The phi meson in nuclear matter in a transport approach

Philipp Gubler

Japan Atomic Energy Agency (JAEA)

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online
September 8, 2021

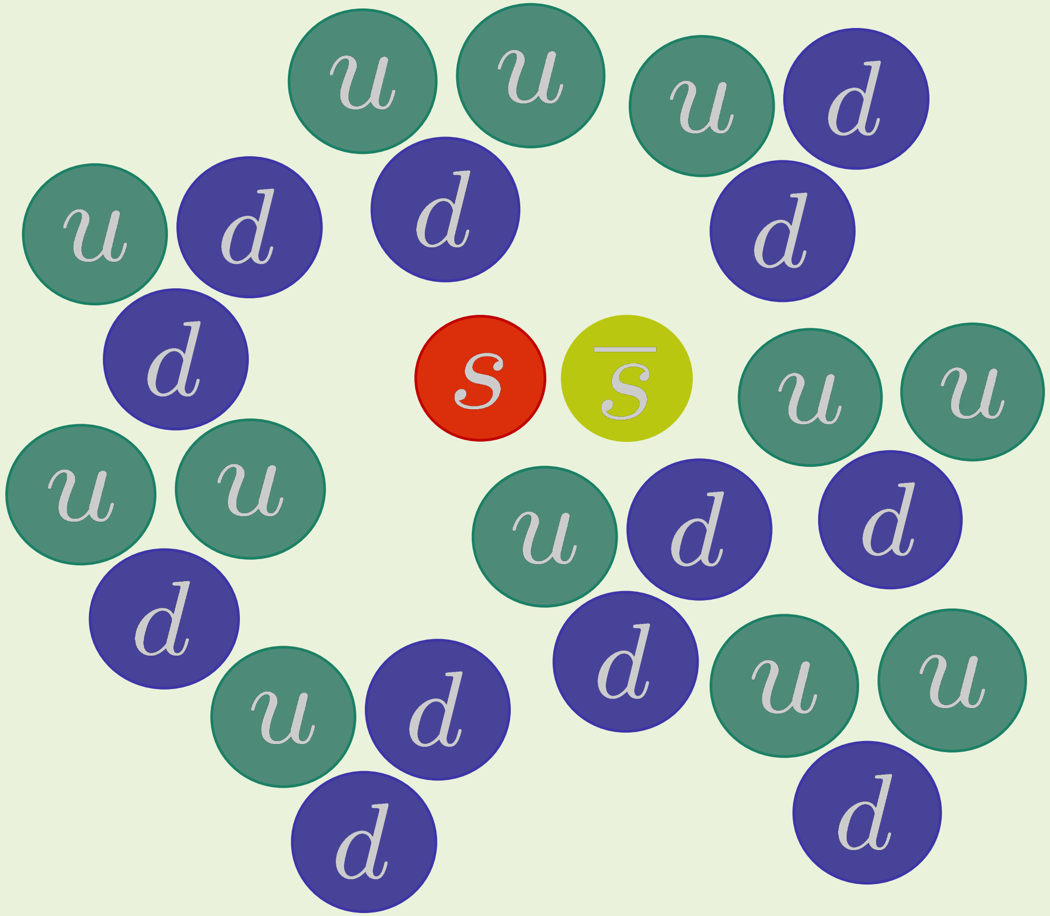
Work done in collaboration with

Elena Bratkovskaya (Frankfurt U./GSI)

ϕ meson

$m_\phi = 1019$ MeV

$\Gamma_\phi = 4.3$ MeV

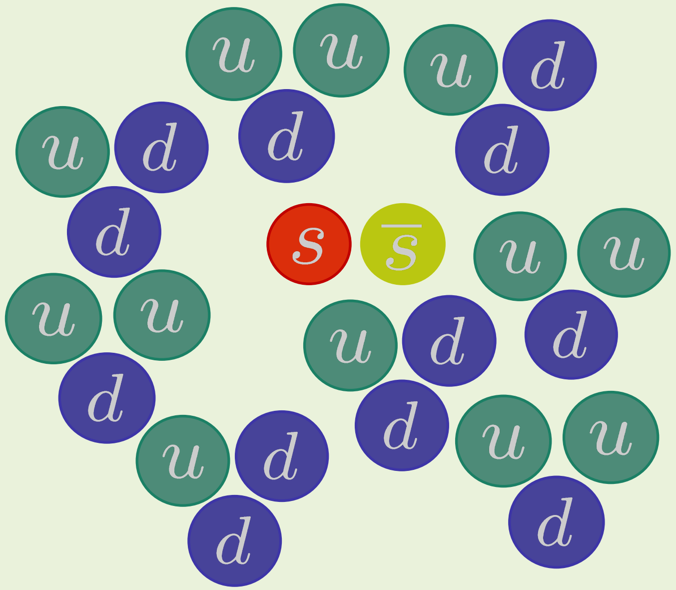


Motivation: clarify the relation between hadron masses and chiral symmetry

$\langle 0|\overline{u}u|0\rangle$ ↘

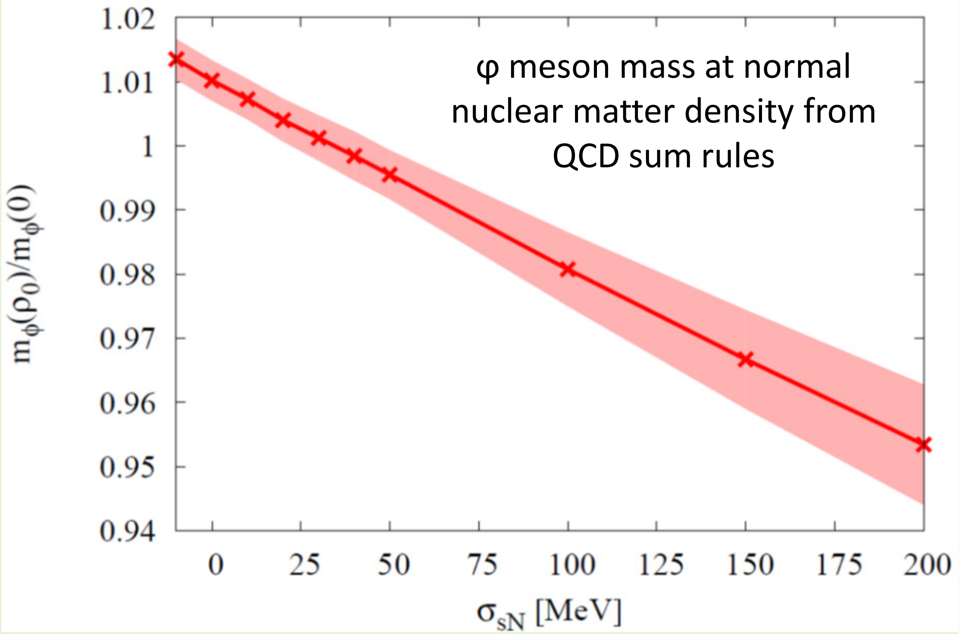
$\langle 0|\overline{d}d|0\rangle$ ↘

$\langle 0|\overline{s}s|0\rangle$ ↘



→ m_ϕ ↘ ?

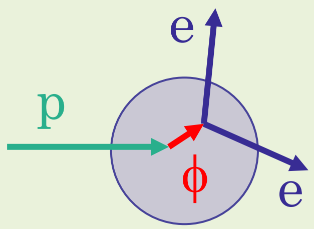
P. Gubler and K. Ohtani, Phys. Rev. D **90**, 094002 (2014).



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

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 ± 0.007

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

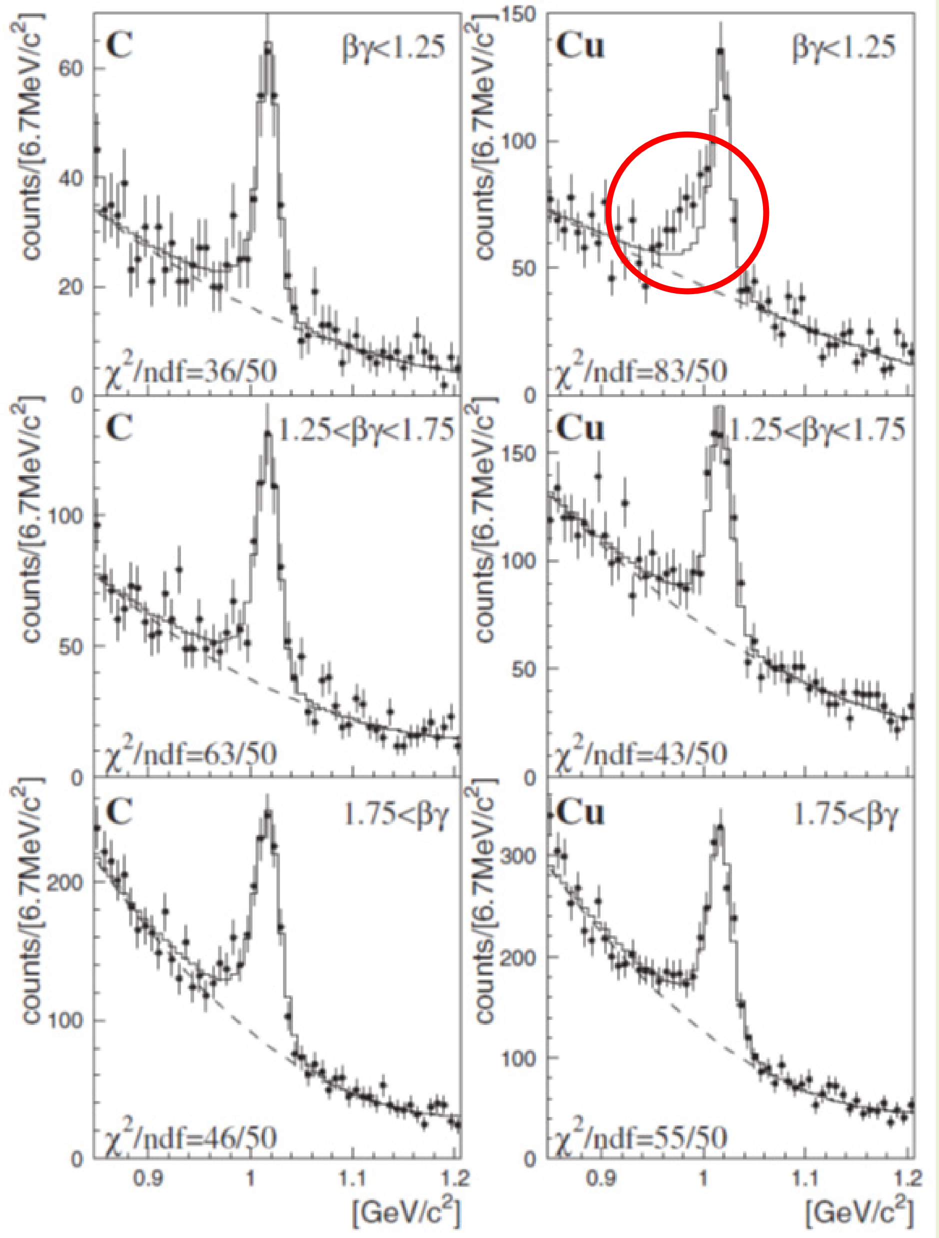
k_2: 2.6 ± 1.5

Is currently measured again at the J-PARC E16 experiment with 100x increased statistics

slow φs

intermediate φs

fast φs



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

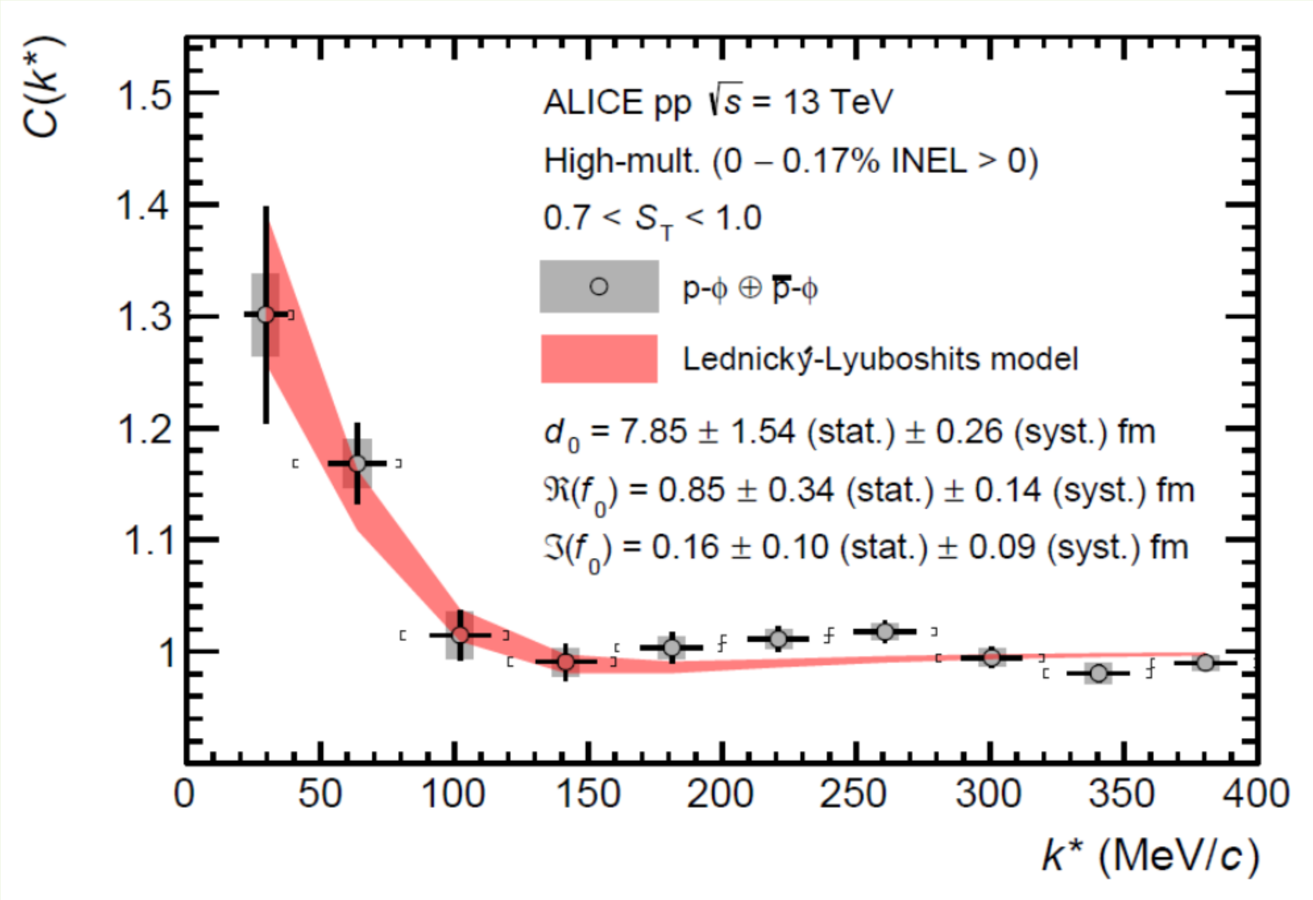
R. Muto et al. (E325 Collaboration), Phys. Rev. Lett. **98**, 042501 (2007).

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), arXiv:2105.05578 [nucl-ex].

New experimental results

ALICE

Fit of the correlation function data to two simple phenomenological potentials

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

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

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

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

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

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

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

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

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

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

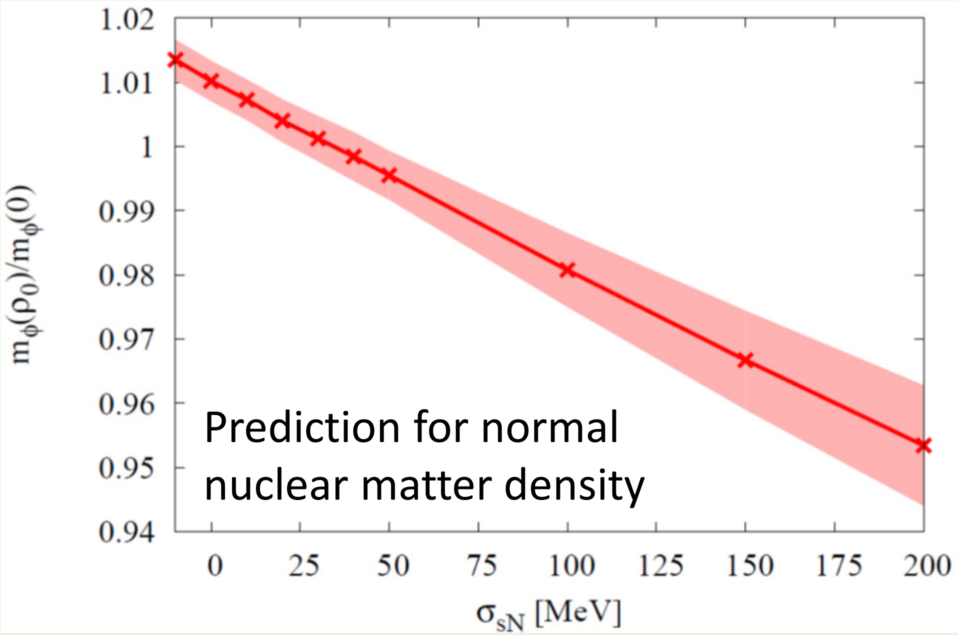
S. Acharya et al. (ALICE Collaboration), arXiv:2105.05578 [nucl-ex].

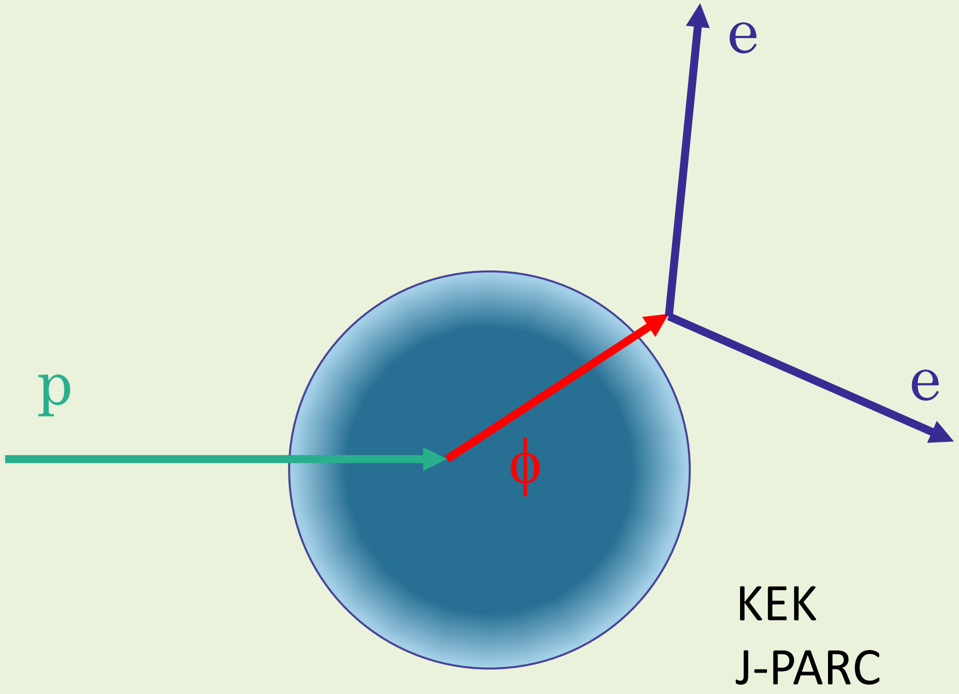
Larger attraction than what was observed at KEK 325, but large statistical and systematic uncertainties

How compare theory with the KEK E325 experiment?

Theory

Experiment





Realistic simulation of pA reaction is needed!

Our tool: a transport approach
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 is included
(dynamical modification of the vector meson spectral function during the simulated reaction)

off-shell terms

Testparticle approach:

$$\frac{d\vec{X}_i}{dt} = \frac{1}{1-C_{(i)}}\frac{1}{2\varepsilon_i}\left[2\vec{P}_i + \vec{\nabla}_{P_i}\,\mathrm{Re}\,\Sigma^{\mathrm{ret}}_{(i)} + \frac{\varepsilon_i^2 - \vec{P}_i^2 - M_0^2 - \mathrm{Re}\,\Sigma^{\mathrm{ret}}_{(i)}}{\tilde{\Gamma}_{(i)}}\vec{\nabla}_{P_i}\tilde{\Gamma}_{(i)}\right],$$

$$\frac{d\vec{P}_i}{dt} = -\frac{1}{1-C_{(i)}}\frac{1}{2\varepsilon_i}\left[\vec{\nabla}_{X_i}\,\mathrm{Re}\,\Sigma^{\mathrm{ret}}_{i} + \frac{\varepsilon_i^2 - \vec{P}_i^2 - M_0^2 - \mathrm{Re}\,\Sigma^{\mathrm{ret}}_{(i)}}{\tilde{\Gamma}_{(i)}}\vec{\nabla}_{X_i}\tilde{\Gamma}_{(i)}\right],$$

$$\frac{d\varepsilon_i}{dt} = \frac{1}{1-C_{(i)}}\frac{1}{2\varepsilon_i}\left[\frac{\partial\,\mathrm{Re}\,\Sigma^{\mathrm{ret}}_{(i)}}{\partial t} + \frac{\varepsilon_i^2 - \vec{P}_i^2 - M_0^2 - \mathrm{Re}\,\Sigma^{\mathrm{ret}}_{(i)}}{\tilde{\Gamma}_{(i)}}\frac{\partial\tilde{\Gamma}_{(i)}}{\partial t}\right],$$

Advantage: vector meson spectra can be chosen freely

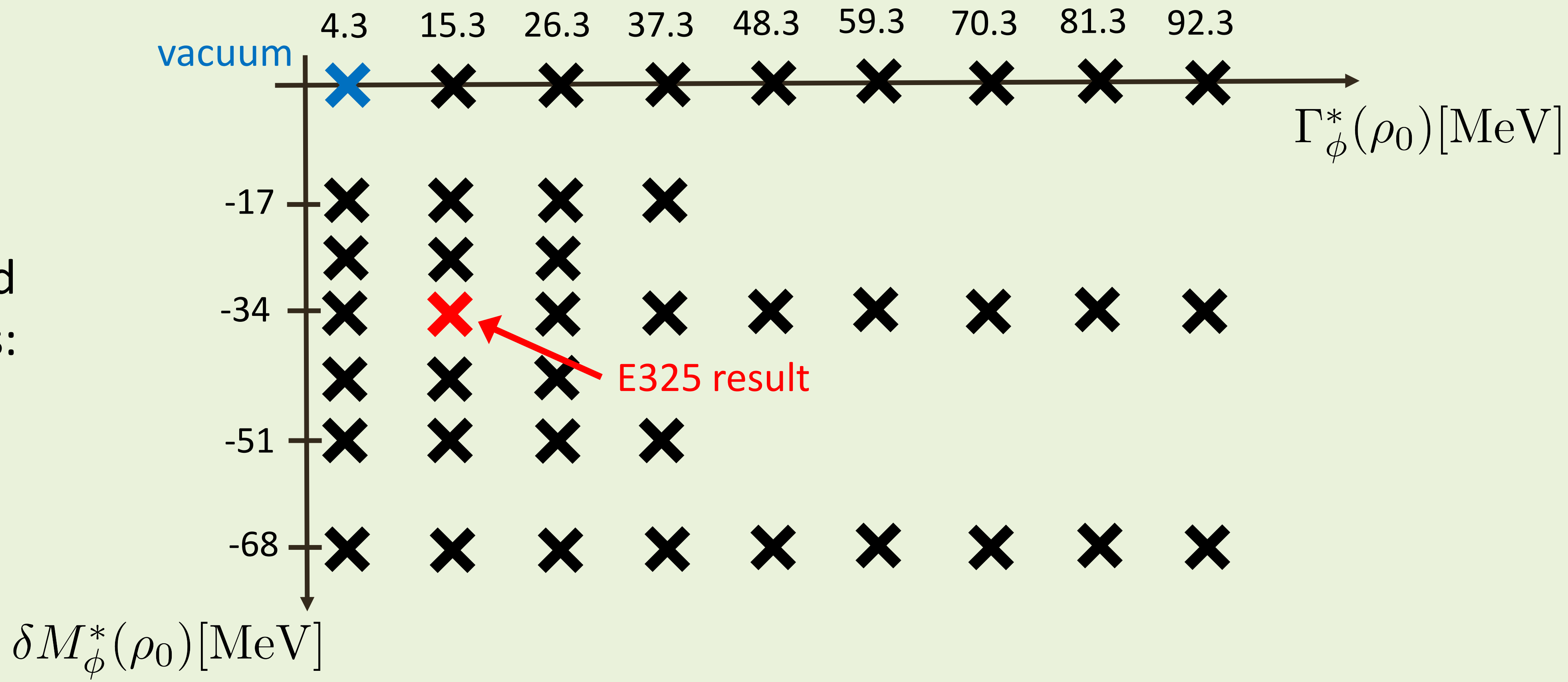
Our choice: a Breit-Wigner with density dependent mass and width

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

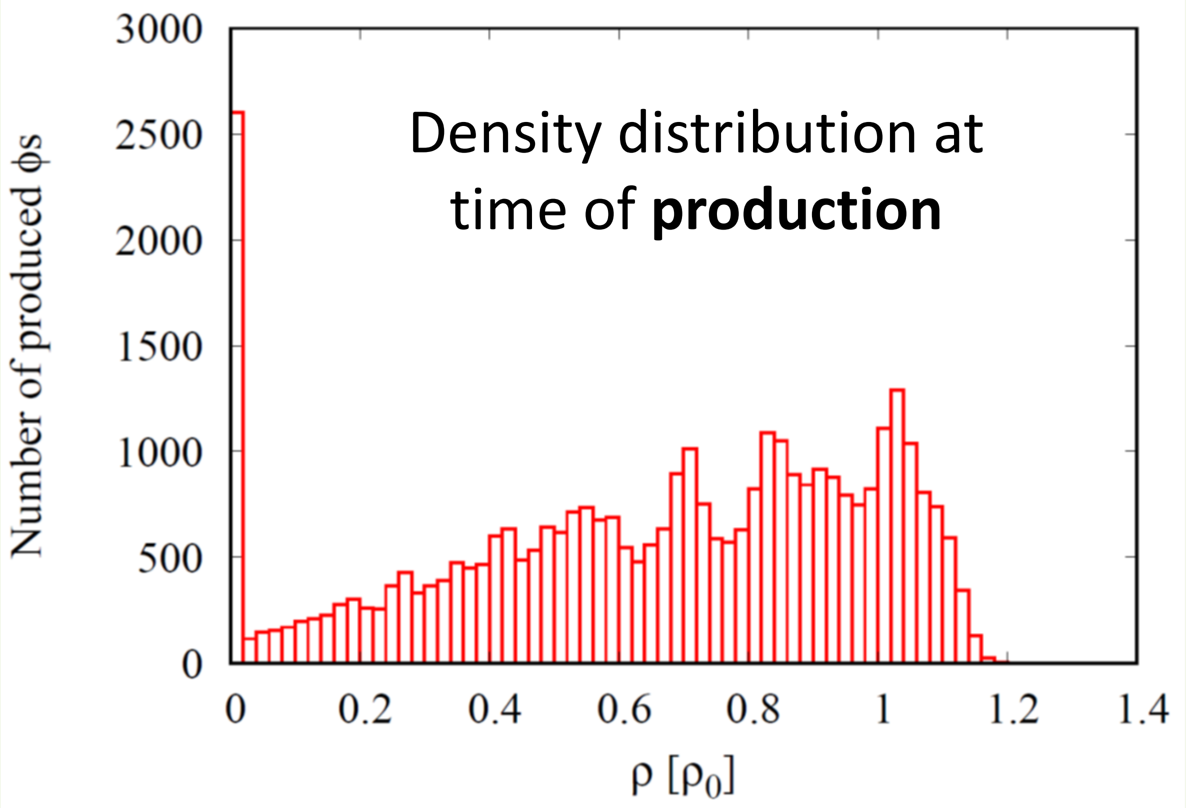
with

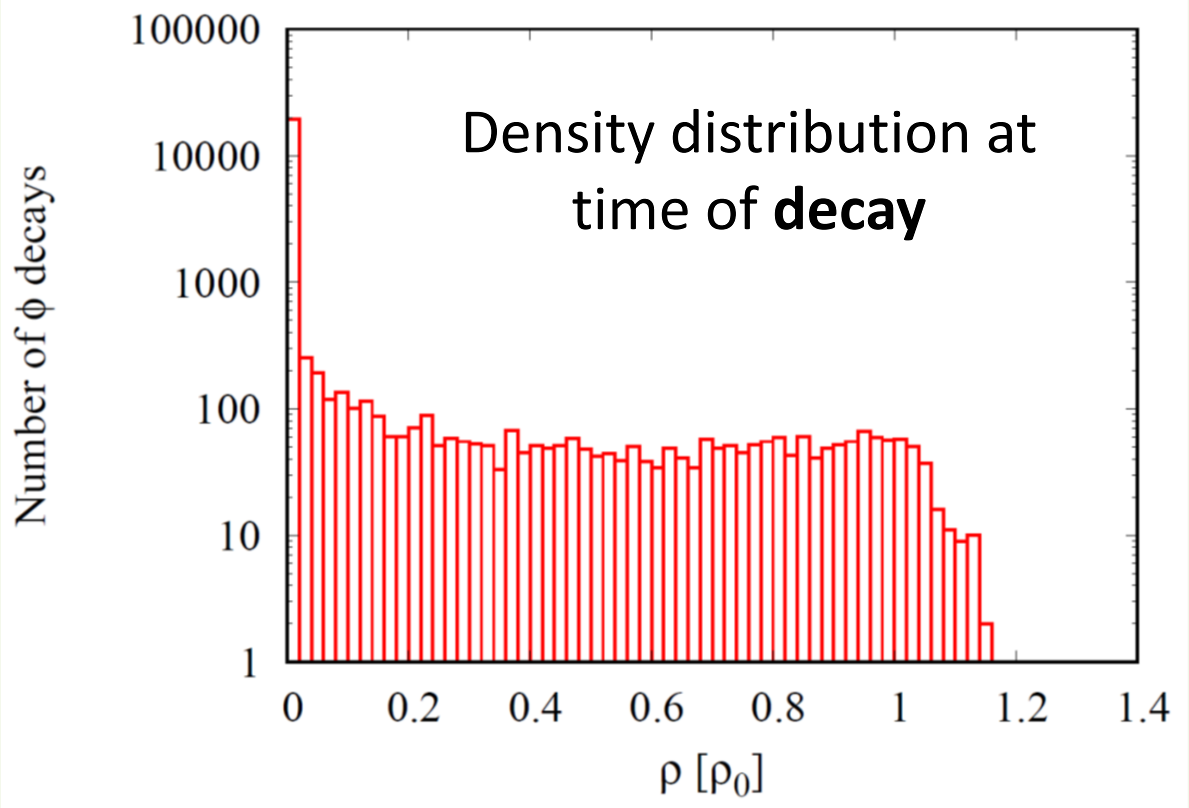
$$\begin{cases} M^*_\phi(\rho) = M^{\mathrm{vac}}_\phi\left(1 - \alpha^\phi \frac{\rho}{\rho_0}\right), \\ \Gamma^*_\phi(M,\rho) = \Gamma^{\mathrm{vac}}_\phi + \alpha^\phi_{\mathrm{coll}}\frac{\rho}{\rho_0} \end{cases}$$

Simulated scenarios:



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

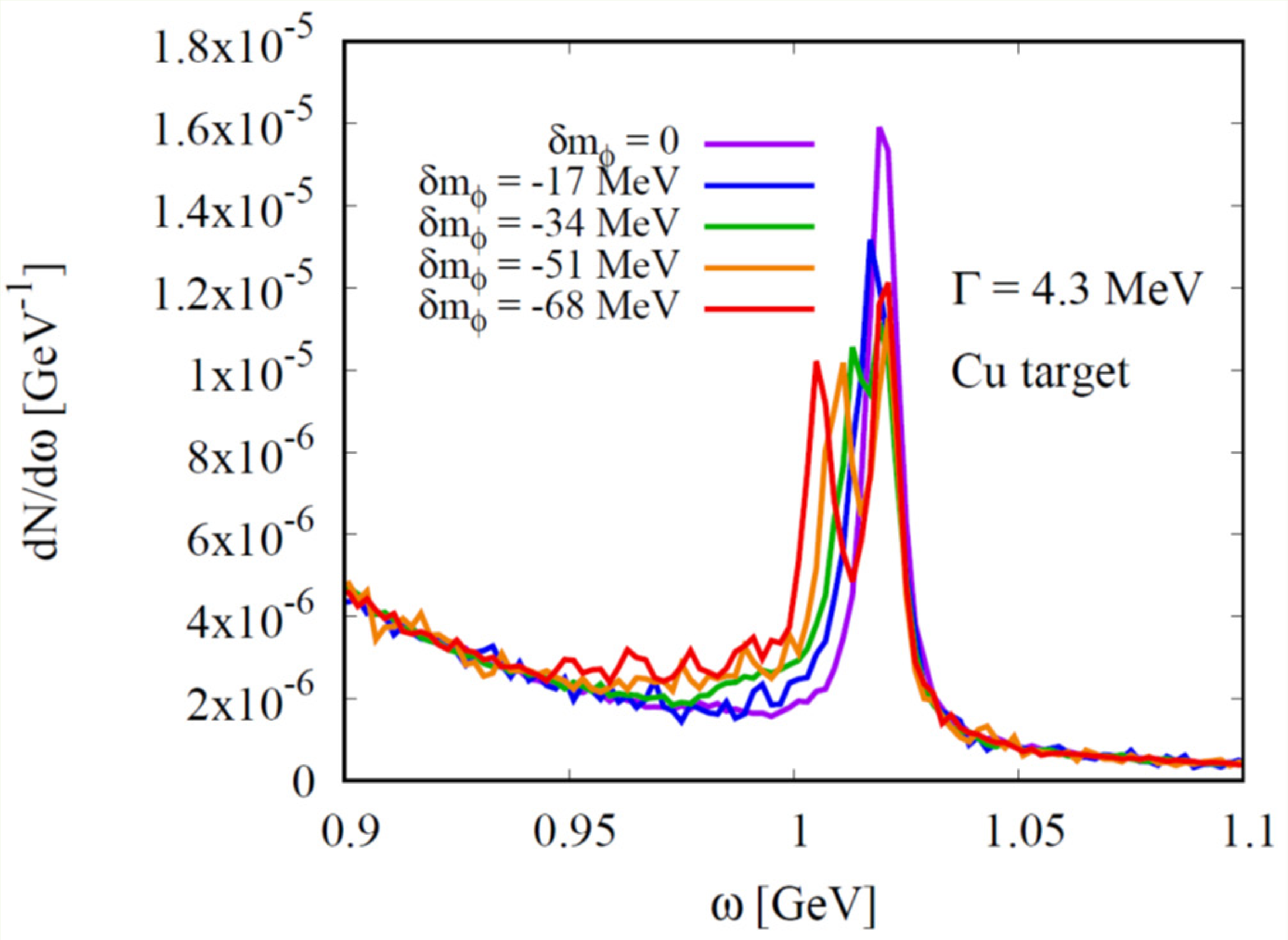




Majority of φ mesons are produced at densities around ρ_0

Majority of φ mesons decay in free space (note the log-scale!)

The dilepton spectrum in the φ meson region



p + Cu at 12 GeV

No acceptance corrections!

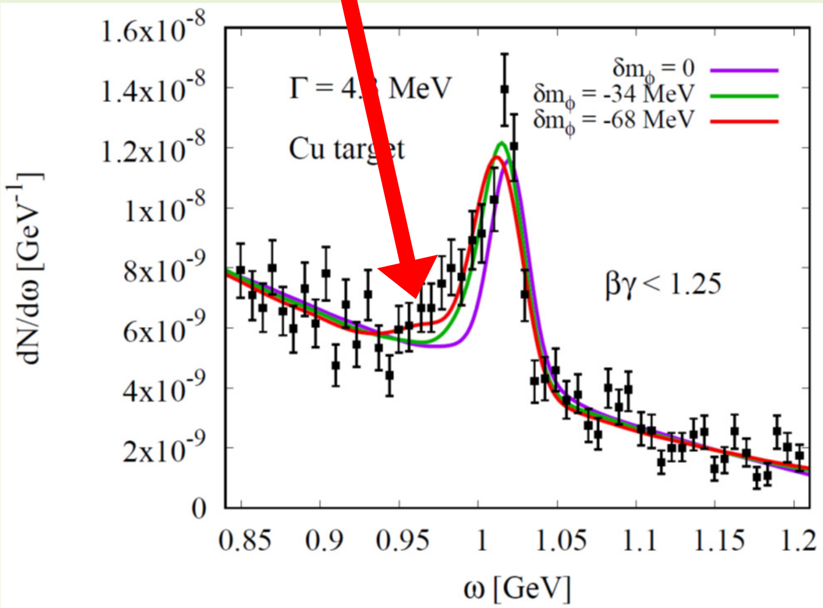
No finite resolution effects!

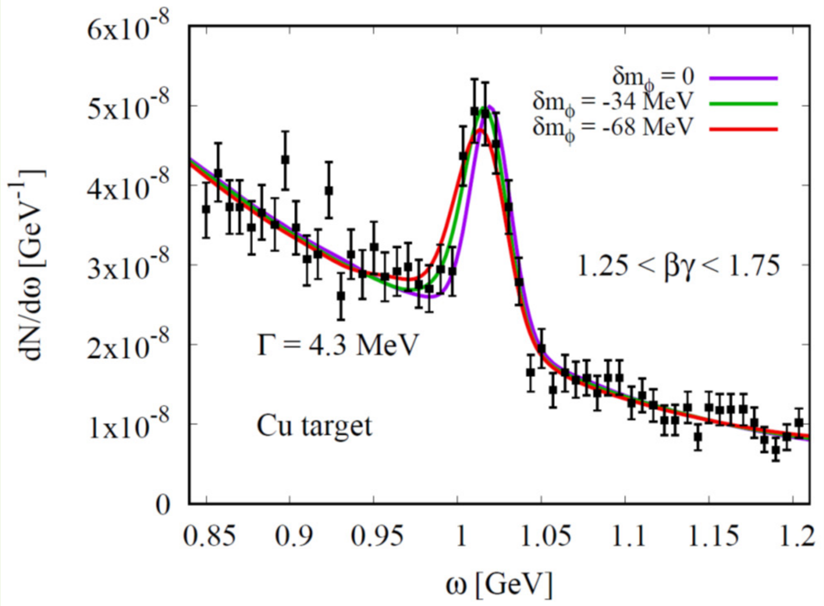
Fits to experimental Copper target data (E325)

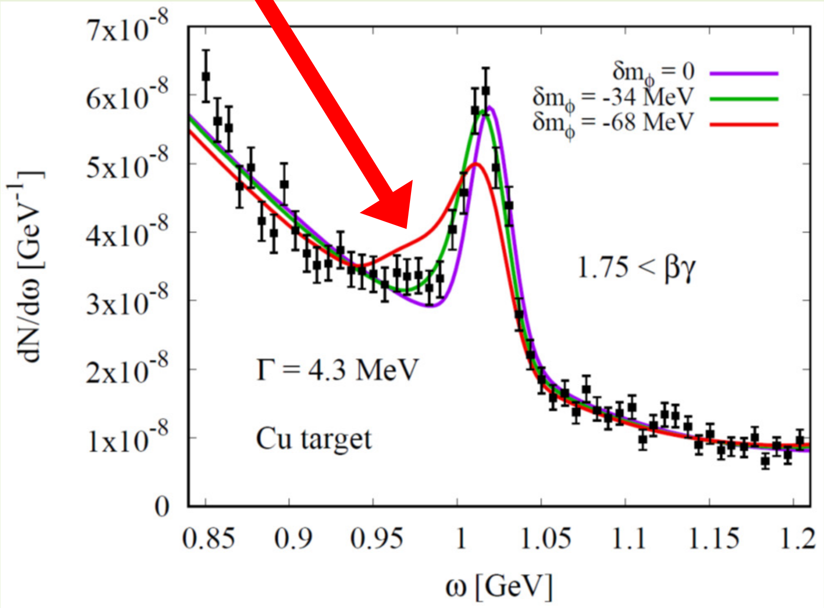
As expected, a significant negative mass shift is needed to reproduce the slow φ data

Surprisingly large effect for fast φs with a large mass shift

→ Related to initial stage of the collision







slow φs

↓

Favors relatively large negative mass shift

intermediate φs

↓

No strong constraints for any modification scenario

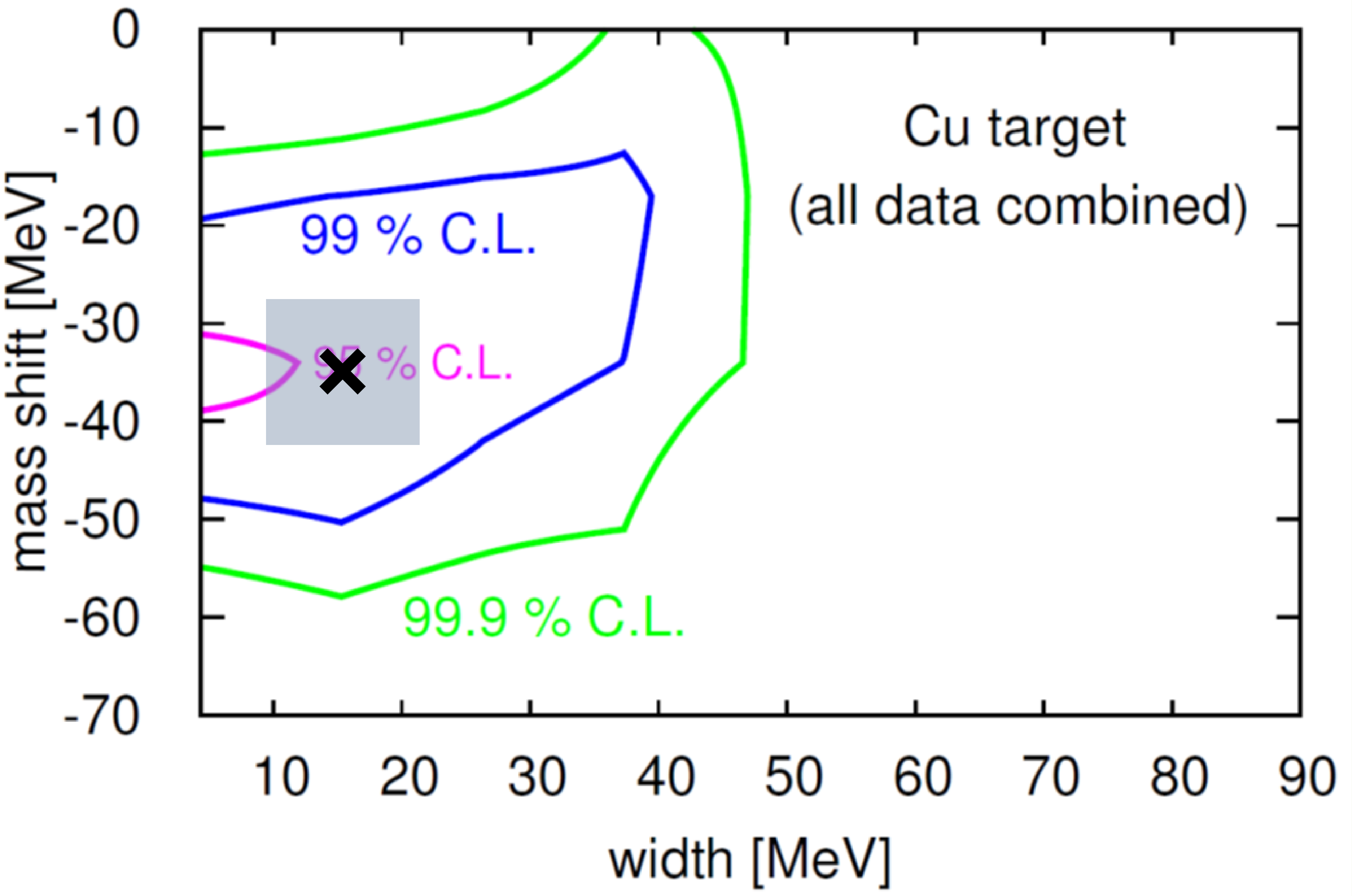
fast φs

↓

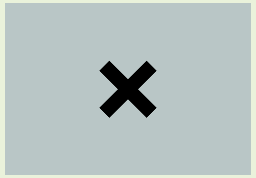
Favors small mass shift

Fits to experimental Copper target data (E325)

Confidence levels of combined Copper data



Conclusion of the E325 Collaboration

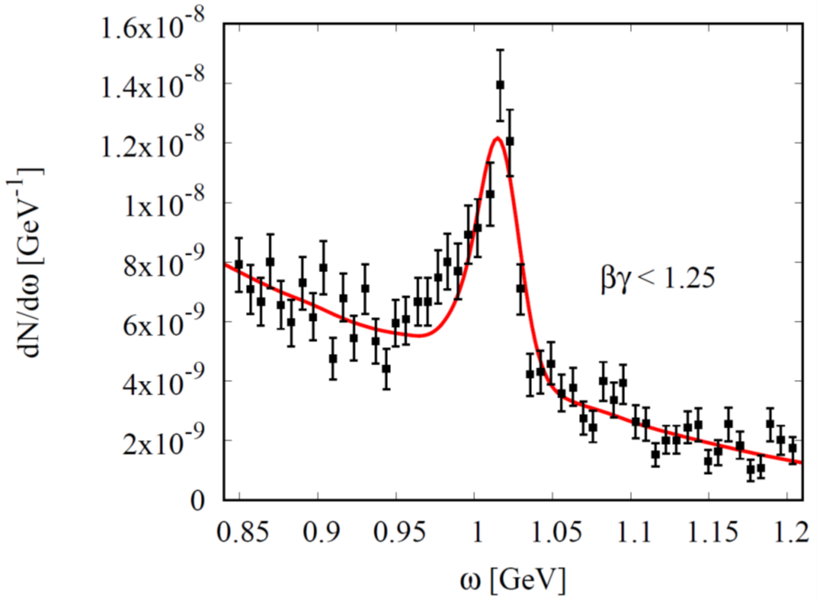


Best fit to E325 data

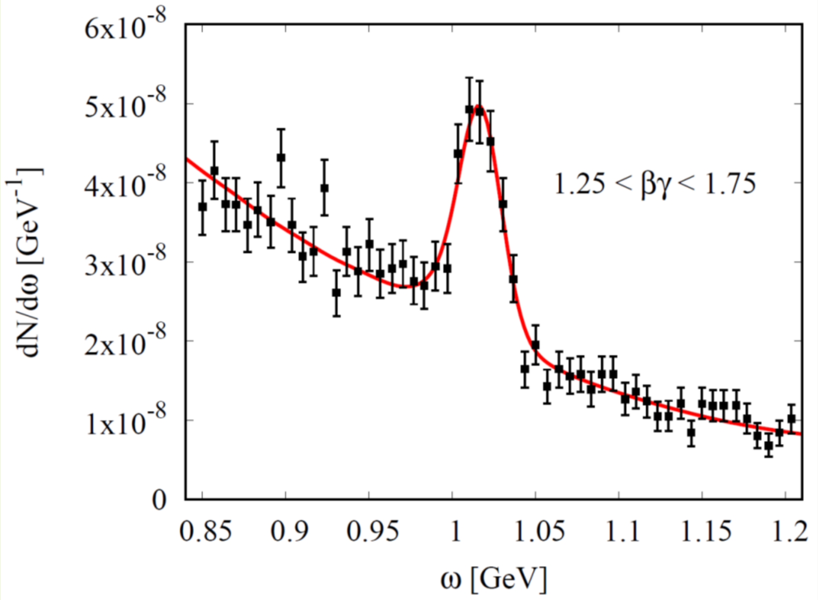
(p + Cu at 12 GeV)

vacuum value

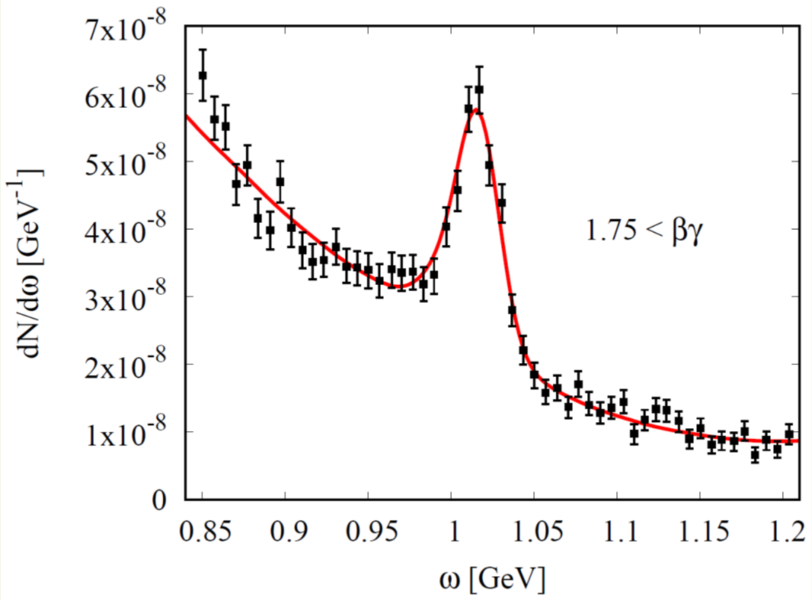
$$\delta m_\phi(\rho_0) = -34\,\mathrm{MeV} \qquad \Gamma(\rho_0) = 4.3\,\mathrm{MeV}$$



slow φs



intermediate φs



fast φs

Summary and Conclusions

★ A lot of new experimental information about the φN interaction is becoming available (LHC, J-PARC, HADES)

★ Studying the modification of the φ meson spectral function experimentally at finite density is non-trivial. A good understanding of the underlying reactions is needed!

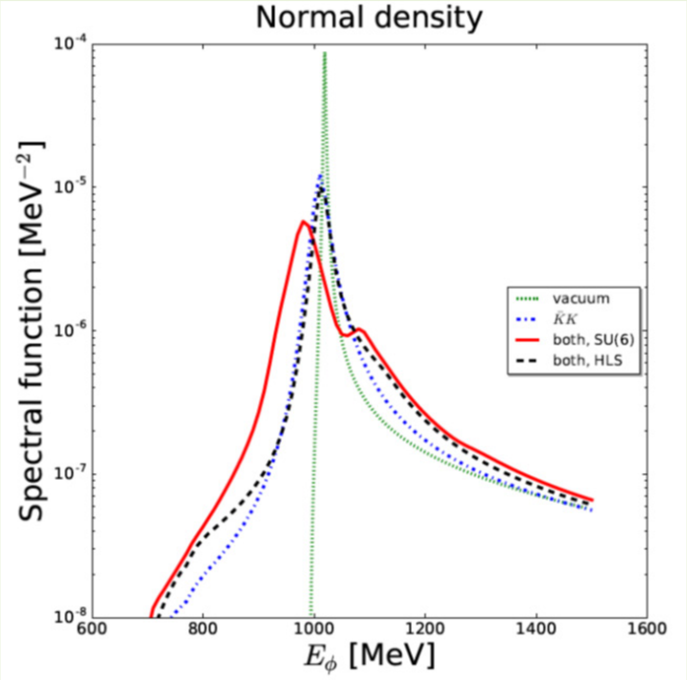
★ We conducted numerical simulations of the pA reactions measured at the E325 experiment at KEK, using the PHSD transport code

Our results indicate that the experimental data favor a **negative mass shift with zero or only small broadening**!

Backup slides

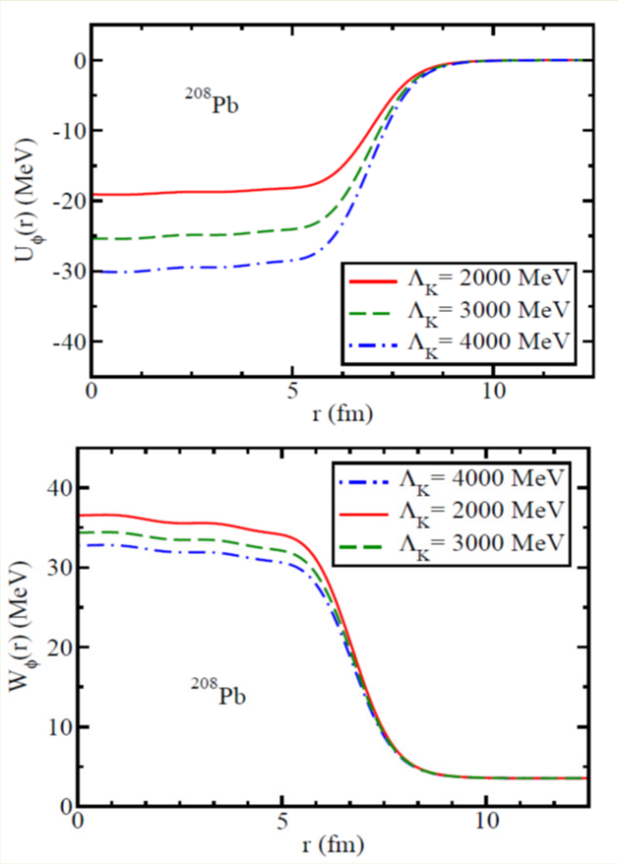
Many theoretical works about the φ meson at finite density in recent years

Spectral functions from hadronic models



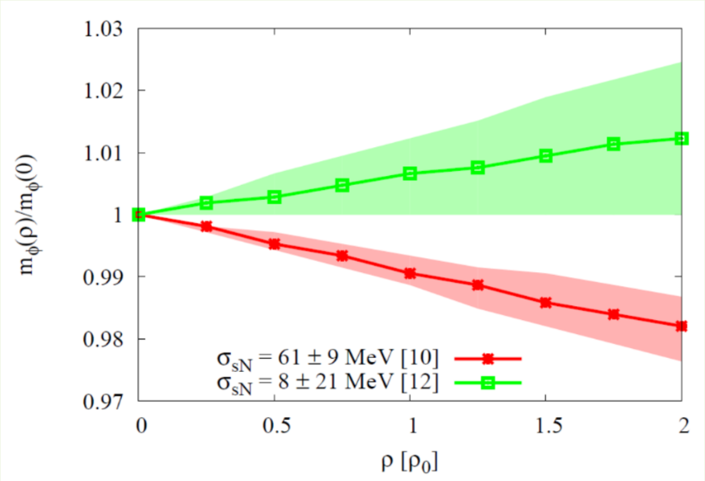
P. Gubler and W. Weise, Phys. Lett. B **751**, 396 (2015).
P. Gubler and W. Weise, Nucl. Phys. A **954**, 125 (2016).
D. Cabrera *et al.*, Phys. Rev. C **95**, 015201 (2017).
D. Cabrera *et al.*, Phys. Rev. C **96**, 034618 (2017).

Possibility of φ-nucleus bound state



J.J. Cobos-Martinez *et al.*, Phys. Lett. B **771**, 113 (2017).
J.J. Cobos-Martinez *et al.*, Phys. Rev. C **96**, 035201 (2017).

Mass shift in nuclear matter from QCD sum rules



P. Gubler and K. Ohtani,
Phys. Rev. D **90**, 094002 (2014).
HJ. Kim *et al.*, Phys. Lett. B **772**, 194 (2017).
HJ. Kim and P. Gubler,
Phys. Lett. B **805**, 135412 (2020).

Recent experimental results

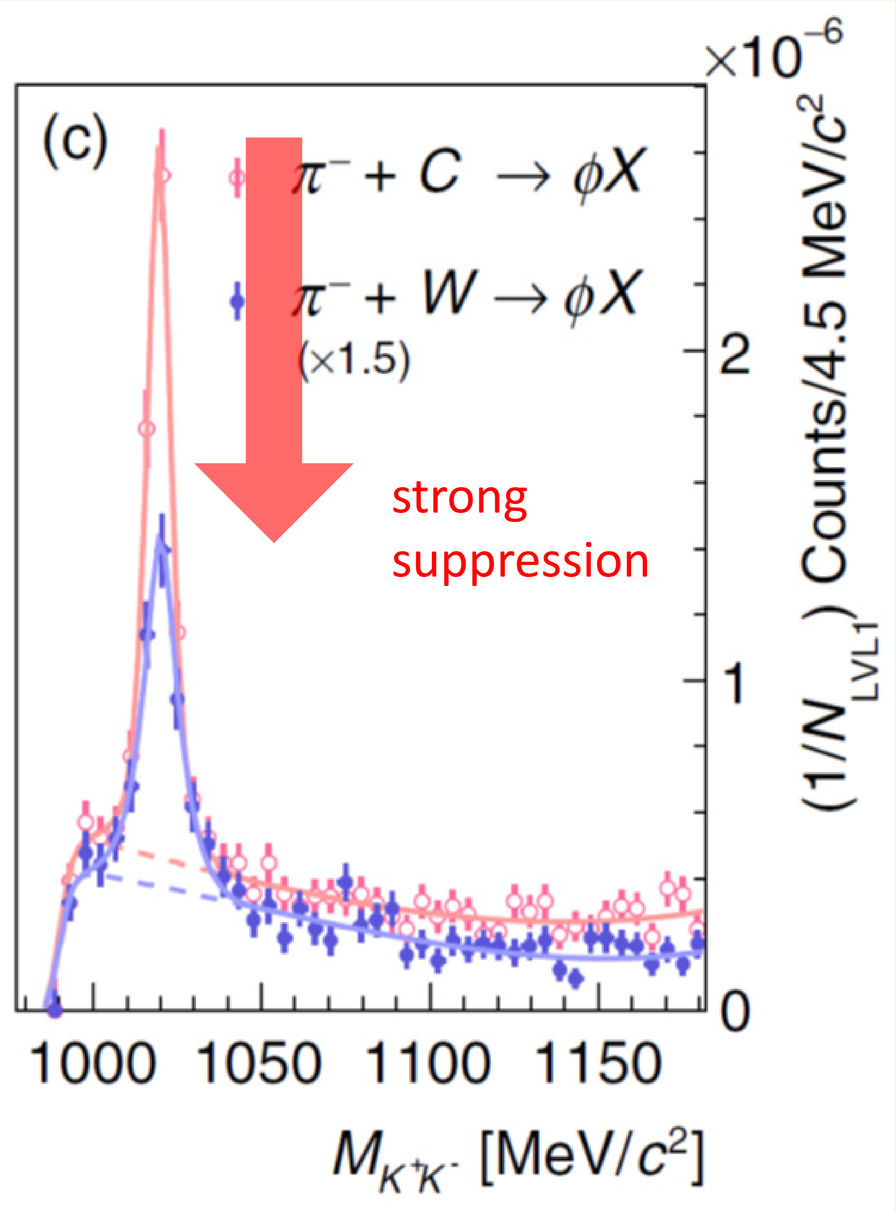
HADES: 1.7 GeV π^-A-reaction

- ★ 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

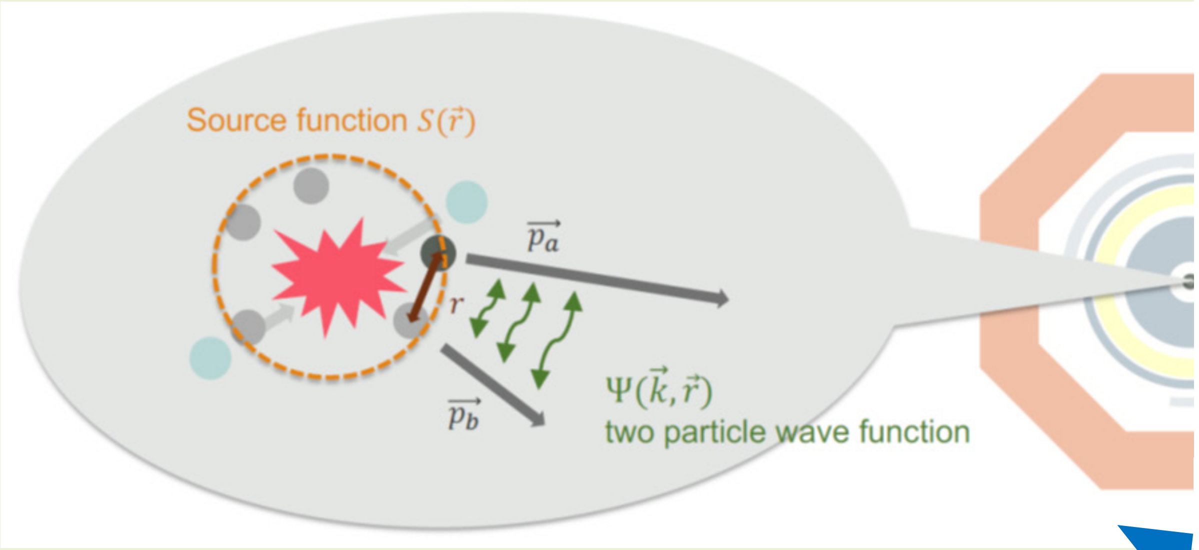
K^+K^- - invariant mass spectrum



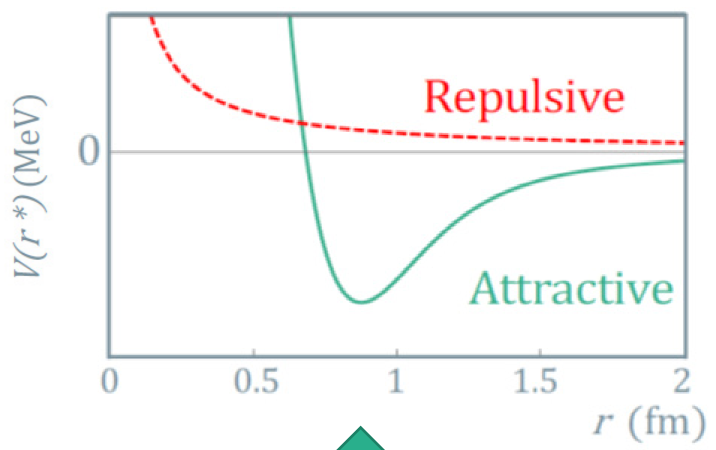
J. Adamczewski-Musch et al. (HADES Collaboration), Phys. Rev. Lett. **123**, 022002 (2019).

New experimental results

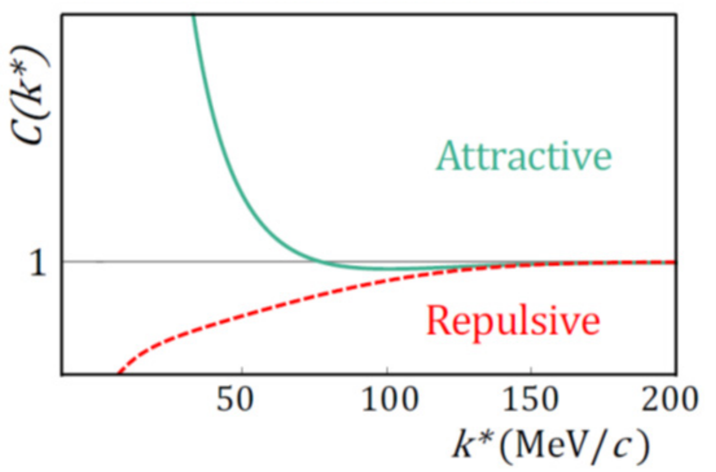
ALICE (Femtoscopy)



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), arXiv:2105.05578 [nucl-ex].

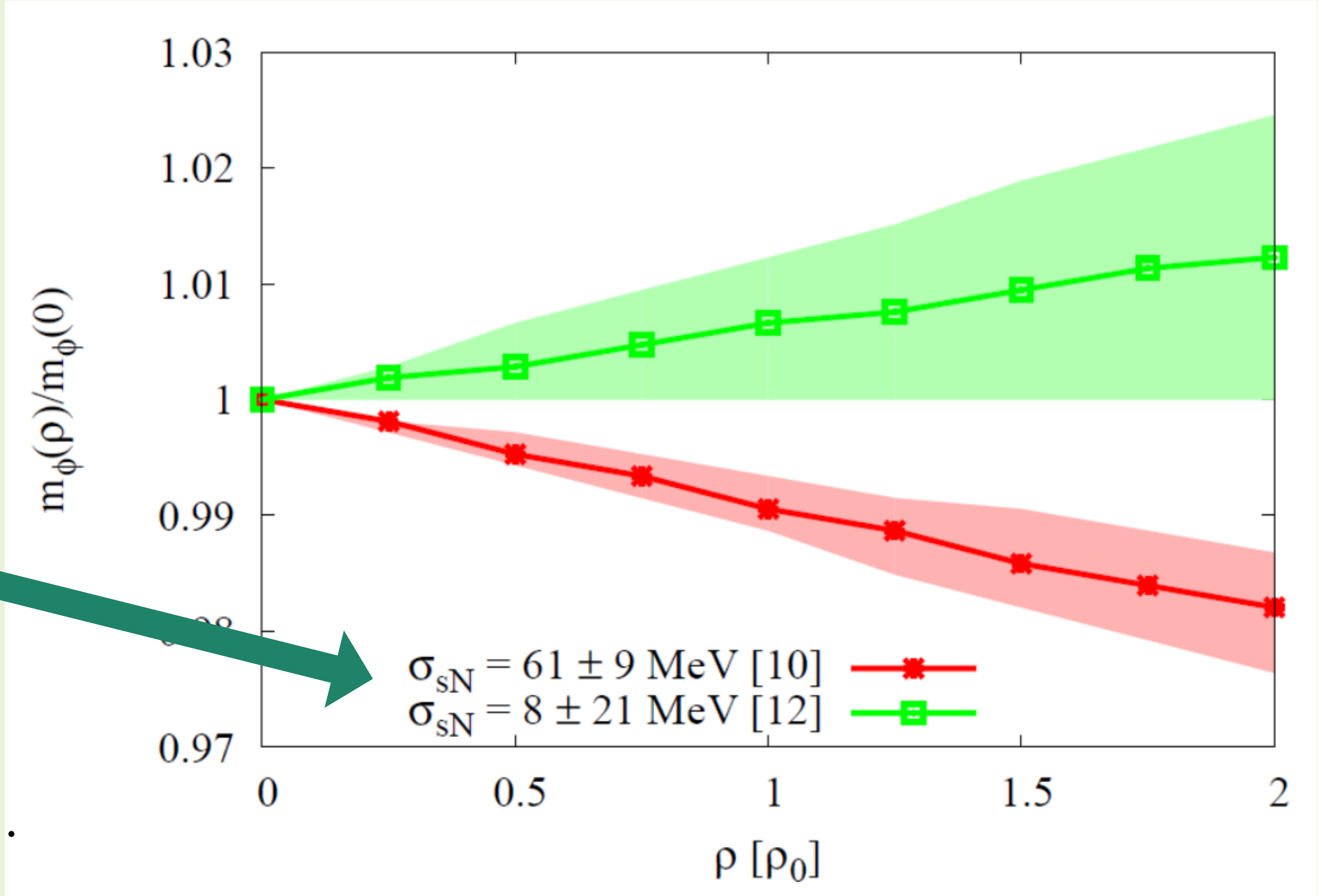
Results for the ϕ meson mass at rest (from QCD sum rules)

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

Strangeness content of the nucleon

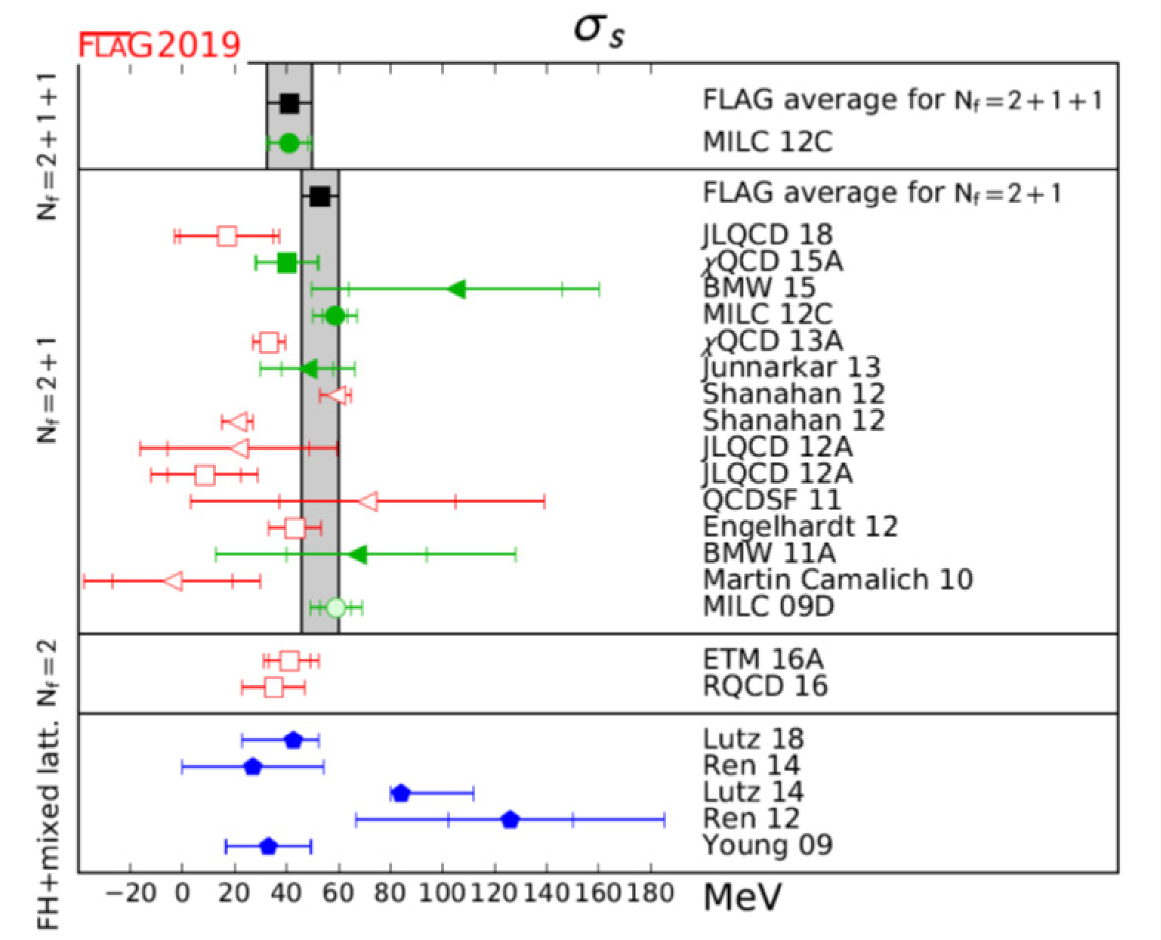
$$\sigma_{sN} = m_s \langle N|\bar{s}s|N\rangle$$

$$\langle \bar{s}s\rangle_\rho = \langle \bar{s}s\rangle_0 + \langle N|\bar{s}s|N\rangle \rho + \dots$$



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

What does lattice QCD say about σ_s?



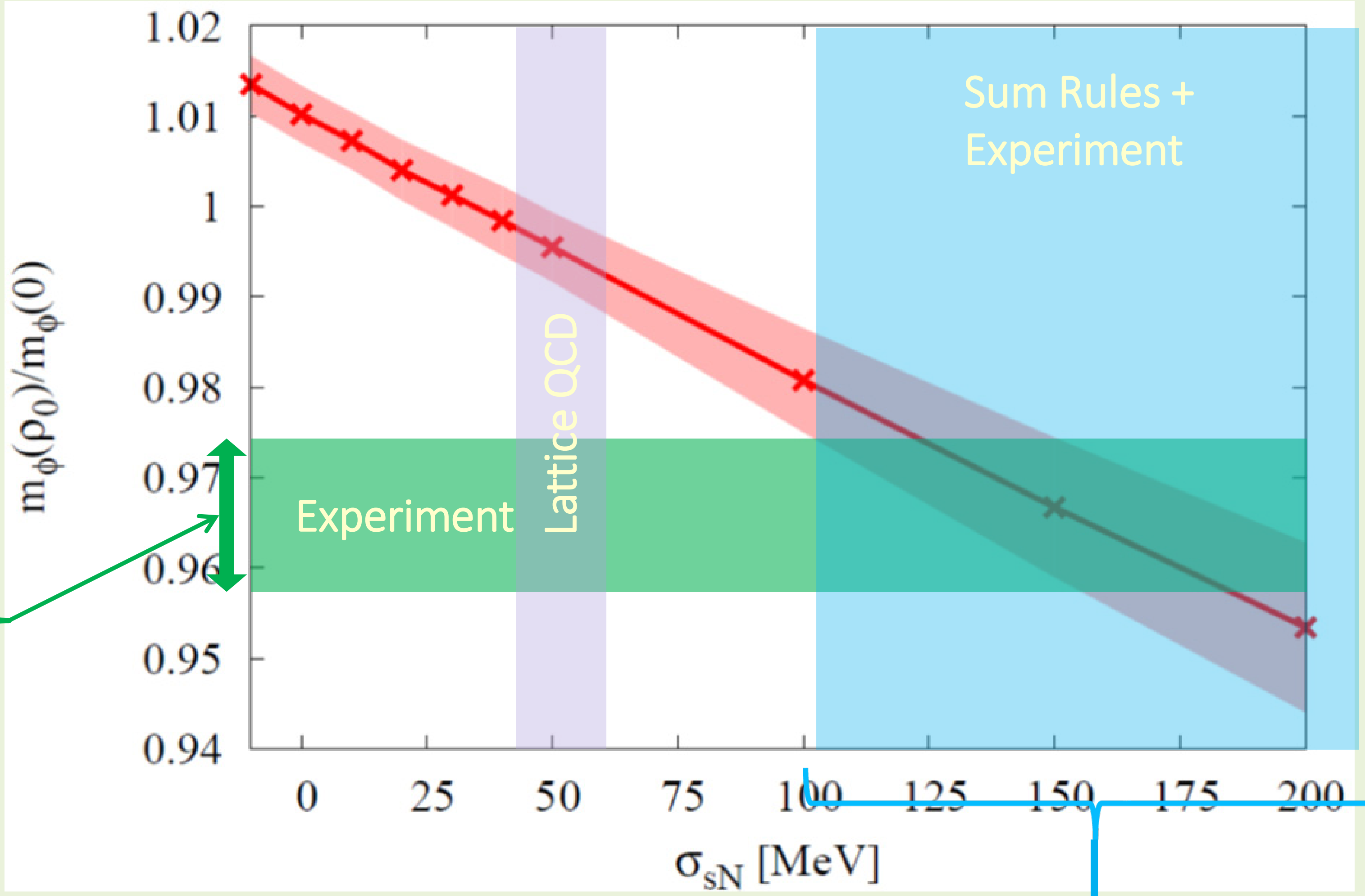
http://flag.unibe.ch/2019/

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

Compare Theory with Experiment

Not consistent?

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



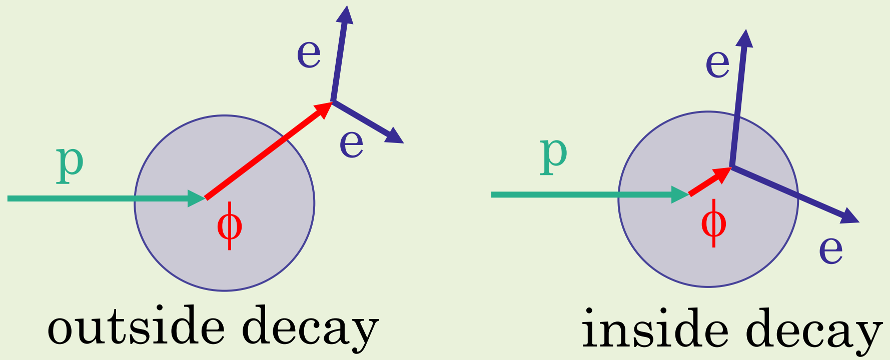
$$\sigma_{sN} \sim 160 \pm 50 \text{ MeV}$$

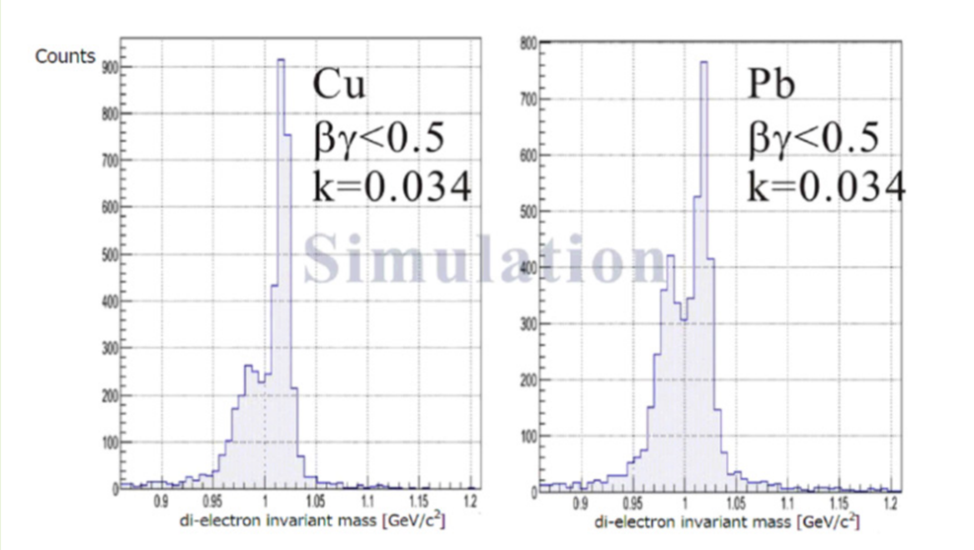
Will be measured again with better statistics at the E16 experiment at J-PARC!

The experimental situation

The E325 Experiment (KEK)

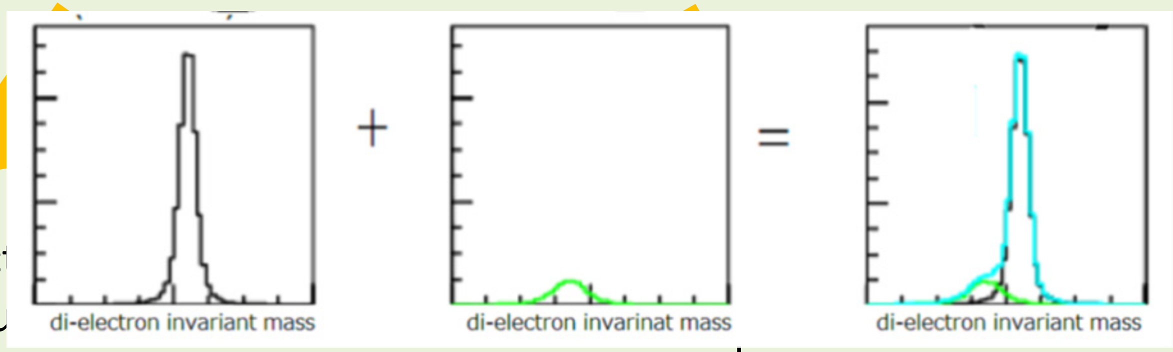
Slowly moving ϕ mesons are produced in 12 GeV p+A reactions and are measured through di-leptons.





Y. Morino et. al. (J-PARC E16 Collaboration), JPS Conf. Proc. 8, 022009 (2015).

No effect
(only vacuu



ϕ-meson

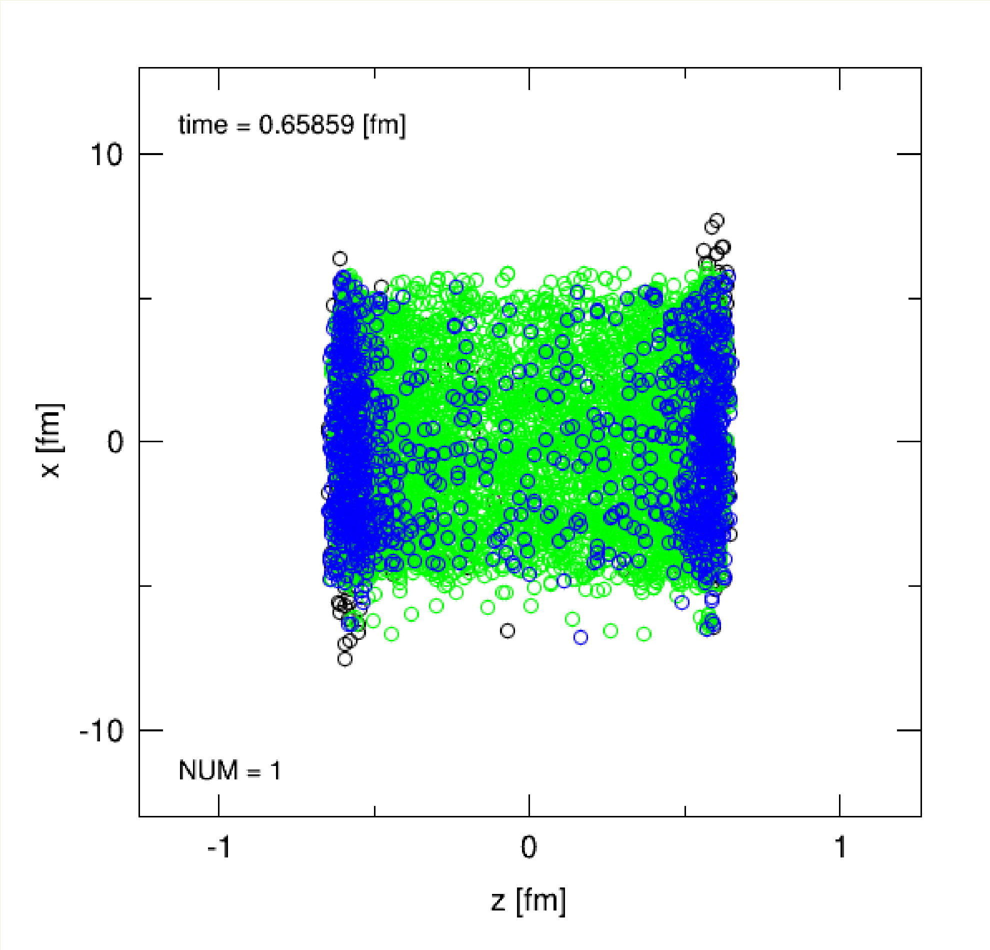
Our tool: a transport code
PHSD (Parton Hadron String Dynamics)

W. Cassing and E. Bratkovskaya, Phys. Rev. C **78**, 034919 (2008).

Example:

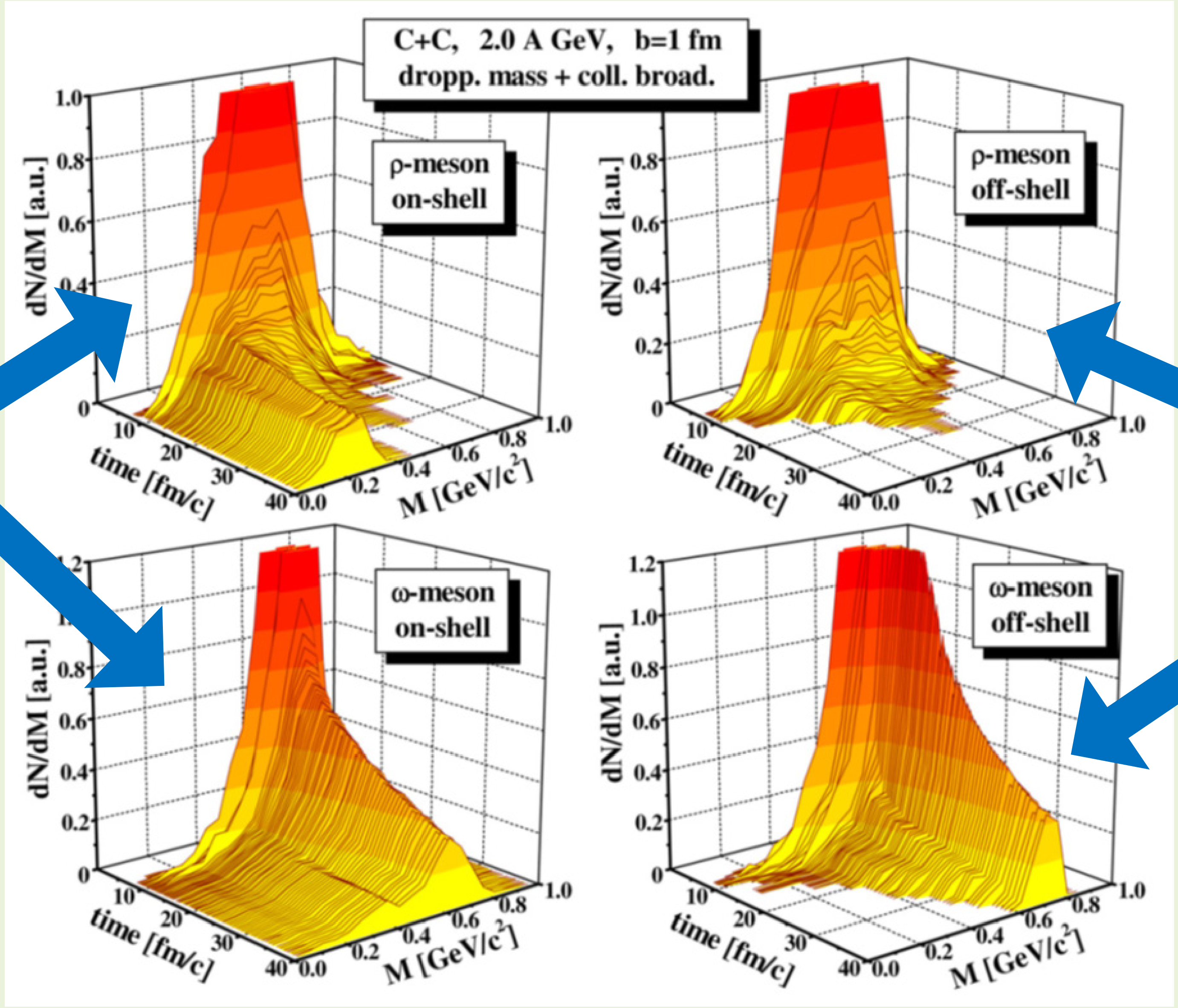
Au+Au collision at 200 GeV
b = 2 fm

nucleons
quarks
gluons



The importance of off-shell contributions

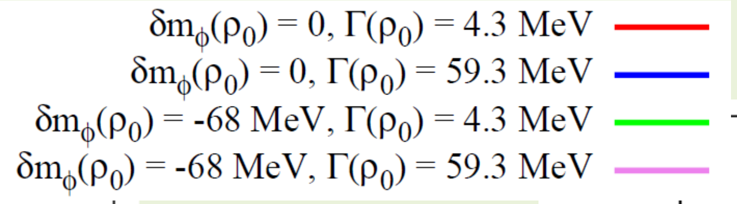
Only on-shell contributions: Vacuum spectral function are not recovered at late time of the reaction



Off-shell contributions included: correct behavior

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

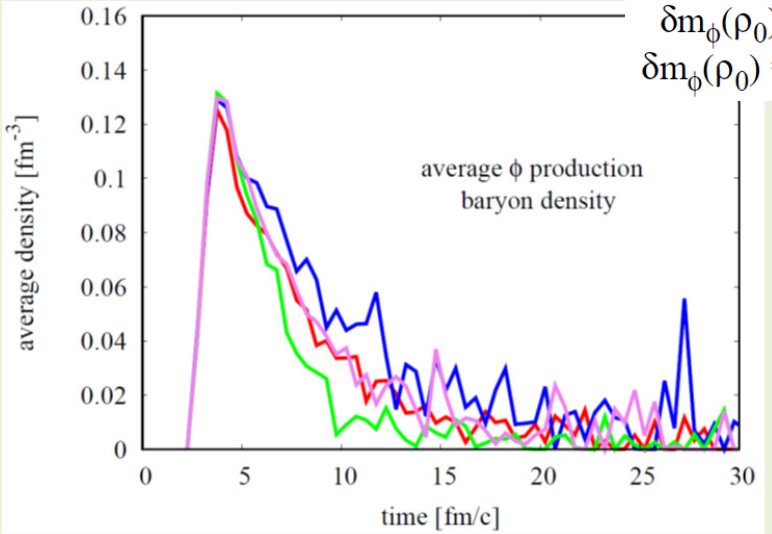
What density does the φ feel in the reaction (p+Cu/C at 12 GeV)?

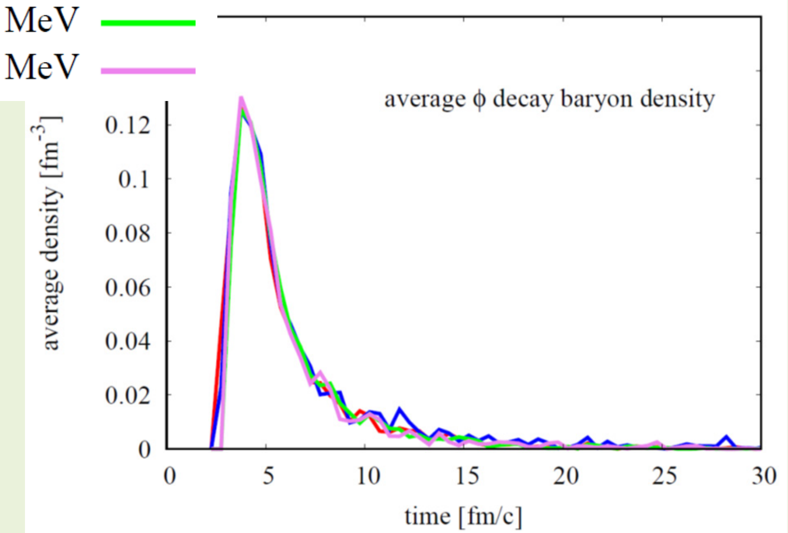


Production

Decay

Cu target

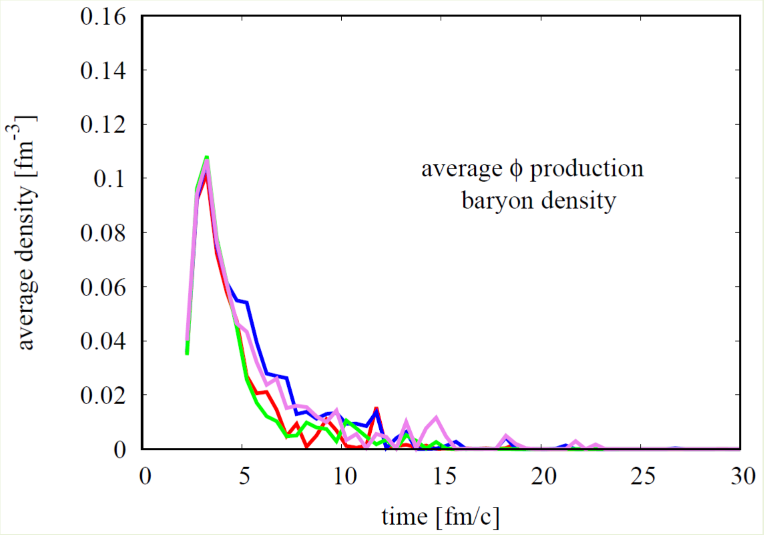


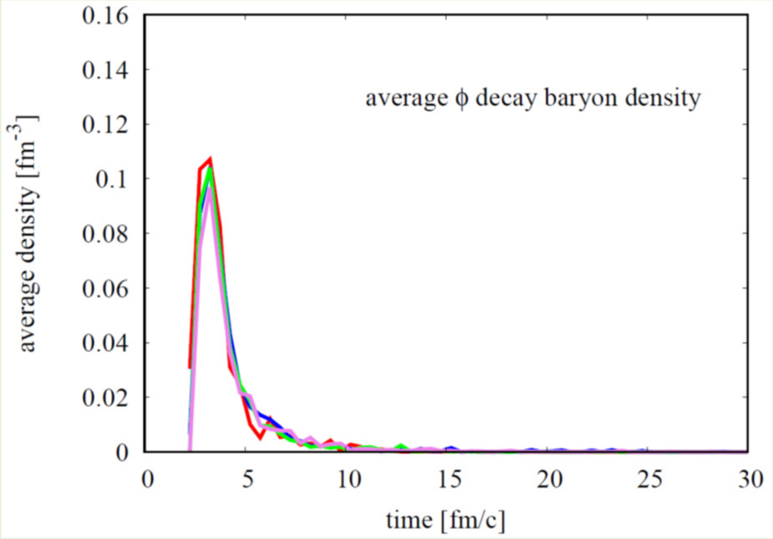


φ mesons are on average created at a density significantly below ρ_0

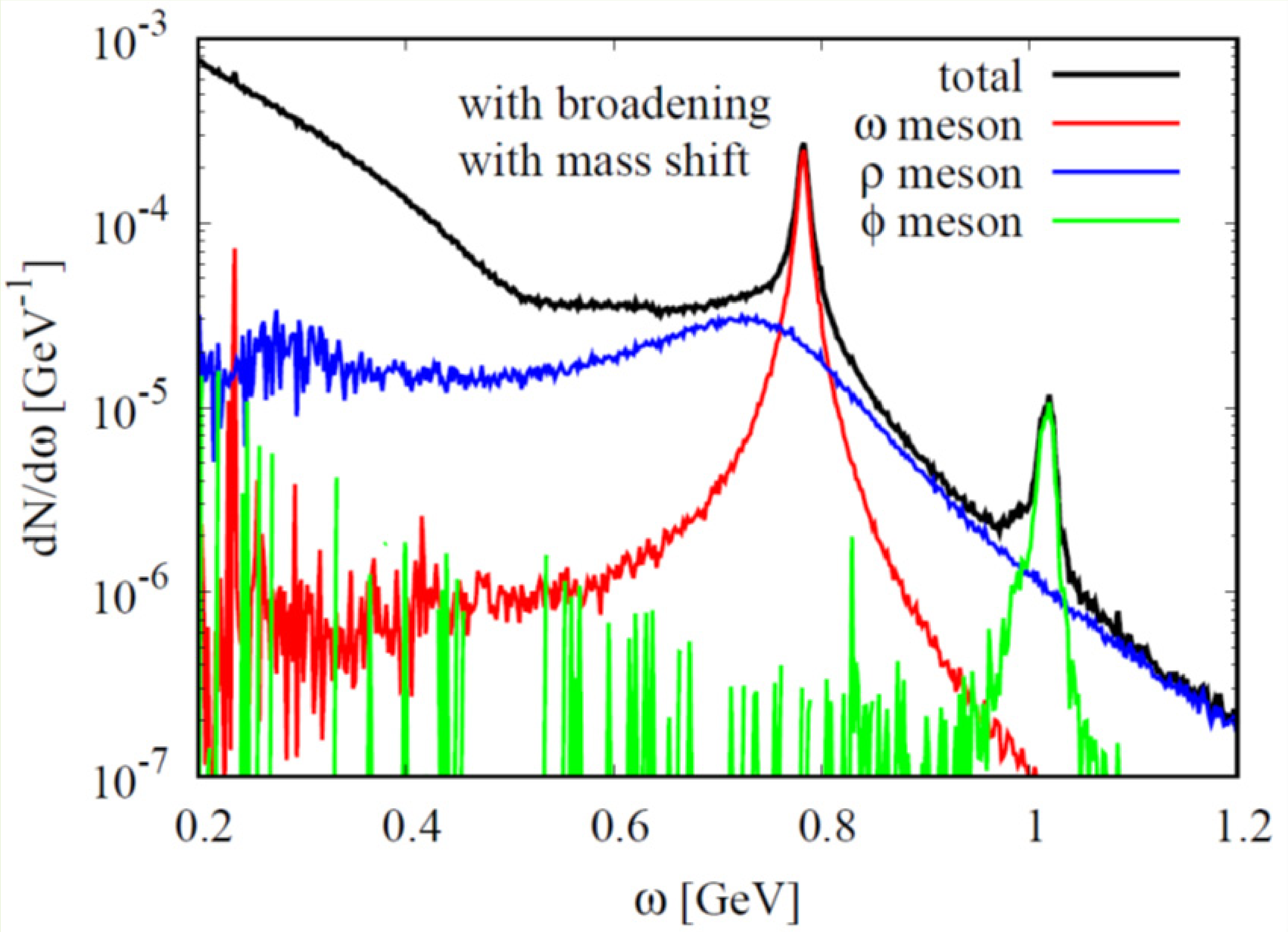
φ mesons on average decay at a density significantly below ρ_0

C target





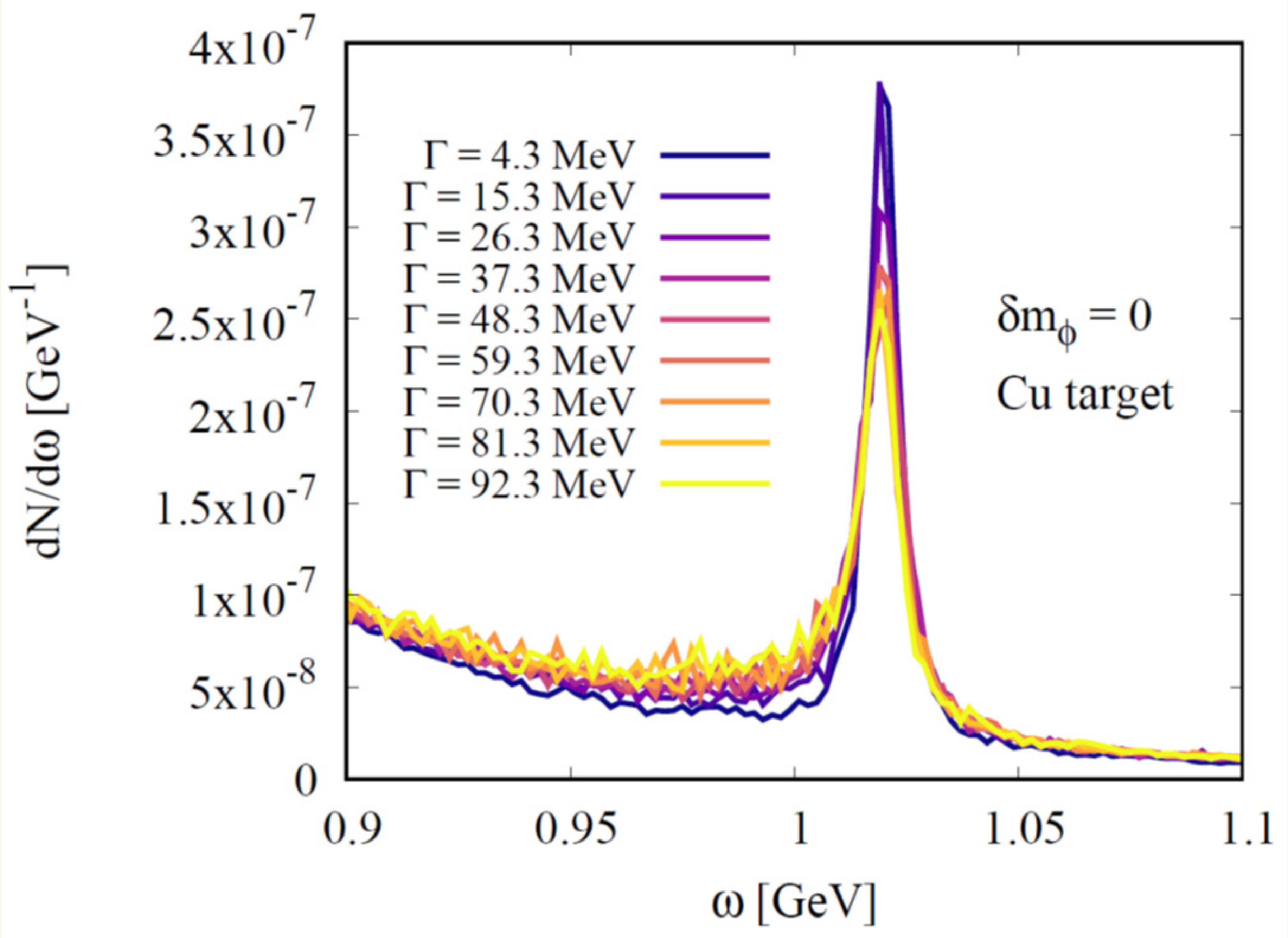
The dilepton spectrum



p+Cu at 12 GeV

The φ meson peak is clearly visible.

The dilepton spectrum in the φ meson region



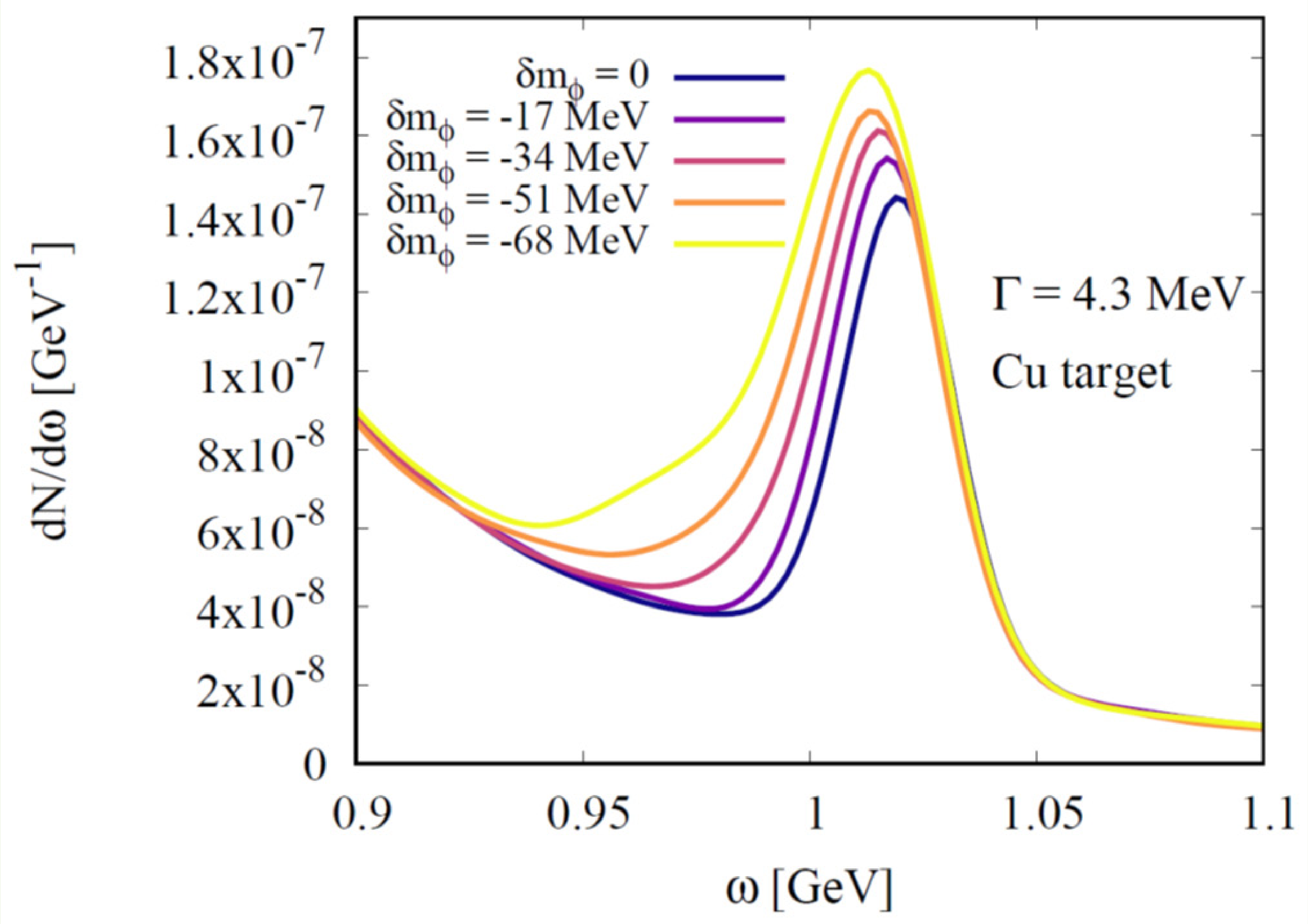
p + Cu at 12 GeV

No acceptance corrections!

No finite resolution effects!

Preliminary

The dilepton spectrum in the φ meson region

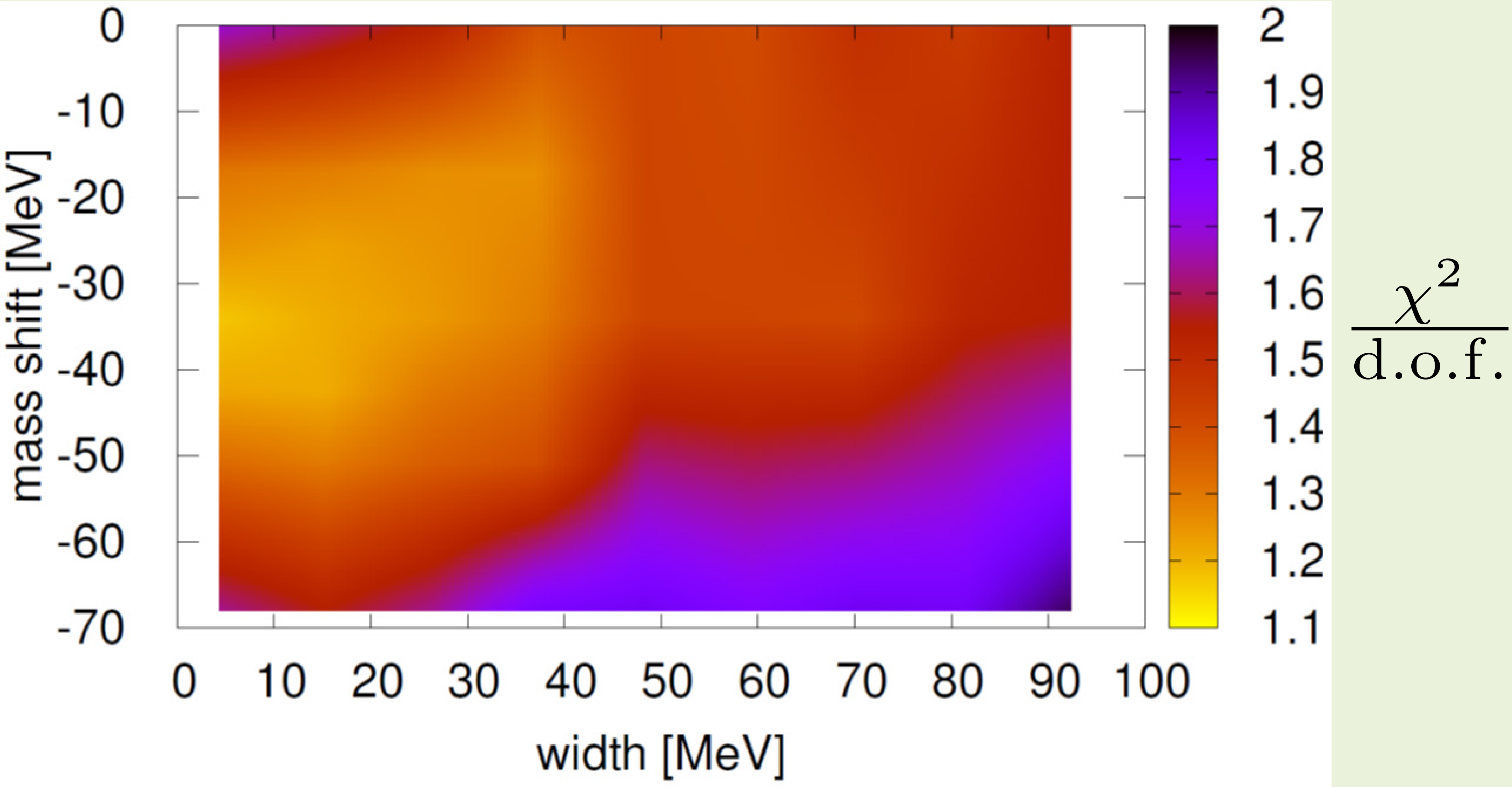


p + Cu at 12 GeV

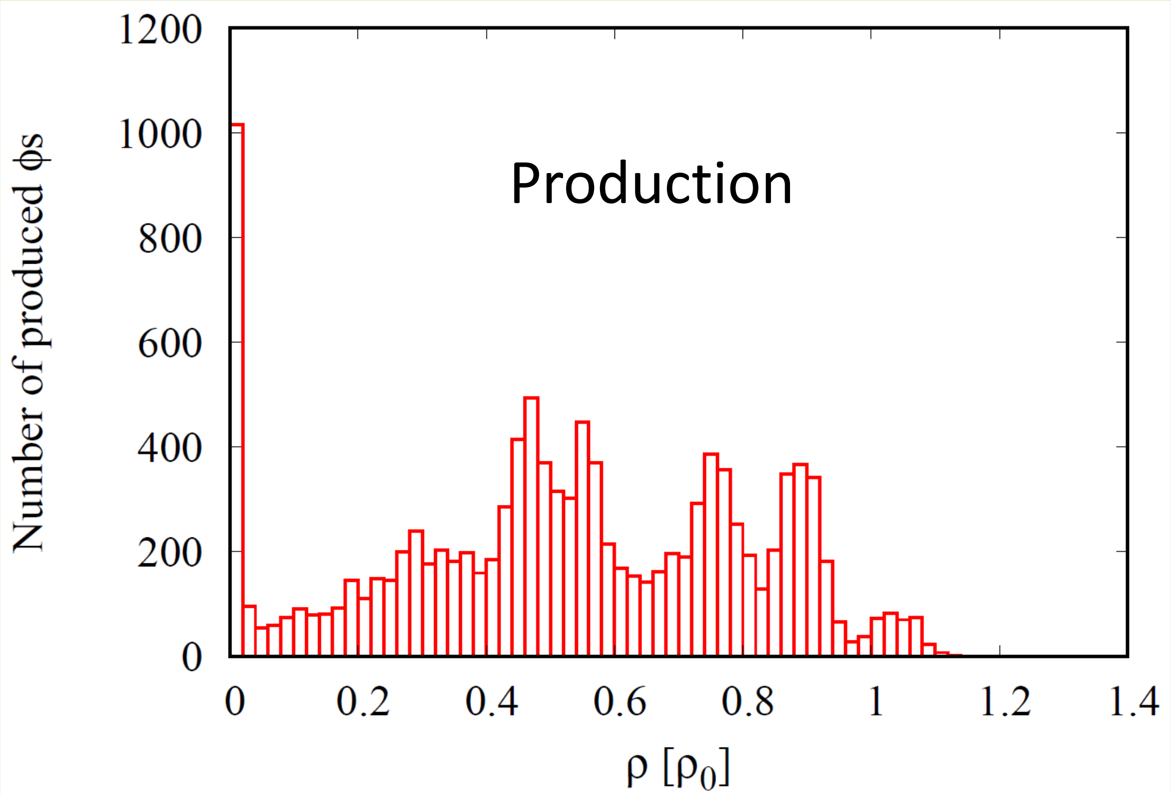
With acceptance corrections!

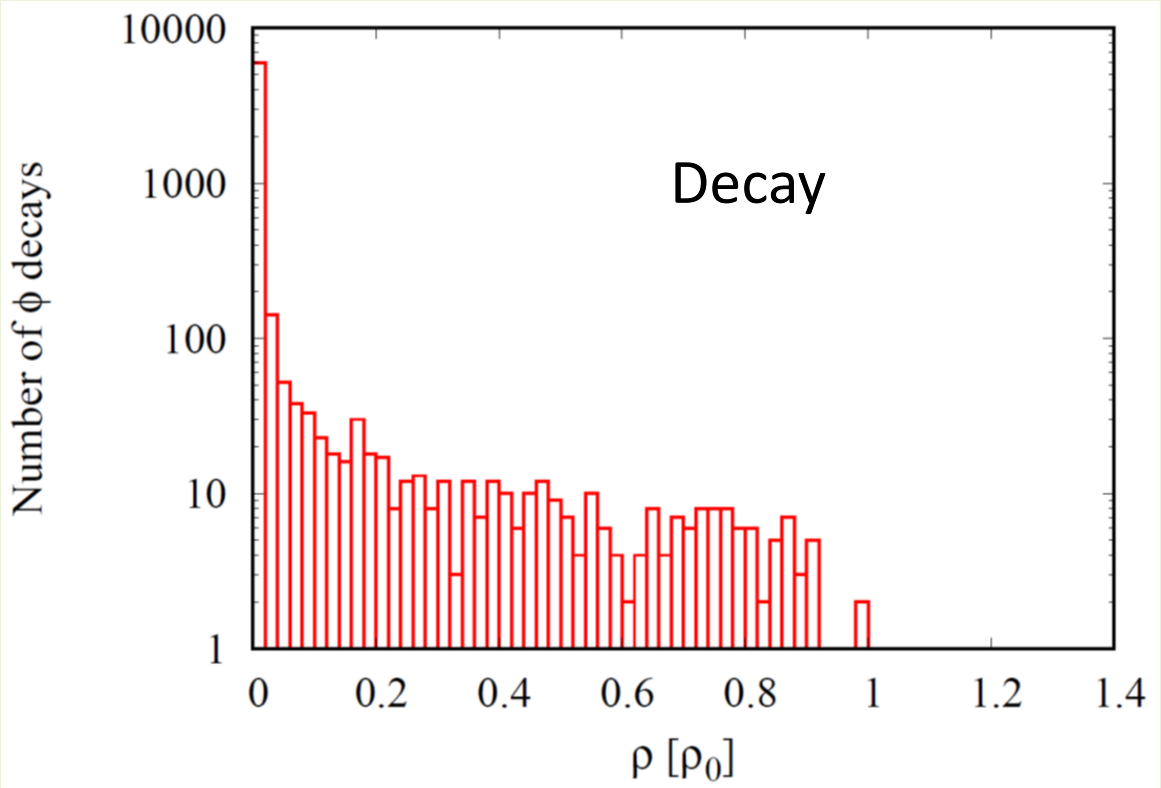
With finite resolution effects!

All Copper data combined



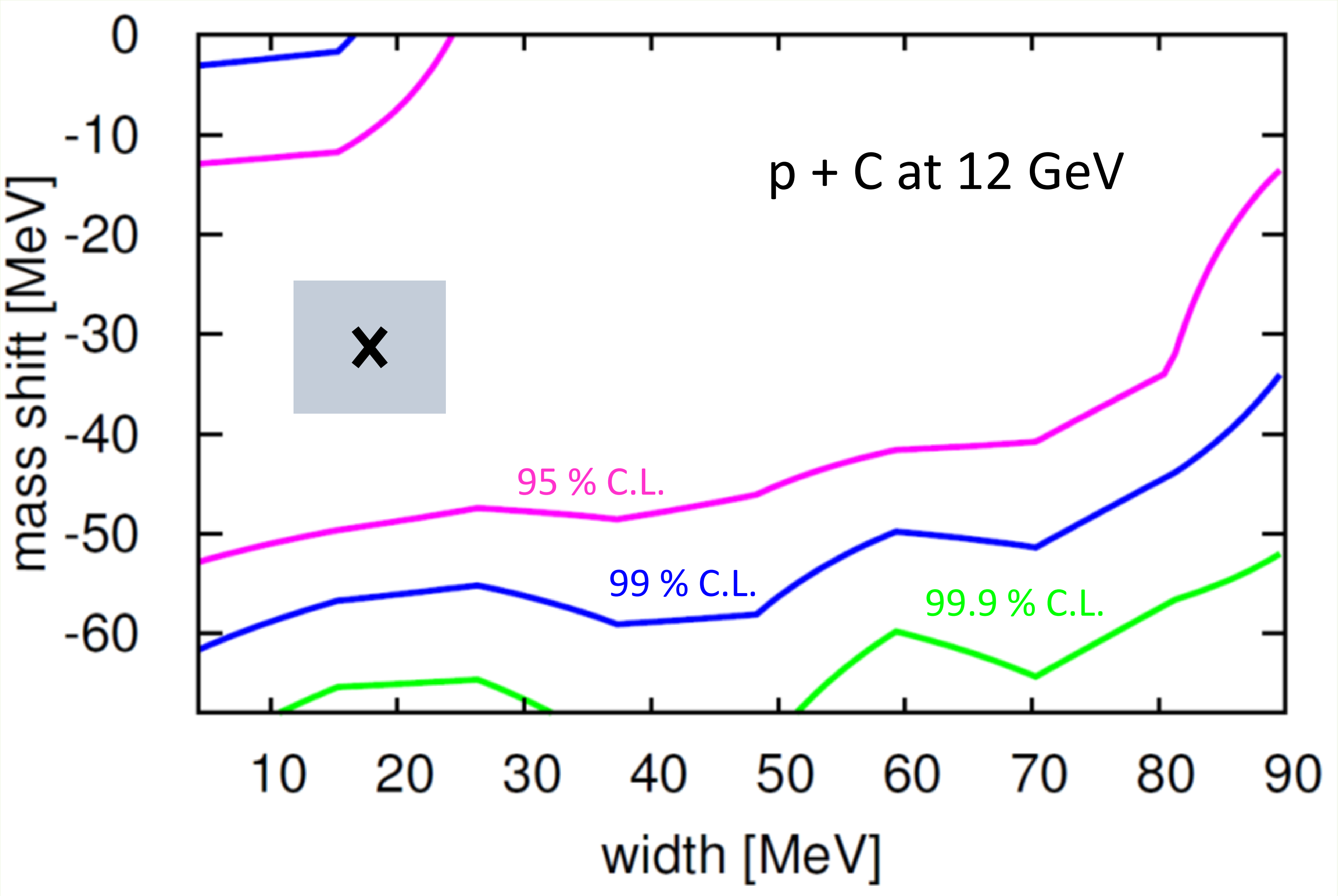
What density does the φ feel in the reaction (p+C at 12 GeV)?





Fits to experimental Carbon target data (E325)

Confidence levels of combined Carbon data



Conclusion of the E325 Collaboration

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!

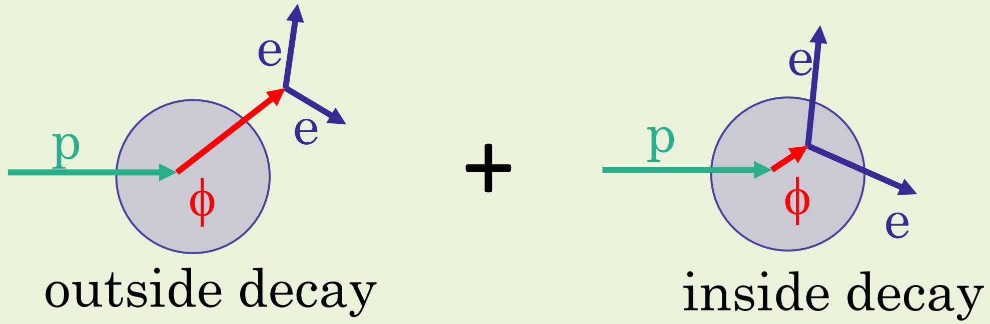
Background: $a\omega^2 + b\omega + c$

ϕ meson signal: $A\rho_{\phi,\mathrm{PHSD}}(\omega)$

Dilepton spectrum: $$\rho(\omega) = a\omega^2 + b\omega + c + A\rho_{\phi,\mathrm{PHSD}}(\omega)$$

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

Experimental di-lepton spectrum



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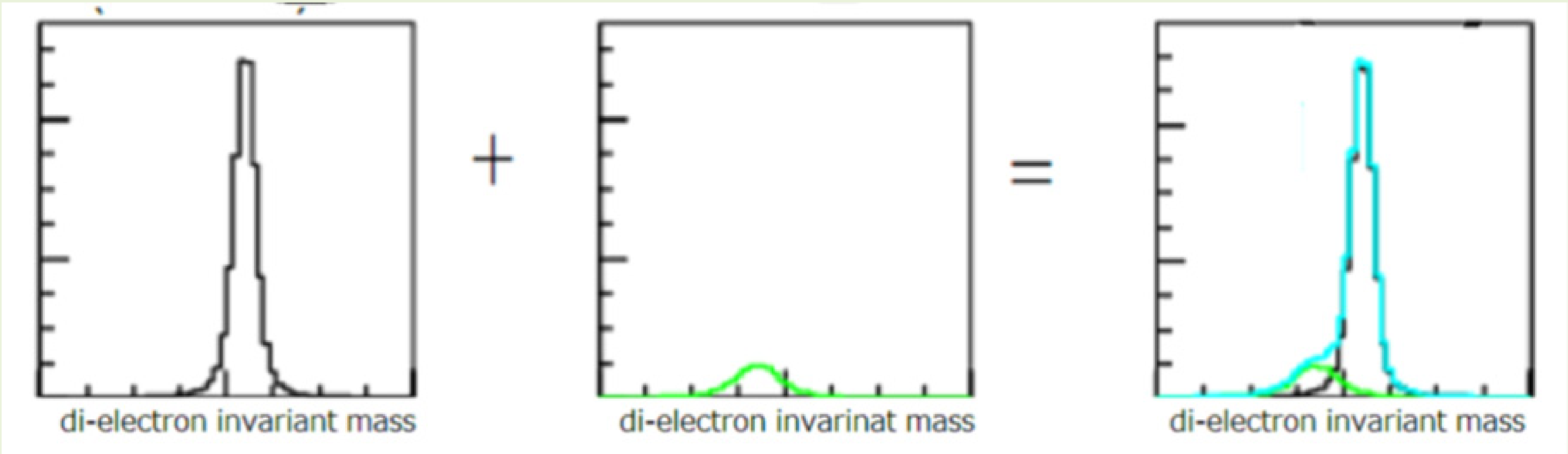
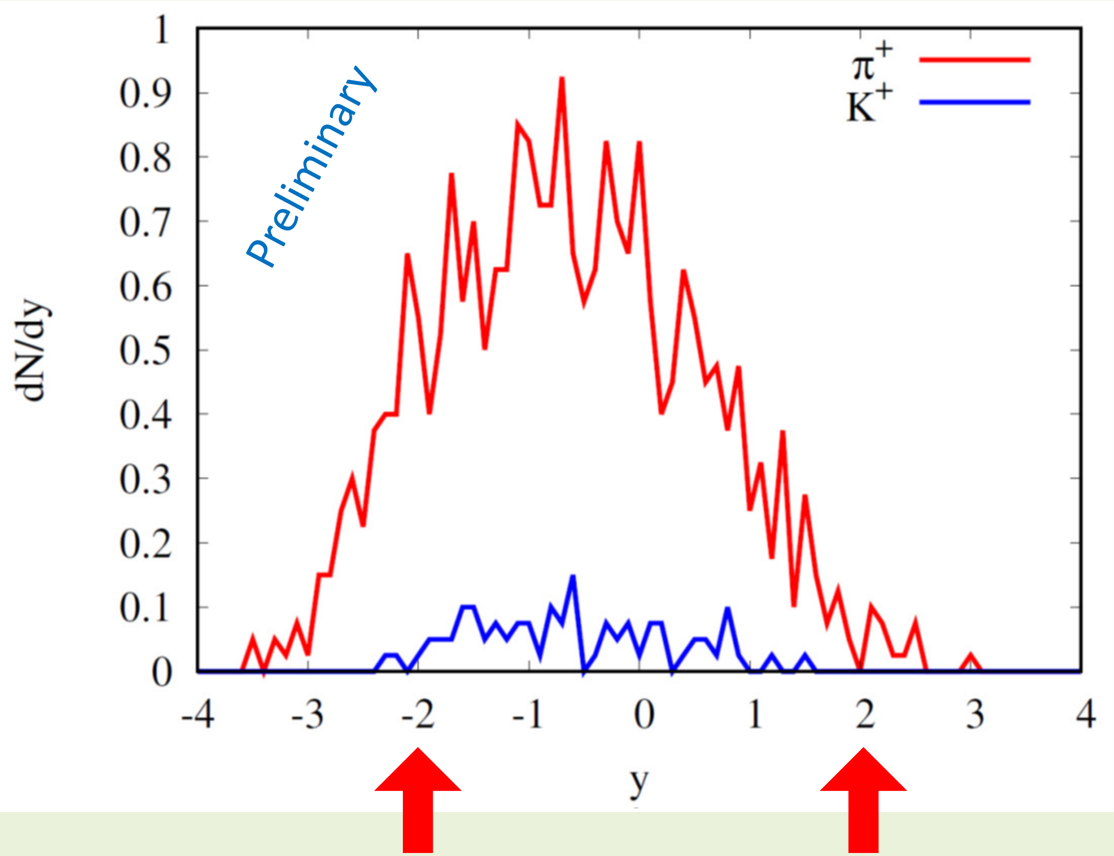
Experimentally observed spectrum



A first look at a reaction to be probed at J-PARC:
pA collisions with initial proton energy of 30 GeV

A first look at the reaction: Rapidity distribution of protons/mesons



nucleon target after collision

projectile proton after collision

Due to the large collision energy, the incoming proton passes through the target nucleus

Our tool: a transport code
PHSD (Parton Hadron String Dynamics)

W. Casssing and E. Bratkovskaya, Phys. Rev. C **78**, 034919 (2008).
W. Cassing and E. Bratkovskaya, Phys. Rept. **308**, 65 (1999).
W. Cassing, V. Metag, U. Mosel and K. Niita, Phys. Rept. **188**, 363 (1990).

Basic Ingredient 1: Solve a Vlasov-Uehling-Uhlenbeck type equation for each particle type

$$\left(\frac{\partial}{\partial t} + \frac{\boldsymbol{p}_1}{m} \cdot \frac{\partial}{\partial \boldsymbol{r}} - \frac{\partial}{\partial \boldsymbol{r}} U_{\mathrm{BHF}}(\boldsymbol{r}; t) \cdot \frac{\partial}{\partial \boldsymbol{p}_1}\right) f(\boldsymbol{r}, \boldsymbol{p}_1; t) = \left(\frac{\partial f}{\partial t}\right)_{\mathrm{coll}}$$

mean field (tuned to reproduce nuclear matter properties)

particle distribution function

Basic Ingredient 2: „Testparticle“ approach

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

Structure of QCD sum rules for the phi meson

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

<u>In Vacuum</u>

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

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

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

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

Structure of QCD sum rules for the phi meson

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

In Nuclear Matter

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

$$\langle \overline{s}s\rangle_\rho = \langle \overline{s}s\rangle_0 + \langle N|\overline{s}s|N\rangle\rho + \dots$$

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

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

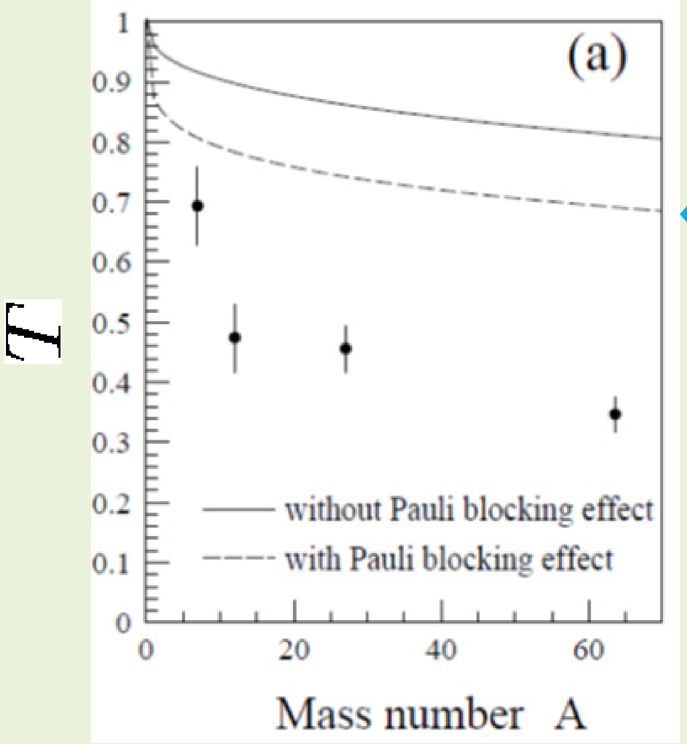
Dim. 6: $$c_6(\rho) = c_6(0) + \rho\Big[-\frac{896}{81}\kappa_N \pi^3 \alpha_s \langle \overline{s}s\rangle\langle N|\overline{s}s|N\rangle - \frac{5}{6}A_4^s M_N^3\Big]$$

Other experimental results

There are some more experimental results on the ϕ-meson width in nuclear matter, based on the measurement of the transparency ratio T:

$$T = \frac{\sigma_{\gamma A \to \phi X}}{A\sigma_{\gamma N \to \phi X}}$$

Measured at SPring-8 (LEPS)



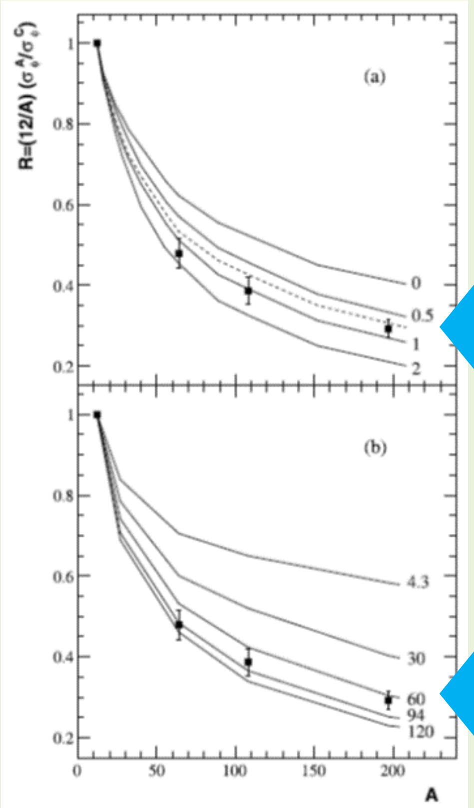
$\Gamma_\phi(\rho_0) \simeq 30\,\mathrm{MeV}$

Theoretical calculation:

D. Cabrera, L. Roca, E. Oset , H. Toki and M.J. Vicente Vacas, Nucl. Phys. **A733**, 130 (2004).

T. Ishikawa et al, Phys. Lett. B **608**, 215 (2005).

Measured at COSY-ANKE



Theoretical calculation:

V.K. Magas, L. Roca and E. Oset, Phys. Rev. C **71**, 065202 (2005).

$\Gamma_\phi(\rho_0) \simeq 27\,\mathrm{MeV}$

Theoretical calculation:

E. Ya. Paryev, J. Phys. G **36**, 015103 (2009).

$\Gamma_\phi(\rho_0) \simeq 73\,\mathrm{MeV}$

A. Polyanskiy et al, Phys. Lett. B **695**, 74 (2011).