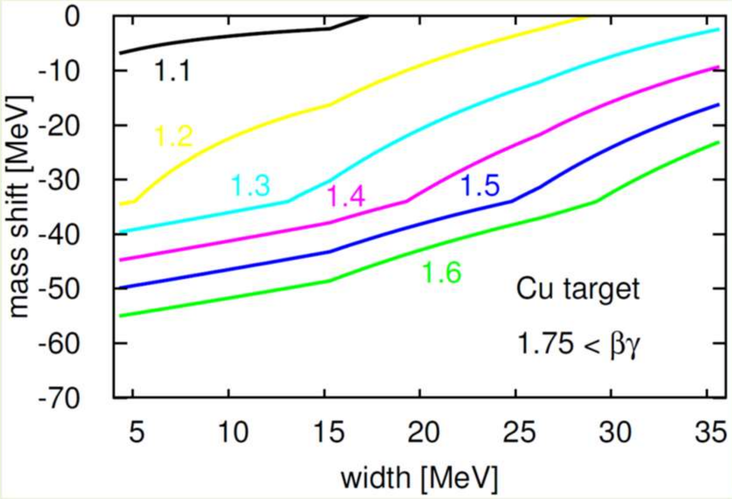


slow φs

Favors negative mass shift



intermediate φs



fast φs

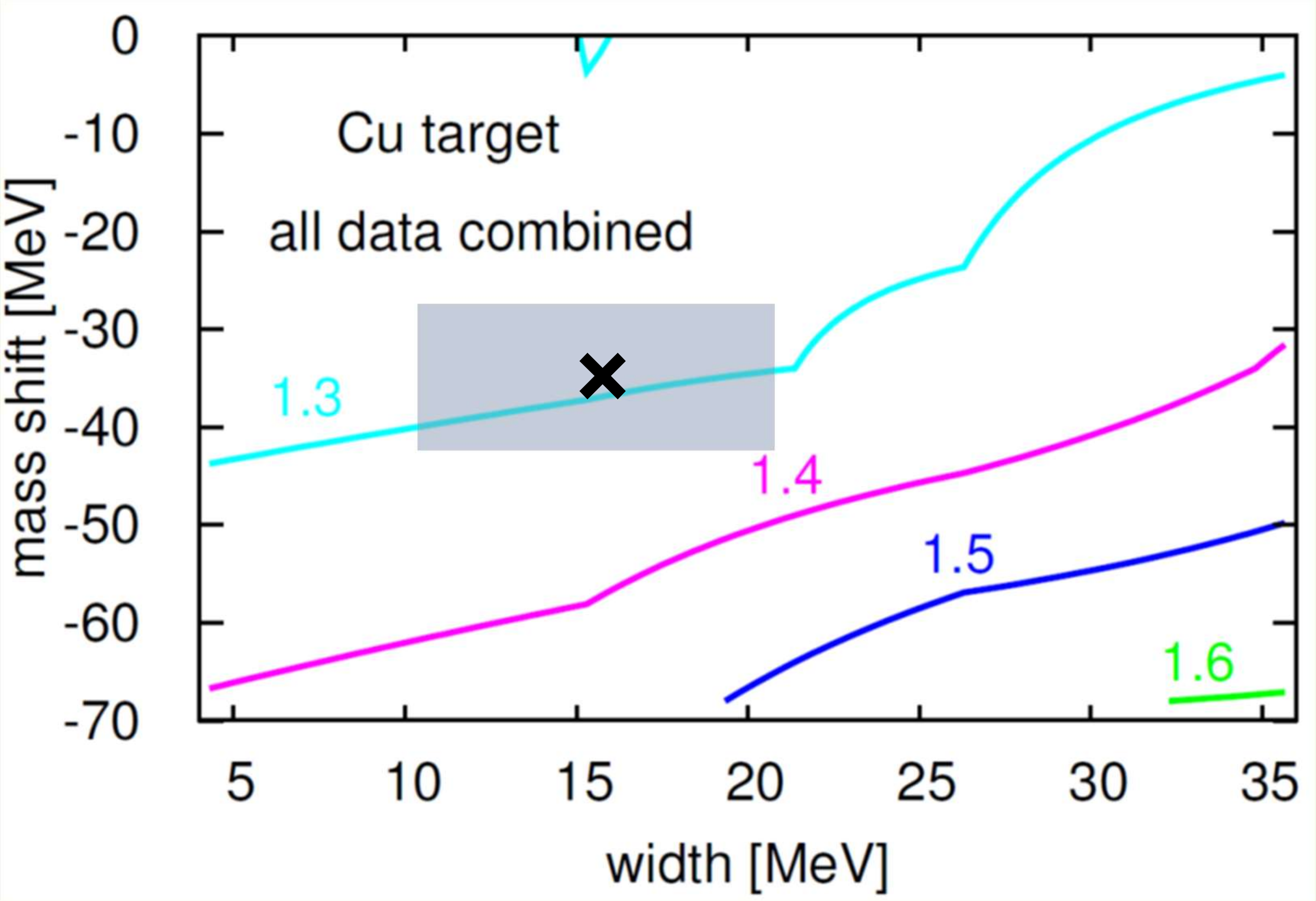
Favors no mass shift

Need momentum dependent mass shift??

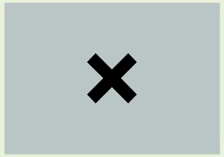
Fit to experimental Copper target data (E325)

(all βγ-bins combined)

Preliminary



Conclusion of the E325 Collaboration

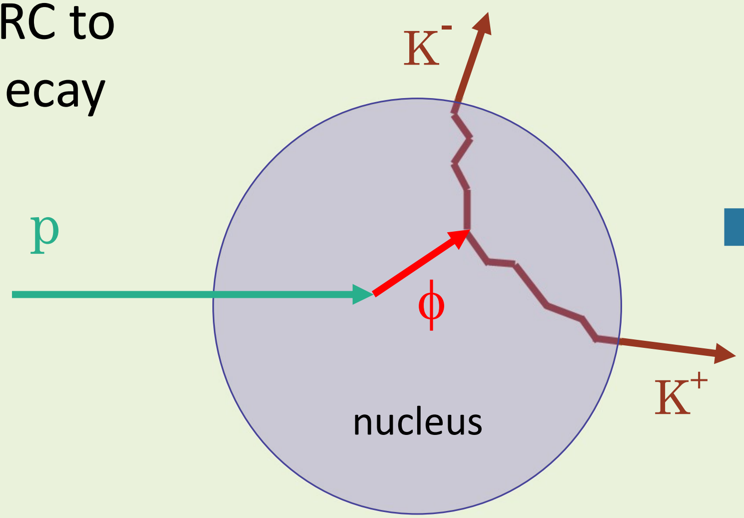


Outlook

- ★ A lot of new experimental information about the φN interaction is becoming available (LHC, J-PARC, HADES)

→ Many opportunities for theorists !

- ★ New proposal at J-PARC to measure the $K^+ + K^-$ decay



→ **Accurate information about the KN interaction will be essential**

↓

Can be done using the recently updated PHSD code

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

Summary and Conclusions

★ Relating modification of QCD condensates with hadron properties in nuclear matter is a non-trivial multi-step process

QCD condensates ⟷ Hadronic spectrum ⟷ Experimental data

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

$\sigma_{sN} < 35$ MeV ↗ Increasing φ meson mass in nuclear matter

$\sigma_{sN} > 35$ MeV ↘ Decreasing φ meson mass in nuclear matter

★ For studying the modification of the φ meson spectral function experimentally at finite density, a good understanding of the underlying reactions is needed

★ We conducted numerical simulations of the pA reactions measured at the E325 experiment at KEK, using the PHSD transport code

→ The E325 data are consistent with a wide range of mass shift and broadening scenarios

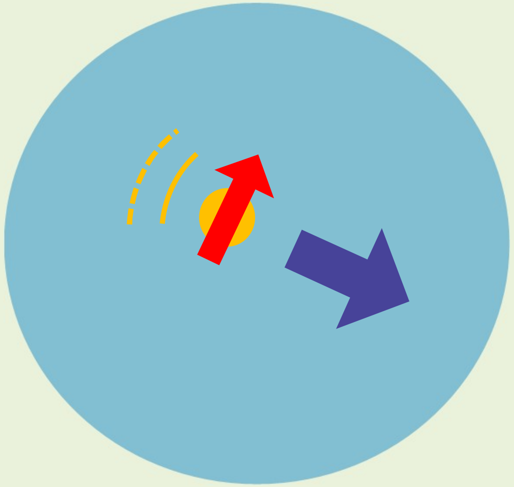
Backup slides

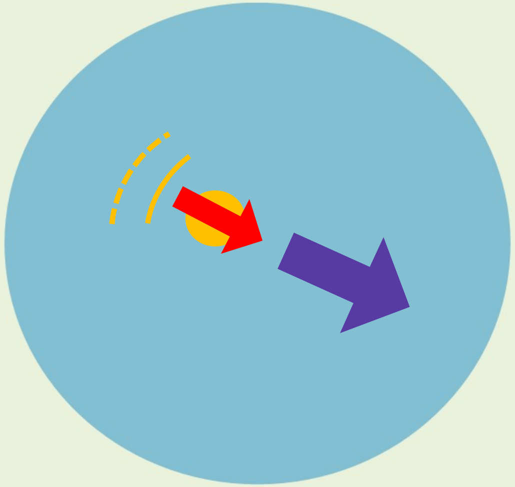
The non-zero momentum case:
Disentangling longitudinal and transverse components

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

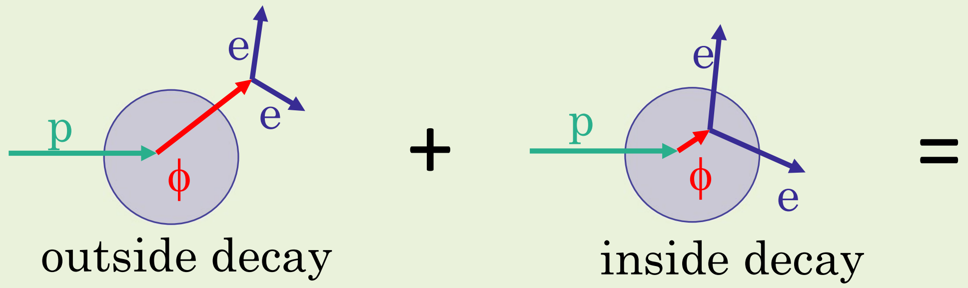
$$\Pi_L(\omega^2, \vec{q}^{\,2}) = \tfrac{1}{\vec{q}^{\,2}}\Pi_{00}$$

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

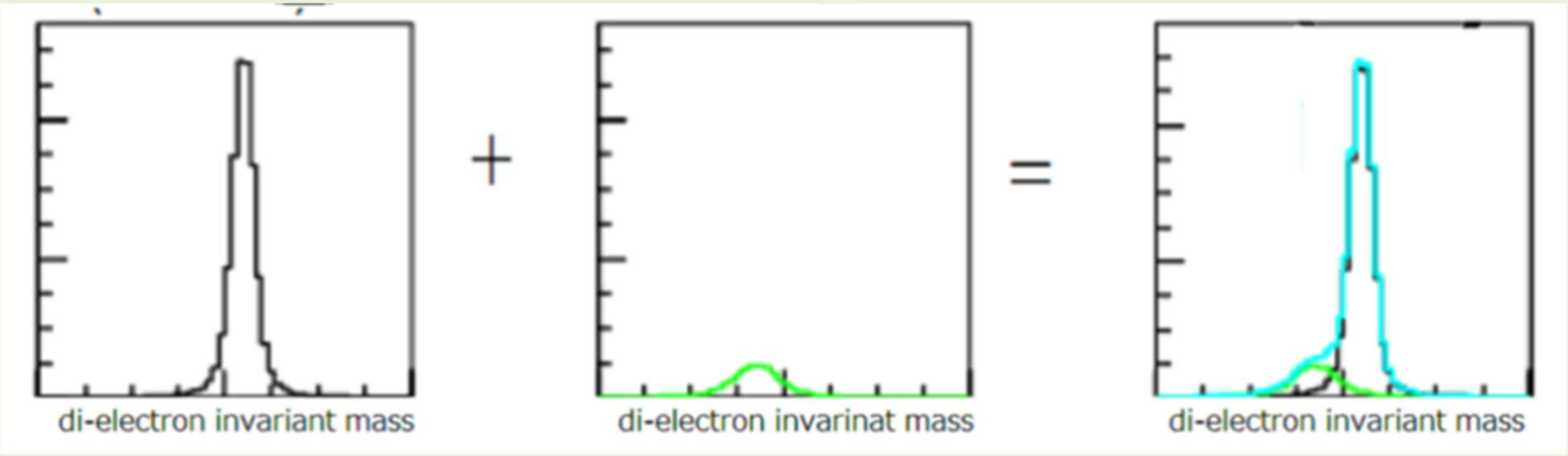




Experimental di-lepton spectrum

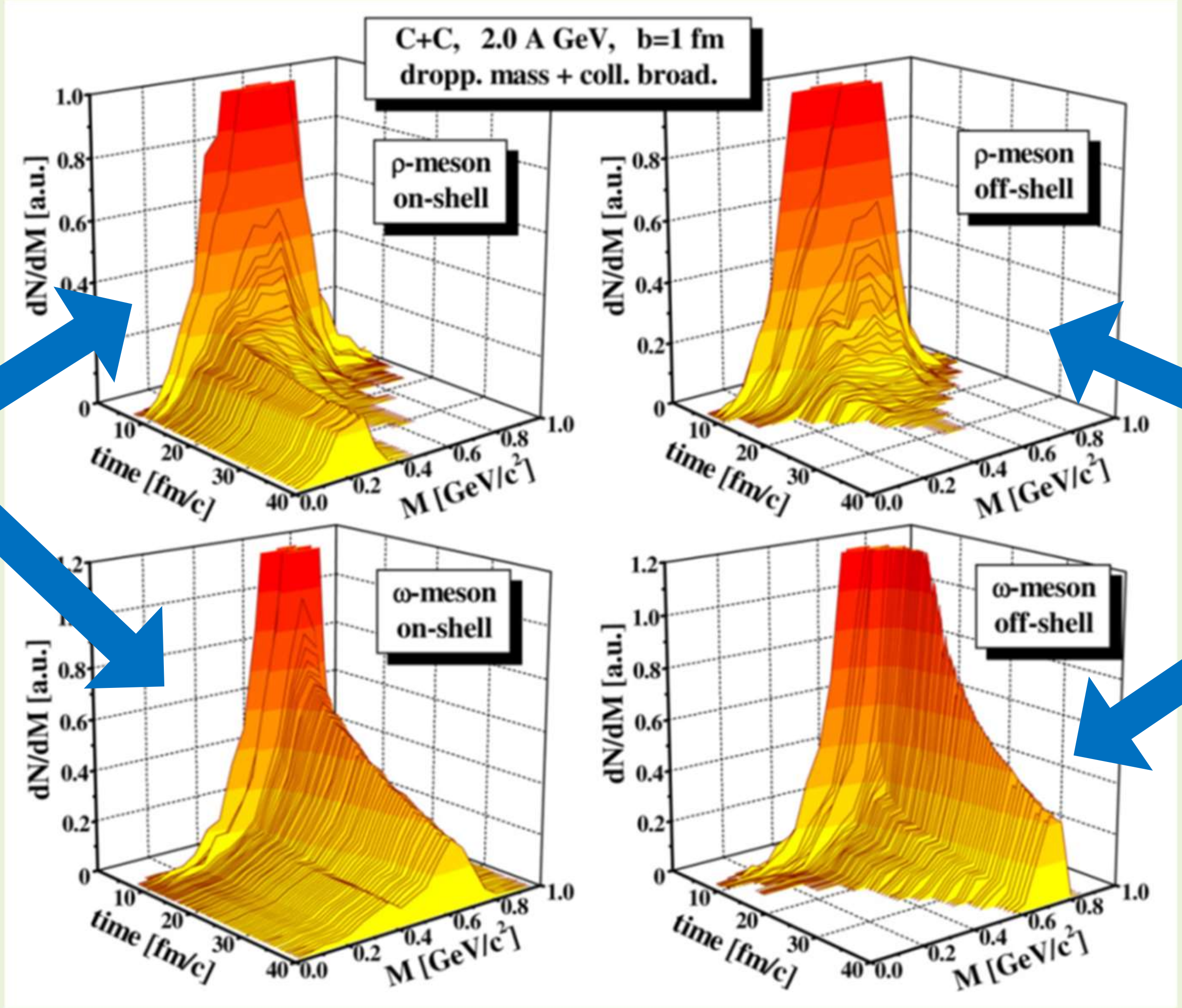


Experimentally
observed spectrum



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

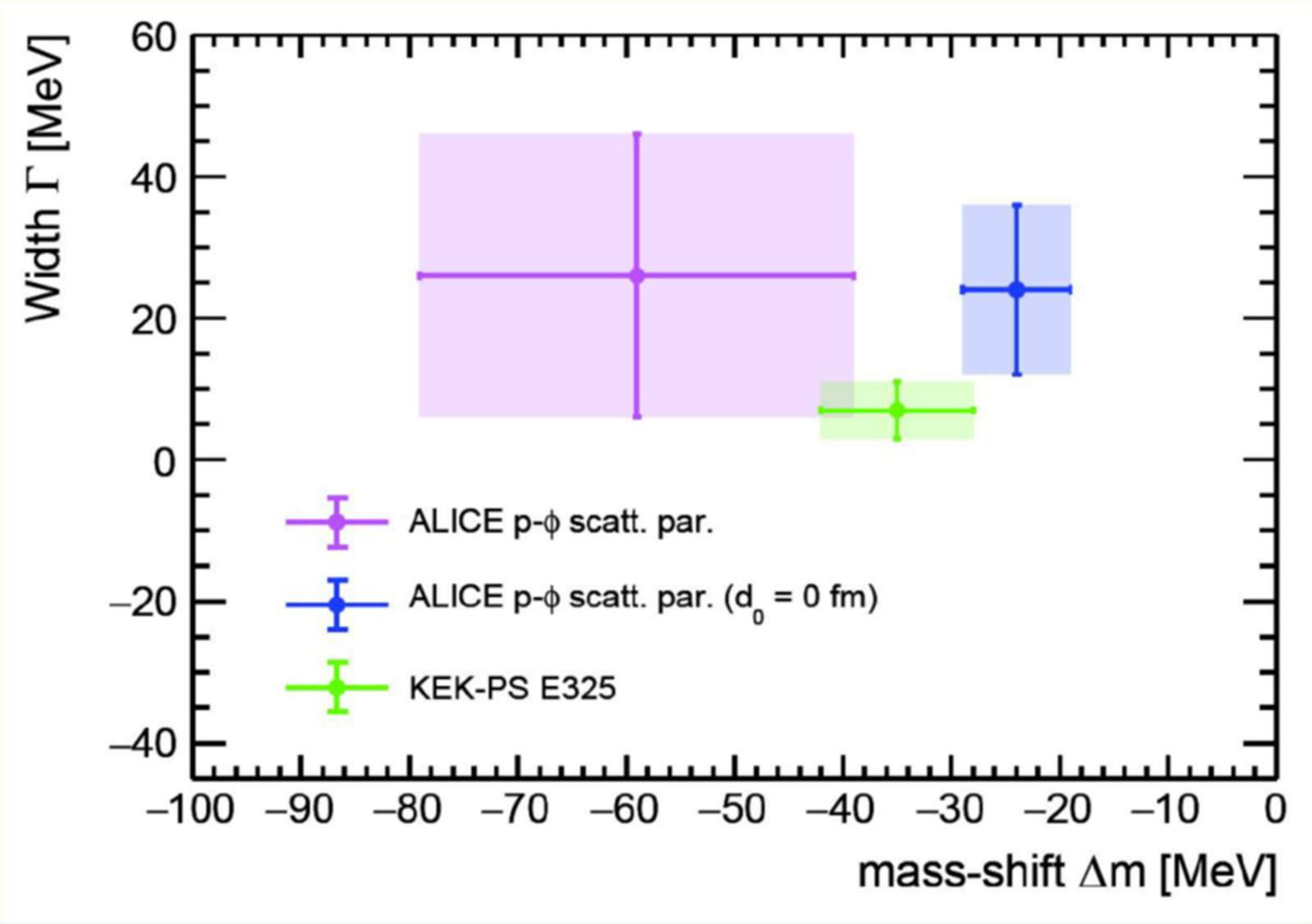
Taken from: E.L. Bratkovskaya and W. Cassing, Nucl. Phys. A **807**, 214 (2008).

Relation between optical potential and scattering length

$$U(r) \approx \frac{1}{2m}\, 4\pi\rho\, \frac{b}{1+b/d_0} \approx \frac{1}{2m}\, 4\pi\rho\, b$$

$$b = f_0 \left(1 + \frac{m_\phi}{m_{proton}}\right)$$

scattering length

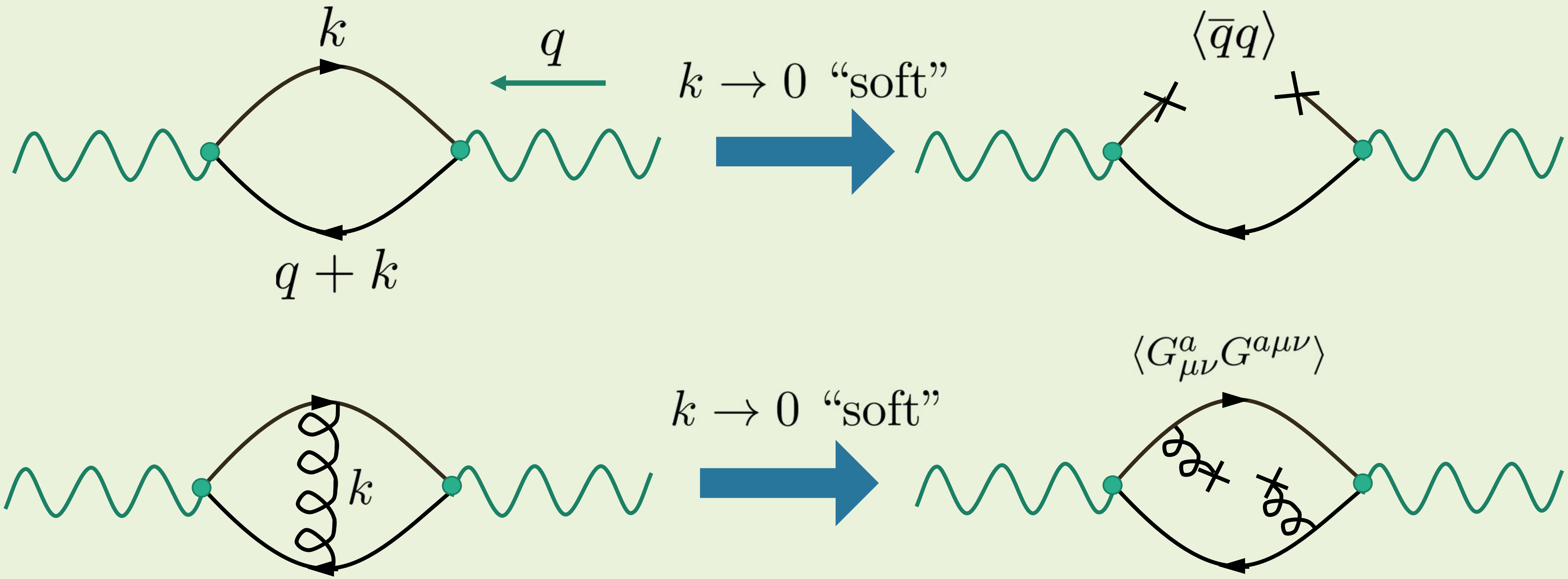


Information provided by the TUM/ALICE group

More on the operator product expansion (OPE)

Perturbative part

Non-perturbative (condensate) part

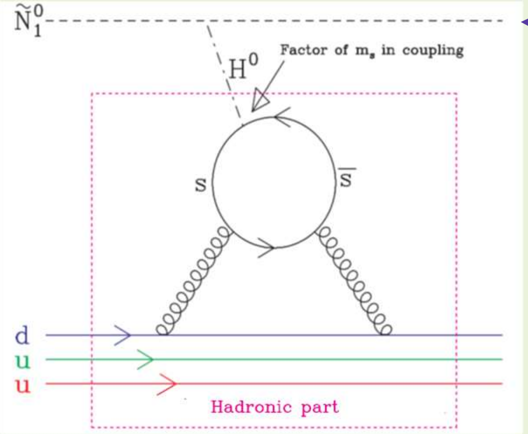


All intermediate four-momenta are in the perturbative ("hard") regime

"Soft", non-perturbative contributions are treated as condensates

The strangeness content of the nucleon: $\sigma_{sN} = m_s \langle N|\bar{s}s|N\rangle$

Important parameter for dark-matter searches!



Neutralino:
Linear superposition of the Super-partners of the Higgs, the photon and the Z-boson

Adapted from:
W. Freeman and D. Toussaint (MILC Collaboration), Phys. Rev. D **88**, 054503 (2013).

$$\sigma^{(\text{nucleon})}_{\text{scalar}} = \frac{8G_F^2}{\pi} M_Z^2 m_{\text{red}}^2 \left[\frac{F_h I_h}{m_h^2} + \frac{F_H I_H}{m_H^2}\frac{M_Z}{2}\sum_q \langle N|\bar{q}q|N\rangle \sum_i P_{\tilde{q}_i}\left(A_{\tilde{q}_i}^2 - B_{\tilde{q}_i}^2\right)\right]^2$$

most important contribution

$$I_{h,H} = k^{h,H}_{u-\text{type}} g_u + \boxed{k^{h,H}_{d-\text{type}} g_d}$$

dominates

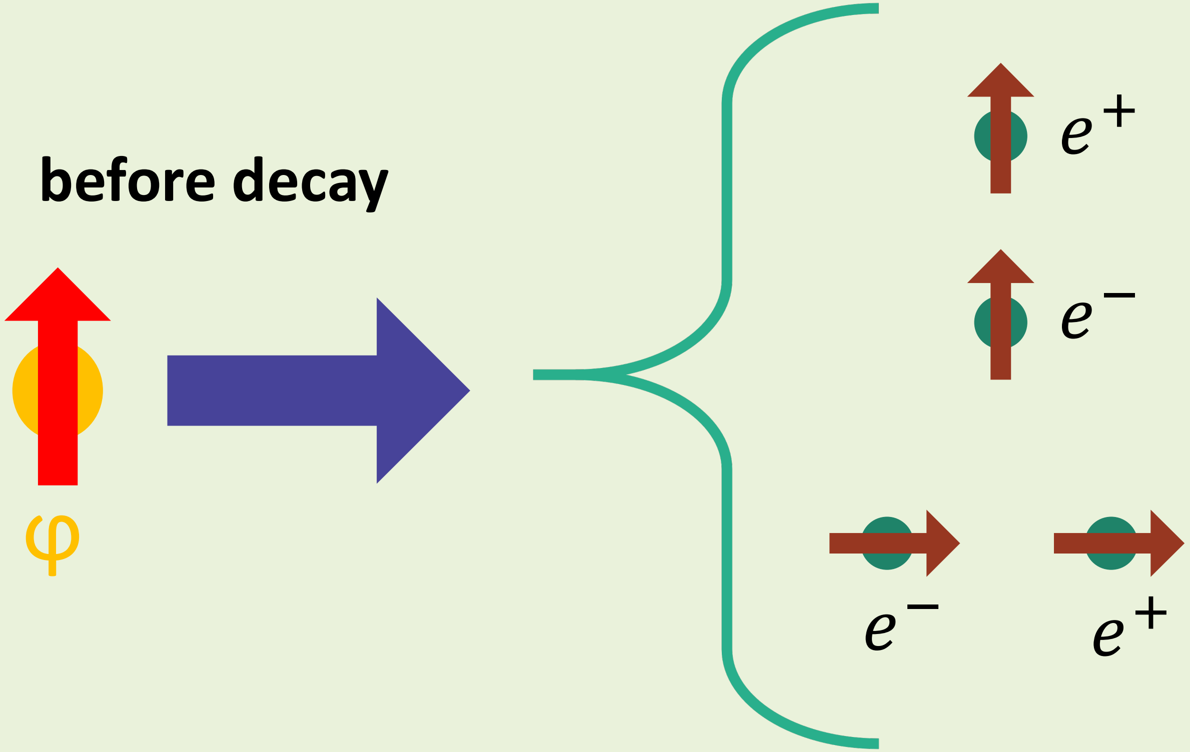
$$g_d = \frac{2}{27}\left(m_N + \frac{23}{4}\sigma_{\pi N} + \frac{25}{2}\sigma_{sN}\right)$$

A. Bottino, F. Donato, N. Fornengo and S. Scopel, Asropart. Phys. **18**, 205 (2002).

A simple example of dilepton decay of a longitudinally polarized φ

before decay

after decay



decay perpendicular to
the φ meson momentum:
allowed

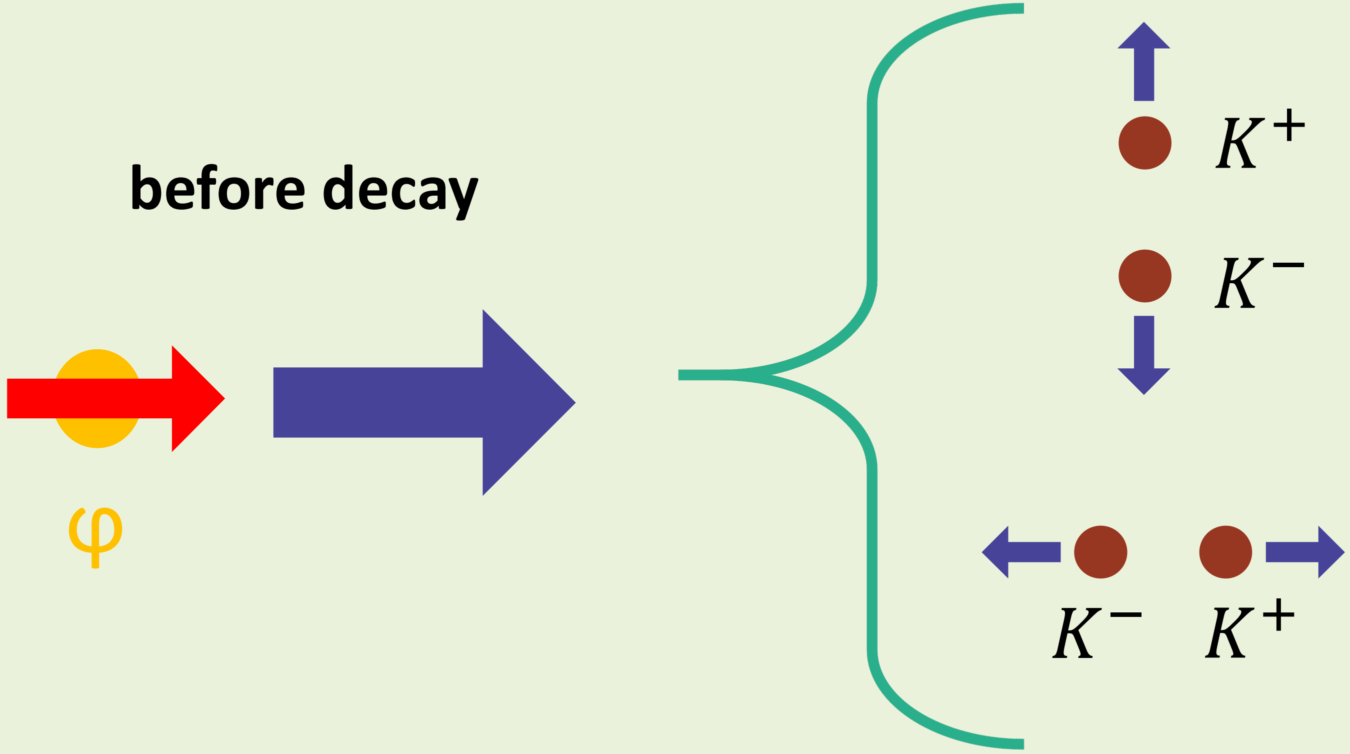
decay parallel to the
φ meson momentum:
not allowed

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

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

before decay

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



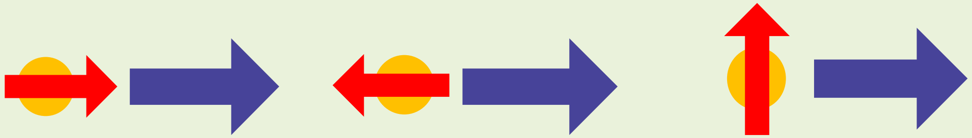
after decay

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

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

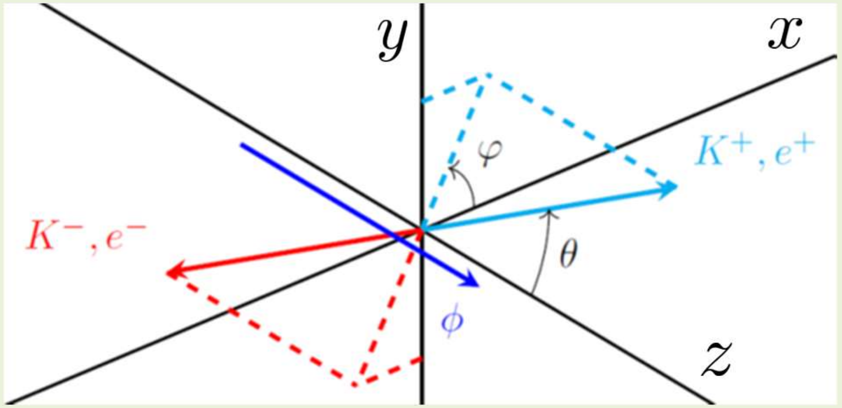
measurement in this direction can be used to observe purely longitudinal mode

Full angular distribution of dilepton decay



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

Longitudinal polarization



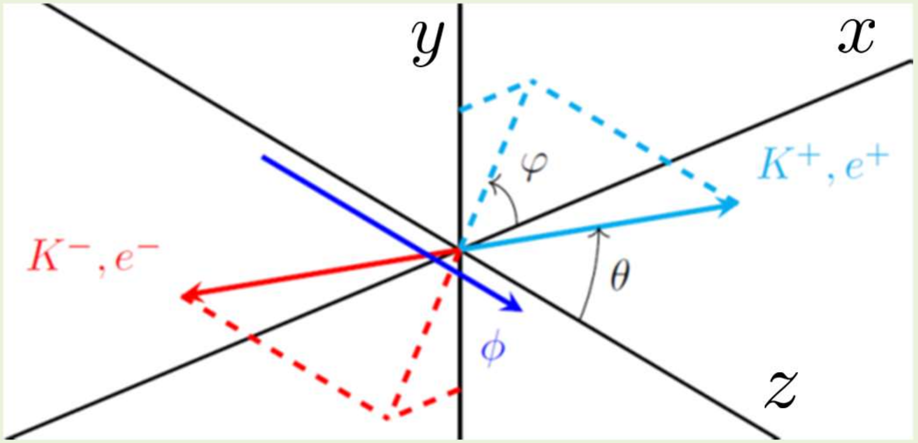
θ: polar angle

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

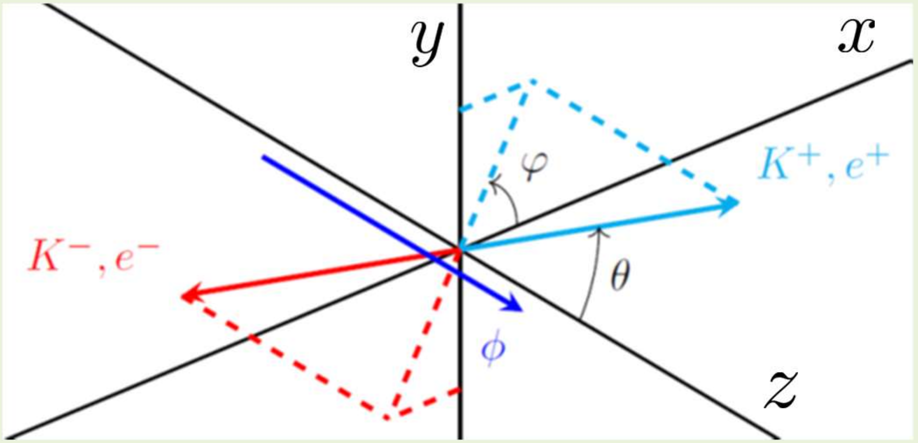
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\Omega} = \frac{3}{16\pi}\left[1 + \cos^2\theta + \rho_{00}(1 - 3\cos^2\theta) + \dots\right]$$

ϕ-dependent terms

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

Unpolarized case: vanishing θ-dependence

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



θ: polar angle
ϕ: azimuthal angle

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

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

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

ϕ-dependent terms