Hadrons in nuclear matter – theory and simulations

Philipp Gubler (JAEA)

P. Gubler, M. Ichikawa, T. Song and E. Bratkovskaya, Phys. Rev. C **111**, 034908 (2025).
R. Ejima, C. Sasaki, P. Gubler and K. Shigaki, Phys. Rev. C **111**, 055201 (2025).
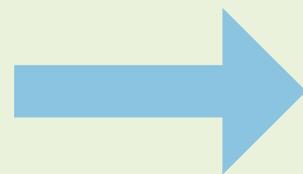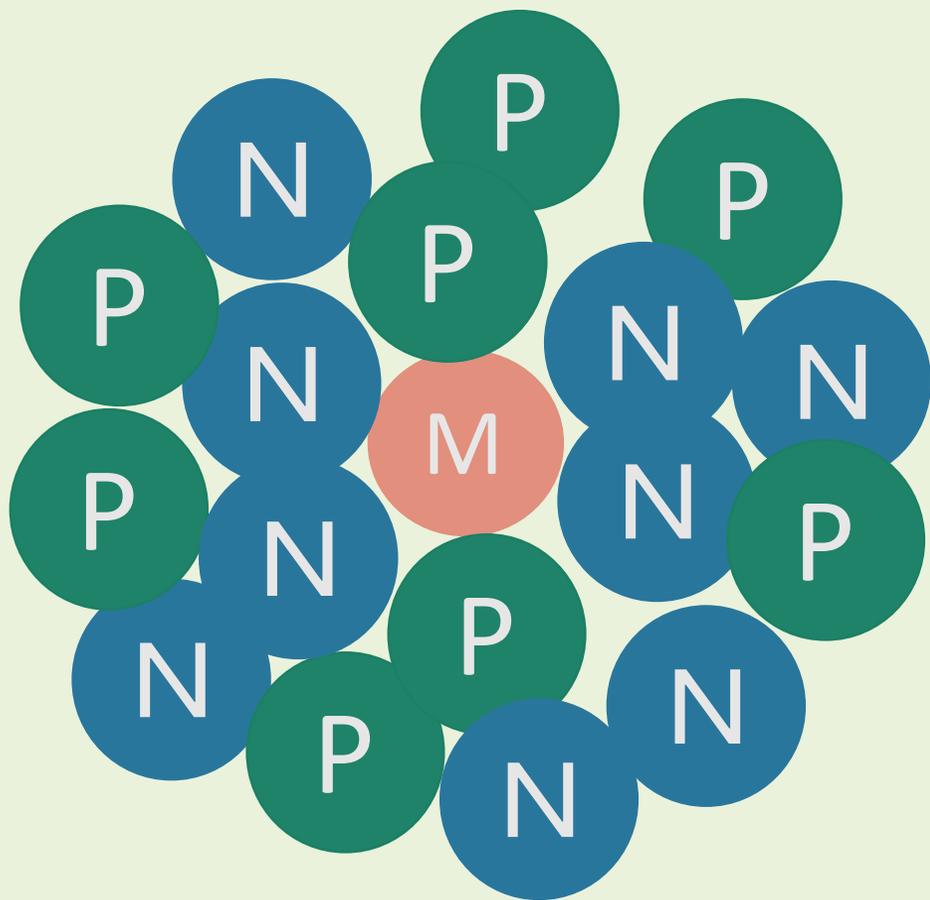M. Ichikawa et al., (KEK-PS E325 Collaboration), Prog. Theor. Exp. Phys. **2025**, 093D01 (2025).
G. Balassa et al., arXiv:2508.11344 [hep-ph] (To be published in Prog. Theor. Exp. Phys.).

Talk at the "International Conference on the Structure of Baryons (BARYON2025)",
Jeju Island, South Korea
November 12, 2025

Work done in collaboration with:

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T. Song (GSI)
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S.H. Lee (Yonsei U.)
M. Naruki (Kyoto U.)
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G. Balassa (Yonsei U.)
G. Wolf (Wigner I.)

History

Early motivation

Scaling Effective Lagrangians in a Dense Medium

G. E. Brown

Department of Physics, State University of New York at Stony Brook, Stony Brook, New York 11794

Mannque Rho

Service de Physique Théorique, Centre d'Etudes Nucléaires de Saclay, 91191 Gif-sur-Yvette, France
(Received 8 January 1991)

By using effective chiral Lagrangians with a suitable incorporation of the scaling property of QCD, we establish the approximate *in-medium* scaling law, $m_\sigma^*/m_\sigma \approx m_N^*/m_N \approx m_\rho^*/m_\rho \approx m_\omega^*/m_\omega \approx f_\pi^*/f_\pi$. This has a highly nontrivial implication for nuclear processes at and above nuclear-matter density. Some concrete cases are cited in this paper.

G.E. Brown and M. Rho, Phys. Rev. Lett. **66**, 2720 (1991).

QCD sum rules for vector mesons in the nuclear medium
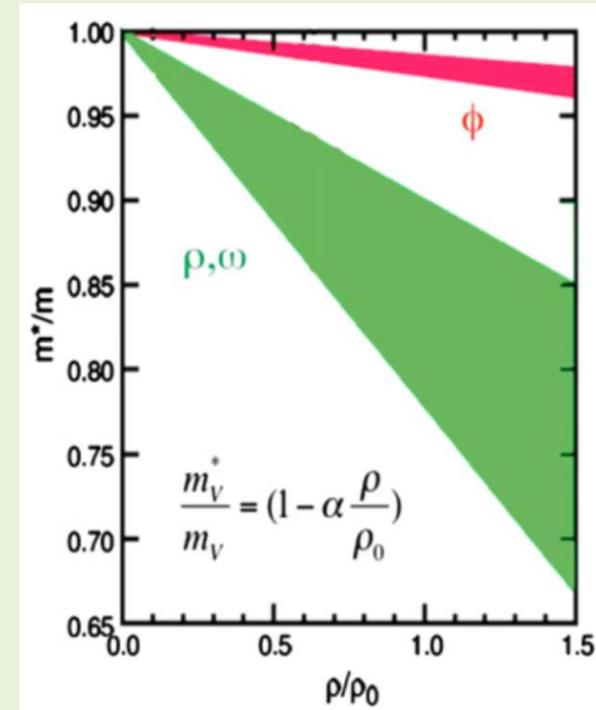
Tetsuo Hatsuda

Institute for Nuclear Theory, University of Washington, HN-12, Seattle, Washington 98195

Su Houng Lee

Department of Physics, Yonsei University, Seoul 120-749, Korea
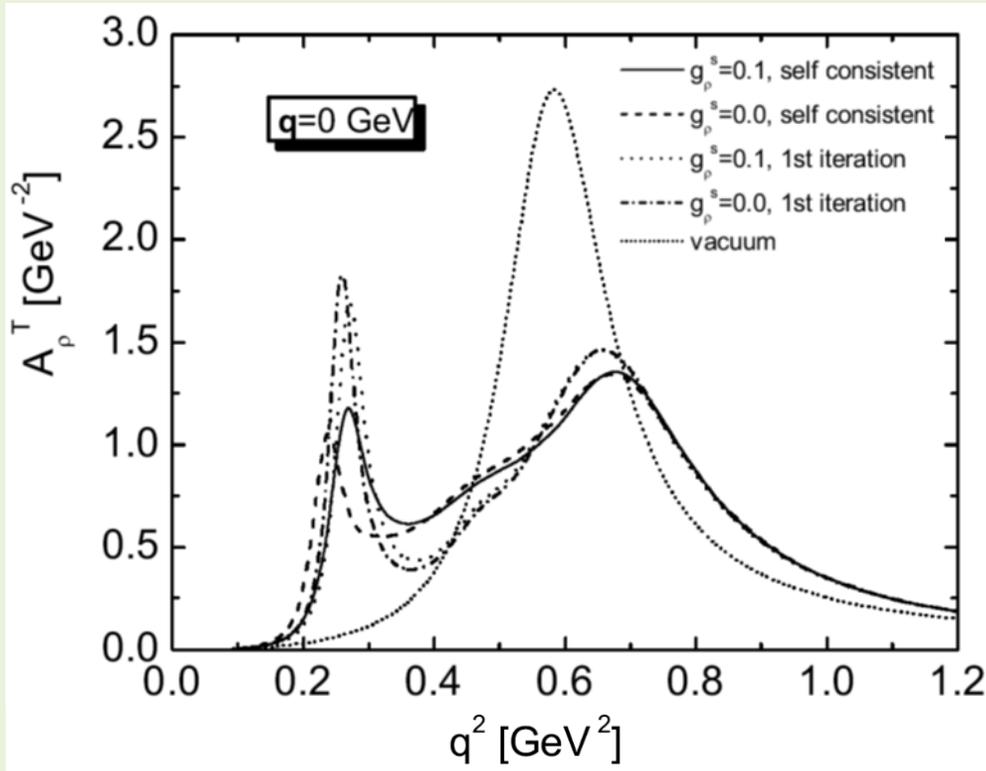(Received 8 July 1991)

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

"Brown-Rho scaling"

$$\frac{m_\rho(\rho)}{m_\rho(0)} \simeq \frac{m_\omega(\rho)}{m_\omega(0)} \simeq \left(\frac{\langle \bar{q}q \rangle_\rho}{\langle \bar{q}q \rangle_0}\right)^\alpha$$

Vector mesons as probe of chiral symmetry in nuclear matter?
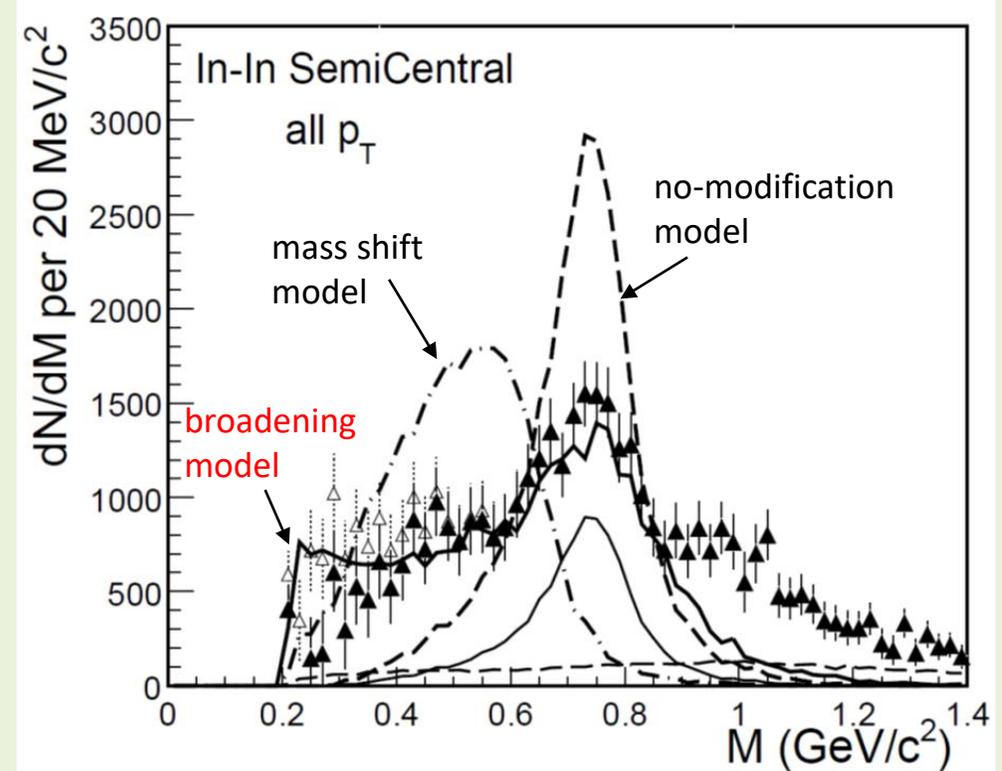
History

Reality turns out to be more complicated

ρ meson spectral function at normal nuclear matter density
from a hadronic (resonance-nucleon-hole) model

Di-muon invariant mass spectrum from 158 AGeV In-In collisions from CERN SPS

M. Post, S. Leupold and U. Mosel, Nucl. Phys. A **741**, 81 (2004).

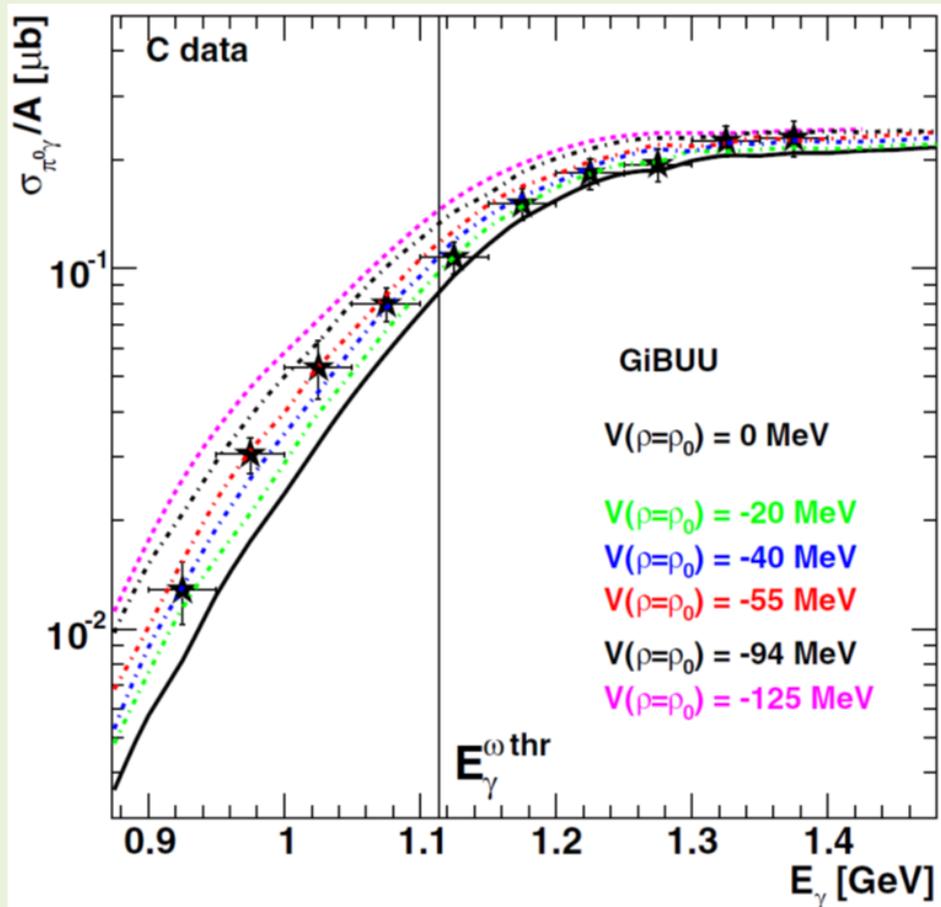R. Arnaldi et al. (NA60 Collaboration), Phys. Rev. Lett. **96**, 162302 (2006).

➡ Instead of having a mass shift, the ρ meson appears to be mostly **broadened in heavy-ion collisions**

(For pA and γA collisions, see also
M. Naruki et al. (KEK), PRL **96**, 092301 (2006).
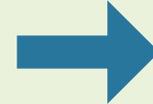R. Nasseripour et al. (CLAS), PRL **99**, 262302 (2007).)

Recent developments

Focus on narrow resonances

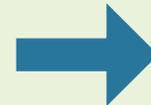Excitation function of **ω mesons from photoproduction** on a C target (MAMI-C)

V. Metag et al., Prog. Part. Nucl. Phys. **67**, 530 (2012).

Combination of excitation function data and transport simulation (GiBUU):

$$\mathrm{Re}V_\omega(\rho_0) = -(29 \pm 19(\mathrm{stat}) \pm 20(\mathrm{syst}))\,\mathrm{MeV}$$

Combination of transparency ratio data and hadronic models:

$$\mathrm{Im}V_\omega(\rho_0) = -(48 \pm 12(\mathrm{stat}) \pm 9(\mathrm{syst}))\,\mathrm{MeV}$$

V. Metag et al., Prog. Part. Nucl. Phys. **97**, 199 (2017).

See however, below findings from photoproduction and pA collisions, which reach different conclusions:
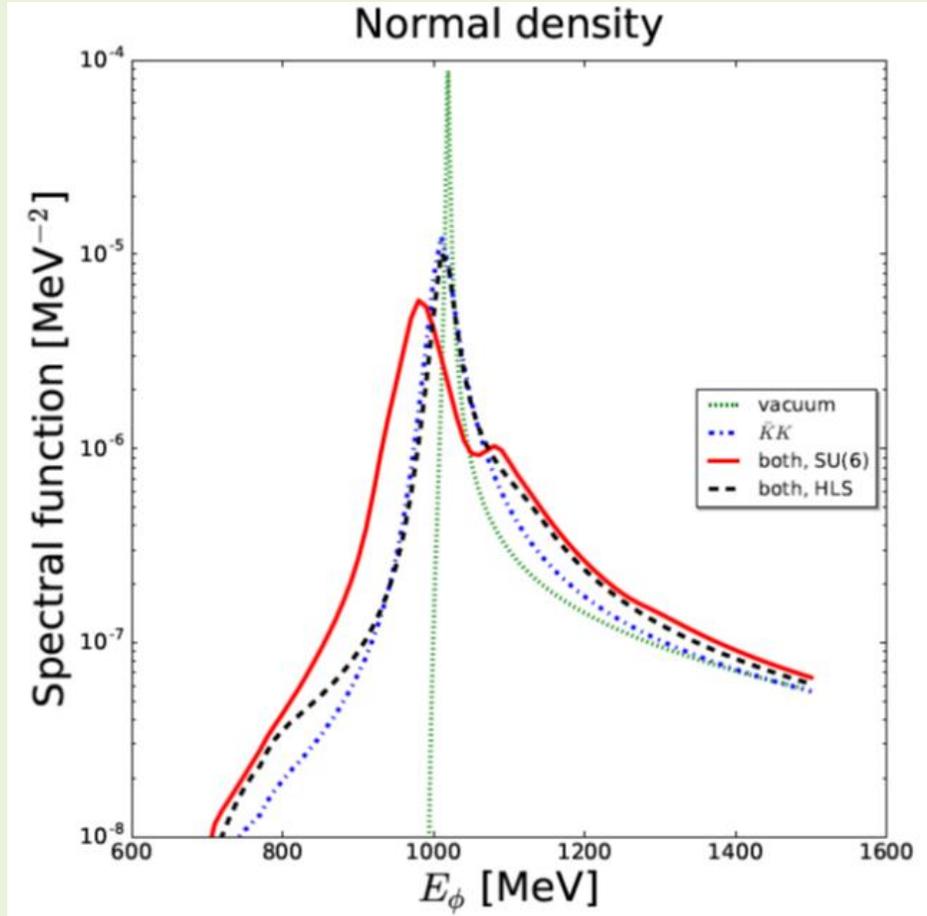
T. Ishikawa et al. (ELPH), Phys. Rev. C **101**, 052201 (2020).

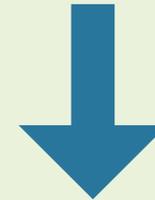W. Nakai et al. (KEK E325), Prog. Theor. Exp. Phys. **2025**, 093C01 (2025).

Recent developments

Focus on narrow resonances

φ meson spectral function from hadronic models

Normal density

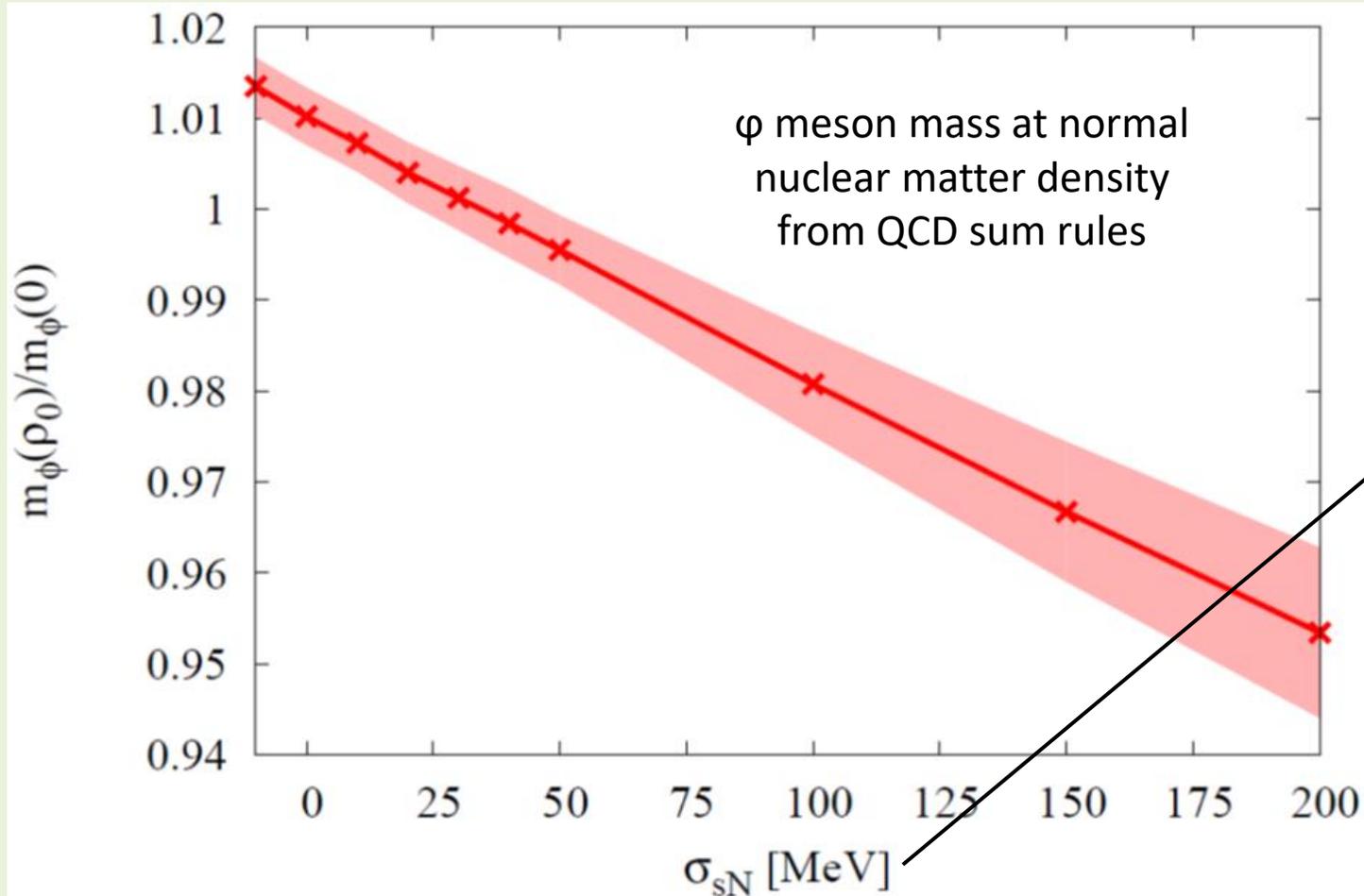D. Cabrera, A.N. Hiller Blin and M.J. Vicente Vacas,
Phys. Rev. C **95**, 015201 (2017).

★ Isolated peak → no interference effects

★ No (strong) coupling to nuclear resonances

The φ meson is an ideal candidate to study its spectral modification in nuclear matter!

Why should we be interested?

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

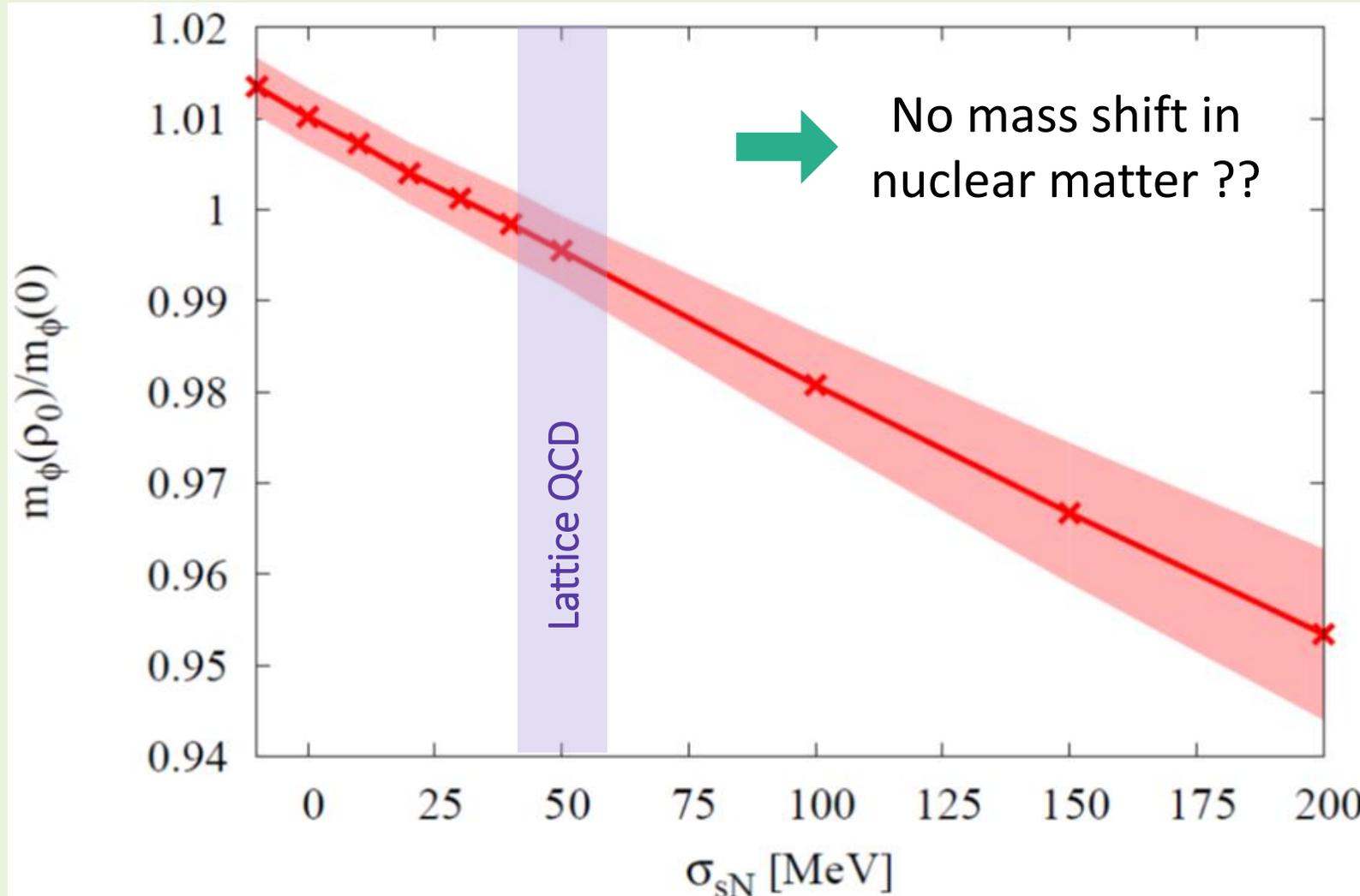φ meson mass at normal nuclear matter density from QCD sum rules

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

$$|\langle \bar{s}s \rangle_\rho| = |\langle \bar{s}s \rangle_0| - \frac{\rho}{m_s} \sigma_{sN} + \dots$$
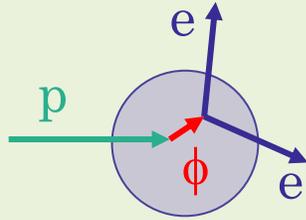
P. Gubler and K. Ohtani, Phys. Rev. D **90**, 094002 (2014).

Combine QCD sum rules with lattice QCD

No mass shift in nuclear matter ??

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

Previous experimental results

KEK
E325

p → ⊙ φ ↗ e ↗ e

12 GeV
pA-reaction

Pole mass: $\dfrac{m_\phi(\rho)}{m_\phi(0)} = 1 - k_1 \dfrac{\rho}{\rho_0}$
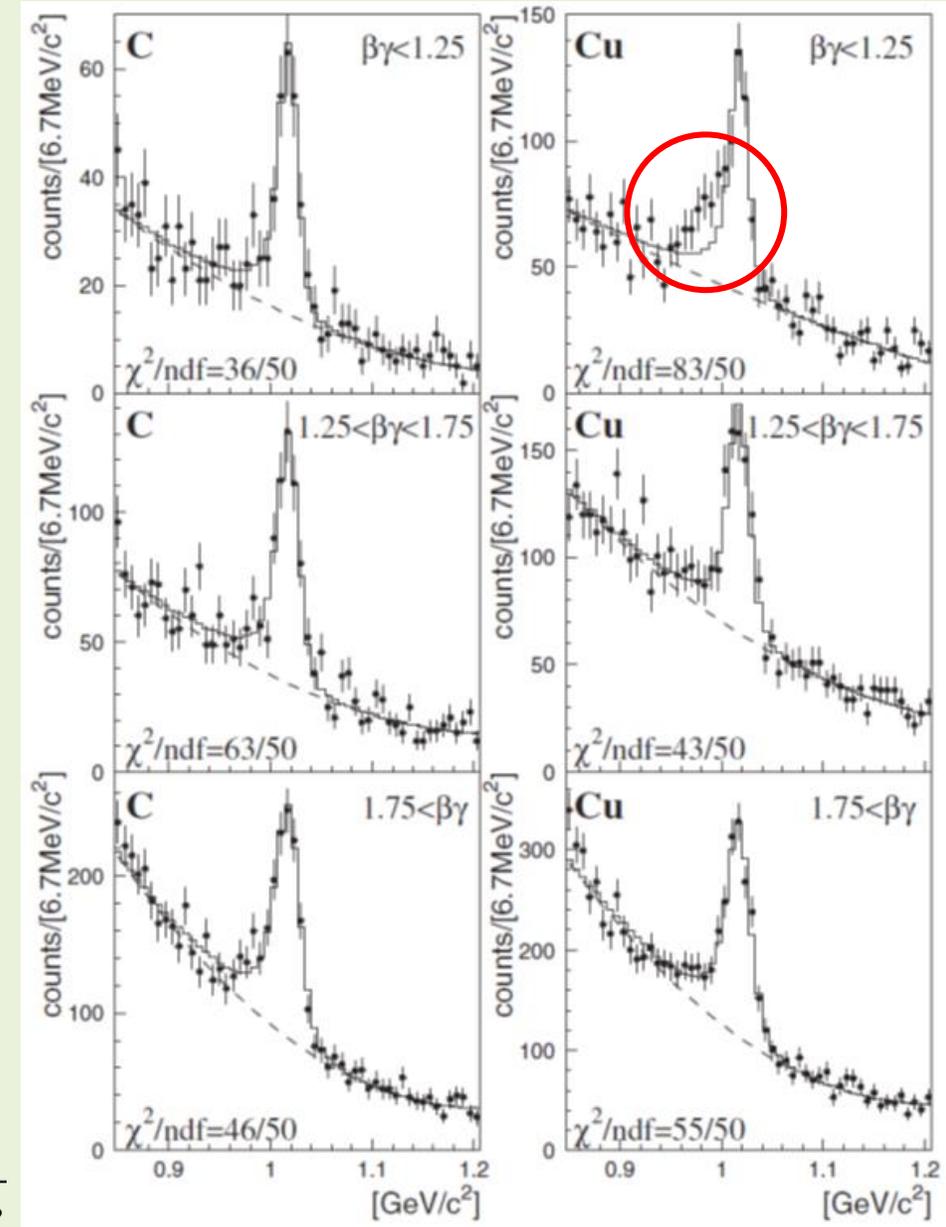
0.034 ± 0.007

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

2.6 ± 1.5

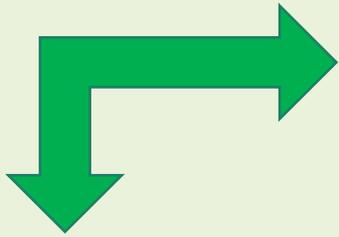Measurement is being repeated with
$\sim$ 100x increased statistics at the
J-PARC E16 experiment!

slow φs

intermediate
φs

fast φs

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

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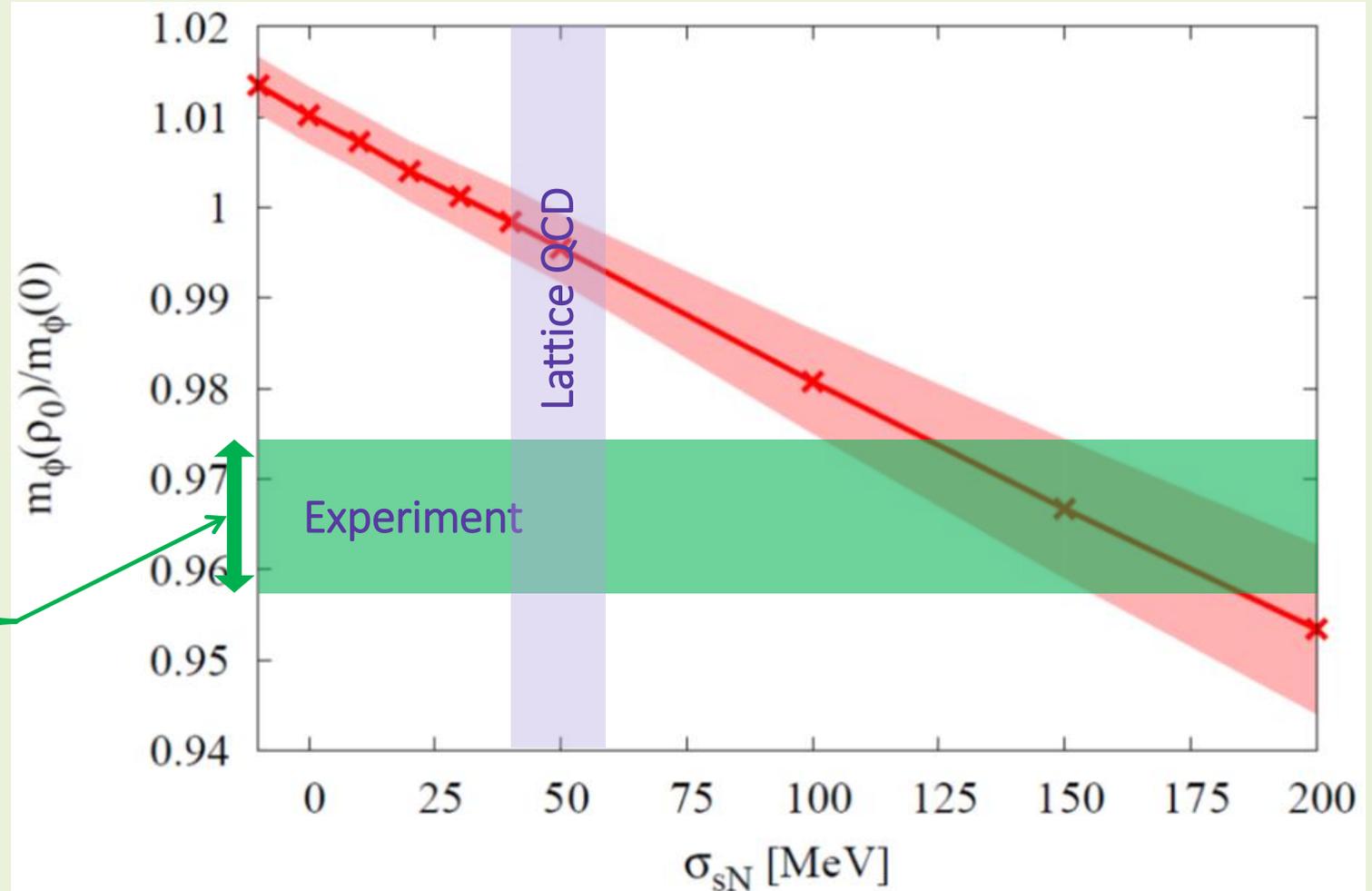
Compare Theory with Experiment

Not consistent?

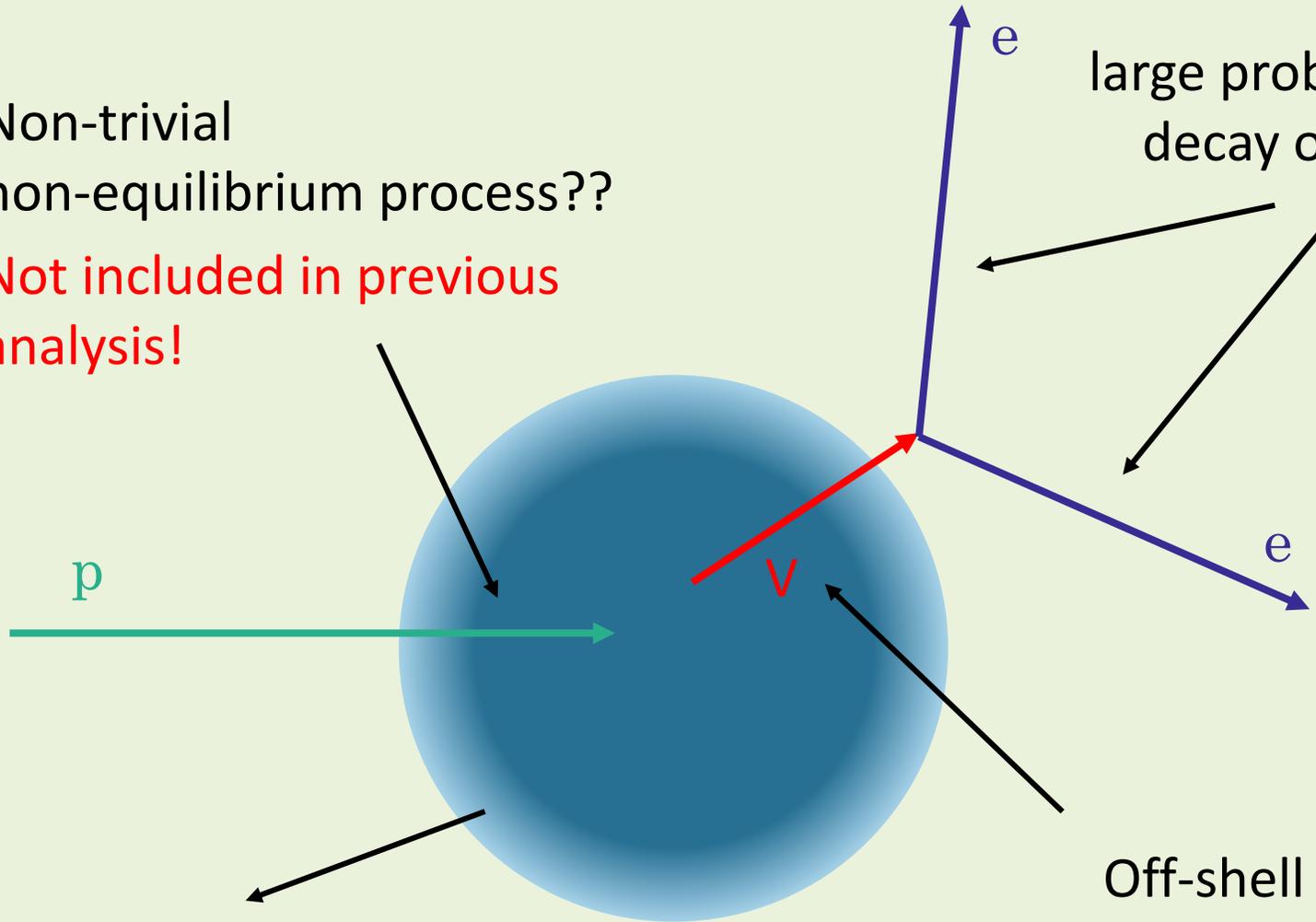Measurement will be repeated at the E16 experiment at J-PARC (with 100 times increased statistics!)

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

Non-trivial
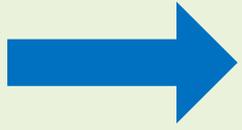non-equilibrium process??
Not included in previous
analysis!

large probability of vector meson
decay outside of the nucleus

e

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)

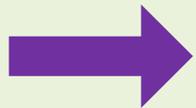E.L. Bratkovskaya and W. Cassing, Nucl. Phys. A **807**, 214 (2008).
W. Cassing and E.L. Bratkovskaya, Phys. Rev. C **78**, 034919 (2008).

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

➡ Motion/deformation of target is taken into account!

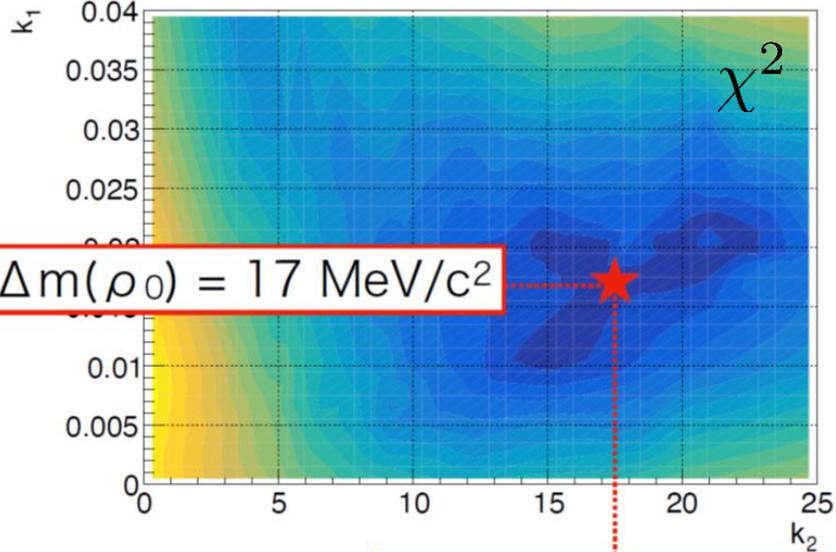★ Off-shell dynamics of vector mesons and kaons is included

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

Comparison with KEK E325 dilepton data

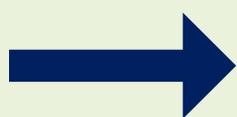Case of density dependent partial decay width Γ^{ee}

➡️ **Momentum dependence** is needed to explain the data!

➡️ **Smaller mass shift, stronger broadening and larger errors**
than in the original E325 analysis!

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

Comparison with KEK E325 dilepton data

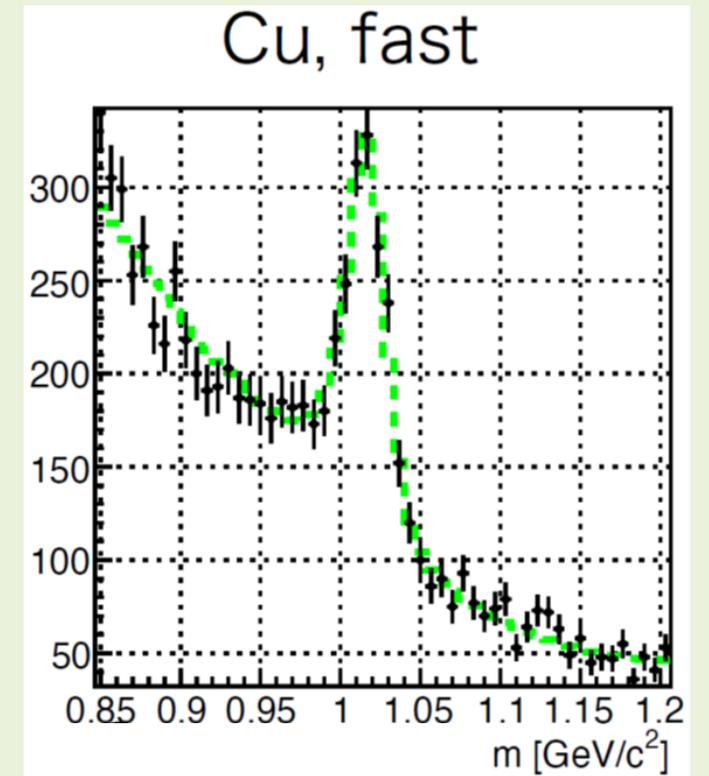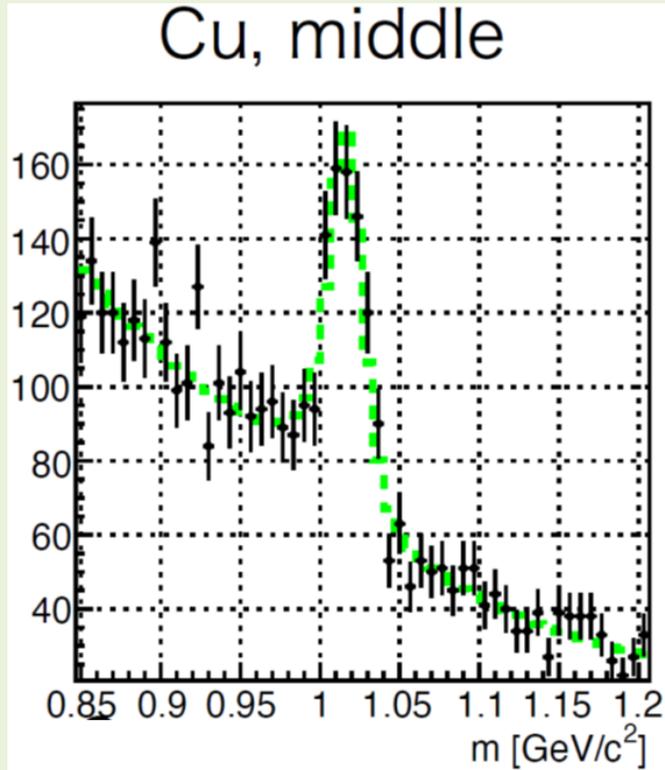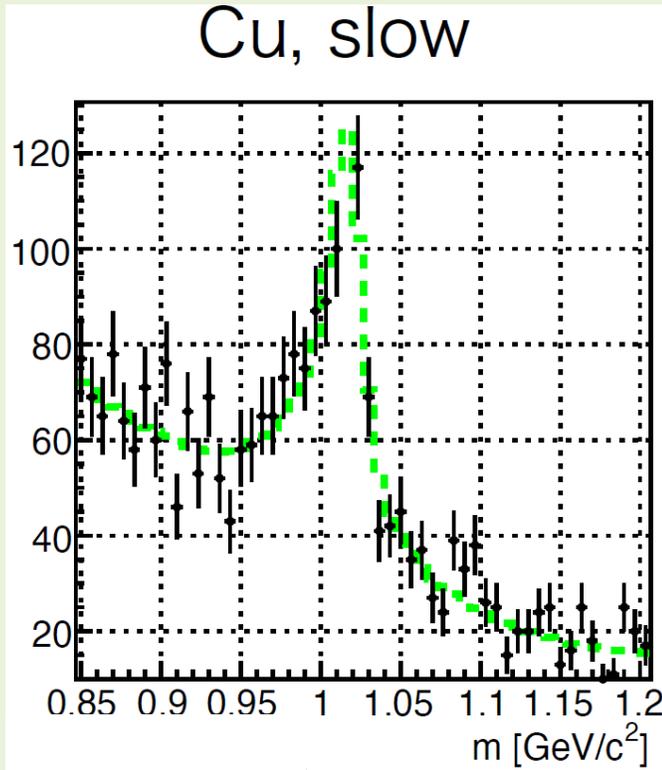Cu, slow   Cu, middle   Cu, fast

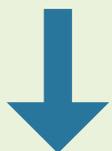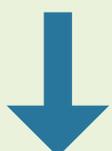➡ **Momentum dependence** is needed to explain the data!

➡ **Smaller mass shift, stronger broadening and larger errors** than in the original E325 analysis!

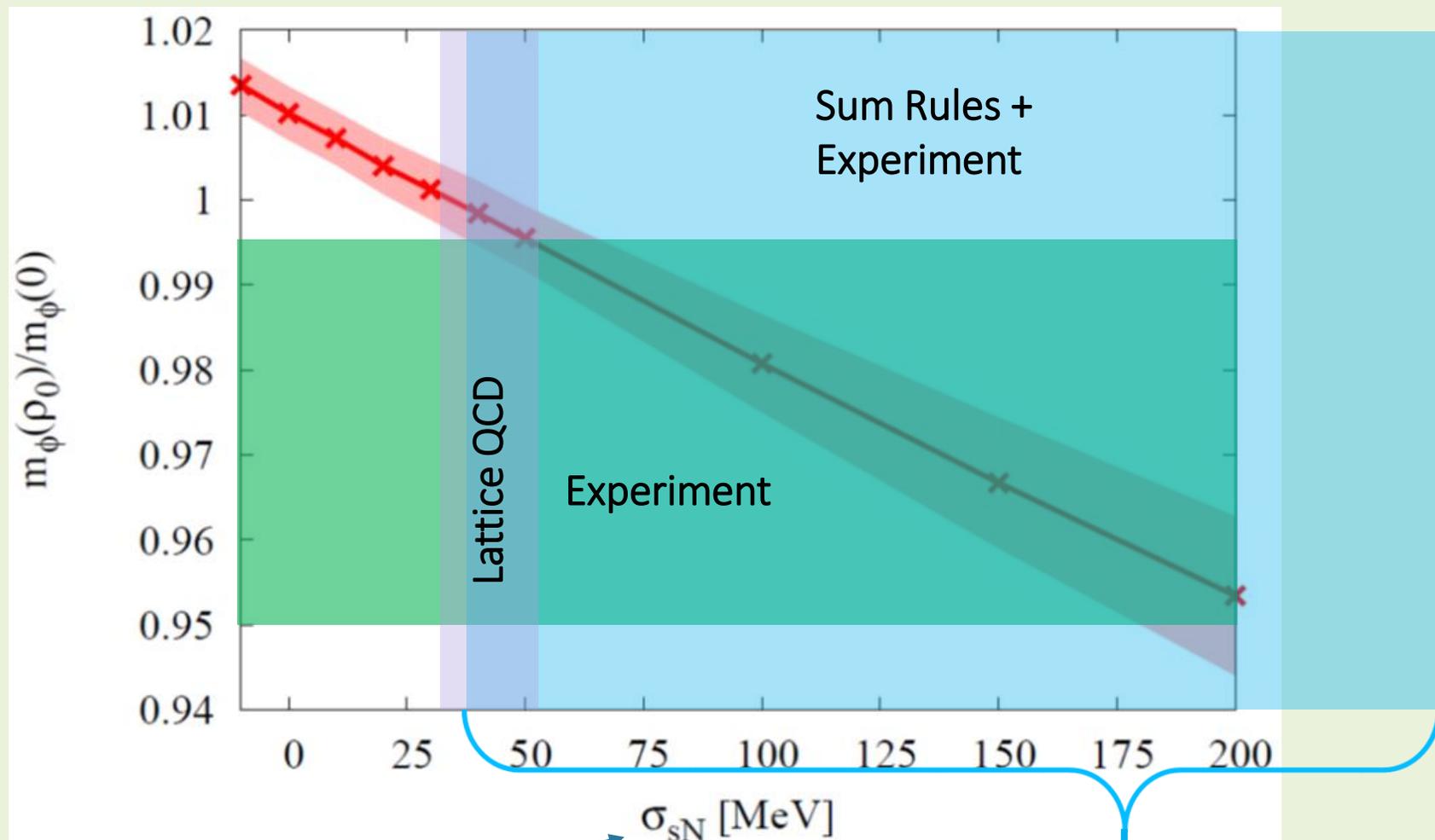# New comparison between theory and experiment

Problem solved???

↓
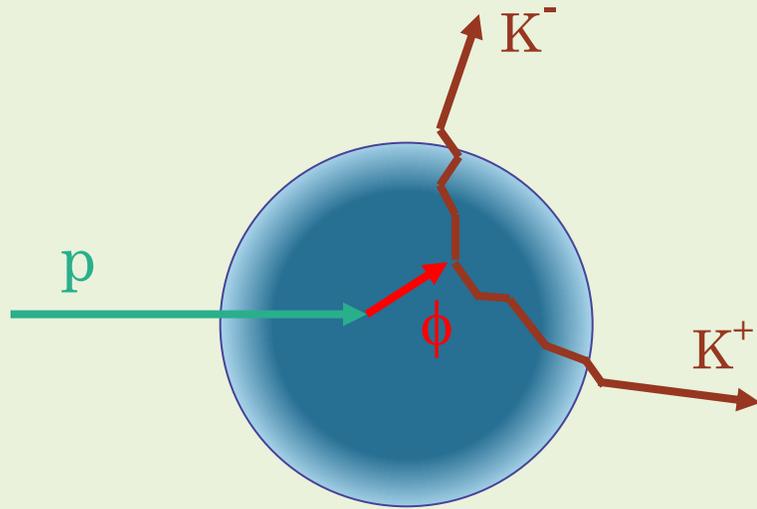
Need more precise data!

↓

Stay tuned for J-PARC E16

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

$$\sigma_{sN} \sim 140 \pm 100 \text{ MeV}$$

Outlook to J-PARC E16/E88

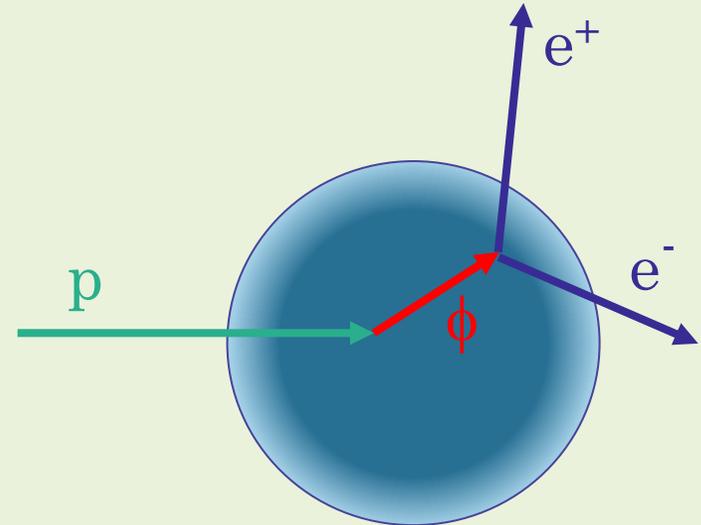# Simulation results with BuBUU

BuBUU (Budapest BUU): BUU type off-shell transport approach

Used mean fields to parametrize the K and Kbar interactions with the nuclear medium

Model		Mean Field Expression	Parameter Values
M1	K^+	$U_{K+} = 0$	–
	K^-	$U_{K-} = 0$	–
M2	K^+	$U_{K+} = a_2 \cdot \rho$	$a_2 = 0.167 \, [\text{GeV} \cdot \text{fm}^3]$
	K^-	$U_{K-} = -a_2 \cdot \rho$	
M3	K^+	$U_{K+} = a_3 \cdot \rho$	$a_3 = 0.167 \, [\text{GeV} \cdot \text{fm}^3]$
	K^-	$U_{K-} = -\rho(b_3 + c_3 \cdot e^{-d_3 \cdot p_K})$	$b_3 = 0.341 \, [\text{GeV} \cdot \text{fm}^3],$
			$c_3 = 0.823 \, [\text{GeV} \cdot \text{fm}^3],$
			$d_3 = 2.5 \, [\text{GeV}^{-1}]$
M4	K^+, K^-	Momentum dependent mean fields derived from a chiral unitary approach	

G. Balassa et al., arXiv:2508.11344 [hep-ph] (To be published in Prog. Theor. Exp. Phys.).

Simulation results with BuBUU

30 GeV pA collisions, Pb target, mass shift $\Delta m_\varphi(\rho_0)$ = -34 MeV is assumed

G. Balassa et al., arXiv:2508.11344 [hep-ph] (To be published in Prog. Theor. Exp. Phys.).

Possible observation of chiral mixing?

Simple idea:

Charge conjugation (C) symmetry is broken in nuclear matter

➡️ Non-trivial mixing between different modes can occur

Here we consider the Vector – Axial-vector mixing in the strange quark sector

R. Ejima, C. Sasaki, P. Gubler and K. Shigaki, Phys. Rev. C **111**, 055201 (2025).

Potential signal strengths for different mixing scenarios

Signals for 30 GeV pA collisions, Pb target, E16 Run2 statistics

R. Ejima, C. Sasaki, P. Gubler and K. Shigaki, Phys. Rev. C **111**, 055201 (2025).

Summary and conclusions

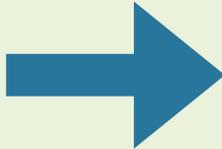★ The φ-meson is and ideal probe to study potential mass shifts in nuclear matter

★ With the PHSD transport approach, we can now study pA reactions more reliably ➡ **Changed conclusions from previous analysis of experimental data**

★ More precise data will be needed to determine the φ meson mass shift in nuclear matter

★ The J-PARC E16 and E88 have the potential to **extract the nature of the spectral modification of the φ-meson** in nuclear matter and to possibly **observe the chiral mixing phenomenon** in nuclear matter for the first time

Backup slides

Simple hadronic model including C-symmetry breaking

$$\mathcal{L} = 2c\epsilon^{0\mu\nu\lambda}\text{tr}\left[\partial_\mu V_\nu \cdot A_\lambda + \partial_\mu A_\nu \cdot V_\lambda\right]$$

Can be understood from an anomalous ω-φ-f1 coupling with a coherent ω-field: $\langle\omega_0\rangle \sim \rho$

 tree-level V-A mixing!

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

However, the coupling c is model dependent:

$$c = 1.0\frac{\rho}{\rho_0}\text{ [GeV]}$$

from holographic QCD

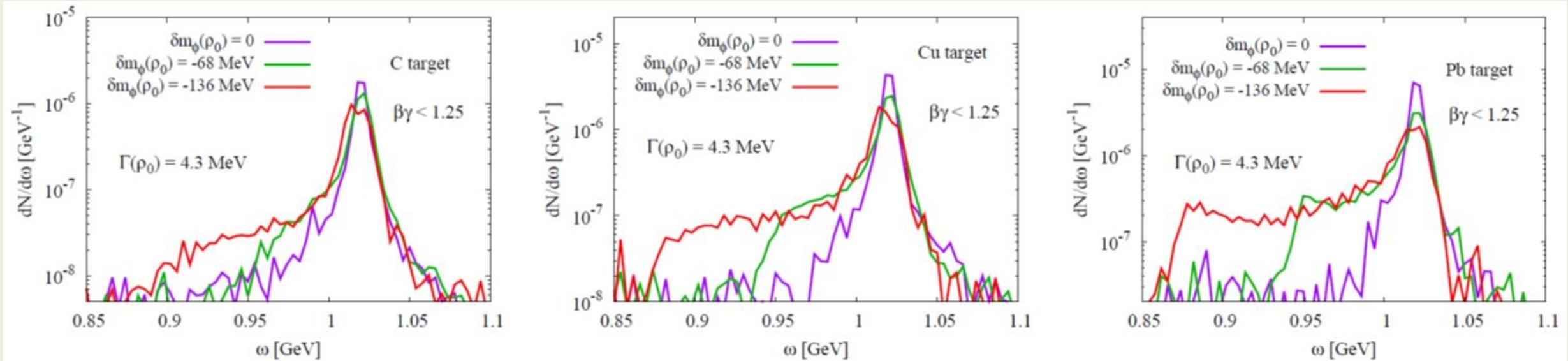S. K. Domokos and J. A. Harvey,
Phys. Rev. Lett. **99**, 141602 (2007).

$$c = 0.1\frac{\rho}{\rho_0}\text{ [GeV]}$$

from gauged WZW action

M. Harada and C. Sasaki,
Phys. Rev. C **80**, 054912 (2009).

The obtained dilepton spectrum (without experimental effects)
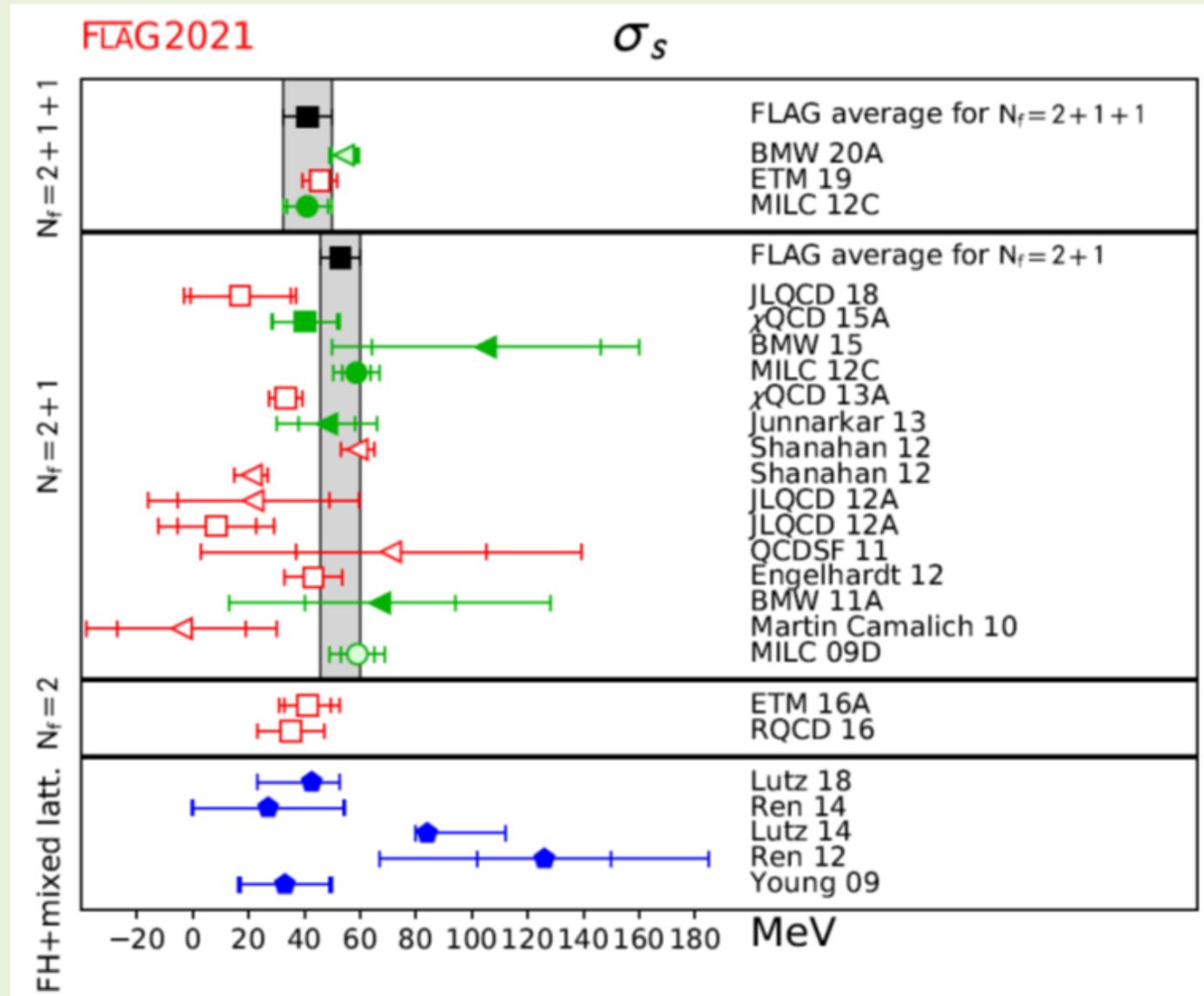
Pure mass shift scenarios (no broadening)

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).

What does lattice QCD say about the strange sigma term?

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

Introduction

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

E16/E88 experiments at J-PARC

Pion induced φ meson production

P95 experiment at J-PARC

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

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).

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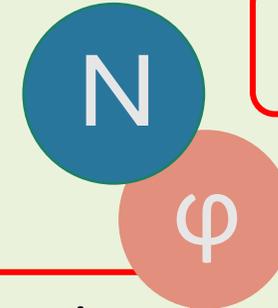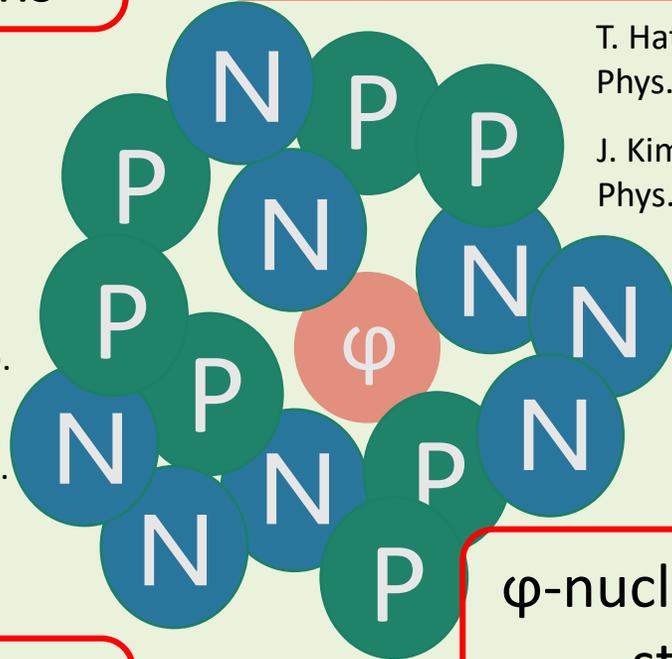
E. Chizzali et al.,
Phys. Lett. B **848**, 138358 (2024).

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?

Exotic dispersion relations

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

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

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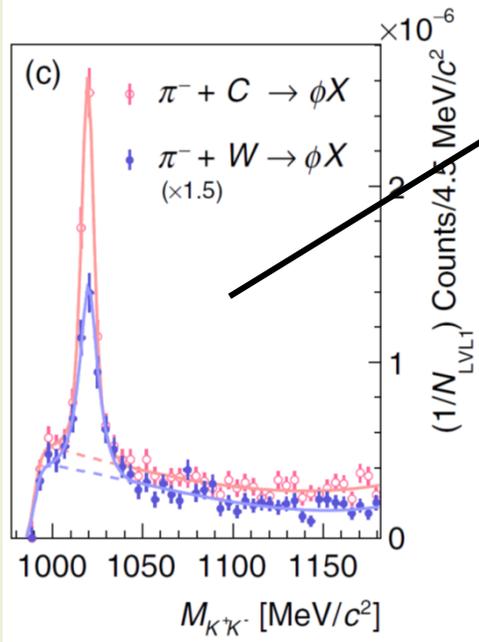Phys. Rev. C **110**, 065202 (2024).

Lattice QCD (HAL)

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

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).

ALICE: pp

Measurement of φN correlation

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

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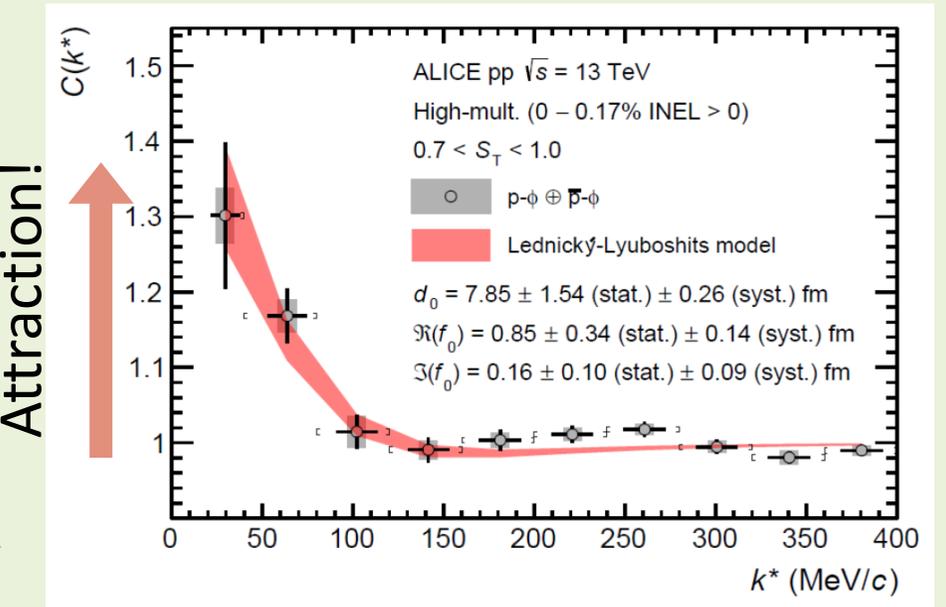the total φ meson production
cross section:

★ **Attractive φ-nucleus potential:**
   -(50 - 100) MeV

★ **Small imaginary part:**
   20 – 25 MeV

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

Attraction!

Large negative mass shift?
Small broadening?

★ Photoproduction measurements
I.I. Strakovsky et al. (CLAS),
Phys. Rev. C **101**, 045201 (2020).
$|a_0| = 0.063 \pm 0.010 \, \text{fm}$
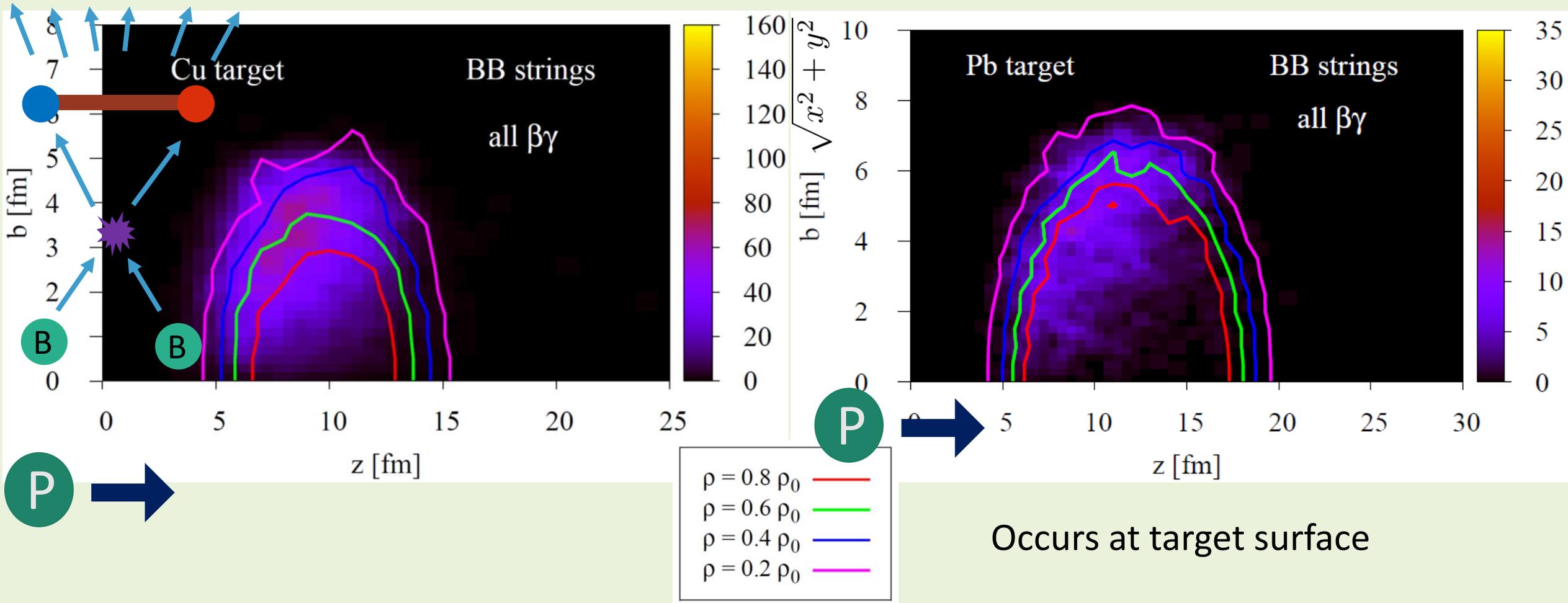
★ Hadronic Effective theory
calculations

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

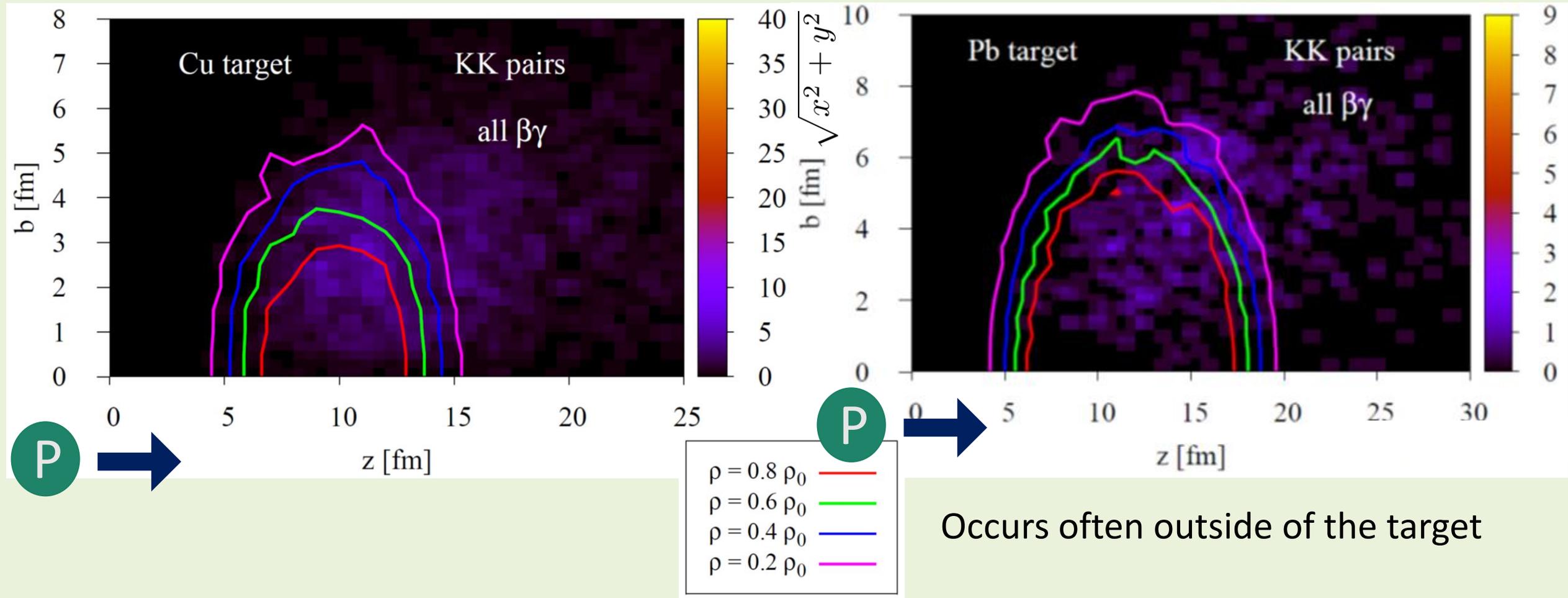$$a_0^{3/2} = 1.43(23)_{\text{stat.}} \left(^{+36}_{-06}\right)_{\text{syst.}} \text{fm}$$

How are φ mesons produced in 12 GeV pA collisions?

Production through initial high-energy collisions (via strings)

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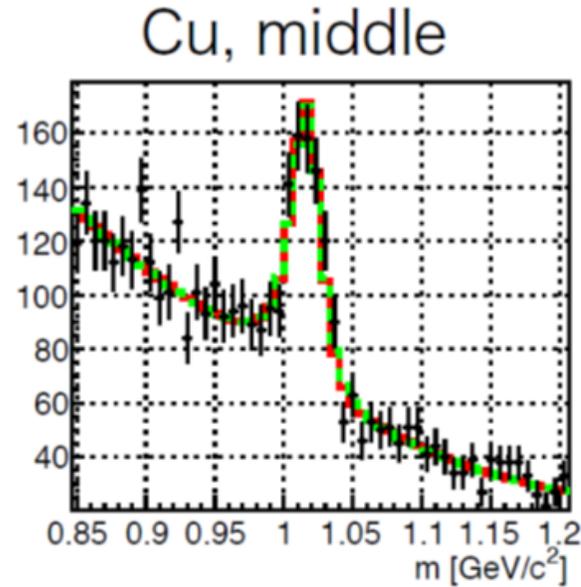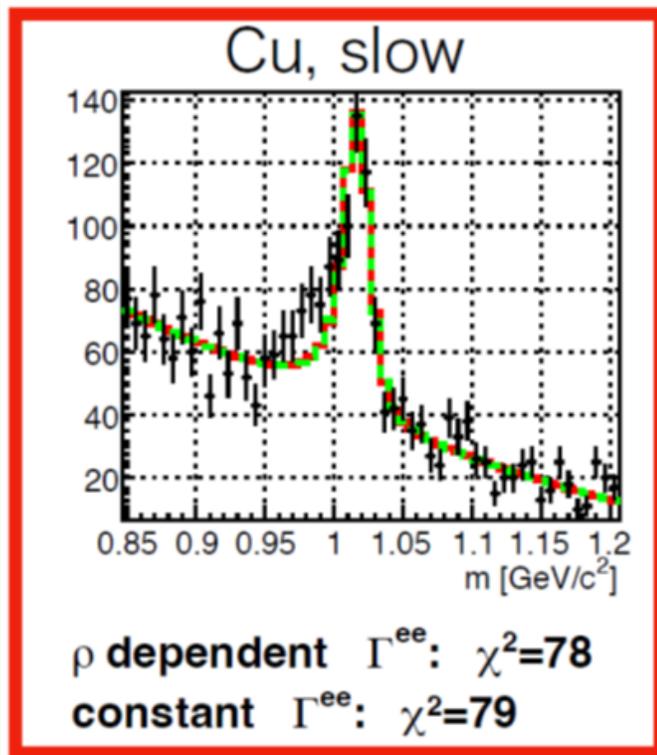
P. Gubler, M. Ichikawa, T. Song and E. Bratkovskaya, Phys. Rev. C **111**, 034908 (2025).

How are φ mesons produced?

Production through secondary low-energy hadron collisions
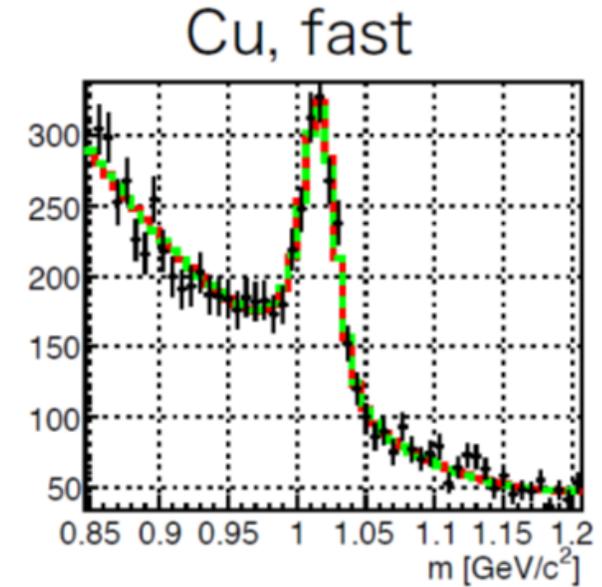

Occurs often outside of the target

Comparison with KEK E325 dilepton data

First trial:
Momentum-independent mass shift and decay width

Cu, slow
ρ dependent Γ^{ee}: χ^2=78
constant Γ^{ee}: χ^2=79

Cu, middle
ρ dependent Γ^{ee}: χ^2=44
constant Γ^{ee}: χ^2=44

Cu, fast
ρ dependent Γ^{ee}: χ^2=57
constant Γ^{ee}: χ^2=56

Experimental data don't seem to be well reproduced.

M. Ichikawa, P. Gubler, M. Naruki and S. Yokkaichi, in preparation.

QCD sum rules

Provides relation between QCD condensates and the hadron spectrum

$$\chi(x) = \bar{s}(x)\gamma_\mu s(x)$$

$$\Pi(q^2) = i \int d^4x\, e^{iqx} \langle T[\chi(x)\bar{\chi}(0)]\rangle_\rho$$

spectral function

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

q^2

OPE

$\langle \bar{q}q \rangle_\rho,$

$\langle G^a_{\mu\nu} G^{a\mu\nu} \rangle_\rho,$

$\langle \bar{q}\sigma_{\mu\nu}\frac{\lambda^a}{2} G^{a\mu\nu} q \rangle_\rho,$

$\langle \bar{q}q\bar{q}q \rangle_\rho,$

scalar condensates:
same for longitudinal and transverse modes

$\langle \mathcal{ST}\bar{q}\gamma^\alpha iD^\beta q \rangle_\rho,$

$\langle \mathcal{ST} G^{a\alpha}_\mu G^{a\mu\beta} \rangle_\rho,$

$\langle \mathcal{ST}\bar{q}\gamma^\alpha iD^\beta iD^\gamma iD^\delta q \rangle_\rho$

non-scalar condensates:
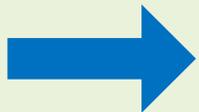**cause difference between longitudinal and transverse modes**

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!

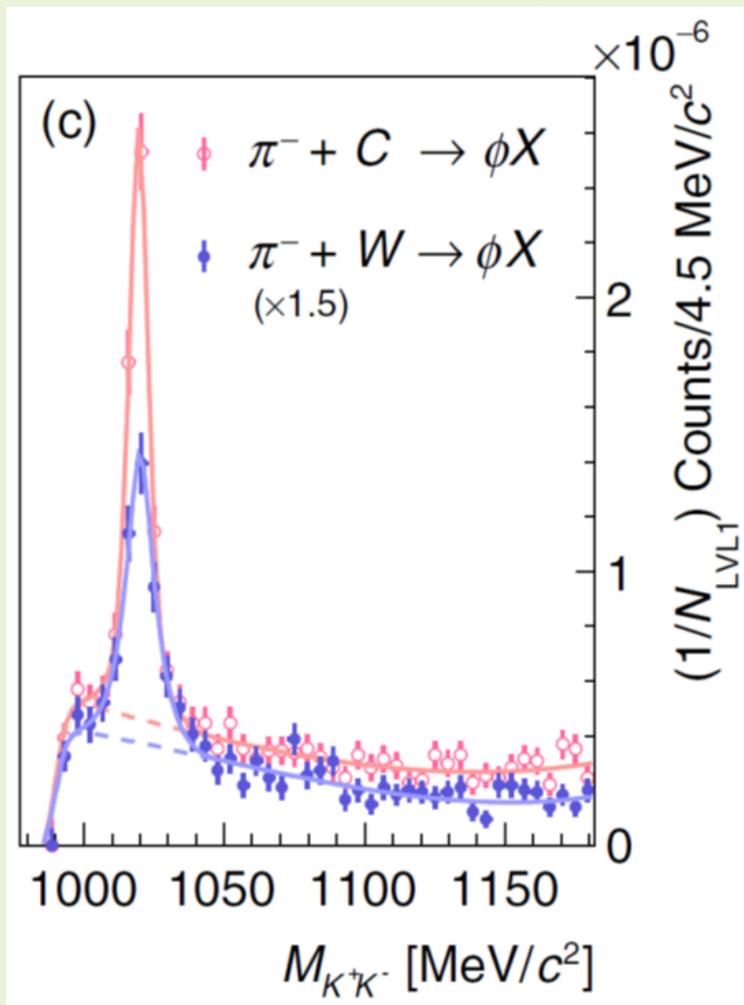However, the above prescription seems problematic if a φN bound state (or resonance) is formed.

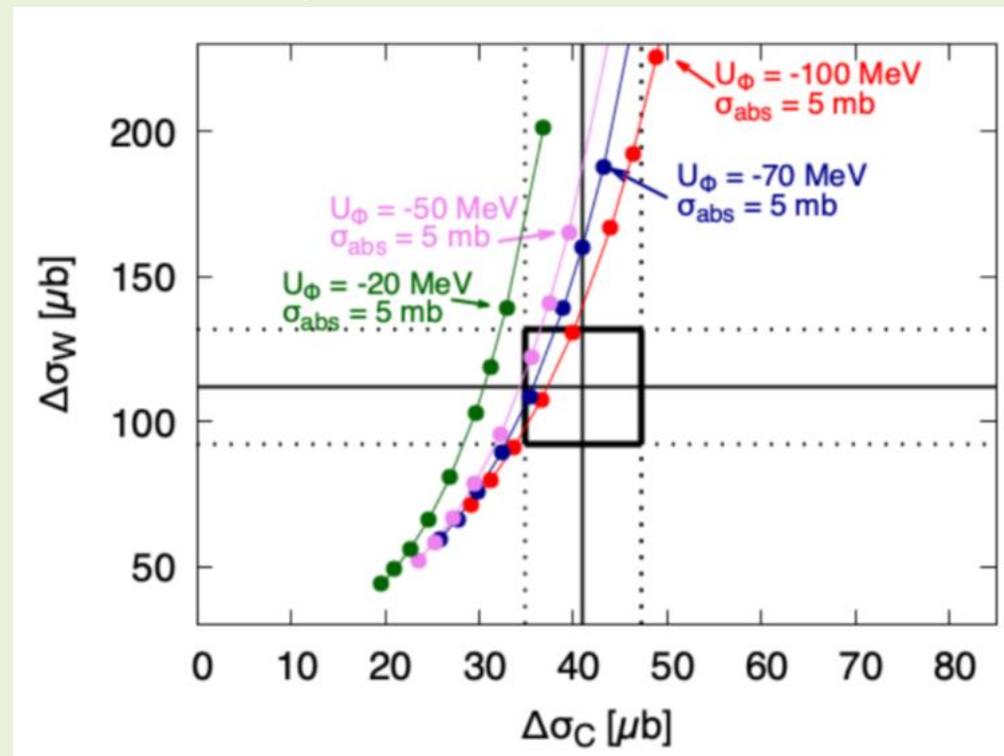→ Need better theoretical understanding!

More recent results

HADES: 1.7 GeV π⁻A-reaction

K⁺K⁻ - invariant mass spectrum

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

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

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

➤ **Attractive φ-nucleus potential:**
-(50 - 100) MeV

➤ **Relatively small imaginary part:**
20 – 25 MeV

Experimental di-lepton spectrum