The φ meson in nuclear matter from theory and experiment

Philipp Gubler (JAEA)



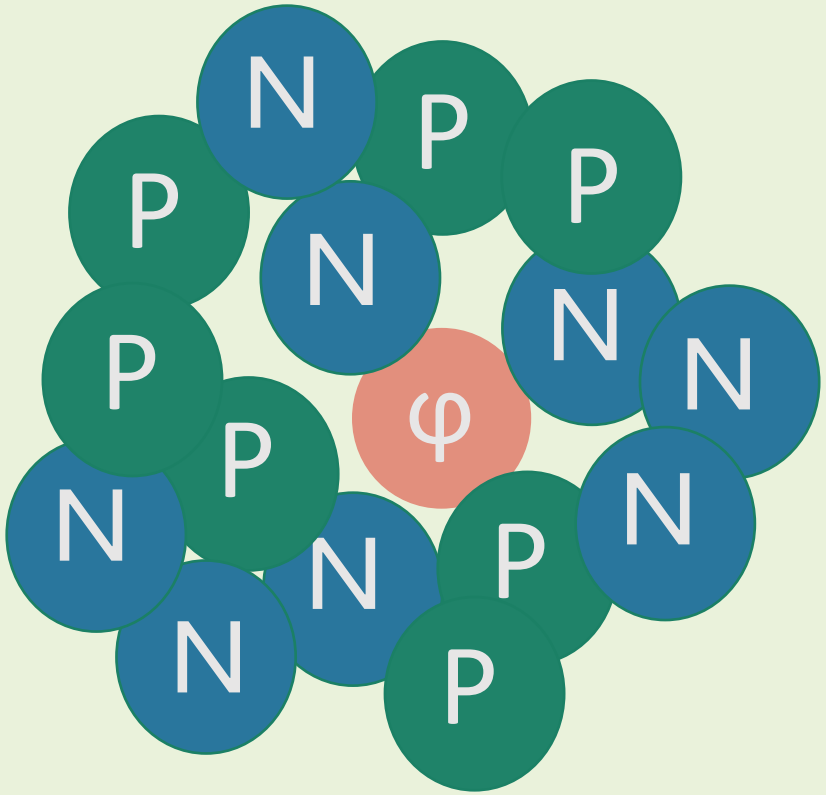
P. Gubler, M. Ichikawa, T. Song and E. Bratkovskaya, Phys. Rev. C **111**, 034908 (2025).
M. Ichikawa et al., (KEK-PS E325 Collaboration), Prog. Theor. Exp. Phys. **2025**, 093D01 (2025).
A.J. Arifi, P. Gubler and K. Tsushima, Phys. Rev. D **114**, 034041 (2026).

Talk at "Fundamental Problems in Subatomic Physics 2026"
Cairns, Australia
September 26, 2026

Work done in collaboration with:

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T. Song (GSI)
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M. Naruki (Kyoto U.)
S. Yokkaichi (RIKEN)
KEK-PS E325 Collaboration
A.J. Arifi (JAEA)
K. Tsushima (Sao Paulo F. U.)

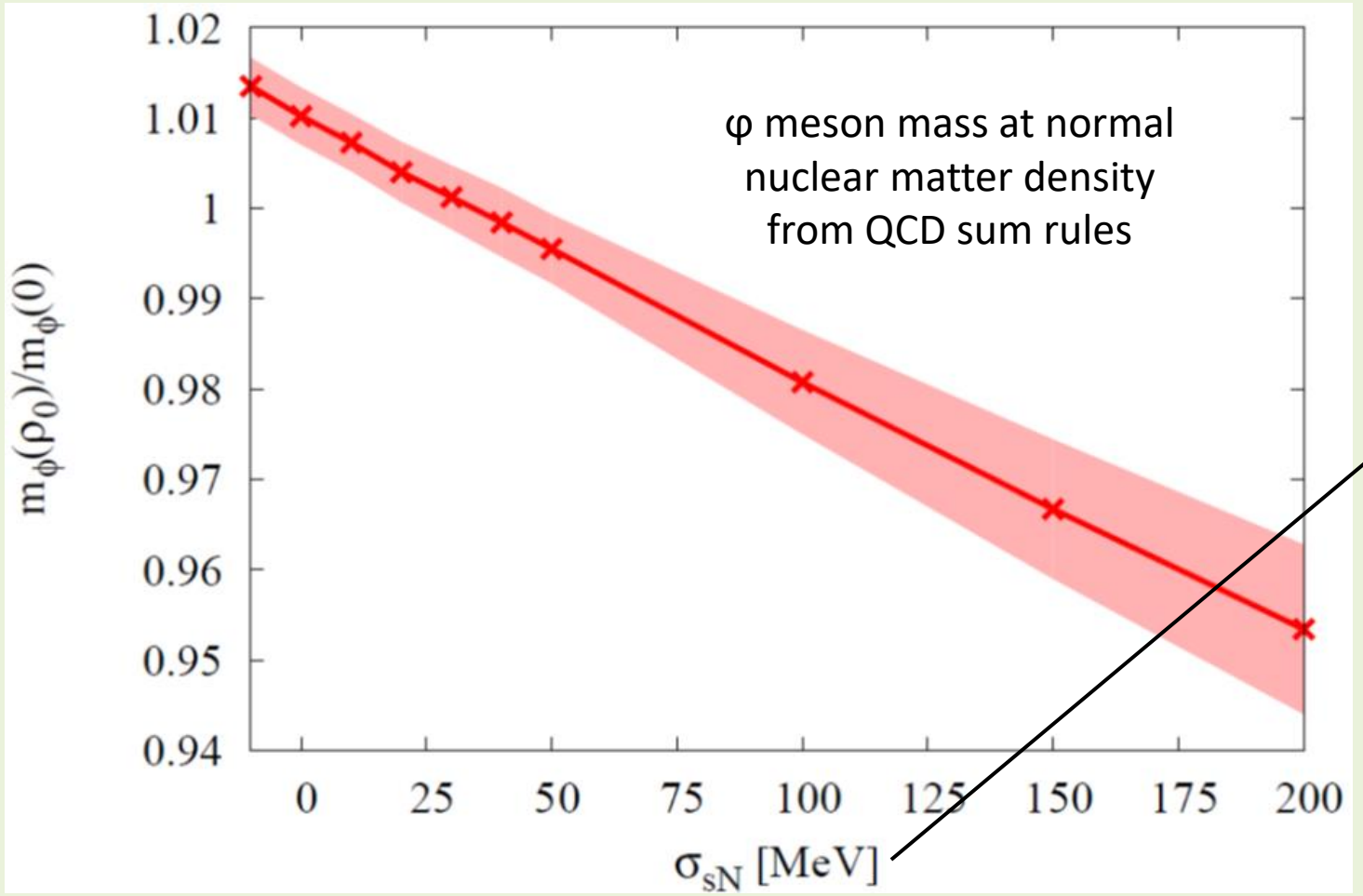
Mass of the φ meson in nuclear matter



$$m_\phi \searrow ?$$

Why should we be interested?

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



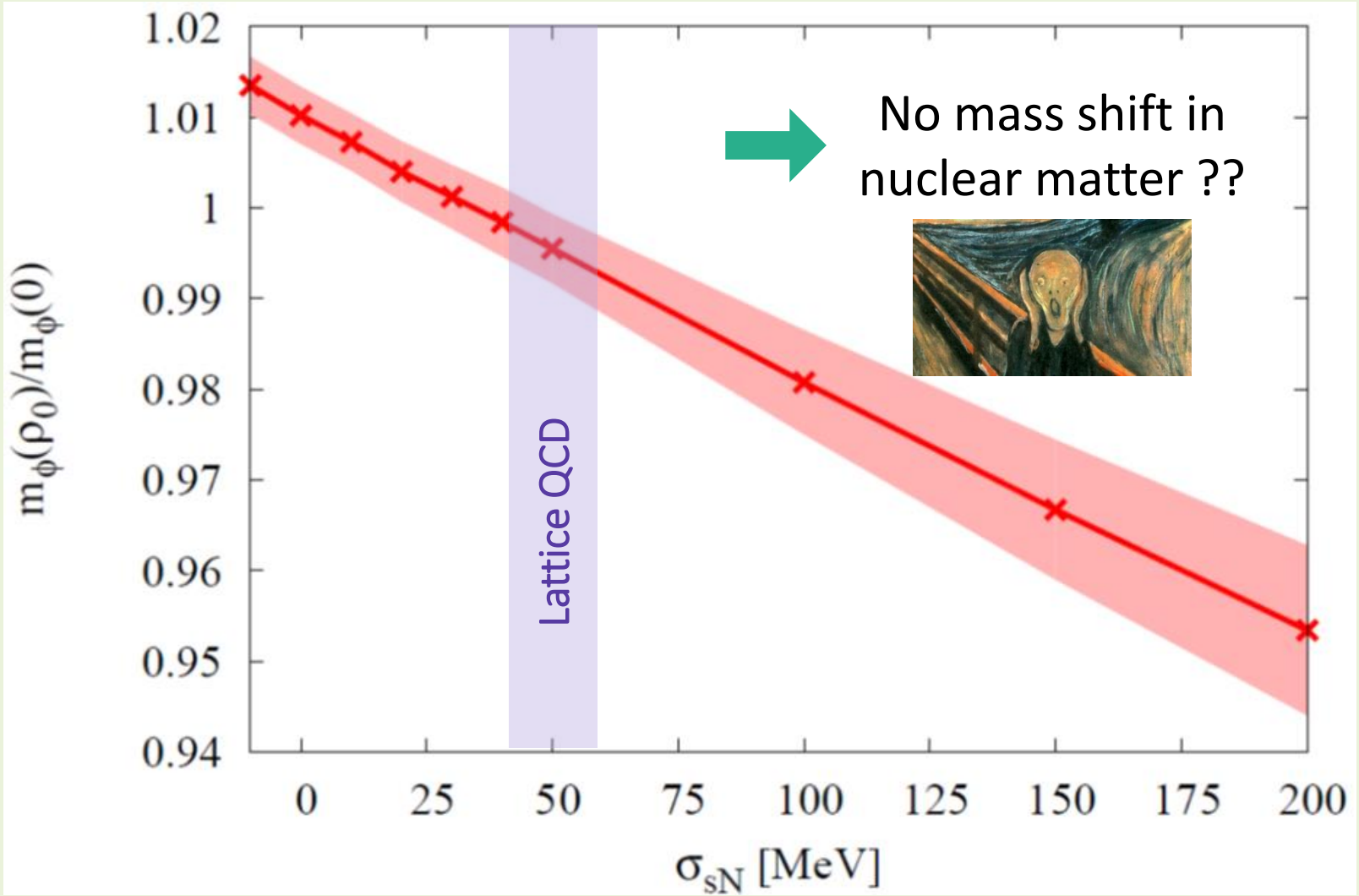
P. Gubler and K. Ohtani, Phys. Rev. D **90**, 094002 (2014).

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

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

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

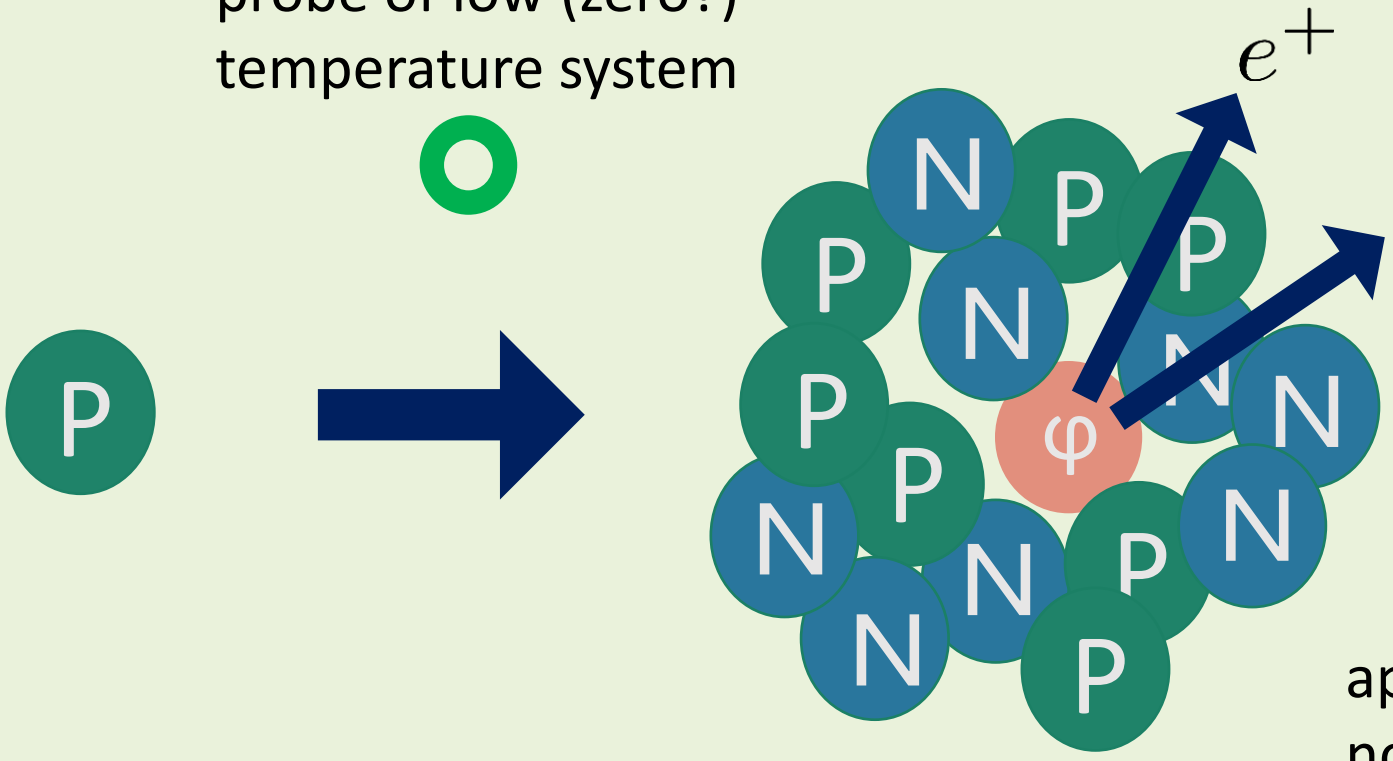
Combine QCD sum rules with lattice QCD



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

What about experiment?

probe of low (zero?) temperature system



no distortion of signal due to interaction with nuclear medium

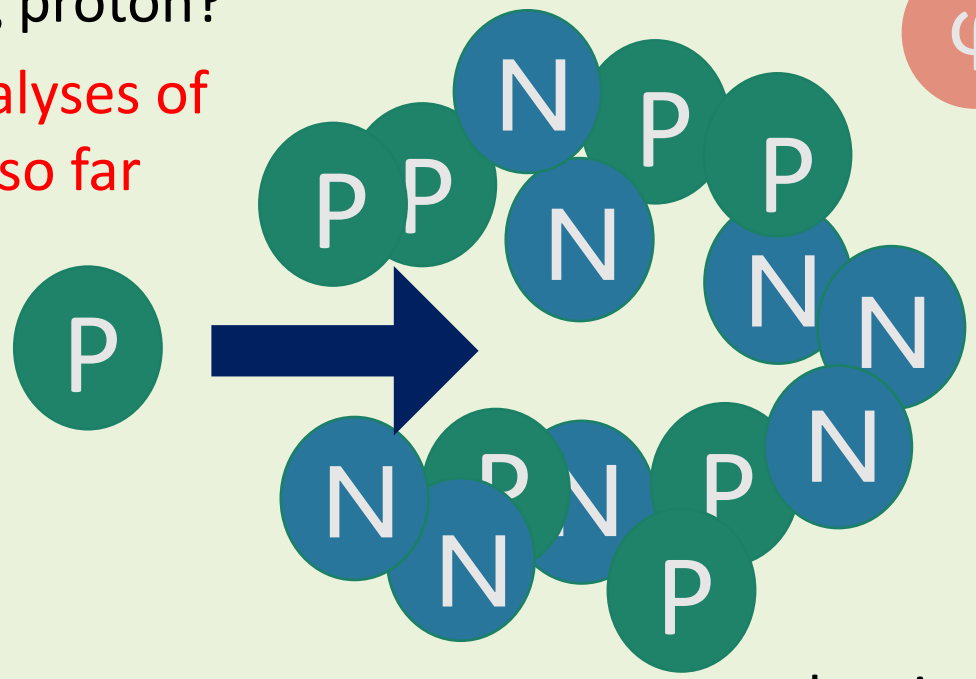
approximate density: normal nuclear density ρ_0

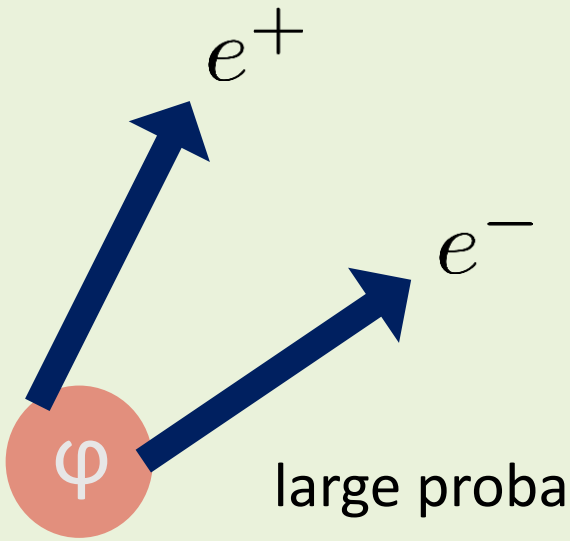
E325 (KEK)
E16 (J-PARC)

Challenges…

Distortion of the target nucleus due to the incoming proton?

Not included in analyses of experimental data so far





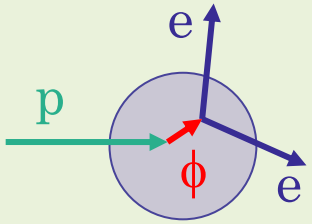
large probability of vector meson decay outside of the nucleus

density much below ρ_0 at the nuclear surface

E325 (KEK)
E16 (J-PARC)

Available 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

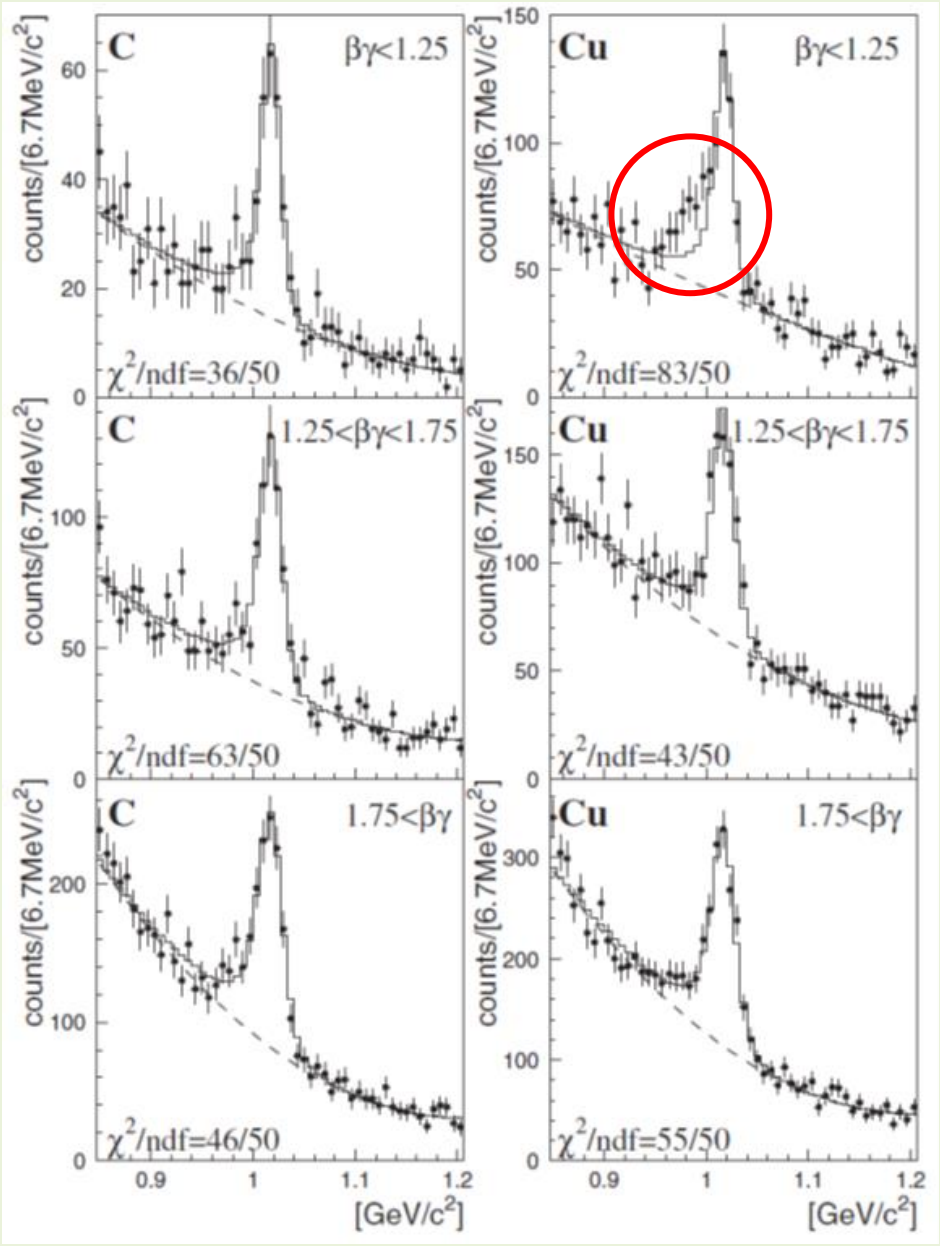
Pole width: $$\frac{\Gamma_\phi(\rho)}{\Gamma_\phi(0)} = 1 + k_2 \frac{\rho}{\rho_0}$$

2.6 ± 1.5

slow φs

intermediate φs

fast φs



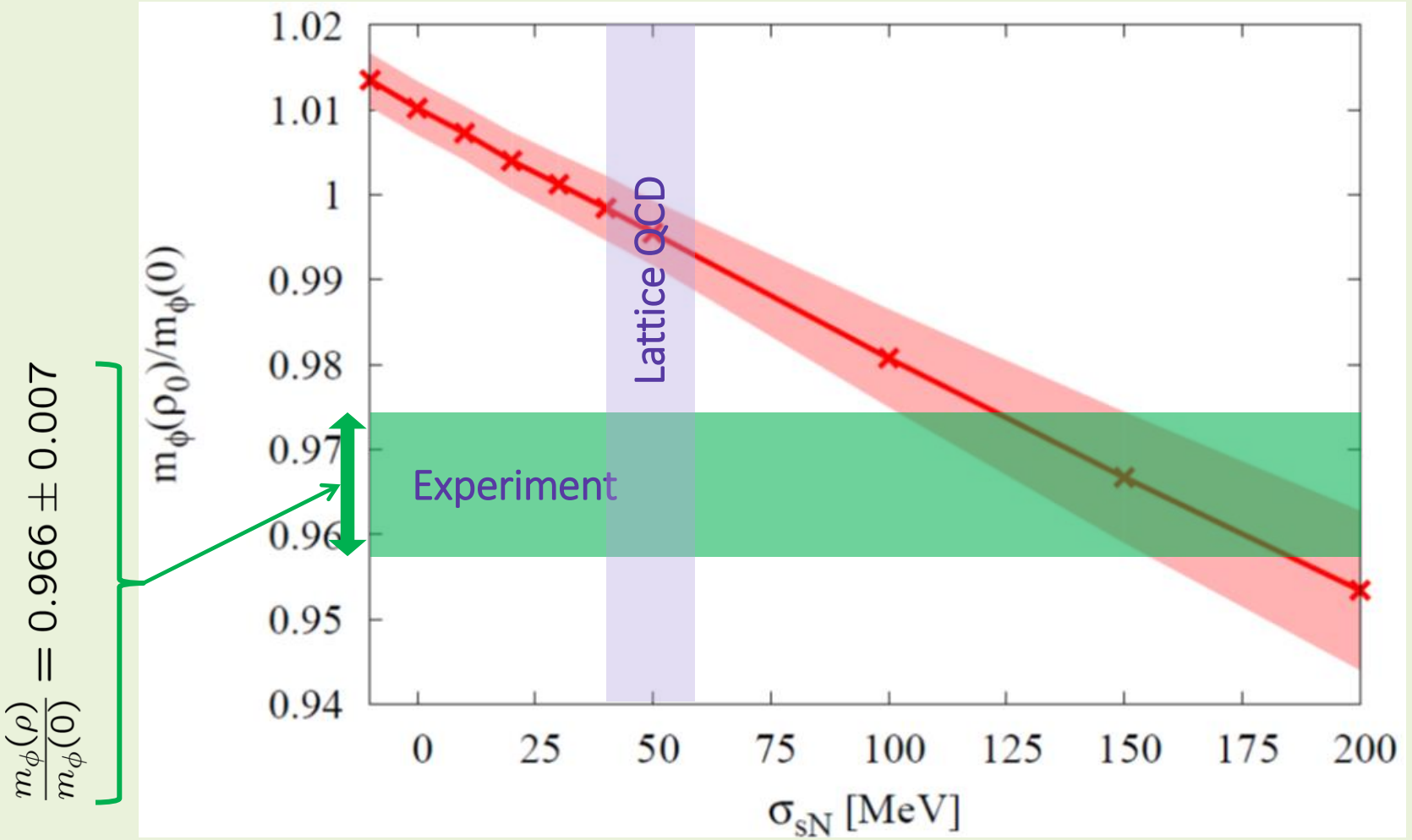
$$\beta\gamma = \frac{|\vec{p}|}{m_\phi}$$

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

Compare Theory with Experiment

Not consistent?

Better understanding of the proton-nucleus reaction is needed!



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

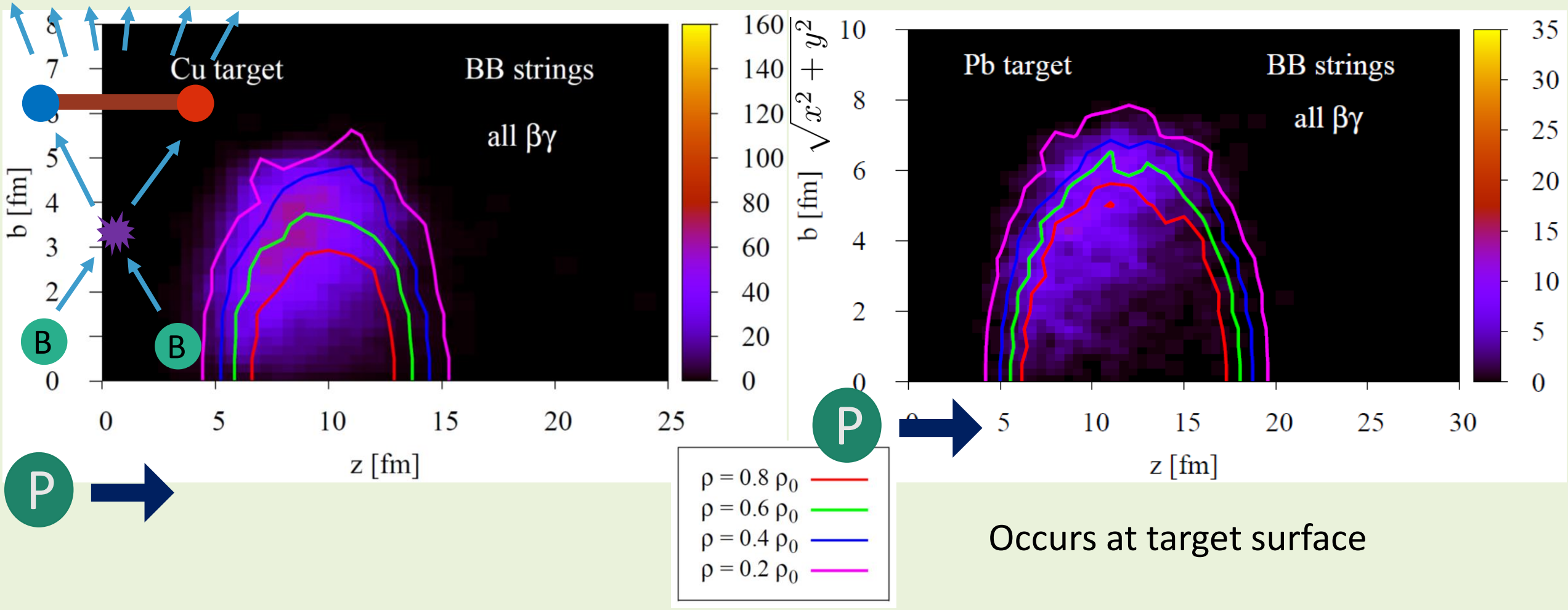
→ We use a relativistic Breit-Wigner with density dependent mass and width

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

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)

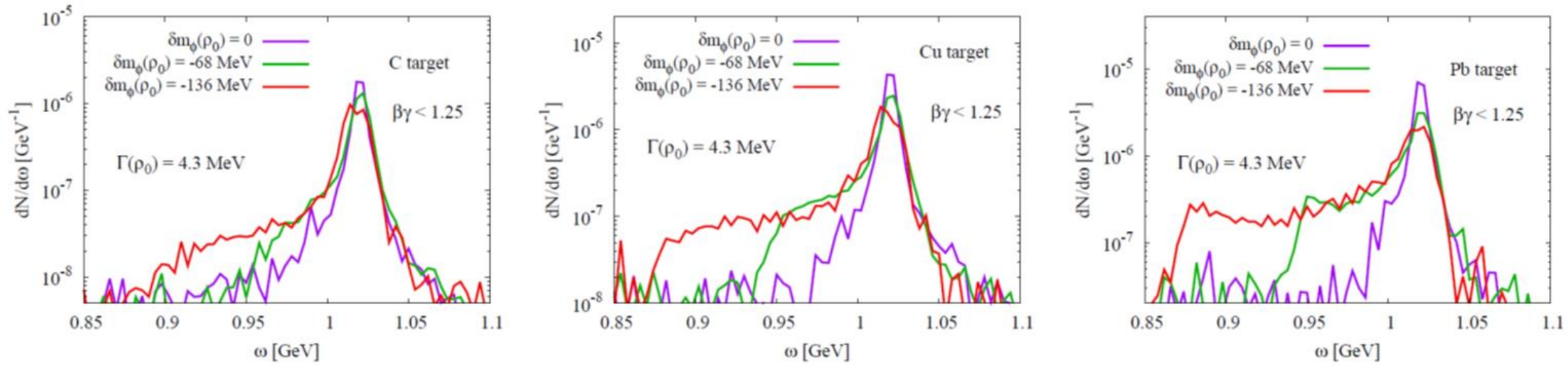


Occurs at target surface

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

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)

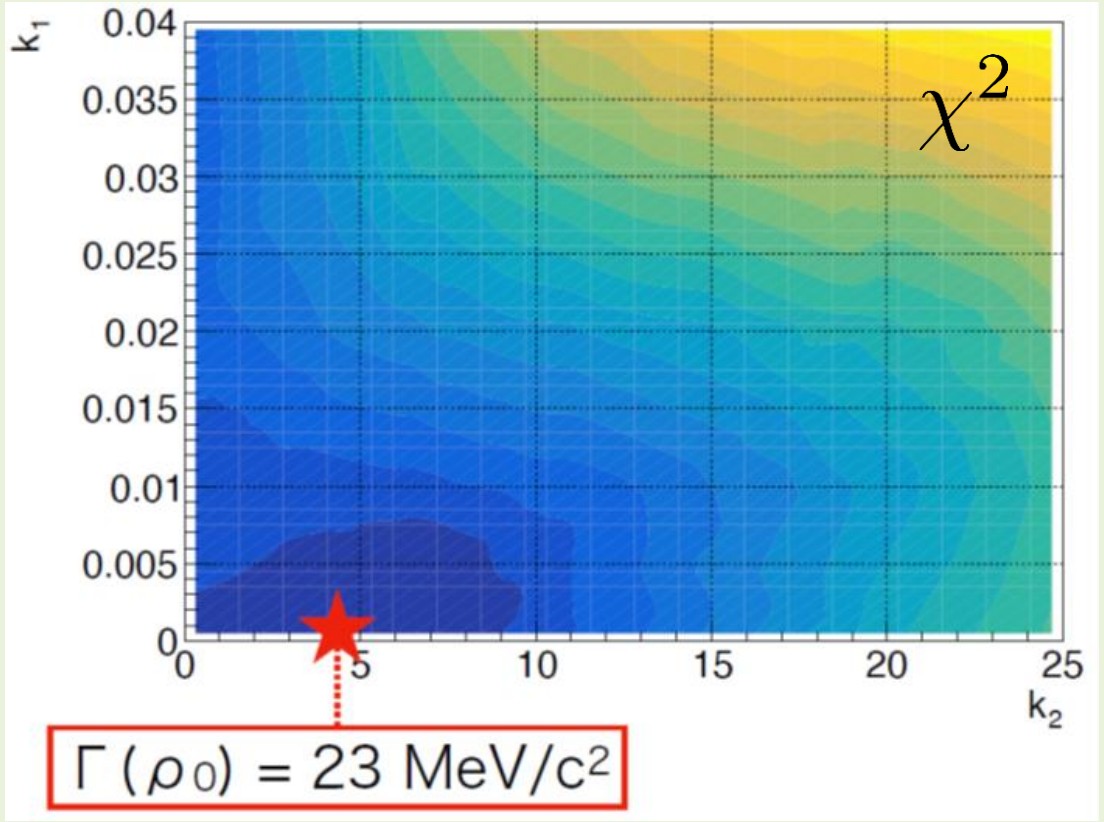
Secondary peak can be generated for sufficient large mass shift scenario if the target is large enough (Pb here)

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

Comparison with KEK E325 dilepton data

First trial:

Momentum-independent mass shift and decay width



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

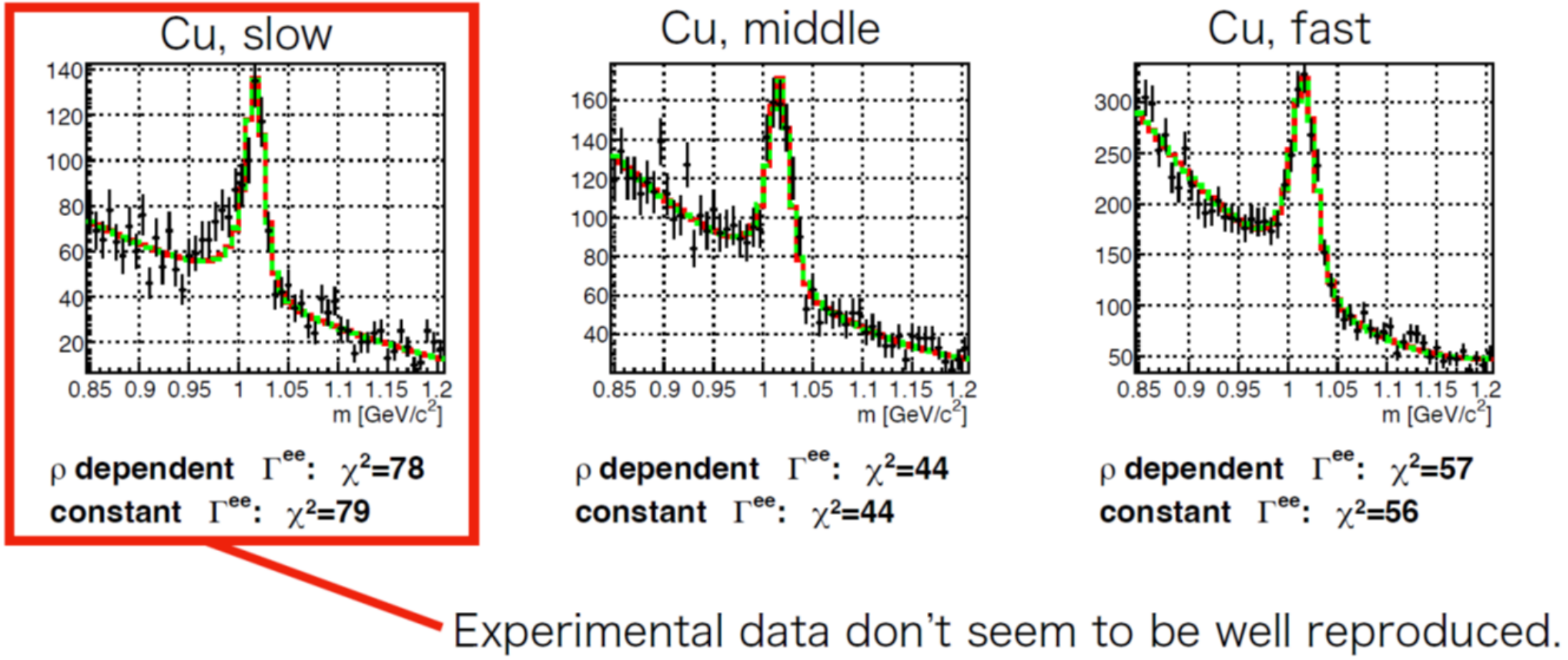
$$\frac{\Gamma_\phi(\rho)}{\Gamma_\phi(0)} = 1 + k_2 \frac{\rho}{\rho_0}$$

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

Comparison with KEK E325 dilepton data

First trial:

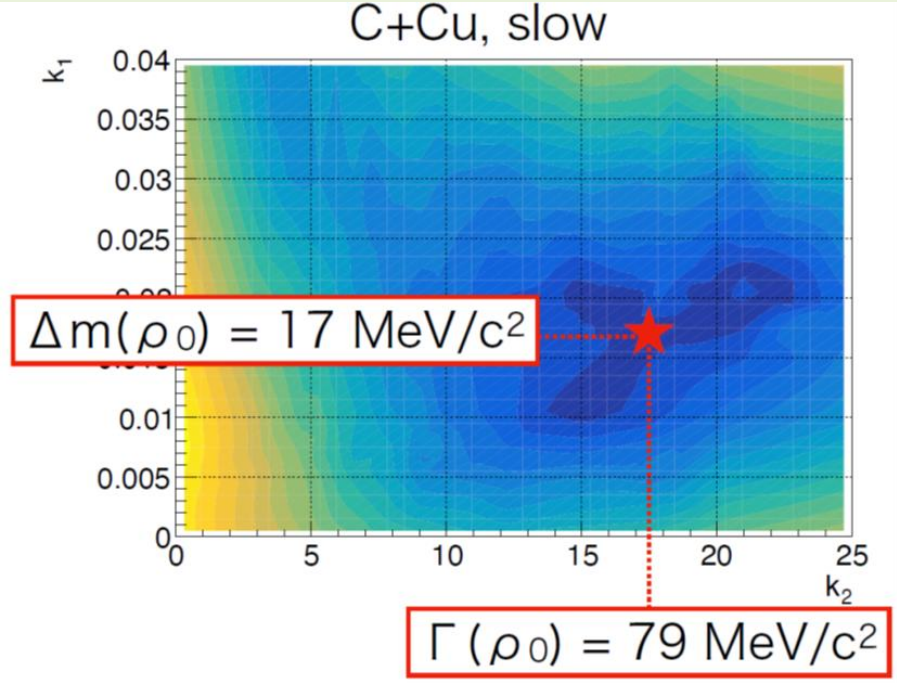
Momentum-independent mass shift and decay width

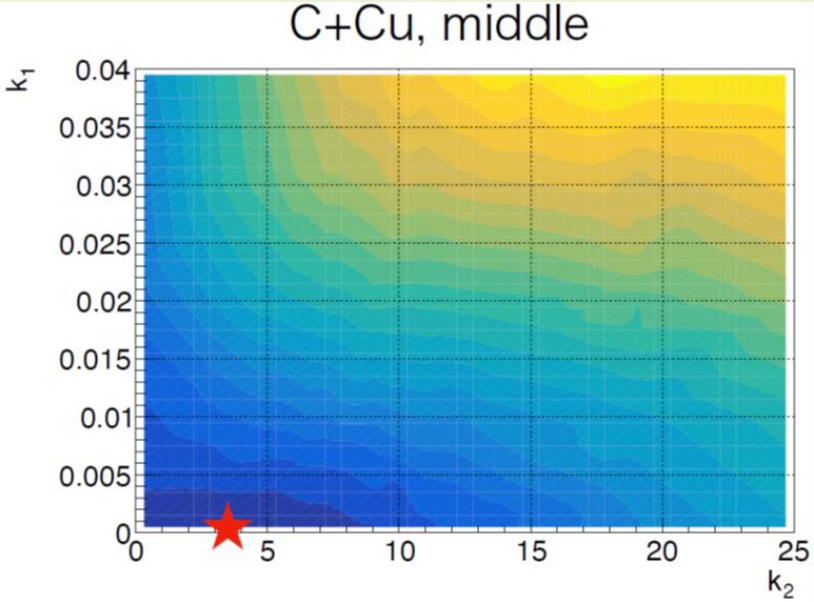


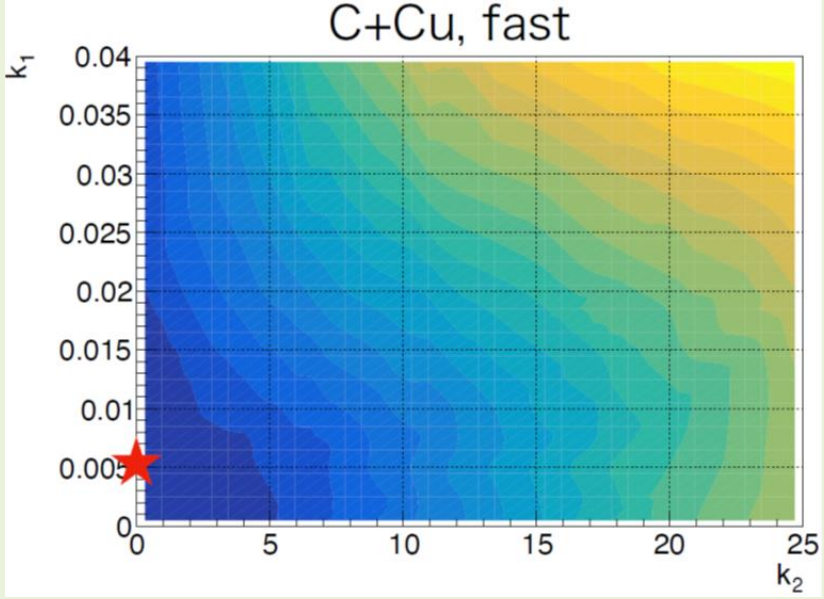
M. Ichikawa, P. Gubler, et al., (KEK-PS E325 Collaboration), Prog. Theor. Exp. Phys. **2025** 093D01 (2025).

Comparison with KEK E325 dilepton data

Momentum-<u>dependent</u> mass shift and decay width







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

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

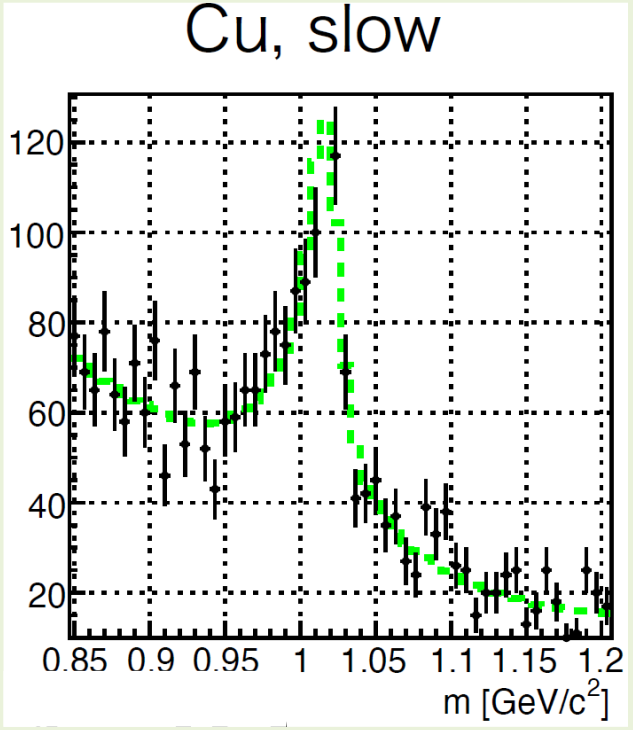
$$\frac{\Gamma_\phi(\rho)}{\Gamma_\phi(0)} = 1 + k_2 \frac{\rho}{\rho_0}$$

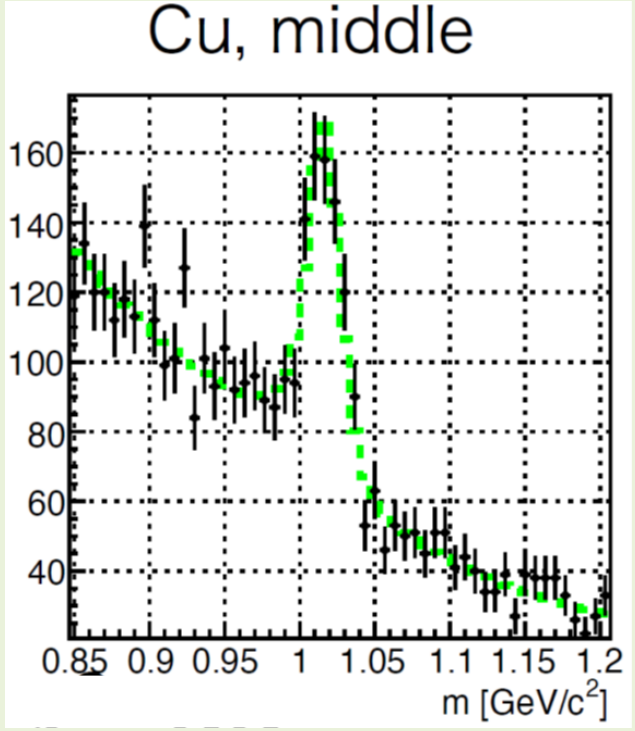
M. Ichikawa, P. Gubler, et al., (KEK-PS E325 Collaboration), Prog. Theor. Exp. Phys. **2025**, 093D01 (2025).

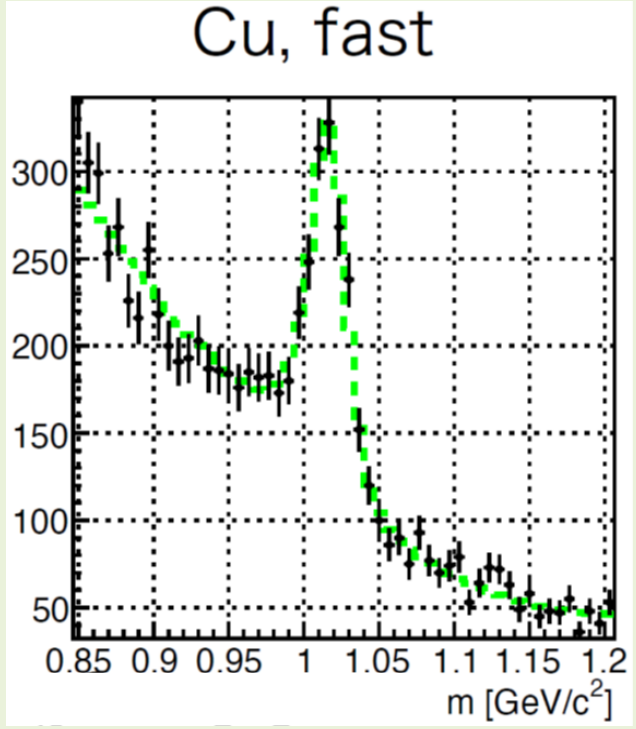
Comparison with KEK E325 dilepton data

Second trial:

Momentum-dependent mass shift and decay width







→ **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).

New comparison between theory and experiment

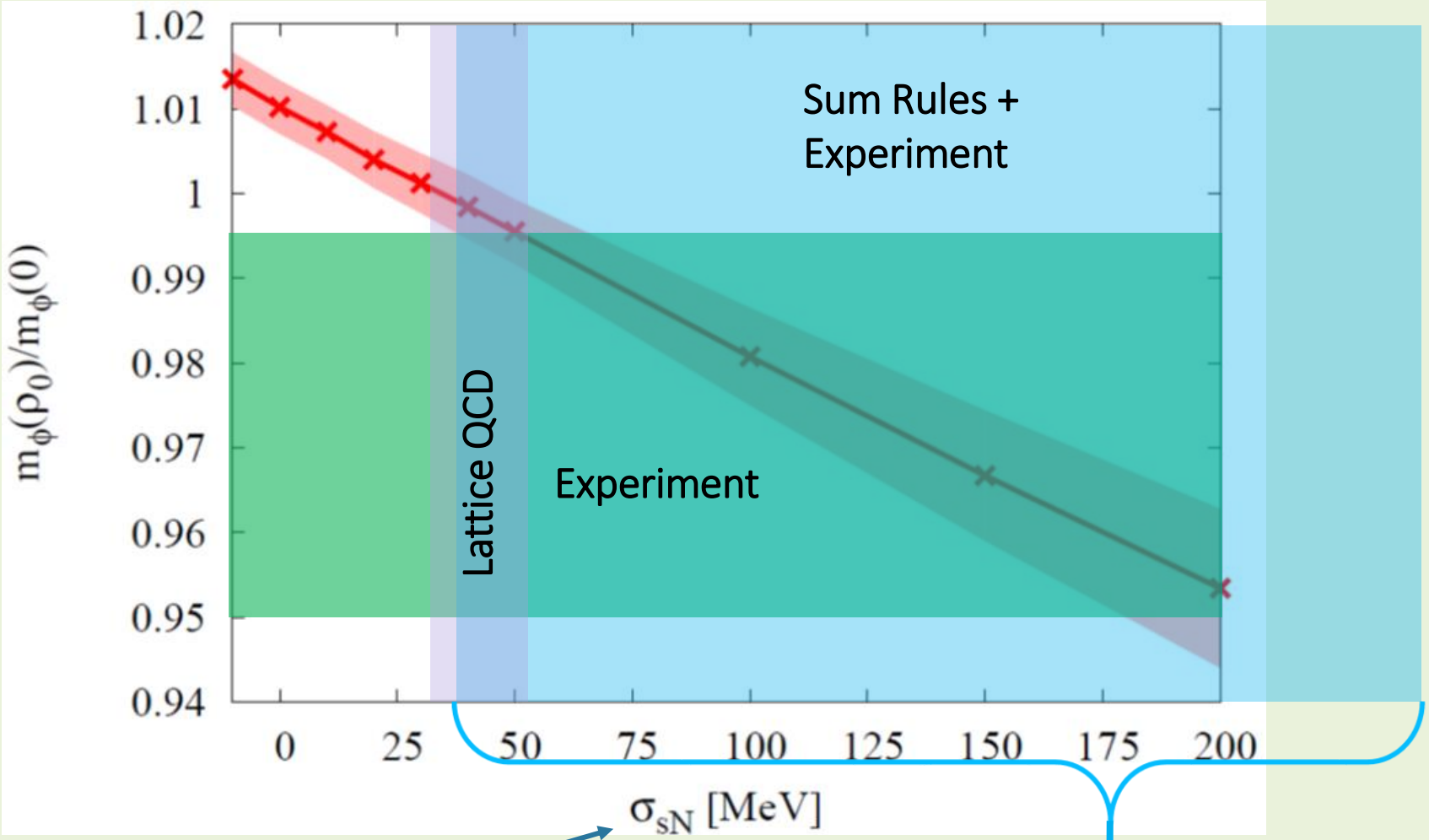
Problem solved???

↓

Need more precise data!

↓

Stay tuned for J-PARC E16



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

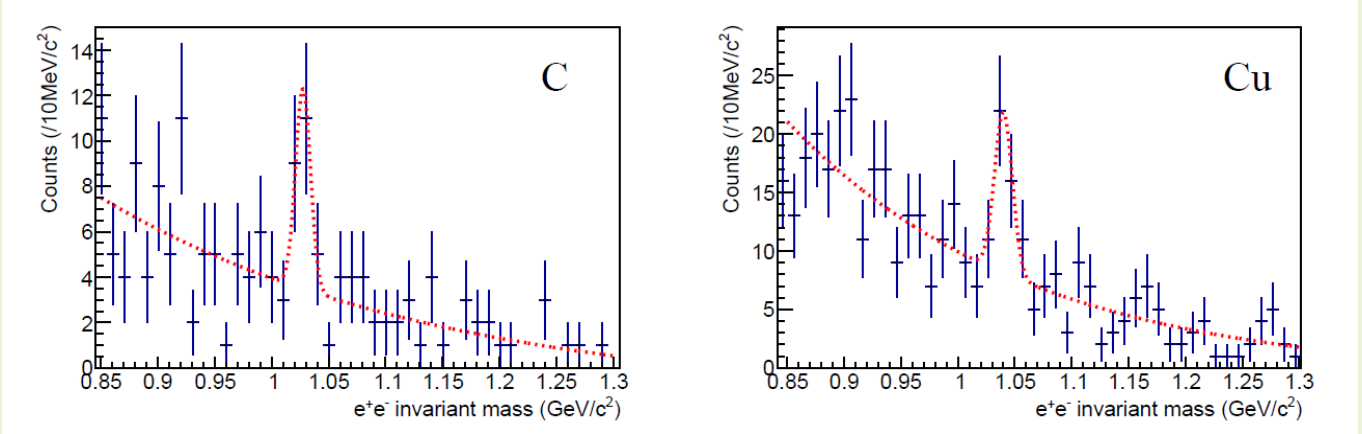
$\sigma_{sN} \sim 140 \pm 100$ MeV

News Flash

First results by the J-PARC E16 have appeared!

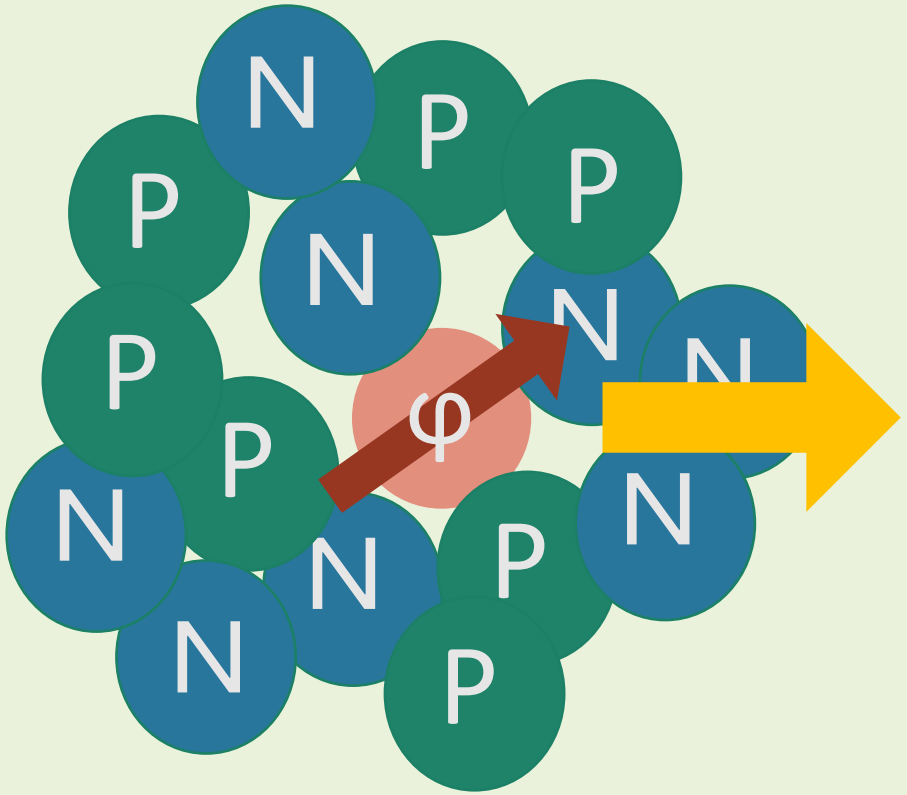
First measurement of ϕ meson production in 30 GeV proton-nucleus reactions via di-electron decay at J-PARC

(J-PARC E16 collaboration)



S. Nakasuga et al., Prog. Theor. Exp. Phys. **2026**, 043D03 (2026).

Mass of the φ meson in nuclear matter



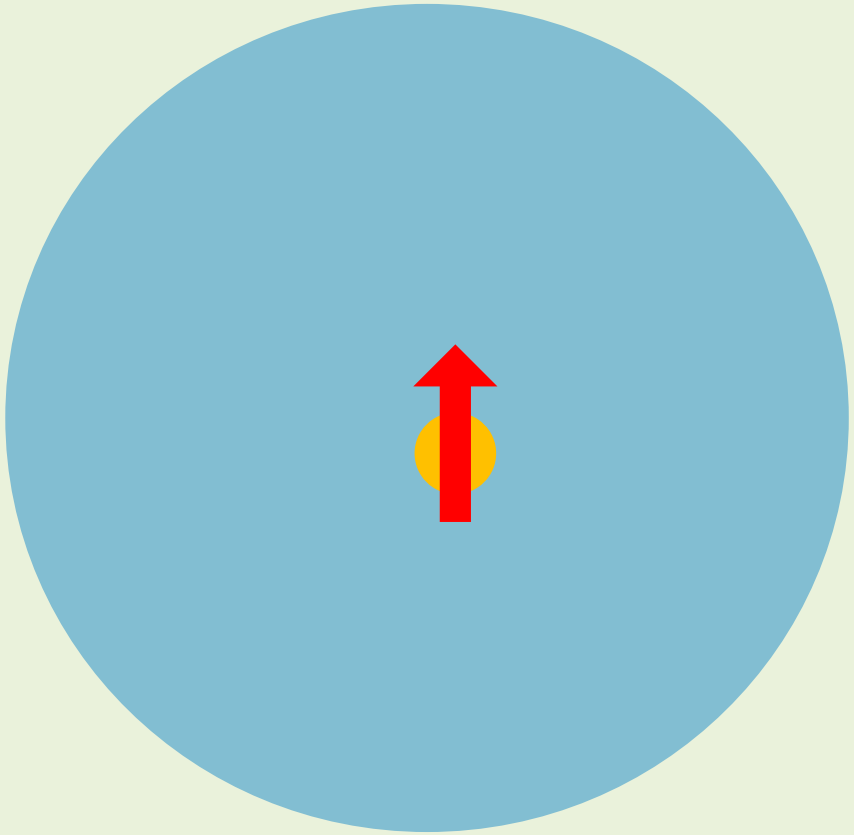
Probe of broken Lorentz symmetry

m_ϕ ?

To be measured at the J-PARC Saφre/E88 experiment!

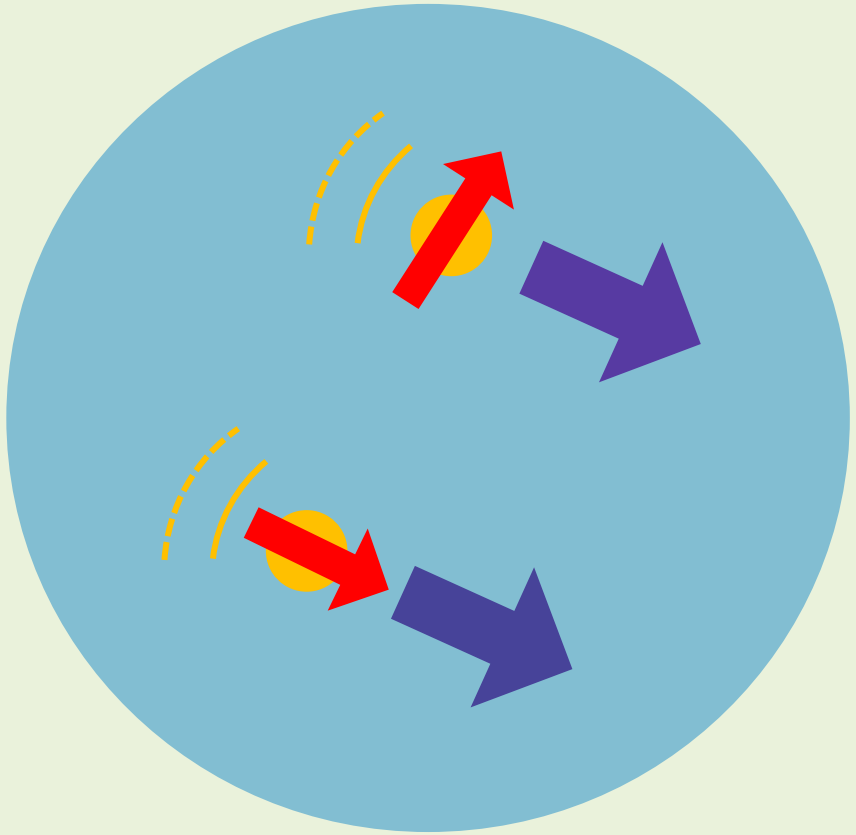
Role of spin

meson at rest in nuclear matter



spin direction does not change physics
(rotational symmetry)

meson moving in nuclear matter



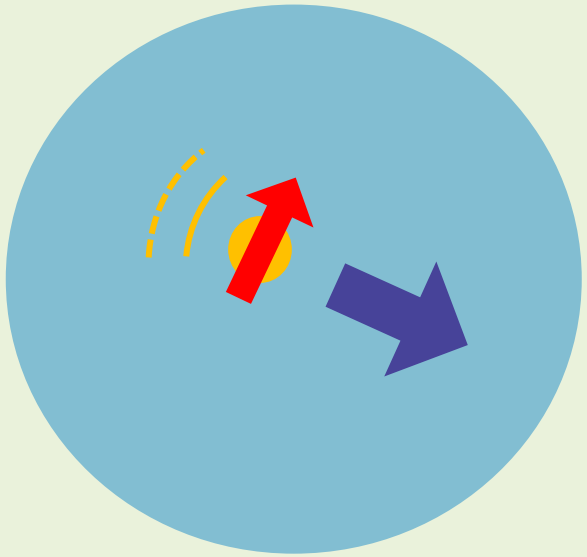
spin direction changes physics
(broken rotational symmetry)

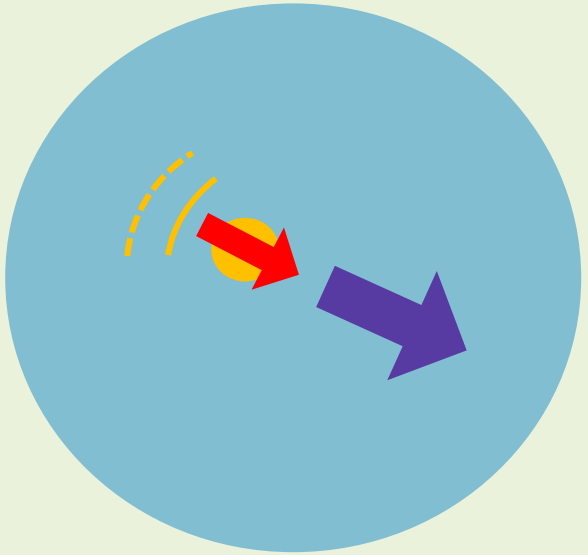
The non-zero momentum case: Disentangling longitudinal and transverse components

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

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

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





QCD sum rules

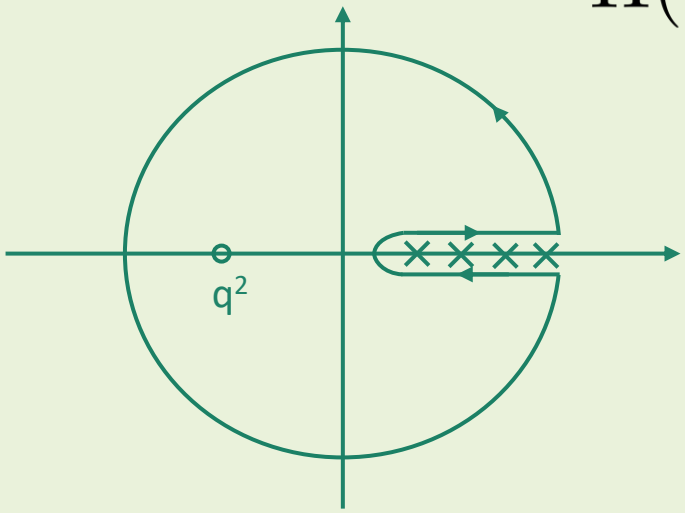
M.A. Shifman, A.I. Vainshtein and V.I. Zakharov, Nucl. Phys. B**147**, 385 (1979); B**147**, 448 (1979).

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

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

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

OPE

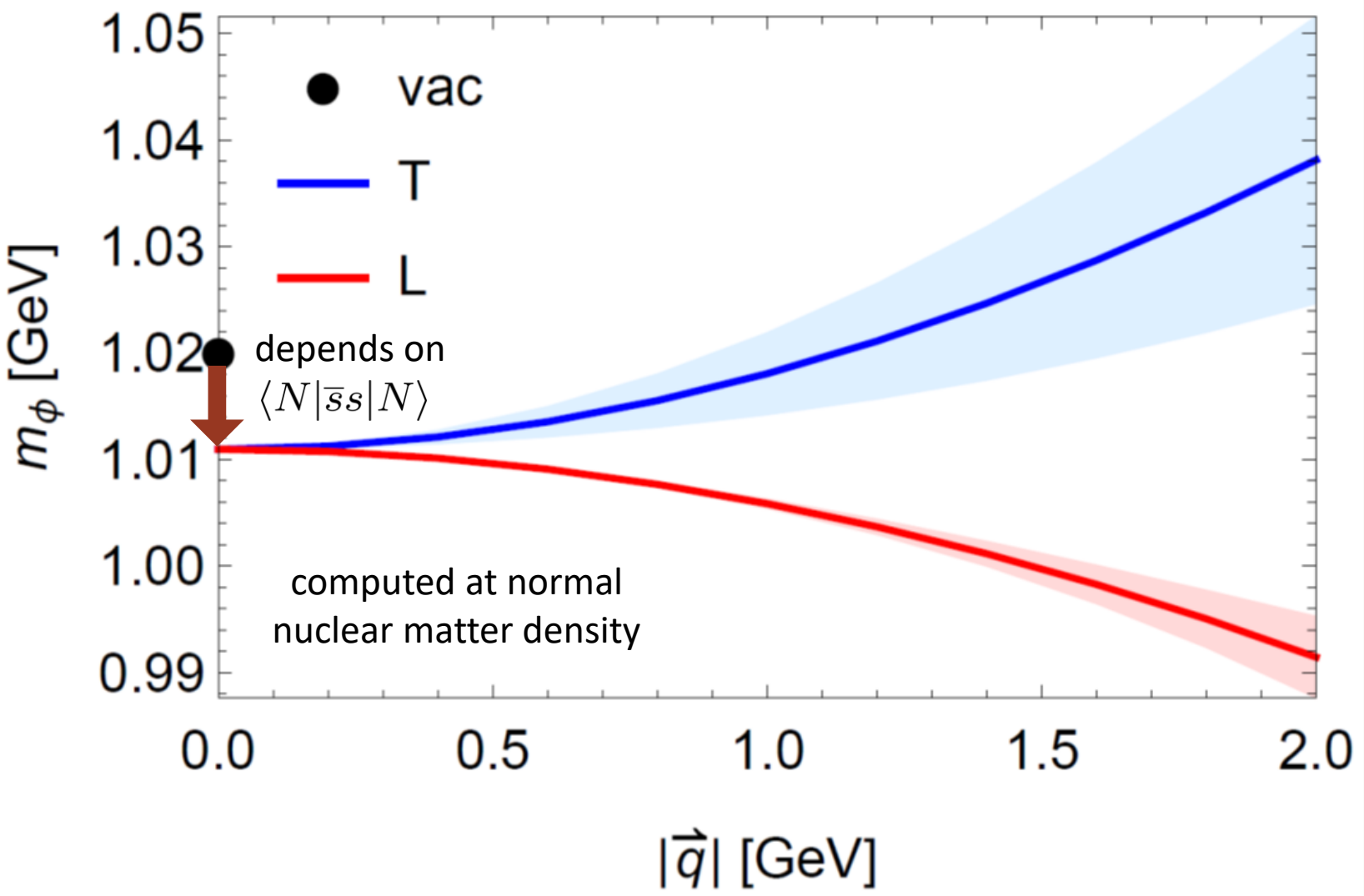
$\langle \bar{q}q \rangle_\rho$,
$\langle G^a_{\mu\nu} G^{a\mu\nu} \rangle_\rho$,
$\langle \bar{q}\sigma_{\mu\nu}\frac{\lambda^a}{2} G^{a\mu\nu} q \rangle_\rho$,
$\langle \bar{q}q\bar{q}q \rangle_\rho$,

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

Results for the ϕ meson mass with non-zero momentum



caused by

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

caused by

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

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

Can the polarization splitting be understood more intuitively?

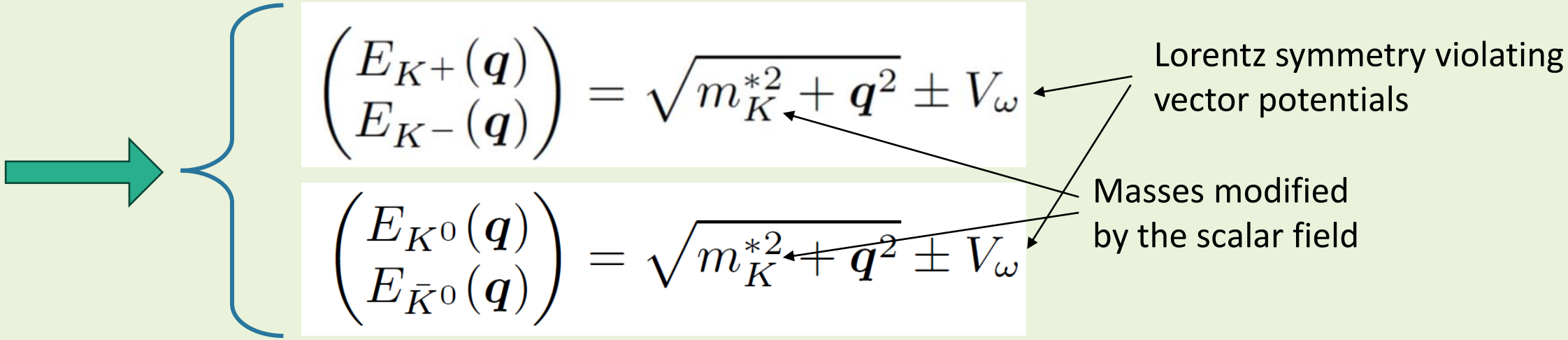
Use a simple model that includes Lorentz symmetry breaking effects in nuclear matter: the Quark-Meson Coupling (QMC) model

Core idea:

Meson mean fields couple to quarks inside hadrons.
Hadron structure changes in-medium.

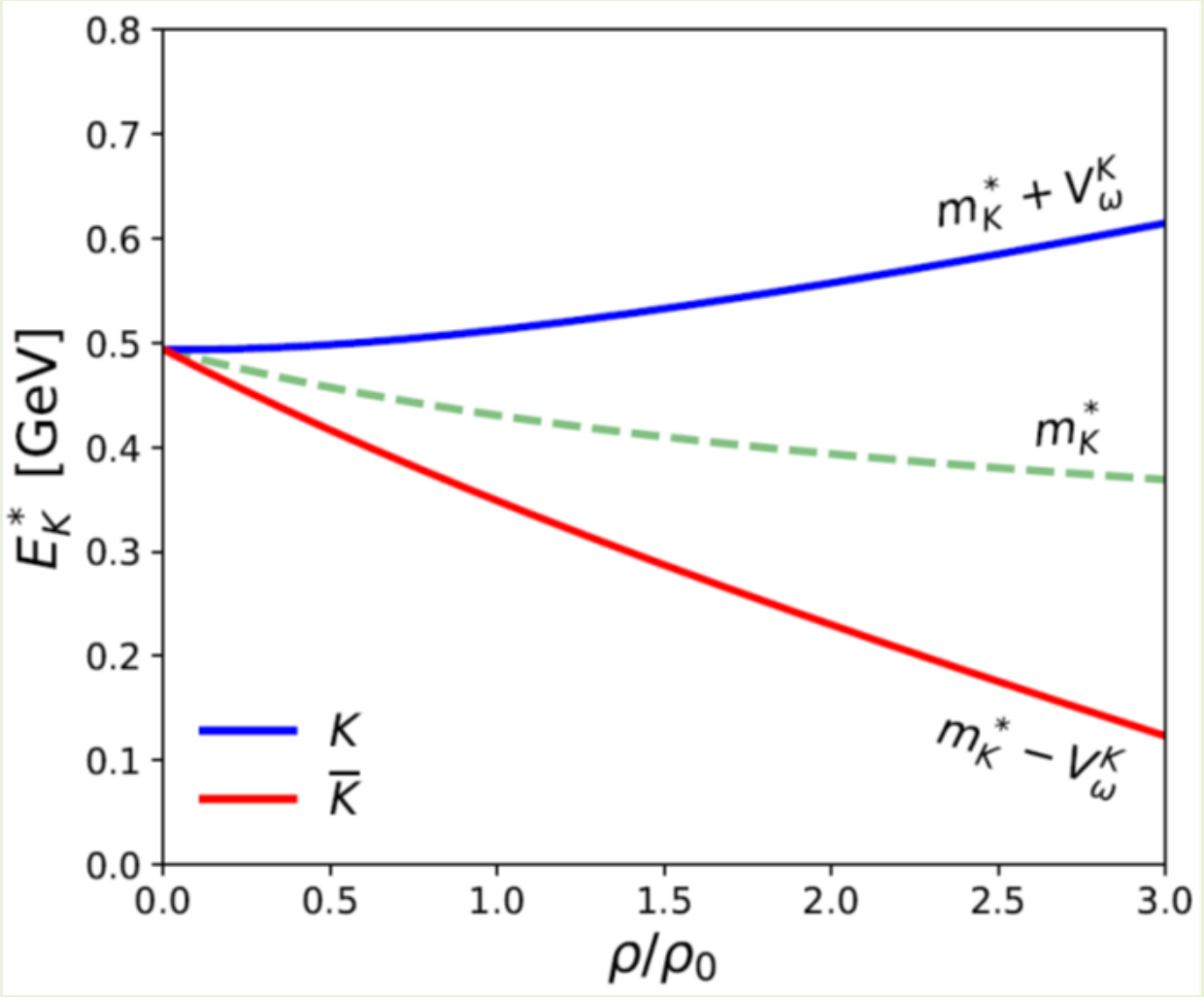
Fields:

σ (scalar): lowers quark mass → attraction between nuclei
ω^0 (vector): shifts energies (violates Lorentz symmetry) → short range repulsion between nuclei



Apply the QMC model to the φ meson in nuclear matter

The kaon properties in nuclear matter



A.J. Arifi, P. Gubler and K. Tsushima, Phys. Rev. D **114**, 034041 (2026).

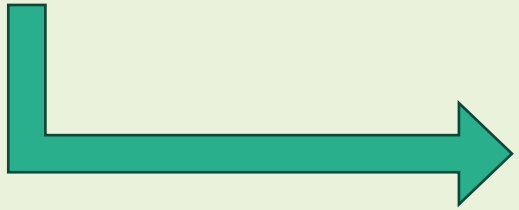
Apply the QMC model to the φ meson in nuclear matter

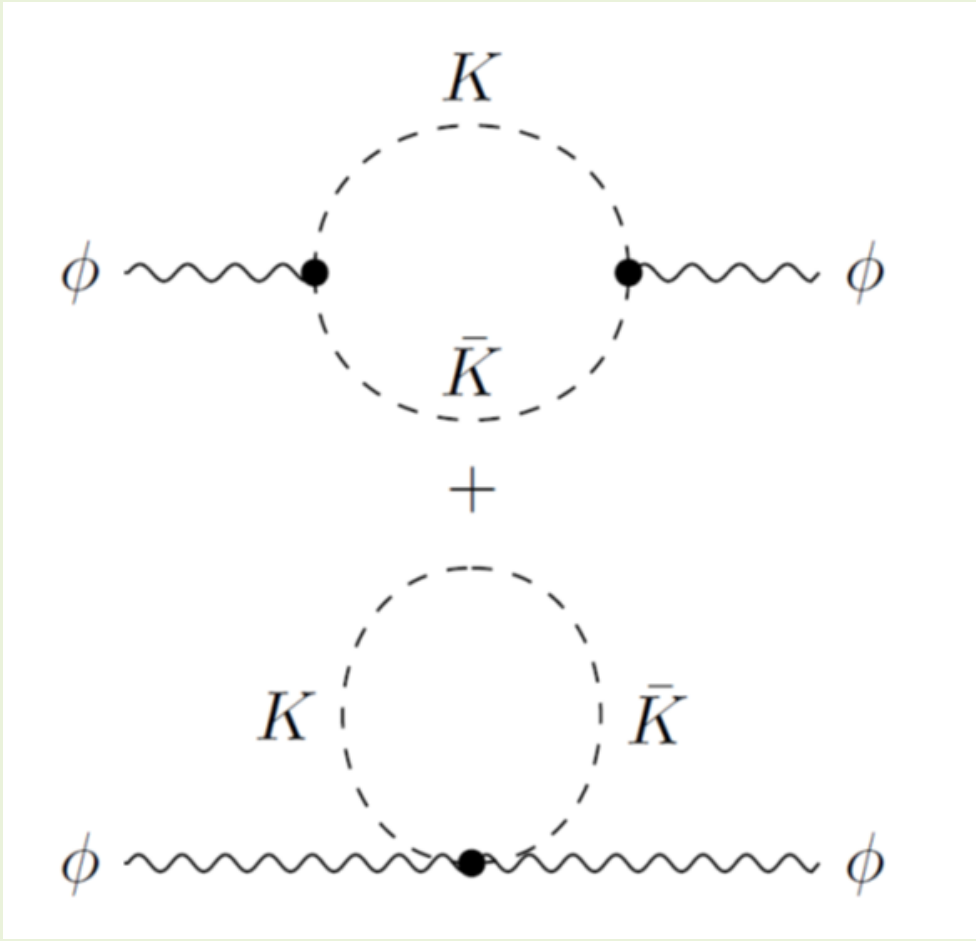
Compute the φ meson self-energy with kaon masses and energies determined by the QMC model and carry out the spin (polarization) projection

$$\mathcal{L}_{\phi K \bar{K}} = i g_\phi \phi^\mu \left[\bar{K} (\partial_\mu K) - (\partial_\mu \bar{K}) K \right]$$

$$\mathcal{L}_{\phi\phi K \bar{K}} = g_\phi^2 \phi^\mu \phi_\mu \bar{K} K$$

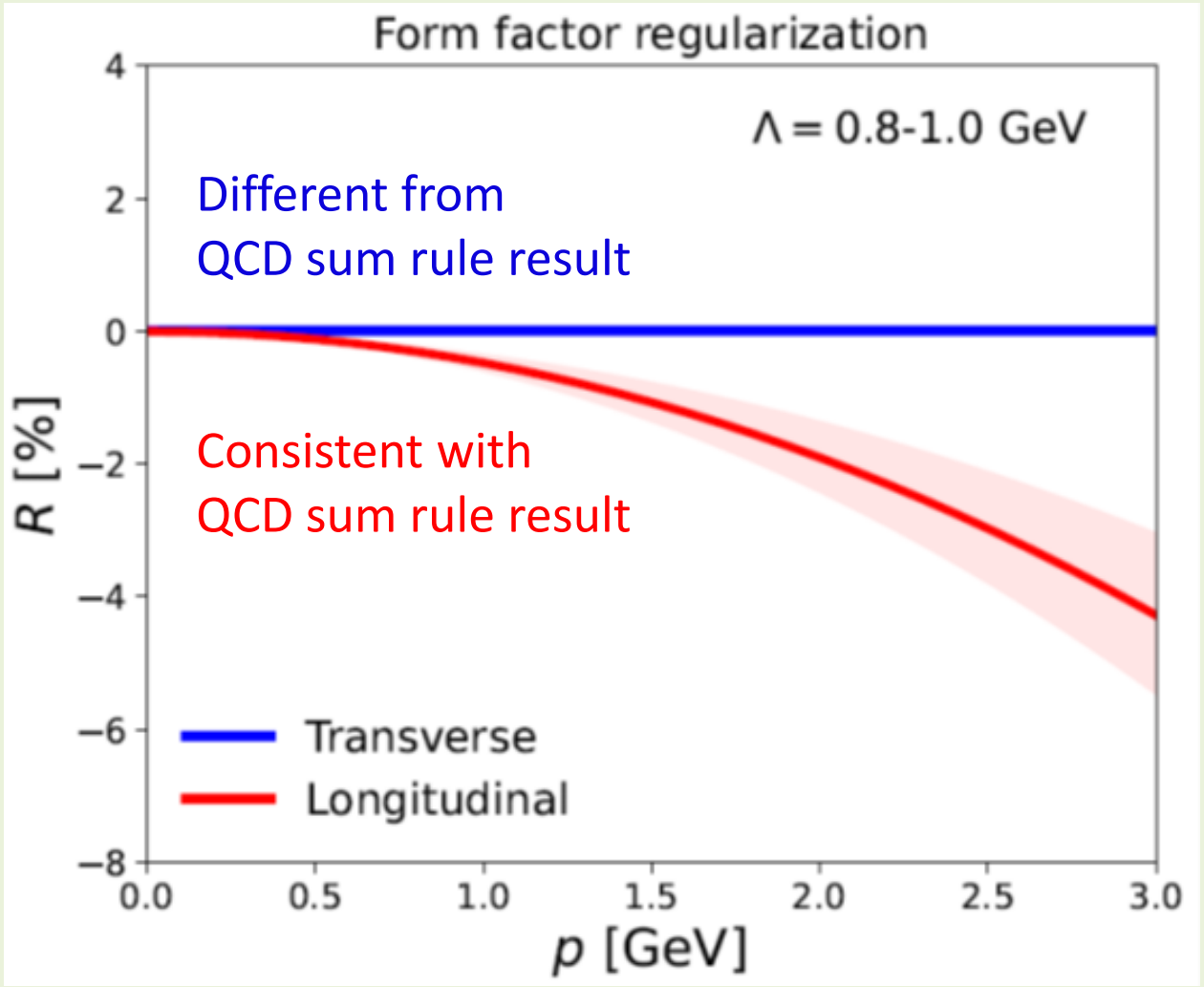
Motivated by local gauge symmetry considerations





Apply the QMC model to the φ meson in nuclear matter

Results for the φ meson mass changes at normal nuclear matter density



A.J. Arifi, P. Gubler and K. Tsushima, Phys. Rev. D **114**, 034041 (2026).

Summary and conclusions

★ The ϕ-meson mass shift in nuclear matter is constrained by the behavior of chiral symmetry at finite density in the strange quark sector

★ With the PHSD transport approach, we can now study pA reactions more reliably

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

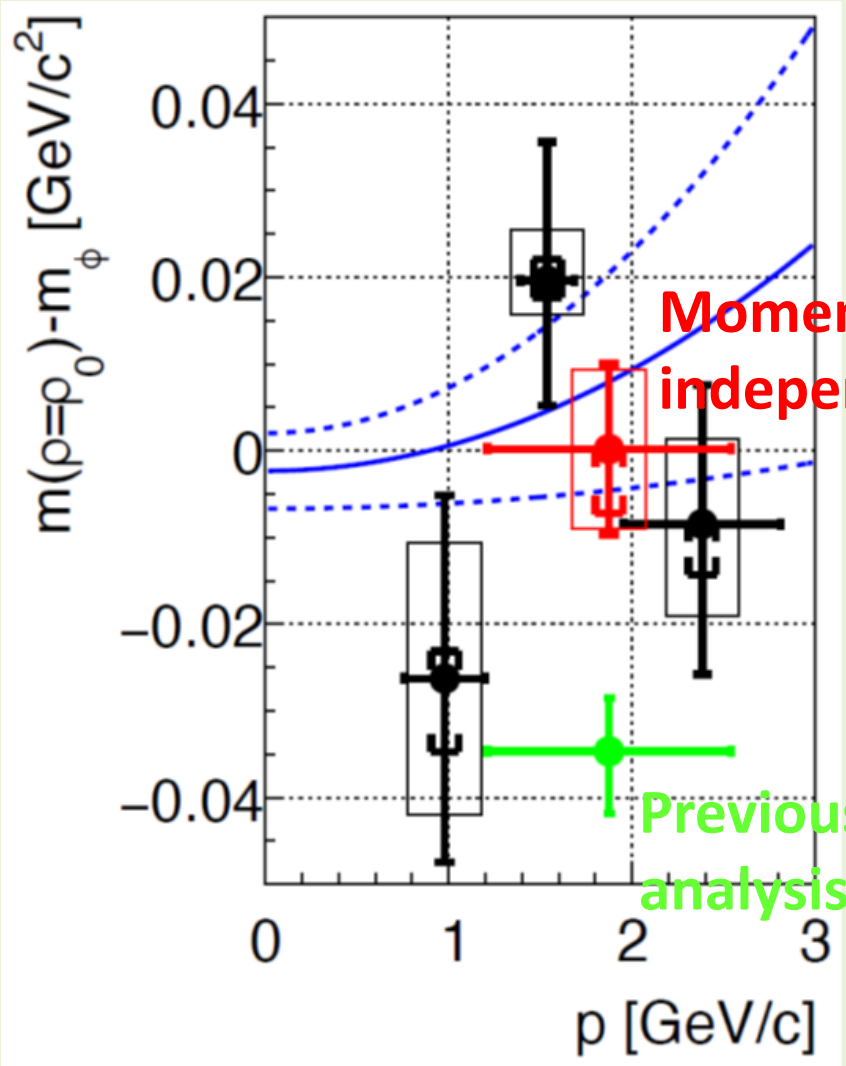
★ The φ meson mass in nuclear matter and non-zero momentum depends on the spin configuration

→ **To be measured at the J-PARC Saφre/E88 experiment**

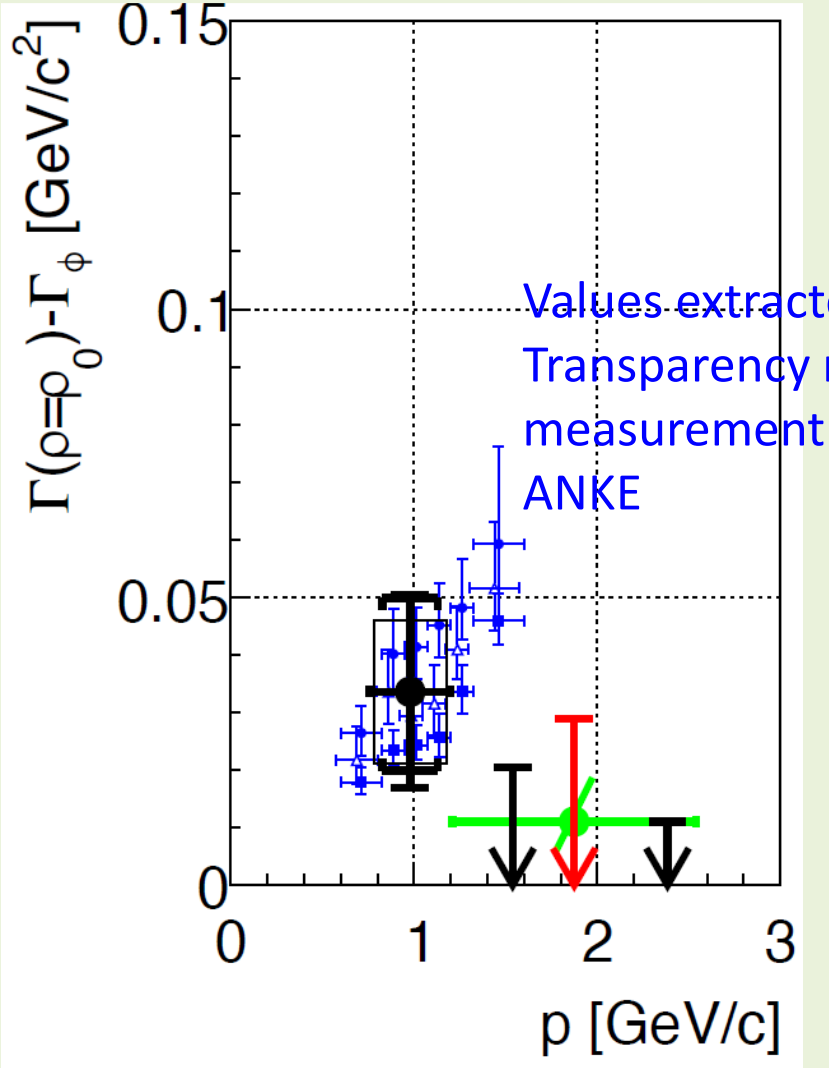
Backup slides

Final analysis results

Mass shift at ρ_0

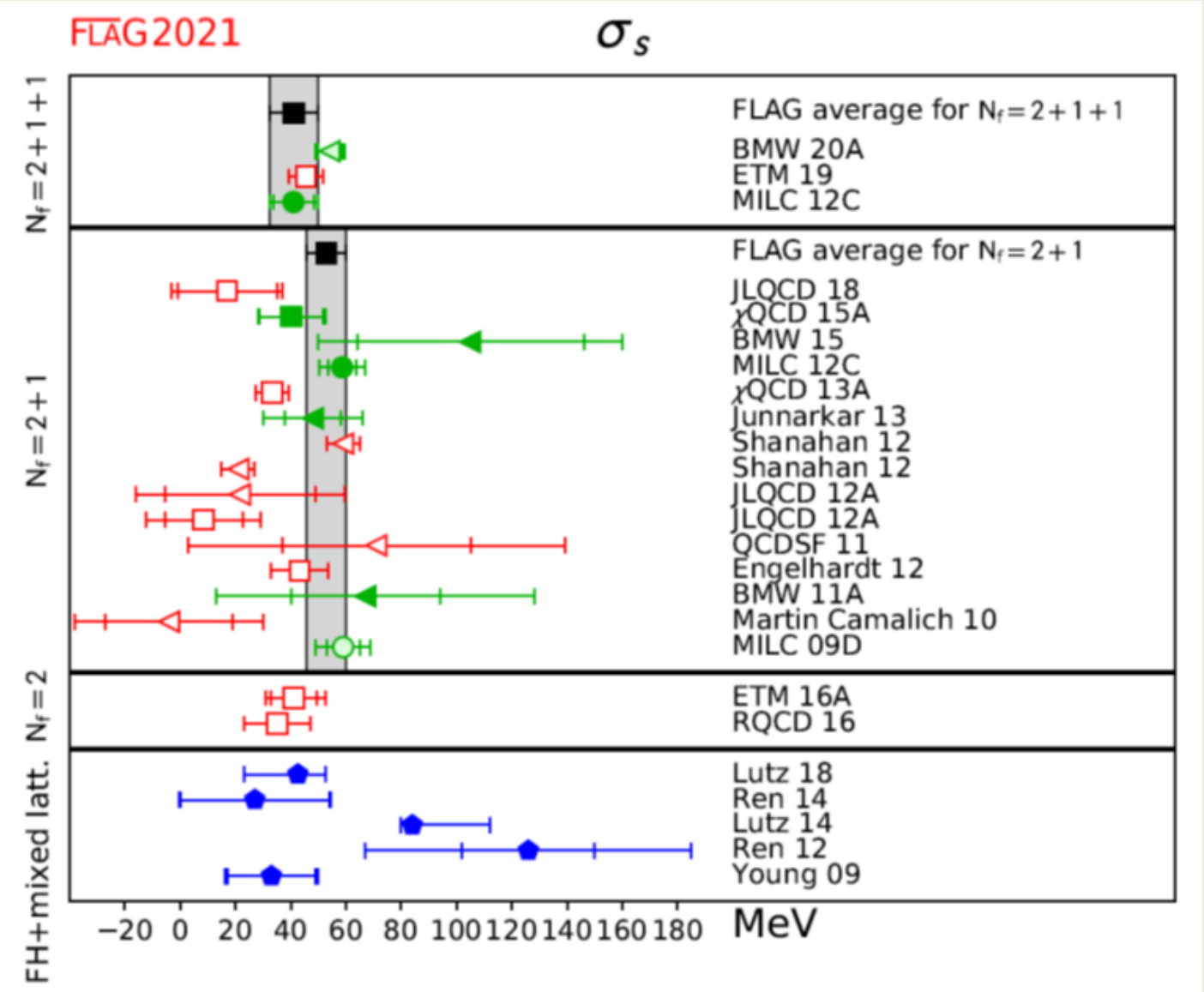


Width shift at ρ_0



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

What does lattice QCD say about the strange sigma term?



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

Possible connection the between the φ meson mass shift in nuclear matter and the φN scattering length?

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

Valid within the linear density approximation

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

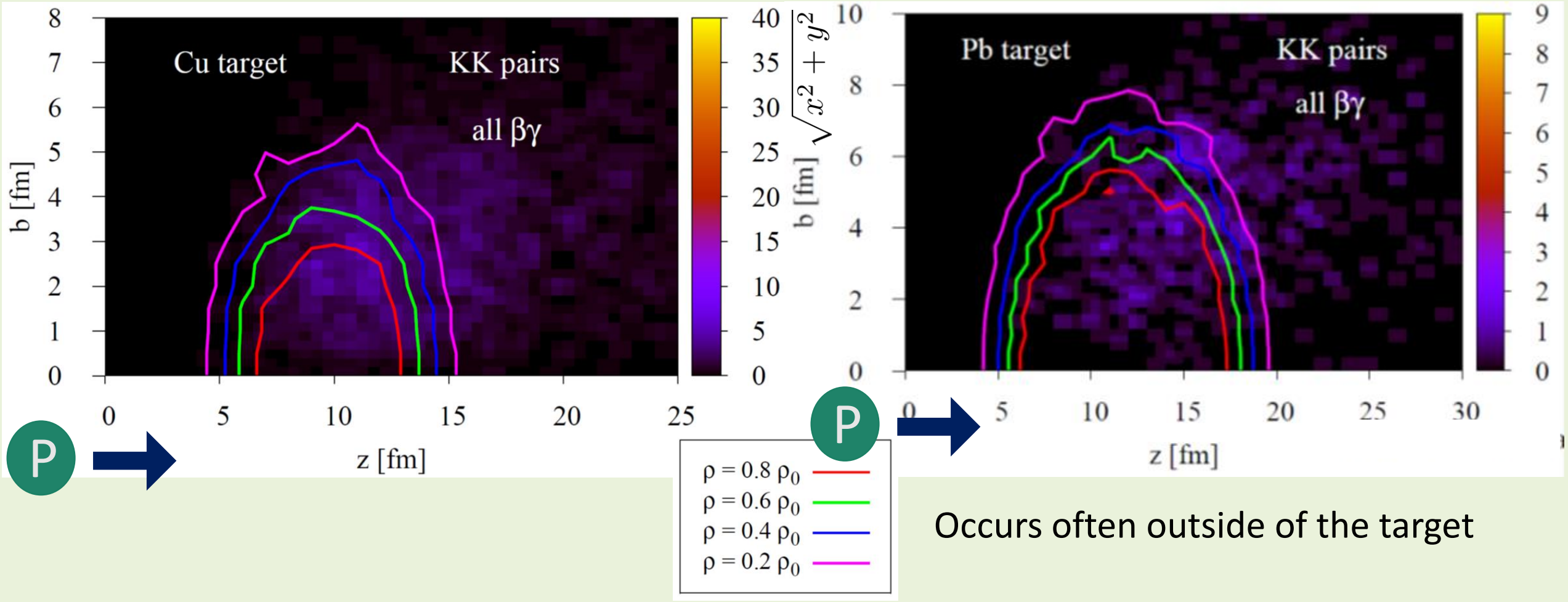
Y. Liu et al., Phys. Rev. D **106**, 074507 (2022).

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

→ Need better theoretical understanding!

How are φ mesons produced?

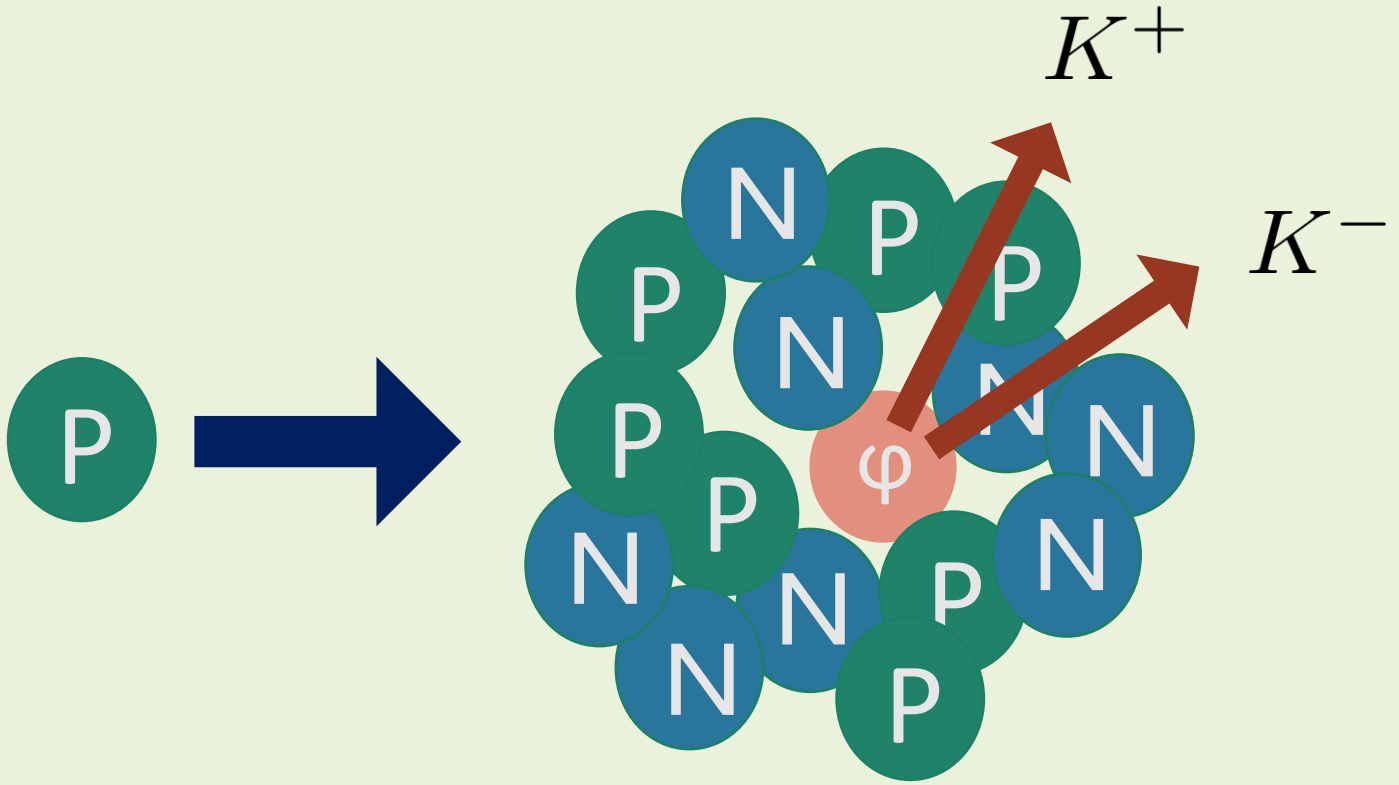
Production through secondary low-energy hadron collisions



Occurs often outside of the target

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

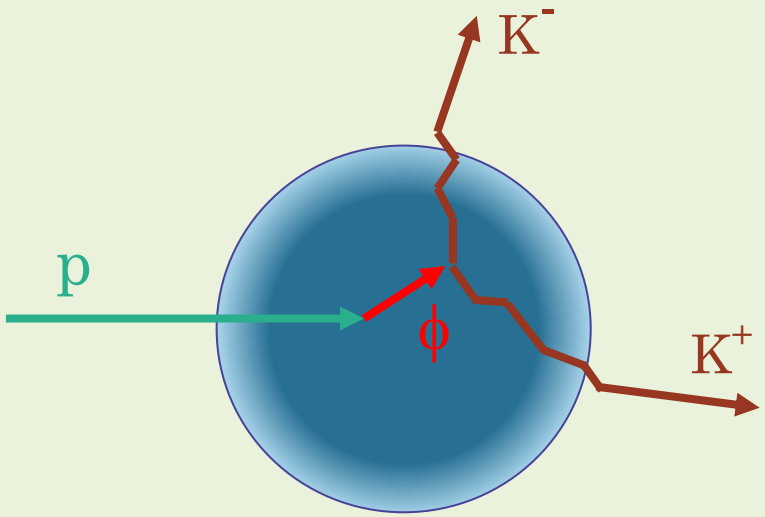
What about the K^+K^- spectrum?



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

J-PARC E16 vs. E88

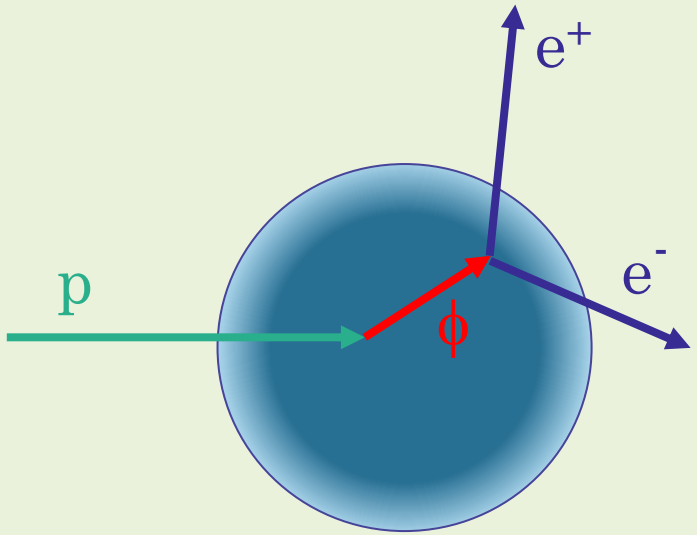
E88



Good statistics ⭕

Distorted in-medium signal due to strong interaction ❌

E16



Bad statistics ❌

Clear in-medium φ meson signal ⭕

Simulations using a realistic transport approach are needed to estimate the strong KN and KbarN interactions

Simulation results with BuBUU

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

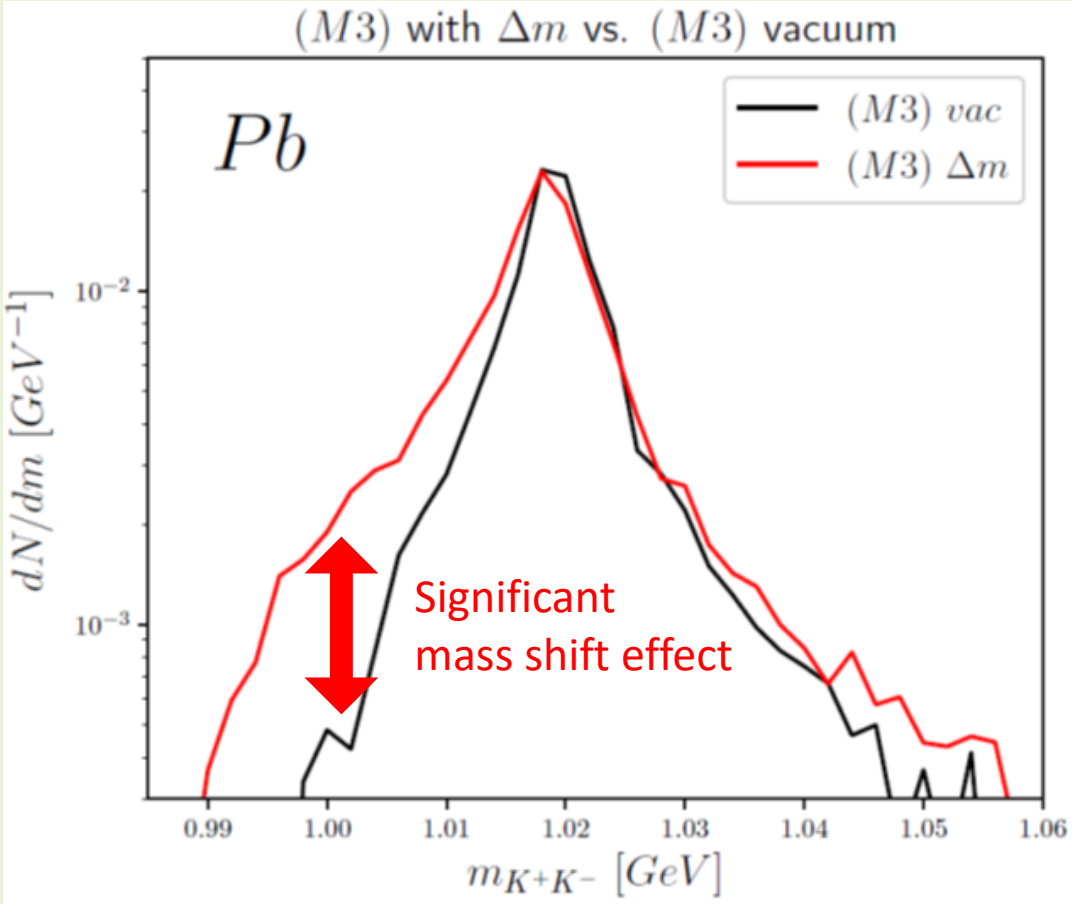
Used mean fields to parametrize the K and Kbar interactions with the nuclear medium

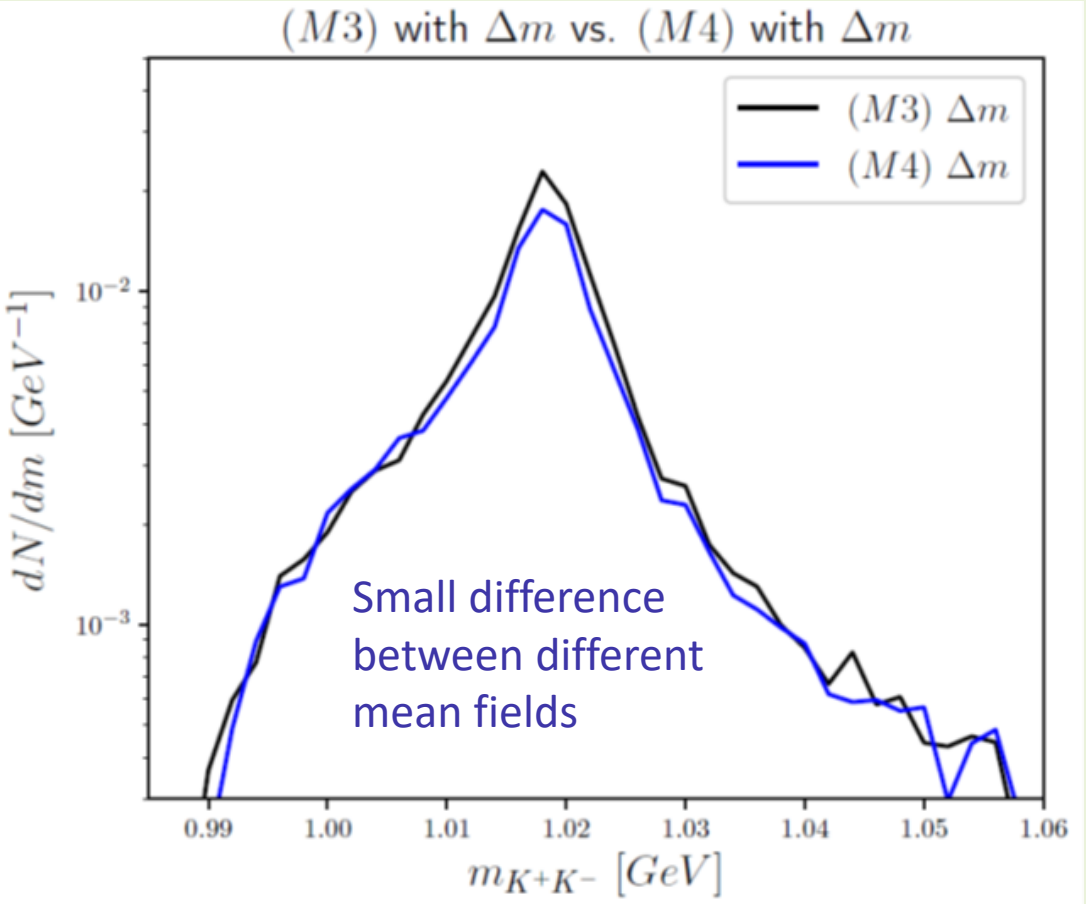
Model		Mean Field Expression	Parameter Values
M1	K^+	$U_{K^+} = 0$	–
	K^-	$U_{K^-} = 0$	–
M2	K^+	$U_{K^+} = a_2 \cdot \rho$	$a_2 = 0.167\ [\mathrm{GeV} \cdot \mathrm{fm}^3]$
	K^-	$U_{K^-} = -a_2 \cdot \rho$	
M3	K^+	$U_{K^+} = a_3 \cdot \rho$	$a_3 = 0.167\ [\mathrm{GeV} \cdot \mathrm{fm}^3]$
	K^-	$U_{K^-} = -\rho(b_3 + c_3 \cdot e^{-d_3 \cdot p_K})$	$b_3 = 0.341\ [\mathrm{GeV} \cdot \mathrm{fm}^3]$, $c_3 = 0.823\ [\mathrm{GeV} \cdot \mathrm{fm}^3]$, $d_3 = 2.5\ [\mathrm{GeV}^{-1}]$
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



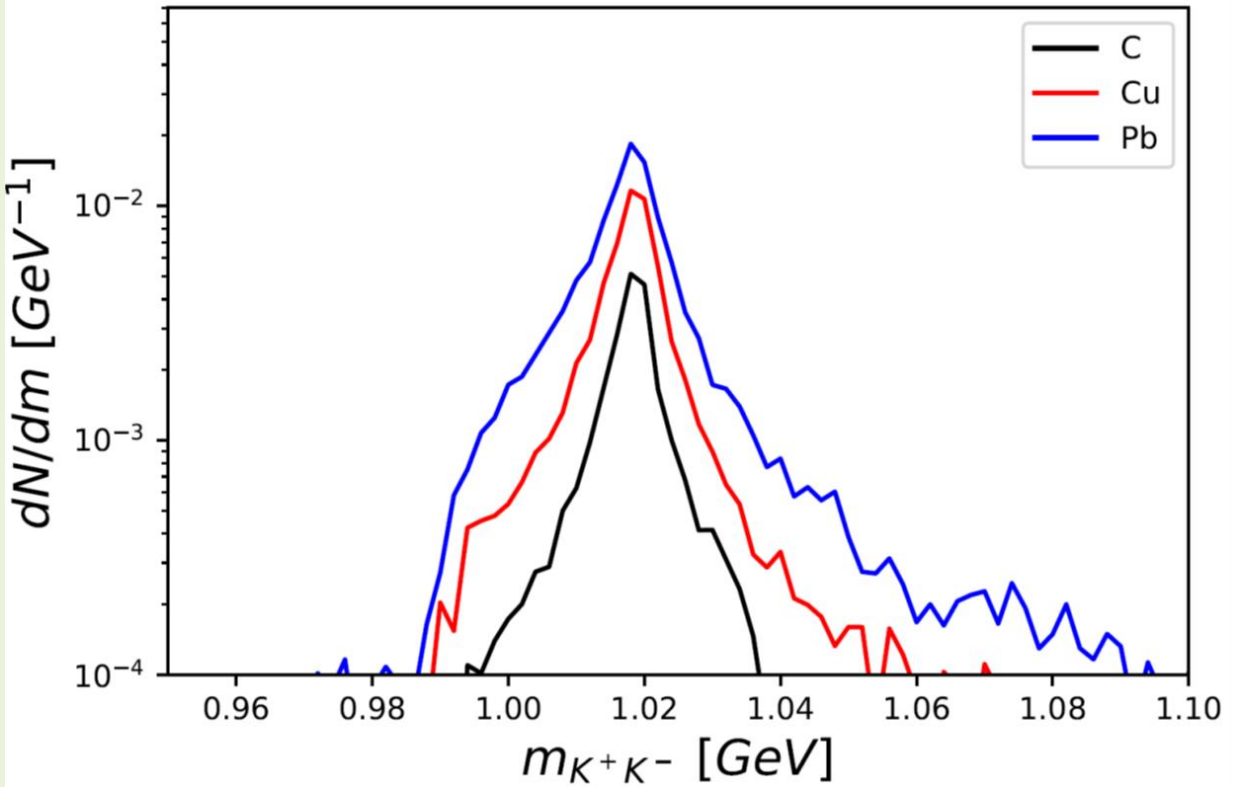


G. Balassa et al., arXiv:2508.11344 [hep-ph] (To be published in Prog. Theor. Exp. Phys.).

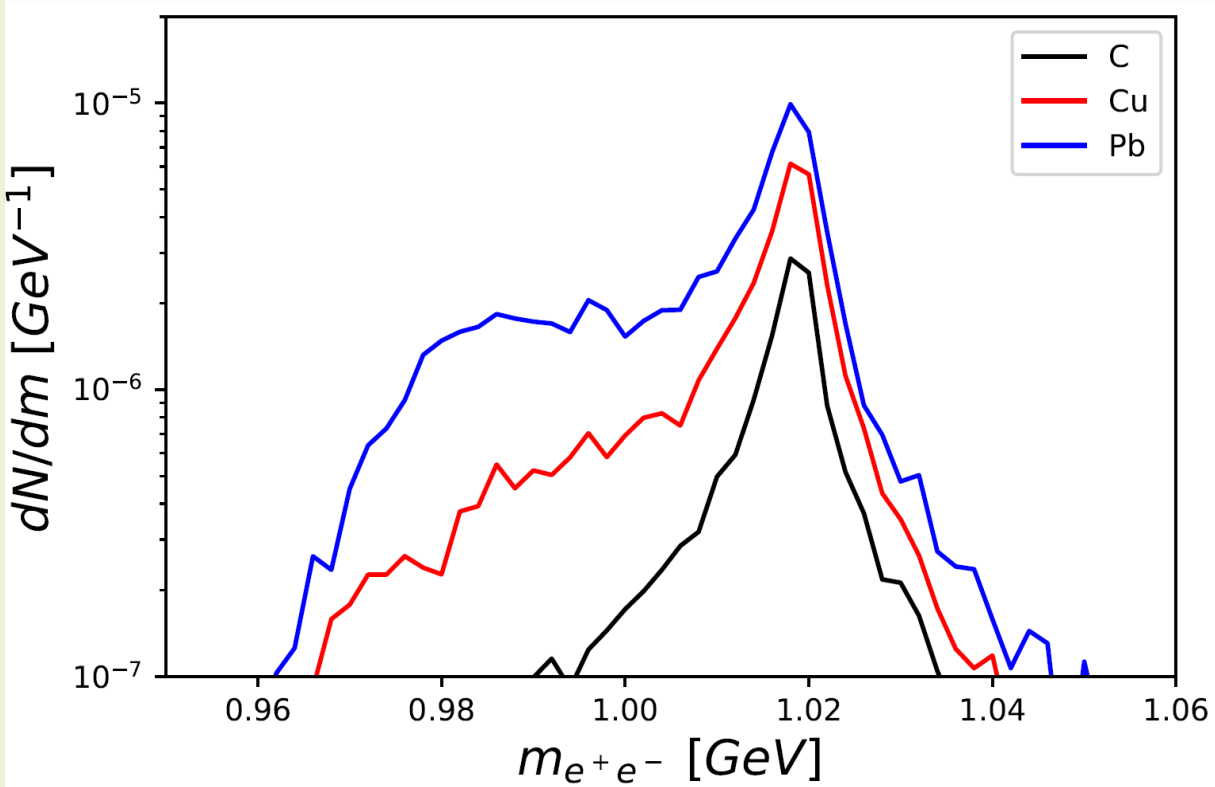
Comparative study of the K^+K^- and e^+e^- spectrum

(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).

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

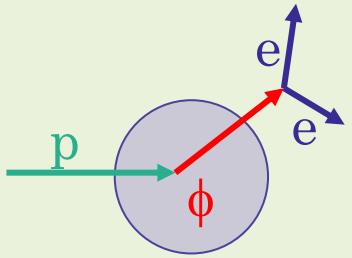
→ Generally difficult to achieve in most transport models specialized in high-energy collisions, but is realized is some low-energy codes

→ 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

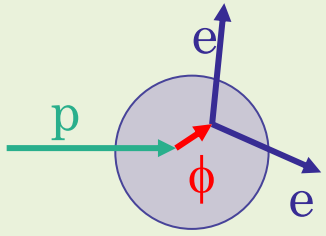
→ Relevant for E88, as kaons generated in dense matter are mass shifted

Experimental di-lepton spectrum



outside decay

+



inside decay

=

Experimentally observed spectrum

