Phi meson properties in nuclear matter

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Talk at the "APCTP Focus Program in Nuclear Physics 2021 Part I: Hadron properties in a nuclear medium from the quark and gluon degrees of freedom",
online
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Work done in collaboration with
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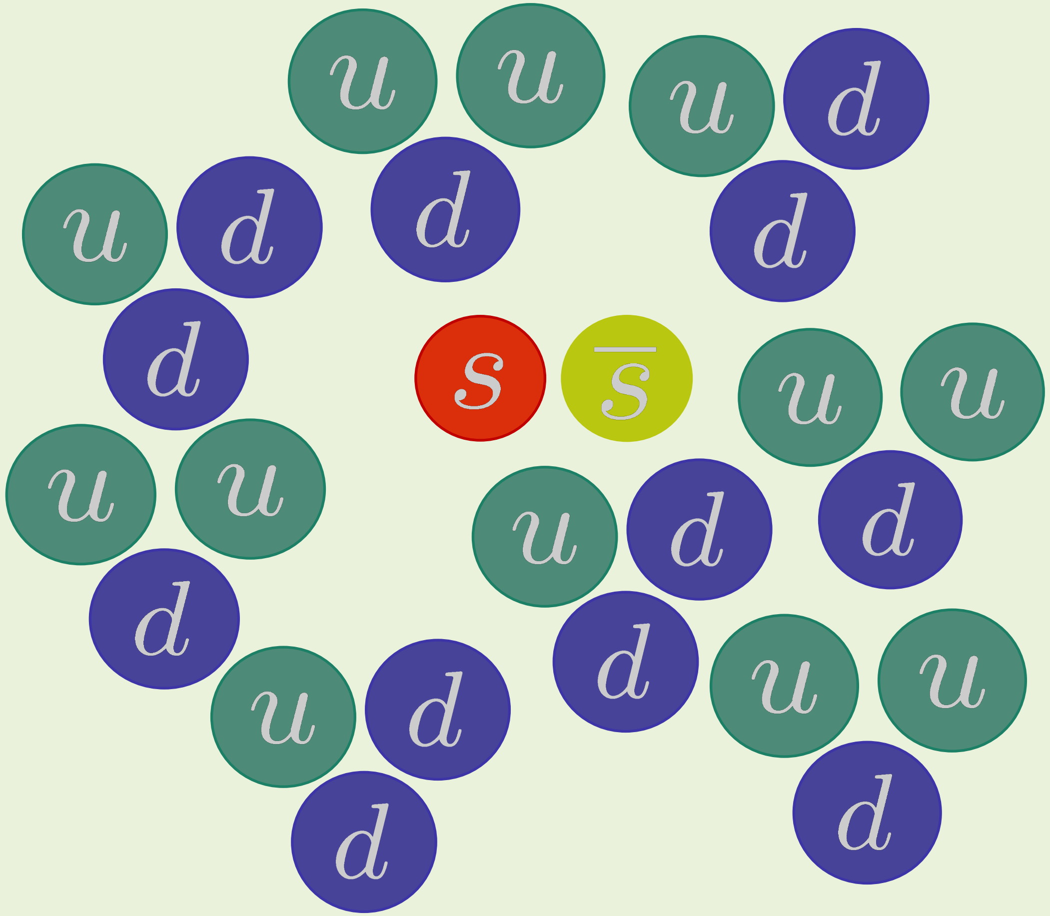
HyungJoo Kim (APCTP/Yonsei U.)
Keisuke Ohtani (Tokyo Tech)

ϕ meson

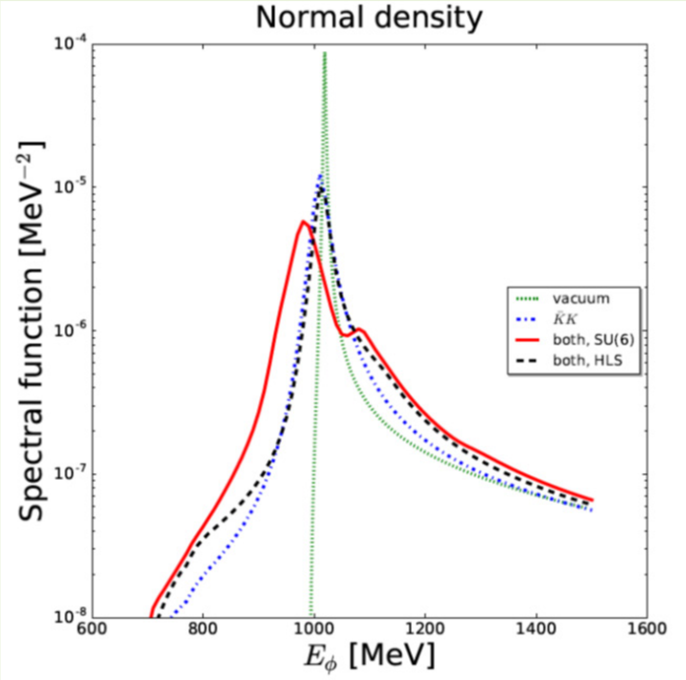
m_{ϕ} = 1019 MeV

Γ_{ϕ} = 4.3 MeV



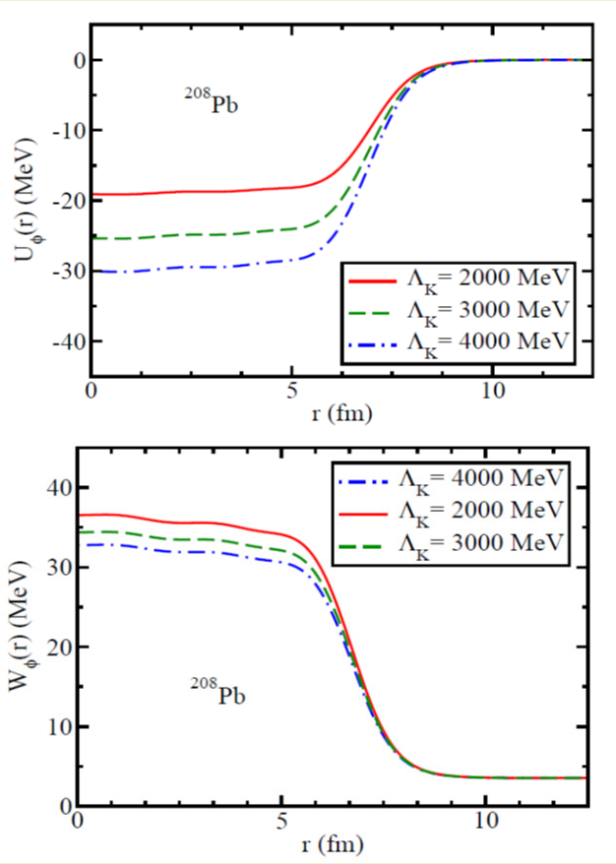
Many theoretical works about the φ meson at finite density in recent years

Spectral functions from hadronic models



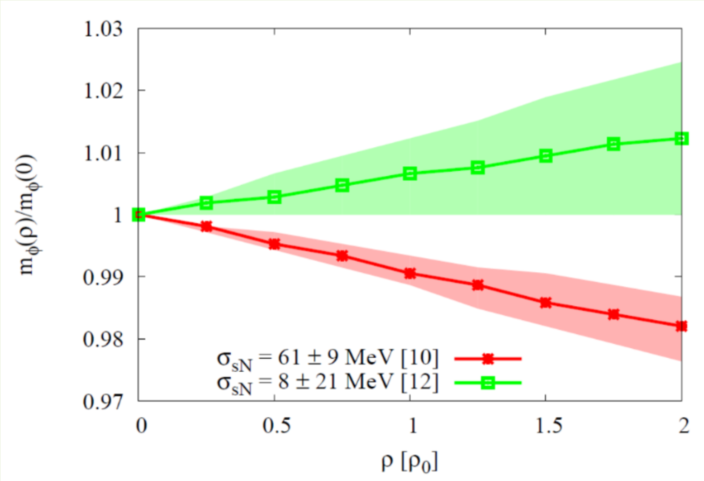
P. Gubler and W. Weise, Phys. Lett. B **751**, 396 (2015).
P. Gubler and W. Weise, Nucl. Phys. A **954**, 125 (2016).
D. Cabrera *et al.*, Phys. Rev. C **95**, 015201 (2017).
D. Cabrera *et al.*, Phys. Rev. C **96**, 034618 (2017).

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).

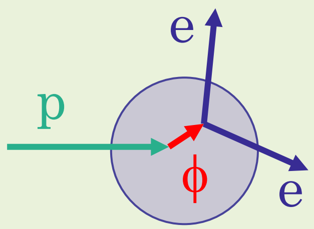
Mass shift in nuclear matter from QCD sum rules



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).

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

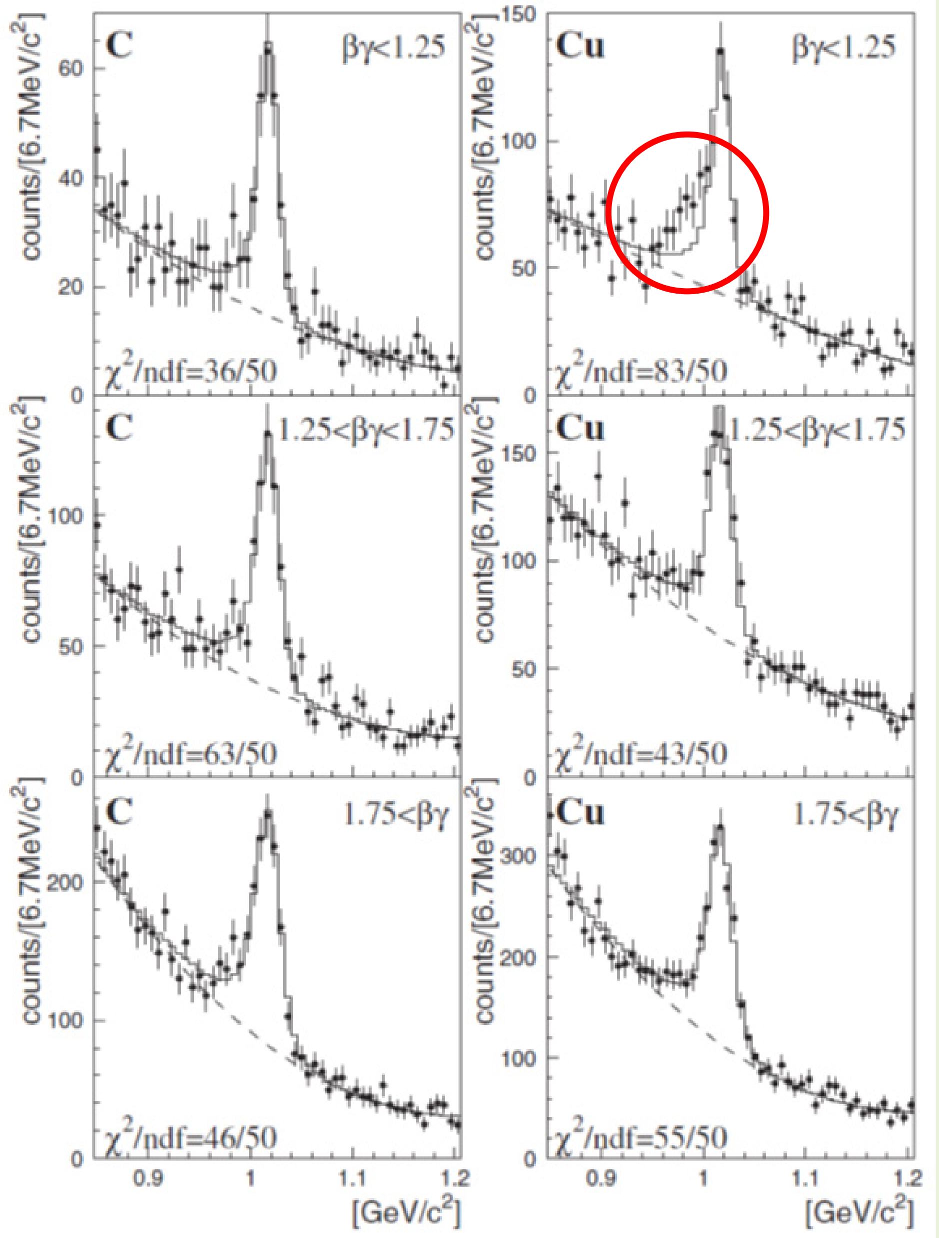
k_2: 2.6 ± 1.5

slow φs

intermediate φs

fast φs

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



To be measured again at the J-PARC E16 experiment with 100x increased statistics!

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

Recent experimental results

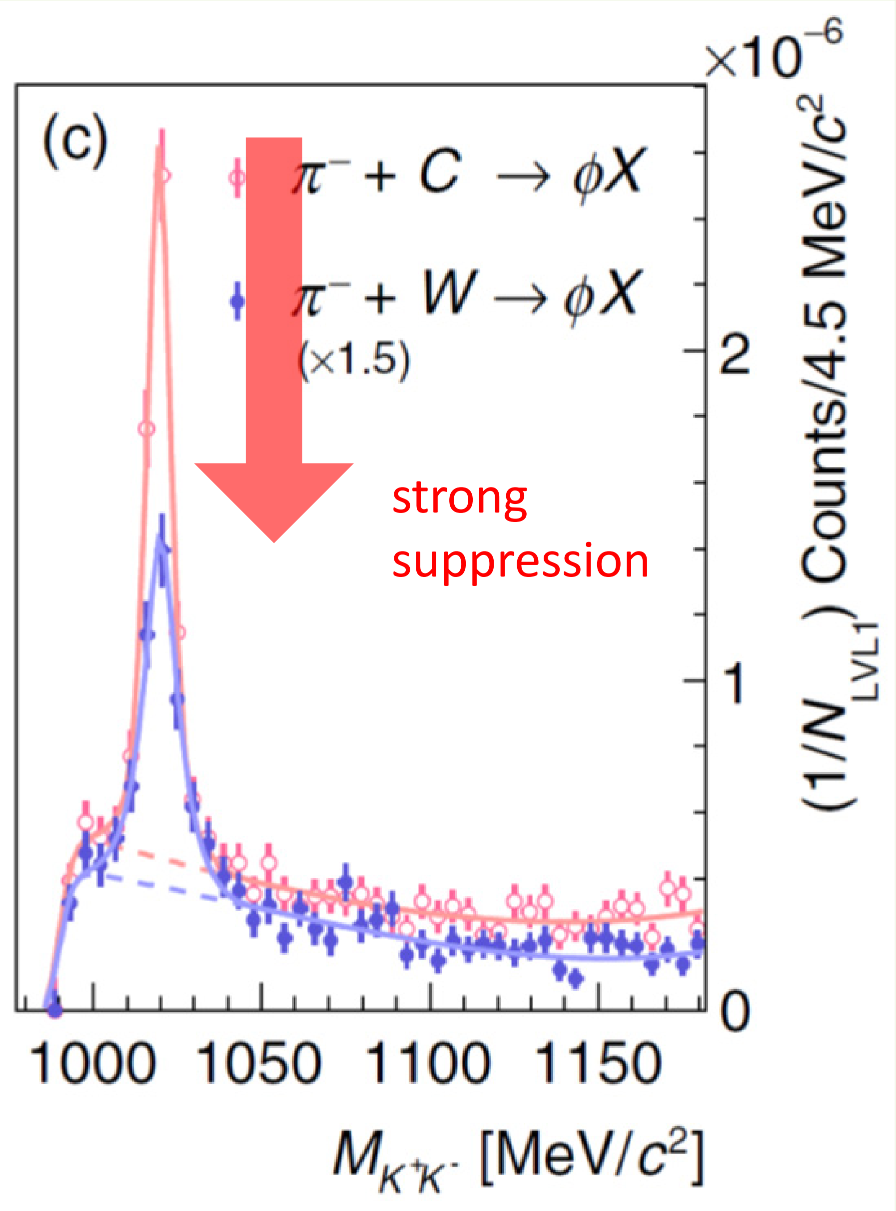
HADES: 1.7 GeV π^-A-reaction

★ 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

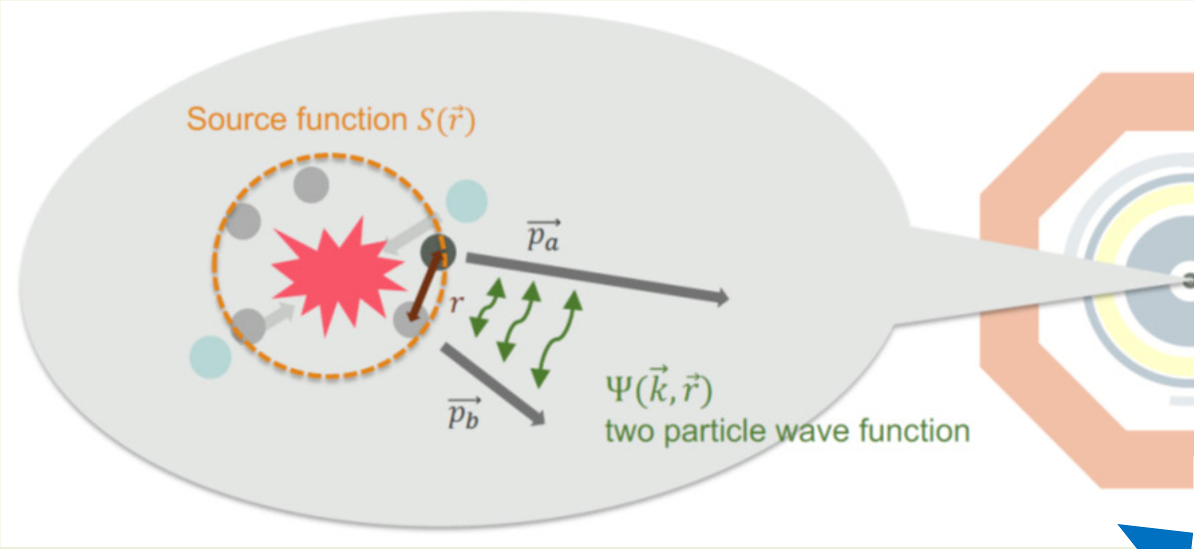
K^+K^- - invariant mass spectrum



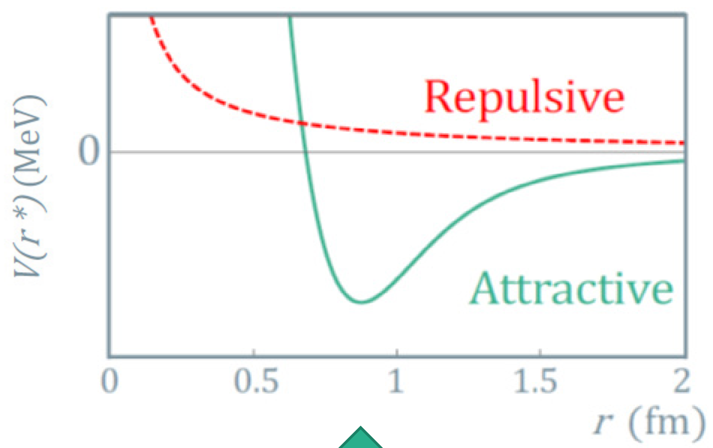
J. Adamczewski-Musch et al. (HADES Collaboration), Phys. Rev. Lett. **123**, 022002 (2019).

New experimental results

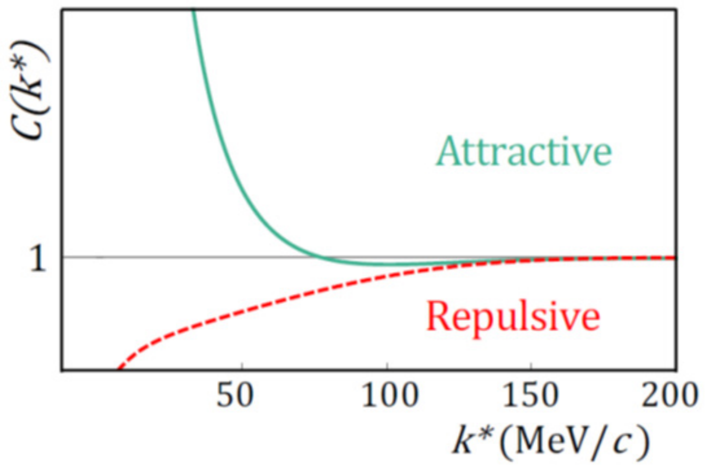
ALICE (Femtoscopy)



Interaction potential



Correlation function



The observable to be measured: the correlation function:

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

Emission source (Gaussian)

Relative momentum of the particle pair

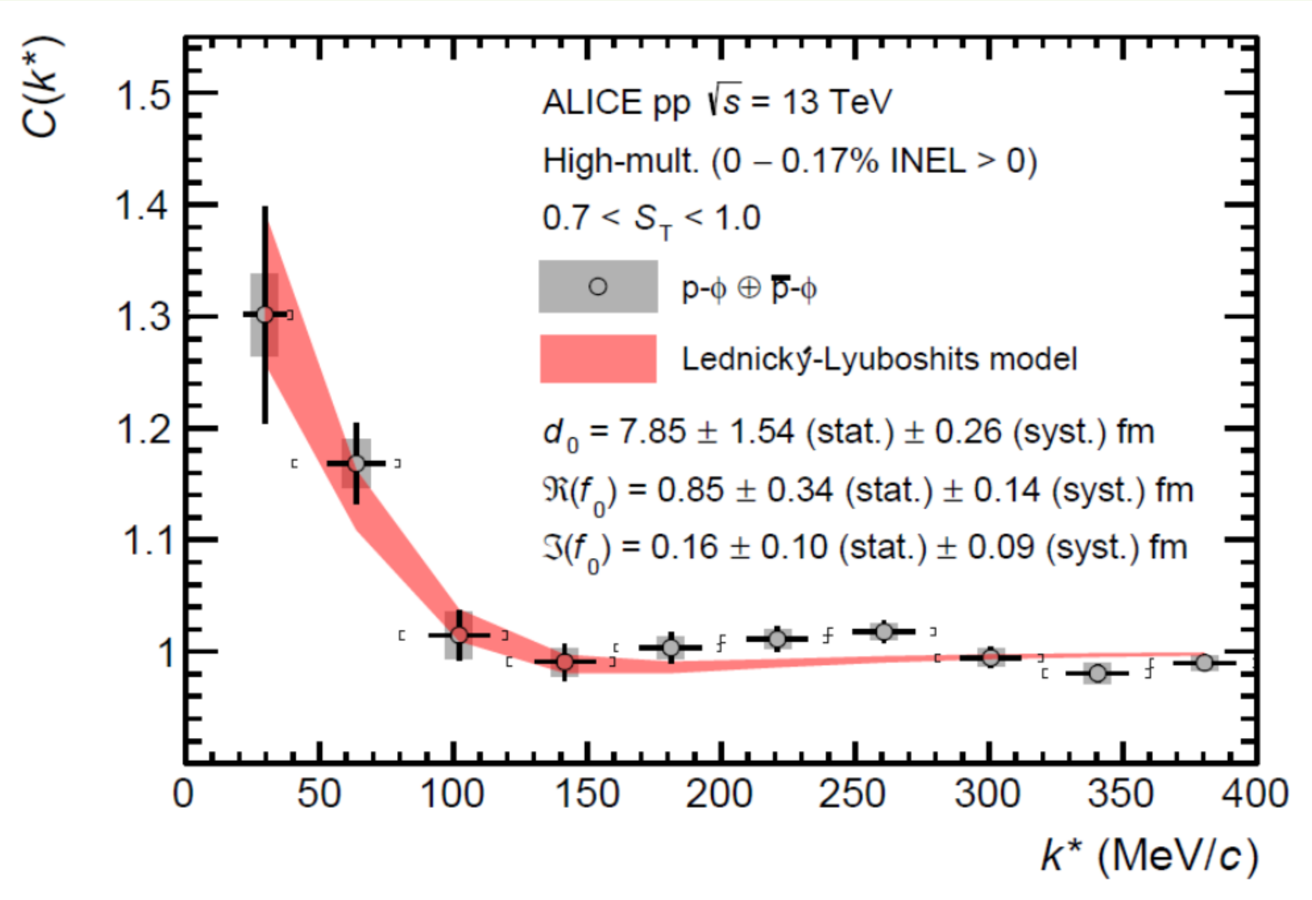
S. Acharya et al. (ALICE Collaboration), arXiv:2105.05578 [nucl-ex].

New experimental results

ALICE

Measurement of φN the correlation function

Attraction!



Information about the 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 ?

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

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

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

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

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

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

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

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

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

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

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

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

Recent results from theory

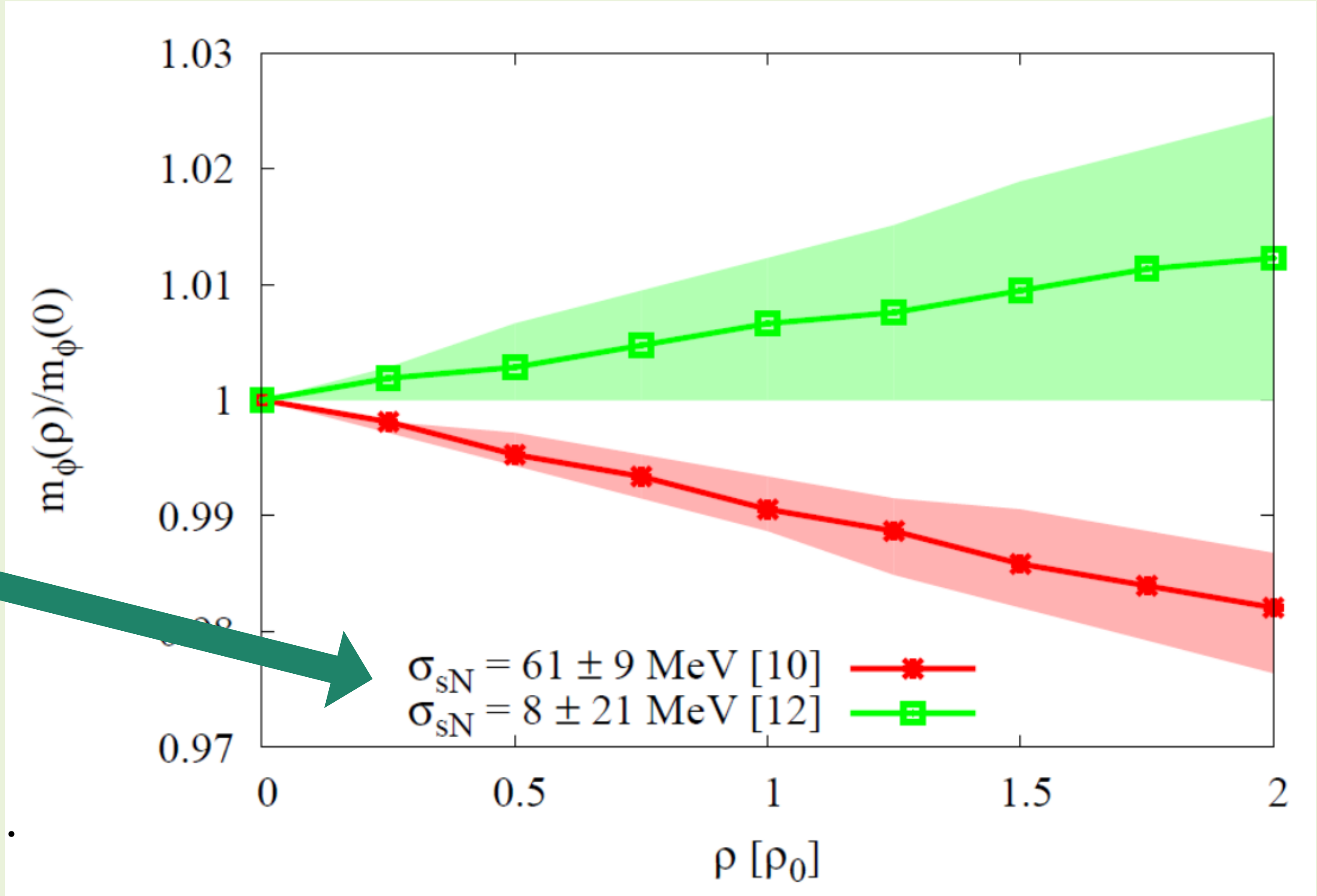
Results for the ϕ meson mass at rest (from QCD sum rules)

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

Strangeness content of the nucleon

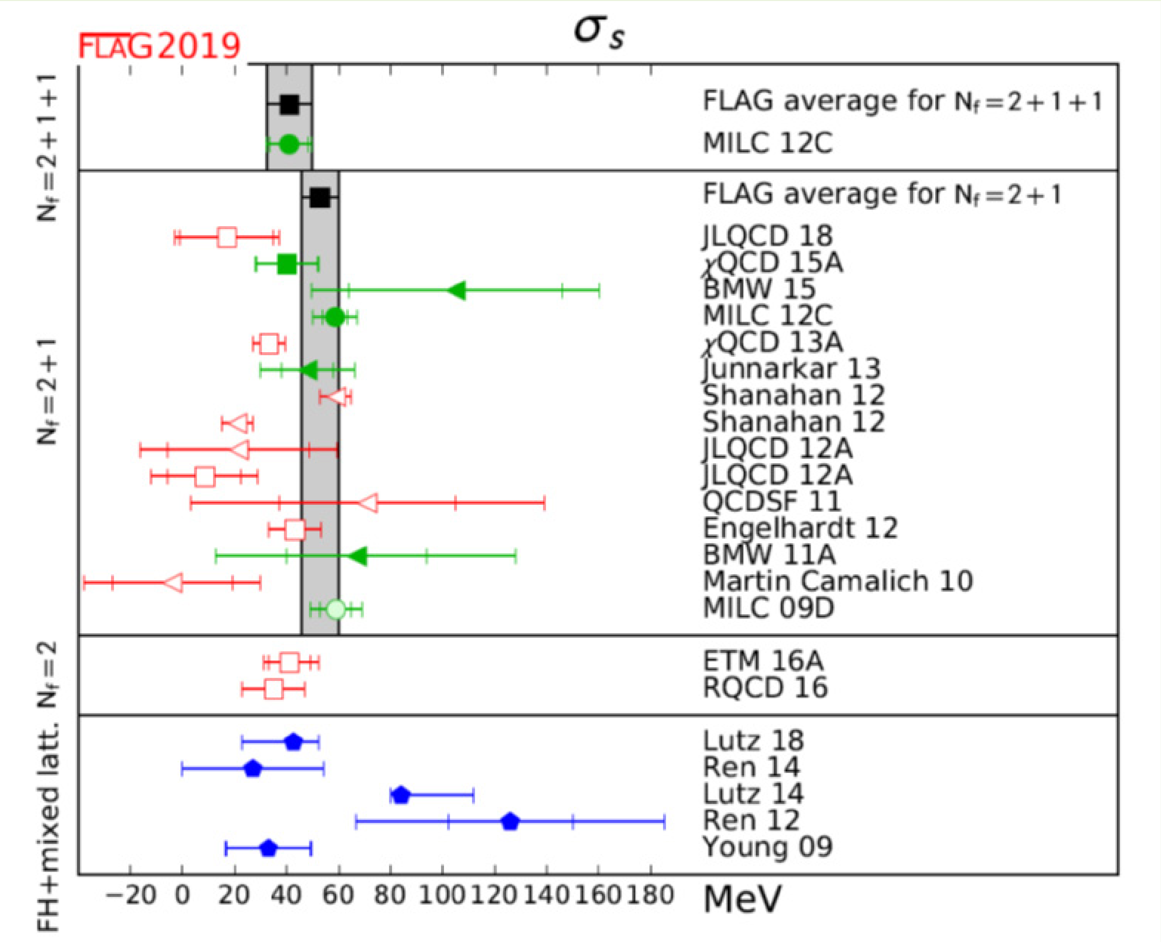
$$\sigma_{sN} = m_s \langle N|\overline{s}s|N\rangle$$

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



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

What does lattice QCD say about σ_s?



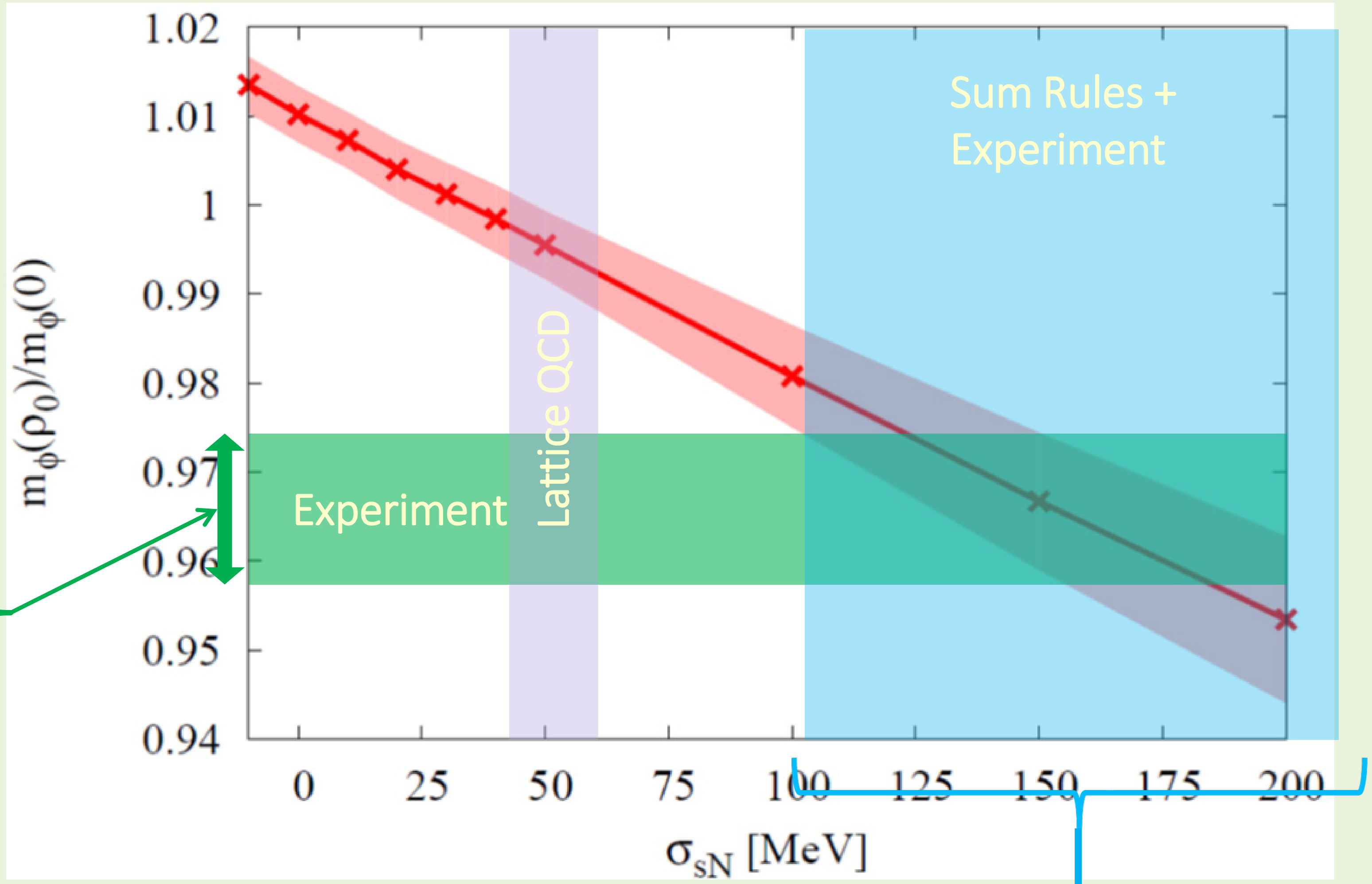
http://flag.unibe.ch/2019/

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?

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

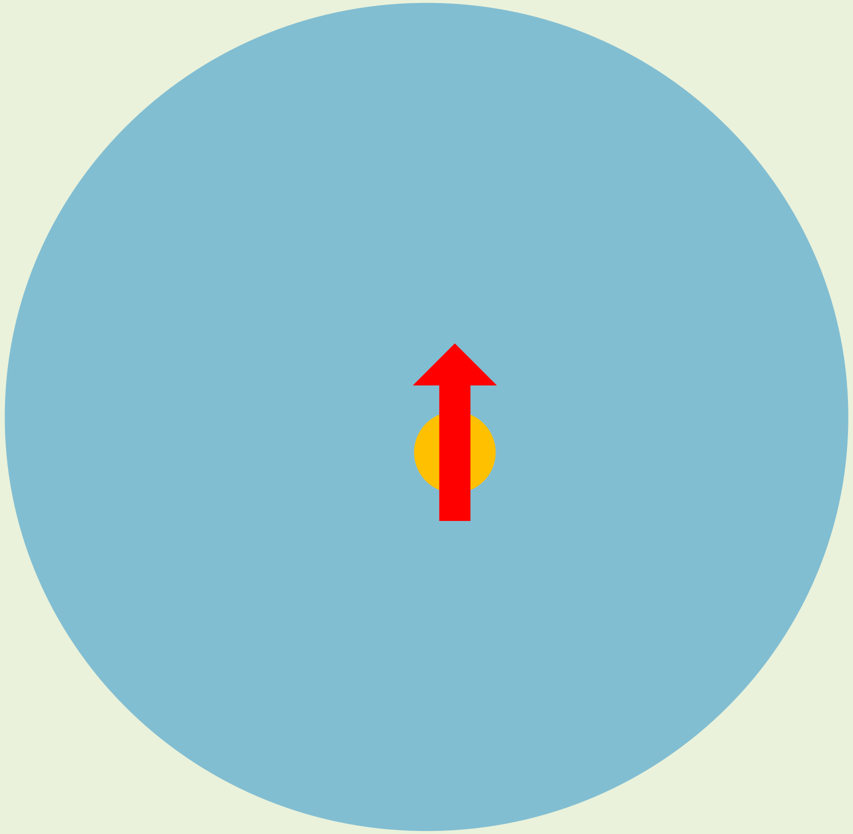


$$\sigma_{sN} \sim 160 \pm 50 \text{ MeV}$$

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

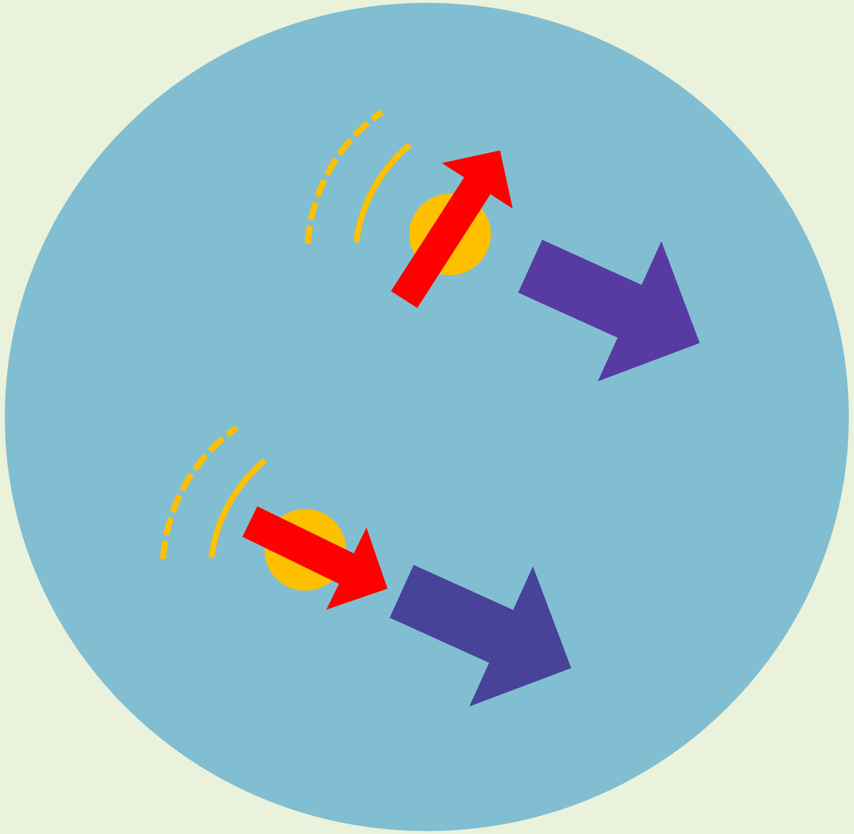
Effect of momentum

vector meson at rest in nuclear matter



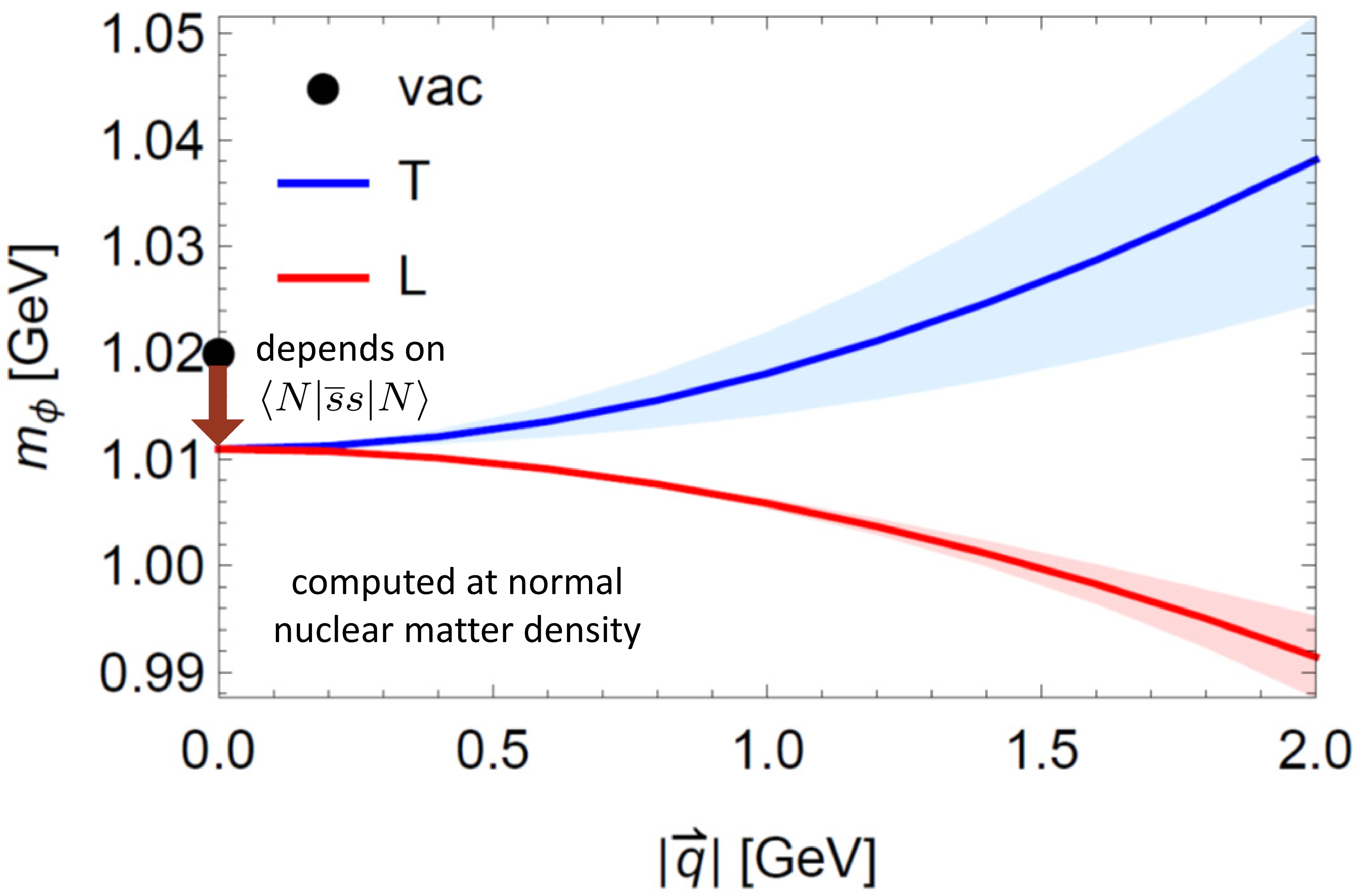
spin direction does not change physics
(rotational symmetry)

vector meson moving in nuclear matter



spin direction changes physics
(broken rotational symmetry)

Results for the ϕ meson mass with non-zero momentum



caused by

$$\langle N|\mathcal{ST}\bar{s}\gamma^{\alpha}iD^{\beta}s|N\rangle$$
$$+$$
$$\langle N|\mathcal{ST}G^{a\alpha}_{\mu}G^{a\mu\beta}|N\rangle$$

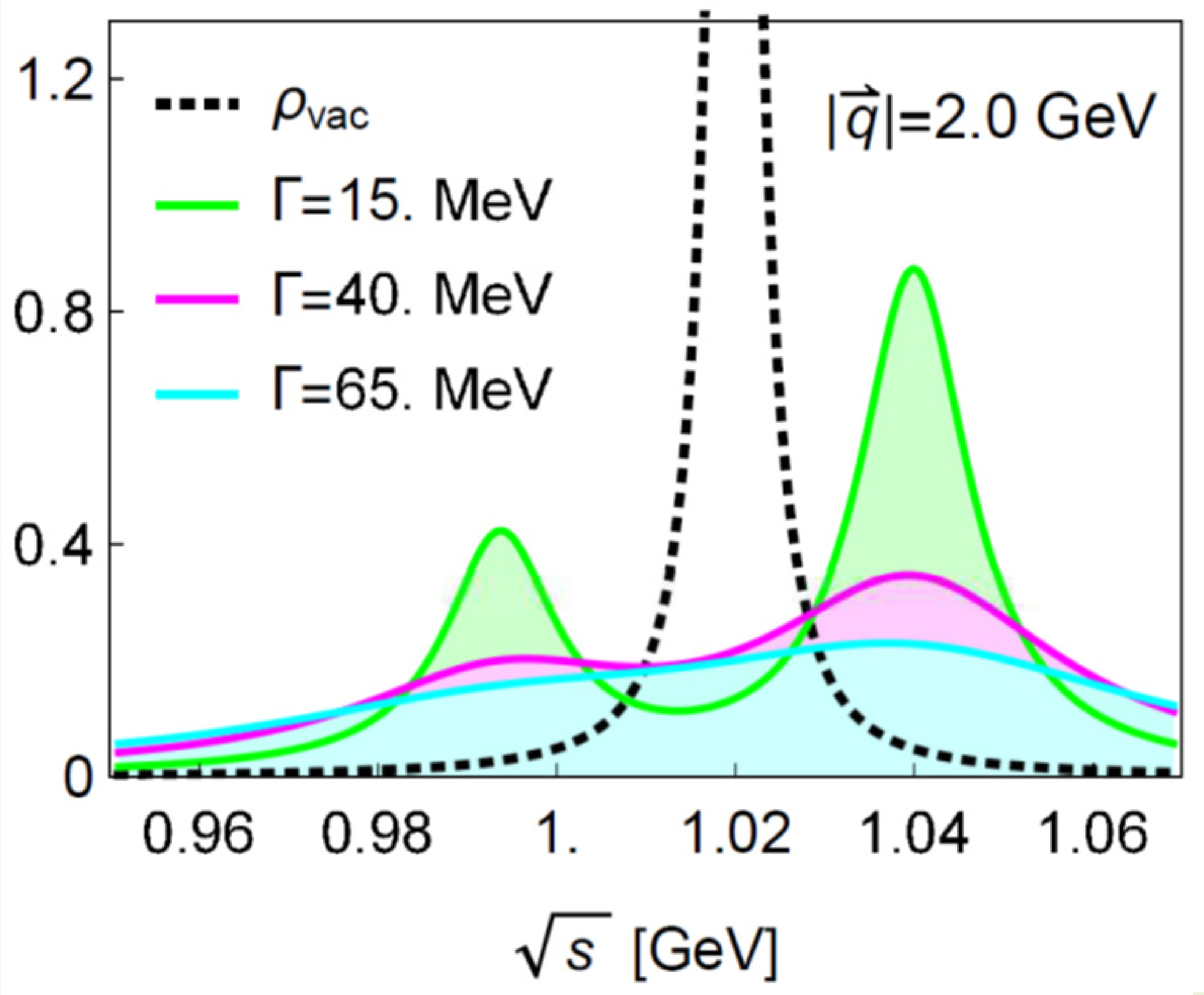
caused by

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

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

The angle-averaged di-lepton spectrum

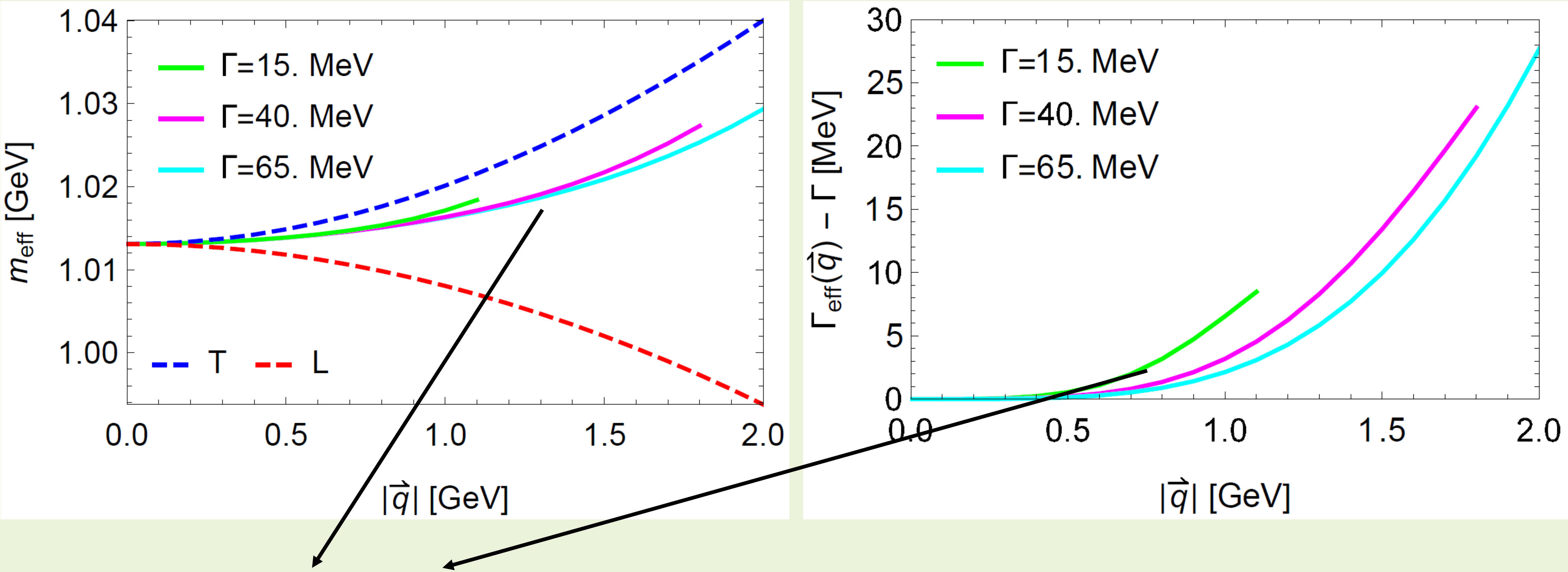
A double peak?



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

The angle-averaged di-lepton spectrum

Momentum-dependent mass and width

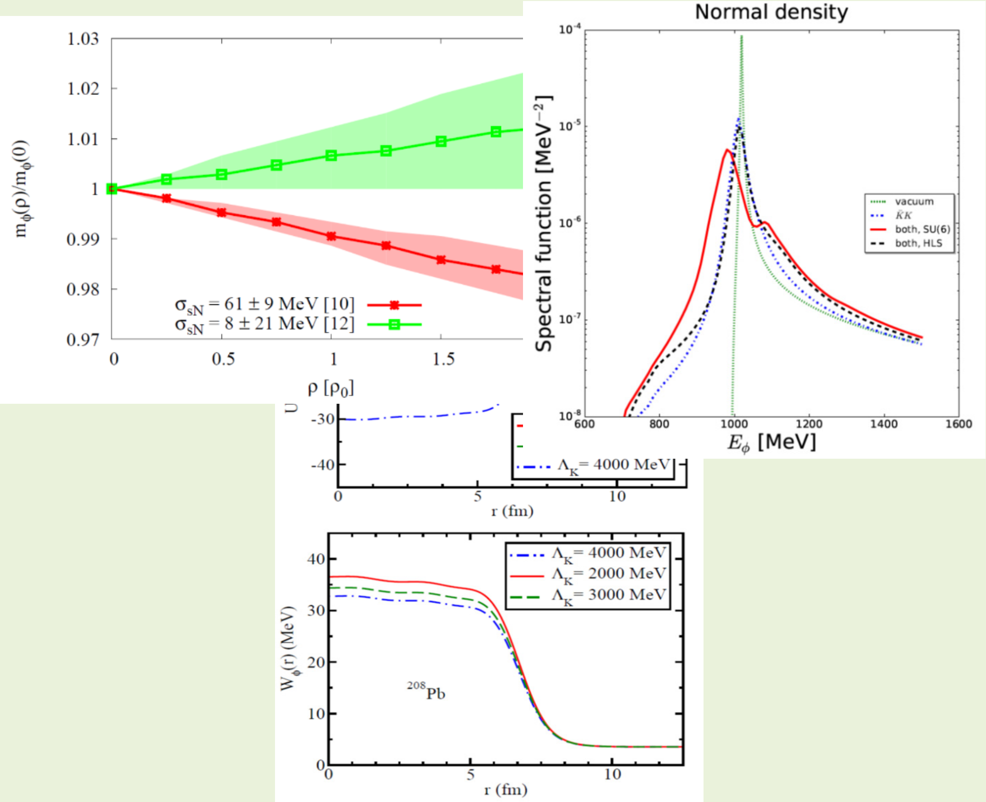


Results of one-peak fits

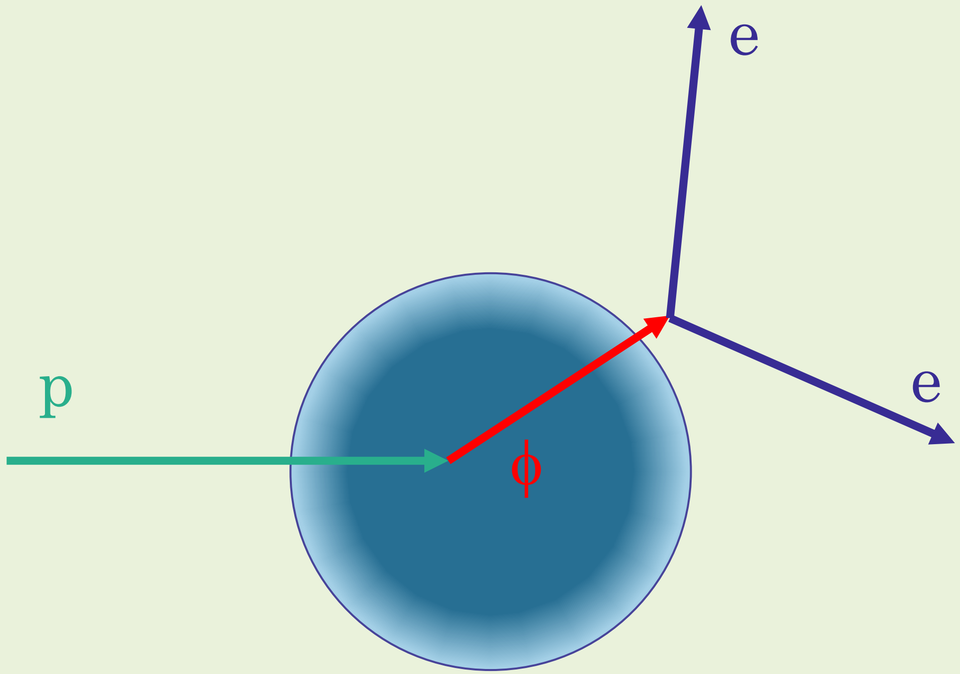
H.J. Kim and P. Gubler, Phys. Lett. B 805, 135412 (2020).

How compare theory with 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).

Most important feature for our purposes:
Off-shell dynamics of vector mesons
(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

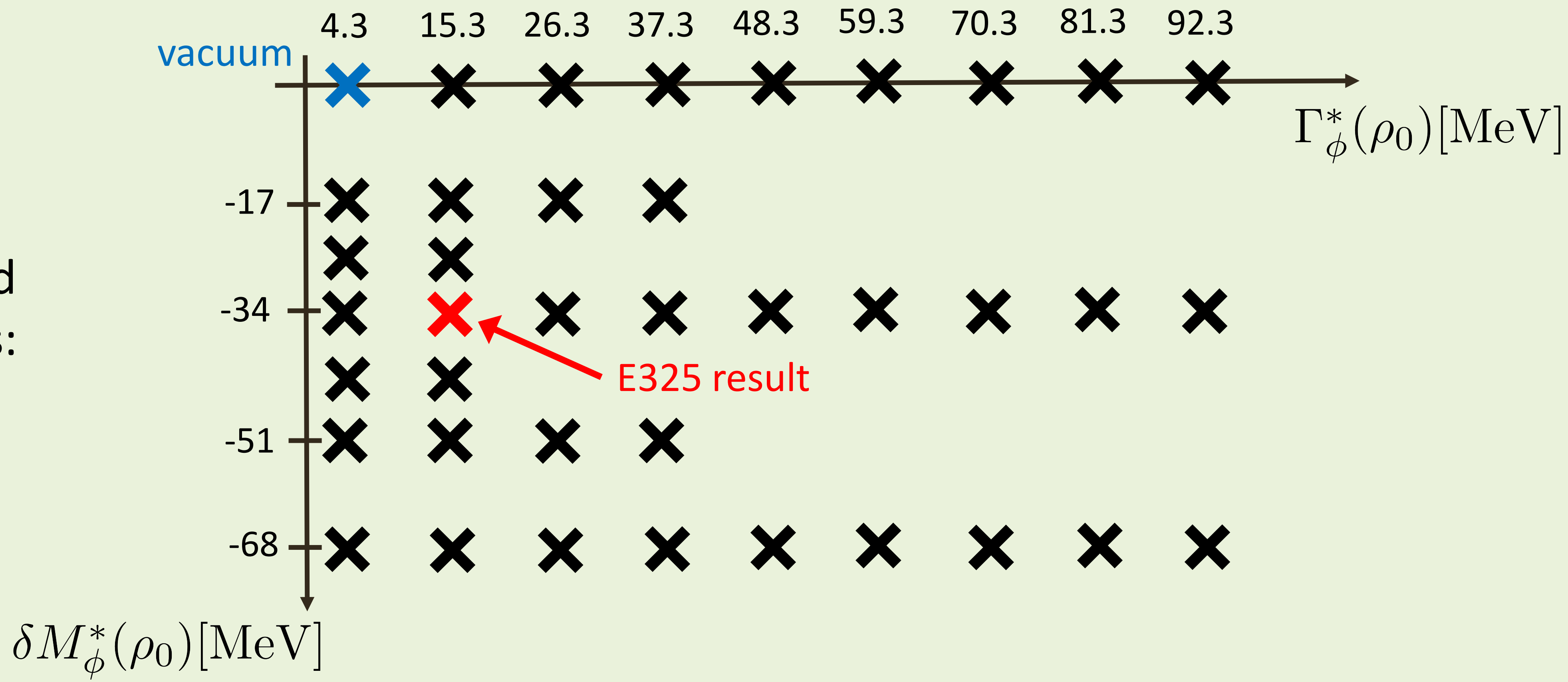
Our choice: a Breit-Wigner with density dependent mass and width

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

with

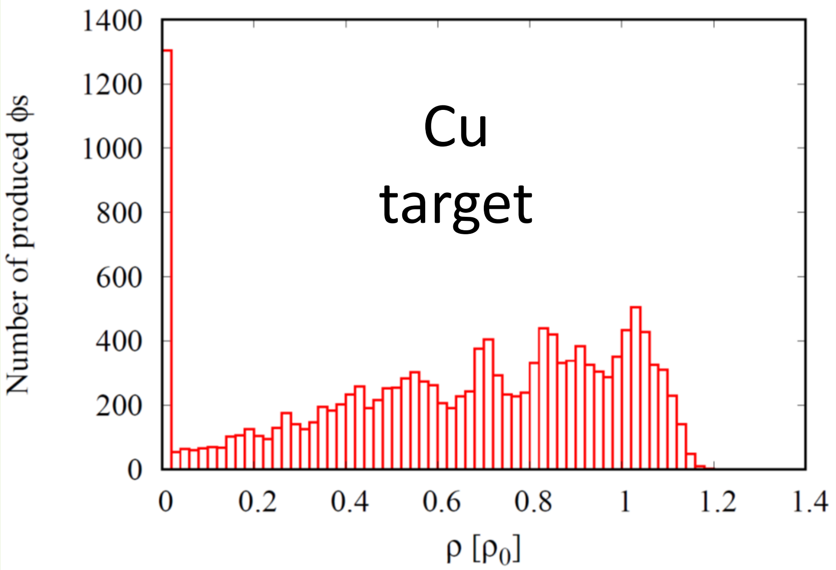
$$\begin{cases} M^*_\phi(\rho) = M^{\text{vac}}_\phi\left(1-\alpha^\phi\frac{\rho}{\rho_0}\right), \\ \Gamma^*_\phi(M,\rho) = \Gamma^{\text{vac}}_\phi + \alpha^\phi_{\text{coll}}\frac{\rho}{\rho_0} \end{cases}$$

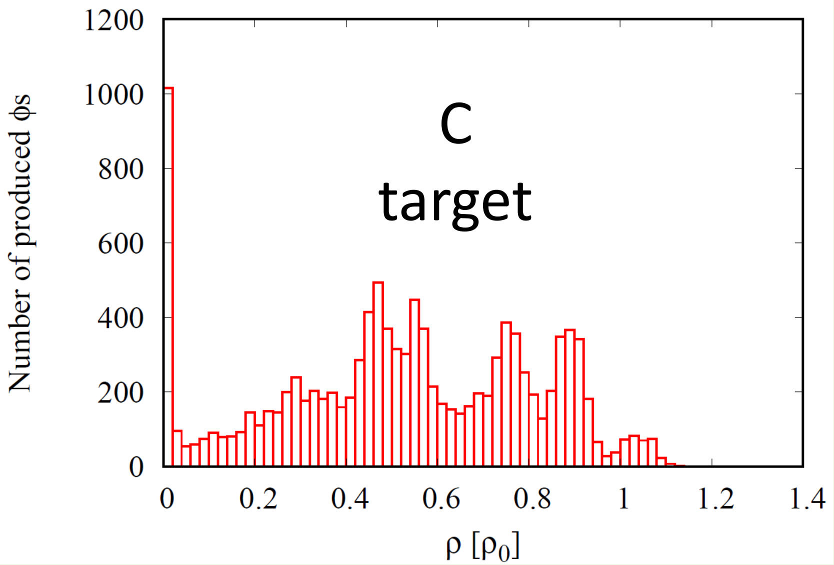
Simulated scenarios:



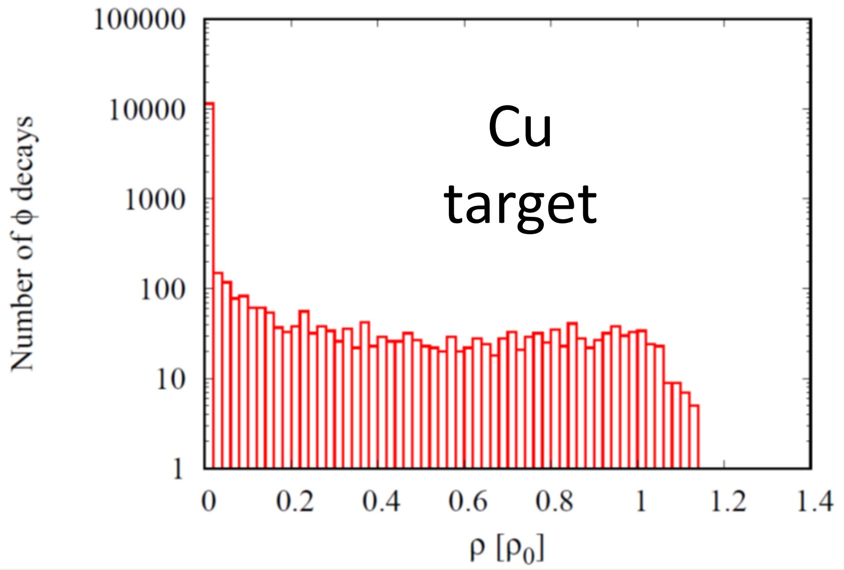
What density does the φ feel in the reaction (p+Cu/C at 12 GeV)?

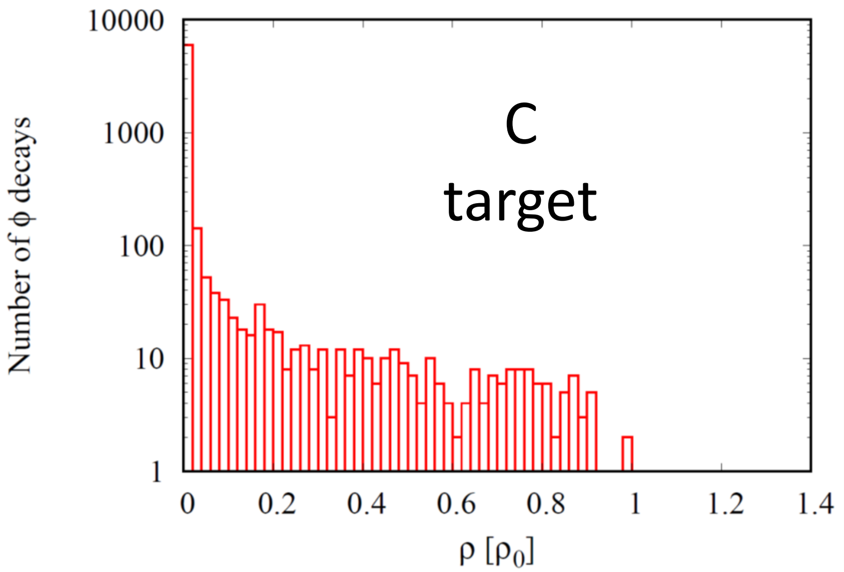
Production



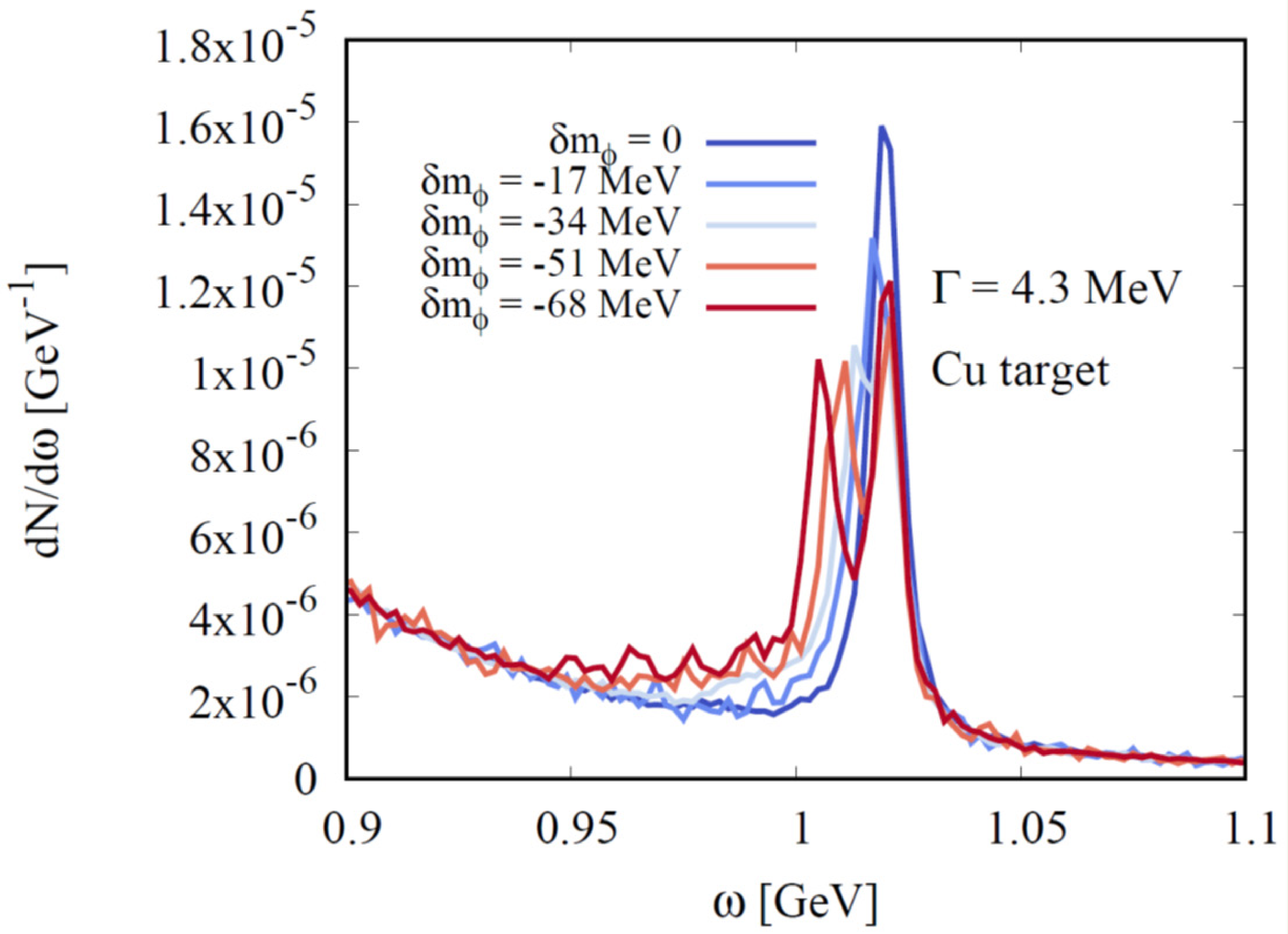


Decay





The dilepton spectrum in the φ meson region

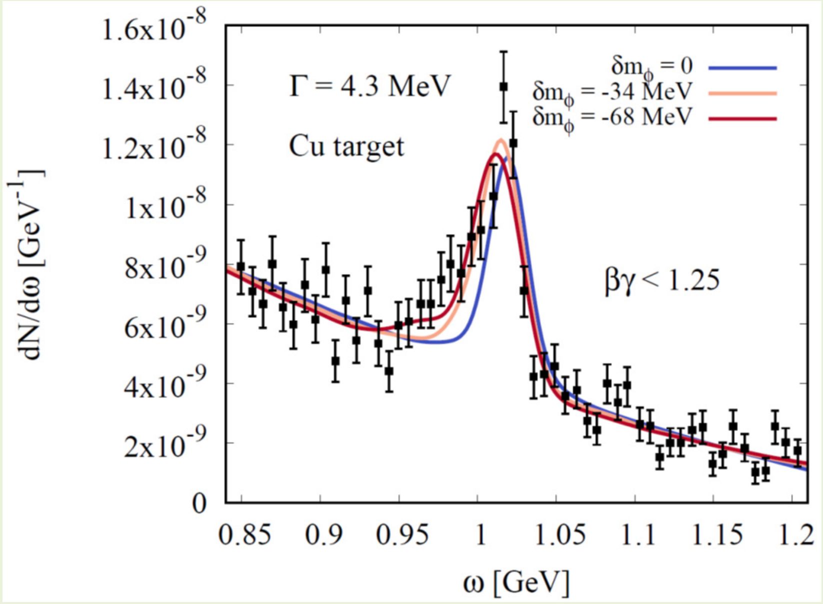


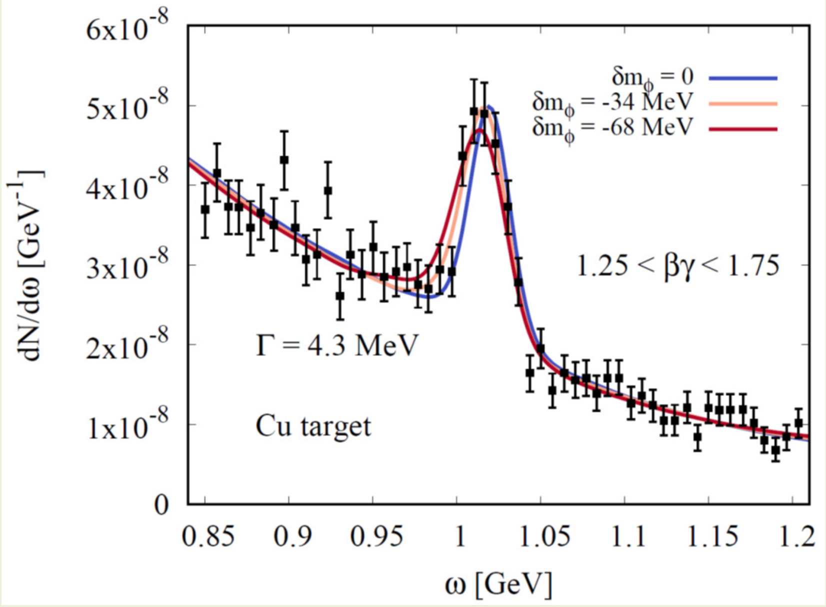
p + Cu at 12 GeV

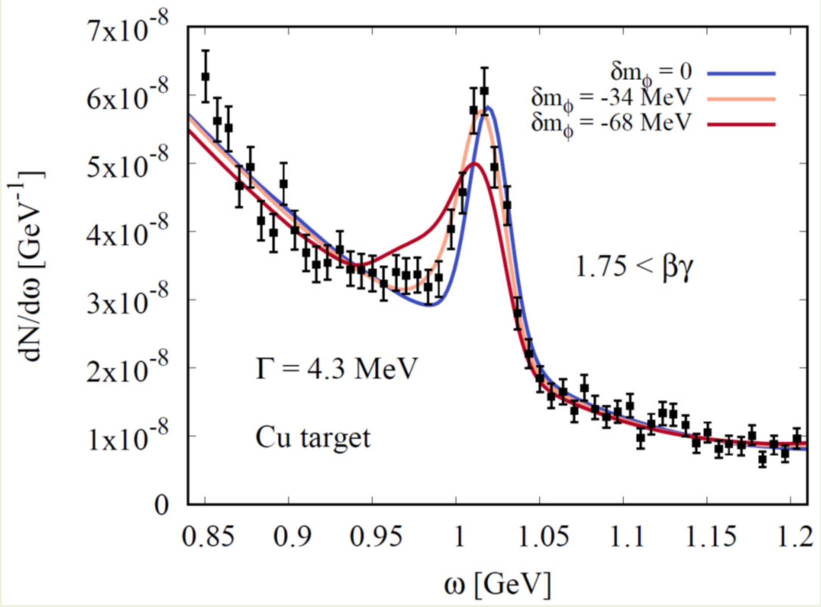
No acceptance corrections!

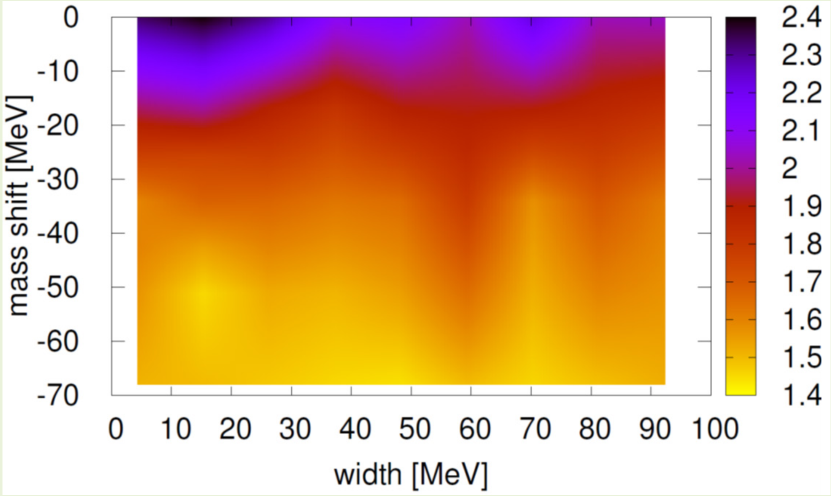
No finite resolution effects!

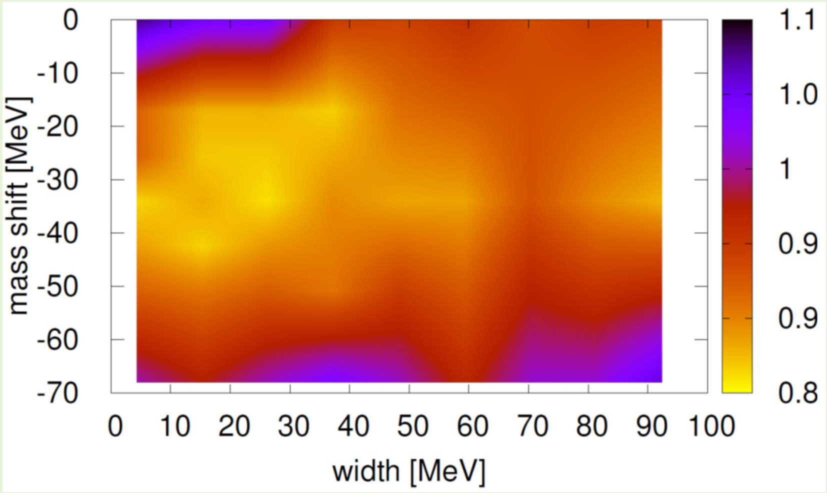
Fits to experimental Copper target data (E325)

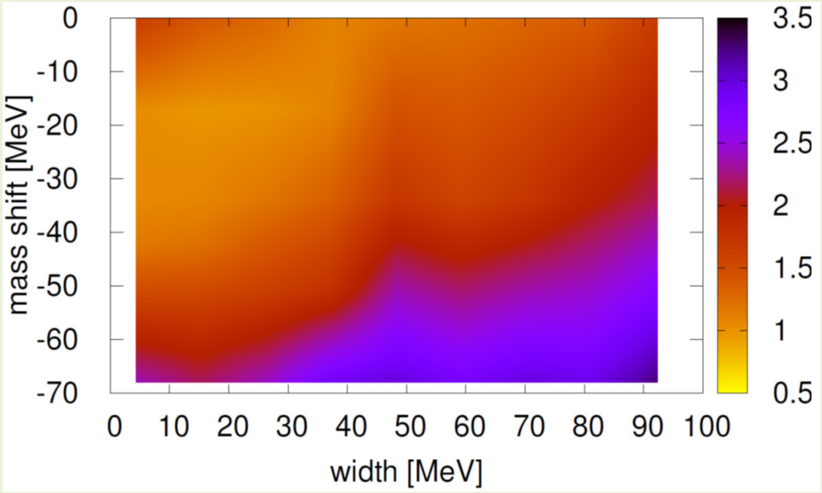








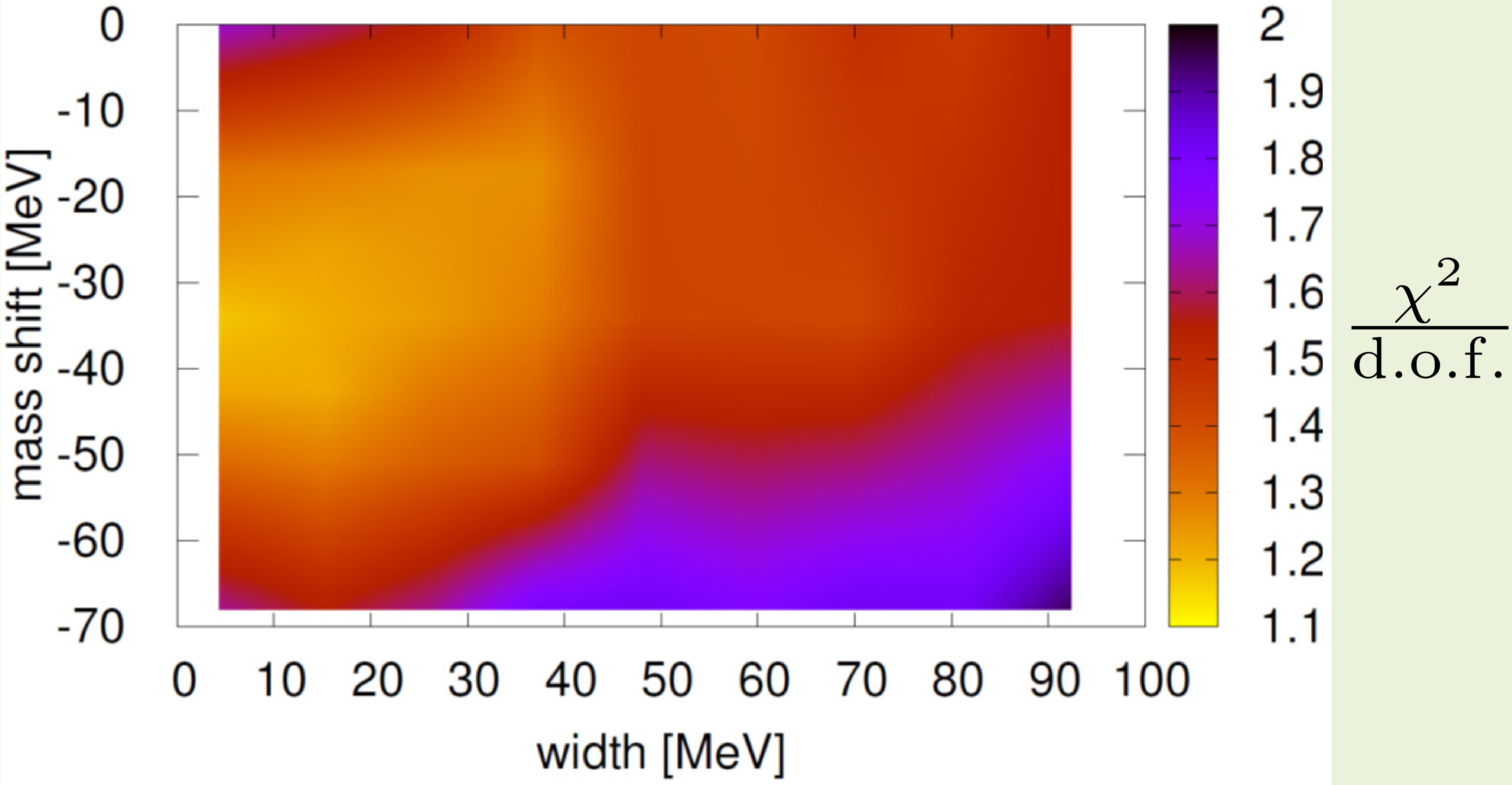




Favors relatively large negative mass shift!

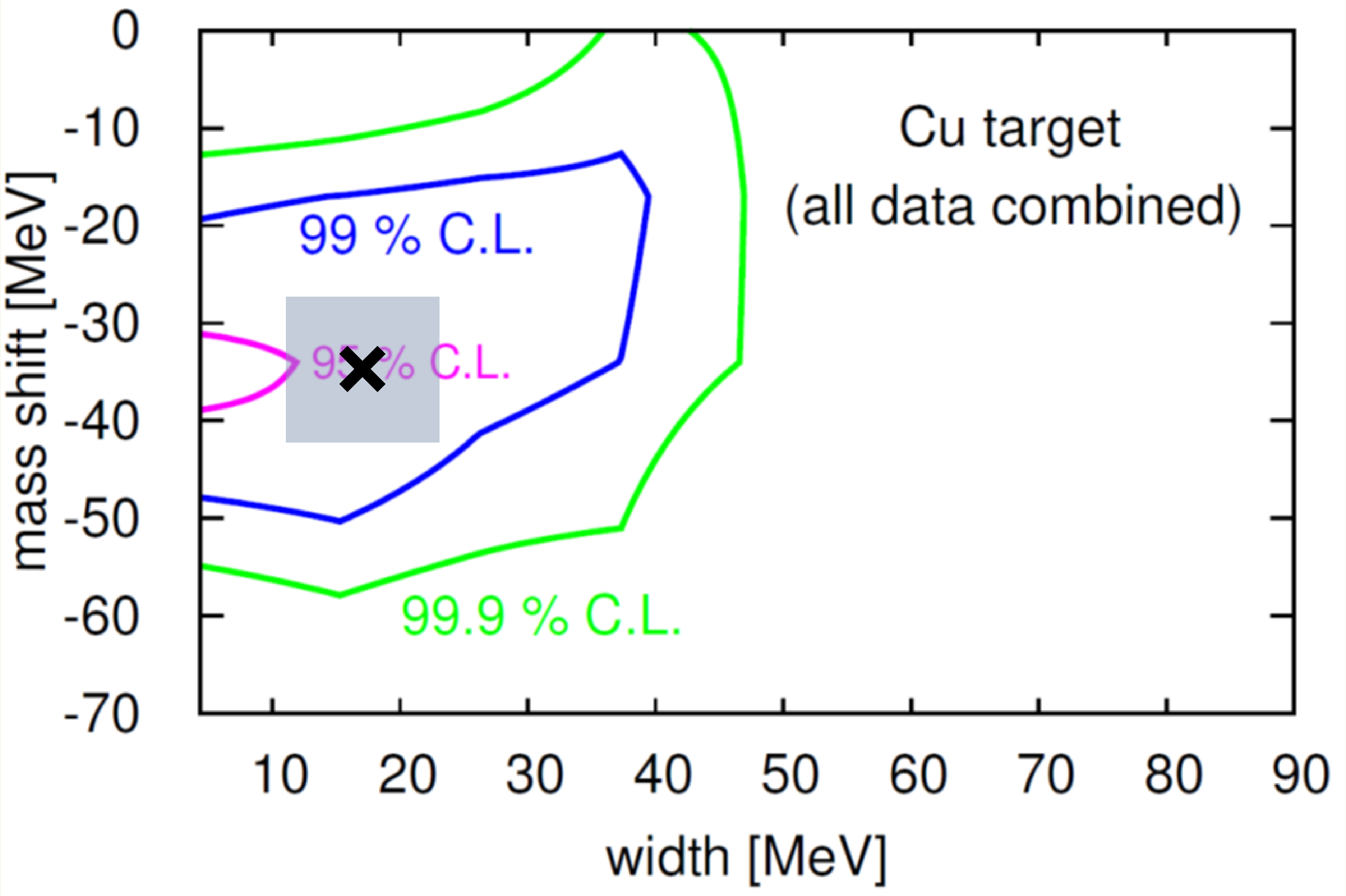
Favors small mass shift!

All Copper data combined

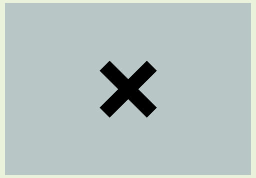


Fits to experimental Copper target data (E325)

Confidence levels of combined Copper data

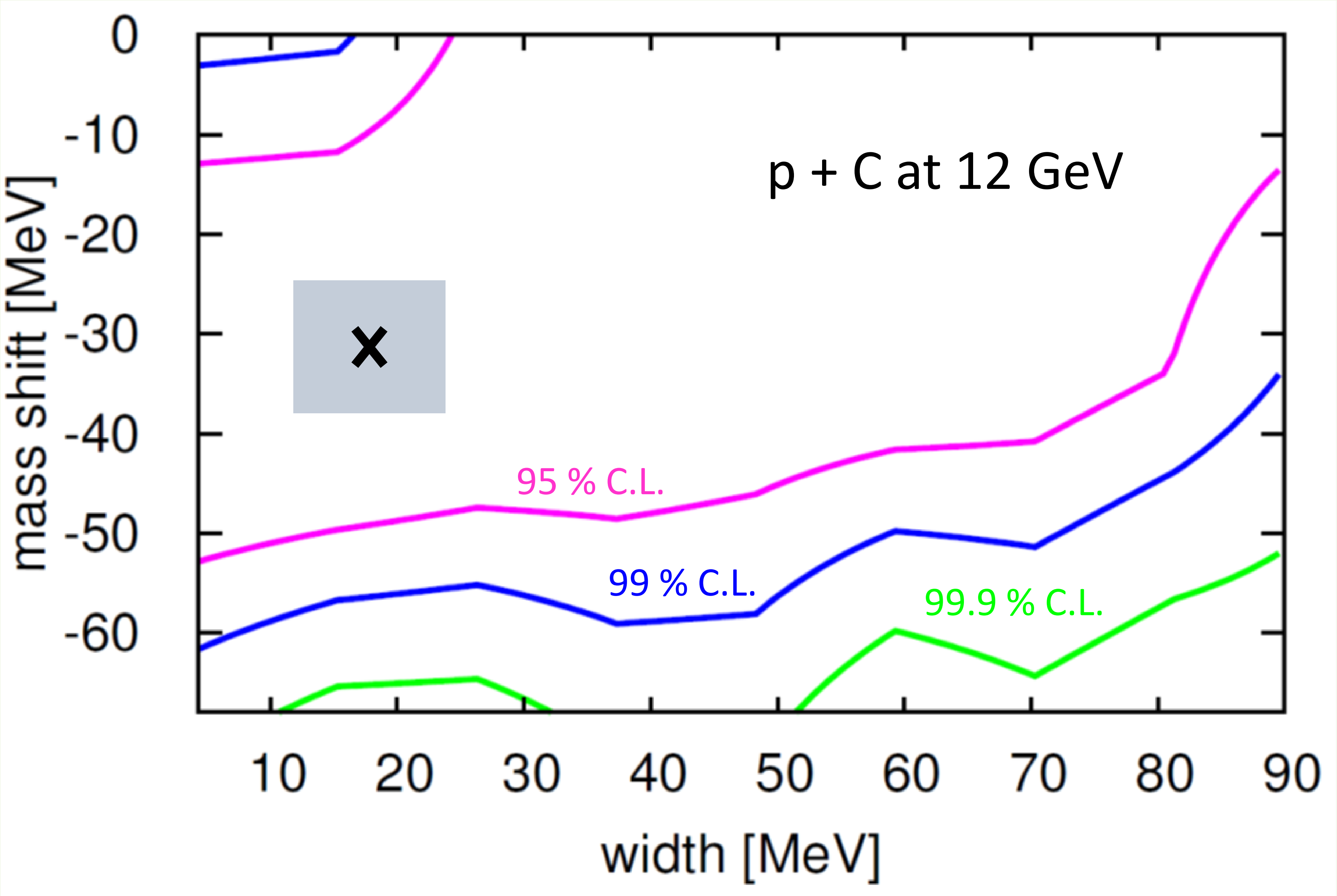


Conclusion of the E325 Collaboration

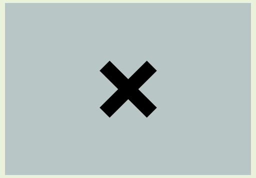


Fits to experimental Carbon target data (E325)

Confidence levels of combined Carbon data



Conclusion of the E325 Collaboration

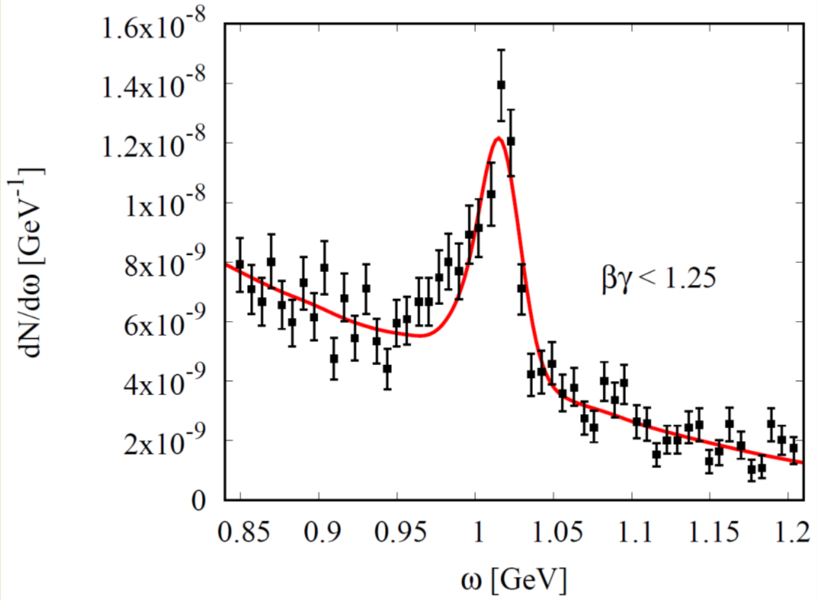


Best fit to E325 data

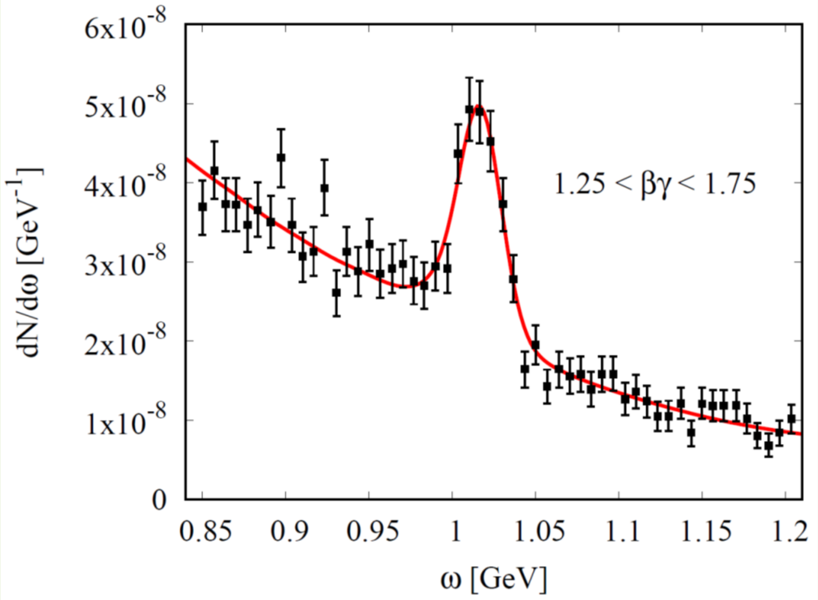
(p + Cu at 12 GeV)

vacuum value

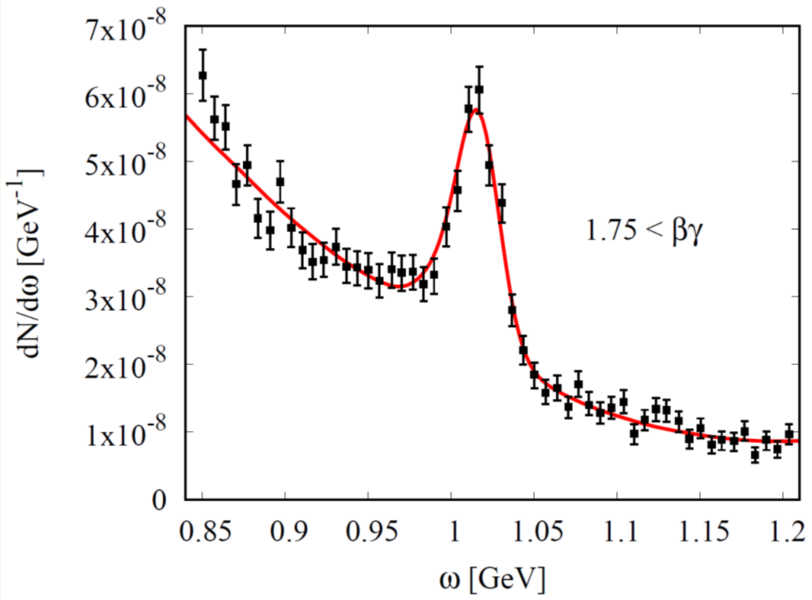
$$\delta m_\phi(\rho_0) = -34\,\mathrm{MeV} \qquad \Gamma(\rho_0) = 4.3\,\mathrm{MeV}$$



slow φs



intermediate φs



fast φs

Summary and Conclusions

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

★ 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!

★ Numerical simulations of the pA reactions to measured at the E325 experiment at KEK, using the PHSD transport code, are in progress.

⬇

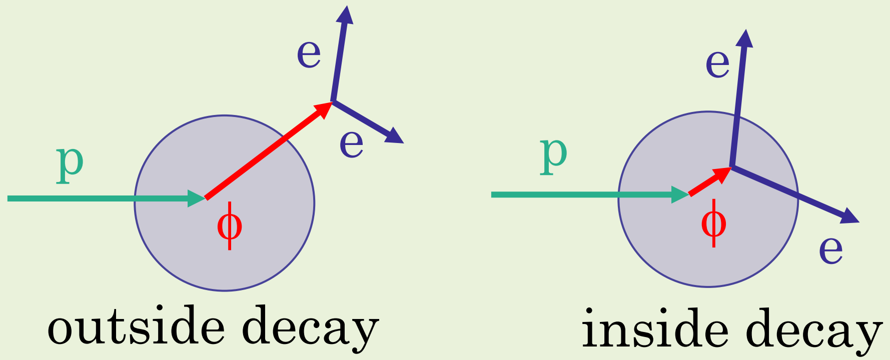
Frist results indicate that the experimental data favor a **negative mass shift with none or only small broadening**!

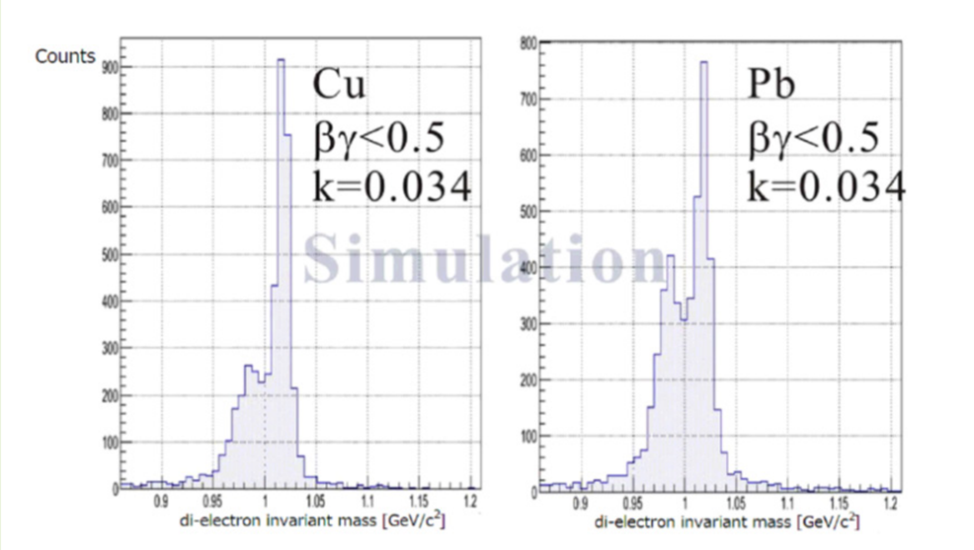
Backup slides

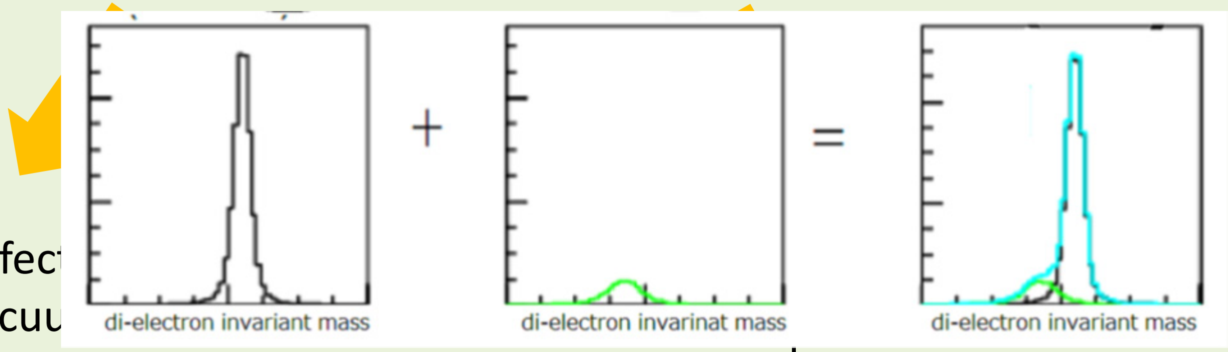
The experimental situation

The E325 Experiment (KEK)

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







No effect
(only vacuu

ϕ-meson

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

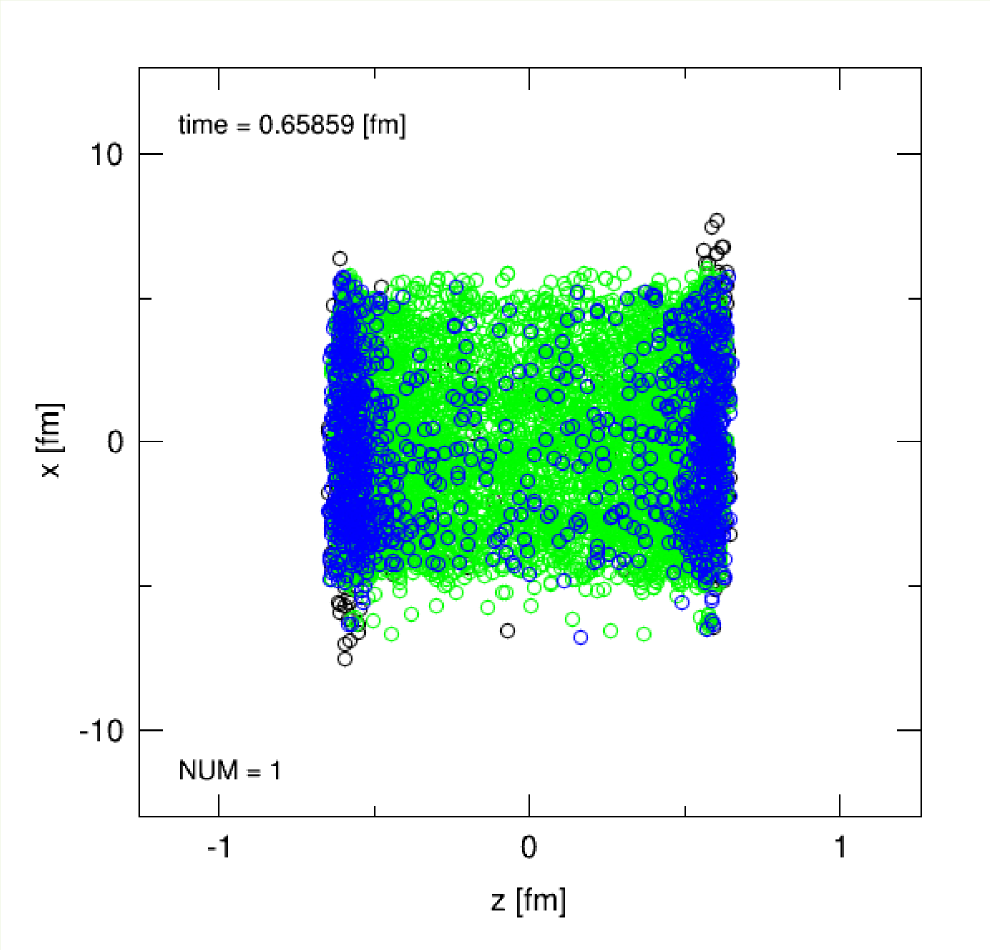
Our tool: a transport code
PHSD (Parton Hadron String Dynamics)

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

Example:

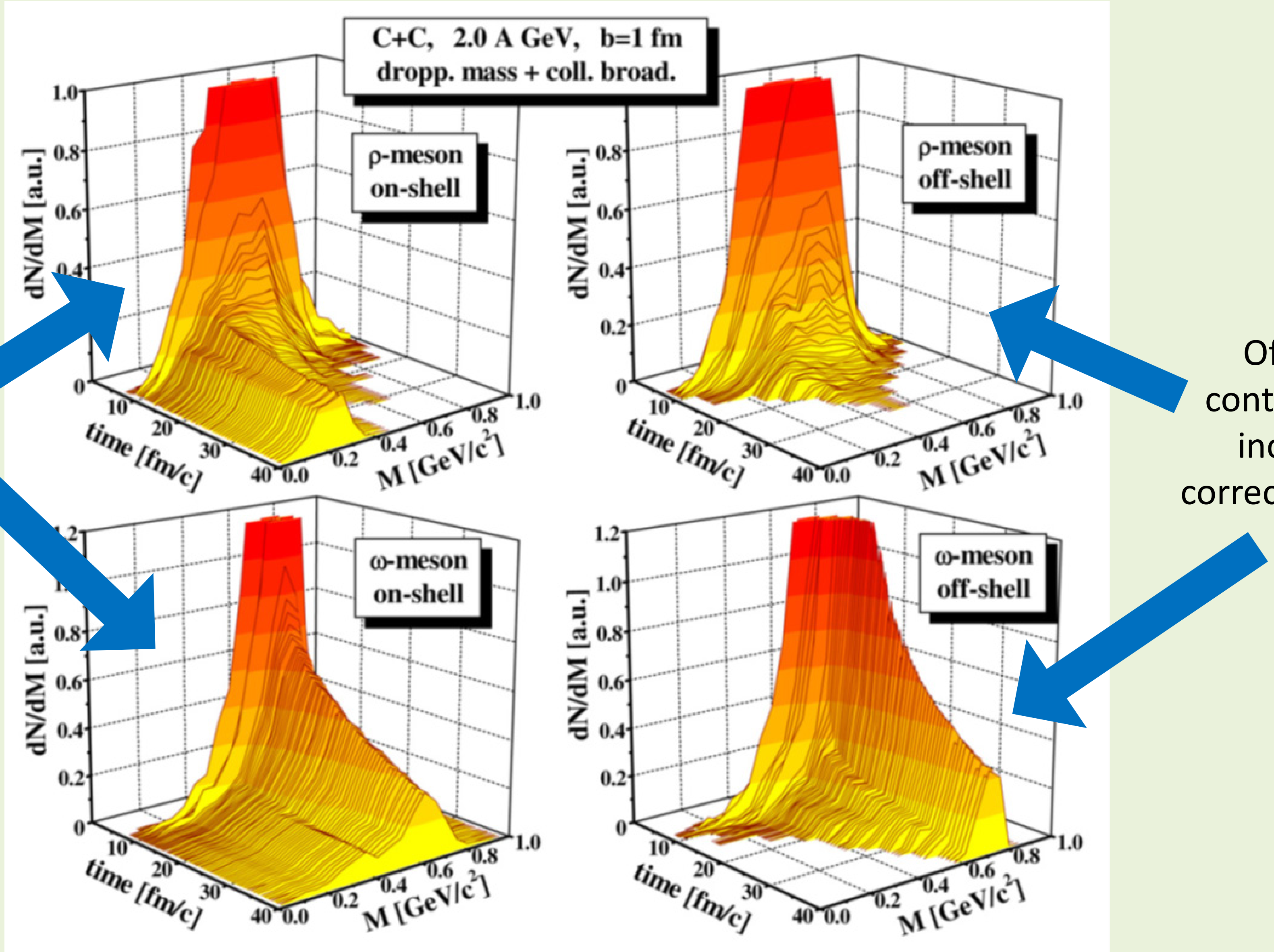
Au+Au collision at 200 GeV
b = 2 fm

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

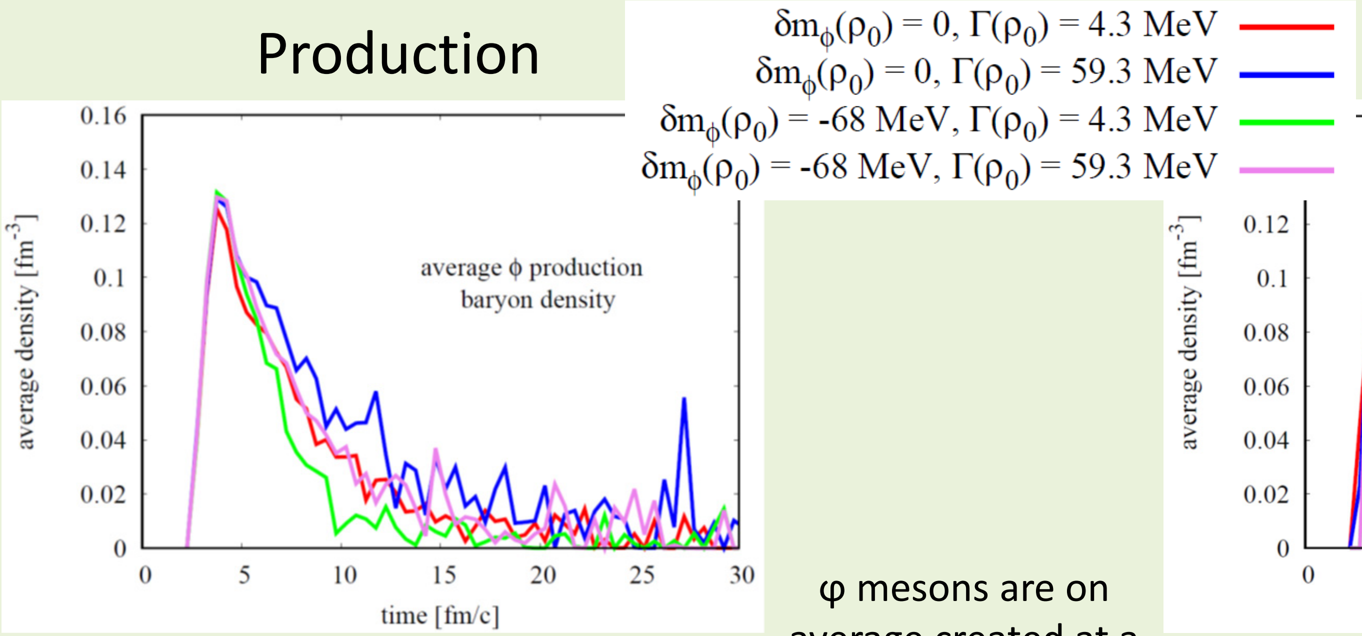
Taken from: E.L. Bratkovskaya and W. Cassing, Nucl. Phys. A **807**, 214 (2008).

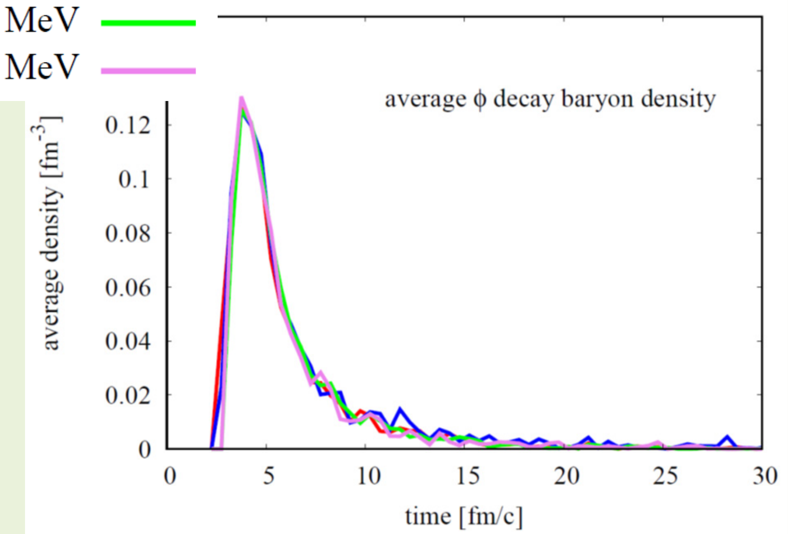
What density does the φ feel in the reaction (p+Cu/C at 12 GeV)?

Production

Decay

Cu target

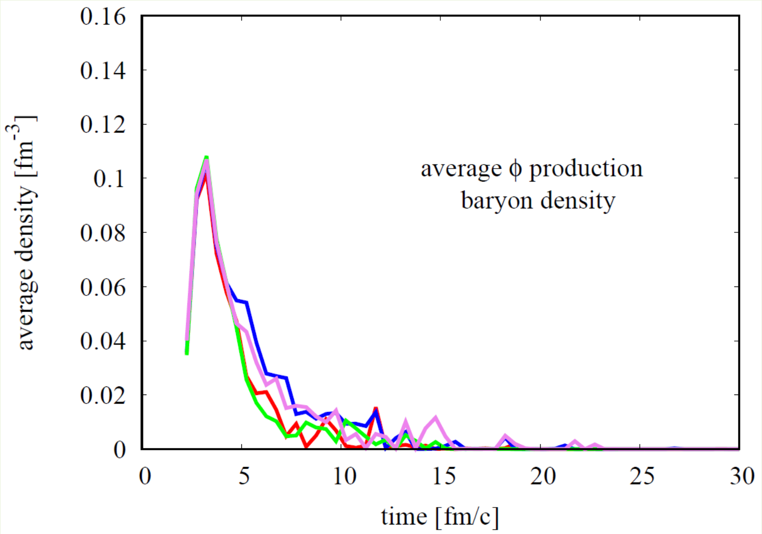


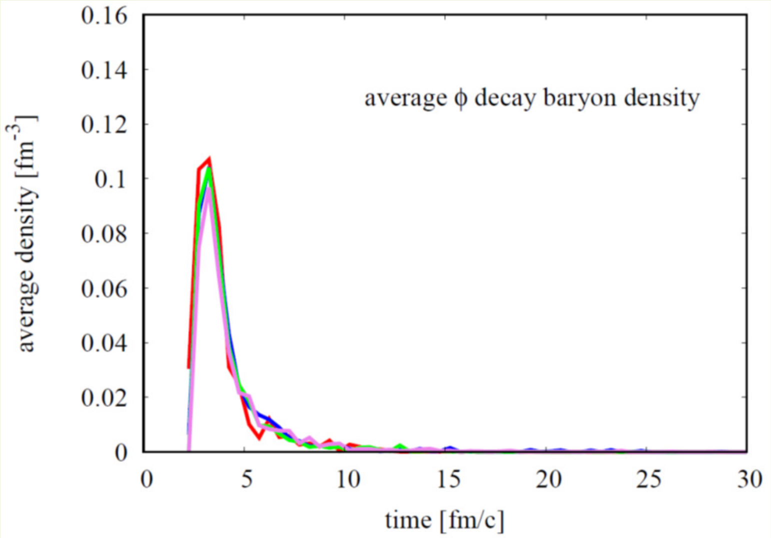


φ mesons are on average created at a density significantly below ρ_0

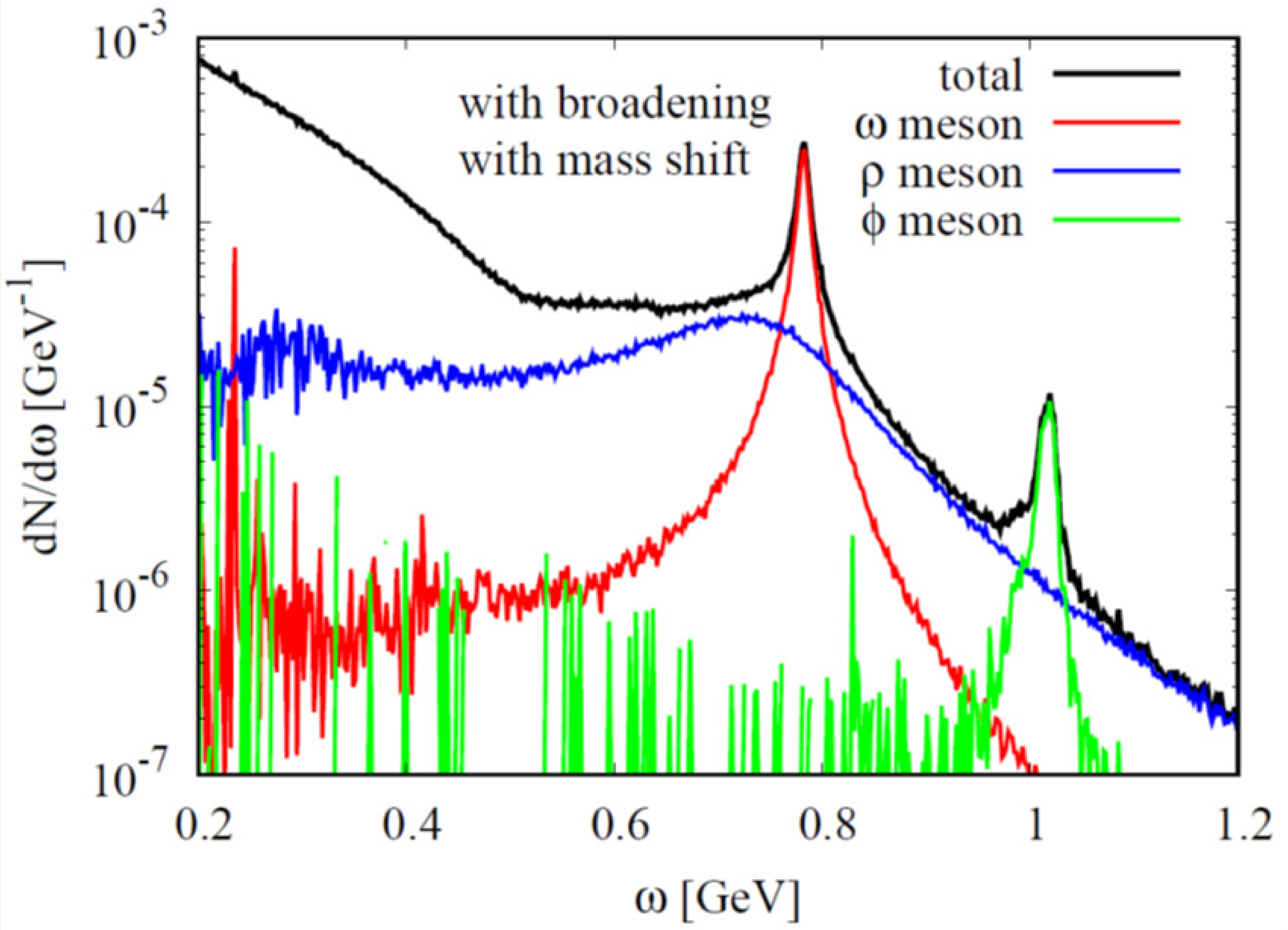
φ mesons on average decay at a density significantly below ρ_0

C target





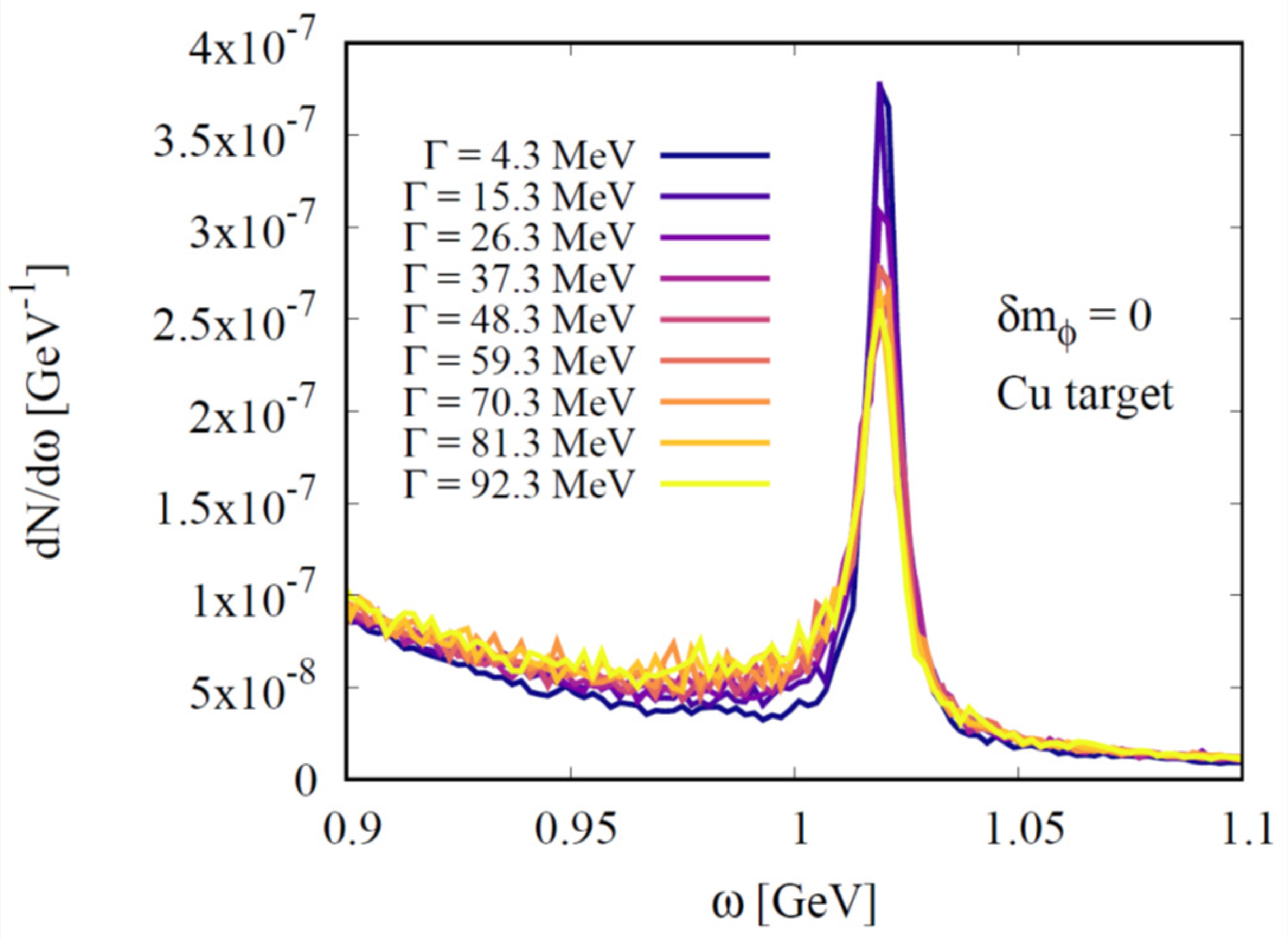
The dilepton spectrum



p+Cu at 12 GeV

The φ meson peak is clearly visible.

The dilepton spectrum in the φ meson region



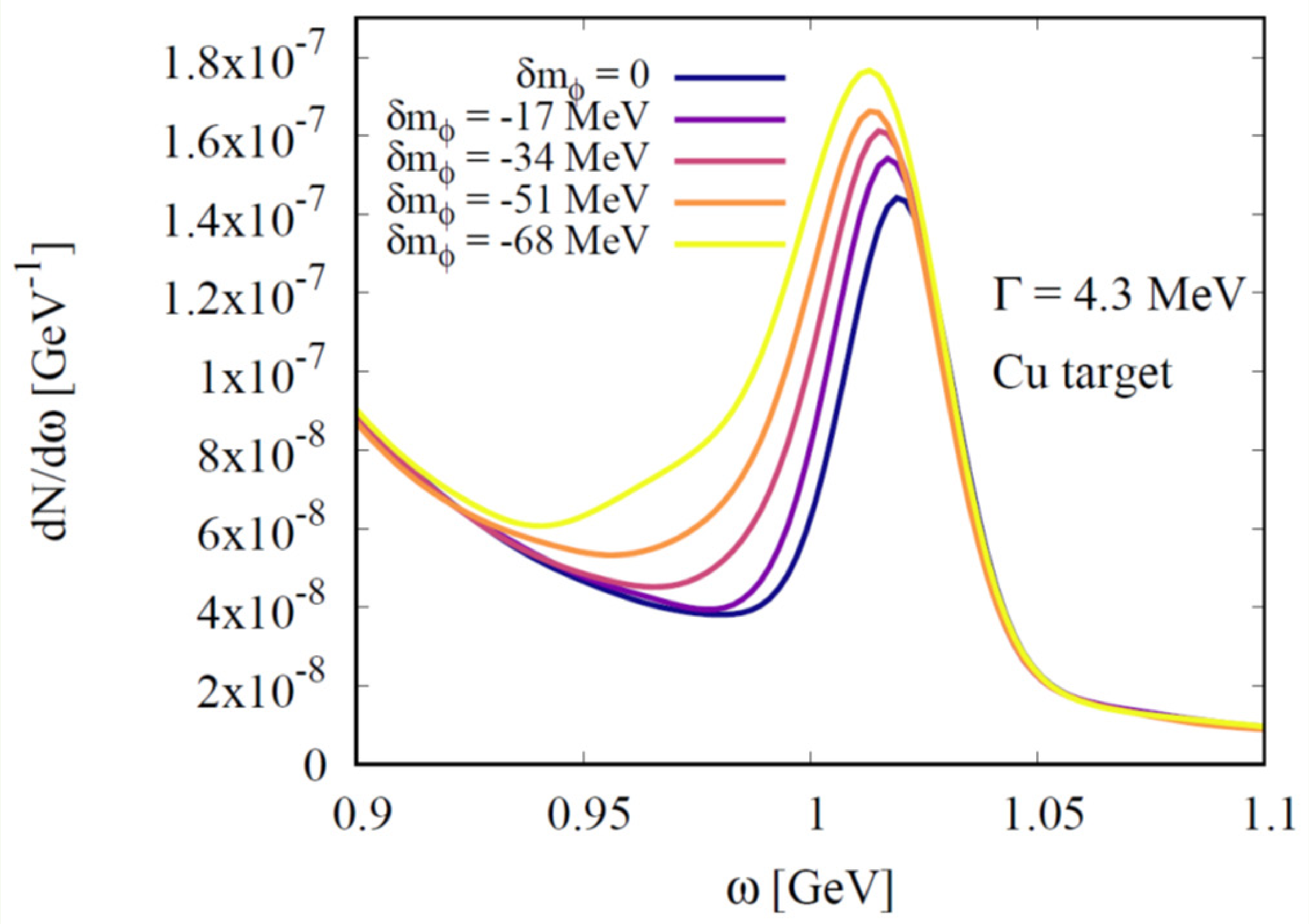
p + Cu at 12 GeV

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!

Preliminary

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!

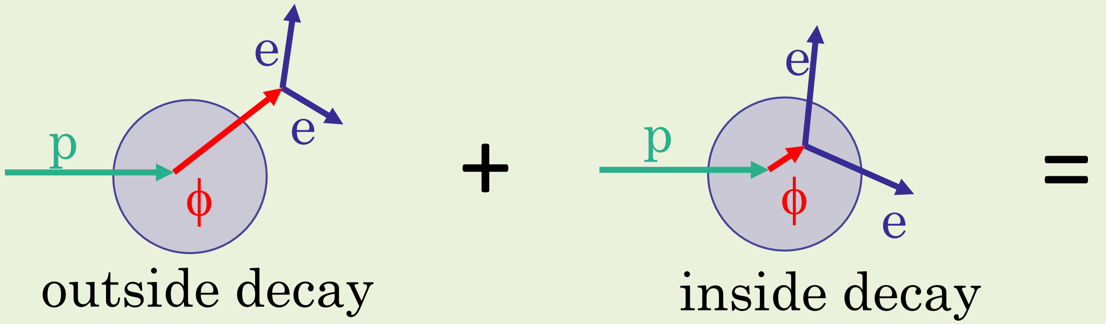
Background: $a\omega^2 + b\omega + c$

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

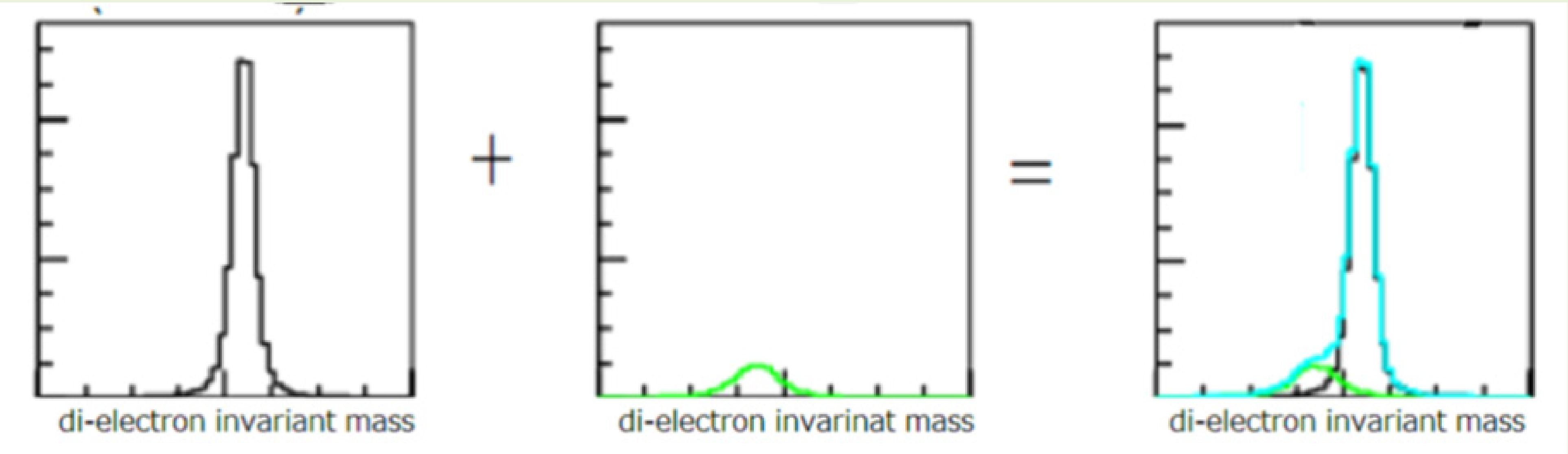
Dilepton spectrum: $$\rho(\omega) = \underbrace{a\omega^2 + b\omega + c}_{\text{Background}} + \underbrace{A\rho_{\phi,\mathrm{PHSD}}(\omega)}_{\phi\text{ meson signal}}$$

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

Experimental di-lepton spectrum

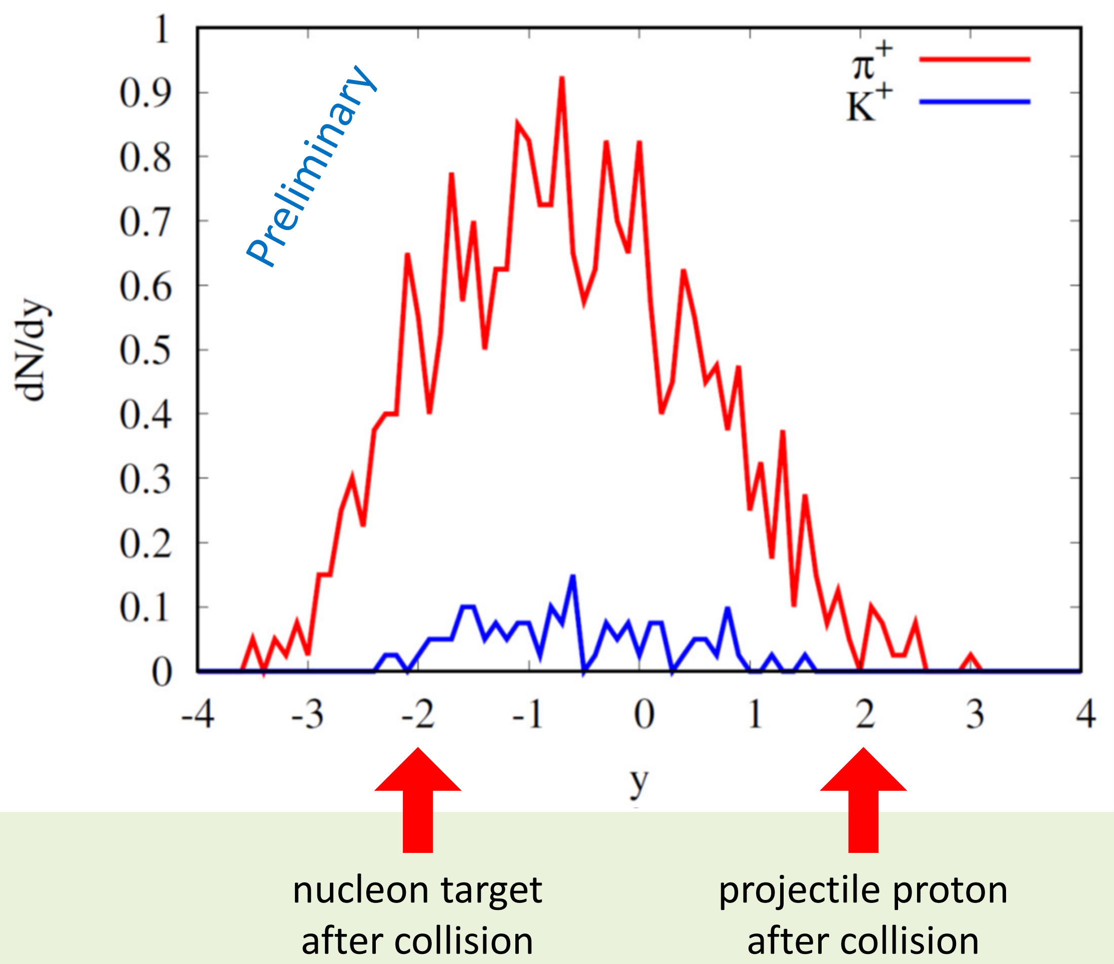


Experimentally observed spectrum



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

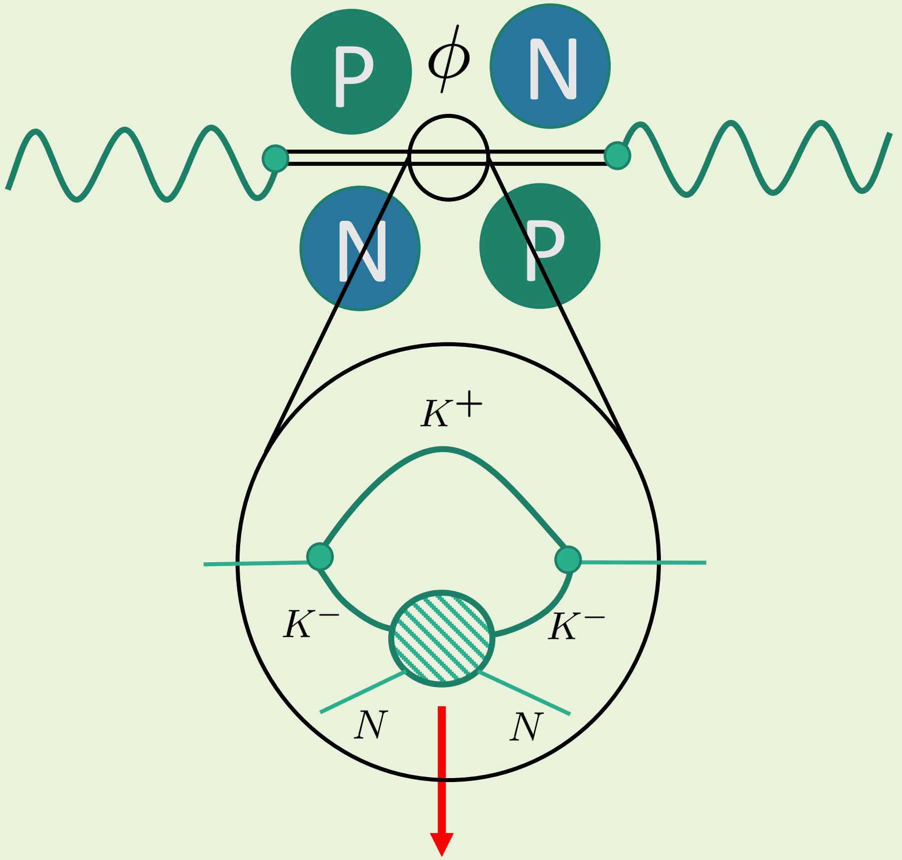
A first look at the reaction:
Rapidity distribution of protons/mesons



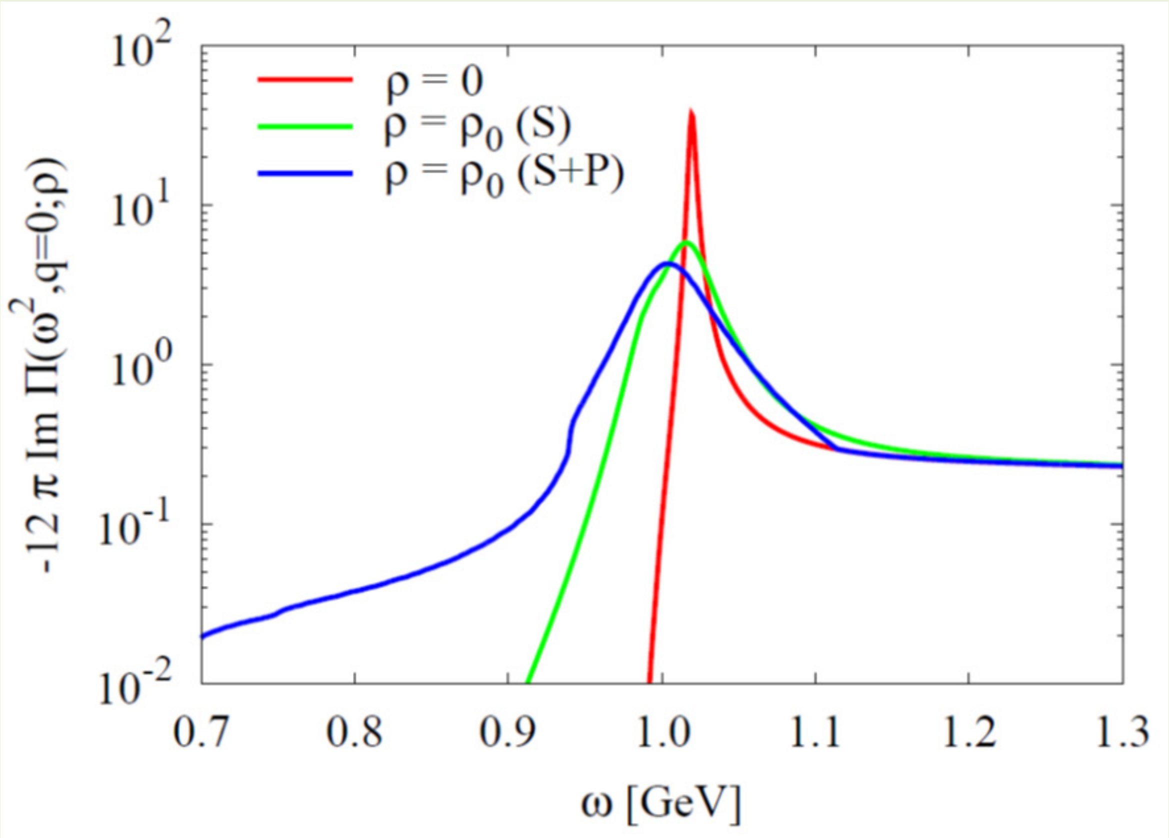
Due to the large collision energy, the incoming proton passes through the target nucleus

Recent theoretical works about the ϕ

based on hadronic models



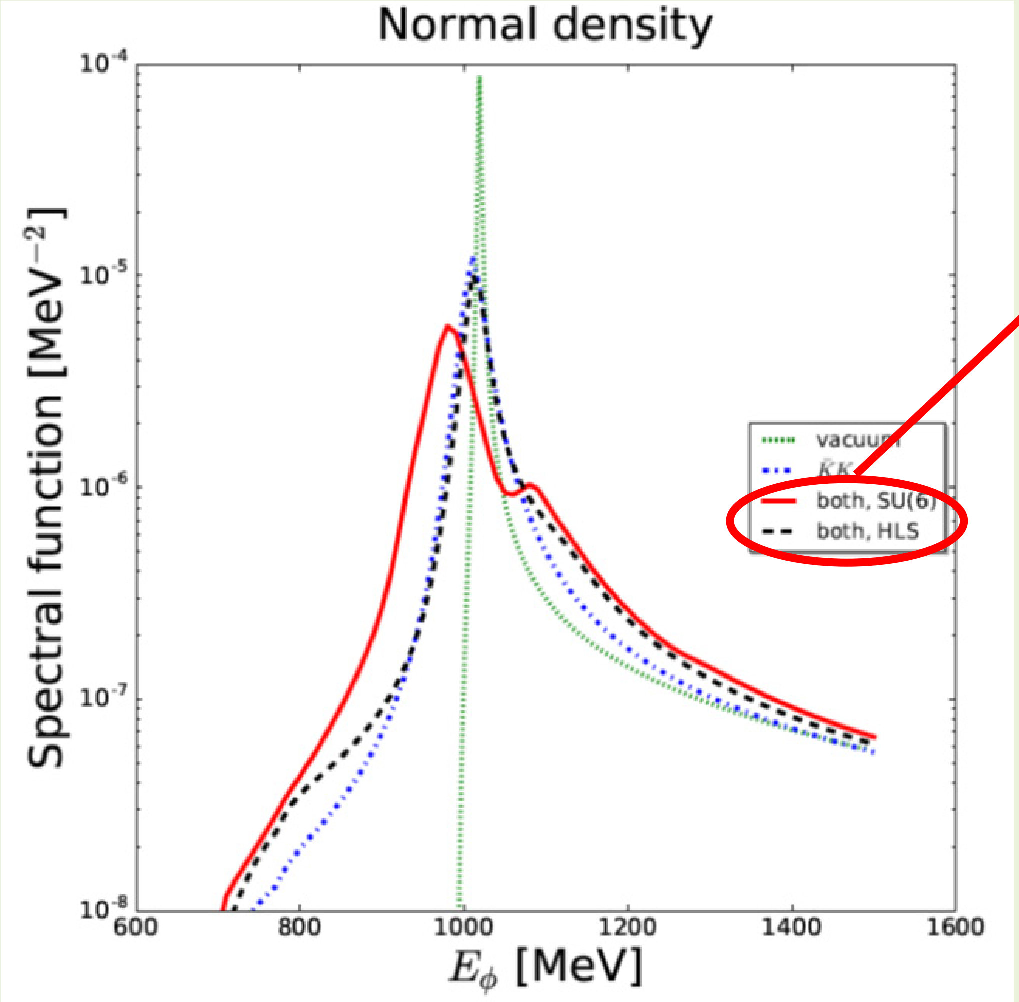
Forward $\bar{K}N$ (or KN) scattering amplitude



P. Gubler and W. Weise, Phys. Lett. B **751**, 396 (2015).
P. Gubler and W. Weise, Nucl. Phys. A **954**, 125 (2016).

Recent theoretical works about the ϕ

based on hadronic models



D. Cabrera, A.N. Hiller Blin and M.J. Vicente Vacas, Phys. Rev. C **95**, 015201 (2017).

large dependence on details of the model incorporating Baryon - Vector meson interaction

SU(6): Spin-Flavor Symmetry extension of standard flavor SU(3)

HLS: Hidden Local Symmetry

Common features:

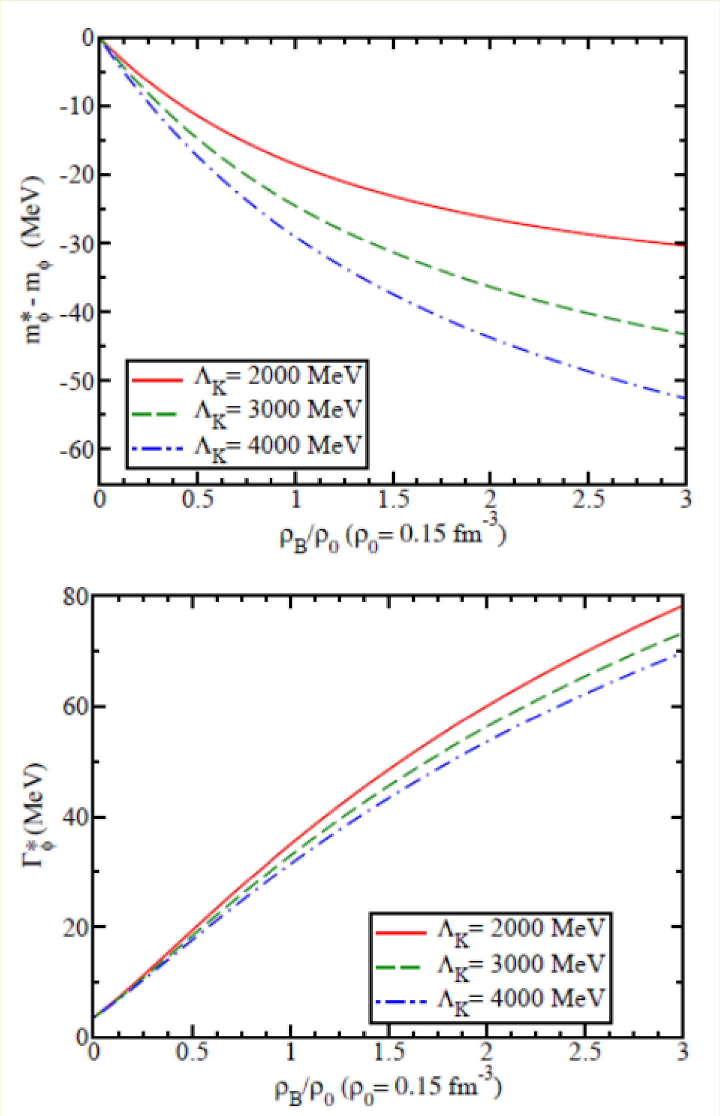
strong broadening, small negative mass shift

See also:

D. Cabrera, A.N. Hiller Blin and M.J. Vicente Vacas, Phys. Rev. C **96**, 034618 (2017).

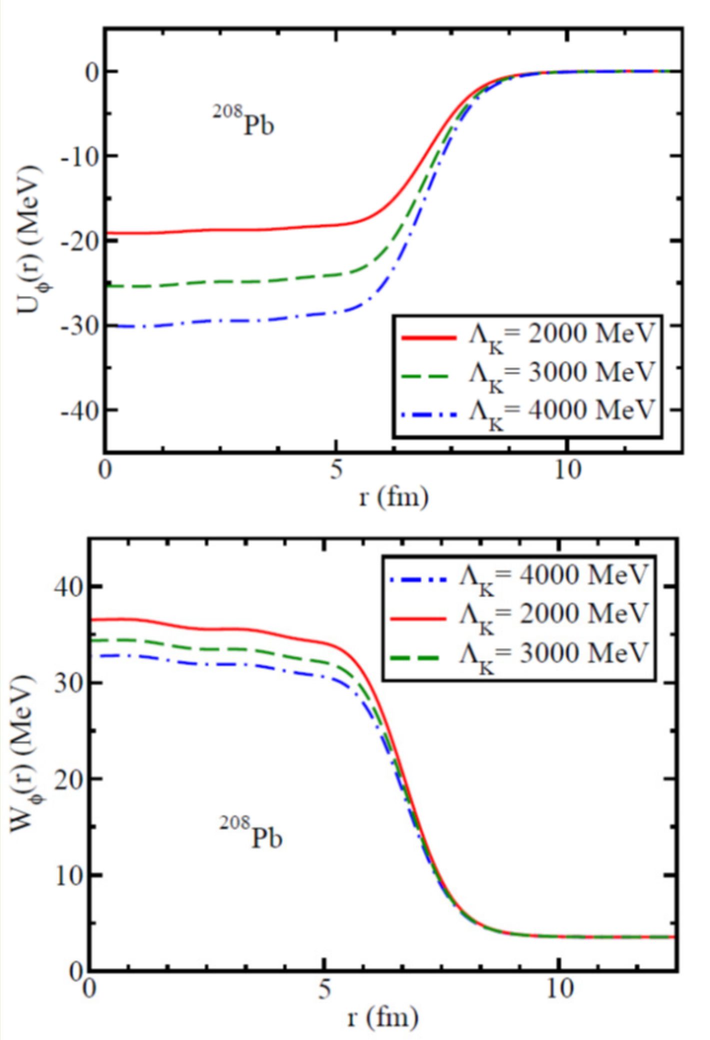
Recent theoretical works about the ϕ

based on the quark-meson coupling model



J.J. Cobos-Martinez, K. Tsushima, G. Krein and A.W. Thomas, Phys. Lett. B **771**, 113 (2017).
J.J. Cobos-Martinez, K. Tsushima, G. Krein and A.W. Thomas, Phys. Rev. C **96**, 035201 (2017).

$$V_{\phi A}(r) = U_\phi(r) - \frac{i}{2} W_\phi(r)$$



		$\Lambda_K = 2000$		$\Lambda_K = 3000$		$\Lambda_K = 4000$	
		E	$\Gamma/2$	E	$\Gamma/2$	E	$\Gamma/2$
$^4_\phi$He	1s	n (-0.8)	n	n (-1.4)	n	-1.0 (-3.2)	8.3
$^{12}_\phi$C	1s	-2.1 (-4.2)	10.6	-6.4 (-7.7)	11.1	-9.8 (-10.7)	11.2
$^{16}_\phi$O	1s	-4.0 (-5.9)	12.3	-8.9 (-10.0)	12.5	-12.6 (-13.4)	12.4
	1p	n (n)	n	n (n)	n	n (-1.5)	n
$^{40}_\phi$Ca	1s	-9.7 (-11.1)	16.5	-15.9 (-16.7)	16.2	-20.5 (-21.2)	15.8
	1p	-1.0 (-3.5)	12.9	-6.3 (-7.8)	13.3	-10.4 (-11.4)	13.3
	1d	n (n)	n	n (n)	n	n (-1.4)	n
$^{48}_\phi$Ca	1s	-10.5 (-11.6)	16.5	-16.5 (-17.2)	16.0	-21.1 (-21.6)	15.6
	1p	-2.5 (-4.6)	13.6	-7.9 (-9.2)	13.7	-12.0 (-12.9)	13.6
	1d	n (n)	n	n (-0.8)	n	-2.1 (-3.6)	11.1
$^{90}_\phi$Zr	1s	-12.9 (-13.6)	17.1	-19.0 (-19.5)	16.4	-23.6 (-24.0)	15.8
	1p	-7.1 (-8.4)	15.5	-12.8 (-13.6)	15.2	-17.2 (-17.8)	14.8
	1d	-0.2 (-2.5)	13.4	-5.6 (-6.9)	13.5	-9.7 (-10.6)	13.4
	2s	n (-1.4)	n	-3.4 (-5.1)	12.6	-7.4 (-8.5)	12.7
	2p	n (n)	n	n (n)	n	n (-1.1)	n
$^{208}_\phi$Pb	1s	-15.0 (-15.5)	17.4	-21.1 (-21.4)	16.6	-25.8 (-26.0)	16.0
	1p	-11.4 (-12.1)	16.7	-17.4 (-17.8)	16.0	-21.9 (-22.2)	15.5
	1d	-6.9 (-8.1)	15.7	-12.7 (-13.4)	15.2	-17.1 (-17.6)	14.8
	2s	-5.2 (-6.6)	15.1	-10.9 (-11.7)	14.8	-15.2 (-15.8)	14.5
	2p	n (-1.9)	n	-4.8 (-6.1)	13.5	-8.9 (-9.8)	13.4
	2d	n (n)	n	n (-0.7)	n	-2.2 (-3.7)	11.9

Some ϕA bound states might exist, but they have a large width

→ difficult to observe experimentally ?

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

W. Cassing 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

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

In Vacuum

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

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

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

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

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

<u>In Nuclear Matter</u>

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

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

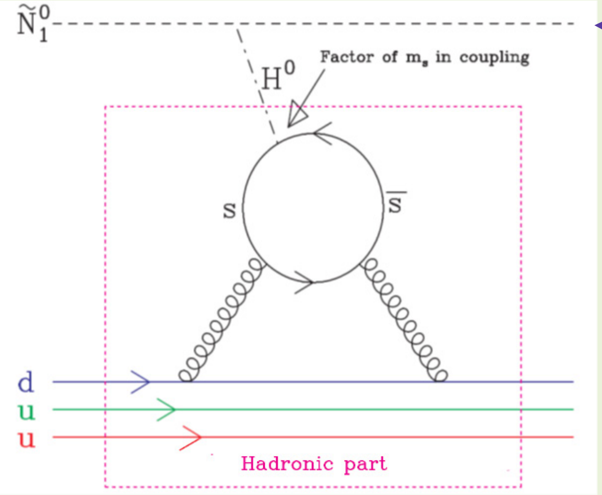
Dim. 2: $$c_2(\rho) = c_2(0)$$

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

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

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

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

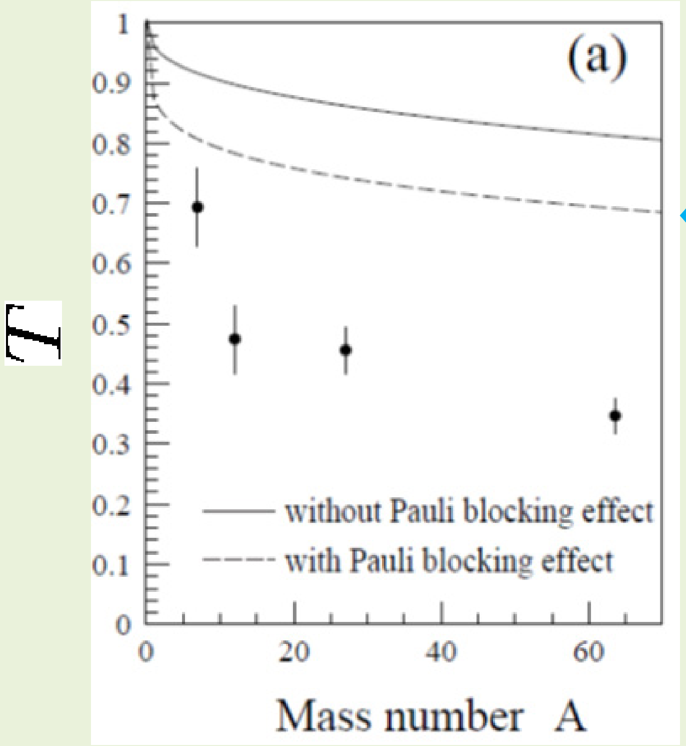
A. Bottino, F. Donato, N. Fornengo and S. Scopel, Asropart. Phys. **18**, 205 (2002).

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)



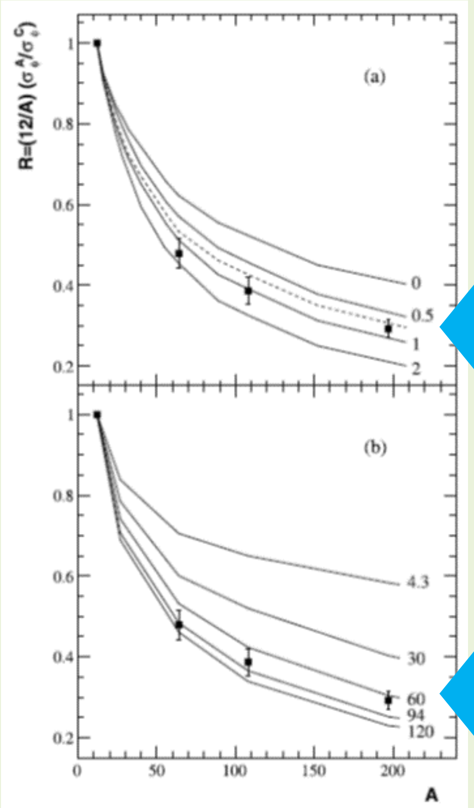
$\Gamma_\phi(\rho_0) \simeq 30\,\mathrm{MeV}$

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).