The phi meson in nuclear matter from dilepton and KK decay channels

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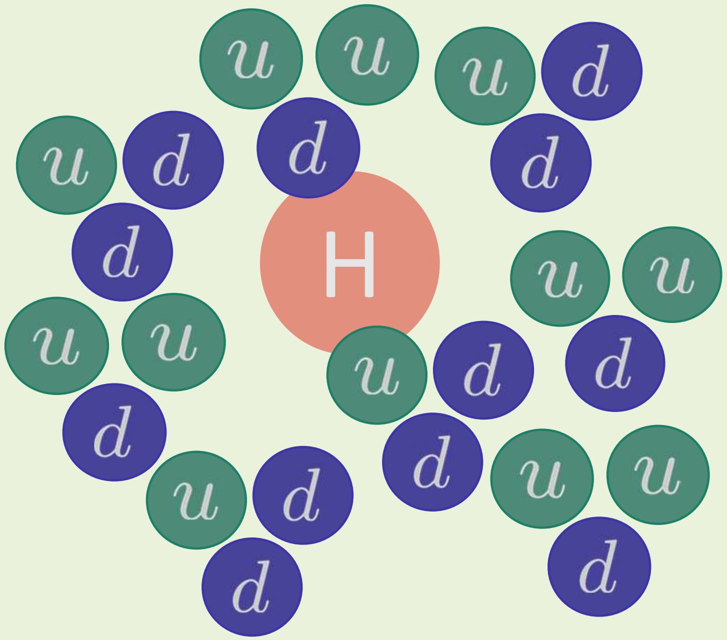
Talk at the Reimei Workshop “Hadrons in dense matter at J-PARC”
Tokai-mura, Japan/Online,
February 22, 2022

Based on work done in collaboration with
Elena Bratkovskaya (Frankfurt/GSI),
Taesoo Song (Frankfurt)
and ongoing discussions with
Su Houng Lee (Yonsei U.)
Hiroyuki Sako (JAEA)

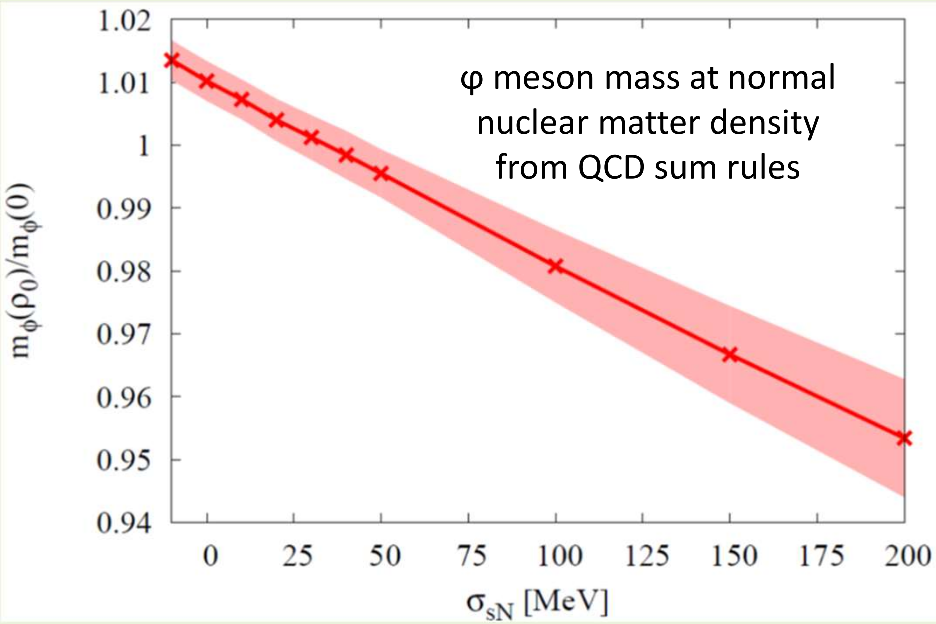
Why should we be interested?

$|\langle \overline{u}u \rangle_\rho|$ ↘
$|\langle \overline{d}d \rangle_\rho|$ ↘
$|\langle \overline{s}s \rangle_\rho|$ ↘

⟹ m_H ↘ ?



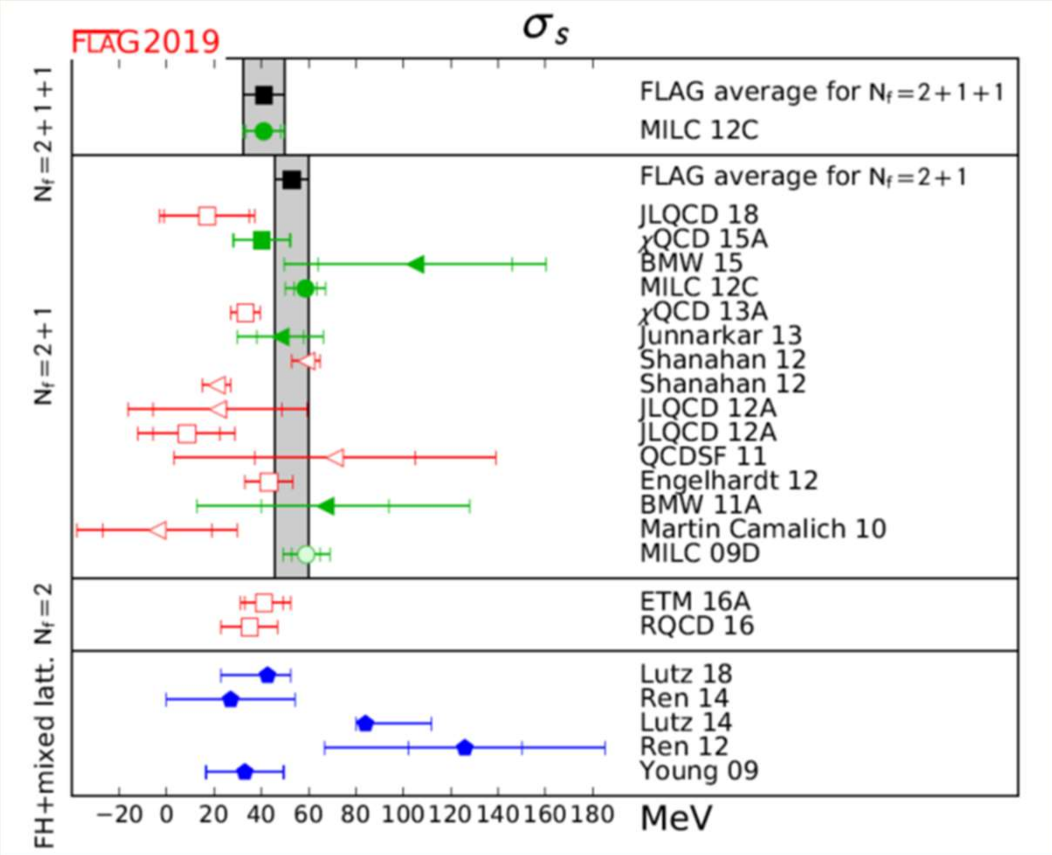
P. Gubler and K. Ohtani, Phys. Rev. D **90**, 094002 (2014).



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

What does lattice QCD say about the strange sigma term?

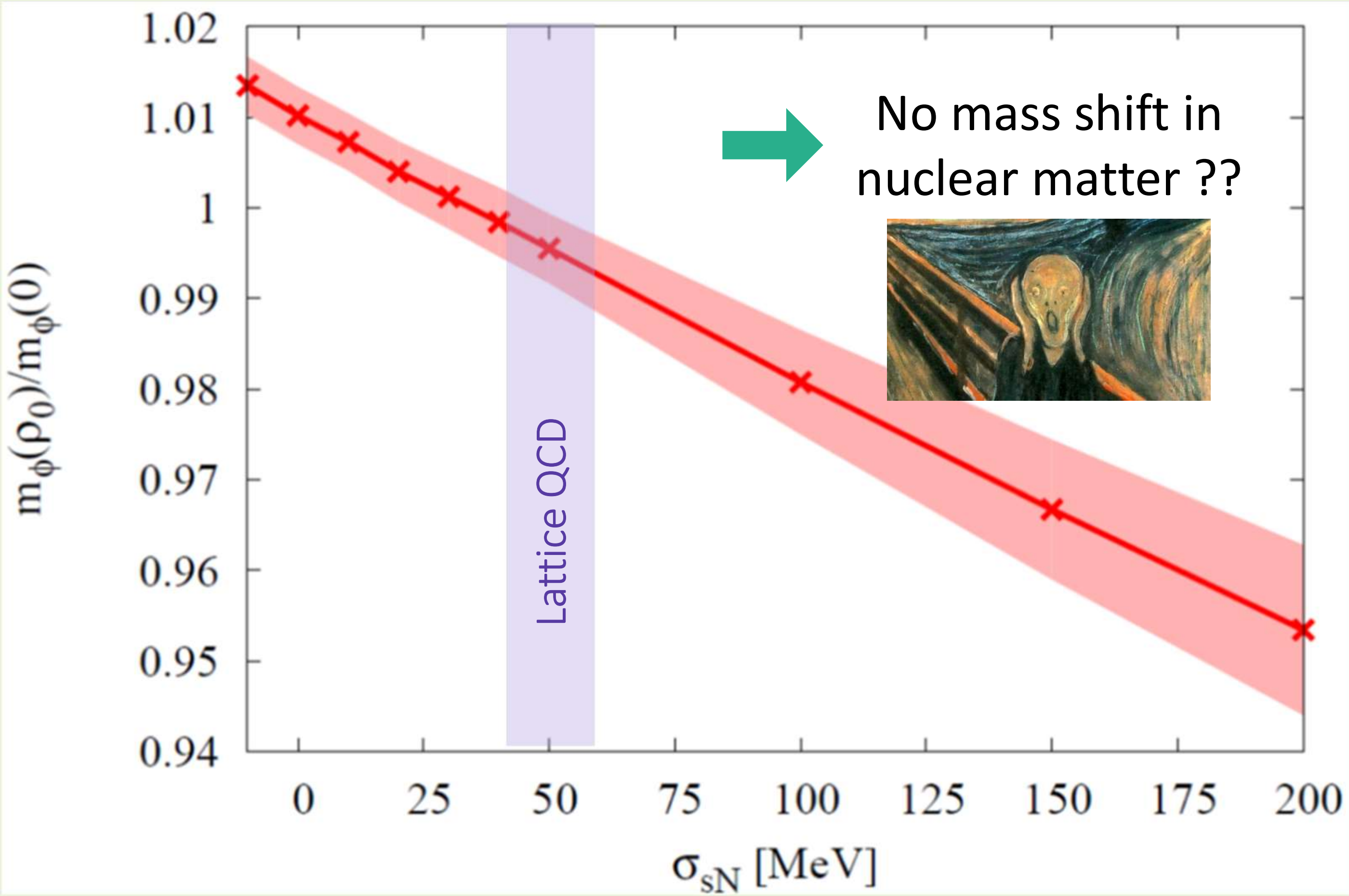
$$\sigma_{sN} = m_s \langle N | \bar{s} s | N \rangle$$



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

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

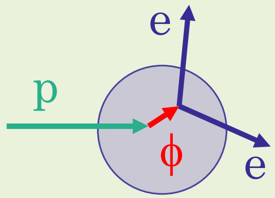
Combine QCD sum rules with lattice QCD



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

Previous experimental results

KEK
E325



12 GeV
pA-reaction

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

0.034 ± 0.007

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

2.6 ± 1.5

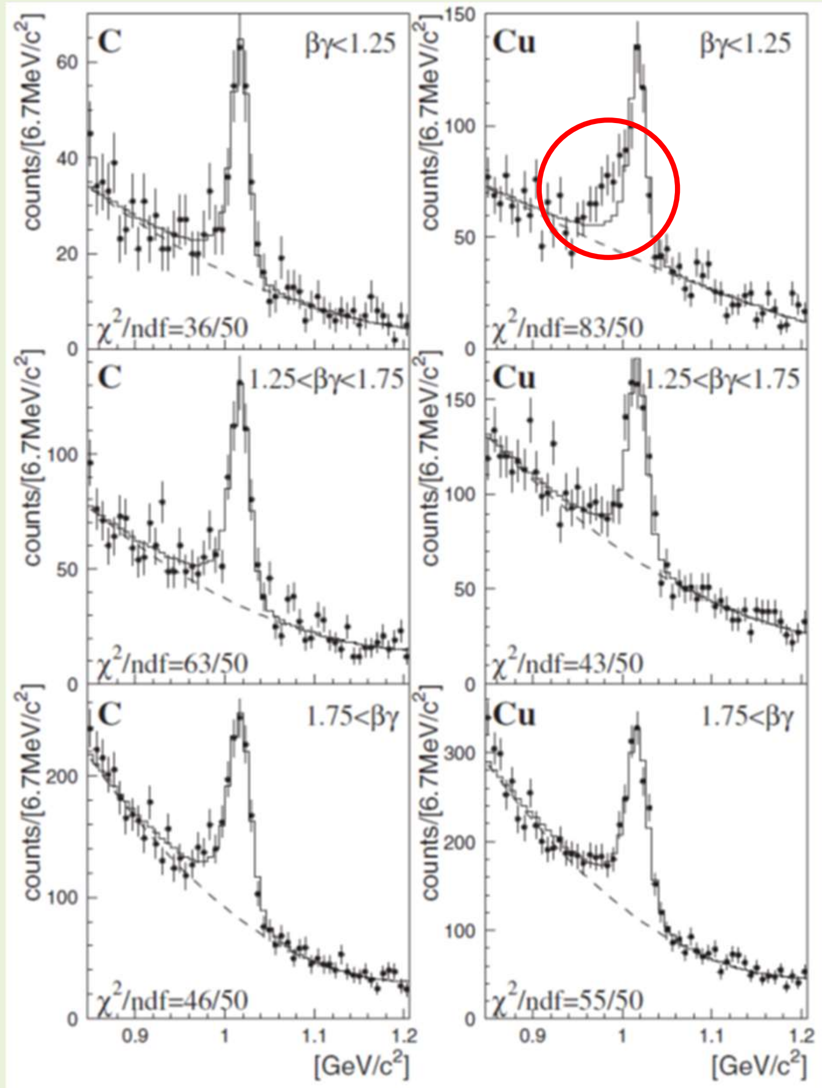
Measurement is being repeated with
~100x increased statistics at the
J-PARC E16 experiment!

slow φs

intermediate
φs

fast φs

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

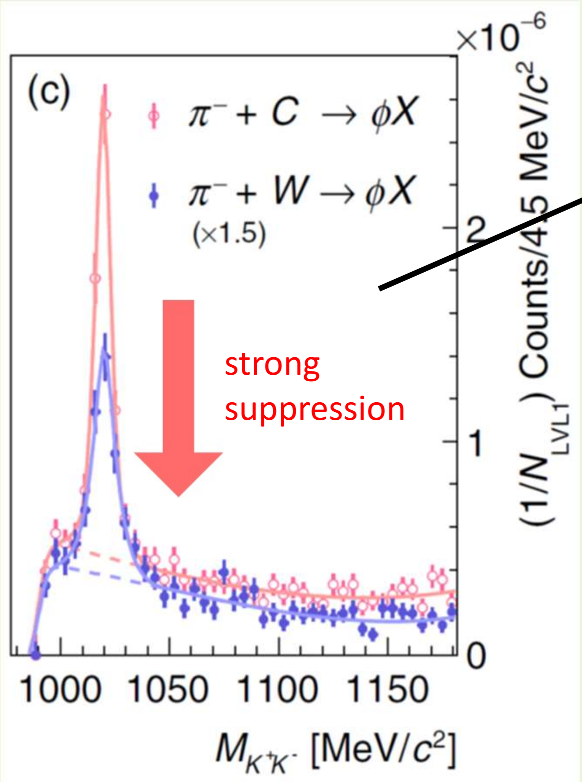


R. Muto et al. (E325 Collaboration), Phys. Rev. Lett. **98**, 042501 (2007).

More recent experiments

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).

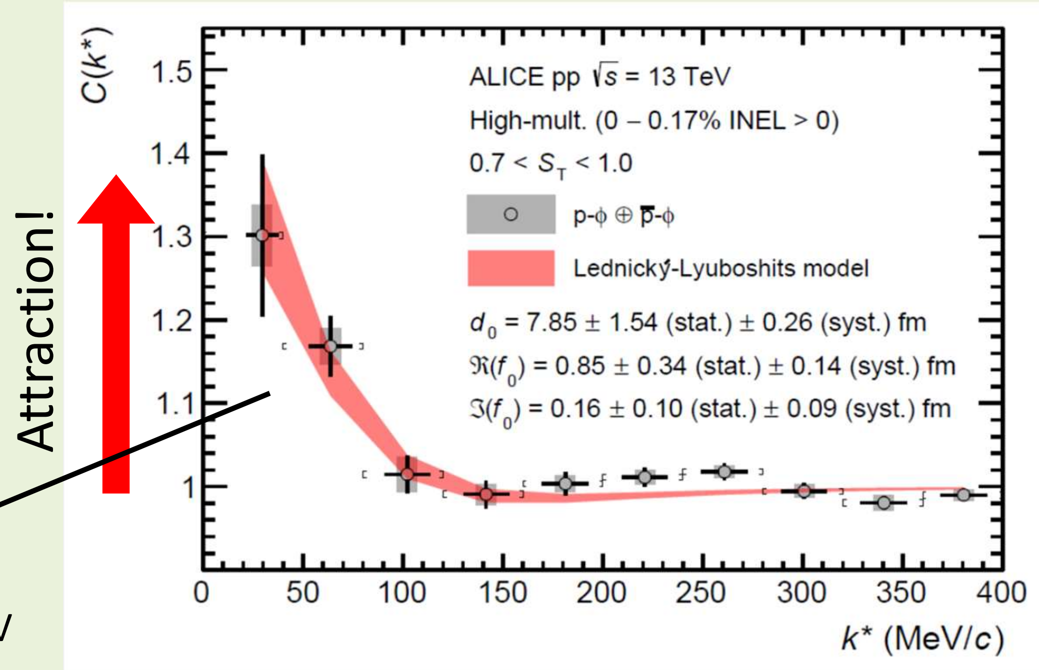
Broadening ?

Negative
mass shift

(-40 MeV ~ -70 MeV
at ρ_0??)

ALICE: pp

Measurement of φN correlation

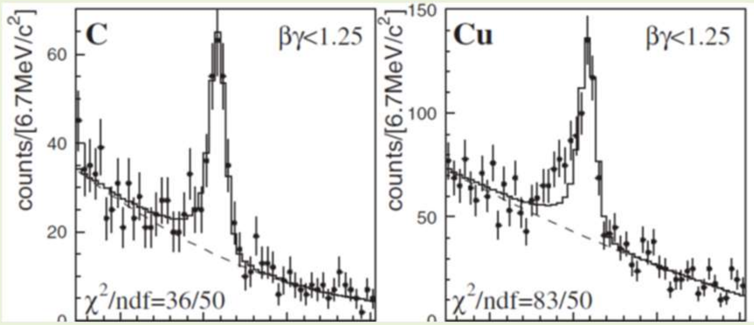


S. Acharya et al. (ALICE Coll.),
Phys. Rev. Lett. **127**, 172301 (2021).

How compare theory with experiment?

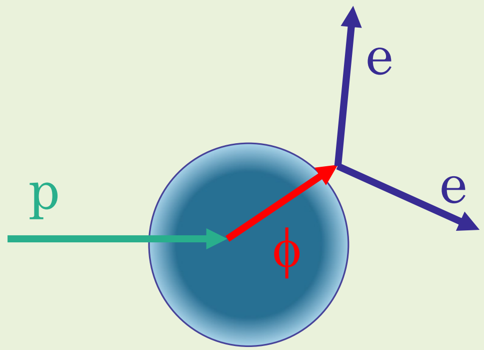
Information useful for theory

Experimental data



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

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:

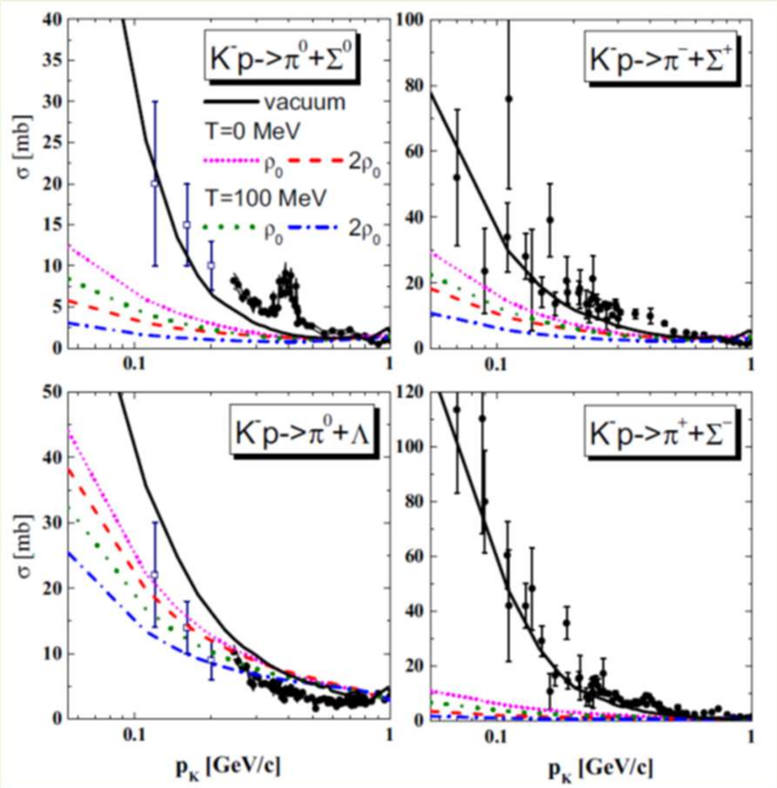
$$\frac{d\vec{X}_i}{dt} = \frac{1}{1-C_{(i)}} \frac{1}{2\varepsilon_i} \left[2\vec{P}_i + \vec{\nabla}_{P_i} \mathrm{Re}\, \Sigma^{\mathrm{ret}}_{(i)} + \frac{\varepsilon_i^2 - \vec{P}_i^2 - M_0^2 - \mathrm{Re}\, \Sigma^{\mathrm{ret}}_{(i)}}{\tilde{\Gamma}_{(i)}} \vec{\nabla}_{P_i} \tilde{\Gamma}_{(i)}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

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

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

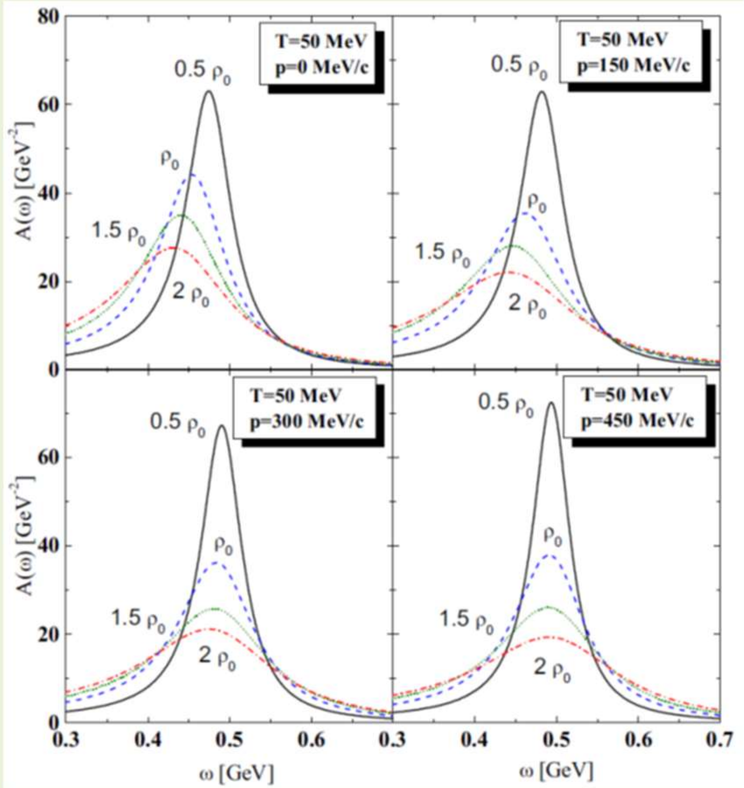
Treatment of KN-interactions

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



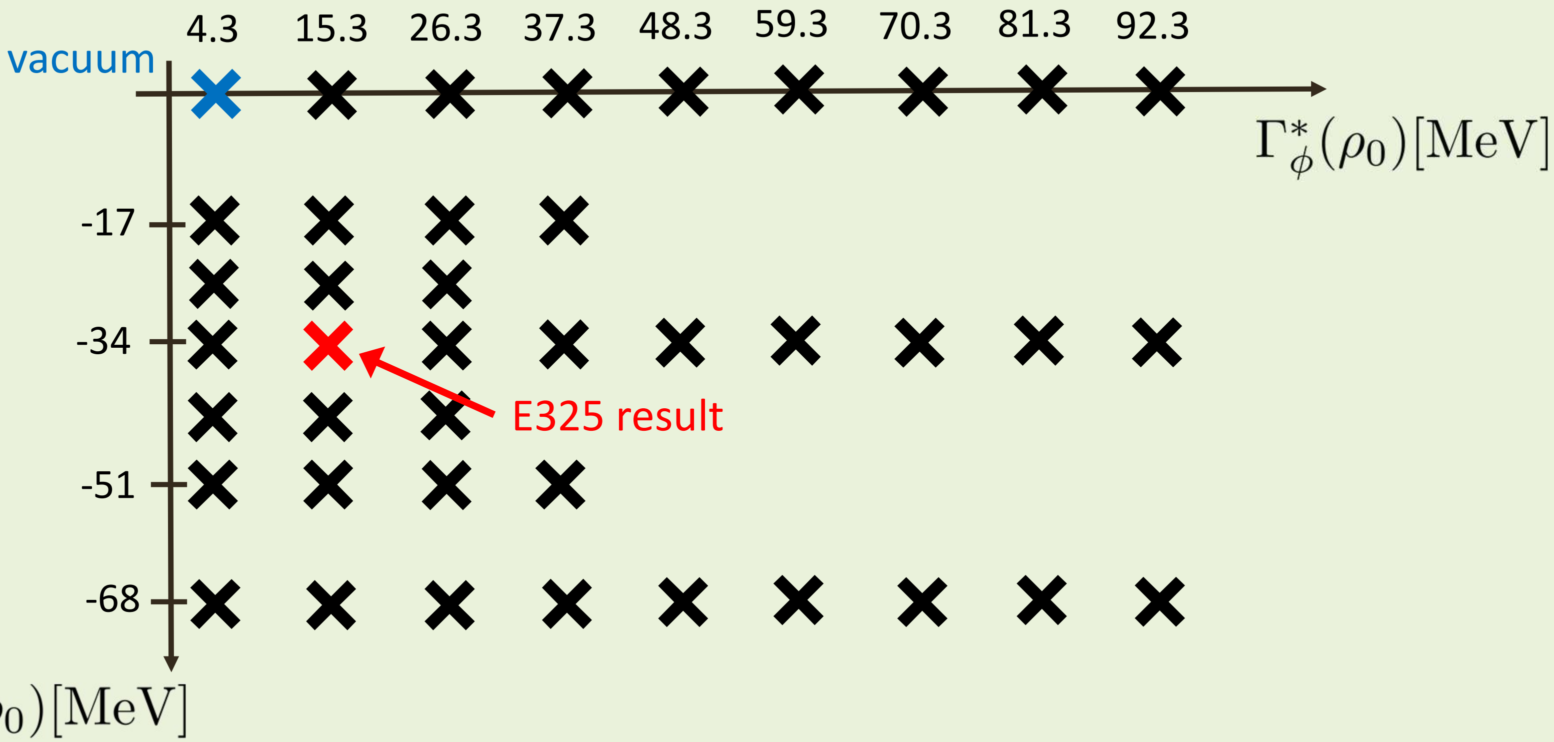
T. Song et al., Phys. Rev. C **103**, 044901 (2021). → See talk later in this session by Taesoo Song

Advantage: vector meson spectra can be chosen freely

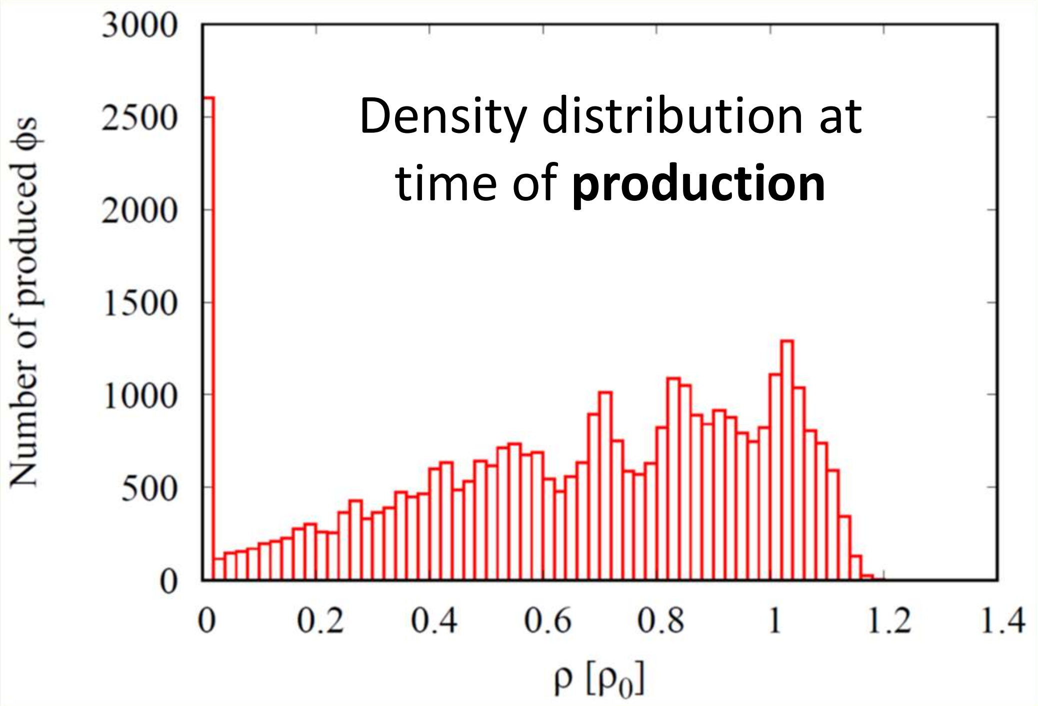
Our choice: a Breit-Wigner with density dependent mass and width

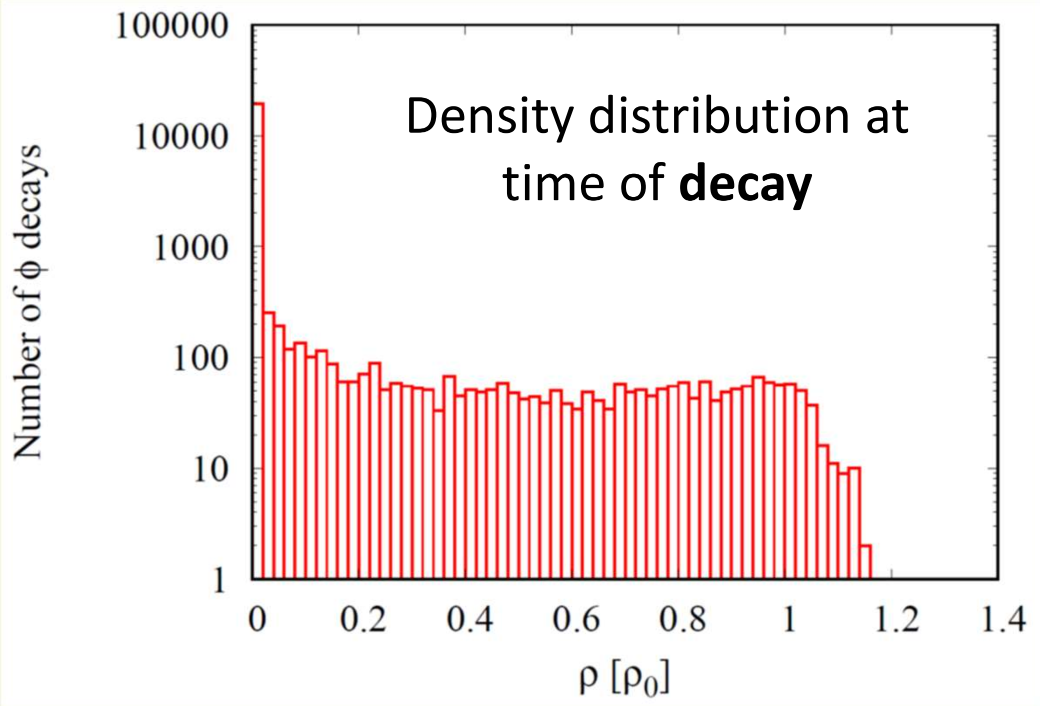
$$A_\phi(M,\rho) = C\,\frac{2}{\pi}\,\frac{M^2\Gamma^*_\phi(M,\rho)}{[M^2-M^{*2}_\phi(\rho)]^2+M^2\Gamma^{*2}_\phi(M,\rho)} \quad \text{with} \quad \begin{cases} M^*_\phi(\rho) = M^{\mathrm{vac}}_\phi\left(1-\alpha^\phi\frac{\rho}{\rho_0}\right), \\ \Gamma^*_\phi(M,\rho) = \Gamma^{\mathrm{vac}}_\phi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

Simulated scenarios:



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

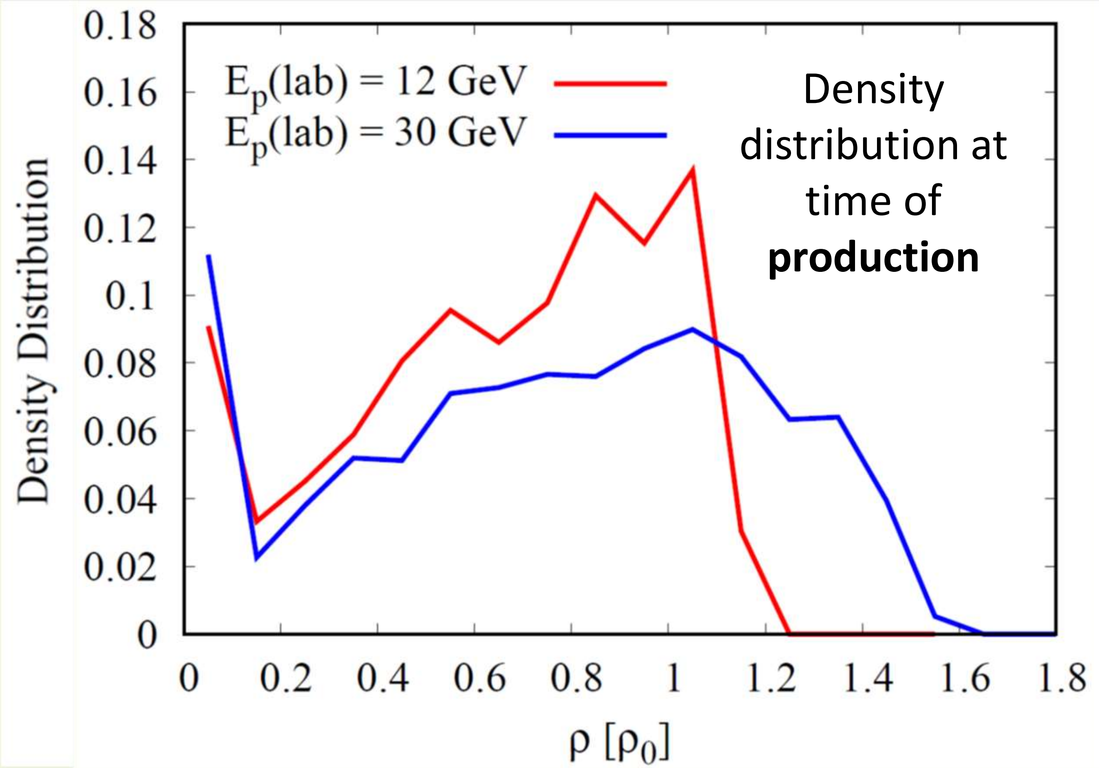


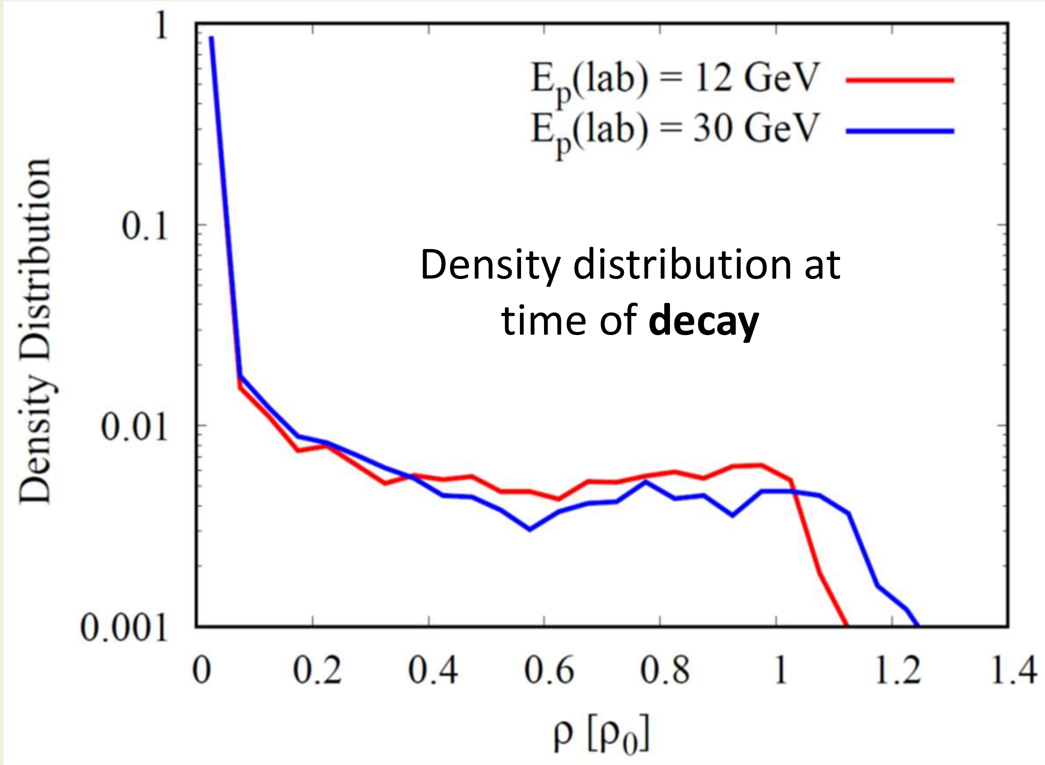


Majority of φ mesons are produced at densities around ρ_0

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

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

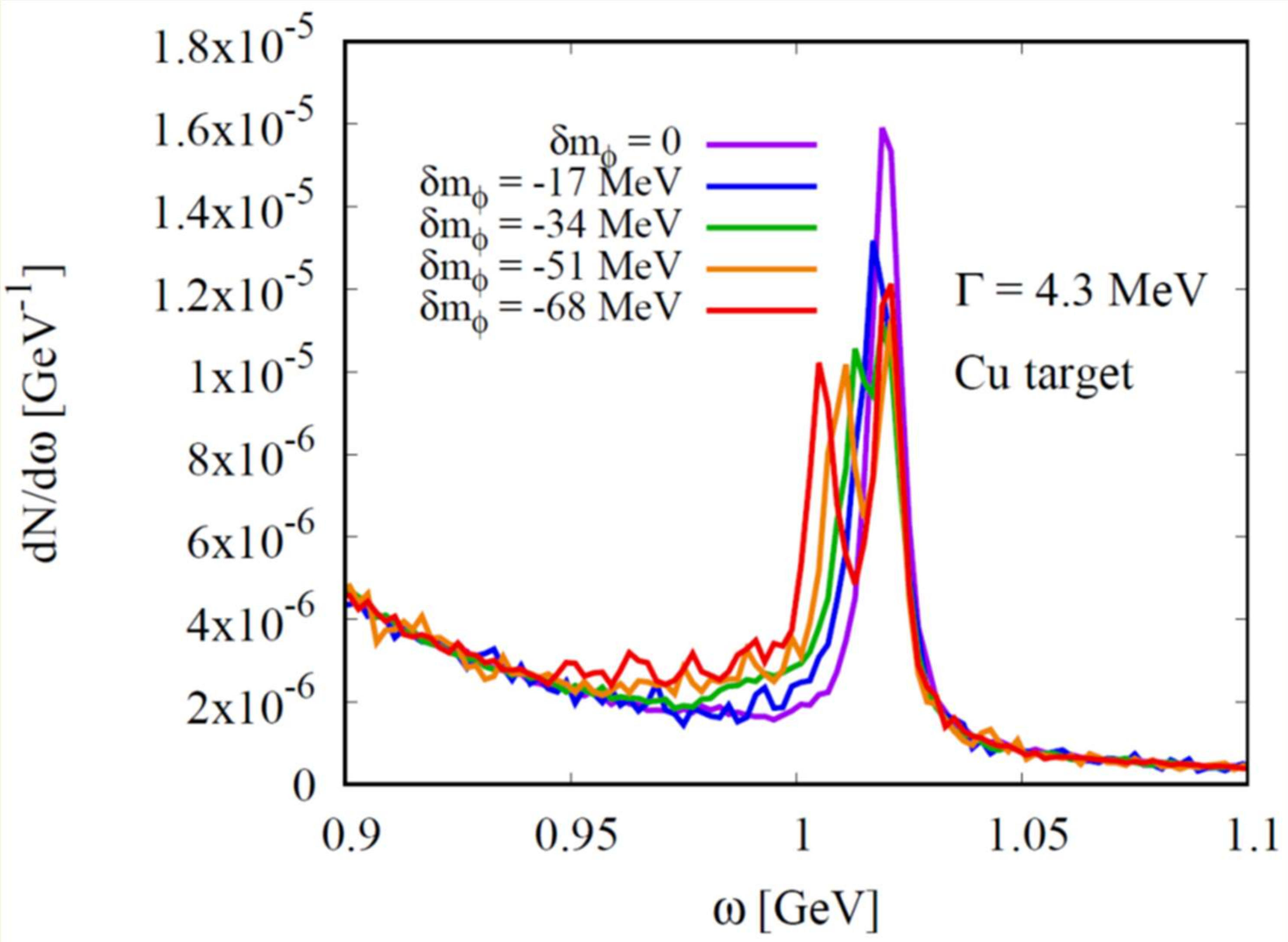




Larger densities are reached for larger incoming proton energy

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

The dilepton spectrum in the φ meson region



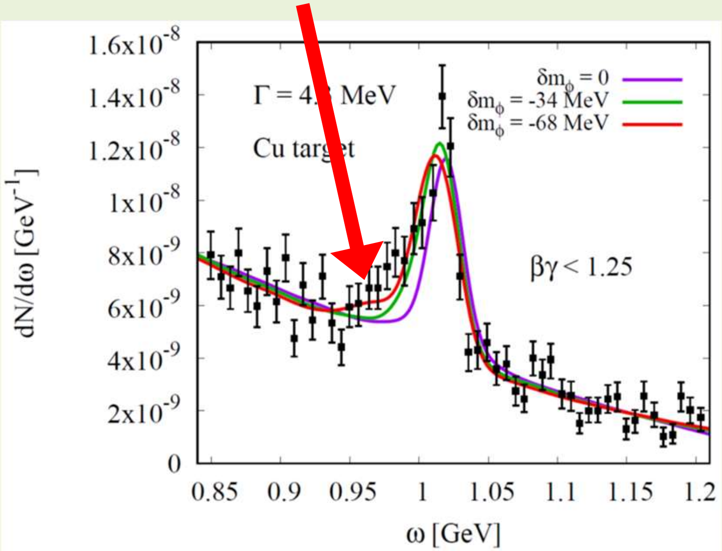
p + Cu at 12 GeV

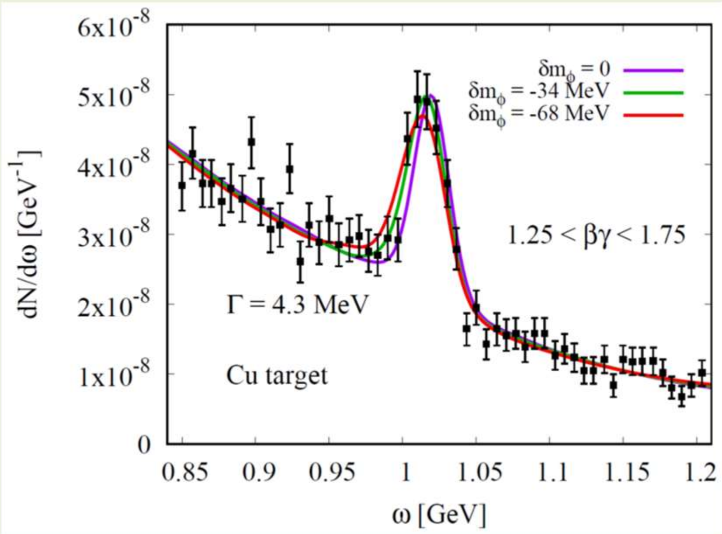
No acceptance corrections!

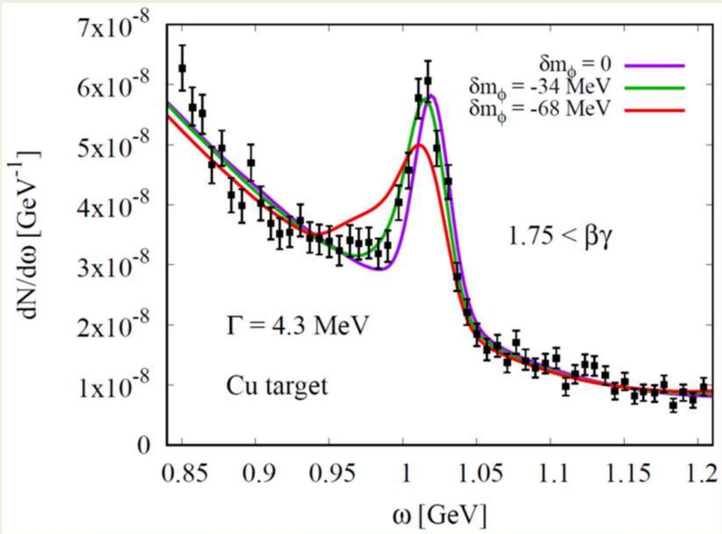
No finite resolution effects!

Fits to experimental Copper target data (E325)

A significant negative mass shift is needed to reproduce the slow φ data







slow φs

Favors relatively large negative mass shift

intermediate φs

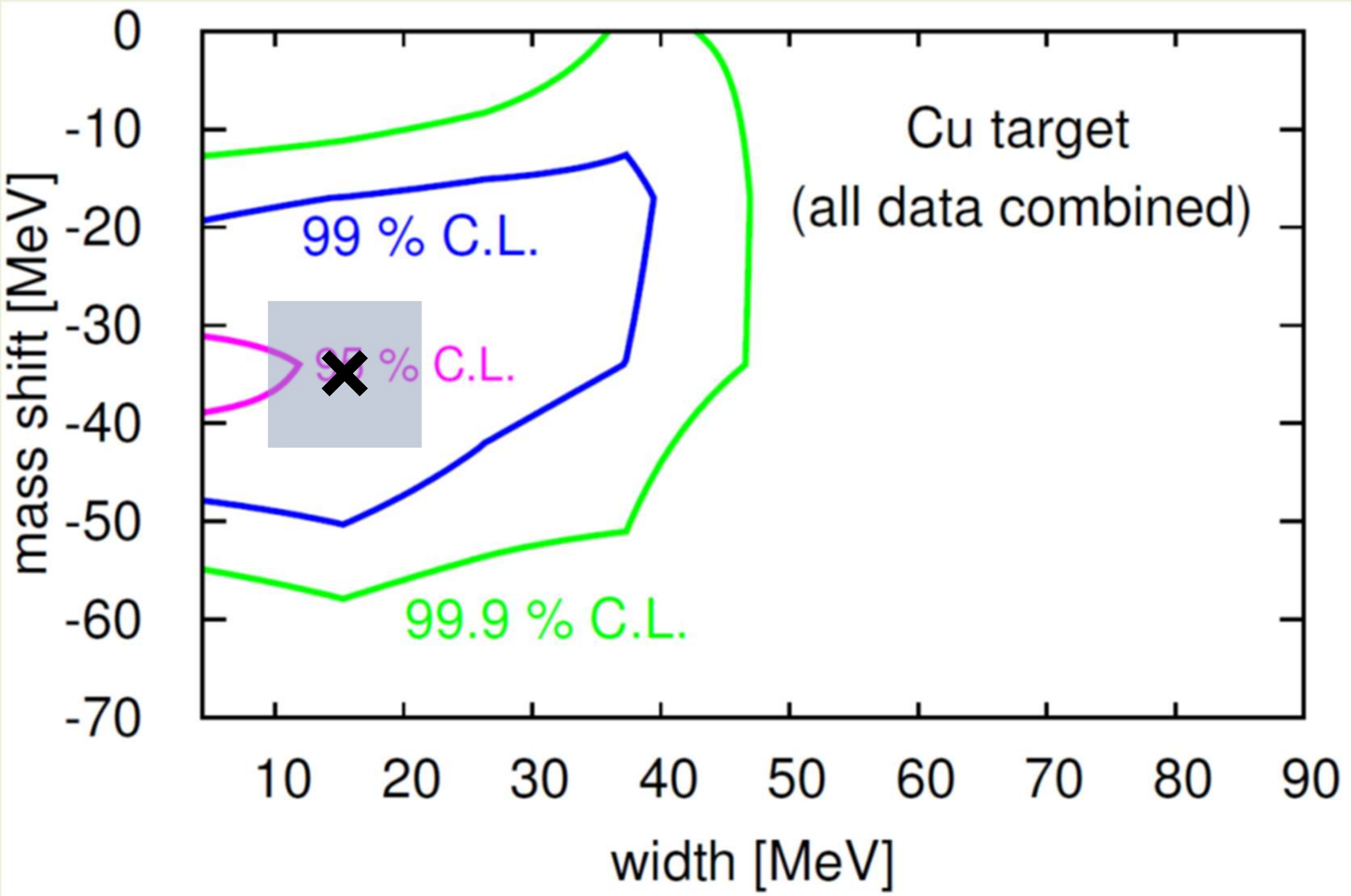
No strong constraints for any modification scenario

fast φs

Favors small mass shift

Fits to experimental Copper target data (E325)

Confidence levels of combined Copper data



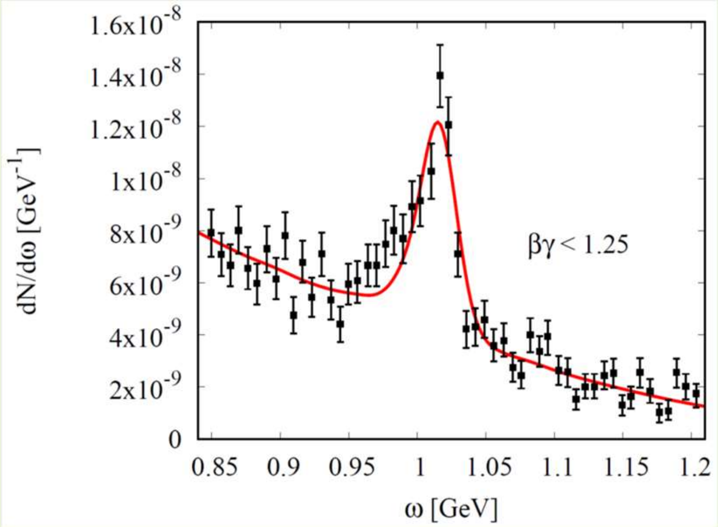
Conclusion of the E325 Collaboration

Best fit to E325 data

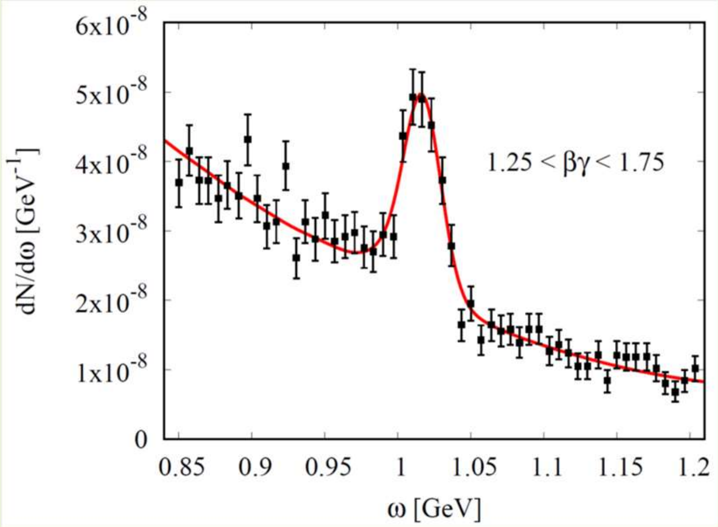
(p + Cu at 12 GeV)

vacuum value

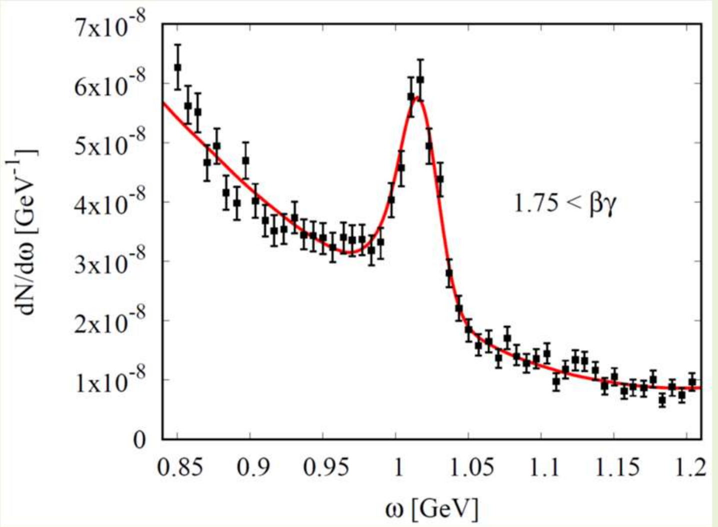
$$\delta m_\phi(\rho_0) = -34\,\mathrm{MeV} \qquad \Gamma(\rho_0) = 4.3\,\mathrm{MeV}$$



slow φs



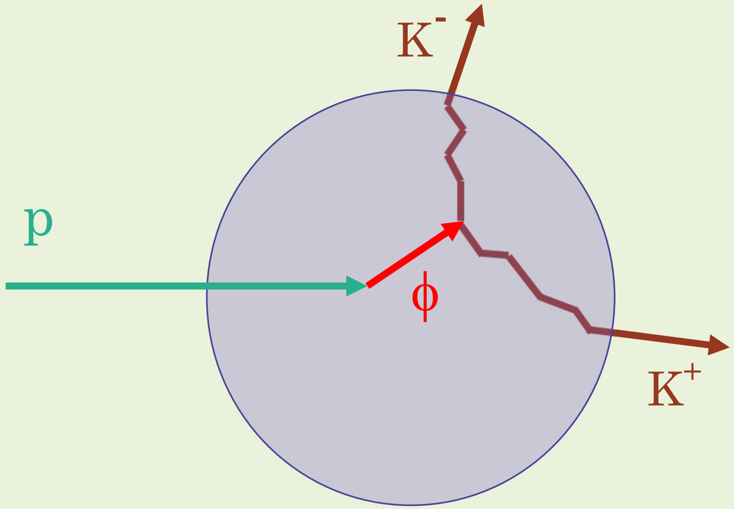
intermediate φs

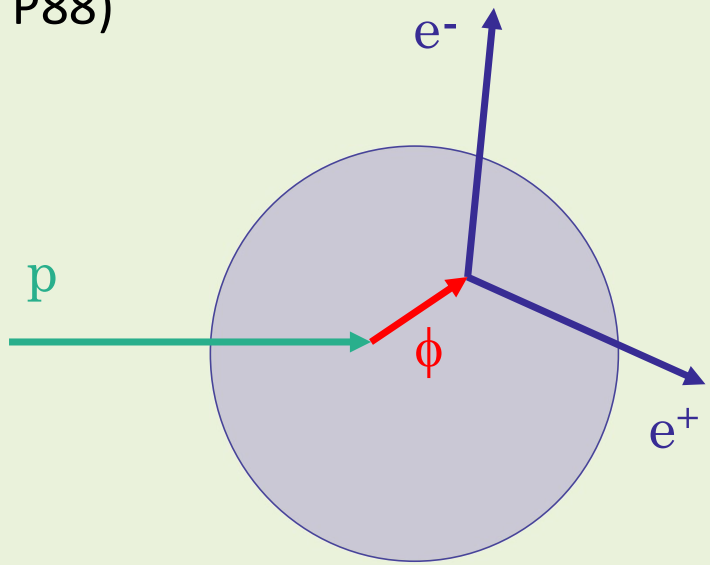


fast φs

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

(new J-PARC proposal P88)

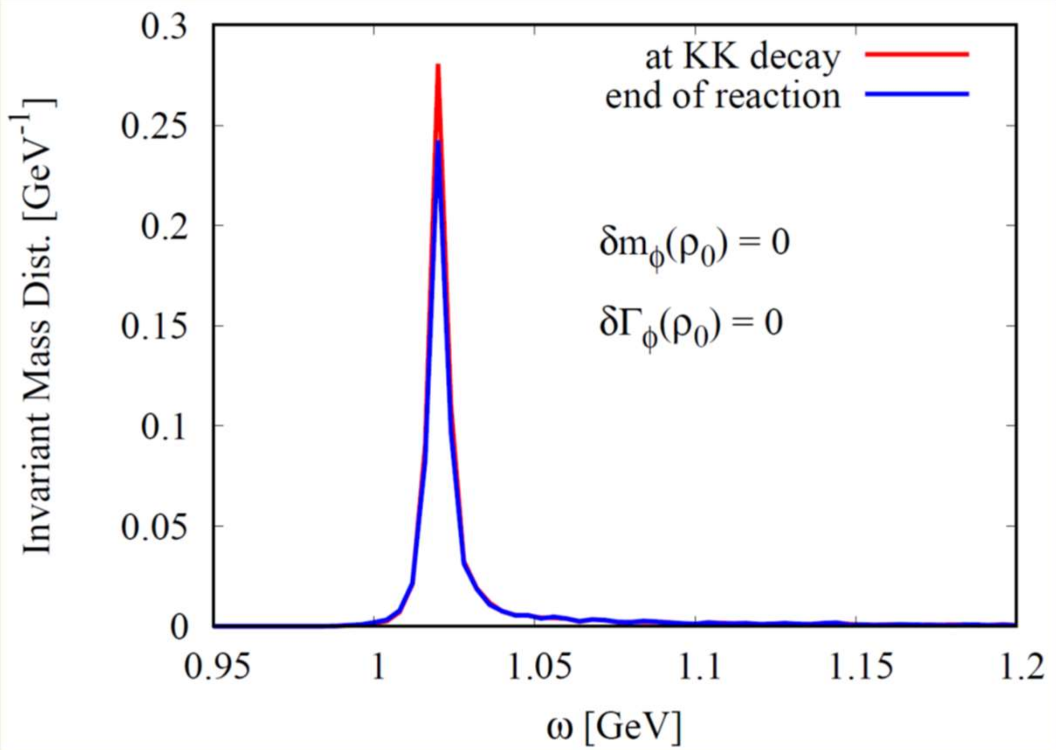


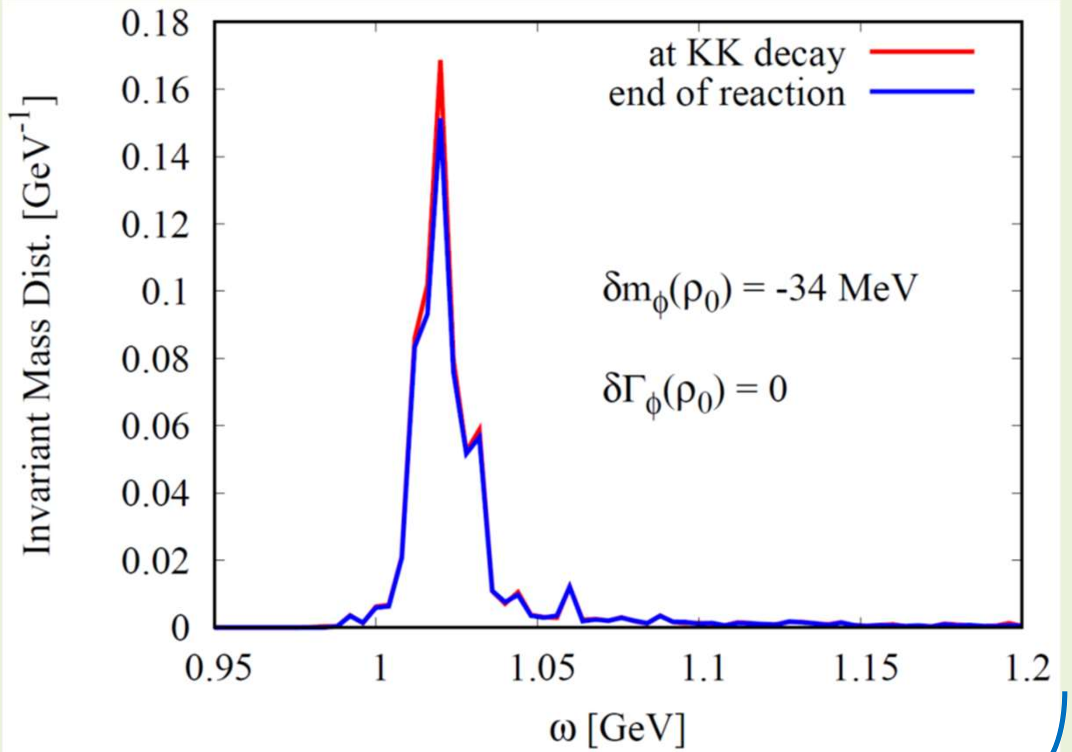


Kaons feel the strong interaction	➡	Distorted in-medium φ meson signal	✗		Kaons do not feel the strong interaction	➡	Clear in-medium φ meson signal	○
Large branching ratio	➡	Good statistics	○		Small branching ratio	➡	Bad statistics	✗

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

(p + Cu at 30 GeV)



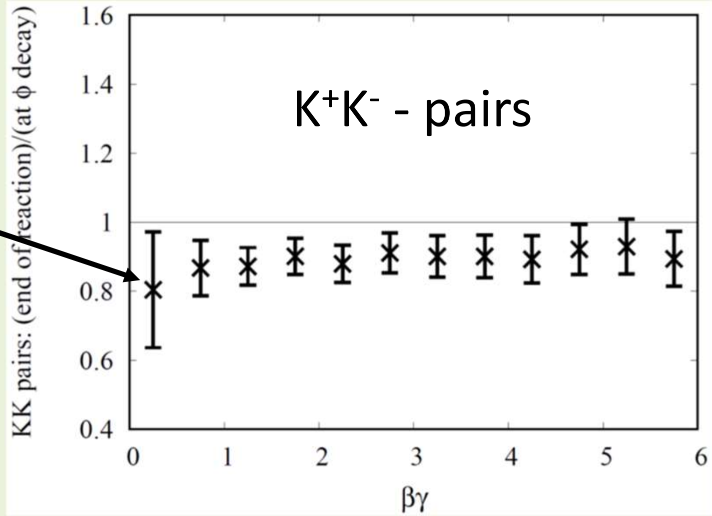


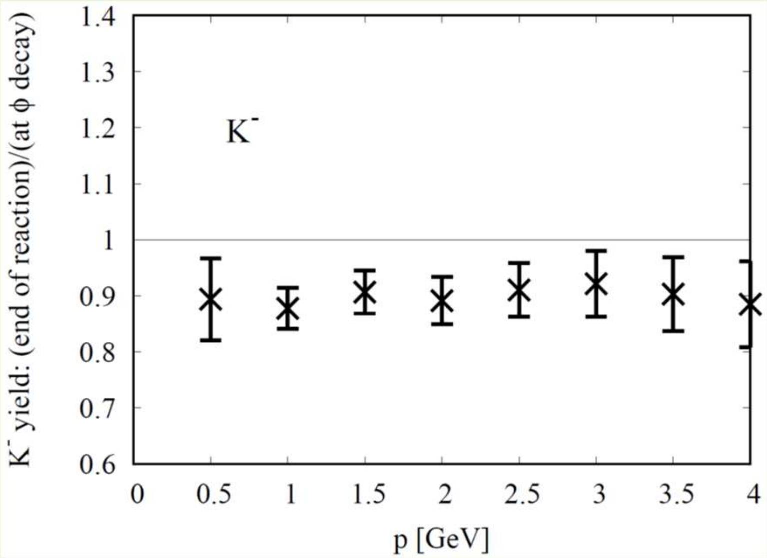
Small distortion effect from the strong KN interaction !?

Absorption of kaons in nuclear matter

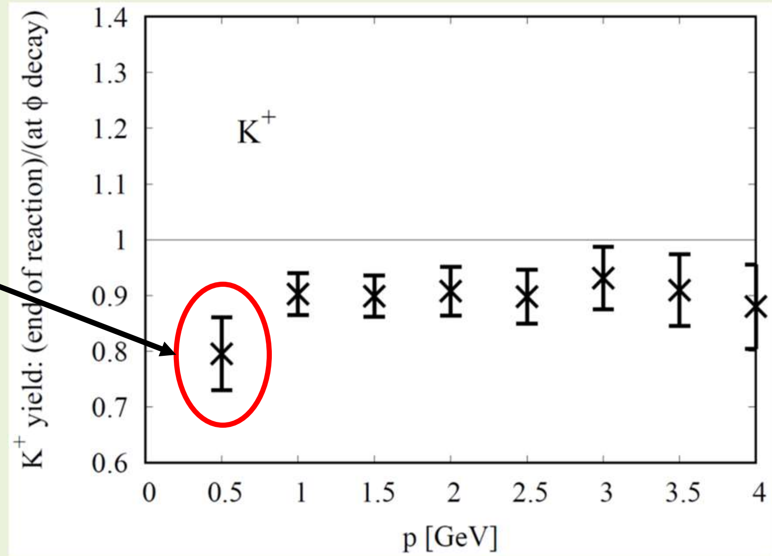
(p + Cu at 30 GeV)

Stronger absorption for lower momenta

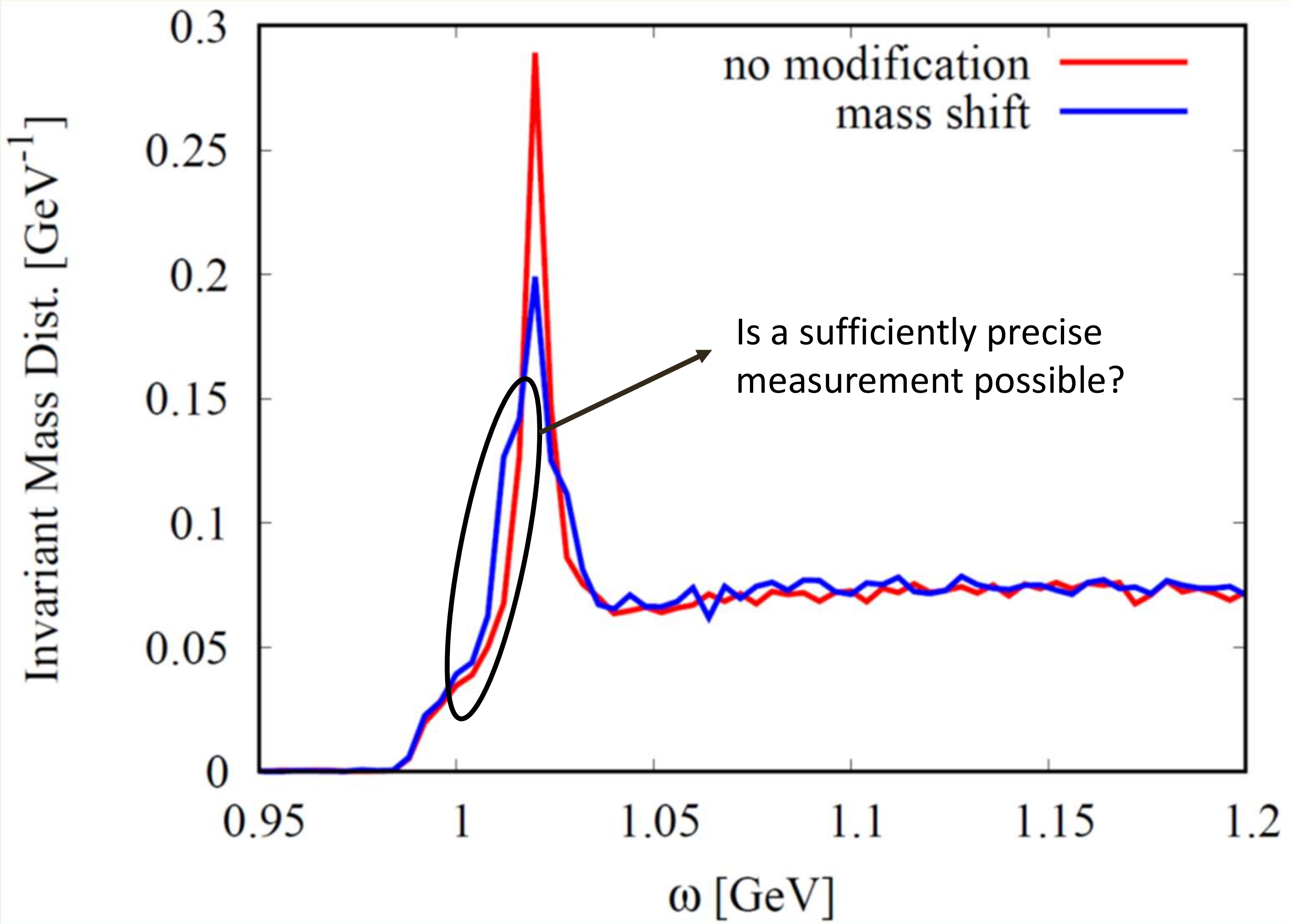




Suppression due to repulsive K^+N interaction??



Expected K^+K^- invariant mass spectrum (incl. background)



p + Cu at 30 GeV

No acceptance corrections!

No finite resolution effects!

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

↓

Our results indicate that the experimental data favor a **negative mass shift with zero or only small broadening**!

★ New J-PARC proposal P88 to measure the φ meson K^+K^- decay channel

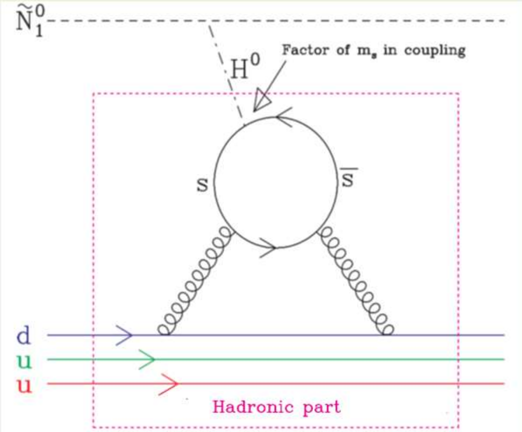
→ Distortion effects due to the strong KN interaction appears to be small

Backup slides

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)

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

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

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

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

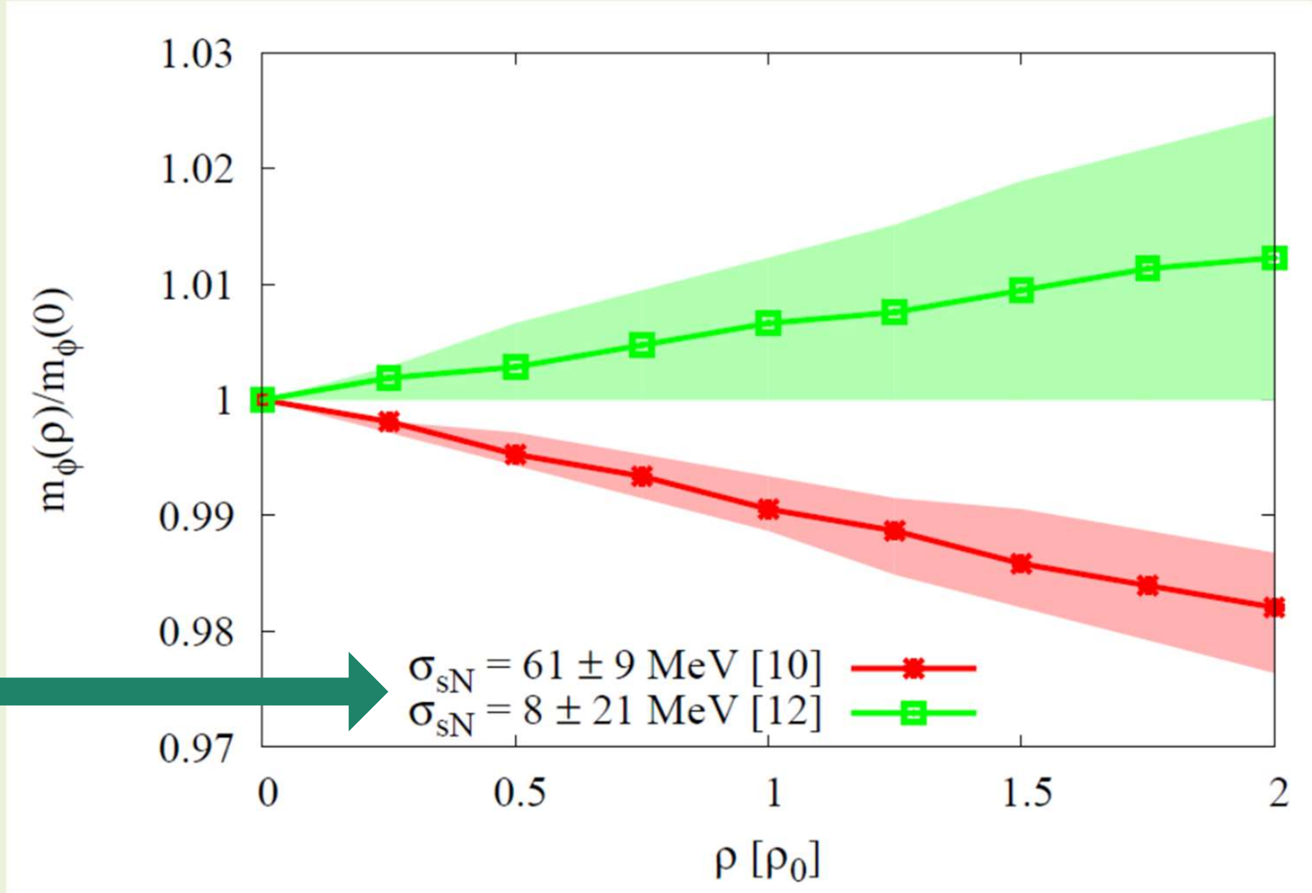
Dim. 6: $c_6(\rho) = c_6(0) + \rho[-\frac{896}{81}\kappa_N \pi^3 \alpha_s\langle\overline{s}s\rangle\langle N|\overline{s}s|N\rangle - \frac{5}{6}A_4^s M_N^3]$

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).

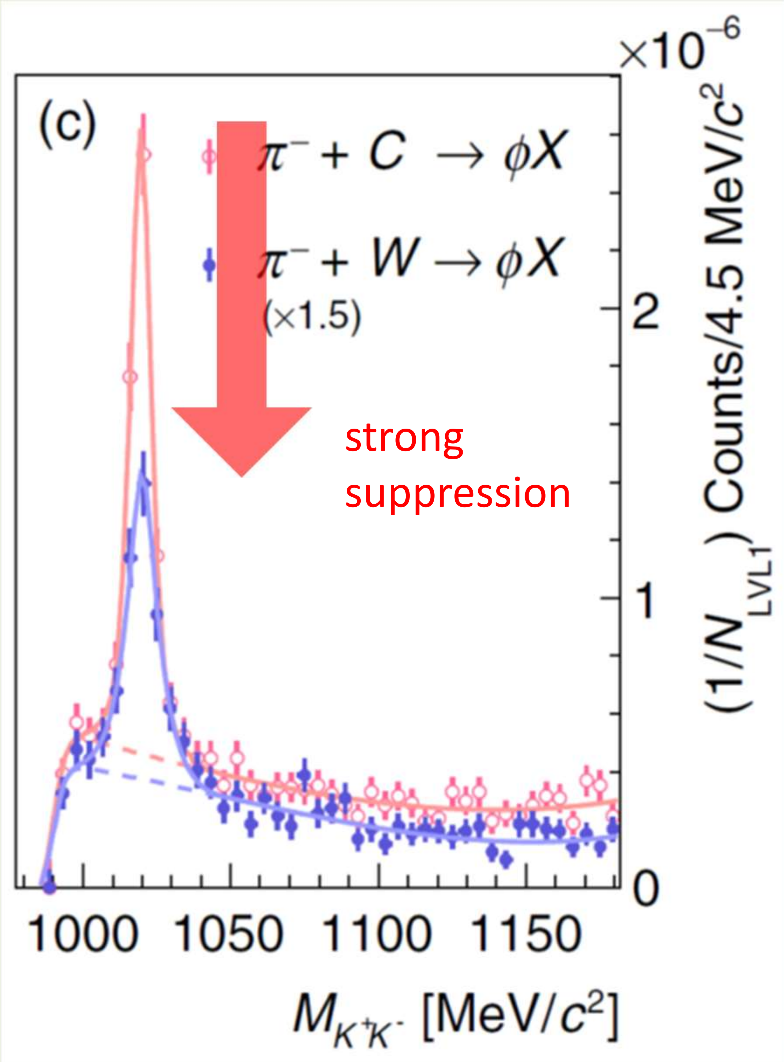
Recent experimental results

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

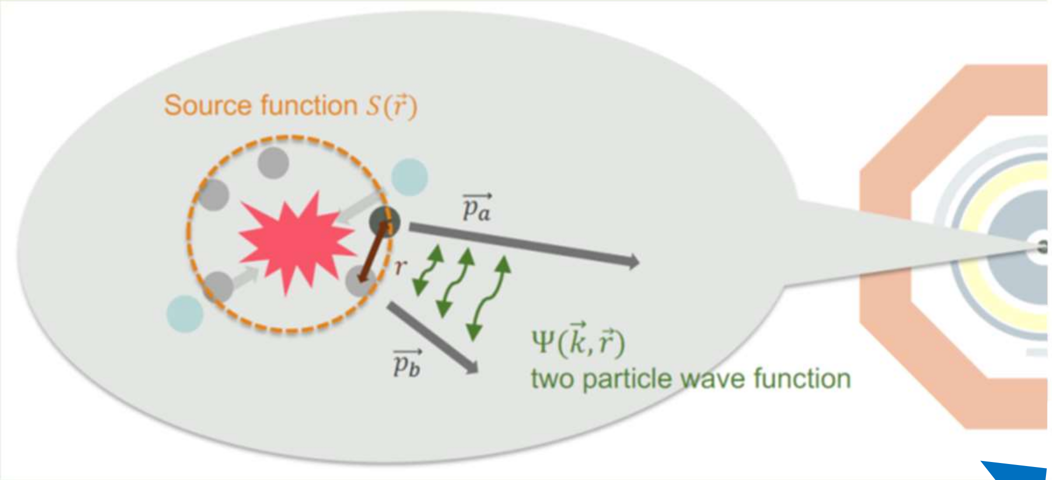
K^+K^- - invariant mass spectrum



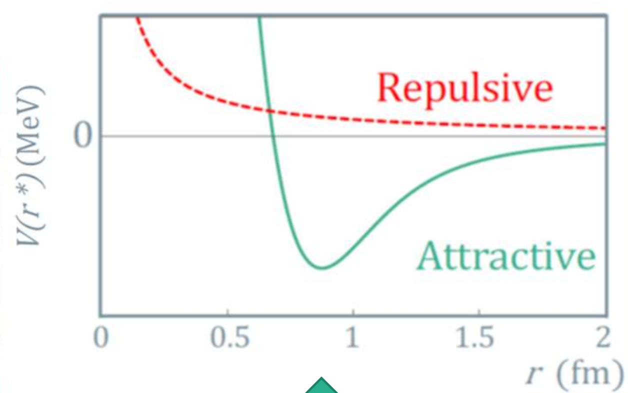
J. Adamczewski-Musch et al. (HADES Collaboration), Phys. Rev. Lett. **123**, 022002 (2019).

New experimental results

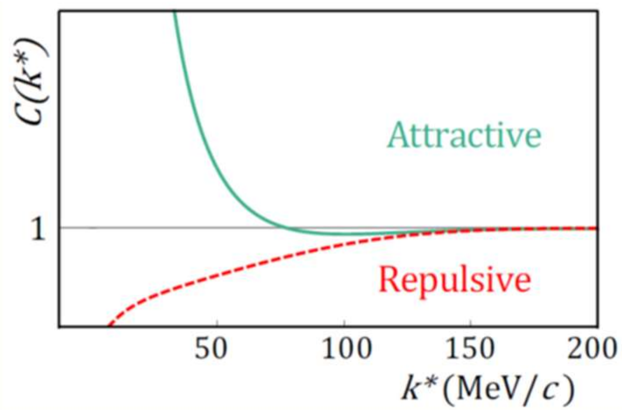
ALICE (Femtoscopy)



Interaction potential



Correlation function



The observable to be measured: the correlation function:

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

Emission source (Gaussian)

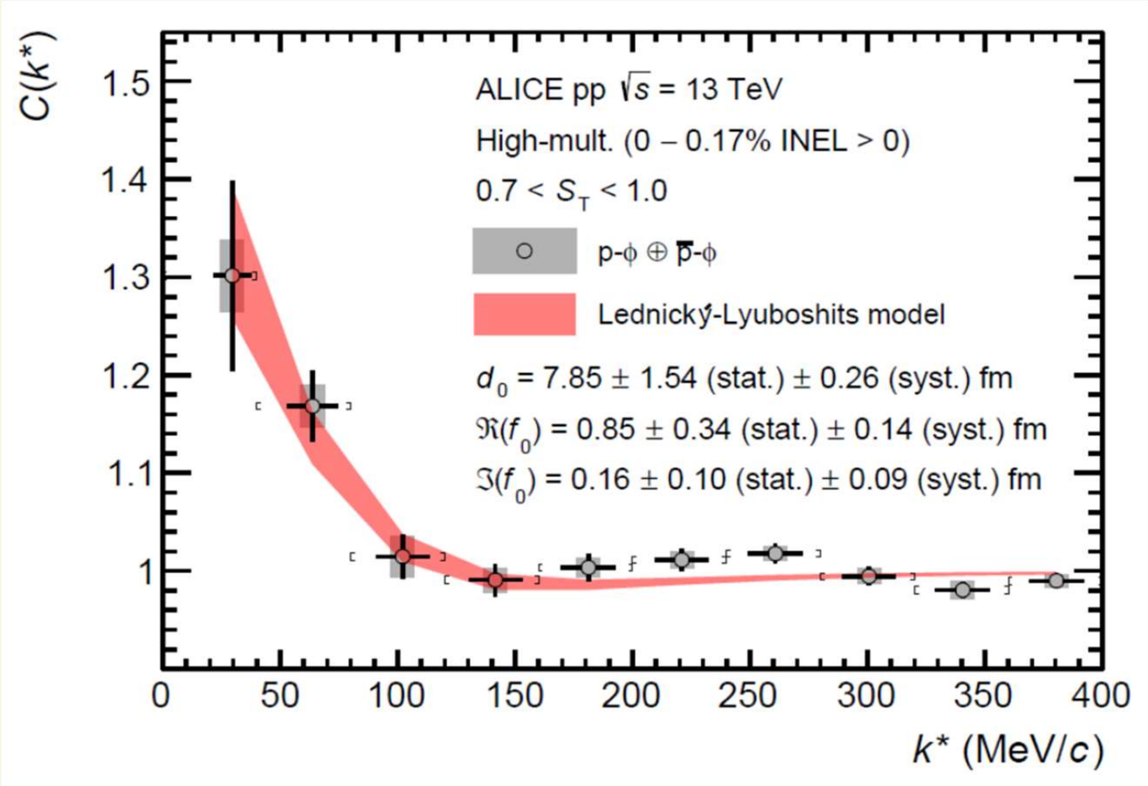
Relative momentum of the particle pair

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Includes mean field (tuned to reproduce nuclear matter properties)

particle distribution function

Basic Ingredient 2: „Testparticle“ approach

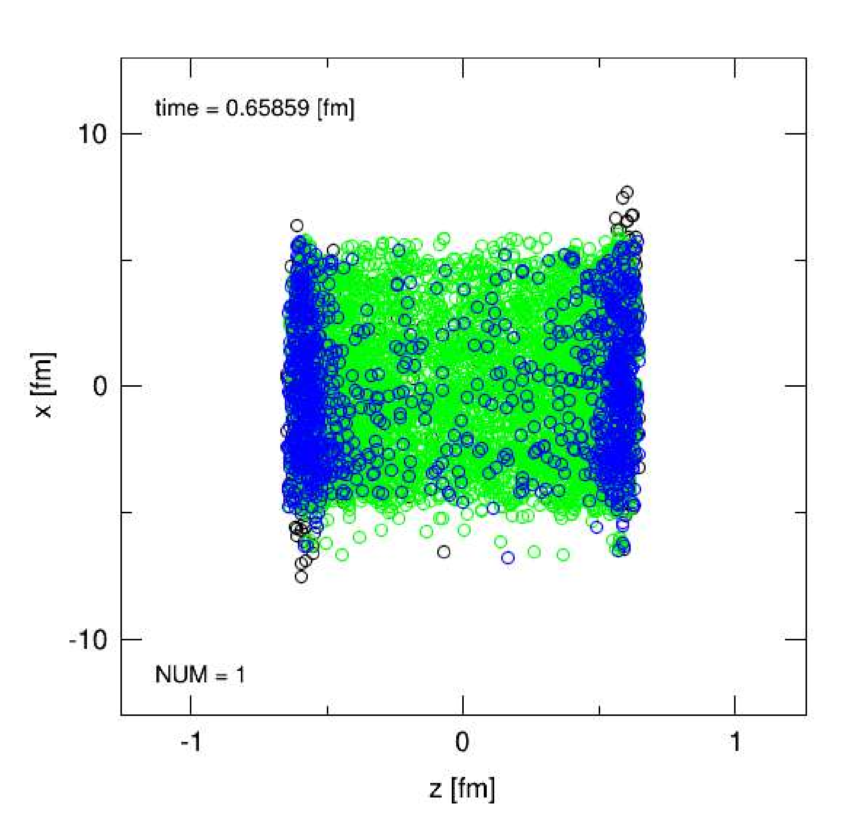
$$f_h(\boldsymbol{r}, \boldsymbol{p}; t) = \frac{1}{N_{\mathrm{test}}} \sum_{i}^{N_h(t) \times N_{\mathrm{test}}} \delta(\boldsymbol{r} - \boldsymbol{r}_i(t))\, \delta(\boldsymbol{p} - \boldsymbol{p}_i(t))$$

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

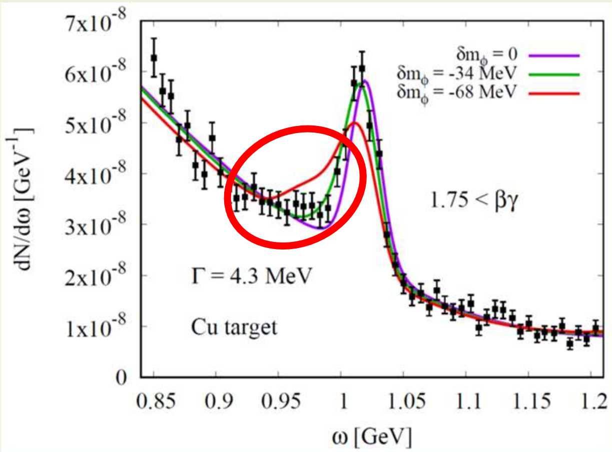
Fit to experimental data is necessary!

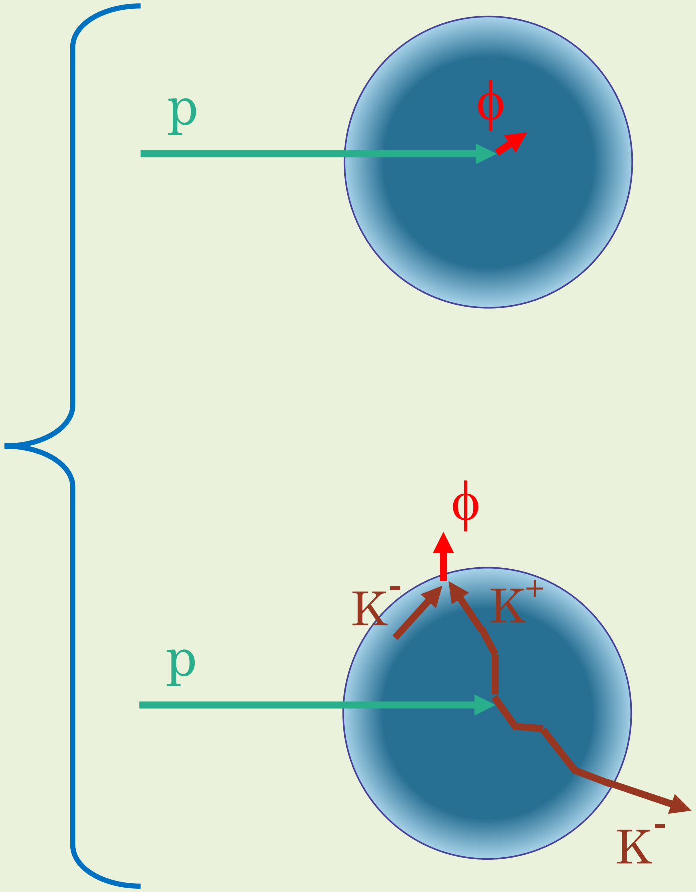
Dilepton spectrum: $$\rho(\omega) = \overbrace{a\omega^2 + b\omega + c}^{\text{Background}} + \overbrace{A\rho_{\phi,\mathrm{HSD}}(\omega)}^{\phi\text{ meson signal}}$$

Fitted to the experimental dilepton spectrum independently for each βγ-region

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

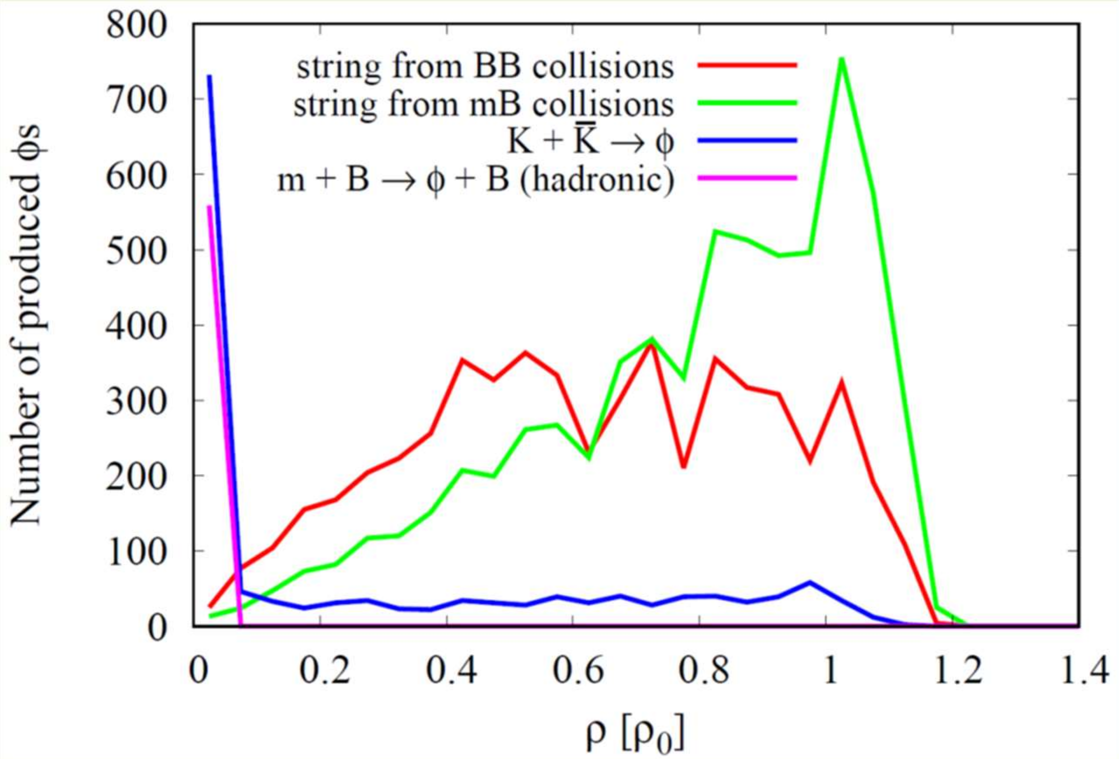
φ mesons are generated from low energy hadronic collisions

small momentum

low density

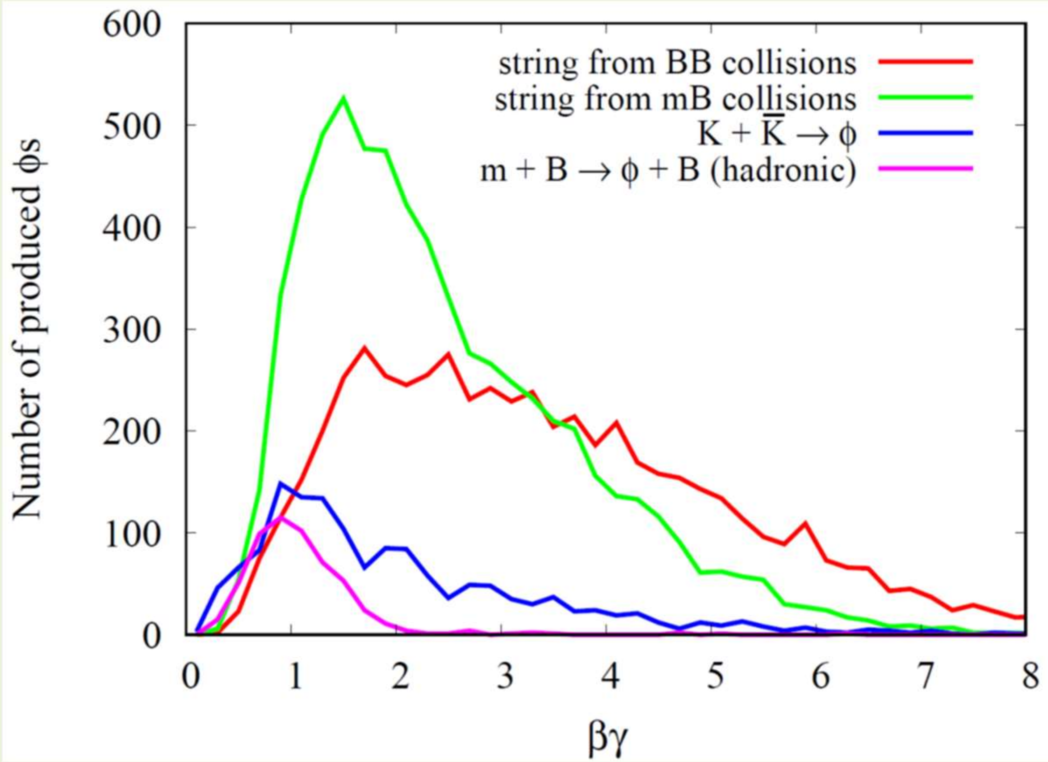
Density and βγ distributions for the different production mechanisms

Density distribution at production



Low energy hadronic production occurs dominantly at the nuclear surface

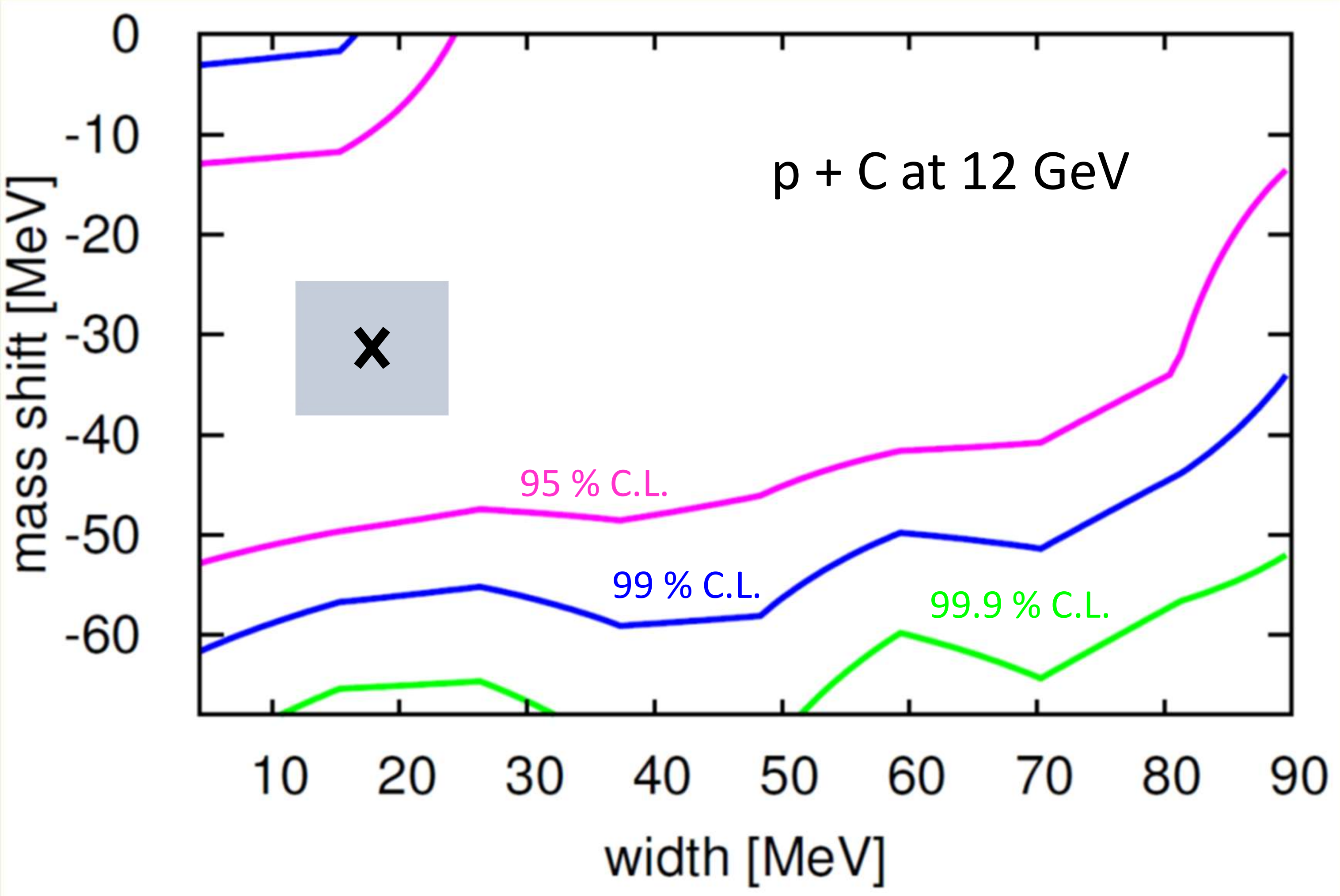
βγ distribution at production



For $\beta\gamma>1.5$, high energy φ meson production via strings dominates

Fits to experimental Carbon target data (E325)

Confidence levels of combined Carbon data



Conclusion of the E325 Collaboration

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