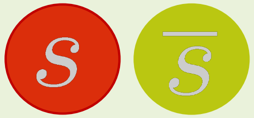
What can be measured at the E16 experiment at J-PARC?

Philipp Gubler, JAEA

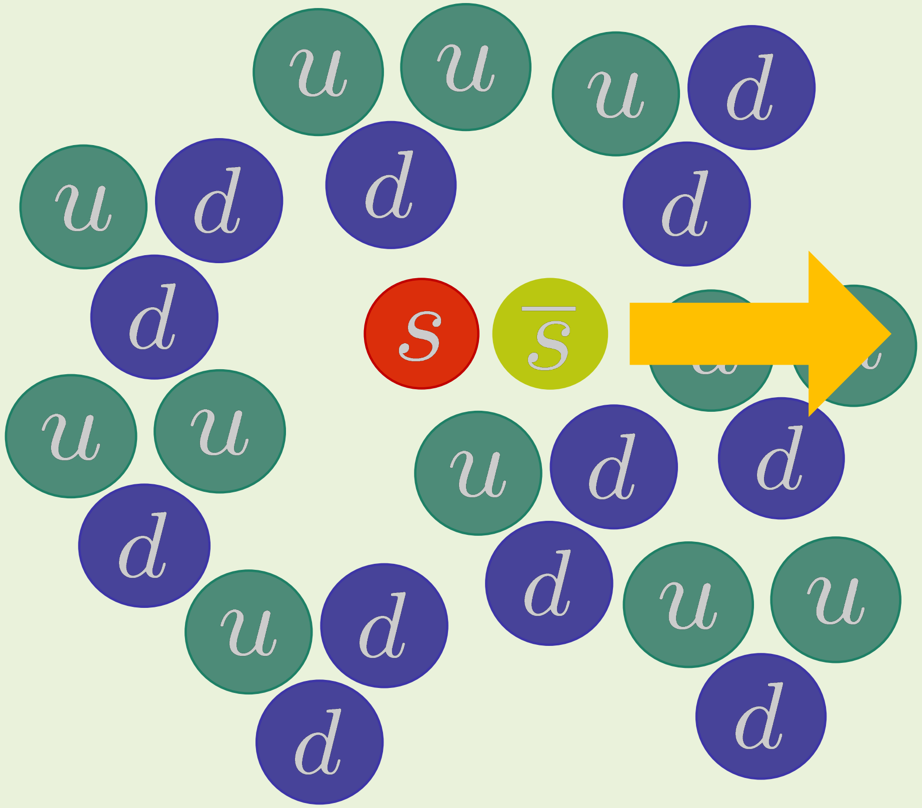
Talk at the “Korea-Japan Joint Workshop on the Present and the Future in Hadron Physics at J-PARC”,
Pukyong National University, Busan, South Korea,
March 4, 2019

φ meson



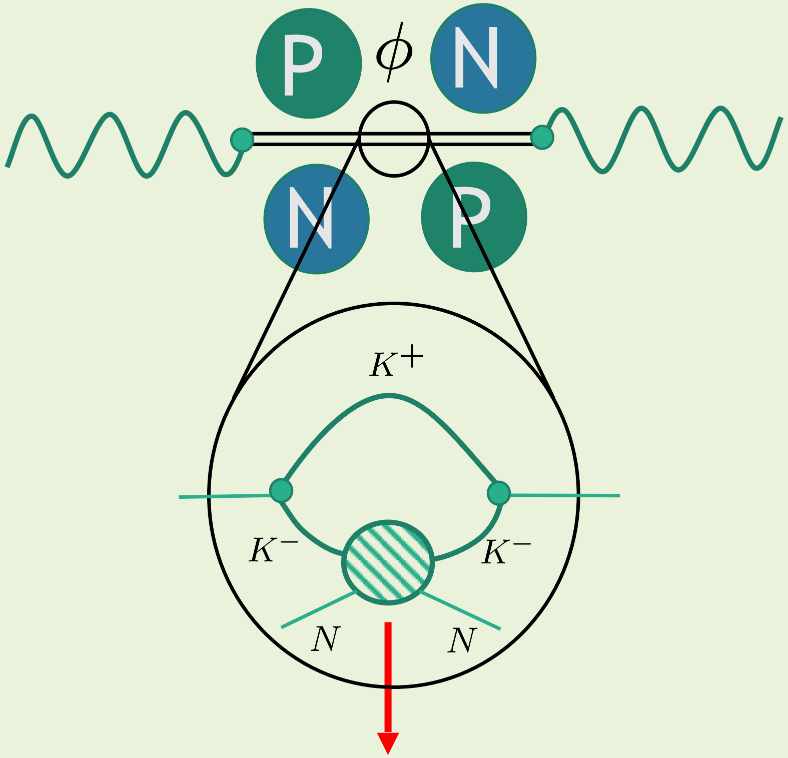
$m_\varphi = 1019$ MeV

$\Gamma_\varphi = 4.3$ MeV

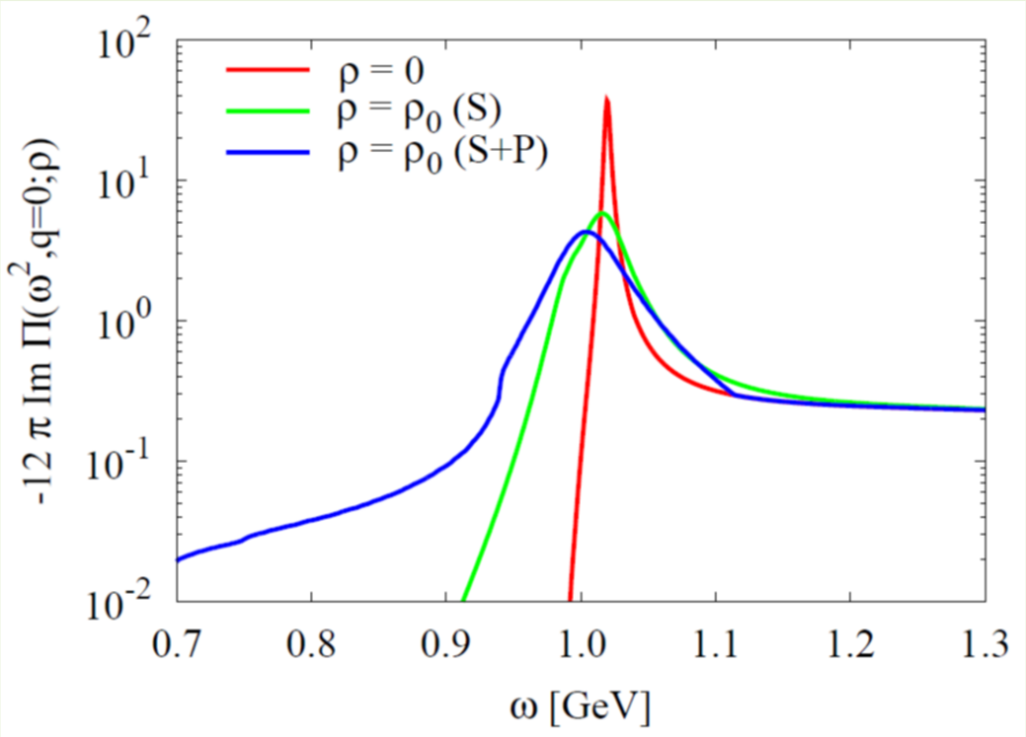


Modification of the φ meson spectral function

based on a hadronic model



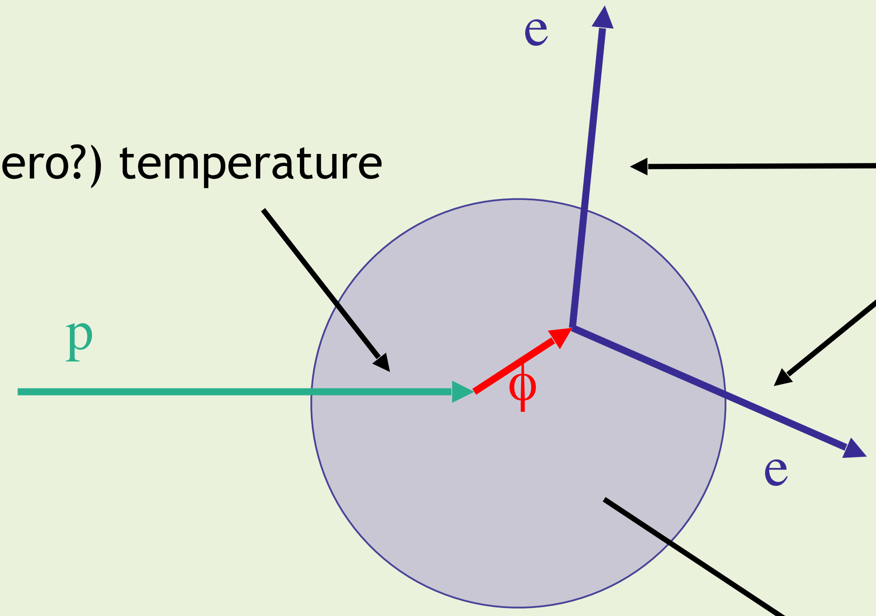
Forward $\bar{K}N$ (or KN) scattering amplitude



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

Vector mesons in experiment

One method: proton induced interactions on nuclei



low (zero?) temperature

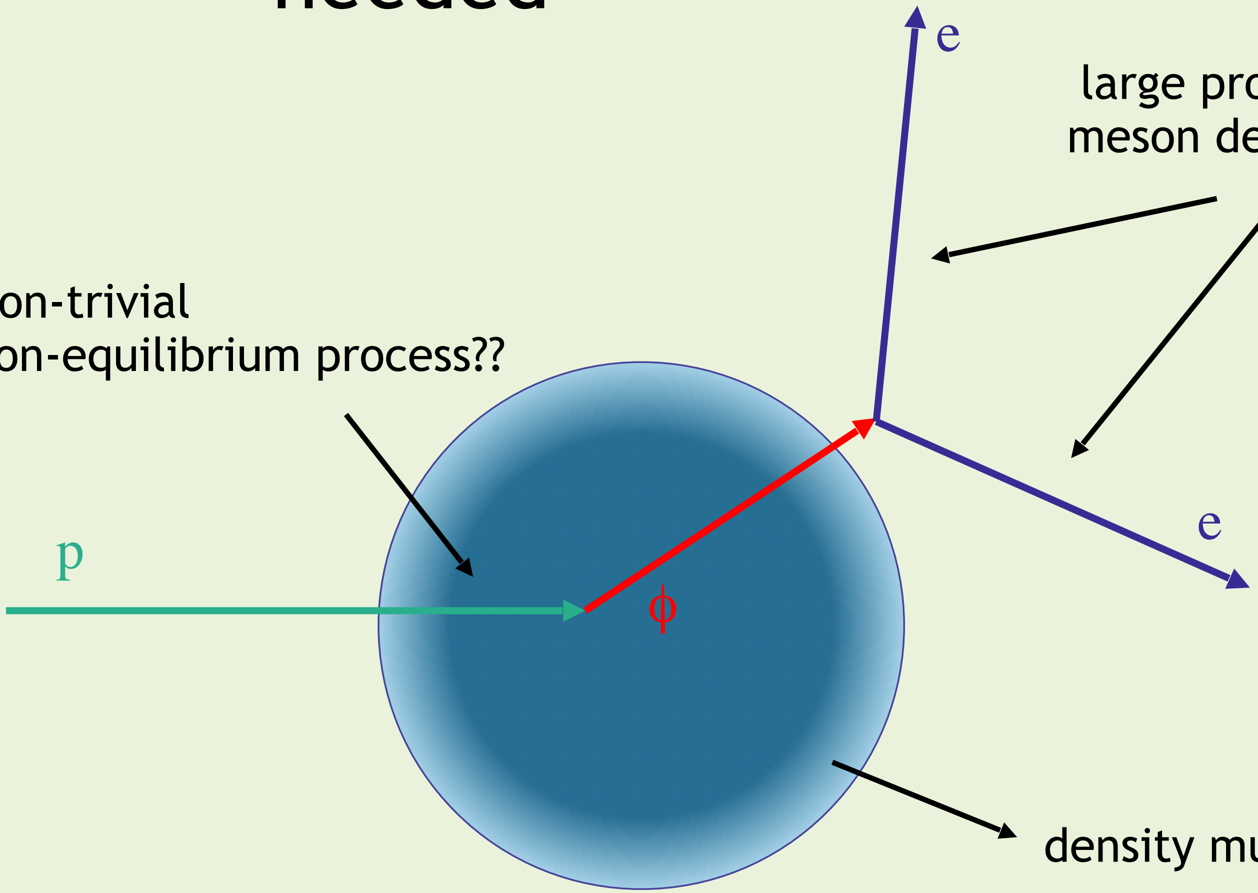
no strong interaction

no distortion of signal due to interaction with nuclear medium

approximate density:
normal nuclear density ρ_0

E325 (KEK)
E16 (J-PARC)

However, some caution is needed

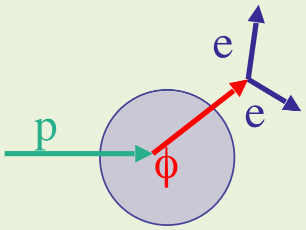


large probability of vector meson decay outside of the nucleus

Non-trivial
non-equilibrium process??

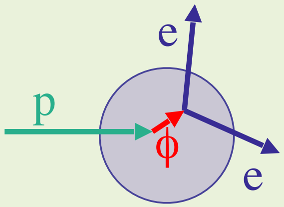
density much below ρ_0

Therefore, uniquely determining the spectral function at normal nuclear matter density is not easy!



outside decay

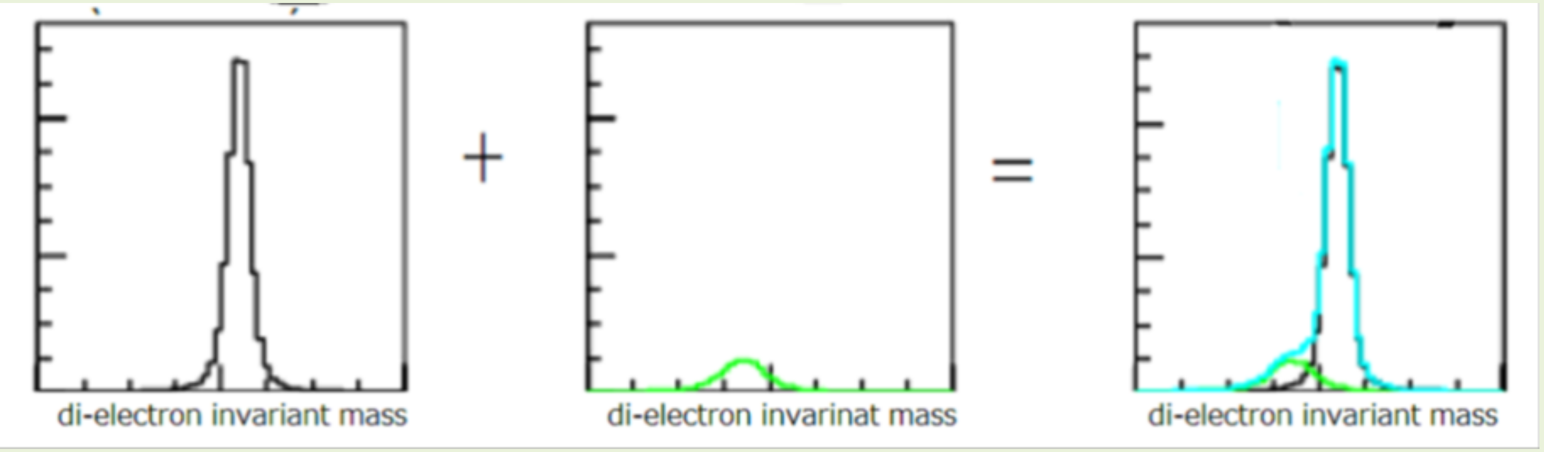
+



inside decay

=

Experimentally
observed spectrum

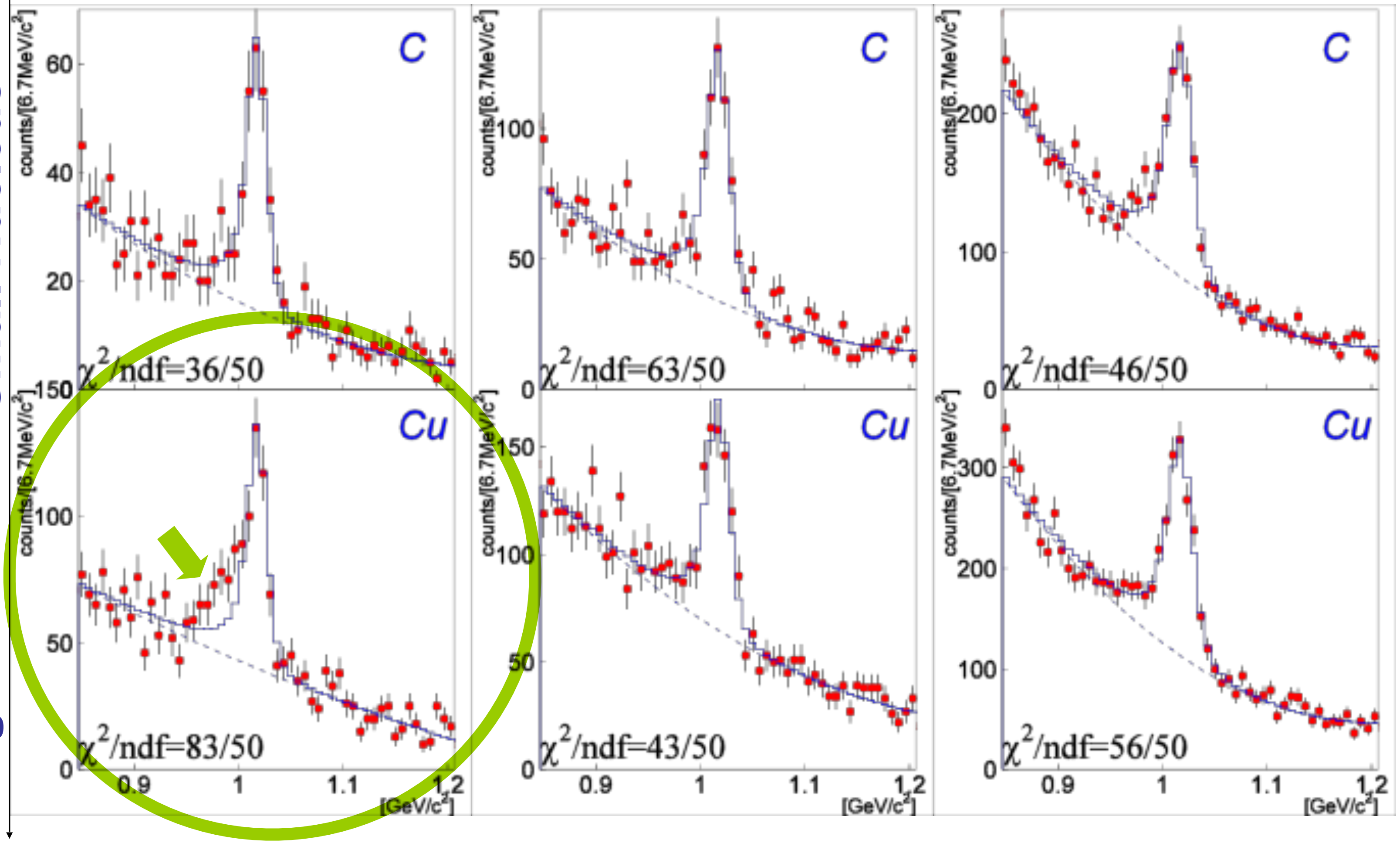


Fitting Results

$\beta\gamma<1.25$ (Slow) **$1.25<\beta\gamma<1.75$** **$1.75<\beta\gamma$ (Fast)**

Small Nucleus

Large Nucleus



Experimental Conclusions

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

Pole mass:

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

0.034 ± 0.007

35 MeV negative mass shift at normal nuclear matter density

Pole width:

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

2.6 ± 1.5

Increased width to 15 MeV at normal nuclear matter density

Caution!

Fit to experimental data is performed with a simple Breit-Wigner parametrization

Too simple??

QCD sum rules

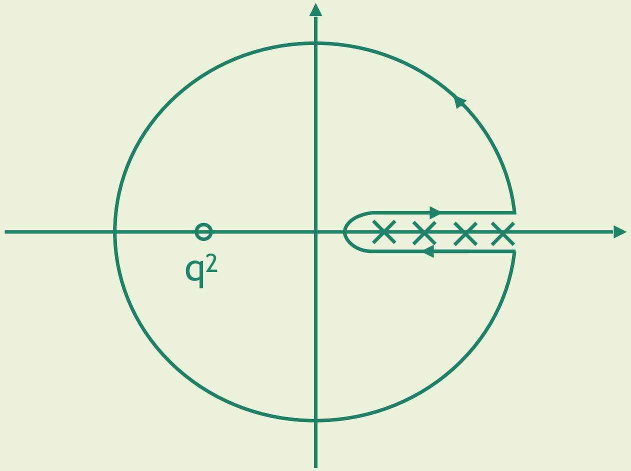
M.A. Shifman, A.I. Vainshtein and V.I. Zakharov, Nucl. Phys. B147, 385 (1979); B147, 448 (1979).

Makes use of the analytic properties of the correlation function:

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

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

$\chi(x) = \bar{c}(x)\gamma_5 d(x)$



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

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)

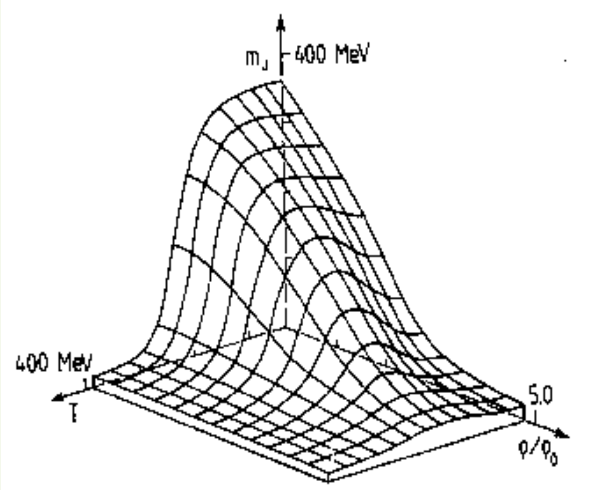
perturbative Wilson coefficients

non-perturbative condensates

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

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

Change in hot or dense matter!



Structure of QCD sum rules for the phi meson

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

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

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

In Nuclear Matter

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

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

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

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

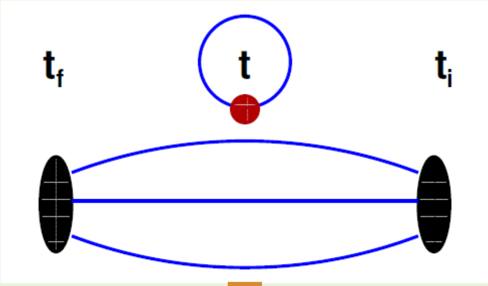
Dim. 6: $c_6(\rho) = c_6(0) + \rho[-\frac{896}{81}\kappa_N\pi^3\alpha_s\langle\bar{s}s\rangle\langle N|\bar{s}s|N\rangle - \frac{5}{6}A_4^s M_N^3]$

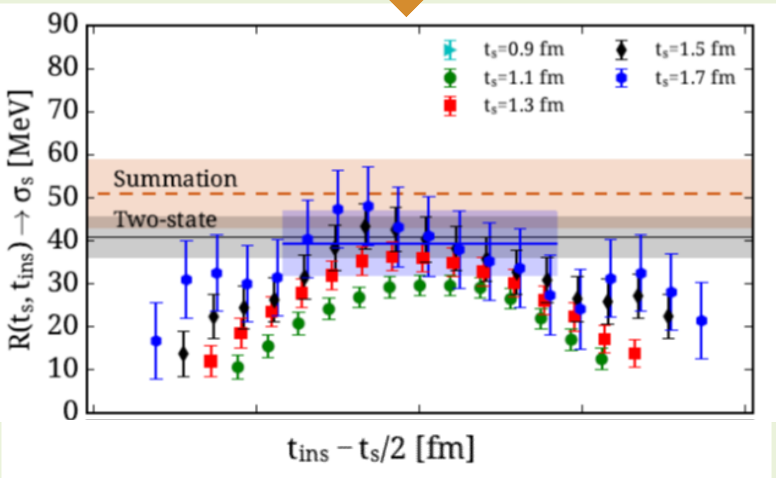
The strangeness content of the nucleon: results from lattice QCD

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

Two methods

Direct measurement

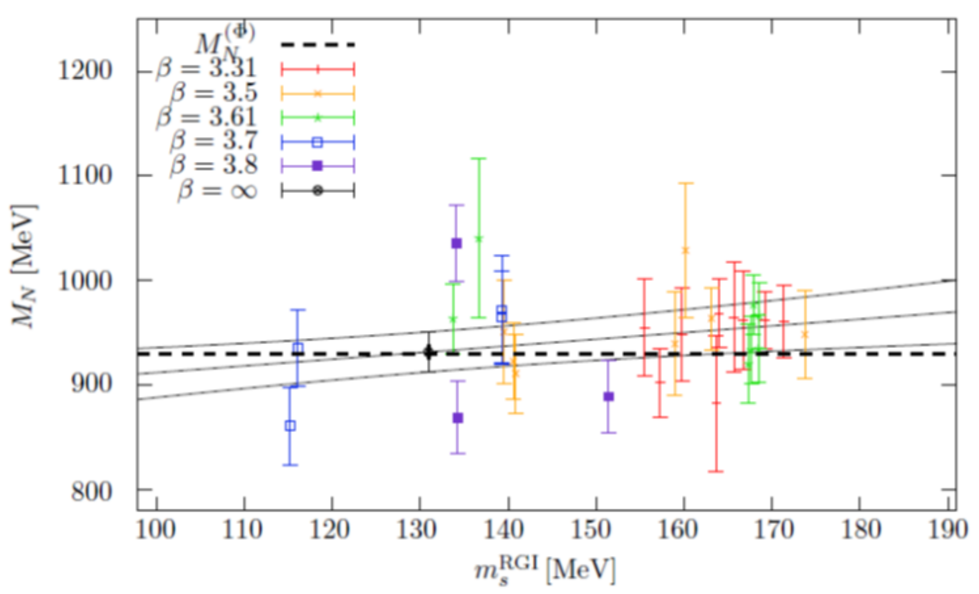




A. Abdel-Rehim et al. (ETM Collaboration), Phys. Rev. Lett. **116**, 252001

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

Recent results from lattice QCD

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

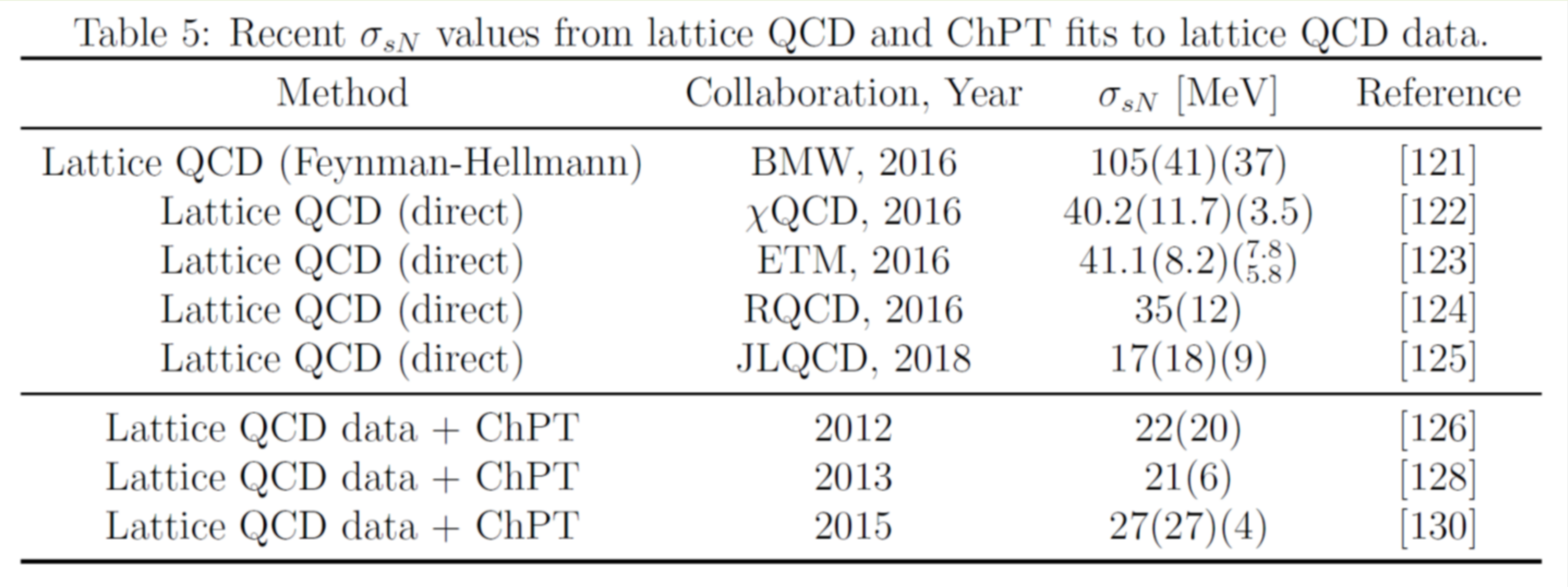


Table 5: Recent σ_{sN} values from lattice QCD and ChPT fits to lattice QCD data.

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	$41.1(8.2)\binom{7.8}{5.8}$	[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]

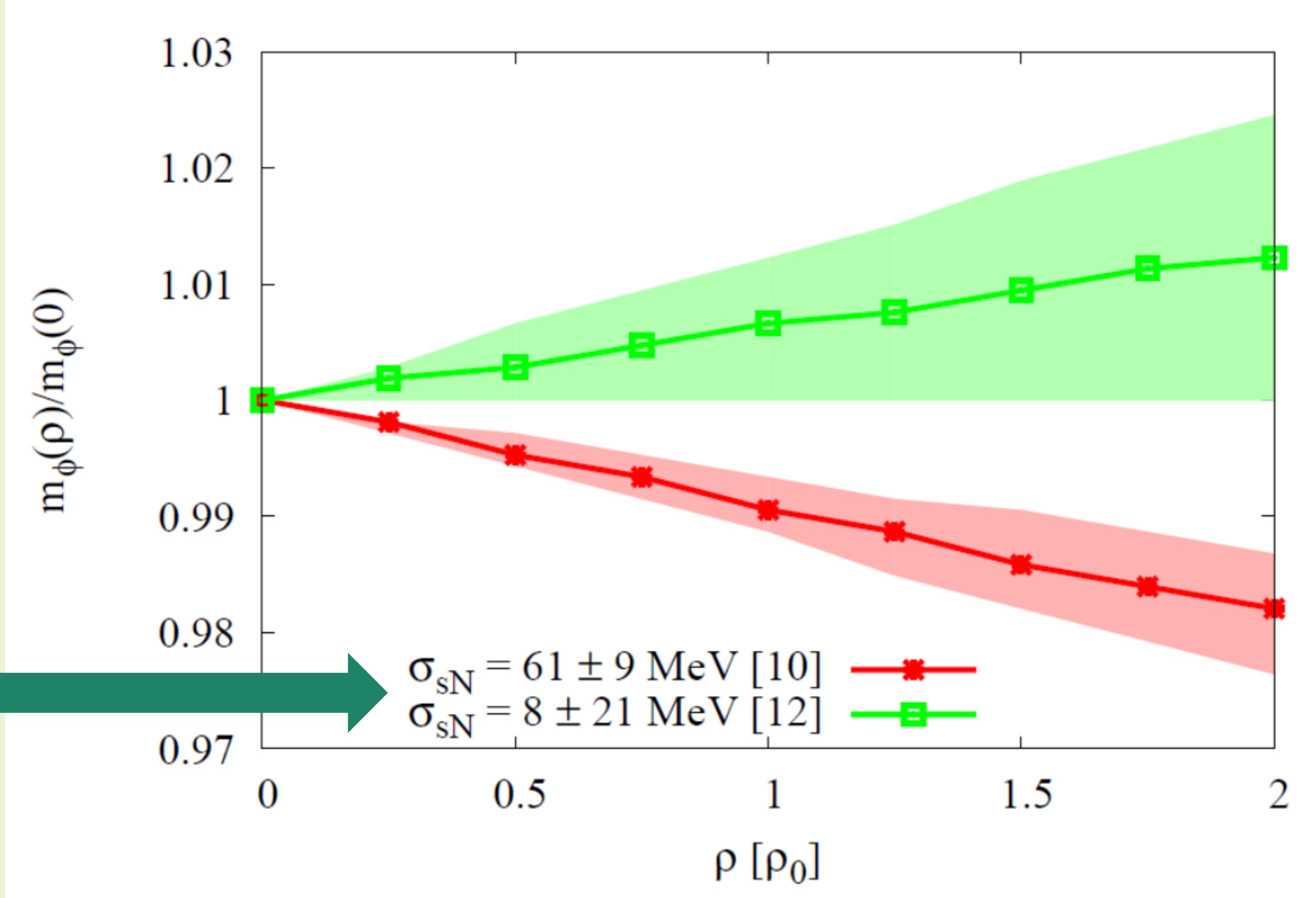
P. Gubler and D. Satow, arXiv:1812:00385 [hep-ph], to be published in Prog. Part. Nucl. Phys.

Results for the φ meson mass

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

Strangeness content of the nucleon

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

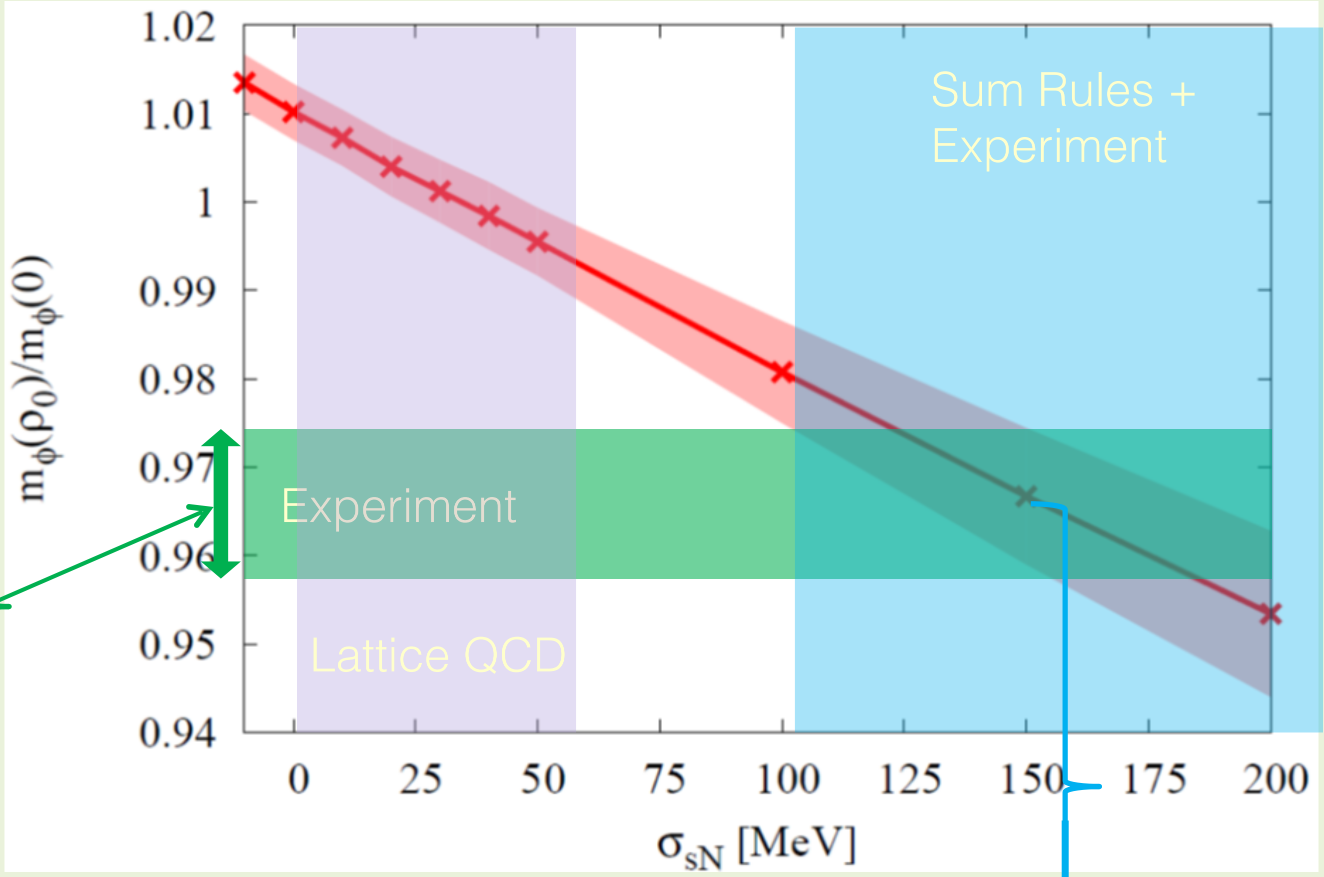


P. Gubler and K. Ohtani, Phys. Rev. D **90**, 094002 (2014).

Compare Theory with Experiment

Not consistent?

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

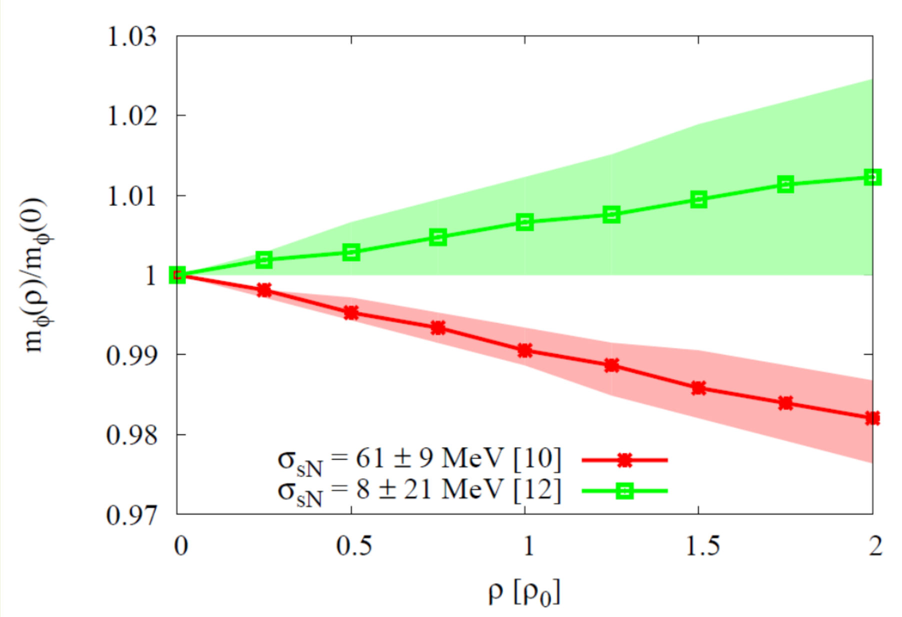


$\sigma_{sN} \sim 160 \pm 50$ MeV

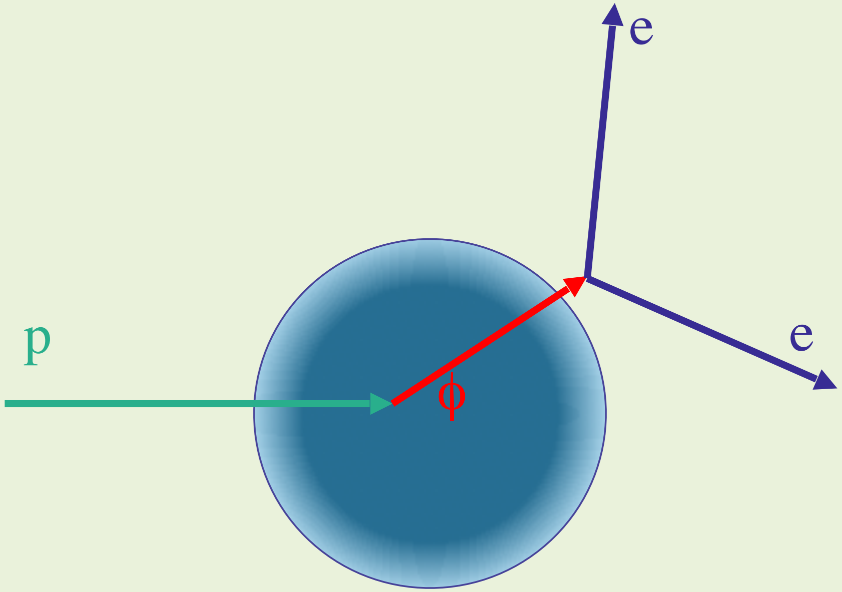
Will soon be measured again with better statistics at the E16 experiment at J-PARC!

How can theoretical results be compared to experiment more accurately?

Theory



Experiment



Realistic simulation of pA reaction is needed!

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

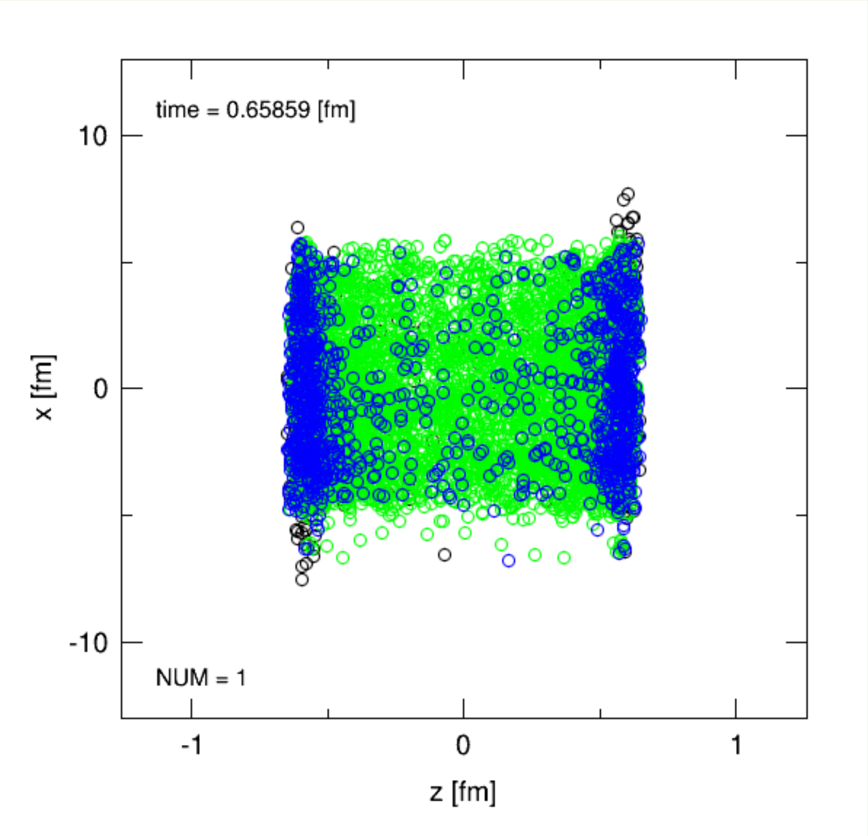
W. Cassing and E. Bratkovskaya, Phys. Rev. C **78**, 034919 (2008).

PHSD:
microscopic transport description of the partonic and hadronic phase in terms of strongly interacting particles

Example:

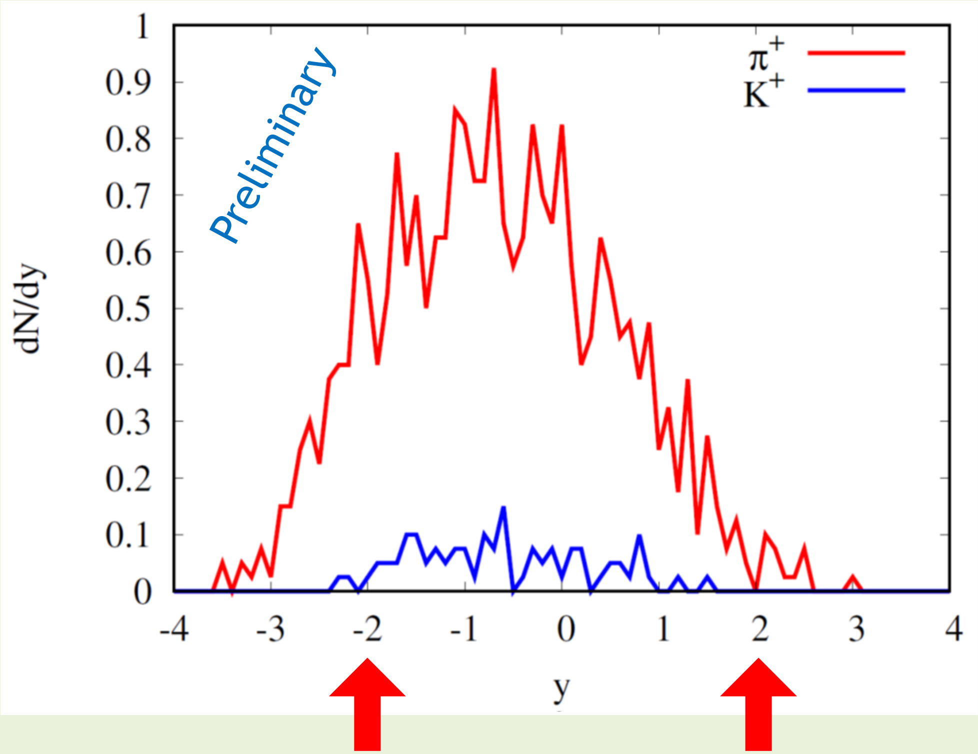
Au+Au collision at 200 GeV
b = 2 fm

nucleons
quarks
gluons



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

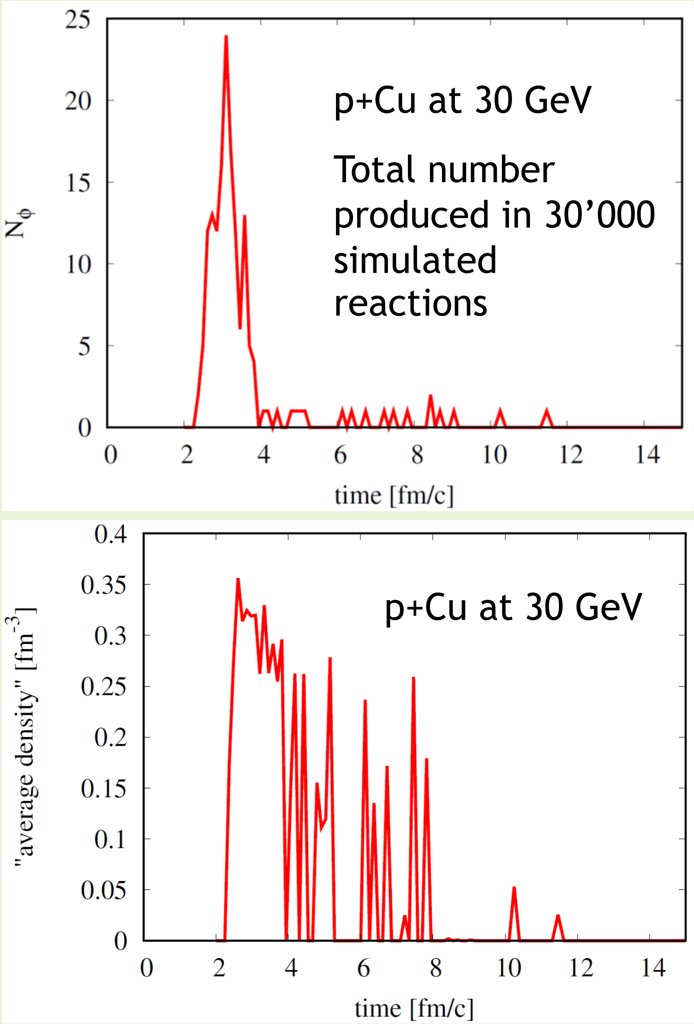
projectile proton
after collision

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

What happens with the ϕ?

All preliminary

Production



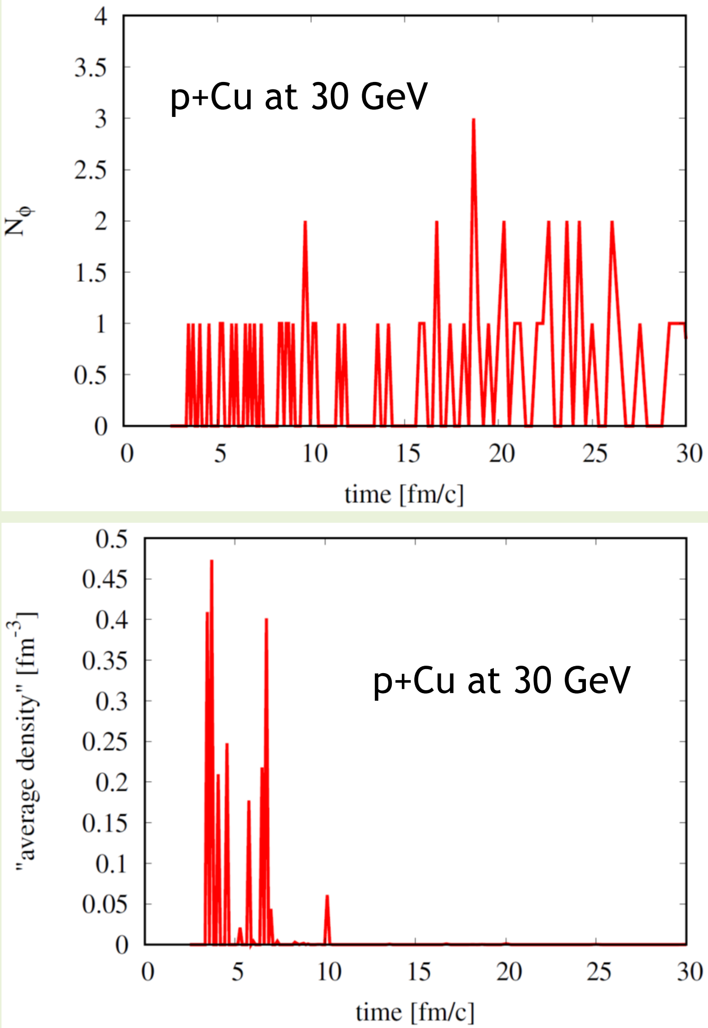
p+Cu at 30 GeV

Total number produced in 30’000 simulated reactions

p+Cu at 30 GeV

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

Decay

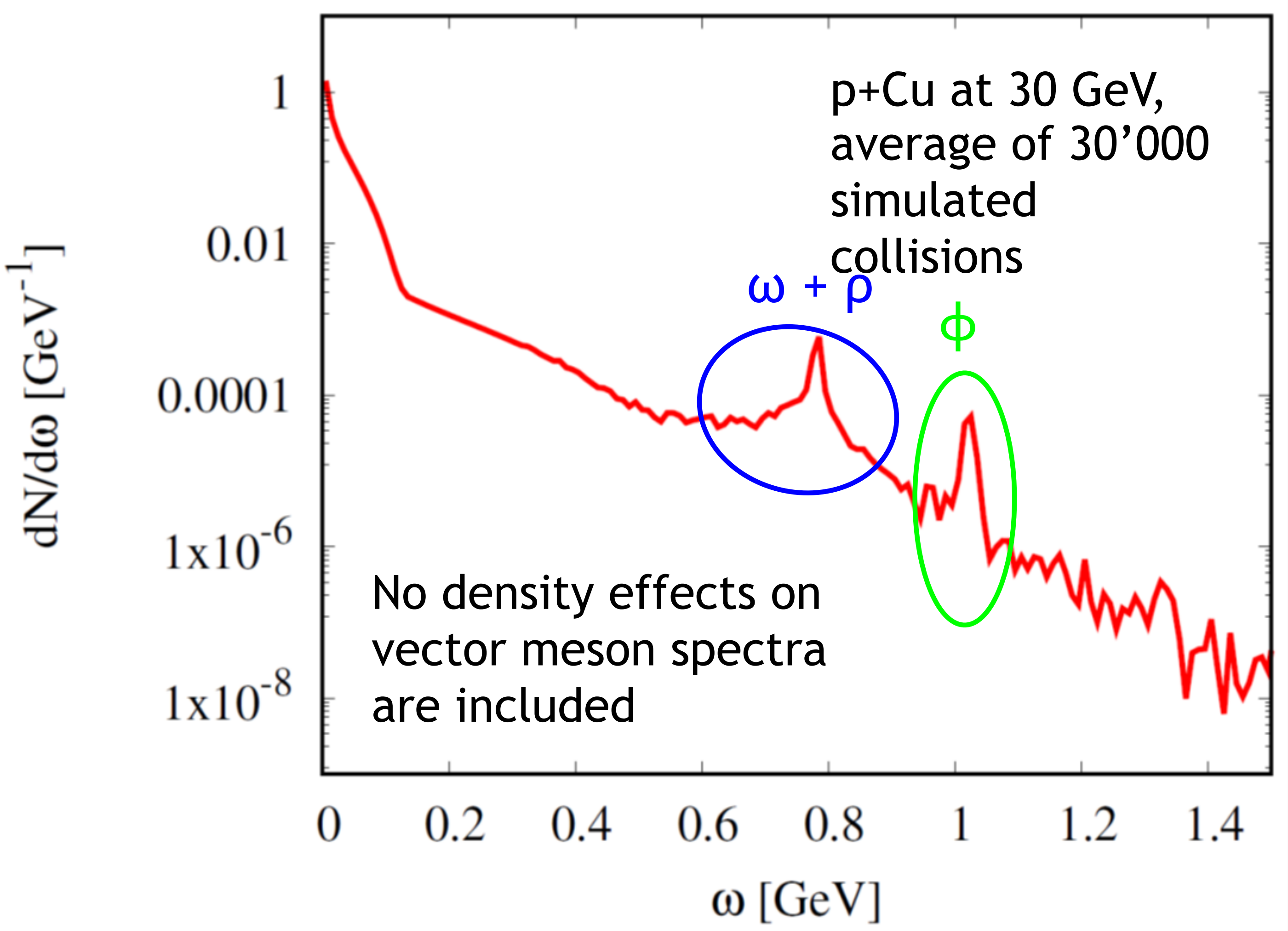


p+Cu at 30 GeV

p+Cu at 30 GeV

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

The dilepton spectrum



p+Cu at 30 GeV, average of 30’000 simulated collisions

No density effects on vector meson spectra are included

The ϕ meson peak is clearly visible, but more statistics are needed to generate the precise dilepton spectrum

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!

★ The φ-meson mass shift in nuclear matter constrains the strangeness content of the nucleon:

$$\sigma_{sN} < 35 \text{ MeV}$$

Increasing φ-meson mass in nuclear matter

$$\sigma_{sN} > 35 \text{ MeV}$$

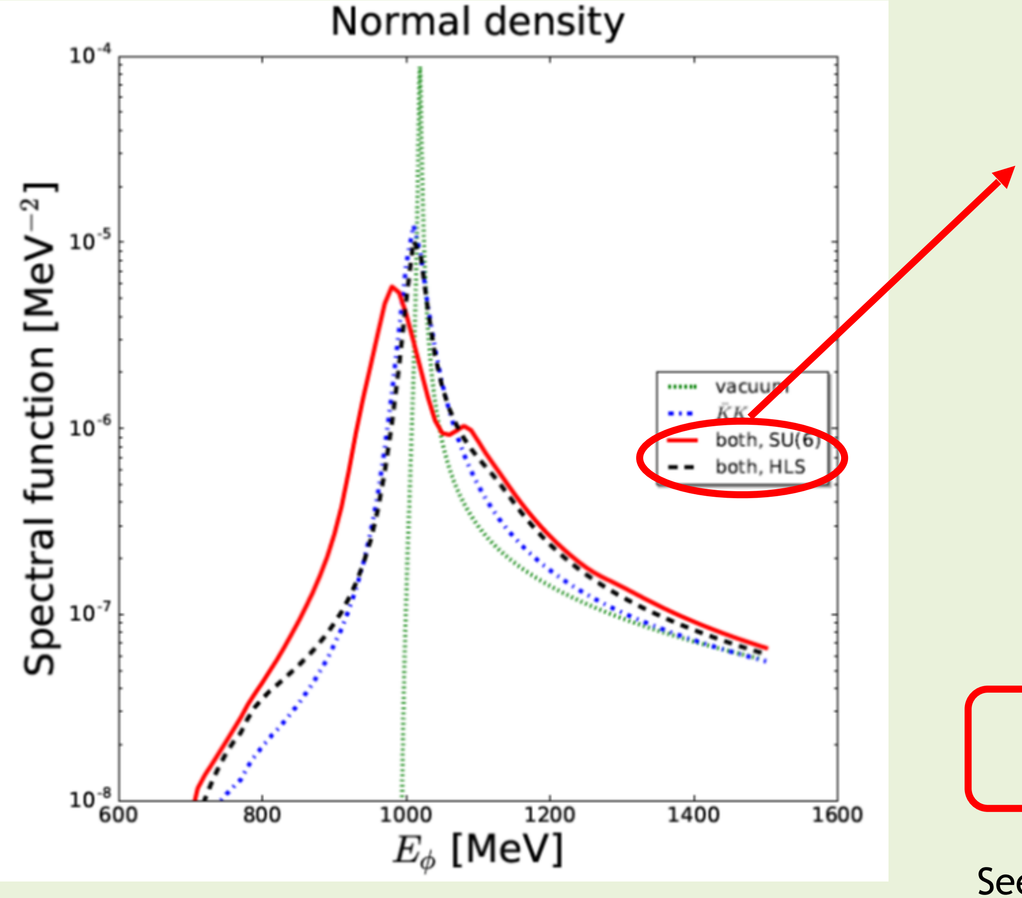
Decreasing φ-meson mass in nuclear matter

★ Numerical simulations of the pA reactions to be measured at the E16 experiment at J-PARC, using the PHSD transport code, are in progress.

Backup slides

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

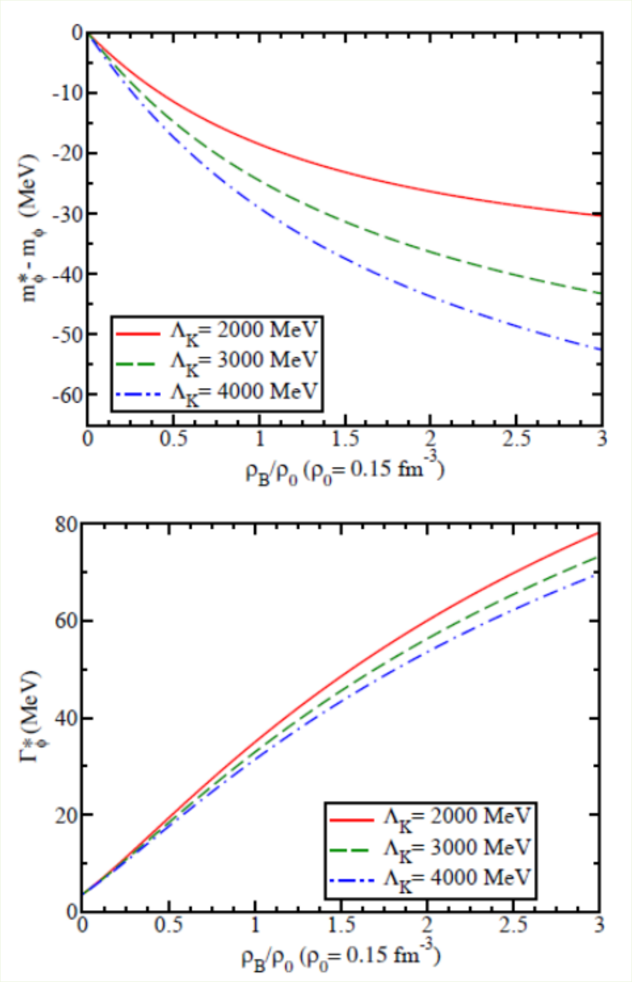
Common features:

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).

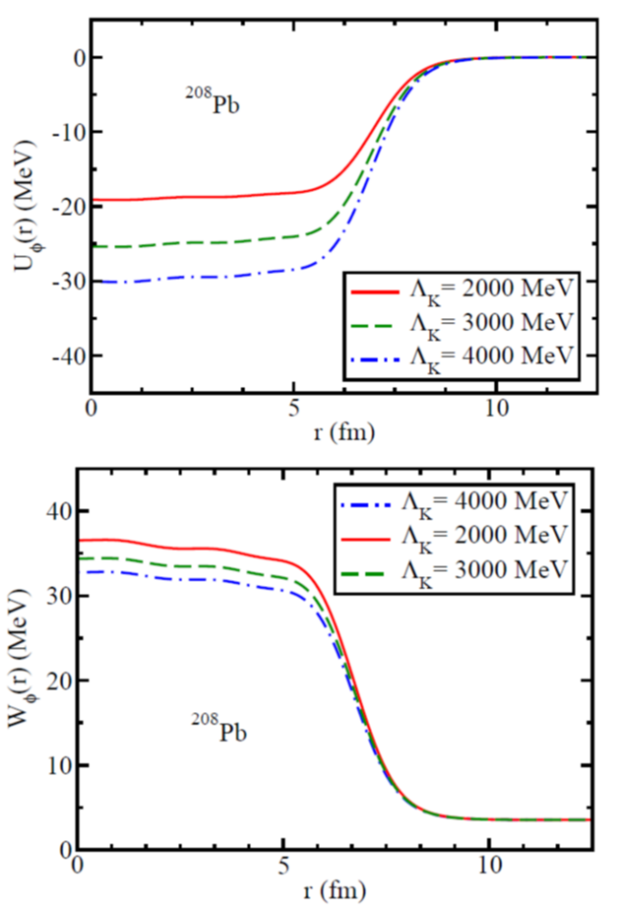
Recent theoretical works about the φ

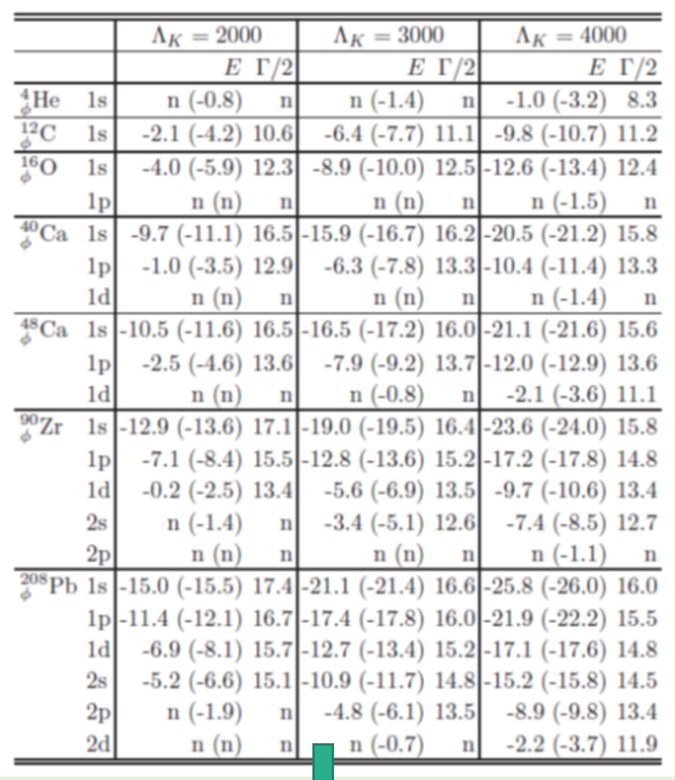
based on the quark-meson coupling model



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

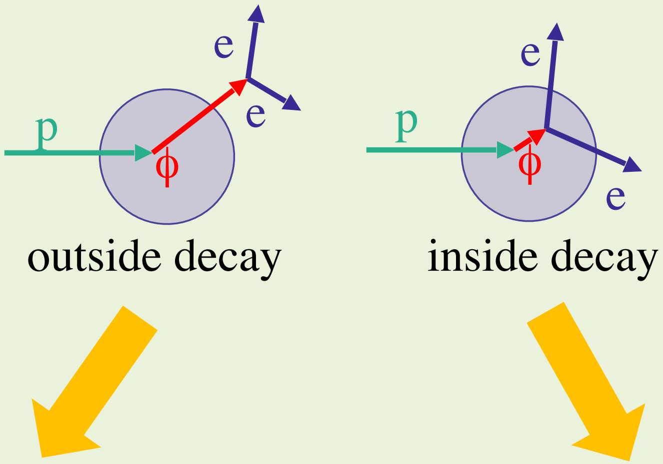
Some φA bound states might exist, but they have a large width

→ difficult to observe experimentally ?

Experimental developments

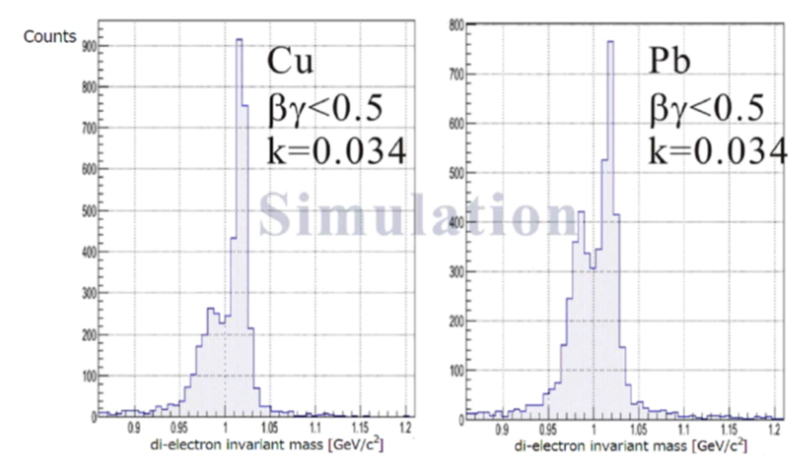
The E325 Experiment (KEK)

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



No effect
(only vacuum)

Di-lepton spectrum
reflects the modified
φ-meson



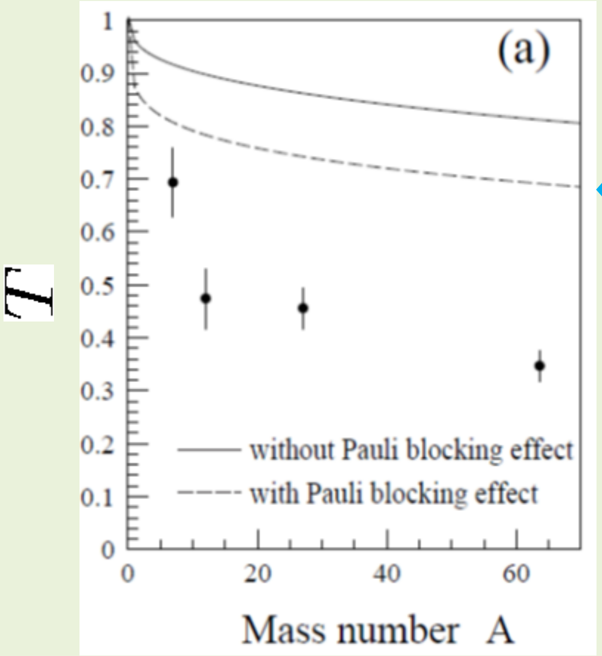
Y. Morino et. al. (J-PARC E16 Collaboration),
JPS Conf. Proc. 8, 022009 (2015).

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)



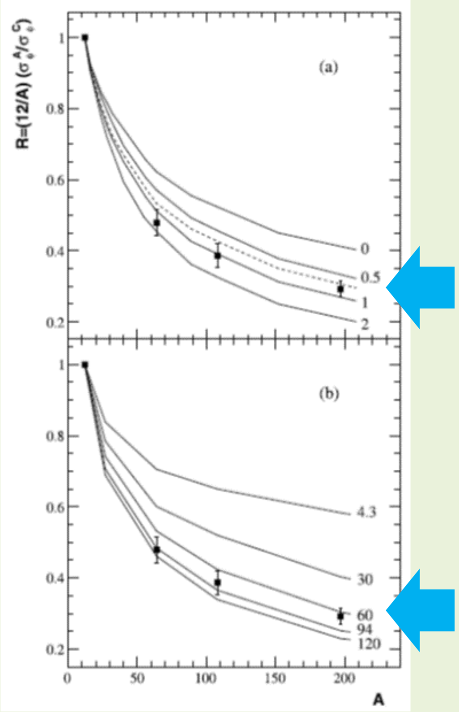
$\Gamma_\phi(\rho_0) \simeq 30\,\text{MeV}$

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).

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

Theoretical calculation:

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

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

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

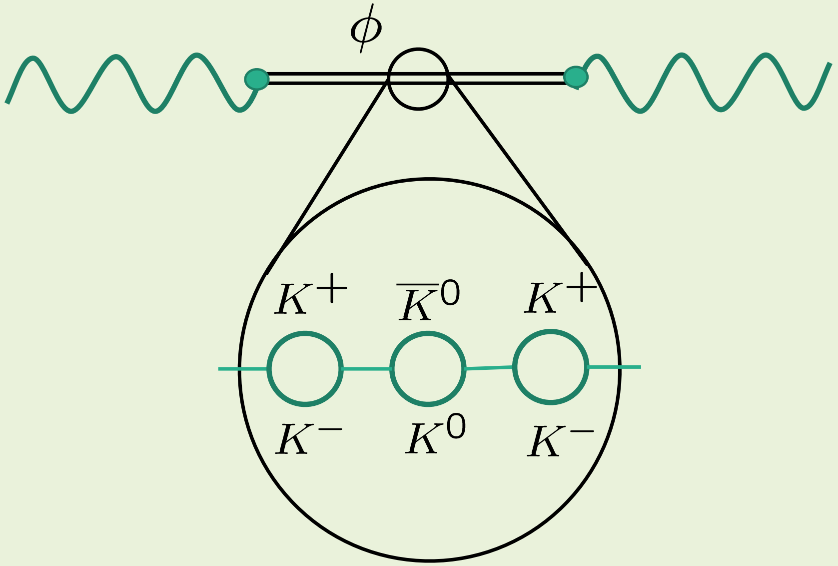
Starting point

$$j_\mu(x) = \tfrac{1}{3}\overline{s}(x)\gamma_\mu s(x)$$

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

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

Rewrite using hadronic degrees of freedom
(vector dominance model)



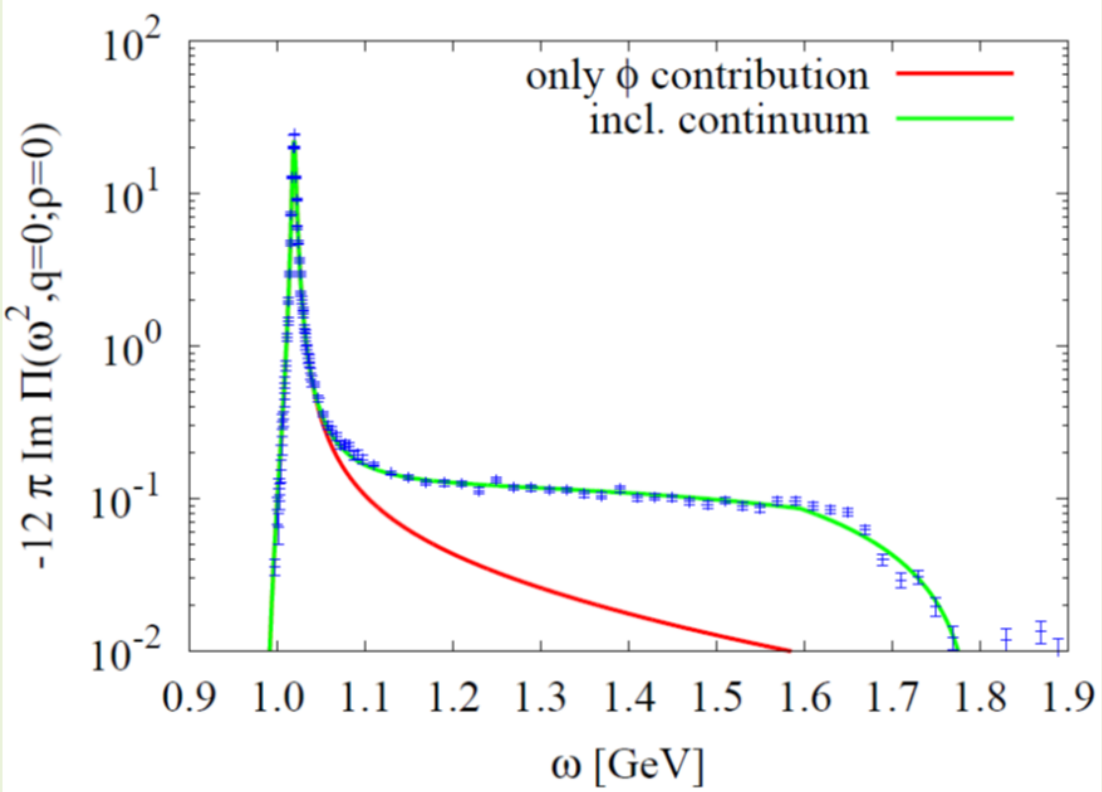
$$\mathrm{Im}\Pi(q^2) = \frac{\mathrm{Im}\Pi_\phi(q^2)}{q^2 g_\phi^2}\left|\frac{(1-a_\phi)q^2-\mathring{m}_\phi^2}{q^2-\mathring{m}_\phi^2-\Pi_\phi(q^2)}\right|^2$$

Kaon loops

Vacuum spectrum

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

(Vacuum)



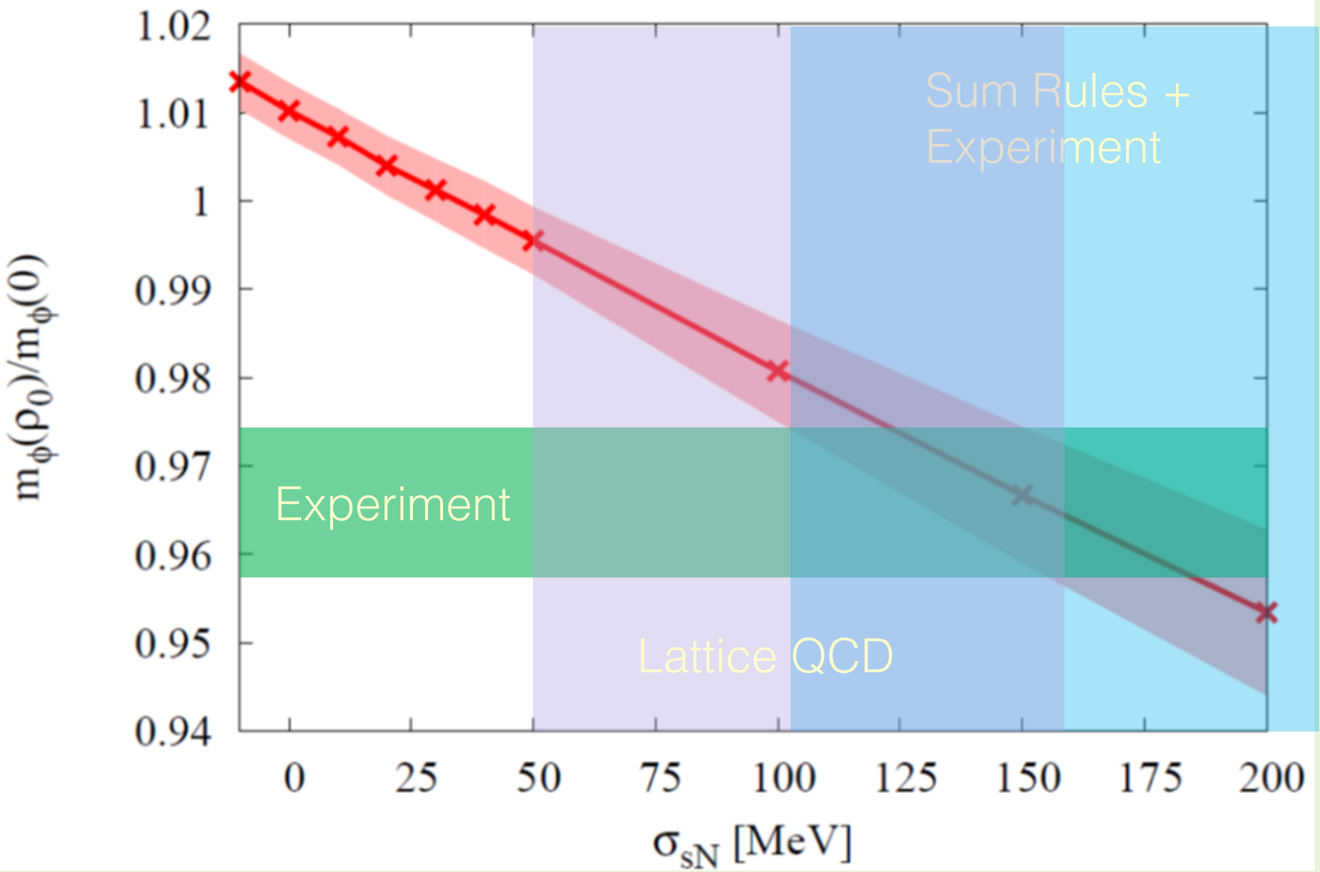
P. Gubler and W. Weise, Phys. Lett. B **751**, 396 (2015).

How is this spectrum modified in nuclear matter?

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

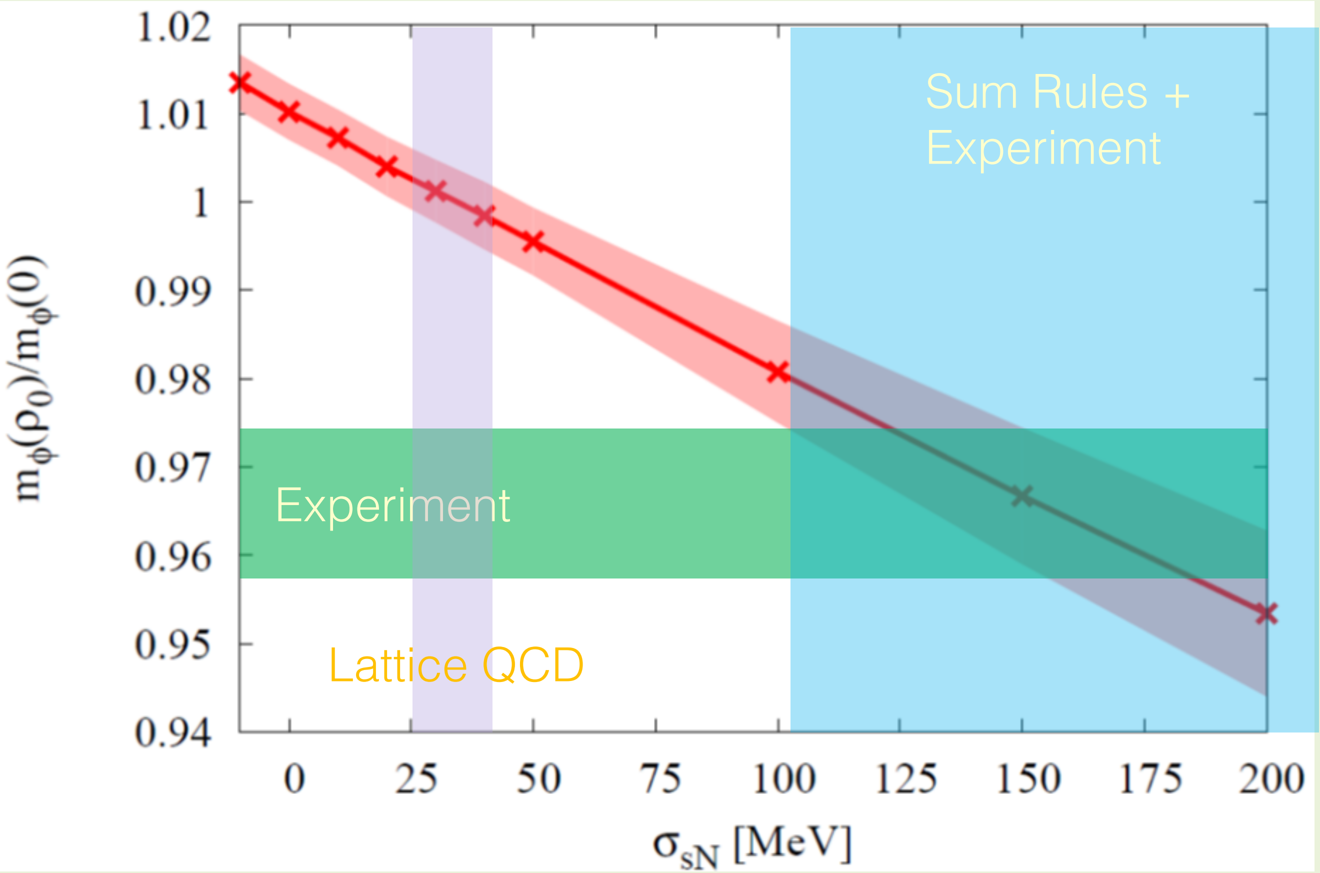
Data from
J.P. Lees et al. (BABAR Collaboration), Phys. Rev. D **88**, 032013 (2013).

BMW version:


1.02
1.01
1
0.99
0.98
0.97
0.96
0.95
0.94
$m_\phi(\rho_0)/m_\phi(0)$
0
25
50
75
100
125
150
175
200
σ_{sN} [MeV]
Sum Rules +
Experiment
Experiment
Lattice QCD

?

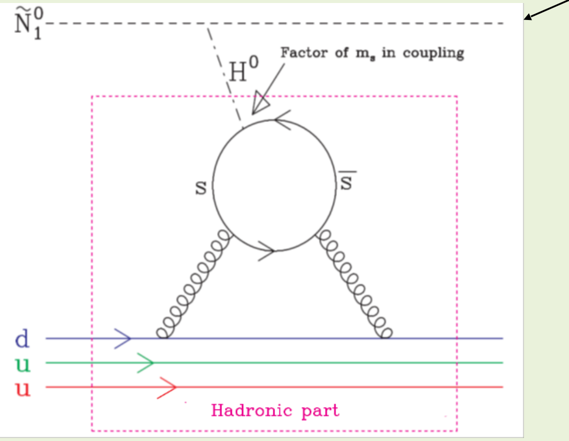
xQCD version:



??

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).

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

most important contribution

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

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).

Problem at finite ρ: sign problem!

$$Z = \int DA \,\mathrm{det}[\not{D} + m - \mu\gamma_0/2] e^{S_{\mathrm{YM}}}$$

Dirac operator

mass matrix

chemical potential

$$(\mathrm{det}[\not{D} + m - \mu\gamma_0/2])^* = \mathrm{det}[\not{D} + m + \mu^*\gamma_0/2]$$

The determinant is complex

$$\Downarrow$$

$$\mathrm{det}[\not{D} + m - \mu\gamma_0/2] = |\,\mathrm{det}[\not{D} + m - \mu\gamma_0/2]| e^{i\theta}$$

$$\Downarrow$$

Standard Monte-Carlo integration is essentially impossible

The basic problem to be solved

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

given
(but only incomplete
and with error)

“Kernel
”

?

This is an ill-posed problem.

But, one may have additional information on ρ(ω), which can help to constrain the problem:

- Positivity: $\rho(\omega) \geq 0$
- Asymptotic values: $\rho(\omega = 0), \rho(\omega = \infty)$

The Maximum Entropy Method

How can one include this additional information and find the most probable image of ρ(ω)?

→ Bayes' Theorem

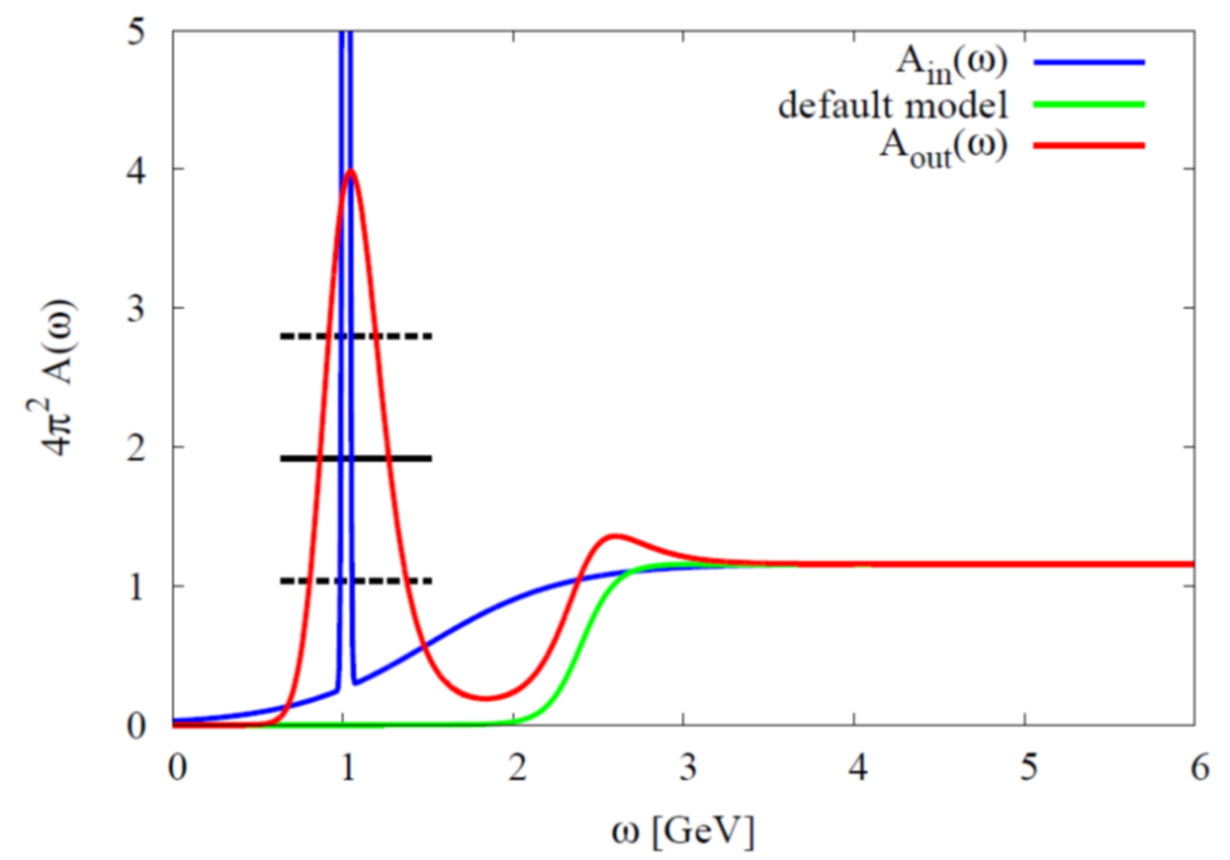
$$P[\rho|G,I] = \frac{P[G|\rho,I]P[\rho|I]}{P[G|I]}$$

likelihood function

prior probability

$$\rightarrow \quad \frac{\delta P[\rho|G,I]}{\delta\rho} = 0$$

Results of test-analysis (using MEM)



Peak position can be extracted, but not the width!

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

$$P[\rho|G,I] = \frac{P[G|\rho,I]P[\rho|I]}{P[G|I]}$$

likelihood function

$$P[G|\rho,I] = \frac{1}{Z_L}e^{-L[\rho]}$$

$$L[\rho] = \frac{1}{2(M_{\max}-M_{\min})}\int_{M_{\min}}^{M_{\max}} dM \frac{\left[G_{OPE}(M) - G_{\rho}(M)\right]^2}{\sigma^2(M)}$$

Corresponds to
ordinary x^2-fitting.

prior probability

$$P[\rho|I] = \frac{1}{Z_s}e^{\alpha S[\rho]}$$

$$S[\rho] = \int_0^{\infty} d\omega \Big[\rho(\omega) - m(\omega) - \rho(\omega)\log\Big(\frac{\rho(\omega)}{m(\omega)}\Big)\Big]$$

(Shannon-Jaynes entropy)

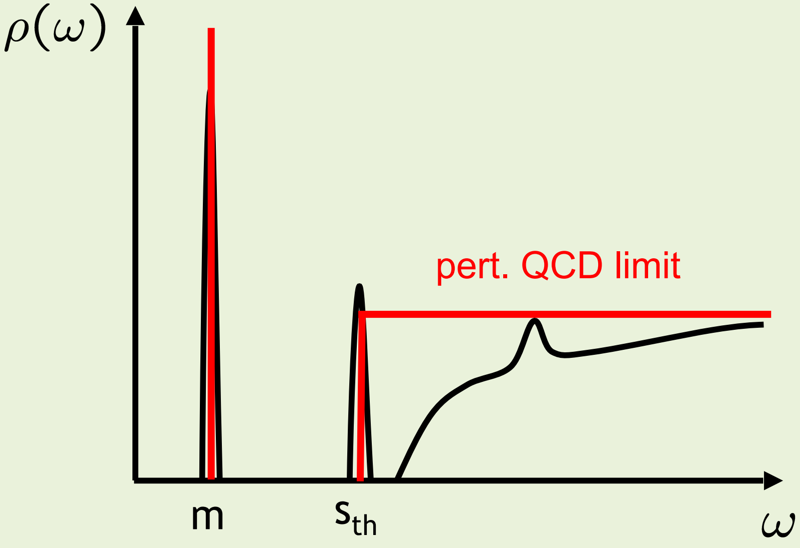
“default model”

M. Jarrel and J.E. Gubernatis, Phys. Rep. 269, 133 (1996).

M.Asakawa, T.Hatsuda and Y.Nakahara, Prog. Part. Nucl. Phys. 46, 459 (2001).

The traditional analysis method

The spectral function is approximated by a “pole + continuum” ansatz:



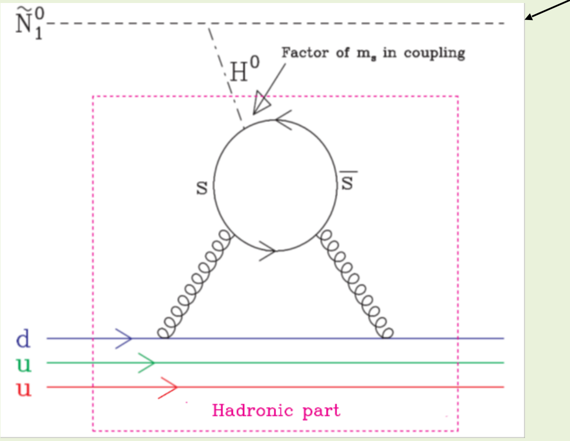
$$\rho(s) = \lambda^2\delta(s - m^2) + \theta(s - s_{\text{th}})\frac{1}{\pi}\text{Im}\Pi^{OPE}(s)$$

Even though this ansatz is very crude, it works quite well in cases for which it is phenomenologically known to be close to reality.

e.g. -charmonium (J/ψ)

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

Important parameter for dark-matter searches:



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

In-nucleus decay fractions for E325 kinematics

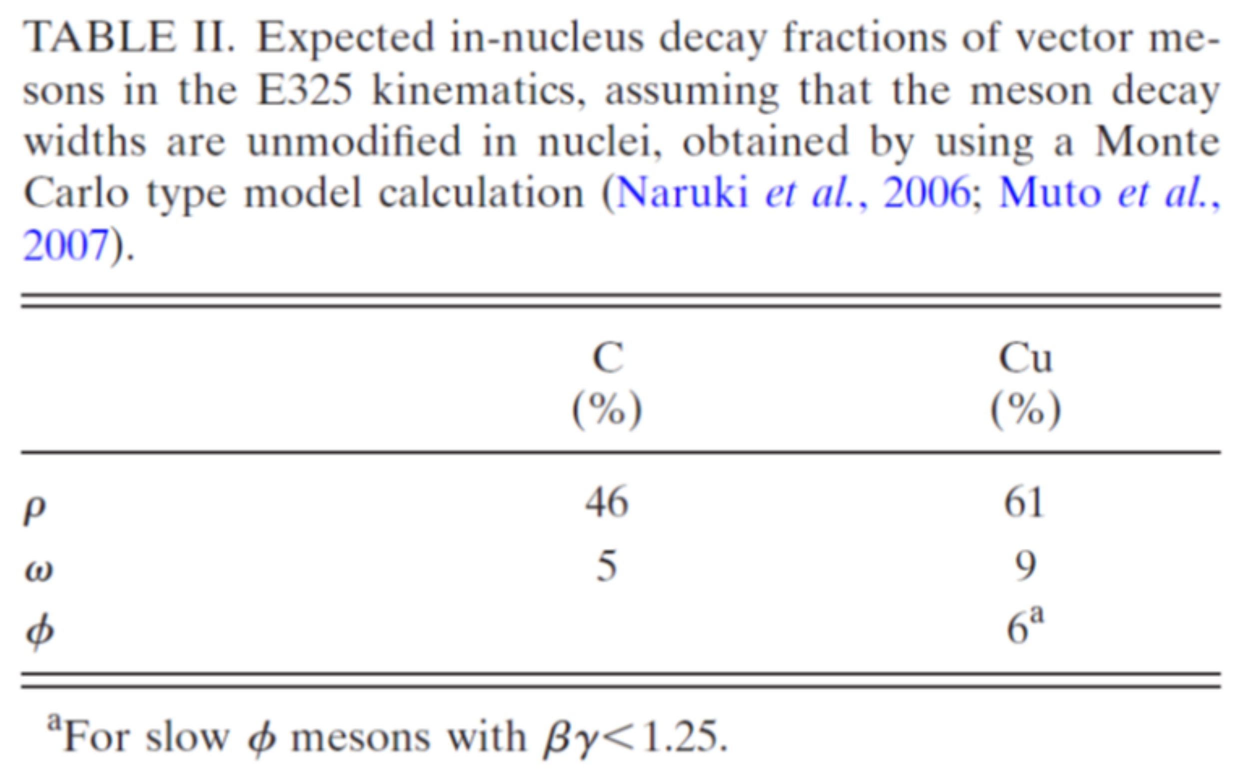


TABLE II. Expected in-nucleus decay fractions of vector mesons in the E325 kinematics, assuming that the meson decay widths are unmodified in nuclei, obtained by using a Monte Carlo type model calculation (Naruki *et al.*, 2006; Muto *et al.*, 2007).

	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).

How can this result be understood?

Let us examine the OPE at finite density more closely:

$$c_2(\rho) = \ c_2(0) + \rho\Big[\underset{\underset{-83\ \text{MeV}}{\Big\updownarrow}}{-\tfrac{2}{27}M_N^0} + \underset{\underset{2.2\sigma_{sN}}{\Big\updownarrow}}{2m_s\langle N|\bar{s}s|N\rangle} + \underset{\underset{38\ \text{MeV}}{\Big\updownarrow}}{A_1^s M_N} \ \underset{\underset{-31\ \text{MeV}}{\Big\updownarrow}}{-\tfrac{7}{12}\tfrac{\alpha_s}{\pi}A_2^g M_N}\Big]$$

↳ $\sim 2.2\rho\Big[(\frac{\sigma_{sN}}{1\text{MeV}}) - 33\Big]\text{MeV}$

↳ Dimension 4 terms governs the behavior of the φ meson

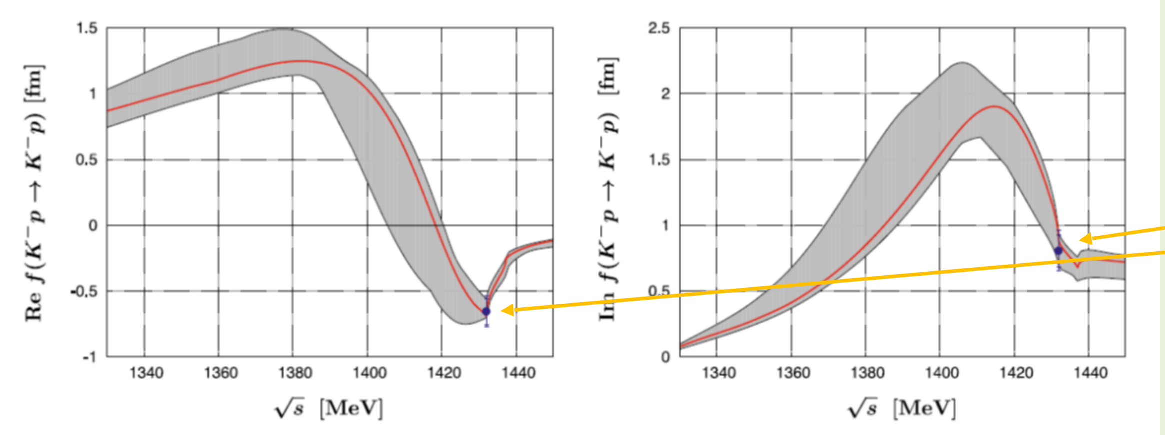
More on the free KN and K̄N scattering amplitudes

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

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

For K̄N: 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)