Charmed matter

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Happy Birthday Tony!

Motivation

Interaction of charm with ordinary matter is interesting for several reasons

- Quark-gluon plasma: J/Ψ suppression
- D-mesons in medium: chiral-symmetry
- J/Ψ: possibly bound to ordinary matter
- Experiments underway: JLab @ 12 GeV, Panda, CBM @ Fair

Nuclear-Bound Quarkonium

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(Received 25 September 1989)

We show that the QCD van der Waals interaction due to multiple-gluon exchange provides a new kind of attractive nuclear force capable of binding heavy quarkonia to nuclei. The parameters of the potential are estimated by identifying multigluon exchange with the Pomeron contributions to elastic meson-nucleon scattering. The gluonic potential is then used to study the properties of $c\bar{c}$ nuclear-bound states. In particular, we predict bound states of the η_c with ^{3}He and heavier nuclei. Production modes and rates are also discussed.

Charmonium bound to nuclear matter

– an exotic nuclear bound state

- nucleons and charmonium have no quarks in common
- interaction has to proceed via gluons – QCD van der Waals
- no Pauli Principle – no short-range repulsion

BE (η_c to A = 9 nucleus) ~ 180 MeV*

*Brodsky, Schmidt & de Téramond, PRL 64, 1011 (1990)

23 October 1997

PHYSICS LETTERS B

ELSEVIER

Physics Letters B 412 (1997) 125–130

Is J/ψ-nucleon scattering dominated by the gluonic van der Waals interaction? [1]

Stanley J. Brodsky [a], Gerald A. Miller [a,2,b]

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Editor: M. Dine

Abstract

The gluon-exchange contribution to J/ψ-nucleon scattering is shown to yield a sizeable scattering length of about -0.25 fm, which is consistent with the sparse available data. Hadronic corrections to gluon exchange which are generated by $\rho\pi$ and $D\bar{D}$ intermediate states of the J/ψ are shown to be negligible. We also propose a new method to study J/ψ-nucleon elastic scattering in the reaction $\pi^+ d \to J/\psi\, pp$.

Here, possibility of J/Ψ binding to nuclei*

Two (independent) mechanisms:

- second order stark effect – octet intermediate state

- D,D* meson-loop – color singlet intermediate state

  ⇓

  D mesons feel

  the nuclear medium

* GK, A.W. Thomas & K. Tsushima

Second-order Stark effect

$H = \frac{\alpha_s}{\pi} \vec{E}^a \cdot \vec{E}^a$ chromo-electric polarizability

$$\boxed{\Delta m_\psi(\rho_B) = -\frac{1}{9} \int dk^2 \left| \frac{\partial \psi(k)}{\partial k} \right|^2 \frac{k}{k^2 \,/\, m_c + \varepsilon} \left\langle \frac{\alpha_s}{\pi} E^2 \right\rangle_N \frac{\rho_B}{2m_N}}$$

$\psi(k)$: charmonium wavefunction

ρ_B : baryon density

m_c, m_N : masses charm quark and nucleon

$\varepsilon = 2m_c - m_\psi$: energy shift octet-charmonium

Numerical results:

$$\left\langle \frac{\alpha_s}{\pi} E^2 \right\rangle_N = 0.5\,\mathrm{GeV}^2 \qquad \alpha_s = 0.84$$

S.H. Lee & C.M. Ko,
PRC 67, 038202 (2003)

ψ : Gaussian - $\langle r^2 \rangle$ same as pot models

$$\Delta m_\psi(\rho_B) = -8\,\mathrm{MeV}$$

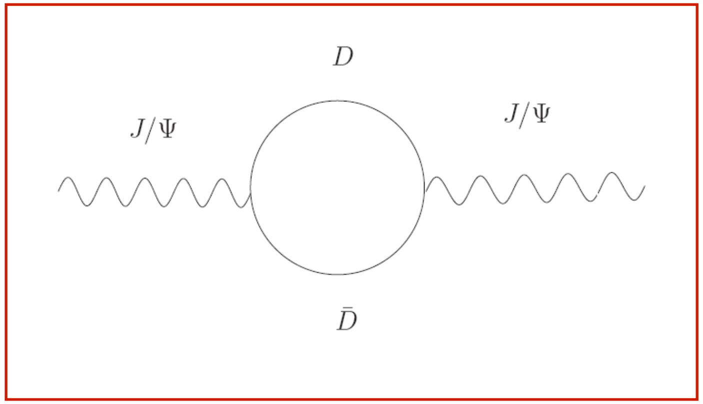
at normal nuclear
matter density

J/Ψ N cross section > 17 mb

$$\Delta m_\psi(\rho_B) = -21\,\mathrm{MeV}$$

Sibirtsev & Voloshin
PRD 71, 076005 (2005)

D-meson loop



Calculate loop with effective Lagrangian

$$\mathcal{L}_{\psi D\bar{D}} = ig_{\psi D\bar{D}}\,\bar{\psi}\left[\bar{D}\left(\partial_{\mu}D\right)-\left(\partial_{\mu}\bar{D}\right)D\right]$$

– need form factors

– need a model for medium dependence of D masses

Potential of J/Ψ in matter

$$i\Sigma_{\psi}^{D\bar{D}}(k^2) = -\frac{8}{3} g^2_{\psi D\bar{D}} \int \frac{d^4q}{(2\pi)^4} F(q^2)\,\Delta_D(q)\,\Delta_{\bar{D}}(k-q)$$

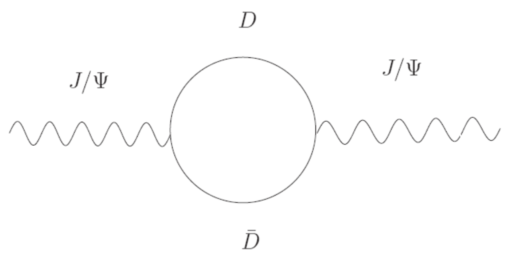
$$m_{\psi}^2 = (m_{\psi}^{(0)})^2 + \Sigma_{\psi}^{D\bar{D}}(k^2 = m_{\psi}^2)$$

$$m_{\psi}^{*2} = (m_{\psi}^{(0)})^2 + \Sigma_{\psi}^{*D\bar{D}}(k^2 = m_{\psi}^{*2})$$

$$\boxed{U_{J/\Psi}(\rho_B) \equiv m_{\psi}^{*} - m_{\psi}}$$

Structure of the mesons
– form factors

Form factor for the loop calculation:



Quark model ($^3P_0$ pair creation):

$$F(q^2) = \gamma^2 \pi^{3/2} \frac{m_\psi^3}{\beta^3} \frac{2^6 r^3 (1+r^2)^2}{(1+2r^2)^5} e^{-q^2/2\beta_D^2(1+2r^2)}, \qquad r = \frac{\beta_\psi}{\beta_D}$$

Phenomenological:

$$F(q^2) = \left[\frac{\Lambda^2 + m_\psi^2}{\Lambda^2 + 4(q^2 + m_D^2)} \right]^2, \qquad g_{\psi D\bar{D}} = 7.7$$

Model for D–mesons in matter

– Quark-Meson Coupling (QMC)*

- quarks are confined in a MIT bag

- in matter: non-overlapping bags,
  scalar (σ) and vector (ω) mean fields couple to quarks

Single quark wavefunction in the bag

$$\boxed{[i\gamma \cdot \partial - (m_q - g_\sigma^q \sigma) + g_\omega^q \gamma \cdot \omega]\psi_q = 0}$$

*P.A.M. Guichon, PLB 200, 235 (1988)
K. Saito, K. Tsushima & A.W. Thomas, Prog. Part. Nucl. Phys. 58, 1 (2007)

Quarks and hadrons in matter

Single quark wave function in the bag

$$\boxed{[i\gamma \cdot \partial - (m_q - g_\sigma^q \sigma) + g_\omega^q \gamma \cdot \omega]\psi_q = 0}$$

linear in σ

Single nucleon wave function in medium

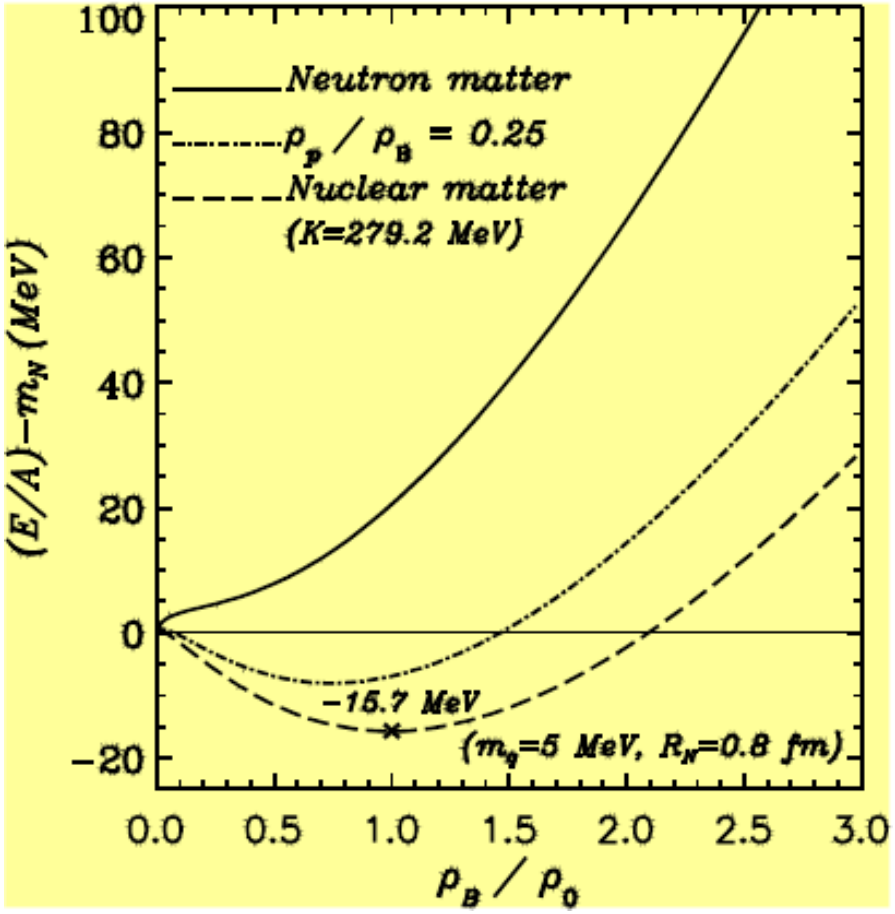
$$[i\gamma \cdot \partial - M_N^* + \gamma \cdot V_\omega^N]\psi_N \approx 0$$

$$M_N^* = M_N - g_\sigma^N \sigma + \frac{d}{2}\left(g_\sigma^N \sigma\right)^2 + \cdots$$

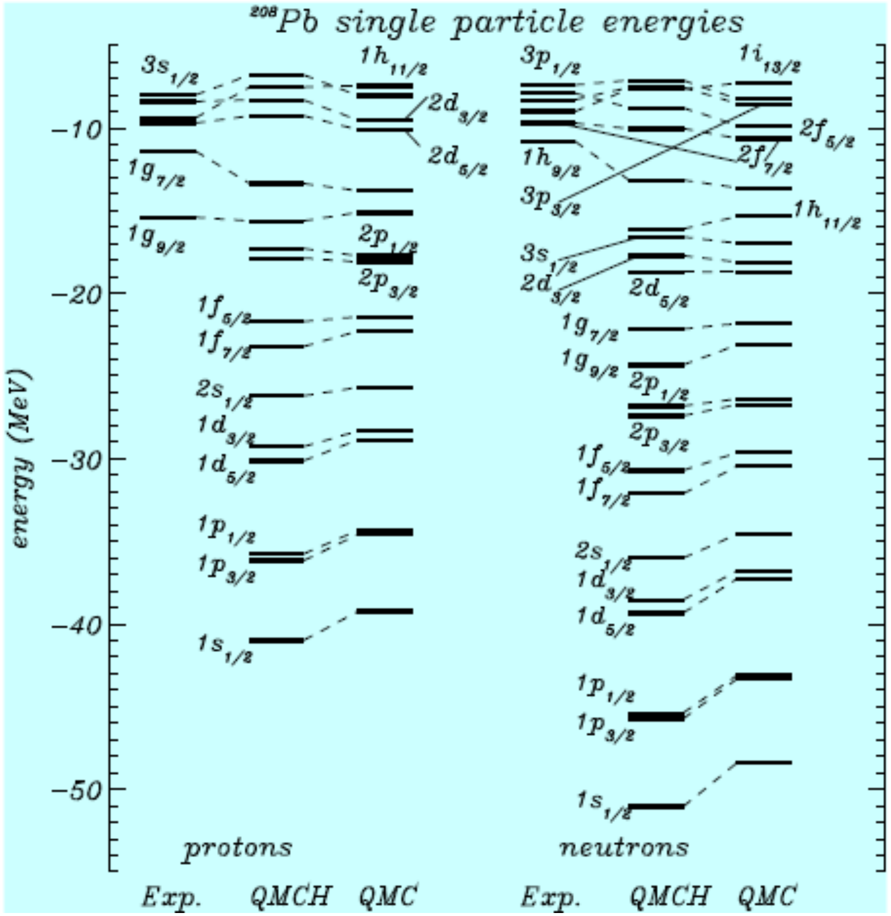
nonlinear in σ

Gross properties of baryonic matter

nuclear matter

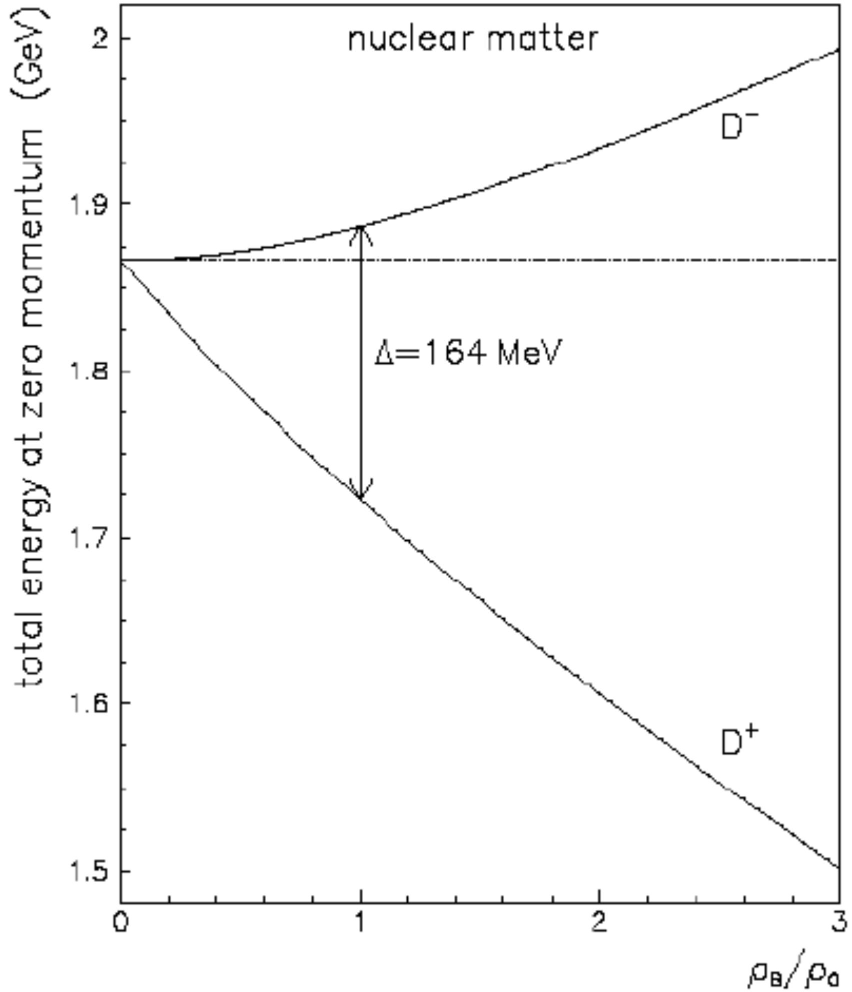


lead nucleus

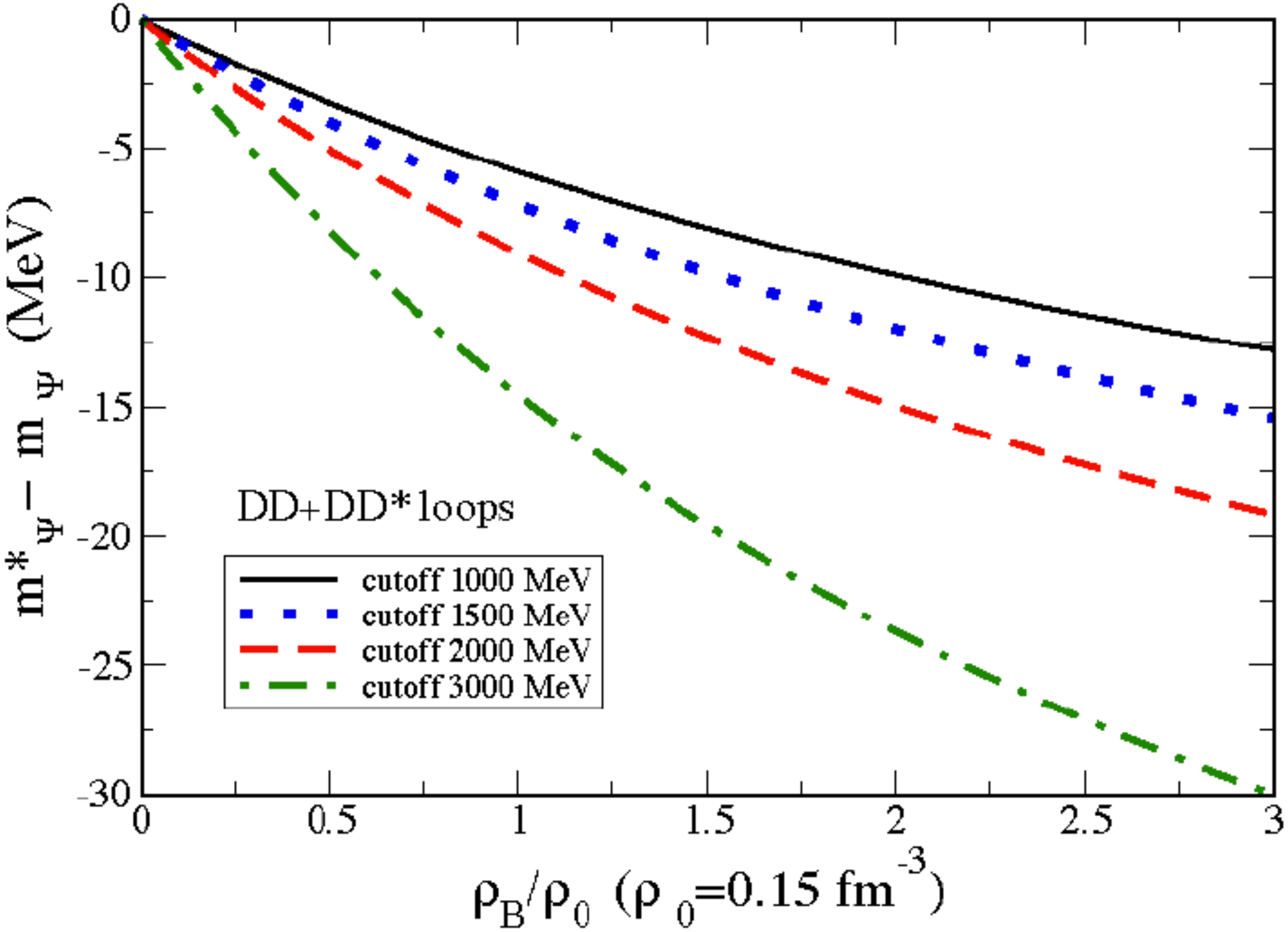


K. Tsushima, …

D mesons in matter



J/Ψ in matter



0
-5
-10
-15
-20
-25
-30
0
0.5
1
1.5
2
2.5
3
$m^*_\Psi - m_\Psi$ (MeV)
ρ_B/ρ_0 (ρ_0=0.15 fm^{-3})
DD+DD* loops
cutoff 1000 MeV
cutoff 1500 MeV
cutoff 2000 MeV
cutoff 3000 MeV

Can J/Ψ be bound to a large nucleus?

Condition for a bound state

- spherical "square-well" radius *a*, depth V_0

$$V_0 > \frac{\pi^2 \hbar^2}{8 m a^2}$$

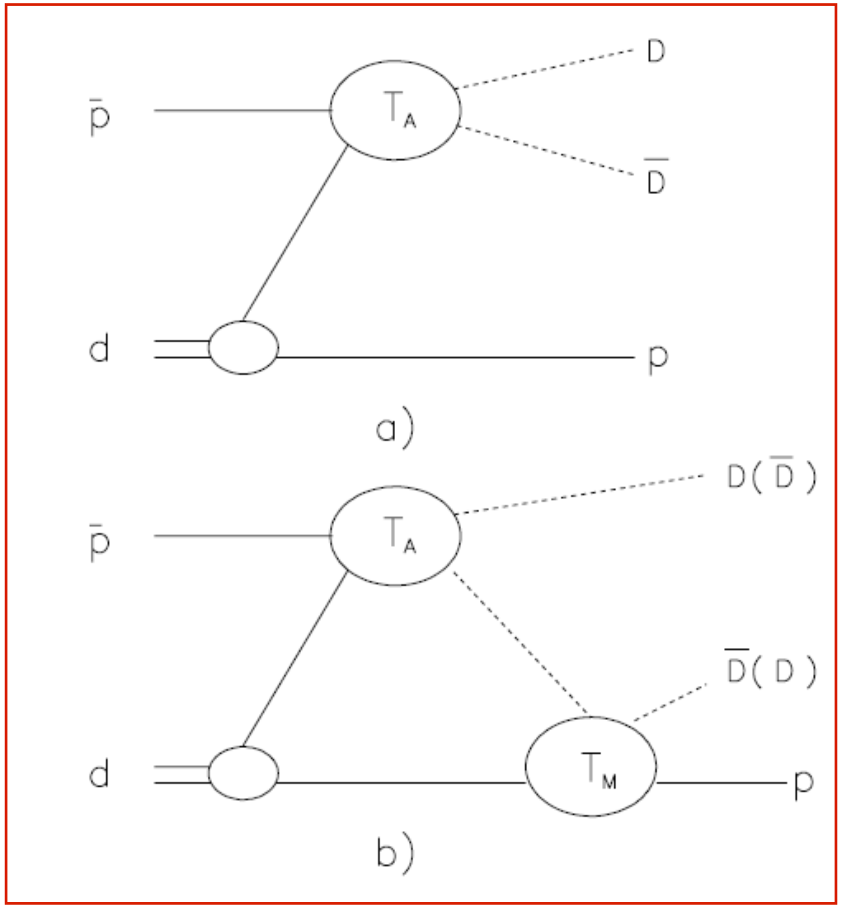
$$a = 5\,\mathrm{fm} \longrightarrow V_0 > 1\ \mathrm{MeV}$$

Many issues:

- J/Ψ moving, not at rest
- Finite nucleus
- Width of D mesons
- Interactions with nucleons
- Production of charmed particles

Antiproton annihilation on the deuteron

$\bar{\text{P}}$anda @ FAIR

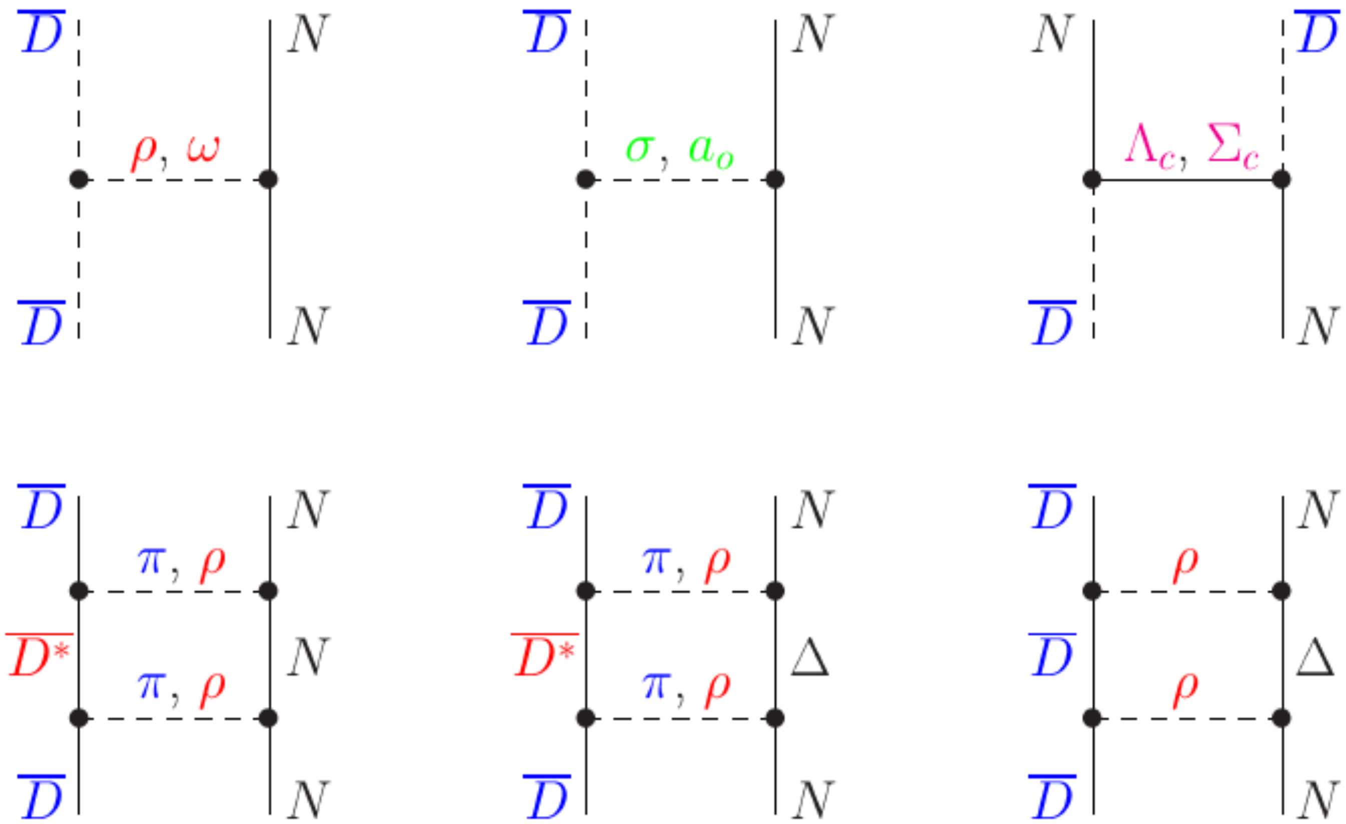


J. Haidenbauer, G. Krein, U.-G. Meissner, A. Sibirtseev

1) Eur. Phys. J. A 33, 107 (2007)

2) Eur. Phys. J. A 37, 55 (2008)

Meson exchange – effective Lagrangians



Couplings: SU(4) symmetry

The Model

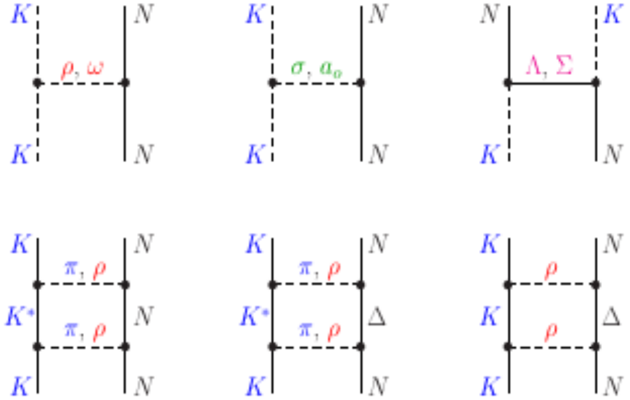
Ingredients:

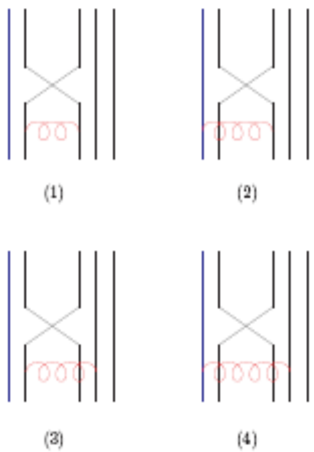
- meson & baryon exchanges (long distances)
- quark-gluon exchanges (short distances)

Important features:

- unitarization of amplitudes, solve Lipmann-Schwinger equation
- include higher partial waves, amplitudes are s and t dependent

Model Based on Previous K^+N Model





Jülich model:

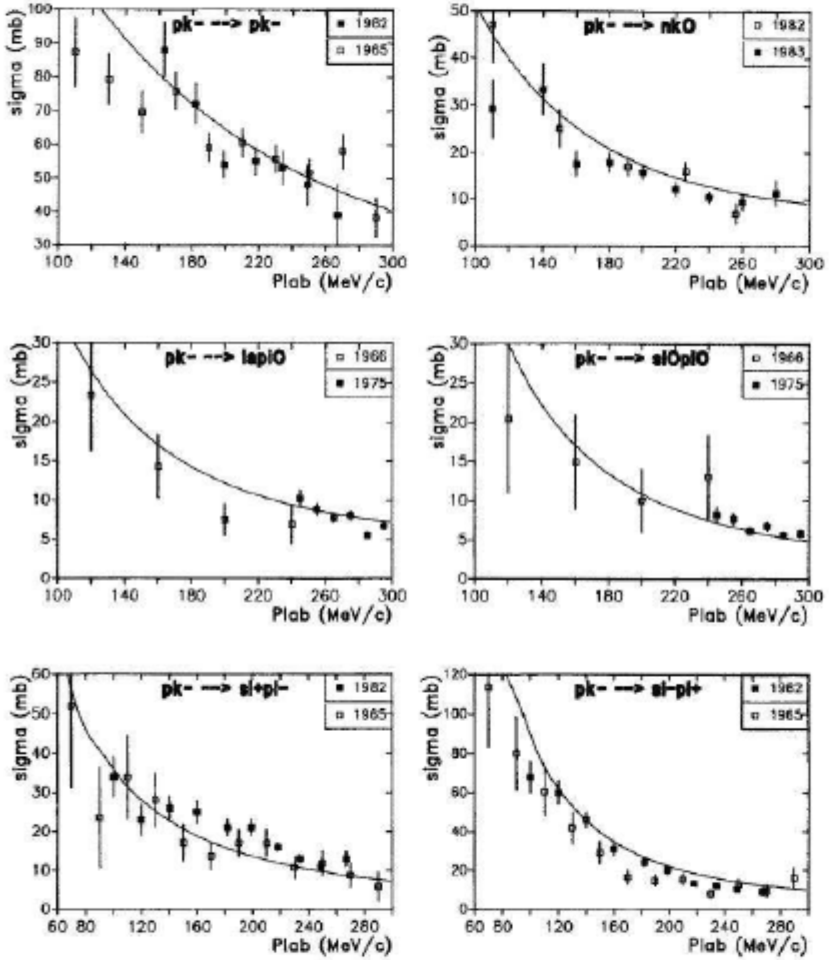
A. Müller-Groeling et al. NPA 513, 557 (1990)
M. Hoffmann et al. NPA 593, 341 (1995)

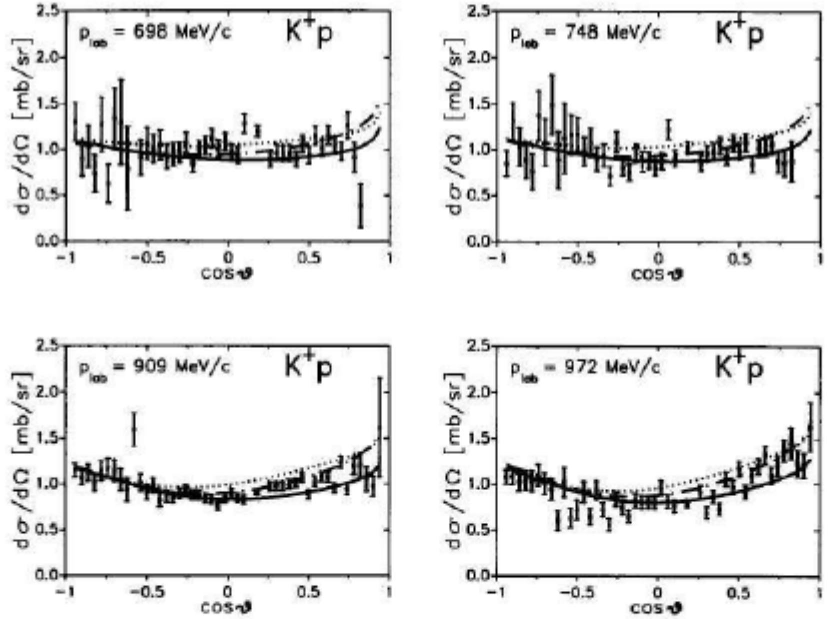
Contains a short-ranged
"repulsive sigma" *m ~ 1.2* GeV

⇓

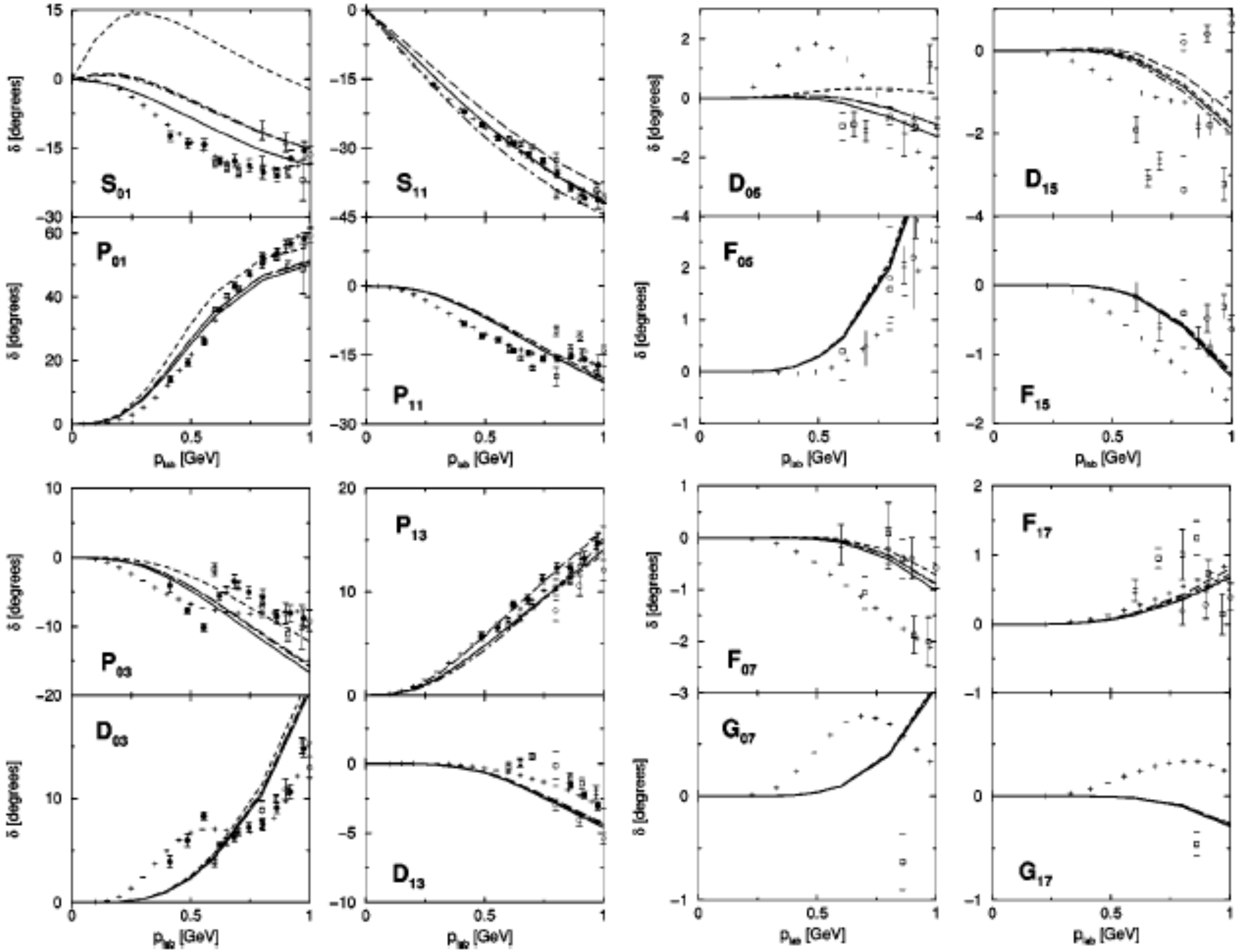
Can be replaced by quark-gluon exchange

D. Hadjimichef, J. Haidenbauer and GK, PRC 66, 055214 (2002)





Model fits observables



and phase shifts

RAPID COMMUNICATIONS

PHYSICAL REVIEW C **68**, 052201(R) (2003)

Influence of a $Z^+(1540)$ resonance on K^+N scattering

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The impact of a $(I=0, J^P=\frac{1}{2}^+)Z^+(1540)$ resonance with a width of 5 MeV or more on the $K^+N(I=0)$ elastic cross section and on the P_{01} phase shift is examined within the KN meson-exchange model of the Jülich group. It is shown that the rather strong enhancement of the cross section caused by the presence of a Z^+ with the above properties is not compatible with the existing empirical information on KN scattering. Only a much narrower Z^+ state could be reconciled with the existing data—or, alternatively, the Z^+ state must lie at an energy much closer to the KN threshold.

DOI: 10.1103/PhysRevC.68.052201 PACS number(s): 13.75.Jz, 12.39.Pn, 14.20.Jn, 21.30.−x

and, if the pentaquark exists, it must be very narrow

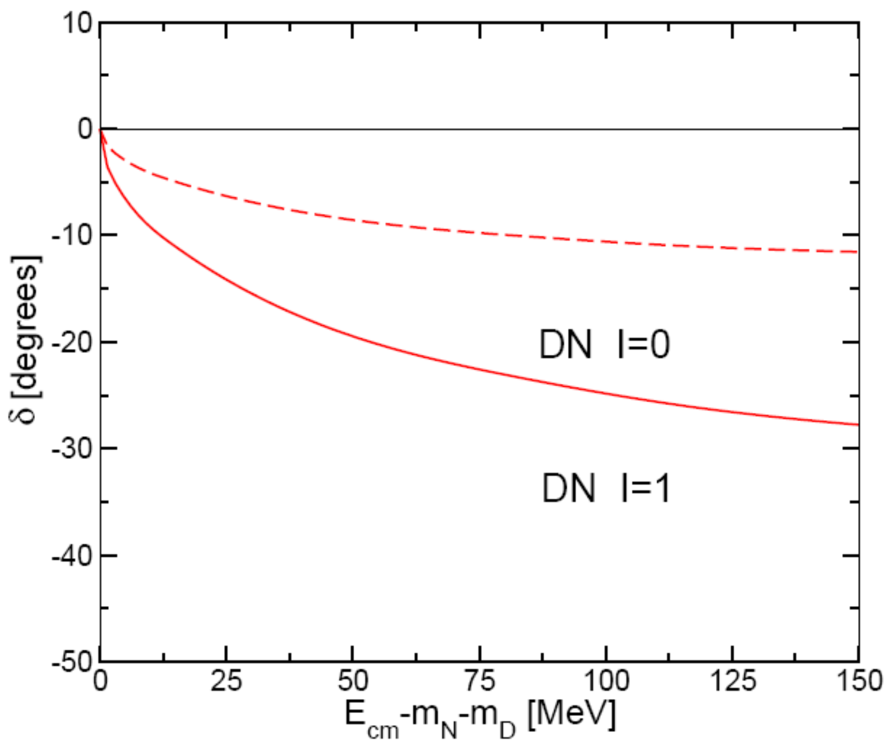
Scattering lengths

a [fm]	Present work	Tólos et al.	Lutz
	$\bar{D}N$		
I = 0 I = 1	+ 0.03 - 0.45	0.0 - 0.29	- 0.16 - 0.26
	DN		
I = 0 I = 1	- 0.41 + i 0.04 - 2.07 + i 0.57	-	- 0.43 + i 0.0 - 0.41 + i 0.0

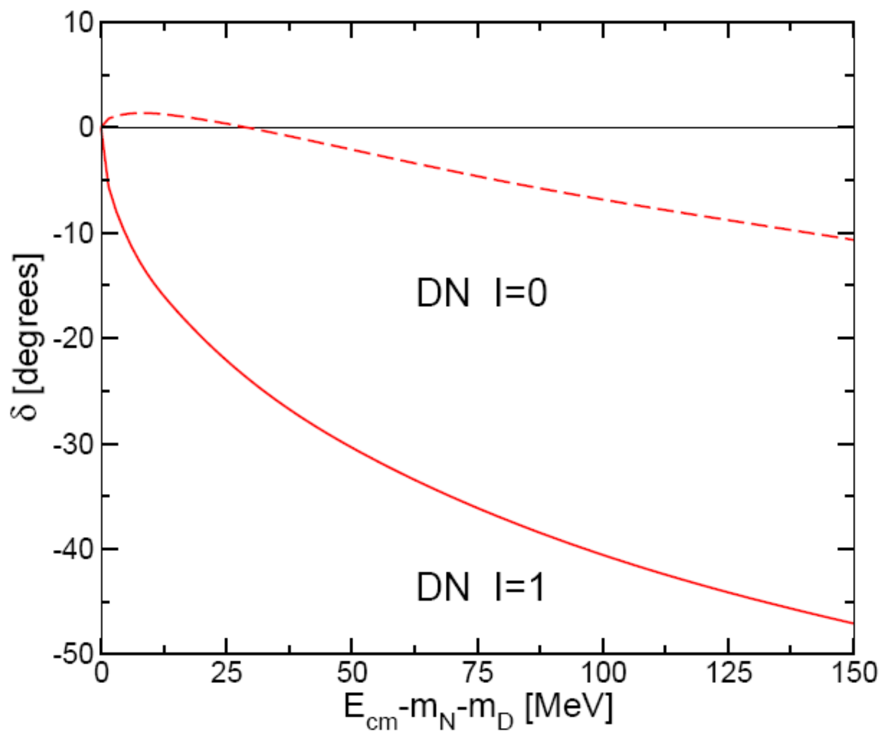
Tólos et al. PRC 77, 015207 (2006)

Lutz & Korpa PLB 633, 43 (2006)

Phase – shifts (s-wave): MEx + OGE



OGE



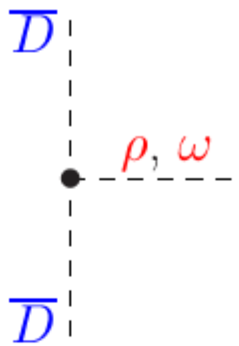
Full: MEx + OGE + ππ

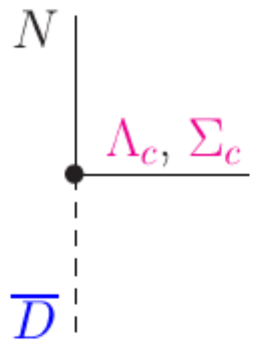
Lessons: 1) quark-gluon contributes with half of the interaction

2) rho and omega (scalars a little) dominant mesonic contributions

SU(4) symmetry breaking ???*

Need to know how good SU(4) is: $m_u < m_s \ll m_c$





SU(4) symmetry: $g_{\bar{D}\bar{D}\rho} = g_{\bar{D}\bar{D}\omega} = g_{KK\rho} = \frac{1}{2} g_{\pi\pi\rho}$

* C.E. Fontoura

Couplings in the quark model: $^3P_0$ model

$q\bar{q}$ creation with quantum numbers of the vacuum

$$H_{q\bar{q}} = g \int d^3x \, \bar{\Psi}(x)\Psi(x)$$

Matrix element

$$\langle BC \mid H_{q\bar{q}} \mid A \rangle = \delta(A - B - C) \, h_{fi}$$

Need meson wave functions:

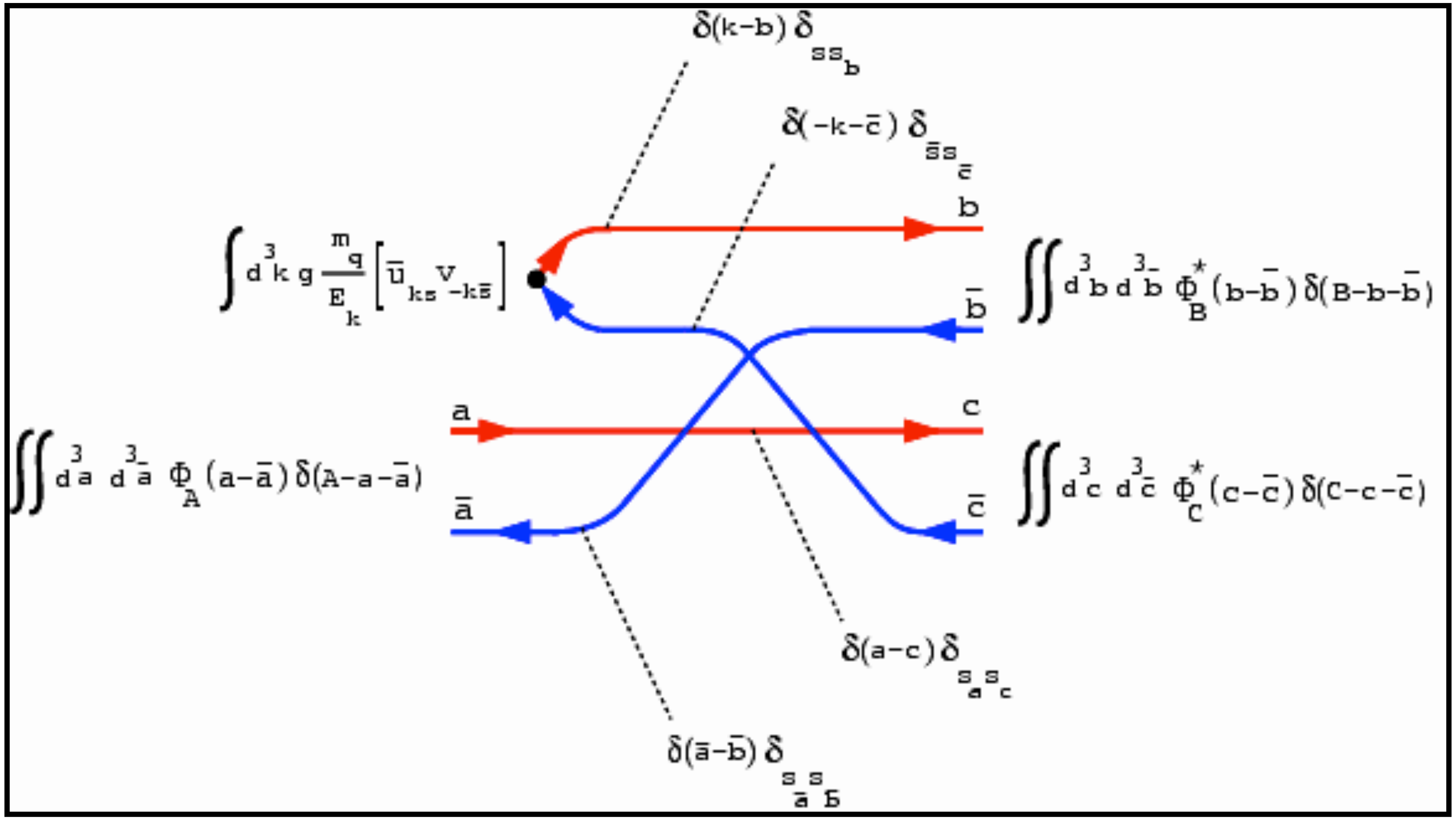


Fig. from Ted Barnes

Wave functions:

$$H = m_1 + \frac{p_1^2}{2m_1} + m_2 + \frac{p_2^2}{2m_2} + F_1 \cdot F_2 \left[\frac{\alpha_c}{r} - \frac{3b}{4} r - \frac{8\pi\alpha_h}{3m_1 m_2} \left(\frac{\sigma^3}{\pi^3} e^{-\sigma^2 r_{12}} \right) \vec{S}_1 \cdot \vec{S}_2 - C \right]$$

$$H \mid \Phi \rangle = E \mid \Phi \rangle, \quad \mid \Phi \rangle = \sum_{n=1}^{N} \Phi_n \mid n \rangle \to \boxed{H_{nn'} \Phi_{n'} = E_N O_{nn'} \Phi_{n'}}$$

$\langle \vec{r} \mid n \rangle = e^{-n\beta^2 r^2 / 2}, \qquad \beta$: variational parameter

$$O_{nn'} = \frac{1}{\beta^3} \left(\frac{2\pi}{n + n'} \right)^{3/2}$$

$$H_{nn'} = \frac{1}{\beta^3} \left(\frac{2\pi}{n + n'} \right)^{3/2} \left[m_1 + m_2 + \frac{3\beta^2}{2\mu} \frac{nn'}{n + n'} + -\frac{4}{3} \alpha_c \beta \sqrt{\frac{2(n + n')}{\pi}} + \frac{b}{8\beta} \sqrt{\frac{8}{\pi(n + n')}} \right.$$

$$\left. + \frac{32\sigma^3 \alpha_h}{9 m_1 m_2 \sqrt{\pi}} \left(\frac{n + n'}{n + n' + 2\sigma^2 / \beta^2} \right)^{3/2} \langle \vec{S}_1 \cdot \vec{S}_2 \rangle + \frac{4}{3} C \right]$$

Results for masses:

	β	M_{cal}	M_{exp}
π	347	139.7	137
ρ	272	770	770
K	362	492.5	495
D	499	1863.3	1867

All values in MeV

SU(4) breaking in the couplings (at $q^2 = 0$)

$$h_{fi}(q^2) = g\,F(q^2)$$

	$g_{\rho\pi\pi} / 2g_{\rho KK}$	$g_{\rho\pi\pi} / 2g_{\rho DD}$	$g_{\rho KK} / g_{\rho DD}$
SU(4) symmetric	*1*	*1*	*1*
SU(4) broken	*1.05*	*1.31*	*1.25*

SU(4) symmetry breaking: at the level of 25% – 30%

SU(4) breaking in baryon-meson couplings

	$g_{N\Lambda_s K} \,/\, g_{N\Lambda_c D}$
SU(4) broken	*1.05*

SU(4) symmetry breaking: very small

DN Experiment: antiproton annihilation on the deuteron – Panda @ FAIR

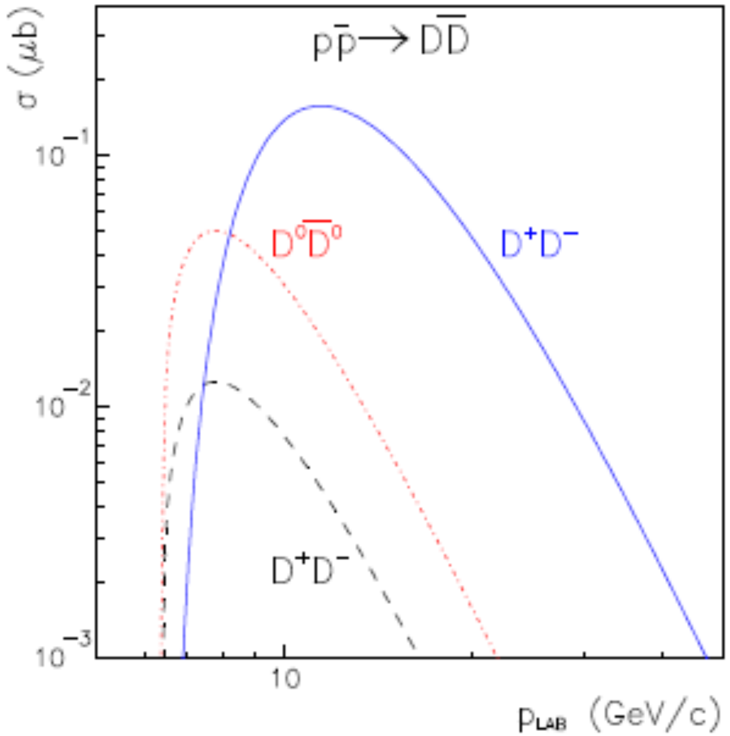


Fig. 6. Predictions for the $\bar{p}p \rightarrow \bar{D}D$ annhilation cross section taken from Refs. [54] (solid line) and [55] (dashed and dash-dotted lines).

←big uncertainties on production of D mesons

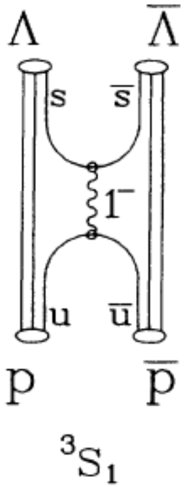
J. Haidenbauer, G. Krein, U.-G. Meissner, A. Sibirtseev
Eur. Phys. J. A 37, 55 (2008)

Production of $\Lambda_c\bar{\Lambda}_c$ *

- extension of Juelich model for $\Lambda\bar{\Lambda}$:

- ISI (OPE + optical potential)
- FSI (optical potentials)
- transition potential (D,D*)

- quark-model transition potential (Kohno & Weise)



$$V^{\bar{p}p\to\bar{\Lambda}\Lambda}(r) = \frac{4}{3}4\pi\frac{\alpha}{m_G^2}\delta_{S1}\delta_{T0}\left(\frac{3}{4\pi\langle r^2\rangle}\right)^{3/2} \times \exp(-3r^2/(4\langle r^2\rangle))$$

*Haidenbauer & GK 0912.2663 [hep-ph]

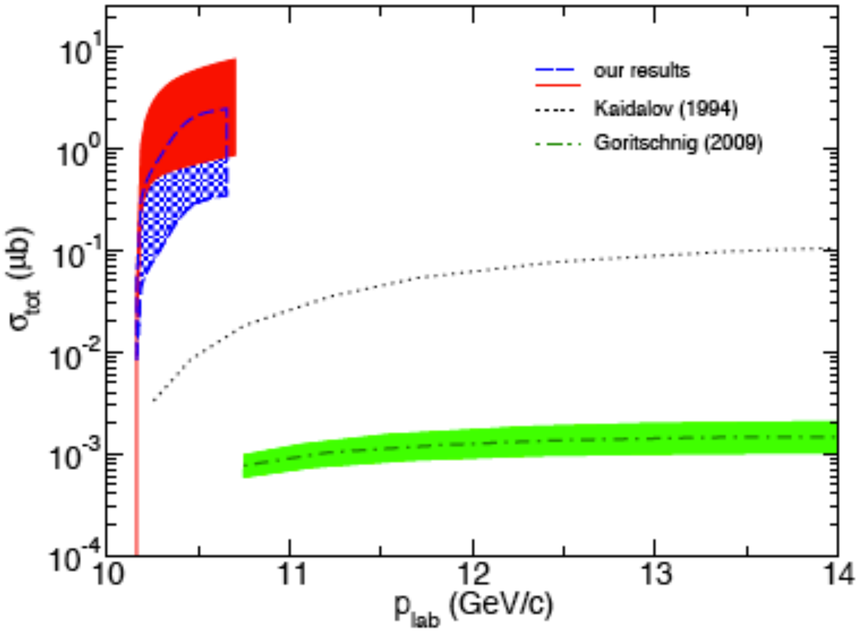


Fig. 4. Total reaction cross sections for $\bar{p}p \to \bar{\Lambda}_c^- \Lambda_c^+$ as a function of the excess energy p_{lab}. The dark (red) shaded band (blue grid) is the prediction of our meson-exchange (quark-gluon) transition potential. The dotted curve is the result from Ref. [4] while the dash-dotted curve and the corresponding (green) band is from Ref. [2].

- production of $\Lambda_c\bar{\Lambda}_c$ ~ 0.1 production of $\Lambda\bar{\Lambda}$

- our results factor 100 – 1000 larger than existing predictions