Extracting phi meson properties in nuclear matter from pA reactions

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Talk at the "9th Asian Triangle Heavy-Ion Conference (ATHIC 2023)"
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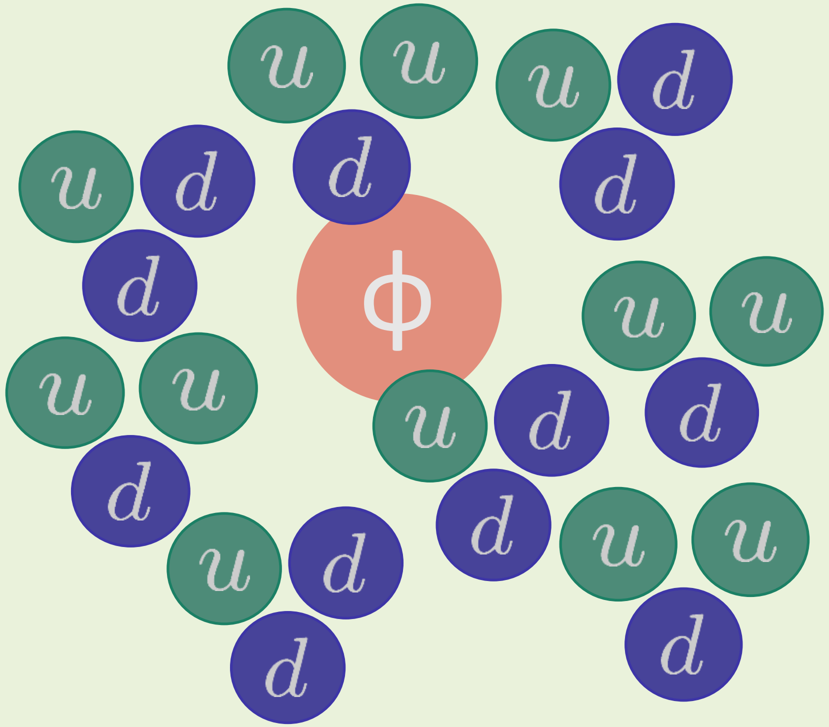
Based on work done in collaboration with
Elena Bratkovskaya (Frankfurt/GSI),
Taesoo Song (GSI)

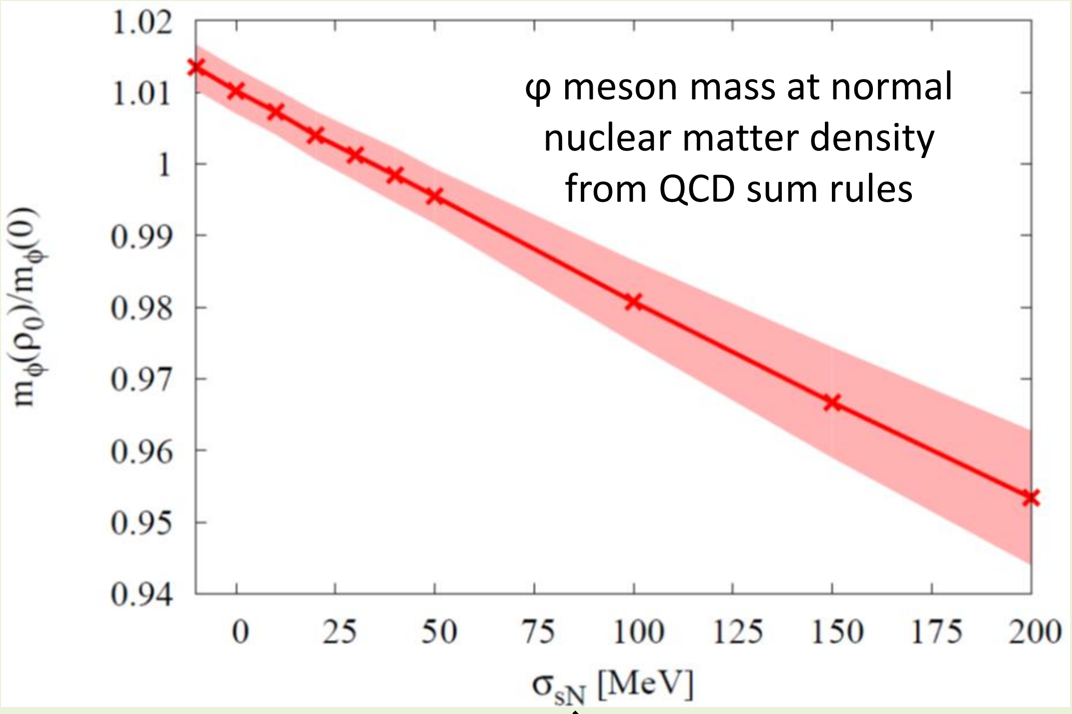
Why should we be interested?

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

$|\langle \bar{s}s \rangle_\rho| \searrow$ → $m_\phi \searrow$?



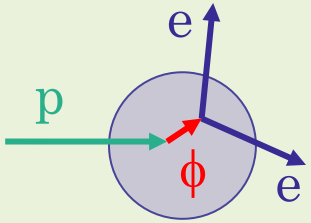
P. Gubler and K. Ohtani, Phys. Rev. D **90**, 094002 (2014).



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

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 ± 0.007

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

k_2: 2.6 ± 1.5

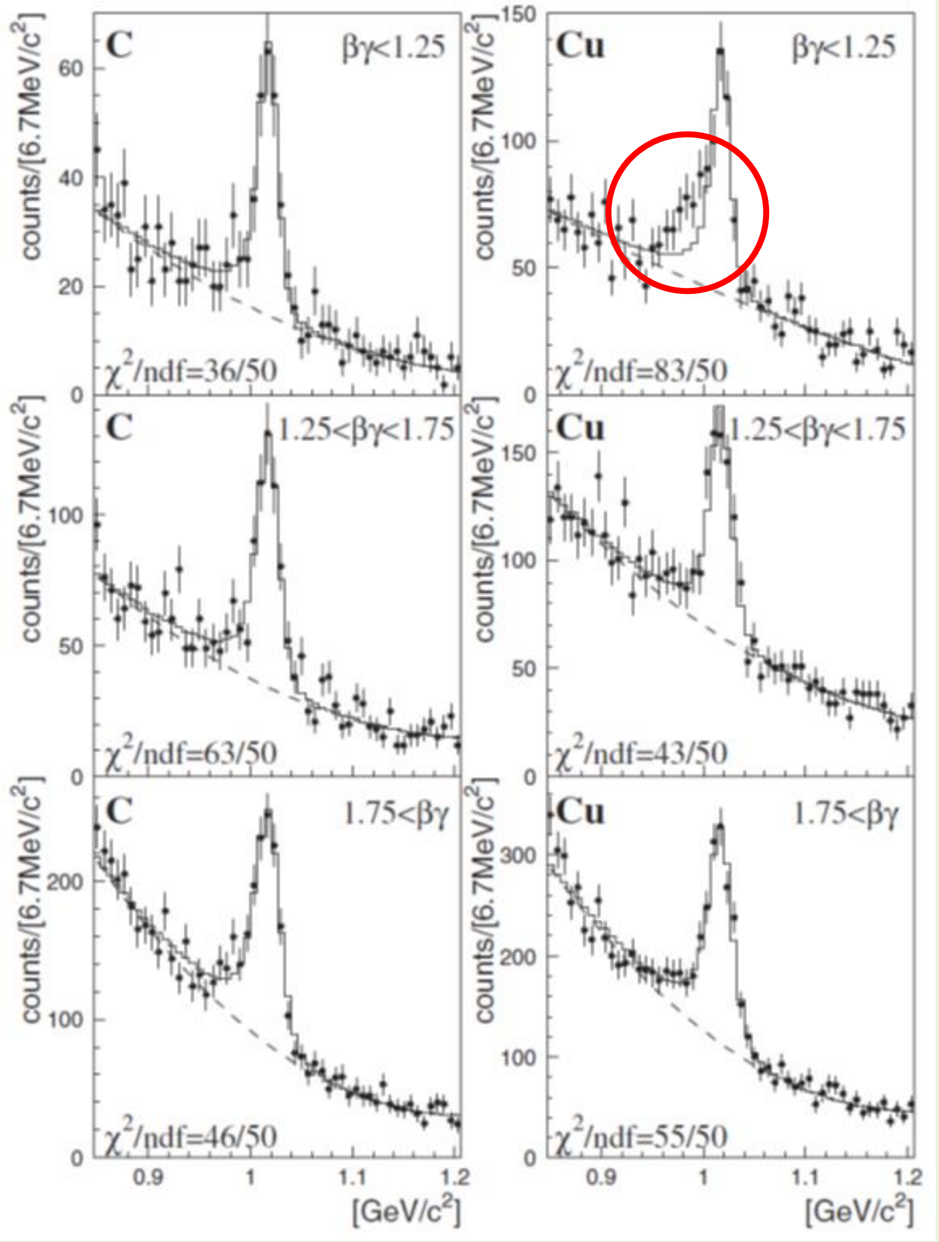
Measurement is being repeated with ~100x increased statistics at the J-PARC E16 experiment!

slow φs

intermediate φs

fast φs

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

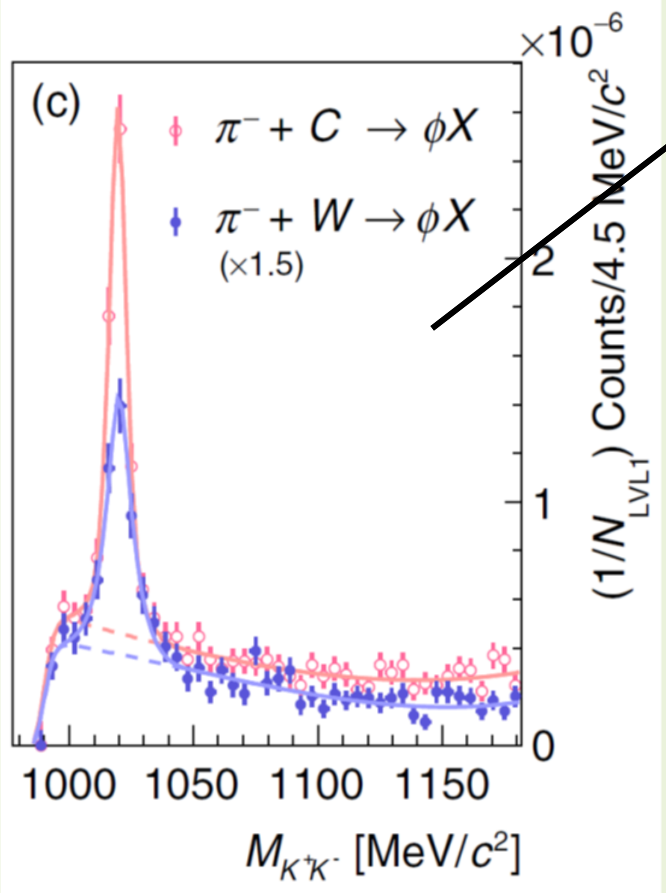


R. Muto et al. (E325 Collaboration), Phys. Rev. Lett. **98**, 042501 (2007).

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:

Attractive φ-nucleus potential of -(50 - 100) MeV

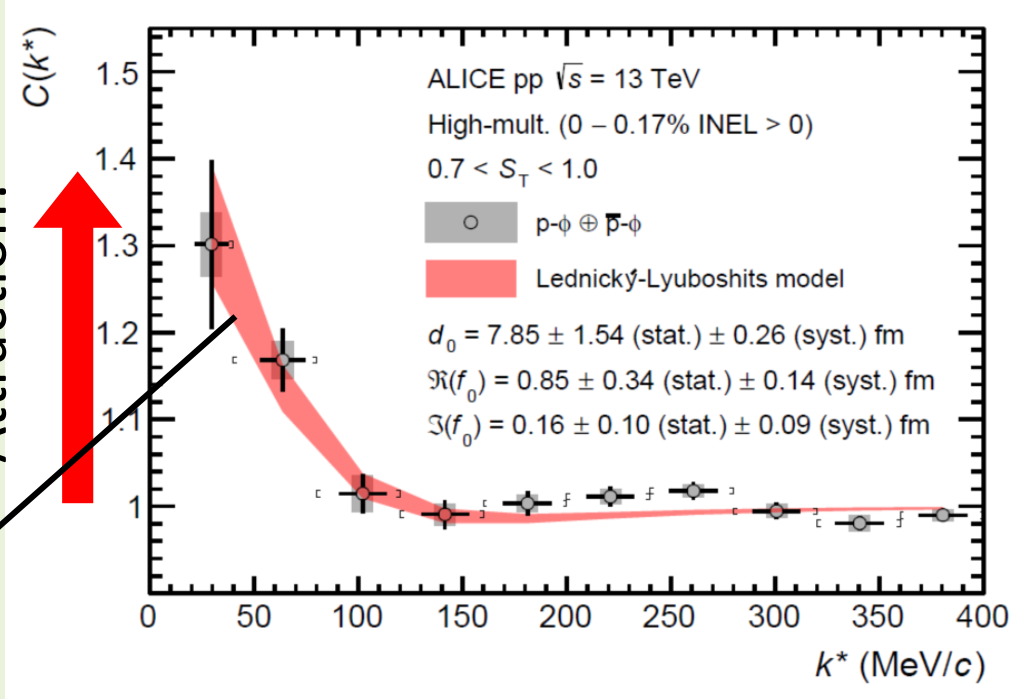
E. Ya. Paryev, Nucl. Phys. A **1032**, 122624 (2023).

Negative mass shift

ALICE: pp

Measurement of φN correlation

Attraction!



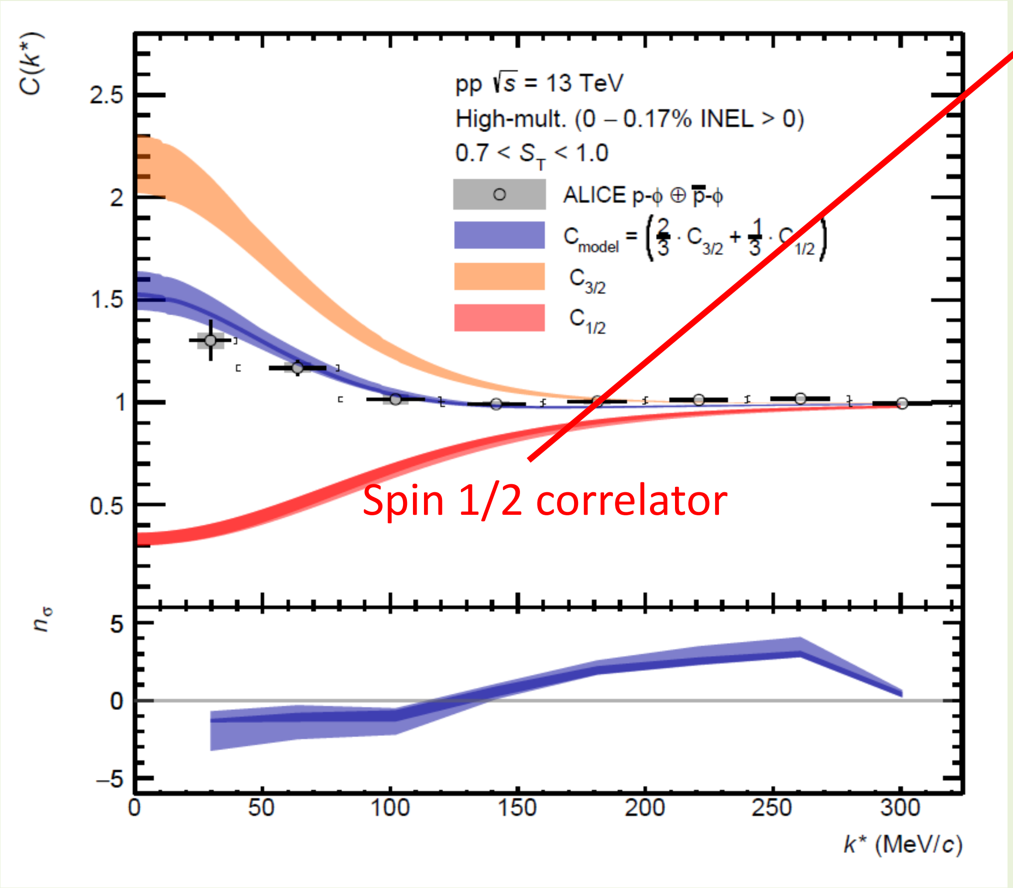
S. Acharya et al. (ALICE Coll.),
Phys. Rev. Lett. **127**, 172301 (2021).

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

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

Even more recent results

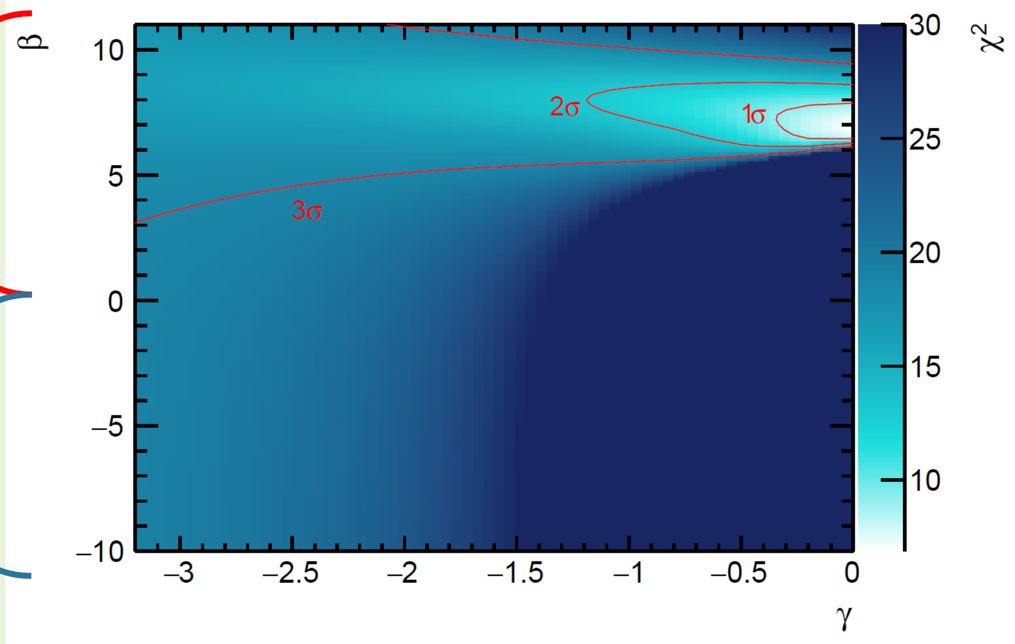
Combination of ALICE pp-data and HAL QCD (spin 3/2) calculation



E. Chizzali et al., arXiv:2212.12690 [nucl-ex].

Bound state?

Repulsive?

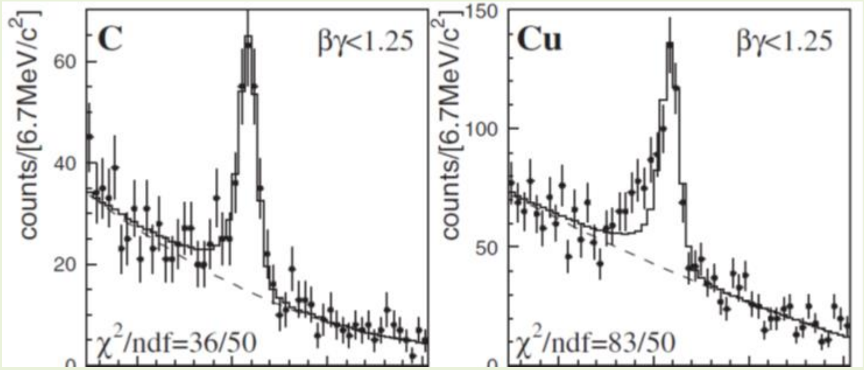


Evidence for φ-N bound state!

How compare theory with experiment?

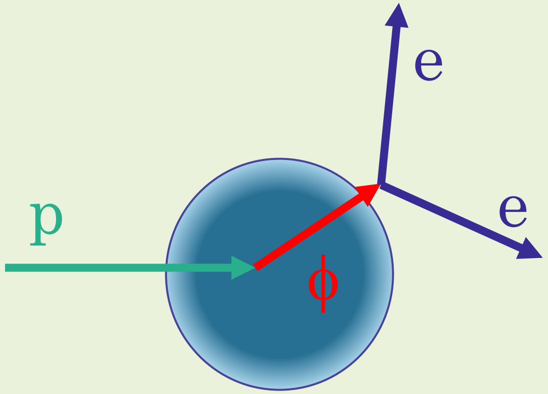
Information useful for theory

Experimental data



- ★ Spectral function as a function of density
- ★ Mass at normal nuclear matter density
- ★ Decay width at normal nuclear matter density

Realistic simulation of pA reaction is needed!



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).

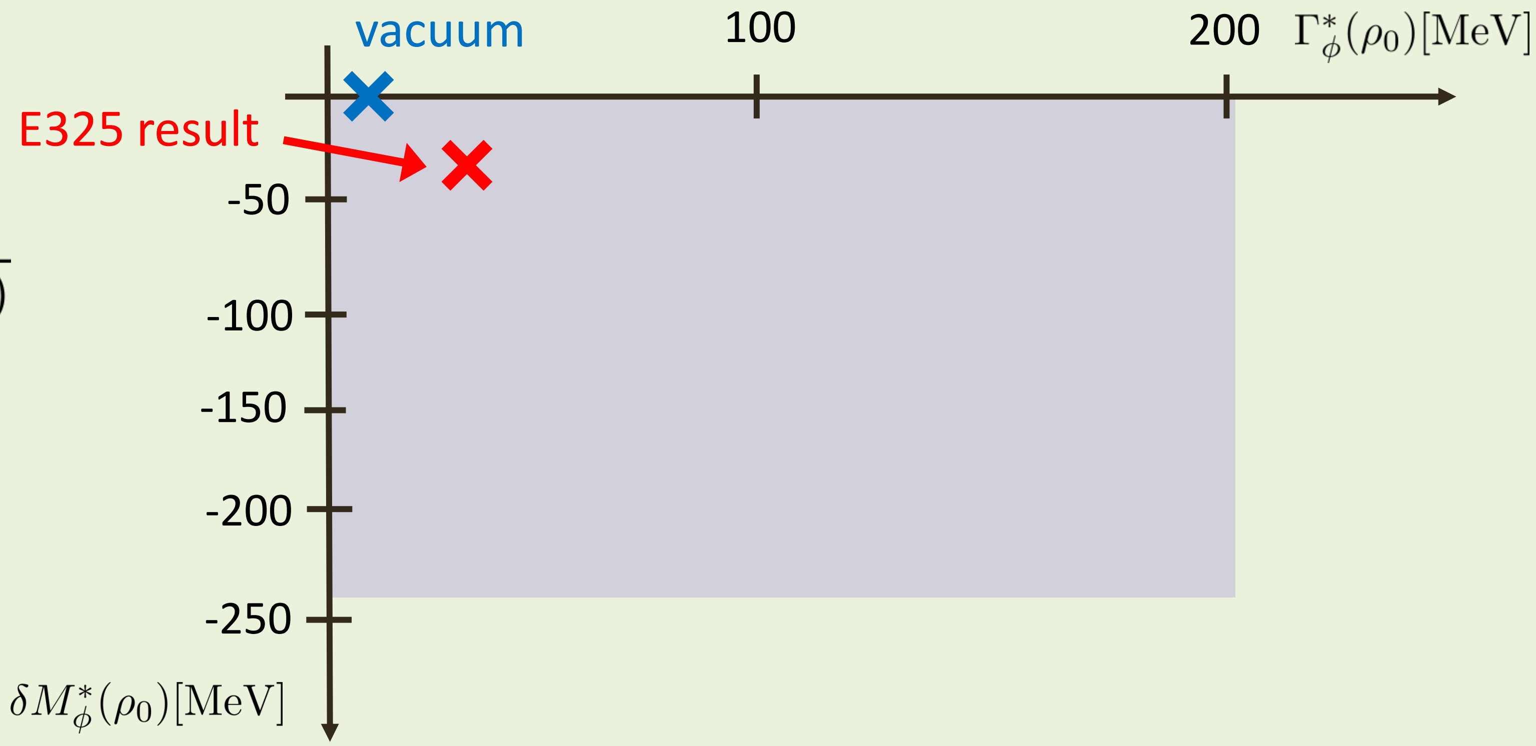
Off-shell dynamics of vector mesons and kaons
(dynamical modification of the mesonic spectral function during the simulated reaction)

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

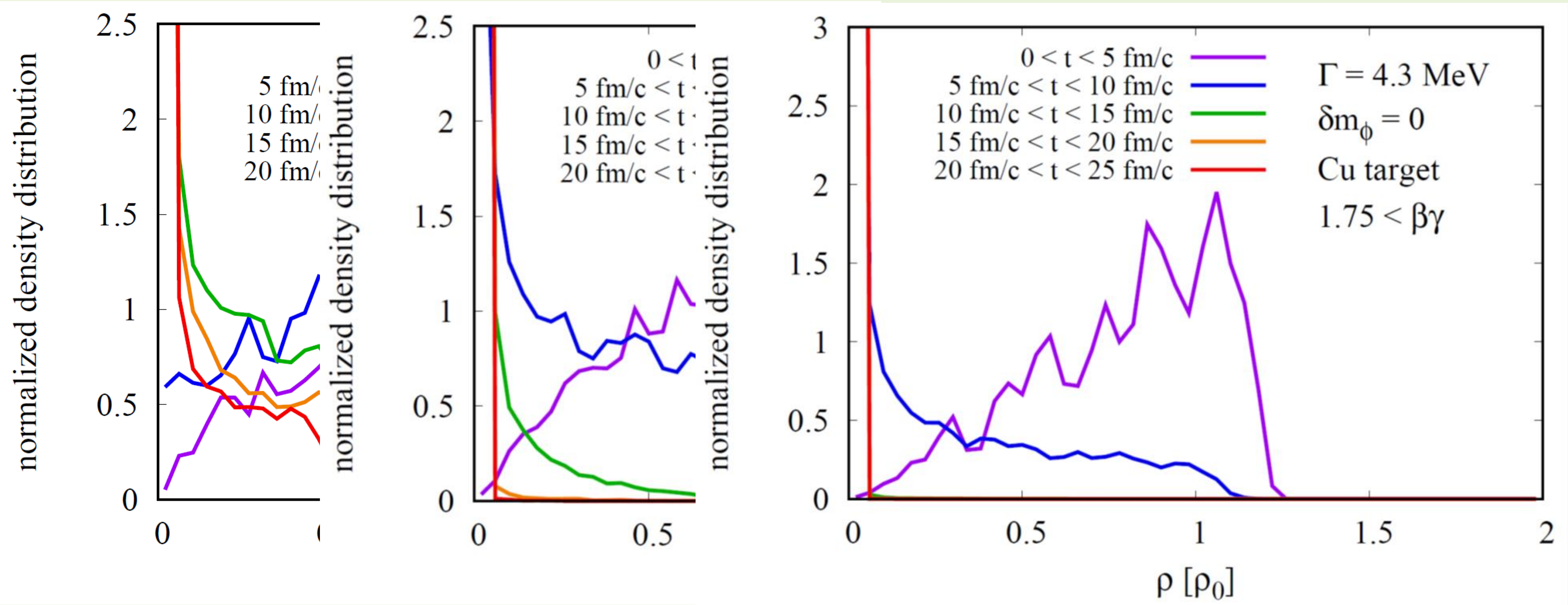
$$C\,\frac{2}{\pi}\,\frac{M^2\Gamma^*_\phi(M,\rho)}{[M^2-M^{*2}_\phi(\rho)]^2+M^2\Gamma^{*2}_\phi(M,\rho)}$$

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

Simulated scenarios:

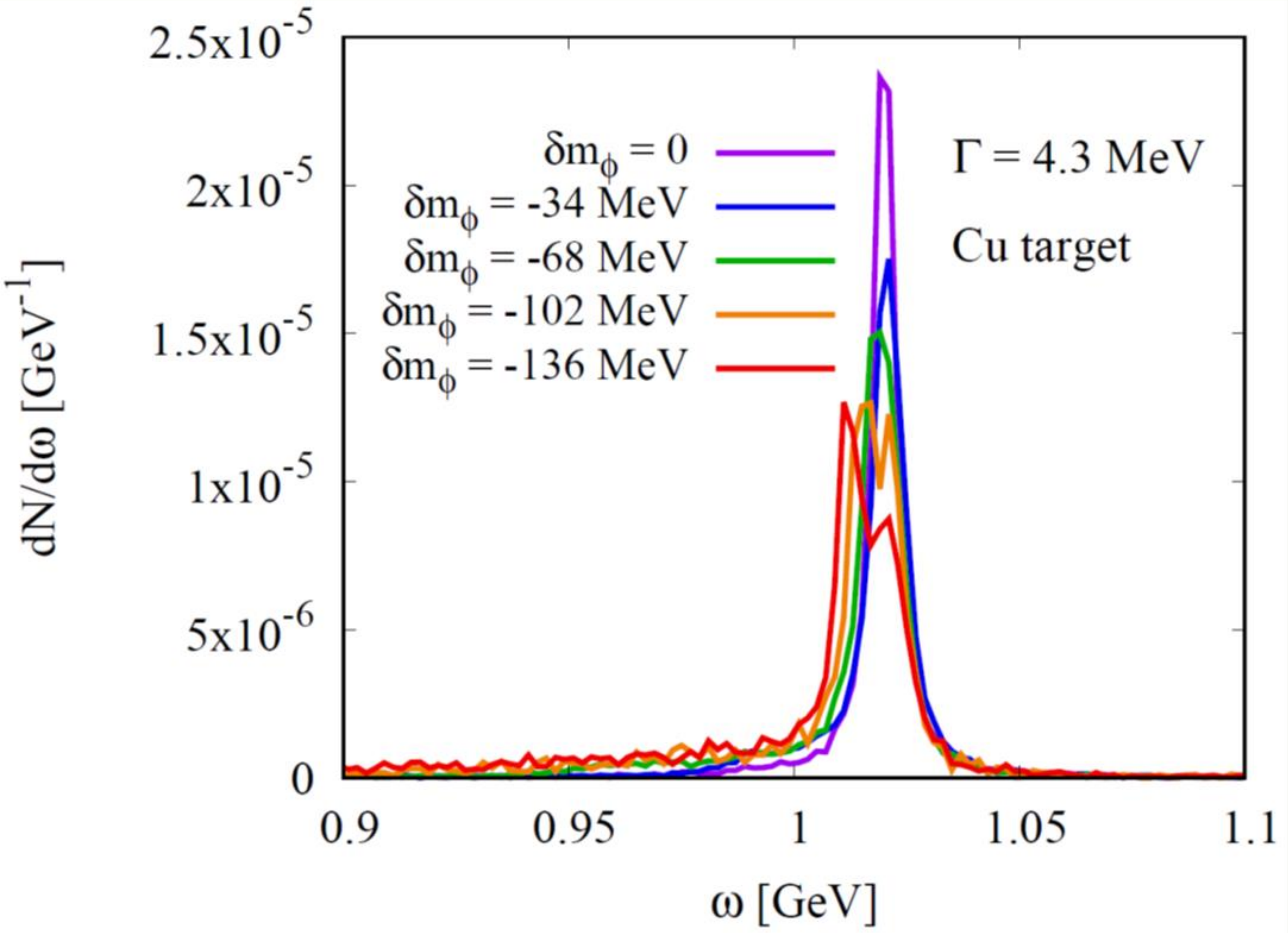


What density does the φ feel in the reaction (p+Cu at 12 GeV)?



slow φs intermediate φs fast φs

The dilepton spectrum in the φ meson region



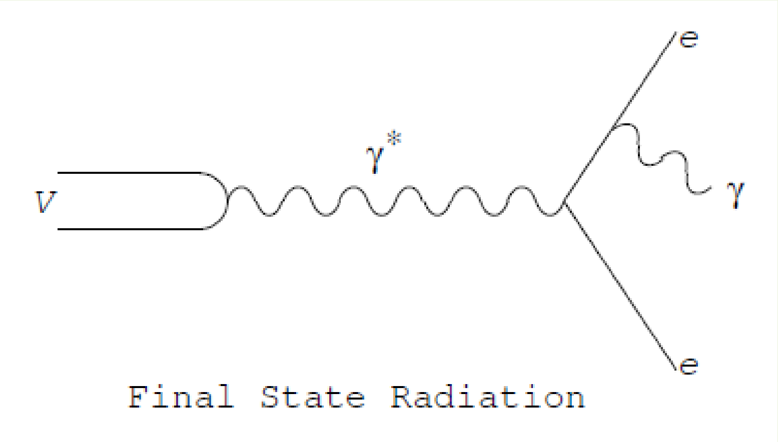
p + Cu at 12 GeV

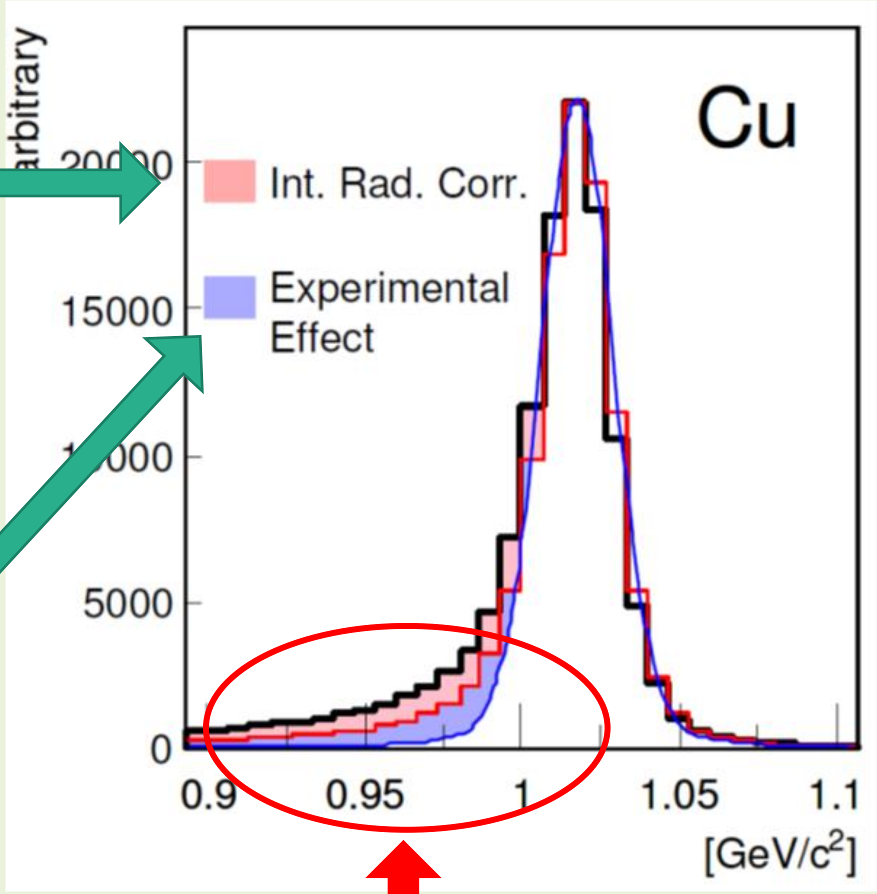
No acceptance corrections!

No finite resolution effects!

No QED effects!

How do experimental rescattering and QED effects modify the dilepton spectrum?





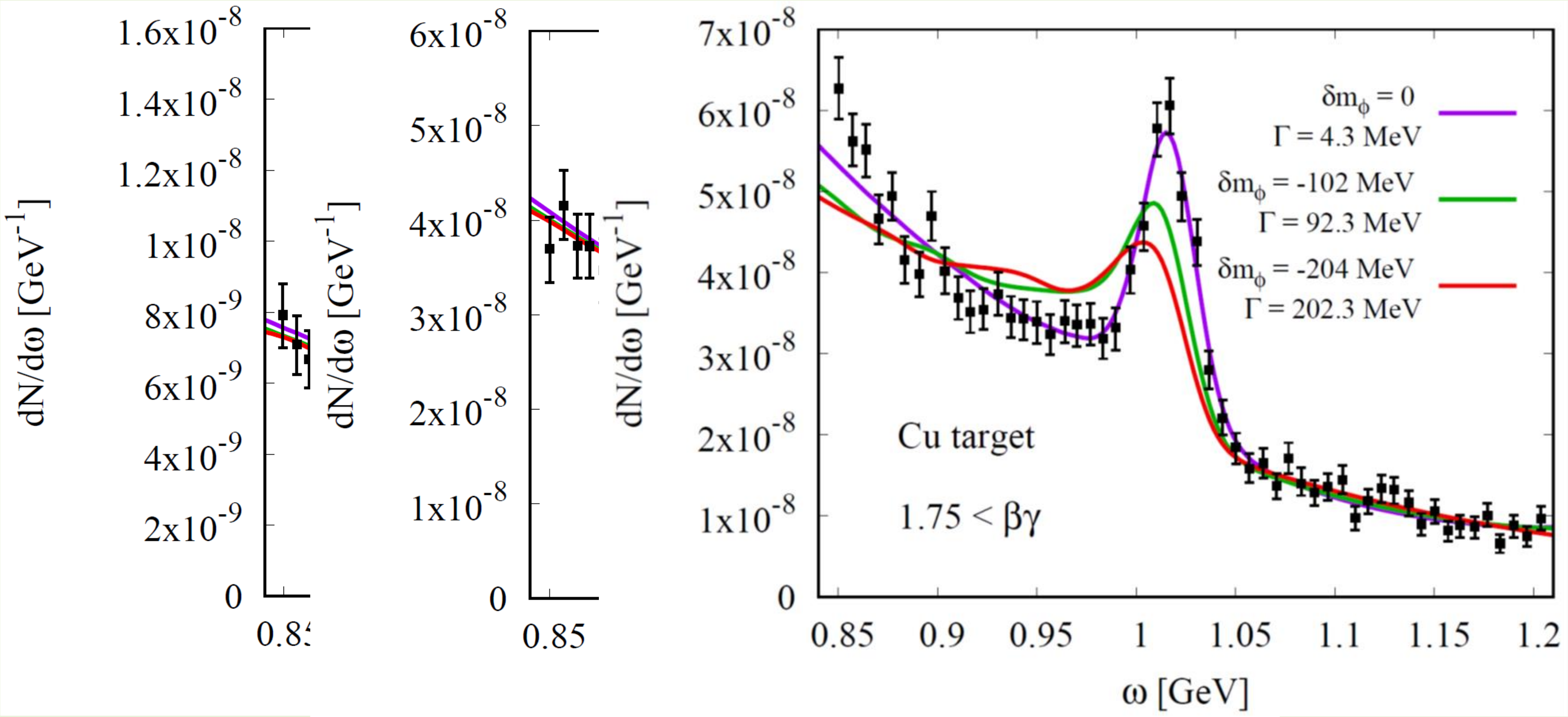
Rescattering effect

(multiple scattering, energy loss)

Similar to the shape expected for a negative mass shift

PhD Thesis of R. Muto, Kyoto U., 2007

Fits to experimental Copper target data (KEK, E325)

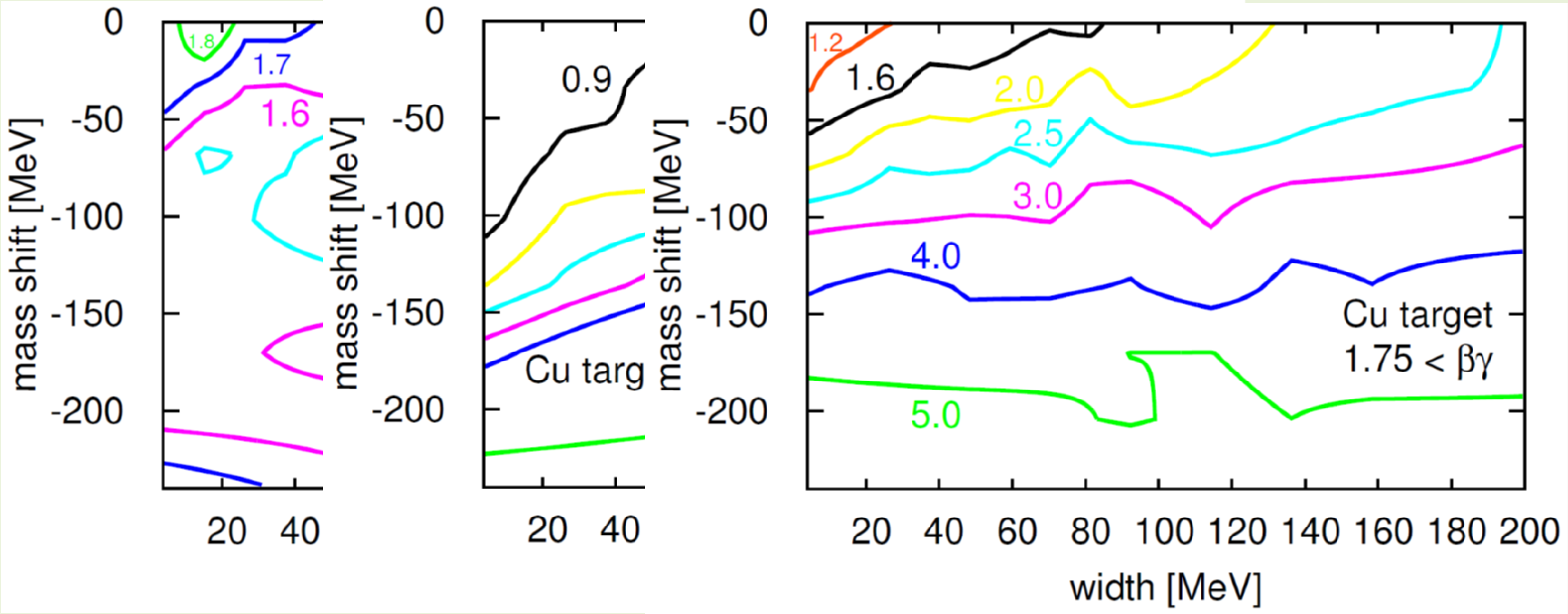


slow φs

intermediate φs

fast φs

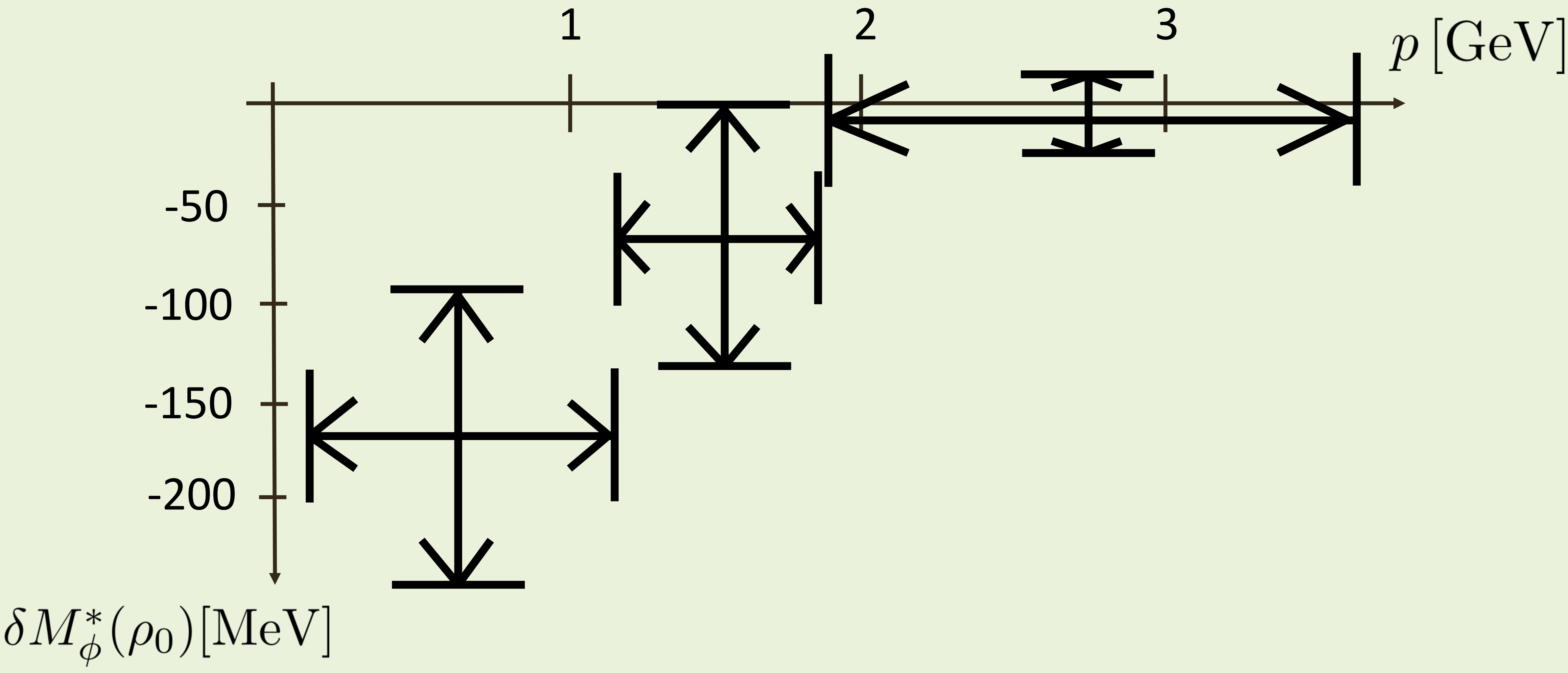
Fits to experimental Copper target data (KEK, E325)



slow φs intermediate φs fast φs

large momentum dependence!

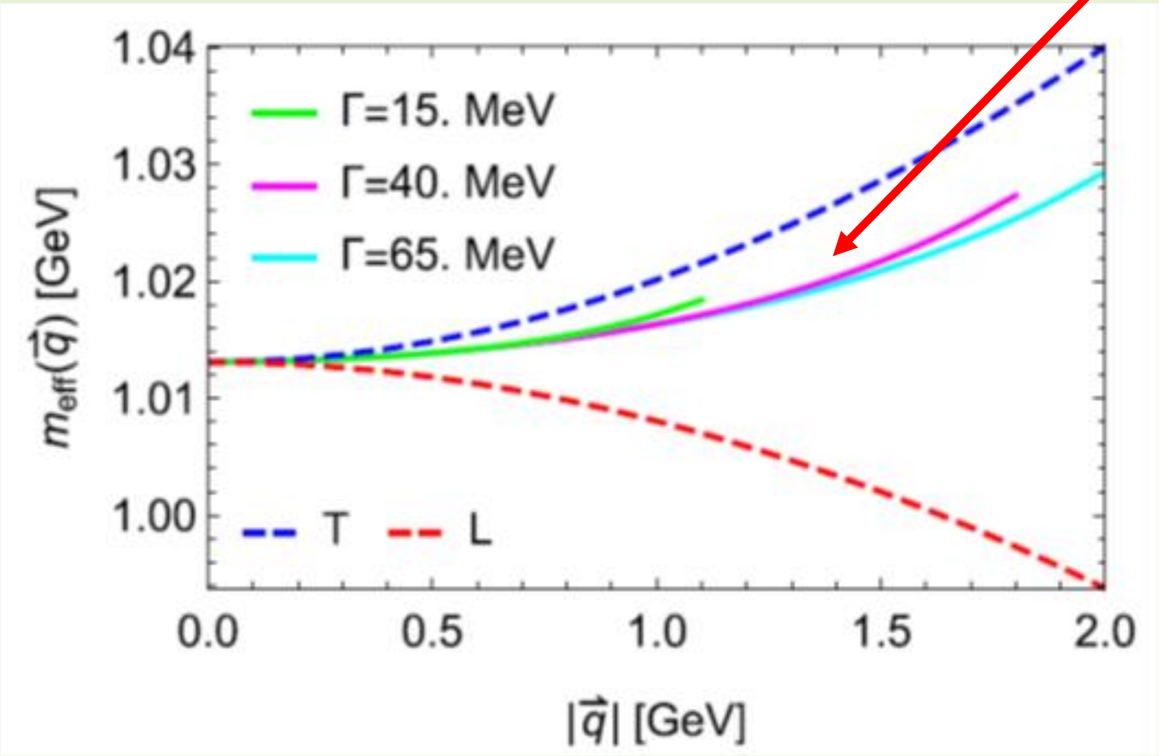
Summary of results for Copper target data (E325)



Most natural interpretation of our results

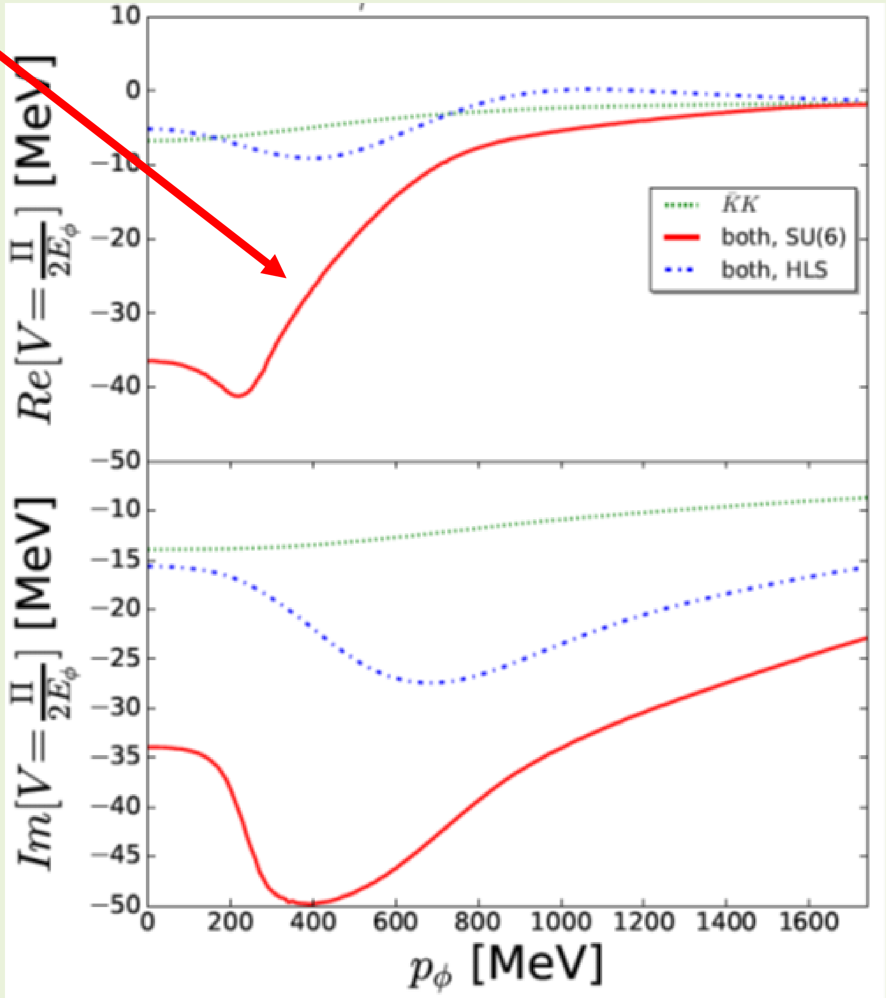
➡ Momentum dependent mass shift

QCD sum rules



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

Hadronic effective theory

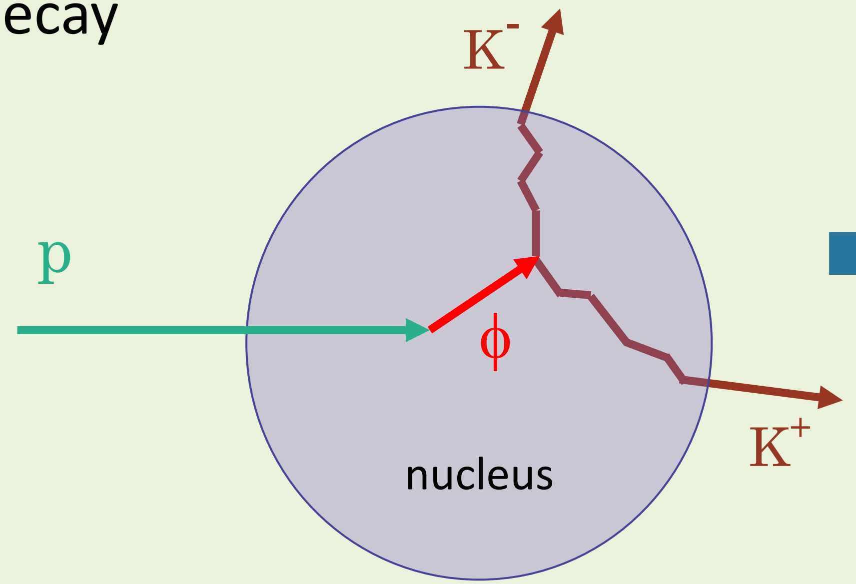


D. Cabrera *et al.*, Phys. Rev. C **95**, 015201 (2017).

Outlook

★ A lot of new experimental information about the φN interaction is becoming available (LHC, J-PARC, HADES) → Many opportunities for theorists!

★ New proposal at J-PARC to measure the $K^+ + K^-$ decay



→ **Accurate information about the KN interaction will be essential**

Summary and Conclusions

★ Relating modification of QCD condensates with hadron properties in nuclear matter is a non-trivial multi-step process

QCD condensates ⟷ Hadronic spectrum ⟷ Experimental data

★ For studying the modification of the φ meson spectral function experimentally at finite density, a good understanding of the underlying reactions is needed

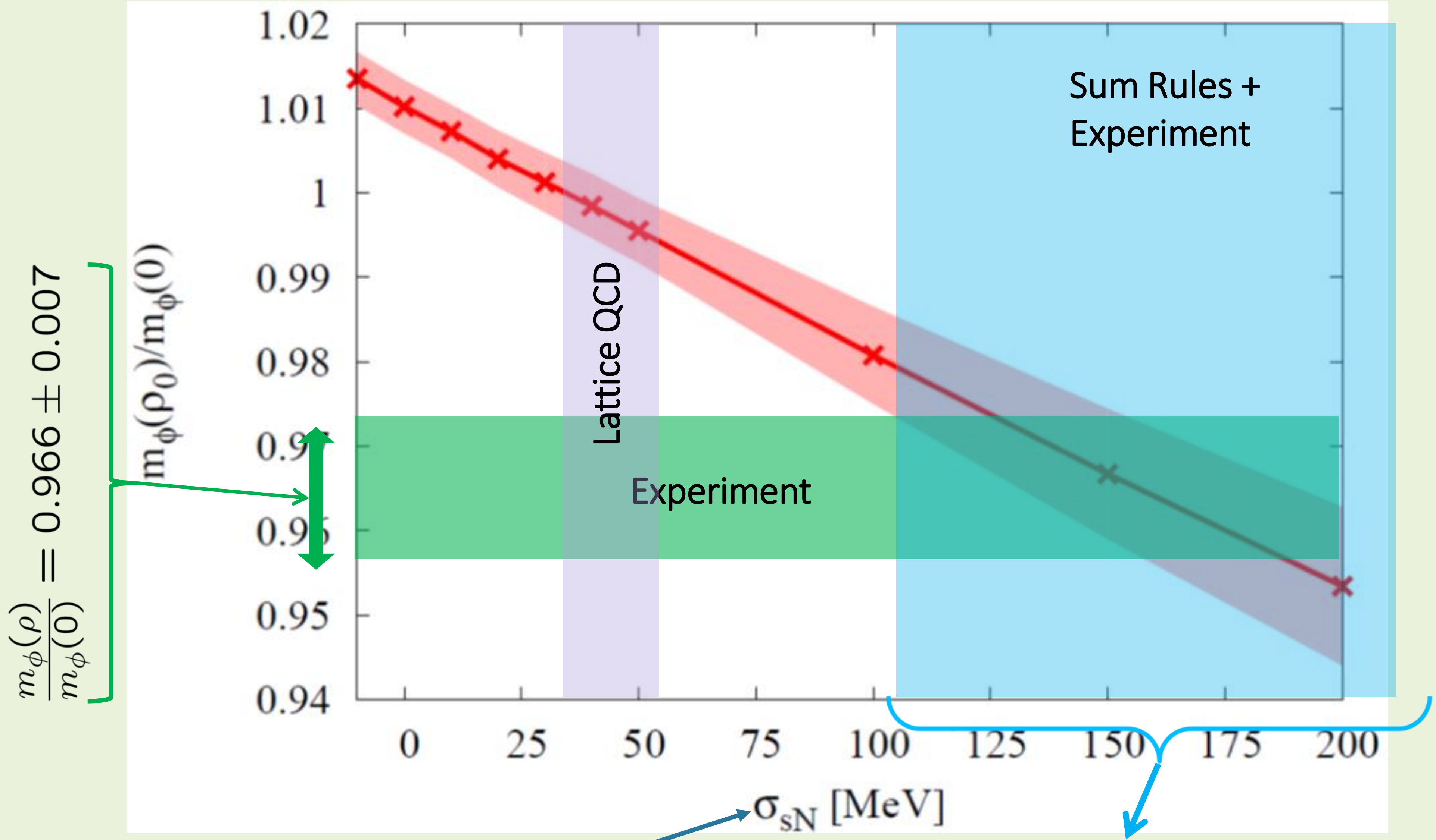
★ We conducted numerical simulations of the pA reactions measured at the E325 experiment at KEK, using the HSD transport code

⇩

Momentum-dependent mass shift is needed to explain the data

Backup slides

Consistency with QCD sum rules and lattice calculations?



Consistency would get much worse if the φ meson mass shift is about -100 MeV!!

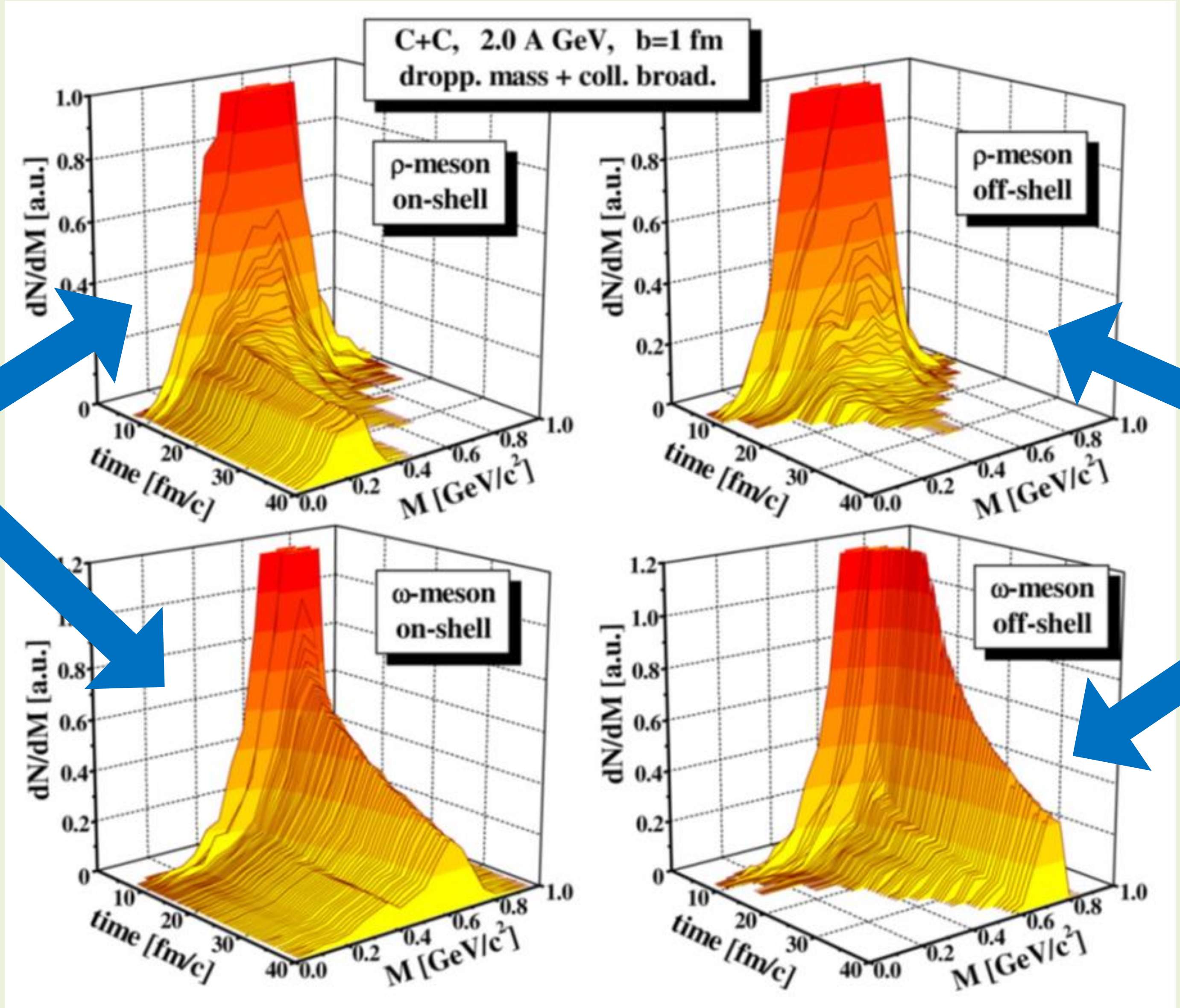
Big puzzle!!

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

$$\sigma_{sN} \sim 160 \pm 50\ \text{MeV}$$

The importance of off-shell contributions

Only on-shell contributions: Vacuum spectral function are not recovered at late time of the reaction



Off-shell contributions included: correct behavior

Taken from: E.L. Bratkovskaya and W. Cassing, Nucl. Phys. A **807**, 214 (2008).

Example of a transport calculation

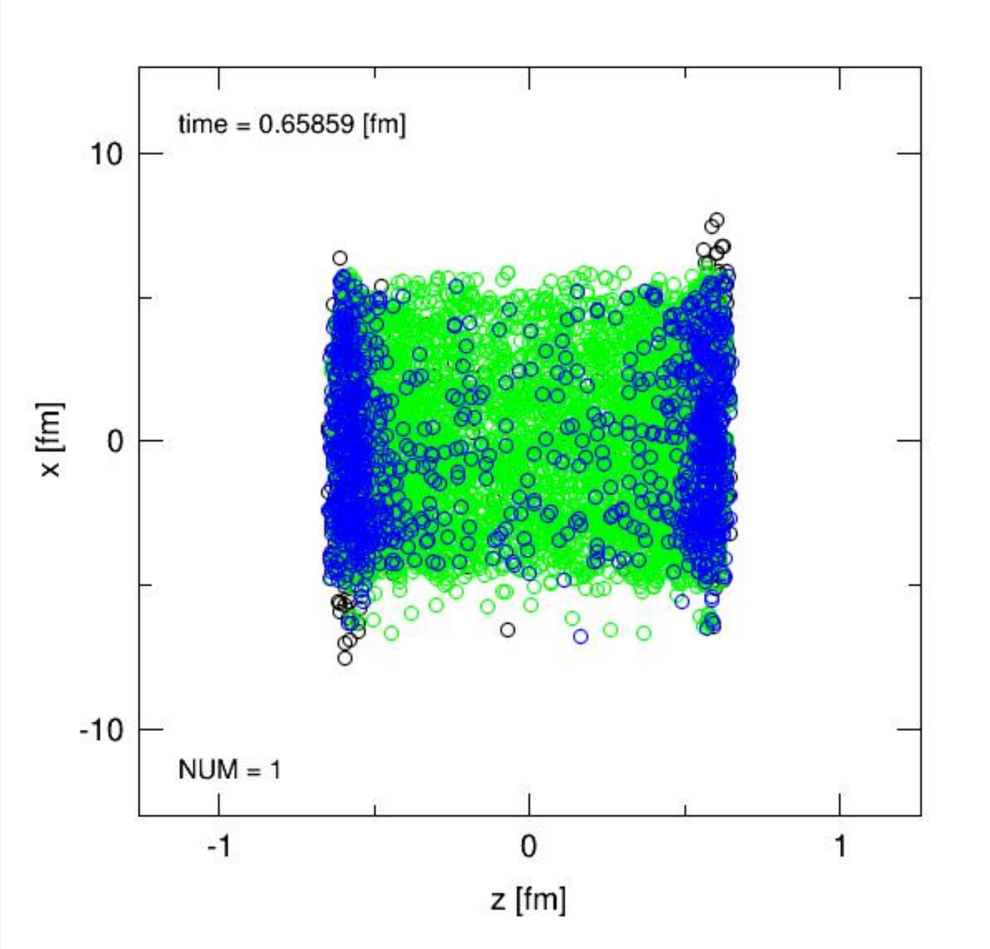
Au+Au collision at $s^{1/2}$ = 200 GeV, b = 2 fm

nucleons

quarks

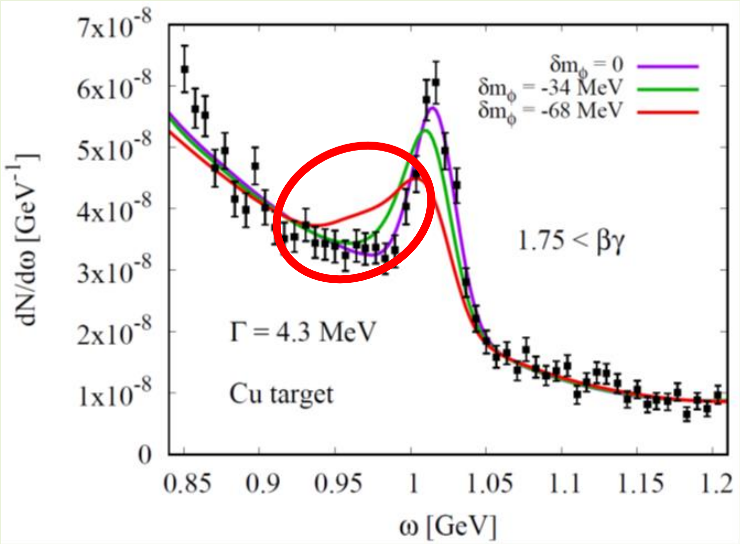
gluons

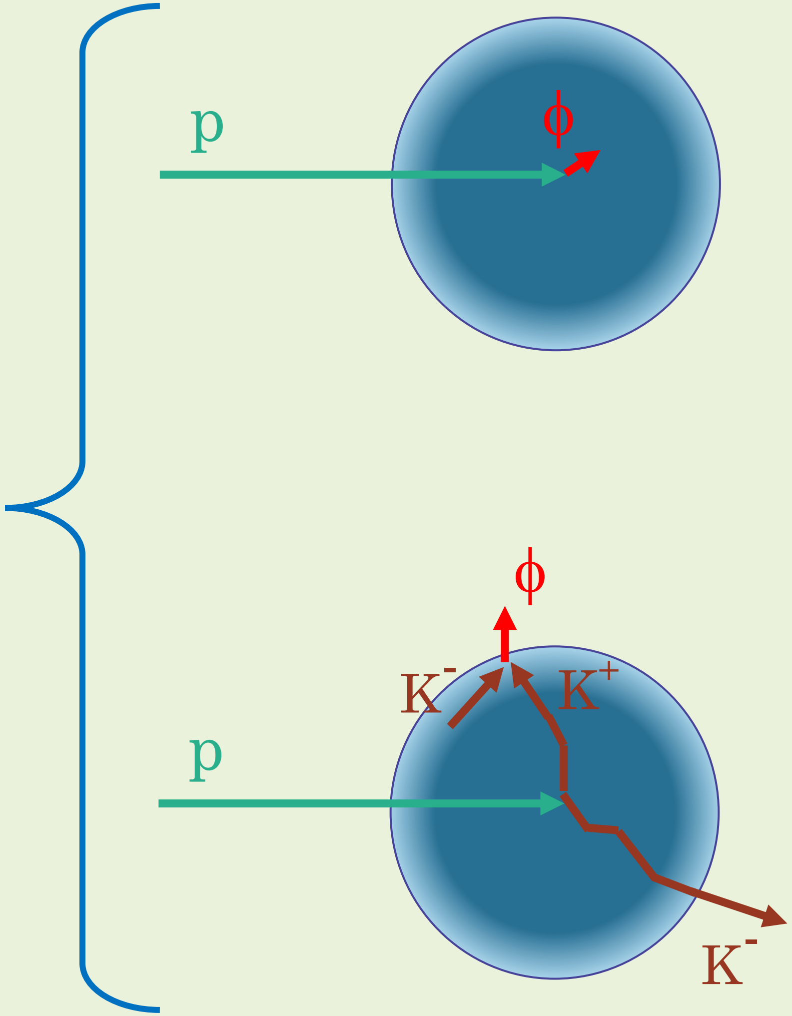
will not be included in the simulations shown in this talk



Reason for large modification for fast φ mesons

→ Initial stage of φ meson production?





φ mesons are generated from high energy collisions (via strings)

→ **large momentum**

→ **high density**

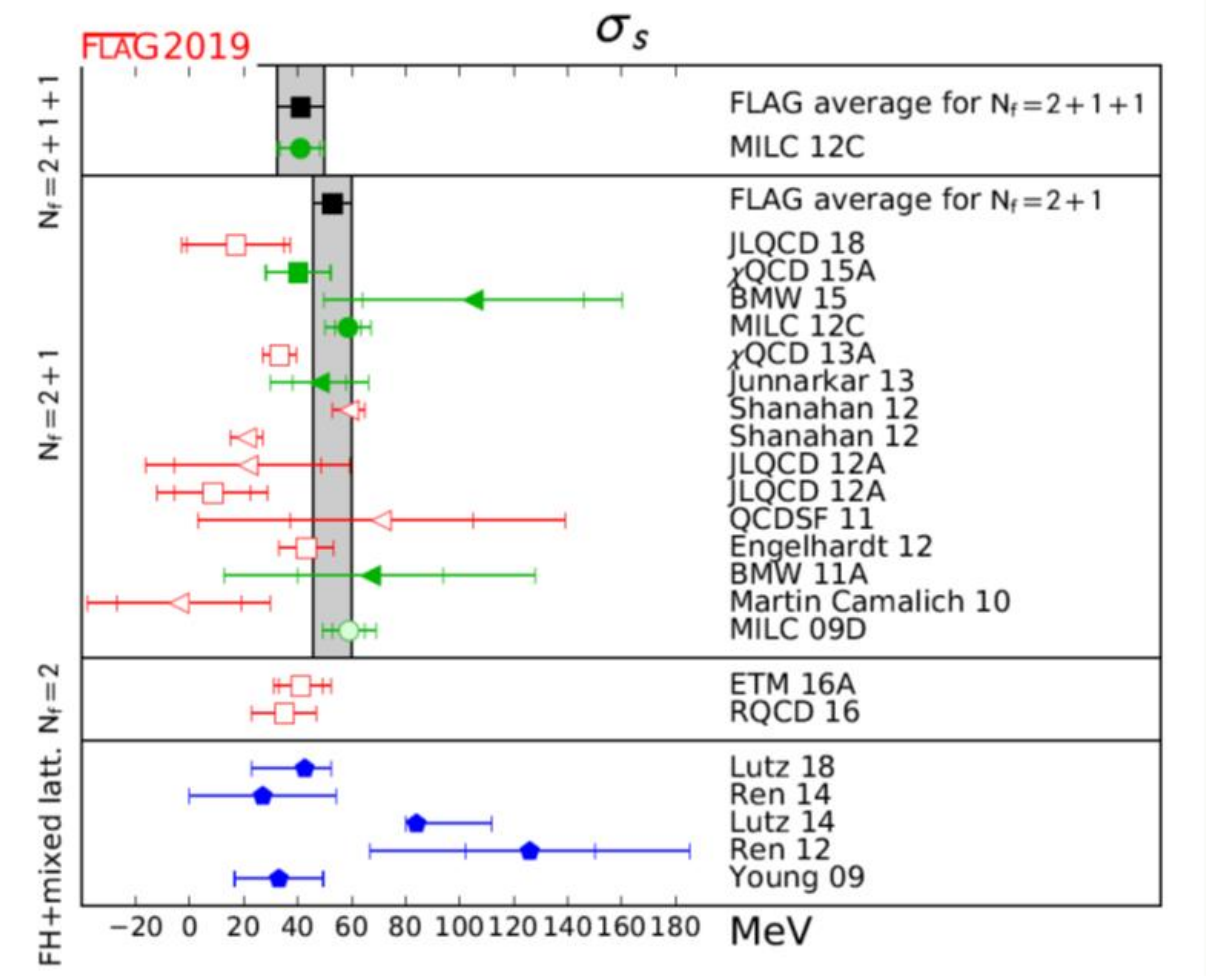
φ mesons are generated from low energy hadronic collisions

→ **small momentum**

→ **low density**

What does lattice QCD say about the strange sigma term?

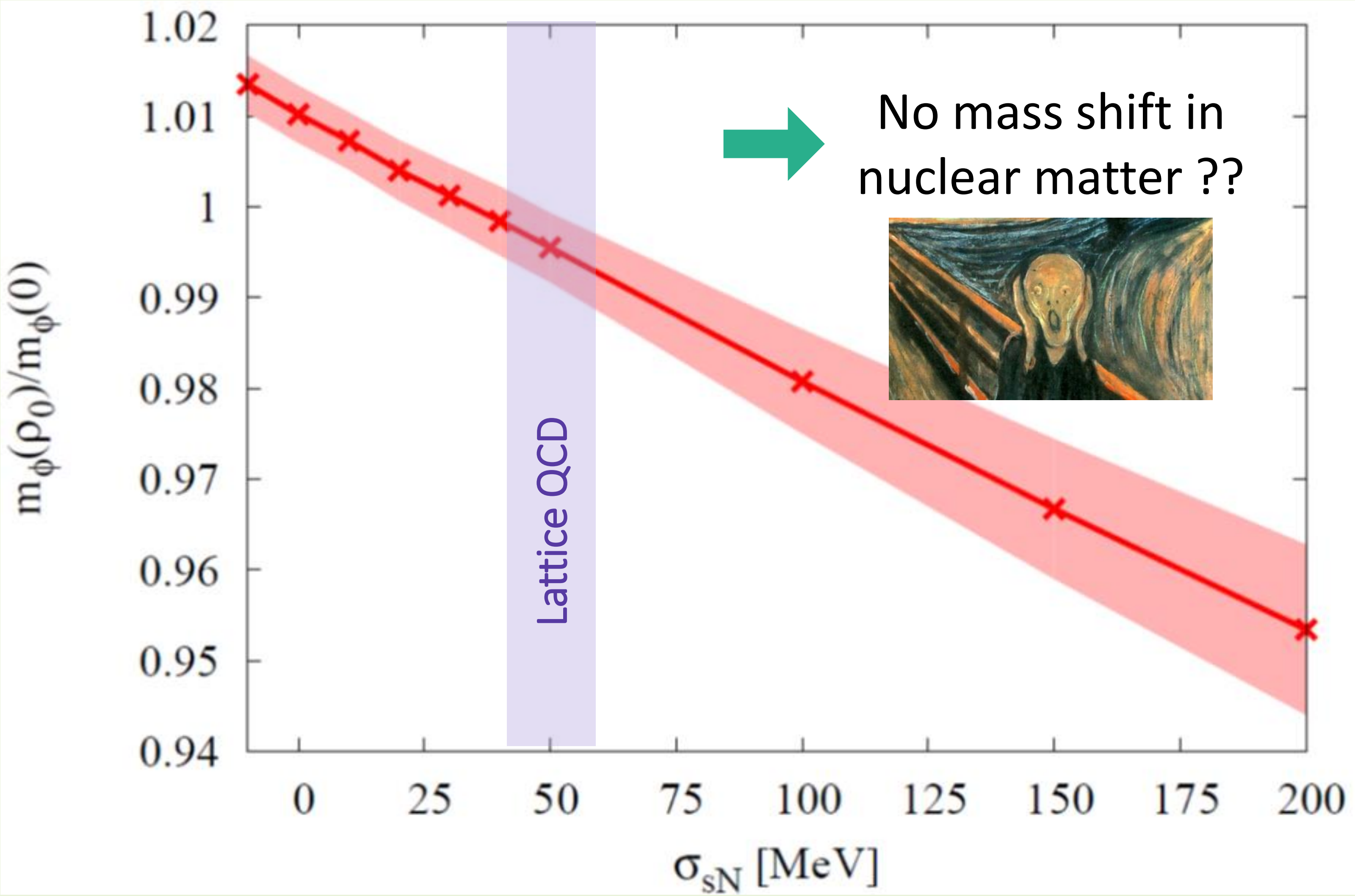
$$\sigma_{sN} = m_s \langle N|\bar{s}s|N\rangle$$



http://flag.unibe.ch/2019/

See also the most recent result of the BMW collaboration: Sz. Borsanyi et al., arXiv:2007.03319 [hep-lat].

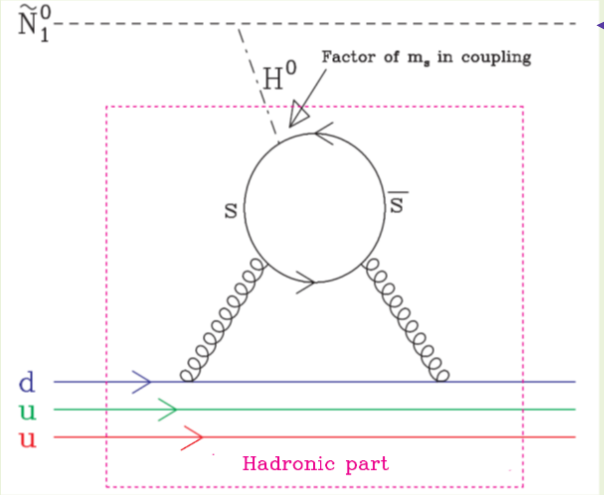
Combine QCD sum rules with lattice QCD



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

The strangeness content of the nucleon: $\sigma_{sN} = m_s\langle N|\bar{s}s|N\rangle$

Important parameter for dark-matter searches!



Neutralino:
Linear superposition of the Super-partners of the Higgs, the photon and the Z-boson

Adapted from:
W. Freeman and D. Toussaint (MILC Collaboration), Phys. Rev. D **88**, 054503 (2013).

$$\sigma^{(\text{nucleon})}_{\text{scalar}} = \frac{8G_F^2}{\pi} M_Z^2 m_{\text{red}}^2 \left[\frac{F_h I_h}{m_h^2} + \frac{F_H I_H}{m_H^2} \frac{M_Z}{2} \sum_q \langle N|\bar{q}q|N\rangle \sum_i P_{\tilde{q}_i}(A^2_{\tilde{q}_i} - B^2_{\tilde{q}_i}) \right]^2$$

most important contribution

$$I_{h,H} = k^{h,H}_{u-\text{type}} g_u + k^{h,H}_{d-\text{type}} g_d$$

dominates

$$g_d = \frac{2}{27}\left(m_N + \frac{23}{4}\sigma_{\pi N} + \frac{25}{2}\sigma_{sN}\right)$$

A. Bottino, F. Donato, N. Fornengo and S. Scopel, Asropart. Phys. **18**, 205 (2002).

Structure of QCD sum rules for the φ meson channel

(after application of the Borel transform)

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

$$\frac{1}{M^2}\int_0^{\infty} ds e^{-\frac{s}{M^2}}\rho(s) = c_0(\rho) + \frac{c_2(\rho)}{M^2} + \frac{c_4(\rho)}{M^4} + \frac{c_6(\rho)}{M^6} + \dots$$

In Vacuum

Dim. 0: $c_0(0) = 1 + \frac{\alpha_s}{\pi}$

Dim. 2: $c_2(0) = -6m_s^2$

Dim. 4: $c_4(0) = \frac{\pi^2}{3}\langle 0|\frac{\alpha_s}{\pi}G^2|0\rangle + 8\pi^2 m_s\langle 0|\overline{s}s|0\rangle$

Dim. 6: $c_6(0) = -\frac{448}{81}\kappa\pi^3\alpha_s\langle 0|\overline{s}s|0\rangle^2$

Structure of QCD sum rules for the φ meson

$$\frac{1}{M^2}\int_0^\infty ds e^{-\frac{s}{M^2}}\rho(s) = c_0(\rho) + \frac{c_2(\rho)}{M^2} + \frac{c_4(\rho)}{M^4} + \frac{c_6(\rho)}{M^6} + \dots$$

At finite density

(within the linear density approximation)

$$\langle \overline{s}s\rangle_\rho = \langle 0|\overline{s}s|0\rangle + \langle N|\overline{s}s|N\rangle\rho + \dots$$

Dim. 0: $c_0(\rho) = c_0(0)$

Dim. 2: $c_2(\rho) = c_2(0)$

Dim. 4: $c_4(\rho) = c_4(0) + \rho[-\frac{2}{27}M_N + \frac{56}{27}m_s\langle N|\overline{s}s|N\rangle + \frac{4}{27}m_q\langle N|\overline{q}q|N\rangle + A_2^s M_N - \frac{7}{12}\frac{\alpha_s}{\pi}A_2^g M_N]$

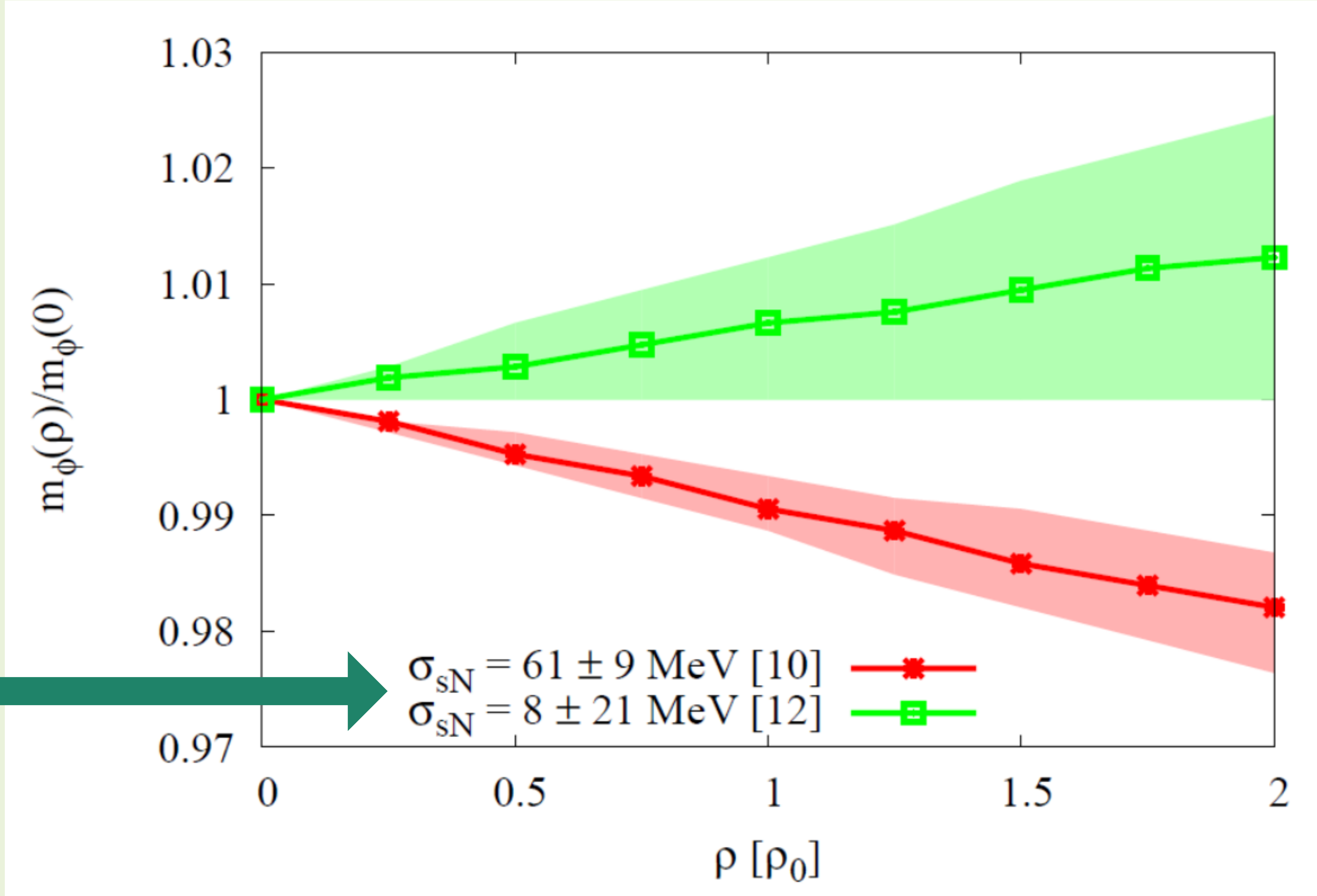
Dim. 6: $c_6(\rho) = c_6(0) + \rho[-\frac{896}{81}\kappa_N\pi^3\alpha_s\langle\overline{s}s\rangle\langle N|\overline{s}s|N\rangle - \frac{5}{6}A_4^s M_N^3]$

Results for the ϕ meson mass at rest

Most important parameter, that determines the behavior of the ϕ meson mass at finite density:

Strangeness content of the nucleon

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



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

Recent experimental results

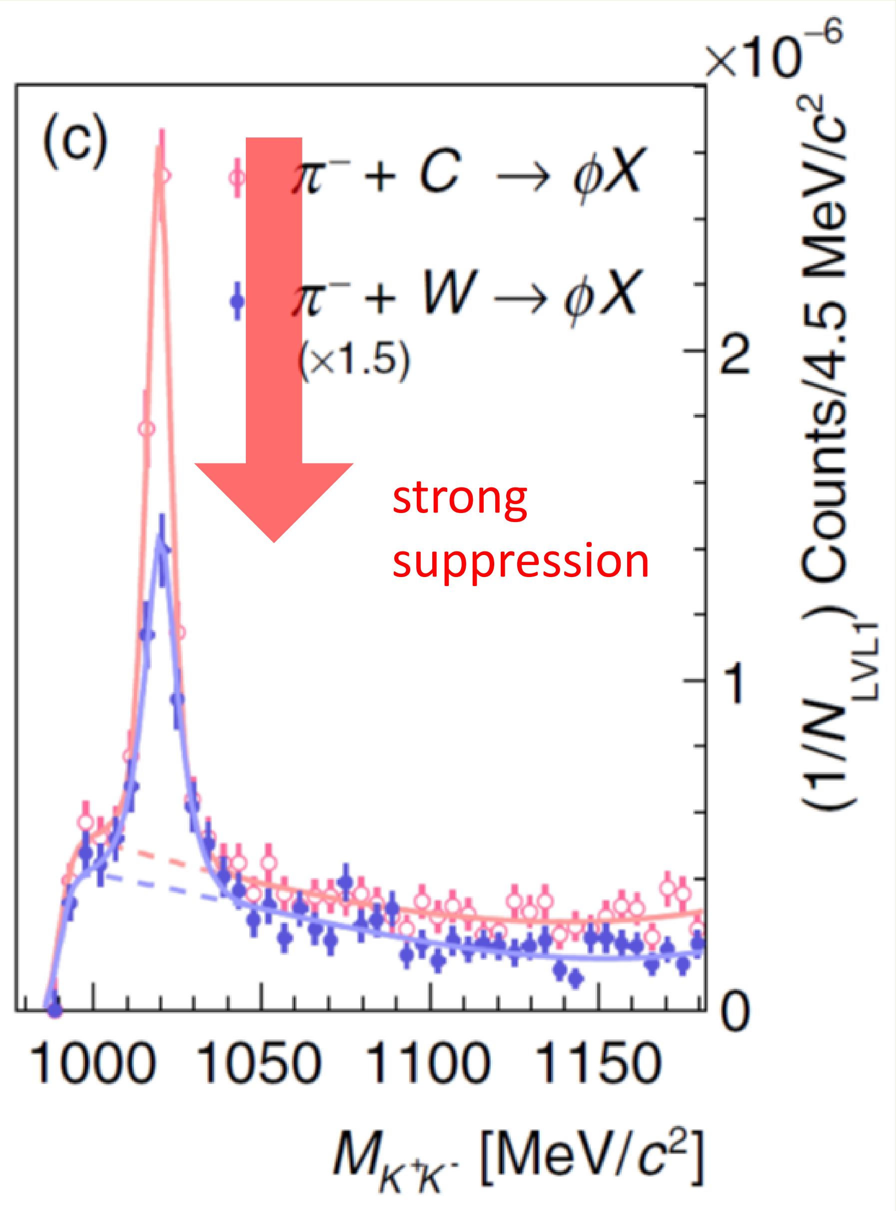
HADES: 1.7 GeV π^-A-reaction

- ★ Larger suppression of K^- in the Tungsten target compared to the Carbon target
- ★ K^-/φ ratio is similar for both Tungsten and Carbon targets

↓

- ★ Observation of large suppression (broadening?) of the φ meson in large nuclei

K^+K^- - invariant mass spectrum

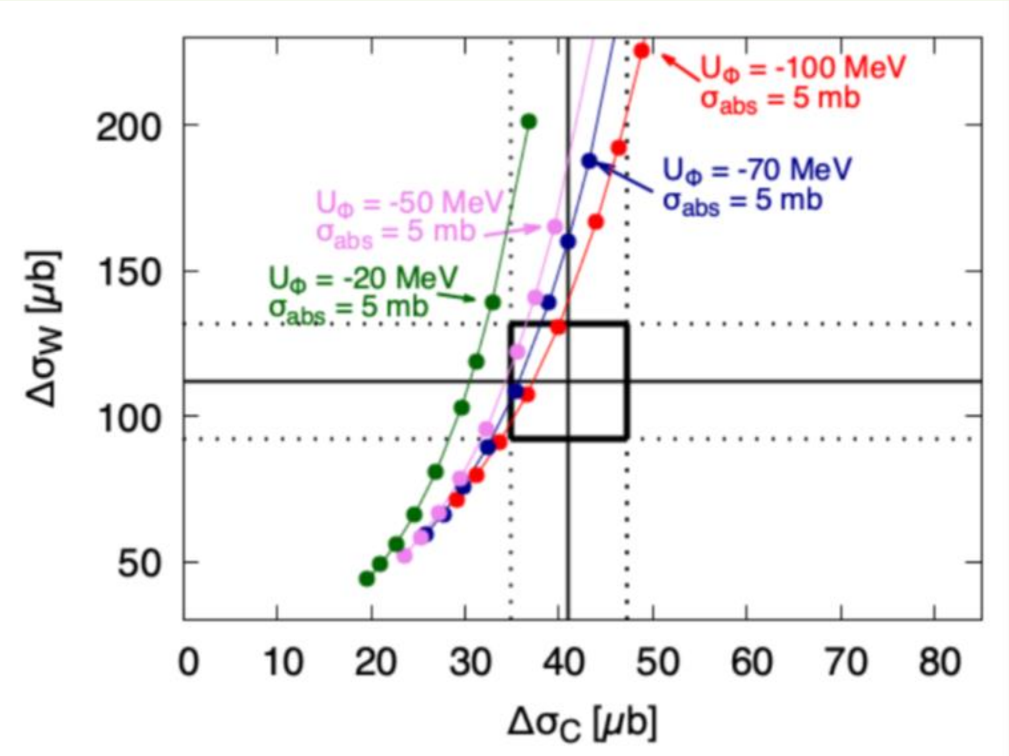


J. Adamczewski-Musch et al. (HADES Collaboration), Phys. Rev. Lett. **123**, 022002 (2019).

Even more recent results

HADES: 1.7 GeV π^-A-reaction

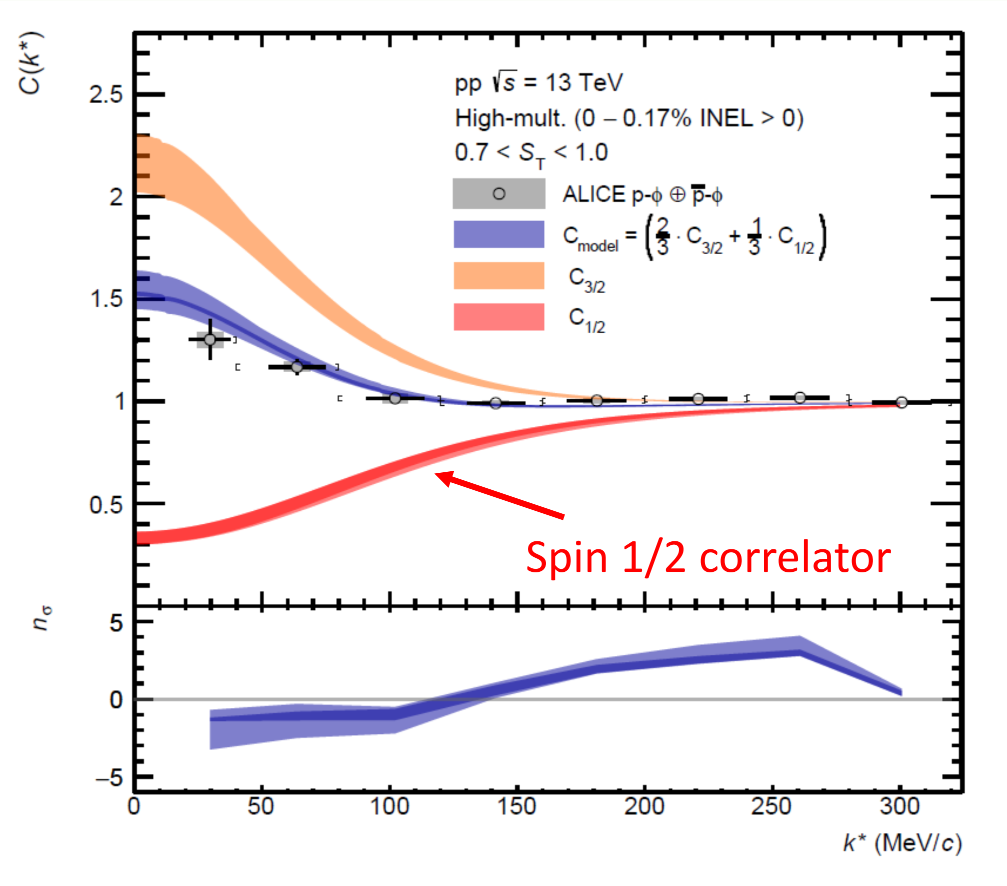
K^+K^- - invariant mass spectrum



Theoretical calculation by E. Ya. Paryev:
E. Ya. Paryev, Nucl. Phys. A **1032**, 122624 (2023).

→ Attractive φ-nucleus potential:
-(50 - 100) MeV

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



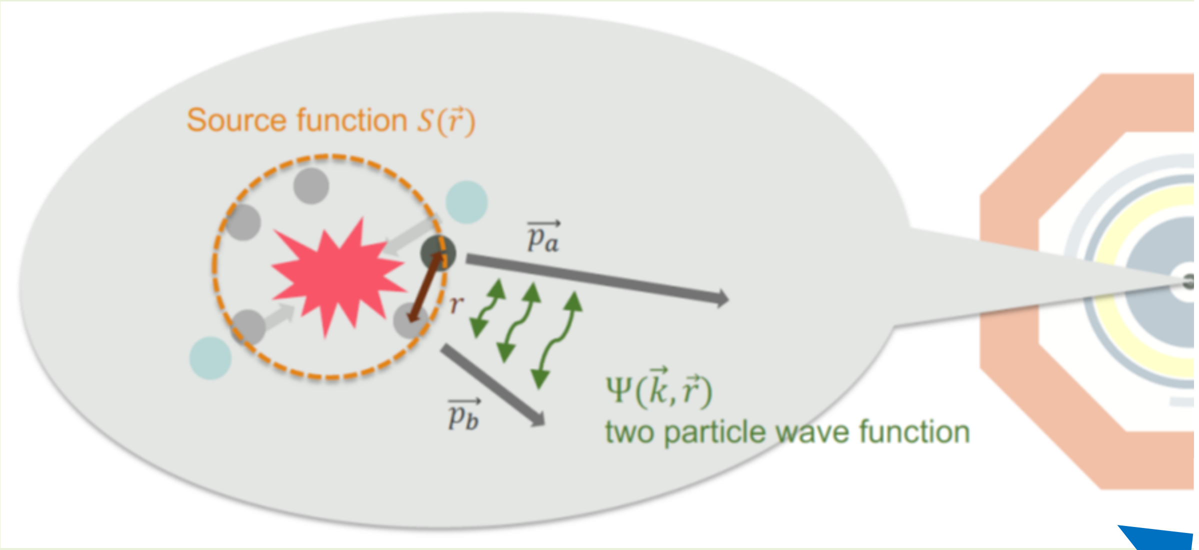
E. Chizzali et al., arXiv:2212.12690 [nucl-ex].

→ Evidence for φ-N bound state!

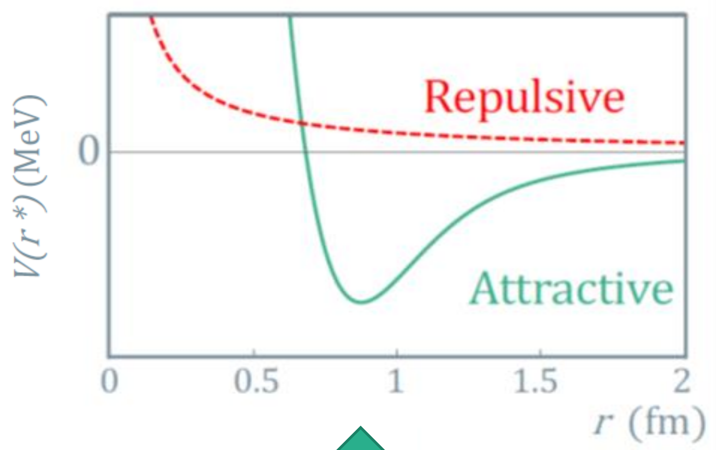
→ Attractive φ-nucleus potential ≈ -100 MeV

New experimental results

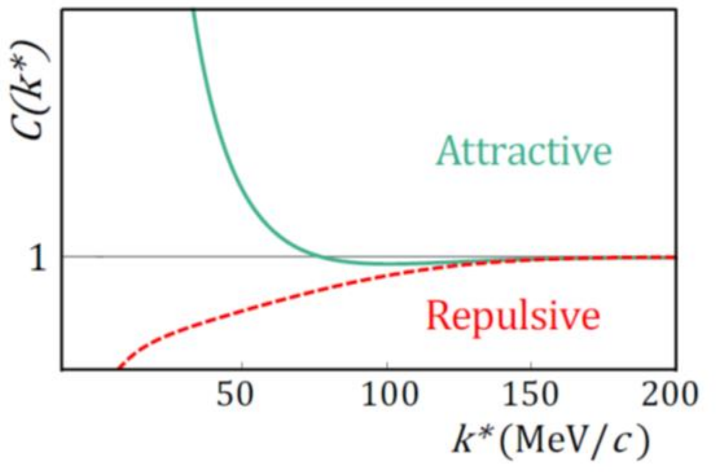
ALICE (Femtoscopy)



Interaction potential



Correlation function



The observable to be measured: the correlation function:

$$C(k) = \mathcal{N}\,\frac{N_{\text{Same}}}{N_{\text{Mixed}}} = \int S(\vec{r})\,|\Psi(\vec{k},\vec{r})|^2\, d^3\vec{r}$$

Emission source (Gaussian)

Relative momentum of the particle pair

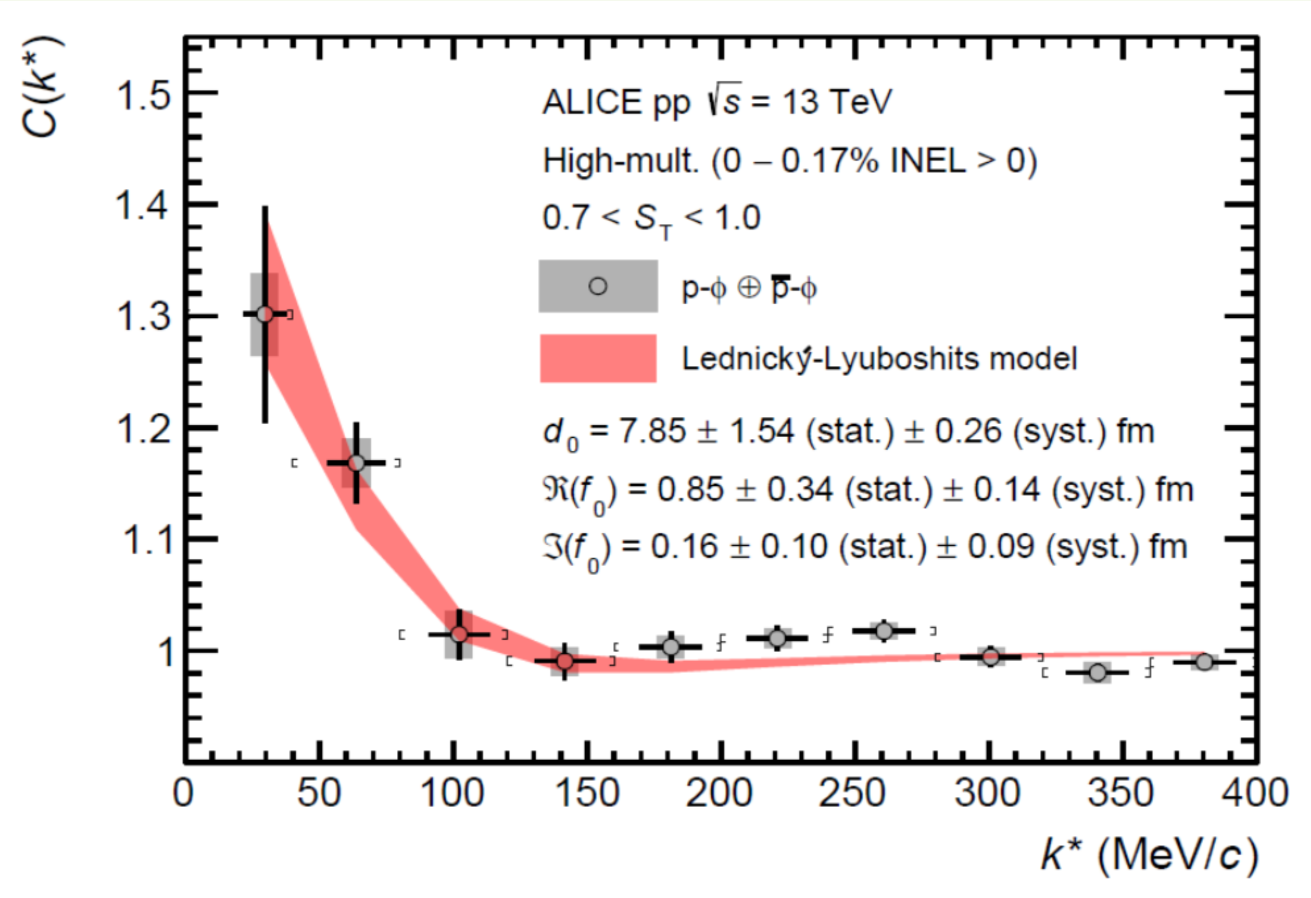
S. Acharya et al. (ALICE Collaboration), Phys. Rev. Lett. **127**, 172301 (2021).

New experimental results

ALICE

Measurement of φN correlation

Attraction!



Extracted φN scattering length

Real part:

$$\mathrm{Re}(f_0) = 0.85 \pm 0.34(\mathrm{stat.}) \pm 0.14(\mathrm{syst.})\ \mathrm{fm}$$

→ Attractive

Imaginary part:

$$\mathrm{Im}(f_0) = 0.16 \pm 0.10(\mathrm{stat.}) \pm 0.09(\mathrm{syst.})\ \mathrm{fm}$$

→ Small absorption/broadening ?

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

New experimental results

ALICE

Fit of the correlation function data to two simple phenomenological potentials

$$E_{\text{int}} = \int d^3\vec{r} \int d^3\vec{r}\,' \rho_N(\vec{r}) V(\vec{r} - \vec{r}\,') \rho_\phi(\vec{r}\,')$$

$\rho_N(\vec{r}) \rightarrow \rho_0$, $\rho_\phi(\vec{r}\,') \rightarrow \delta^{(3)}(\vec{r}\,')$

$$V_{\text{Yukawa}}(r) = -\frac{A}{r} e^{-\alpha r}$$

$$A = 0.021 \pm 0.009\,(\text{stat.}) \pm 0.006\,(\text{syst.})$$

$$\alpha = 65.9 \pm 38.0\,(\text{stat.}) \pm 17.5\,(\text{syst.})\,\text{MeV}$$

$$\rightarrow \quad E_{\text{int}} = -\frac{4\pi A \rho_0}{\alpha^2} = -79.3 \pm 108.8\,\text{MeV}$$

$$V_{\text{Gaussian}}(r) = -V_{\text{eff}} e^{-\mu r^2}$$

$$V_{\text{eff.}} = 2.5 \pm 0.9\,(\text{stat.}) \pm 1.4\,(\text{syst.})\,\text{MeV}$$

$$\mu = 0.14 \pm 0.06\,(\text{stat.}) \pm 0.09\,(\text{syst.})\,\text{fm}^{-2}$$

$$\rightarrow \quad E_{\text{int}} = -\frac{\pi^{3/2} V_{\text{eff}} \rho_0}{\mu^{3/2}} = -45.2 \pm 61.5\,\text{MeV}$$

S. Acharya et al. (ALICE Collaboration), arXiv:2105.05578 [nucl-ex].

→ Larger attraction than what was observed at KEK 325, but large statistical and systematic uncertainties

Our tool: a transport approach

Basic Ingredient 1: Solve a Boltzmann-Uehling-Uhlenbeck (BUU) type equation for each particle type

$$\left(\frac{\partial}{\partial t} + \vec{\nabla}_p \epsilon \cdot \vec{\nabla}_r - \vec{\nabla}_r \epsilon \cdot \vec{\nabla}_p\right) f_a(\vec{r}, \vec{p}; t) = I_{\text{coll}}[f_a(\vec{r}, \vec{p}; t)]$$

Includes mean field (tuned to reproduce nuclear matter properties)

particle distribution function

Basic Ingredient 2: „Testparticle“ approach →

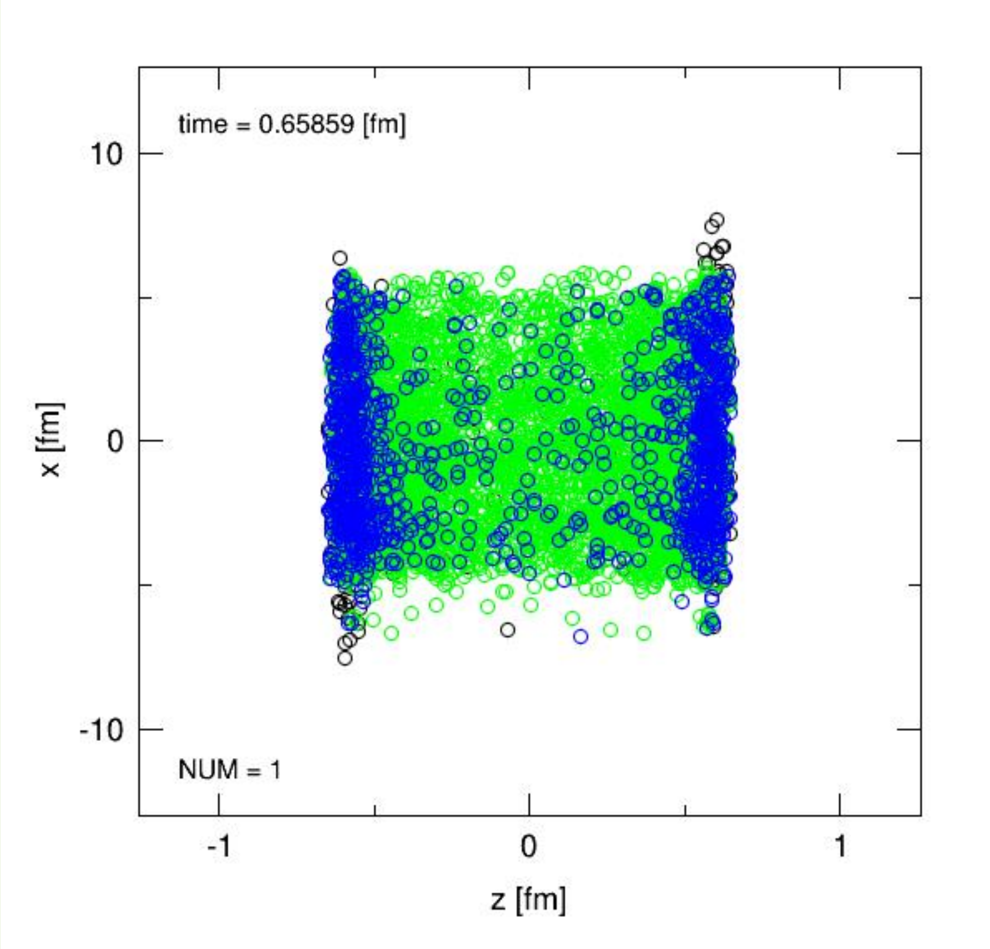
$$f_h(\boldsymbol{r}, \boldsymbol{p}; t) = \frac{1}{N_{\text{test}}} \sum_{i}^{N_h(t) \times N_{\text{test}}} \delta(\boldsymbol{r} - \boldsymbol{r}_i(t))\ \delta(\boldsymbol{p} - \boldsymbol{p}_i(t))$$

Example of a transport calculation

Au+Au collision at $s^{1/2}$ = 200 GeV, b = 2 fm

nucleons
quarks
gluons

will not be included in the simulations shown in this talk



Final step: comparison to experimental data

Potential issues:

- ★ Experimental background is not included in the simulation
- ★ Normalization of the experimental dilepton spectrum is not given

↓

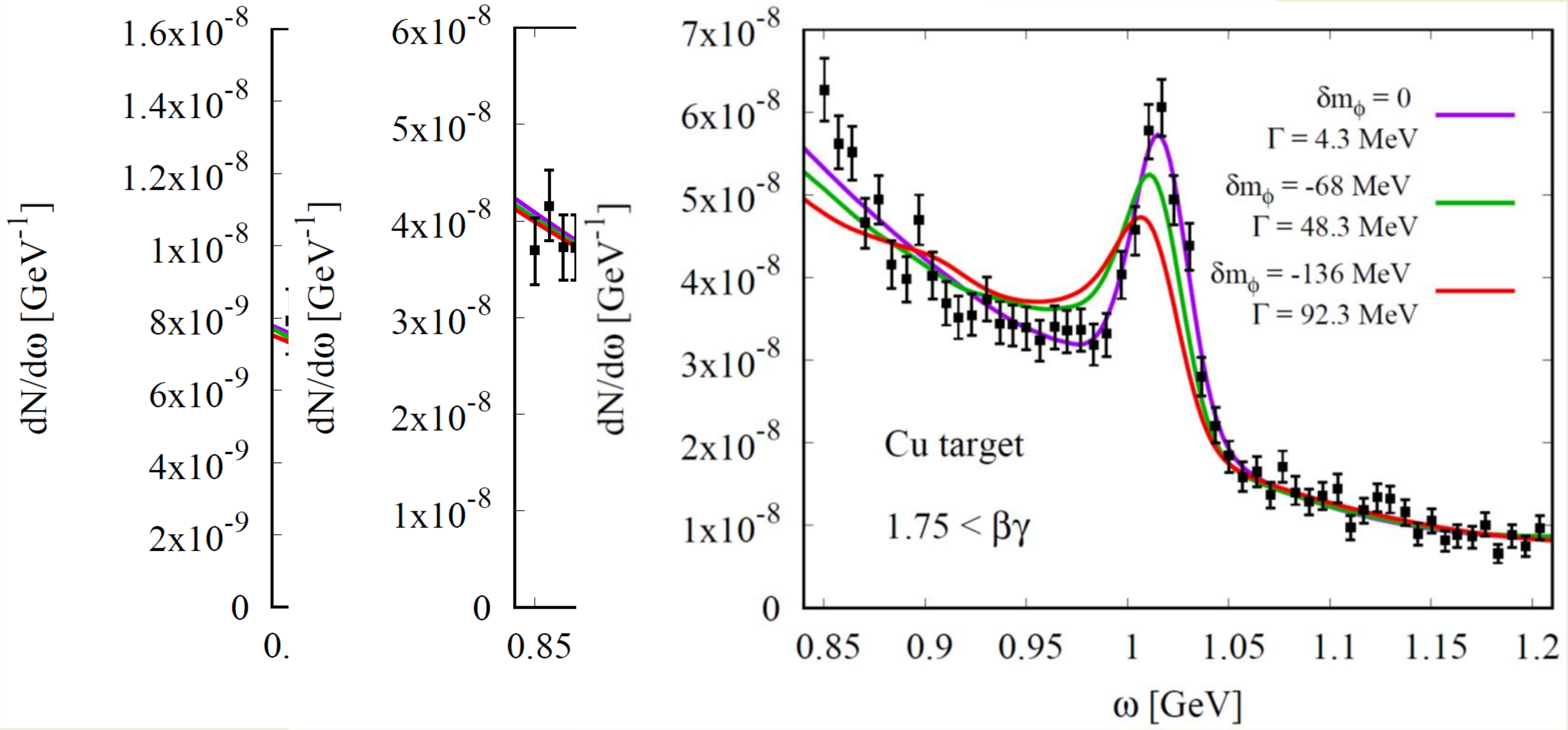
Fit to experimental data is necessary!

Background ($a\omega^2 + b\omega + c$); ϕ meson signal ($A\rho_{\phi,\mathrm{HSD}}(\omega)$)

Dilepton spectrum: $$\rho(\omega) = \underbrace{a\omega^2 + b\omega + c}_{\text{Background}} + \underbrace{A\rho_{\phi,\mathrm{HSD}}(\omega)}_{\phi\text{ meson signal}}$$

a, b, c, A: Fitted to the experimental dilepton spectrum independently for each βγ-region

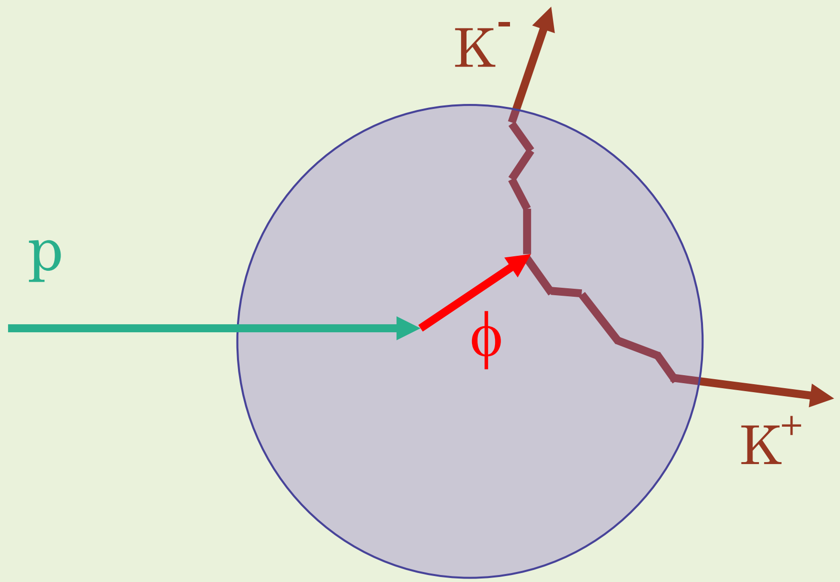
Fits to experimental Copper target data (E325)

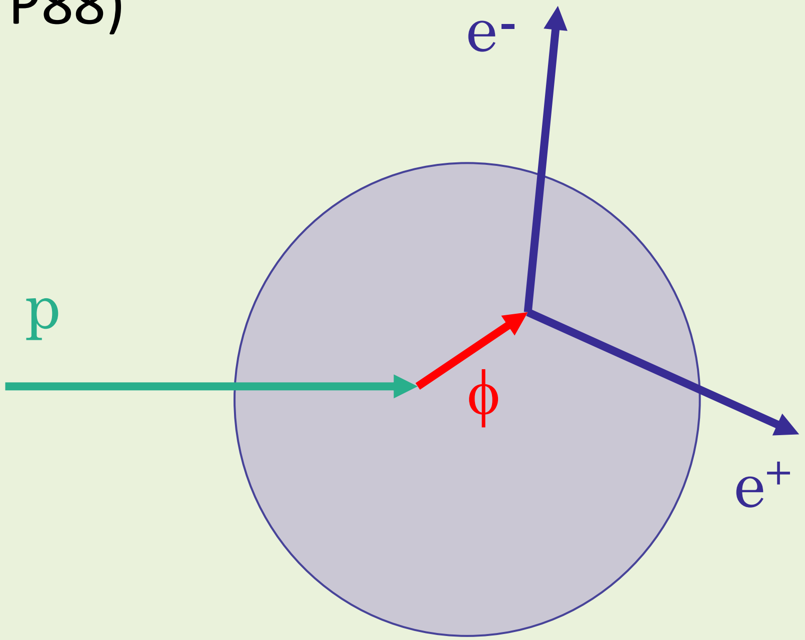


slow φs intermediate φs fast φs

What about the K^+K^- decay channel?

(new J-PARC proposal P88)



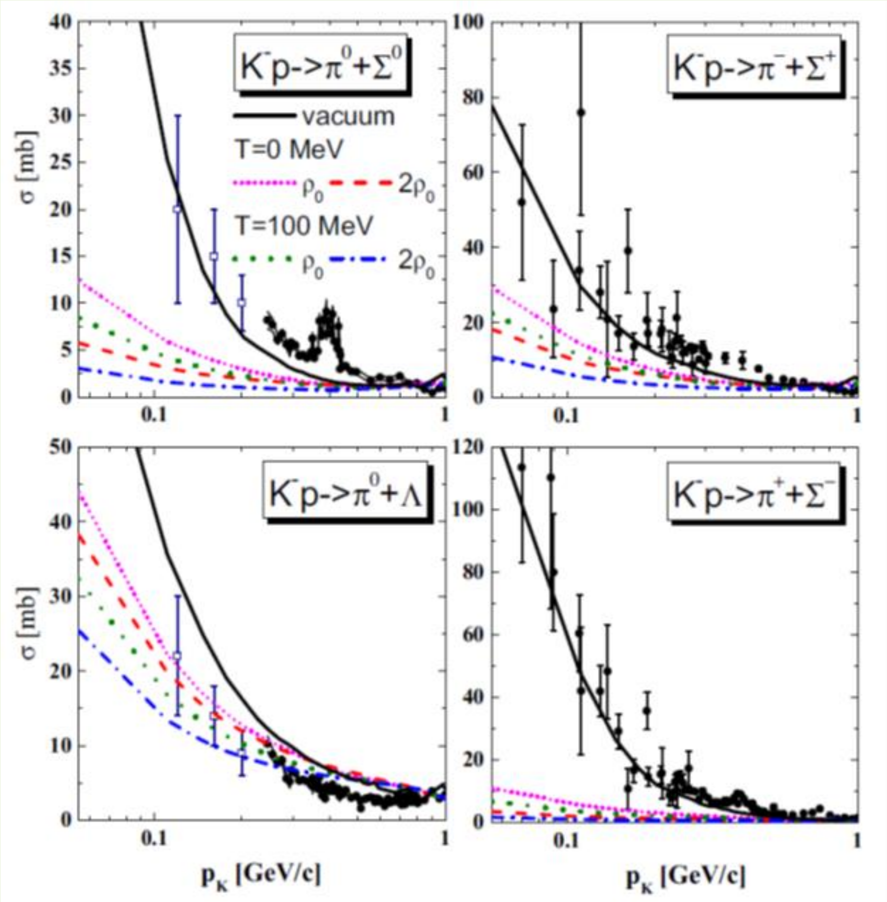


Kaons feel the strong interaction	→	Distorted in-medium φ meson signal	✖
Large branching ratio	→	Good statistics	○

Kaons do not feel the strong interaction	→	Clear in-medium φ meson signal	○
Small branching ratio	→	Bad statistics	✖

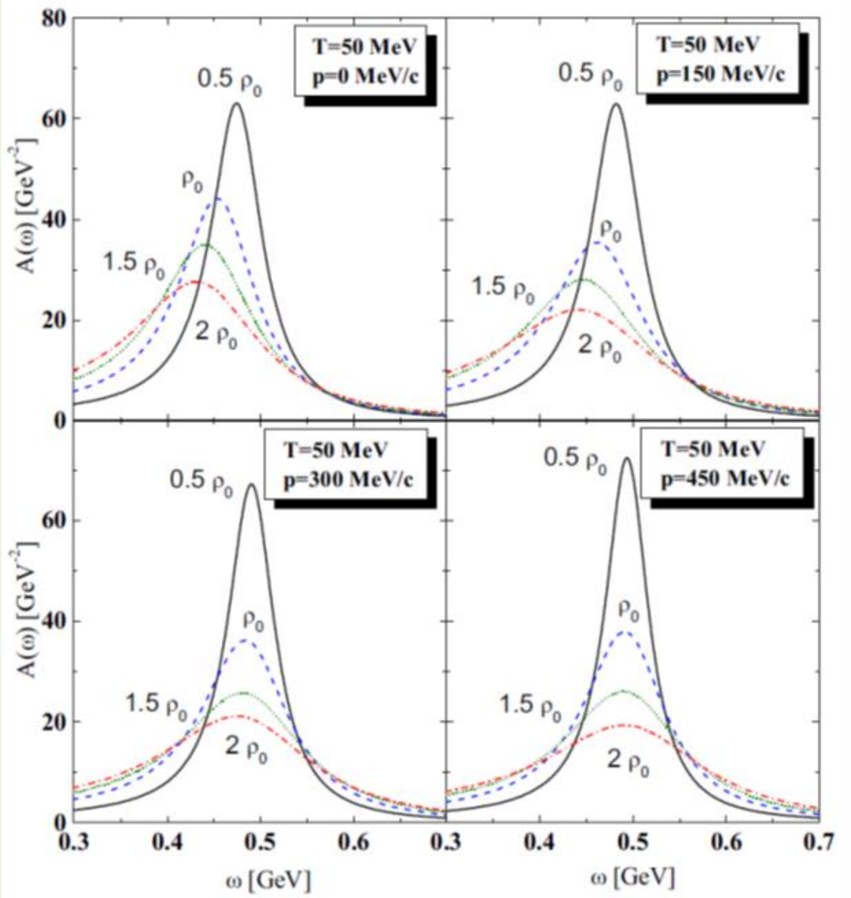
Treatment of KN-interactions

Density dependent cross sections based on the chiral unitary model
(including coupled channels and s-/p-wave of $\bar{K}N$ interactions)



Vacuum and density dependent $\bar{K}N$ cross sections

Density dependent $\bar{K}$ spectral functions



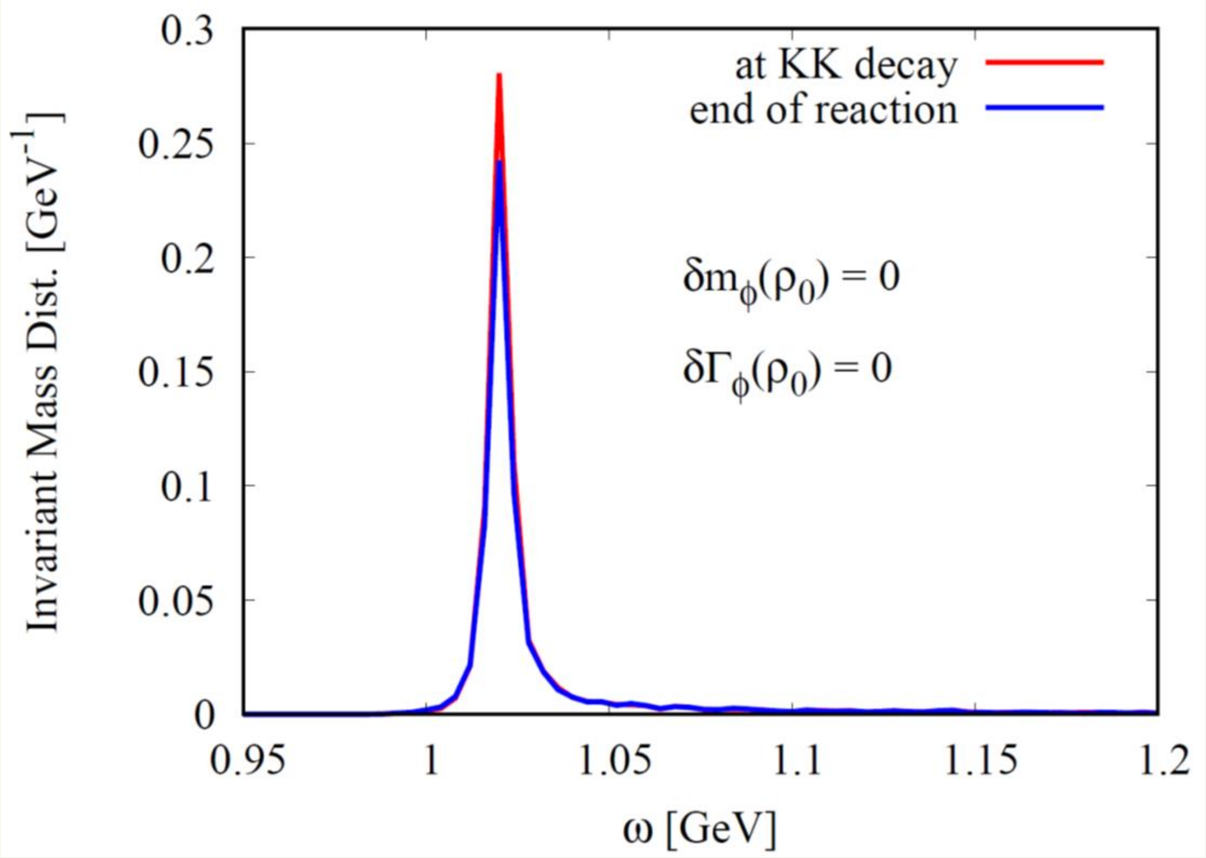
T. Song et al., Phys. Rev. C **103**, 044901 (2021).

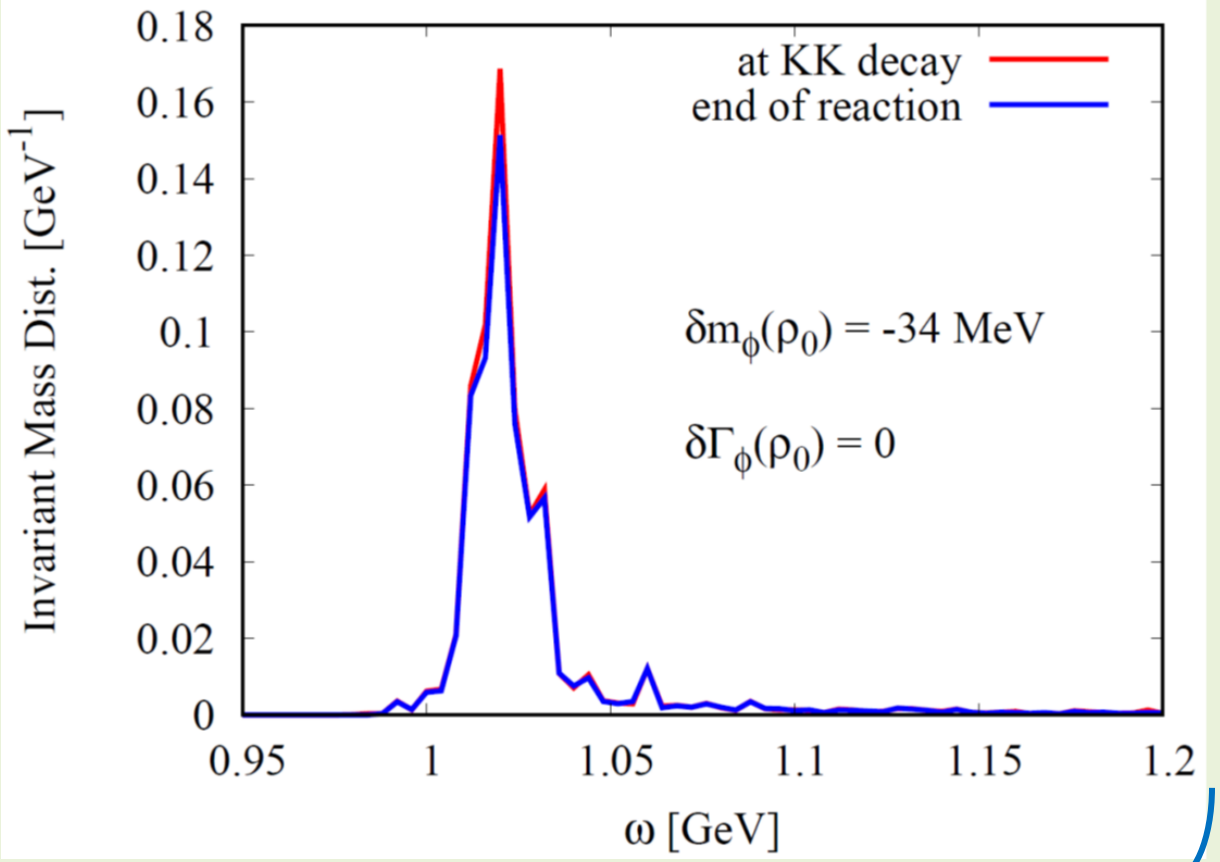
See talk by Laura Tolos on Tuesday

Preliminary

Distortion of the in-medium φ meson signal in the K^+K^- channel

(p + Cu at 30 GeV)





Small distortion effect from the strong KN interaction !?