The phi meson in dense matter from a theoretical perspective

Philipp Gubler (JAEA)

P. Gubler, M. Ichikawa, T. Song and E. Bratkovskaya, Phys. Rev. C **111**, 034908 (2025).
M. Ichikawa, P. Gubler, et al., (KEK-PS E325 Collaboration), Prog. Theor. Exp. Phys. **2025**, 093D01 (2025).
G. Balassa, K. Aoki, P. Gubler, S.H. Lee, H. Sako and G. Wolf, arXiv:2508.11344 [hep-ph] (to be published in PTEP).

Talk at the 15th International Conference on Hypernuclear and Strange Particle Physics (HYP2025),
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October 1, 2025

Work done in collaboration with:

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K. Aoki (KEK)
S.H. Lee (Yonsei U.)
G. Balassa (Yonsei U.)
G. Wolf (Wigner RCP)

Introduction

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

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

E16/E88 experiments at J-PARC

Dilepton/K^+K^- spectra from pA reactions

Partial restoration of chiral symmetry

$|\langle \bar{s}s \rangle_\rho|$ ↘

T. Hatsuda and S.H. Lee,
Phys. Rev. C **46**, R34 (1992).

J. Kim, P. Gubler and S.H. Lee,
Phys. Rev. D **105**, 114053 (2022).

Pion induced φ meson production

P95 experiment at J-PARC

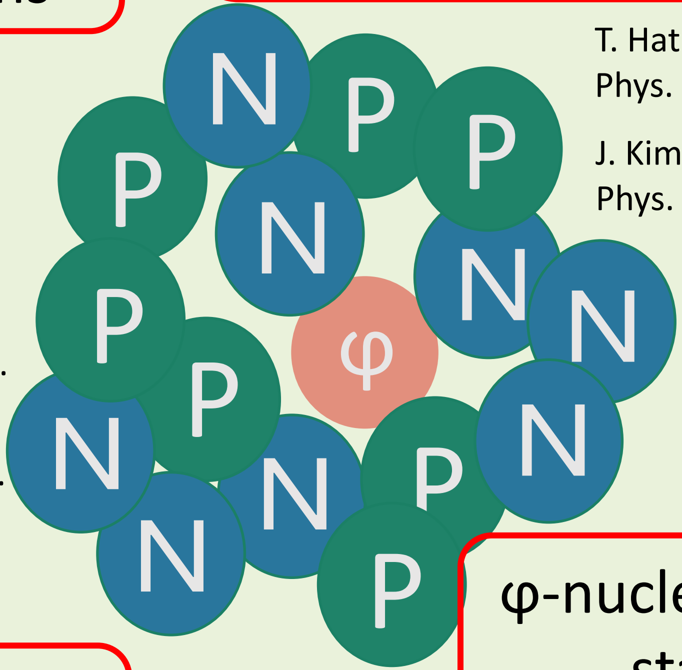
S. Acharya et al. (ALICE Coll.),
Phys. Rev. Lett. **127**, 172301 (2021).

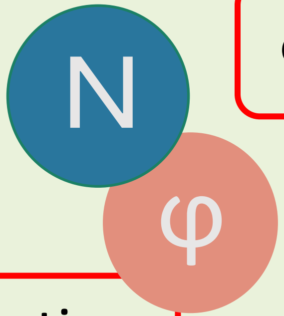
Femtoscopy from LHC

Chiral mixing?

C. Sasaki,
Phys. Rev. D **106**, 054034 (2022).

R. Ejima et al.,
Phys. Rev. C **111**, 055201 (2025).





φN bound state?

E. Chizzali et al.,
Phys. Lett. B **848**, 138358 (2024).

B.-X. Sun et al.,
Commun. Theor. Phys.
75, 055301 (2023).

Photoproduction

I.I. Strakovsky et al.,
Phys. Rev. C **101**, 045201 (2020).

φ-nucleus bound states?

J.J. Cobos-Martínez et al.,
Phys. Rev. C **96**, 035201 (2017).

I. Filikhin et al.,
Phys. Rev. C **110**, 065202 (2024).

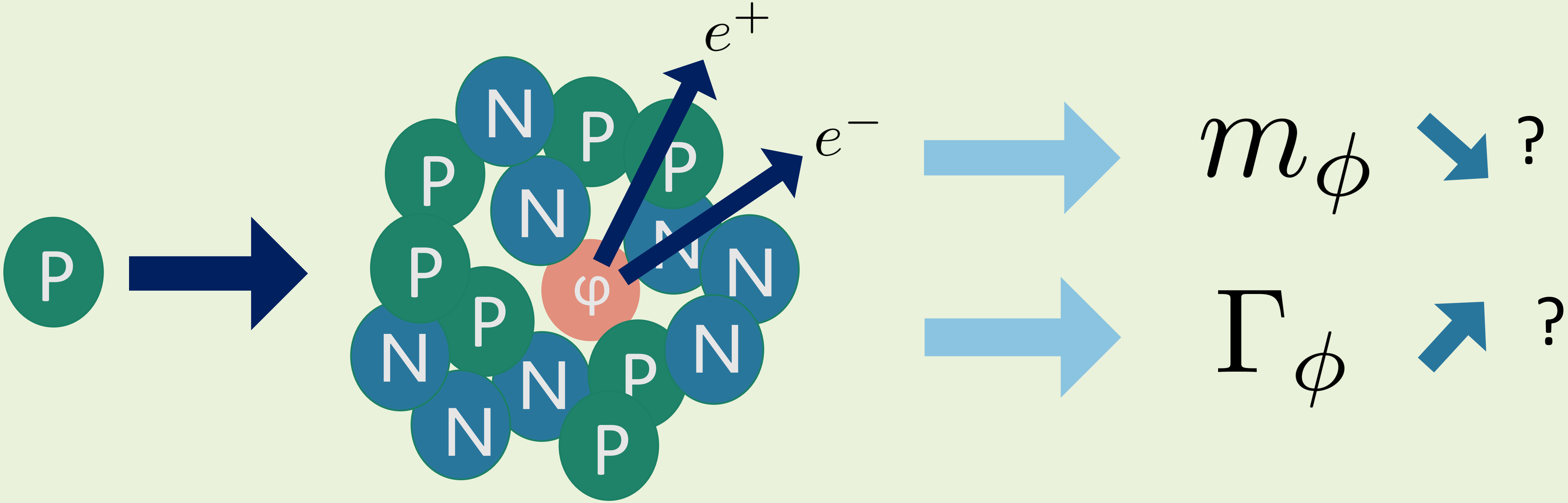
Exotic dispersion relations

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

Lattice QCD (HAL)

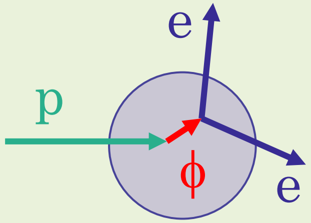
Y. Liu et al.,
Phys. Rev. D **106**, 074507 (2022).

Dilepton spectrum from pA reactions (studied in a transport approach)



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

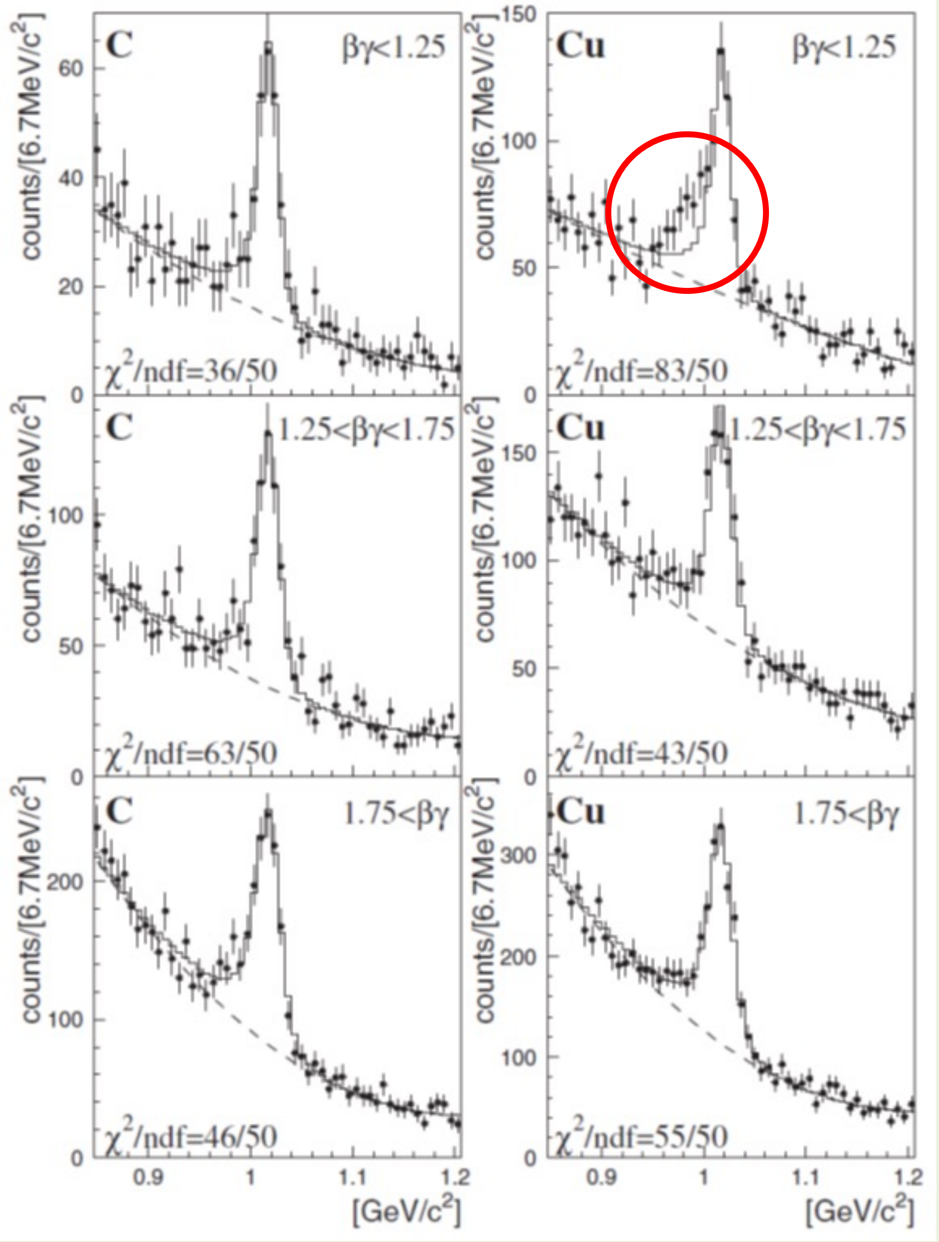
Measurement is being repeated with ~100x increased statistics at the J-PARC E16 experiment!

slow φs

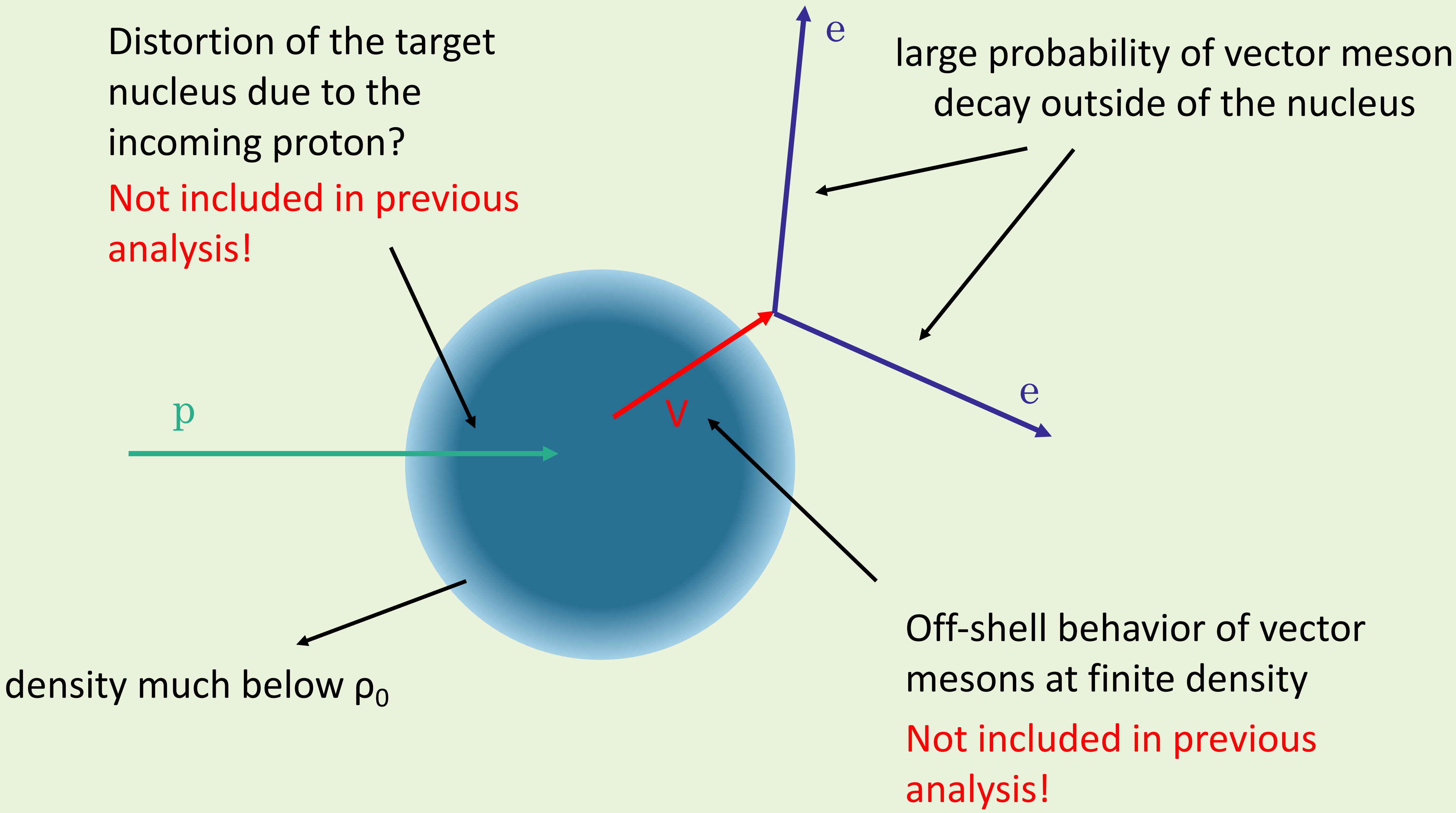
intermediate φs

fast φs

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



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



Distortion of the target nucleus due to the incoming proton?
Not included in previous analysis!
e
large probability of vector meson decay outside of the nucleus
p
V
e
density much below ρ_0
Off-shell behavior of vector mesons at finite density
Not included in previous analysis!

A state-of-the-art transport simulation code: 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).

★ Equations of motion of all particles participating in the reaction are solved

➡ Motion/deformation of target is taken into account!

★ Off-shell dynamics of vector mesons and kaons is included

➡ We use a relativistic Breit-Wigner with density dependent mass and width

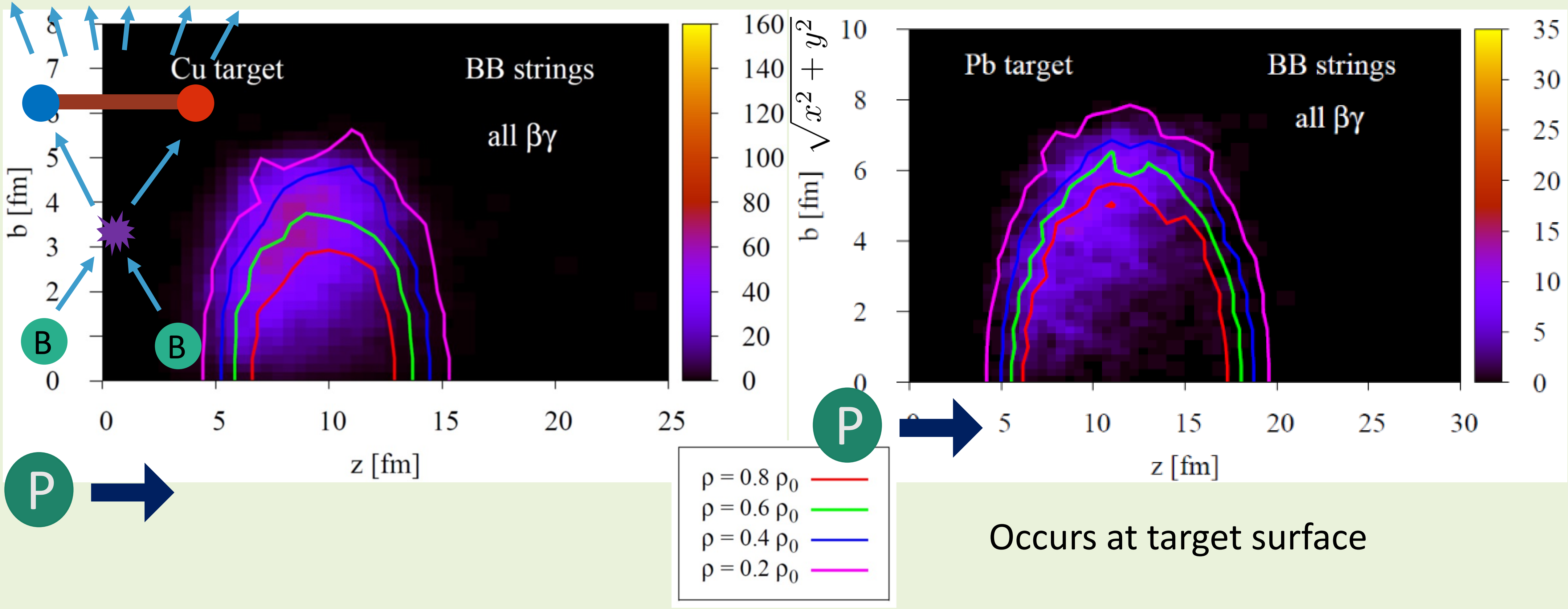
$$C\frac{2}{\pi}\frac{M^2\Gamma^*_\phi(M,\rho)}{[M^2-M^{*2}_\phi(\rho)]^2+M^2\Gamma^{*2}_\phi(M,\rho)}$$

with

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

How are φ mesons produced in 12 GeV pA collisions?

Production through initial high-energy collisions (via strings)



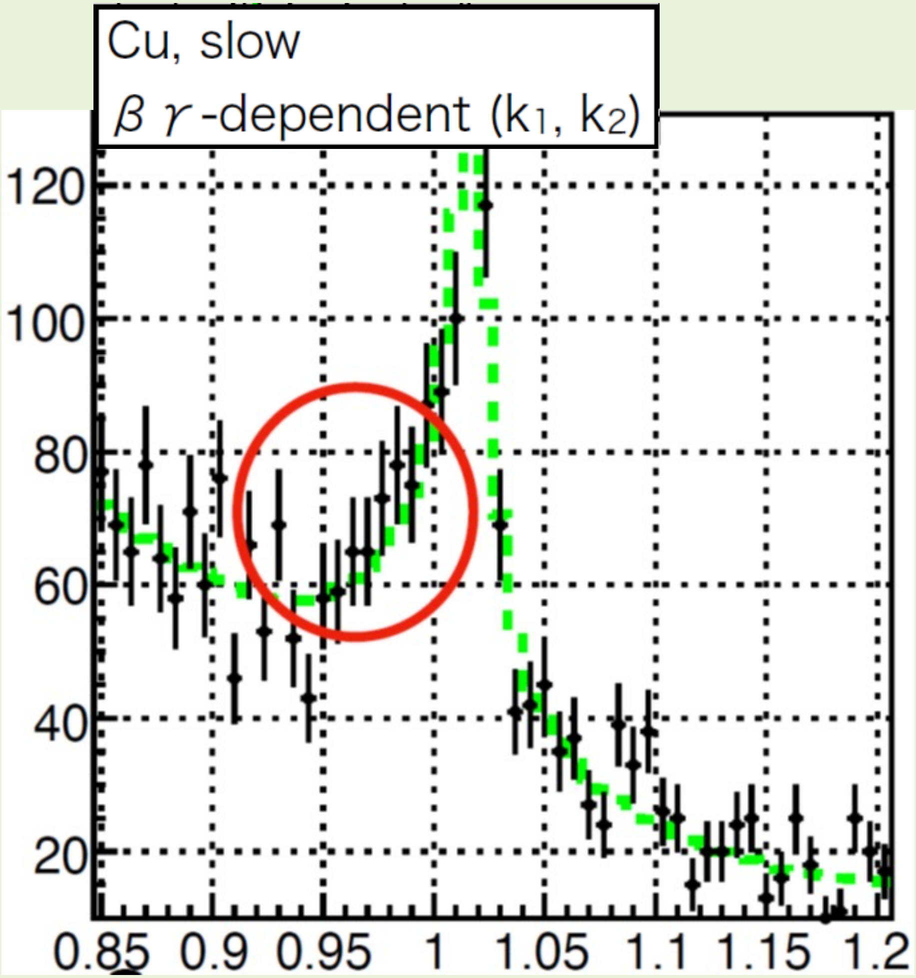
Occurs at target surface

P. Gubler, M. Ichikawa, T. Song and E. Bratkovskaya, Phys. Rev. C **111**, 034908 (2025).

Comparison with KEK E325 dilepton data

Momentum-independent
mass shift and decay width

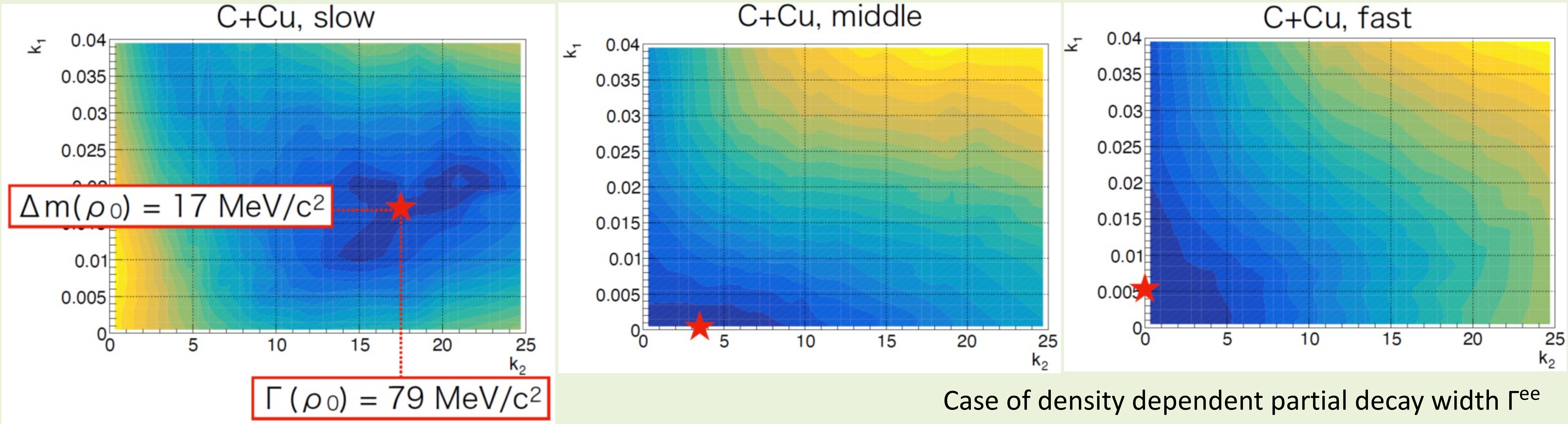
Momentum-dependent
mass shift and decay width



M. Ichikawa, P. Gubler, et al., (KEK-PS E325 Collaboration), Prog. Theor. Exp. Phys. **2025**, 093D01 (2025).

Comparison with KEK E325 dilepton data

Momentum-dependent mass shift and decay width



Case of density dependent partial decay width Γ^{ee}

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

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

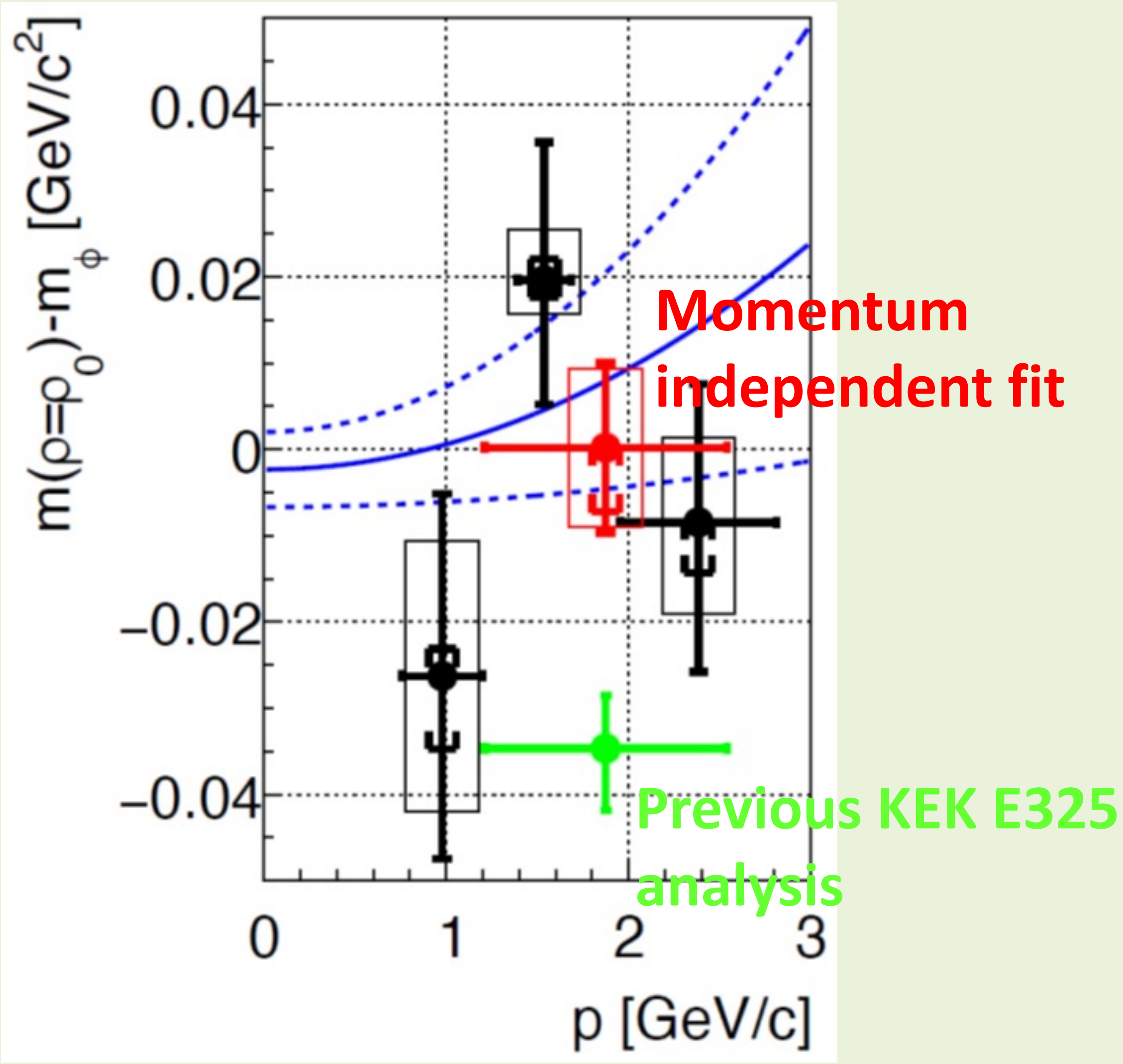
Momentum dependence is needed to explain the data!

Smaller mass shift and stronger broadening than in the original E325 analysis!

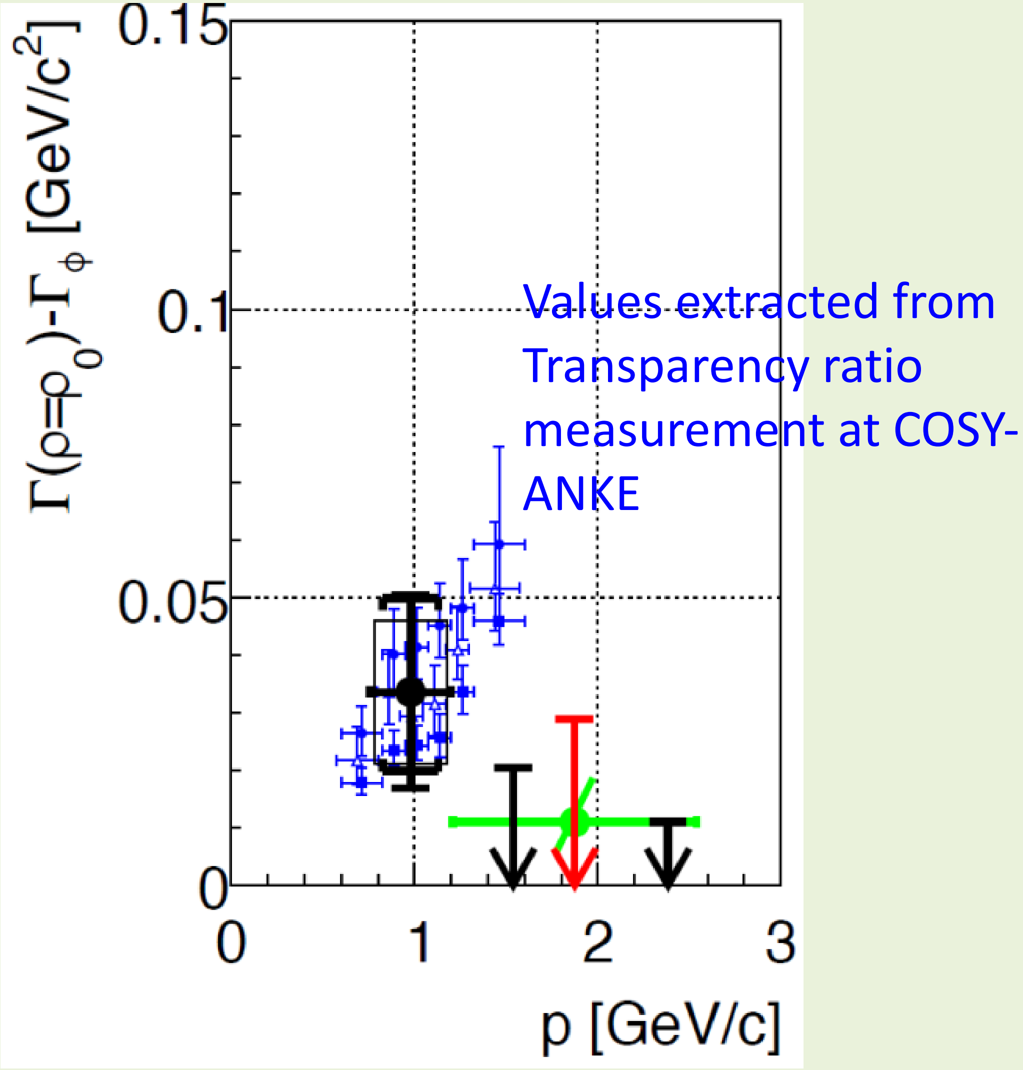
M. Ichikawa, P. Gubler, et al., (KEK-PS E325 Collaboration), Prog. Theor. Exp. Phys. **2025**, 093D01 (2025).

Final analysis results

Mass shift at ρ_0

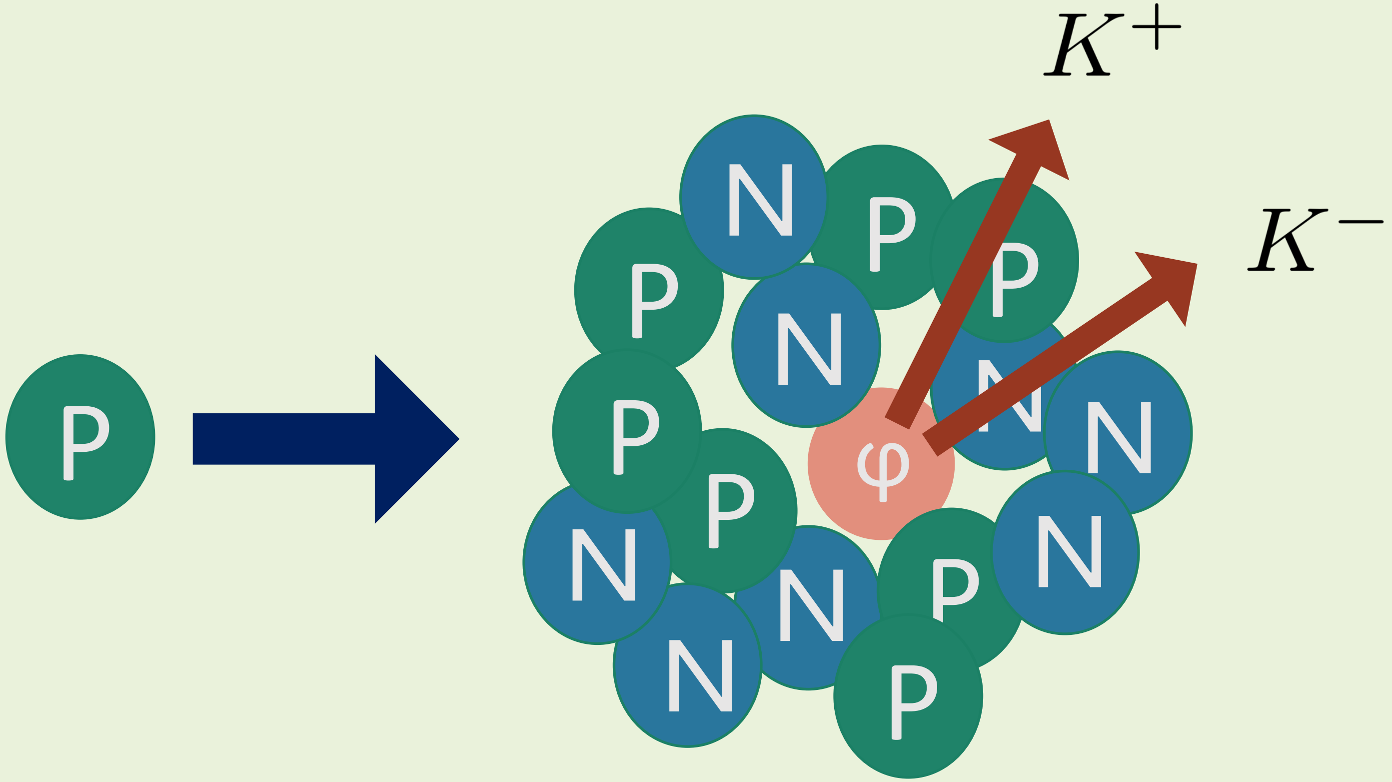


Width shift at ρ_0



M. Ichikawa, P. Gubler, et al., (KEK-PS E325 Collaboration), Prog. Theor. Exp. Phys. **2025**, 093D01 (2025).

What about the K^+K^- spectrum?

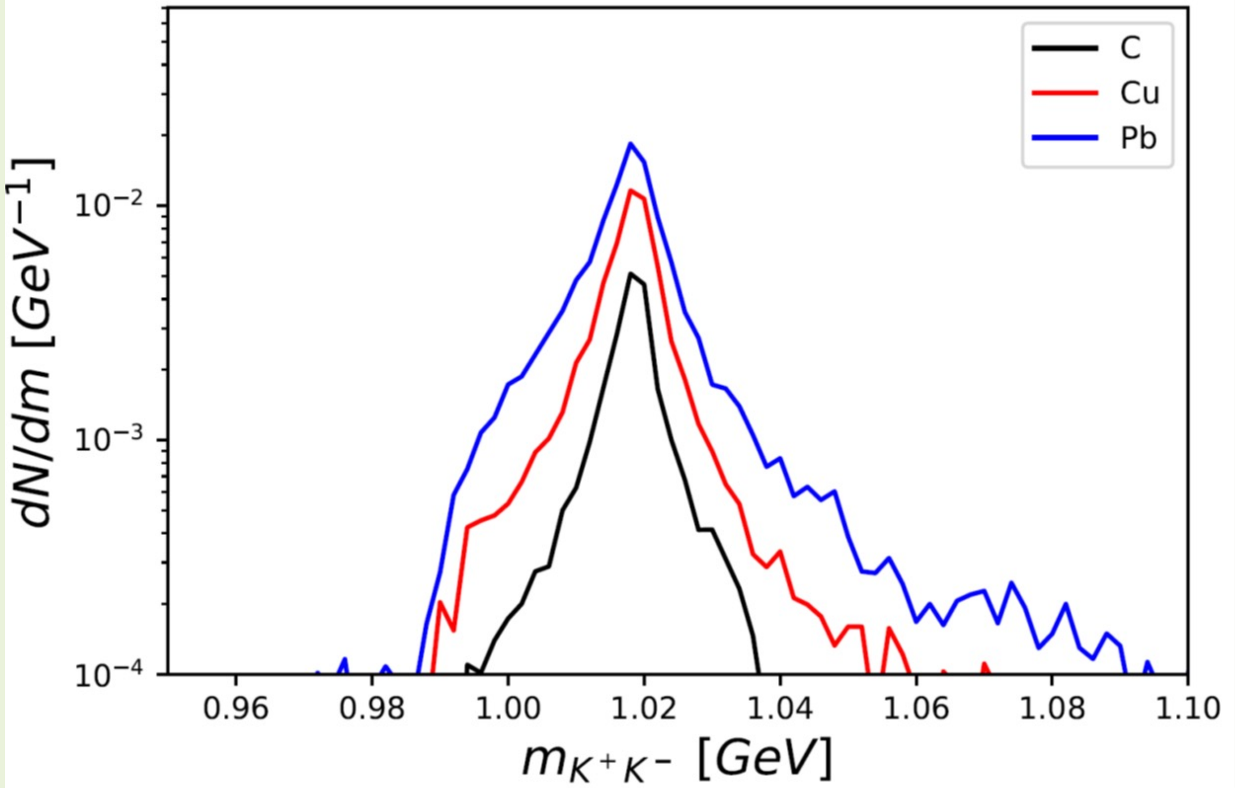


Will be studied at the J-PARC E88/SAPHIRE experiment!

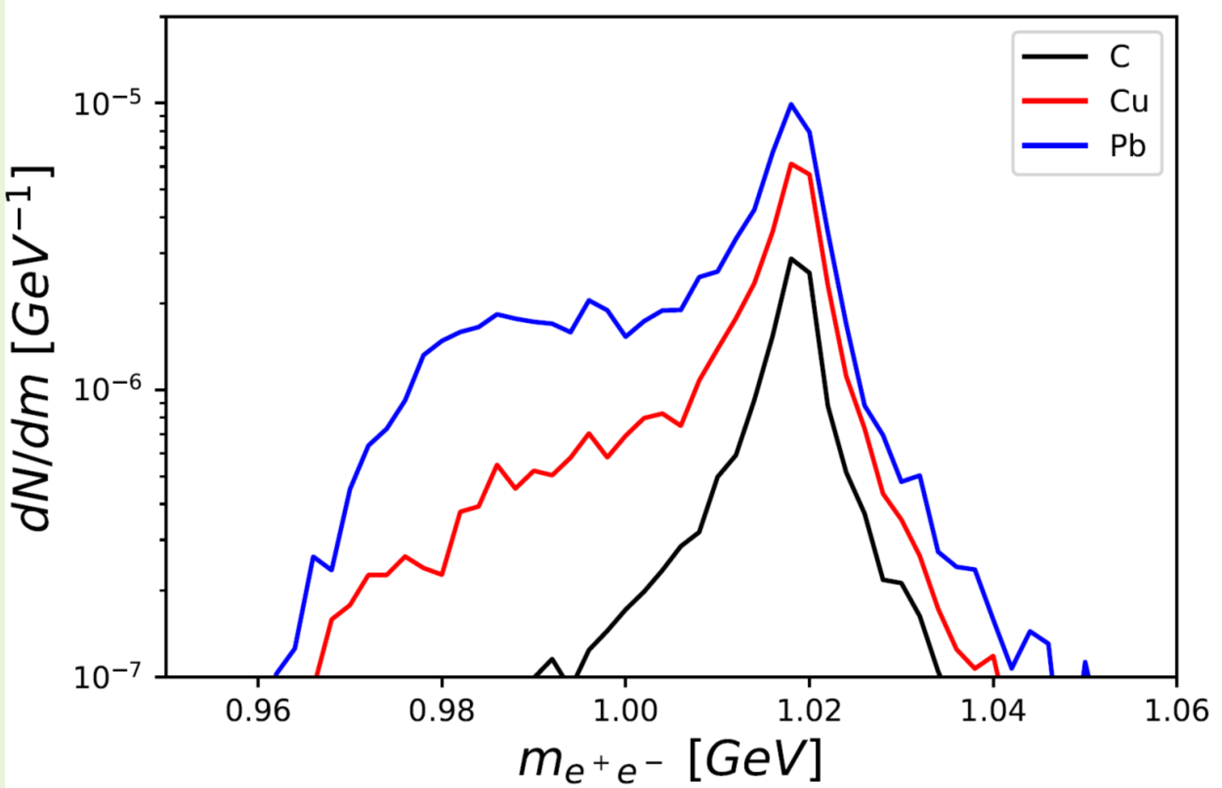
Comparative study of the K^+K^- and e^+e^- spectrum

(under the conditions of the J-PARC E16/E88 experiments: 30 GeV pA induced reactions)

K^+K^- invariant mass spectrum



e^+e^- invariant mass spectrum



→ Smaller effect for K^+K^- because of the closeness of its threshold to the φ meson mass

G. Balassa, K. Aoki, P. Gubler, S.H. Lee, H. Sako and G. Wolf, arXiv:2508.11344 [hep-ph] (to be published in PTEP).

Summary and conclusions

★ With the state-of-the-art PHSD transport approach, we can now study pA reactions more reliably

→ **Changed conclusions from previous analysis of experimental data**

- **Smaller mass shift**
- **Larger broadening**

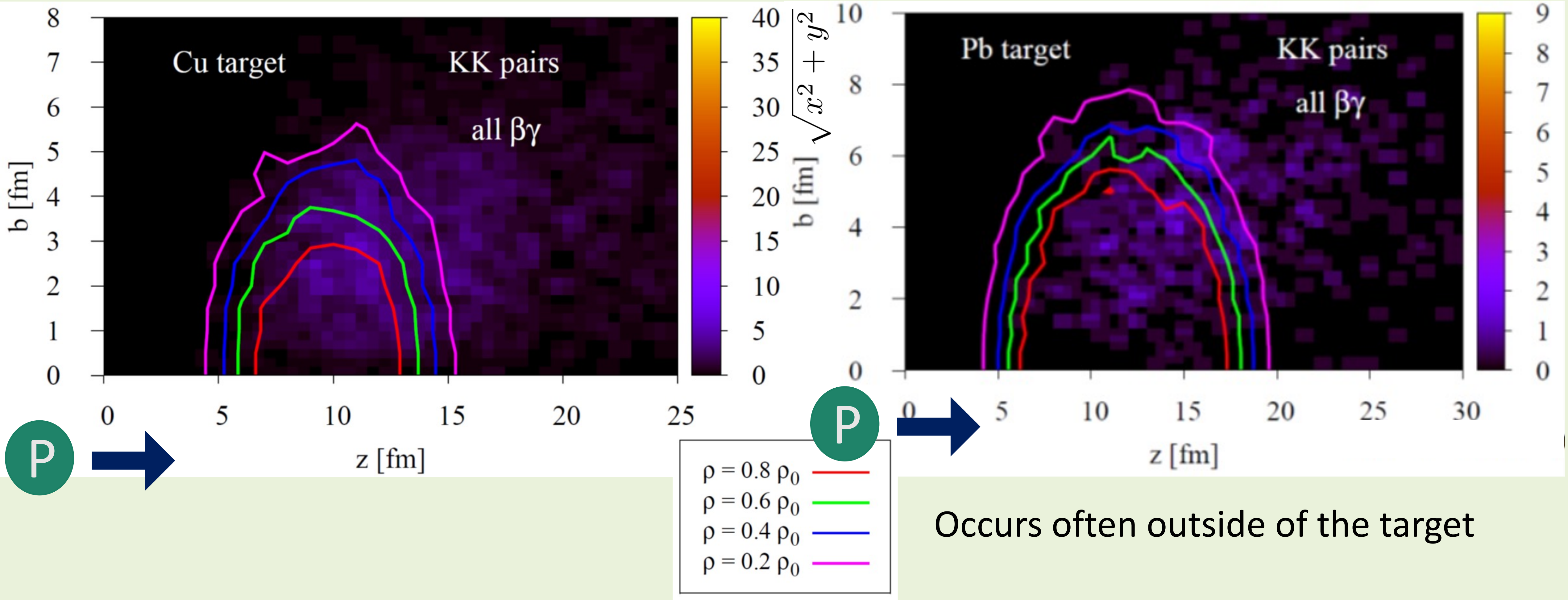
★ Uncertainties are larger than in previous analysis

→ **More precise data from the J-PARC E16 experiment will be needed**

Backup slides

How are φ mesons produced?

Production through secondary low-energy hadron collisions

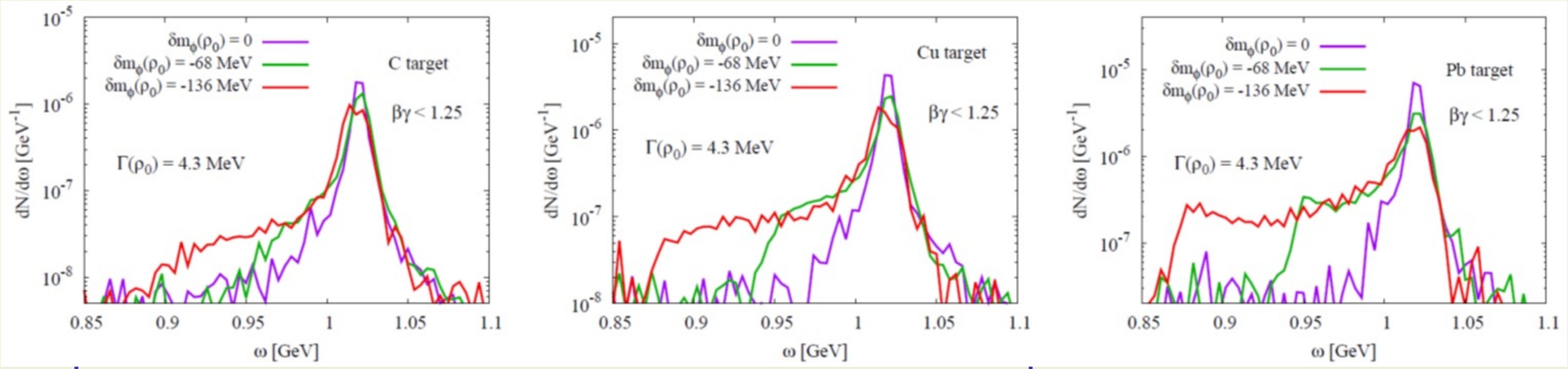


Occurs often outside of the target

P. Gubler, M. Ichikawa, T. Song and E. Bratkovskaya, Phys. Rev. C **111**, 034908 (2025).

The obtained dilepton spectrum (without experimental effects)

Pure mass shift scenarios (no broadening)



No second peak, but only shoulder structure for mass shift scenarios
(even before considering experimental resolution effects)

Secondary peak can be generated for sufficient large mass shift scenario if the target is large enough (Pb here)

P. Gubler, M. Ichikawa, T. Song and E. Bratkovskaya, Phys. Rev. C **111**, 034908 (2025).

Issues of transport approaches

★ Reliability of transport simulations (dependence on different codes and approaches)

→ Need comparison of different codes (including QMC and BUU types)

★ Stability of the (undisturbed) target in the transport approach

→ Generally difficult to achieve in most transport models specialized in high-energy collisions, but is realized is some low-energy codes

→ Not so serious for KEK and J-PARC pA collisions, in which the phi mesons leave the target quickly??

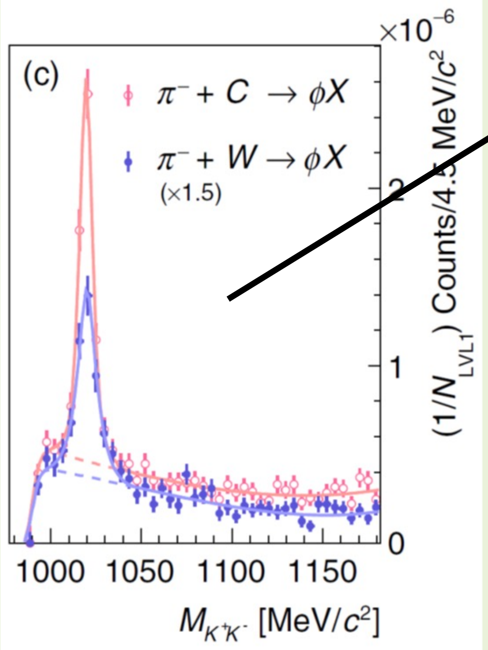
★ Violation of energy or momentum conservation when mass shifted particles leave the dense medium

→ Relevant for E88, as kaons generated in dense matter are mass shifted

Many inconsistencies…

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).

Theoretical analysis of the of the total φ meson production cross section:

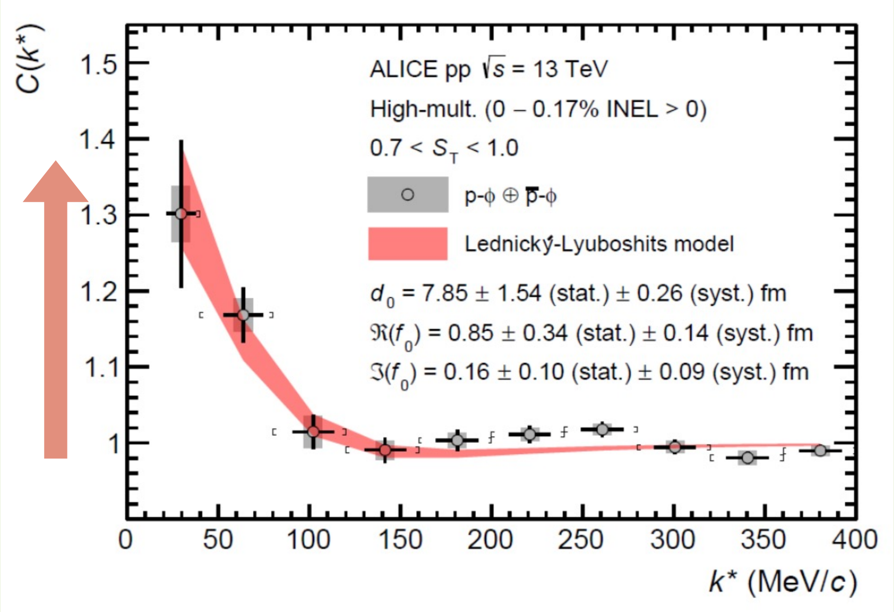
- **Attractive φ-nucleus potential: -(50 - 100) MeV**
- **Small imaginary part: 20 – 25 MeV**

E. Ya. Paryev, Nucl. Phys. A **1032**, 122624 (2023).

ALICE: pp

Measurement of φN correlation

Attraction!



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

Large negative mass shift?
Small broadening?

- Photoproduction measurements
  I.I. Strakovsky et al. (CLAS), Phys. Rev. C **101**, 045201 (2020).
  $$|a_0| = 0.063 \pm 0.010\,\mathrm{fm}$$

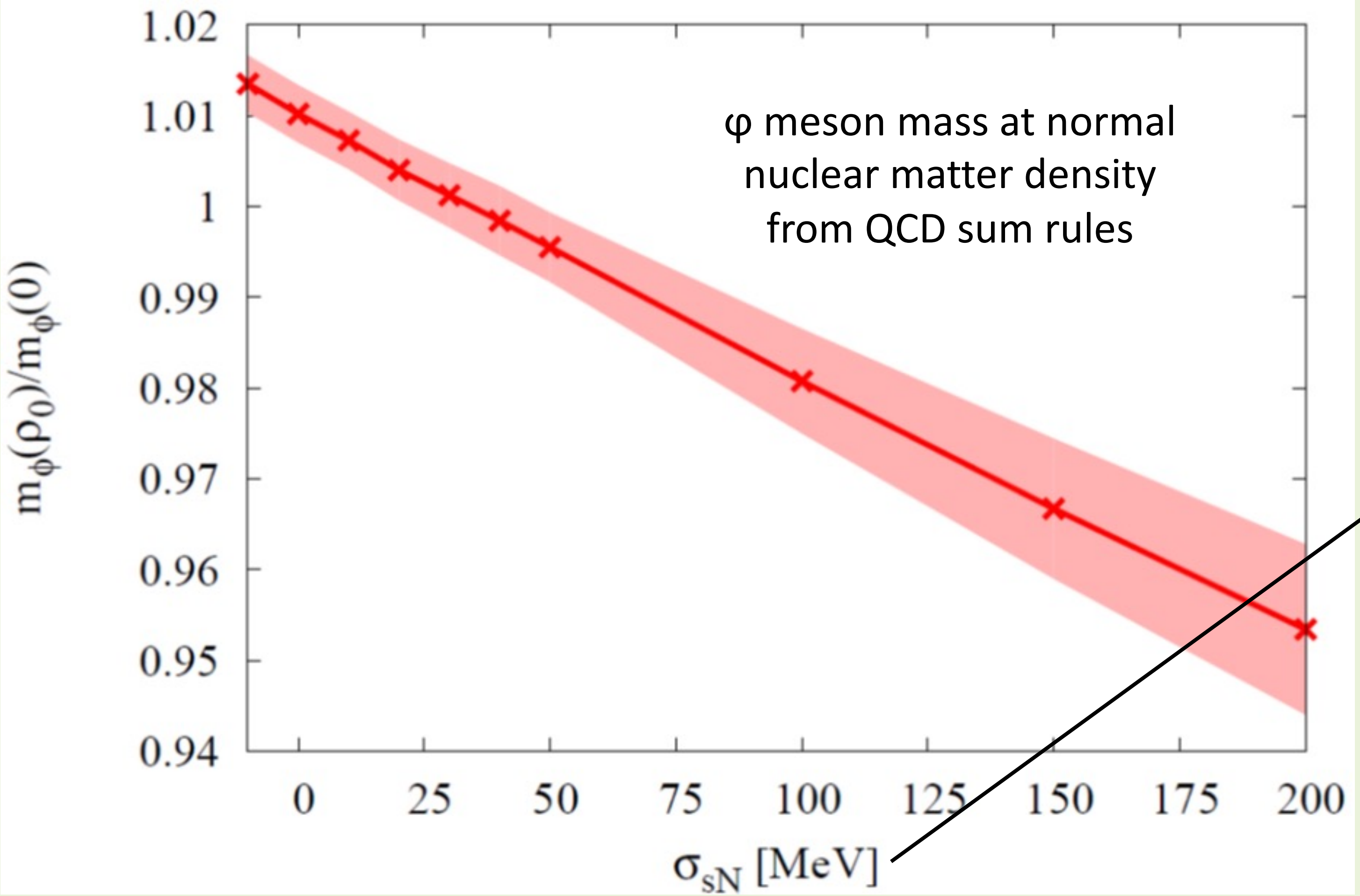
- Hadronic Effective theory calculations

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

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

Why should we be interested?

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



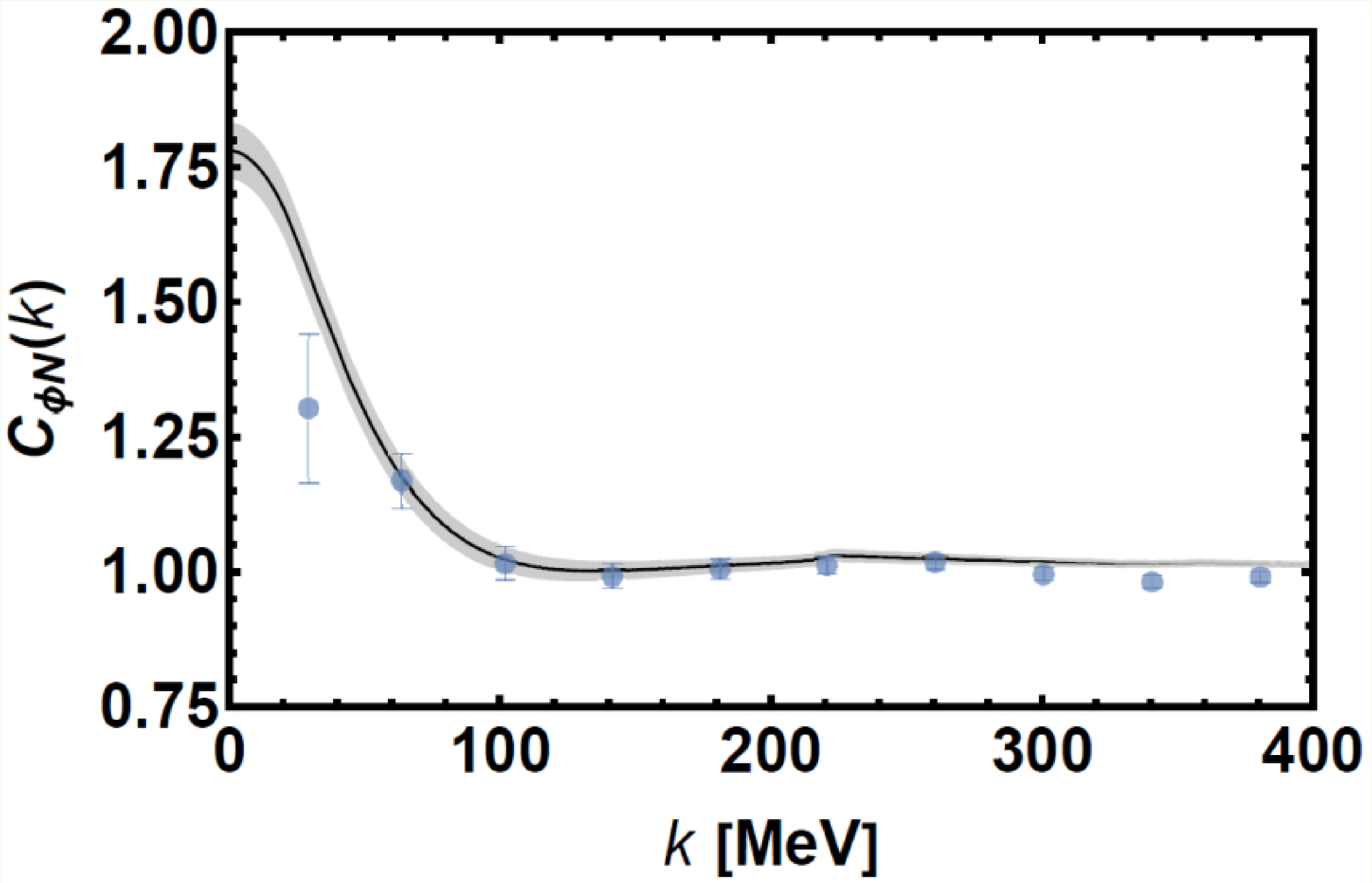
P. Gubler and K. Ohtani, Phys. Rev. D **90**, 094002 (2014).

T. Hatsuda and S.H. Lee, Phys. Rev. C **46**, R34 (1992).

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

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

The obtained correlation function (compared with ALICE data)



Reasonably good agreement without any parameter fitting!

L.M. Abreu, P. Gubler, K.P. Khemchandani, A. Martínez Torres and A. Hosaka, arXiv:2409.05170 [hep-ph].

Simple relation between φN scattering length and φ meson mass shift in nuclear matter

$$V_\phi(\rho) = -\frac{2\pi}{m_\phi}\rho\left(1+\frac{m_\phi}{m_N}\right)a_0$$
$$\simeq -85\frac{\rho}{\rho_0}\left(\frac{a_0}{\text{fm}}\right)\text{MeV}$$

Valid within the linear density approximation

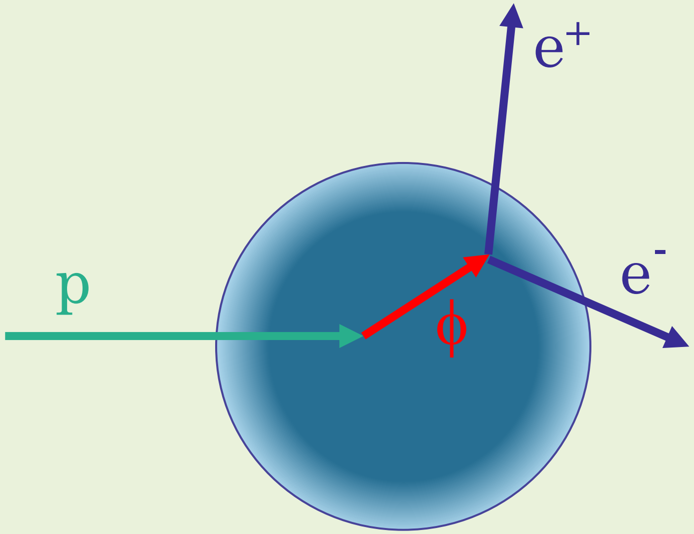
Larger than 100 MeV IF HAL QCD result is true for all spin configurations!

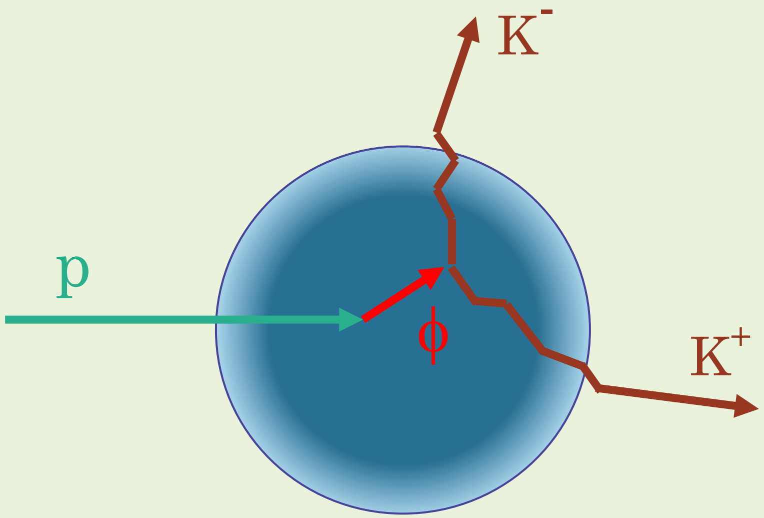
However, the above prescription seems problematic if a φN bound state (or resonance) is formed.

→ Need better theoretical understanding!

Further tasks 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)

→ See talk by L. Oliva

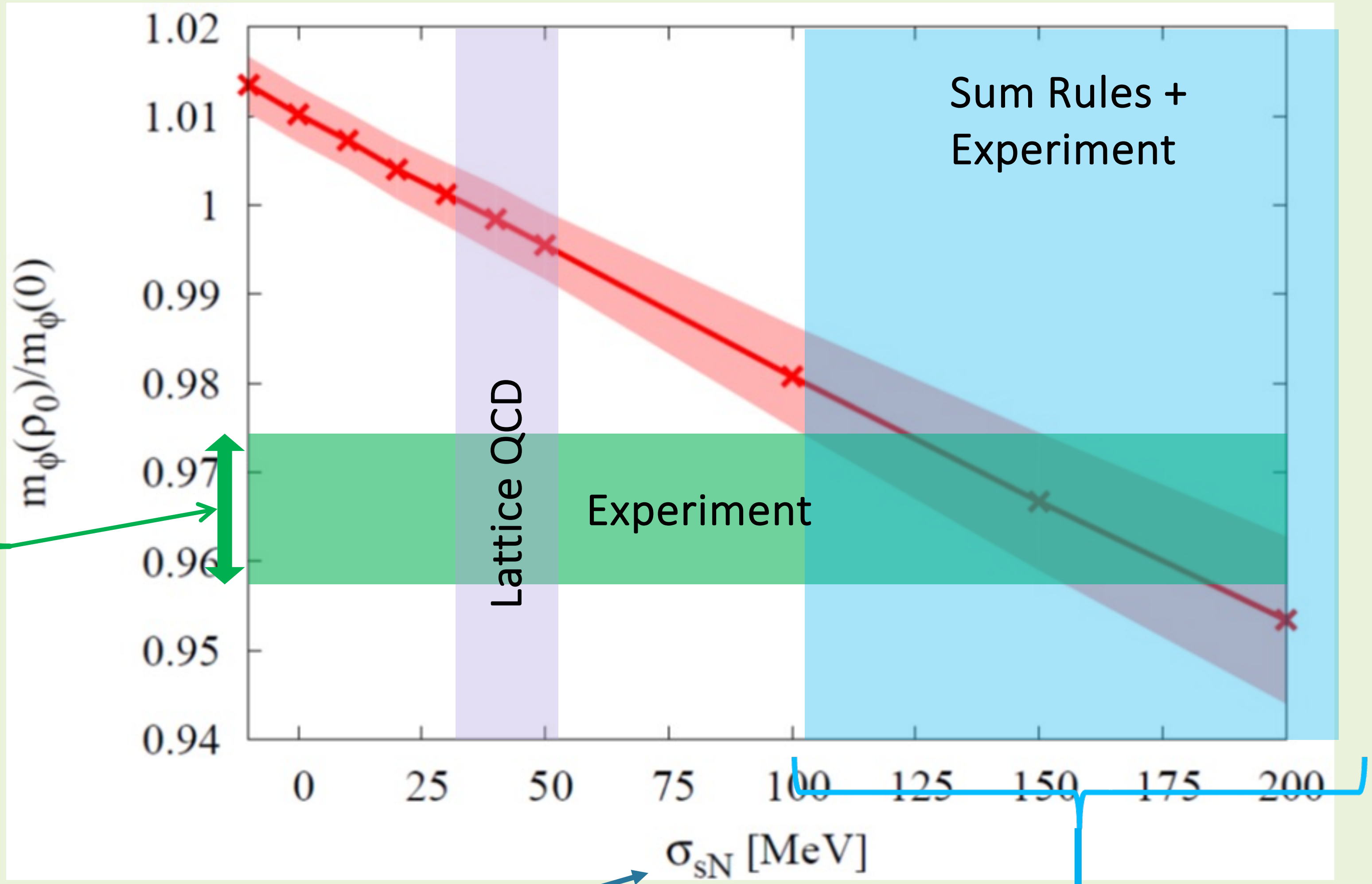
φ meson at rest in nuclear matter

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).

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

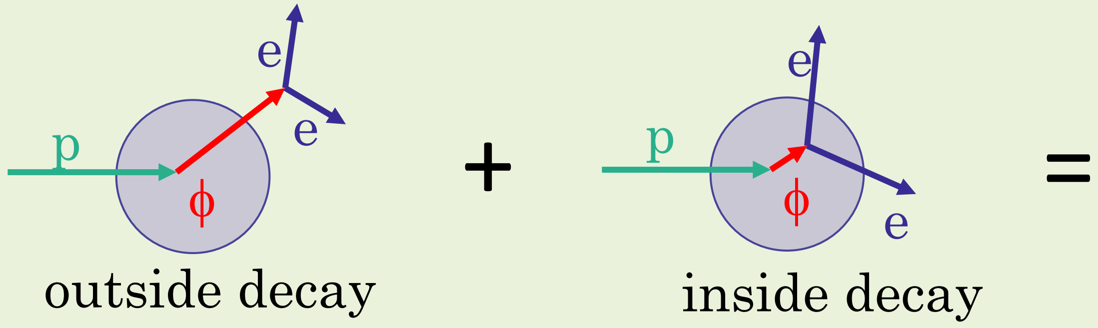


Measurement will be repeated at the J-PARC E16 experiment (with 100 times increased statistics!)

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

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

Experimental di-lepton spectrum



Experimentally observed spectrum