# $\phi$ mesons in cold nuclear matter with resonant $\phi$ $N$ interactions

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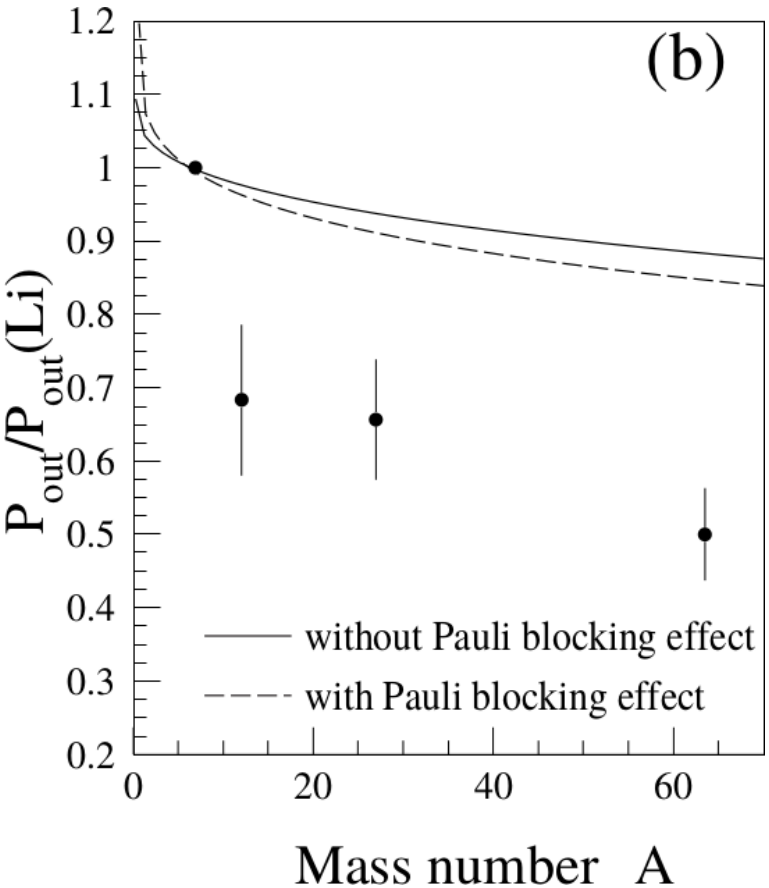
# Contents

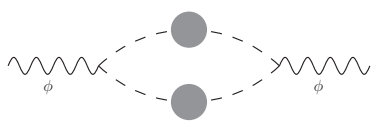
# Motivation

## LEPS photoproduction

$\phi \to K^+K^-$ Ishikawa et al., PLB 608 (2005) 215




- The higher the atomic mass, the lower the transparency.
- Experimental observation of the $\phi$ in-medium transparency much lower than theoretical predictions.

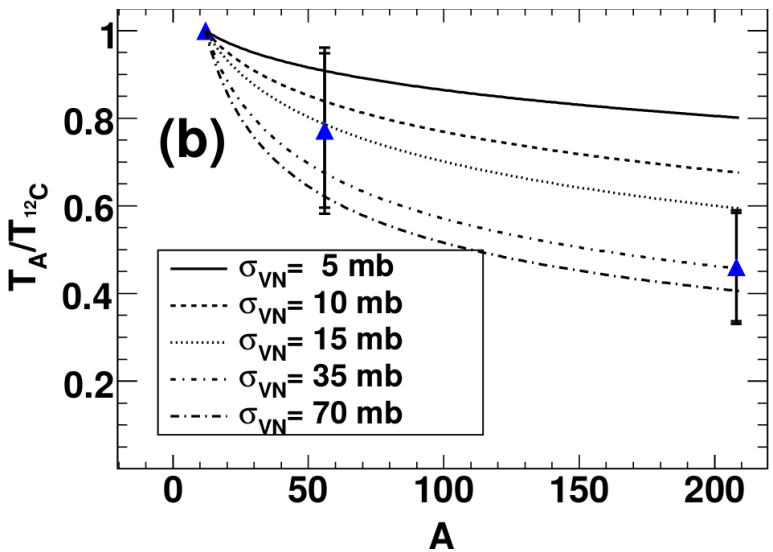



Cabrera et al., NPA 733 (2004) 130

# $\phi$ nuclear transparency ratio

## CLAS photoproduction

$\phi \rightarrow e^+e^-$ Wood et al., PRL 105 (2010) 112301

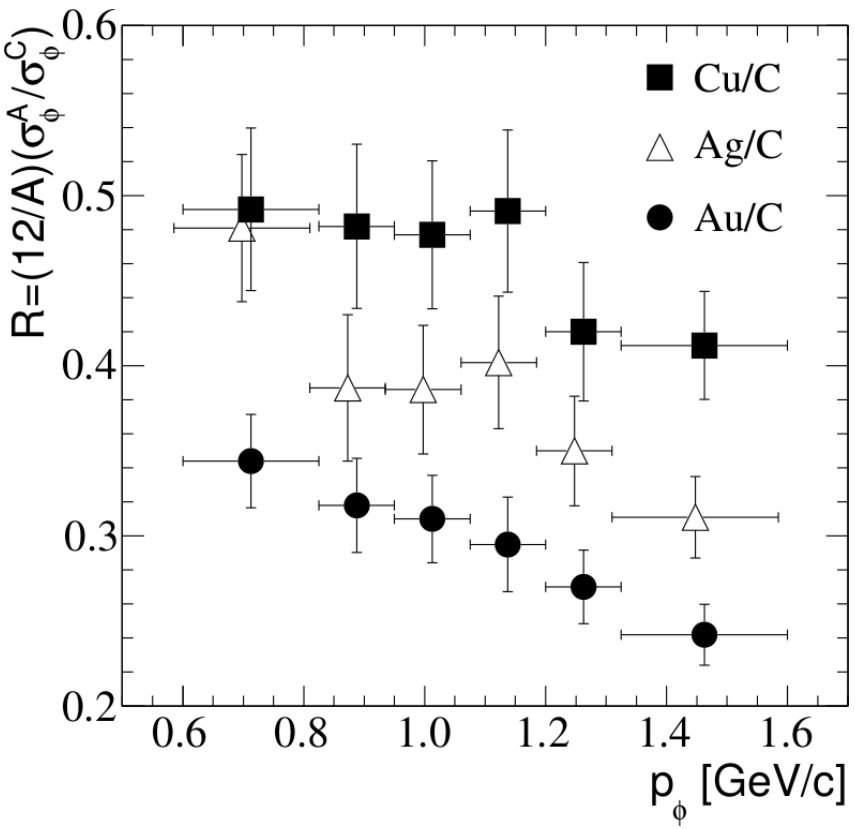



- Glauber calculations with ever growing cross sections.
- High in-medium absorption effects!
- Additional mechanisms needed.

# Momentum dependence

## COSY-ANKE@Jülich $p$ $A$ collisions

$\phi \to K^+K^-$ Hartmann et al., PRC 85 (2012) 035206

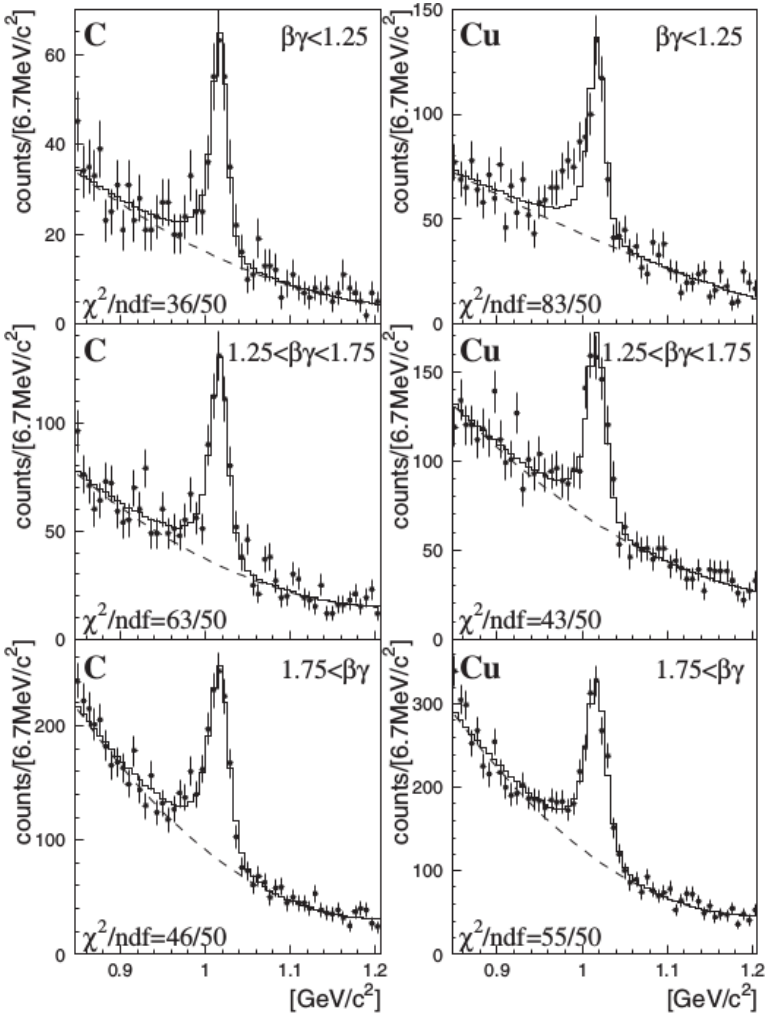



- **Recent results with momentum binning!**
- The transparency ratio **decreases** with momentum.

# Invariant mass distribution

## KEK-PS-E325 $p$ $A$ collisions

$\phi \rightarrow e^+e^-$ Muto et al., PRL 98 (2007) 042501




- For small velocities a shoulder appears to the left of the peak.
- Possible explanation: in-medium mass shift and some broadening!
- Fits with these assumptions reproduce data well.

# Summary of photoproduction and proton collision

**Large absorption in nuclei**
Widths order of magnitude higher than in vacuum:
$\sim 4$ MeV $\Longrightarrow 15 \sim 100$ MeV

Small in-medium **mass shift**

Medium effects **larger than predicted by theoretical models**
from in-medium decay to $\bar{K}\ K$
(In vacuum 83% of the contribution)

# Vector mesons in nuclear medium

- $\rho$, $\omega$ and $\phi$: **Probes with little distortion!**

  Decay into $l^+l^-$ and photons $\Rightarrow$ No strong interaction!
- $\phi$ and $\bar{K}$ $K$ dynamics strongly related. Probe of:
  - chiral dynamics
  - exotic atoms
  - properties of compact stellar objects

# Vector mesons in nuclear medium

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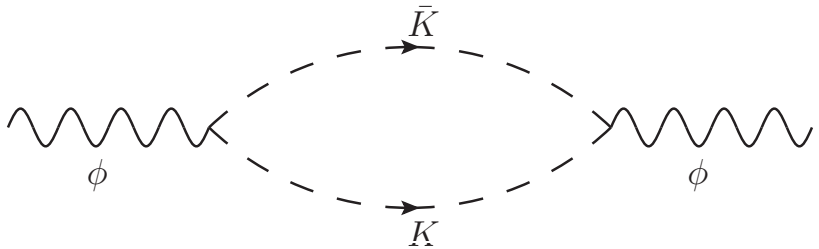
- $\phi$ and $\bar{K}$ $K$ dynamics strongly related. Probe of:
  - chiral dynamics
  - exotic atoms
  - properties of compact stellar objects
- Recent heavy-ion collision experiments:
  - BES at RHIC Blume and Markert, PPNP 66 (2011) 834
  - HADES at GSI Agakishiev et al., EPJA 49 (2013) 34
  - ALICE at LHC Abelev et al., PRC 91 (2015) 024609

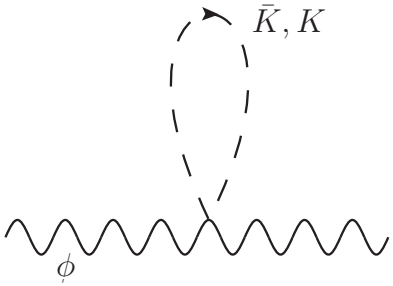
**Deep sub-threshold $\phi$ production**

1.23 A GeV Au+Au collisions Lorenz et al., NPA 931 (2014) 785

Possible missing mechanisms: $\phi$ production reactions, broadening, mass shift

# Previously done: $\phi$ self-energy from $\phi \to \bar{K}K$ decay



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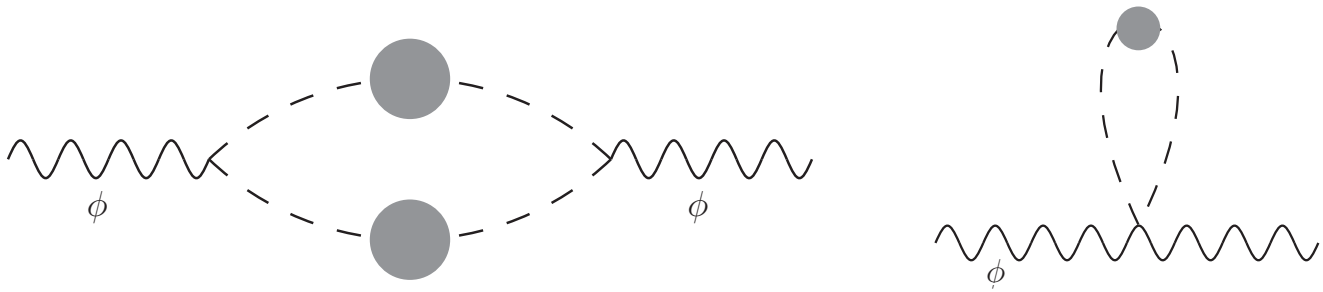


- The kaon propagators have to be dressed

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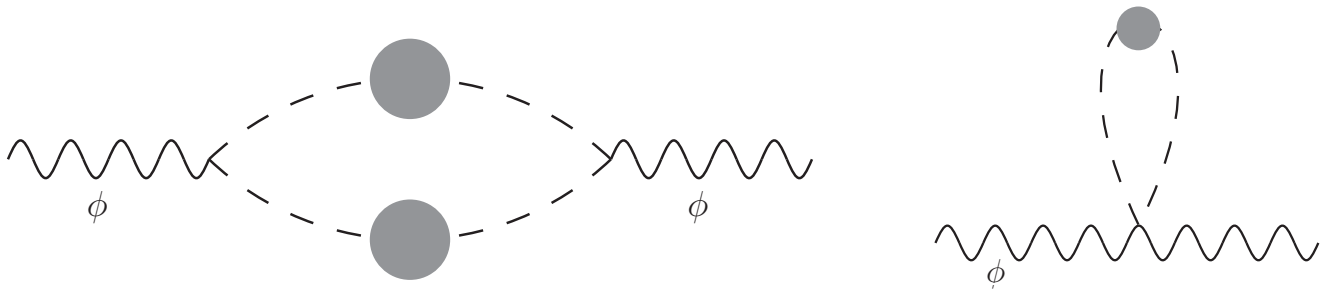
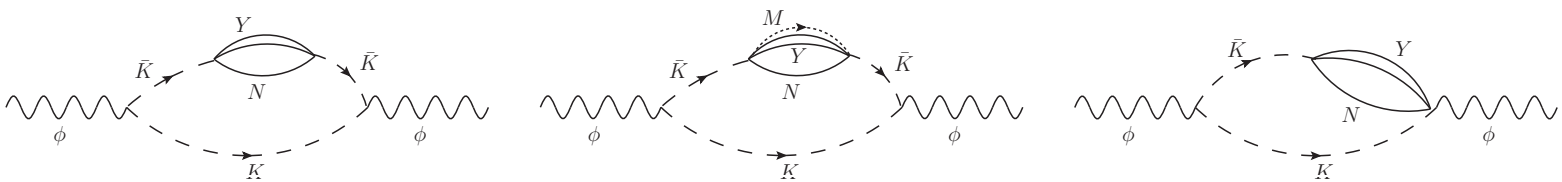


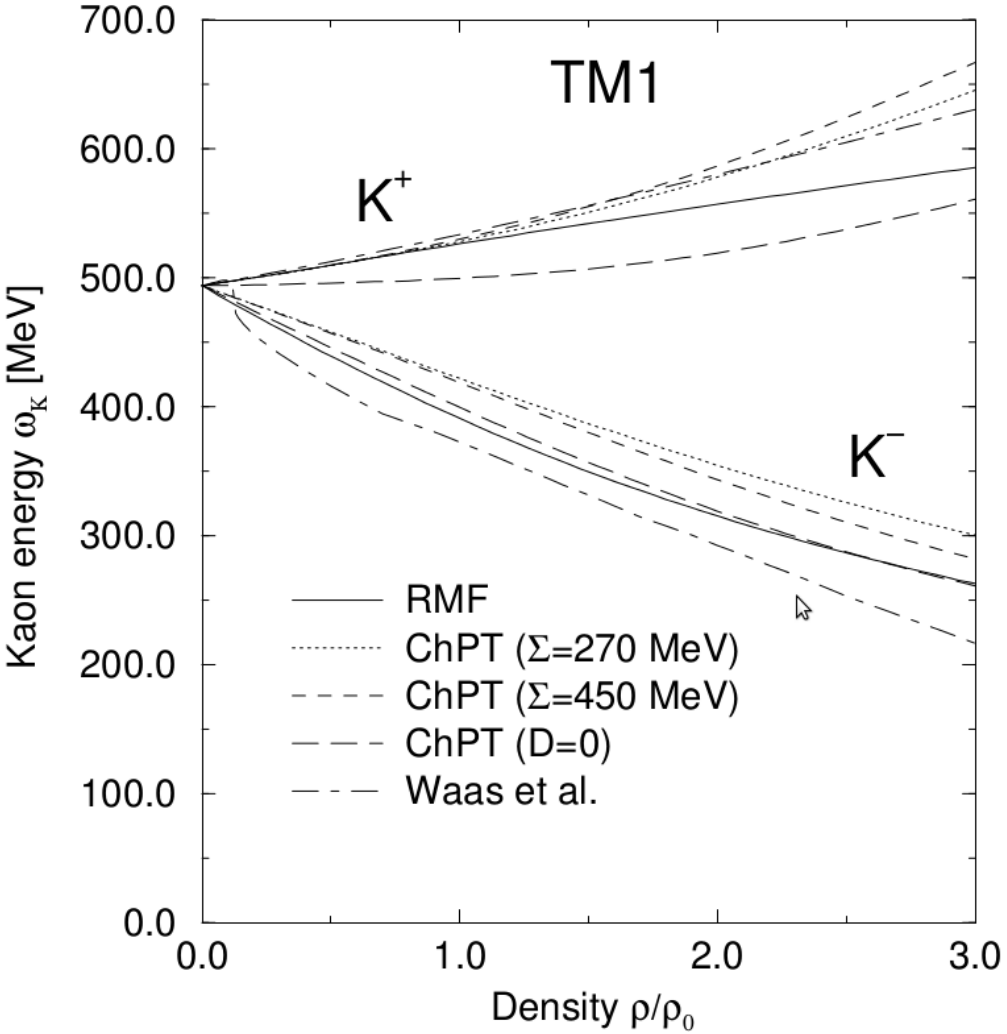

- The kaon propagators have to be dressed
- The $\bar{K}YN(M)$ $P(S)$-wave couplings: $SU(3)$ meson-baryon ChPT

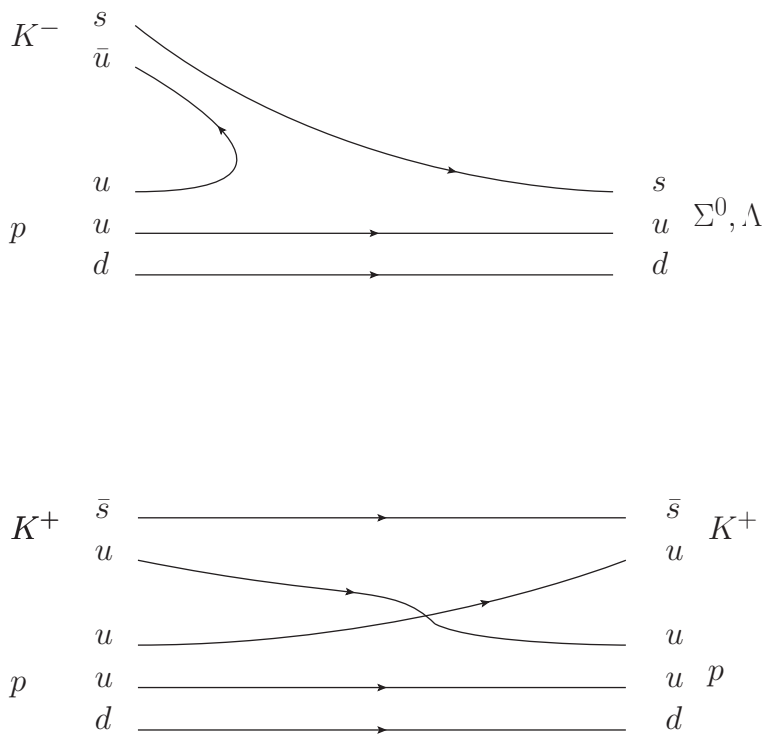



Ko et al., PRC 45 (1992) 1400
Kuwabara and Hatsuda, PTP 94 (1995) 1163
Klingl et al., NPA 624 (1997) 527
Klingl et al., PLB 431 (1998) 254
Oset and Ramos, NPA 679 (2001) 616

Oset et al., PLB 508 (2001) 237
Alvarez-Ruso and Koch, PRC 65 (2002) 054901
Cabrera and Vicente Vacas, PRC 67 (2003) 045203
Cabrera et al., NPA 733 (2004) 130

# In-medium splitting of kaon properties




Schaffner et al., NPA 625 (1997) 325

# Theoretical status of in-medium kaons

- Low energies: $s$-wave interaction
  - $K\ N$ smooth, mild repulsion at normal density
  - $\bar{K}\ N$ strongly dominated by sub-threshold $\Lambda(1405)$: attraction and broadening
- High energies: higher waves

  $\bar{K}\ N \rightarrow Y$ excitations

Lutz, PLB426 (1998) 12
Ramos and Oset, NPA671 (2000) 481
Tolos et al., NPA690 (2001) 547
Tolos et al., PRC74 (2006) 015203
Lutz et al., NPA808 (2008) 124

Tolos et al., PRC78 (2008) 045205
Lutz et al., NPA808 (2008) 124
Tolos et al., PRC78 (2008) 045205
Cabrera et al., PRC 90 (2014) no.5 055207

# The $\phi \to \bar{K} K$ self-energy

$$\Pi_{\phi}^{K\bar{K}}(q) =$$

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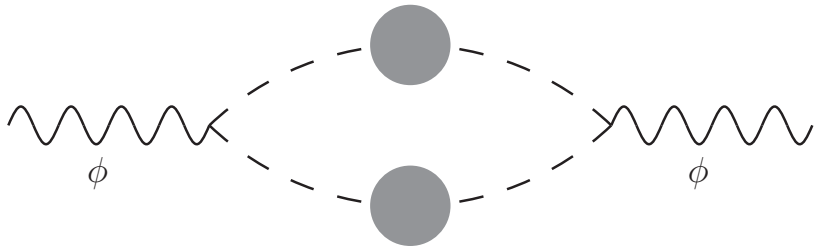


$$\Pi_{\phi}^{K\bar{K}}(q) = 2ig_{\phi}^{2}\frac{4}{3}\int \frac{\mathrm{d}^4k}{(2\pi)^4}\left[\frac{(q\cdot k)^2}{q^2} - k^2\right] D_K(q-k)D_{\bar{K}}(k)$$

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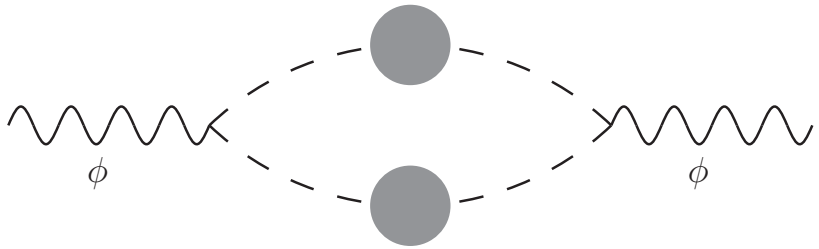


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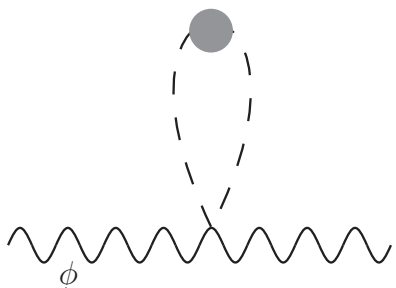
$$-2ig_\phi^2 \int \frac{d^4k}{(2\pi)^4} \left[ D_K(k) + D_{\bar{K}}(k) \right]$$



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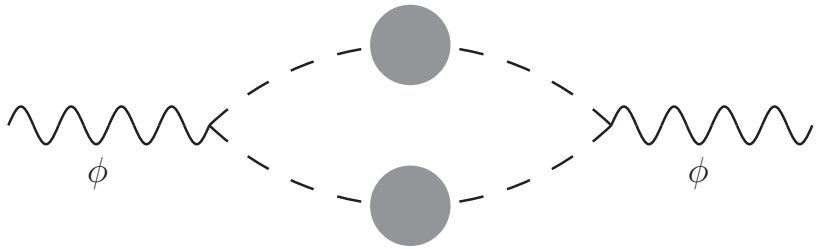


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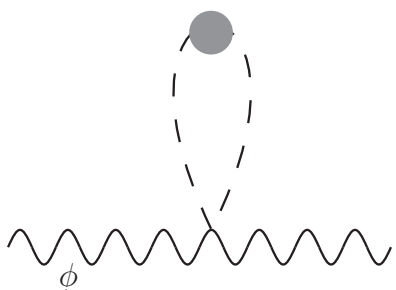
$$-2ig_\phi^2 \int \frac{d^4k}{(2\pi)^4} \left[ D_K(k) + D_{\bar{K}}(k) \right] + \text{vertex corrections}$$



# In-medium kaon propagator and spectral function

**Dressed propagator**

$$D_{\bar{K}(K)}(q^0, \vec{q}; \rho) = \int_0^\infty \mathrm{d}\omega \left( \frac{S_{\bar{K}(K)}(\omega, \vec{q}; \rho)}{q^0 - \omega + \mathrm{i}\eta} - \frac{S_{K(\bar{K})}(\omega, \vec{q}; \rho)}{q^0 + \omega - \mathrm{i}\eta} \right)$$

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**Spectral function**

$$S_{\bar{K}(K)}(q^0, \vec{q}; \rho) = -\frac{1}{\pi} \frac{\mathrm{Im}\Pi_{\bar{K}(K)}(q^0, \vec{q}; \rho)}{|(q^0)^2 - \vec{q}^2 - m_K^2 - \Pi_{\bar{K}(K)}(q^0, \vec{q}; \rho)|^2}$$

# In-medium $\phi$ self-energy from $\phi$ $B$ interactions

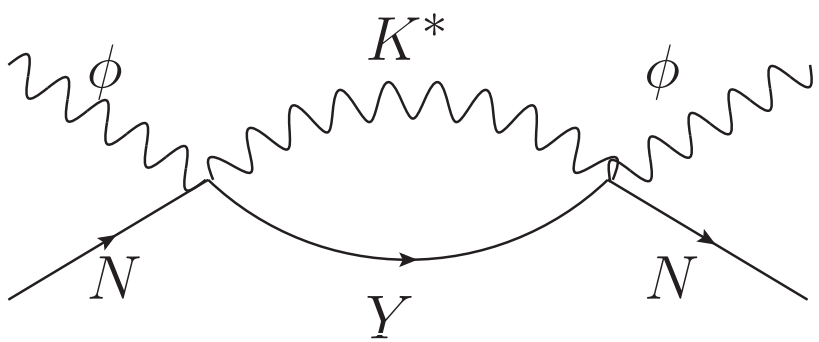
## New work

- Additional contribution to $\phi$ self-energy from direct interactions with baryons.

# In-medium $\phi$ self-energy from $\phi$ $B$ interactions

## New work

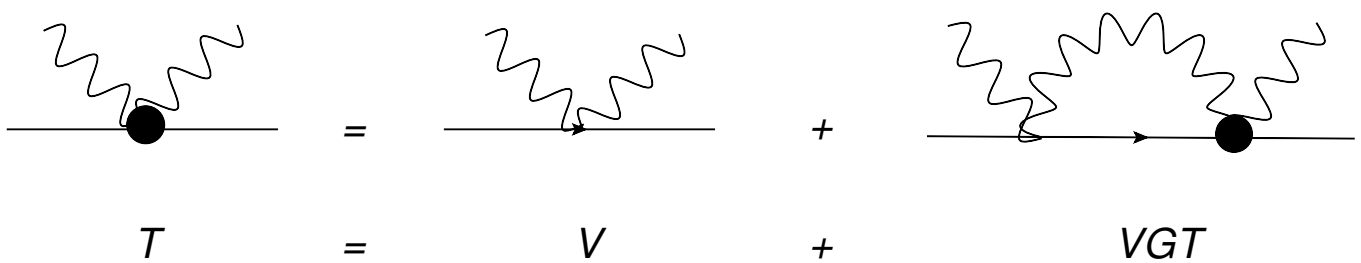
- Additional contribution to $\phi$ self-energy from direct interactions with baryons.
- Direct coupling to nucleon: OZI forbidden! Highly suppressed.
- BUT! $\phi$ $N$ interactions via hyperon loops have been studied.



# Unitarized coupled channels

Comparing two unitarized coupled-channel models:

- HLS formalism. Oset and Ramos, EPJA 44 (2010) 445
  Vector-meson exchange dominates interactions with baryons.
- $SU(6)$ spin-flavor symmetry extension of the chiral Lagrangian. Romanets et al., PRD 85 (2012) 114032

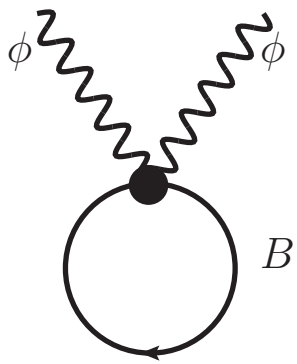


# Contribution from resonant meson-baryon interaction

- Directly above $\phi$ $N$ threshold $\sqrt{s_{\phi\ N}} \sim 2 - 2.1$ GeV: **$N^*$ resonances are generated!** For HLS degenerate in $J^P = 1/2^-, 3/2^-$

- Contribution to self-energy:

$$\Pi_\phi^{\phi N} = \int \frac{\mathrm{d}^3 p}{(2\pi)^3} n(\vec{p})\, T_{\phi N}$$ ✓ Fermi motion



# Medium modifications on $\phi$ $N$ scattering amplitude

## Additionally included in this work

✓ Pauli blocking (affects only nucleons)

Reminder! $T = V + VGT$

$$\delta G^{\text{Pauli}}(P,\rho) = -\int \frac{\mathrm{d}^3 q}{(2\pi^3)} \frac{M_N}{E_N(\vec{p})} \frac{n(\vec{p})}{[P^0 - E_N(\vec{p})]^2 - \omega_\phi^2(\vec{q}) + \mathrm{i}\epsilon}\Big|_{\vec{p}=\vec{P}-\vec{q}}$$

## Future work

✗ Baryon binding potentials

✗ Self-consistency: dressing of $\phi$ propagator in $\phi N$ loop

# Calculated quantities

**$\phi$ nuclear optical potential**

$$V_{\text{opt}} = \frac{\Pi_\phi}{2\omega}$$

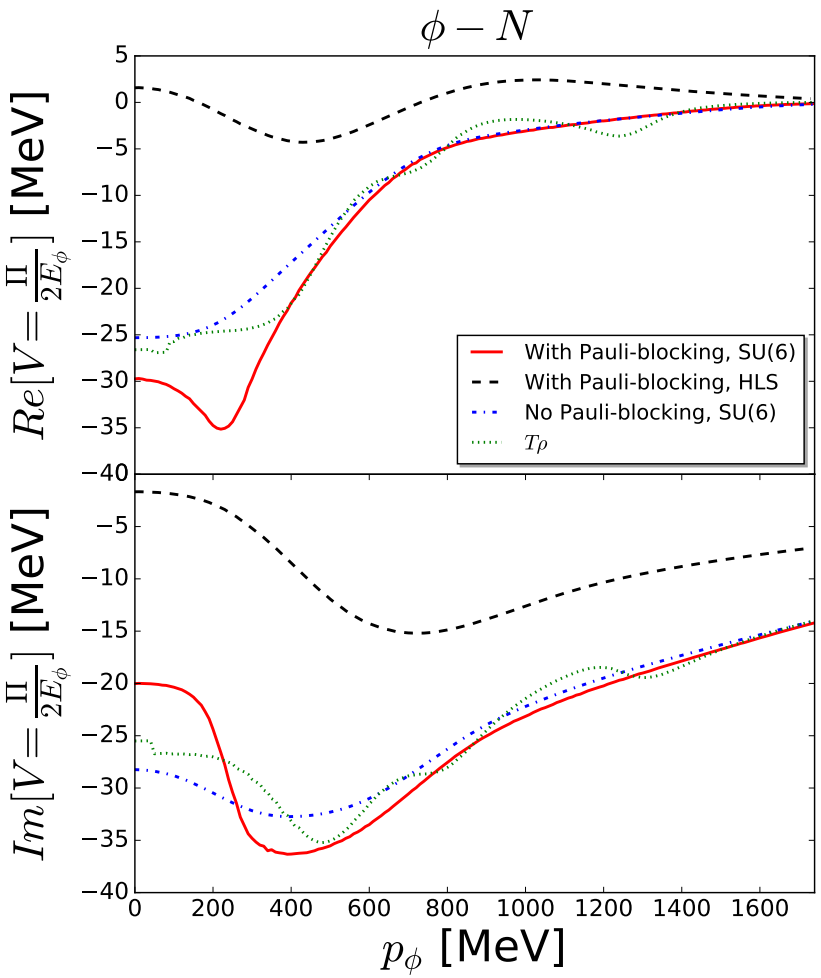
$\text{Re}(V_{\text{opt}}) \sim$ mass shift

$\text{Im}(V_{\text{opt}}) \sim$ width enhancement

**Spectral function**

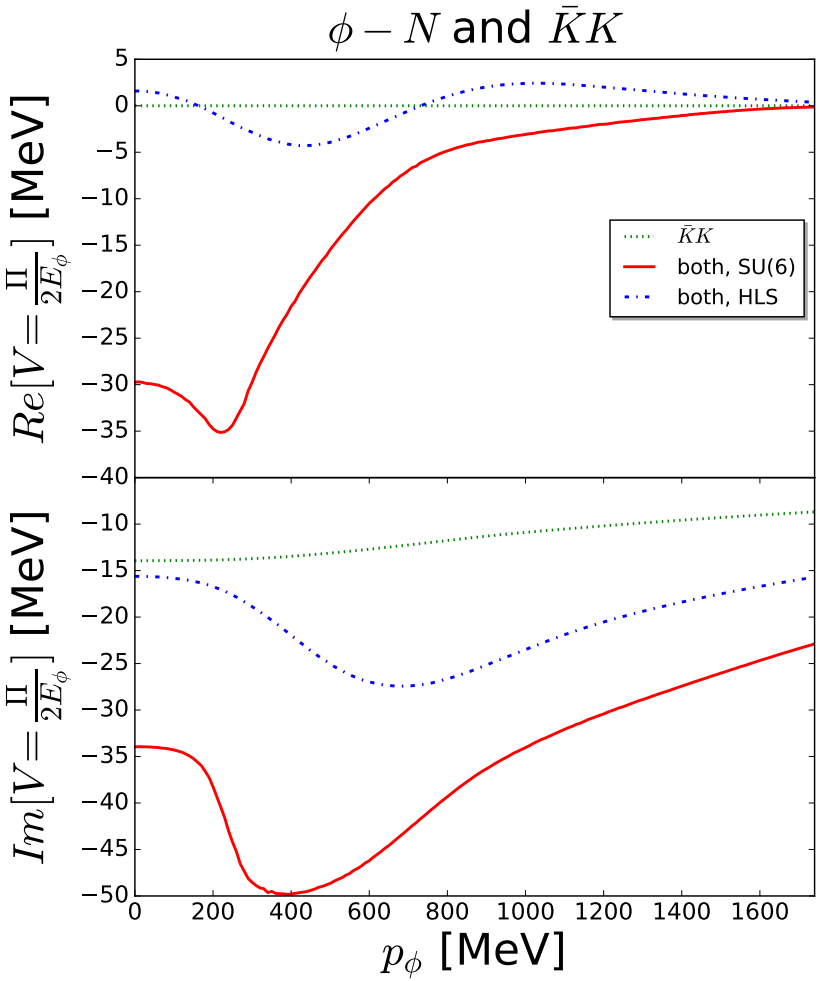
$$S(\omega, \vec{q}) = -\frac{1}{\pi} \frac{\text{Im}\Pi_\phi(\omega, \vec{q})}{|\omega^2 - \vec{q}^2 - m_\phi^2 - \Pi_\phi(\omega, \vec{q})|^2}$$

# $\phi$ optical potential: $\phi$ $N$ contribution



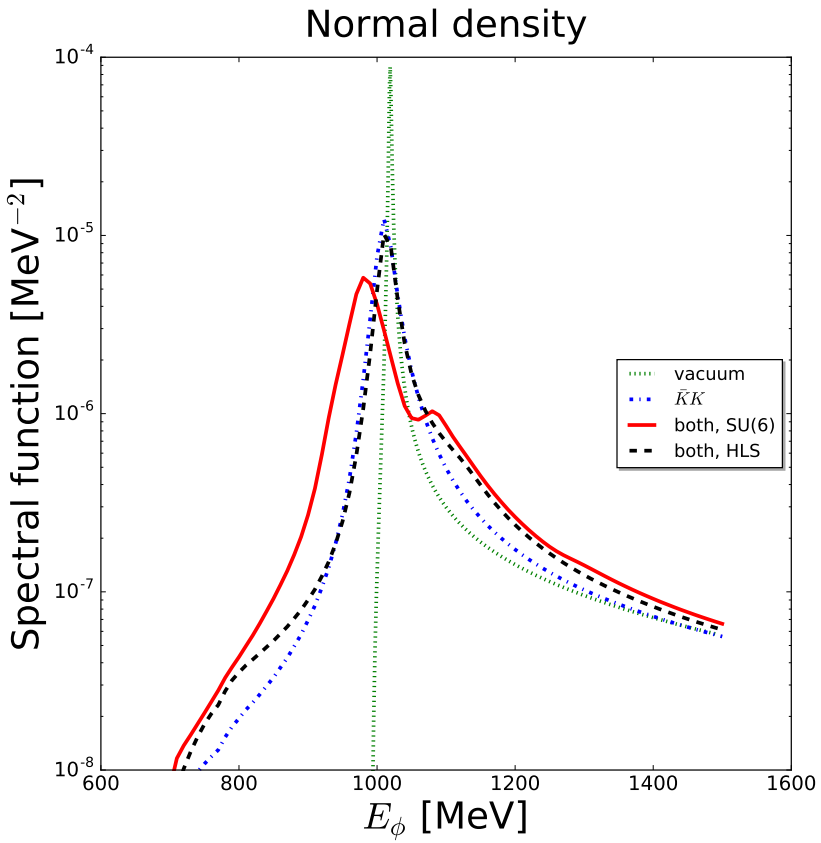

- $\phi$ $N$ interaction induces an attractive potential.
- Considerable energy dependence due to resonant states above threshold.

# $\phi$ optical potential: $\phi\ N + \bar{K}\ K$



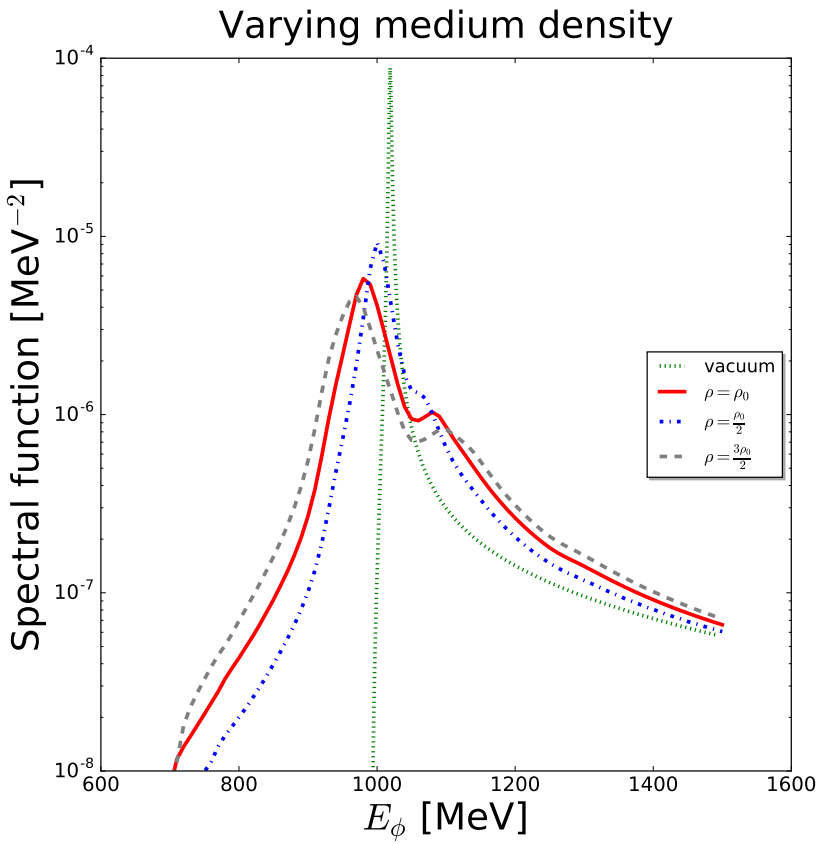

- The contributions from $\phi\ N$ interactions appear to be **larger** than those from $\bar{K}\ K$!
- Widths up to $\sim 70$ MeV at $\rho = \rho_0$ for $\phi$ mesons at rest.

# Spectral function




- Broadening of the vacuum spectral function due to $\bar{K}$ $K$ cloud, with vanishing mass shift.
- Further broadening due to $\phi N$ interaction, new structure.
- Negative mass shift in $SU(6)$ model.
- Second shoulder above the $\phi$ mass — excitation of $N^* N^{-1}$ modes.

# Spectral function at different matter densities




- Shift of the peak to lower $\phi$ energies with rising medium density.
- Further broadening.
- More visible shoulder.

# Summary and outlook

- Resonant $\phi N$ **interactions** are implemented as **novel mechanisms** of $\phi$ in-medium properties.
- Strength similar to $\bar{K}$ $K$-cloud effects (or even stronger).
- $N^*$-like states are generated immediately above $\phi N$ threshold.
- **Large $\phi$ broadening in line with recent nuclear production experiments.**

ありがとう　ございます!

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To do in the future:

- Baryon binding potentials and self-consistency.
- Finite temperature effects: heavy-ion collisions.
- Evaluation of transparency ratio with updated $\phi$ self-energy.

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