The phi meson in nuclear matter from theory and experimental data

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Japan Atomic Energy Agency (JAEA)

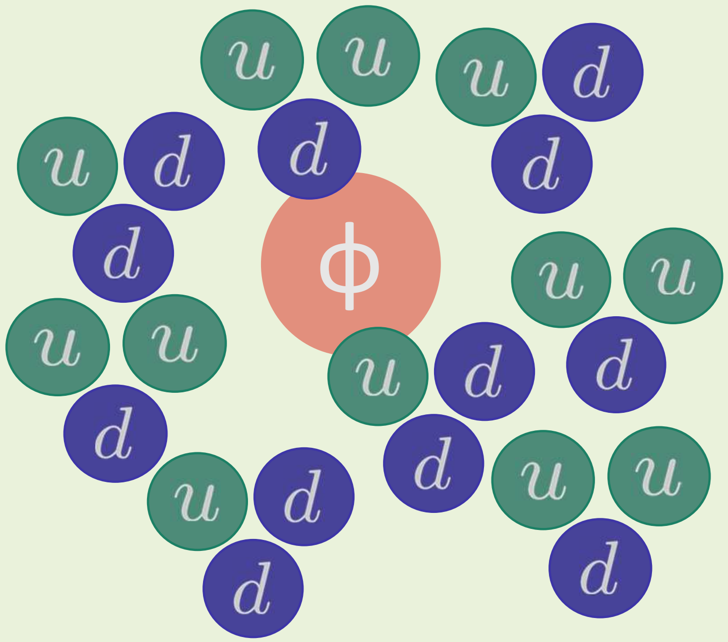
Talk at the "17th International Workshop on Meson Physics"
Krakov, Poland
June 23, 2023

Based on work done in collaboration with
Elena Bratkovskaya (Frankfurt/GSI),
Taesoo Song (GSI)

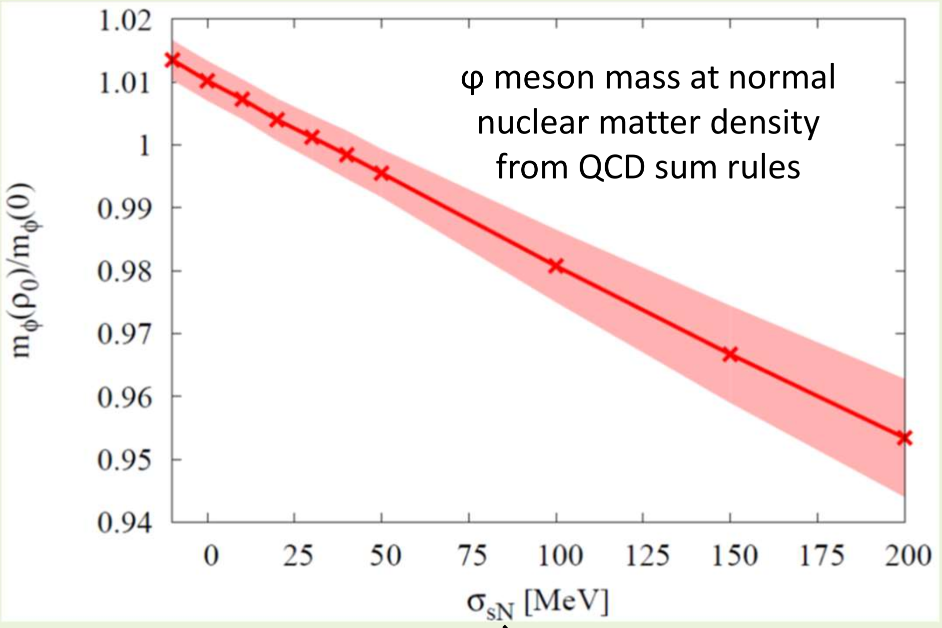
Why should we be interested?

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).

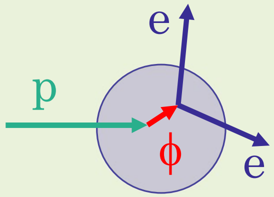


φ meson mass at normal nuclear matter density from QCD sum rules

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

Previous experimental results

KEK
E325



12 GeV
pA-reaction

Pole mass:
$$\frac{m_\phi(\rho)}{m_\phi(0)} = 1 - \underset{\nwarrow 0.034 \pm 0.007}{k_1}\frac{\rho}{\rho_0}$$

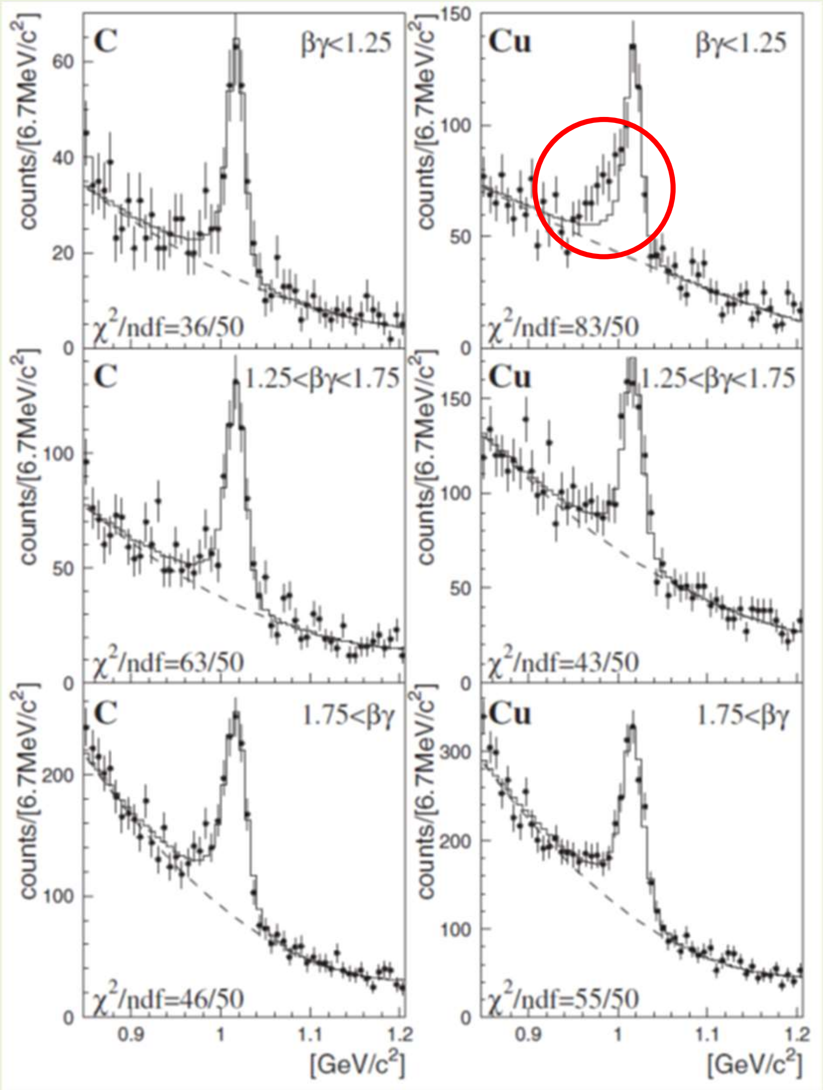
Pole width:
$$\frac{\Gamma_\phi(\rho)}{\Gamma_\phi(0)} = 1 + \underset{\nwarrow 2.6 \pm 1.5}{k_2}\frac{\rho}{\rho_0}$$

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

slow φs

intermediate
φs

fast φs



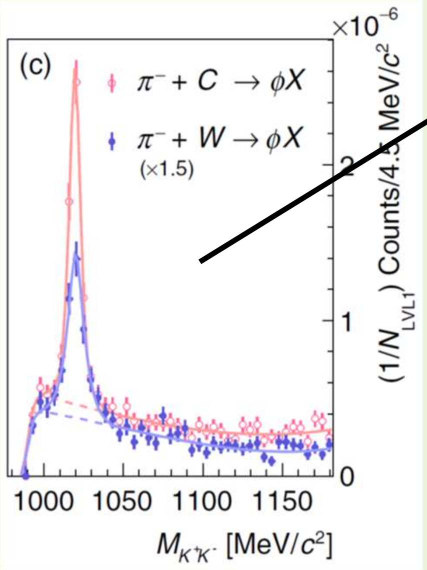
$$\beta\gamma = \frac{|\vec{p}|}{m_\phi}$$

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:

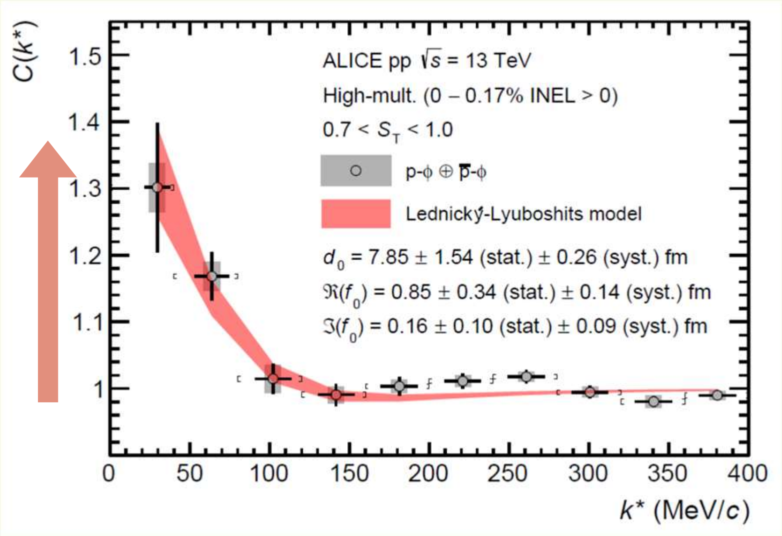
- ★ **Attractive φ-nucleus potential: -(50 - 100) MeV**
- ★ **Small imaginary part: 20 – 25 MeV**

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).

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

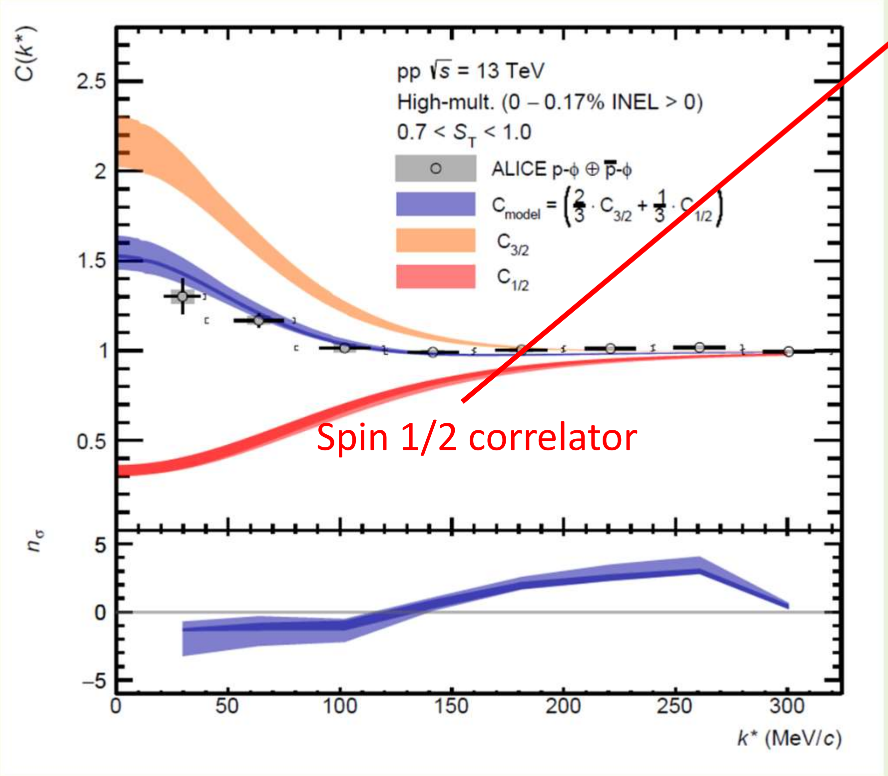
★ Hadronic Effective theory calculations

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

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

Even more recent results

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



Spin 1/2 correlator

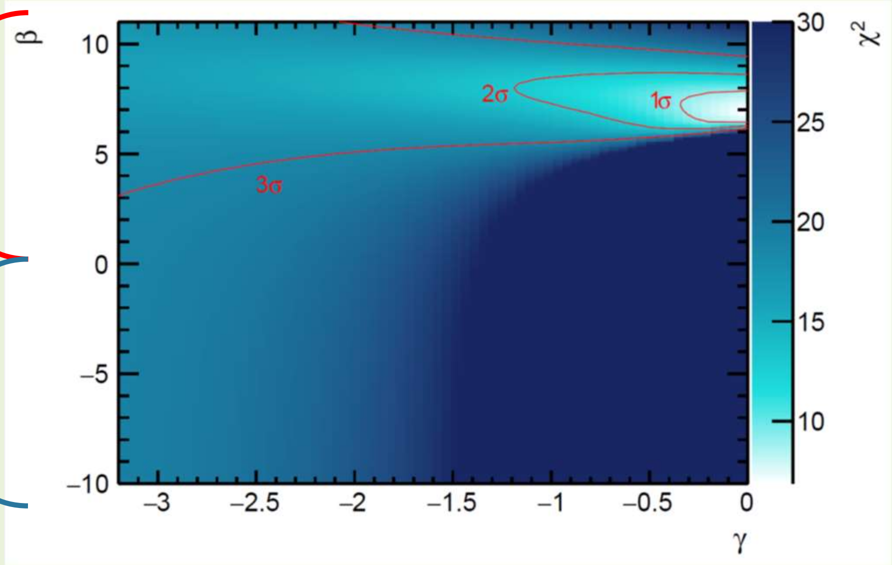
E. Chizzali et al., arXiv:2212.12690 [nucl-ex].

Bound state?

Repulsive?

Bound state

Repulsive

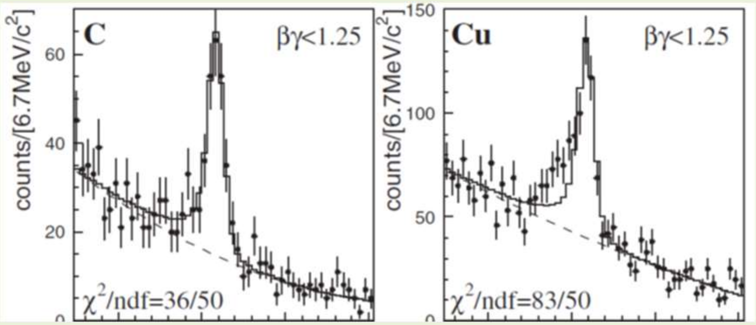


➡ Evidence for φ-N bound state!

How compare theory with experiment?

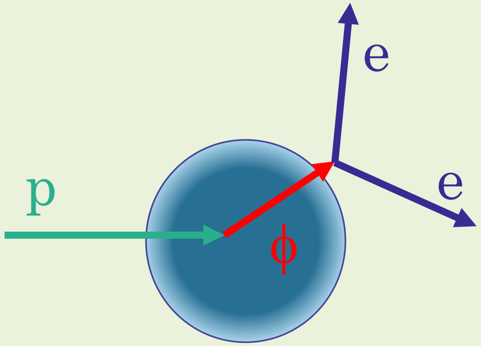
Information useful for theory

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).

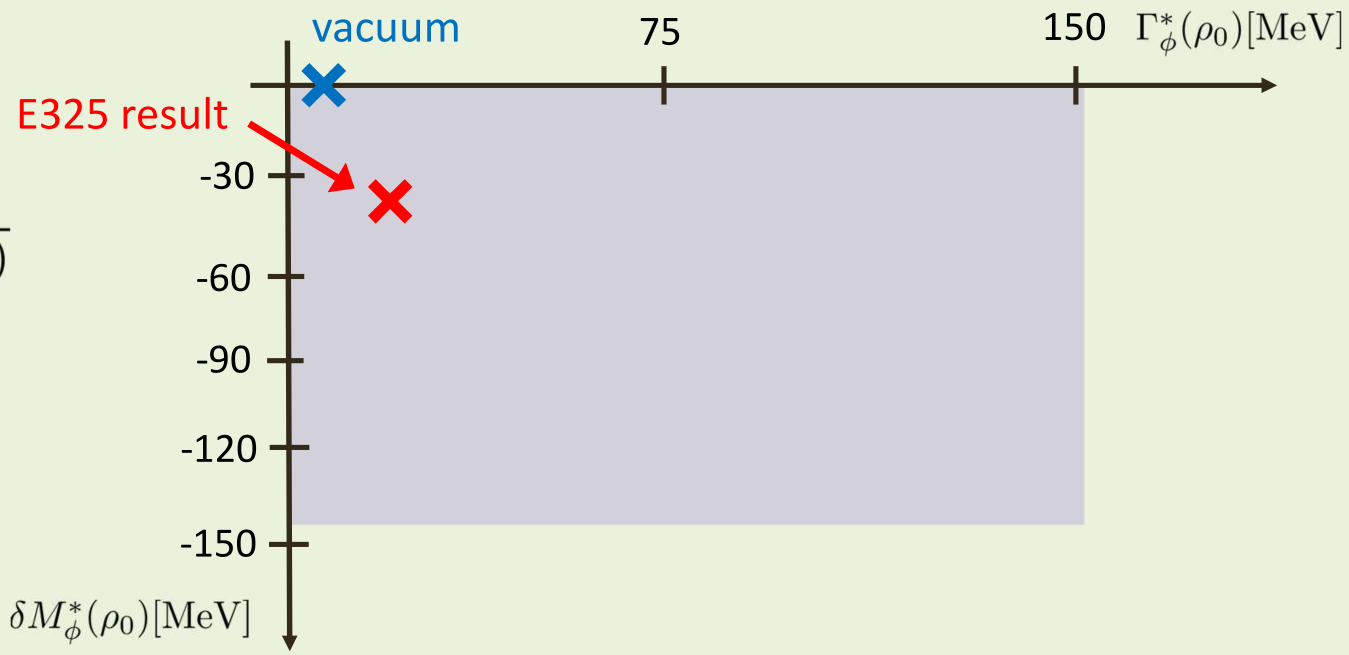
Off-shell dynamics of vector mesons and kaons
(dynamical modification of the mesonic spectral function during the simulated reaction)

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

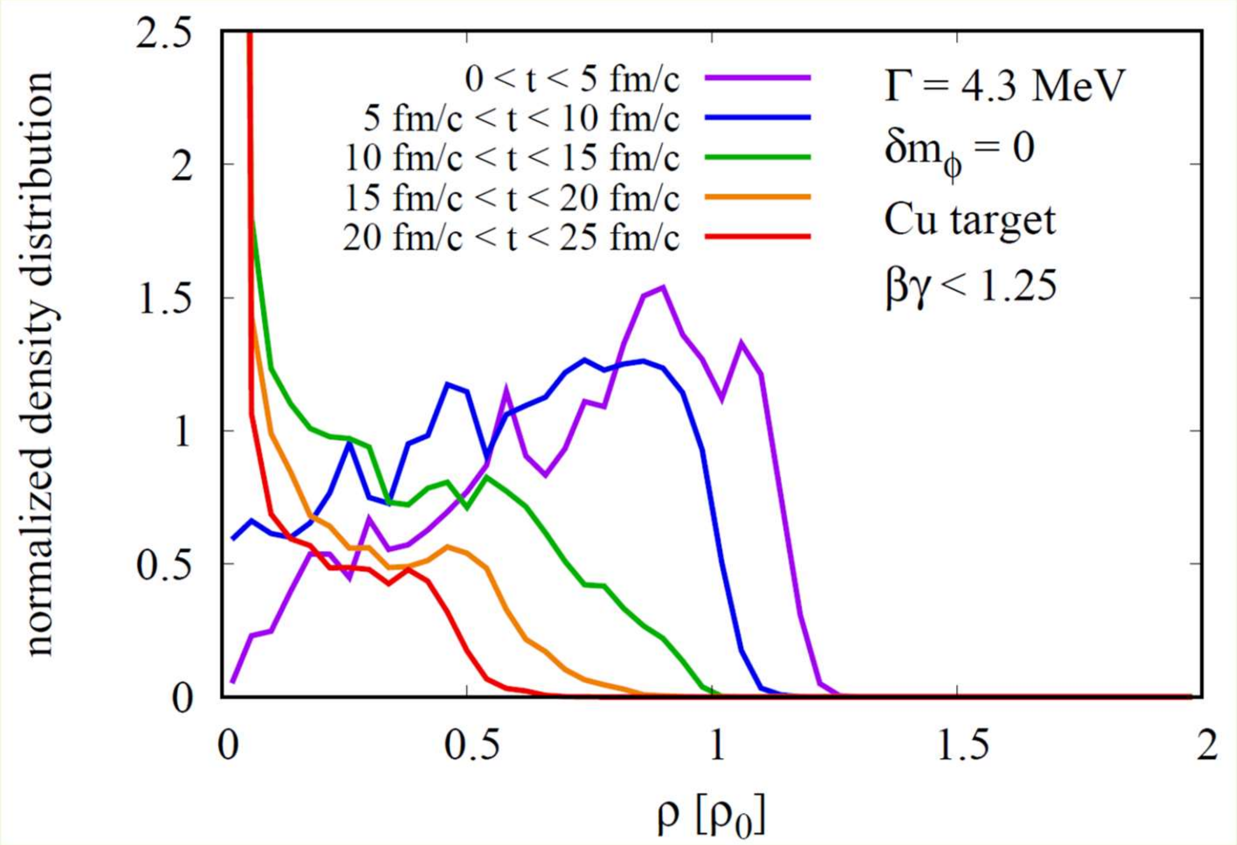
$$C\,\frac{2}{\pi}\,\frac{M^2\Gamma^*_\phi(M,\rho)}{[M^2-M^{*2}_\phi(\rho)]^2+M^2\Gamma^{*2}_\phi(M,\rho)}$$

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

Simulated scenarios:



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



slow φs

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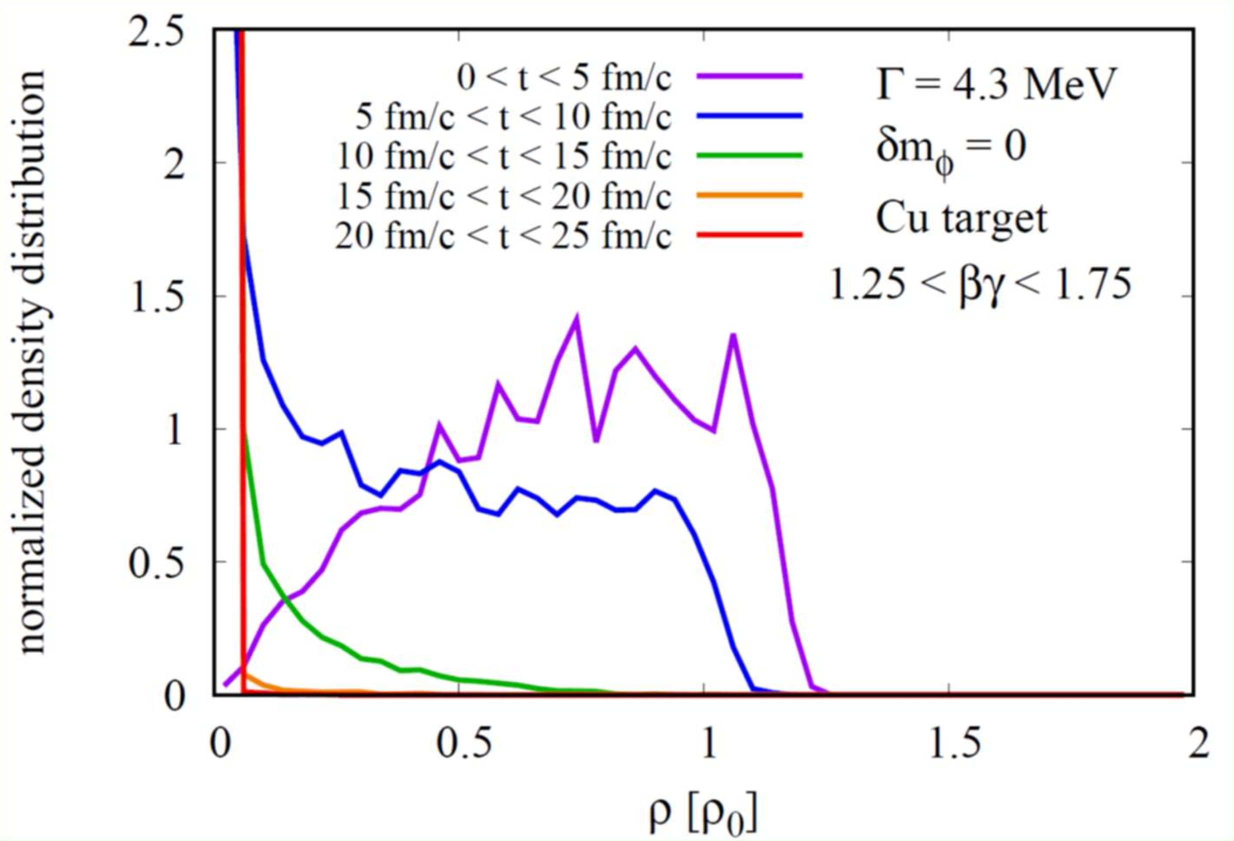
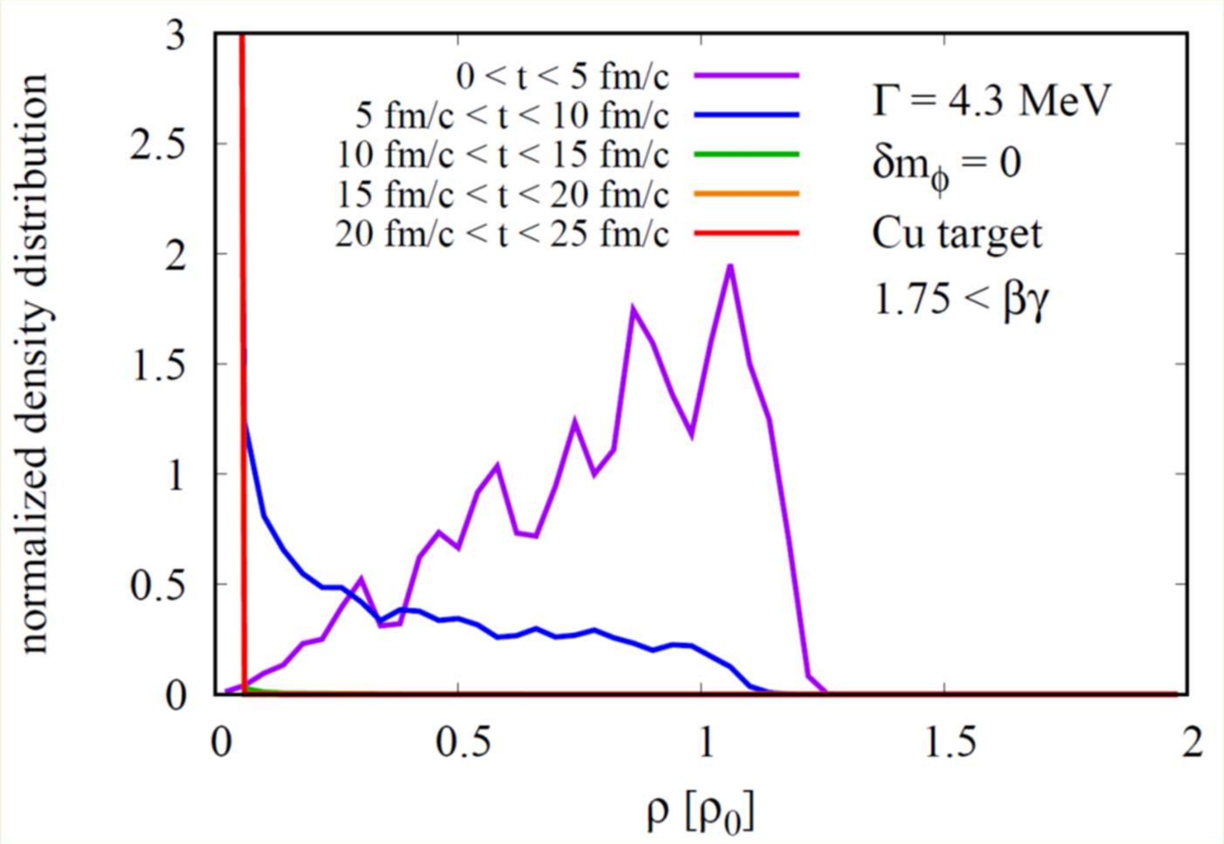


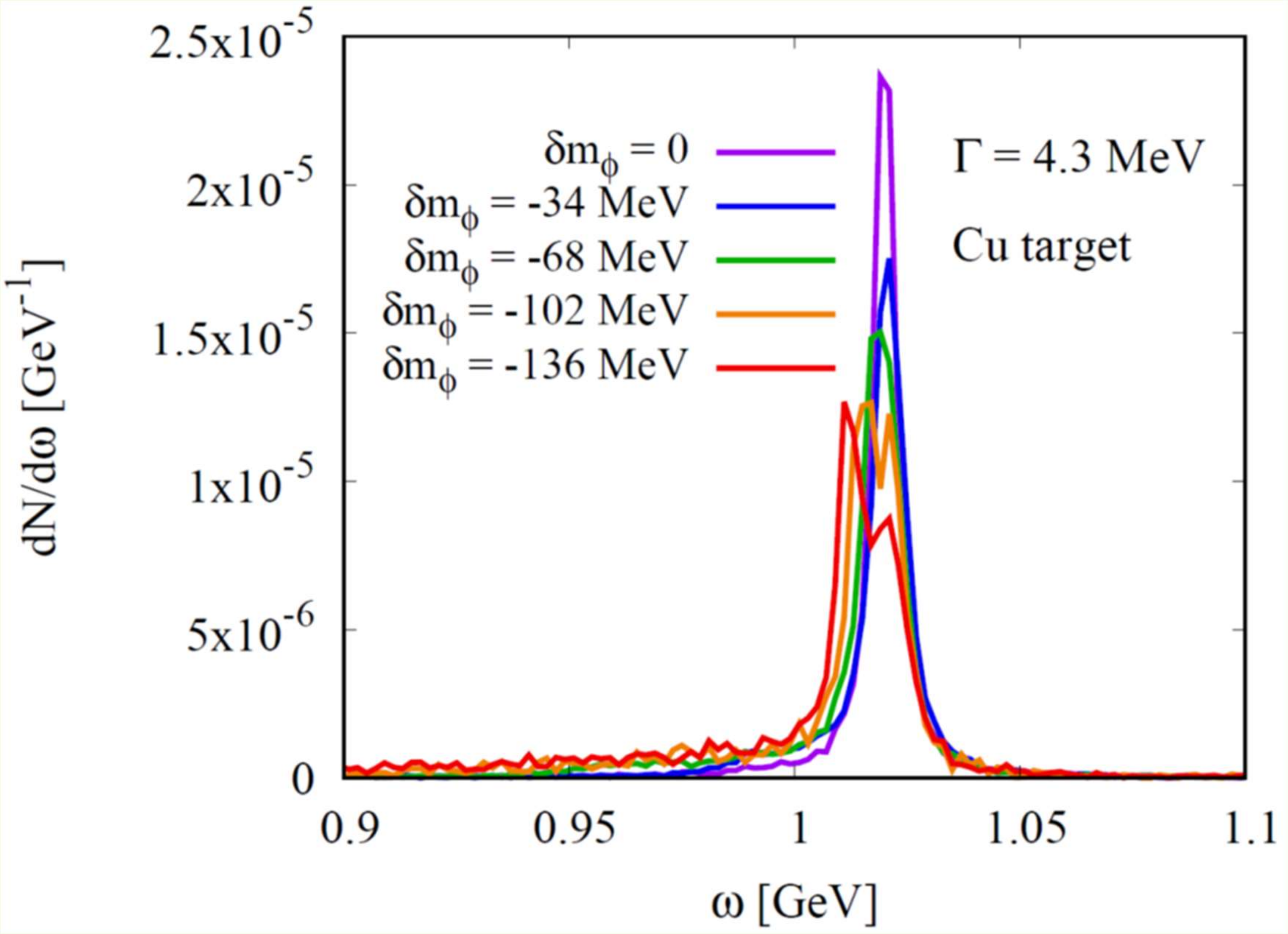
intermediate φs

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



fast φs

The dilepton spectrum in the φ meson region



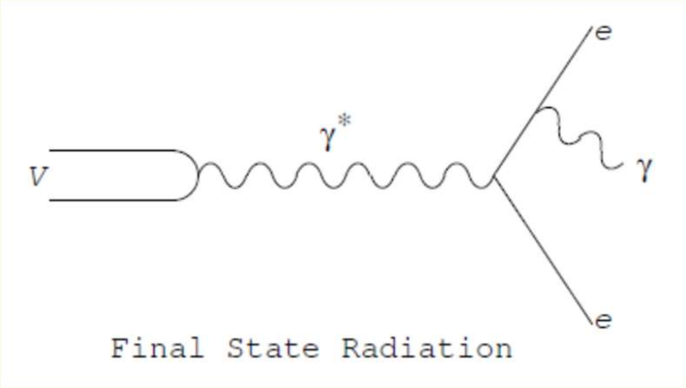
p + Cu at 12 GeV

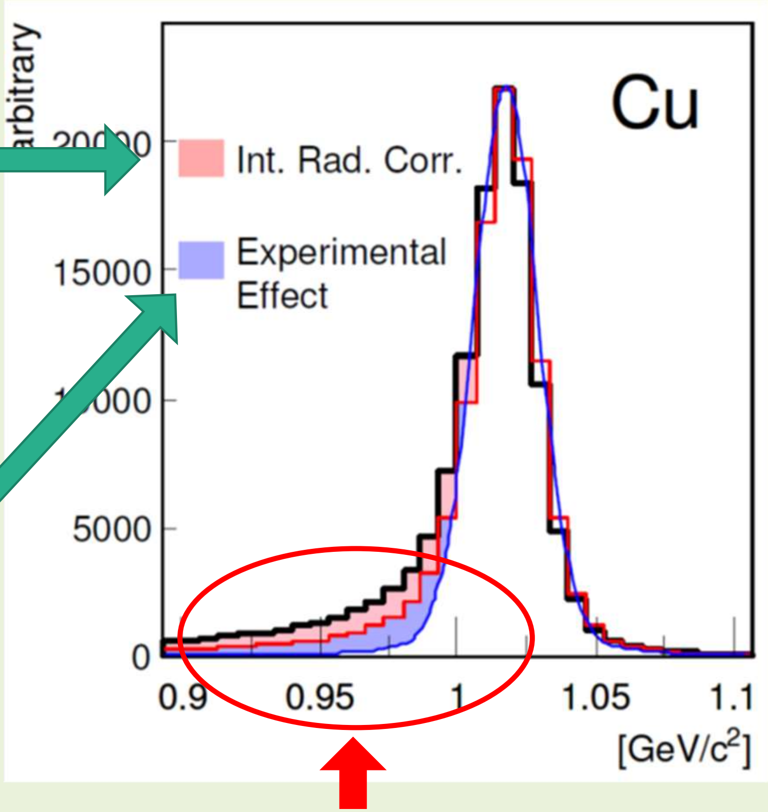
No acceptance corrections!

No finite resolution effects!

No QED effects!

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





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

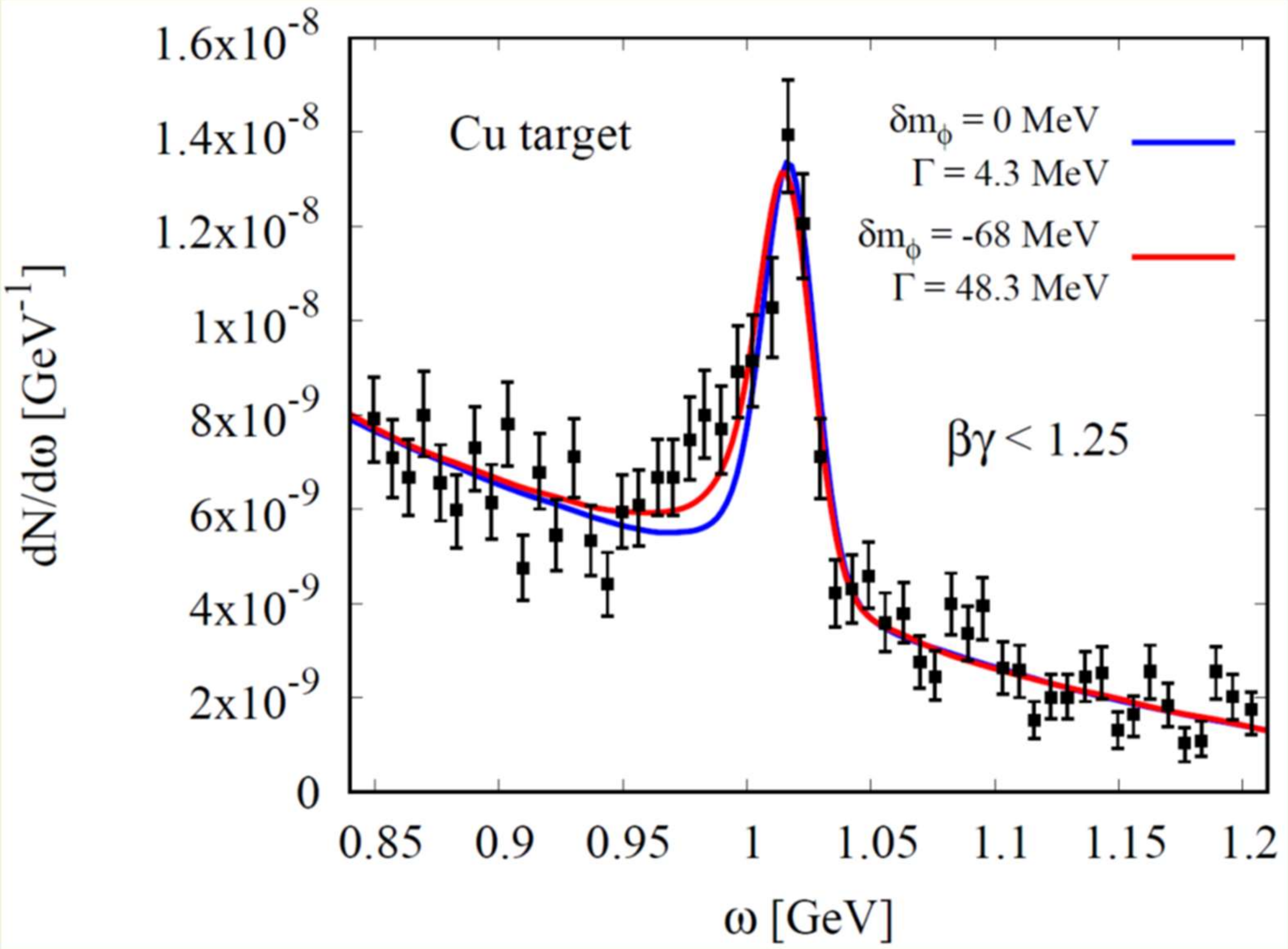
Rescattering effect

(multiple scattering, energy loss)

Similar to the shape expected for a negative mass shift

Fits to experimental Copper target data (KEK, E325)

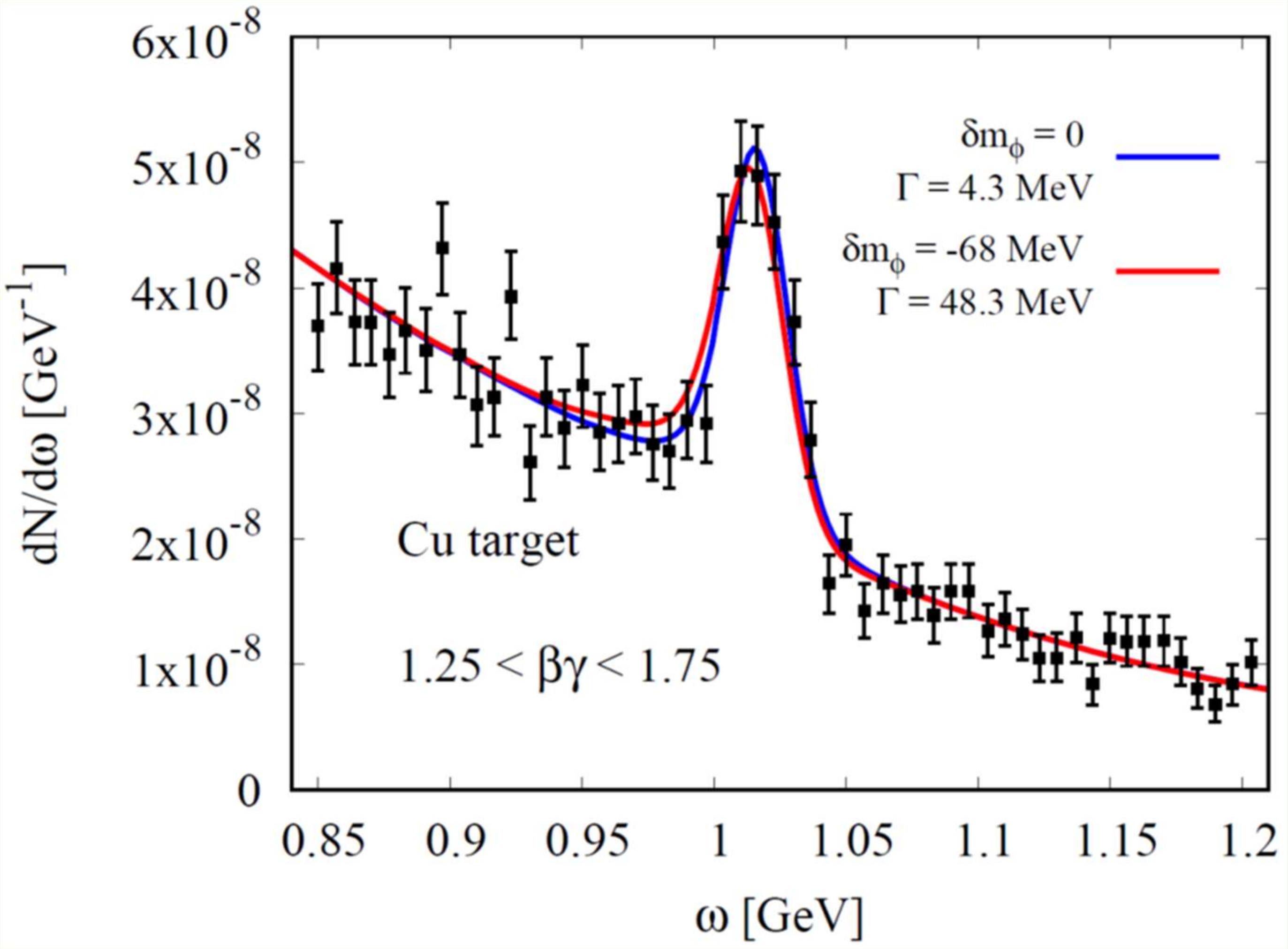
Preliminary



slow φs

Fits to experimental Copper target data (KEK, E325)

Preliminary



intermediate φs

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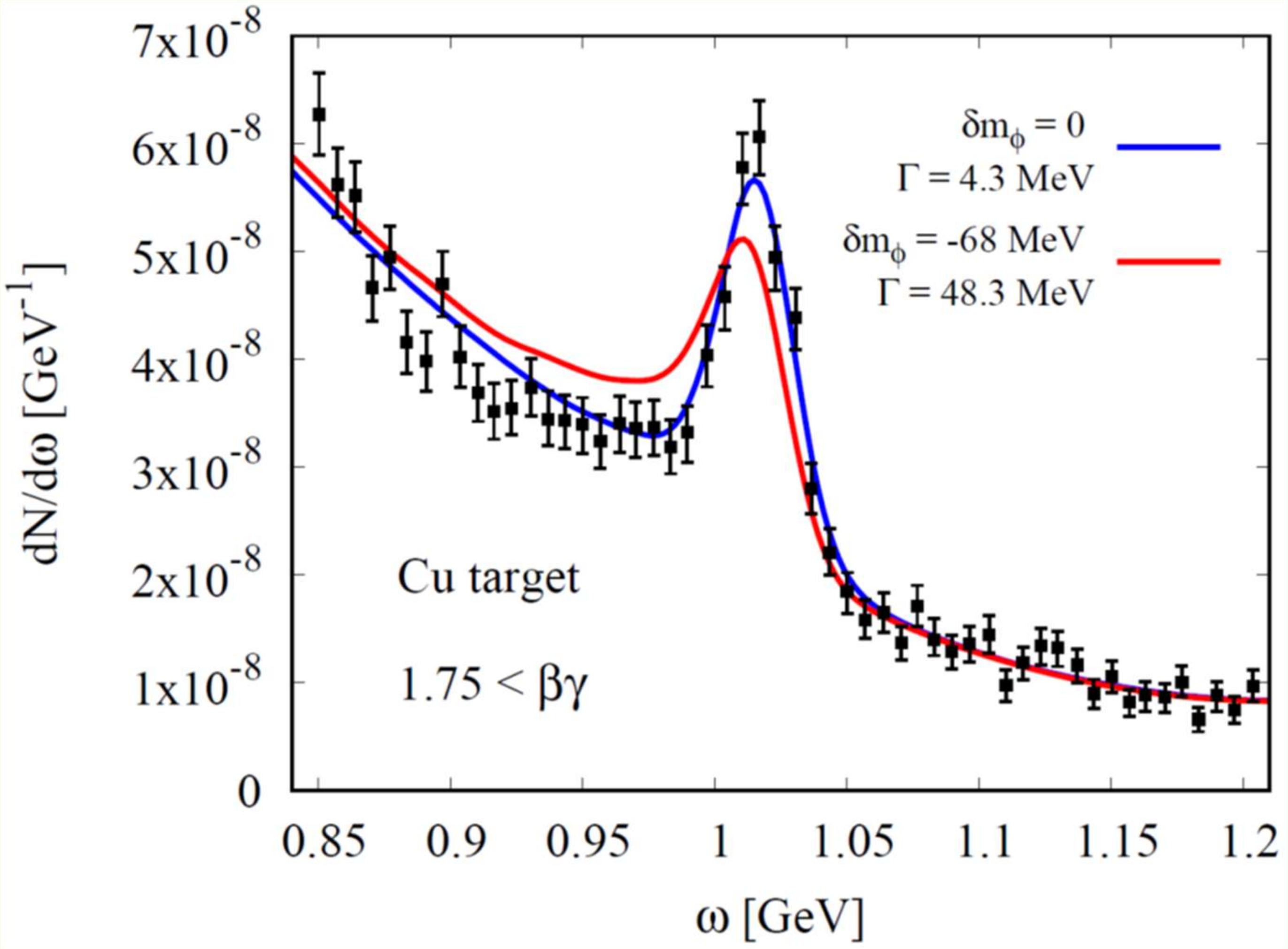

fast φs

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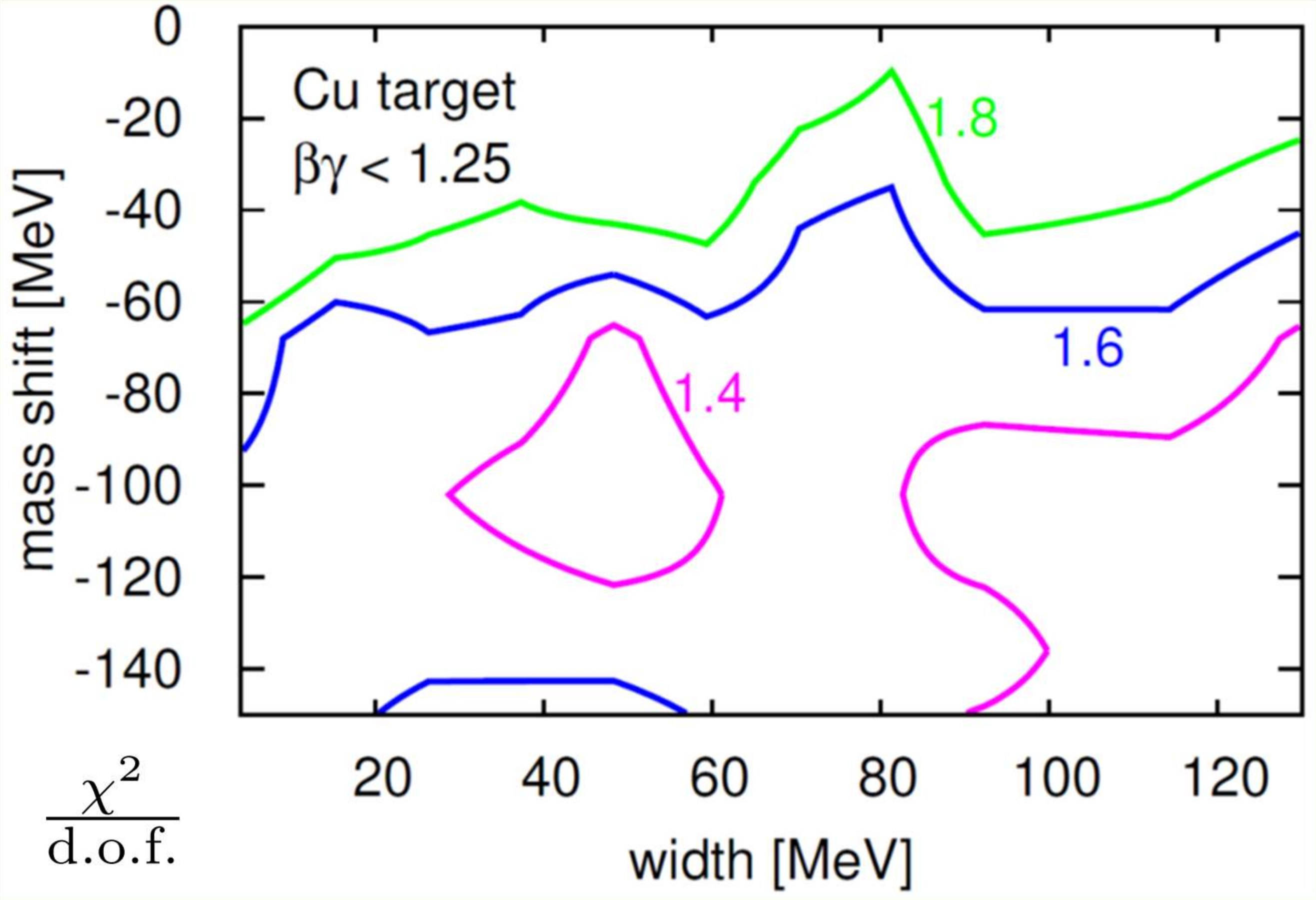

slow φs

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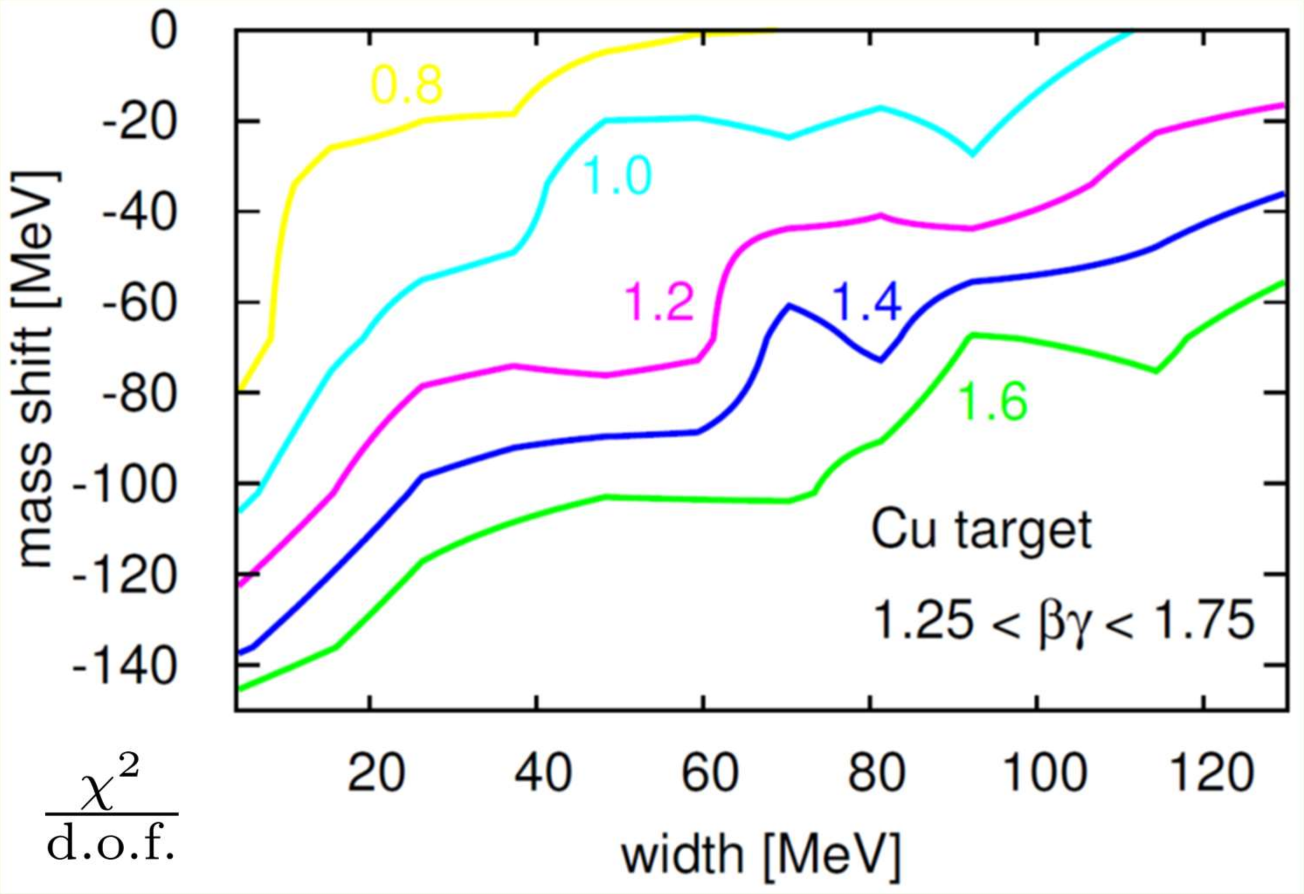
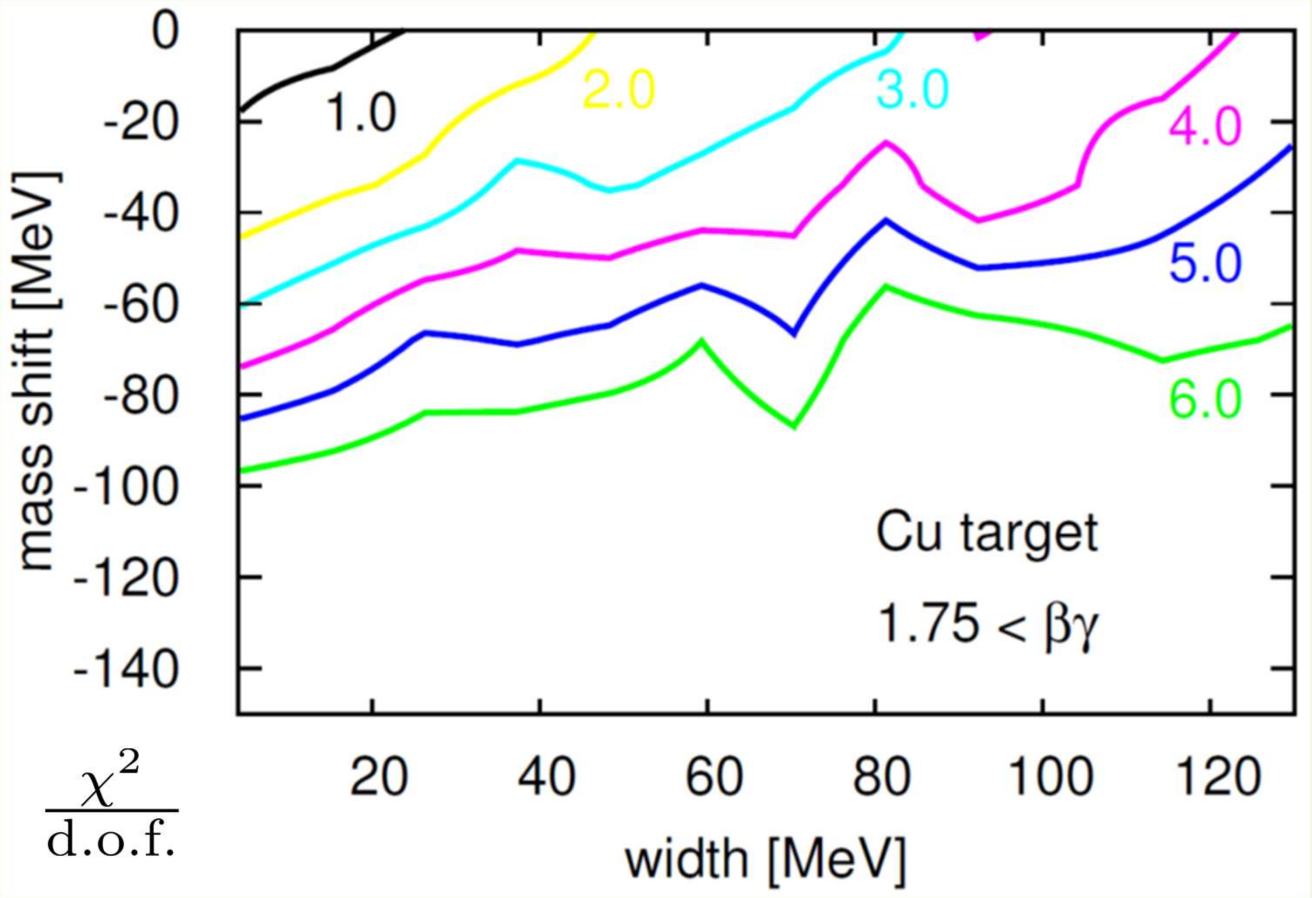
Preliminary



intermediate φs

Fits to experimental Copper target data (KEK, E325)

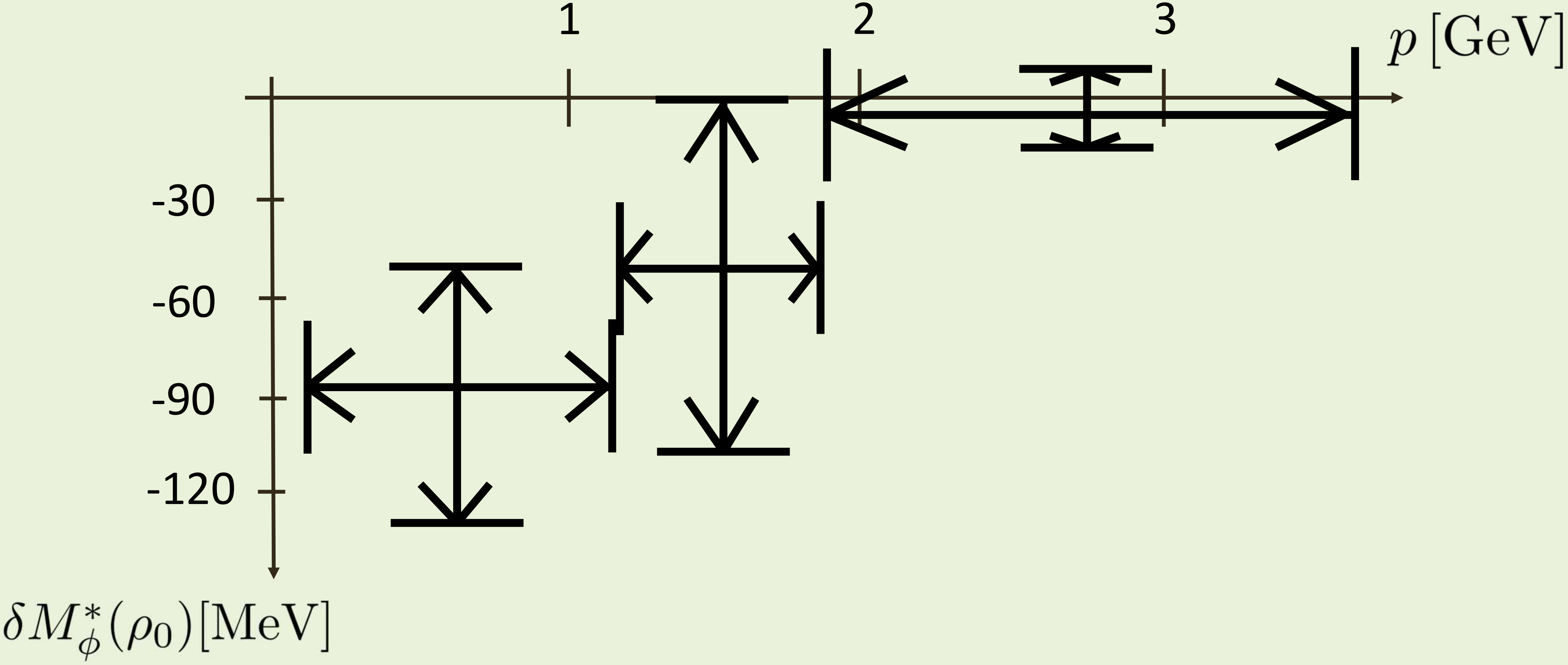
Preliminary



fast φs

large momentum dependence needed to explain the data!

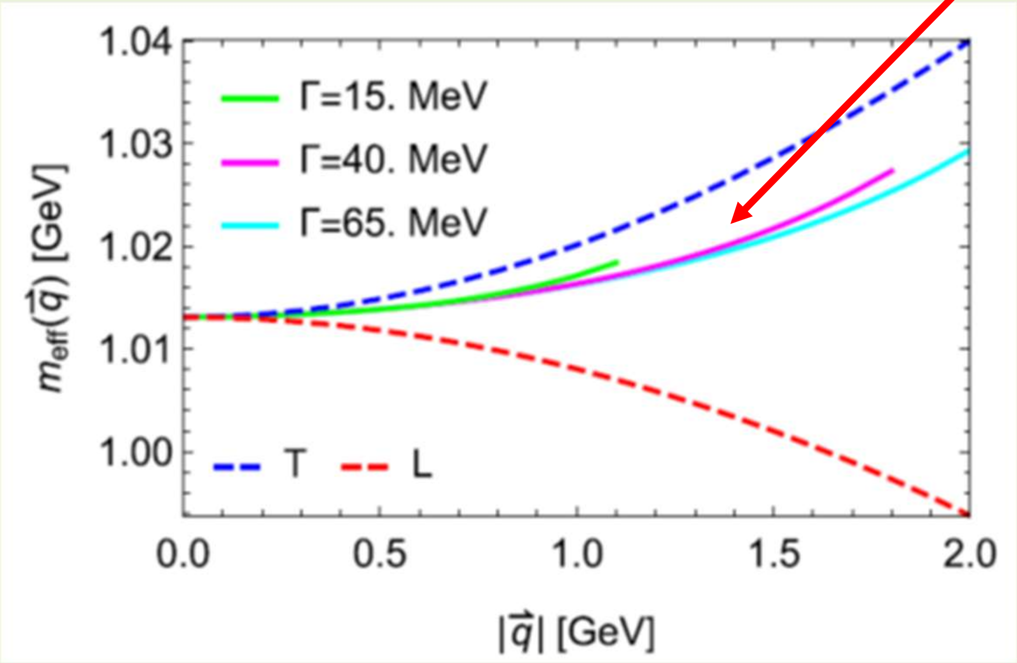
Summary of results for Copper target data (E325)



Most natural interpretation of our results

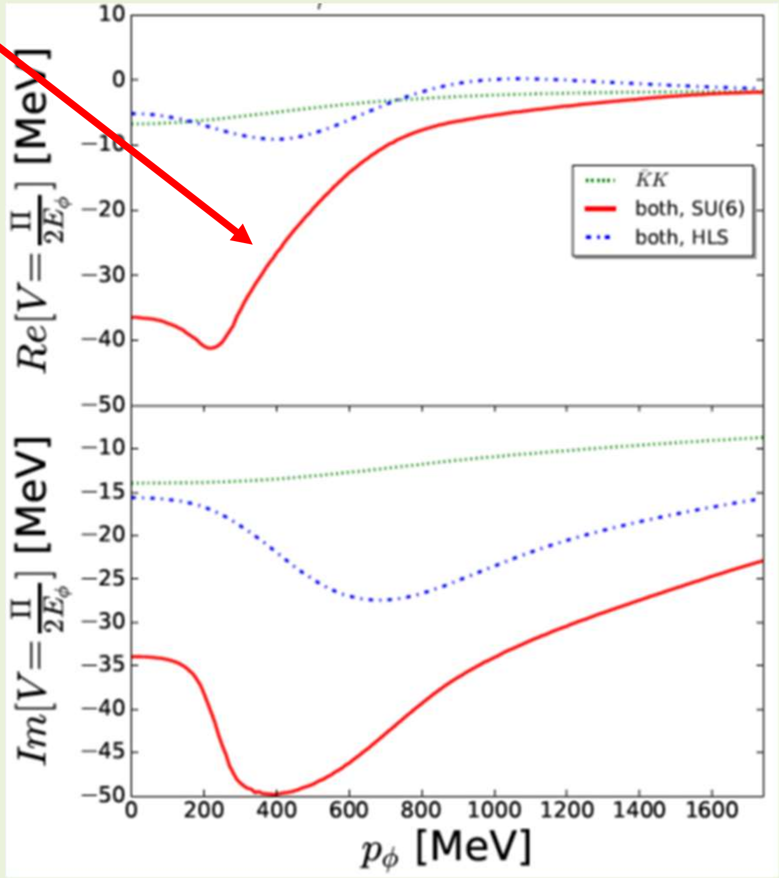
→ Momentum dependent mass shift

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).

Summary and Conclusions

★ A lot of new experimental information about the φN and φ-nucleus interactions is becoming available (LHC, J-PARC, HADES, …)

→ Many opportunities for theorists!

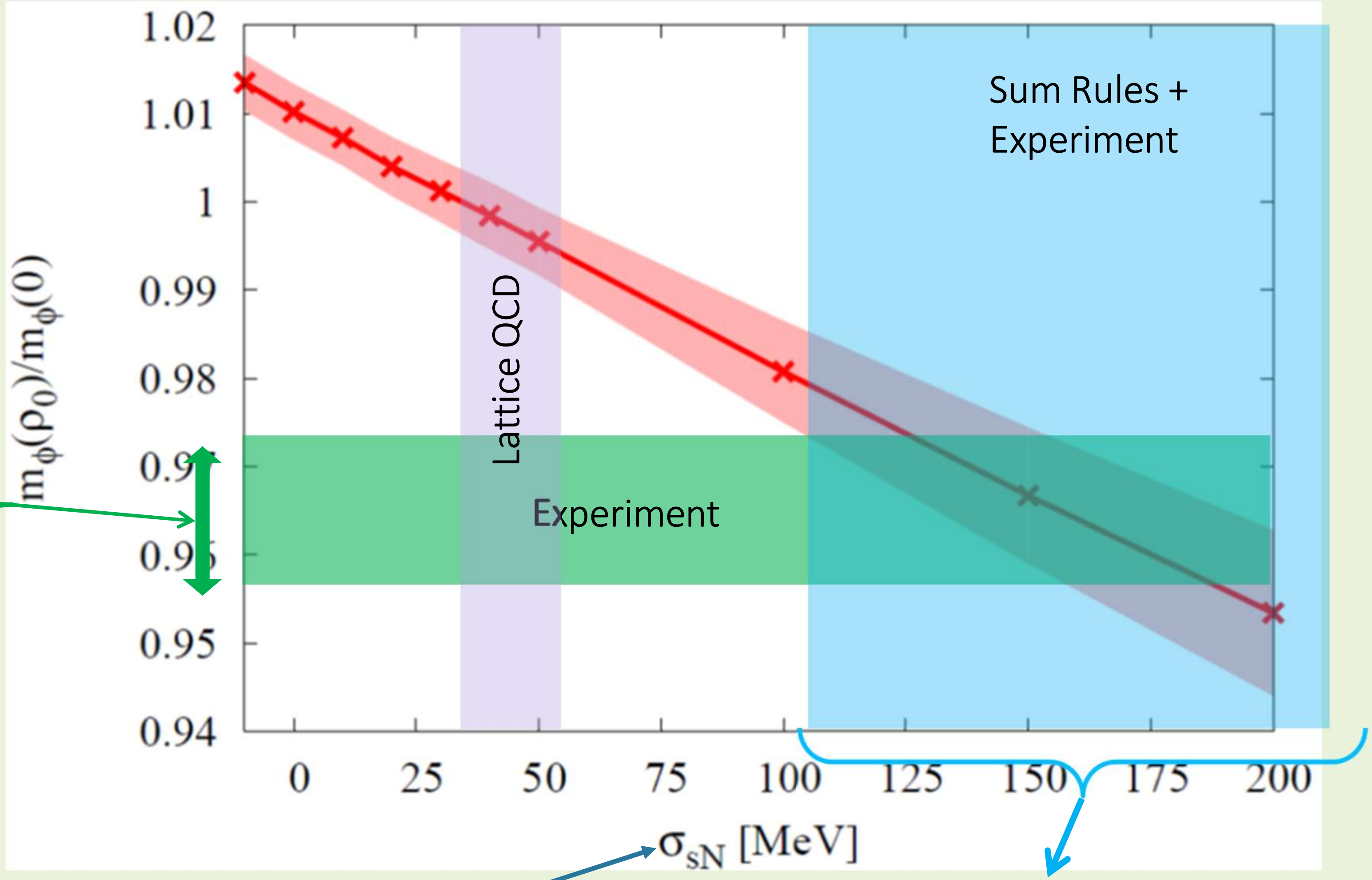
★ We conducted numerical simulations of the pA reactions measured at the E325 experiment at KEK, using the PHSD transport code

↓

Momentum-dependent mass shift is needed to explain the data

Backup slides

Consistency with QCD sum rules and lattice calculations?



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

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

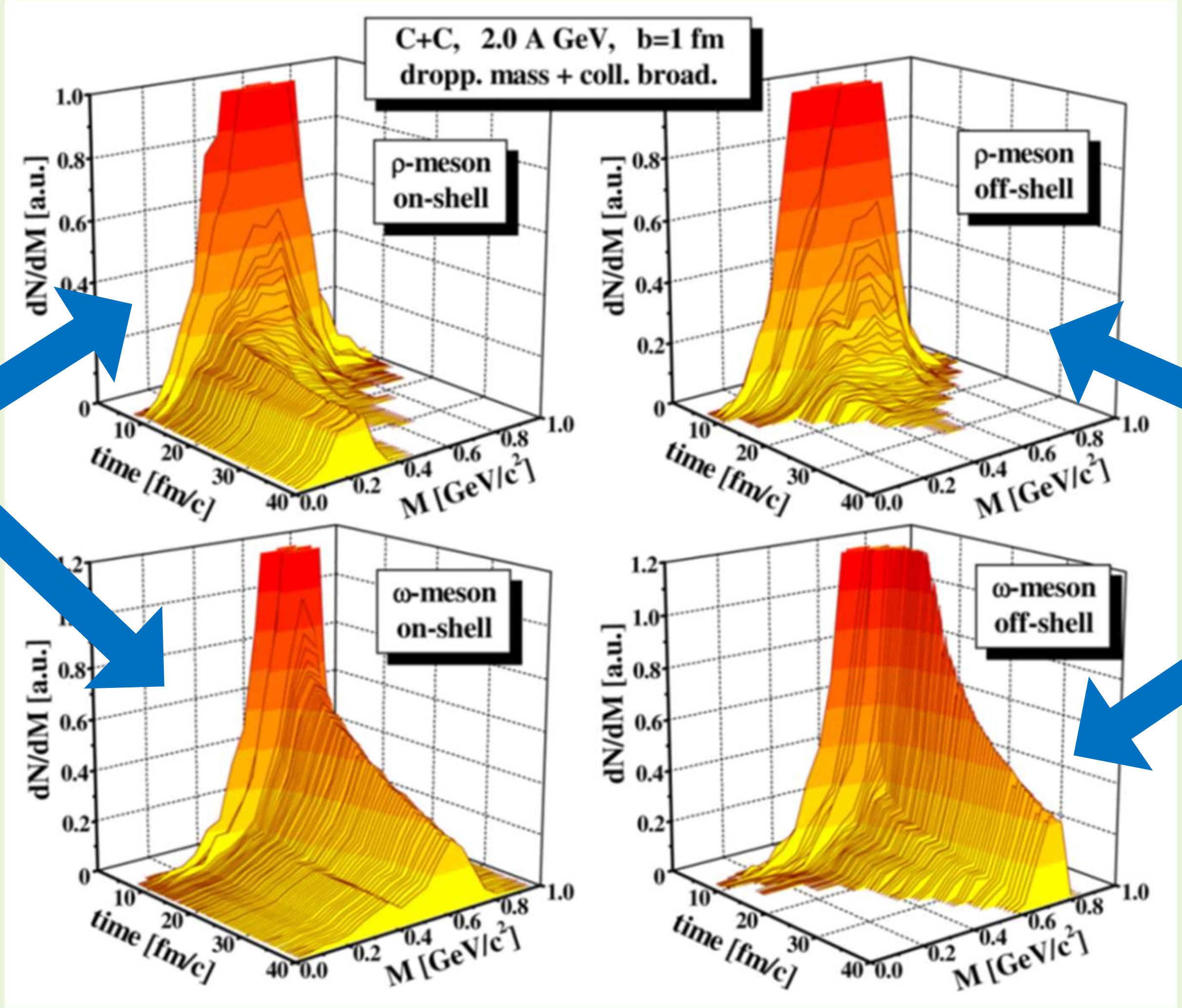
Big puzzle!!

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

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

The importance of off-shell contributions

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

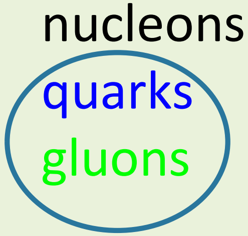


Off-shell
contributions
included:
correct behavior

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

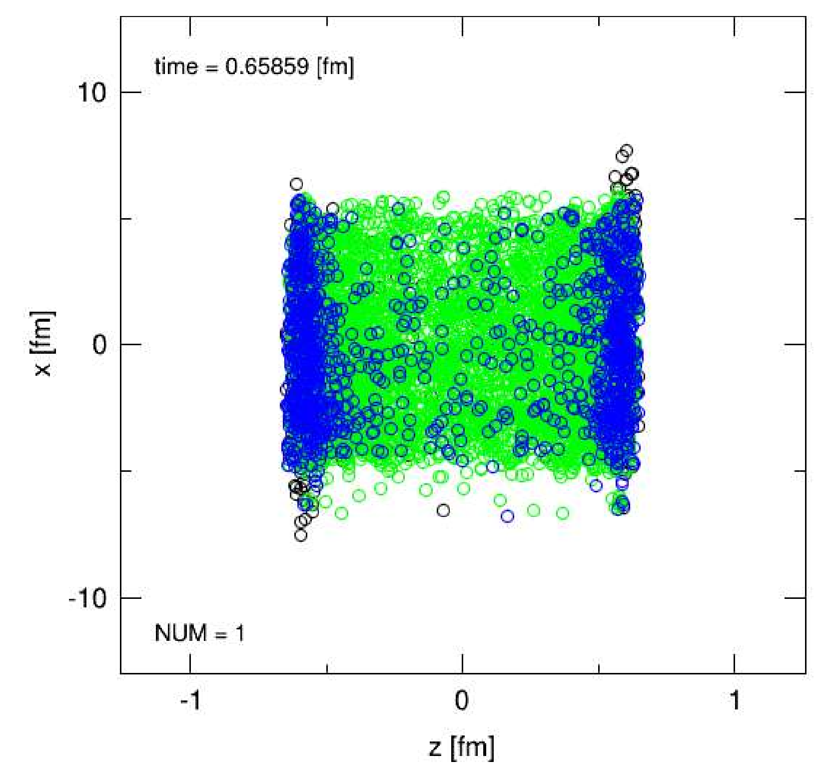


nucleons

quarks

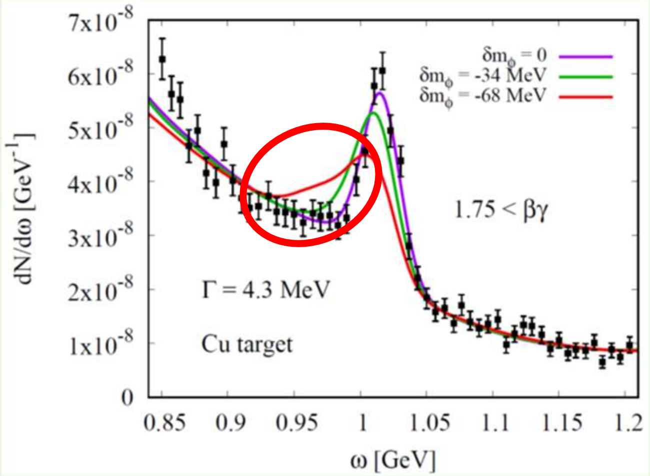
gluons

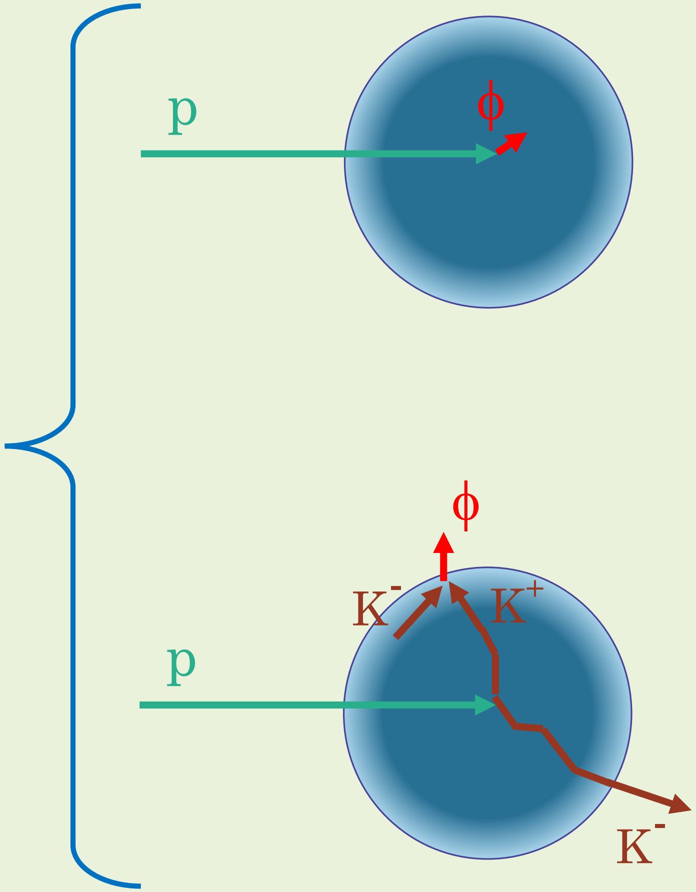
will not be included in the simulations shown in this talk



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**

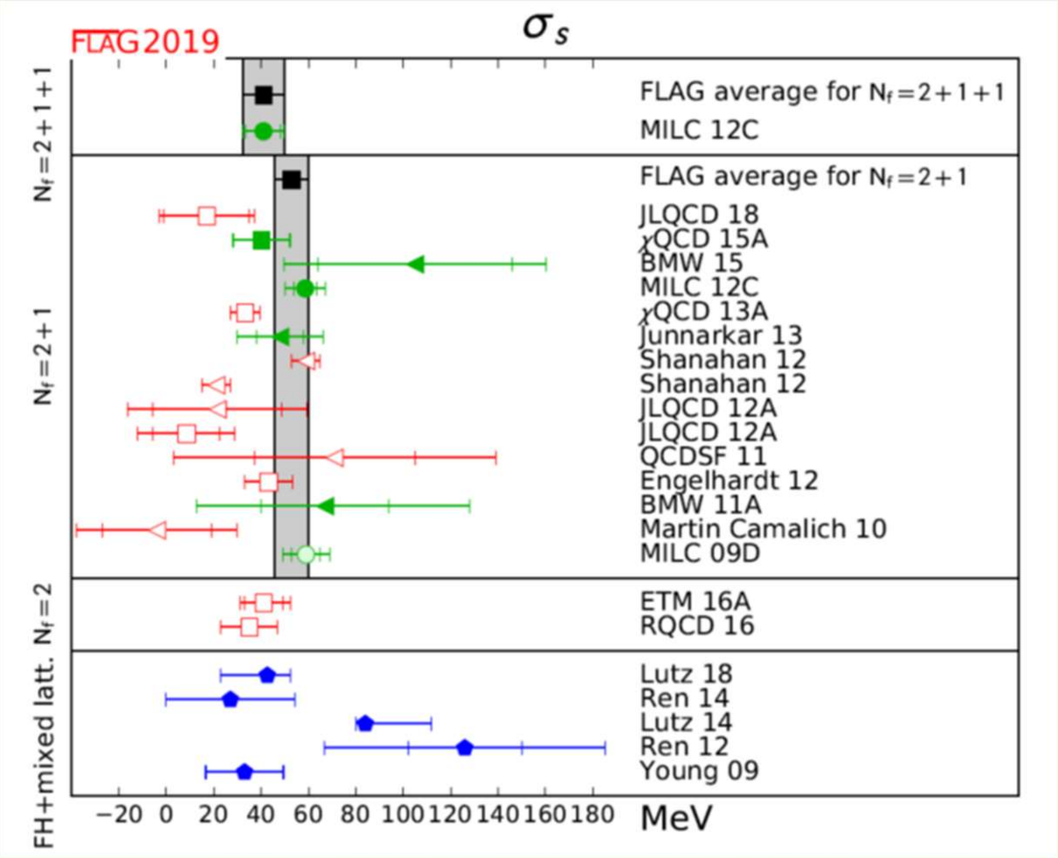
φ mesons are generated from low energy hadronic collisions

⇒ **small momentum**

⇒ **low density**

What does lattice QCD say about the strange sigma term?

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

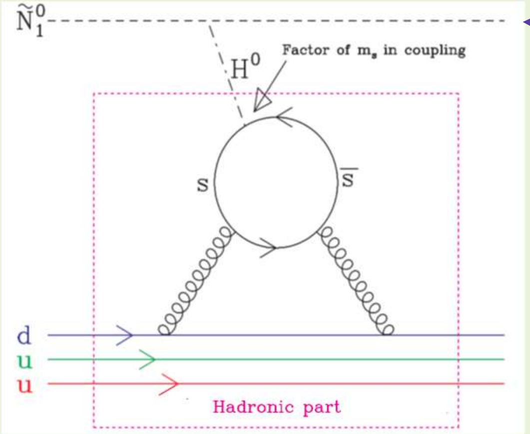


http://flag.unibe.ch/2019/

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

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).

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

most important contribution

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

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)

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

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

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

Dim. 4: $c_4(\rho) = c_4(0) + \rho[-\frac{2}{27}M_N + \frac{56}{27}m_s\langle N|\overline{s}s|N\rangle$

$+\frac{4}{27}m_q\langle N|\overline{q}q|N\rangle + A_2^s M_N - \frac{7}{12}\frac{\alpha_s}{\pi}A_2^g M_N]$

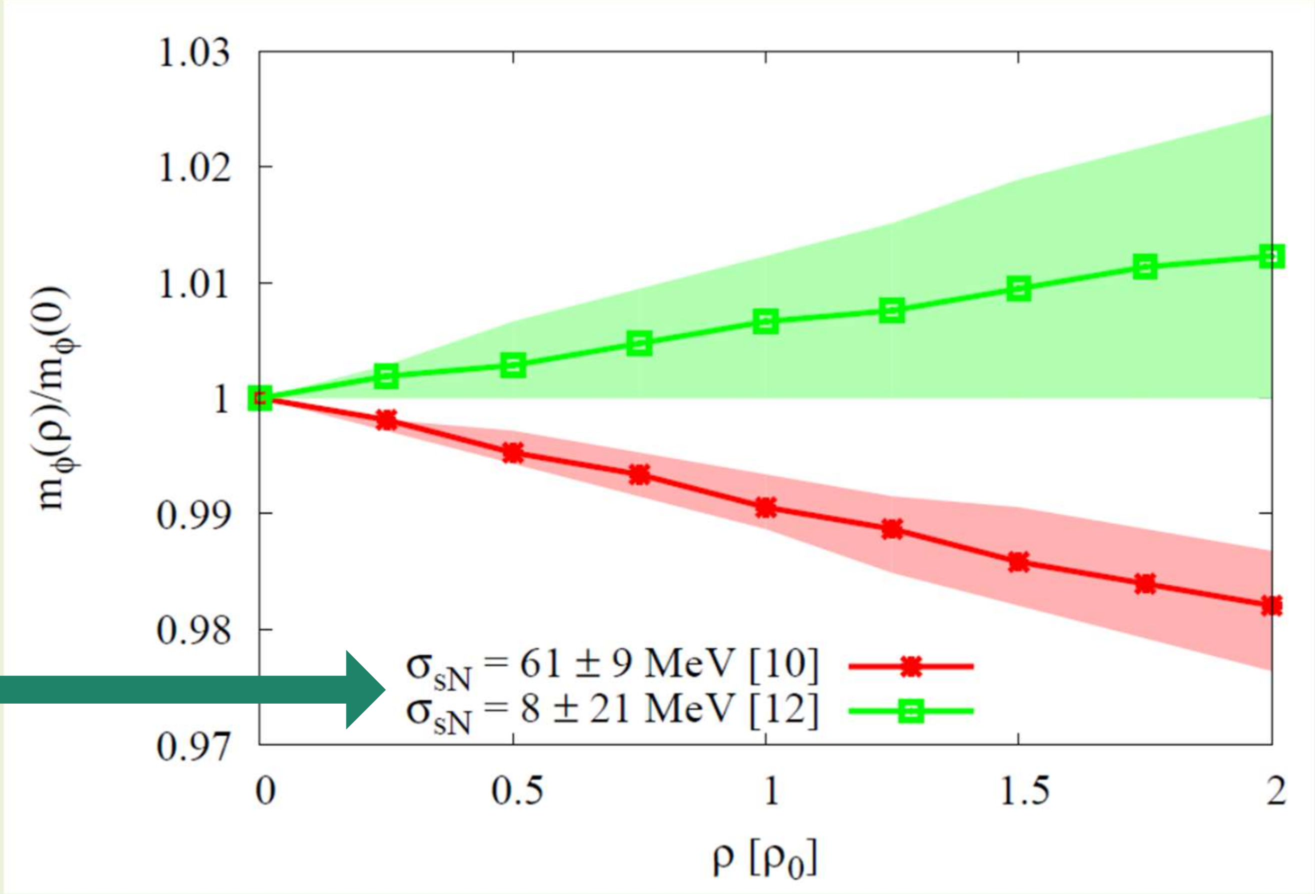
Dim. 6: $c_6(\rho) = c_6(0) + \rho[-\frac{896}{81}\kappa_N \pi^3 \alpha_s\langle\overline{s}s\rangle\langle N|\overline{s}s|N\rangle - \frac{5}{6}A_4^s M_N^3]$

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

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



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

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!

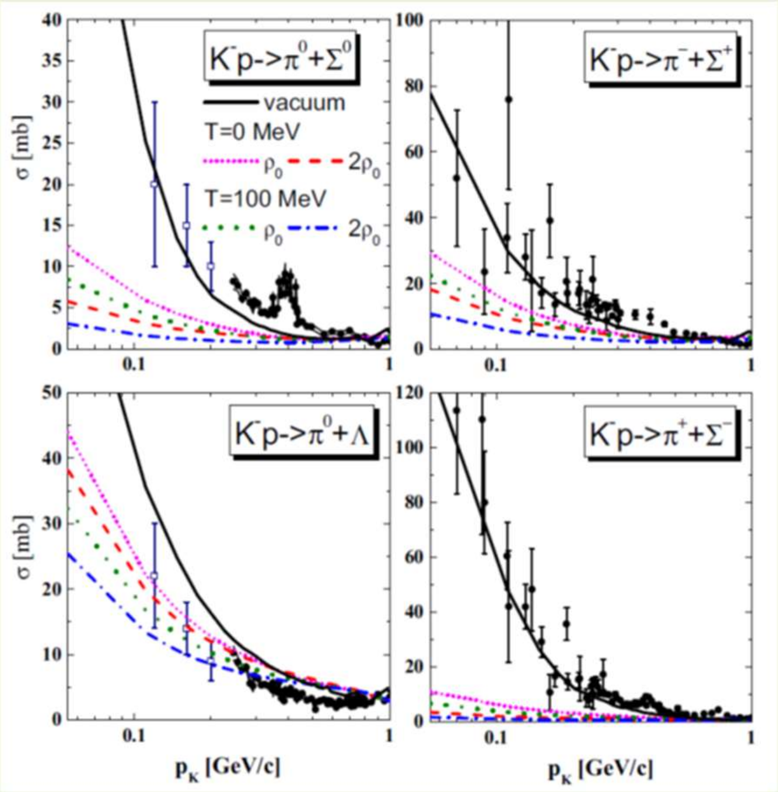
Dilepton spectrum:

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

Fitted to the experimental dilepton spectrum independently for each βγ-region

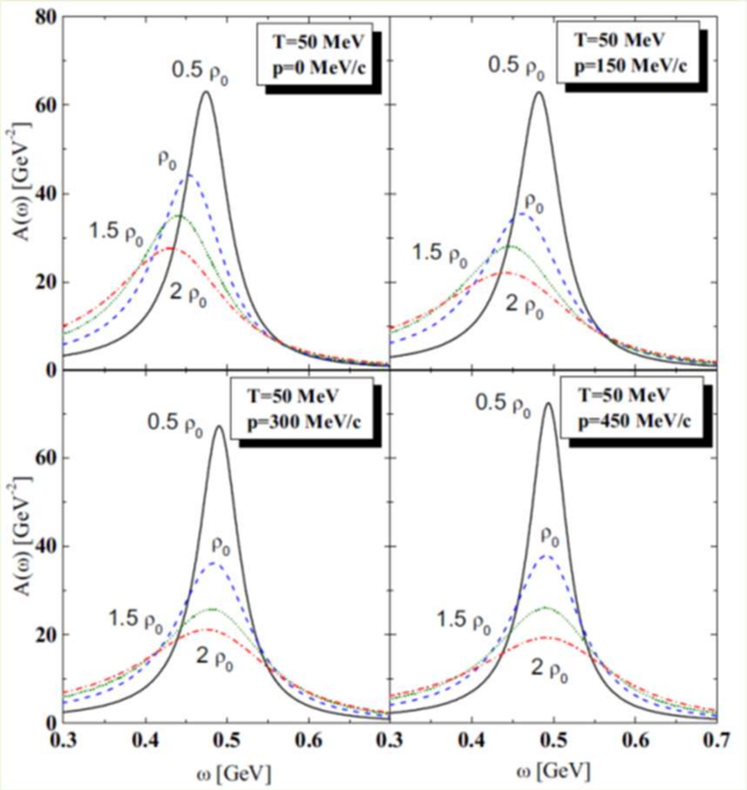
Treatment of KN-interactions

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