Coupled-channel unitarized theory in matter: strangeness and charm in the nuclear medium

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IEEC

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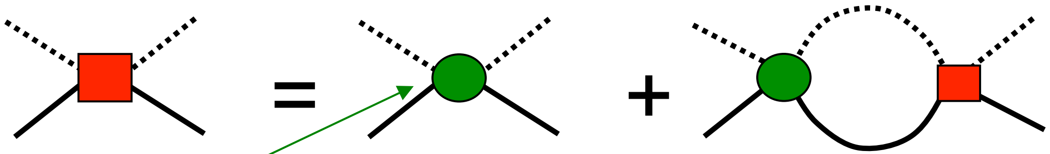
Self-consistent coupled-channel unitarized theory in matter: meson-baryon case

Free space

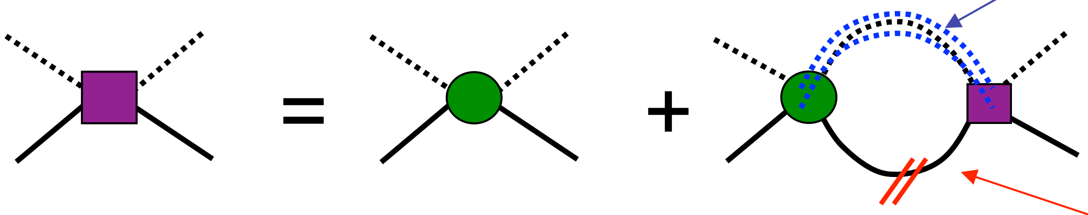


transition potential

$$T_{ij} = V_{ij} + V_{il}\, G_l\, T_{lj}$$

meson dressing

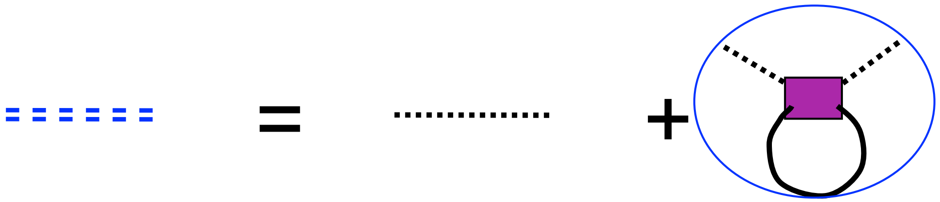
Medium



Pauli blocking and baryon dressing

$$T_{ij}(\rho,T) = V_i + V_{il}\, G_l(\rho,T)\, T_{lj}(\rho,T)$$

Dressed meson:



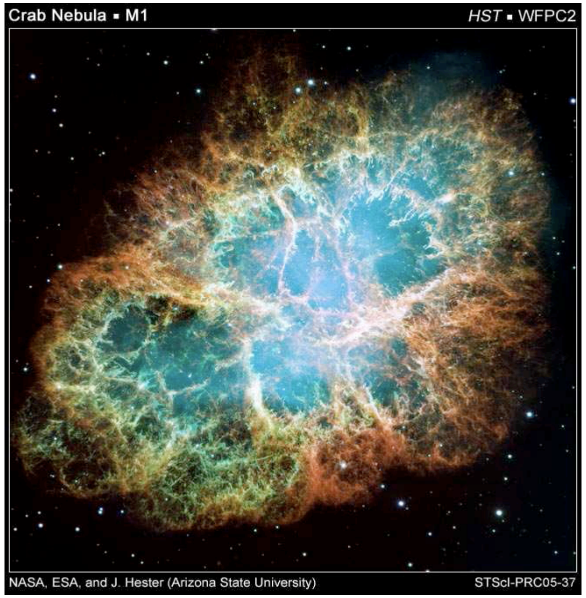
Π self-energy

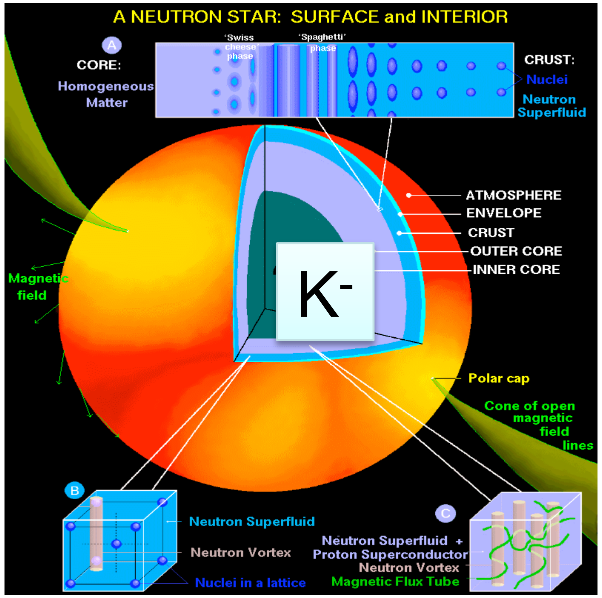
Strange mesons: $\bar{K}$, K & $\bar{K}^*$

- In-medium properties of K and $\bar{K}$ mesons
- $\bar{K}^*$ properties in nuclear matter

in collaboration with
D. Cabrera, R. Molina, A. Ramos and E. Oset

Experimental scenarios



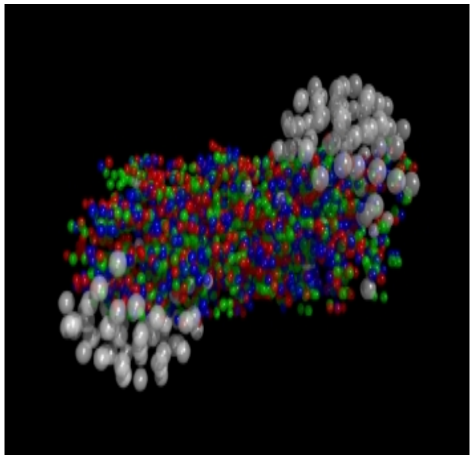


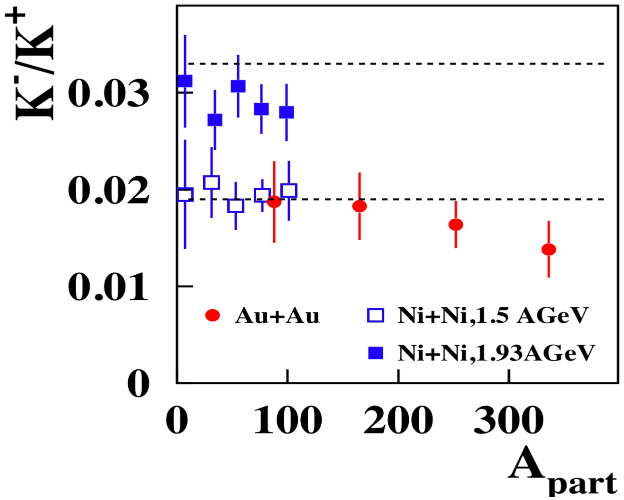
Kaon condensation in neutron stars

Kaplan and Nelson '86,..

GSI data (KaoS/FOPI/..)

Foerster et al (KaoS) '07,
Crochet et al (FOPI)'00,
Wisniewski et al (FOPI) '00,
Fuchs'06,..





Foerster (KaoS) '07

In-medium theoretical models for kaons

- Relativistic mean field models *Schaffner et al '94; ..*
- Phenomenological models *Friedman and Gal '07; ..*

$U_{K^-}(\rho_0) \sim$ -100 to -200 MeV and $U_K(\rho_0) \sim$ 30 MeV

- Unitarized theories in coupled-channels using meson-exchange models or chiral dynamics

$U_{K^-}(\rho_0) \sim$ -50 to -80 MeV and $U_K(\rho_0) \sim$ 30 MeV

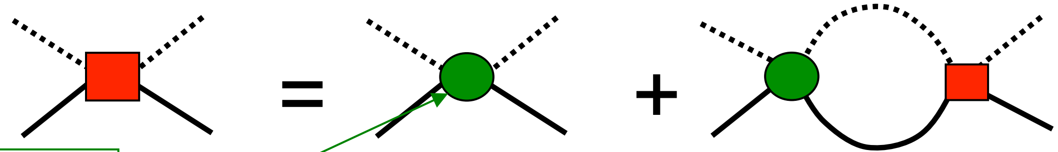
- ***s-wave*** KN interaction governed by $\Lambda(1405)$
  attraction due to modified $\Lambda(1405)$ in the medium[1,2,3] using a self-consistent coupled-channel approach[3,4,5] :
  - bound K^- states by 30-60 MeV but with comparable widths [3,5]
  - and $\Lambda(1405)$ is a superposition of two states[6]

- ***p-wave* (and beyond)** contributions to KN interaction[5,7]
  not important for atoms but important for HIC (large momentum)[8]

[1]Koch '94; Waas et al, '97
[2]Lutz '98; Schaffner-Bielich et al, '00
[3]Ramos and Oset '00
[4]Kaiser et al '97;Oset and Ramos '98; Lutz et al '02
[5]LT et al '01; LT et al '02
[6]Jido et al '03; Magas et al '05
[7]Jido et al '02; LT et al '06; Lutz et al '02; LT et al '08; Lutz et al '08
[8]LT et al '03; Cassing et al '03

Kaons in dense nuclear matter:
Selfconsistent coupled-channel formalism

Free space

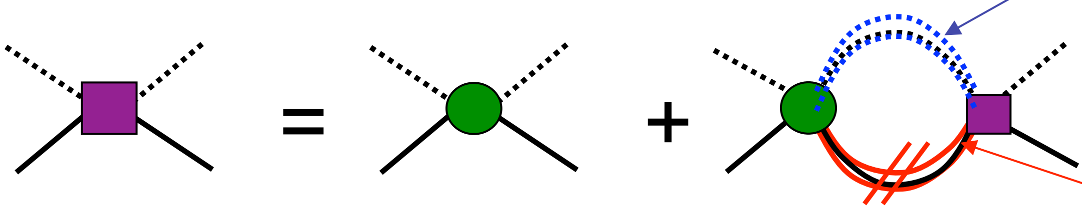


from LO χ lagrangian
in low-energy approx.
$(q^2/M_V^2 \rightarrow 0)$: WT

$$T_{ij} = V_{ij} + V_{il}\ G_l\ T_{lj}$$

meson dressing

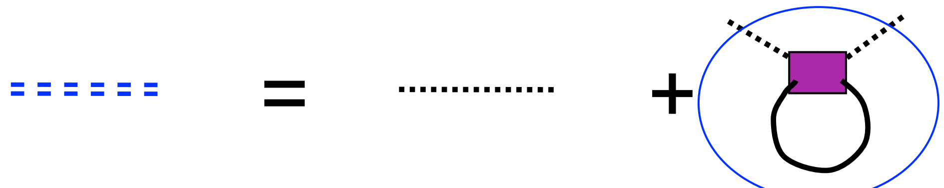
Medium



Pauli blocking
and
baryon dressing

$$T_{ij}(\rho,T) = V_{ij} + V_{il}\ G_l(\rho,T)\ T_{lj}(\rho,T)$$

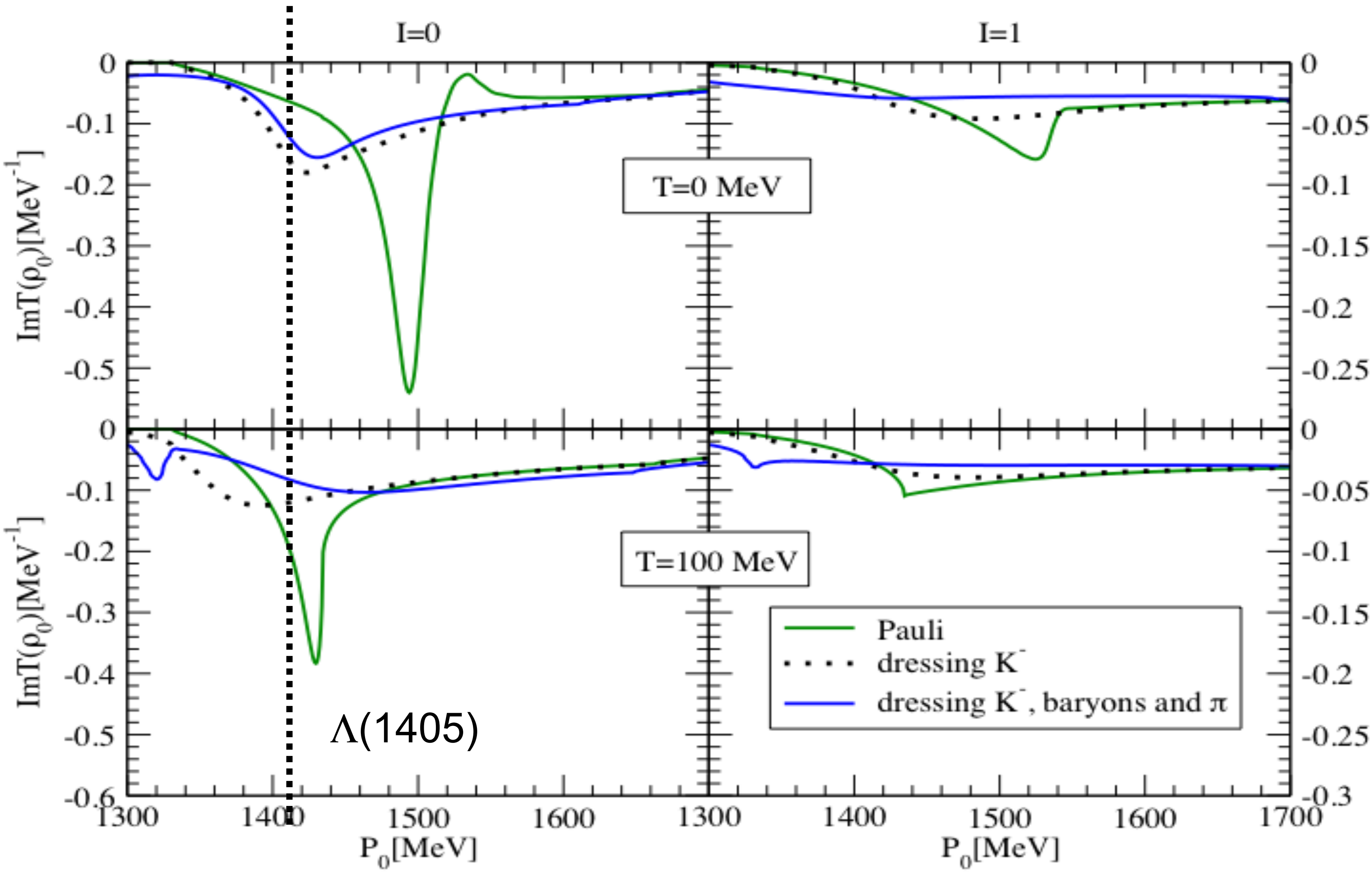
Dressed meson:



Π self-energy

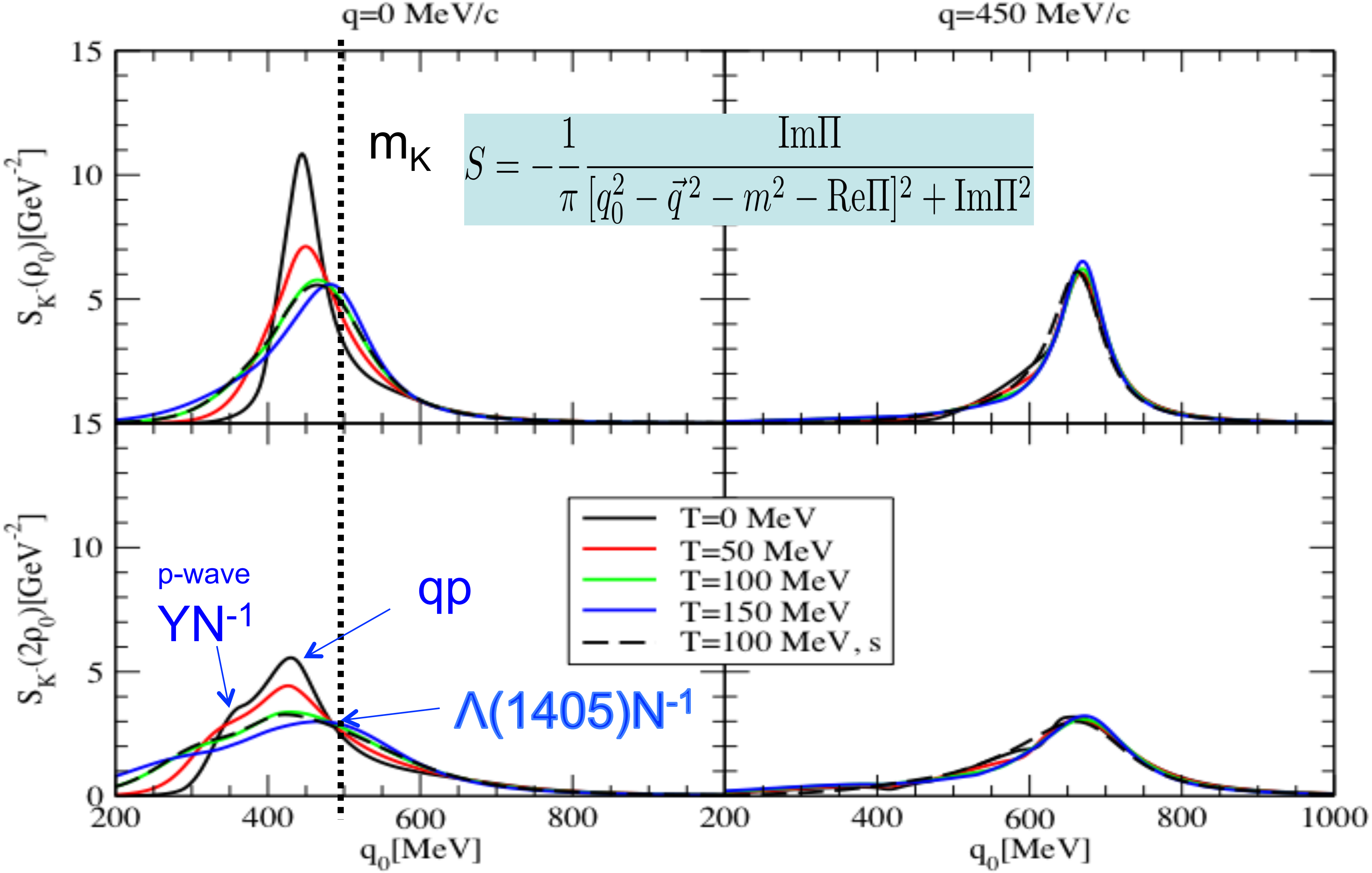
$\bar{K}$ meson

The model generates dynamically the $\Lambda(1405)$



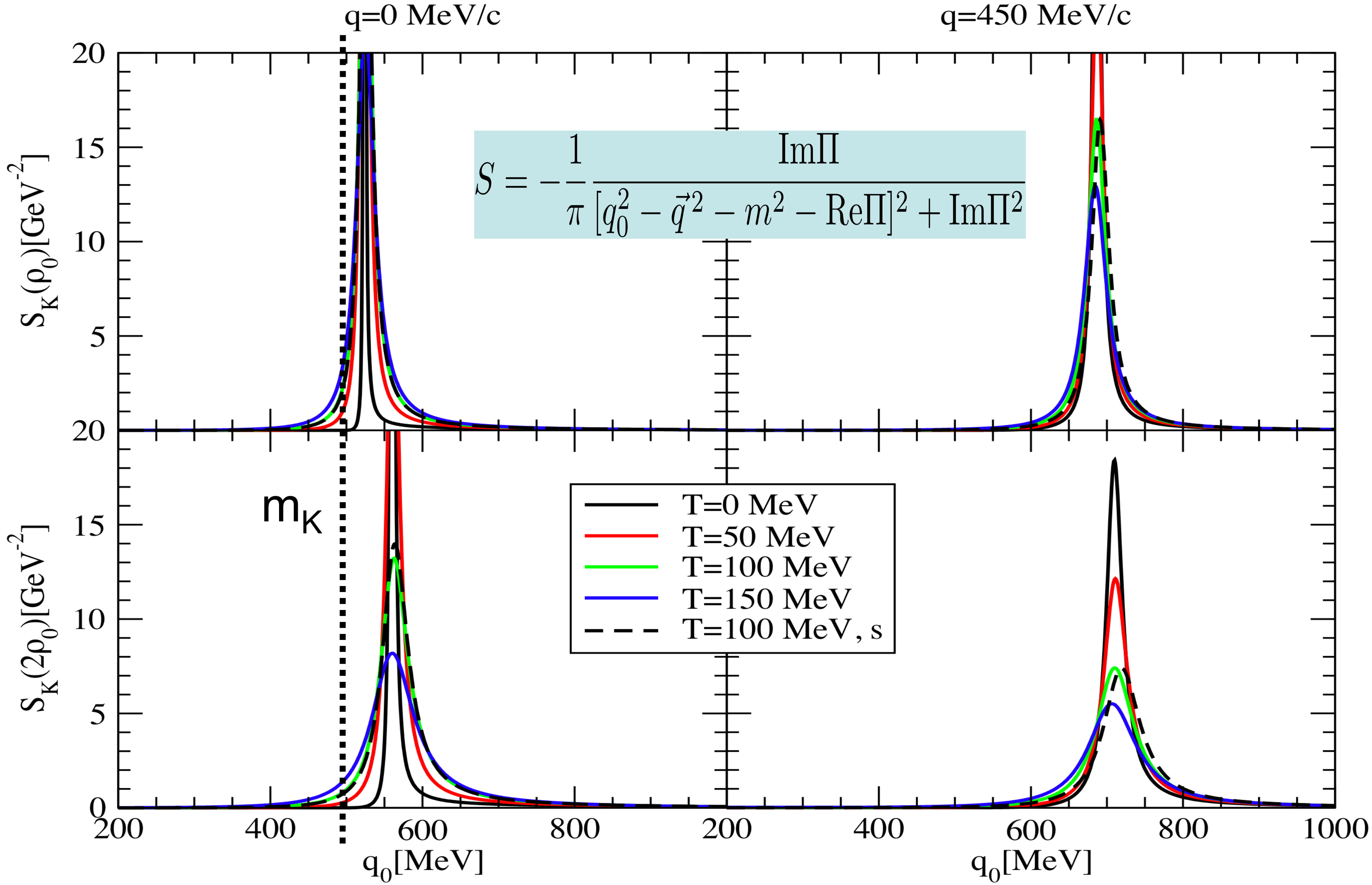
LT, Ramos and Oset, PRC 74 (2006) 15203
LT, Cabrera and Ramos, PRC 78 (2008) 045205

$\bar{K}$ meson



q=0 MeV/c
q=450 MeV/c
m_K
$S = -\frac{1}{\pi}\frac{\mathrm{Im}\Pi}{[q_0^2 - \vec{q}^{\,2} - m^2 - \mathrm{Re}\Pi]^2 + \mathrm{Im}\Pi^2}$
$S_{K^-}(\rho_0)[GeV^{-2}]$
$S_{K^-}(2\rho_0)[GeV^{-2}]$
15
10
5
15
10
5
0
p-wave
YN^{-1}
qp
$\Lambda(1405)N^{-1}$
T=0 MeV
T=50 MeV
T=100 MeV
T=150 MeV
T=100 MeV, s
200
400
600
800
200
400
600
800
1000
q_0[MeV]
q_0[MeV]

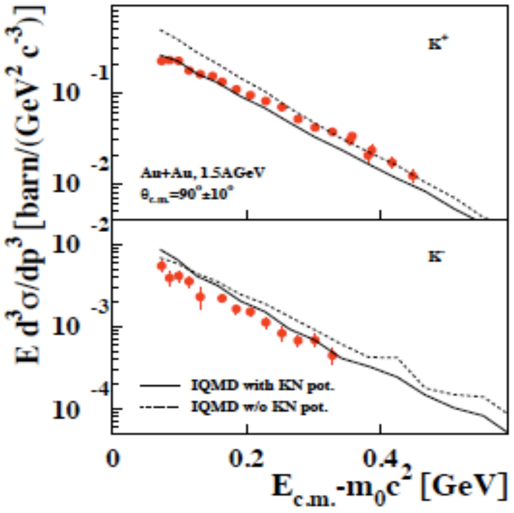
K meson



q=0 MeV/c
q=450 MeV/c
$$S = -\frac{1}{\pi}\frac{\mathrm{Im}\Pi}{[q_0^2 - \vec{q}^{\,2} - m^2 - \mathrm{Re}\Pi]^2 + \mathrm{Im}\Pi^2}$$
$S_K(\rho_0)[GeV^{-2}]$
$S_K(2\rho_0)[GeV^{-2}]$
m_K
T=0 MeV
T=50 MeV
T=100 MeV
T=150 MeV
T=100 MeV, s
q_0[MeV]
q_0[MeV]

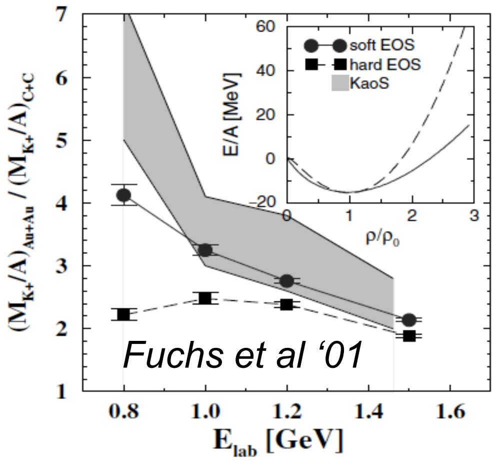
Strangeness production at GSI (KaoS)

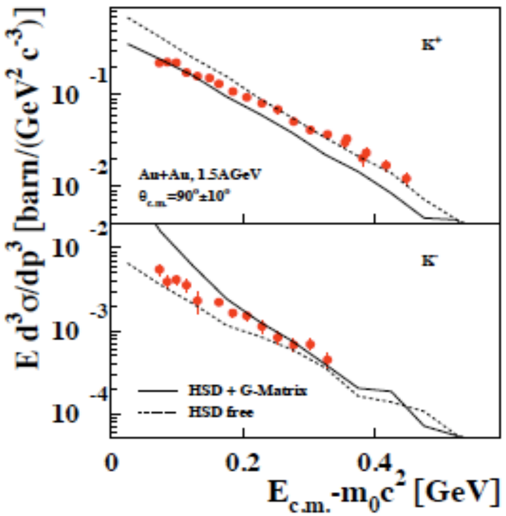
Foerster et al (KaoS) '07



From systematics of the experimental results and detailed comparison to transport model calculations:

- K^+ probe a soft EoS





- K^+ and K^- yields are coupled by strangeness exchange:

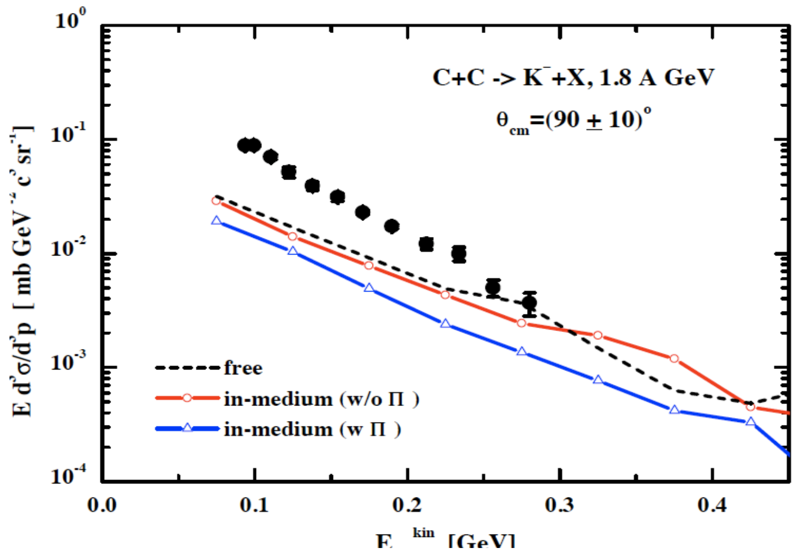
$$NN \rightarrow K^+YN$$
$$K^-N \Leftrightarrow \pi Y$$

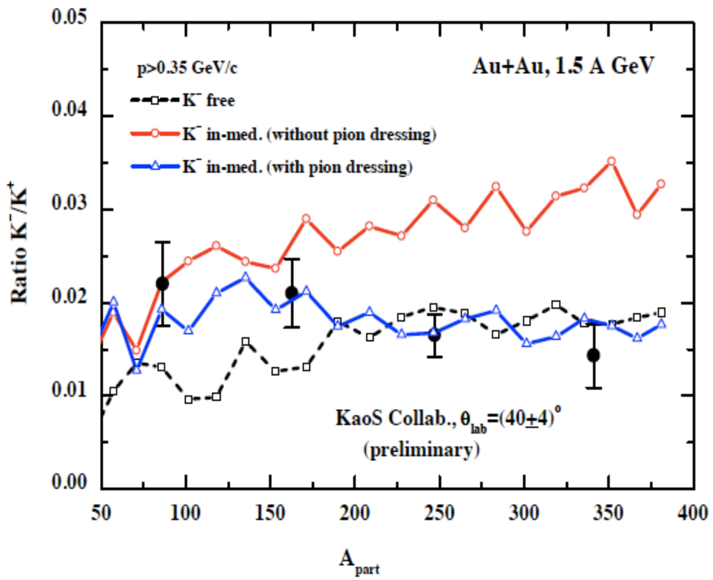
- K^+ and K^- exhibit different freeze-out conditions
- No clear conclusion about medium modifications on K^-

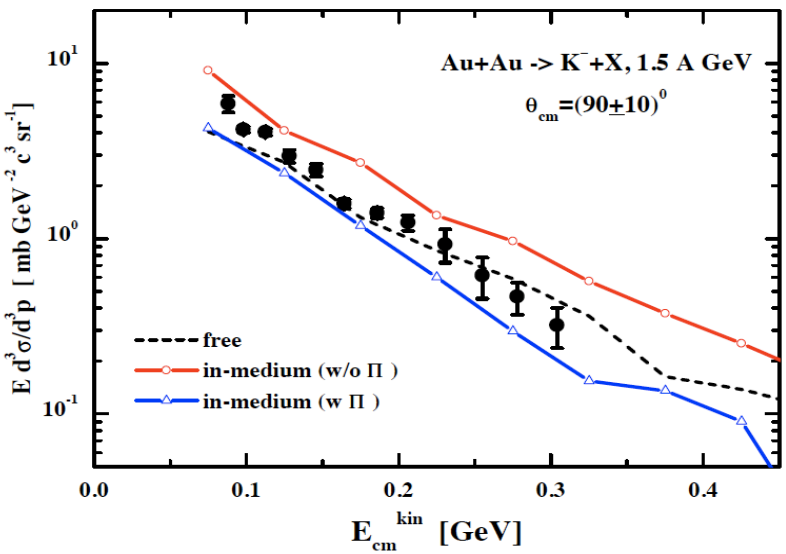
Recent report on strangeness production close to threshold in proton-nucleus and heavy-ion collisions *Hartnack et al. Phys. Rept. 510 (2012) 119*

Antikaon production in A+A at SIS within offshell model

BUU transport model with G-matrix for antikaons taking, as bare interaction, Juelich meson-exchange model *Cassing, LT, Bratkovskaya, Ramos, NPA 727 (2003) 59*







No convincing description of all spectra simultaneously.

Need of off-shell transport and a realistic many-body model for antikaons in matter

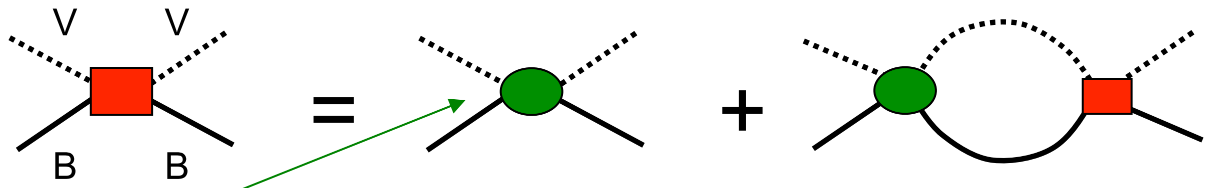
$\bar{K}^*$ meson in dense matter

Free space

within the local hidden gauge formalism

Bando, Kugo, Uehara, Yamawaki and Yanagida, PRL 54, 1215 (1985); Phys. Rep. 164, 217 (1988); Harada and K. Yamawaki, Phys. Rept. 381, 1 (2003); Meissner, Phys. Rept. 161, 213 (1988)

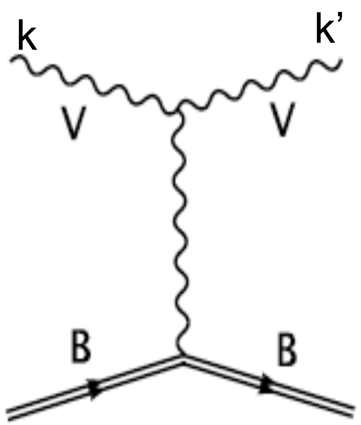
using a coupled-channel unitary approach



$\bar{K}^*N$
$\omega\Lambda$, $\omega\Sigma$
$\rho\Lambda$, $\rho\Sigma$
$\Phi\Lambda$, $\phi\Sigma$
$\bar{K}^*\Xi$

$$T_{ij} = V_{ij} + V_{il}\, G_l\, T_{lj}$$

transition potential



$$\mathcal{L}_{III}^{(3V)} = ig\langle (V^\mu \partial_\nu V_\mu - \partial_\nu V_\mu V^\mu) V^\nu \rangle$$

$$\mathcal{L}_{BBV} = g\left(\langle \bar{B}\gamma_\mu [V^\mu, B] \rangle + \langle \bar{B}\gamma_\mu B \rangle \langle V^\mu \rangle \right)$$

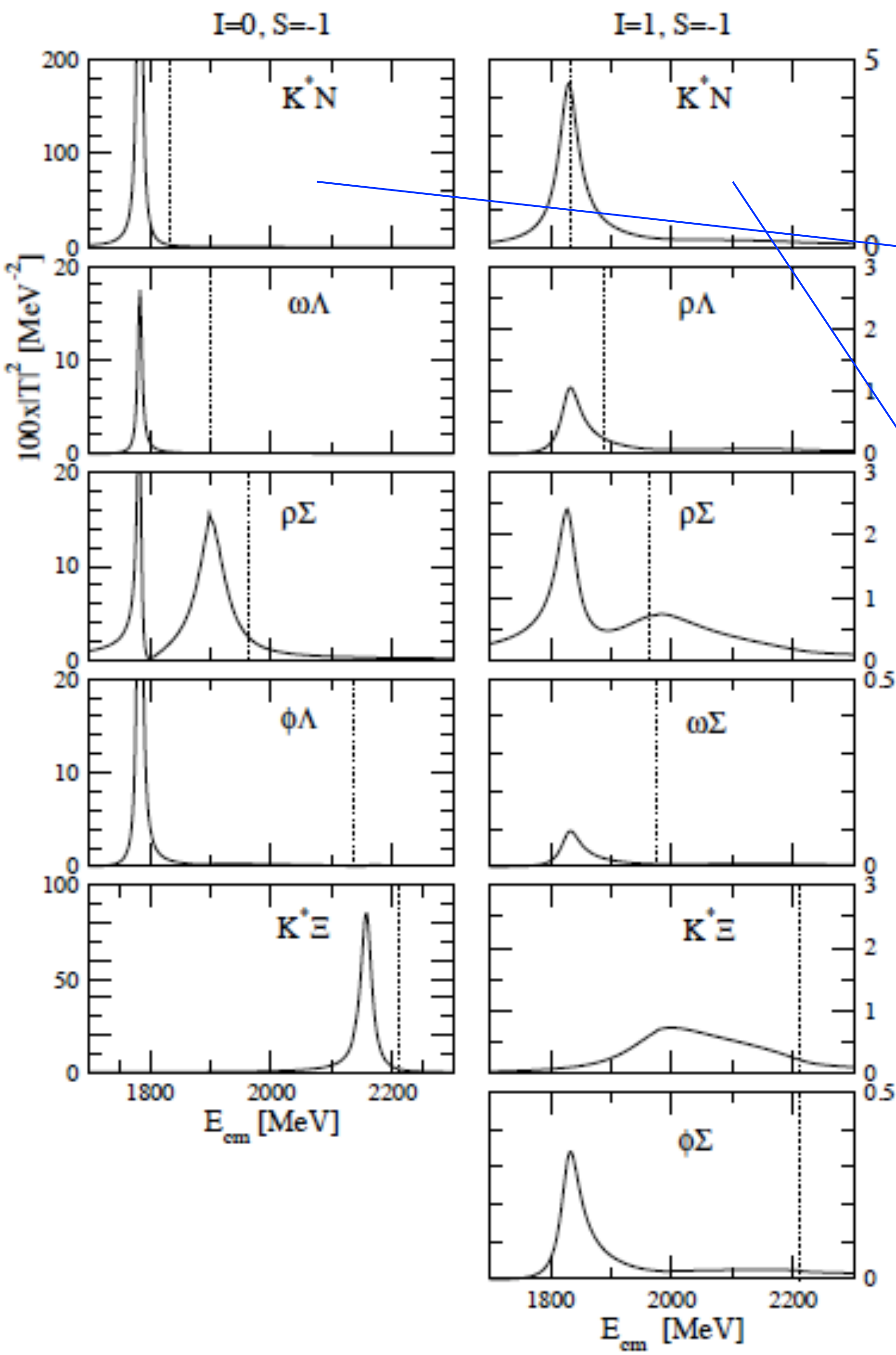
Klingl, Kaiser, Weise, NPA 624 (1997) 527

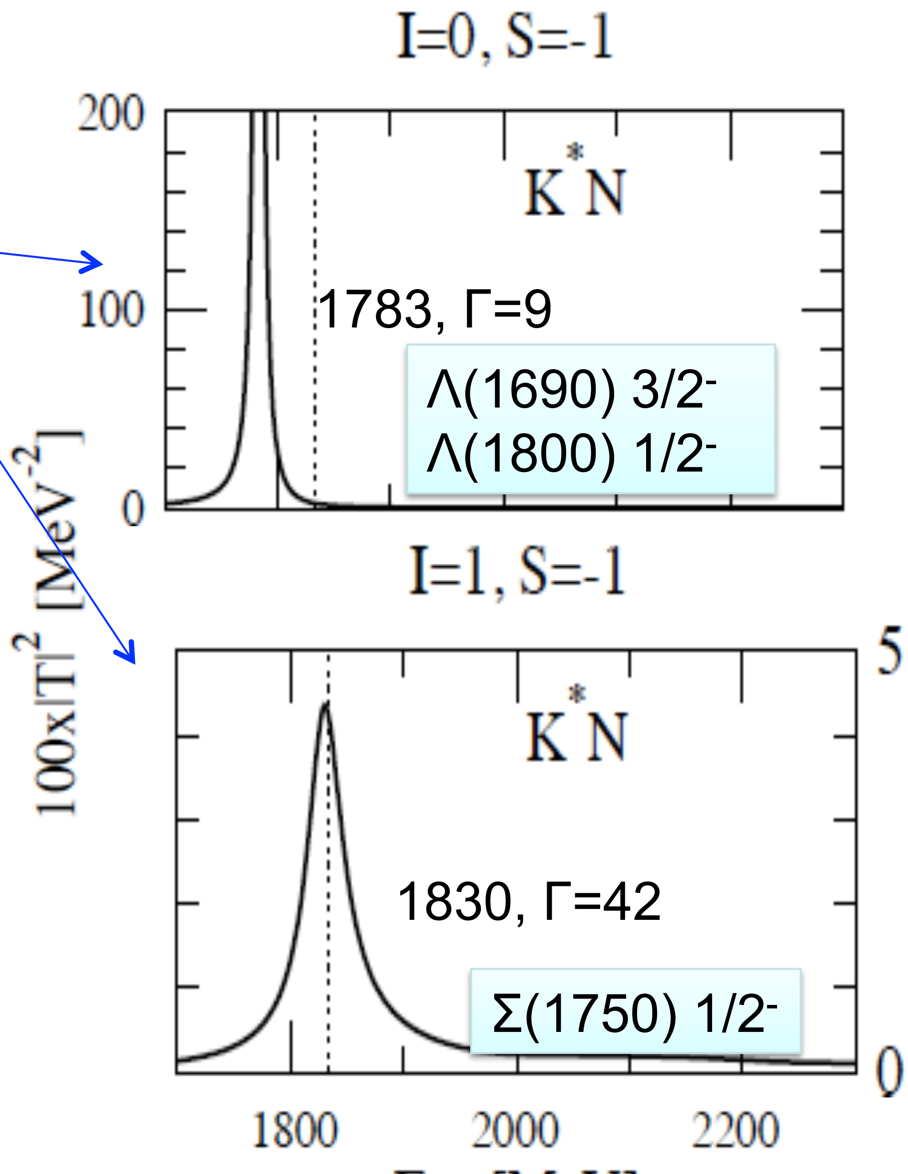
$$g = \frac{M_V}{2f}$$

in $\vec{q}/M_V \to 0$ approximation

$$V_{ij} = -C_{ij} \frac{1}{4f^2} \left(k^0 + k'^0\right) \vec{\epsilon}\vec{\epsilon}'$$

Oset, Ramos, EPJA 44 (2010) 445



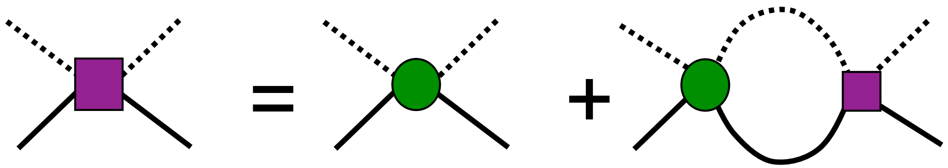


T=V+VGT

G incorporates width of vector mesons (from PP decay)

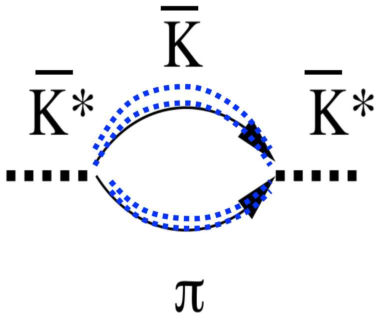
$$S = -\frac{1}{\pi}\frac{\mathrm{Im}\Pi}{[q_0^2 - \vec{q}^{\,2} - m^2 - \mathrm{Re}\Pi]^2 + \mathrm{Im}\Pi^2}$$

Medium

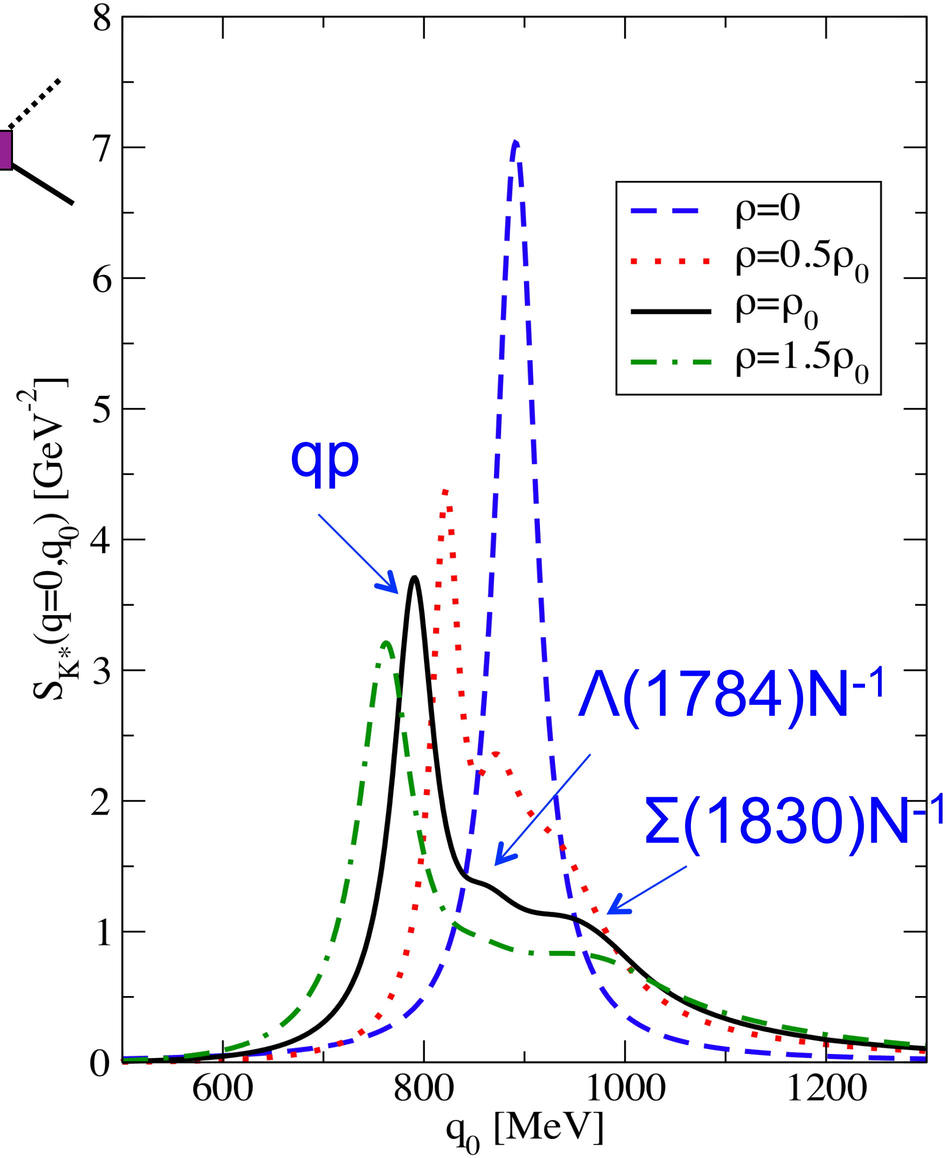


$$T_{ij} = V_{ij} + V_{il}\,G_l\,T_{lj}$$

and

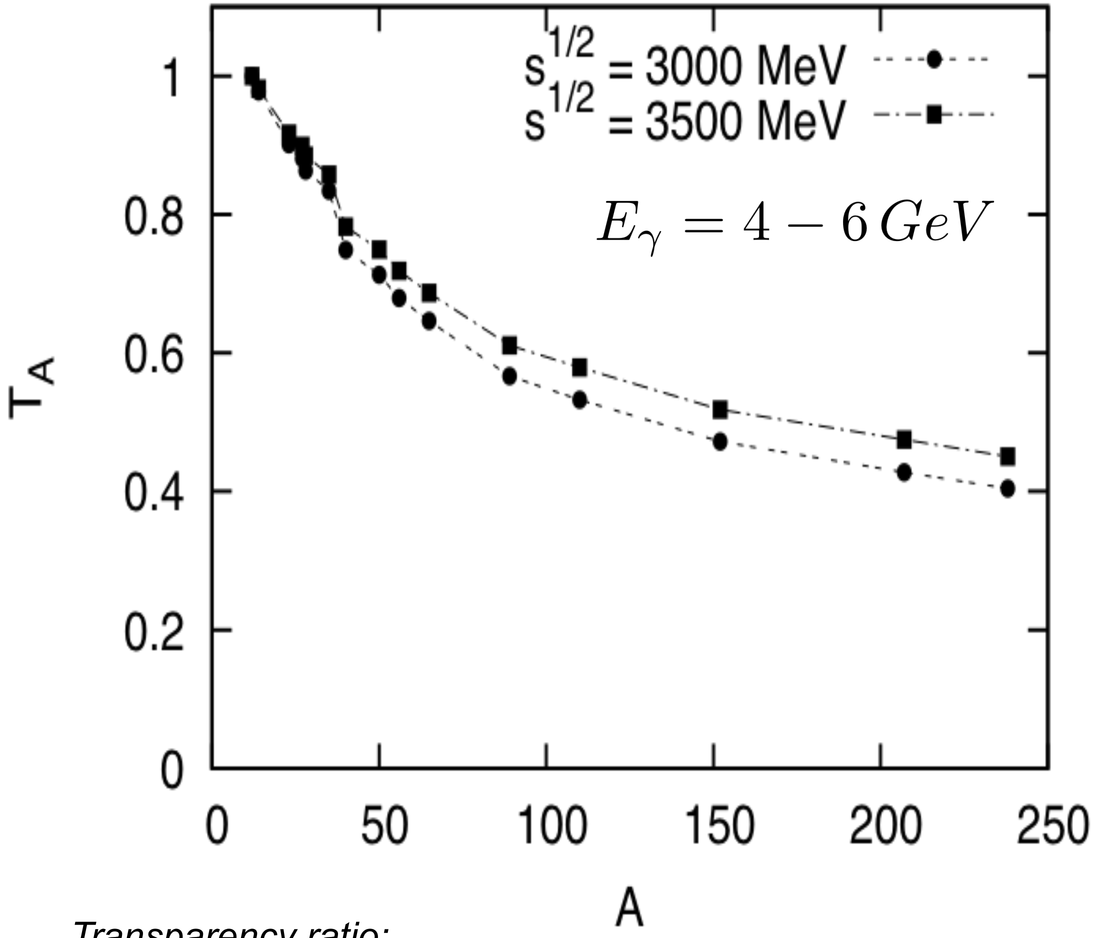


LT, Molina, Ramos and Oset, Phys. Rev. C 82, 045210 (2010)



Experimentally??

Transparency ratio in $\gamma\, A \rightarrow K^+ \bar{K}^{*-} A'$



Transparency ratio:
ω: Kaskulov, Hernandez and Oset, EPJA 31 (2007) 245
ϕ:Cabrera, Roca, Oset, Toki, Vicente-Vacas, NPA 733 (2004) 130

$$\tilde{T}_A = \frac{\sigma_{\gamma A \rightarrow K^+\ K^{*-}\ A'}}{A\, \sigma_{\gamma N \rightarrow K^+\ K^{*-}\ N}}$$

$$T_A = \frac{\tilde{T}_A}{\tilde{T}_{^{12}C}}$$

"survival probability"

$$\tilde{T}_A \propto \exp\left\{ \int_0^\infty dl \frac{\mathrm{Im}\Pi_{K^{*-}}(\rho(\vec{r}\,'))}{|\vec{p}_{K^{*-}}|} \right\}$$

40-60% reduction in heavy nuclei (A=50-250) with respect to ^{12}C

Open charm mesons: D, $\bar{D}$ & D*

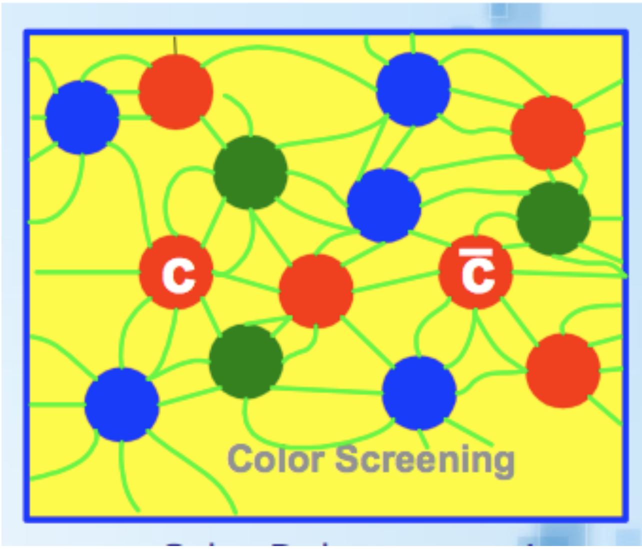
- DN and D*N interactions with HQSS
- D mesic nuclei

in collaboration with
C. Garcia-Recio, J. Nieves, O. Romanets
and L.L. Salcedo

Experimental scenarios

J/Ψ suppression

Gonin et al (NA50) ’96, Matsui and Satz ’86



taken from Hirano@CISS07

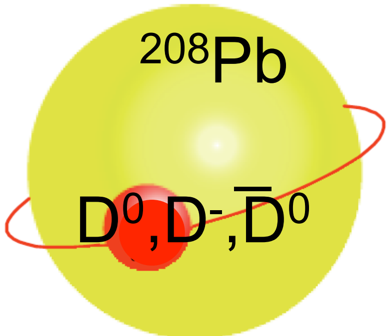
but also comover scattering

$$J/\Psi + \pi \rightarrow D + \bar{D}$$

Capella, Ferreiro, Vogt, Wang, Bratkovskaya, Cassing, Andronic..

D-mesic nuclei

Tsushima et al ’99,
Garcia-Recio et al ‘10



In-medium theoretical models for open charm

- Predictions from
  - QMC model *Tsushima et al., PRC 59 (1999) 2824, Sibirtsev et al., EPJA 6 (1999) 351;…*
  - QCD sum-rule model *Hayashigaki, PLB 487 (2000) 96; Weise, Hirschegg'01, 249*
    Hilger, Thomas and Kaempfer, PRC 79 (2009) 025202
    Hilger, Kaempfer and Leupold PRC 84 (2011) 045202; …
  - Chiral model *Mishra et al., PRC 69 (2004) 015202; Mishra et al, PRC 79 (2009) 024908;..*

- From self-consistent coupled-channel approaches:
  - D meson self-energy with a potential for u-, d- and c- quarks as bare interaction *LT, Schaffner-Bielich and Mishra, PRC 70 (2004) 025203;*
    LT, Schaffner-Bielich and Stoecker, PLB 635 (2006) 85 (finite T!)
  - D and D meson self-energy with a bare interaction saturated by a t-channel vector meson exchange
    Lutz and Korpa, PLB 633 (2006) 43
  - D meson self-energy using modified t-->0 limit (WT) + scalar-isoscalar attractive term (Σ_{DN}) *Mizutani and Ramos, PRC 74 (2006) 065201;*
    LT, Ramos and Mizutani, PRC 78 (2008) 015207
  - Incorporate heavy-quark spin symmetry (HQSS)

DN and D*N interactions with HQSS

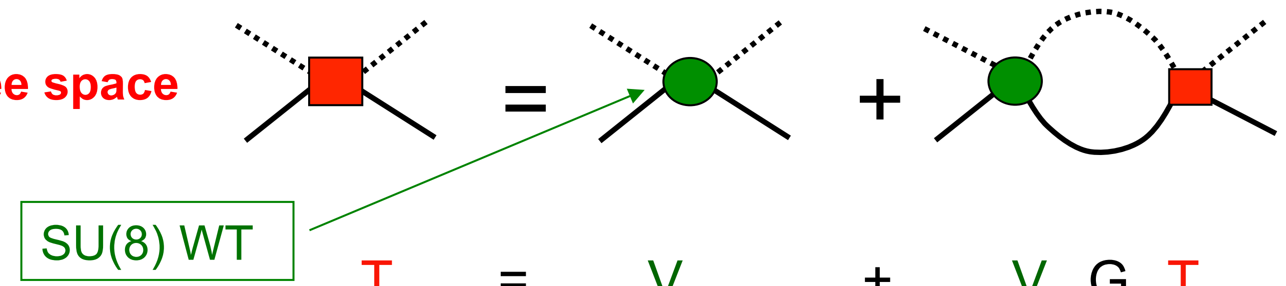
Spin interactions vanish for infinitely massive quarks. Thus, heavy hadrons come in doublets (unless spin of the light degrees of freedom is zero), which are degenerated in the infinite quark-mass limit. Example: D and D* mesons.

This leads to extend SU(3) WT to a SU(8) model in order to incorporate HQSS (no c cbar pairs)

Garcia-Recio et al., PRD 79 (2009) 054004;
LT et al., PRC 80 (2010) 065202;
Gamermann et al., PRD 81 (2010) 094016 ;
Garcia-Recio et al. , PLB 690 (2010) 369;
Garcia-Recio et al. PRC 85 (2012) 025203;
Romanets et al. PRD 85 (2012) 114032

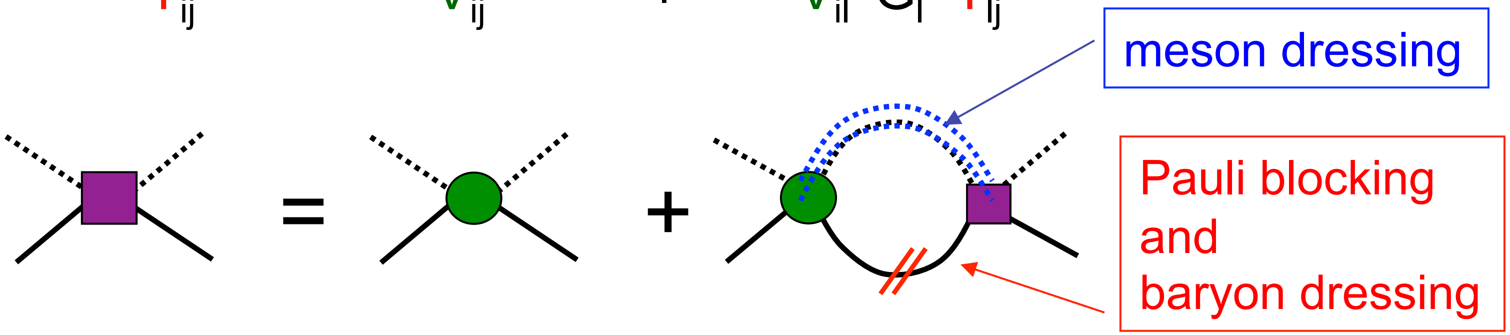
Open charm in dense nuclear matter:
selfconsistent coupled-channel procedure

Free space



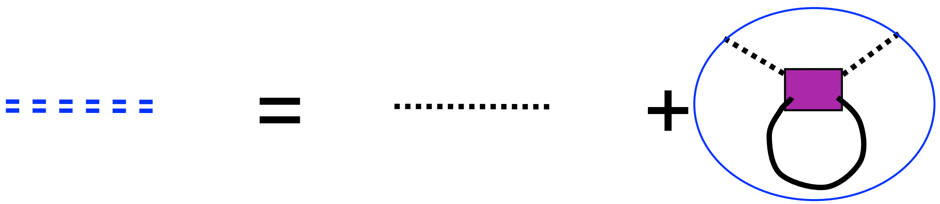
$$T_{ij} = V_{ij} + V_{il}\, G_l\, T_{lj}$$

Medium



$$T_{ij}(\rho,T) = V_{ij} + V_{il}\, G_l(\rho,T)\, T_{lj}(\rho,T)$$

Dressed meson:



Π self-energy

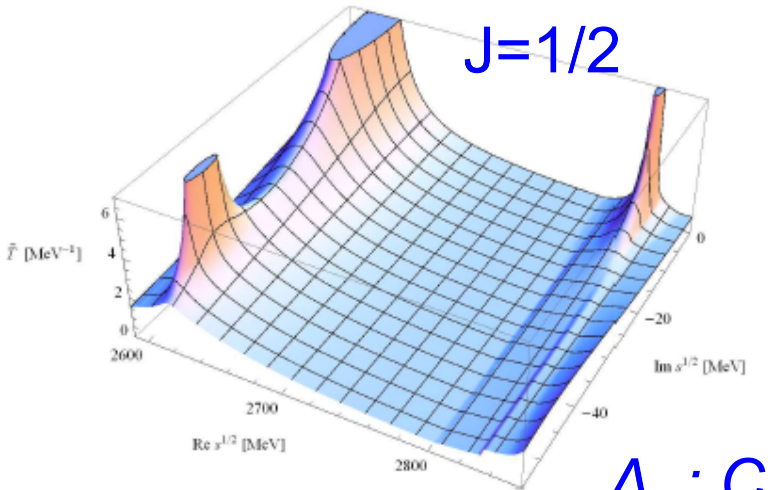
Free space

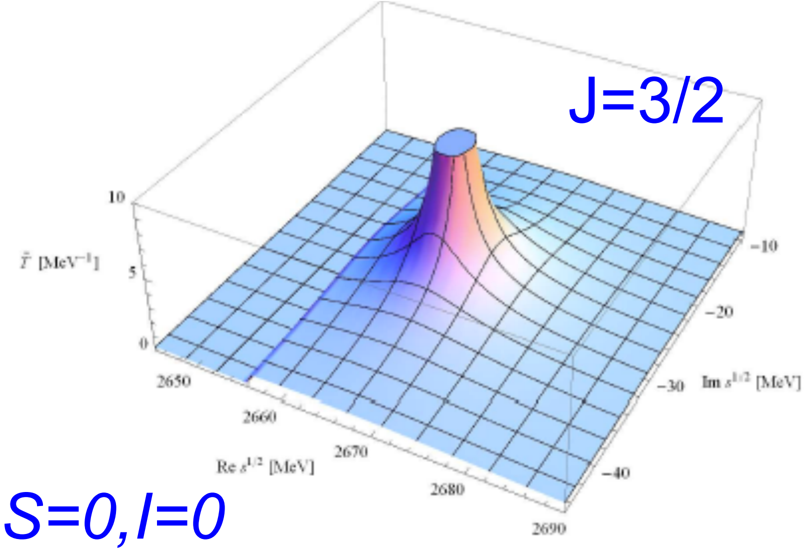
Garcia-Recio et al., PRD 79 (2009) 054004;
Romanets et al. PRD 85 (2012) 114032

$$T_{ij}(s) \approx \frac{g_i g_j}{\sqrt{s} - \sqrt{s_R}}$$

coupling constant

mass and width





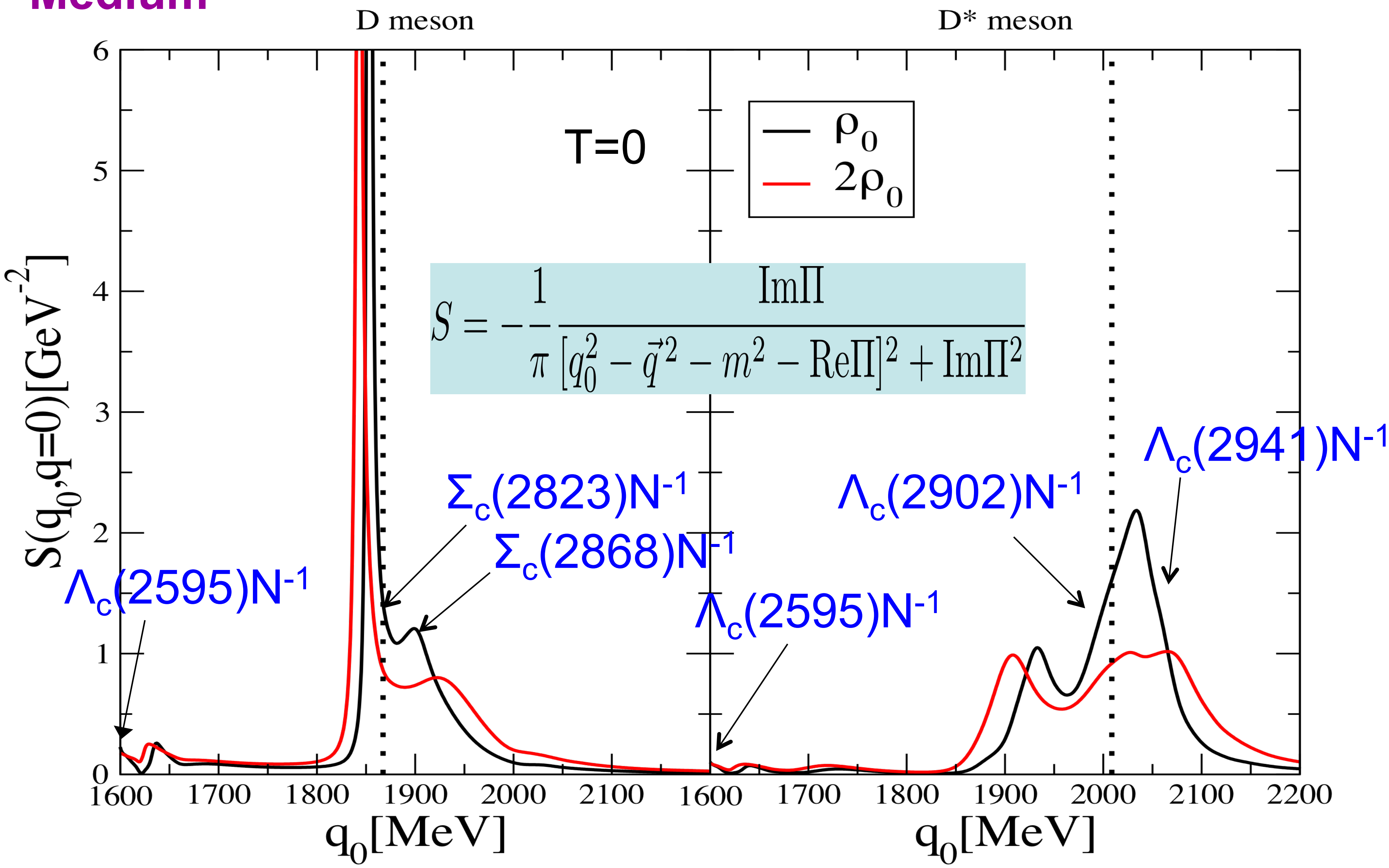
Λ_c: C=1,S=0,I=0

SU(8) irrep	SU(6) irrep	SU(3) irrep	M_R	Γ_R	Couplings to main channels	Status PDG	J
168	**$15_{2,1}$**	**3^*_2**	2617.3	89.8	$\mathbf{g_{\Sigma_c\pi} = 2.3}$, $g_{ND} = 1.6$, $g_{ND^*} = 1.4$, $g_{\Sigma_c\rho} = 1.3$		1/2
168	**$15_{2,1}$**	**3^*_4**	2666.6	53.7	$\mathbf{g_{\Sigma^*_c\pi} = 2.2}$, $g_{ND^*} = 2.0$, $g_{\Sigma_c\rho} = 0.8$, $g_{\Sigma^*_c\rho} = 1.3$	$\Lambda_c(2625)$ ***	3/2
168	**$21_{2,1}$**	**3^*_2**	2618.8	1.2	$\mathbf{g_{\Sigma_c\pi} = 0.3}$, $g_{ND} = 3.5$, $g_{ND^*} = 5.6$, $g_{\Lambda D_s} = 1.4$, $g_{\Lambda D^*_s} = 2.9$, $g_{\Lambda_c\eta'} = 0.9$	$\Lambda_c(2595)$ ***	1/2
120	**$21_{2,1}$**	**3^*_2**	2828.4	0.8	$\mathbf{g_{ND} = 0.3}$, $g_{\Lambda_c\eta} = 1.1$, $g_{\Xi_c K} = 1.6$, $g_{\Lambda D^*_s} = 1.1$, $g_{\Sigma_c\rho} = 1.1$, $g_{\Sigma^*_c\rho} = 1.0$, $g_{\Xi^*_c K^*} = 0.8$		1/2

Simultaneous self-consistent calculation of the D and D* meson self-energies and, hence, spectral functions

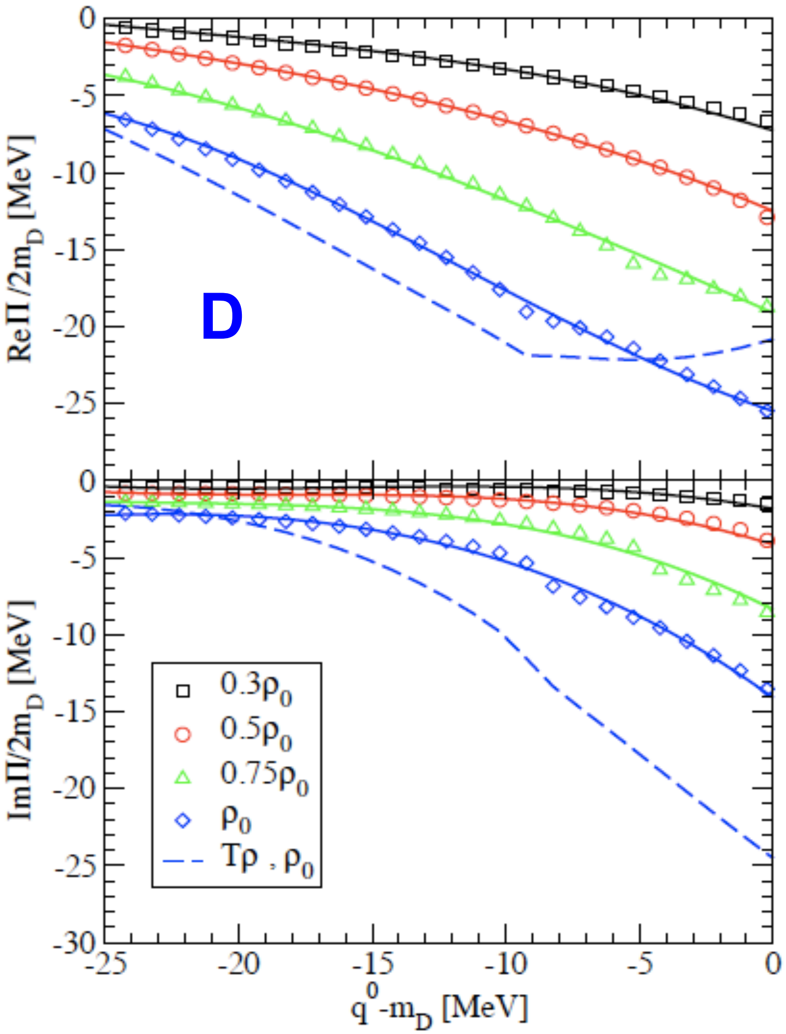
LT et al., PRC 80 (2010) 065202

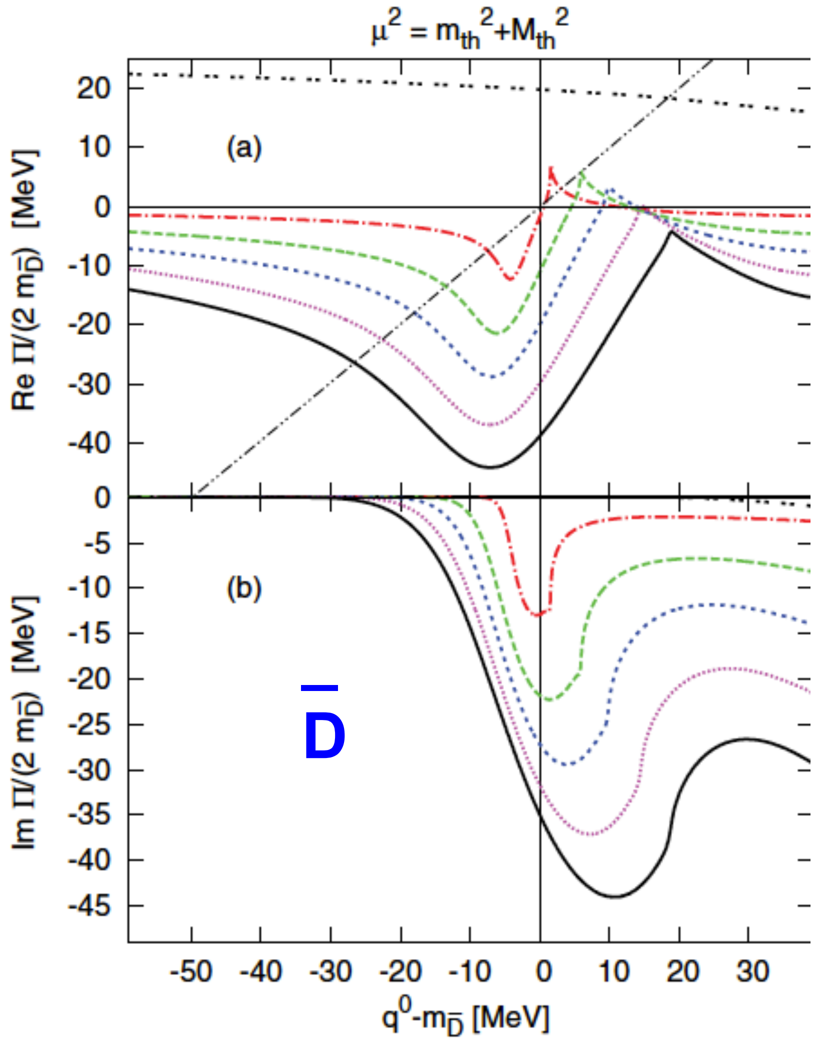
Medium



$$S = -\frac{1}{\pi}\frac{\mathrm{Im}\Pi}{[q_0^2 - \vec{q}^{\,2} - m^2 - \mathrm{Re}\Pi]^2 + \mathrm{Im}\Pi^2}$$

Optical potential for D and $\bar{D}$ mesons





Strong energy dependence. What about D mesic nuclei?

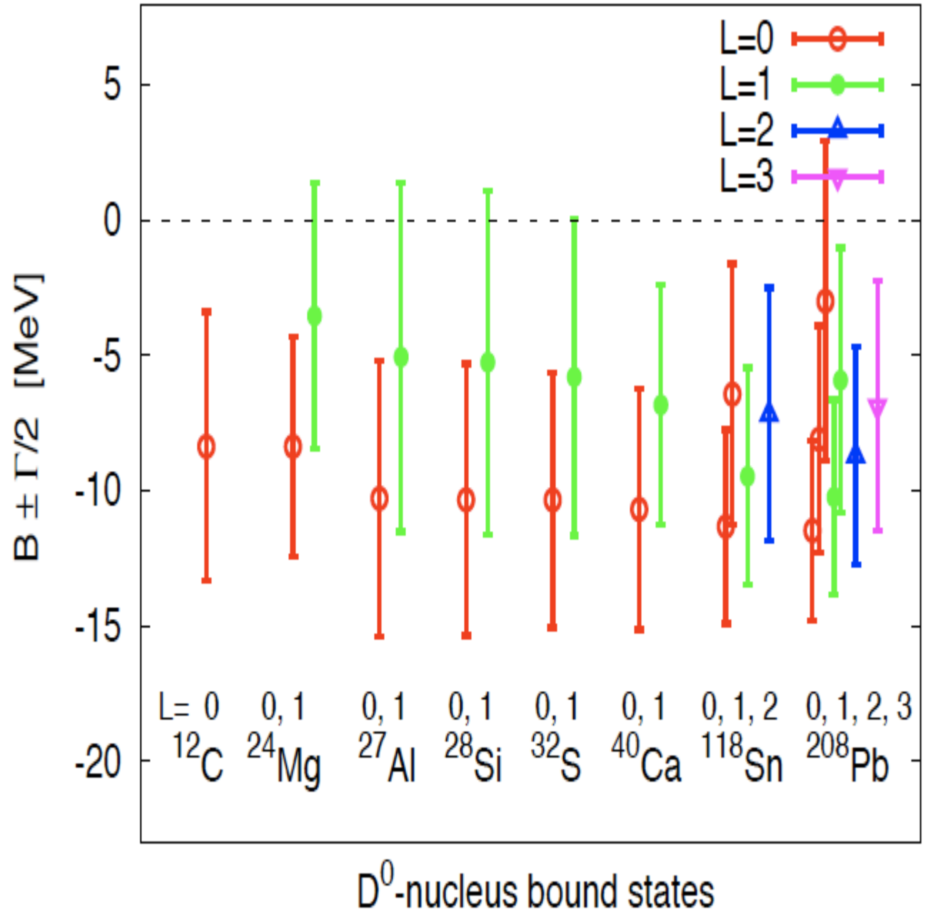
LT et al., PRC 80 (2010) 065202;

Garcia-Recio et al. , PLB 690 (2010) 369; Garcia-Recio et al. PRC 85 (2012) 025203

D-mesic nuclei

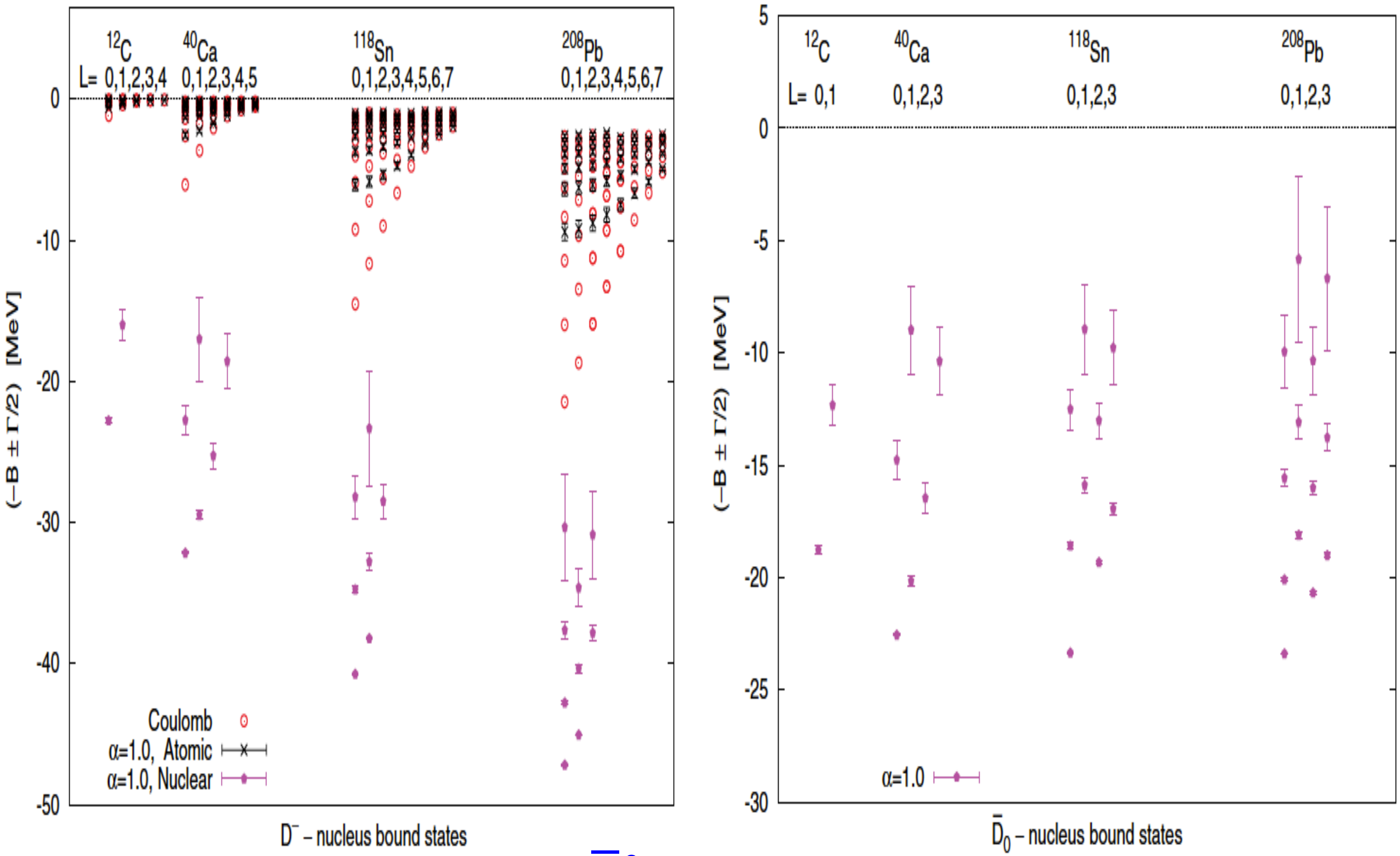
Solving Schroedinger equation...

$$\left[-\frac{\nabla^2}{2m_{\rm red}} + V_{\rm coul}(r) + V_{\rm opt}(r)\right]\Psi = (-B - i\Gamma/2)\Psi$$



Weakly bound D^0-nucleus states with important widths in contrast to previous QMC models *Tsushima et al. PRC 59 (1999) 282)* and D^+ do not bound

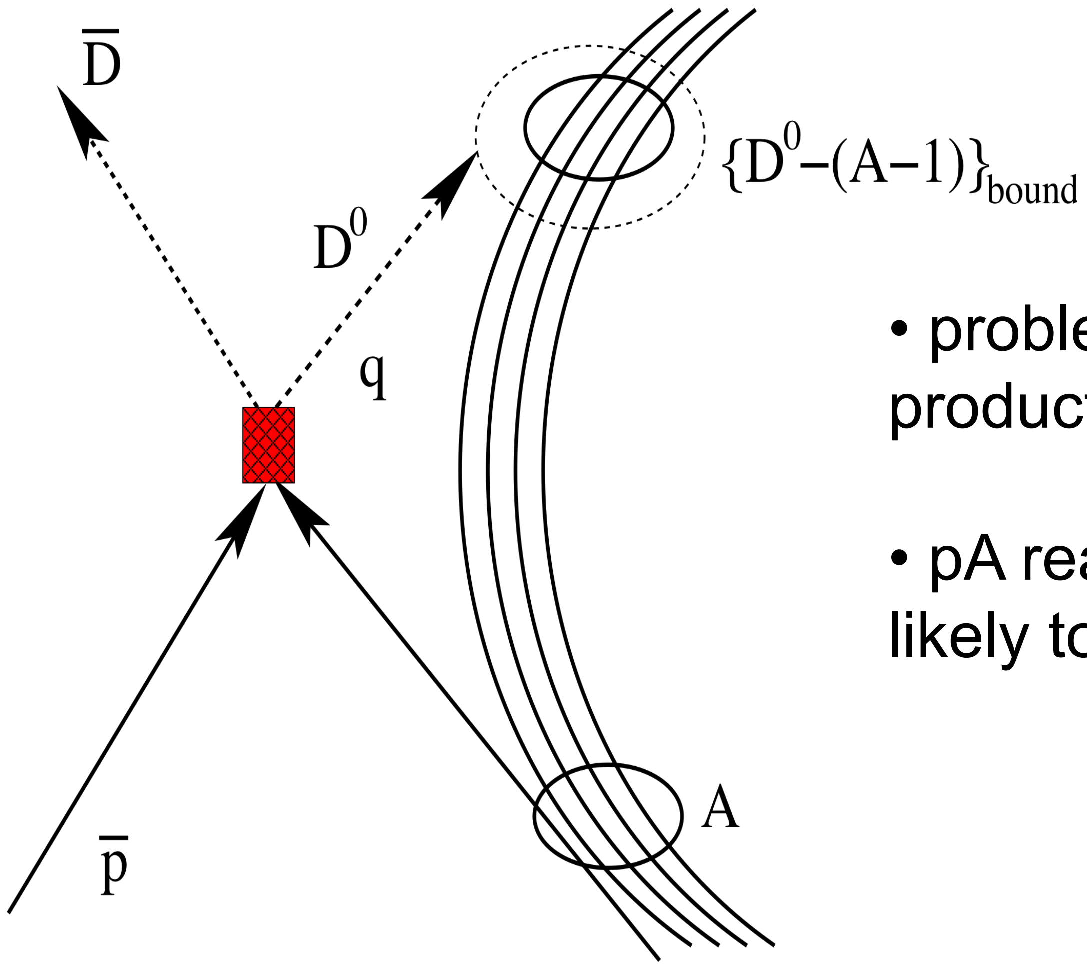
Garcia-Recio et al., PLB 690 (2010) 369



D^- and $\bar{D}^0$ bound in nuclei!

Garcia-Recio et al. PRC 85 (2012) 025203

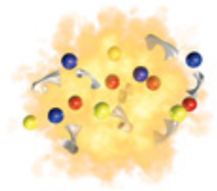
Experimental observation is, though, a difficult task



PANDA@FAIR?

- problem: $\bar{p}$A will have a low production rate
- pA reaction seems more likely to trap a D^0 in nuclei

Present and Future



- it is an exciting moment
- moving from strangeness to charm
- a lot of theoretical effort is needed
- but in close connection to experiments