The phi meson moving in nuclear ~~and hot~~ matter

Philipp Gubler (JAEA)

L.M. Abreu, P. Gubler, K.P. Khemchandani, A. Martínez Torres and A. Hosaka, Phys. Lett. B **860**, 139175 (2025).
H.J. Kim and P. Gubler, Phys. Lett. B **805**, 135412 (2020).
I.W. Park, H. Sako, K. Aoki, P. Gubler and S.H. Lee, Phys. Rev. D **107**, 074033 (2023).
R. Ejima, C. Sasaki, P. Gubler and K. Shigaki, Phys. Rev. C **111**, 055201 (2025).

Talk at the Reimei workshop on in-medium modification of vector mesons @ Yonsei
Seoul, South Korea
March 8, 2026

Work done in collaboration with:

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I.W. Park (Yonsei U.)
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S.H. Lee (Yonsei U.)
R. Ejima (Hiroshima U.)
C. Sakai (Wroclav U.)
K. Shigaki (Hiroshima U.)

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/πA reactions

Chiral mixing?

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

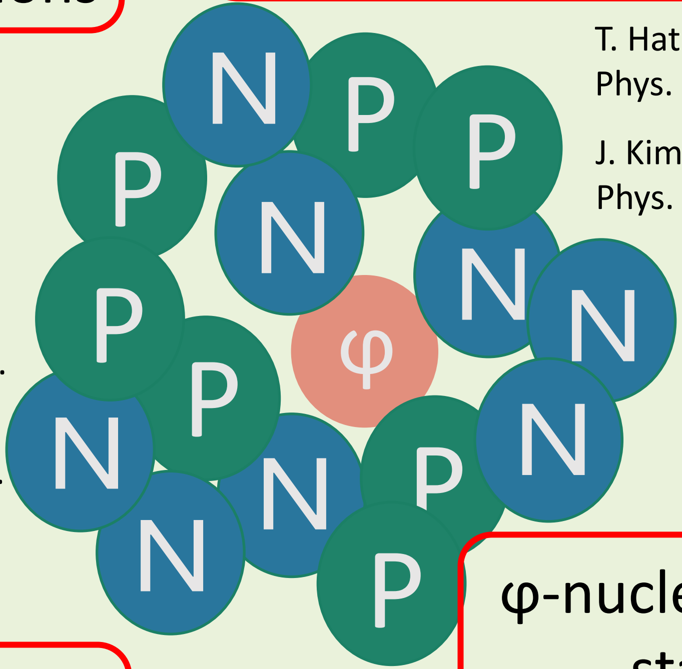
R. Ejima et al.,
Phys. Rev. C **111**, 055201 (2025).

Exotic dispersion relations

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

Partial restoration of chiral symmetry

$$\left|\langle \bar{s}s \rangle_\rho\right| \searrow$$



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).

φ-nucleus bound states?

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

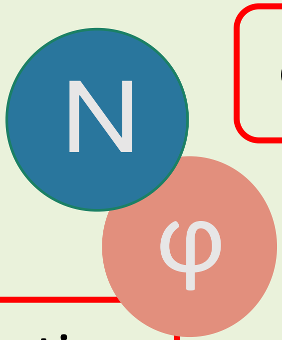
I. Filikhin et al.,
Phys. Rev. C **110**, 065202 (2024).

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



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

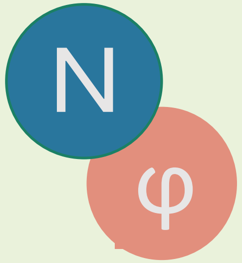
I.I. Strakovsky et al.,
Phys. Rev. C **101**, 045201 (2020).

Lattice QCD (HAL)

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

Topics of this talk

1.

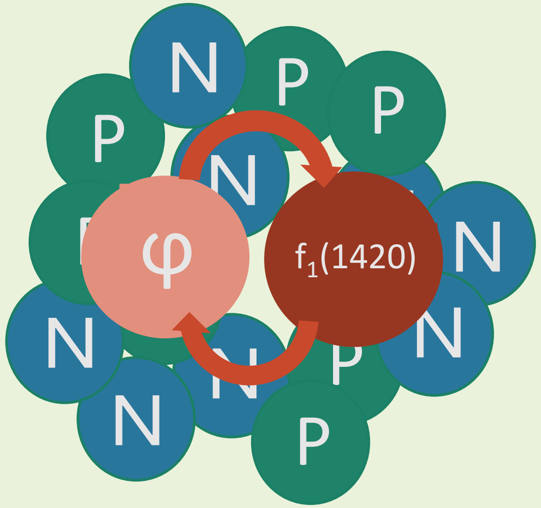


What is the nature is this interaction?

2.

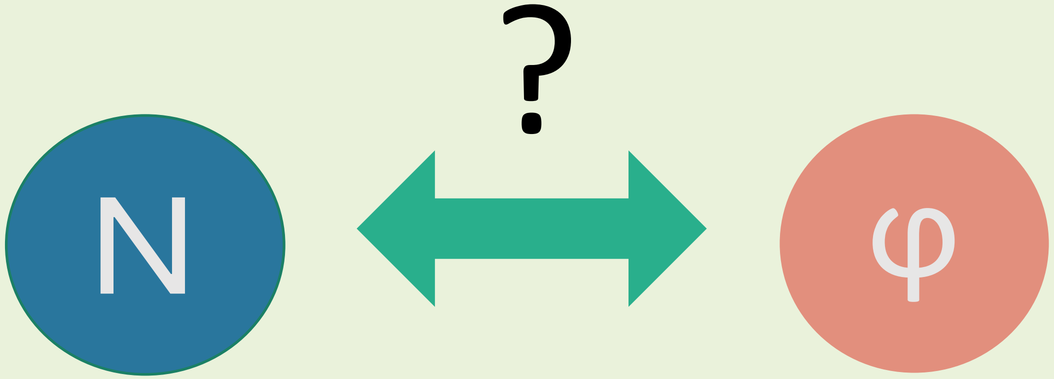
m_ϕ ?

3.



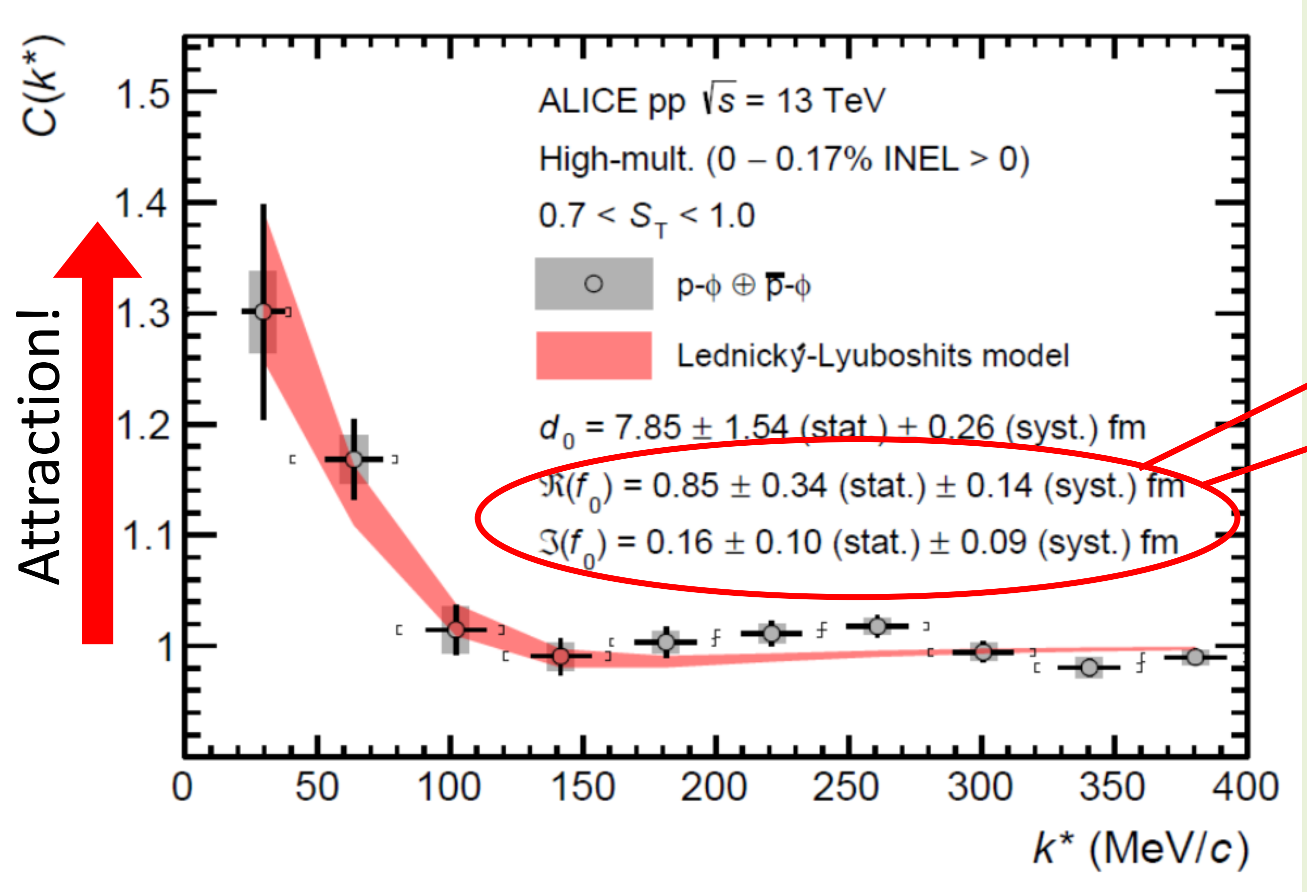
Measurable at J-PARC?

Nature of the φN interaction



ALICE: pp

φN correlation function



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

★ Strongly attractive

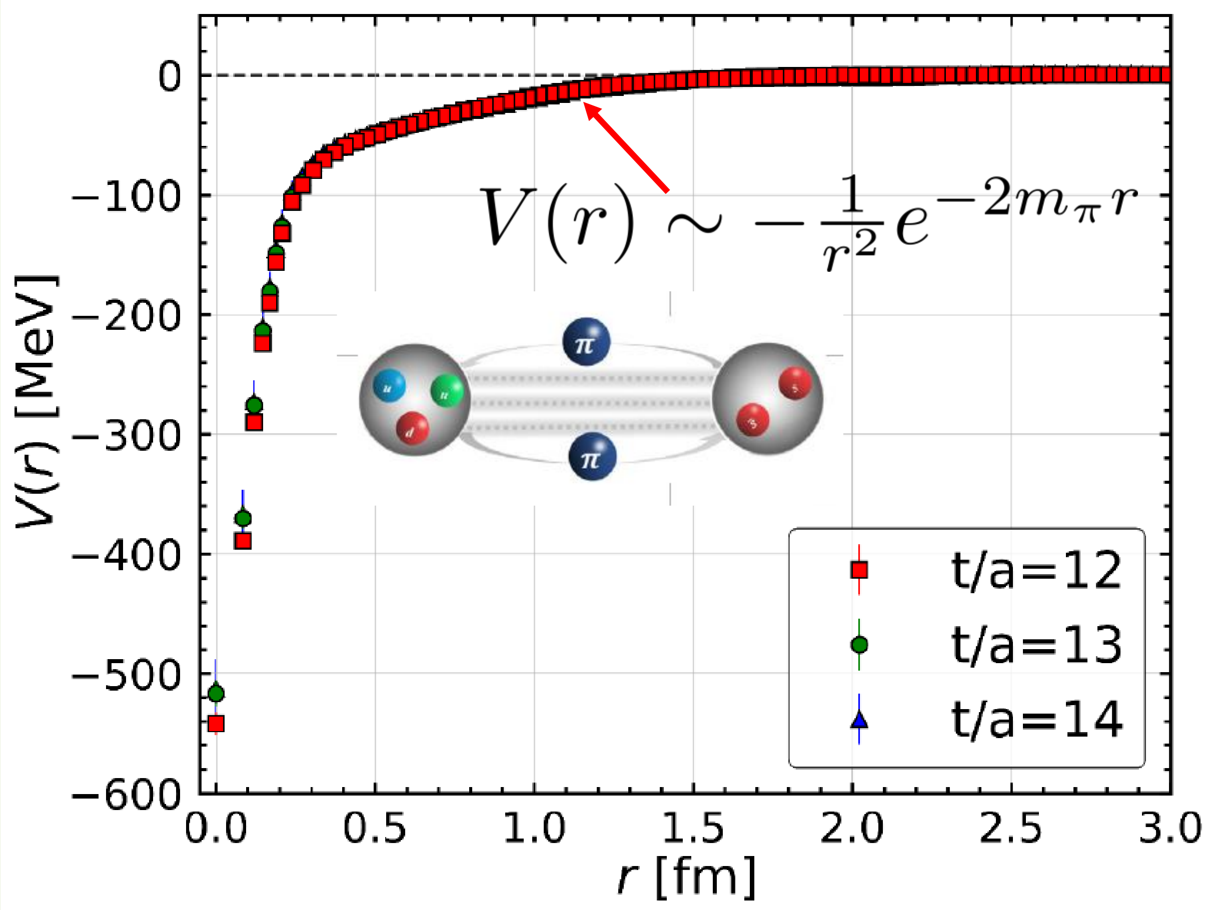
★ Small absorption

Bound state in spin 1/2 channel?

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

φN potential from HAL QCD

Spin 3/2 channel

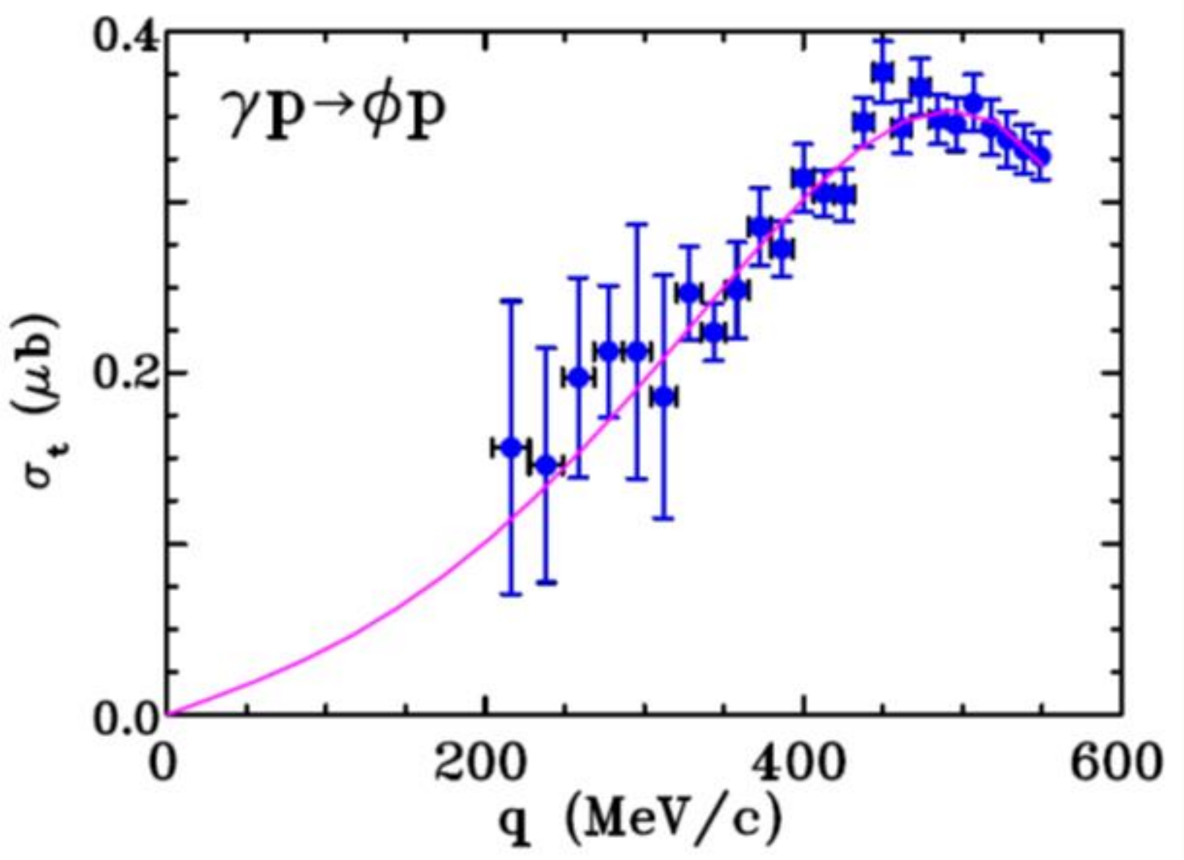


$$a_0^{3/2} = 1.43(23)_{\text{stat.}} \left(^{+36}_{-06}\right)_{\text{syst.}} \text{ fm}$$

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

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

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

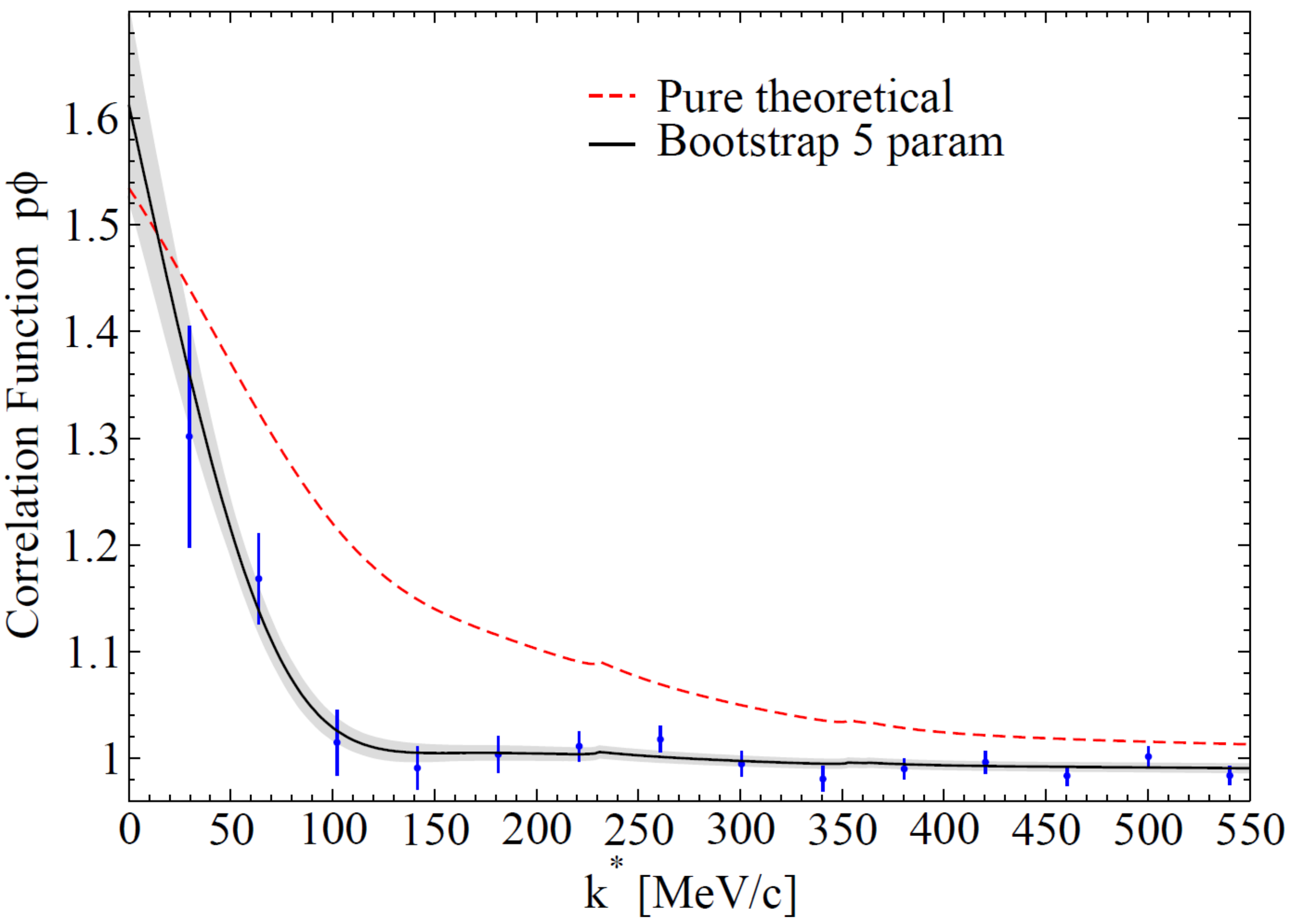
$$|a_0| = 0.063 \pm 0.010\,\mathrm{fm}$$

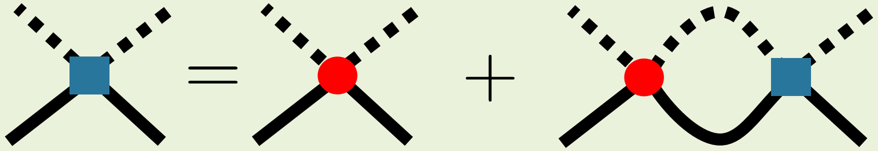
Consistent with weak φN interaction

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

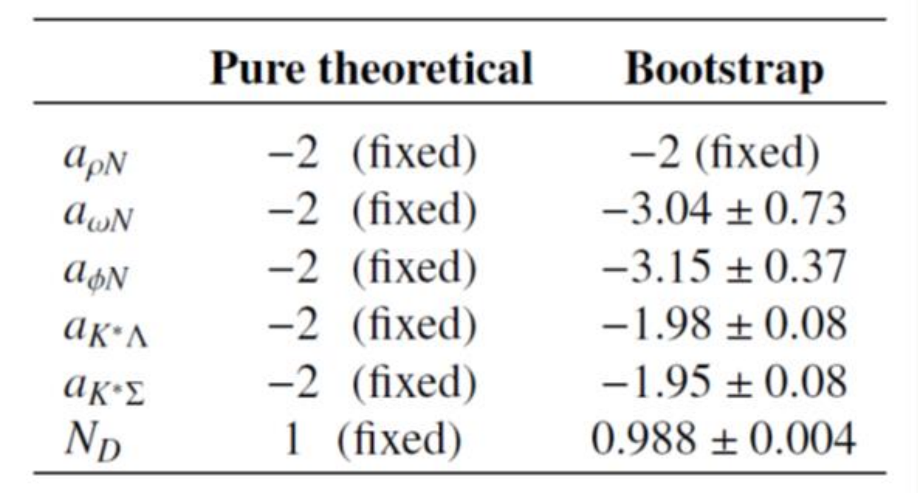
New analysis of the ALICE data

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





Coupled channel approach, 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

First theoretical analysis of the ALICE data

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

Obtained scattering length and effective range

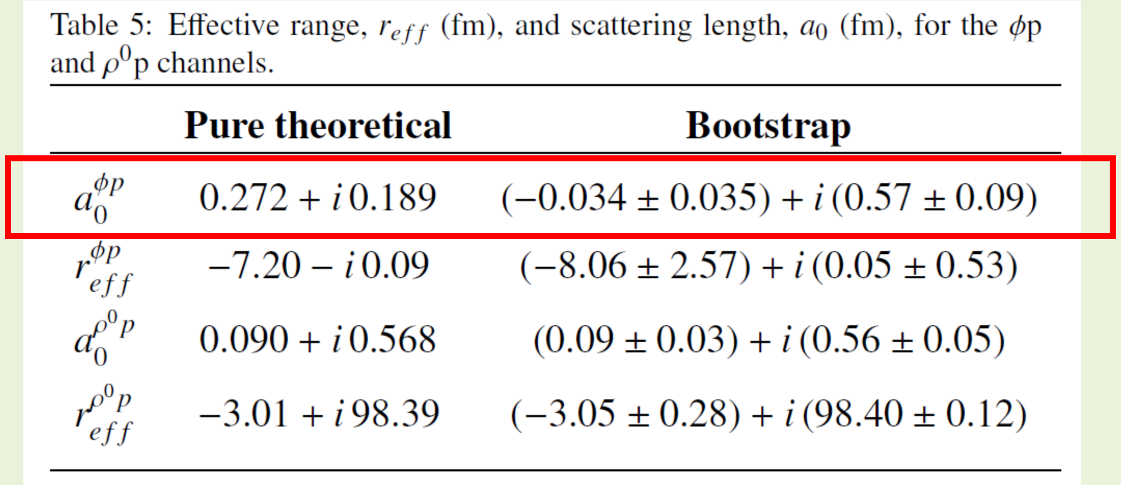
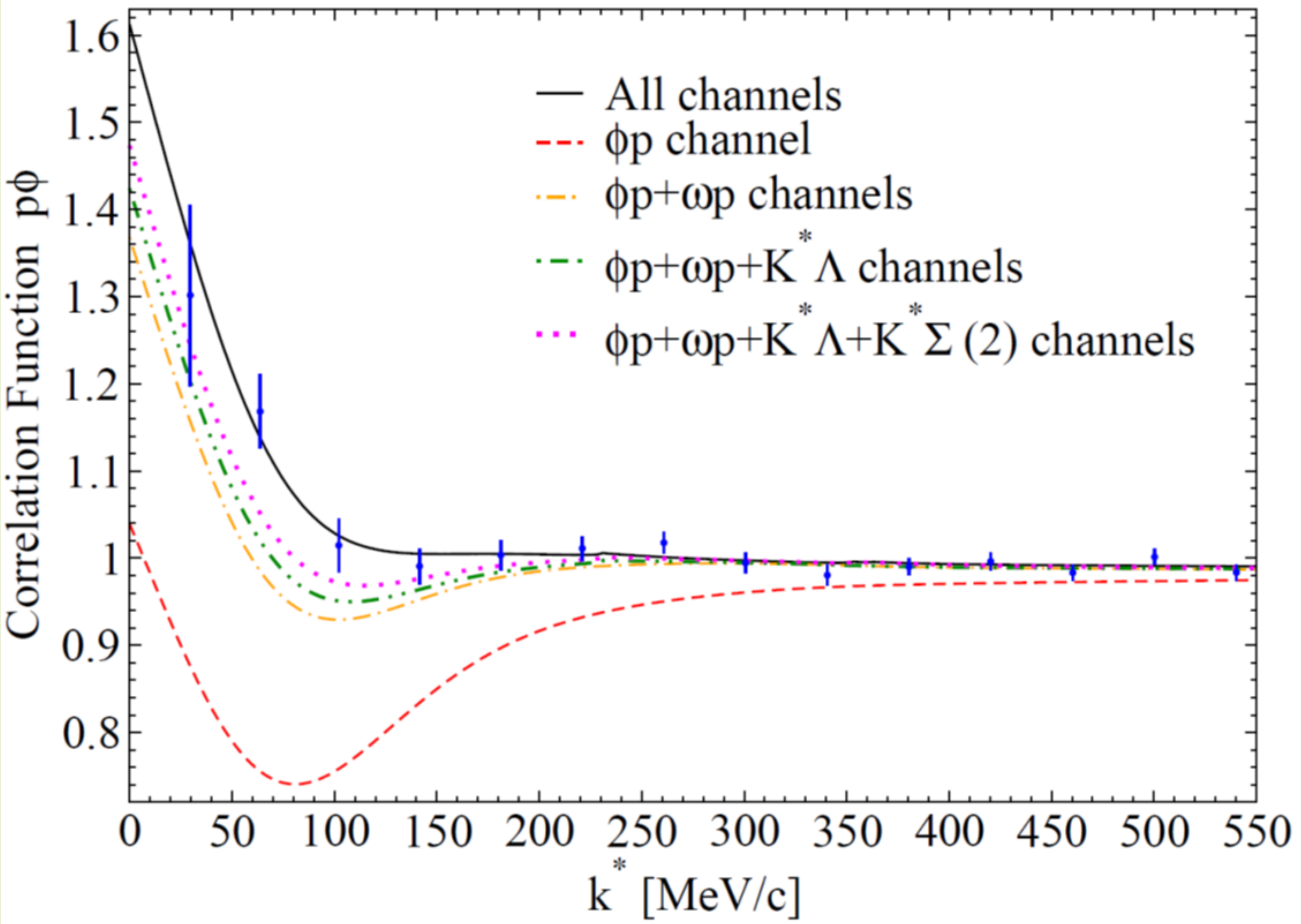


Table 5: Effective range, r_{eff} (fm), and scattering length, a_0 (fm), for the ϕp and ρ^0p channels.

	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



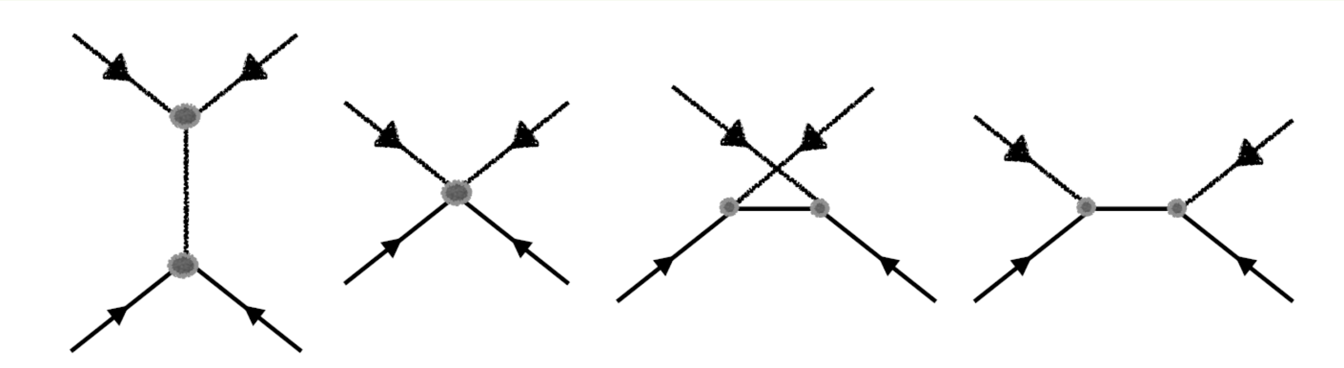
A newer analysis of the ALICE data

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

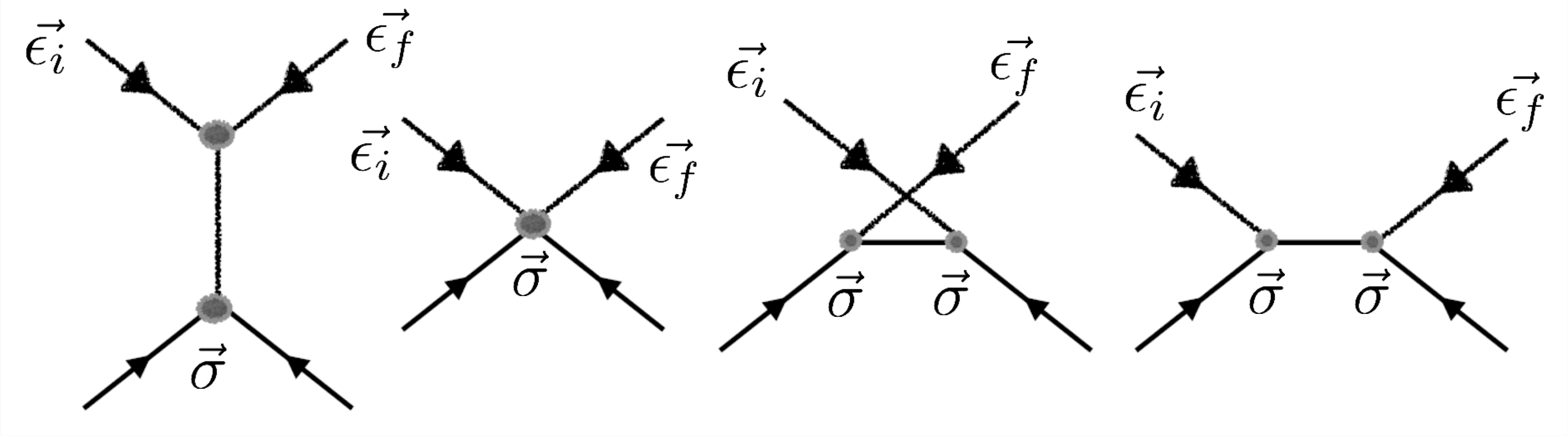
Starting point:
Hadronic Meson-Baryon interaction Lagrangian

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

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



Crucial ingredient: spin dependent vector meson-baryon interactions



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

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

Considered so far
in Feijoo et al.

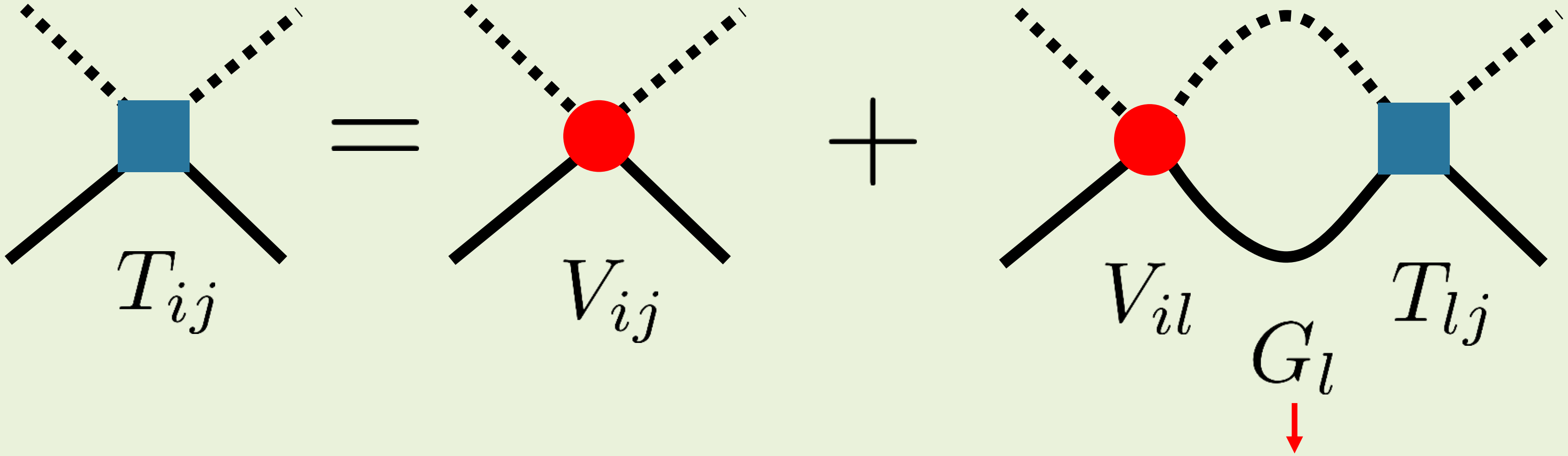
New!
Depend on spin configuration of the φN system (spin 1/2 or 3/2)

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

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

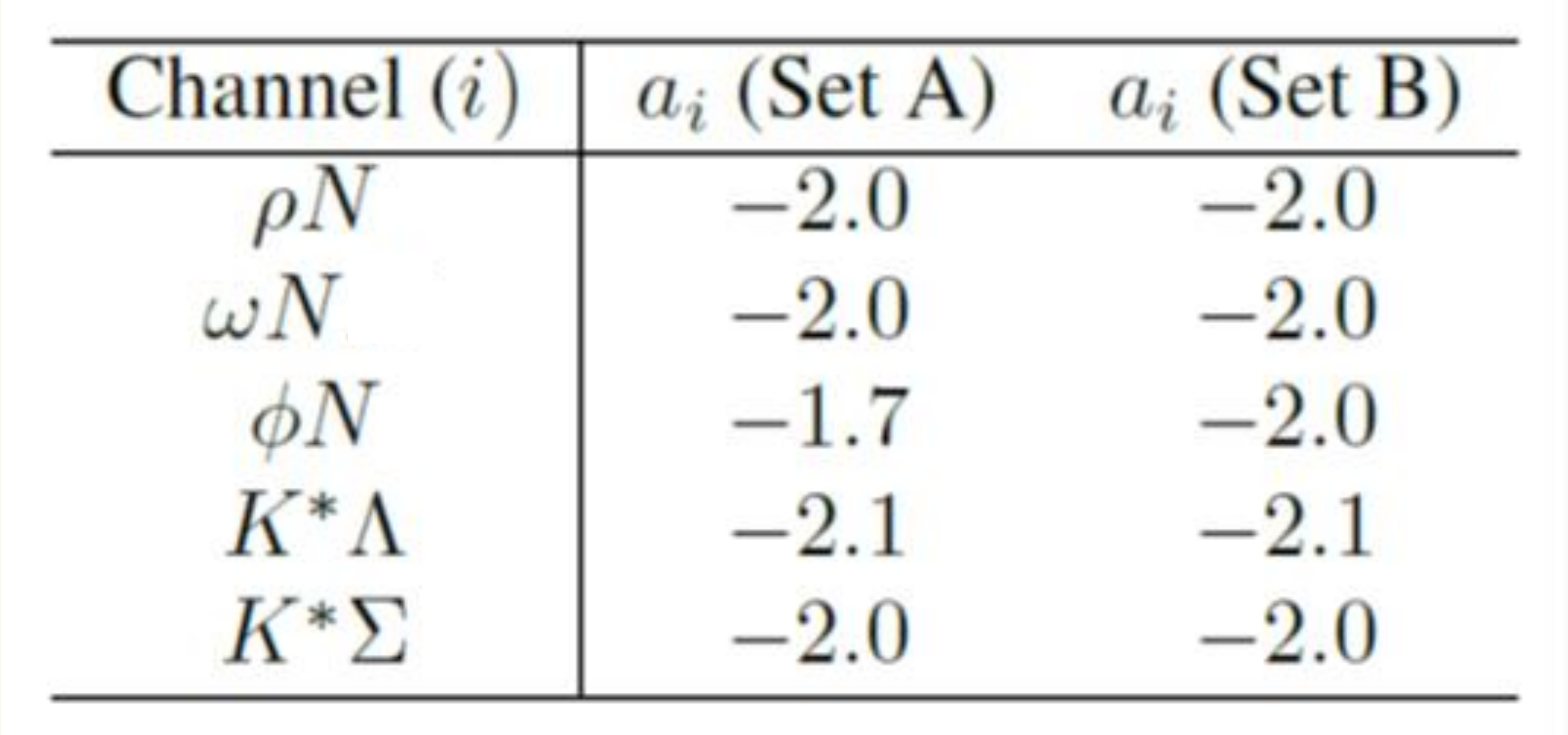


Emergence of subtraction constants, which are parameters of the model

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:



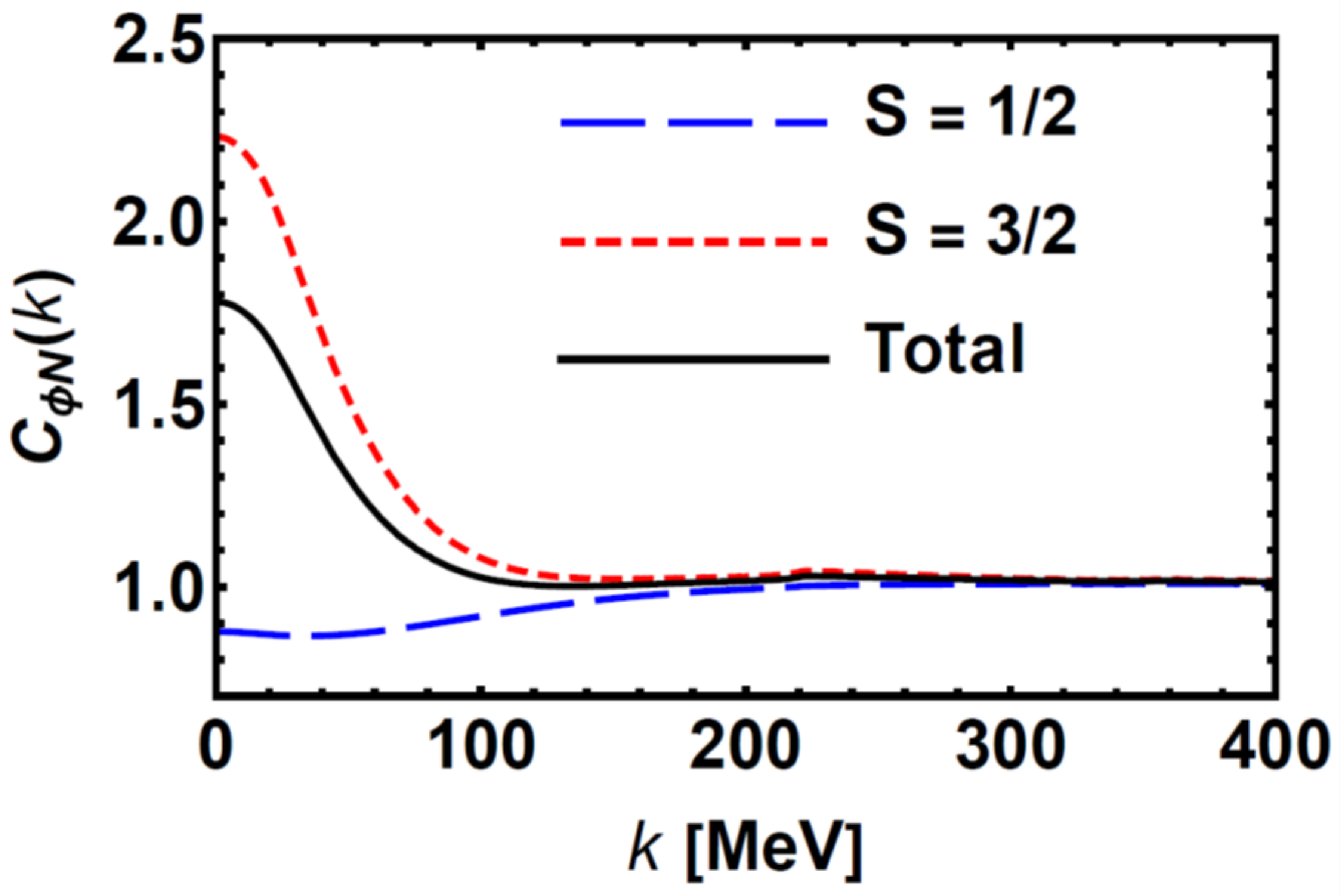
Channel (i)	a_i (Set A)	a_i (Set B)
ρN	-2.0	-2.0
ωN	-2.0	-2.0
ϕN	-1.7	-2.0
$K^*\Lambda$	-2.1	-2.1
$K^*\Sigma$	-2.0	-2.0

All are close to the “natural” value of $a_i = -2$

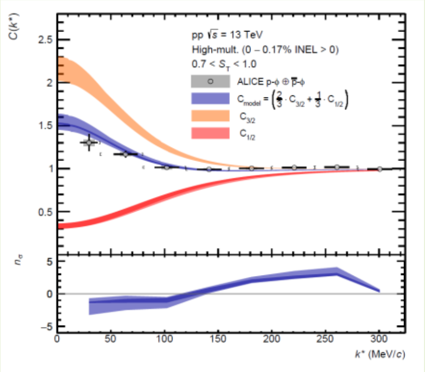
Only the value in the φN channel is modified, to study the change in the respective interaction strength

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)

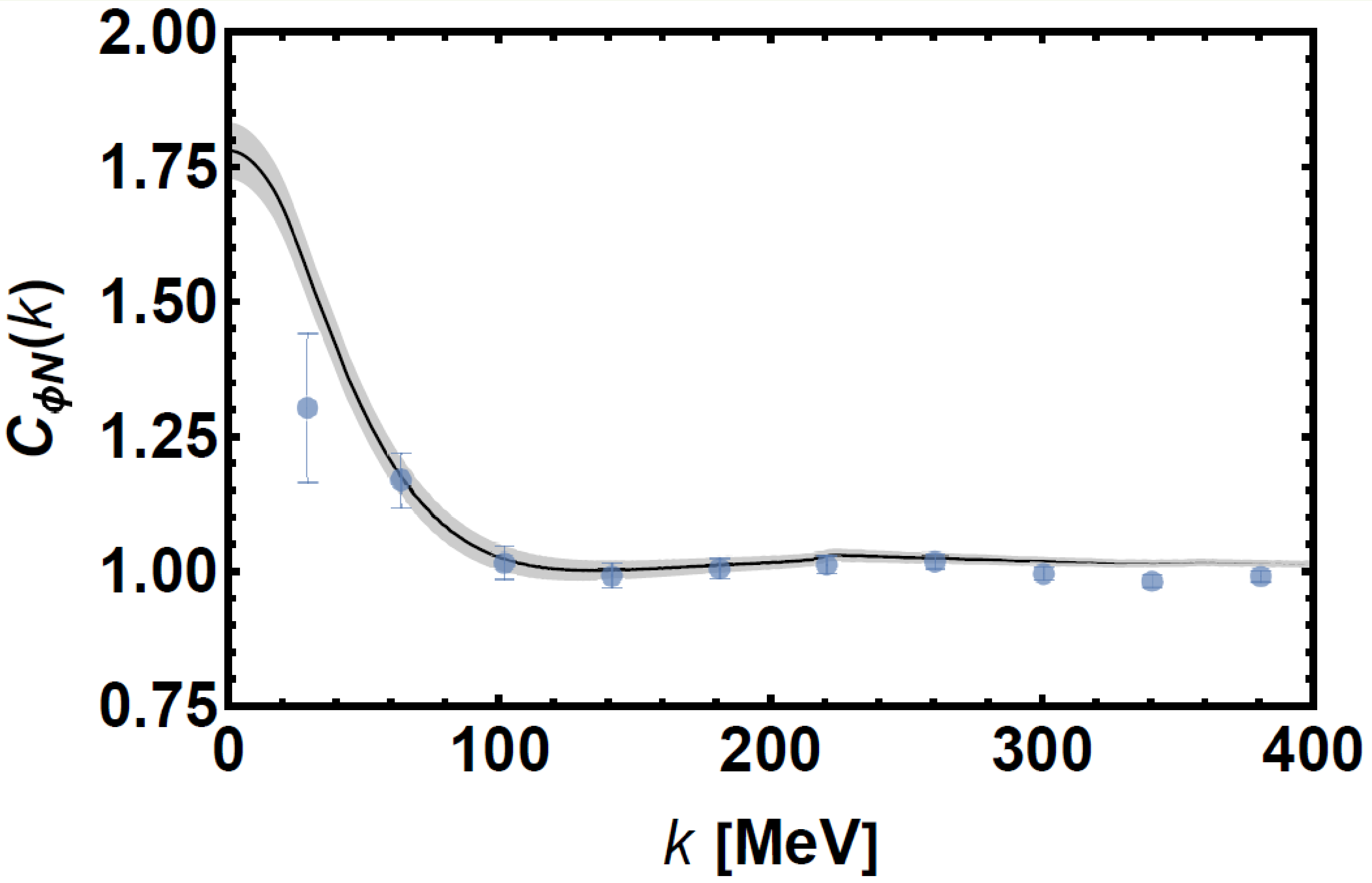


Qualitatively similar to
E. Chizzali et al.,
Phys. Lett. B **848**, 138358 (2024).



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

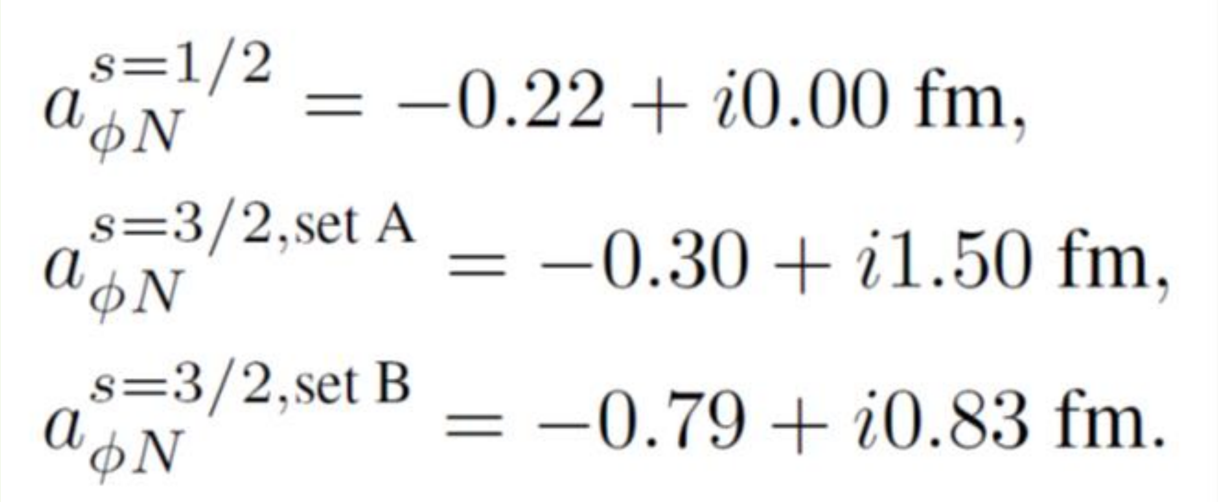
The obtained correlation function (compared with ALICE data)



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

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

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

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

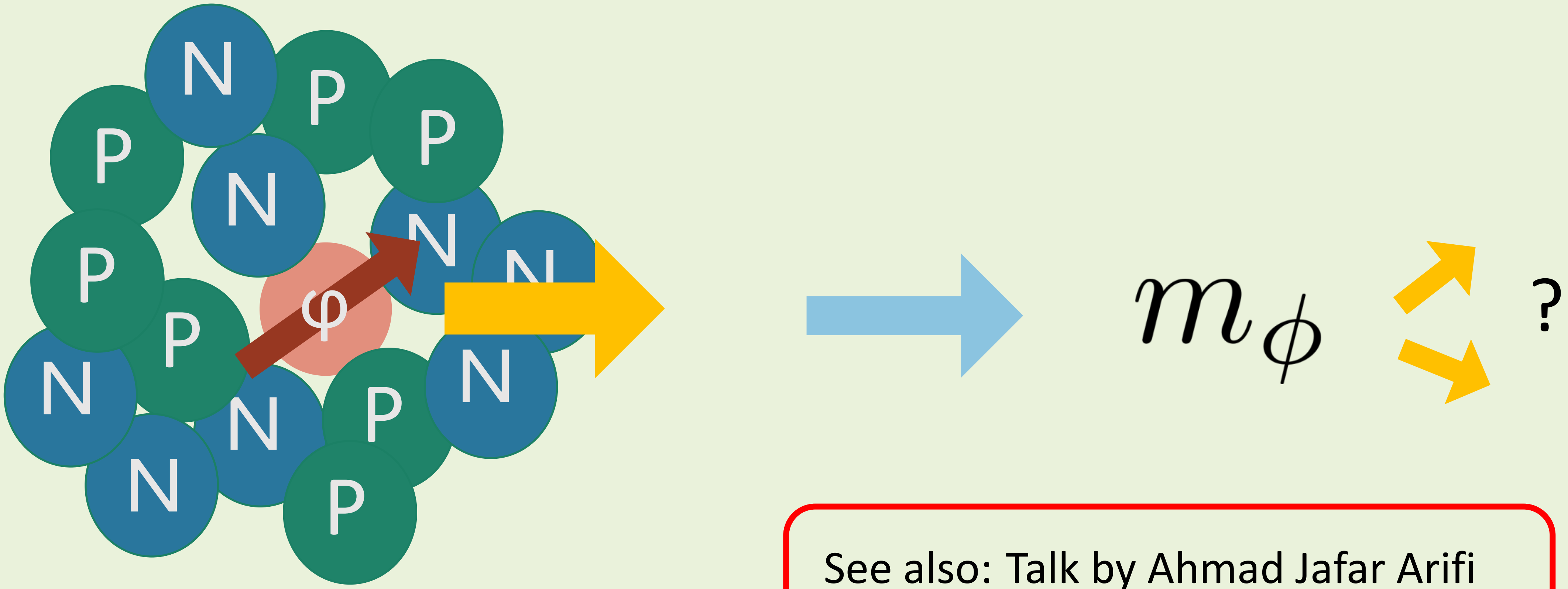
Valid within the linear density approximation

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!

Role of spin

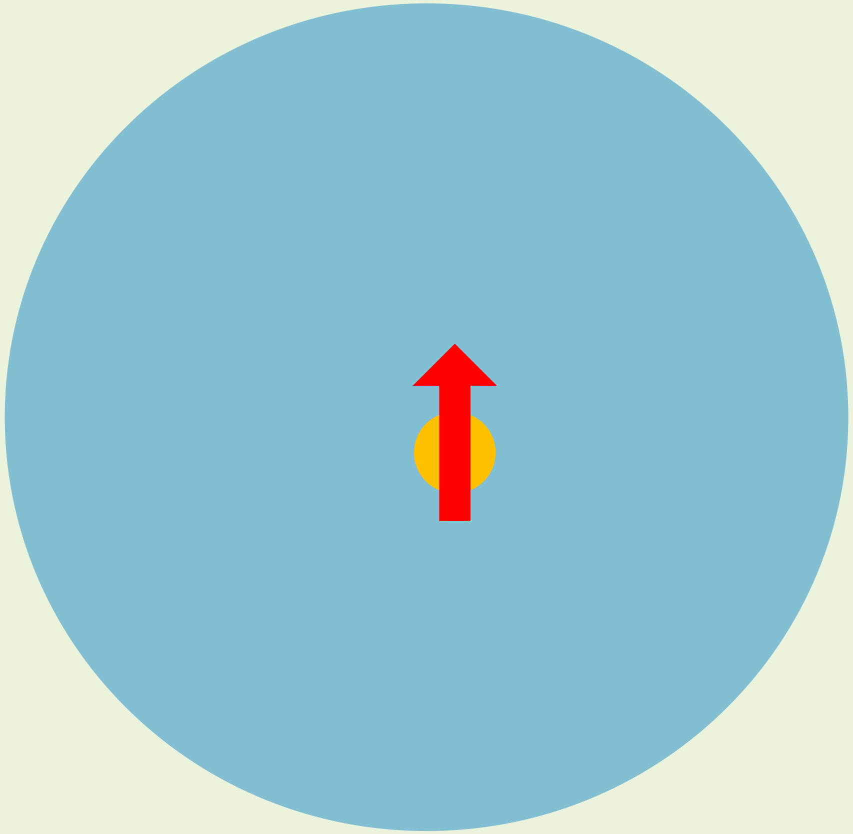


m_ϕ

See also: Talk by Ahmad Jafar Arifi
Tuesday, 10.40

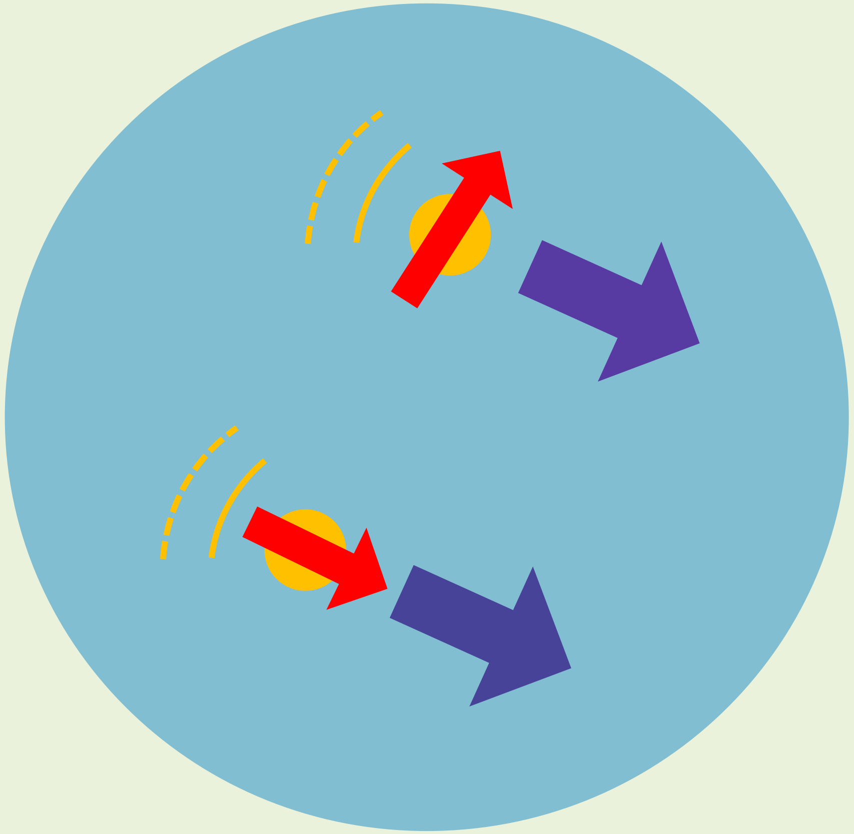
Role of spin

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 ϕ meson with non-zero momentum

$$\frac{1}{\omega^2 - m_\phi^2(0)}$$

zero momentum

$$\frac{1}{\omega^2 - \vec{q}^{\,2} - m_{\phi,L}^2(\vec{q}^{\,2})}$$

longitudinal part

$$\frac{1}{\omega^2 - \vec{q}^{\,2} - m_{\phi,T}^2(\vec{q}^{\,2})}$$

transverse part

non-zero momentum $\vec{q}$

QCD sum rules

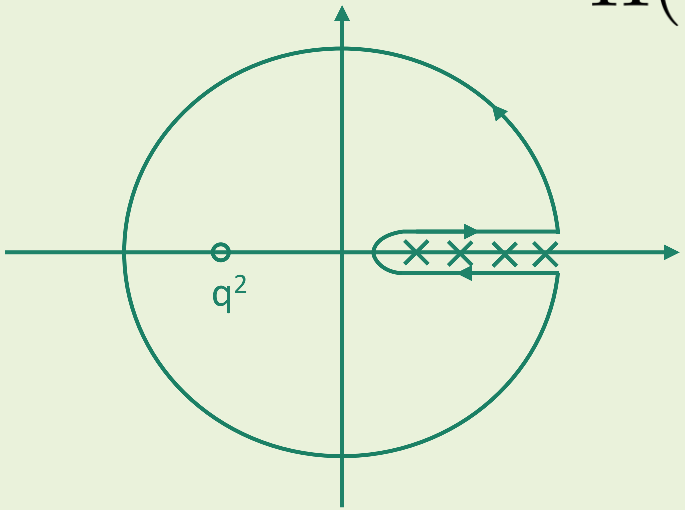
M.A. Shifman, A.I. Vainshtein and V.I. Zakharov,
Nucl. Phys. B**147**, 385 (1979); B**147**, 448 (1979).

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

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

$\Downarrow$ OPE

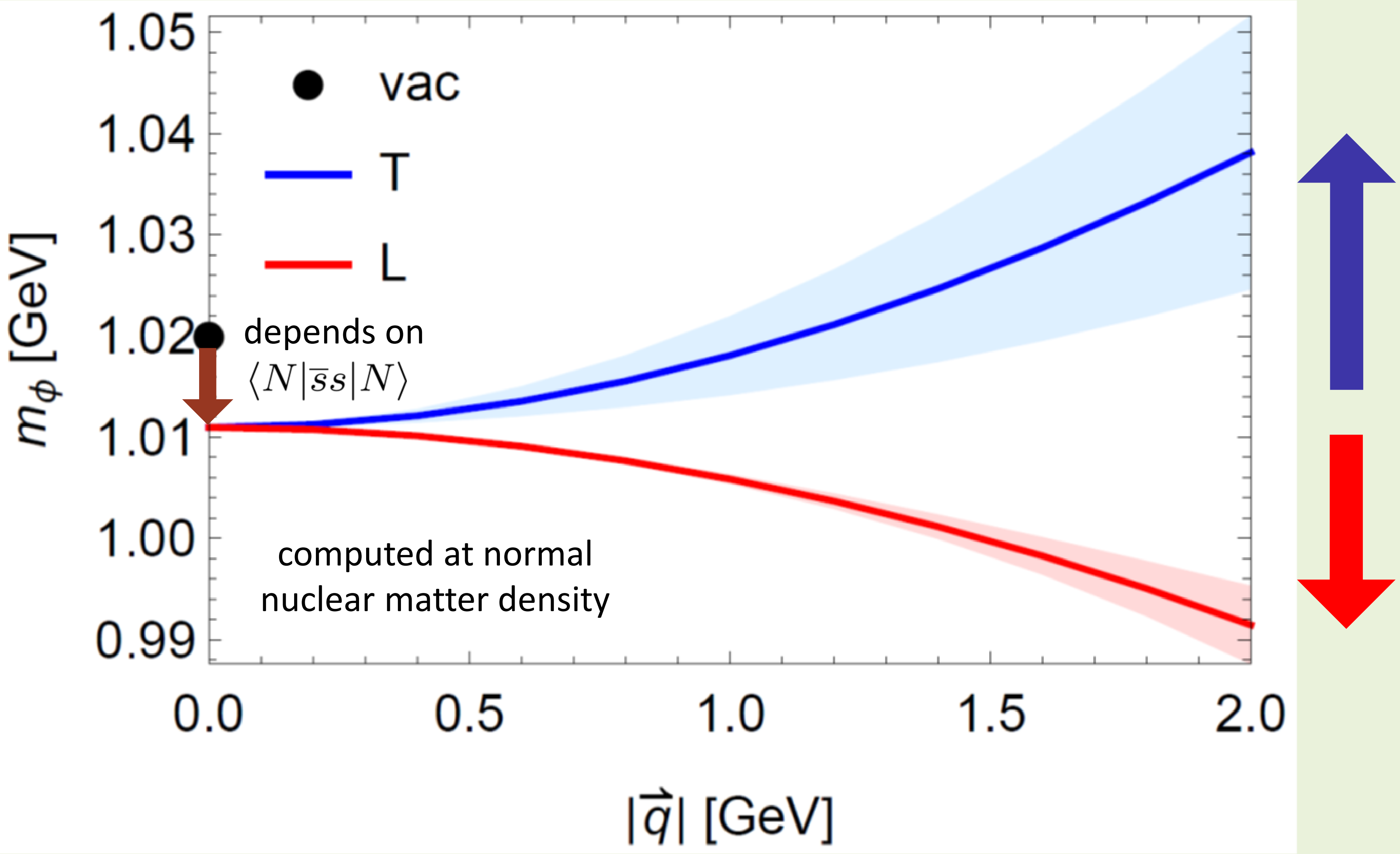
$\langle\bar{q}q\rangle_\rho,$
$\langle G^a_{\mu\nu}G^{a\mu\nu}\rangle_\rho,$
$\langle\bar{q}\sigma_{\mu\nu}\frac{\lambda^a}{2}G^{a\mu\nu}q\rangle_\rho,$
$\langle\bar{q}q\bar{q}q\rangle_\rho,$

scalar condensates:
same for longitudinal and transverse modes

$\langle\mathcal{S}\mathcal{T}\bar{q}\gamma^\alpha iD^\beta q\rangle_\rho,$
$\langle\mathcal{S}\mathcal{T}G^{a\alpha}_{\mu}G^{a\mu\beta}\rangle_\rho,$
$\langle\mathcal{S}\mathcal{T}\bar{q}\gamma^\alpha iD^\beta iD^\gamma iD^\delta q\rangle_\rho$

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

Results for the ϕ meson mass with non-zero momentum



depends on $\langle N|\bar{s}s|N\rangle$

computed at normal nuclear matter density

caused by

$$\langle N|\mathcal{S}\mathcal{T}\,\bar{s}\gamma^{\alpha}iD^{\beta}s|N\rangle$$

$$+$$

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

caused by

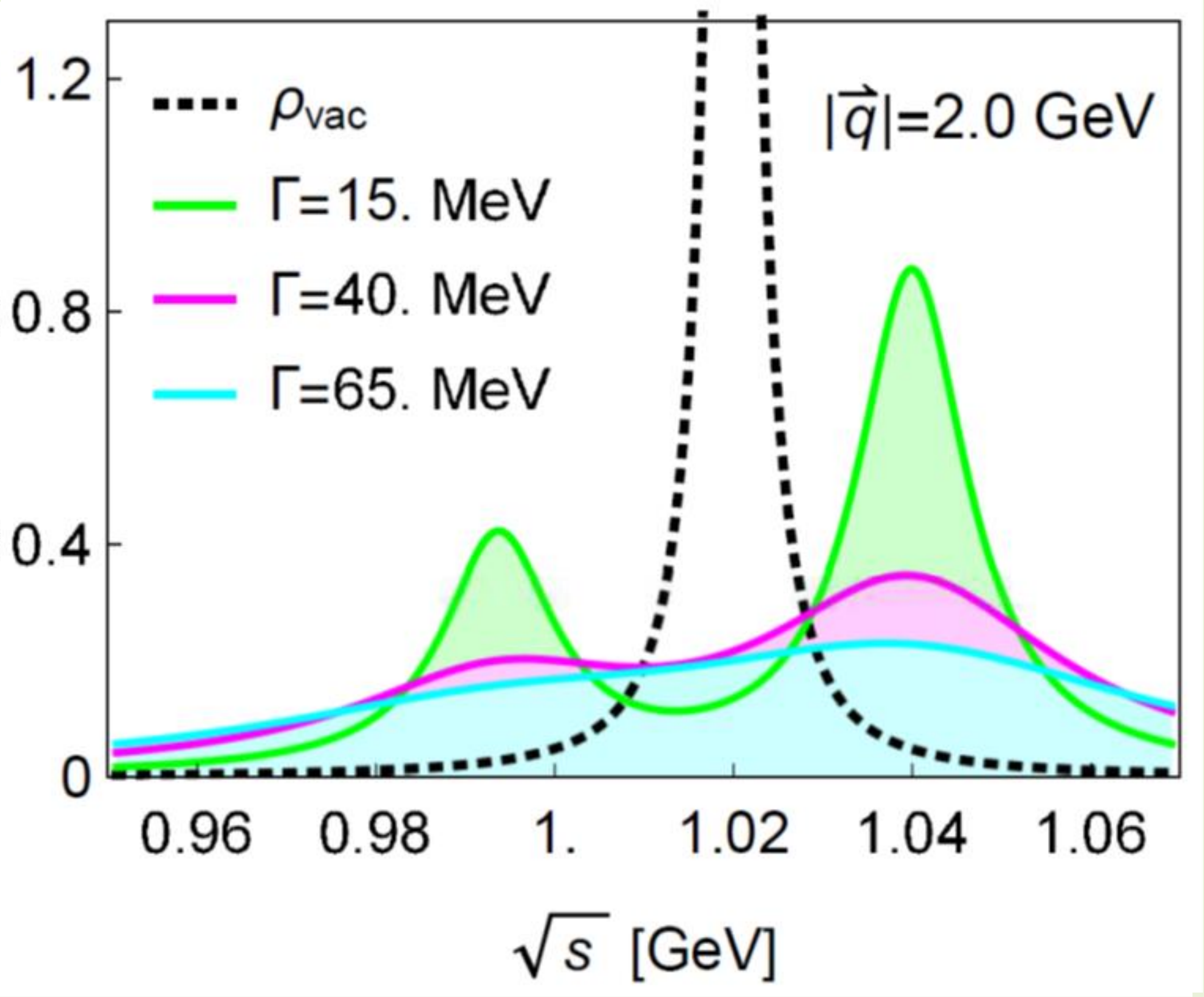
$$\langle N|\mathcal{S}\mathcal{T}\,G^{a\alpha}_{\mu}G^{a\mu\beta}|N\rangle$$

Any sizable effect on polarization?

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

The angle-averaged di-lepton spectrum

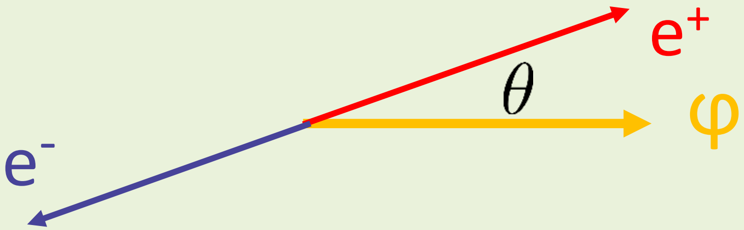
A double peak?



Computed at normal nuclear matter density

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

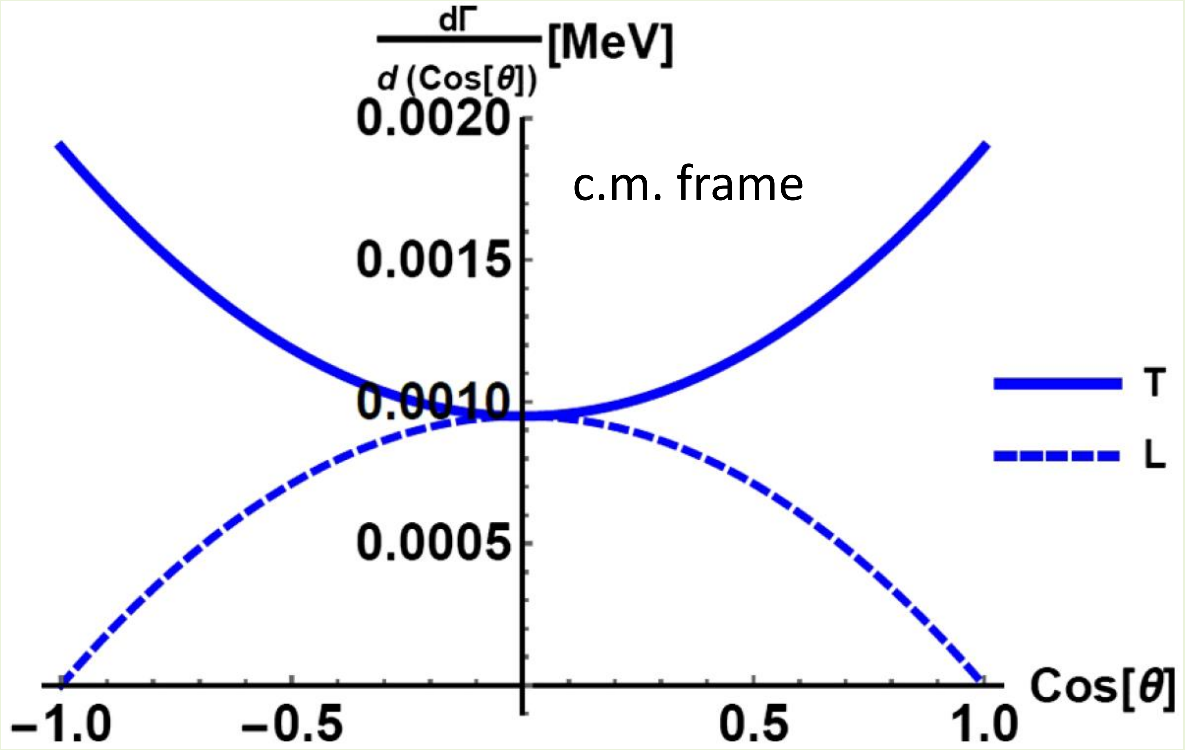
Angular distributions of φ meson dilepton and K^+K^- decays



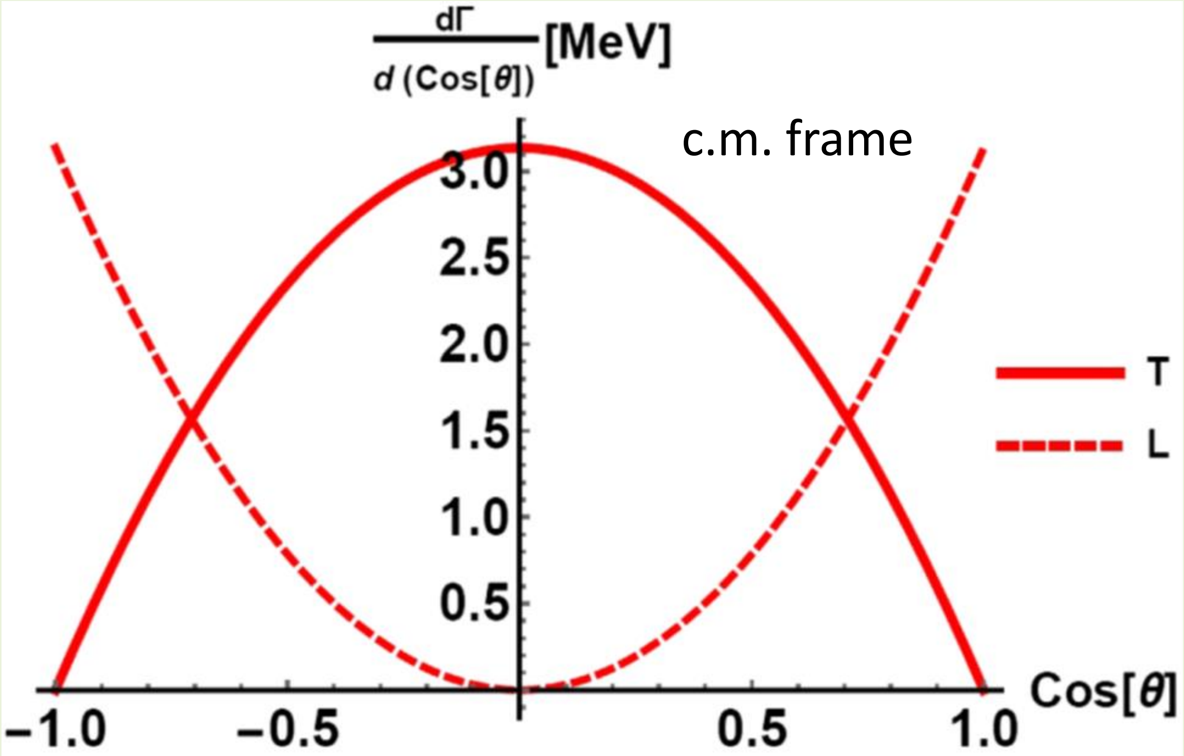
Preferred mode for polarization measurement

Ideal for the J-PARC E88 experiment!

Dilepton decay angular distribution

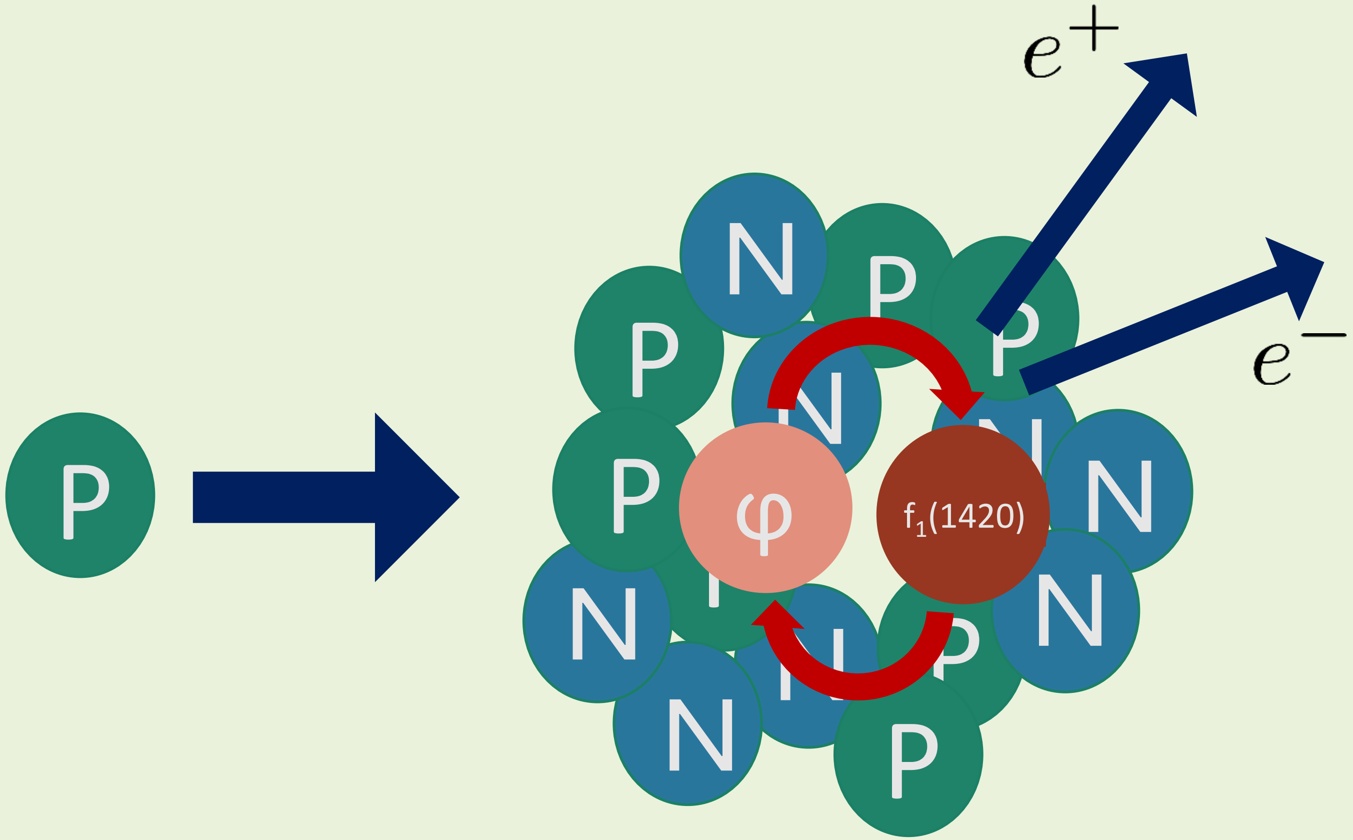


K^+K^- decay angular distribution



I.W. Park, H. Sako, K. Aoki, P. Gubler and S.H. Lee, Phys. Rev. D **107**, 074033 (2023).

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

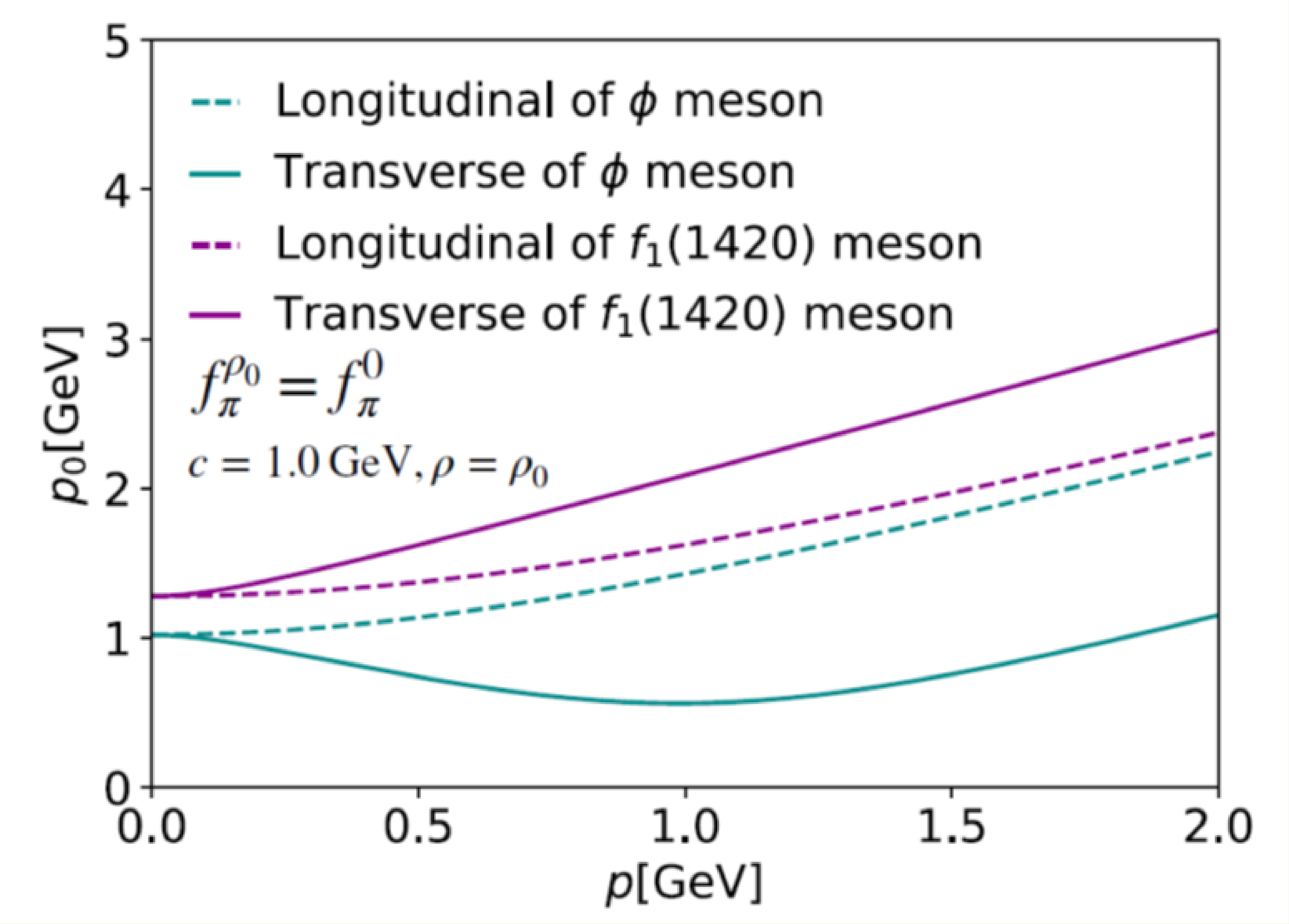
S. K. Domokos and J. A. Harvey,
Phys. Rev. Lett. **99**, 141602 (2007).

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

from gauged WZW action

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

Resulting dispersion relations (at ρ= ρ_0)



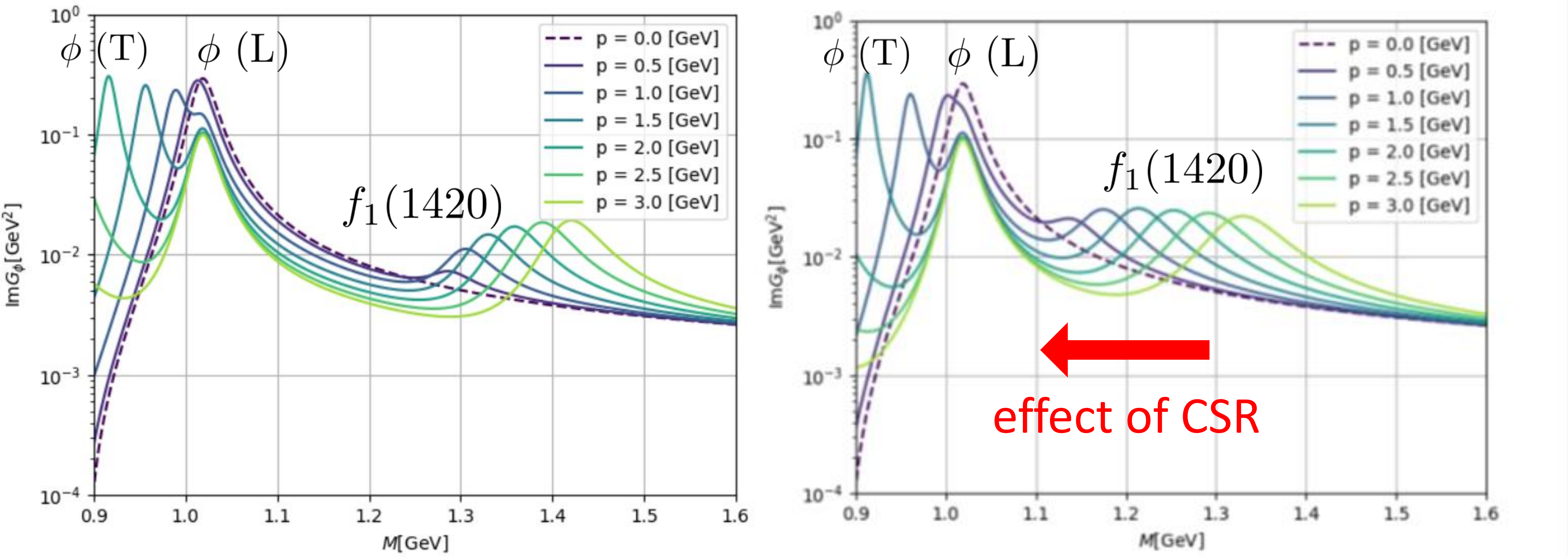
C. Sasaki, Phys. Rev. D **106**, 054034 (2022).

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

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

without CSR

with CSR



effect of 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

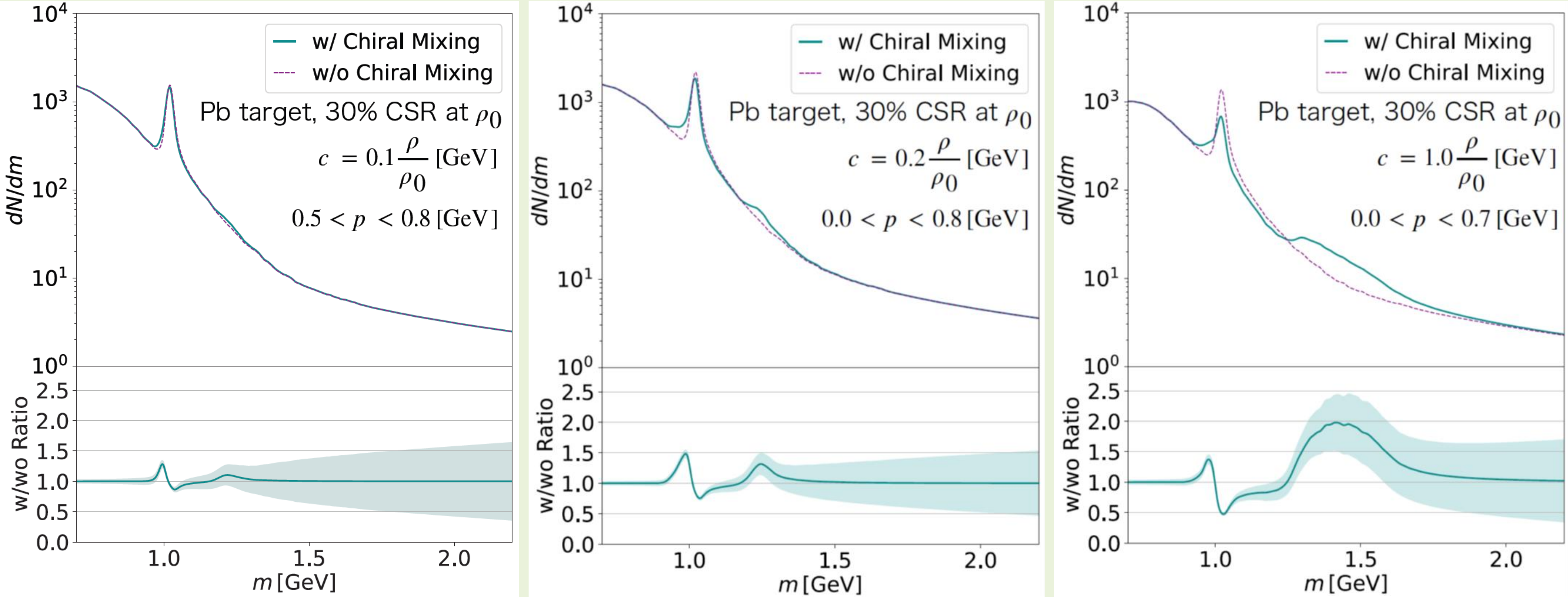
$$I(M) = \int \left[\int \boxed{\mathrm{Im}G_V(s,\vec{p},\rho)} \boxed{\frac{dN}{d\vec{p}\,d\rho\,dt}} \frac{d\vec{p}}{2p_0}\, d\rho\, dt + \int \boxed{\mathrm{Bkg}(s,\vec{p})}\, d\vec{p} \right] \boxed{g(M-s)}\, ds$$

Taken from the Sasaki-model (previous slide)

Background, obtained simulation of experimental conditions:
JAM → Geant4

Invariant mass distributions for different mixing strengths

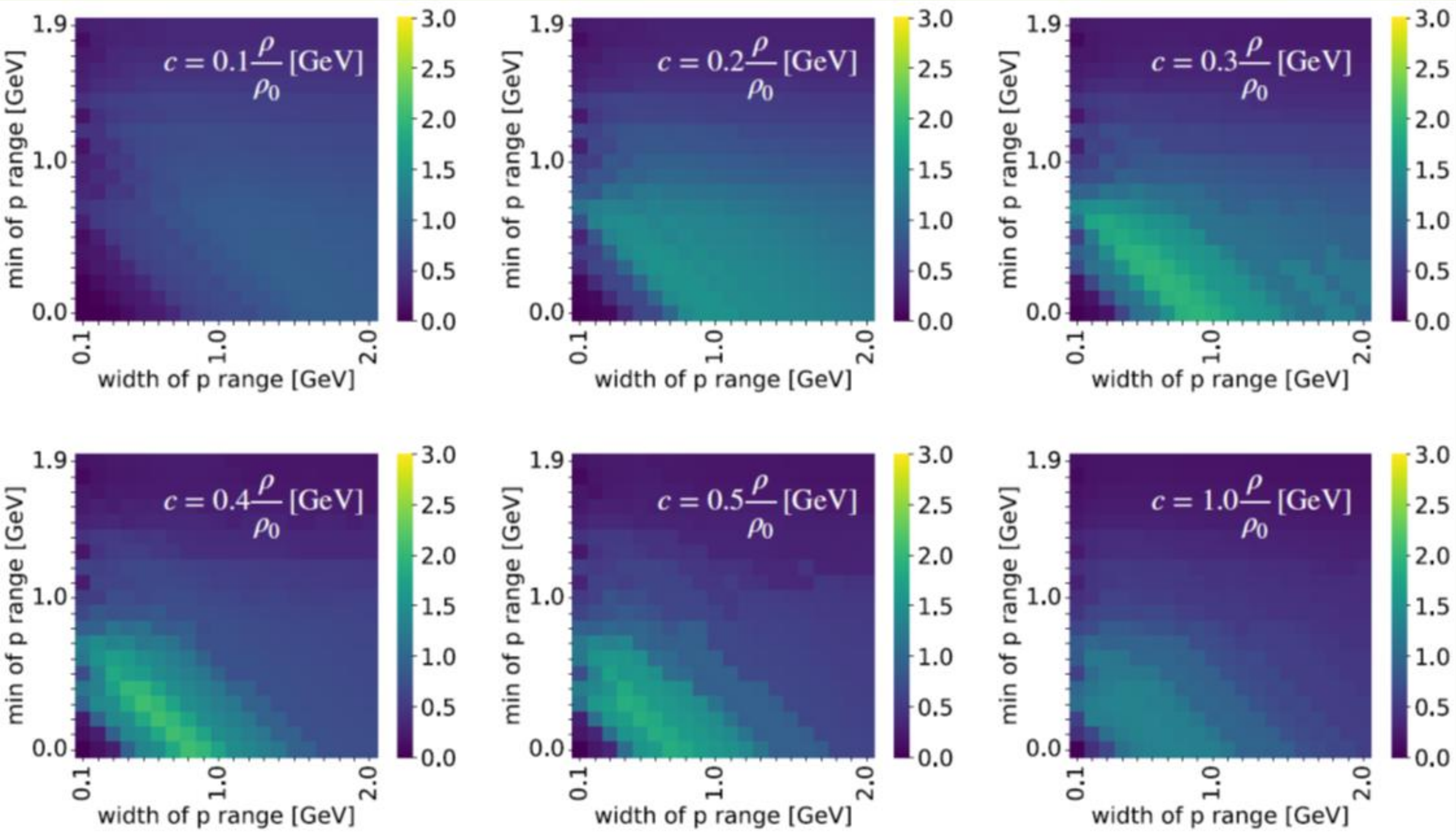
30 GeV pA collisions, Pb target, E16 Run2 statistics



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).

Summary and conclusions

★ 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

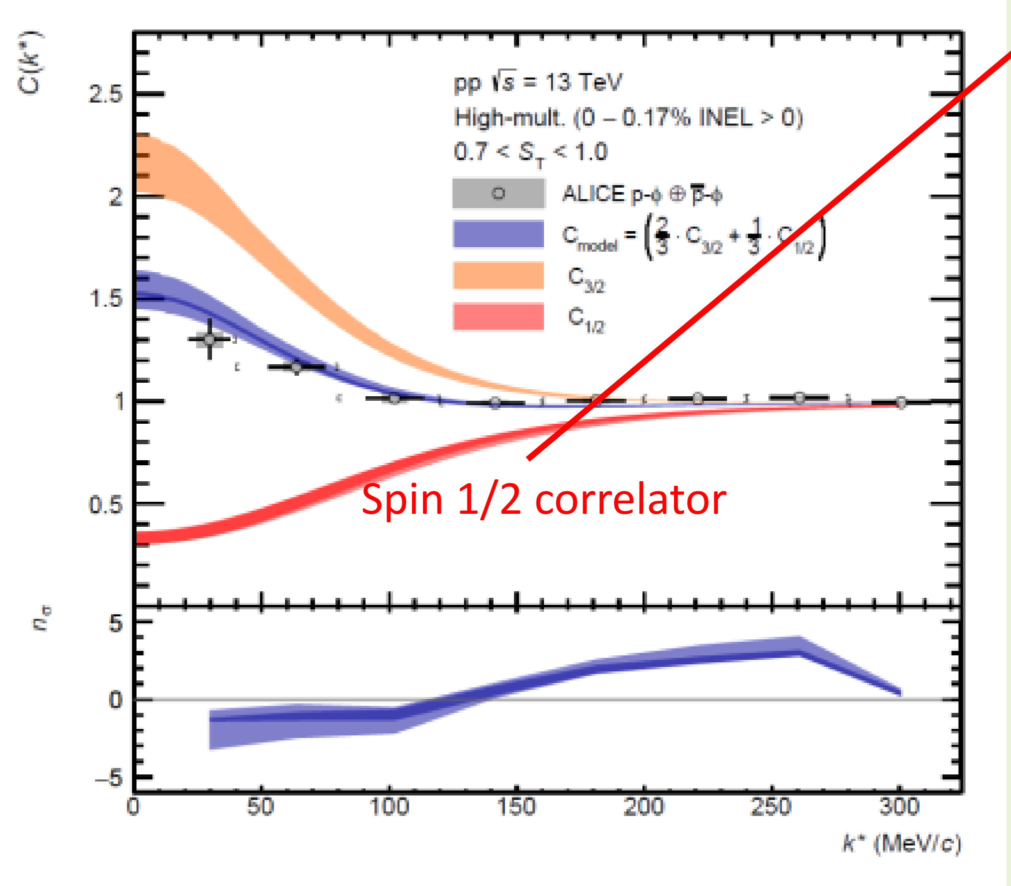
★ More precise data will be needed to determine the φ meson mass shift in nuclear matter

★ 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

Even more recent results

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



Spin 1/2 correlator

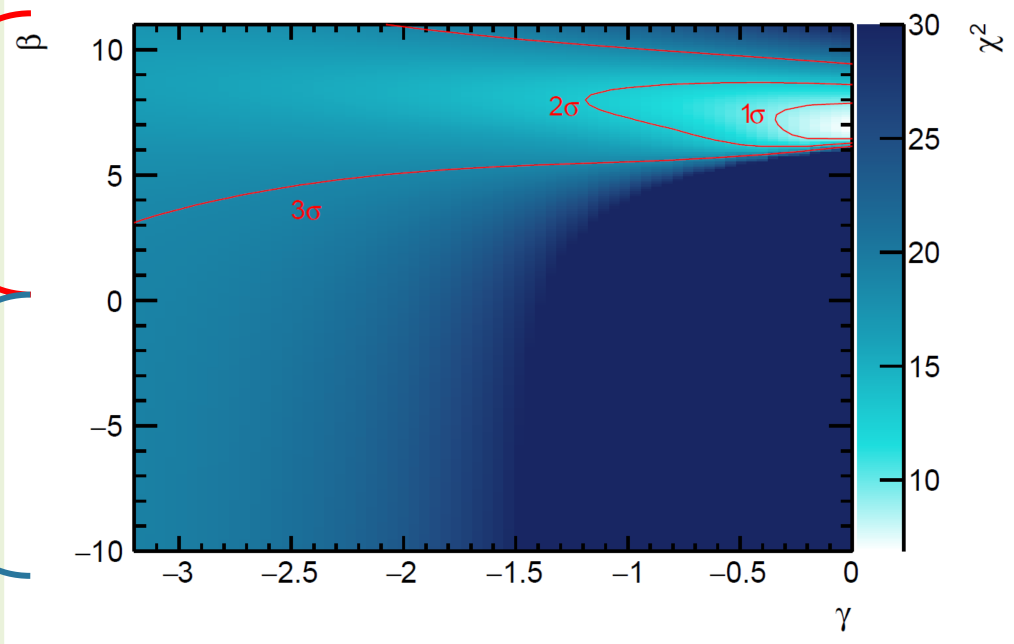
E. Chizzali et al., Phys. Lett. B **848**, 138358 (2024).

Bound state?

Repulsive?

Attractive

Repulsive



Evidence for φ-N bound state!