Simulating pA reactions to study the phi meson in nuclear matter at J-PARC

Philipp Gubler
Japan Atomic Energy Agency (JAEA)

Talk at the 1st CENuM Workshop for Hadronic Physics

Inha University, Incheon, South Korea

June 18, 2019

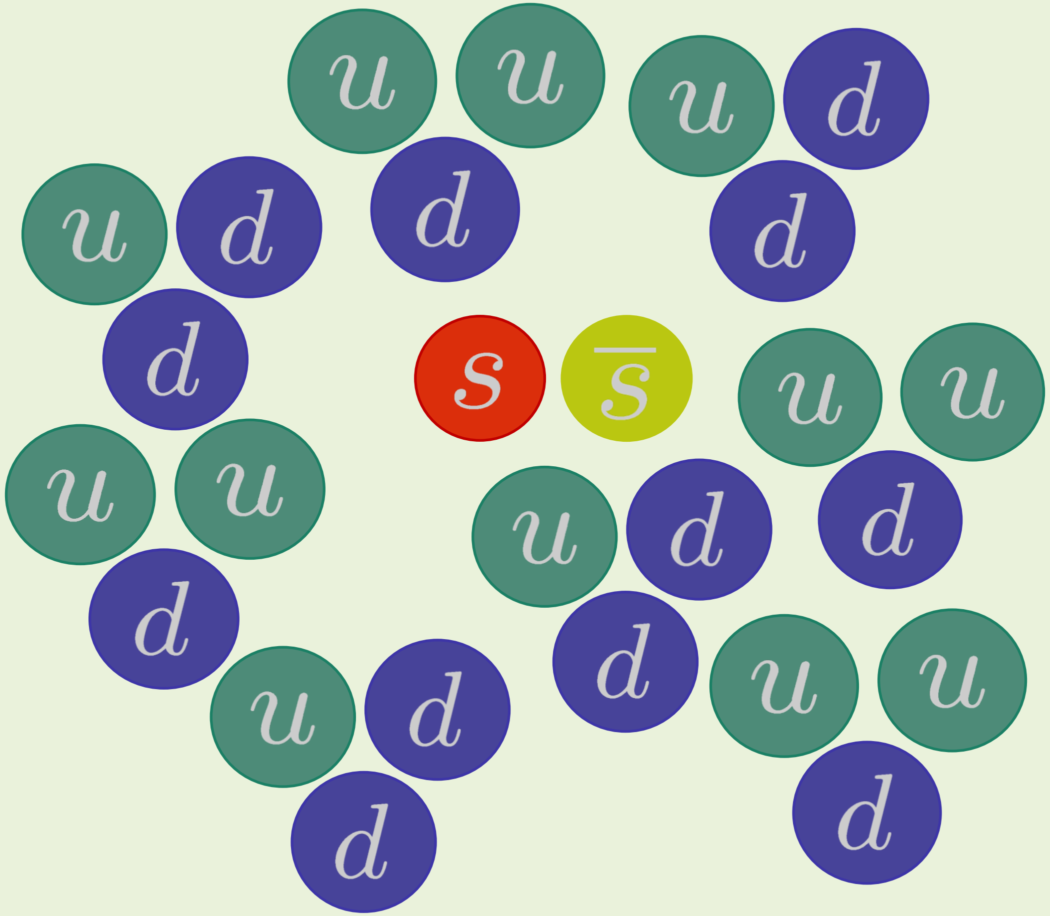
Work done in collaboration with

Elena Bratkovskaya (Frankfurt U./GSI)

ϕ meson

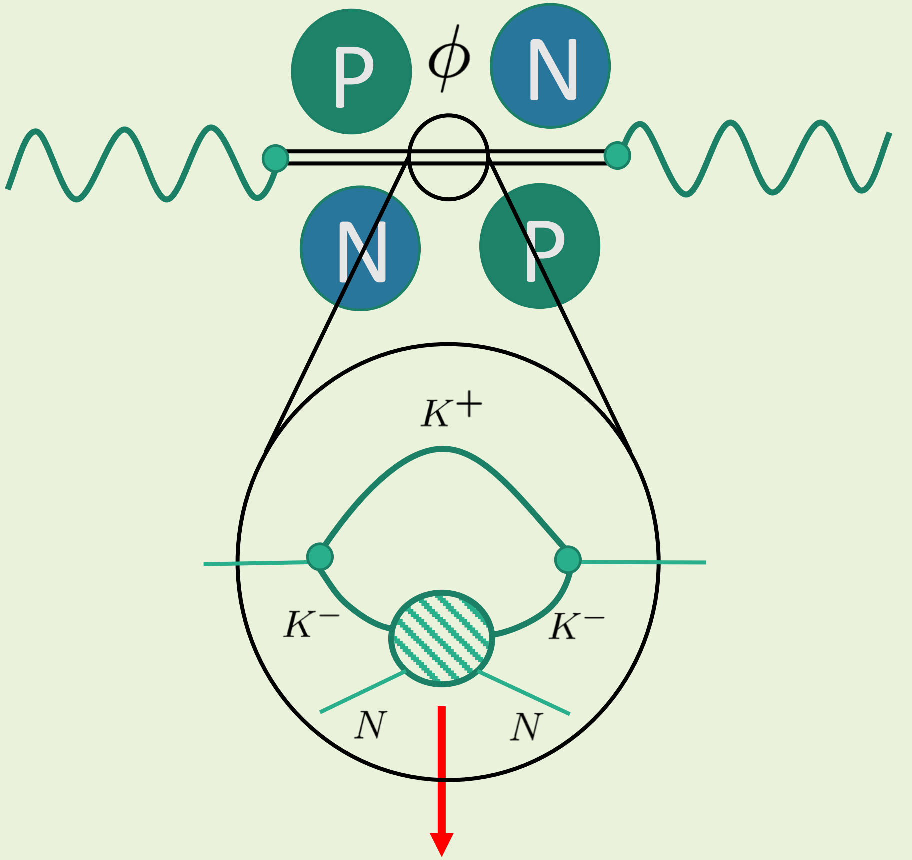
m_ϕ = 1019 MeV

Γ_ϕ = 4.3 MeV

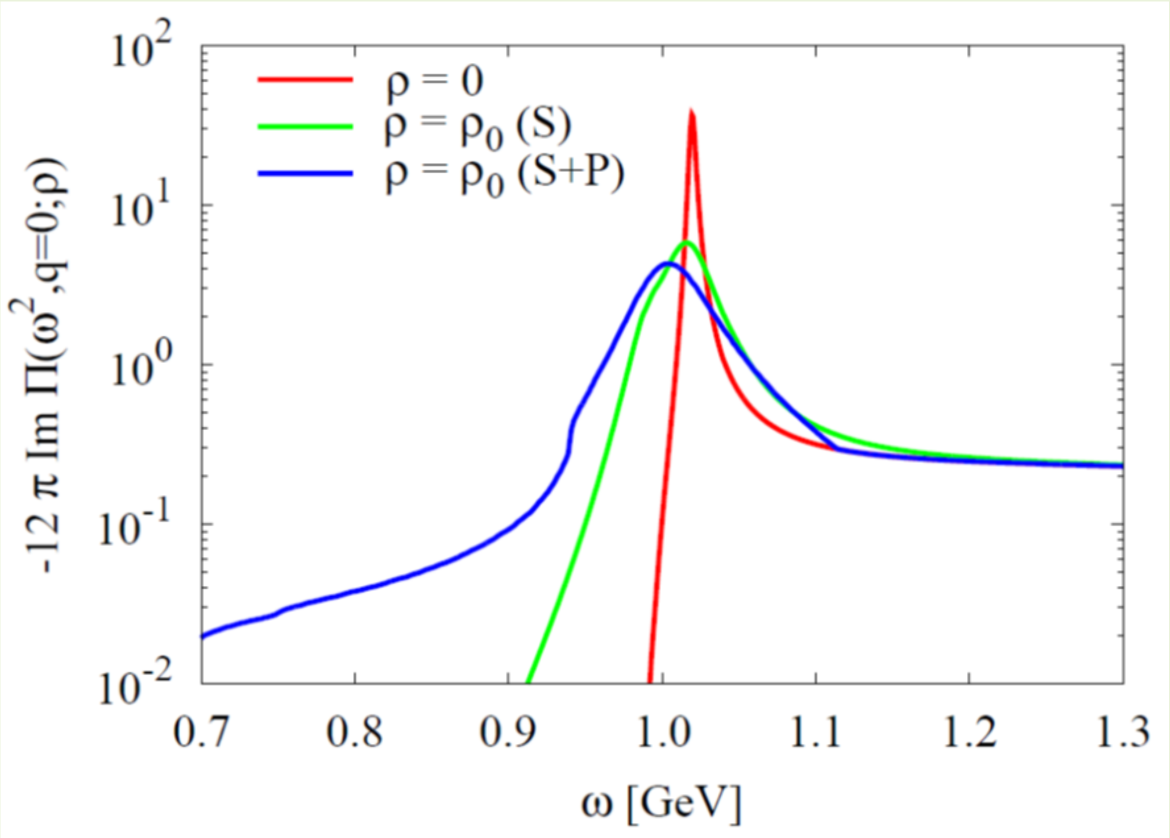


Recent theoretical works about the ϕ

based on hadronic models



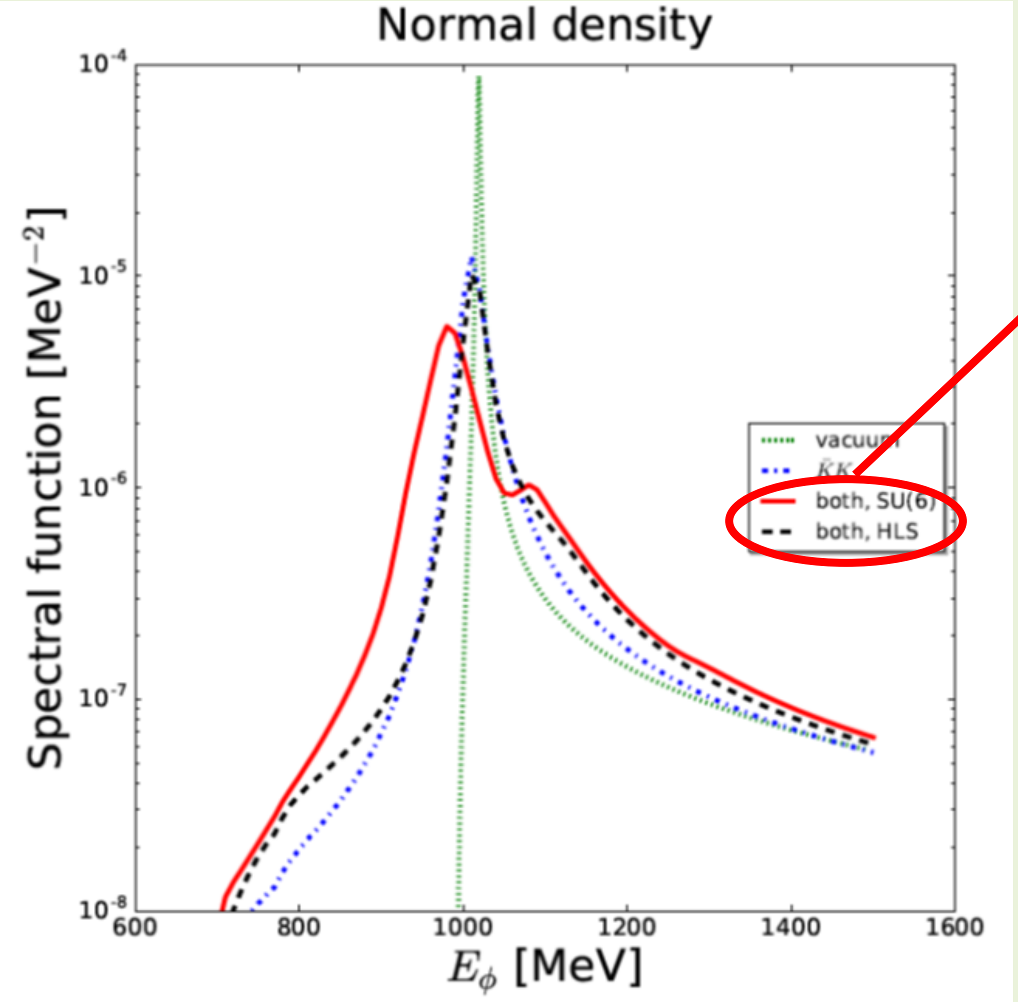
Forward $\bar{K}$N (or KN) scattering amplitude



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

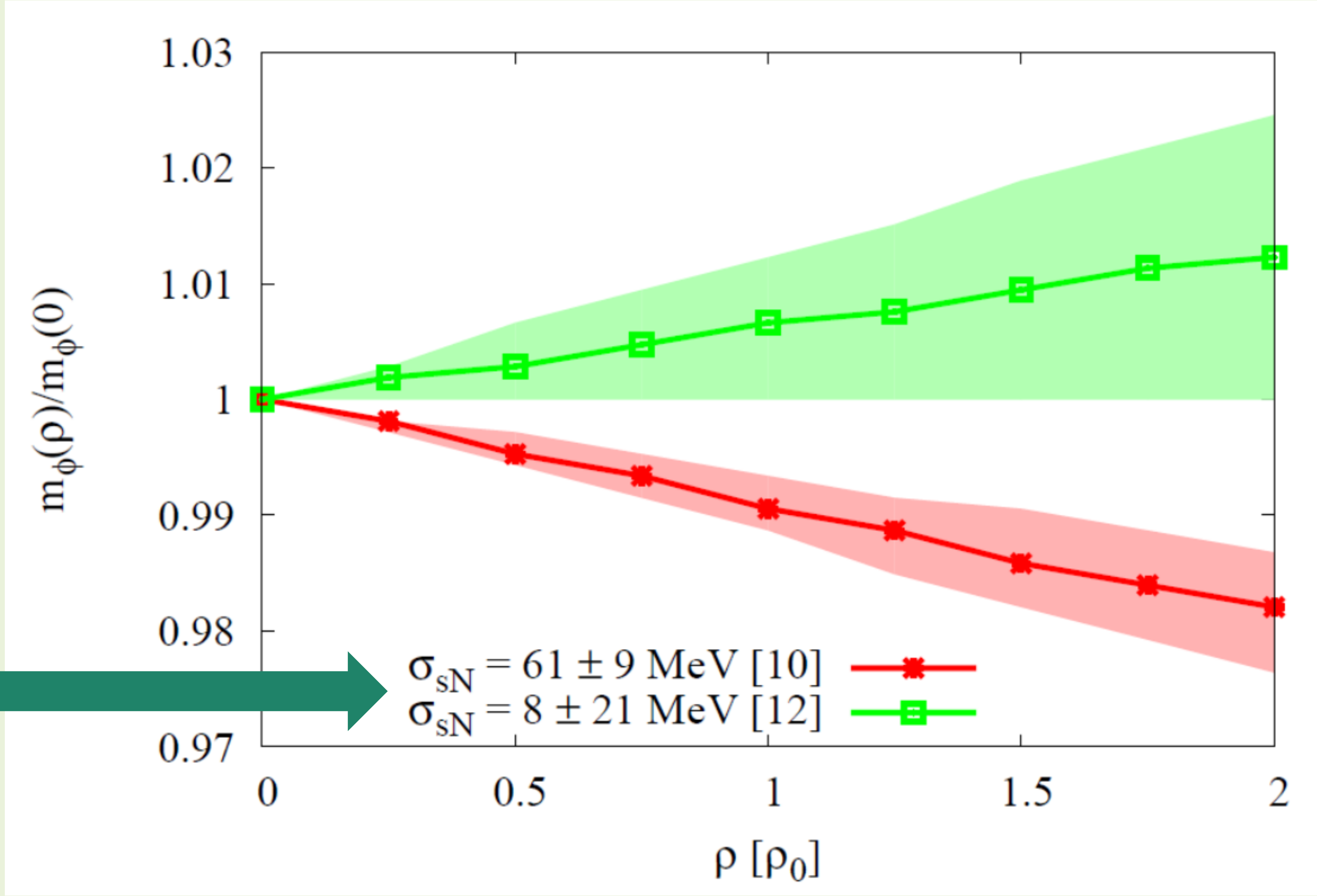
See also:
D. Cabrera, A.N. Hiller Blin and M.J. Vicente Vacas, Phys. Rev. C **96**, 034618 (2017).

ϕ meson mass at finite density from QCD sum rules

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

Strangeness content of the nucleon

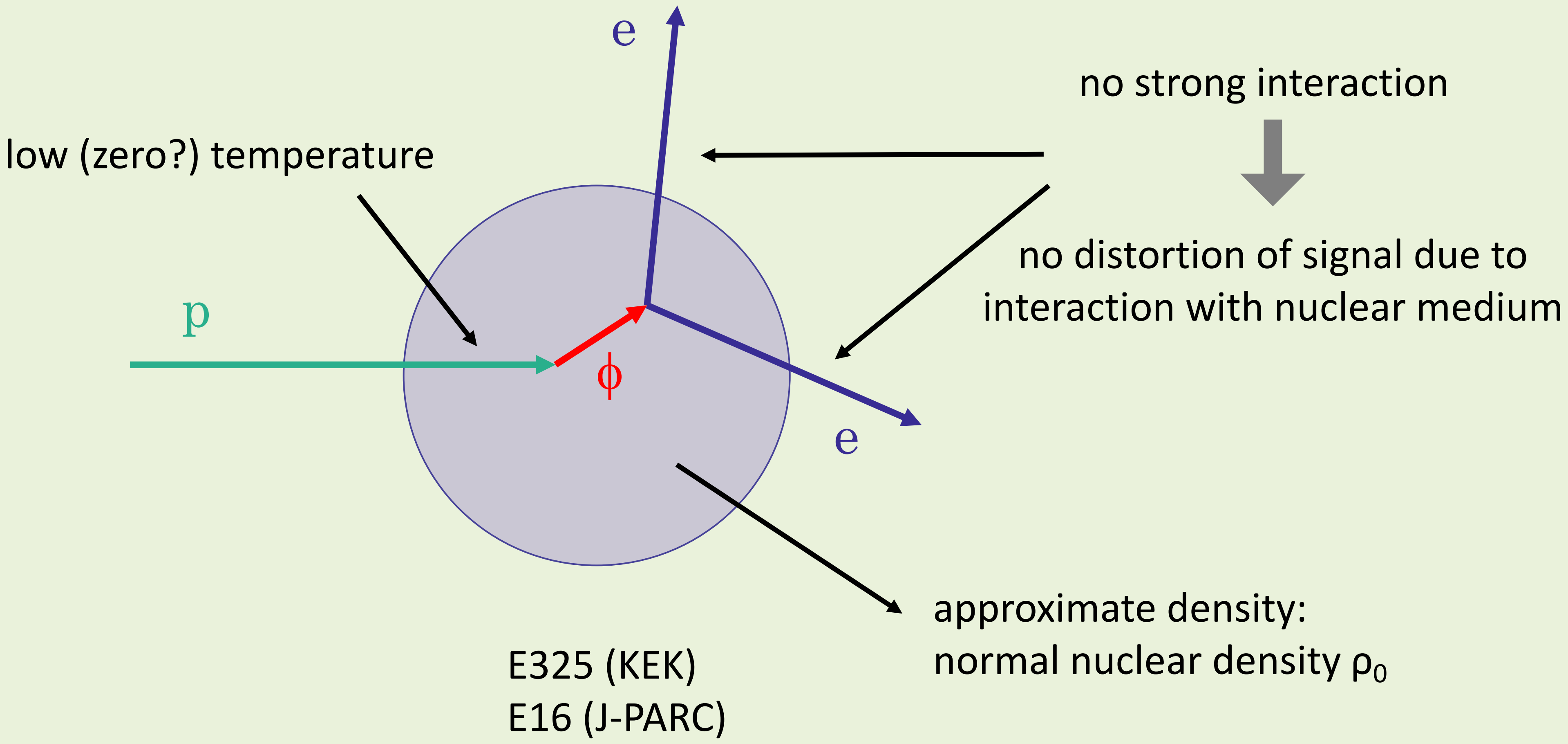
$$\sigma_{sN} = m_s \langle N|\bar{s}s|N\rangle$$



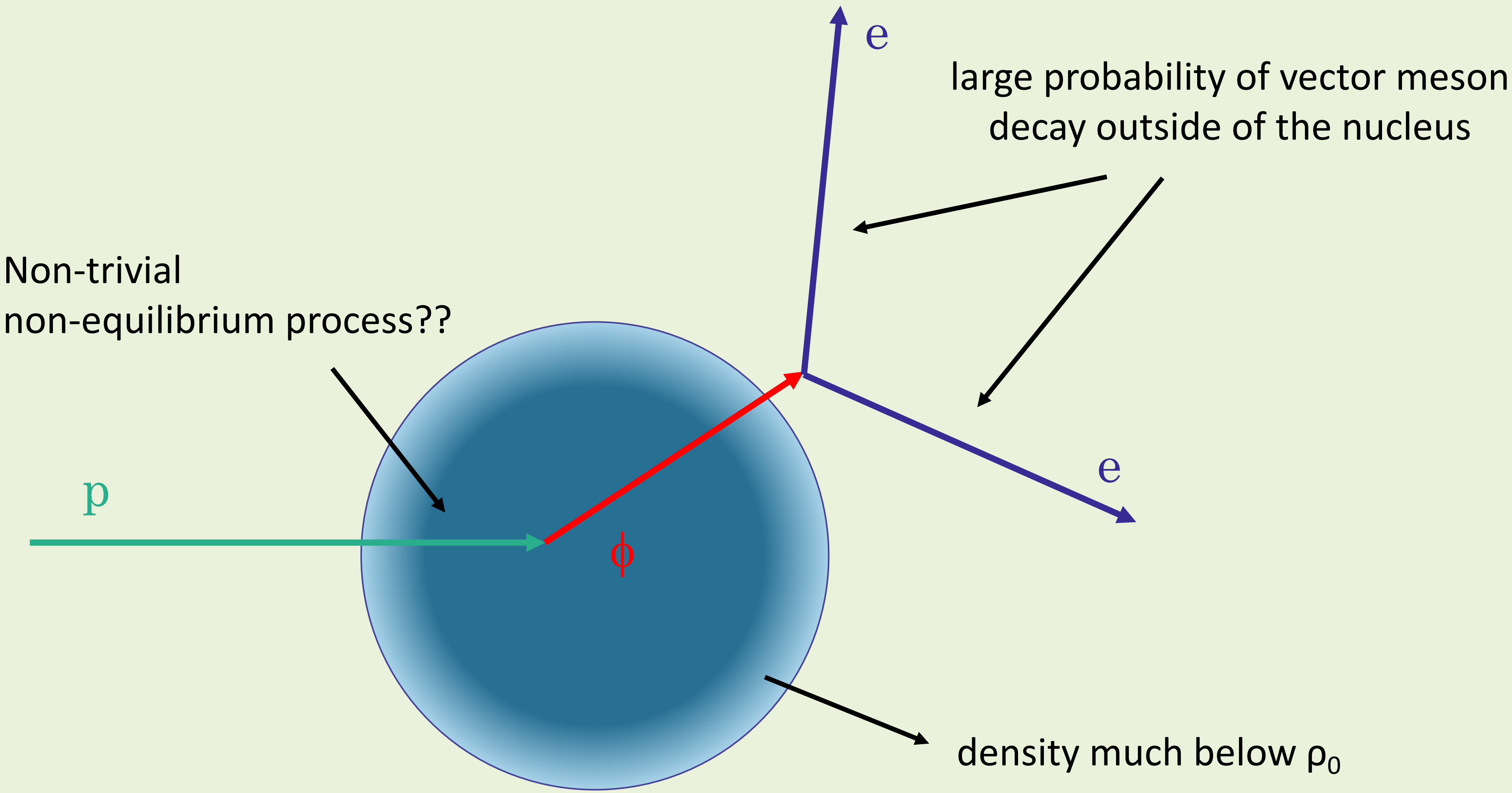
P. Gubler and K. Ohtani, Phys. Rev. D **90**, 094002 (2014).

Vector mesons in experiment

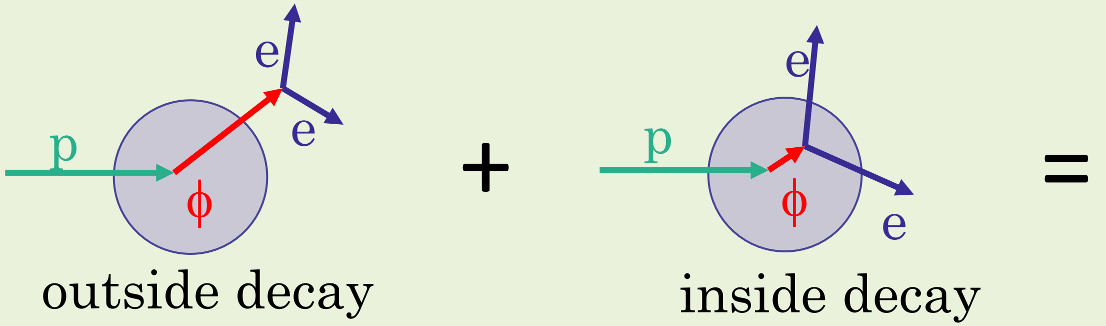
One method: proton induced interactions on nuclei



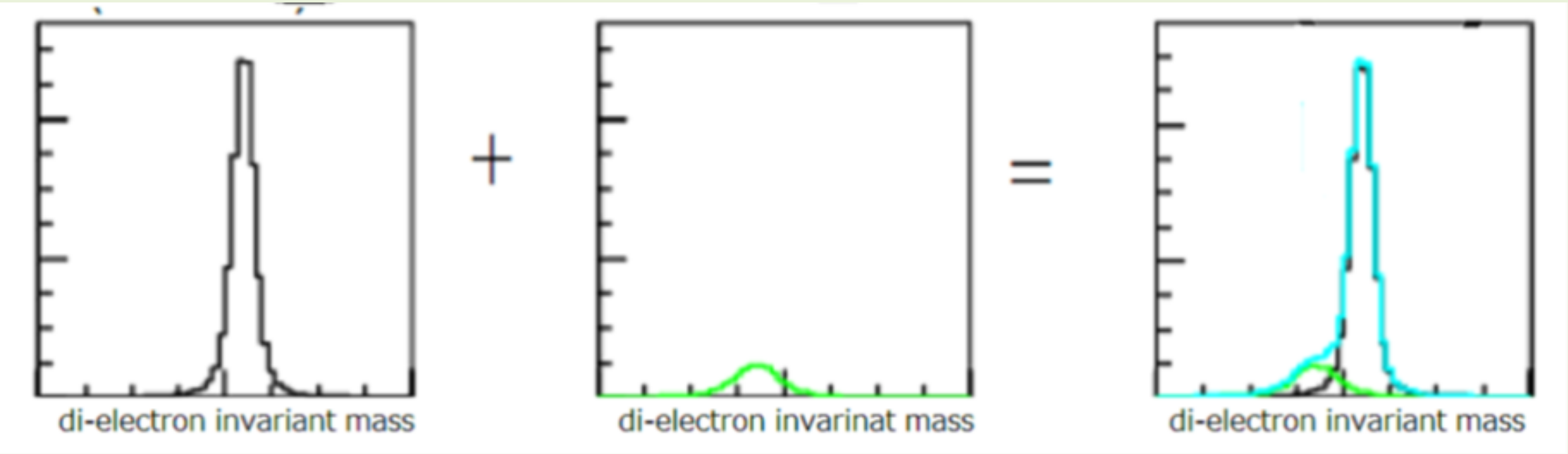
However, some caution is needed



Experimental di-lepton spectrum



Experimentally observed spectrum



Experimental results

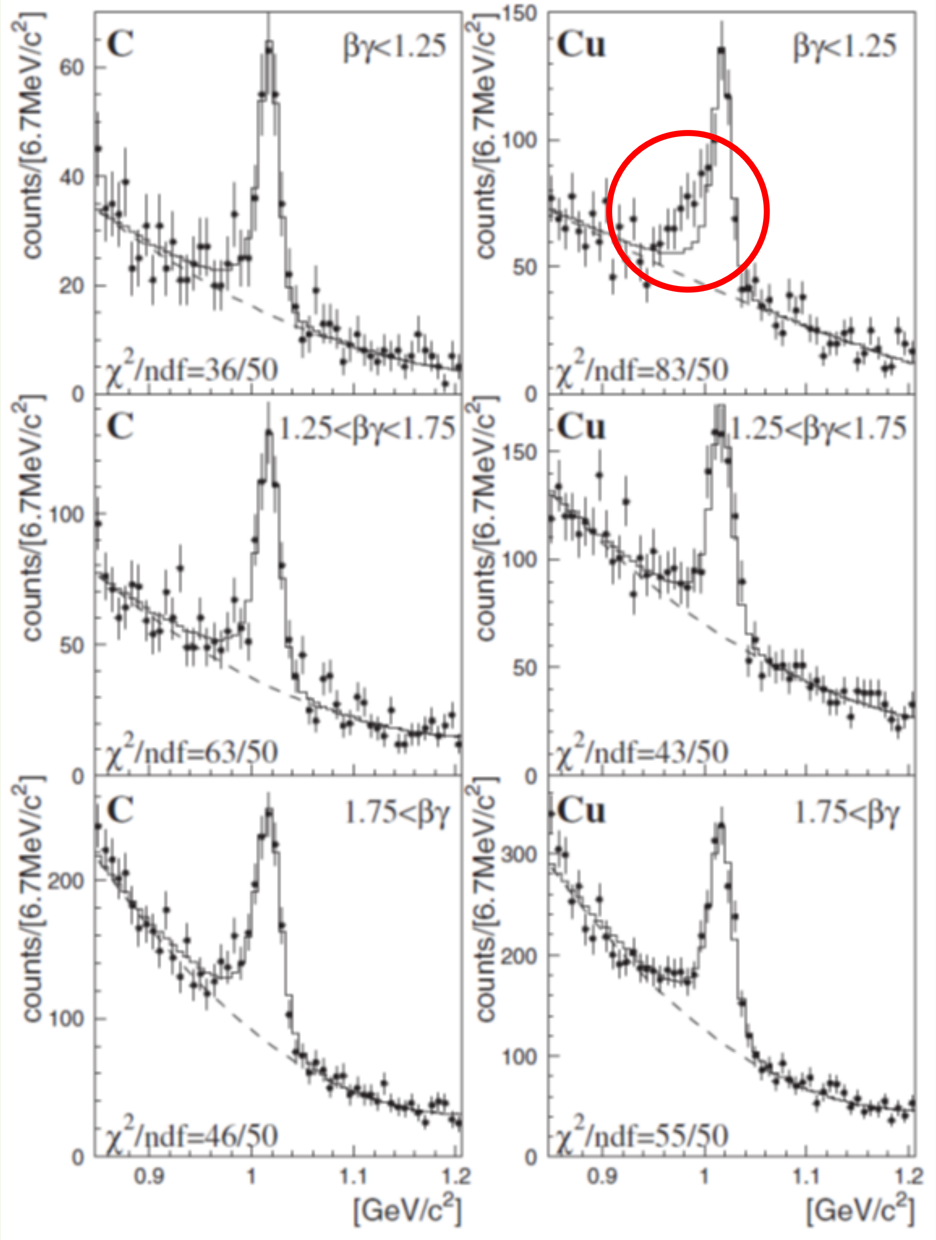
(E325, KEK)

Pole mass: $$\frac{m_\phi(\rho)}{m_\phi(0)} = 1 - k_1 \frac{\rho}{\rho_0}$$

0.034 ± 0.007

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

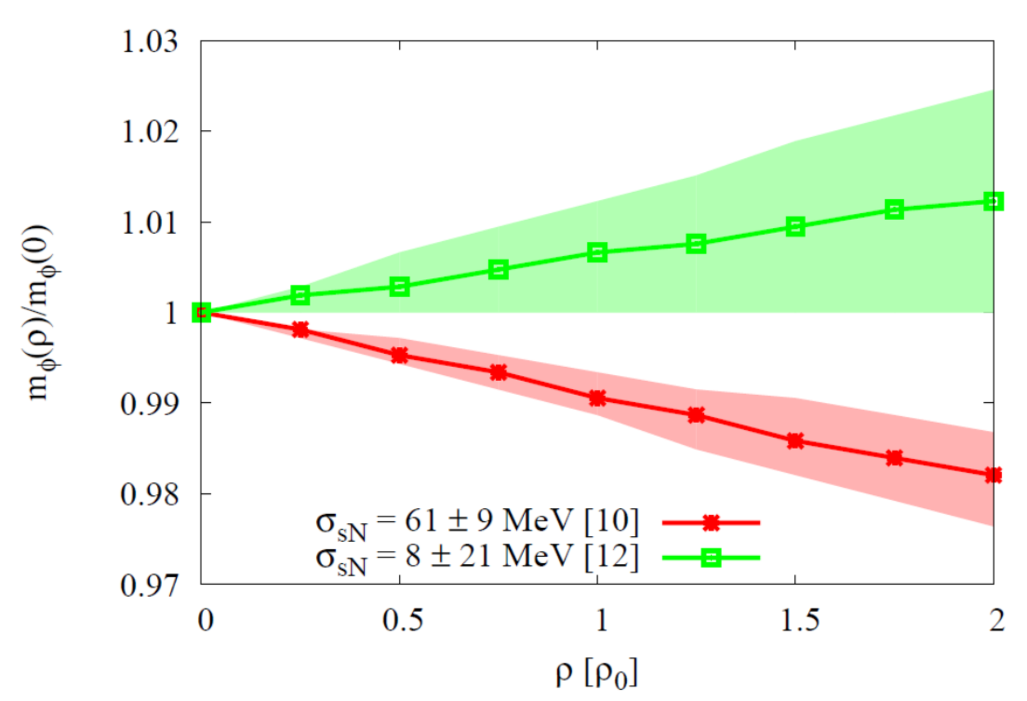
2.6 ± 1.5



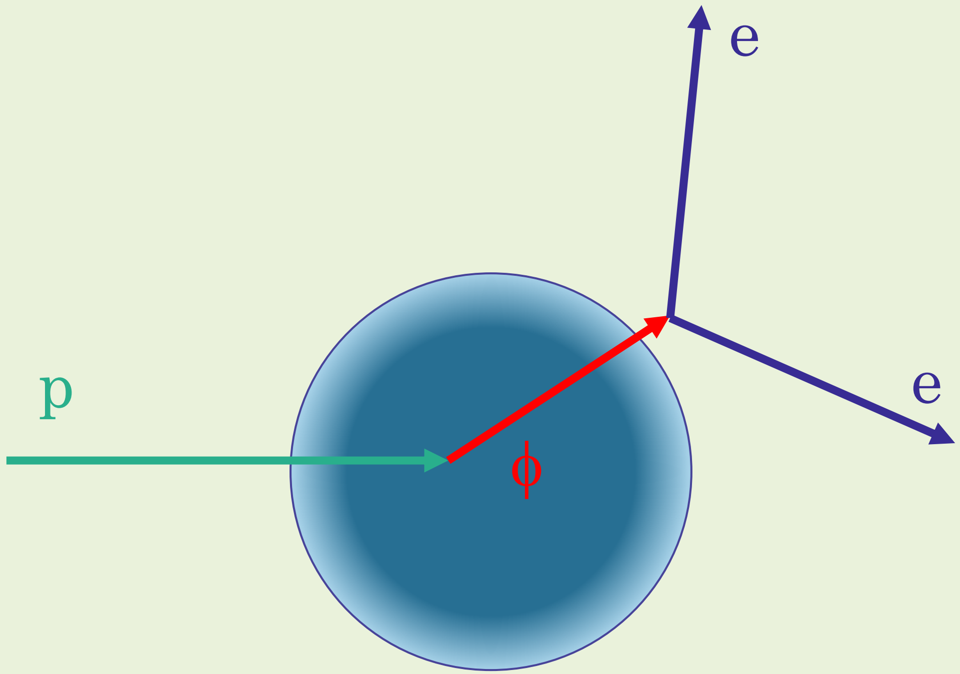
R. Muto et al. (E325 Collaboration), Phys. Rev. Lett. **98**, 042501 (2007).

How compare theory with experiment?

Theory



Experiment



Realistic simulation of pA reaction is needed!

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).

Starting point: The 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

PHSD (Parton Hadron String Dynamics)

Basic Ingredient: „Testparticle“ approach

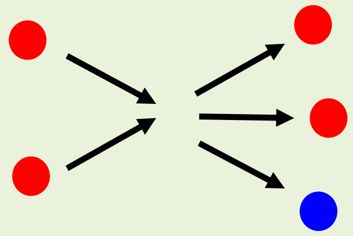
$$f_h(\mathbf{r},\mathbf{p};t) = \frac{1}{N_{\text{test}}} \sum_i^{N_h(t) \times N_{\text{test}}} \delta(\mathbf{r} - \mathbf{r}_i(t))\, \delta(\mathbf{p} - \mathbf{p}_i(t))$$

$$\dot{\boldsymbol{p}}_i = -\boldsymbol{\nabla}_r U(\boldsymbol{r}_i)\,, \qquad \dot{\boldsymbol{r}}_i = \boldsymbol{p}_i / \sqrt{m^2 + \boldsymbol{p}_i^2}$$

The classical equation of motion are solved for each particle separately

If particles collide with large enough energy

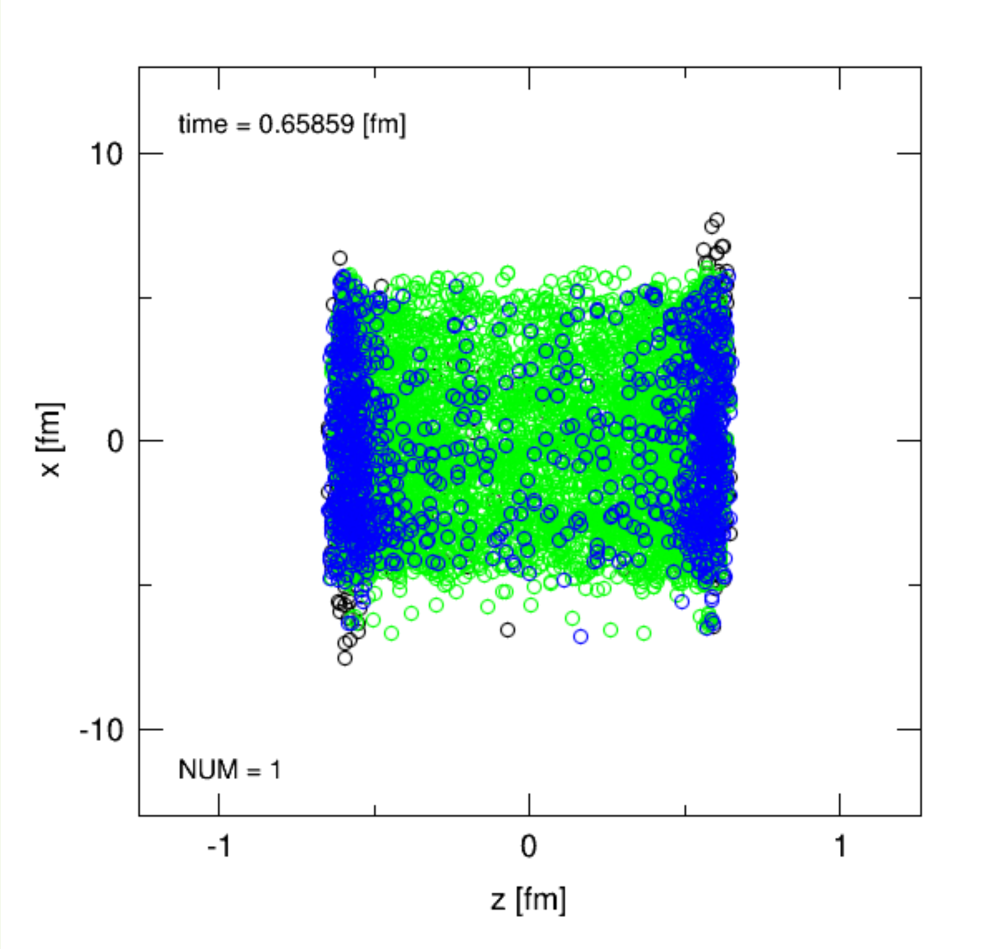
New particles are produced according to experimental cross-sections or models



Example of a PHSD calculation

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

nucleons
quarks
gluons



Advantage: vector meson spectra can be chosen freely

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

$$A_V(M,\rho) = C\,\frac{2}{\pi}\,\frac{M^2\Gamma^*_V(M,\rho)}{[M^2-M_0^{*2}(\rho)]^2+M^2\Gamma^{*2}_V(M,\rho)}$$

with

$$\begin{cases} M_0^*(\rho) = M_0\left(1-\alpha\frac{\rho}{\rho_0}\right) \\ \Gamma_V^*(M,\rho) = \Gamma_V(M)+\alpha_{\mathrm{coll}}\frac{\rho}{\rho_0} \end{cases}$$

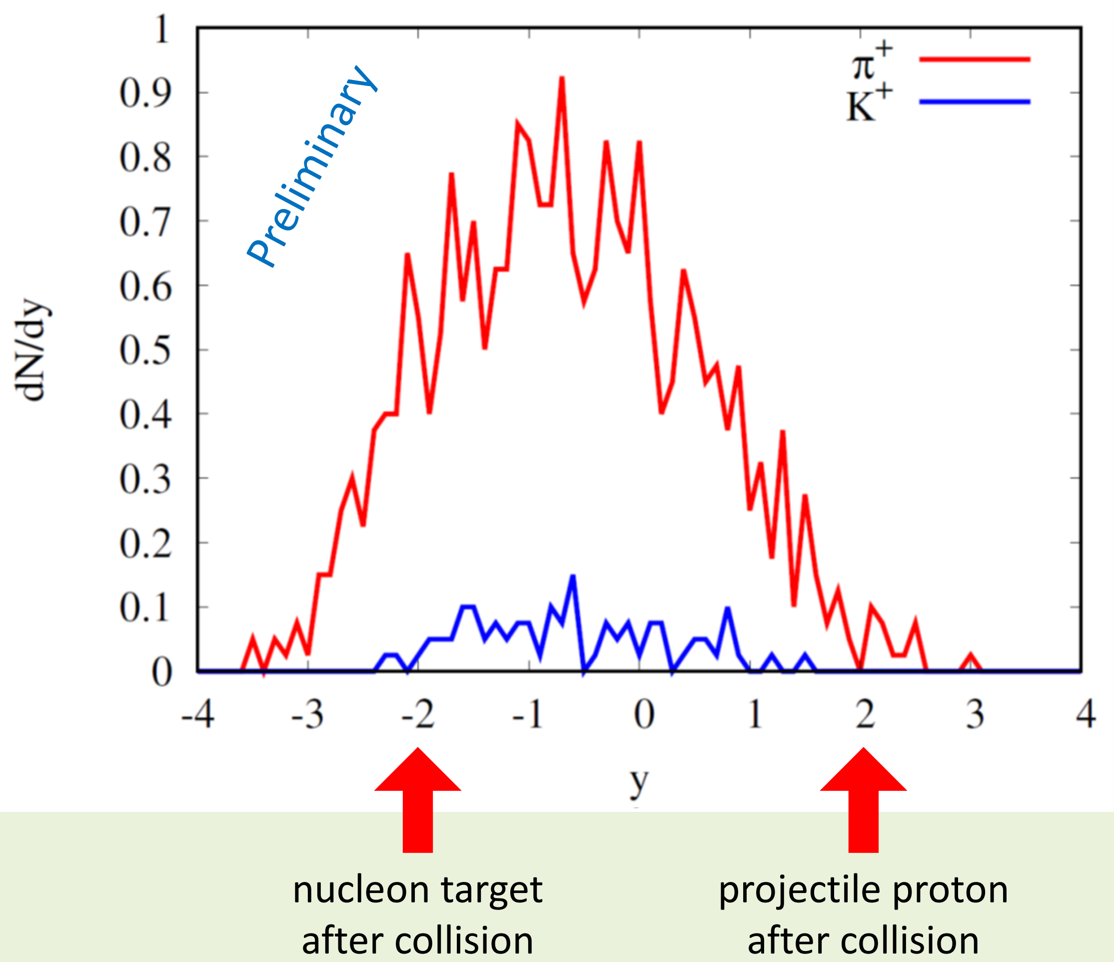
and

$$\begin{cases} \alpha = 0.034 \\ \alpha_{\mathrm{coll}} = 11\ \mathrm{MeV} \end{cases}$$

(corresponds to the result found in the E325 experiment)

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

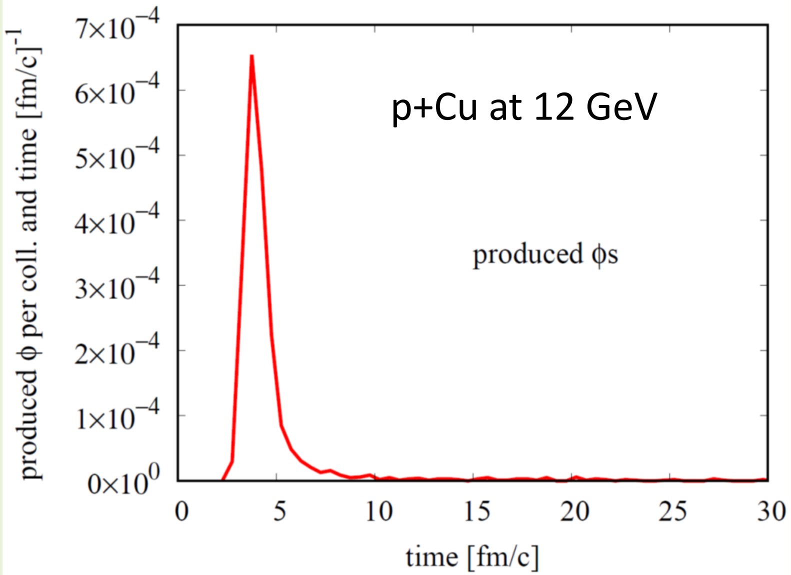


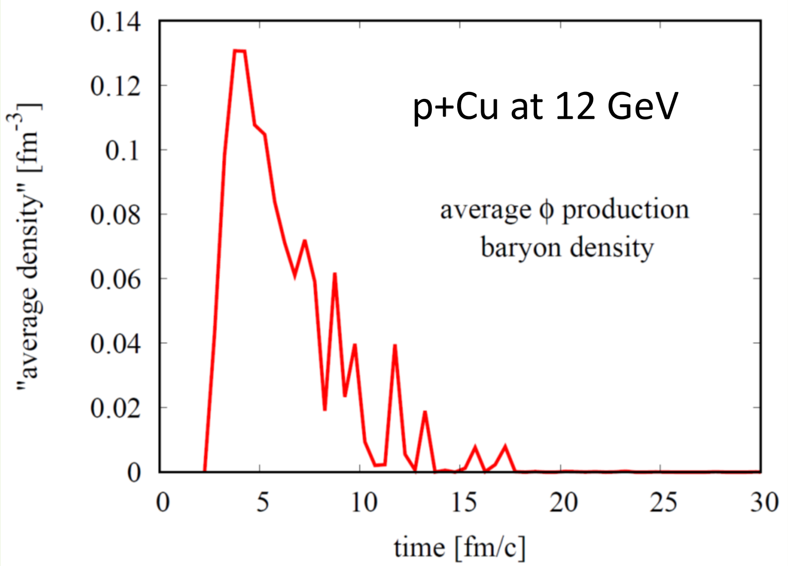
Due to the large collision energy, the incoming proton passes through the target nucleus

What happens with the φ?

All preliminary

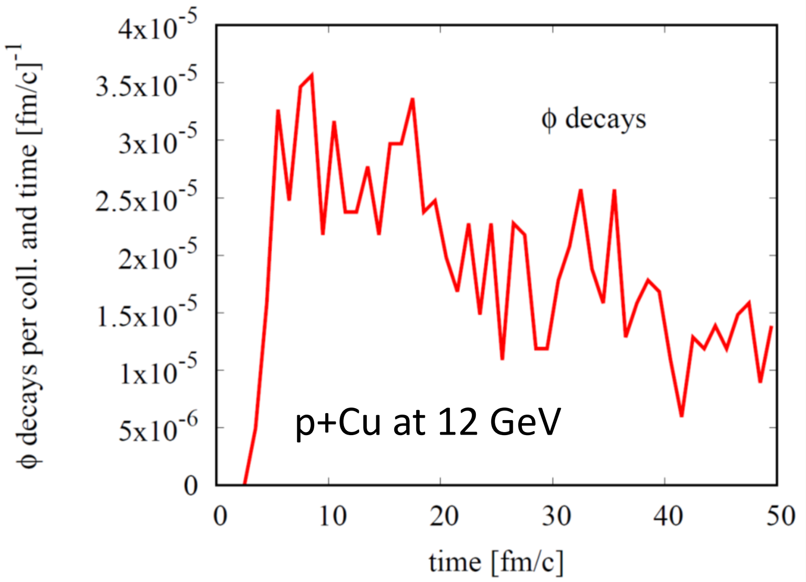
Production

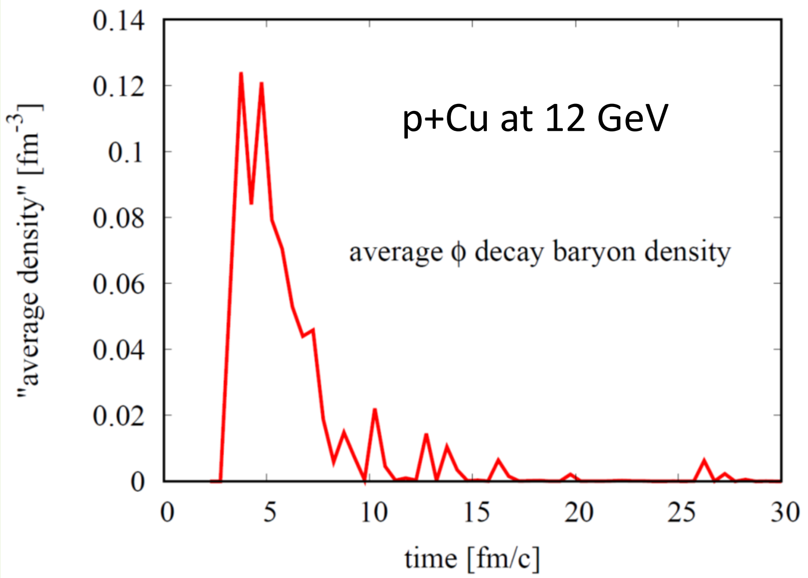




Almost all φ mesons are created at early collision time and at large density

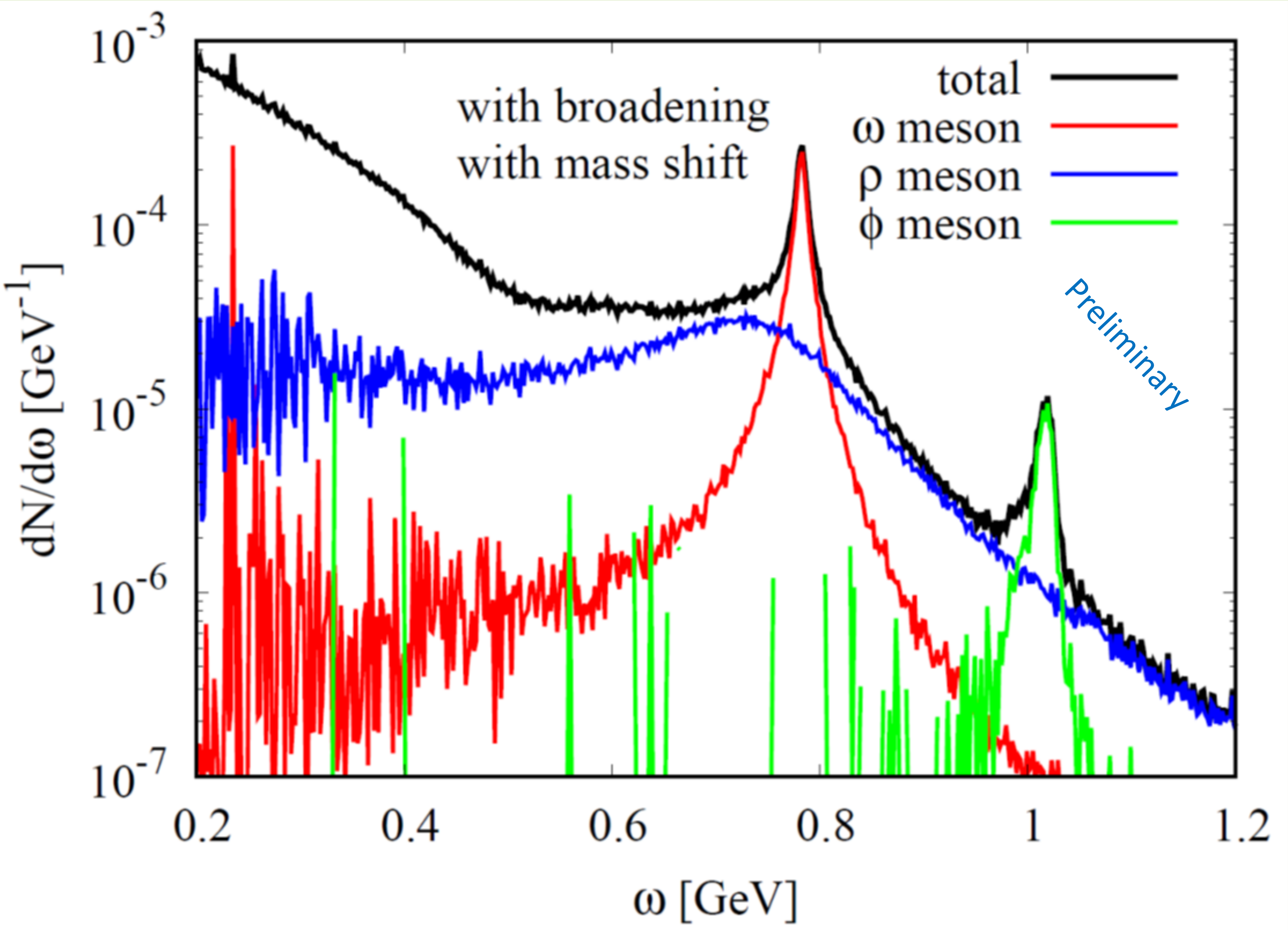
Decay





Only φ mesons which decay early, decay in a dense environment

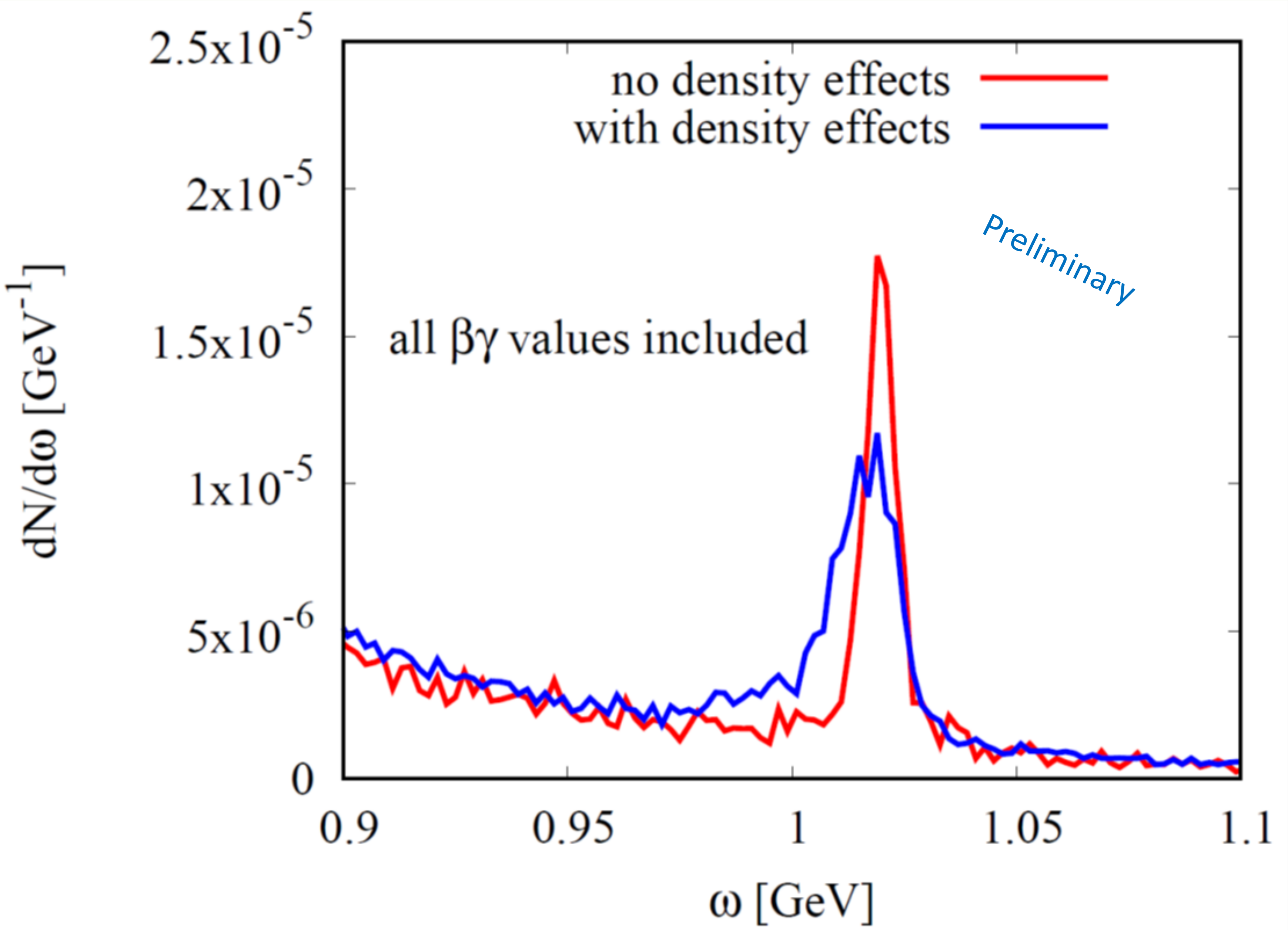
The dilepton spectrum



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

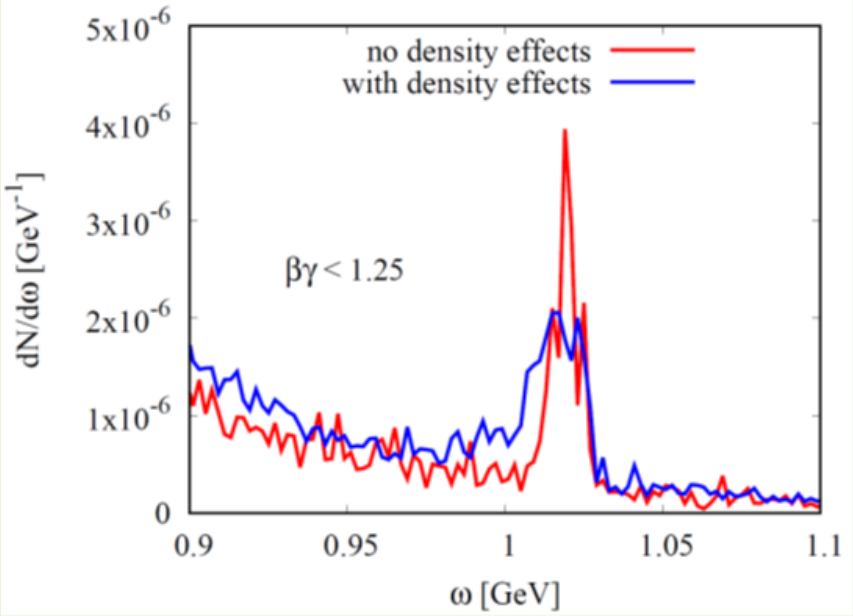
no acceptance corrections

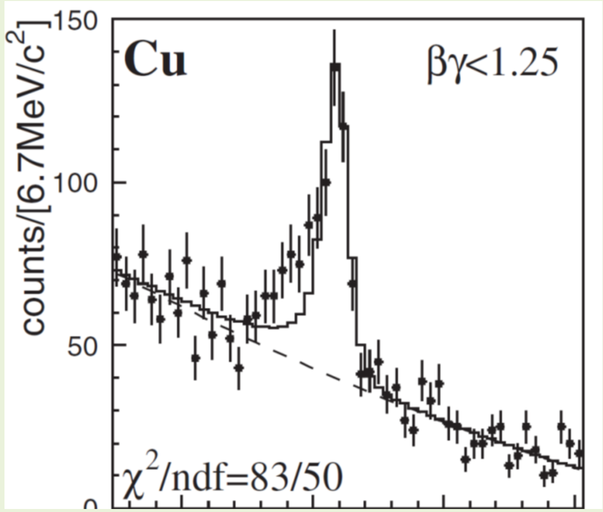
no finite resolution effects

All preliminary

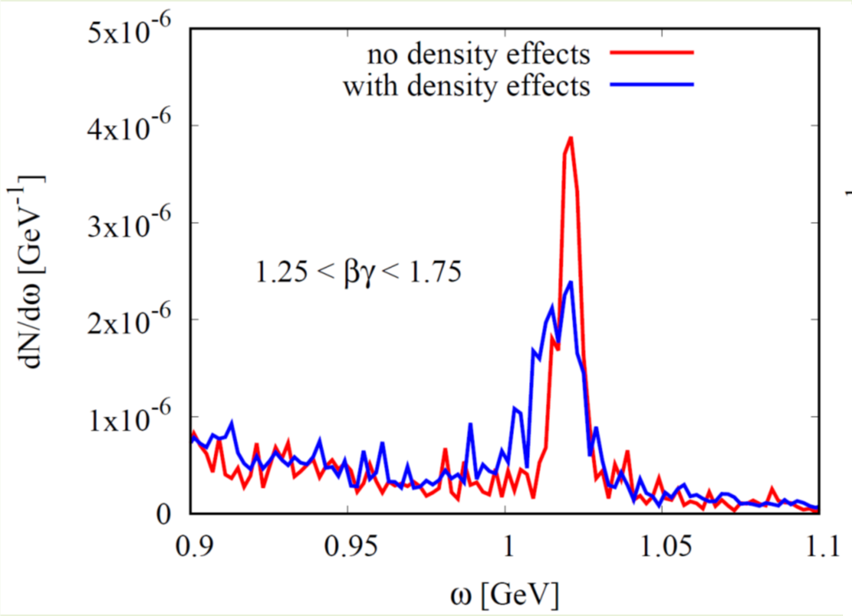
Divided into different βγ regions

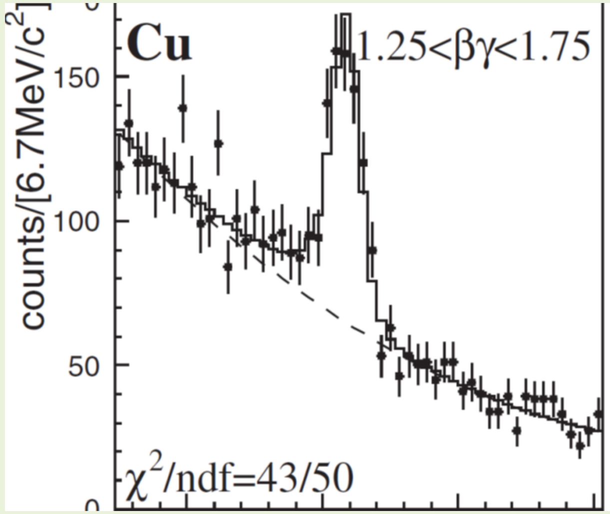
slow



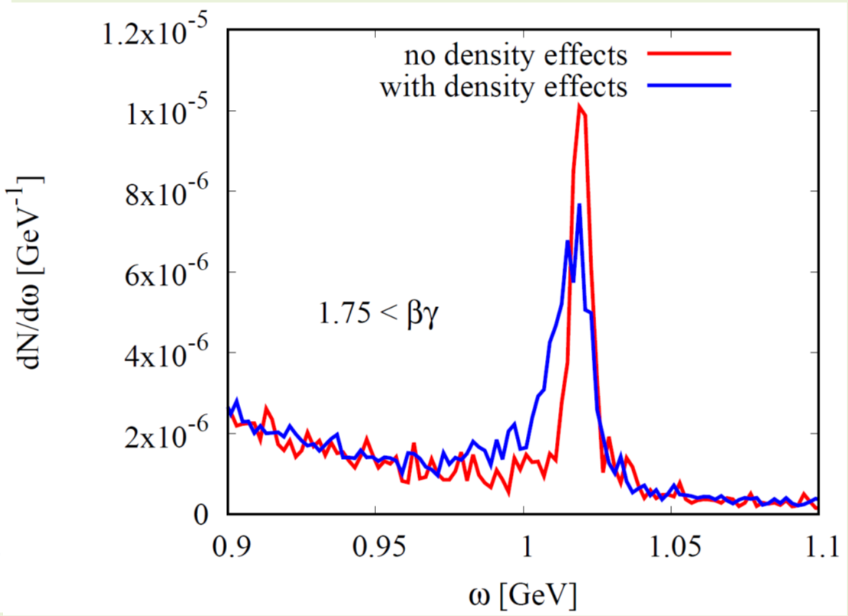


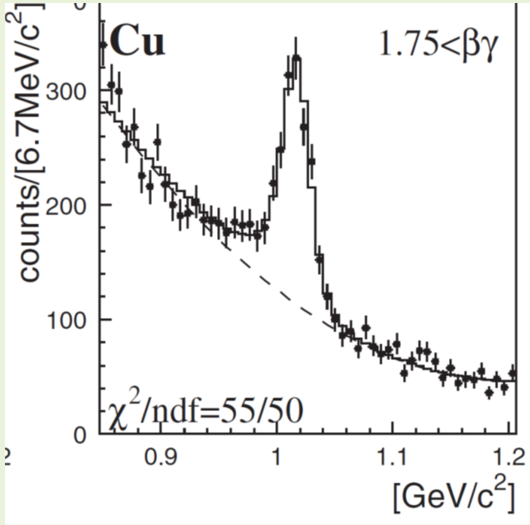
middle





fast

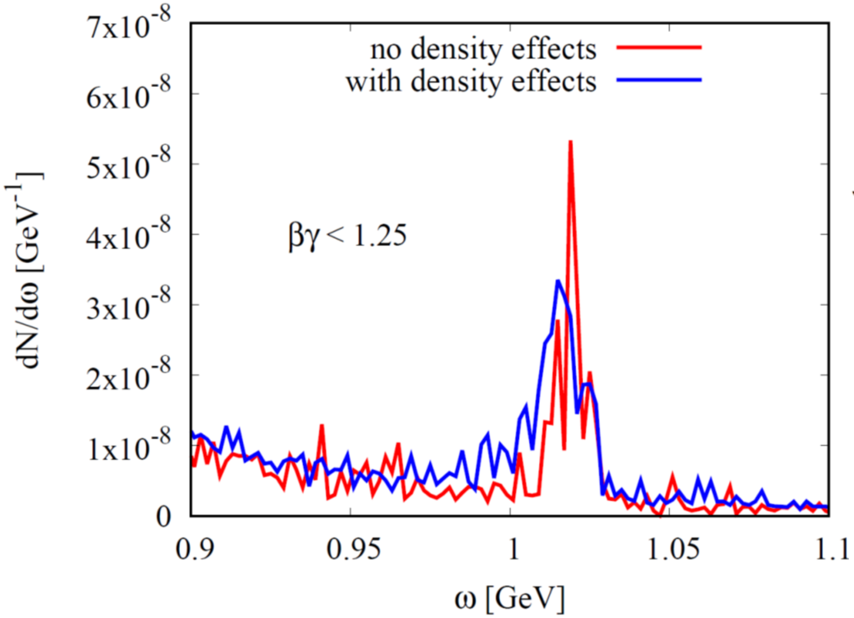


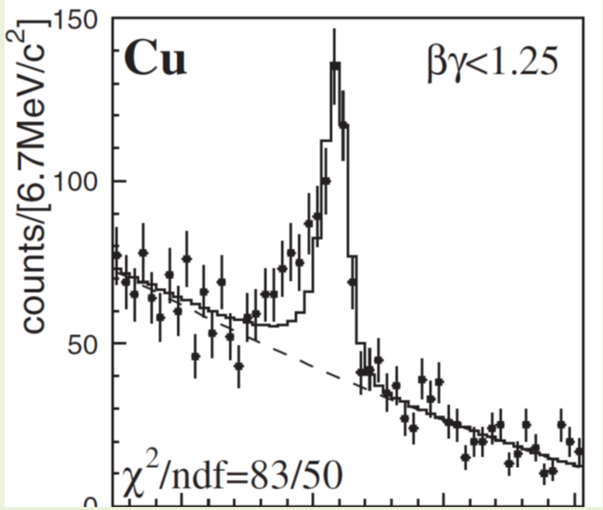


All preliminary

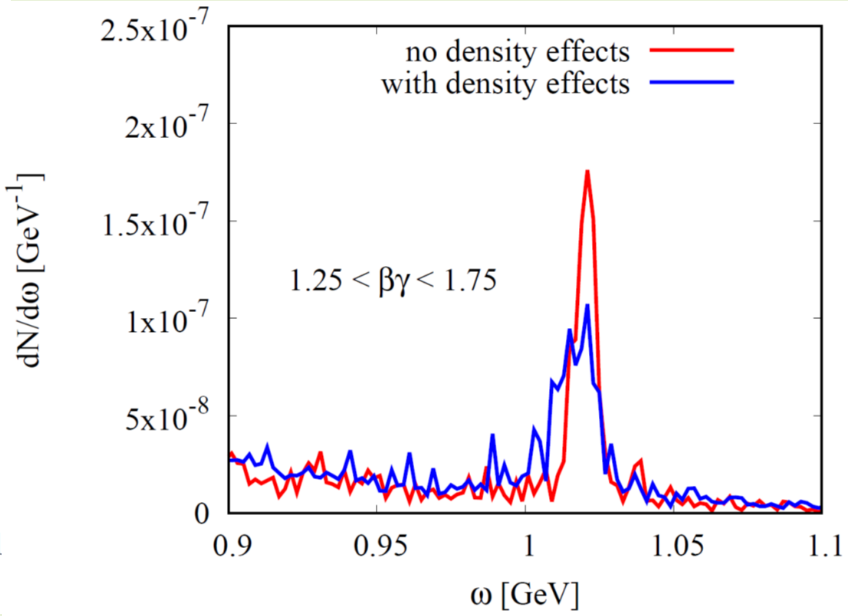
Taking into account acceptance corrections

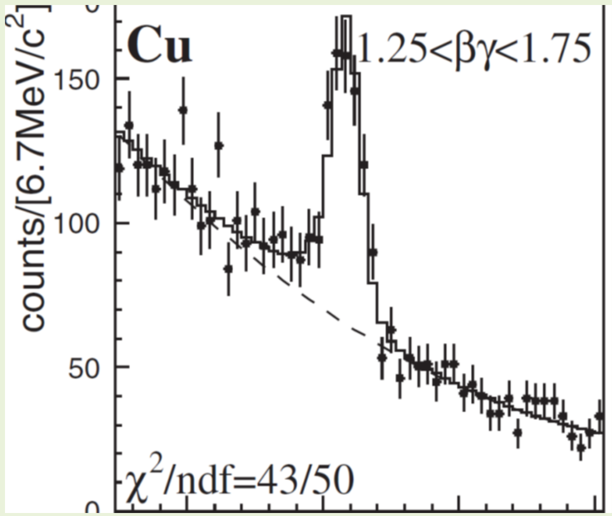
slow



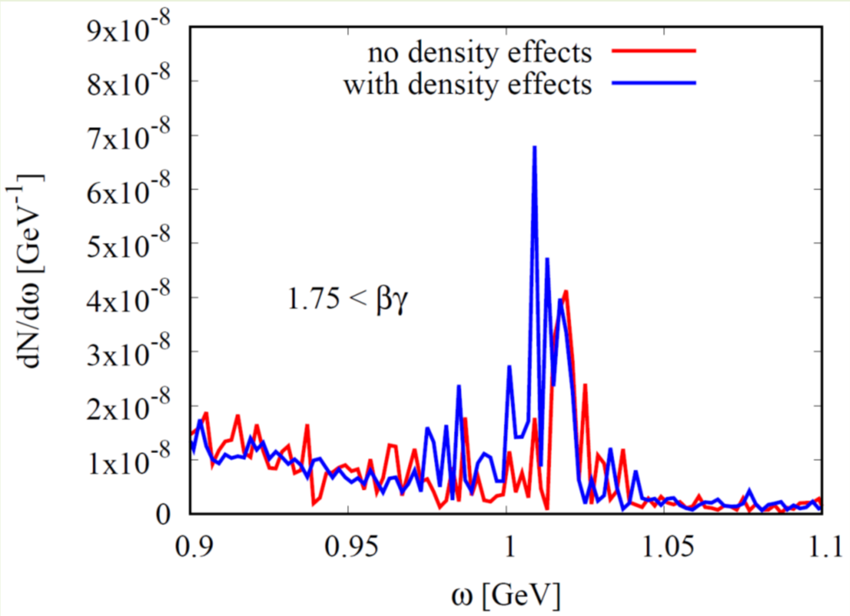


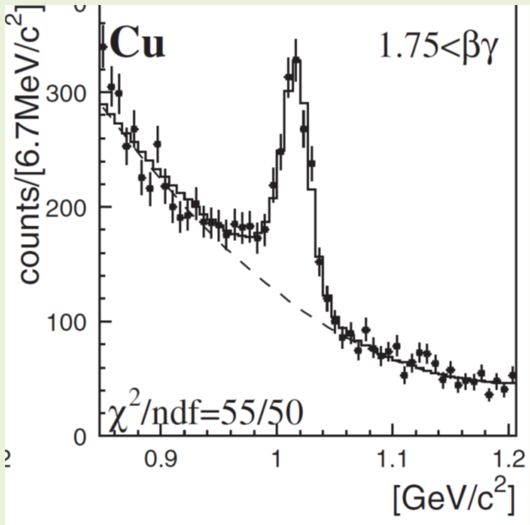
middle



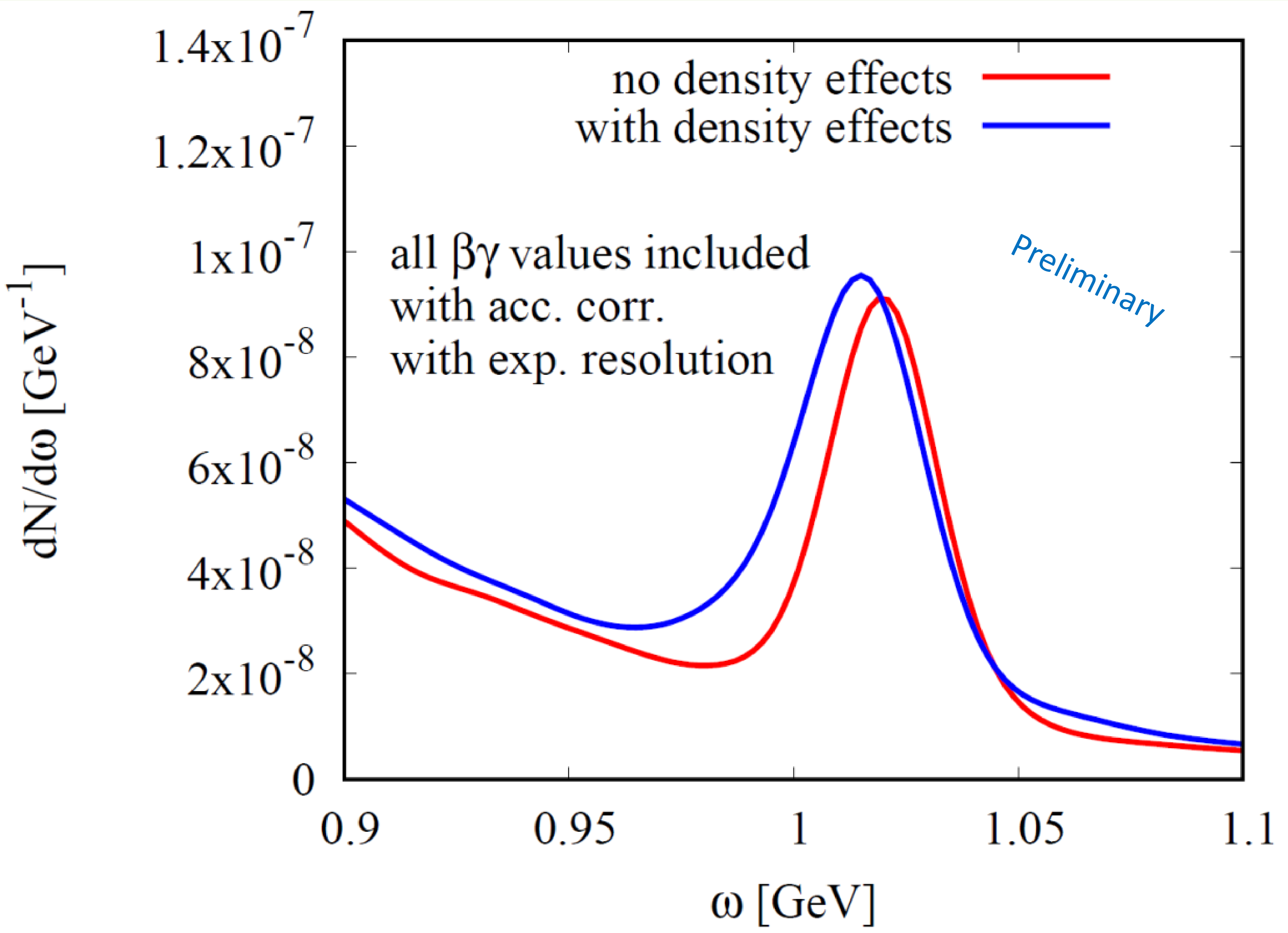


fast





The dilepton spectrum in the φ meson region



p+Cu at 12 GeV

with acceptance corrections

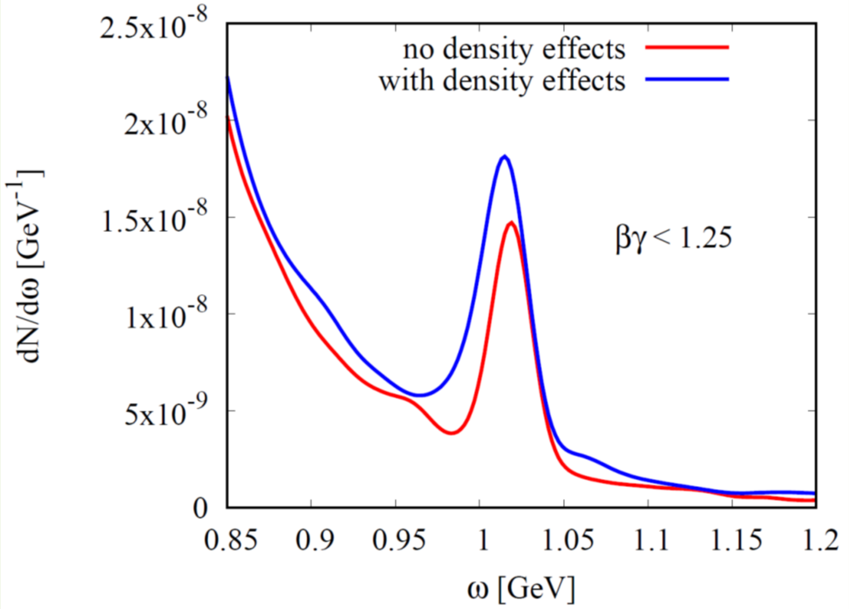
with finite resolution effects

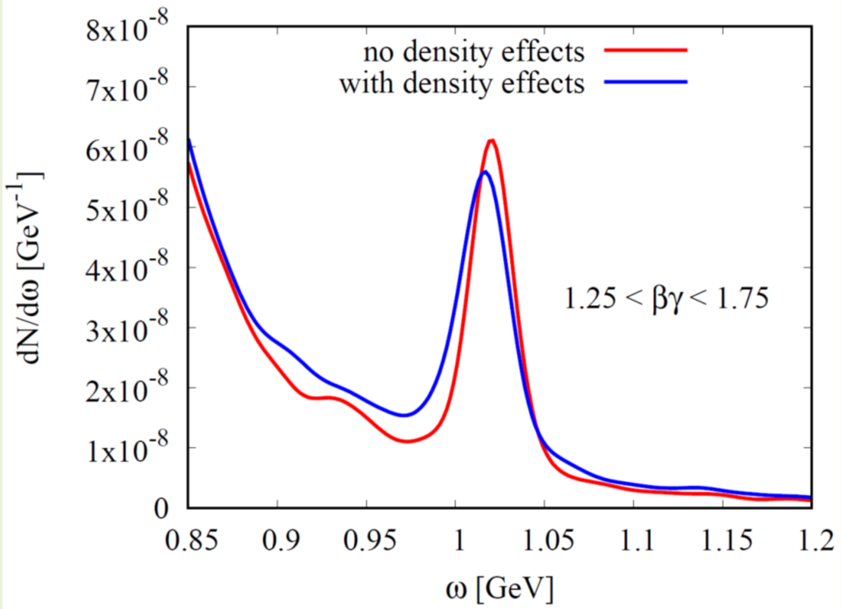
All preliminary

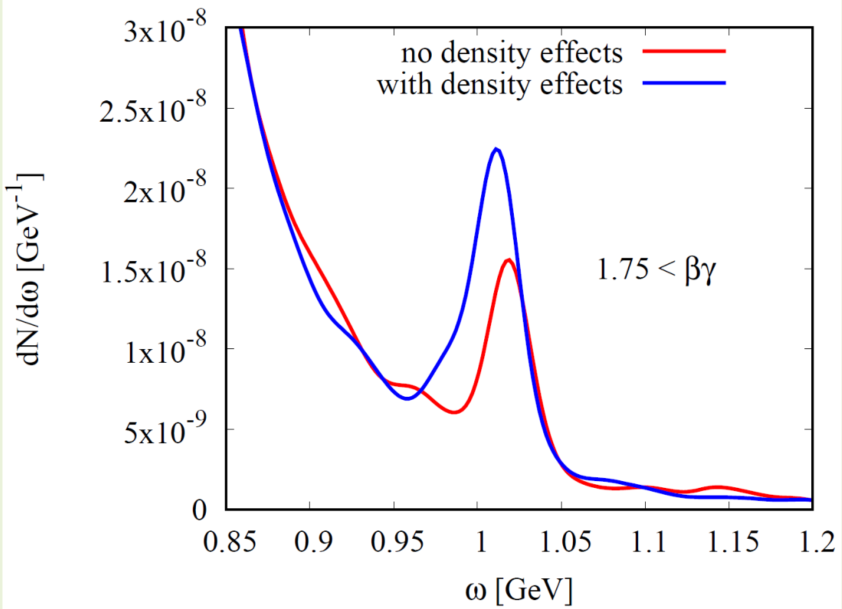
Divided into different βγ regions

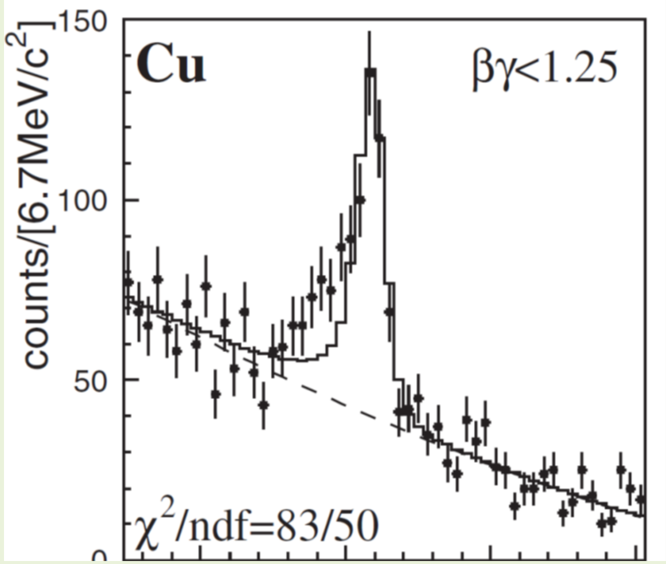
(with acceptance corrections)
(with finite resolution)

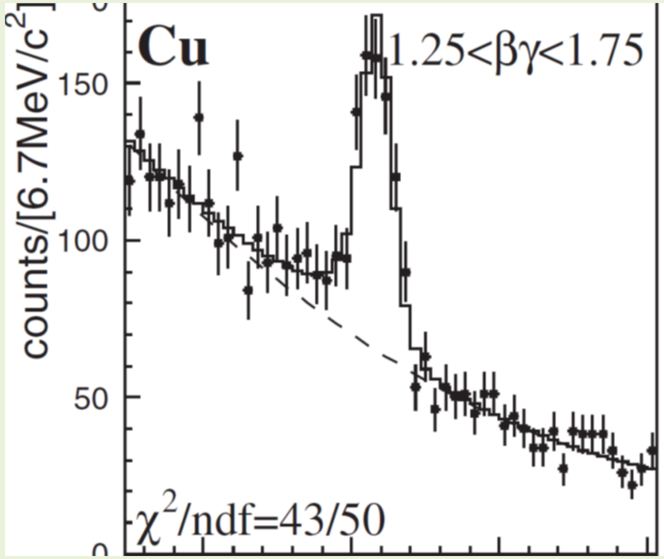
slow | middle | fast

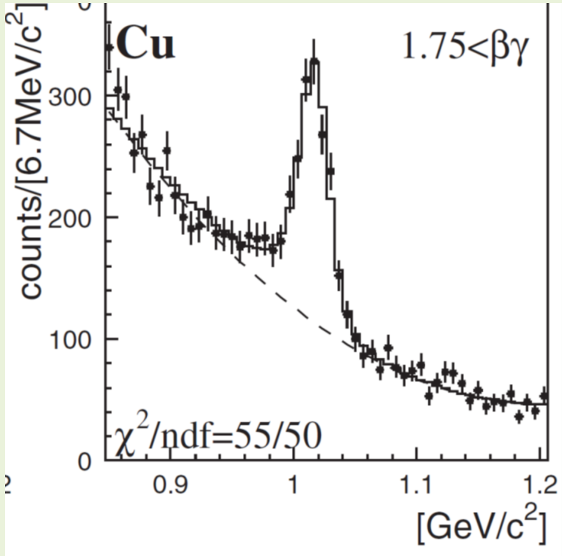












To be done

★ Accumulate more statistics

★ Determine which spectral function best reproduces the E325 experimental data (might not be unique)

★ Make predictions for the E16 experiment at J-PARC

★ Incorporate non-trivial (Lorentz violating) momentum dependence of the spectral function into the simulation

Summary and Conclusions

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

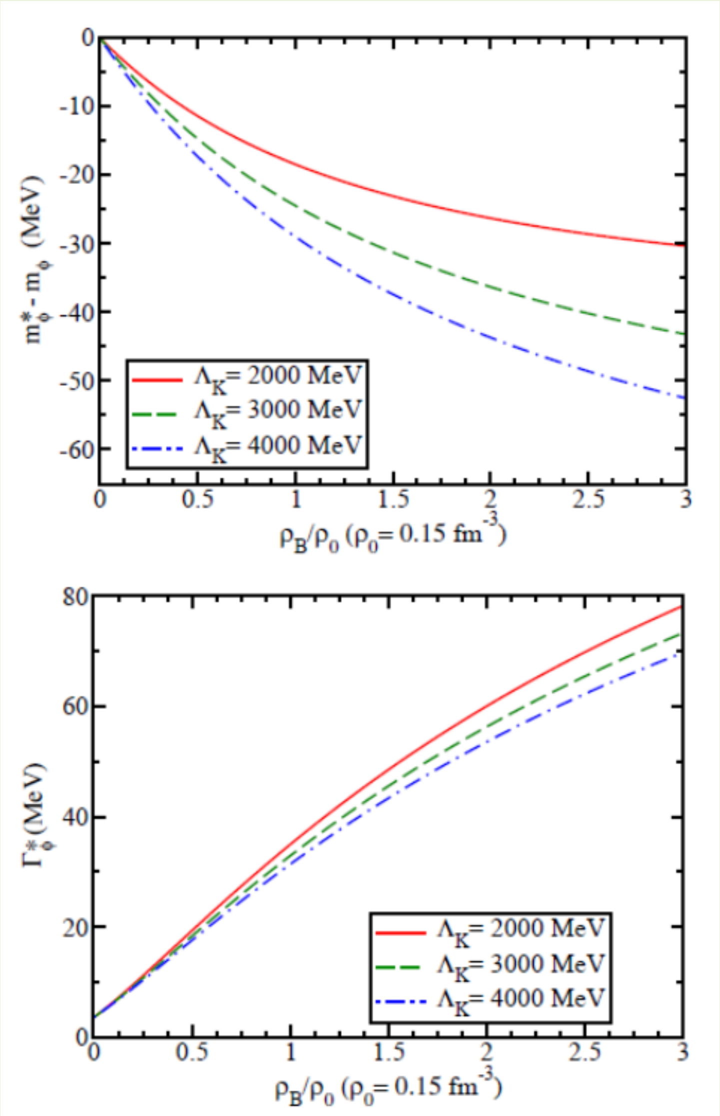
★ Numerical simulations of the pA reactions to measured at the E325 experiment at KEK, using the PHSD transport code, are in progress.

★ Results will provide important insights for the future E16 experiment at J-PARC

Backup slides

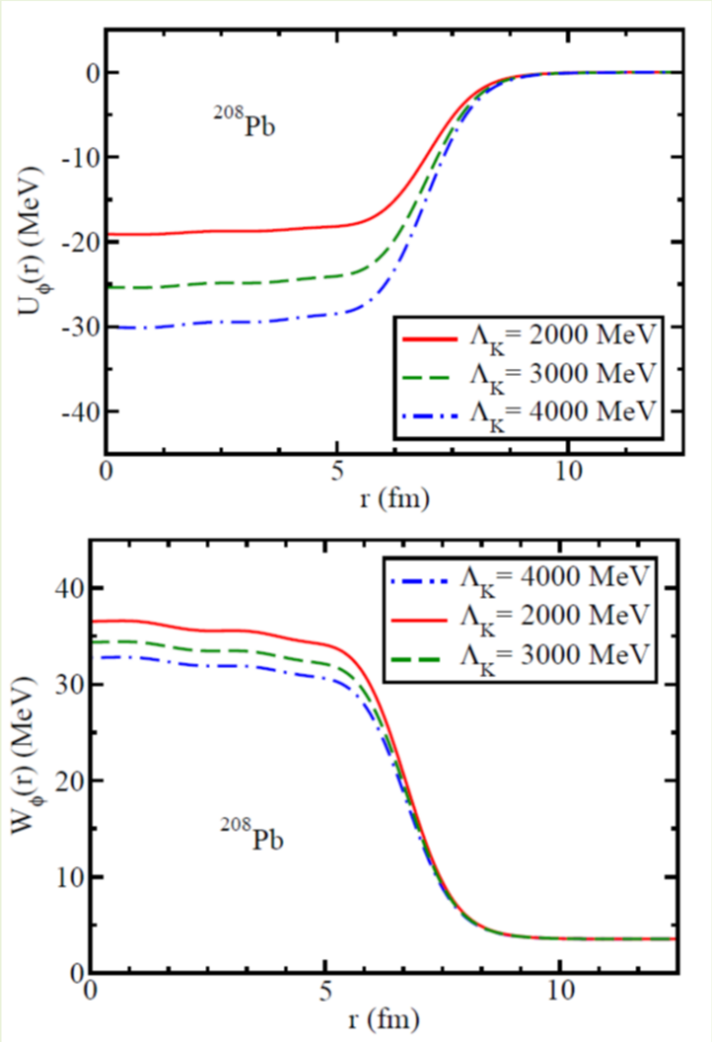
Recent theoretical works about the φ

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

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

mean field (tuned to reproduce nuclear matter properties)

particle distribution function

Basic Ingredient 2: „Testparticle“ approach

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

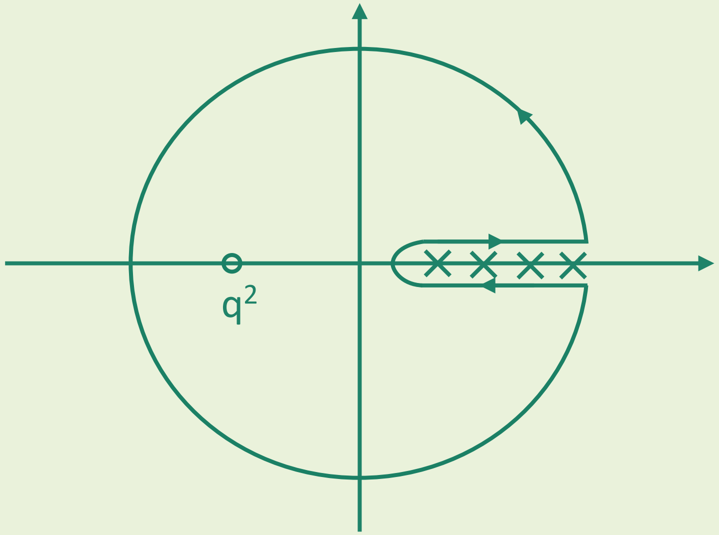
M.A. Shifman, A.I. Vainshtein and V.I. Zakharov,
Nucl. Phys. B147, 385 (1979); B147, 448 (1979).

QCD sum rules

Makes use of the analytic properties of the correlation function:

$$\Pi(q^2) = i\int d^4x e^{iqx}\langle T[\chi(x)\bar{\chi}(0)]\rangle$$

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



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

is calculated "perturbatively", using OPE

spectral function of the operator χ

After the Borel transformation:

$$G_{OPE}(M^2) = \frac{1}{\pi}\int_0^\infty ds \frac{1}{M^2} e^{-\frac{s}{M^2}} \mathrm{Im}\Pi(s)$$

More on the operator product expansion (OPE)

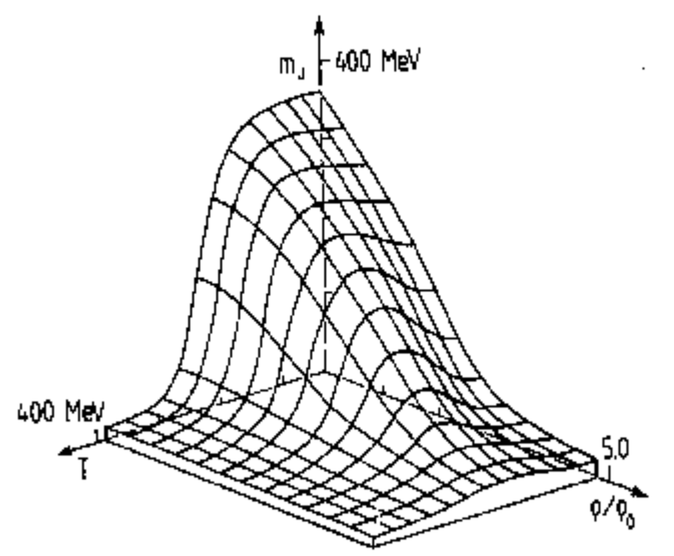
perturbative Wilson coefficients

non-perturbative condensates

$$i\int d^4x e^{iqx}\langle 0|T\{\chi(x)\overline{\chi}(0)\}|0\rangle = C_I(q^2)I+\sum_n C_n(q^2)\langle 0|O_n|0\rangle$$

$$\begin{aligned}\langle 0|O_n|0\rangle = &\langle 0|\overline{q}q|0\rangle,\\ &\langle 0|G^a_{\mu\nu}G^{a\mu\nu}|0\rangle,\\ &\langle 0|\overline{q}\sigma_{\mu\nu}\frac{\lambda^a}{2}G^{a\mu\nu}q|0\rangle,\\ &\langle 0|\overline{q}q\overline{q}q|0\rangle,\ldots\end{aligned}$$

Change in hot or dense matter!



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

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

<u>In Nuclear Matter</u>

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

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

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

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

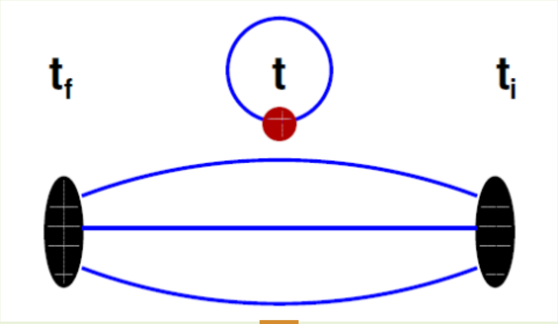
Dim. 6: $c_6(\rho) = c_6(0) + \rho[-\frac{896}{81}\kappa_N \pi^3 \alpha_s \langle \overline{s}s\rangle\langle N|\overline{s}s|N\rangle - \frac{5}{6}A_4^s M_N^3]$

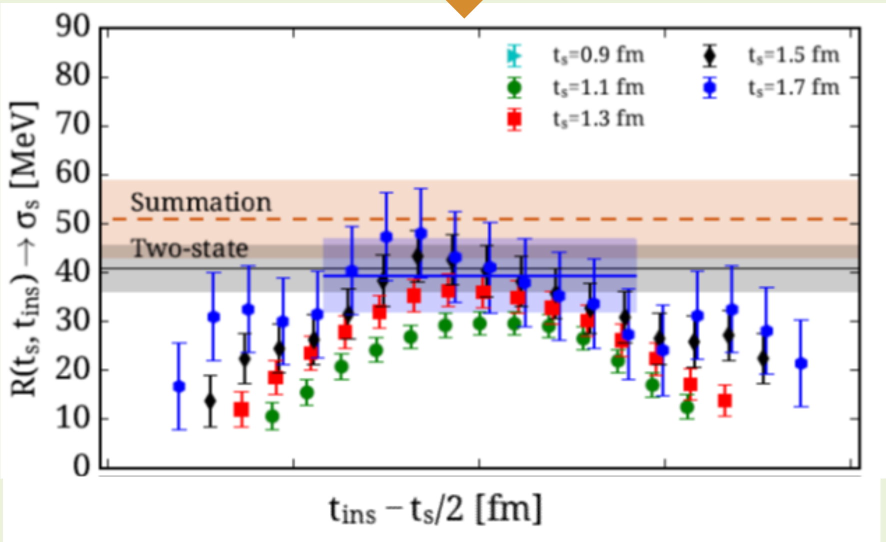
The strangeness content of the nucleon: results from lattice QCD

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

Two methods

Direct measurement

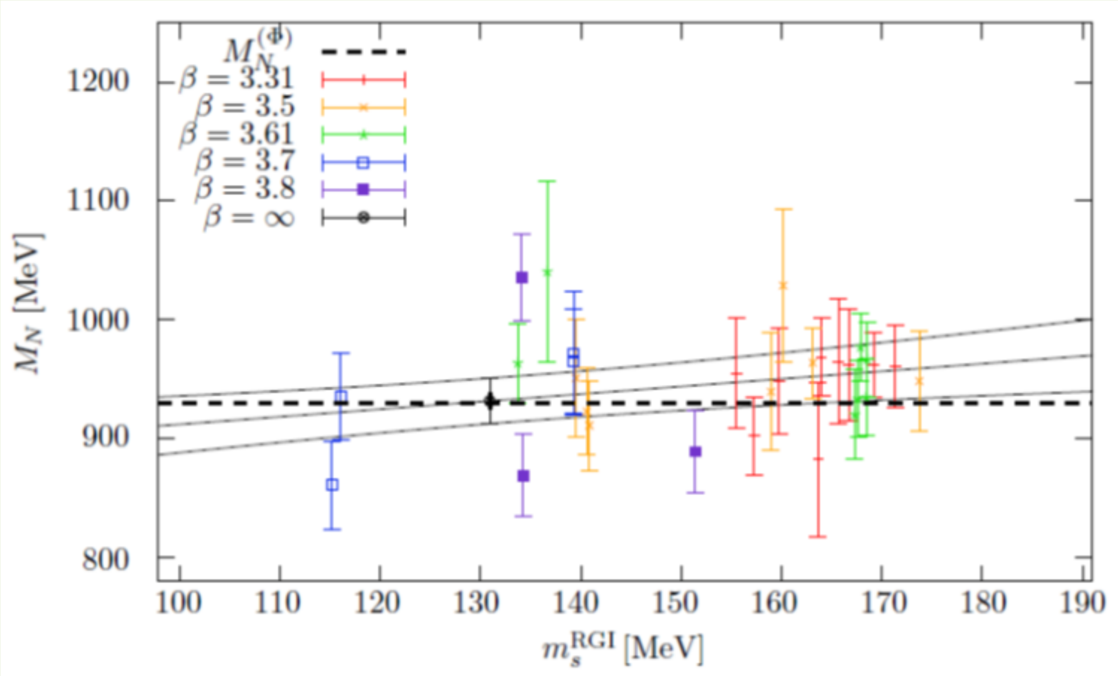




A. Abdel-Rehim et al. (ETM Collaboration), Phys. Rev. Lett. **116**, 252001 (2016).

Feynman-Hellmann theorem

$$\sigma_{sN} = m_s \frac{\partial m_N}{\partial m_s}$$



S. Durr et al. (BMW Collaboration), Phys. Rev. Lett. **116**, 172001 (2016).

Recent results from lattice QCD

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

Table 5: Recent σ_{sN} values from lattice QCD and ChPT fits to lattice QCD data.

Method	Collaboration, Year	σ_{sN} [MeV]	Reference
Lattice QCD (Feynman-Hellmann)	BMW, 2016	105(41)(37)	[121]
Lattice QCD (direct)	χQCD, 2016	40.2(11.7)(3.5)	[122]
Lattice QCD (direct)	ETM, 2016	$41.1(8.2)(^{7.8}_{5.8})$	[123]
Lattice QCD (direct)	RQCD, 2016	35(12)	[124]
Lattice QCD (direct)	JLQCD, 2018	17(18)(9)	[125]
Lattice QCD data + ChPT	2012	22(20)	[126]
Lattice QCD data + ChPT	2013	21(6)	[128]
Lattice QCD data + ChPT	2015	27(27)(4)	[130]

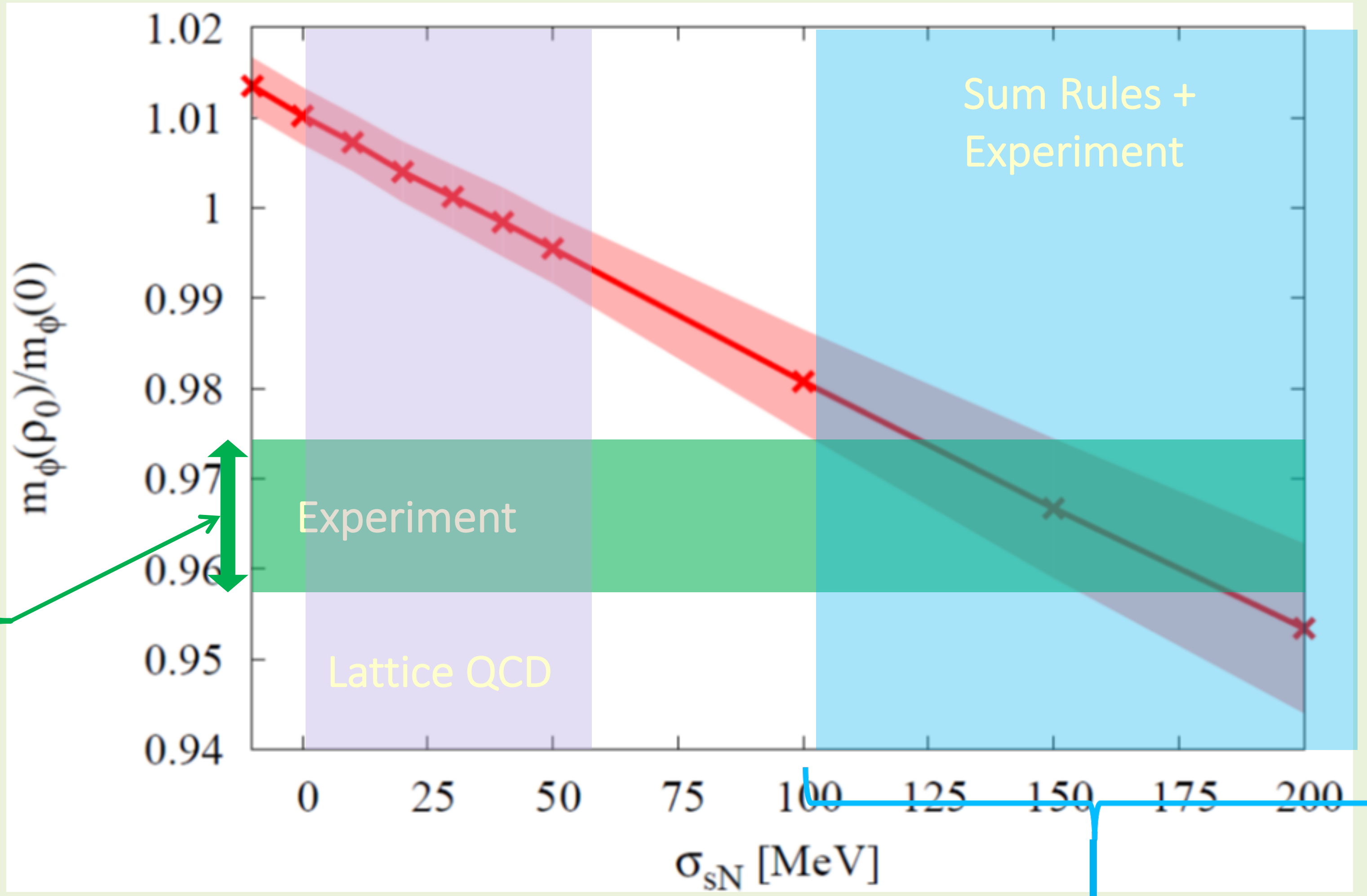
P. Gubler and D. Satow, arXiv:1812:00385 [hep-ph],
to be published in Prog. Part. Nucl. Phys.

Compare Theory with Experiment

Not consistent?

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

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



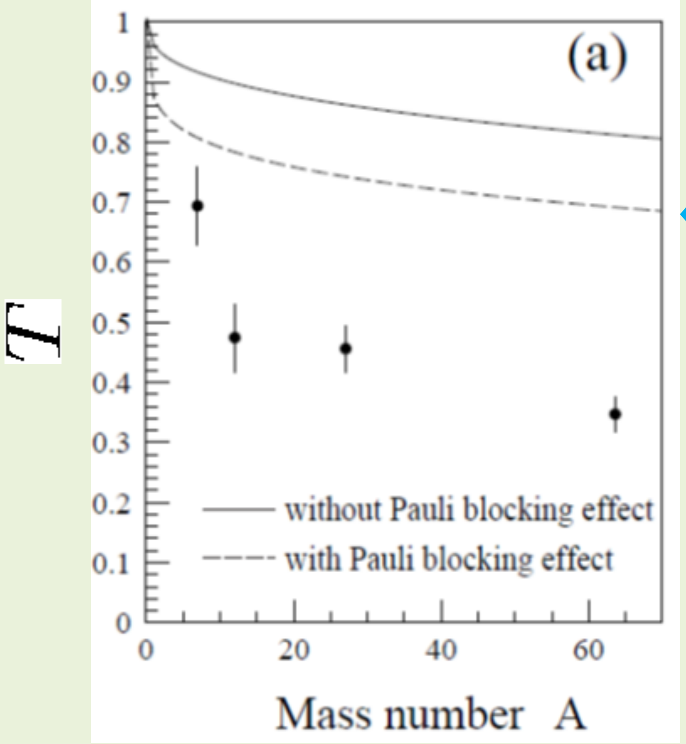
$$\sigma_{sN} \sim 160 \pm 50 \text{ MeV}$$

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)



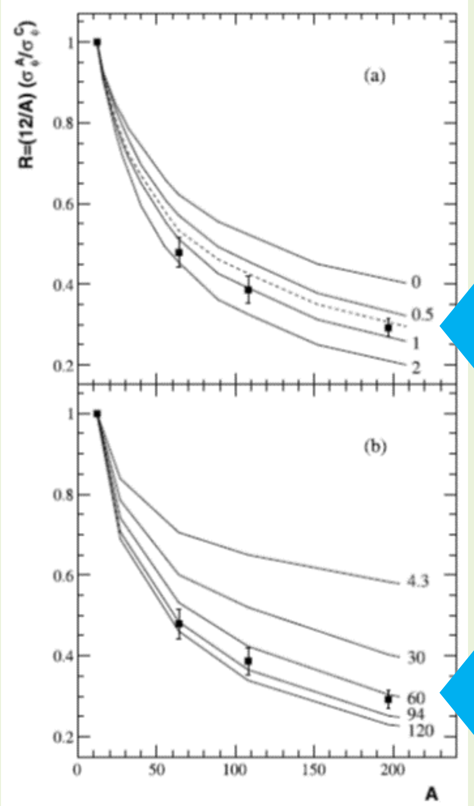
$\Gamma_\phi(\rho_0) \simeq 30\,\mathrm{MeV}$

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).

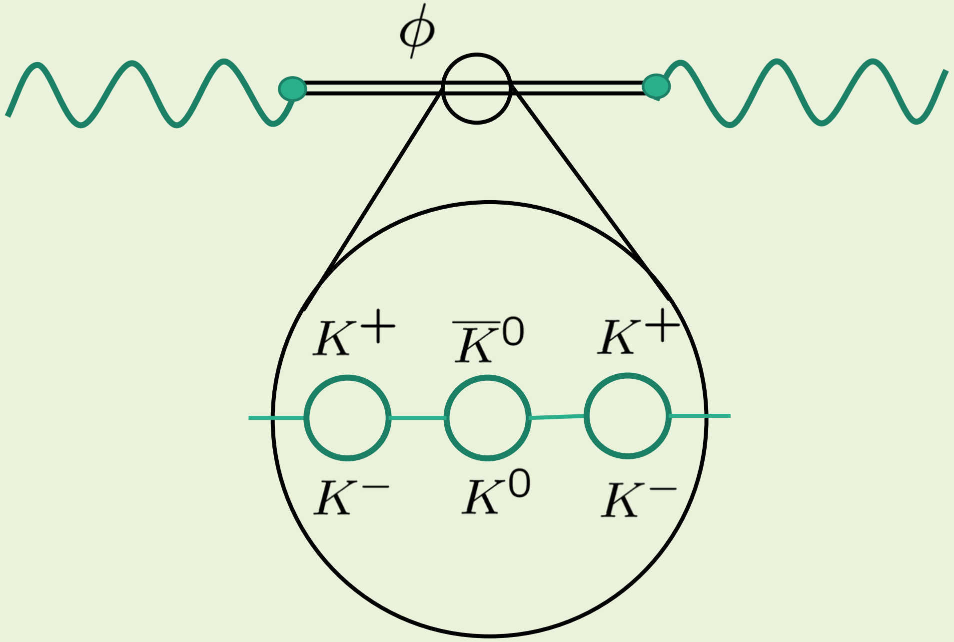
Starting point

$j_\mu(x) = \frac{1}{3}\bar{s}(x)\gamma_\mu s(x)$

$$\Pi_{\mu\nu}(q) = i\int d^4x e^{iqx}\langle T[j_\mu(x)j_\nu(0)]\rangle_\rho$$

$\Pi(q^2) = \frac{1}{3q^2}\Pi^\mu_\mu(q)$

Rewrite using hadronic degrees of freedom
(vector dominance model)



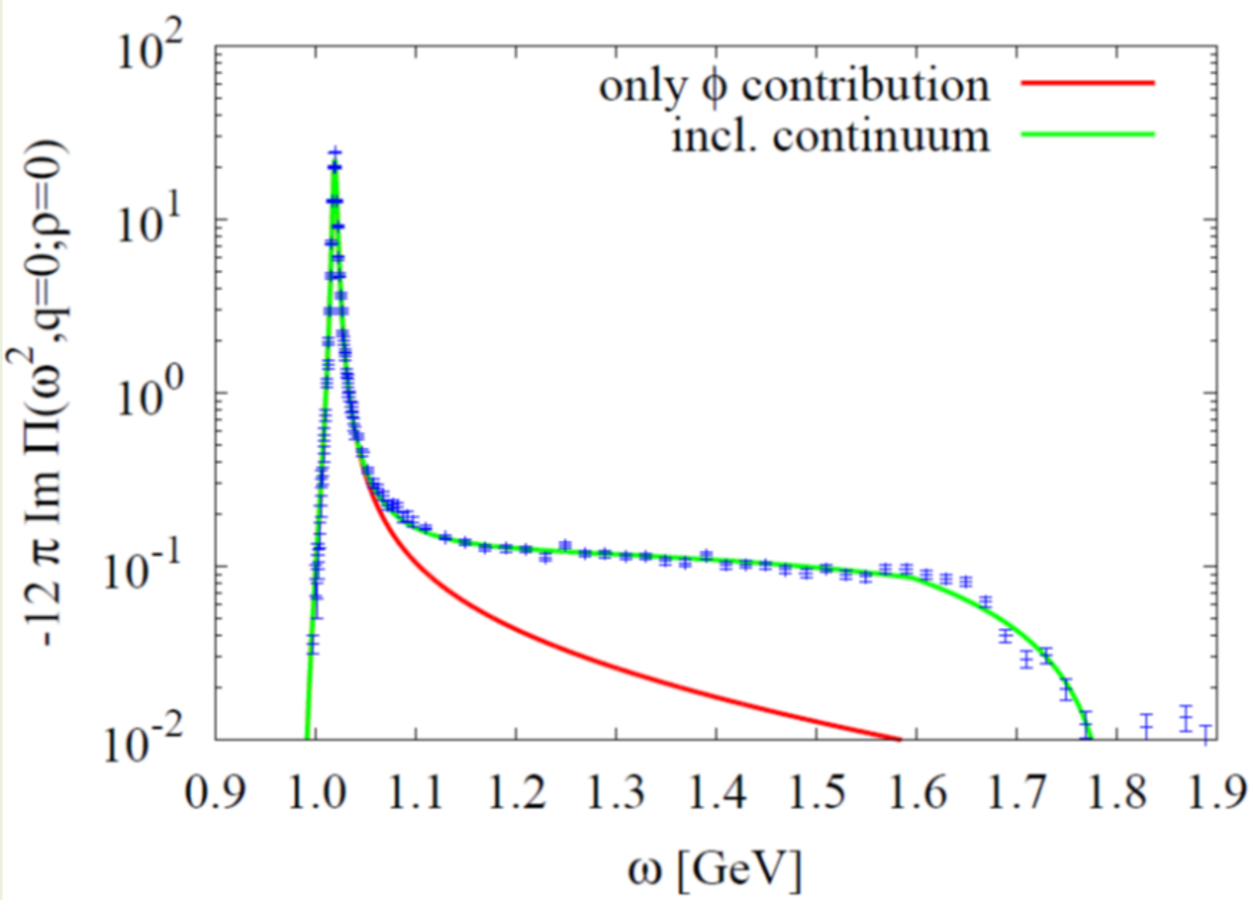
$$\mathrm{Im}\Pi(q^2) = \frac{\mathrm{Im}\Pi_\phi(q^2)}{q^2 g_\phi^2}\left|\frac{(1-a_\phi)q^2-\mathring{m}_\phi^2}{q^2-\mathring{m}_\phi^2-\Pi_\phi(q^2)}\right|^2$$

Kaon loops

Vacuum spectrum

$$\frac{\sigma(e^+e^-\to K^+K^-)}{\sigma(e^+e^-\to \mu^+\mu^-)}$$

(Vacuum)



How is this spectrum modified in nuclear matter?

Is the (modified) spectral function consistent with QCD sum rules?

P. Gubler and W. Weise, Phys. Lett. B **751**, 396 (2015).

Data from
J.P. Lees et al. (BABAR Collaboration), Phys. Rev. D **88**, 032013 (2013).

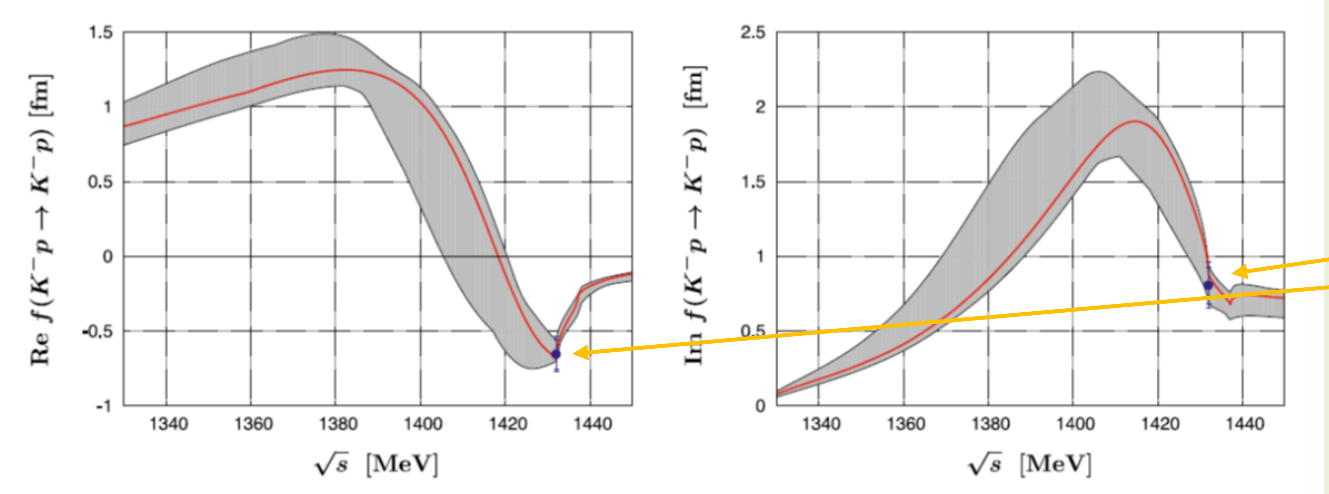
More on the free KN and $\bar{K}$N scattering amplitudes

For KN: Approximate by a real constant (↔ repulsion)

T. Waas, N. Kaiser and W. Weise, Phys. Lett. B **379**, 34 (1996).

For $\bar{K}$N: Use the latest fit based on SU(3) chiral effective field theory, coupled channels and recent experimental results (↔ attraction)

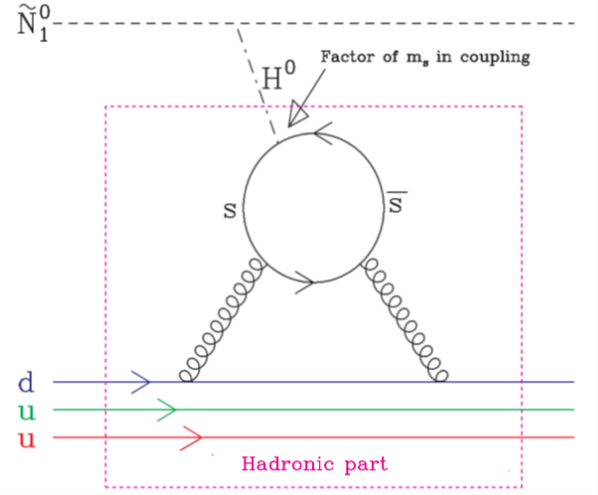
Y. Ikeda, T. Hyodo and W. Weise, Nucl. Phys. A **881**, 98 (2012).



K^-p scattering length obtained from kaonic hydrogen (SIDDHARTA Collaboration)

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).

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

most important contribution

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

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).

In-nucleus decay fractions for E325 kinematics

TABLE II. Expected in-nucleus decay fractions of vector mesons in the E325 kinematics, assuming that the meson decay widths are unmodified in nuclei, obtained by using a Monte Carlo type model calculation (Naruki *et al.*, 2006; Muto *et al.*, 2007).

	C (%)	Cu (%)
ρ	46	61
ω	5	9
ϕ		6[a]

[a]For slow ϕ mesons with $\beta\gamma < 1.25$.

Taken from: R.S. Hayano and T. Hatsuda, Rev. Mod. Phys. **82**, 2949 (2010).