Phi meson properties in nuclear matter from dilepton spectra in a transport approach

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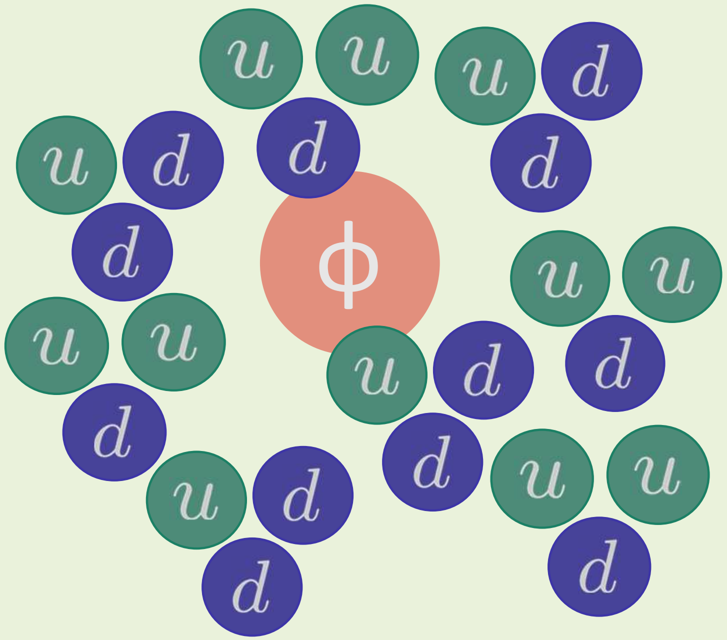
Talk at the 15th Quark Confinement and the Hadron Spectrum Conference
Stavanger, Norway
August 5, 2022

Based on work done in collaboration with Elena Bratkovskaya (Frankfurt/GSI),

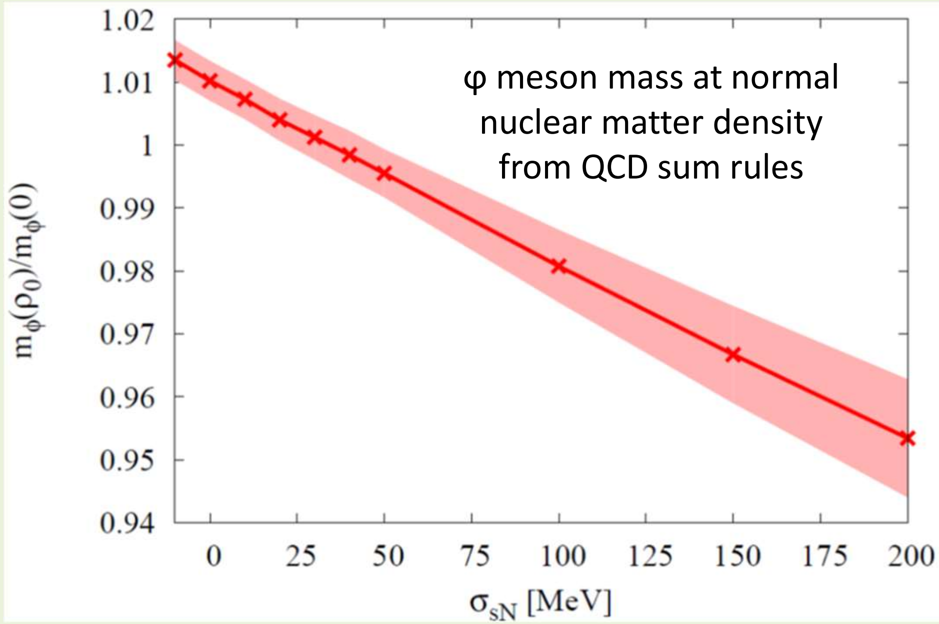
Why should we be interested?

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

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



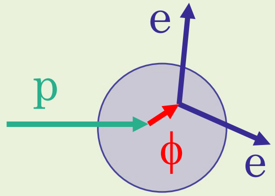
P. Gubler and K. Ohtani, Phys. Rev. D **90**, 094002 (2014).



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

Previous experimental results

KEK
E325



12 GeV
pA-reaction

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

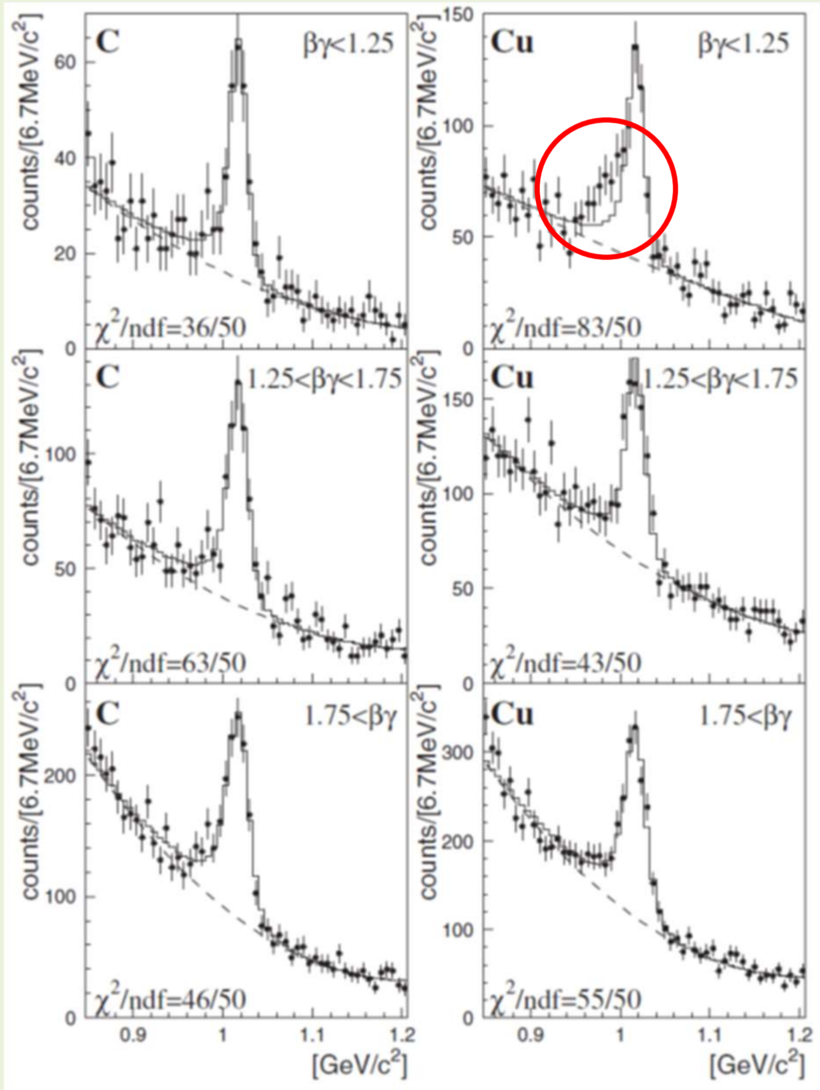
Measurement is being repeated with
~100x increased statistics at the
J-PARC E16 experiment!

slow φs

intermediate φs

fast φs

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

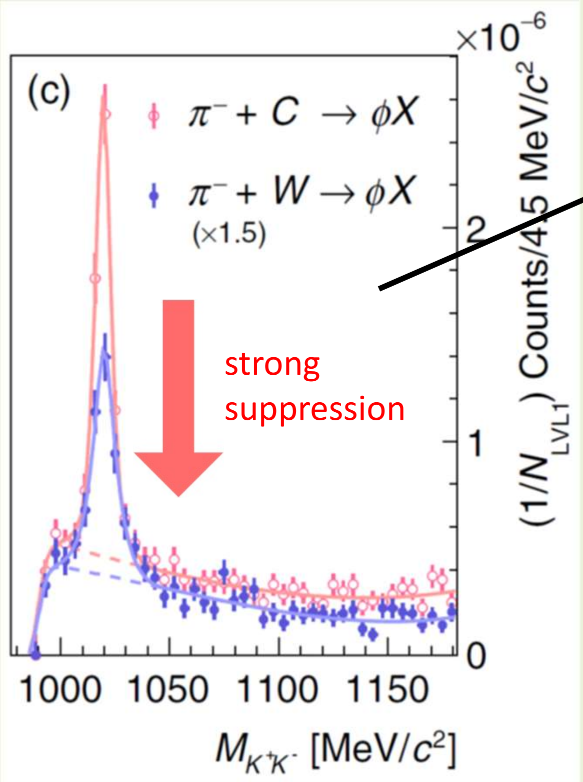


R. Muto et al. (E325 Collaboration), Phys. Rev. Lett. **98**, 042501 (2007).

More recent results

HADES: 1.7 GeV π^-A-reaction

K^+K^- - invariant mass spectrum



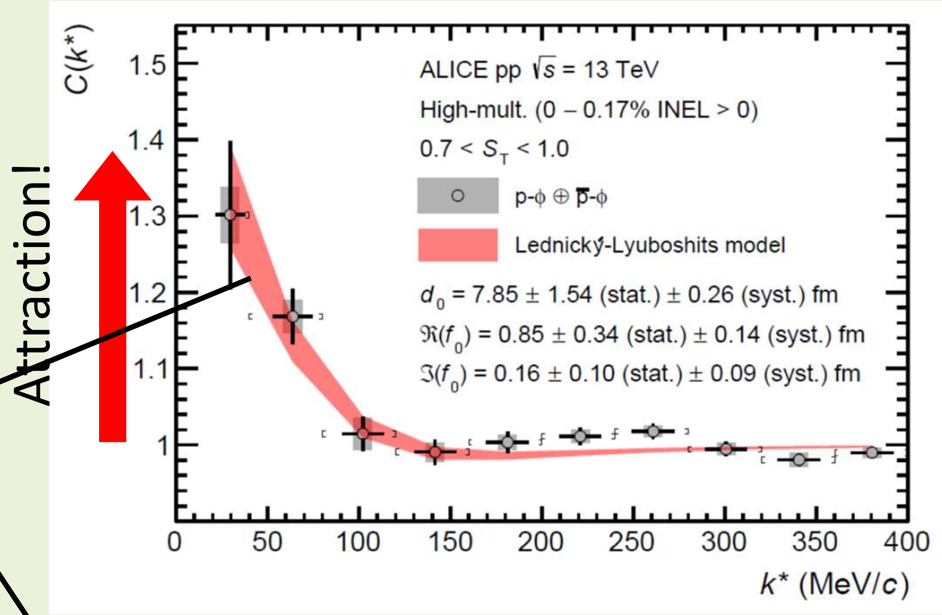
J. Adamczewski-Musch et al. (HADES Coll.), Phys. Rev. Lett. **123**, 022002 (2019).

Broadening ?

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), arXiv:2205.10544 [hep-lat].

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

How compare theory with experiment?

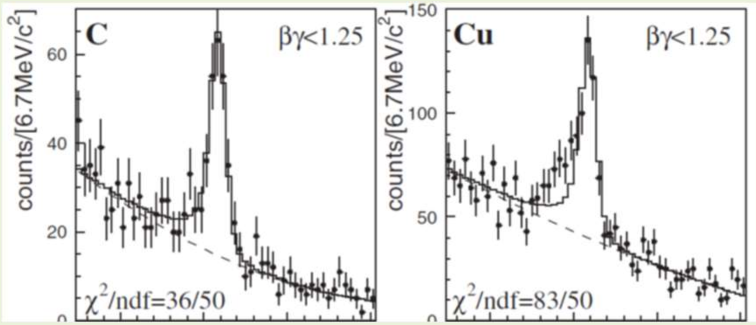
Information useful for theory

★ Spectral function as a function of density

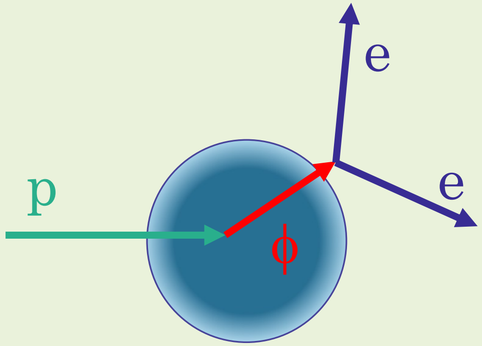
★ Mass at normal nuclear matter density

★ Decay width at normal nuclear matter density

Experimental data



Realistic simulation of pA reaction is needed!



Our tool: 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:

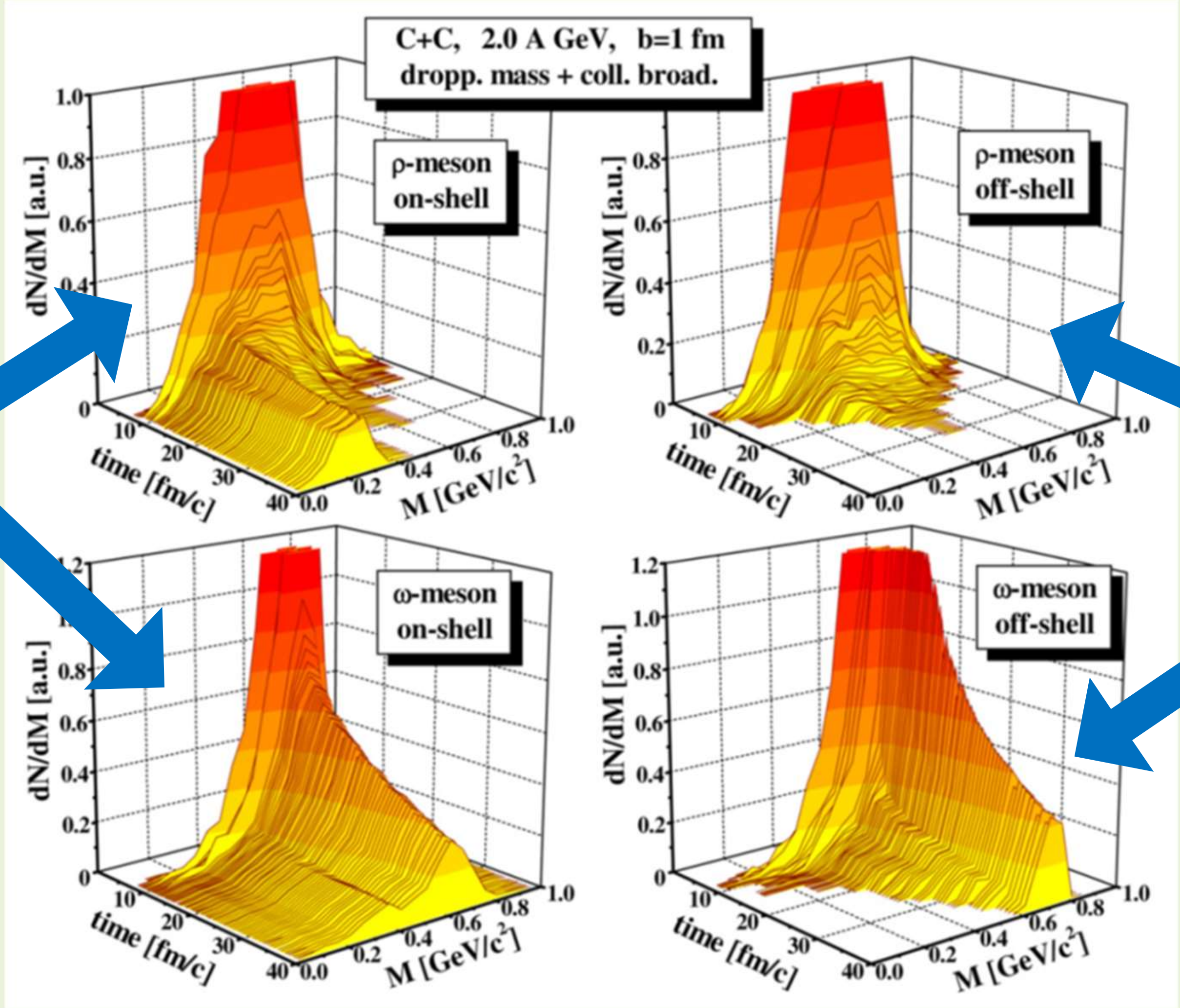
$$\frac{d\vec{X}_i}{dt} = \frac{1}{1-C_{(i)}}\frac{1}{2\varepsilon_i}\left[2\vec{P}_i + \vec{\nabla}_{P_i}\,\mathrm{Re}\,\Sigma^{\mathrm{ret}}_{(i)} + \frac{\varepsilon_i^2 - \vec{P}_i^2 - M_0^2 - \mathrm{Re}\,\Sigma^{\mathrm{ret}}_{(i)}}{\tilde{\Gamma}_{(i)}}\vec{\nabla}_{P_i}\tilde{\Gamma}_{(i)}\right],$$

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

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

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).

Advantage: vector meson spectra can be chosen freely

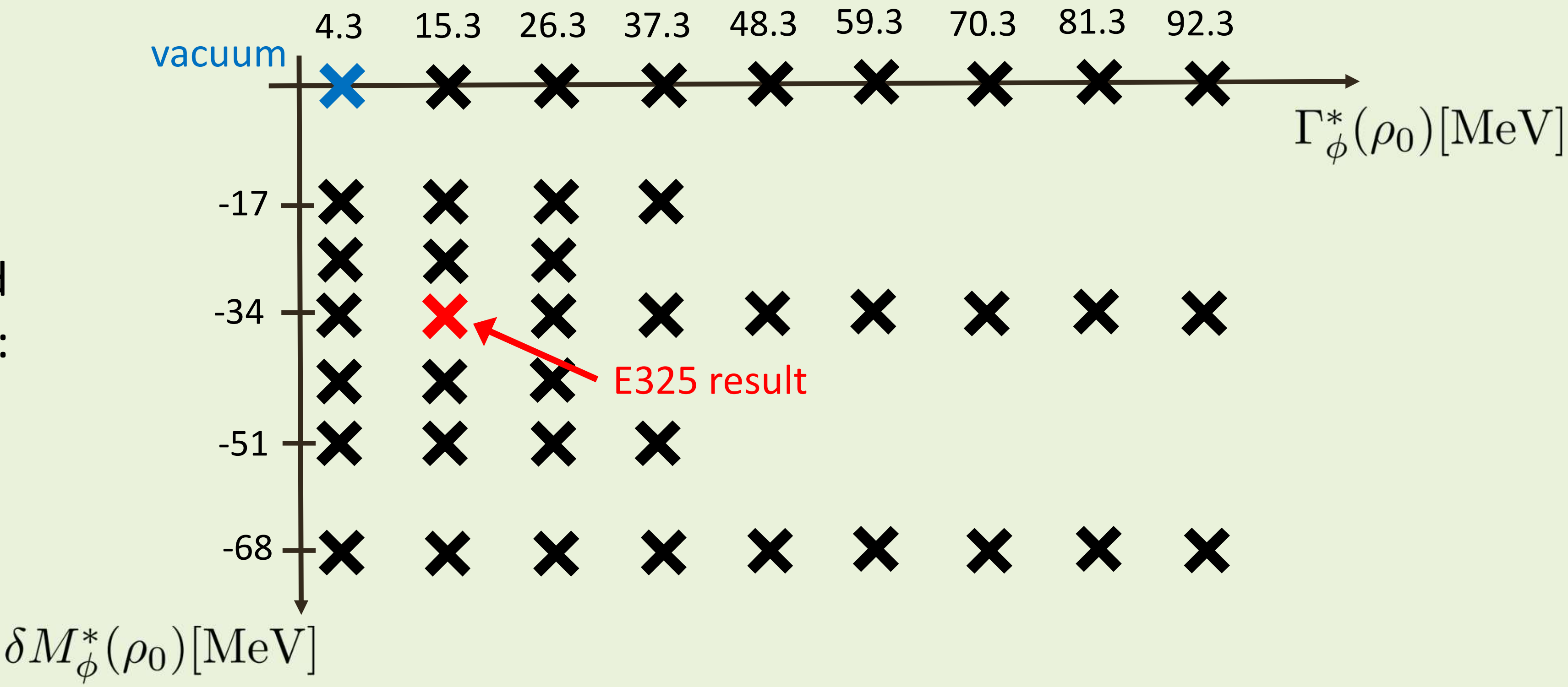
Our choice: a Breit-Wigner with density dependent mass and width

$$A_\phi(M,\rho) = C\,\frac{2}{\pi}\,\frac{M^2\Gamma^*_\phi(M,\rho)}{[M^2-M^{*2}_\phi(\rho)]^2+M^2\Gamma^{*2}_\phi(M,\rho)}$$

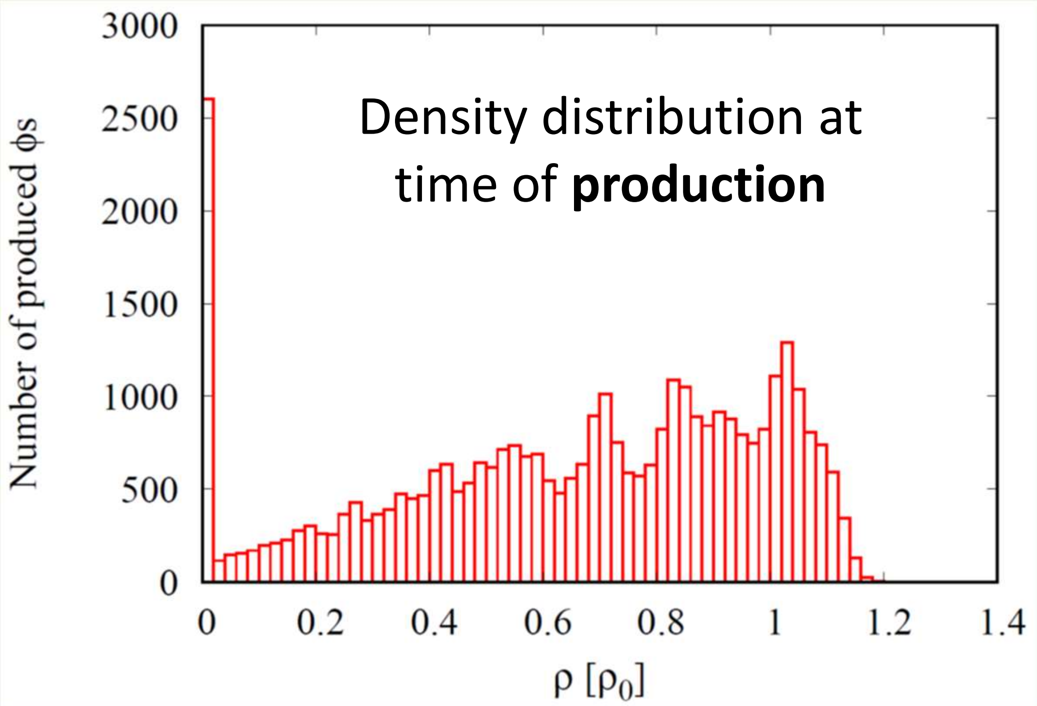
with

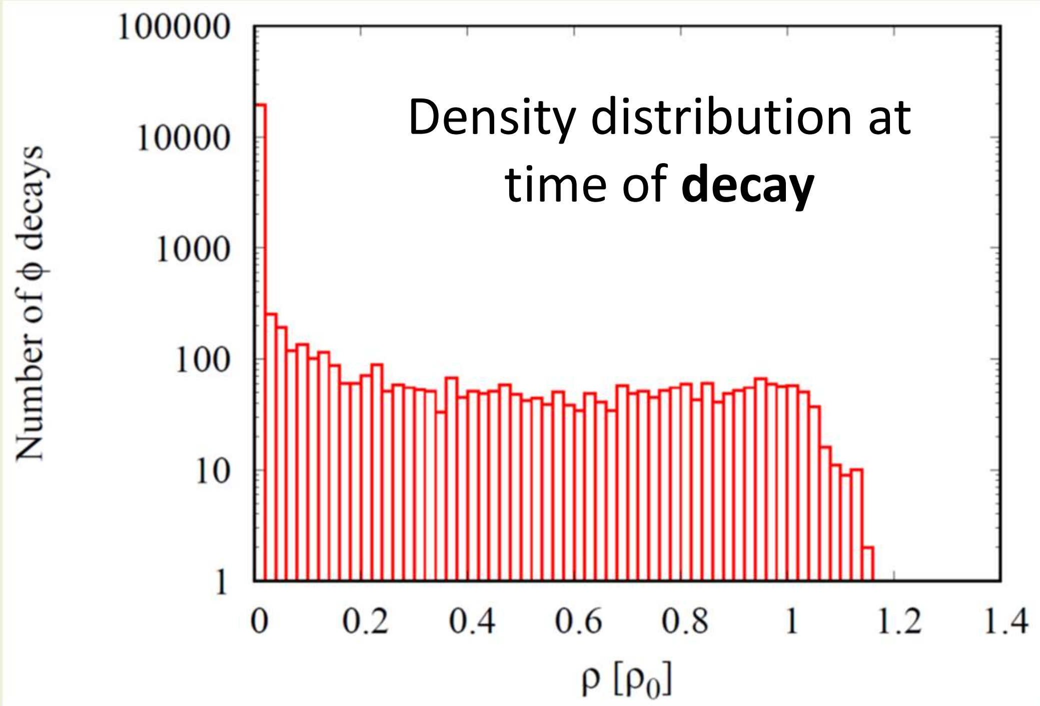
$$\begin{cases} M^*_\phi(\rho) = M^{\rm vac}_\phi\left(1-\alpha^\phi\frac{\rho}{\rho_0}\right), \\ \Gamma^*_\phi(M,\rho) = \Gamma^{\rm vac}_\phi + \alpha^\phi_{\rm coll}\frac{\rho}{\rho_0} \end{cases}$$

Simulated scenarios:



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

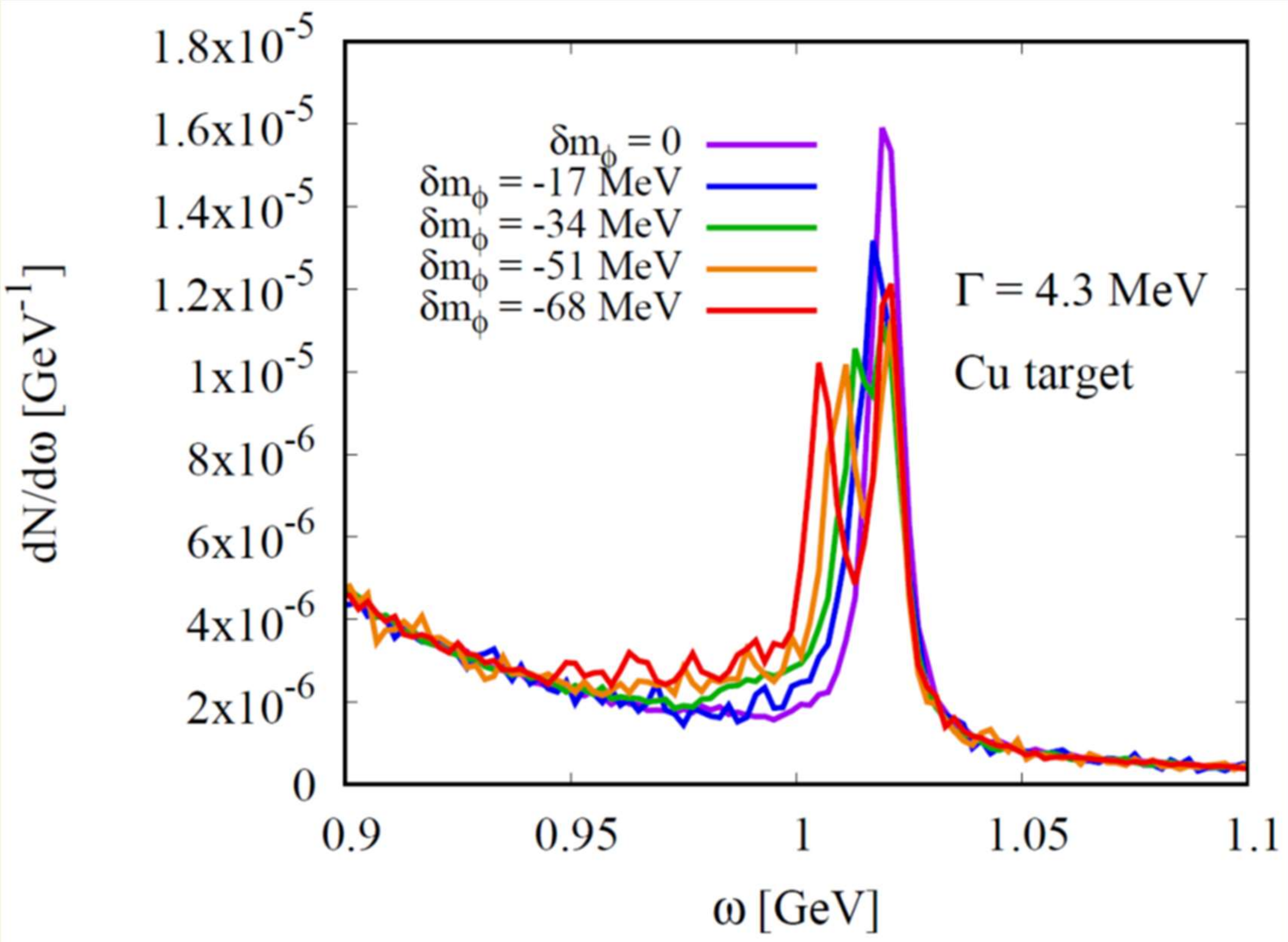




Majority of φ mesons are produced at densities around ρ_0

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

The dilepton spectrum in the φ meson region



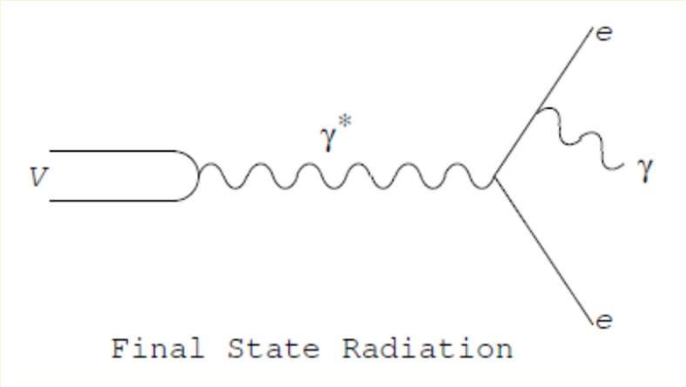
p + Cu at 12 GeV

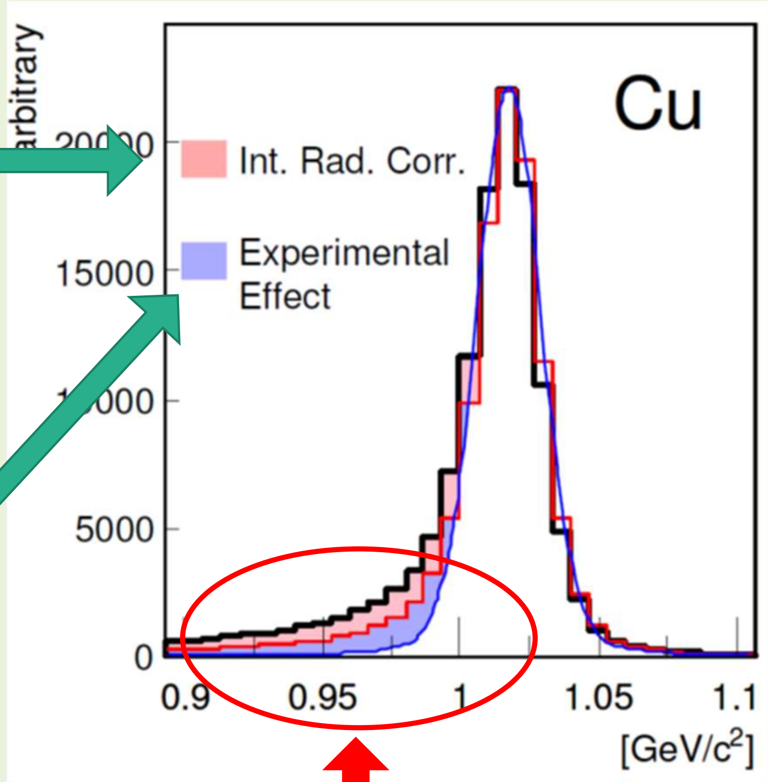
No acceptance corrections!

No finite resolution effects!

No QED effects!

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)

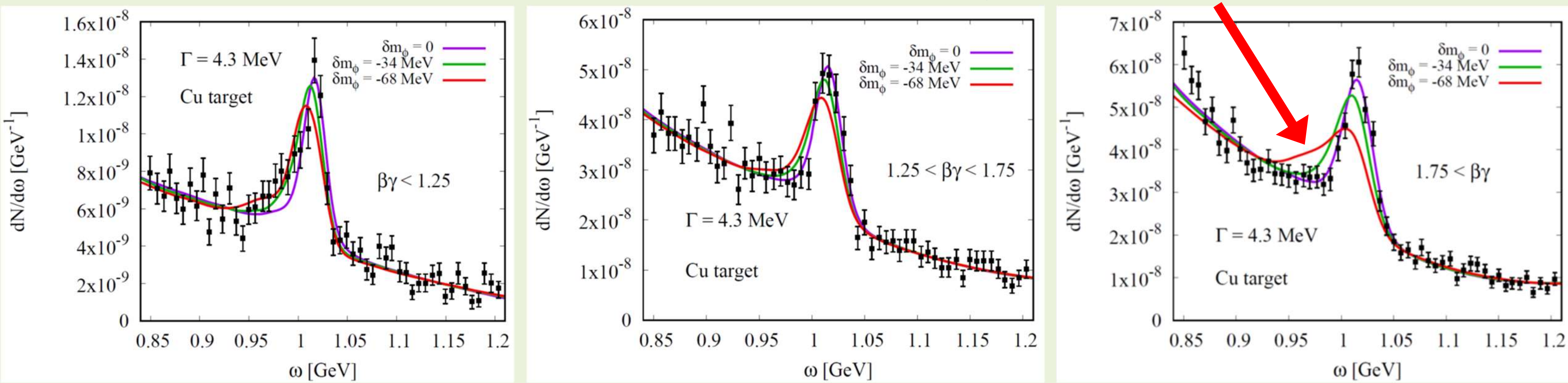
Similar to the shape expected for a negative mass shift

Preliminary

Fits to experimental Copper target data (E325)

Surprisingly large effect for fast φs with a large mass shift

→ Related to initial stage of the collision??



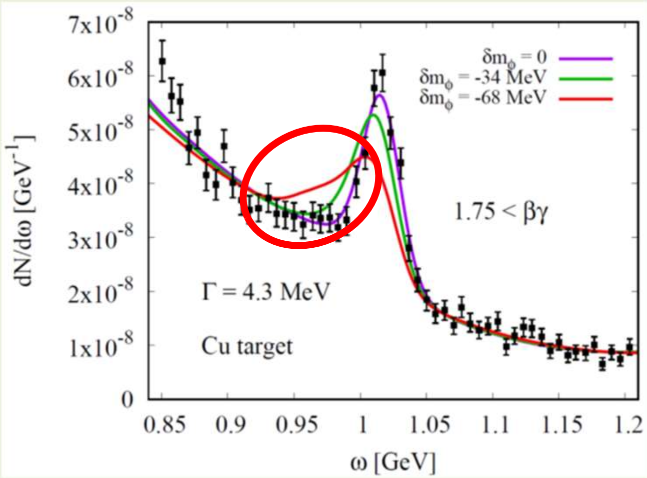
slow φs | intermediate φs | fast φs

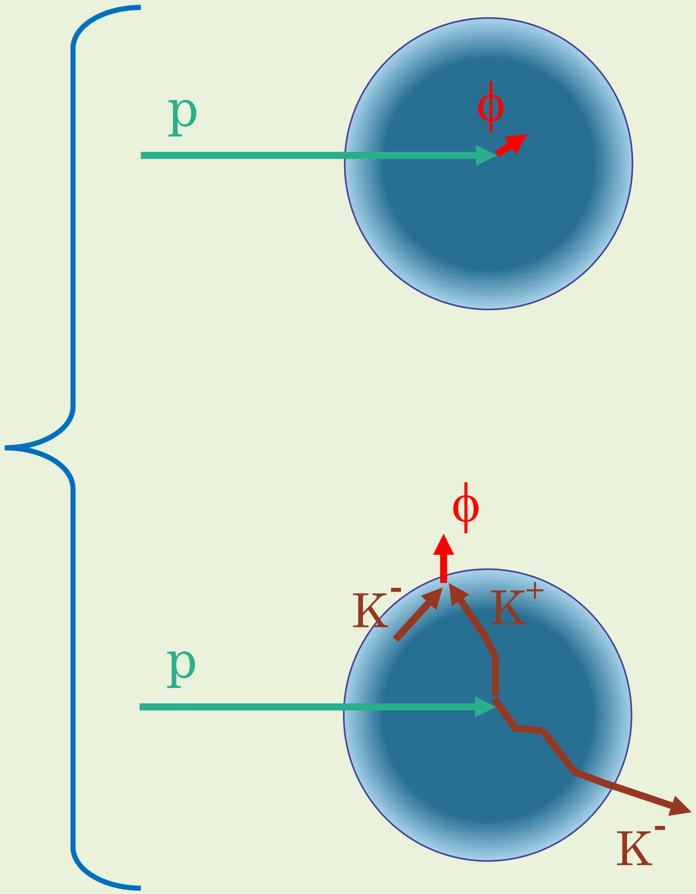
Favors negative mass shift

Favor no mass shift scenario

Reason for large modification for fast φ mesons

➡ Initial stage of φ meson production?





φ mesons are generated from high energy collisions (via strings)

➡ **large momentum**

➡ **high density**

φ mesons are generated from low energy hadronic collisions

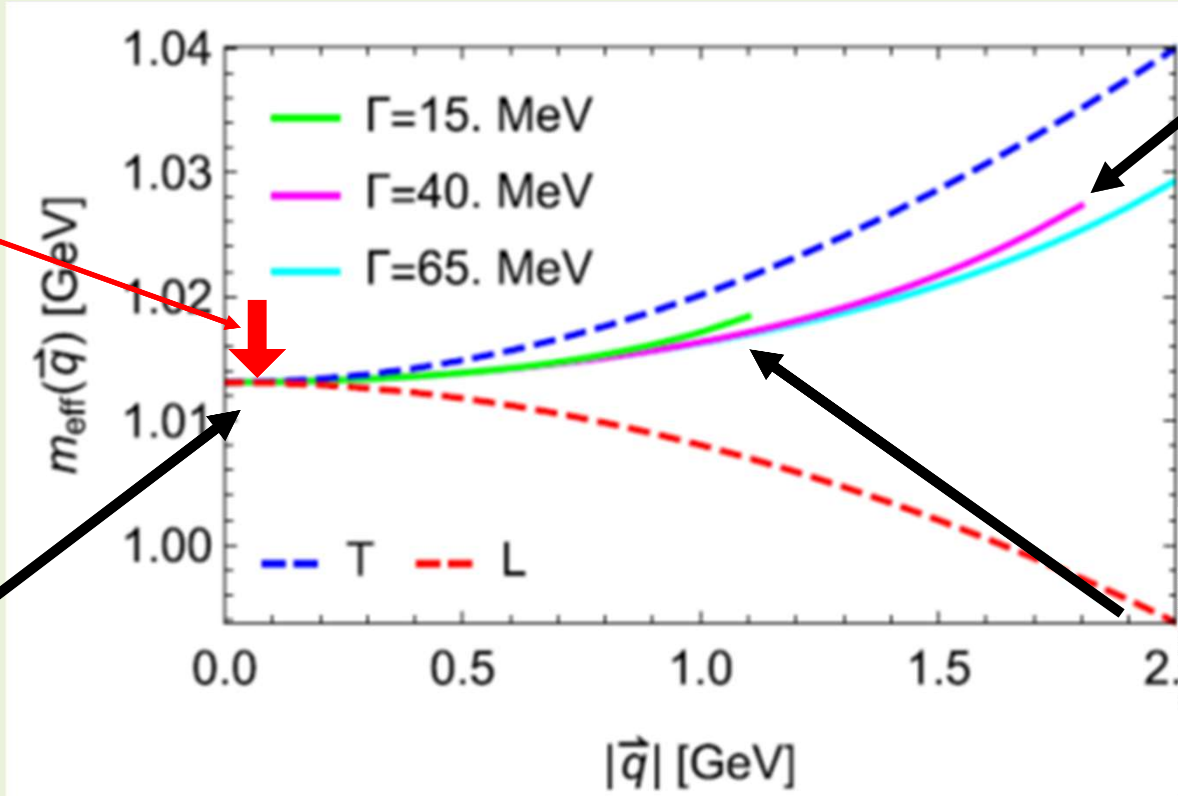
➡ **small momentum**

➡ **low density**

Most natural interpretation of our results

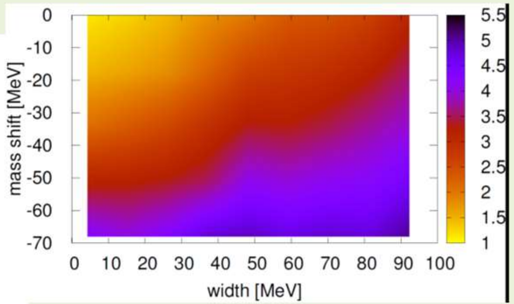
→ Momentum dependent mass shift

negative mass shift
at zero momentum



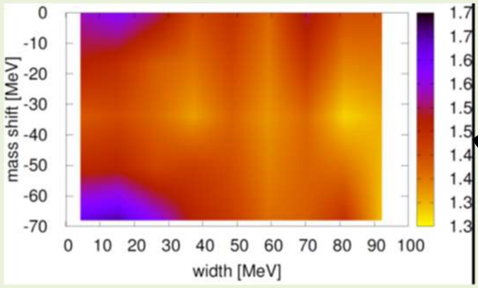
H.J. Kim and P. Gubler, Phys. Lett. B **805**, 135412 (2020).

fast φs



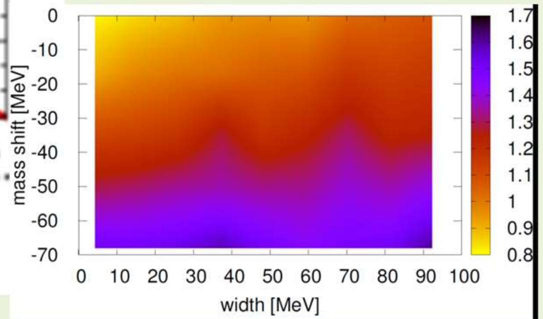
χ^2/d.o.f values

slow φs



χ^2/d.o.f values

intermediate φs



χ^2/d.o.f values

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

★ 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 HSD transport code

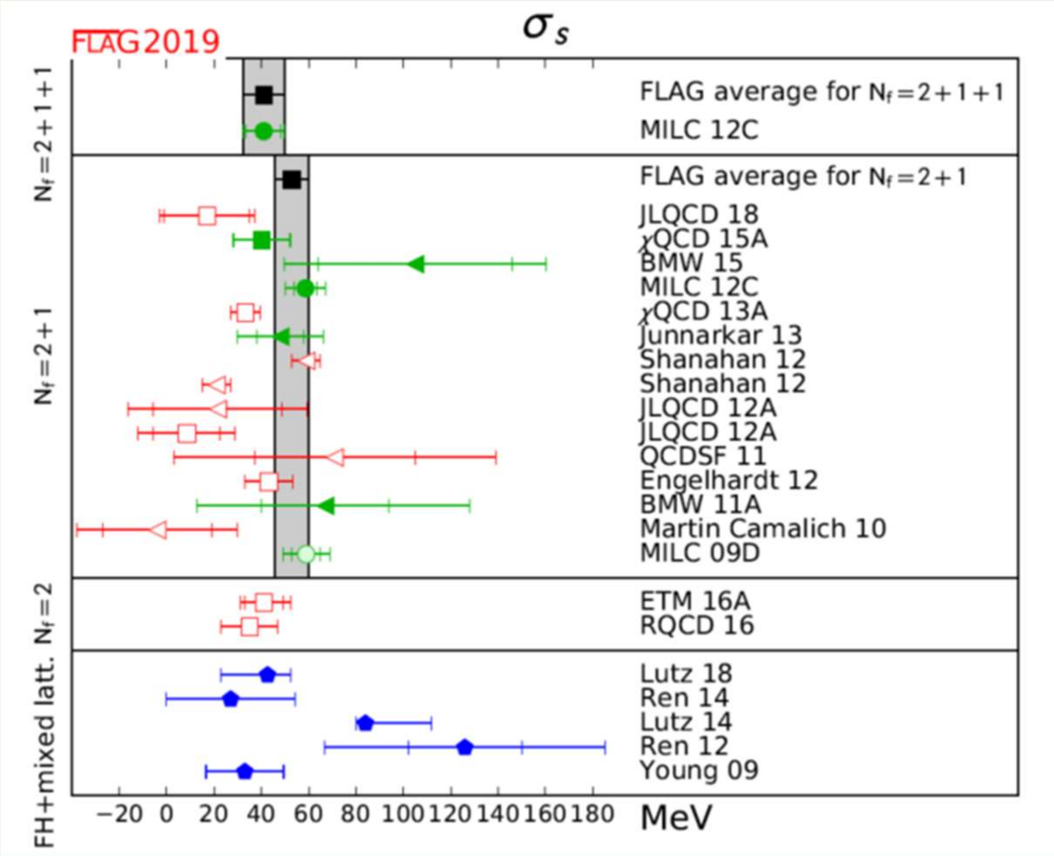
⬇

Momentum-dependent mass shift is needed to explain the data

Backup slides

What does lattice QCD say about the strange sigma term?

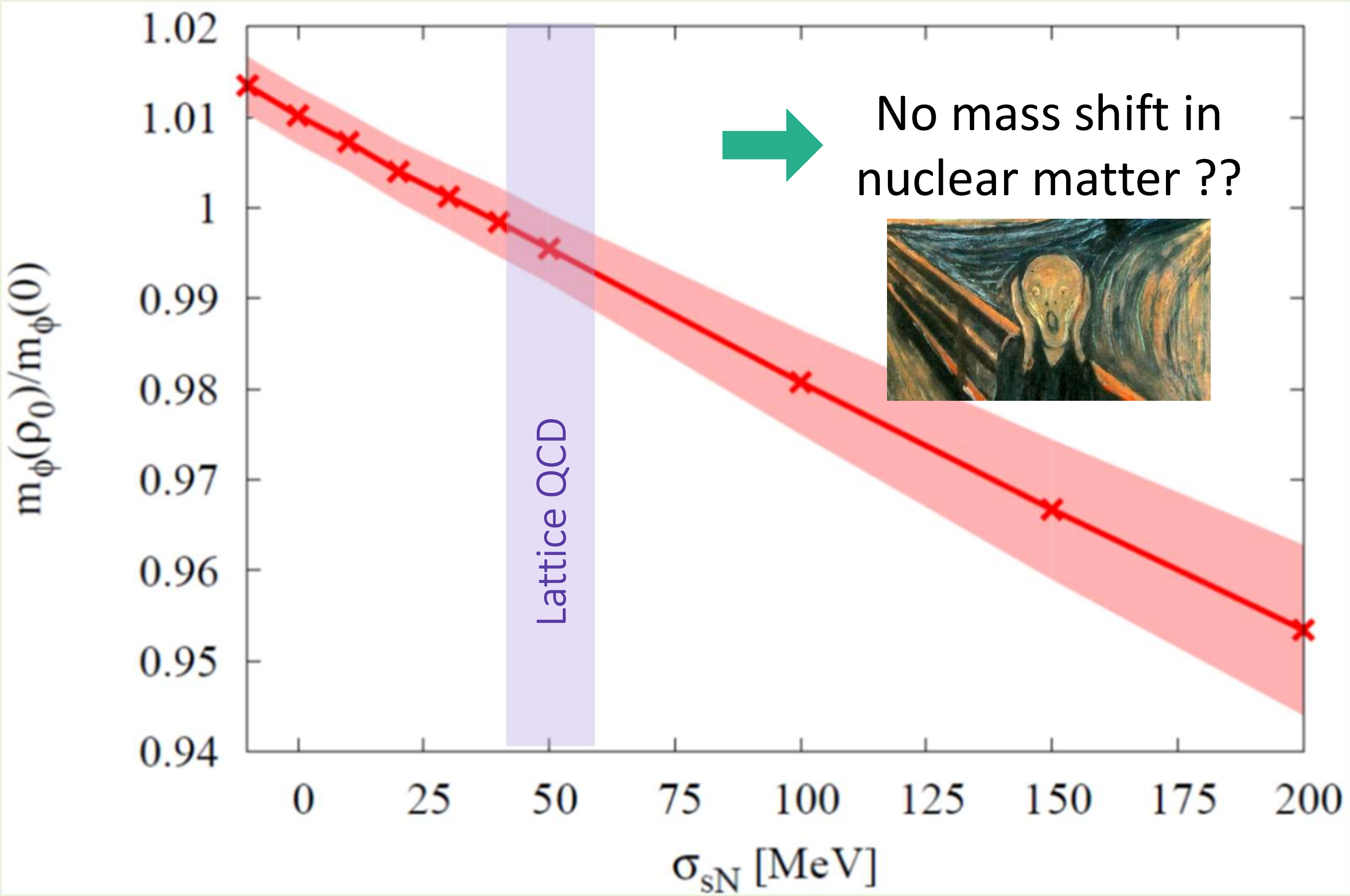
$$\sigma_{sN} = m_s \langle N | \bar{s}s | N \rangle$$



http://flag.unibe.ch/2019/

See also the most recent result of the BMW collaboration: Sz. Borsanyi et al., arXiv:2007.03319 [hep-lat].

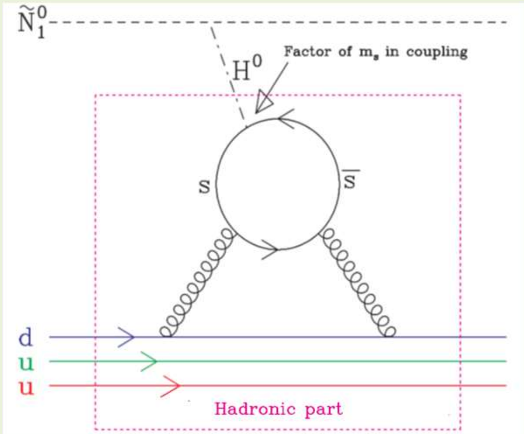
Combine QCD sum rules with lattice QCD



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

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).

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

most important contribution

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

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).

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)

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

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

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

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

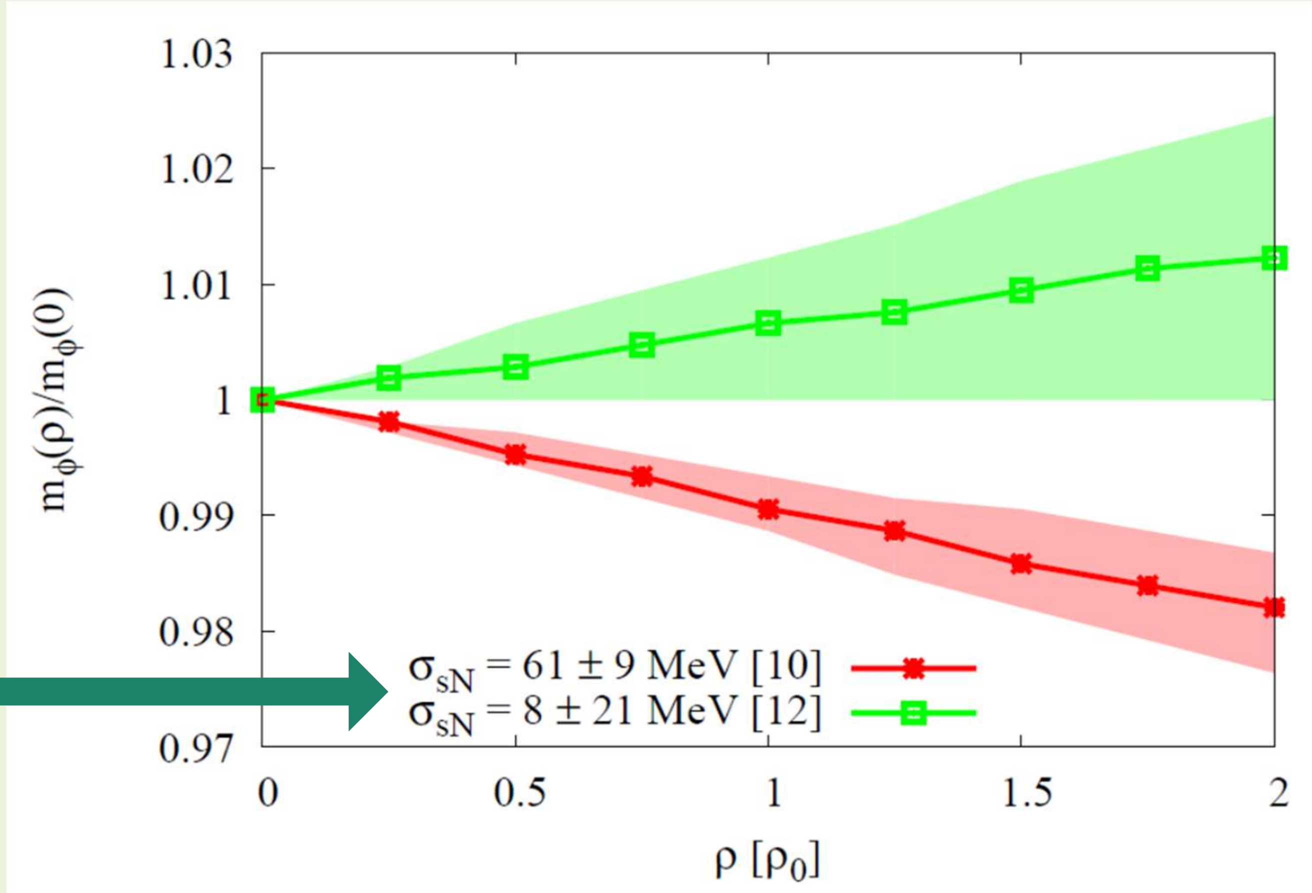
Dim. 6: $c_6(\rho) = c_6(0) + \rho[-\frac{896}{81}\kappa_N \pi^3 \alpha_s \langle\bar{s}s\rangle\langle N|\bar{s}s|N\rangle - \frac{5}{6}A_4^s M_N^3]$

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).

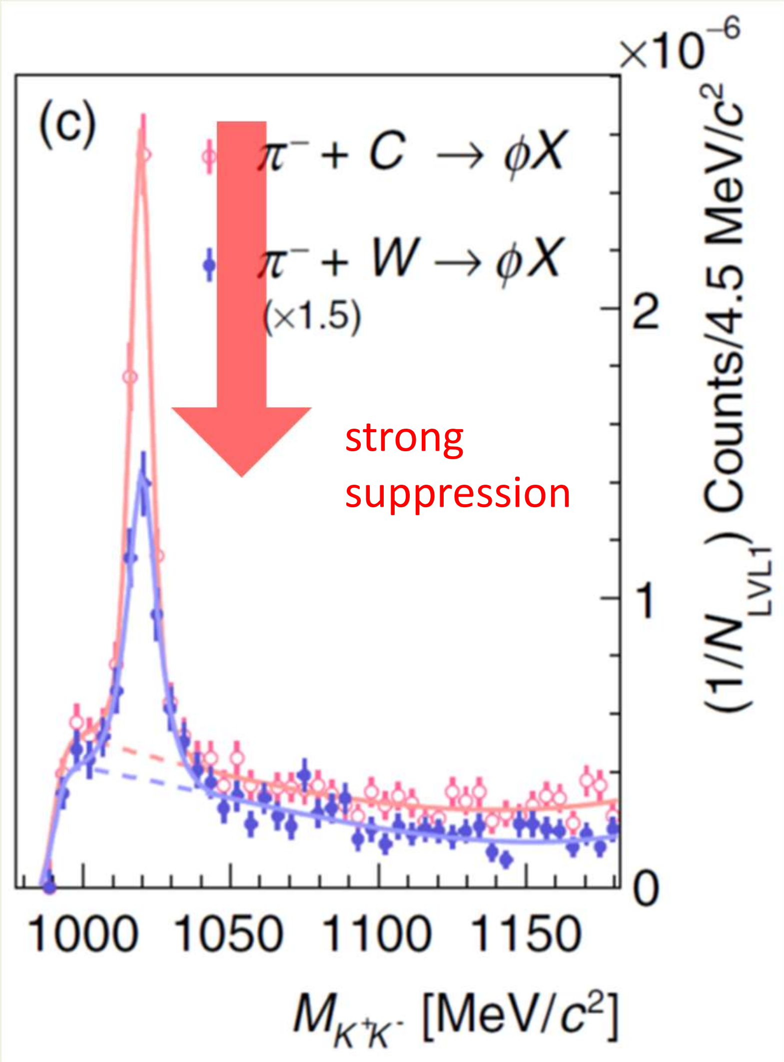
Recent experimental results

HADES: 1.7 GeV π^-A-reaction

- ★ Larger suppression of K^- in the Tungsten target compared to the Carbon target
- ★ K^-/φ ratio is similar for both Tungsten and Carbon targets

- ★ Observation of large suppression (broadening?) of the φ meson in large nuclei

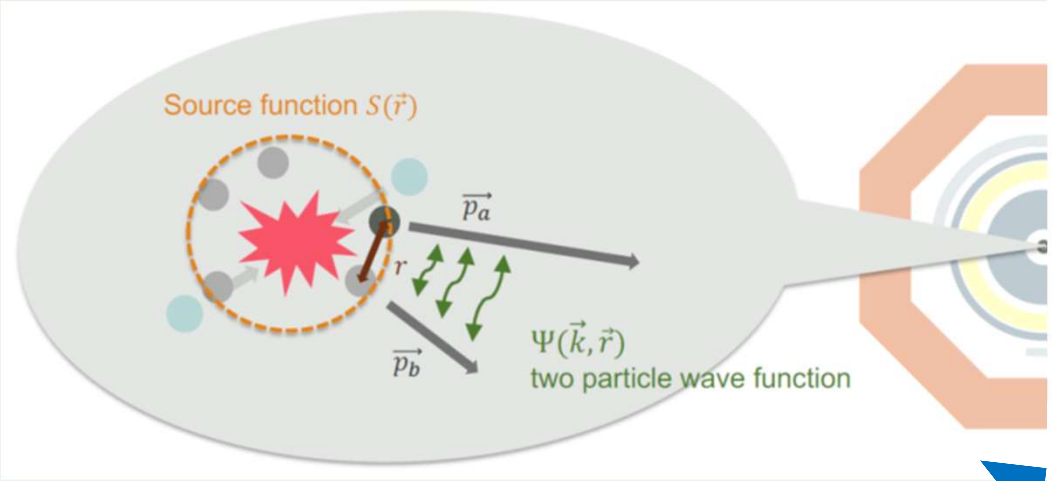
K^+K^- - invariant mass spectrum



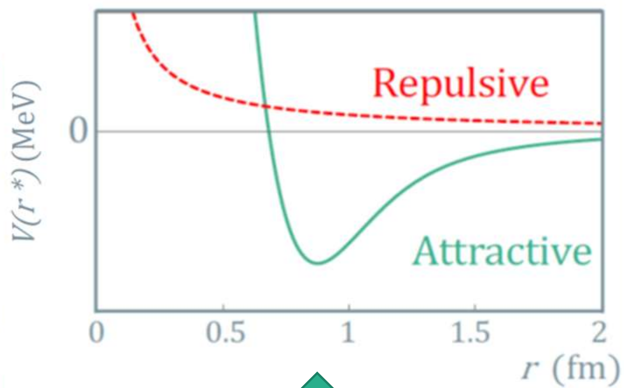
J. Adamczewski-Musch et al. (HADES Collaboration), Phys. Rev. Lett. **123**, 022002 (2019).

New experimental results

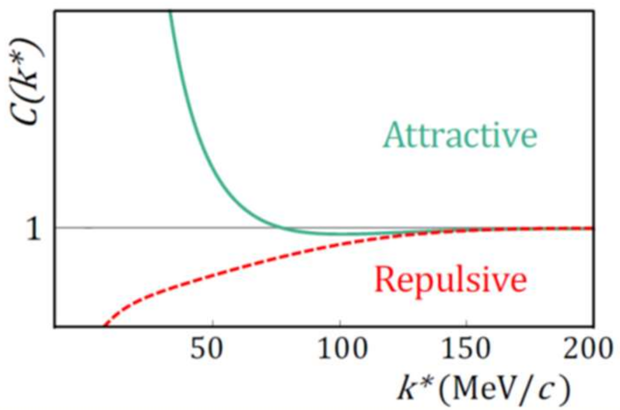
ALICE (Femtoscopy)



Interaction potential



Correlation function



The observable to be measured: the correlation function:

$$C(k) = \mathcal{N}\frac{N_{\text{Same}}}{N_{\text{Mixed}}} = \int S(\vec{r})|\Psi(\vec{k},\vec{r})|^2 d^3\vec{r}$$

Emission source (Gaussian)

Relative momentum of the particle pair

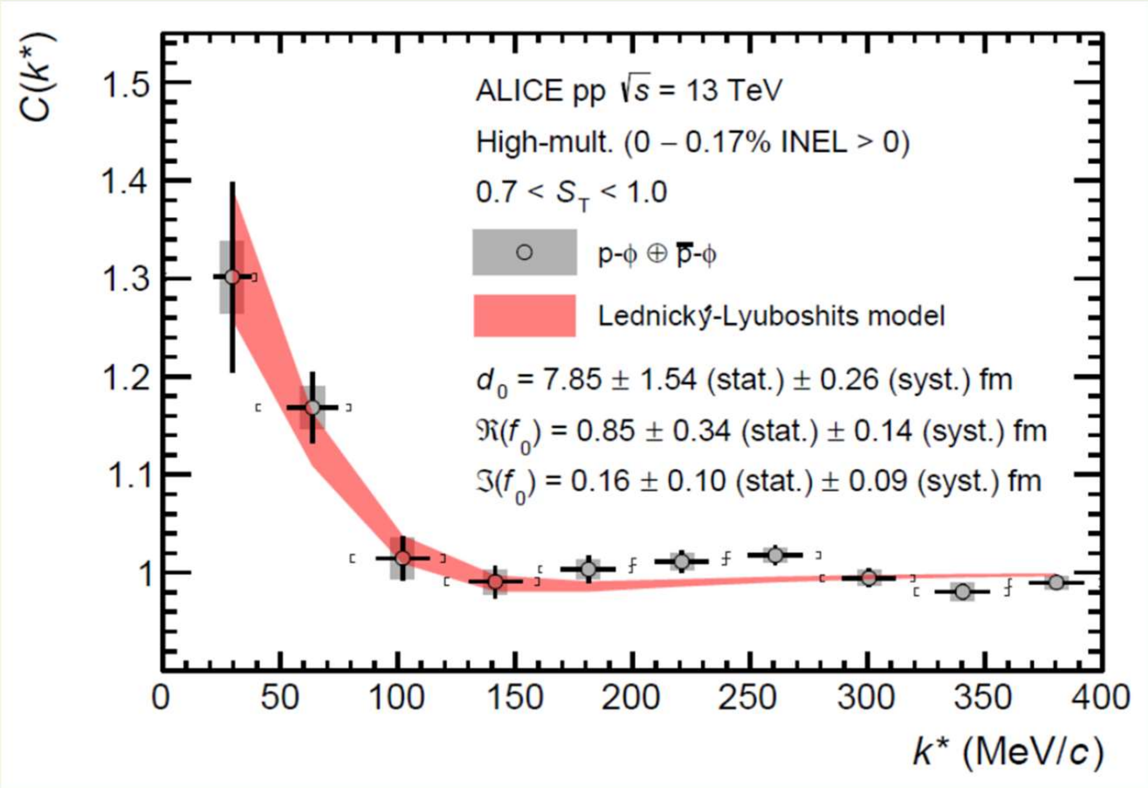
S. Acharya et al. (ALICE Collaboration), Phys. Rev. Lett. **127**, 172301 (2021).

New experimental results

ALICE

Measurement of φN correlation

Attraction!



Extracted φN scattering length

Real part:

$$\mathrm{Re}(f_0) = 0.85 \pm 0.34(\mathrm{stat.}) \pm 0.14(\mathrm{syst.})\,\mathrm{fm}$$

→ Attractive

Imaginary part:

$$\mathrm{Im}(f_0) = 0.16 \pm 0.10(\mathrm{stat.}) \pm 0.09(\mathrm{syst.})\,\mathrm{fm}$$

→ Small absorption/broadening ?

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

New experimental results

ALICE

Fit of the correlation function data to two simple phenomenological potentials

$$E_{\text{int}} = \int d^3\vec{r} \int d^3\vec{r}\,' \rho_N(\vec{r}) V(\vec{r}-\vec{r}\,') \rho_\phi(\vec{r}\,')$$

$\rho_N(\vec{r}) \rightarrow \rho_0$, $\rho_\phi(\vec{r}\,') \rightarrow \delta^{(3)}(\vec{r}\,')$

$$V_{\text{Yukawa}}(r) = -\frac{A}{r} e^{-\alpha r}$$

$$A = 0.021 \pm 0.009\,(\text{stat.}) \pm 0.006\,(\text{syst.})$$

$$\alpha = 65.9 \pm 38.0\,(\text{stat.}) \pm 17.5\,(\text{syst.})\,\text{MeV}$$

$\Rightarrow$

$$E_{\text{int}} = -\frac{4\pi A \rho_0}{\alpha^2} = -79.3 \pm 108.8\,\text{MeV}$$

$$V_{\text{Gaussian}}(r) = -V_{\text{eff}} e^{-\mu r^2}$$

$$V_{\text{eff.}} = 2.5 \pm 0.9\,(\text{stat.}) \pm 1.4\,(\text{syst.})\,\text{MeV}$$

$$\mu = 0.14 \pm 0.06\,(\text{stat.}) \pm 0.09\,(\text{syst.})\,\text{fm}^{-2}$$

$\Rightarrow$

$$E_{\text{int}} = -\frac{\pi^{3/2} V_{\text{eff}} \rho_0}{\mu^{3/2}} = -45.2 \pm 61.5\,\text{MeV}$$

S. Acharya et al. (ALICE Collaboration), arXiv:2105.05578 [nucl-ex].

$\Rightarrow$ Larger attraction than what was observed at KEK 325, but large statistical and systematic uncertainties

Our tool: a transport approach

Basic Ingredient 1: Solve a Boltzmann-Uehling-Uhlenbeck (BUU) type equation for each particle type

$$\left(\frac{\partial}{\partial t} + \vec{\nabla}_p \epsilon \cdot \vec{\nabla}_r - \vec{\nabla}_r \epsilon \cdot \vec{\nabla}_p\right) f_a(\vec{r}, \vec{p}; t) = I_{\text{coll}}[f_a(\vec{r}, \vec{p}; t)]$$

Includes mean field (tuned to reproduce nuclear matter properties)

particle distribution function

Basic Ingredient 2: „Testparticle“ approach

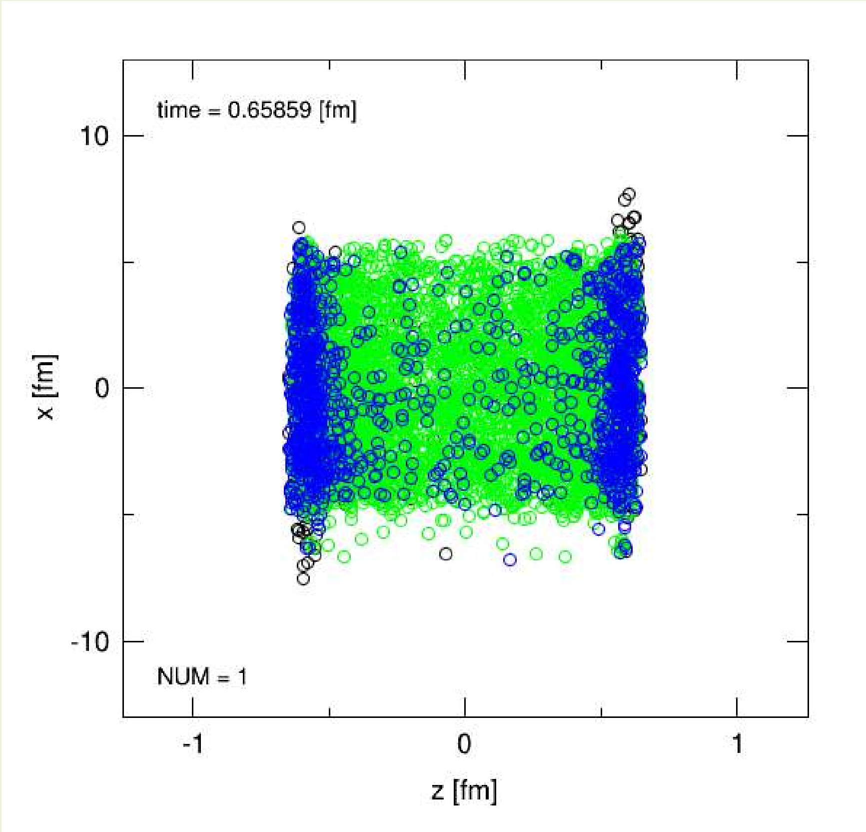
$$f_h(\boldsymbol{r}, \boldsymbol{p}; t) = \frac{1}{N_{\text{test}}} \sum_{i}^{N_h(t) \times N_{\text{test}}} \delta(\boldsymbol{r} - \boldsymbol{r}_i(t))\, \delta(\boldsymbol{p} - \boldsymbol{p}_i(t))$$

Example of a transport calculation

Au+Au collision at $s^{1/2}$ = 200 GeV, b = 2 fm

nucleons
quarks
gluons

will not be included in the simulations shown in this talk



Final step: comparison to experimental data

Potential issues:

- ★ Experimental background is not included in the simulation
- ★ Normalization of the experimental dilepton spectrum is not given

↓

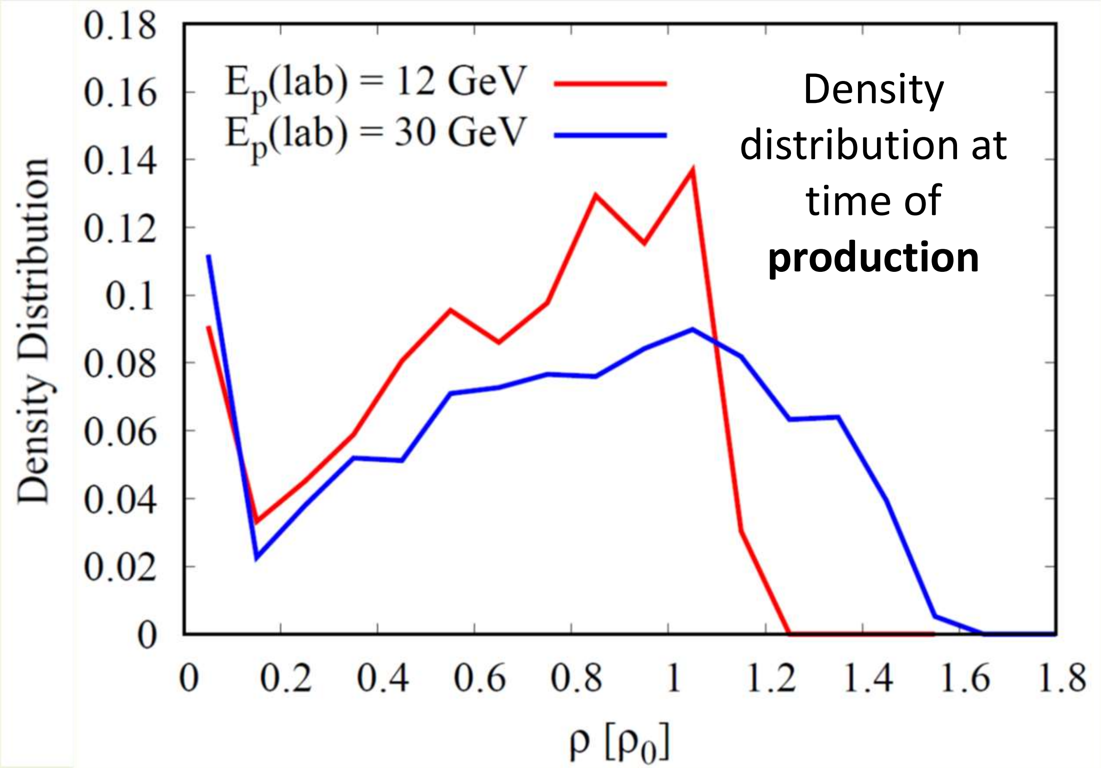
Fit to experimental data is necessary!

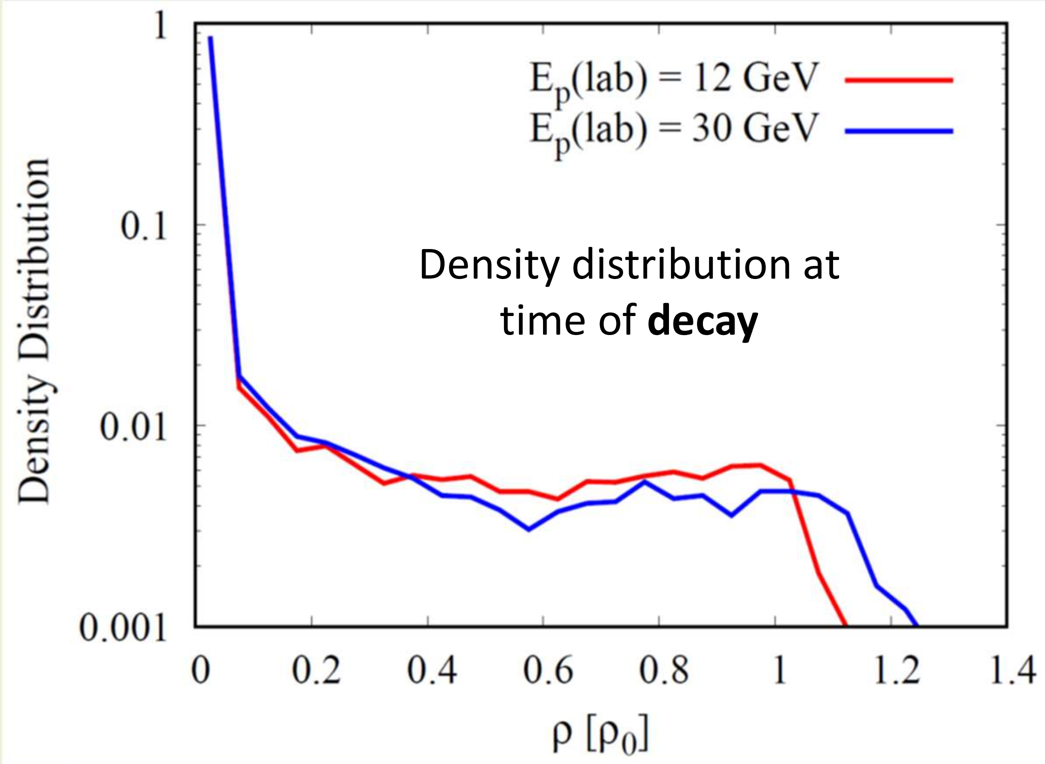
Background — ϕ meson signal

Dilepton spectrum: $\rho(\omega) = \underbrace{a\omega^2 + b\omega + c}_{\text{Background}} + \underbrace{A\rho_{\phi,\mathrm{HSD}}(\omega)}_{\phi\text{ meson signal}}$

Fitted to the experimental dilepton spectrum independently for each βγ-region (a, b, c, A)

What density does the φ feel in different pA (p+Cu) reactions?



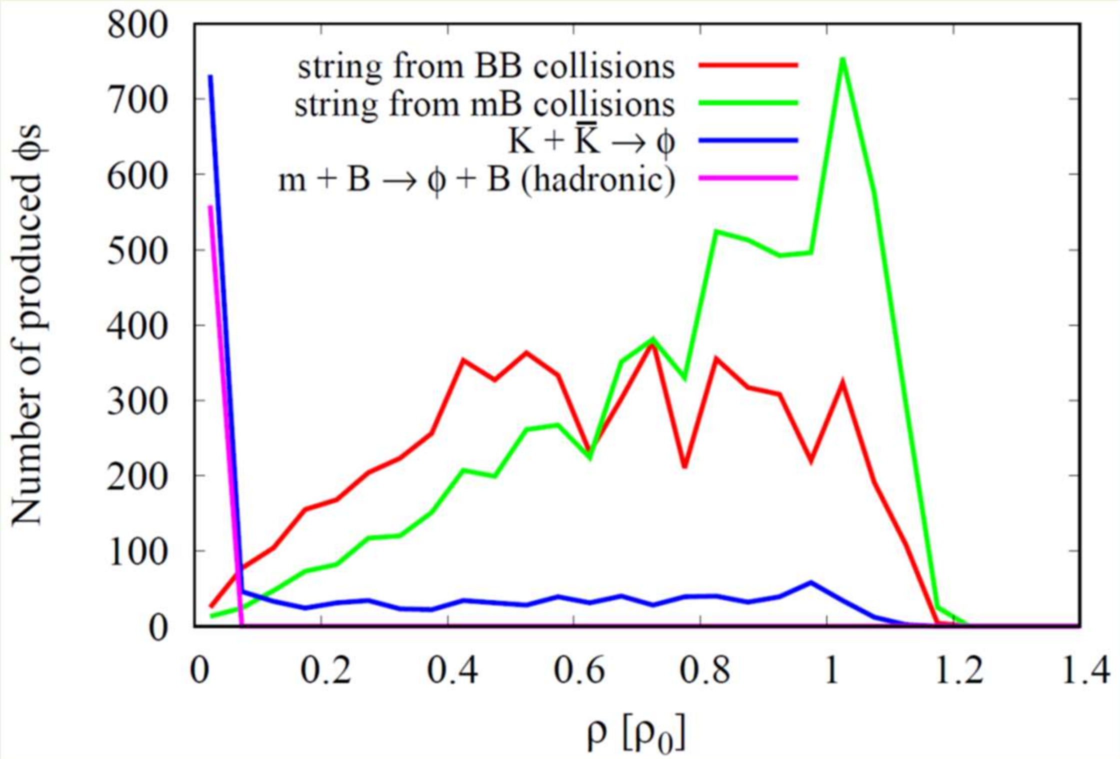


Larger densities are reached for larger incoming proton energy

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

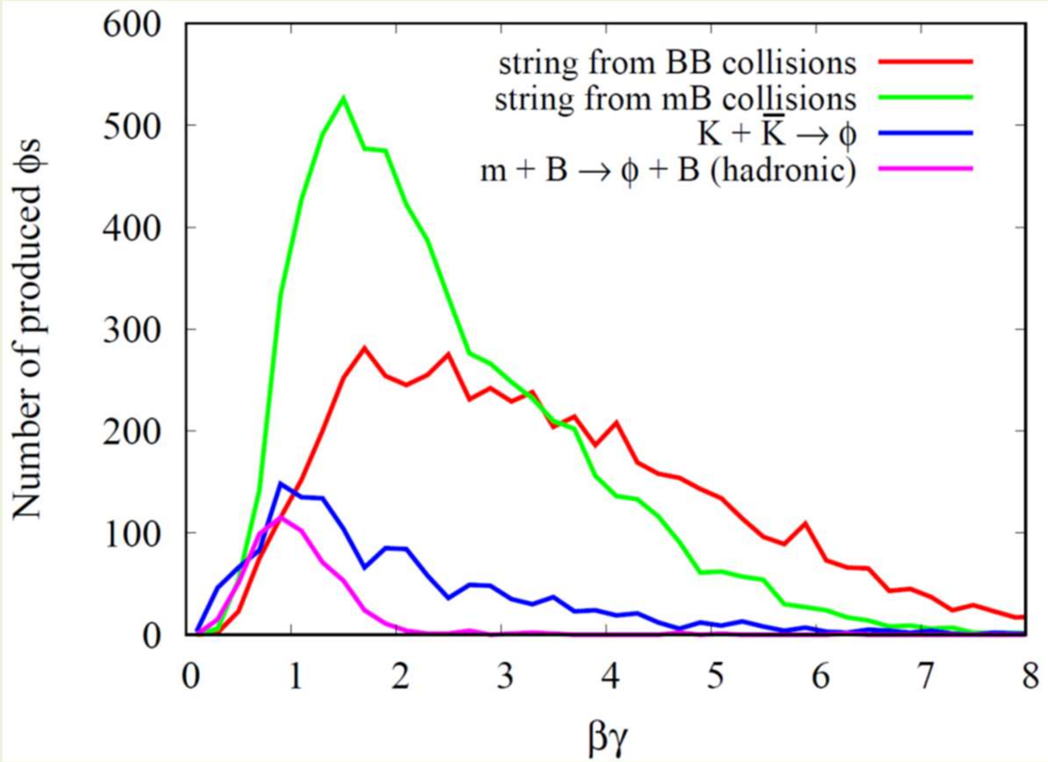
Density and βγ distributions for the different production mechanisms

Density distribution at production



Low energy hadronic production occurs dominantly at the nuclear surface

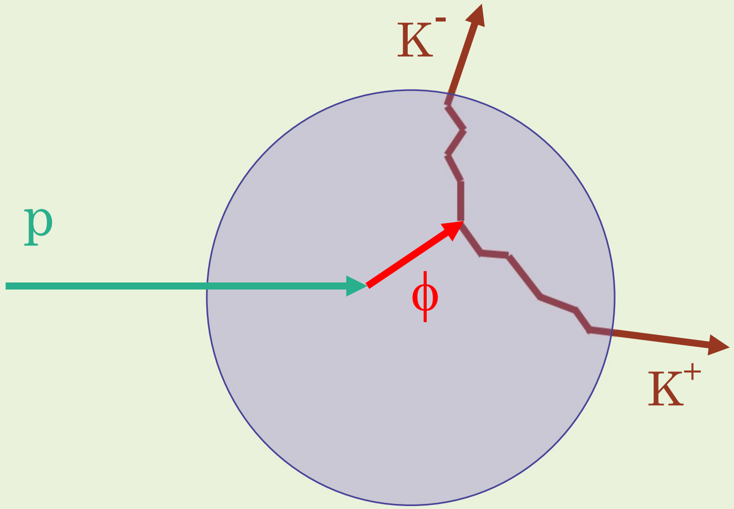
βγ distribution at production

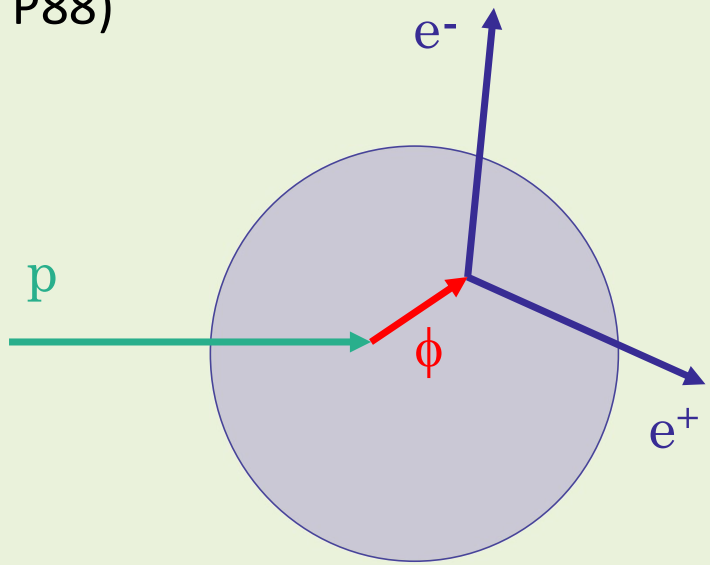


For βγ>1.5, high energy φ meson production via strings dominates

What about the K^+K^- decay channel?

(new J-PARC proposal P88)

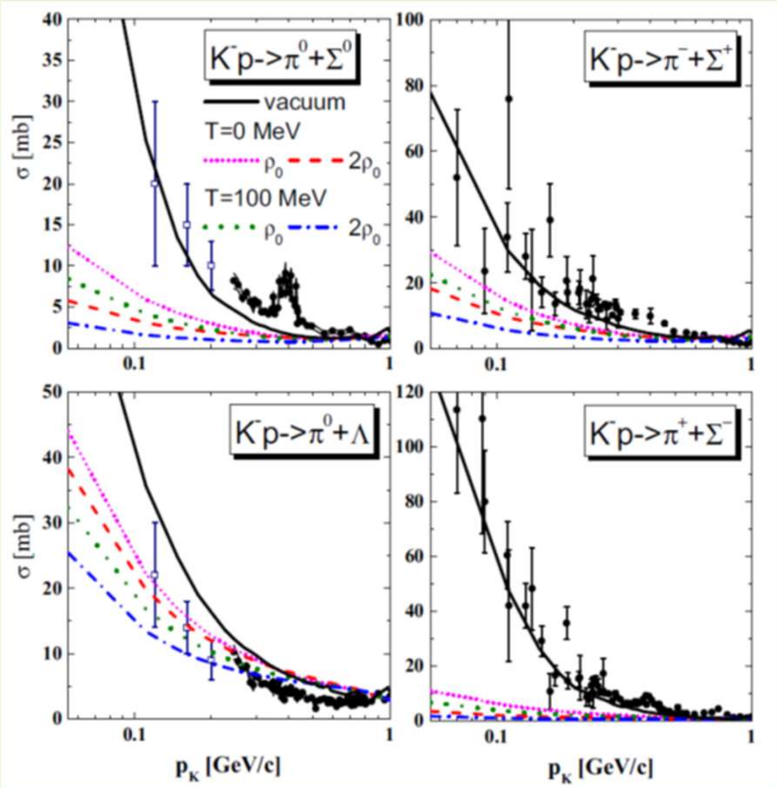




Kaons feel the strong interaction	➡	Distorted in-medium φ meson signal	✗
Large branching ratio	➡	Good statistics	○
Kaons do not feel the strong interaction	➡	Clear in-medium φ meson signal	○
Small branching ratio	➡	Bad statistics	✗

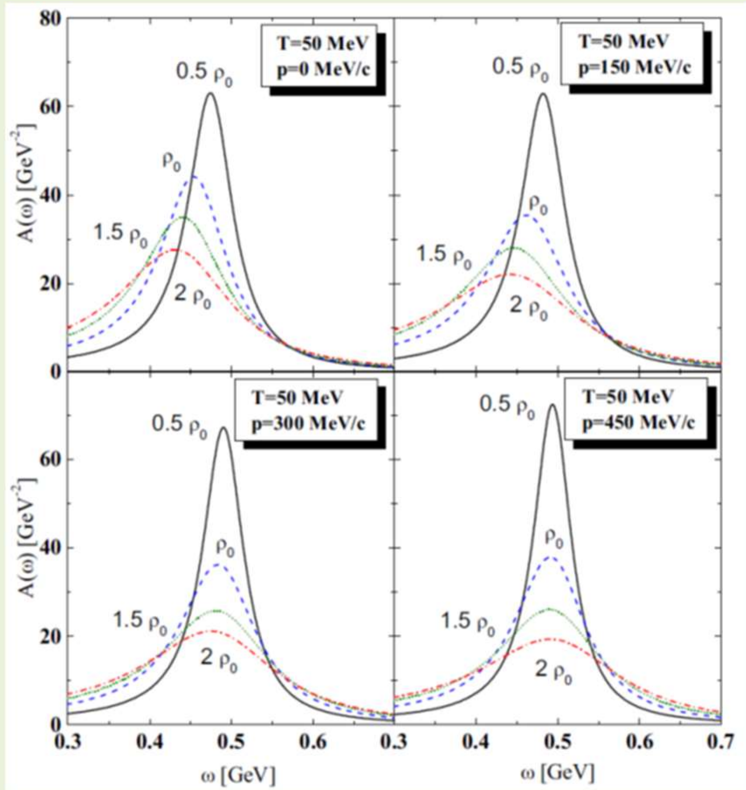
Treatment of KN-interactions

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

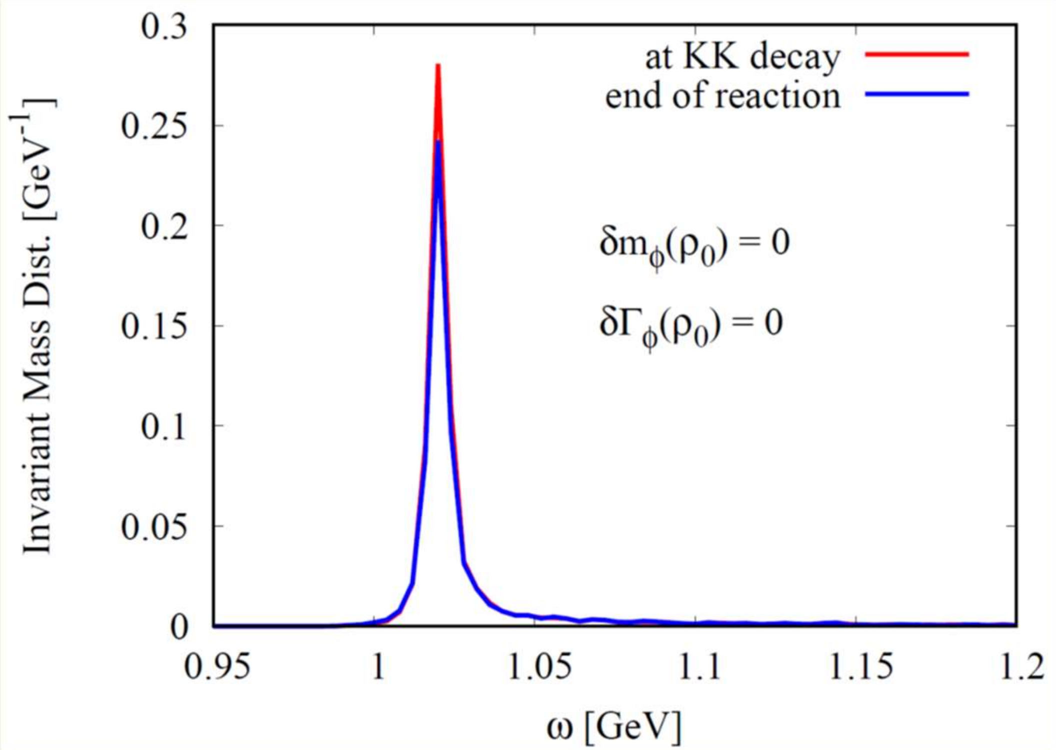


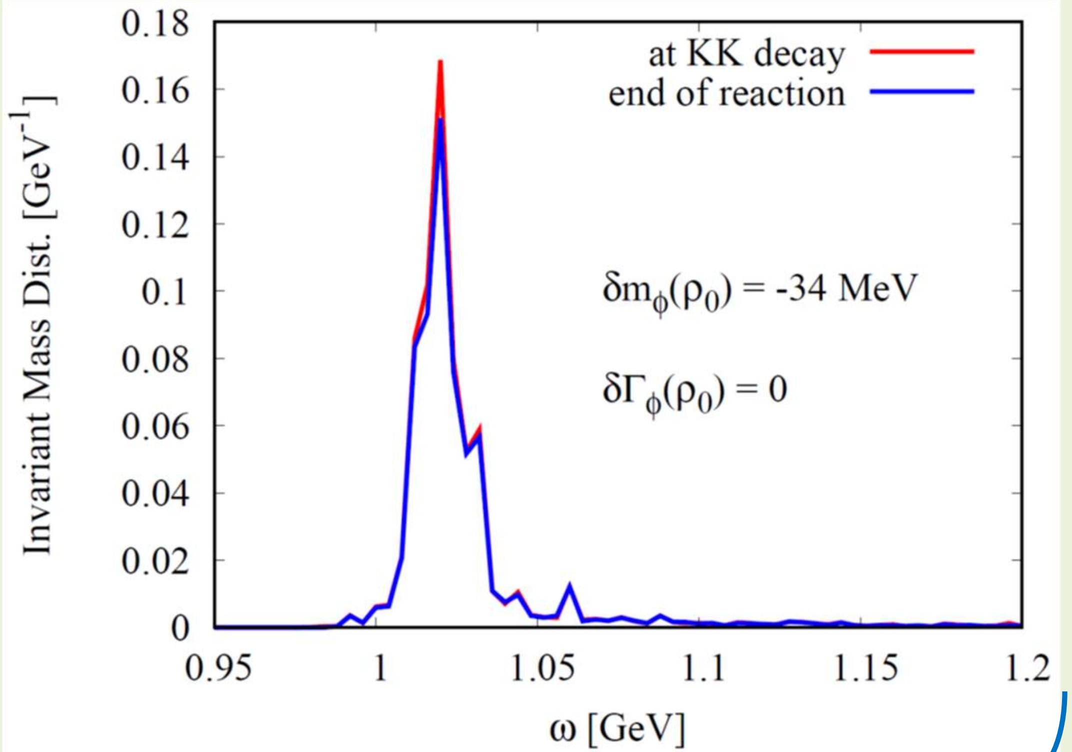
T. Song et al., Phys. Rev. C **103**, 044901 (2021).

See talk by Laura Tolos on Tuesday

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 !?