The phi-N and phi-nucleus interaction from theory and experiment

Philipp Gubler (JAEA)

L.M. Abreu, P. Gubler, K.P. Khemchandani, A. Martínez Torres and A. Hosaka, Phys. Lett. B **860**, 139175 (2025).
P. Gubler, M. Ichikawa, T. Song and E. Bratkovskaya, Phys. Rev. C **111**, 034908 (2025).

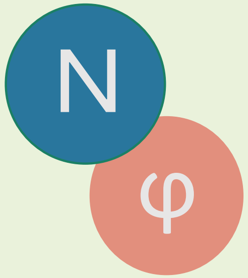
Talk at the "YITP International Workshop on Hadron in Nucleus (HIN2025)",
Yukawa Institute for Theoretical Physics, Kyoto University, Japan,
April 2, 2025

Work done in collaboration with:

L.M. Abreu (U. Federal da Bahia)
K.P. Khemchandani (U. F. de Sao Paulo)
A. Martínez Torres (U. de Sao Paulo)
A. Hosaka (Osaka U./RCNP)
M. Ichikawa (JAEA)
T. Song (GSI)
E. Bratkovskaya (Goethe U. Frankfurt)

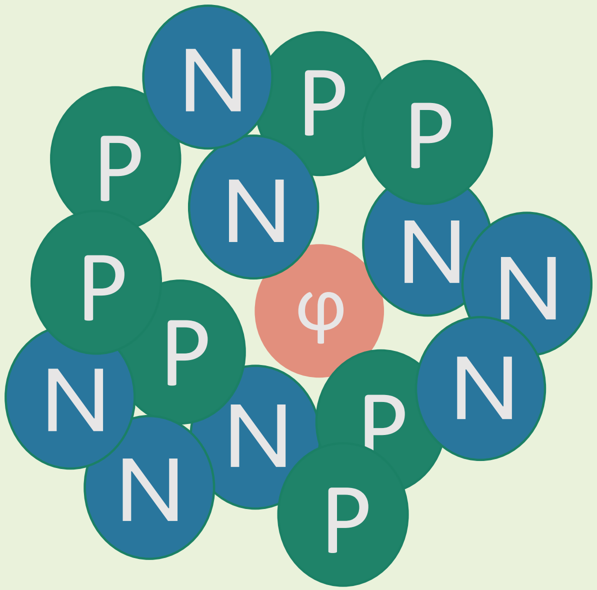
Topics of this talk

1.

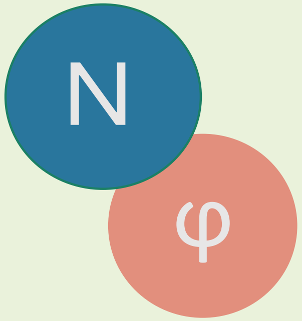


How attractive is this interaction?

2.



How can it be generated from pA collisions?

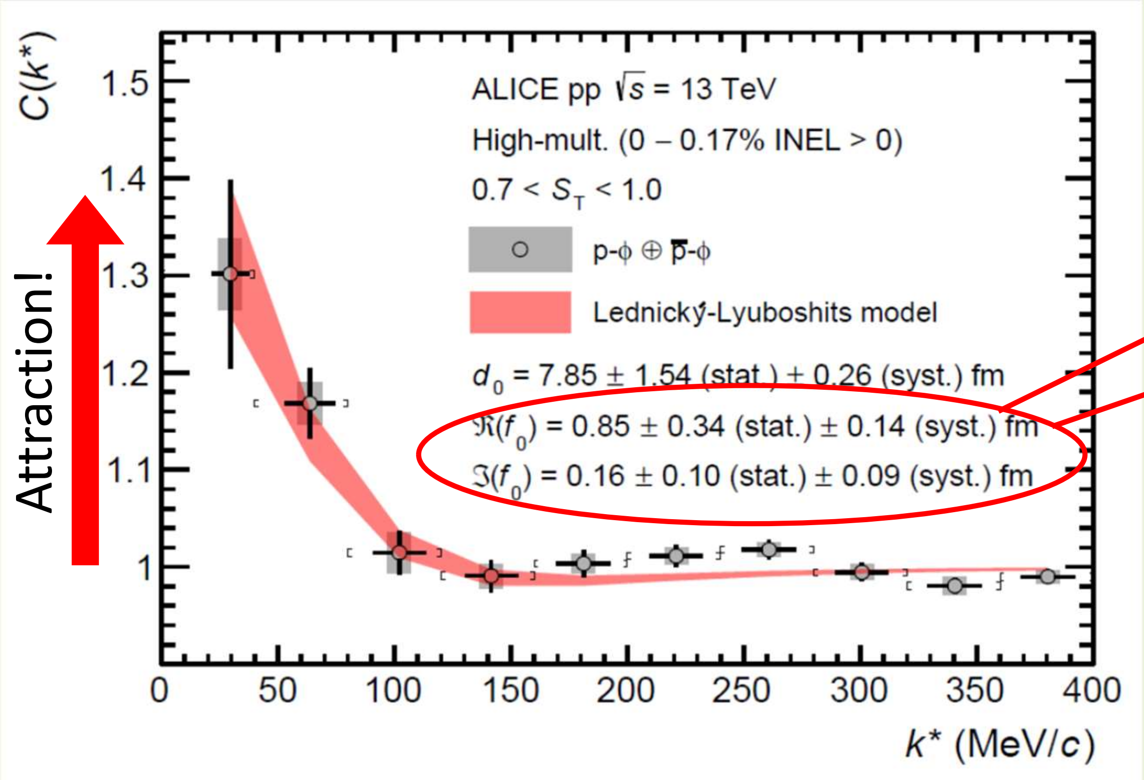


How strong is this interaction?

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



★ Strongly attractive

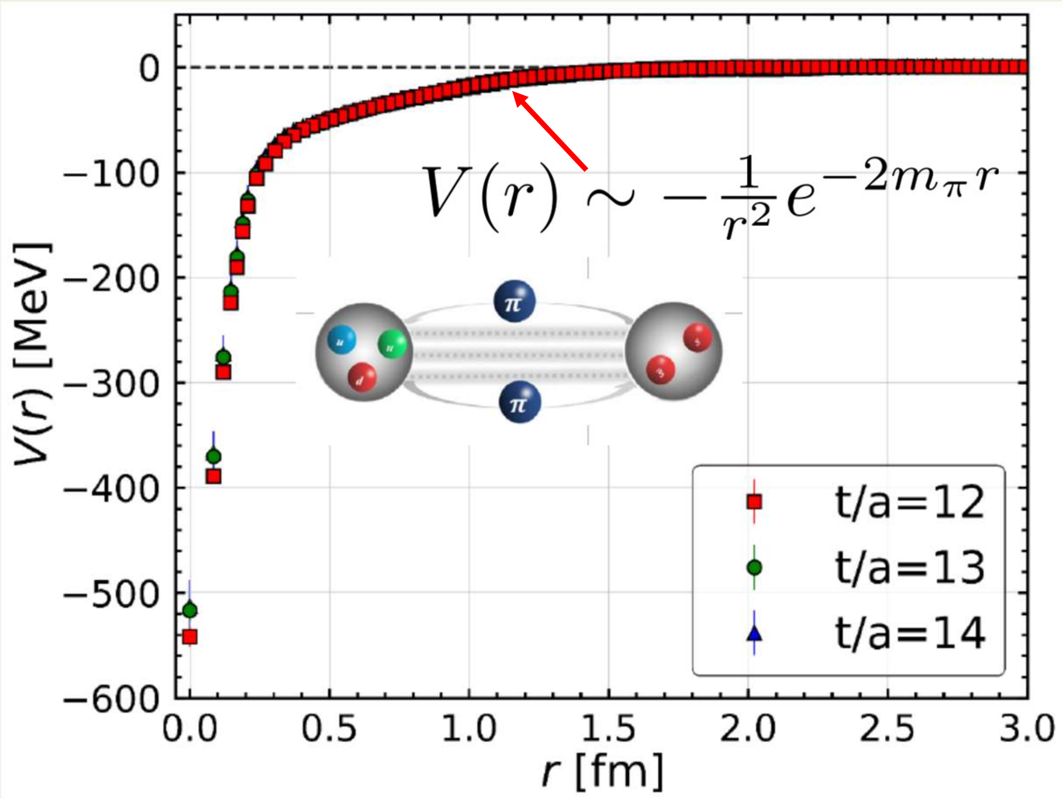
★ Small absorption

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

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

φN potential from HAL QCD

Spin 3/2 channel

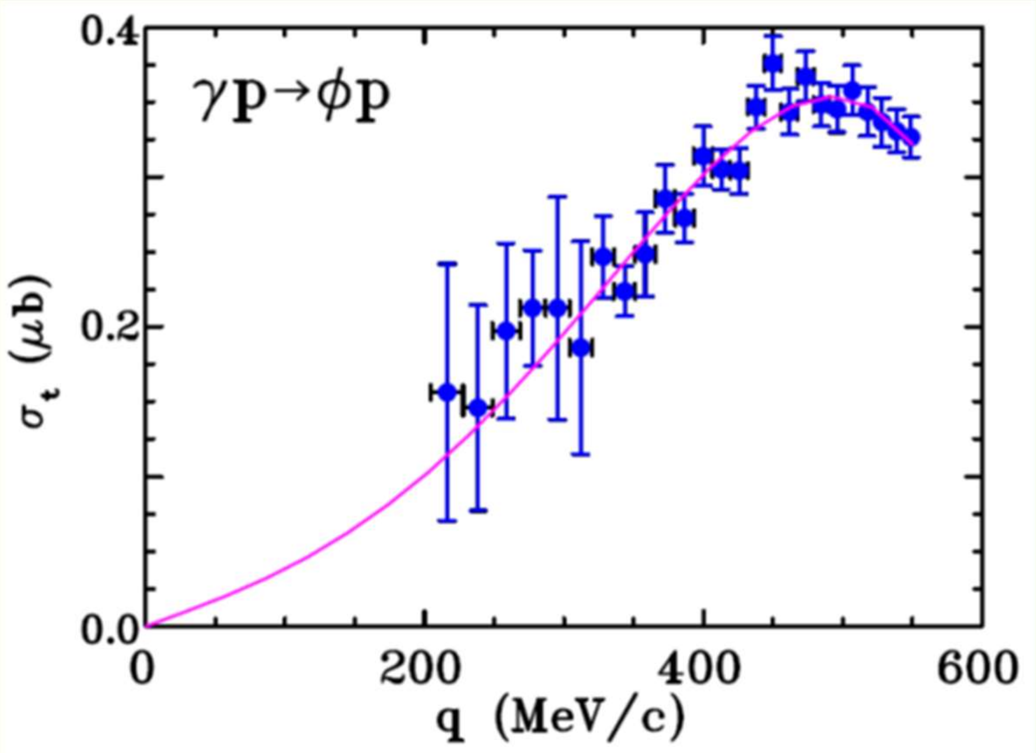


$$a_0^{3/2} = 1.43(23)_{\text{stat.}} \left(^{+36}_{-06}\right)_{\text{syst.}} \text{ fm}$$

Indication for a quite strong and attractive interaction!

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

Photoproduction measurement (CLAS)



Vector meson dominance is assumed

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

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

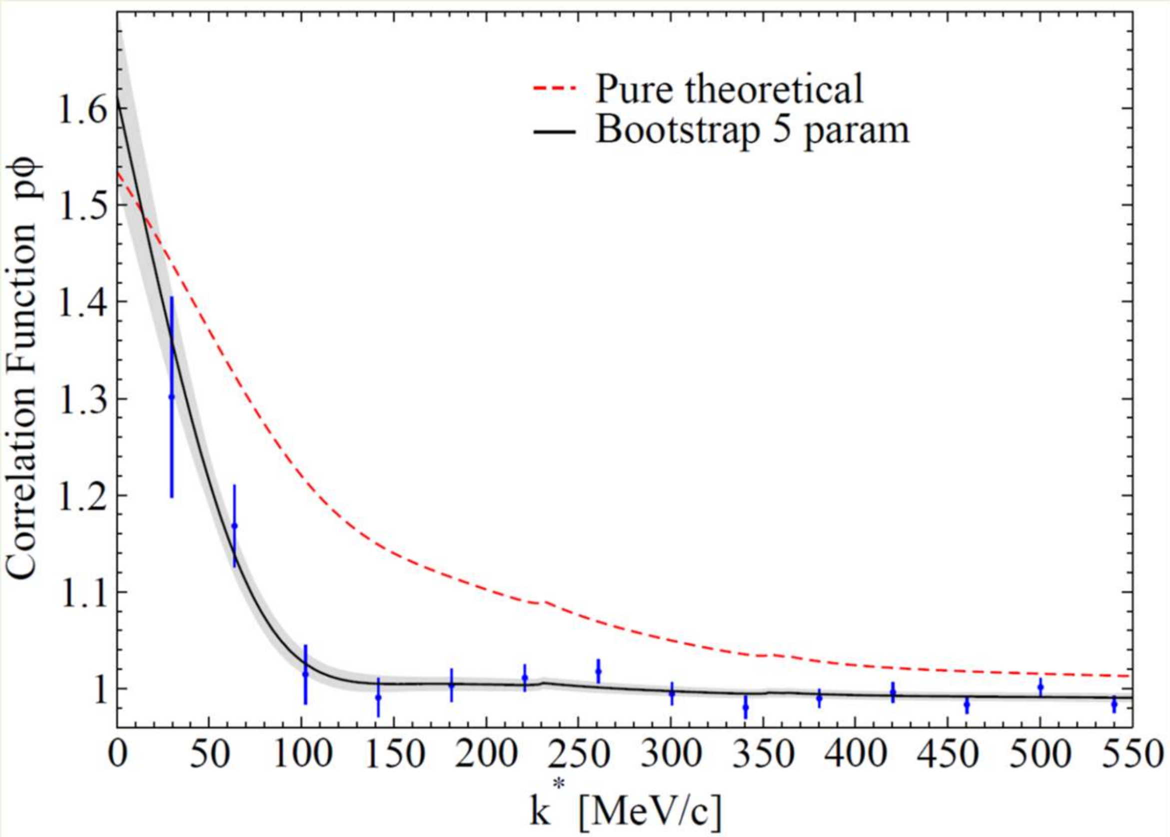
$$|a_0| = 0.063 \pm 0.010\,\mathrm{fm}$$

Consistent with weak φN interaction

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

New analysis of the ALICE data

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



Coupled channel approach (based on the hidden gauge formalism), with subtraction constants as fittable parameters:

	Pure theoretical	Bootstrap
$a_{\rho N}$	−2 (fixed)	−2 (fixed)
$a_{\omega N}$	−2 (fixed)	−3.04 ± 0.73
$a_{\phi N}$	−2 (fixed)	−3.15 ± 0.37
$a_{K^*\Lambda}$	−2 (fixed)	−1.98 ± 0.08
$a_{K^*\Sigma}$	−2 (fixed)	−1.95 ± 0.08
N_D	1 (fixed)	0.988 ± 0.004

New analysis of the ALICE data

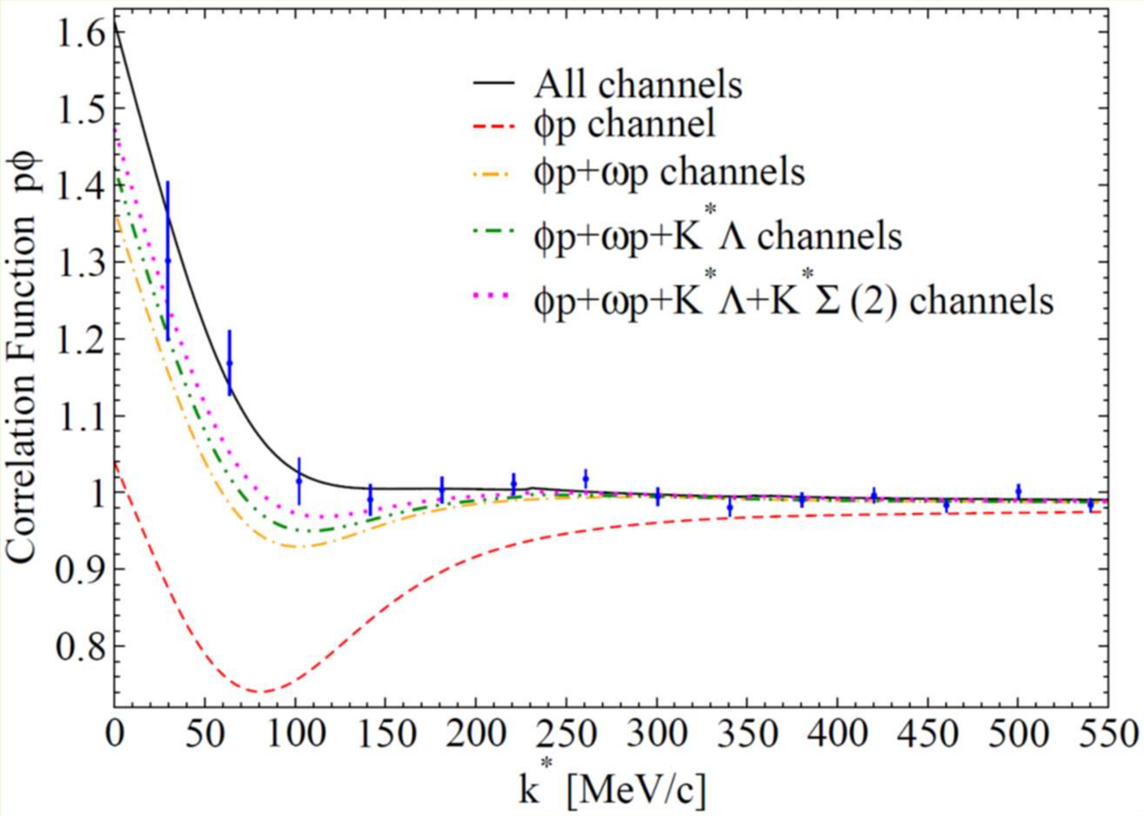
A. Feijoo, M. Korwieser and L. Fabbietti, Phys. Rev. D **111**, 014009 (2025).

Obtained scattering length and effective range

Table 5: Effective range, r_{eff} (fm), and scattering length, a_0 (fm), for the ϕp and ρ^0p channels.

	Pure theoretical	Bootstrap
$a_0^{\phi p}$	$0.272 + i\,0.189$	$(-0.034 \pm 0.035) + i\,(0.57 \pm 0.09)$
$r_{eff}^{\phi p}$	$-7.20 - i\,0.09$	$(-8.06 \pm 2.57) + i\,(0.05 \pm 0.53)$
$a_0^{\rho^0 p}$	$0.090 + i\,0.568$	$(0.09 \pm 0.03) + i\,(0.56 \pm 0.05)$
$r_{eff}^{\rho^0 p}$	$-3.01 + i\,98.39$	$(-3.05 \pm 0.28) + i\,(98.40 \pm 0.12)$

Decomposition into different hadronic channels



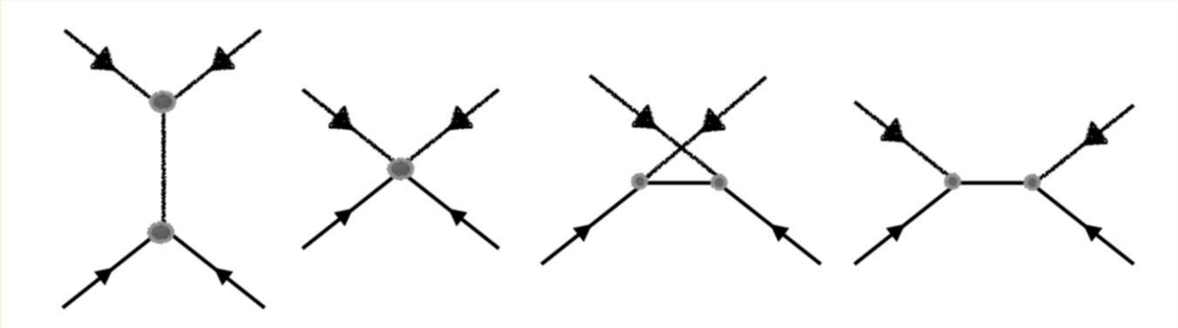
An even newer analysis of the ALICE data

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

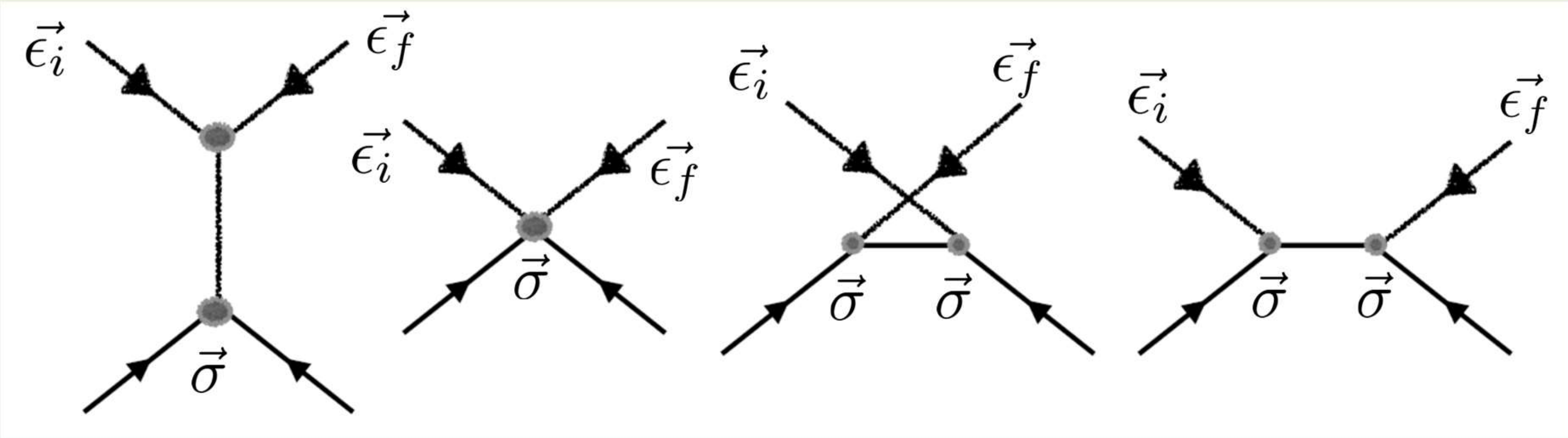
Starting point:
Hadronic Meson-Baryon interaction Lagrangian

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

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



Crucial ingredient: spin dependent vector meson-baryon interactions



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

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

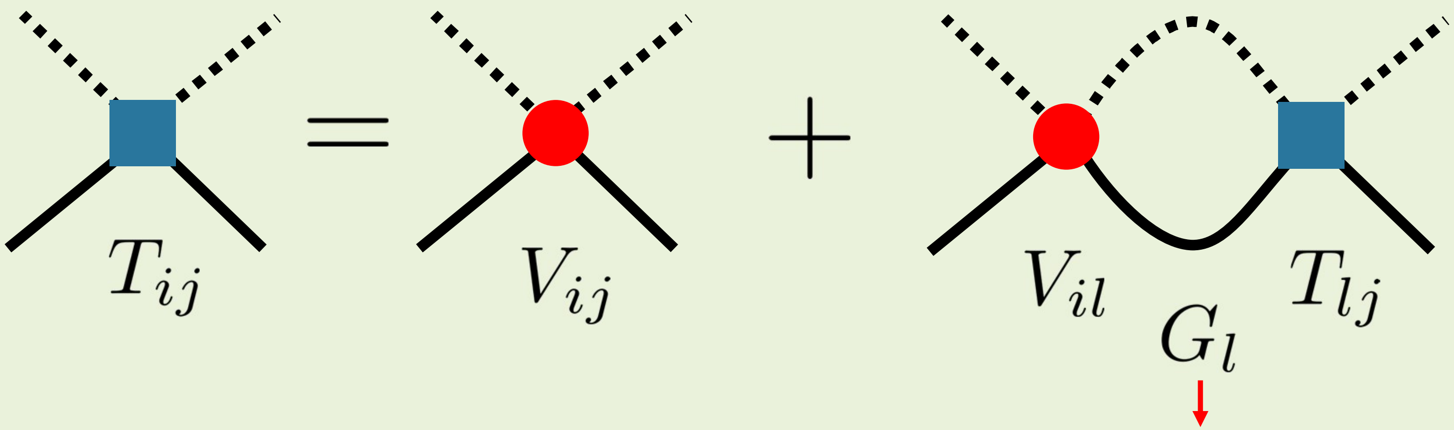
Considered so far
in Feijoo et al.

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

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



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

Emergence of subtraction constants, which are parameters of the model

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:

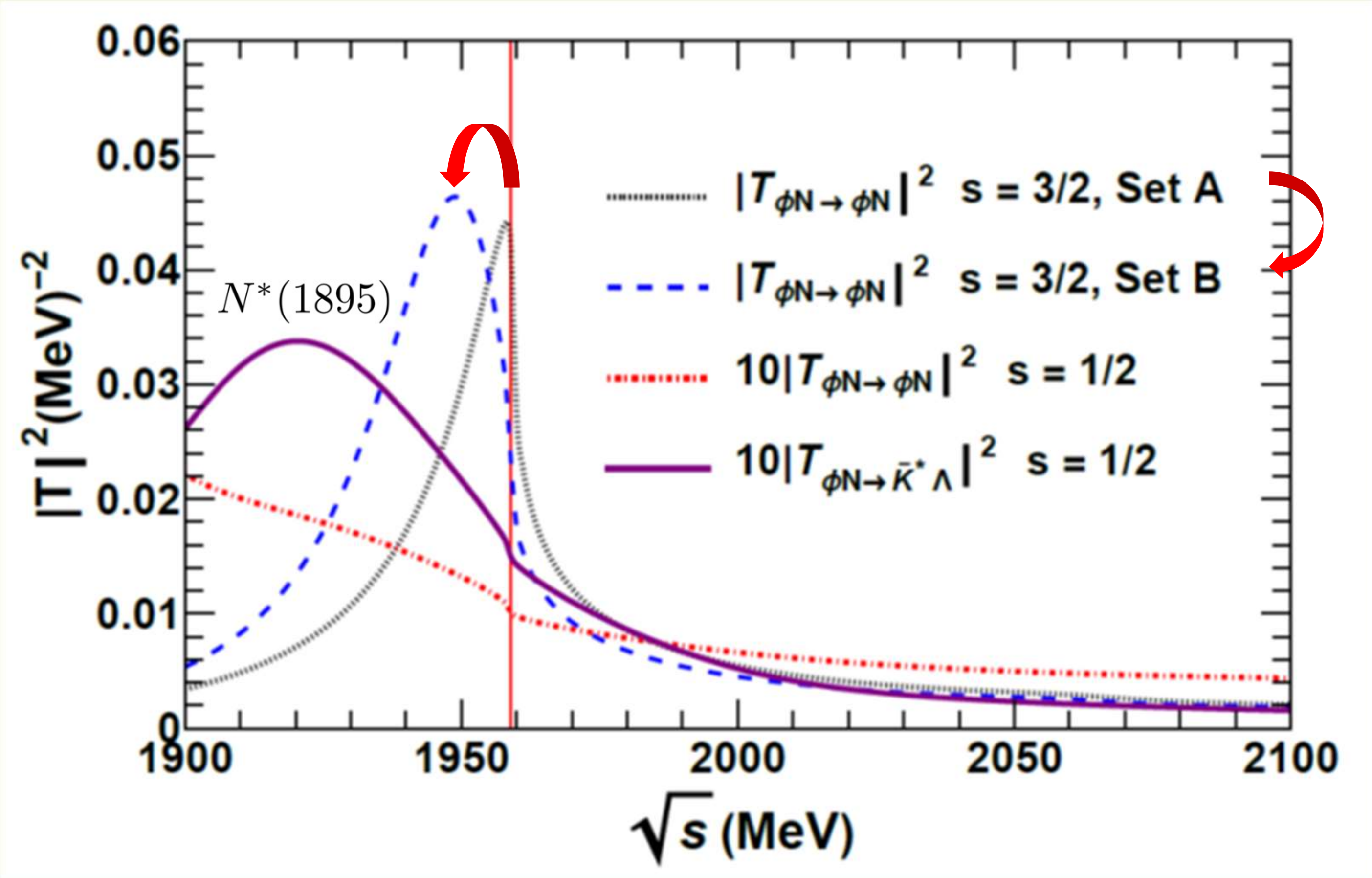
Channel (i)	a_i (Set A)	a_i (Set B)
ρN	-2.0	-2.0
ωN	-2.0	-2.0
ϕN	-1.7	-2.0
$K^*\Lambda$	-2.1	-2.1
$K^*\Sigma$	-2.0	-2.0

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 scattering amplitudes

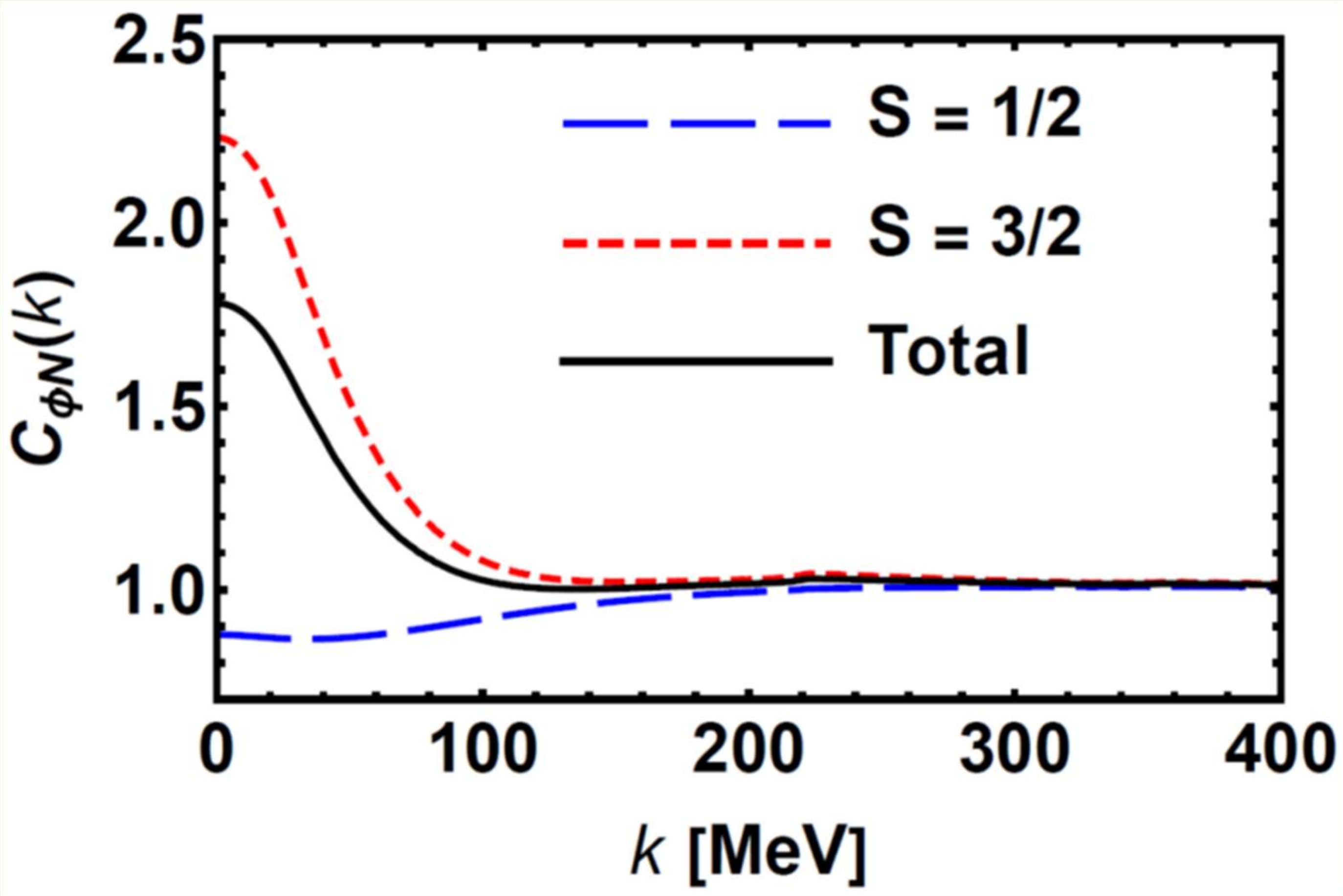


★ For spin 3/2, a state below the φN threshold can be found, depending on the values of the subtraction constants.
However, above the threshold, the differences between the two cases are small.

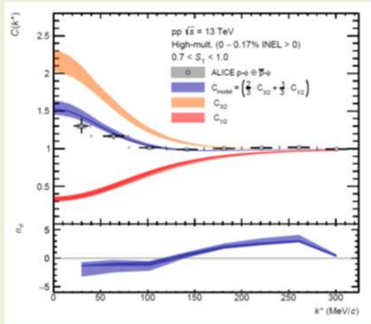
★ The spin 1/2 scattering amplitudes are much weaker than their spin 3/2 counterparts

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)

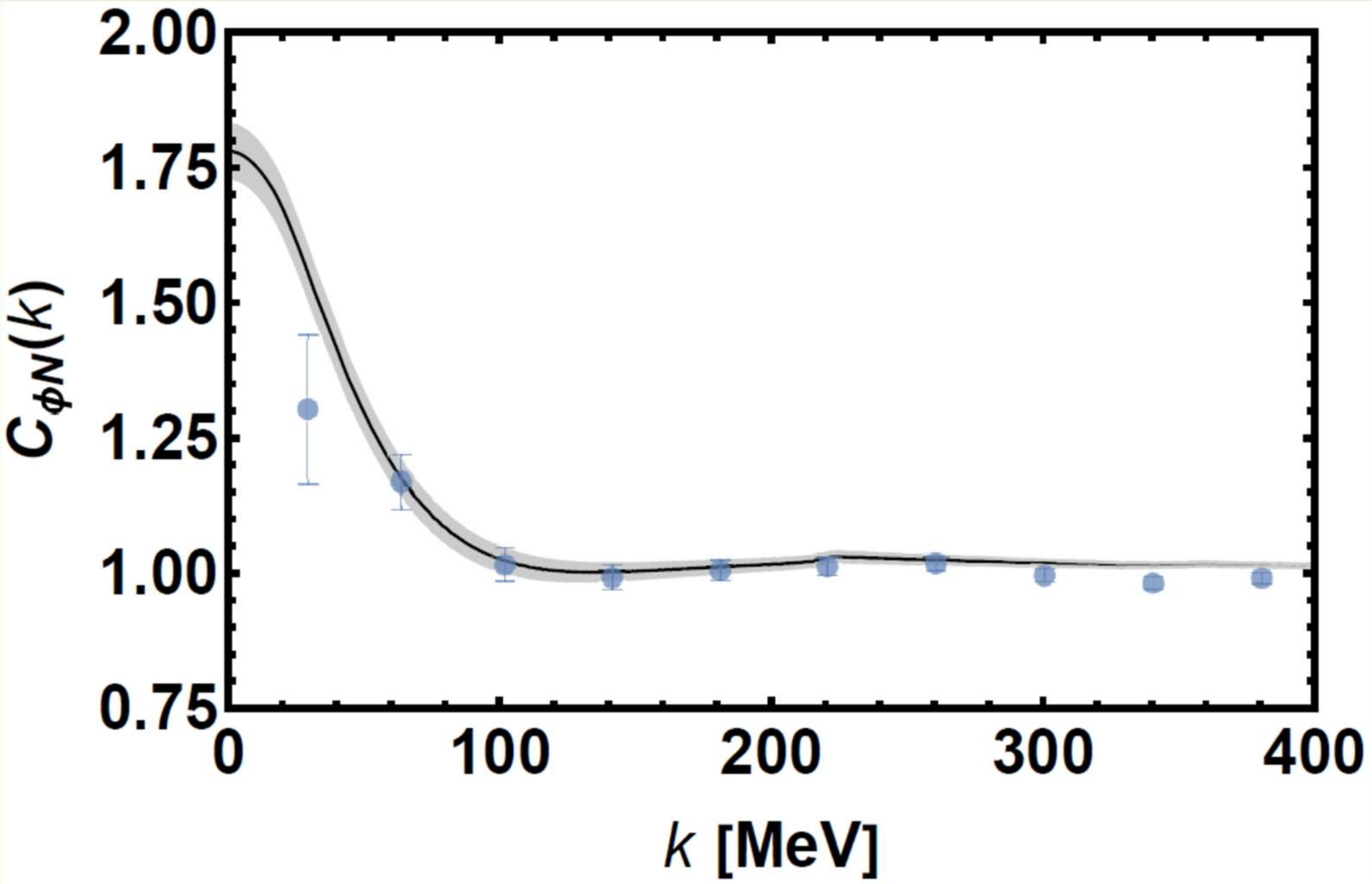


Qualitatively similar to
E. Chizzali et al.,
Phys. Lett. B **848**, 138358 (2024).



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

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!

Correlation function is not very sensitive to the scattering length

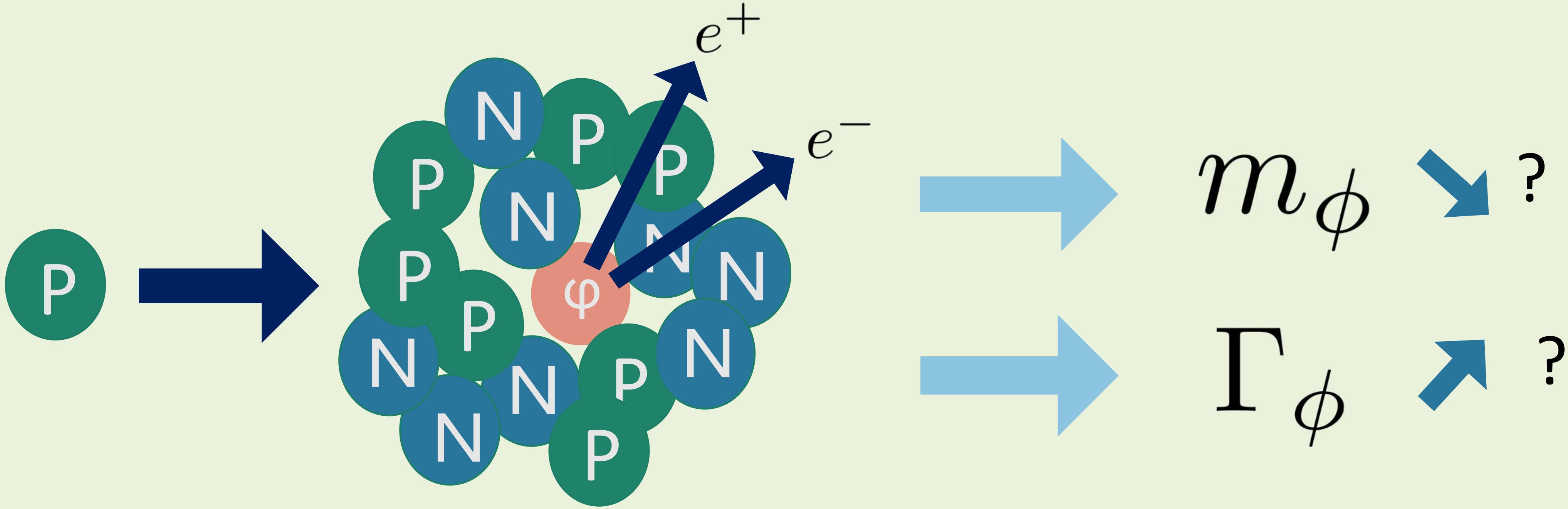
Comparison to mass shift in nuclear matter

$$V_\phi(\rho) = -\frac{2\pi}{m_\phi}\rho\left(1 + \frac{m_\phi}{m_N}\right)a_0$$

$$\simeq -85\frac{\rho}{\rho_0}\left(\frac{a_0}{\text{fm}}\right)\text{ MeV}$$

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

Dilepton spectrum from pA reaction

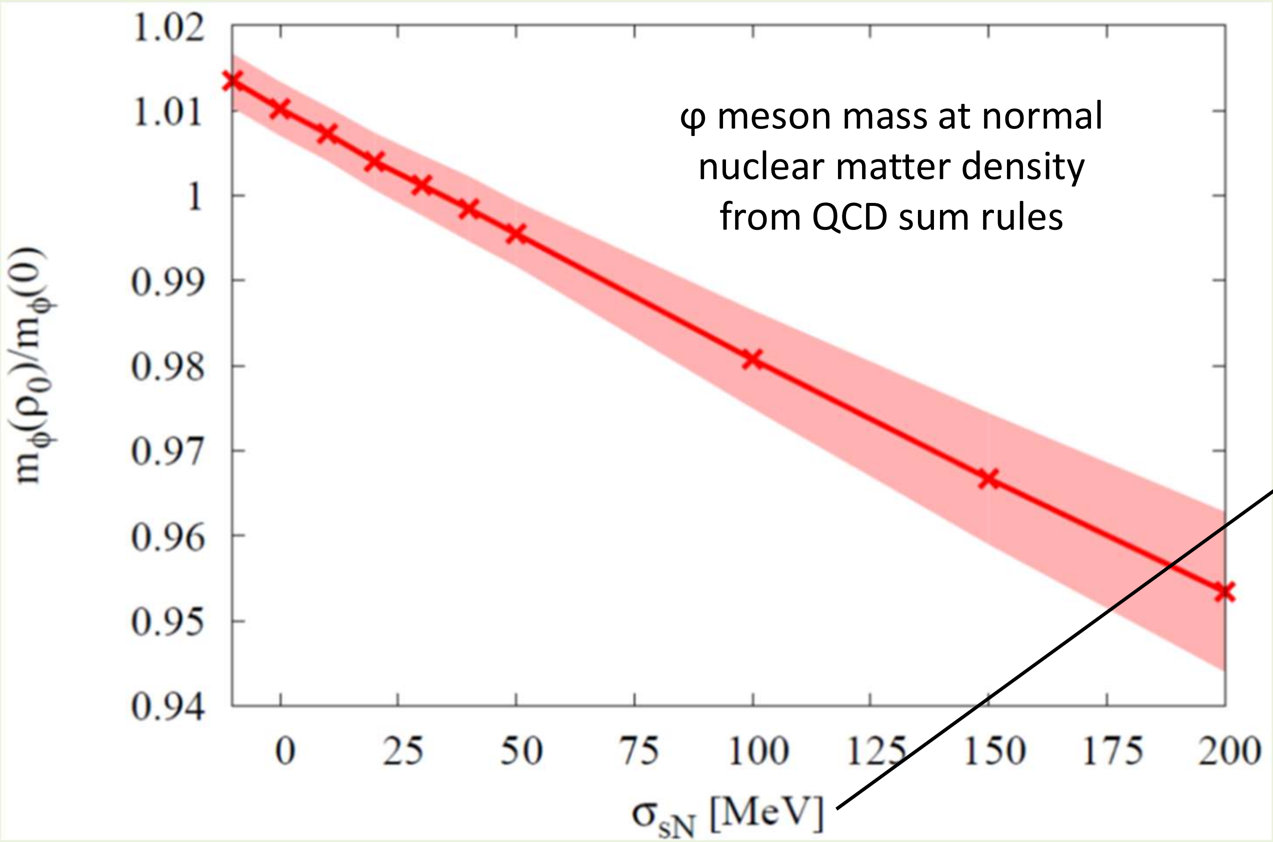


P. Gubler, M. Ichikawa, T. Song and E. Bratkovskaya, Phys. Rev. C **111**, 034908 (2025).

For more, see the talk by Masaya Ichikawa on Friday, April 4, 11.30

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).

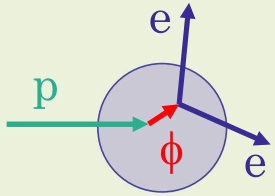
T. Hatsuda and S.H. Lee, Phys. Rev. C **46**, R34 (1992).

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

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

Previous experimental results

KEK
E325



12 GeV
pA-reaction

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

$k_1 = 0.034 \pm 0.007$

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

$k_2 = 2.6 \pm 1.5$

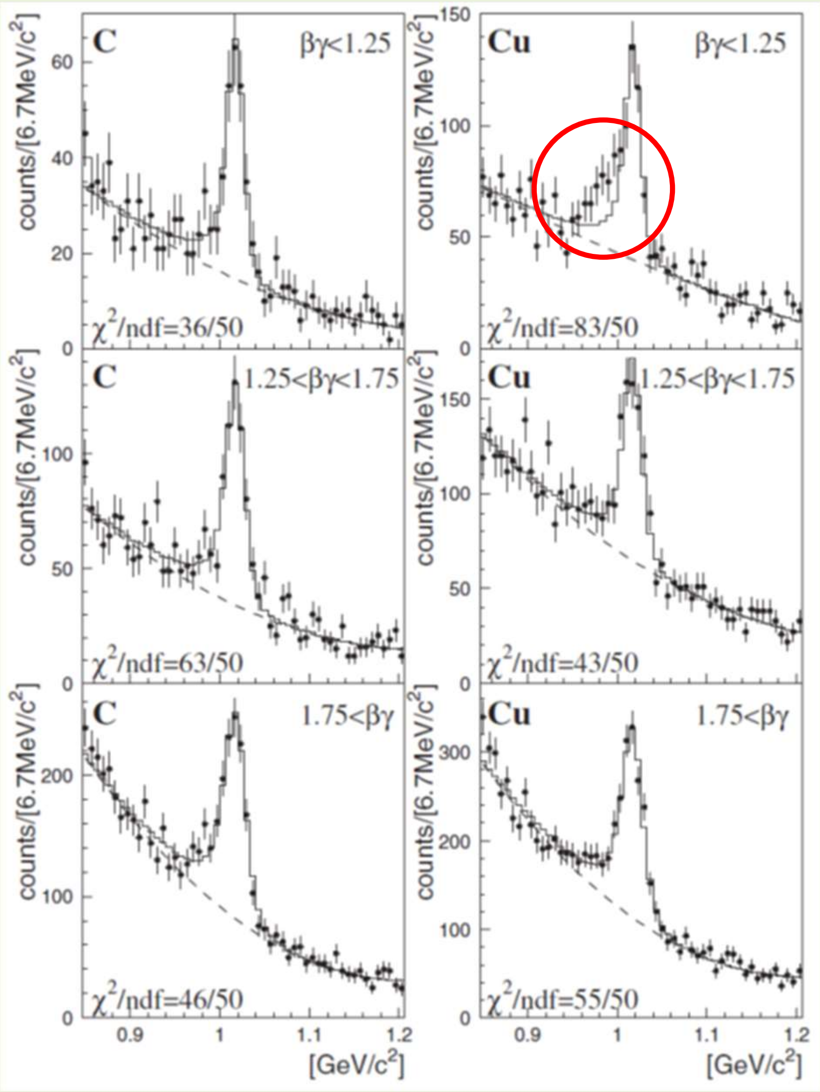
Measurement is being repeated with
~100x increased statistics at the
J-PARC E16 experiment!

slow φs

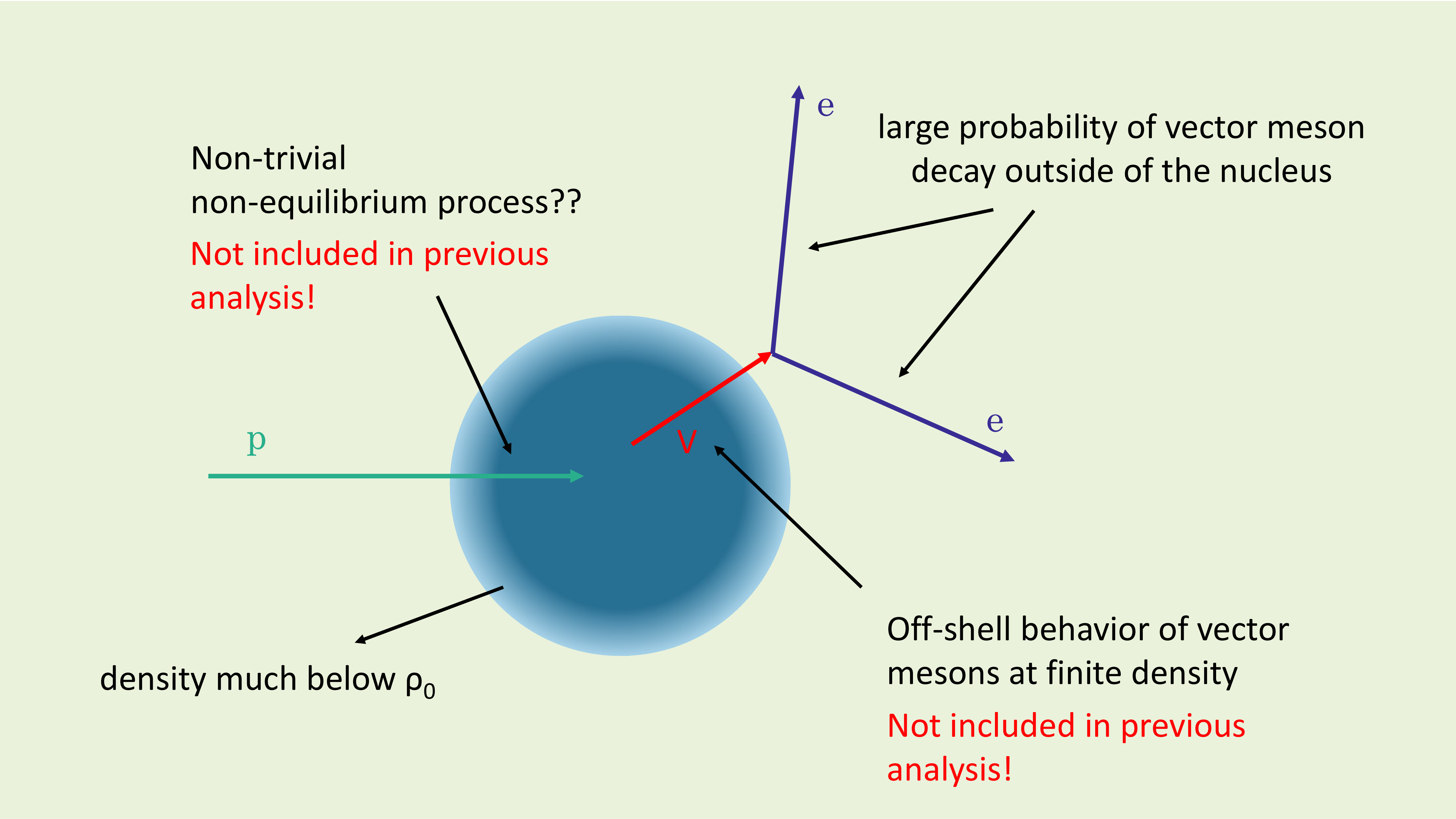
intermediate φs

fast φs

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



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


e
large probability of vector meson decay outside of the nucleus
Non-trivial
non-equilibrium process??
Not included in previous analysis!
p
V
e
density much below ρ0
Off-shell behavior of vector mesons at finite density
Not included in previous analysis!

Our tool: transport simulation
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).

Off-shell dynamics of vector mesons and kaons
(dynamical modification of the mesonic spectral function during the simulated reaction)

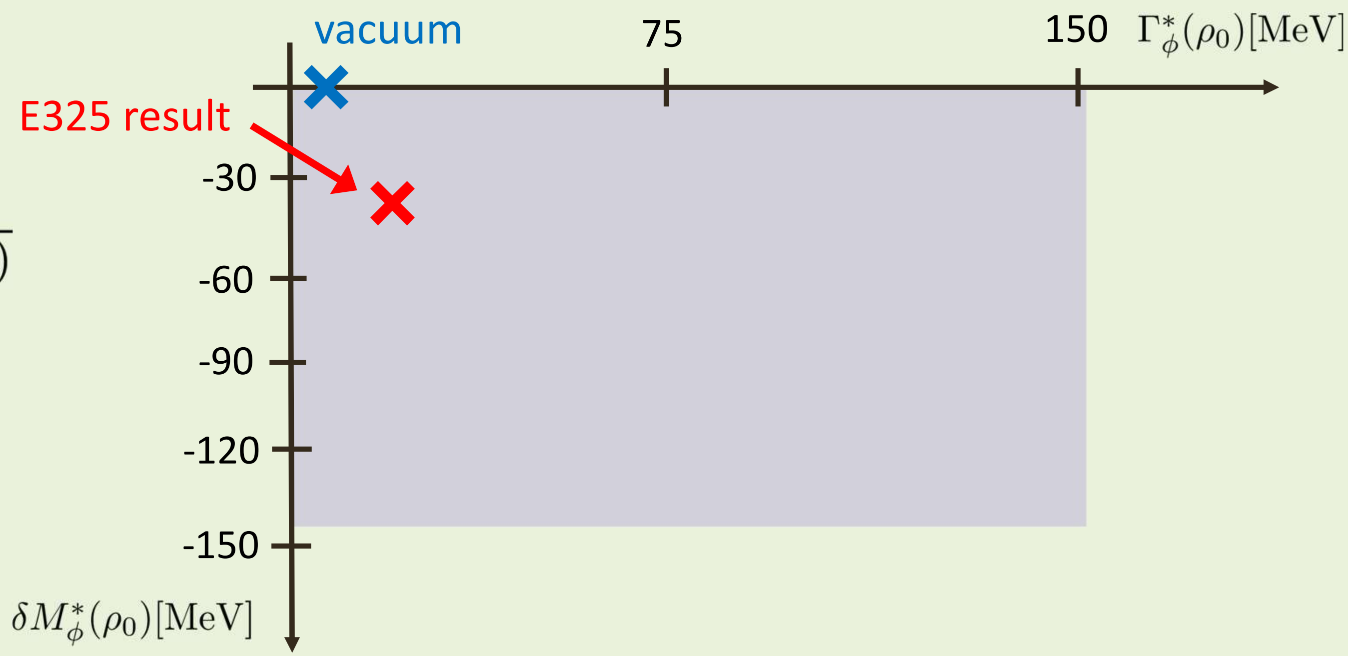
Used spectral function:
Relativistic Breit-Wigner with density dependent mass and width

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

with

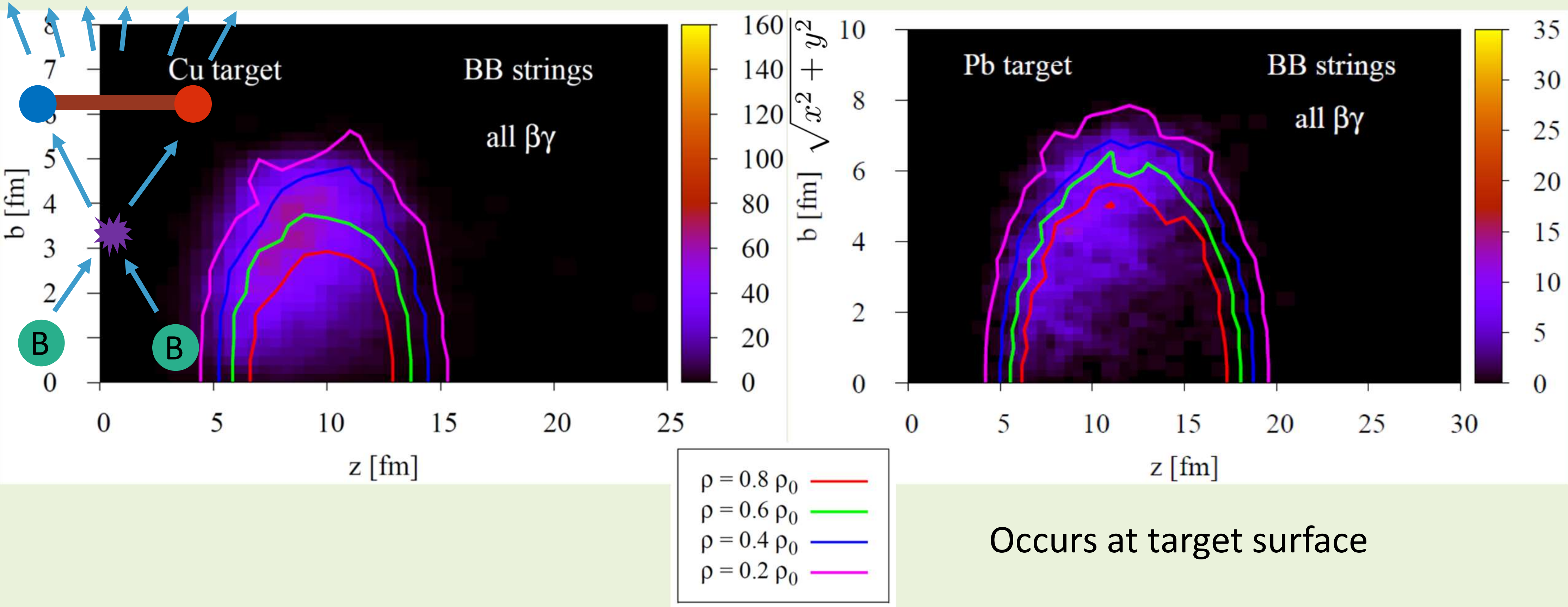
$$\begin{cases} M^*_\phi(\rho) = M^{\text{vac}}_\phi\left(1-\alpha^\phi\frac{\rho}{\rho_0}\right), \\ \Gamma^*_\phi(M,\rho) = \Gamma^{\text{vac}}_\phi + \alpha^\phi_{\text{coll}}\frac{\rho}{\rho_0} \end{cases}$$

Simulated scenarios:



How are φ mesons produced in 12 GeV pA collisions?

Production through initial high-energy collisions (via strings)

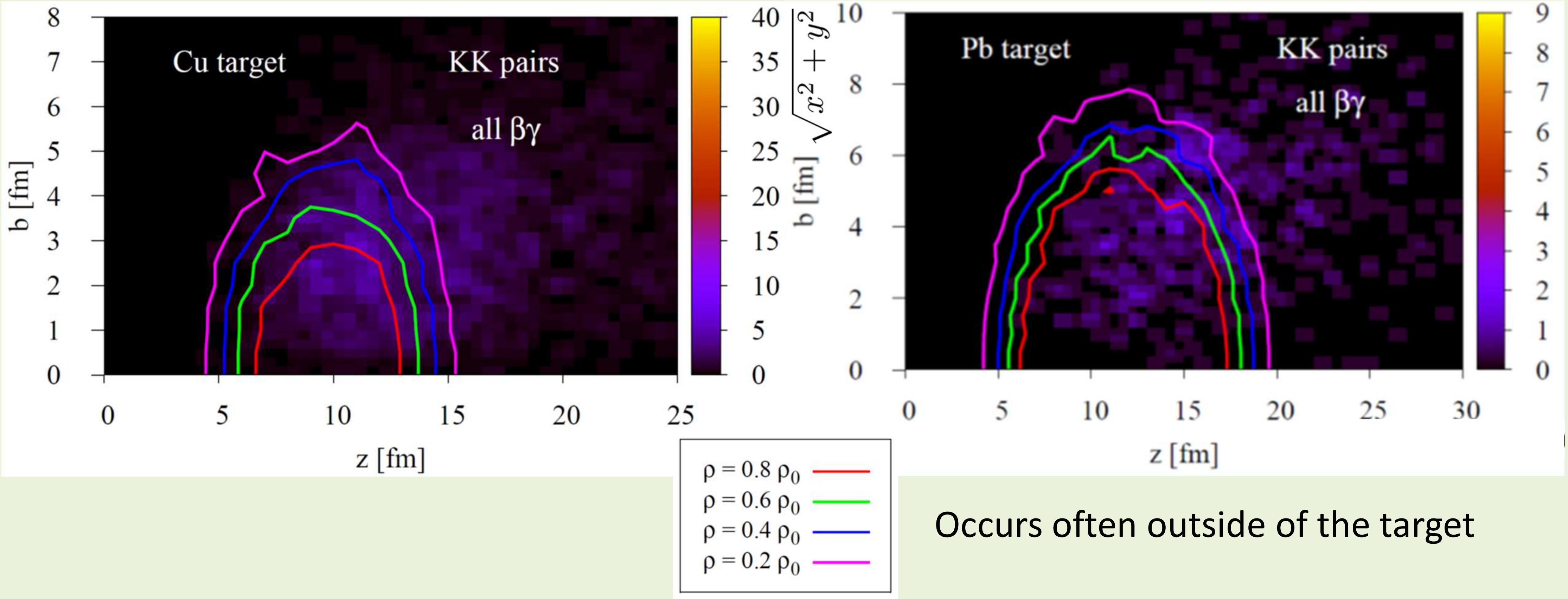


Occurs at target surface

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

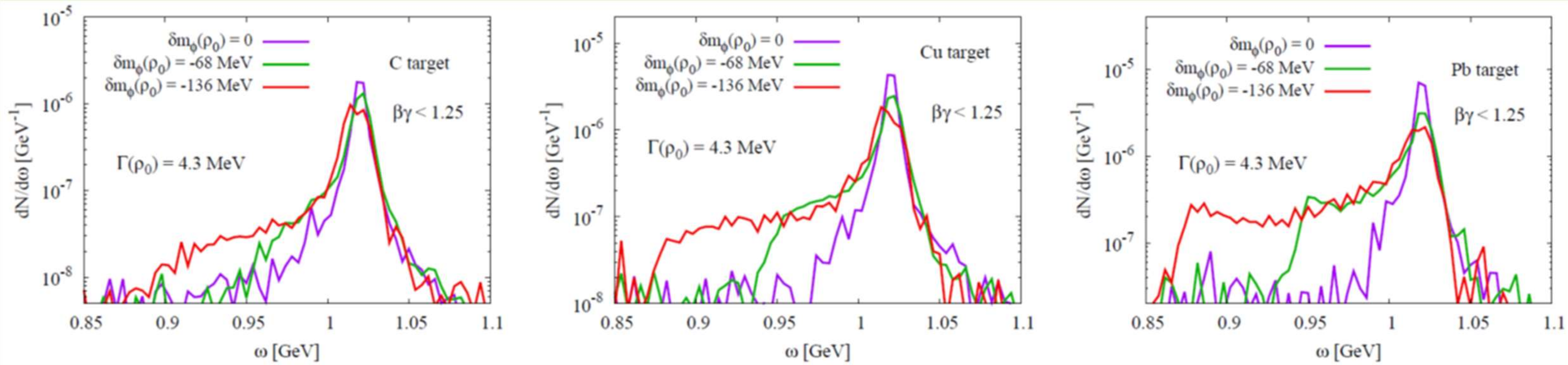


Occurs often outside of the target

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)

For the direct comparison with experimental data, see Masaya's talk!

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

Summary and conclusions

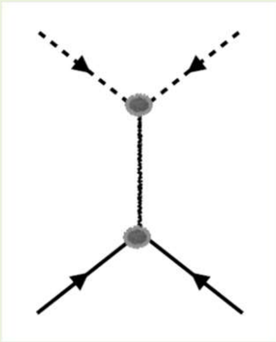
★ A lot of new theoretical and experimental information about the φN interaction is becoming available (LHC, HAL QCD) → **Strong hadronic medium effect?**

★ Several works have by now studied the ALICE Correlation Function data, but the results largely disagree → **Need better data?** **More reliable theory?**

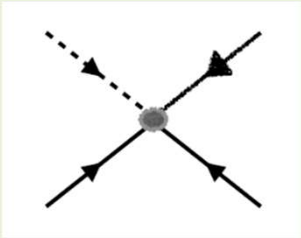
★ With the state-of-the-art PHSD transport approach, we can now study pA reactions more reliably → **Many opportunities for new studies and projects!**

Backup slides

2) Pseudoscalar Meson-Baryon interaction: Based on lowest order chiral Lagrangian



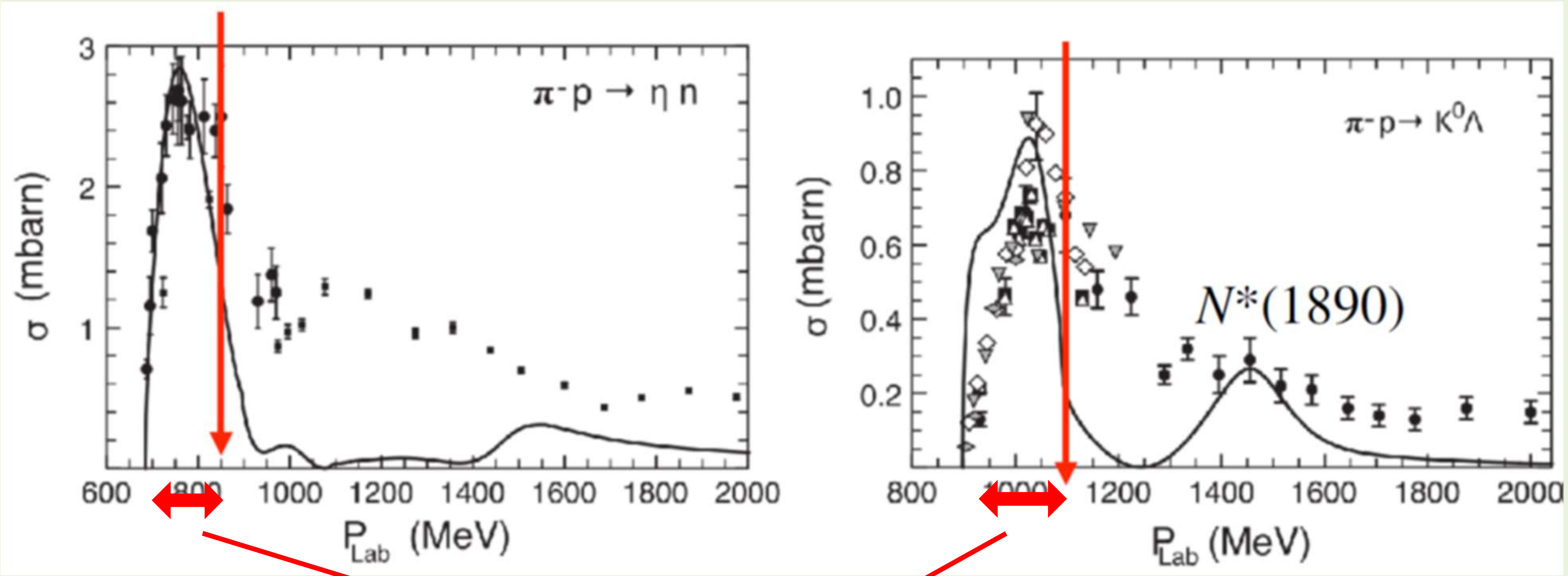
3) Transition between Pseudoscalar and Vector Mesons: Treating Vector meson as gauge boson in nonlinear sigma model (pion photoproduction + vector meson dominance)



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

Next step:
If possible, determine the parameters (subtraction constants) of the model from experimental data

For the spin 1/2 channel, scattering data are available for constraining the model parameters:



Regions used for the fit

K.P. Khemchandani, A. Martínez Torres, H. Nagahiro and A. Hosaka, Phys. Rev. D **88**, 114016 (2013).

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

Next step:
Calculate the correlation function and compare with the ALICE data

We use a generalized Koonin-Pratt formula:

Scattering amplitudes:
See previous slide

$$C_i(k_i) = 1 + 4\pi\theta(q_{max} - k_i) \int_0^\infty drr^2 S_{12}(\vec{r}) \left(\sum_j w_j |j_0(k_i r)\delta_{ji} + T_{ji}(\sqrt{s})\widetilde{G}_j(r;s)|^2 - j_0^2(k_i r) \right)$$

Source function:
Gaussian with radius of approx. 1 fm

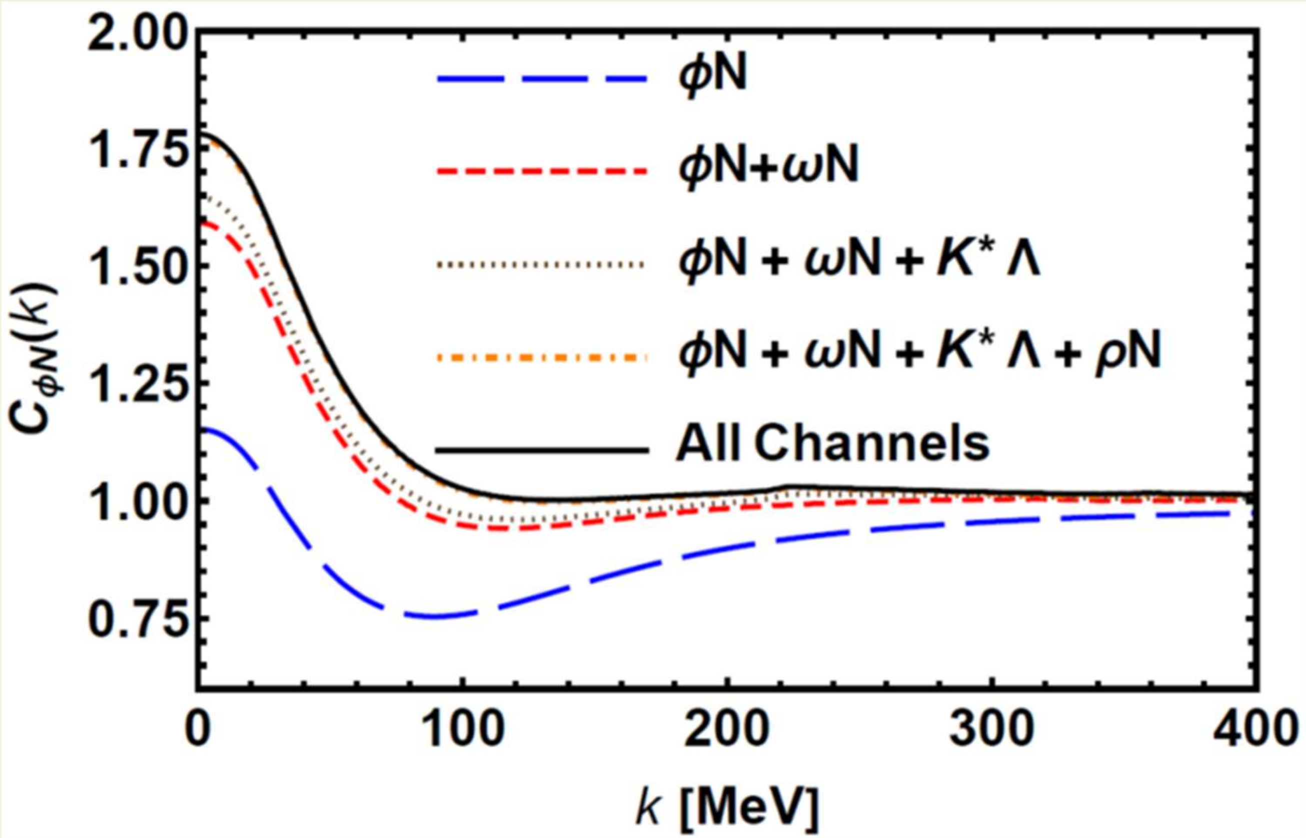
Weights related to the multiplicity of pairs of primary particles created at the initial stage of the collision

j-th channel	$w_j^{(\frac{1}{2})}$	$w_j^{(\frac{3}{2})}$
πN	71	–
ηN	1	–
$K\Lambda$	5	–
$K\Sigma$	5	–
ρN	6.24	6.24
ωN	5.77	5.77
ϕN	1	1
$K^*\Lambda$	0.65	0.65
$K^*\Sigma$	0.42	0.42

Obtained from Thermal-Fist package

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

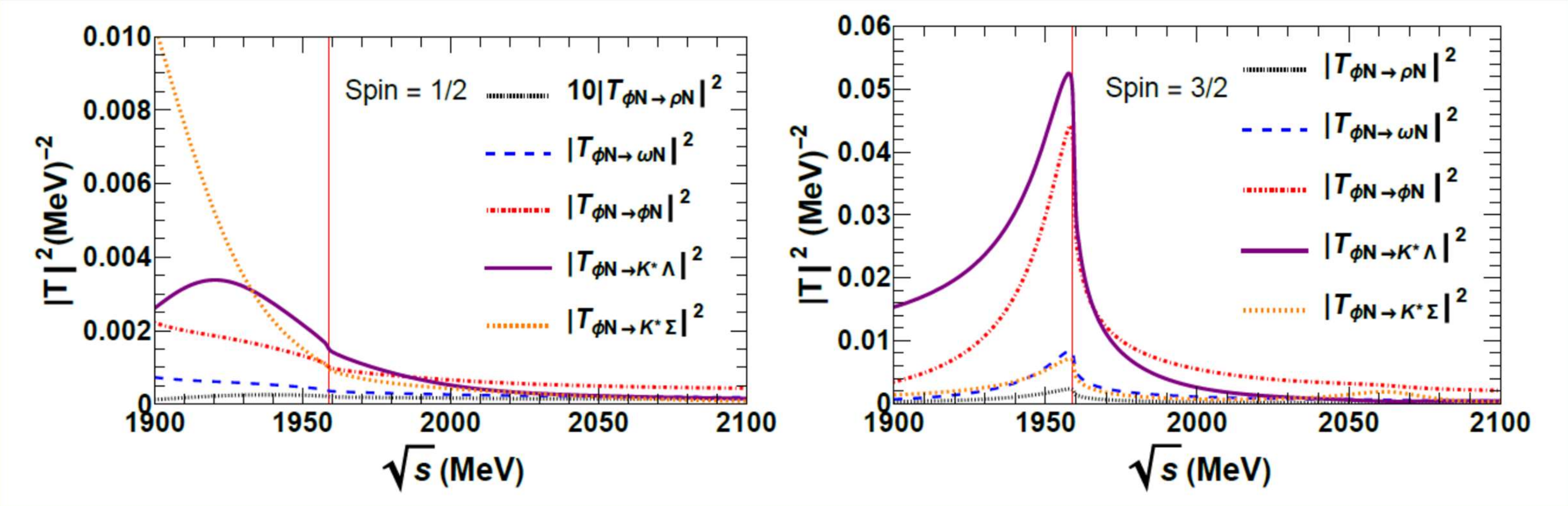
The obtained correlation function (channel decomposed)



Similar to
A. Feijoo et al.,
arXiv:2407.01128 [hep-ph].

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

The scattering amplitudes (channel decomposed)

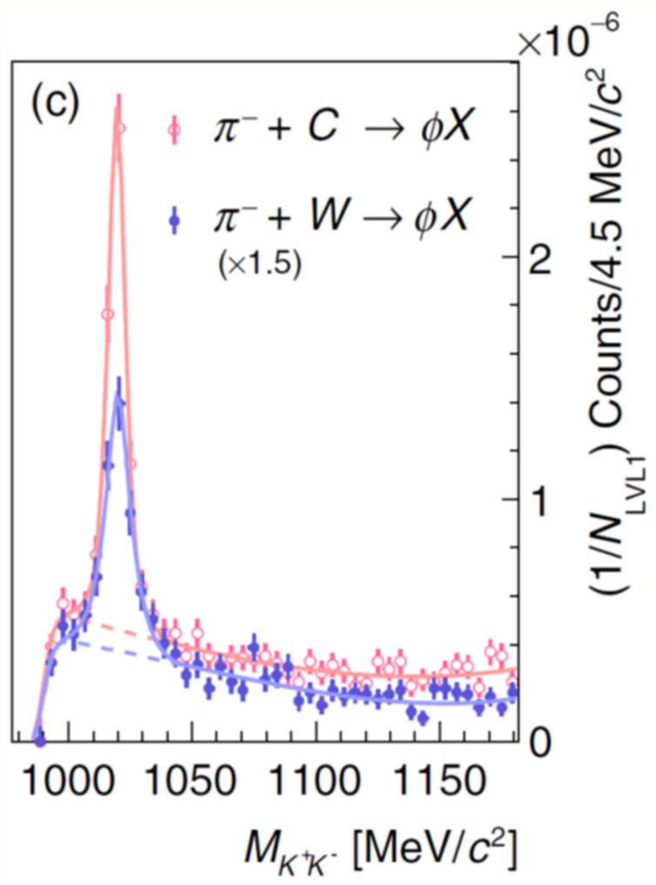


L.M. Abreu, P. Gubler, K.P. Khemchandani, A. Martínez Torres and A. Hosaka, Phys. Lett. B **860**, 139175 (2025).

More recent results

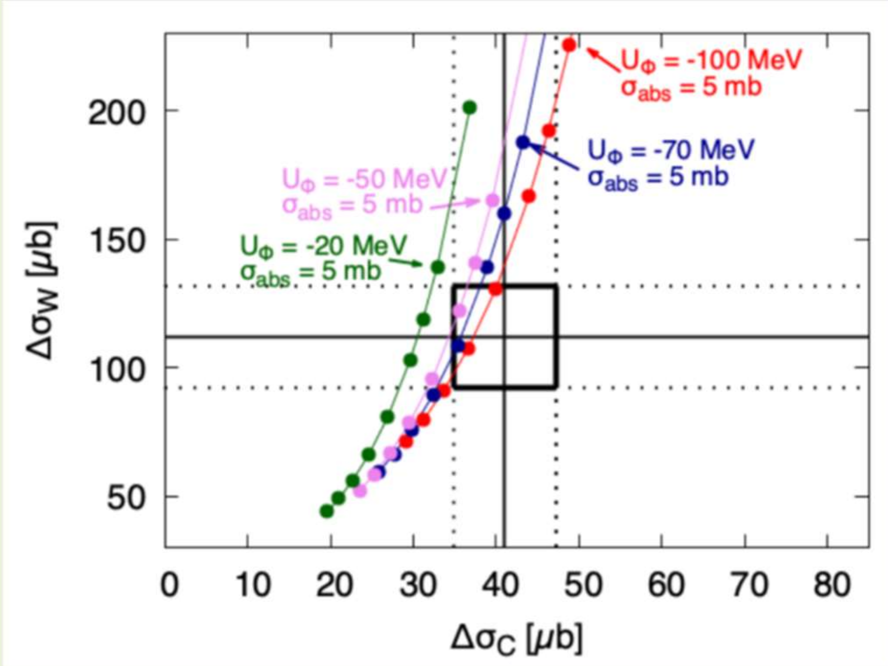
HADES: 1.7 GeV π^-A-reaction

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:

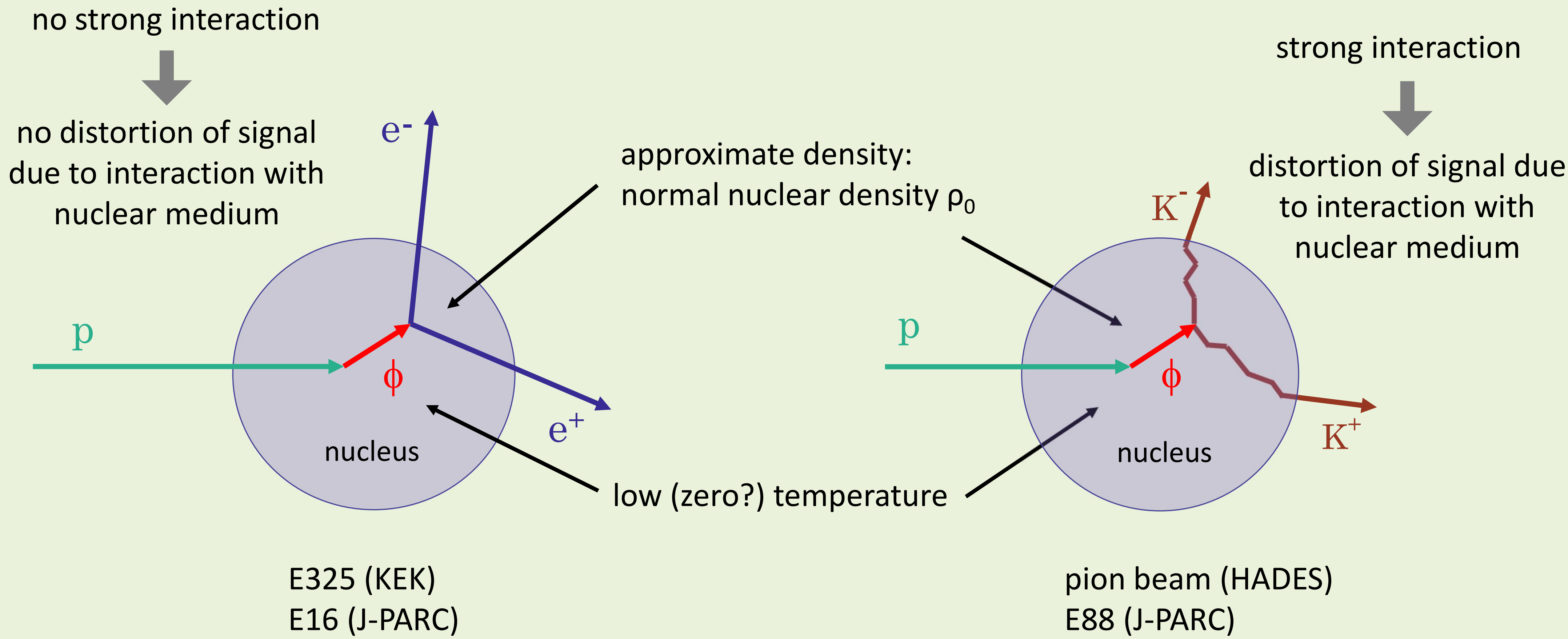


E. Ya. Paryev, Nucl. Phys. A **1032**, 122624 (2023).

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

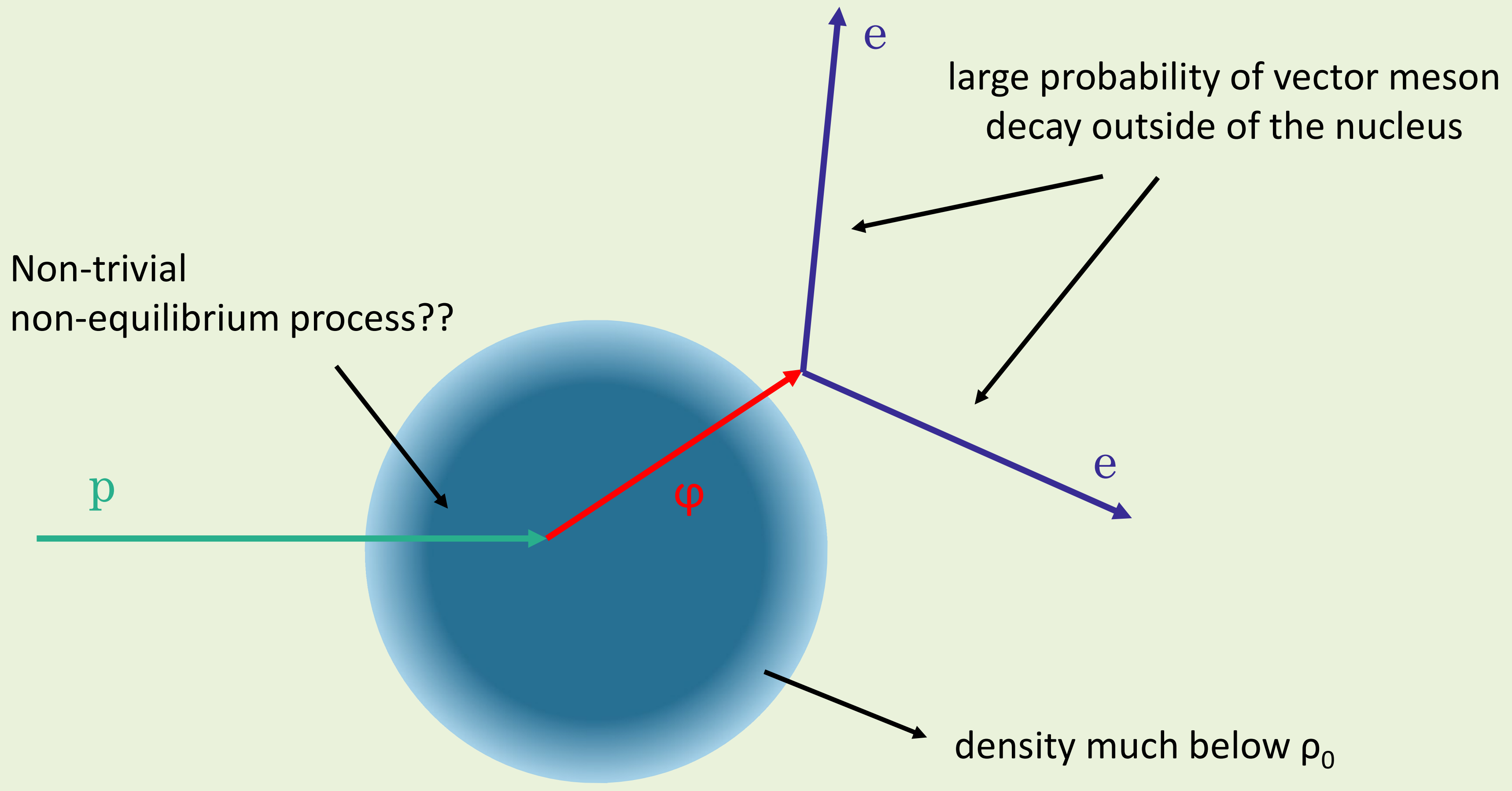
The φ meson in pA collisions

Experiments to be discussed in this talk



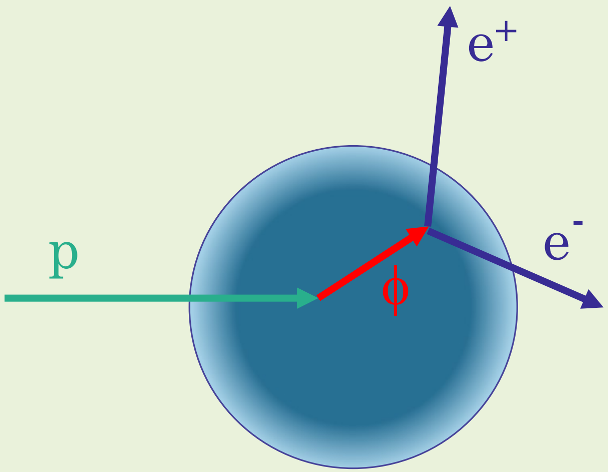
In reality, things are more complicated…

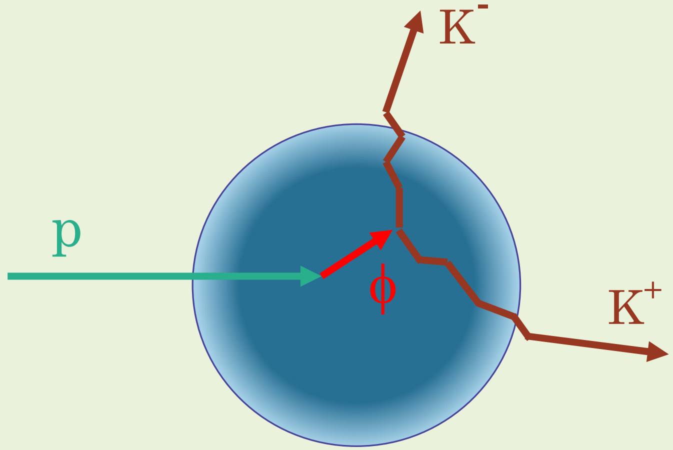
Proton induced generation of vector mesons in nuclei



Further tasks for theory

Have a good understanding of the production mechanisms of the φ mesons in nuclei from pA reactions.





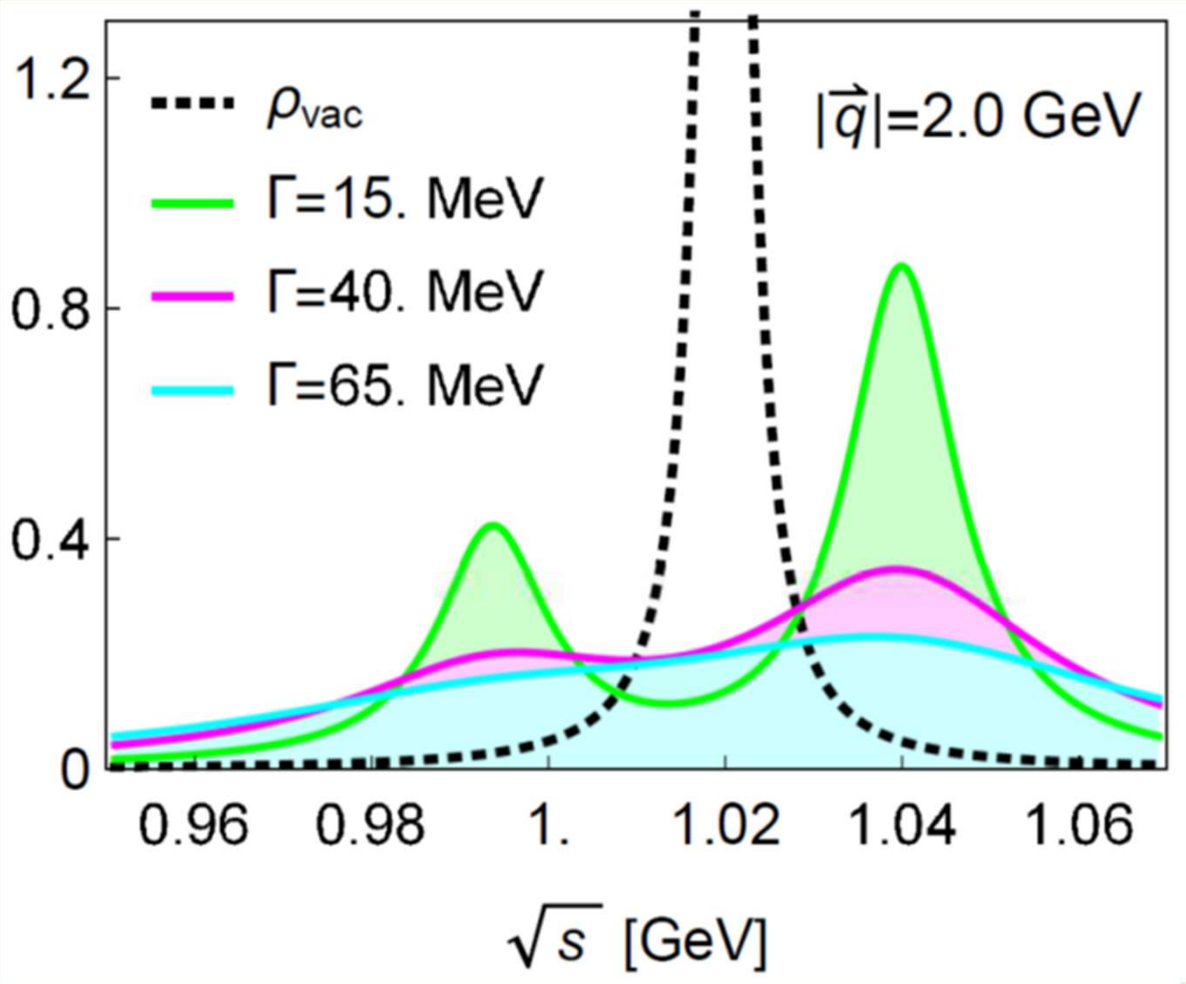
- ★ Where (and at what densities) is the φ meson produced and where does it decay?
- ★ How do the final state interactions of the decay particles influence the decay spectrum (especially for K^+K^-)?

➡ Realistic transport simulations using a transport approach (calculations using the PHSD code are ongoing)

➡ See talk by L. Oliva

The angle-averaged di-lepton spectrum

A double peak?



Computed at normal nuclear matter density

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

φ meson at rest in nuclear matter

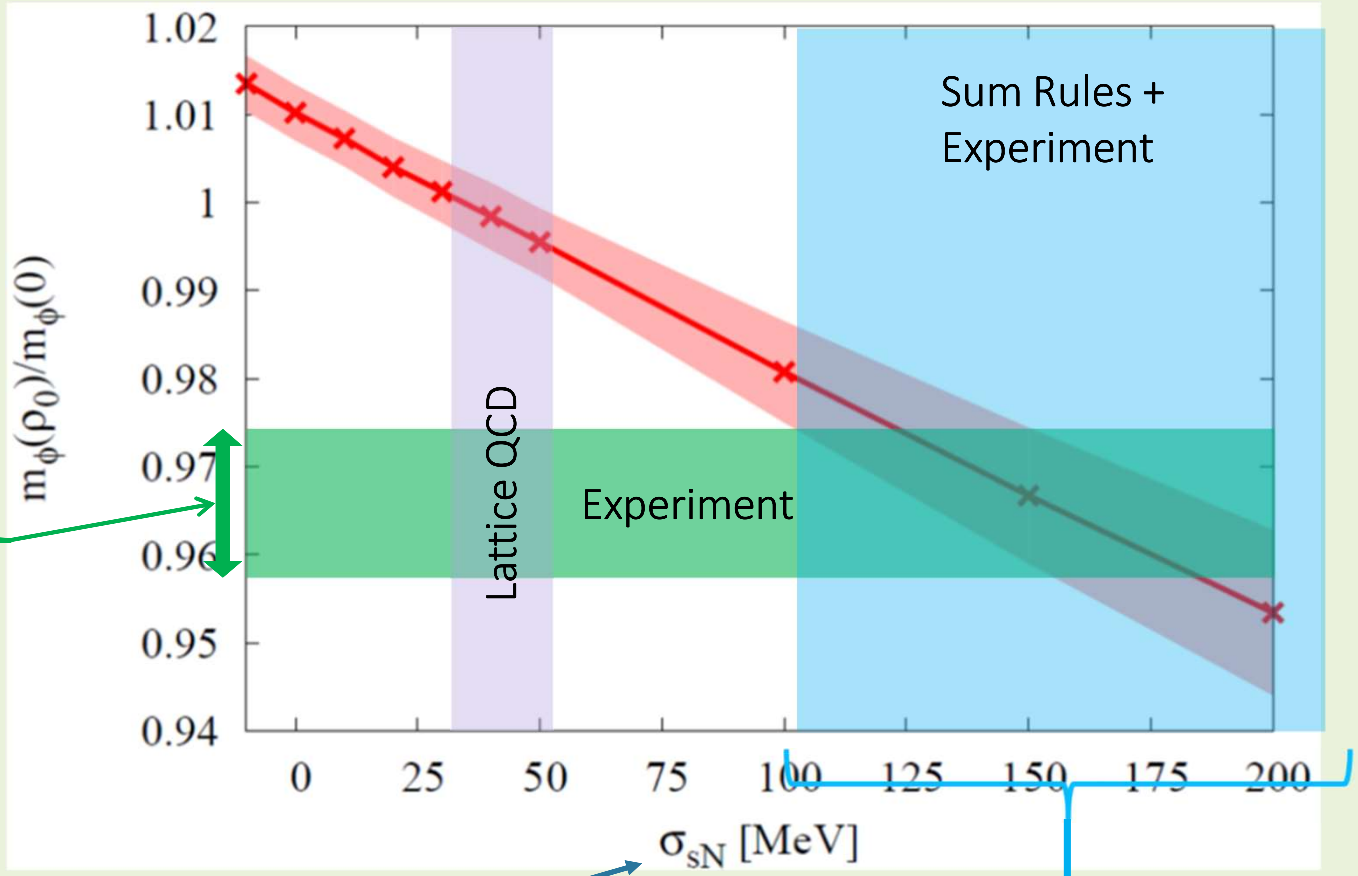
The φ meson mass in nuclear matter probes the strange quark condensate at finite density!

Not consistent?

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

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

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



$$\sigma_{sN} = m_s \langle N | \bar{s}s | N \rangle \qquad \sigma_{sN} \sim 160 \pm 50 \text{ MeV}$$