The ϕ-N and ϕ-nucleus interaction from nuclear collisions

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).
L.M. Abreu, P. Gubler, K.P. Khemchandani, A. Martínez Torres and A. Hosaka, Phys. Lett. B **860**, 139175 (2025).

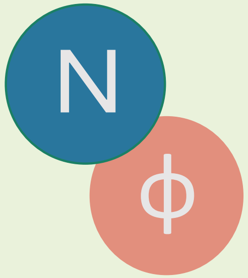
Talk at International Workshop on Origin of Mass and Matter in the Universe
POSTEC, Pohang, South Korea
July 22, 2026

Work done in collaboration with:

M. Ichikawa (RIKEN/Tokyo U.)
T. Song (GSI)
E. Bratkovskaya (Goethe U. Frankfurt)
M. Naruki (Kyoto U.)
S. Yokkaichi (RIKEN)
KEK-PS E325 Collaboration
L.M. Abreu (Bahia U.)
K.P. Khemchandani (S. Paulo F. U.)
A. Martínez Torres (S. Paulo U.)
A. Hosaka (RCNP, Osaka U.)

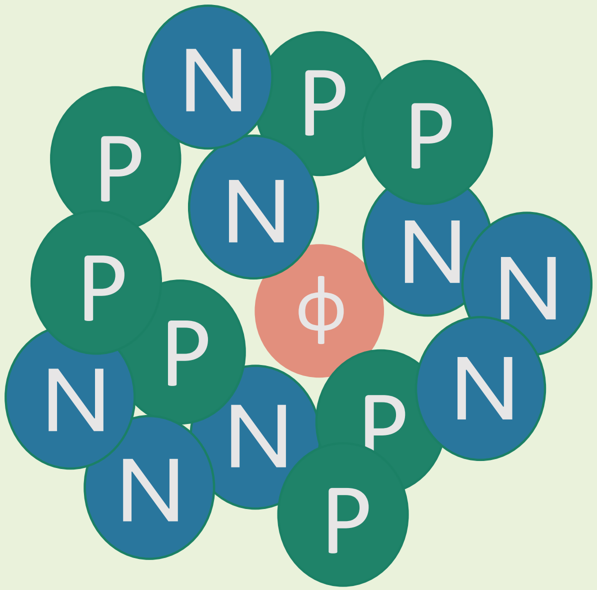
Topics of this talk

1.



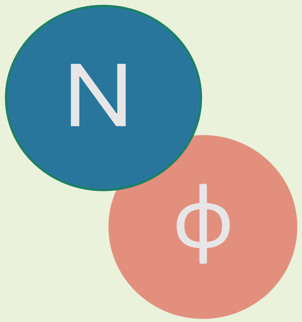
How attractive is this interaction?

2.



$\Rightarrow$ m_ϕ $\searrow$?

$\Rightarrow$ Γ_ϕ $\nearrow$?

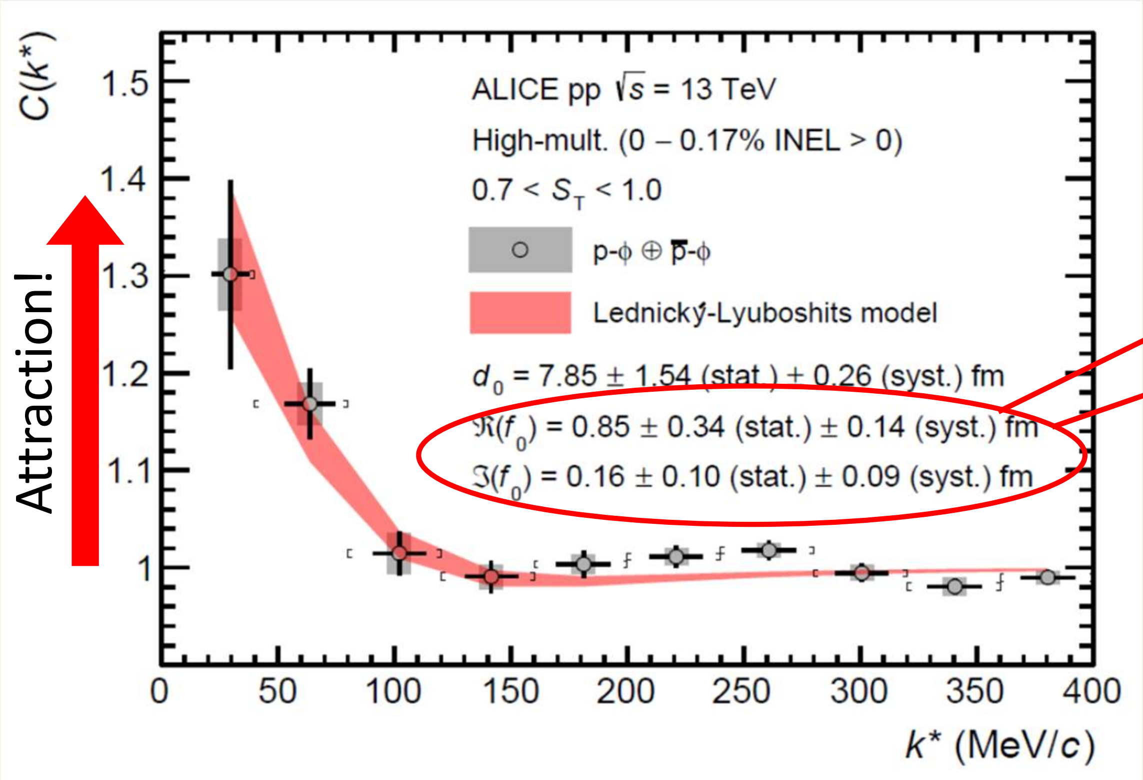


How strong/attractive
is this interaction?

L.M. Abreu, P. Gubler, K.P. Khemchandani, A. Martínez Torres and A. Hosaka,
Phys. Lett. B **860**, 139175 (2025).

ALICE: pp

ϕN correlation function



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

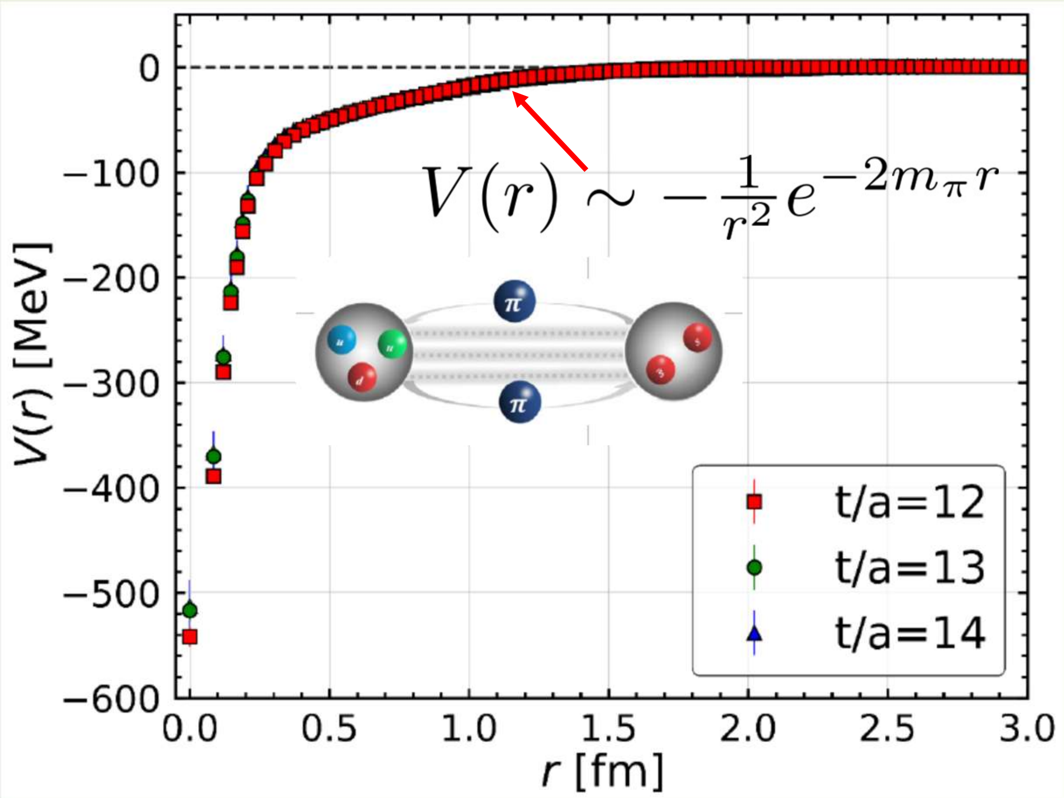
★ Strongly attractive

★ Small absorption

Caution:
Spin averaged value with non-trivial weights (thanks to Kamiya-san!)

ϕN potential from HAL QCD

Spin 3/2 channel



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

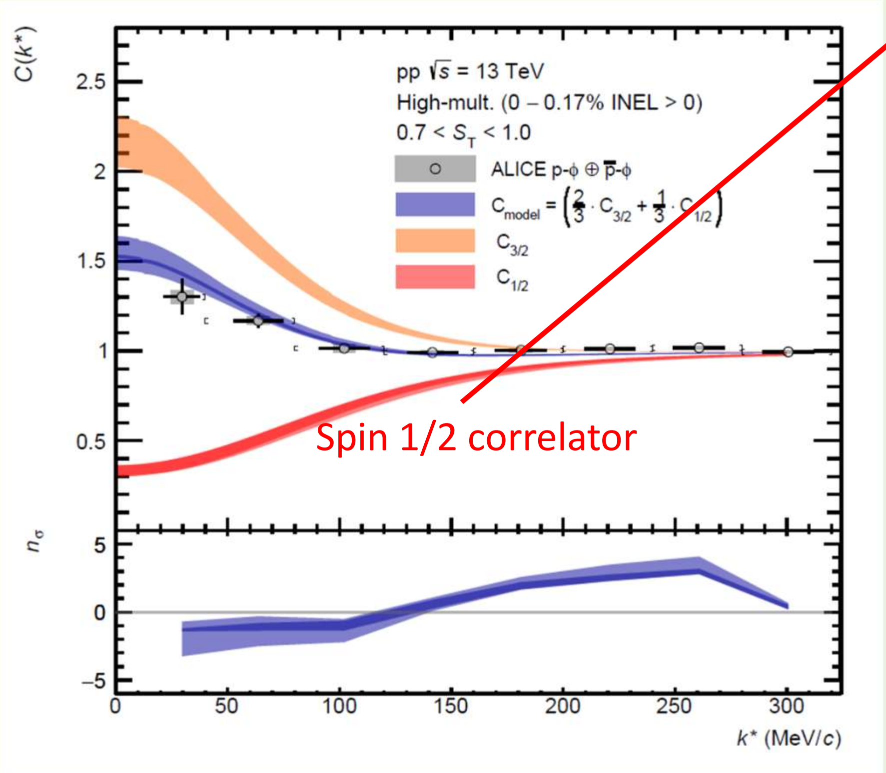
Indication for a quite strong and attractive interaction!

For a discussion of the two-pion contribution to the VN potential, see: S. Yeo, I.W. Park and S.H. Lee, Phys. Rev. D **112**, 094044 (2025).

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

Even more recent results

Combination of ALICE pp-data and HAL QCD (spin 3/2) calculation



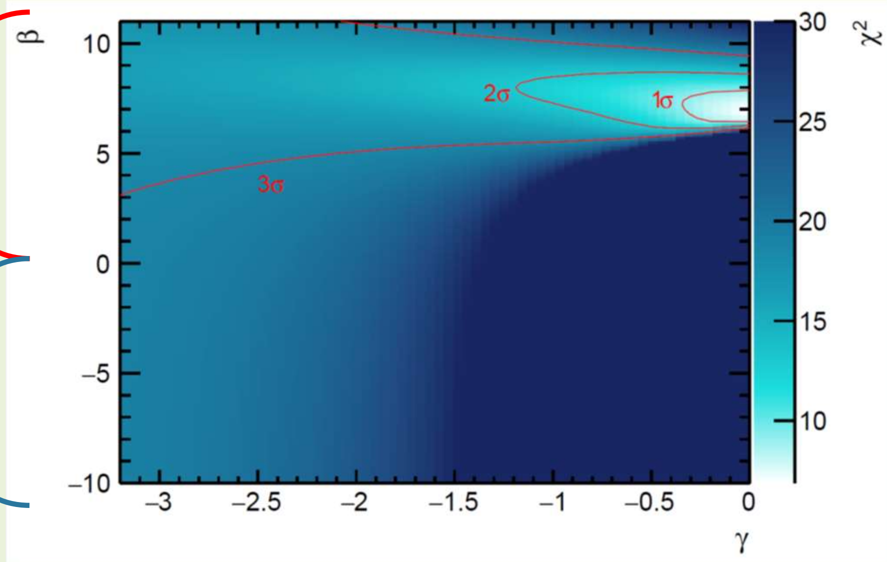
E. Chizzali et al., Phys. Lett. B **848**, 138358 (2024).

Bound state?

Repulsive?

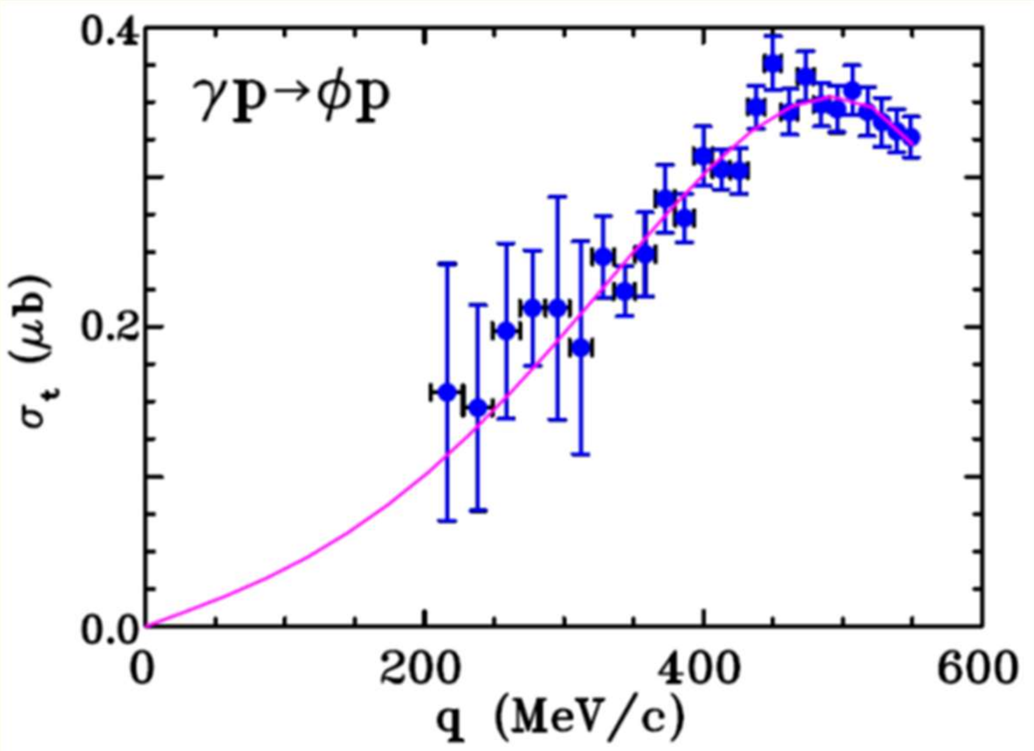
Attractive

Repulsive



Evidence for ϕ-N bound state!

Photoproduction measurement (CLAS)



Vector meson dominance is assumed

$$\frac{d\sigma^{\gamma p \to V p}}{d\Omega}\Big|_{\rm thr} = \frac{q}{k}\frac{1}{64\pi}|T^{\gamma p \to V p}|^2$$

$$= \frac{q}{k}\frac{\pi\alpha}{g_V^2}\frac{d\sigma^{V p \to V p}}{d\Omega}\Big|_{\rm thr} = \frac{q}{k}\frac{\pi\alpha}{g_V^2}|\alpha_{V p}|^2$$

$$|a_0| = 0.063 \pm 0.010\,\mathrm{fm}$$

Consistent with weak ϕN interaction

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

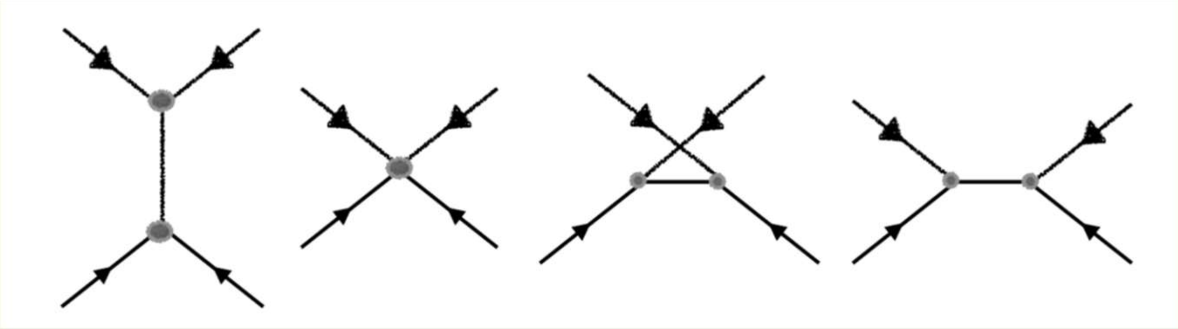
An even newer analysis of the ALICE data

L.M. Abreu, P. Gubler, K.P. Khemchandani, A. Martínez Torres and A. Hosaka, Phys. Lett. B **860**, 139175 (2025).

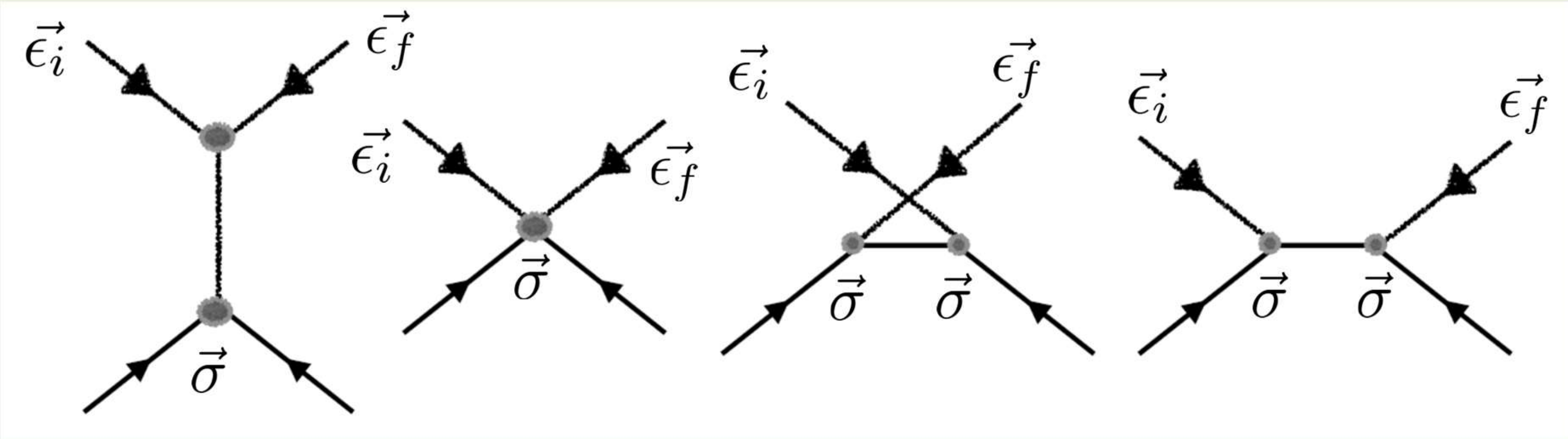
Starting point:
Hadronic Meson-Baryon interaction Lagrangian

1) Vector Meson-Baryon interaction: Based on Hidden Local Symmetry

$$\begin{aligned}\mathcal{L}_{VB} \quad &= -g\Bigg\{\langle \bar{B}\gamma_\mu [V_8^\mu, B]\rangle + \langle \bar{B}\gamma_\mu B\rangle\langle V_8^\mu\rangle + \frac{1}{4M}\Big(F\langle \bar{B}\sigma_{\mu\nu}[V_8^{\mu\nu}, B]\rangle \\ &+D\langle \bar{B}\sigma_{\mu\nu}\{V_8^{\mu\nu}, B\}\rangle\Big) + \langle \bar{B}\gamma_\mu B\rangle\langle V_0^\mu\rangle + \frac{C_0}{4M}\langle \bar{B}\sigma_{\mu\nu}V_0^{\mu\nu}B\rangle\Bigg\},\end{aligned}$$



Crucial ingredient: spin dependent vector meson-baryon interactions



$$\boxed{\vec{\epsilon_i} \cdot \vec{\epsilon_f}}$$

$$\boxed{\vec{\sigma} \cdot (\vec{\epsilon_i} \times \vec{\epsilon_f}) \qquad (\vec{\sigma} \cdot \vec{\epsilon_i})(\vec{\sigma} \cdot \vec{\epsilon_f})}$$

Considered previously in
A. Feijoo, M. Korwieser and L. Fabbietti,
Phys. Rev. D **111**, 014009 (2025).

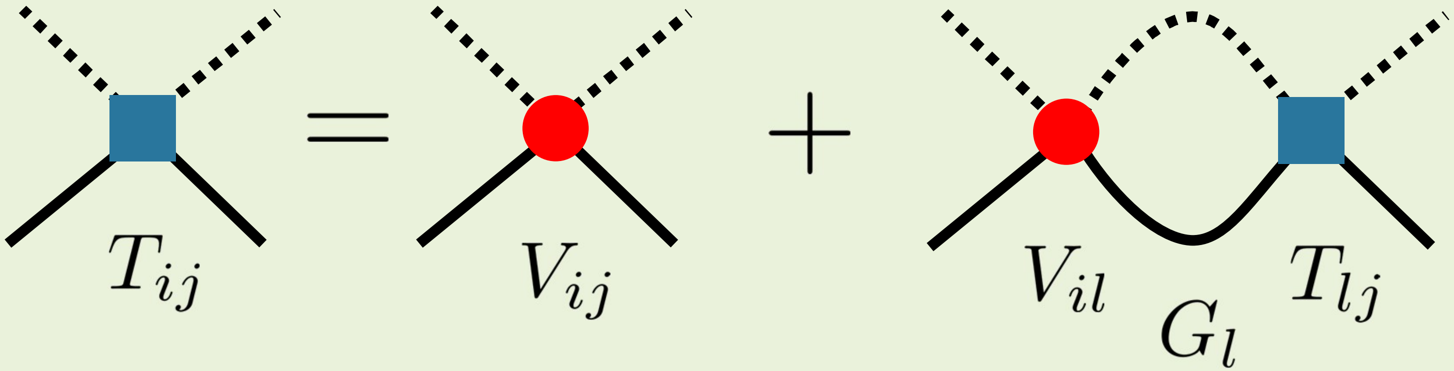
New!
Depend on spin configuration of the ϕN system (spin 1/2 or 3/2)

L.M. Abreu, P. Gubler, K.P. Khemchandani, A. Martínez Torres and A. Hosaka, Phys. Lett. B **860**, 139175 (2025).

Next step:

Solve the Bethe-Salpeter equation in the Vector Meson-Baryon channel of interest to obtain the full scattering amplitude T

$$T_{ij} = V_{ij} + V_{il} G_l T_{lj}$$



Emergence of subtraction constants, which are parameters of the model

Loop contains divergence that needs to be regulated. We use dimensional regularization

L.M. Abreu, P. Gubler, K.P. Khemchandani, A. Martínez Torres and A. Hosaka, Phys. Lett. B **860**, 139175 (2025).

For the spin 3/2 channel, we use two data sets to evaluate the corresponding uncertainty:

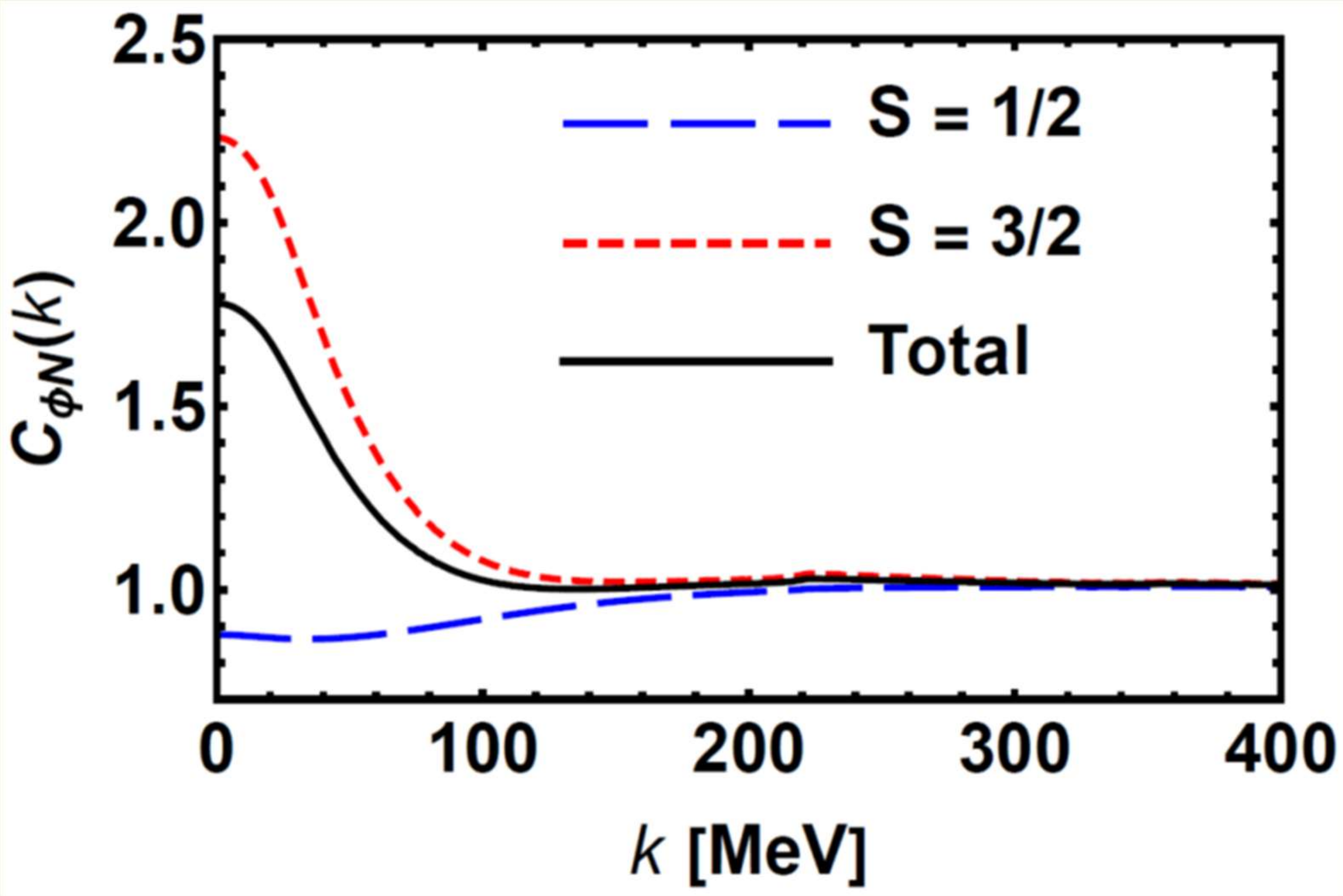
Channel (i)	a_i (Set A)	a_i (Set B)
ρN	-2.0	-2.0
ωN	-2.0	-2.0
ϕN	-1.7	-2.0
$K^*\Lambda$	-2.1	-2.1
$K^*\Sigma$	-2.0	-2.0

All are close to the "natural" value of a_i = -2

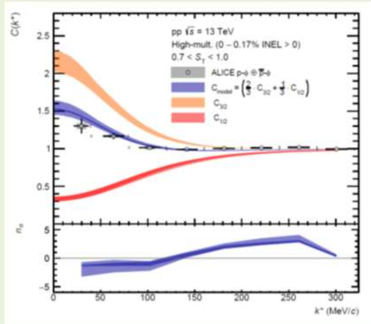
Only the value in the ϕN channel is modified, to study the change in the respective interaction strength

L.M. Abreu, P. Gubler, K.P. Khemchandani, A. Martínez Torres and A. Hosaka, Phys. Lett. B **860**, 139175 (2025).

The obtained correlation function (spin decomposed)



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



L.M. Abreu, P. Gubler, K.P. Khemchandani, A. Martínez Torres and A. Hosaka, Phys. Lett. B **860**, 139175 (2025).

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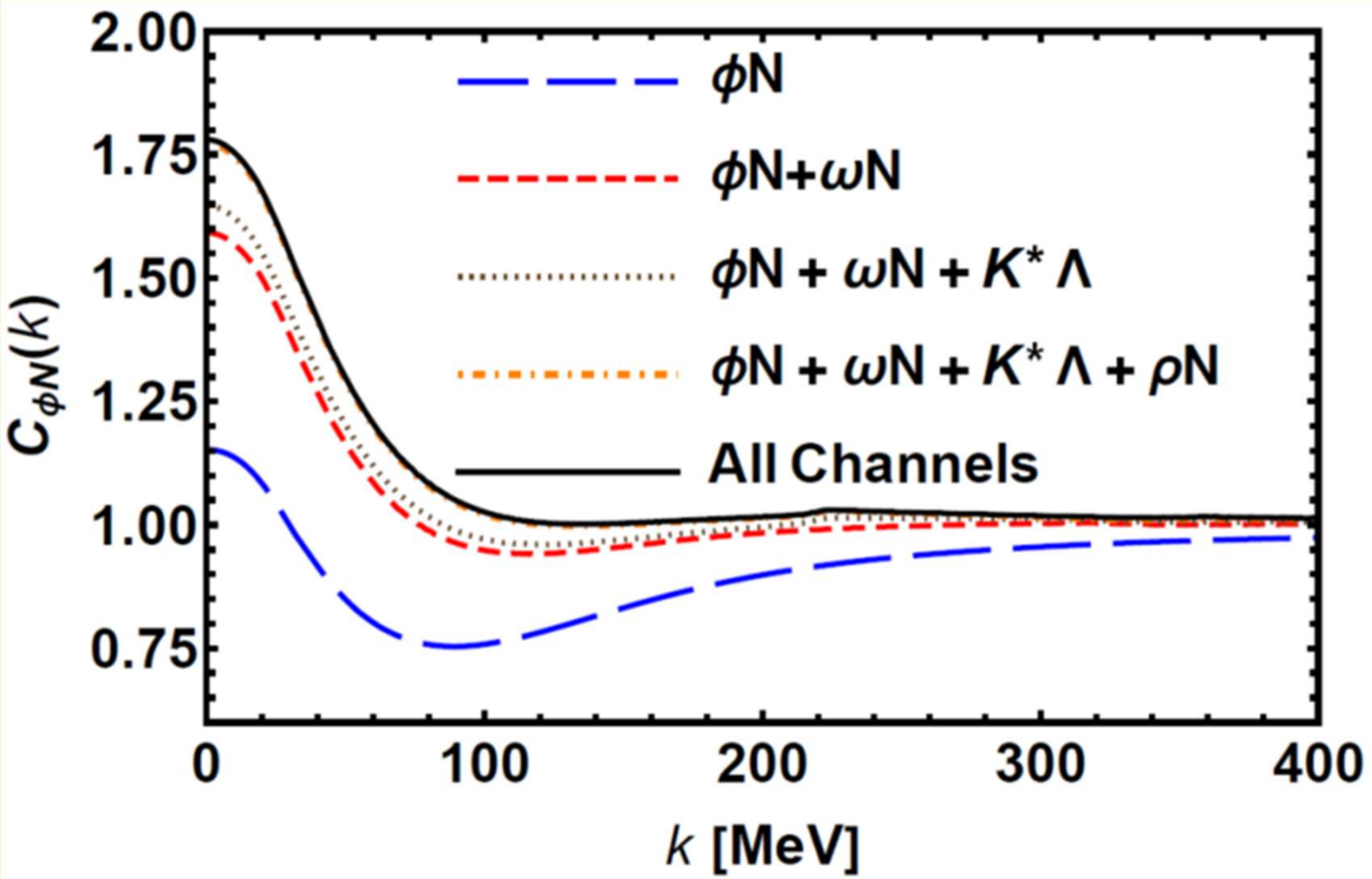
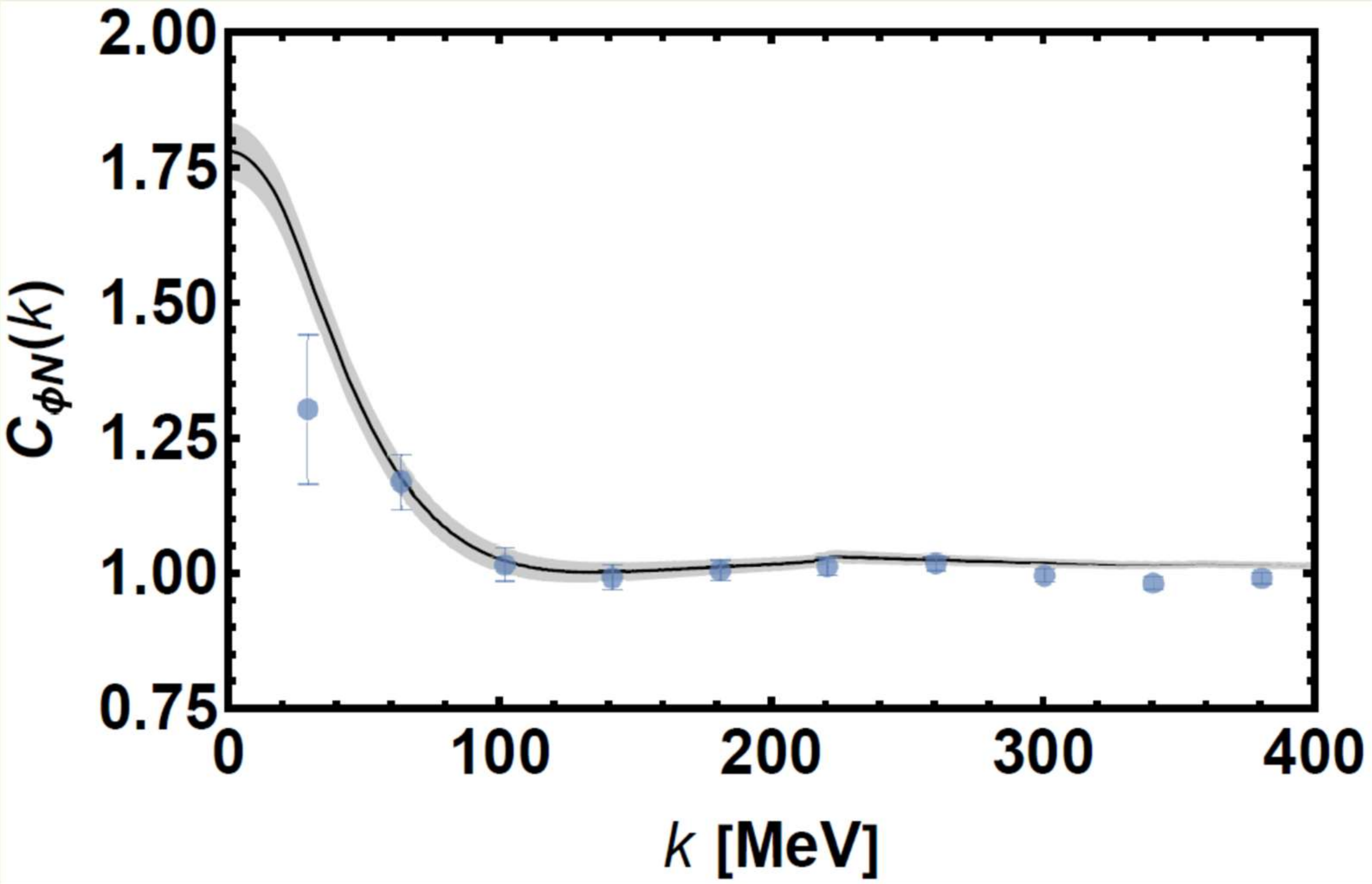


L.M. Abreu, P. Gubler, K.P. Khemchandani, A. Martínez Torres and A. Hosaka, Phys. Lett. B **860**, 139175 (2025).

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, Phys. Lett. B **860**, 139175 (2025).

The obtained scattering lengths

$$a_{\phi N}^{s=1/2} = -0.22 + i0.00 \text{ fm},$$
$$a_{\phi N}^{s=3/2,\text{set A}} = -0.30 + i1.50 \text{ fm},$$
$$a_{\phi N}^{s=3/2,\text{set B}} = -0.79 + i0.83 \text{ fm}.$$

Large model parameter dependence!

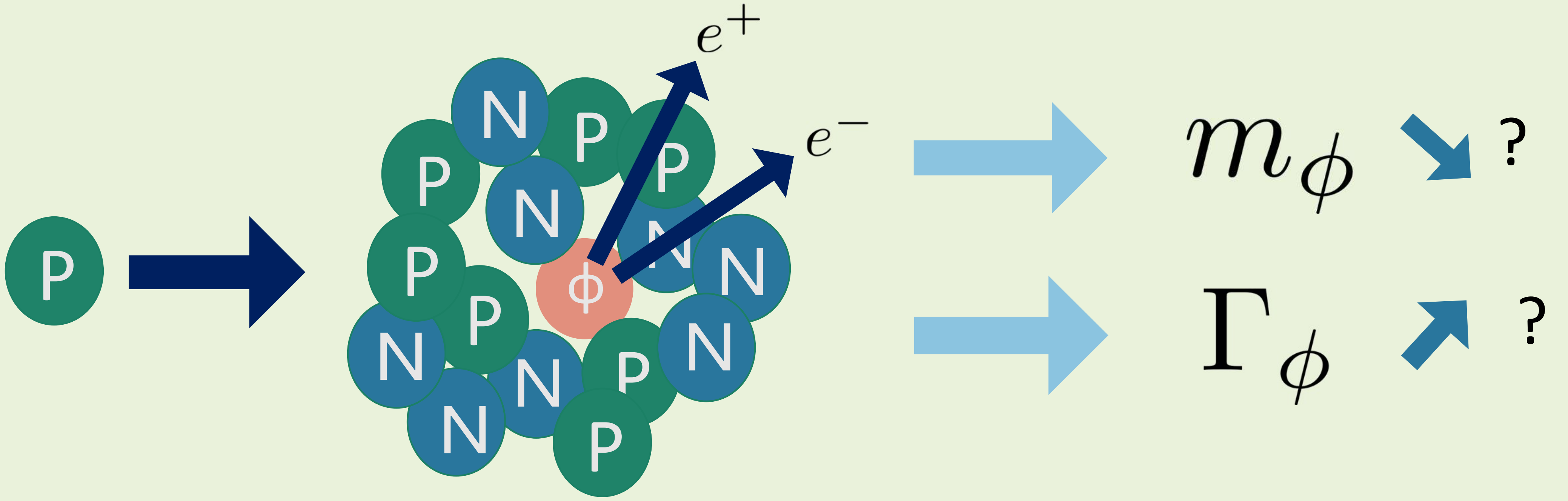
Comparison to mass shift in nuclear matter

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

Correlation function is not very sensitive to the scattering length

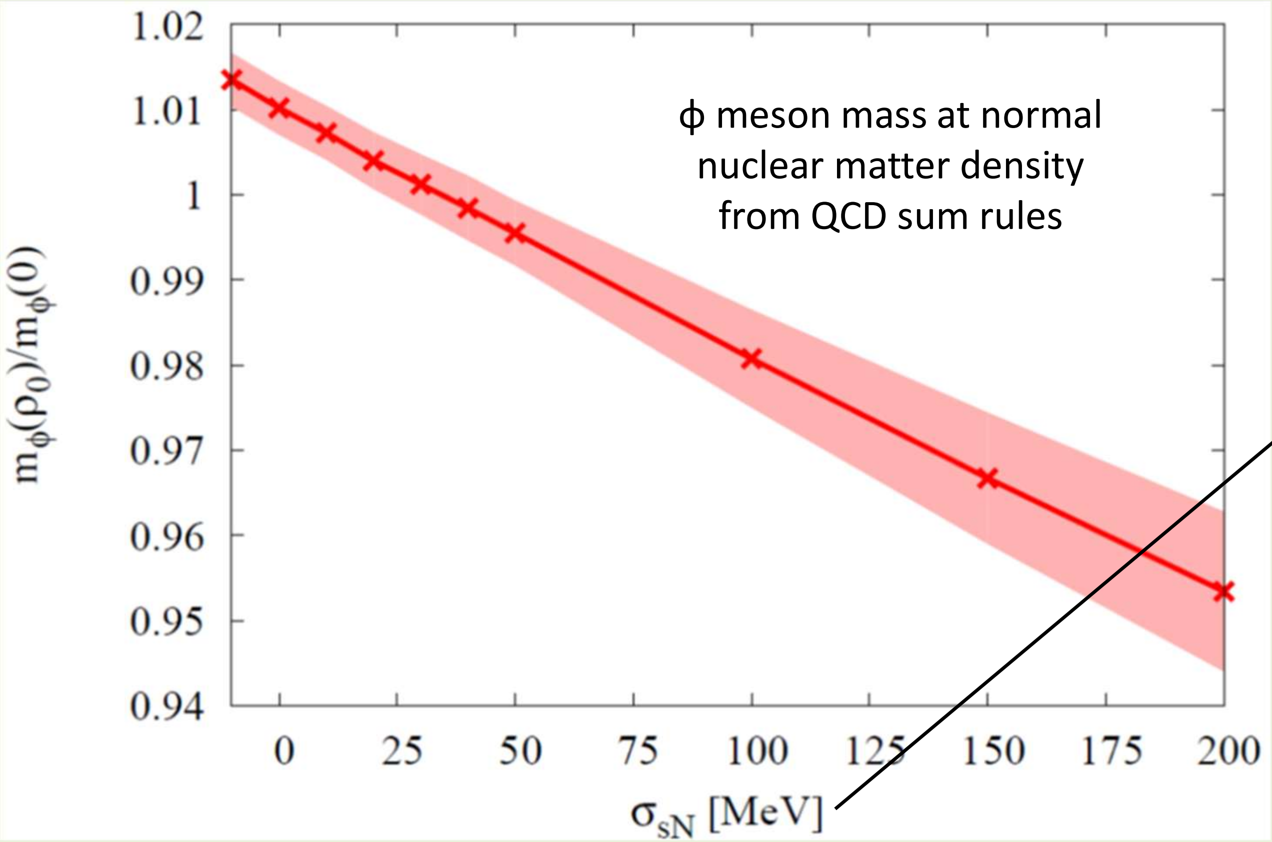
L.M. Abreu, P. Gubler, K.P. Khemchandani, A. Martínez Torres and A. Hosaka, Phys. Lett. B **860**, 139175 (2025).

Transport simulations of pA reactions to study the ϕ properties in nuclear matter



Why should we be interested?

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



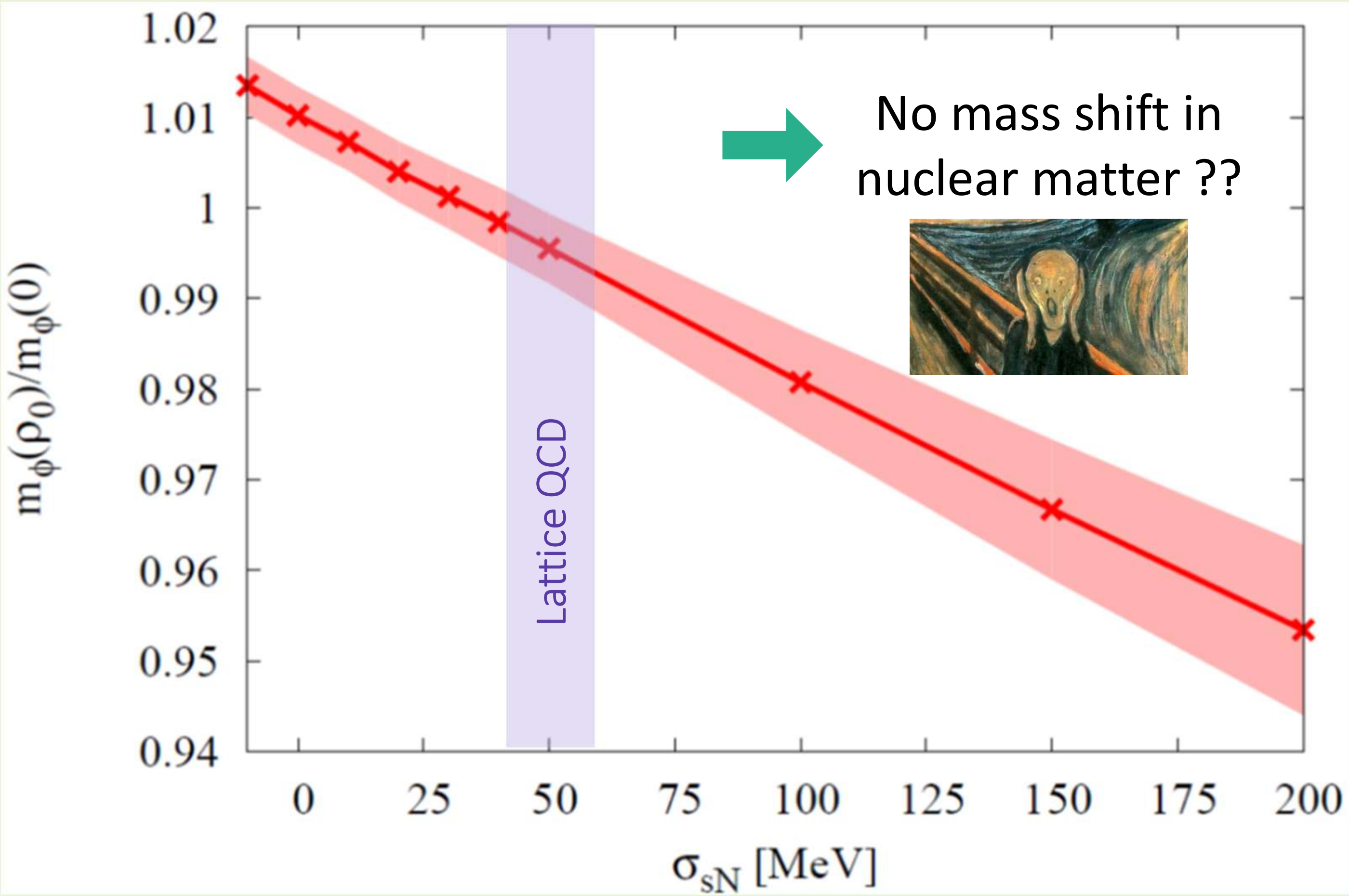
P. Gubler and K. Ohtani, Phys. Rev. D **90**, 094002 (2014).

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

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

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

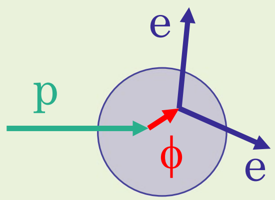
Combine QCD sum rules with lattice QCD



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

Previous experimental results

KEK
E325



12 GeV
pA-reaction

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

k_1: 0.034 ± 0.007

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

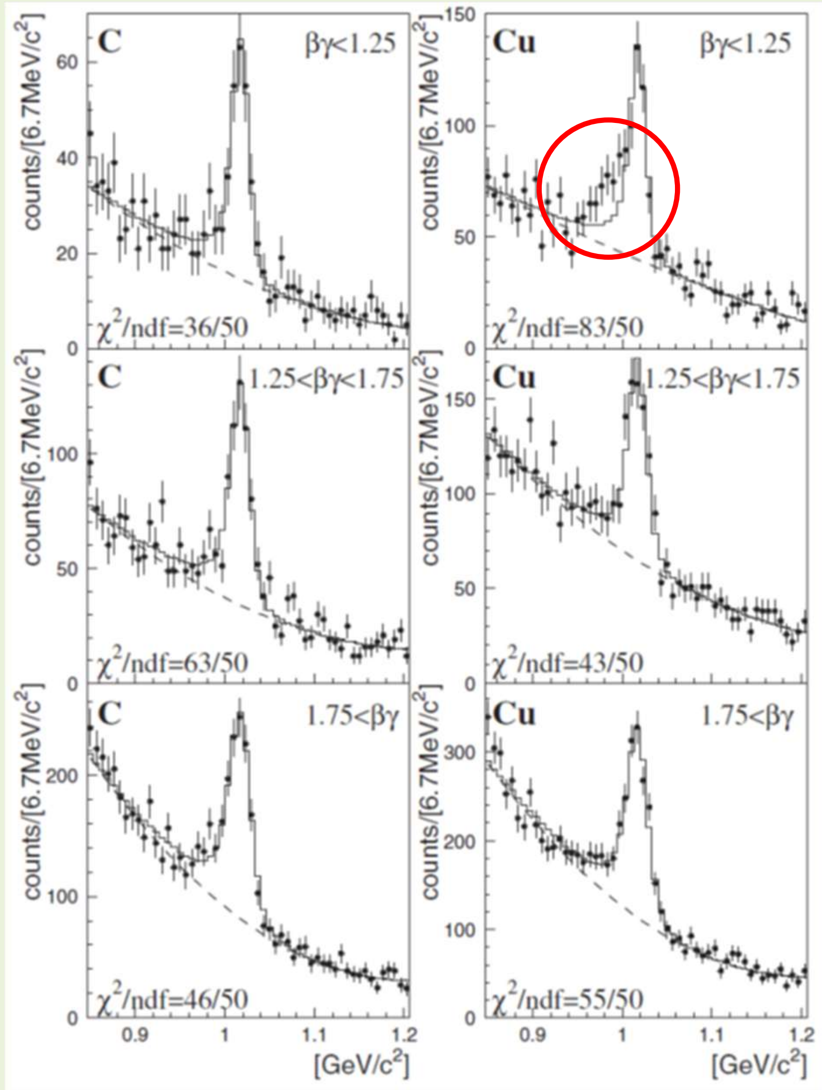
k_2: 2.6 ± 1.5

slow ϕs

intermediate ϕs

fast ϕs

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

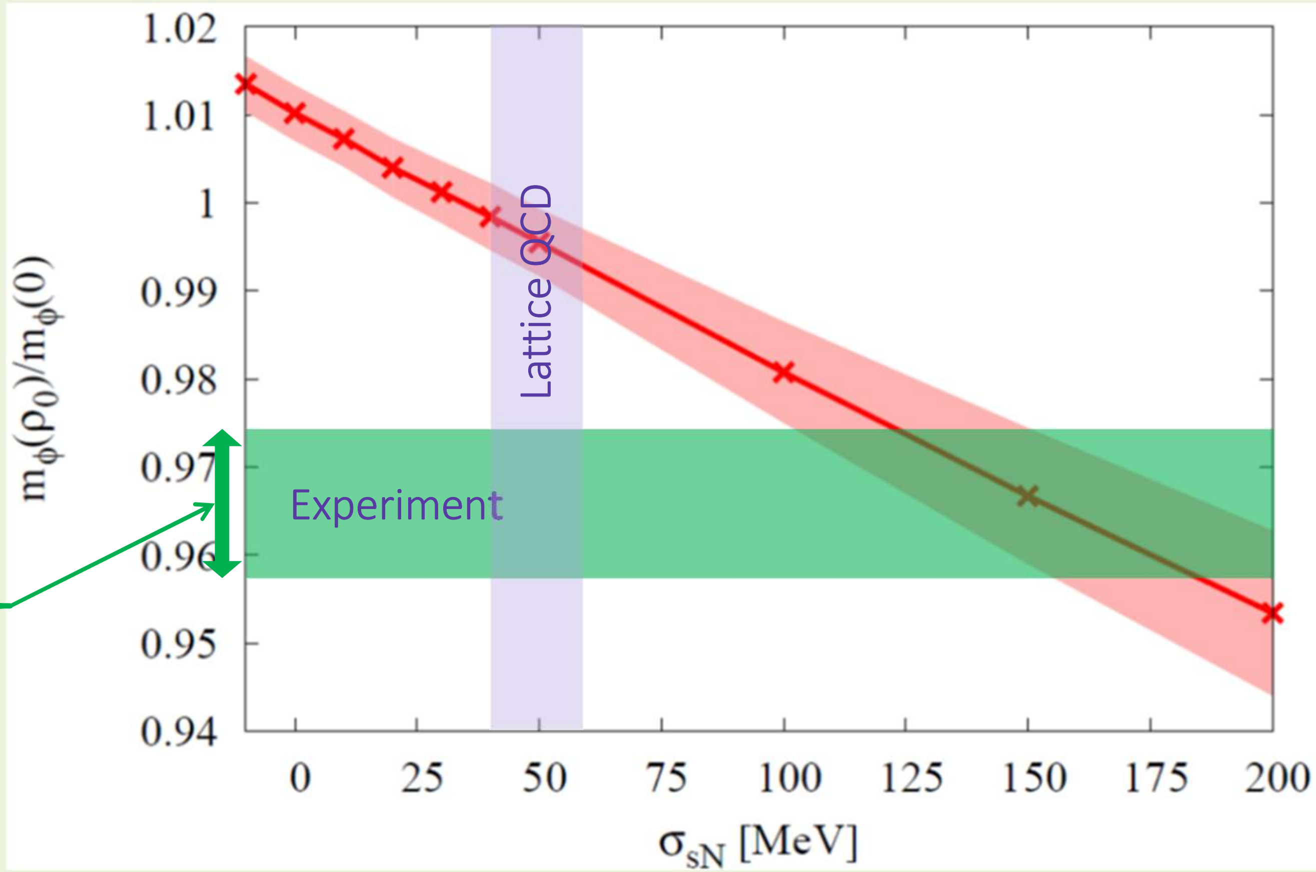


R. Muto et al. (E325 Collaboration), Phys. Rev. Lett. **98**, 042501 (2007).

Compare Theory with Experiment

Not consistent?

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

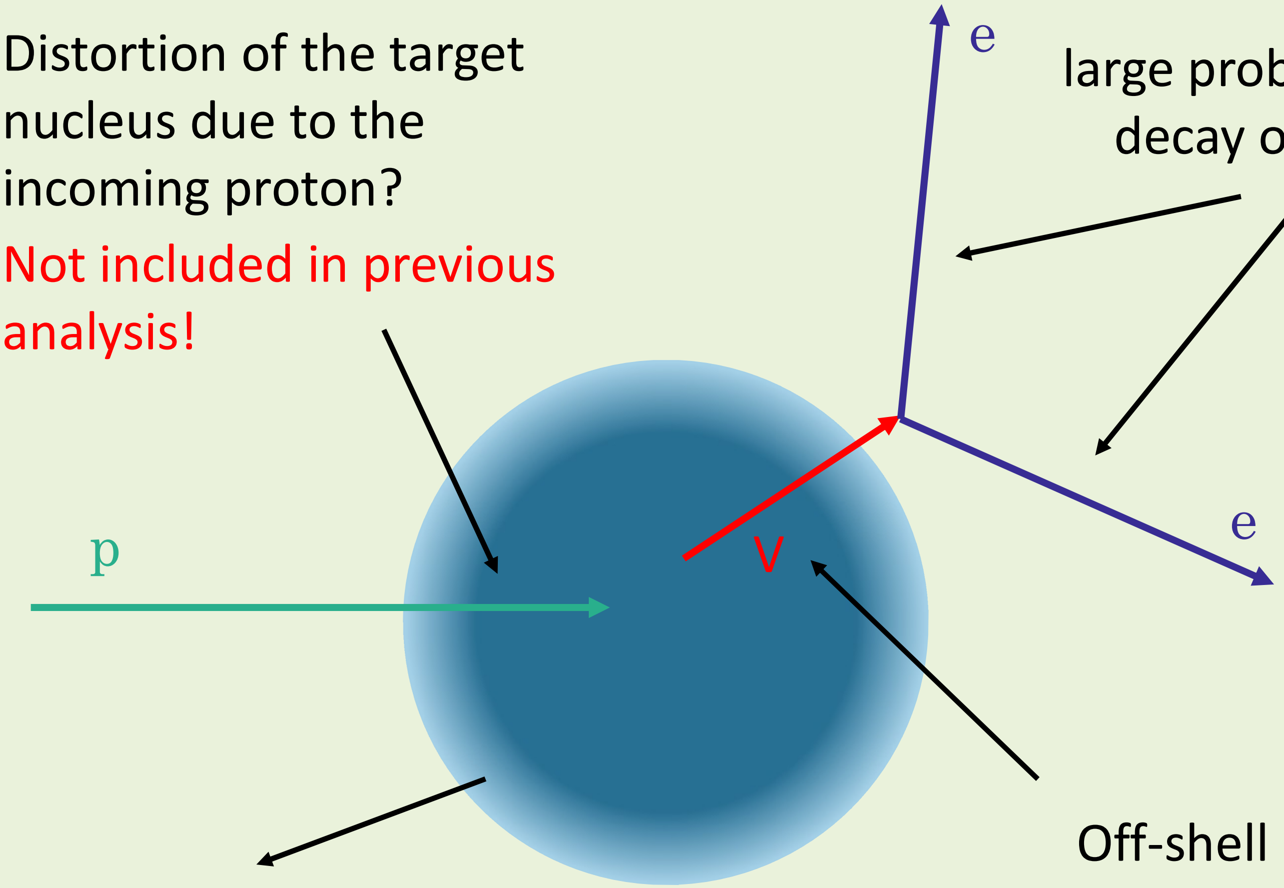


Measurement will be repeated at the E16 experiment at J-PARC (with 100 times increased statistics!)

Distortion of the target nucleus due to the incoming proton?

Not included in previous analysis!

large probability of vector meson decay outside of the nucleus



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!

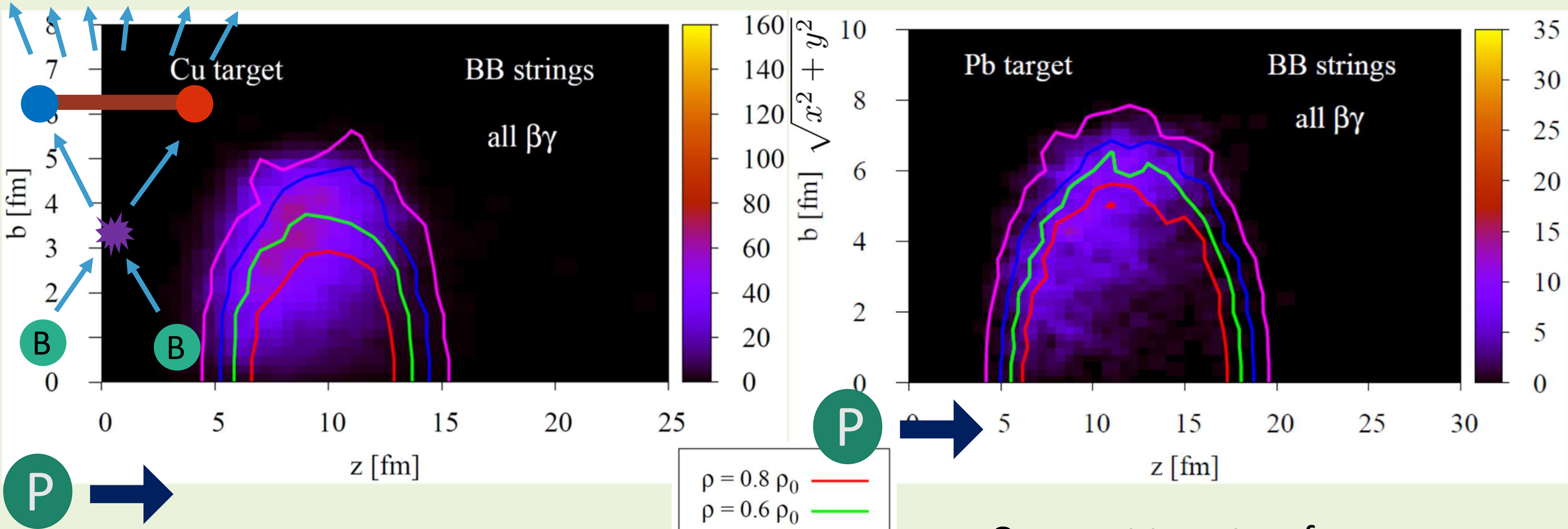
★ Off-shell dynamics of vector mesons and kaons is included

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

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

How are ϕ mesons produced in 12 GeV pA collisions?

Production through initial high-energy collisions (via strings)

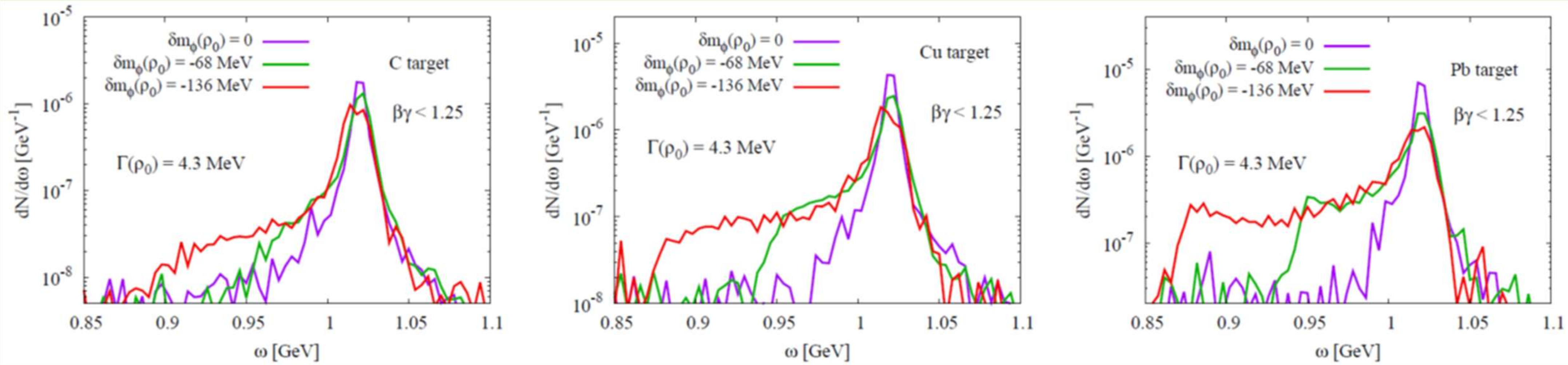


Occurs at target surface

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)

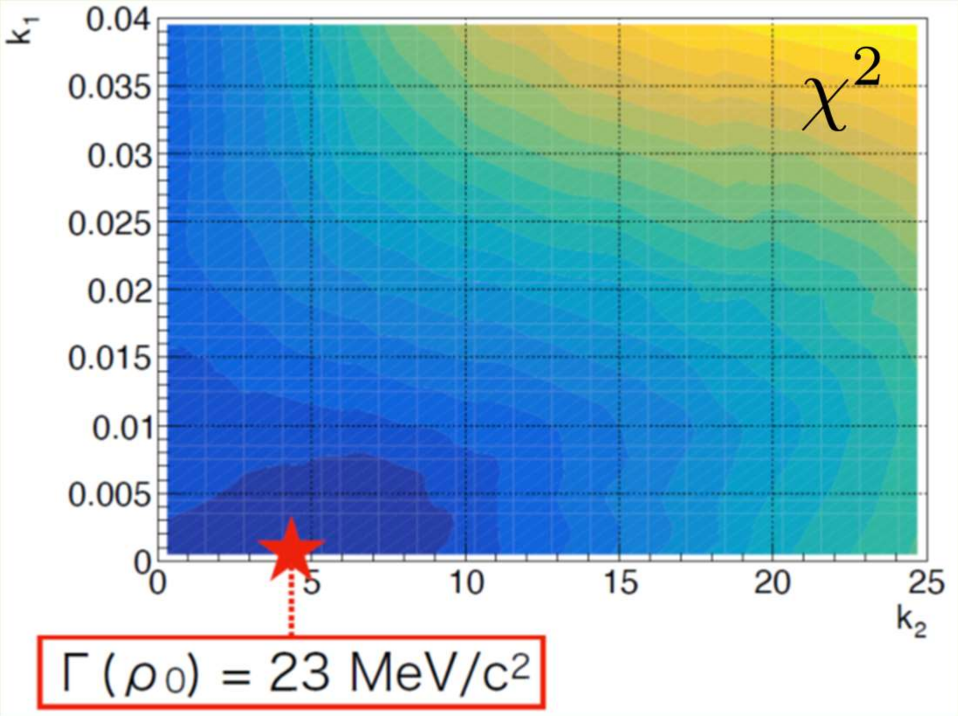
P. Gubler, M. Ichikawa, T. Song and E. Bratkovskaya, Phys. Rev. C **111**, 034908 (2025).

Comparison with KEK E325 dilepton data

First trial:

Momentum-independent mass shift and decay width

Increased mass shift



Increased broadening

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

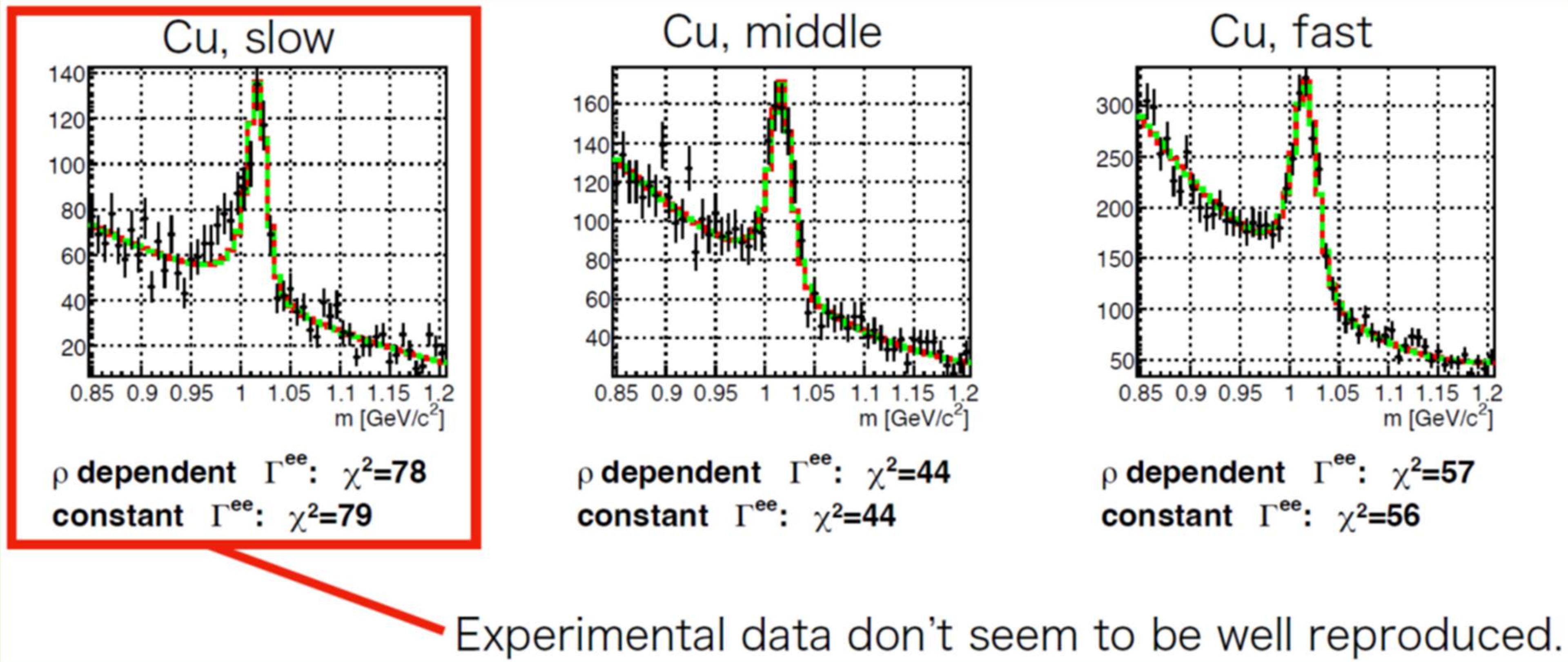
$$\frac{\Gamma_\phi(\rho)}{\Gamma_\phi(0)} = 1 + k_2 \frac{\rho}{\rho_0}$$

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:

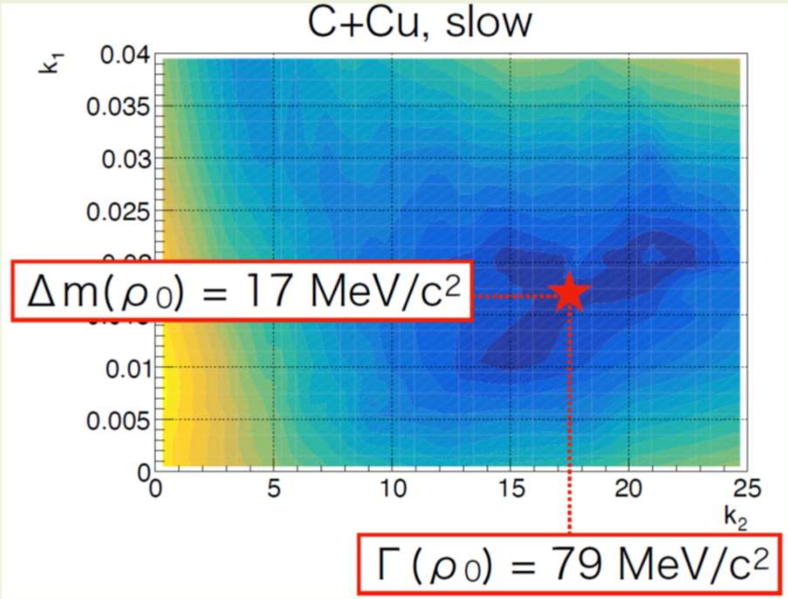
Momentum-independent mass shift and decay width

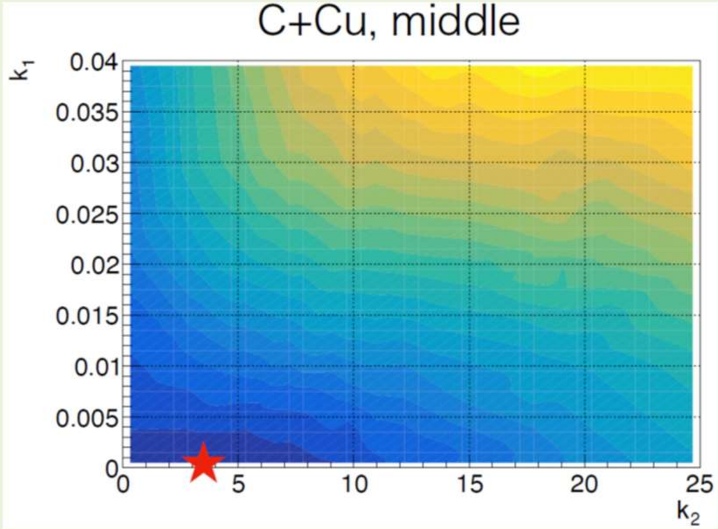


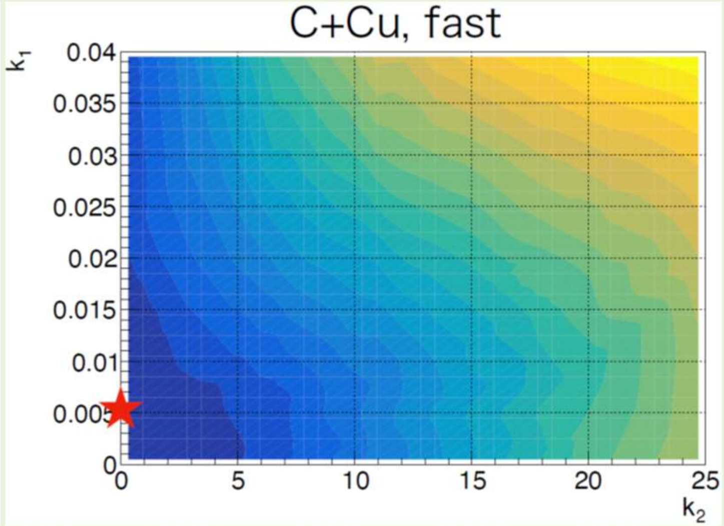
M. Ichikawa, P. Gubler, et al., (KEK-PS E325 Collaboration), Prog. Theor. Exp. Phys. **2025** 093D01 (2025).

Comparison with KEK E325 dilepton data

Momentum-dependent mass shift and decay width







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

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

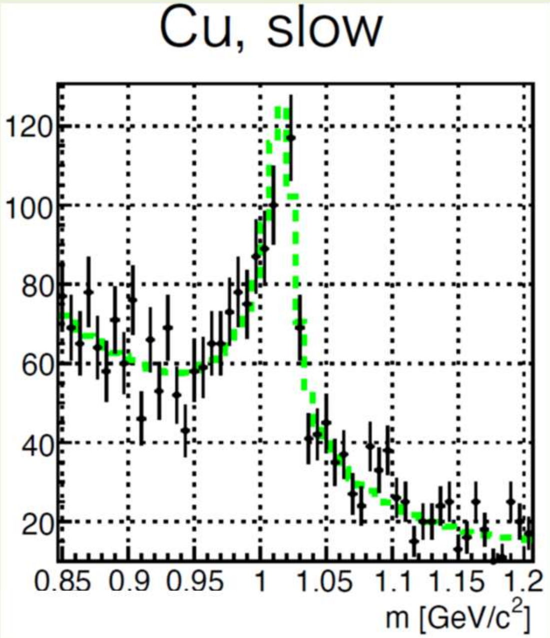
$$\frac{\Gamma_\phi(\rho)}{\Gamma_\phi(0)} = 1 + k_2 \frac{\rho}{\rho_0}$$

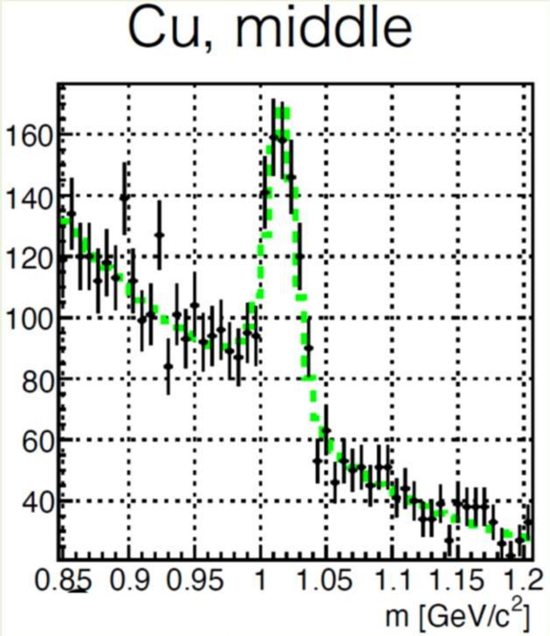
M. Ichikawa, P. Gubler, et al., (KEK-PS E325 Collaboration), Prog. Theor. Exp. Phys. **2025**, 093D01 (2025).

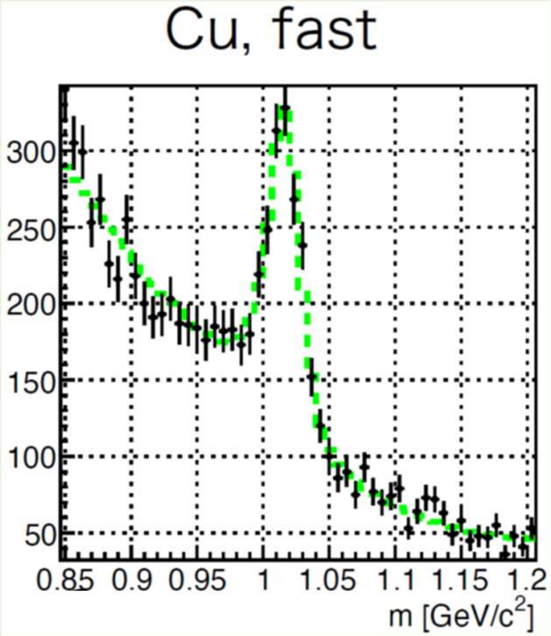
Comparison with KEK E325 dilepton data

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!

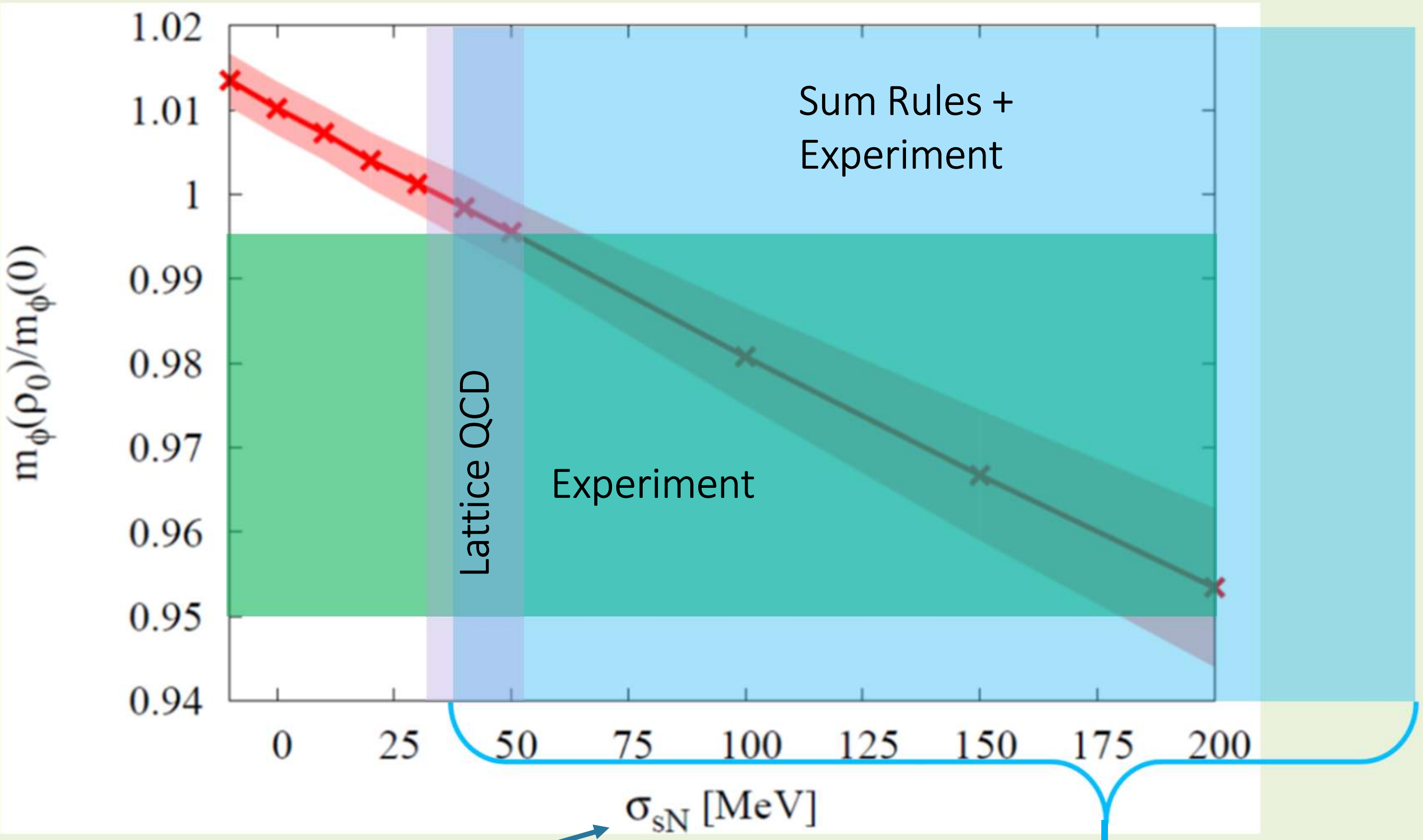
M. Ichikawa, P. Gubler, et al., (KEK-PS E325 Collaboration), Prog. Theor. Exp. Phys. **2025** 093D01 (2025).

New comparison between theory and experiment

Problem solved???

Need more precise data!

Stay tuned for J-PARC E16



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

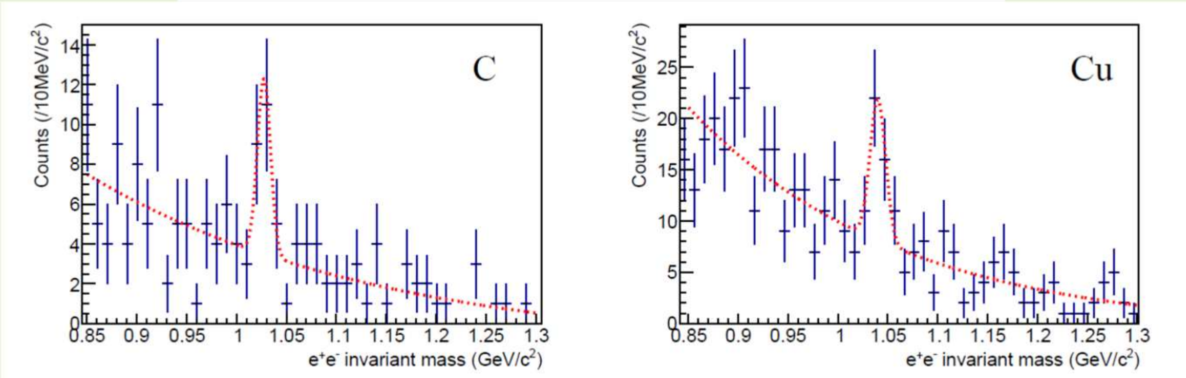
$$\sigma_{sN} \sim 140 \pm 100 \text{ MeV}$$

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)



See the talk by Satomi Nakasuga!
(Friday morning)

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

Summary and conclusions

★ The ϕN ALICE femtoscopy data can be reproduced in a coupled channel effective theory approach, but sensitivity on scattering data is low → **Need better data!**

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

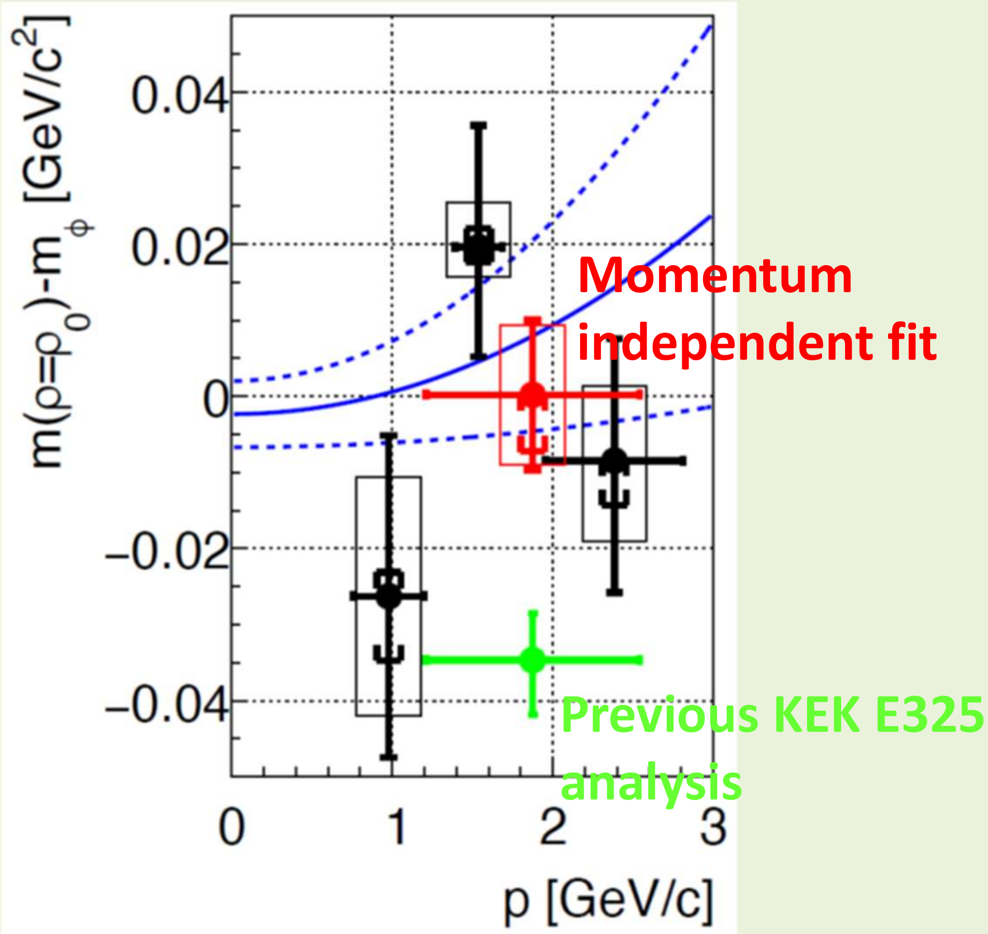
★ With the PHSD transport approach, we can now study pA reactions more reliably → **Changed conclusions from previous analysis of experimental data**

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

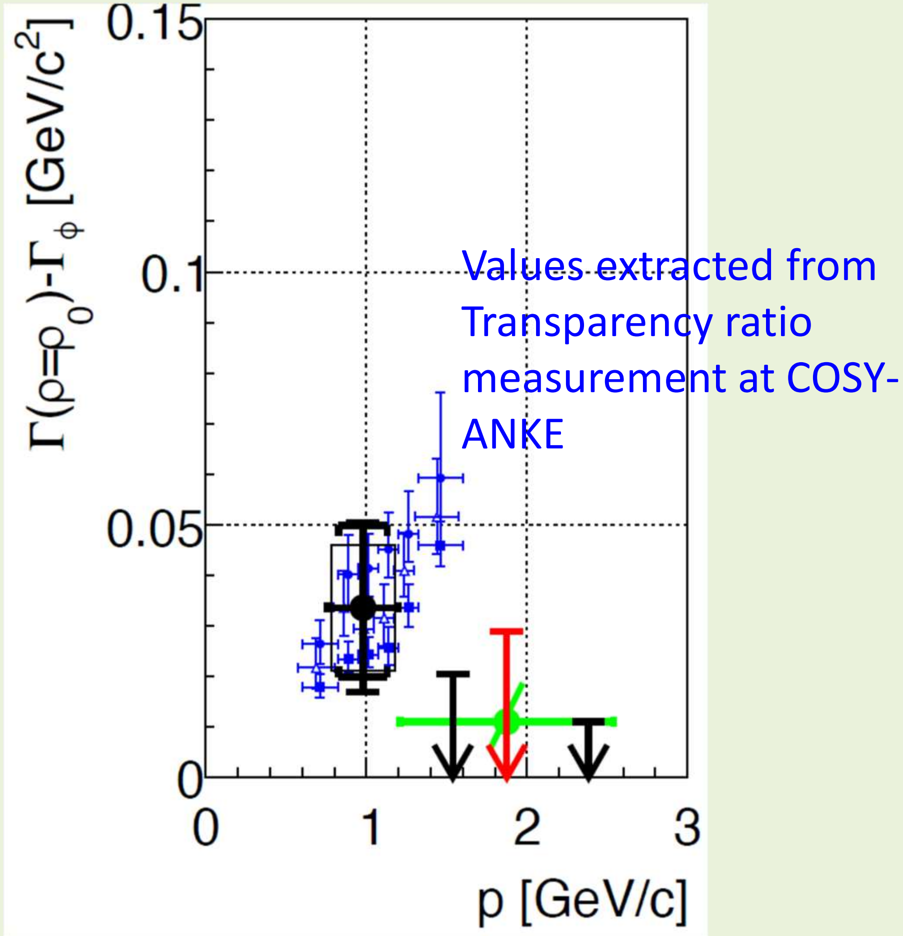
Backup slides

Final analysis results

Mass shift at ρ_0

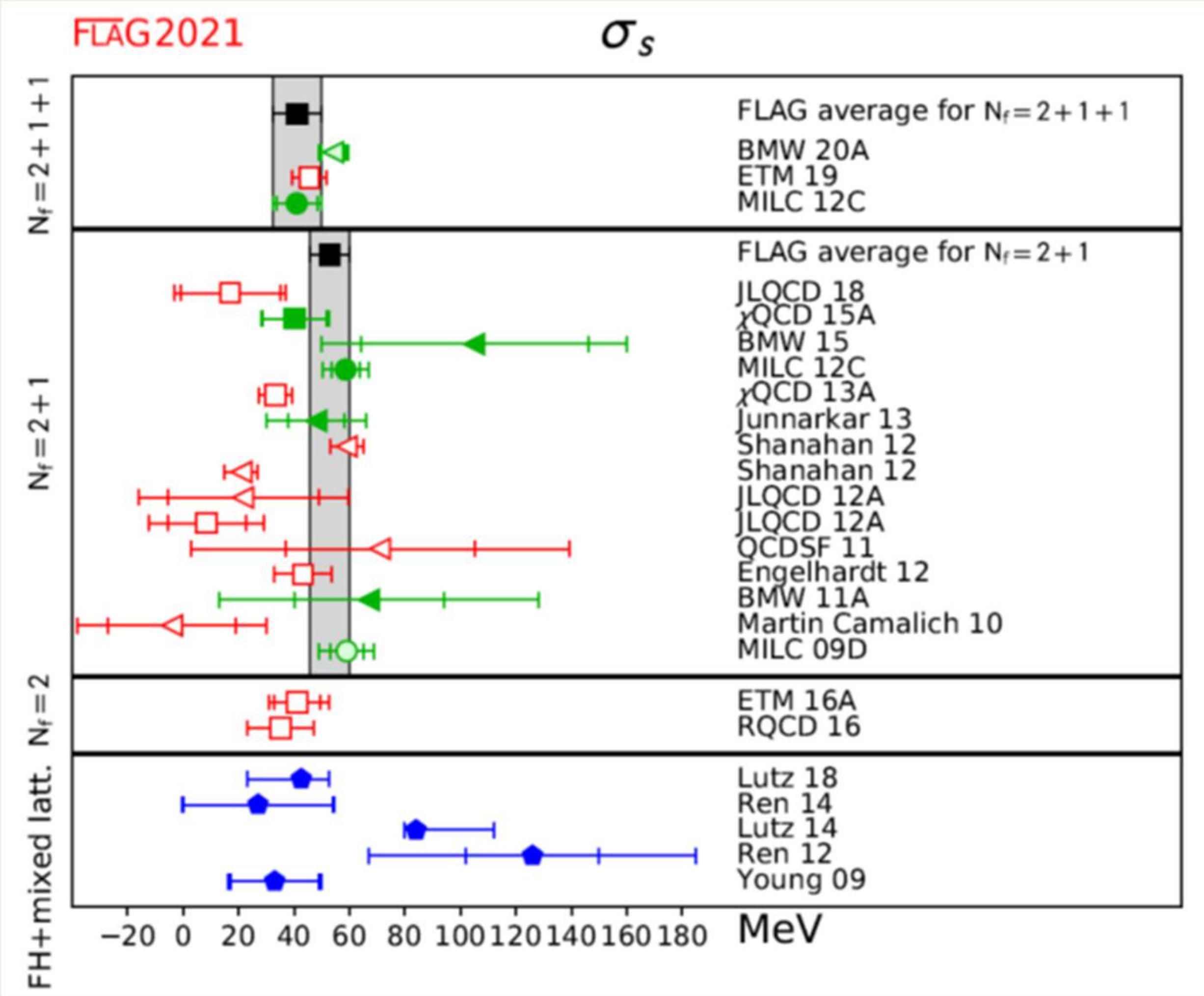


Width shift at ρ_0



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?

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

Valid within the linear density approximation

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

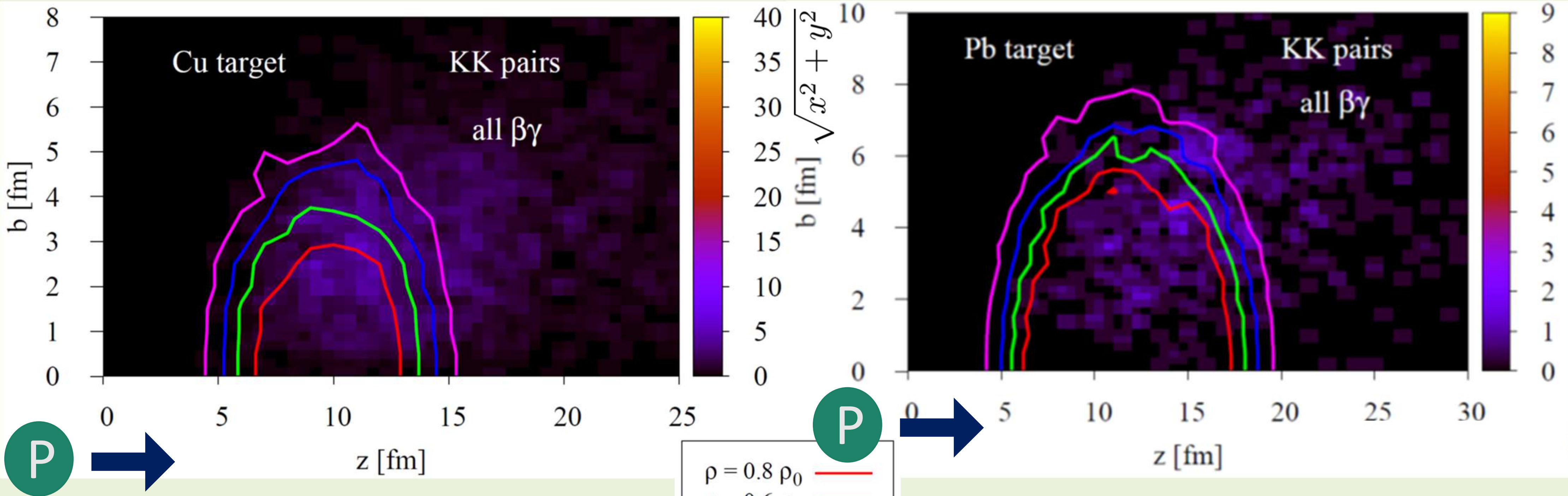
Y. Liu et al., Phys. Rev. D **106**, 074507 (2022).

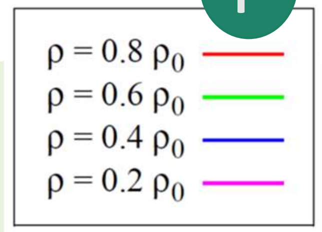
However, the above prescription seems problematic if a ϕN bound state (or resonance) is formed.

→ Need better theoretical understanding!

How are ϕ mesons produced?

Production through secondary low-energy hadron collisions

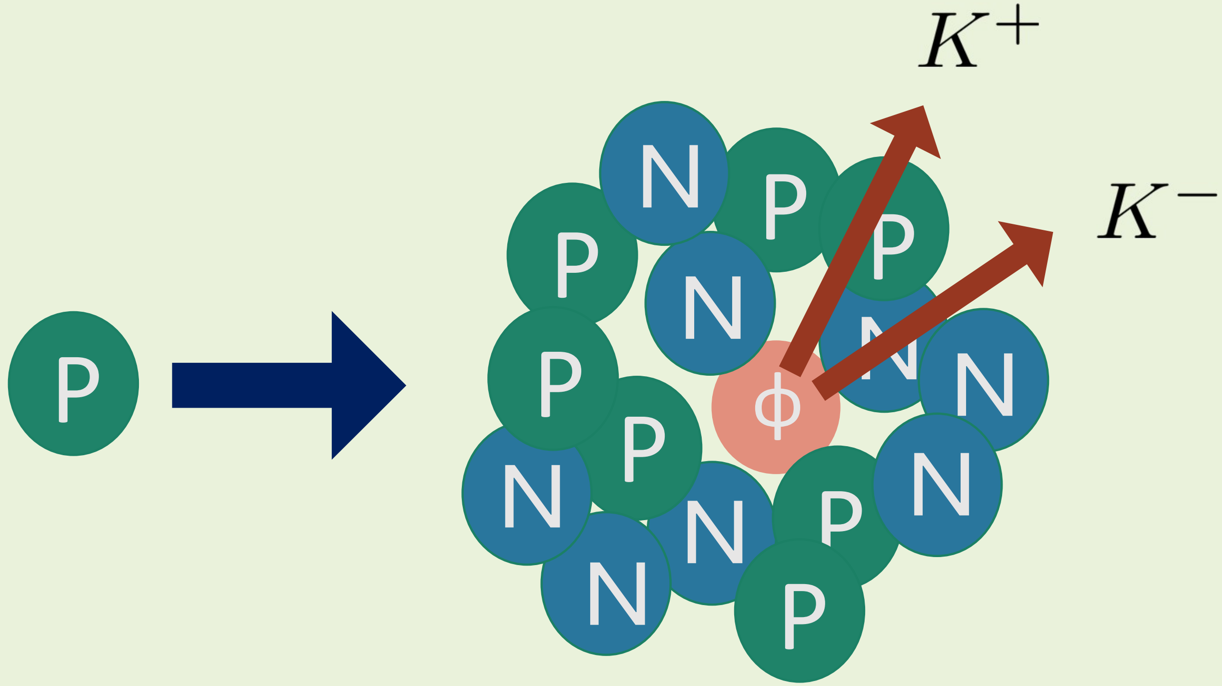




Occurs often outside of the target

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

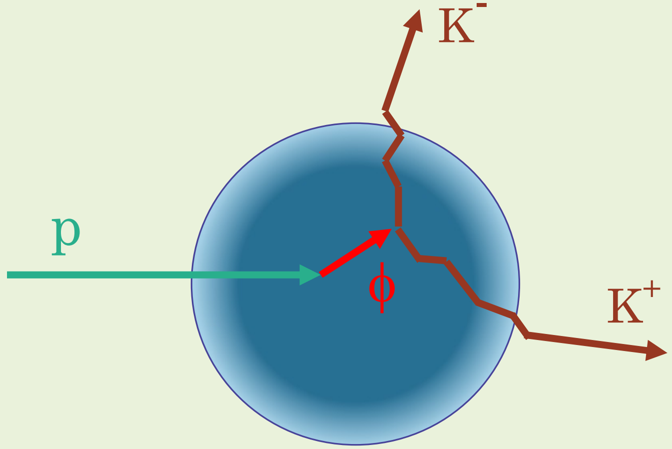
What about the K^+K^- spectrum?



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

J-PARC E16 vs. E88

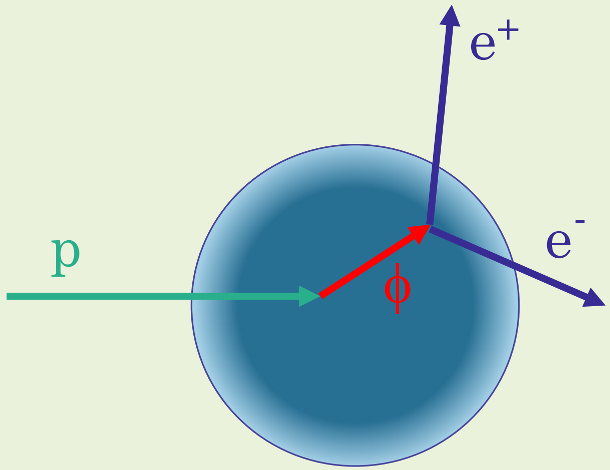
E88



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

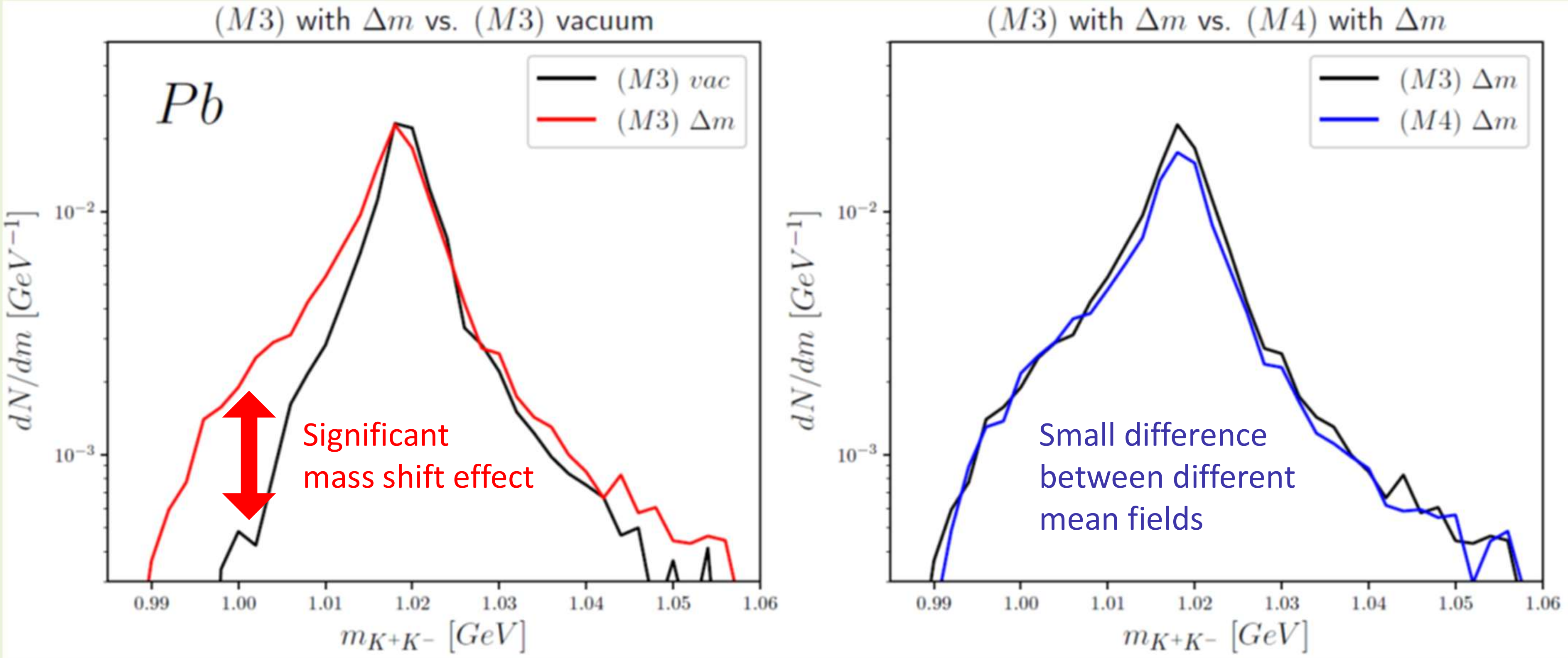
Used mean fields to parametrize the K and Kbar interactions with the nuclear medium

Model		Mean Field Expression	Parameter Values
M1	K^+	$U_{K^+} = 0$	–
	K^-	$U_{K^-} = 0$	–
M2	K^+	$U_{K^+} = a_2 \cdot \rho$	$a_2 = 0.167$ [GeV $\cdot$ fm^3]
	K^-	$U_{K^-} = -a_2 \cdot \rho$	
M3	K^+	$U_{K^+} = a_3 \cdot \rho$	$a_3 = 0.167$ [GeV $\cdot$ fm^3]
	K^-	$U_{K^-} = -\rho(b_3 + c_3 \cdot e^{-d_3 \cdot p_K})$	$b_3 = 0.341$ [GeV $\cdot$ fm^3],
			$c_3 = 0.823$ [GeV $\cdot$ fm^3],
			$d_3 = 2.5$ [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 $\Delta m_{\phi}(\rho_0)$ = -34 MeV is assumed

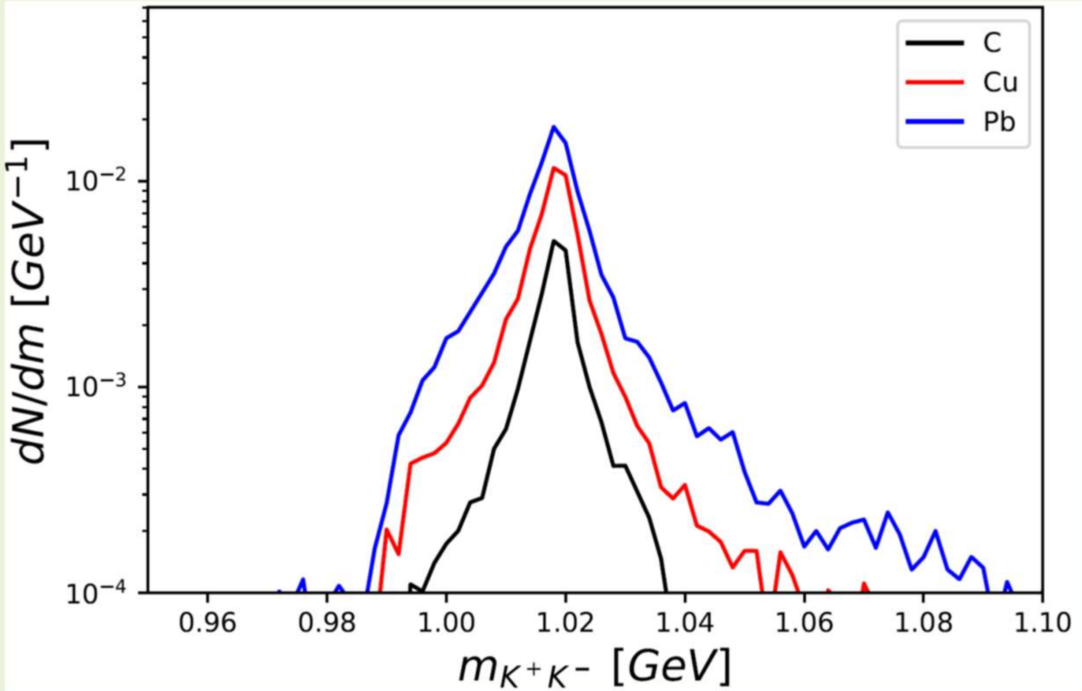


G. Balassa et al., arXiv:2508.11344 [hep-ph] (To be published in Prog. Theor. Exp. Phys.).

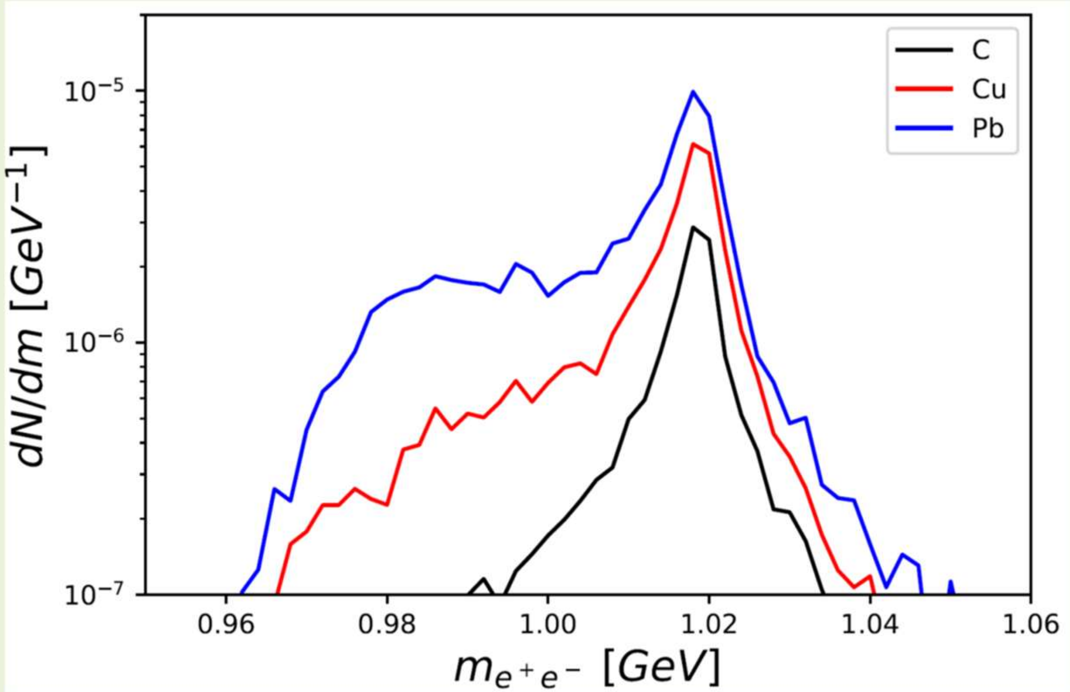
Comparative study of the K^+K^- and e^+e^- spectrum

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

K^+K^- invariant mass spectrum



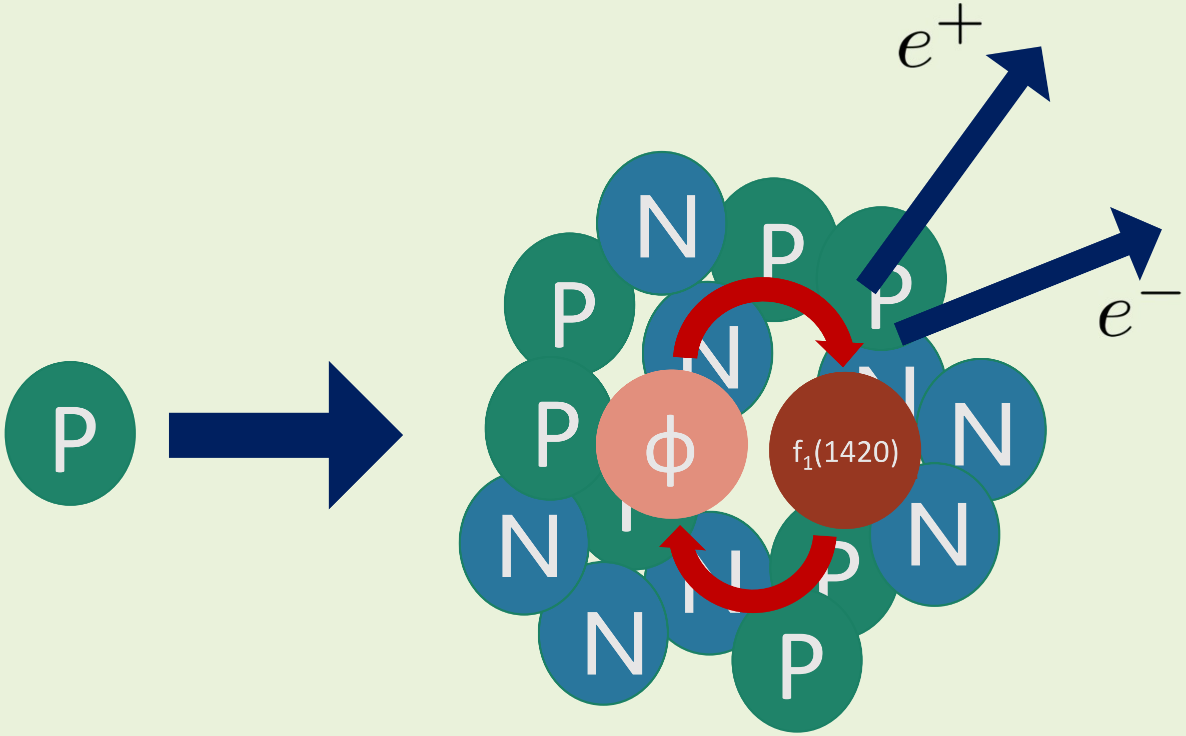
e^+e^- invariant mass spectrum



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).

Possible observation of chiral mixing?



New peak in dilepton spectrum??

Simple hadronic model including C-symmetry breaking

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

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:

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

from holographic QCD

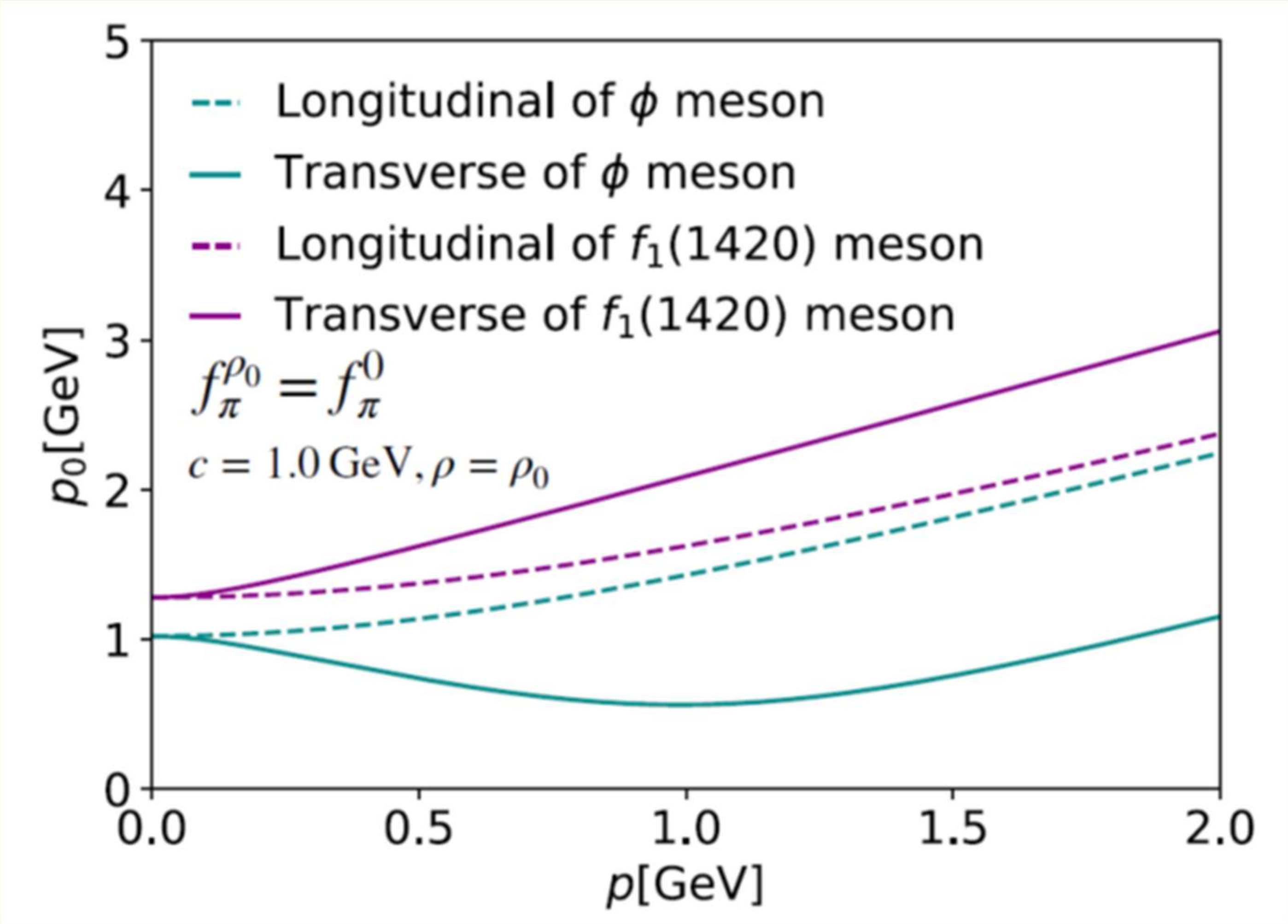
S. K. Domokos and J. A. Harvey,
Phys. Rev. Lett. **99**, 141602 (2007).

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

from gauged WZW action

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

Resulting dispersion relations (at $\rho = \rho_0$)

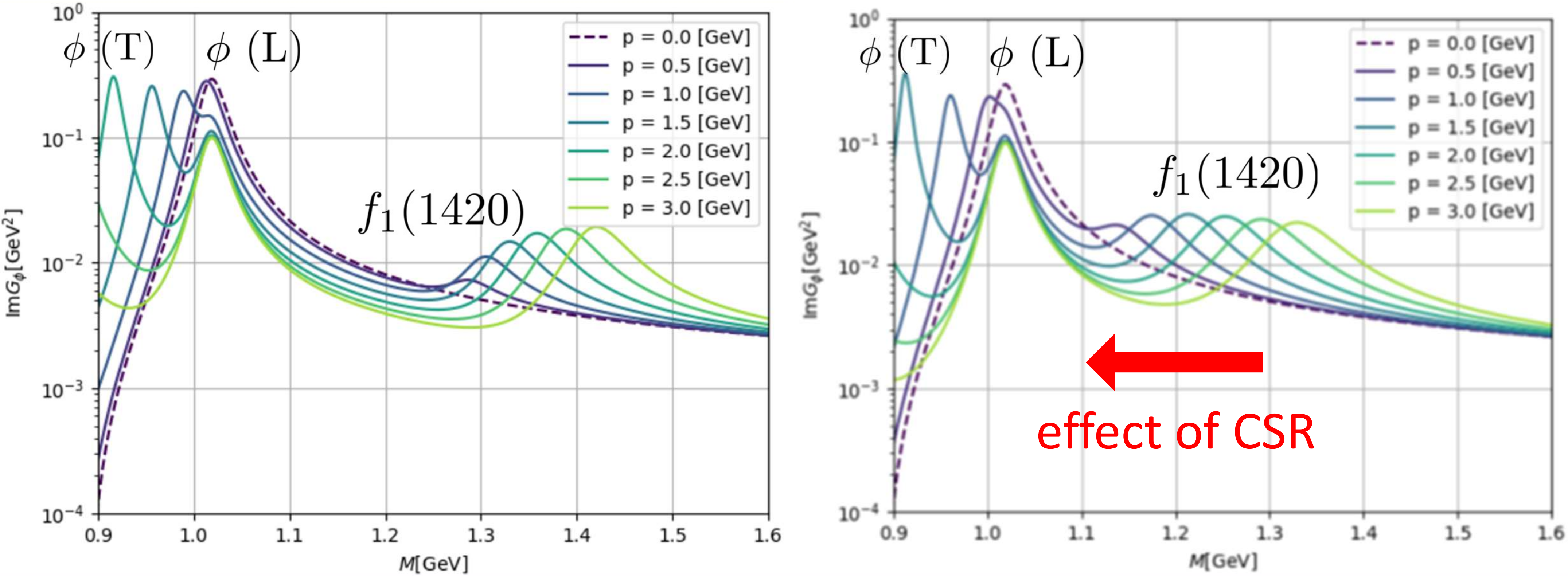


C. Sasaki, Phys. Rev. D **106**, 054034 (2022).

Resulting spectral functions (at $\rho = \rho_0$)

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

without CSR | with CSR



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

Experimentally measurable invariant mass distribution

Computed using a state-of-the art transport simulation (PHSD)

See talk by M. Ichikawa

Convoluted by Gaussian to take into account experimental resolution

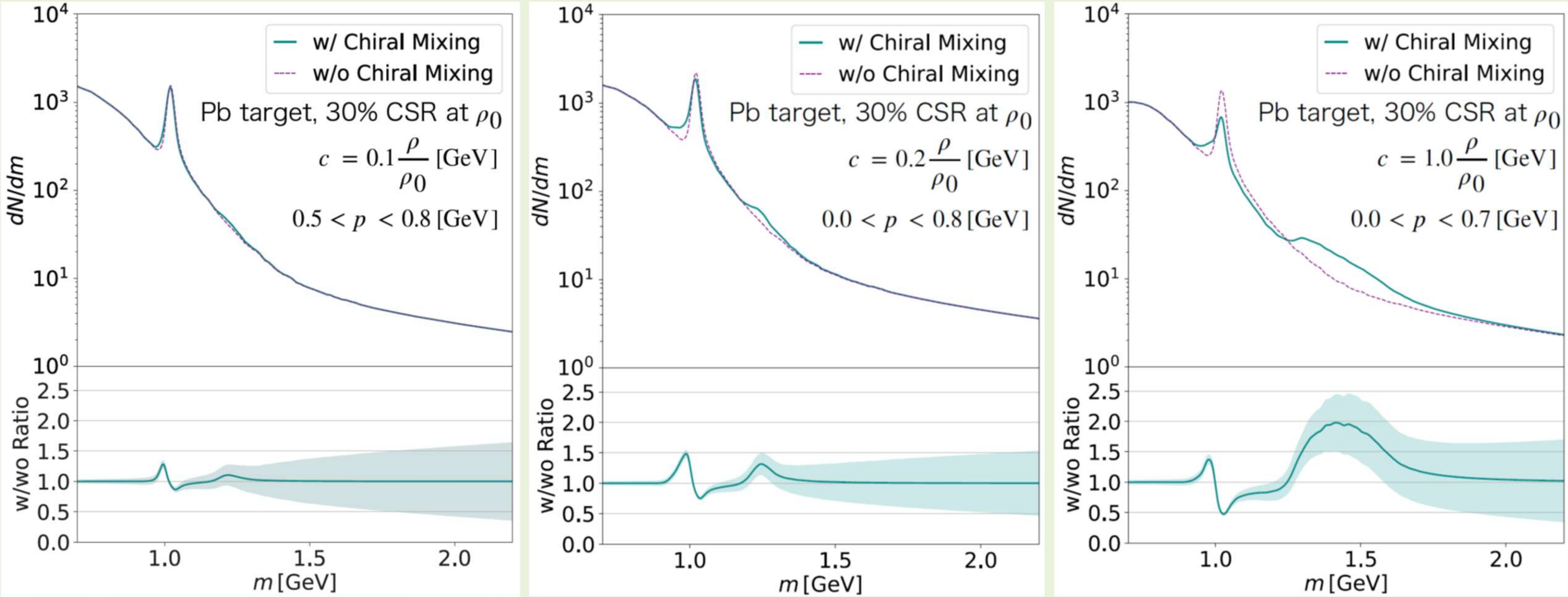
$$I(M) = \int \left[\int \boxed{\mathrm{Im} G_V(s, \vec{p}, \rho)} \boxed{\frac{dN}{d\vec{p}\,d\rho\,dt}} \frac{d\vec{p}}{2p_0} d\rho\, dt + \int \boxed{\mathrm{Bkg}(s, \vec{p})} d\vec{p} \right] \boxed{g(M - s)} ds$$

Taken from the Sasaki-model (previous slide)

Background, obtained simulation of experimental conditions:
JAM → Geant4

Invariant mass distributions for different mixing strengths

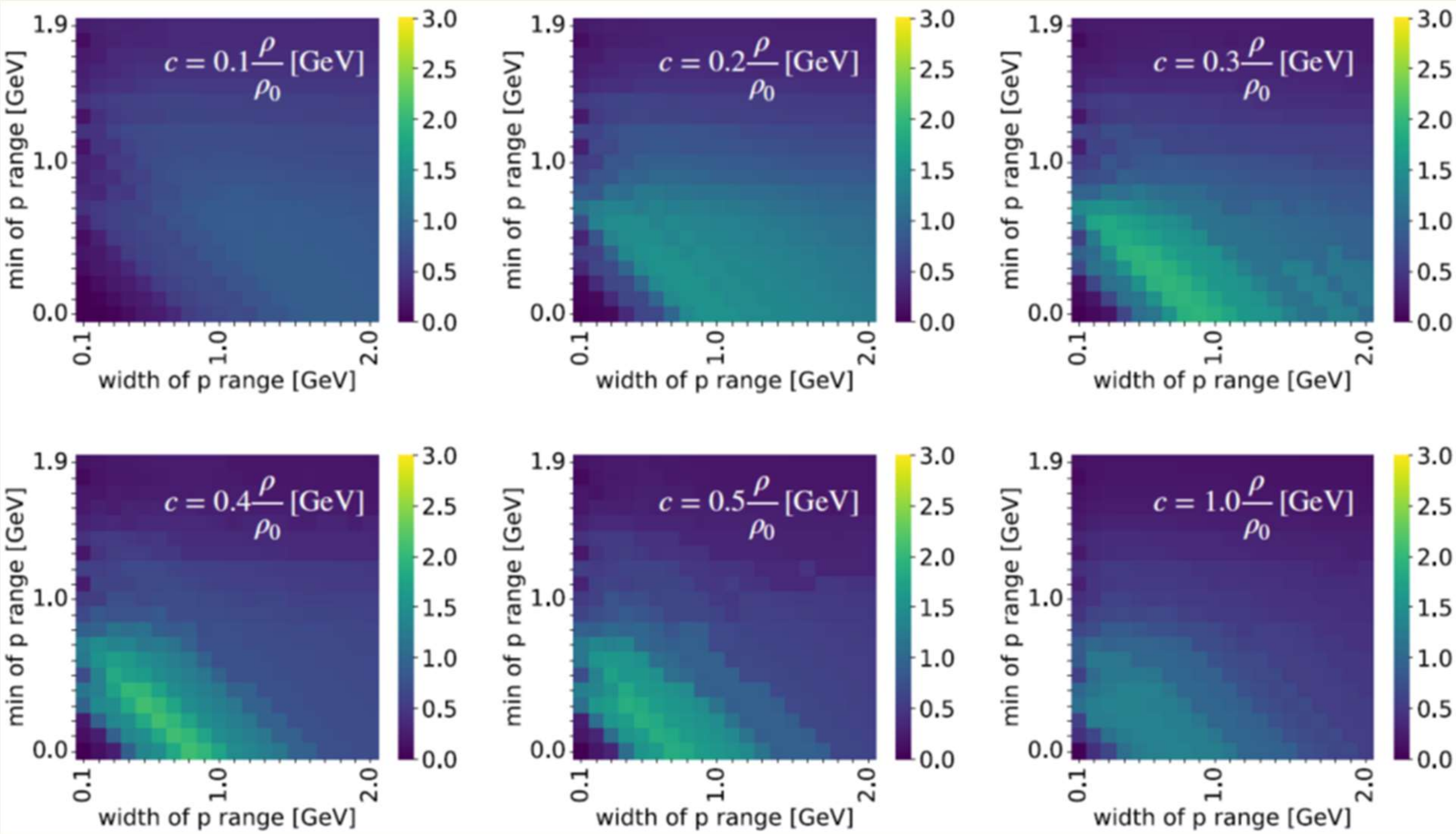
30 GeV pA collisions, Pb target, E16 Run2 statistics



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).

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).

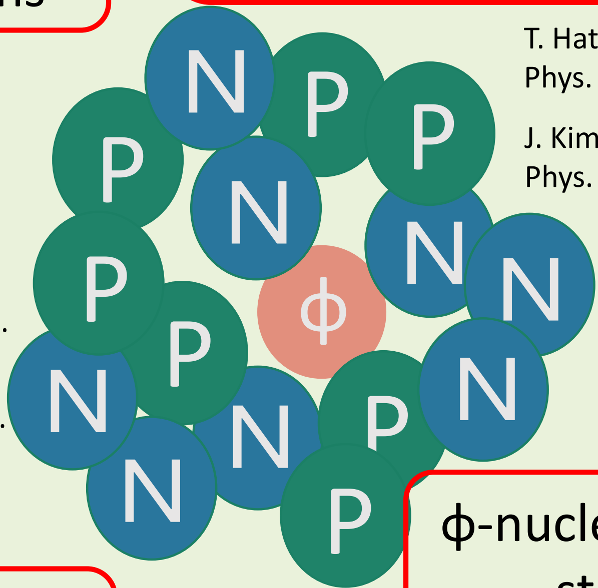
J. Kim, P. Gubler and S.H. Lee,
Phys. Rev. D **105**, 114053 (2022).

Pion induced ϕ meson production

P95 experiment at J-PARC

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

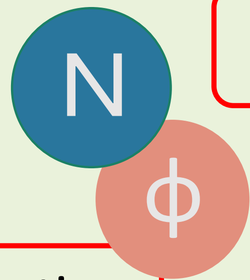
Femtoscopy from LHC



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).

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??

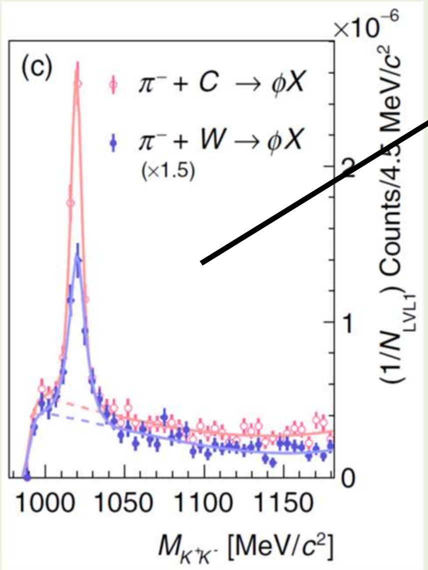
★ Violation of energy or momentum conservation when mass shifted particles leave the dense medium

→ 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:

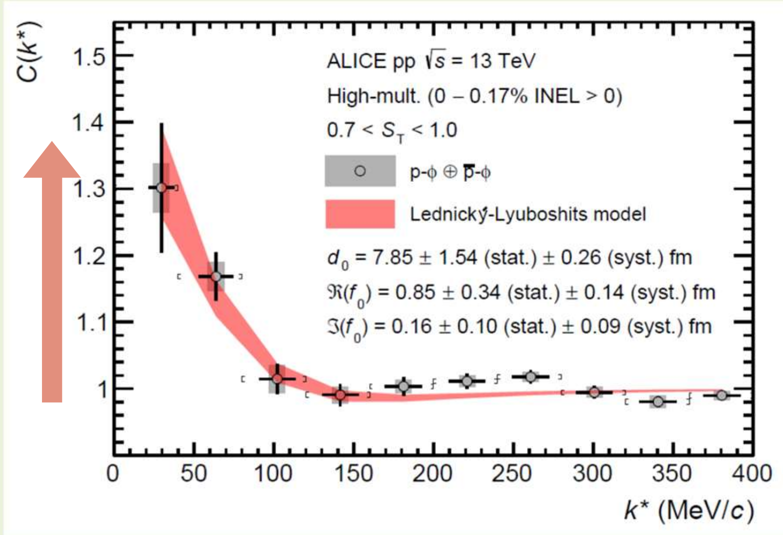
- **Attractive ϕ-nucleus potential: -(50 - 100) MeV**
- **Small imaginary part: 20 – 25 MeV**

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).

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

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

$$\begin{aligned} V_\phi(\rho) &= -\frac{2\pi}{m_\phi}\rho\Big(1+\frac{m_\phi}{m_N}\Big)a_0 \\ &\simeq -85\frac{\rho}{\rho_0}\Big(\frac{a_0}{\mathrm{fm}}\Big)\,\mathrm{MeV} \end{aligned}$$

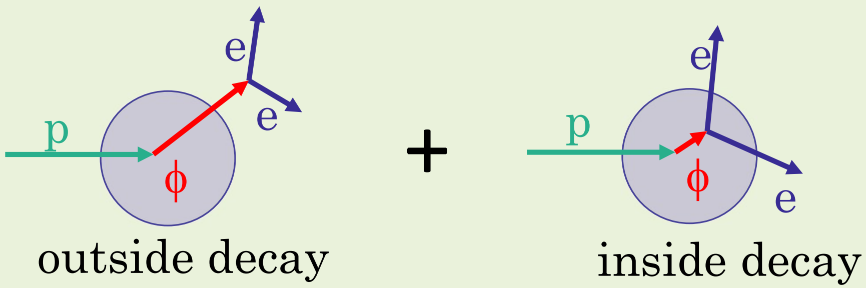
Valid within the linear density approximation

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!

Experimental di-lepton spectrum



= Experimentally observed spectrum