Charmed hadrons in nuclear matter

Gastão Krein
Instituto de Física Teórica, São Paulo

RANP 2013
Takeshi Kodama's Fest

23-27 September 2013
Centro Brasileiro de Pesquisas Físicas
Rio de Janeiro - Brazil

誕生日おめでとう Takeshi

私たちはあなたがブラジルの物理学のためにしたすべてに

心より感謝いたします.

誕生日おめでとう Takeshi, watashi tachi

はあなたがブラジルの物理学

のためにしたすべてに

kokoroyori 感謝 itashimasu.

Happy birthday Takeshi

... and thank you very much,

from the deepest of our hearts,

for all you have done for physics in Brazil

Outline

- Motivation
- J/Ψ in matter
- DN interaction
- SU(4) flavor symmetry in couplings
- Conclusions & perspectives

Interaction of charm with ordinary matter

- Understanding of the nuclear force at QCD level; role of glue

(origin of hadron masses & confinement)

- D-mesons in medium: chiral-symmetry restoration

- J/Ψ, η_c, D $\cdots$: possibly bound to ordinary matter

- Quark-gluon plasma

Experiments underway:

JLab @ 12 GeV, Panda & CBM @ Fair, JPARC

Charmonium binding in nuclear matter

- an exotic nuclear state

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

- Nucleons and charmonium have no valence quarks in common

- Interaction has to proceed via gluons – QCD van der Waals

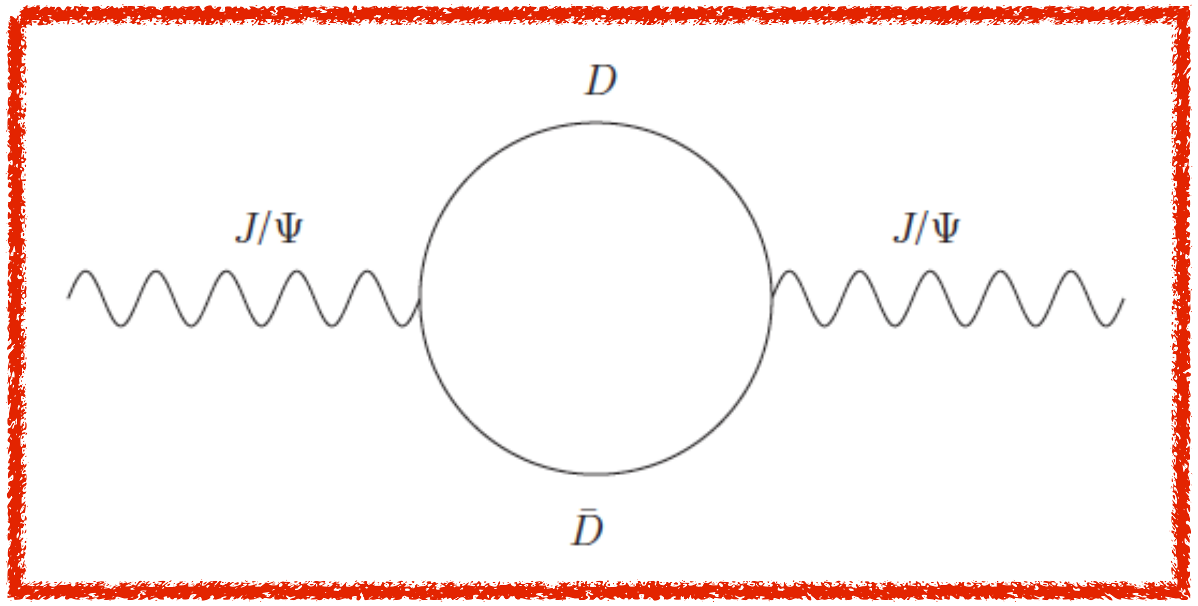
- No Pauli Principle – no short-range repulsion

- Also, binding via D,D* meson loop - interaction with nucleons

BE ~ 10 - 20 MeV

GK, A.W. Thomas & K. Tsushima PLB 697, 136 (2011)
K. Tsushima, D. Lu, GK & A.W. Thomas PRC 83, 065208 (2011)

D,D*-meson loops



Calculate loop with effective Lagrangians

– need coupling constants & form factors

– need a model for medium dependence of D masses

Effective Lagrangians

– SU(4) flavor symmetry

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

$$\mathcal{L}_{\psi DD^*} = \frac{g_{\psi DD^*}}{m_\psi}\, \varepsilon_{\alpha\beta\mu\nu} \left(\partial^\alpha \psi^\beta\right) \left[\left(\partial_\mu \bar{D}^{*\nu}\right) D + \bar{D}\,(\partial_\mu D^{*\nu})\right]$$

$$\begin{aligned}
\mathcal{L}_{\psi D^* D^*} &= i g_{\psi D^* D^*} \left\{\psi^\mu \left[\left(\partial_\mu \bar{D}^{*\nu}\right) D^*_\nu - \bar{D}^{*\nu}\,(\partial_\mu D^*_\nu)\right]\right. \\
&+ \left[(\partial_\mu \psi^\nu)\, \bar{D}^*_\nu - \psi^\nu \left(\partial_\mu \bar{D}^*_\nu\right)\right] D^{*\mu} \\
&+ \left. \bar{D}^{*\mu} \left[\psi^\nu\,(\partial_\mu D^*_\nu) - (\partial_\mu \psi^\nu)\, D^*_\nu\right]\right\}
\end{aligned}$$

J/Ψ single-particle energies in nuclei

– solve a Klein-Gordon equation, D, D* masses QMC model

		$\Lambda_{D,D^*} = 1500$ MeV	$\Lambda_{D,D^*} = 2000$ MeV
		E (MeV)	E (MeV)
$^{4}_{\Psi}$He	1*s*	−4.19	−5.74
$^{12}_{\Psi}$C	1*s*	−9.33	−11.21
	1*p*	−2.58	−3.94
$^{16}_{\Psi}$O	1*s*	−11.23	−13.26
	1*p*	−5.11	−6.81
$^{40}_{\Psi}$Ca	1*s*	−14.96	−17.24
	1*p*	−10.81	−12.92
	1*d*	−6.29	−8.21
	2*s*	−5.63	−7.48
$^{90}_{\Psi}$Zr	1*s*	−16.38	−18.69
	1*p*	−13.84	−16.07
	1*d*	−10.92	−13.06
	2*s*	−10.11	−12.22
$^{208}_{\Psi}$Pb	1*s*	−16.83	−19.10
	1*p*	−15.36	−17.59
	1*d*	−13.61	−15.81
	2*s*	−13.07	−15.26

GK, A.W. Thomas & K. Tsushima PLB 697, 136 (2011)
K. Tsushima, D. Lu, GK & A.W. Thomas PRC 83, 065208 (2011)

Are those binding energies large enough to bind a J/Ψ to a large nucleus?

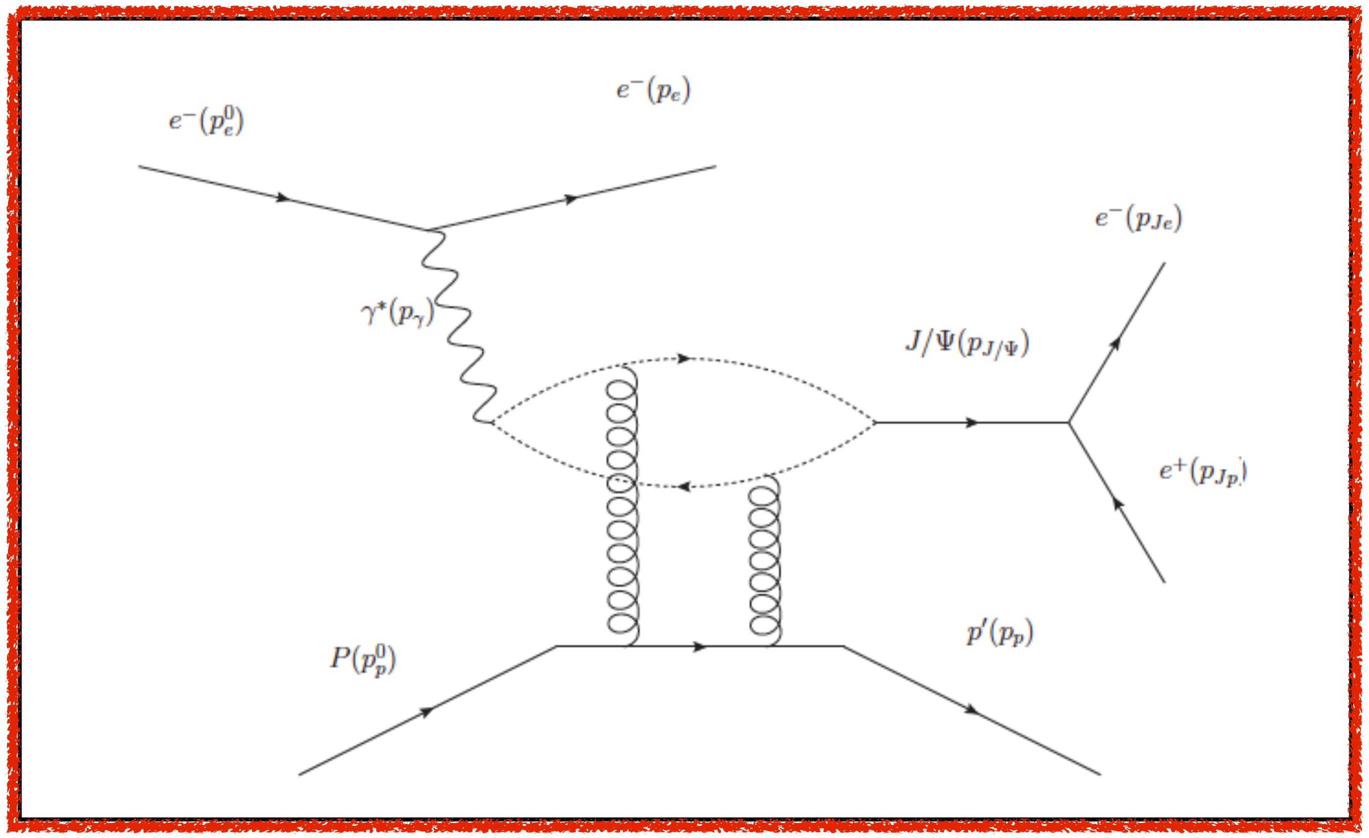
Condition for a bound state:

- spherical "square-well" radius R, depth V_0

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

$$R = 5\,\mathrm{fm} \rightarrow V_0 > 1\,\mathrm{MeV}$$

ATHENNA* collaboration JLab @ 12 GeV



Z.-E. Meziani (Co-spokesperson/Contact)
N. Sparveris (Co-spokesperson)
Z.W. Zhao (Co-spokesperson)

*A J/Ψ THreshold Electroproduction on the Nucleon and Nuclei Analysis

Issues:

1) Interaction of D mesons with nucleons

2) SU(4) flavor symmetry

3) Width of D mesons

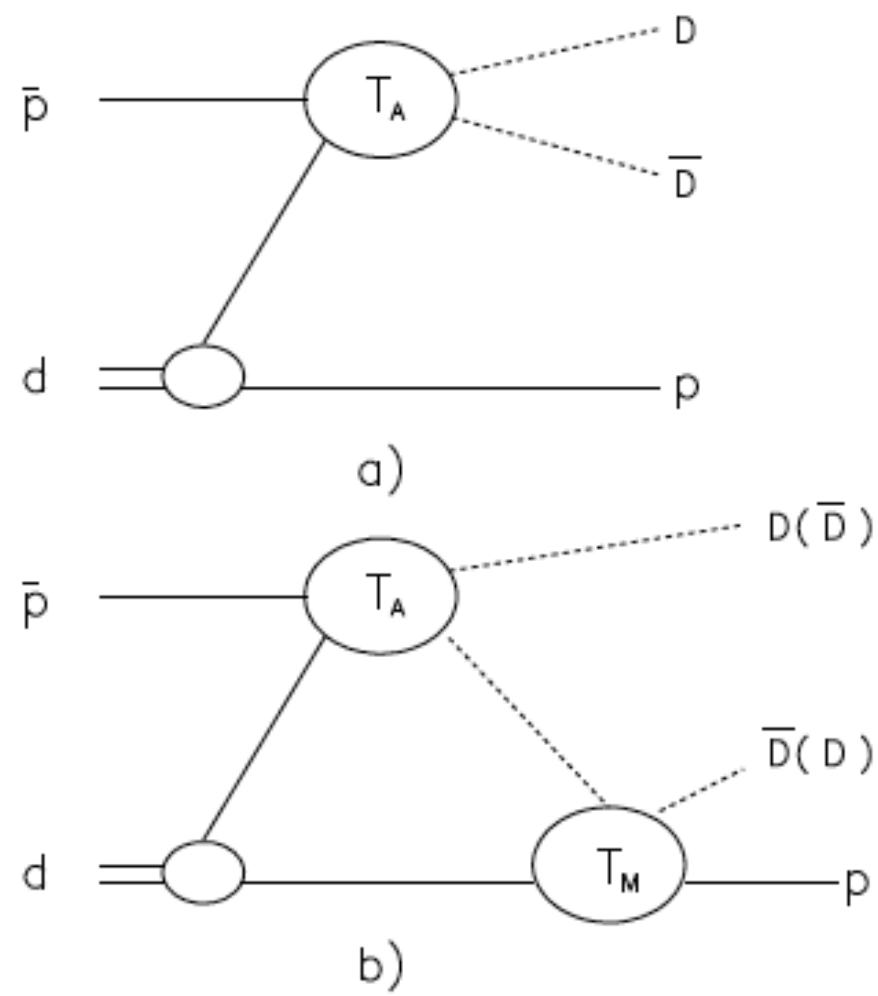
4) J/Ψ moving, not at rest

5) . . .

Next: 1) and 2)

Experiment
- antiproton annihilation on the deuteron*

P̄anda @ FAIR

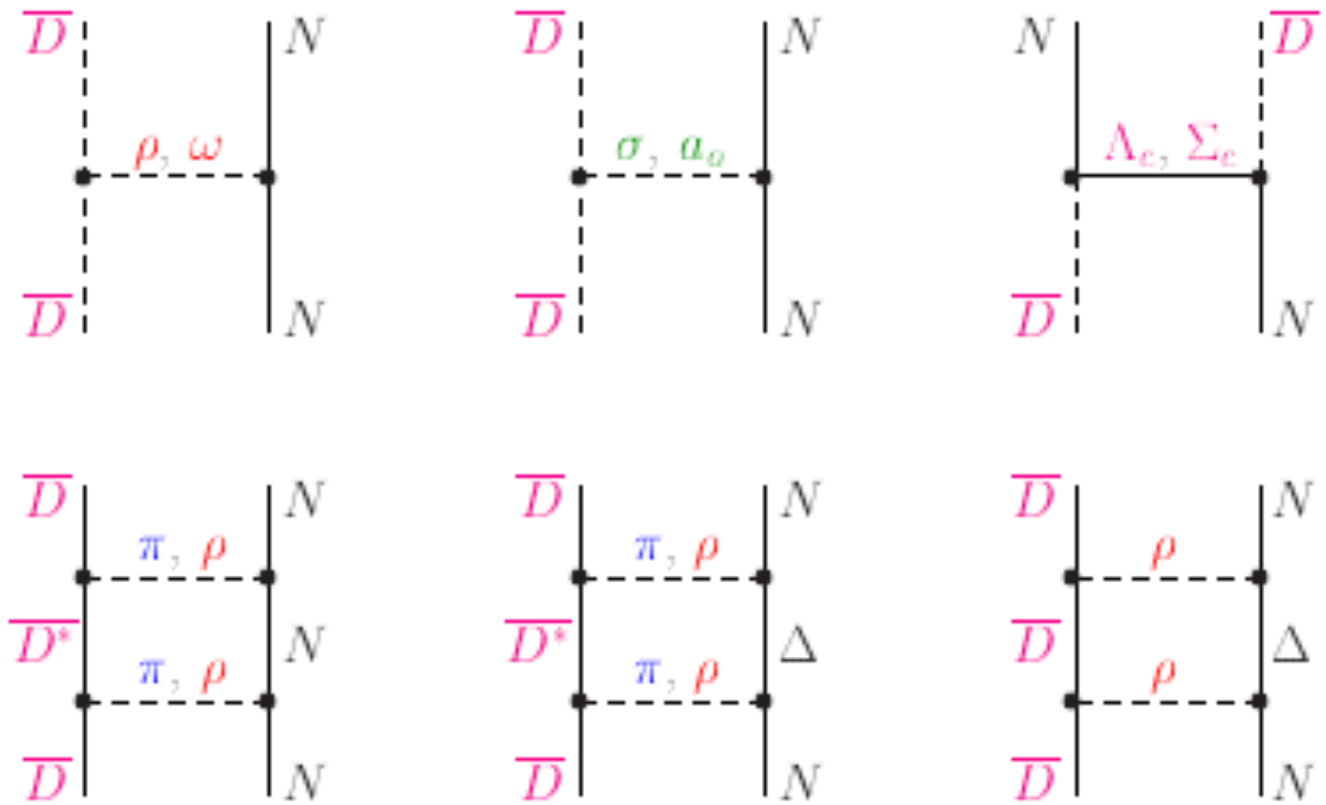


* J. Haidenbauer, G. Krein, U.-G. Meissner, A. Sibirtsev

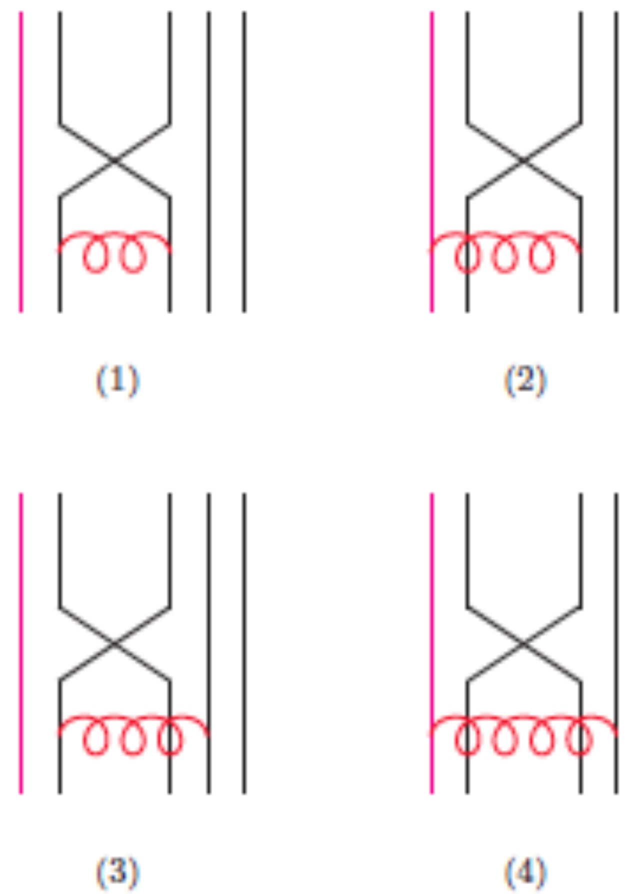
1) Eur. Phys. J. A 33, 107 (2007)

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

$\overline{D}$N interaction
– meson + quark exchange



+



MEX: SU(4)-flavor symmetry for couplings, same cutoffs as KN

QEX: change quark masses (wave functions)

Meson-meson-meson vertices

$$\mathcal{L}_{PPV} = g_{PPV}\Phi_P(x)\partial_\mu\Phi_P(x)\Phi_V^\mu(x)$$

$$\mathcal{L}_{VVP} = \frac{g_{VVP}}{m_V} i\epsilon_{\mu\nu\tau\delta}\partial^\mu\Phi_V^\nu(x)\partial^\tau\Phi_V^\delta(x)\Phi_P(x)$$

Baryon-baryon-meson vertices

$$\mathcal{L}_{NNP} = g_{NNP}\bar{\Psi}_N(x)i\gamma^5\Psi_N(x)\Phi_P(x)$$

$$\mathcal{L}_{NNV} = g_{NNV}\bar{\Psi}_N(x)\gamma_\mu\Psi_N(x)\Phi_V^\mu(x) + \frac{f_{NNV}}{4m_N}\bar{\Psi}_N(x)\sigma_{\mu\nu}\Psi_N(x)(\partial^\mu\Phi_V^\nu(x) - \partial^\nu\Phi_V^\mu(x))$$

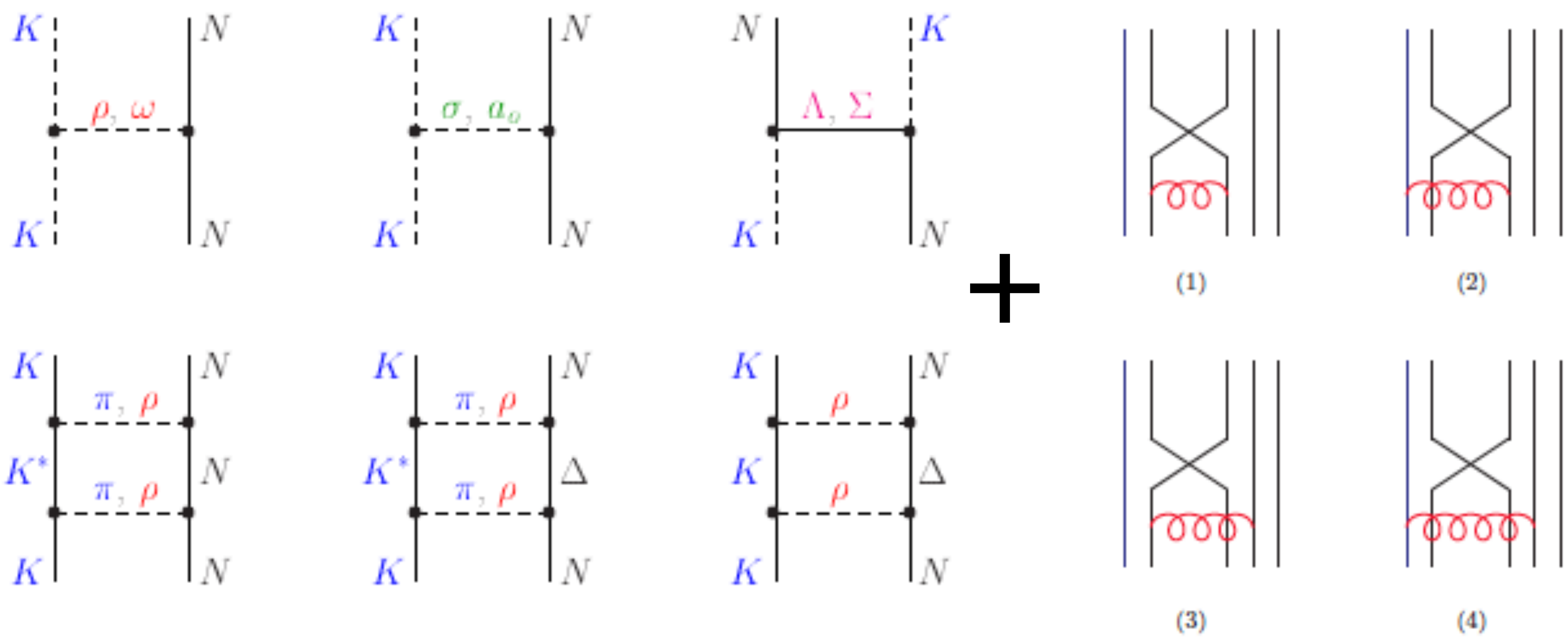
$$\mathcal{L}_{N\Delta P} = \frac{f_{N\Delta P}}{m_P}\bar{\Psi}_{\Delta\mu}(x)\Psi_N(x)\partial^\mu\Phi_P(x) + \text{H.c.}$$

$$\mathcal{L}_{N\Delta V} = \frac{f_{N\Delta V}}{m_V}i(\bar{\Psi}_{\Delta\mu}(x)\gamma^5\gamma_\mu\Psi_N(x) - \bar{\Psi}_N(x)\gamma^5\gamma_\mu\Psi_{\Delta\mu}(x))(\partial^\mu\Phi_V^\nu(x) - \partial^\nu\Phi_V^\mu(x))$$

$$\mathcal{L}_{NYP} = \frac{f_{NYP}}{m_P}(\bar{\Psi}_Y(x)\gamma^5\gamma^\mu\Psi_N(x) + \bar{\Psi}_N(x)\gamma^5\gamma^\mu\Psi_Y(x))\partial_\mu\phi_P(x)$$

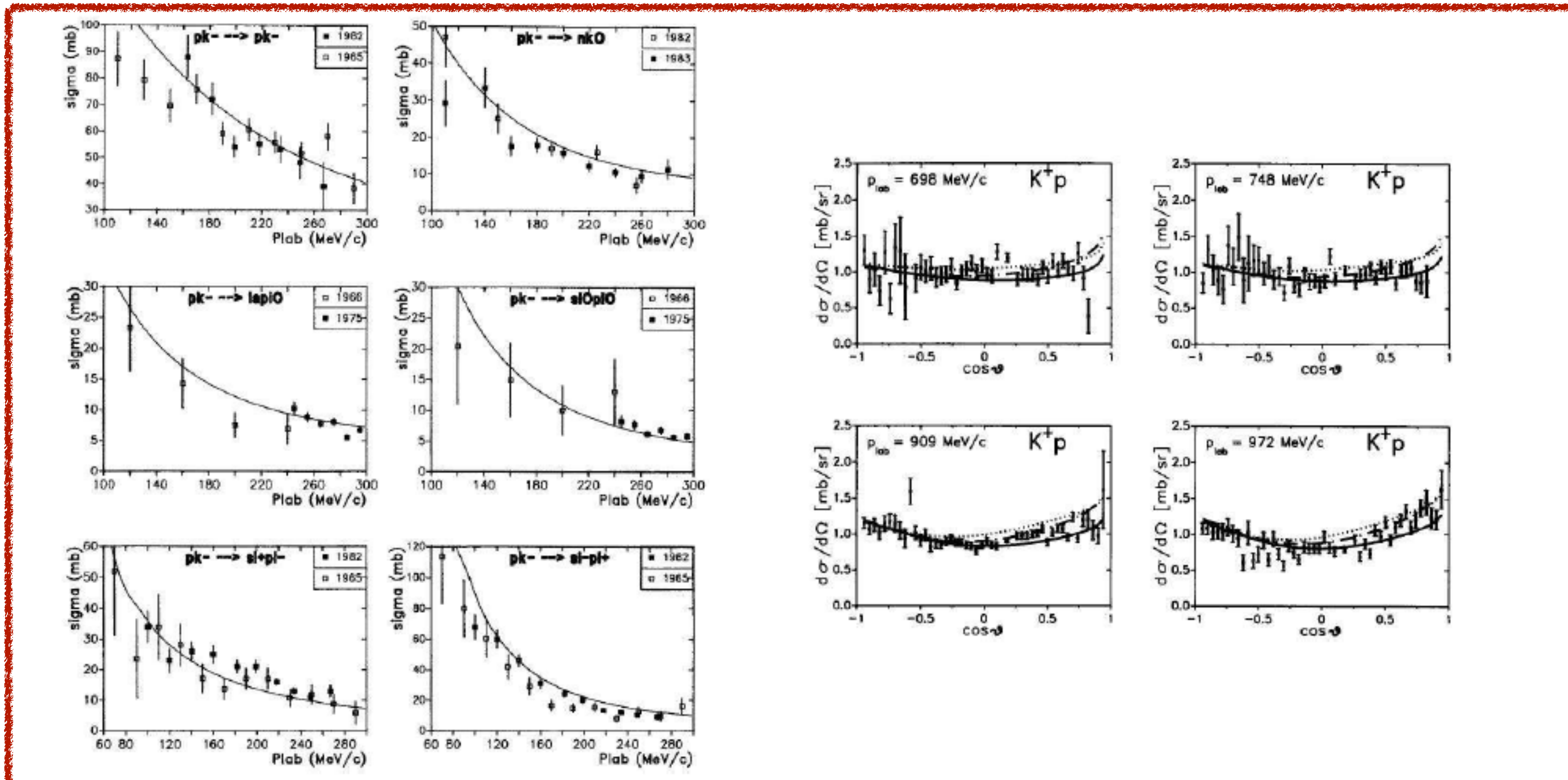
Based on a previous KN Juelich model

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



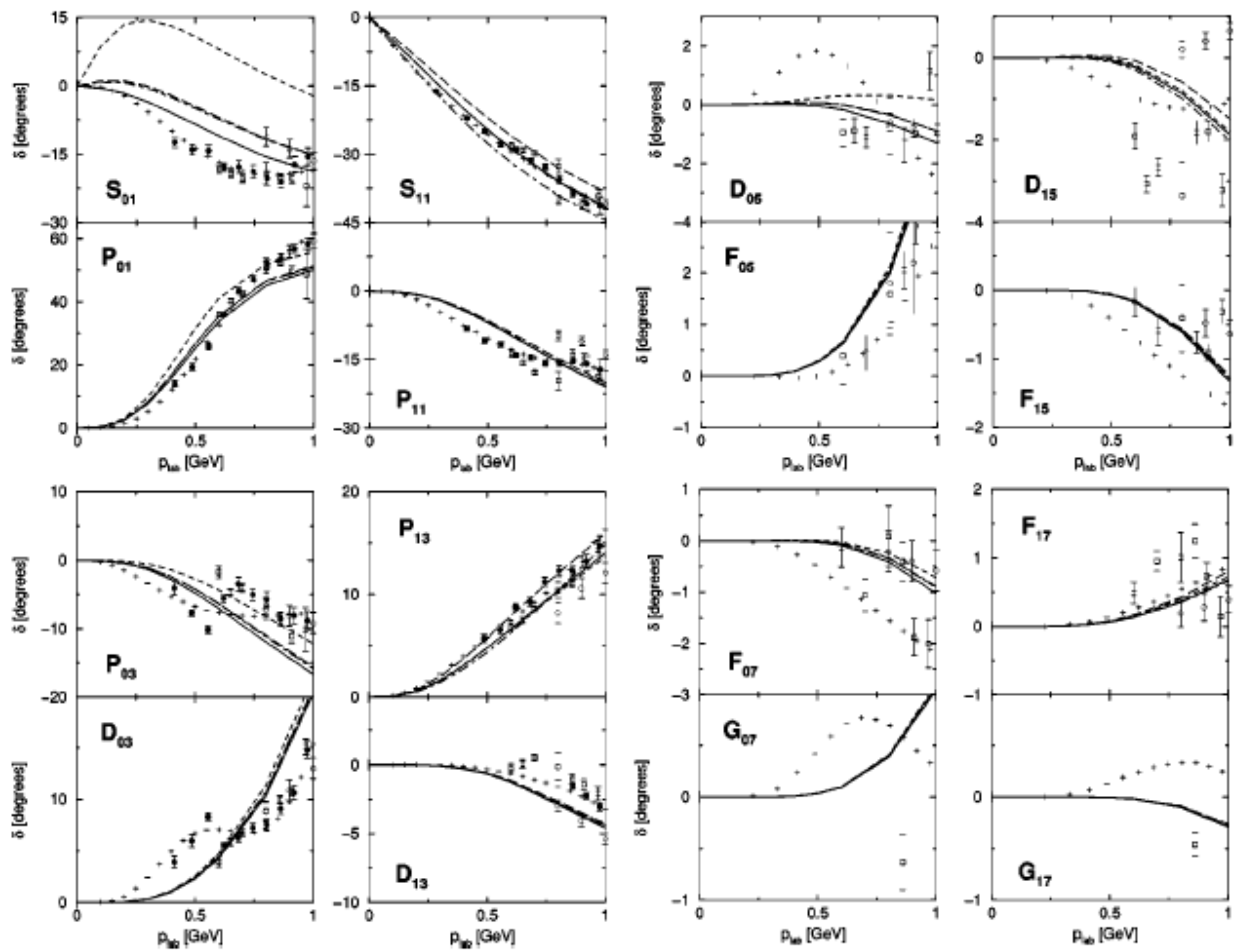
Contains a short-ranged "repulsive scalar" $m \sim 1.2$ GeV → Can be replaced by quark-gluon exchange Hadjimichef, Haidenbauer and GK, PRC 66, 055214 (2002

Model fits available KN data

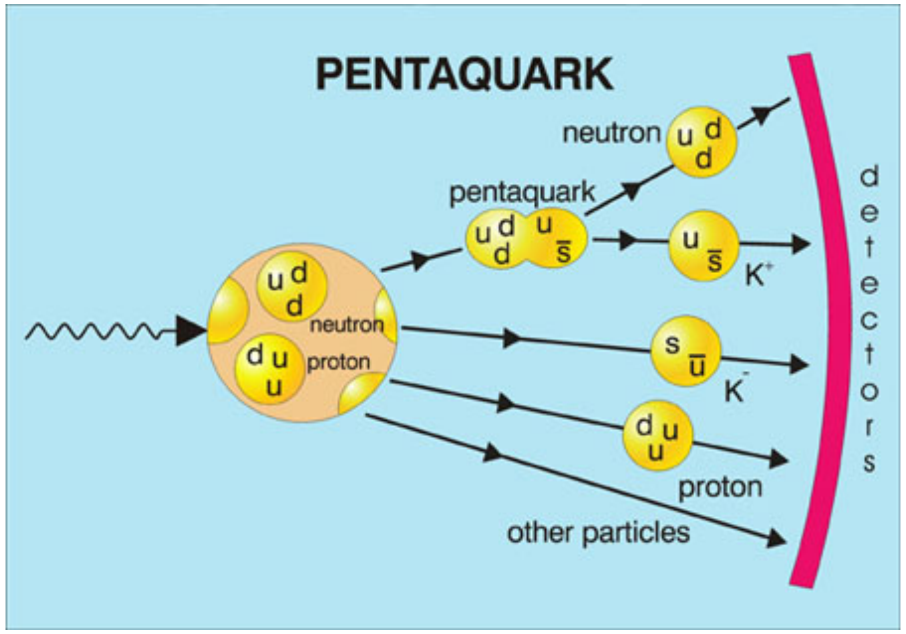


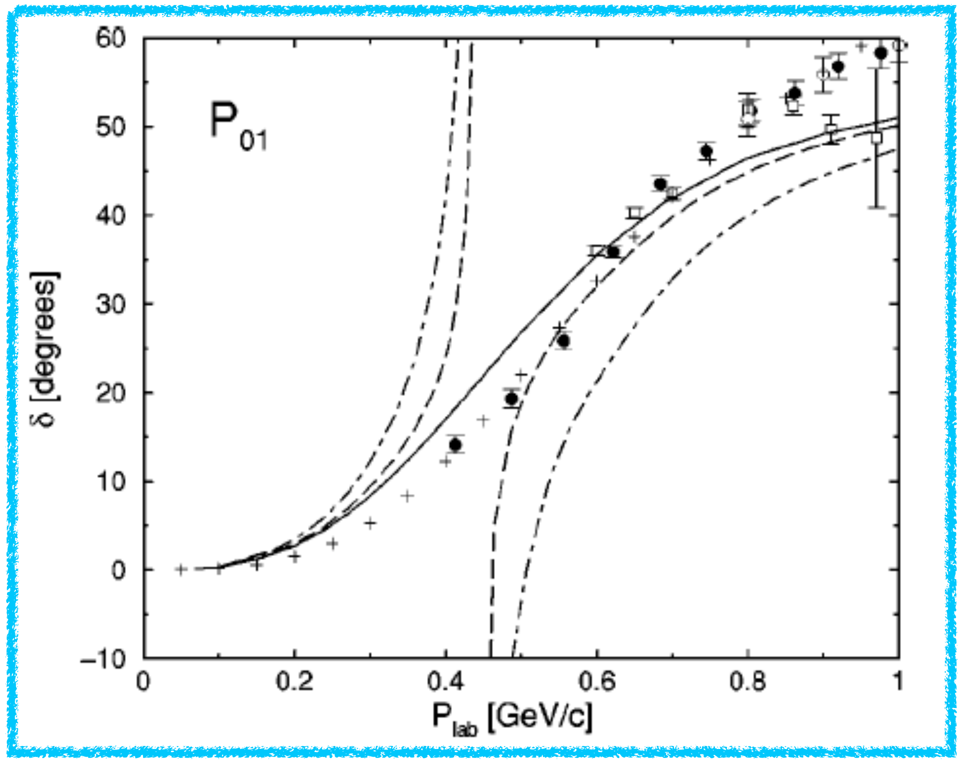
describes even phase shifts

D. HADJIMICHEF, J. HAIDENBAUER, AND G. KREIN PHYSICAL REVIEW C 66, 055214 (2002)



… and helped to kill the pentaquark





RAPID COMMUNICATIONS

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

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

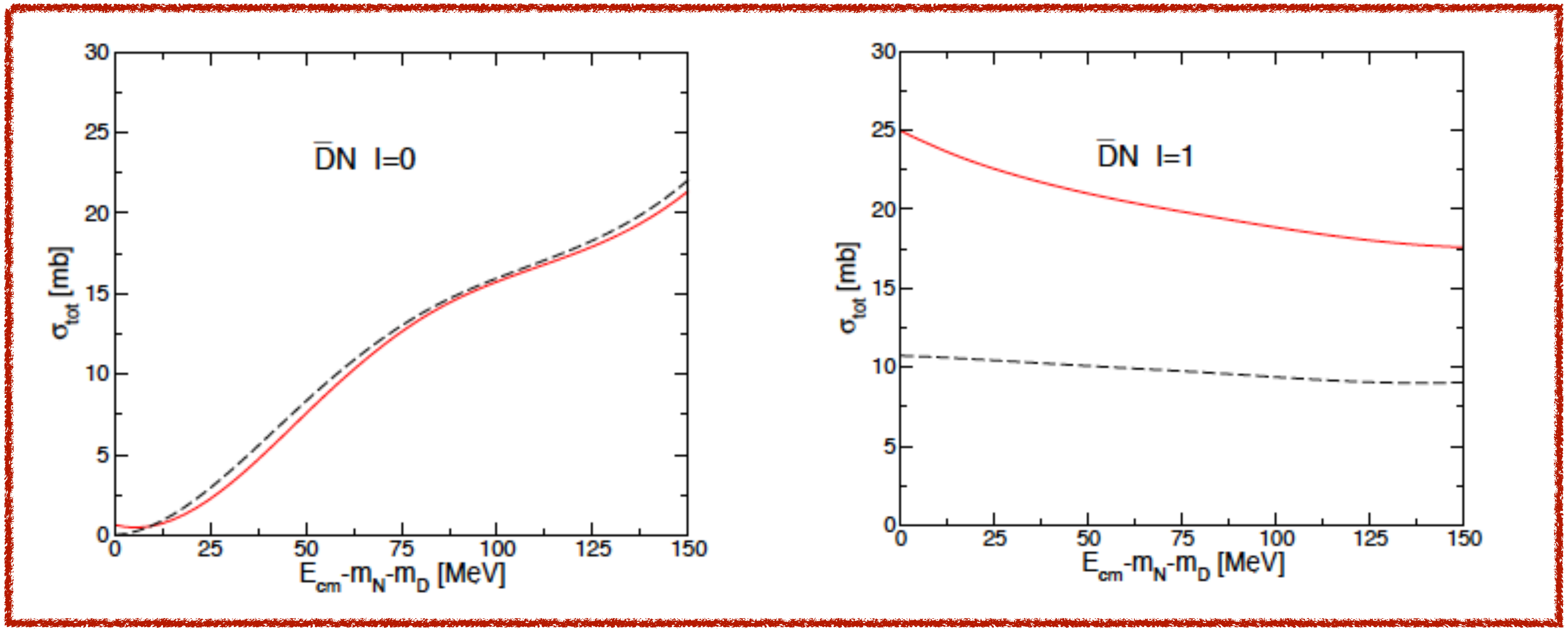
J. Haidenbauer[1] and G. Krein[2]
[1]*Forschungszentrum Jülich, Institut für Kernphysik, D-52425 Jülich, Germany*
[2]*Instituto de Física Teórica, Universidade Estadual Paulista, Rua Pamplona, 145-01405-900 São Paulo, SP, Brazil*
(Received 22 September 2003; published 18 November 2003)

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

Predictions for the PANDA measurement

Use SU(4) symmetry for couplings:



* J. Haidenbauer, G. Krein, U.-G. Meissner, A. Sibirtsev
1) Eur. Phys. J. A 33, 107 (2007)
2) Eur. Phys. J. A 37, 55 (2008)

$\bar{D}N$ interaction

– in a color confining chiral quark model*

Inspired in the QCD Hamiltonian in Coulomb gauge

Derive from the same underlying Hamiltonian:

– constituent quark masses (mass generation)

– hadron wave-functions, hadron masses (confinement)

– effective meson-baryon interaction (nuclear force)

– X-sections, etc (observables)

– density & temperature dependence on hadron masses (not here)

*C.E. Fontoura, GK, and V.E. Vizcarra, Phys. Rev. C 87, 025206 (2013)

Hamiltonian

$$H = H_0 + H_{\text{int}}$$

$$H_0 = \int d\boldsymbol{x}\, \Psi^\dagger(\boldsymbol{x})(-i\boldsymbol{\alpha}\cdot\boldsymbol{\nabla} + \beta m)\Psi(\boldsymbol{x})$$

$$\begin{aligned} H_{\text{int}} = &-\frac{1}{2}\int d\boldsymbol{x}\, d\boldsymbol{y}\, \rho^a(\boldsymbol{x})\, V_C(|\boldsymbol{x}-\boldsymbol{y}|)\, \rho^a(\boldsymbol{y}) \\ &+\frac{1}{2}\int d\boldsymbol{x}\, d\boldsymbol{y}\, J_i^a(\boldsymbol{x})\, D^{ij}(|\boldsymbol{x}-\boldsymbol{y}|)\, J_j^a(\boldsymbol{y}) \end{aligned}$$

$$\rho^a(\boldsymbol{x}) = \Psi^\dagger(\boldsymbol{x})\, T^a\, \Psi(x)$$

$$J_i^a(\boldsymbol{x}) = \Psi^\dagger(\boldsymbol{x})\, T^a \alpha_i\, \Psi(\boldsymbol{x})$$

Input from the lattice

- Coulomb kernel – potential $$V^L_{\text{Coul}}(\vec{k}) = \frac{1}{8L_s^3}\left\langle \sum_{a,\vec{x},\vec{y}} e^{i\vec{k}\cdot(\vec{x}-\vec{y})}[M^{-1}(-\triangle)M^{-1}]^{aa}_{\vec{x}\,\vec{y}} \right\rangle$$

$$V_{\text{Coul}}(q) = \frac{6}{\beta}a^2 V^L_{\text{Coul}}(k,\beta), \qquad q_i(k_i) = \frac{2}{a}\sin\left(\frac{\pi k_i}{L_i}\right)$$

- Fit from simulations*

$$V_{\text{Coul}}(q) = \frac{8\pi\sigma_{\text{Coul}}}{q^4} + \frac{4\pi C}{q^2} \qquad \begin{cases} \sigma_{\text{Coul}} = (552\,\text{MeV})^2 \\ C = 6 \end{cases}$$

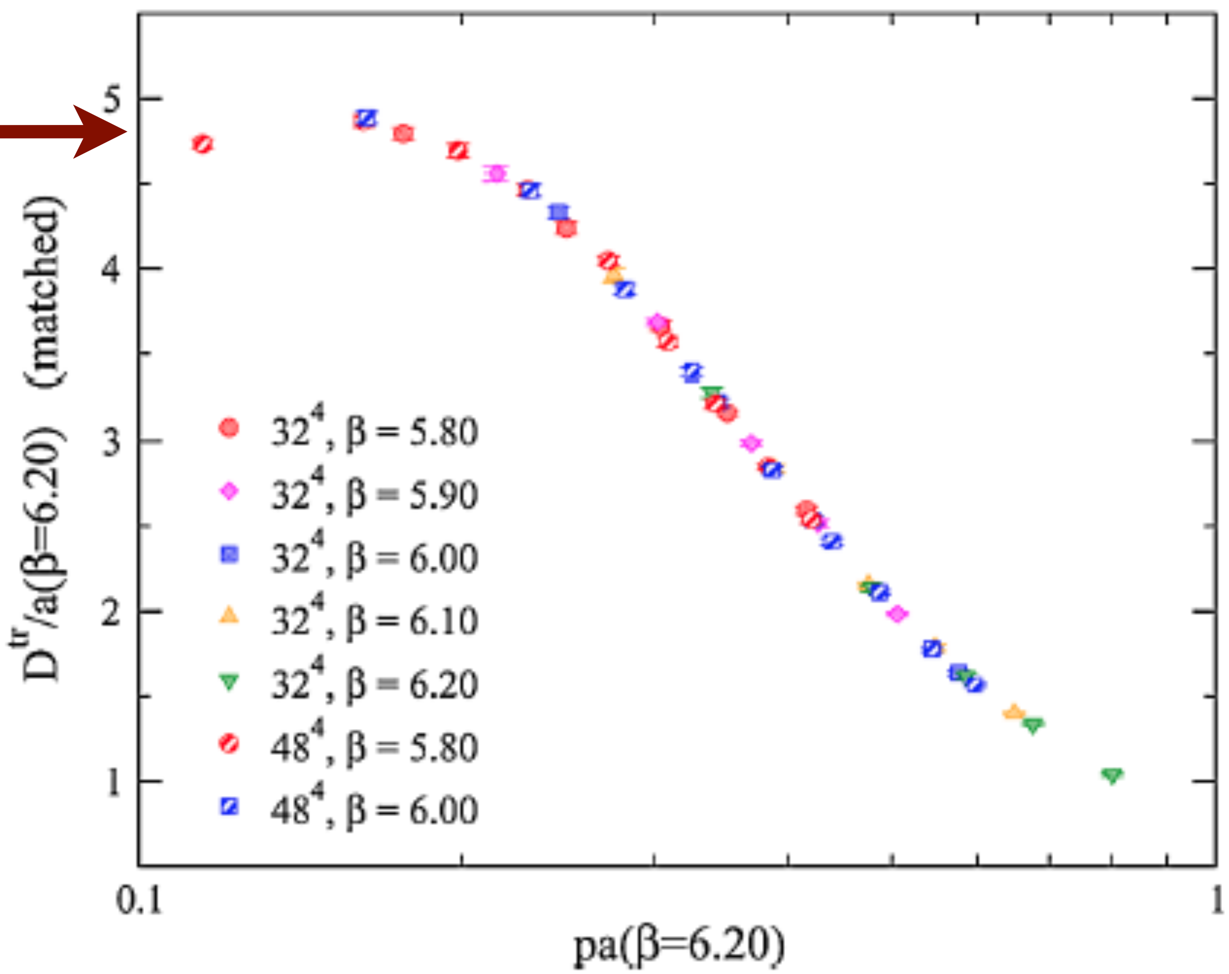
*A. Voigt, E.-M. Ilgenfritz, M. Muller-Preussker, Phys. Rev. D 78, 014501(2008)

Transverse-gluon propagator

$$D_{ij}^{ab}(\vec{k}) = \langle \tilde{A}_i^a(\vec{k})\tilde{A}_j^b(-\vec{k})\rangle = \delta^{ab}\left(\delta_{ij} - \frac{p_i(\vec{k})p_j(\vec{k})}{p^2}\right)D_{\mathrm{tr}}(p)$$

$$p_i(\vec{k}) \equiv \frac{2}{a}\sin\left(\frac{\pi k_i}{L}\right)$$

finite in the infrared



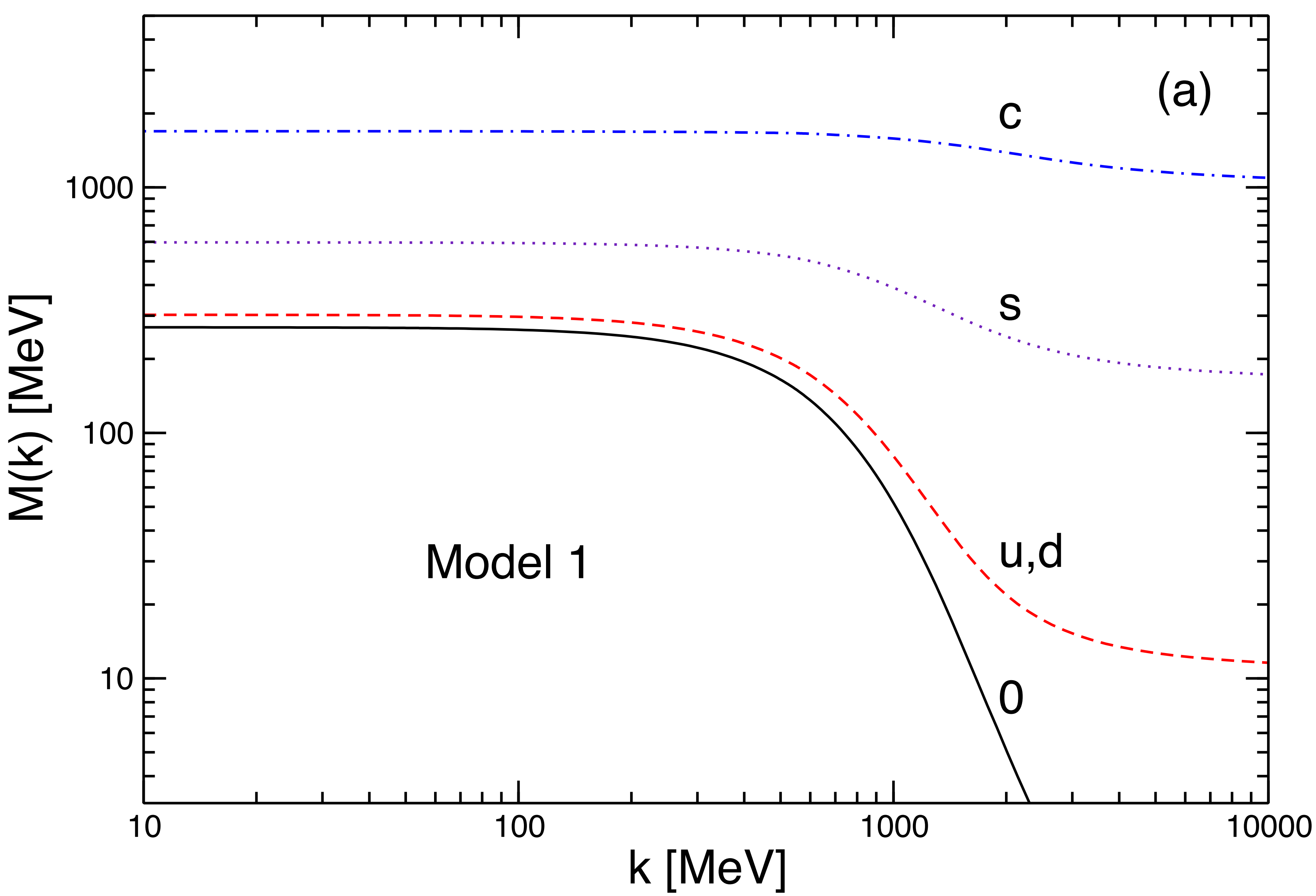
From the same Hamiltonian:

- dynamically generated quark masses
- hadron wavefunctions (color singlets only)
- hadron-hadron interactions
- X-sections, phase-shifts, ...

Quark mass function

- dynamical chiral symmetry breaking

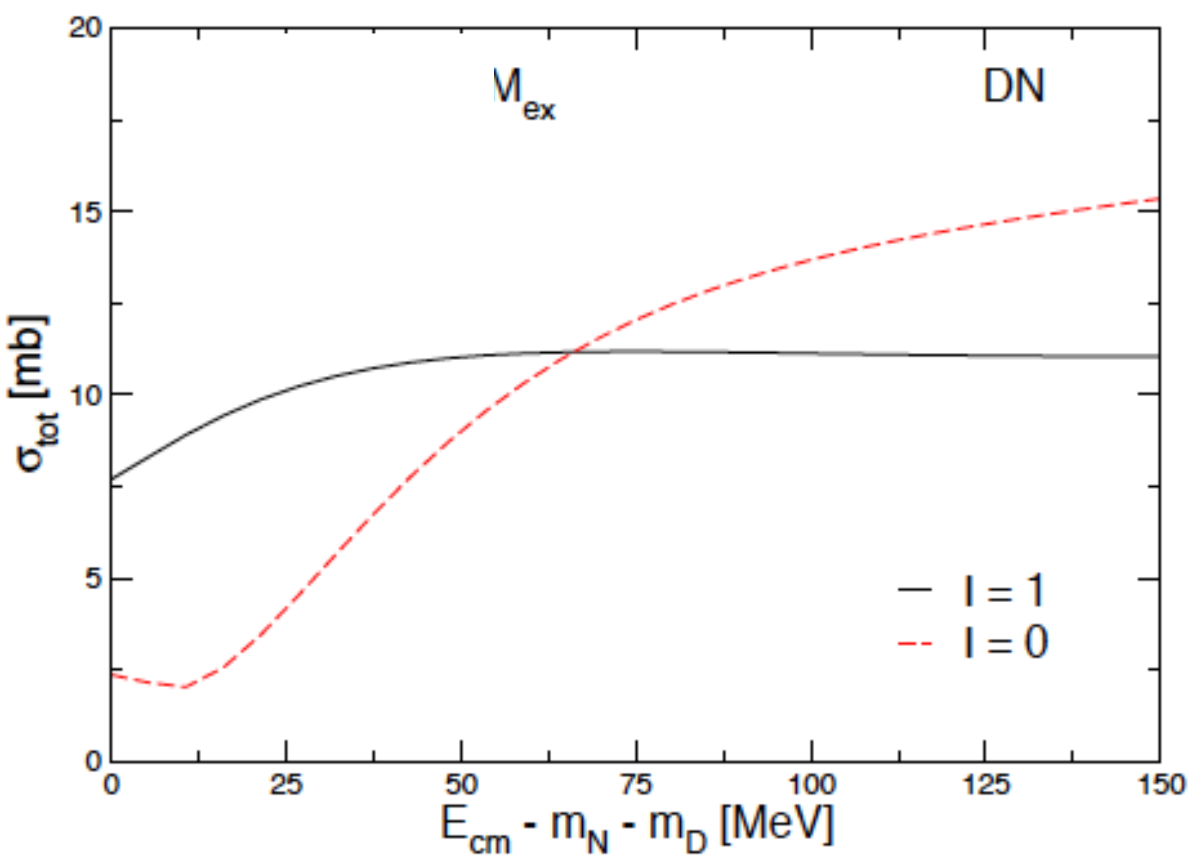
(Dyson-Schwinger equation)



Cross-sections

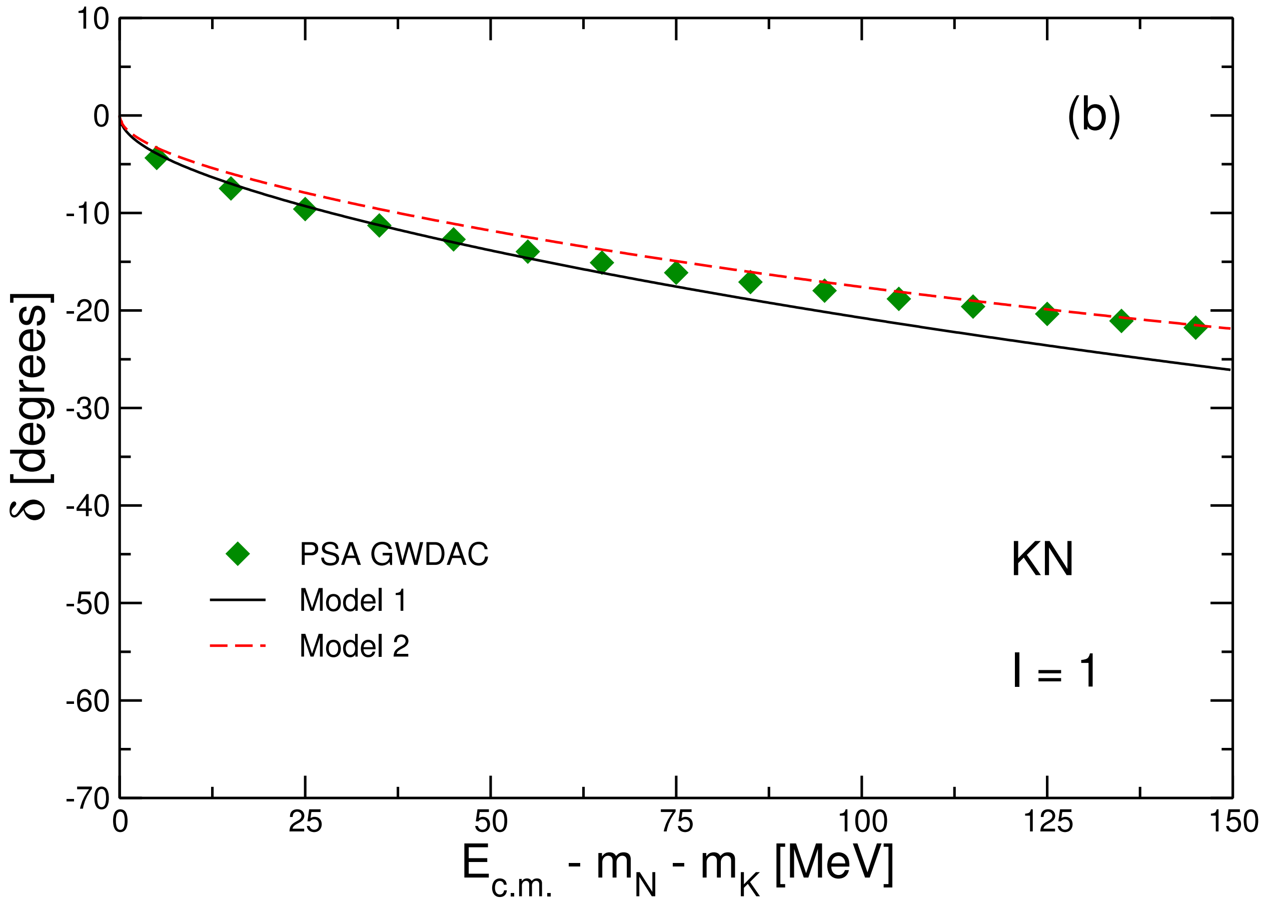
- short-distance: quark interchange
- long-distance: meson-exchange (mainly rho, omega sigma)

$\bar{D}N$

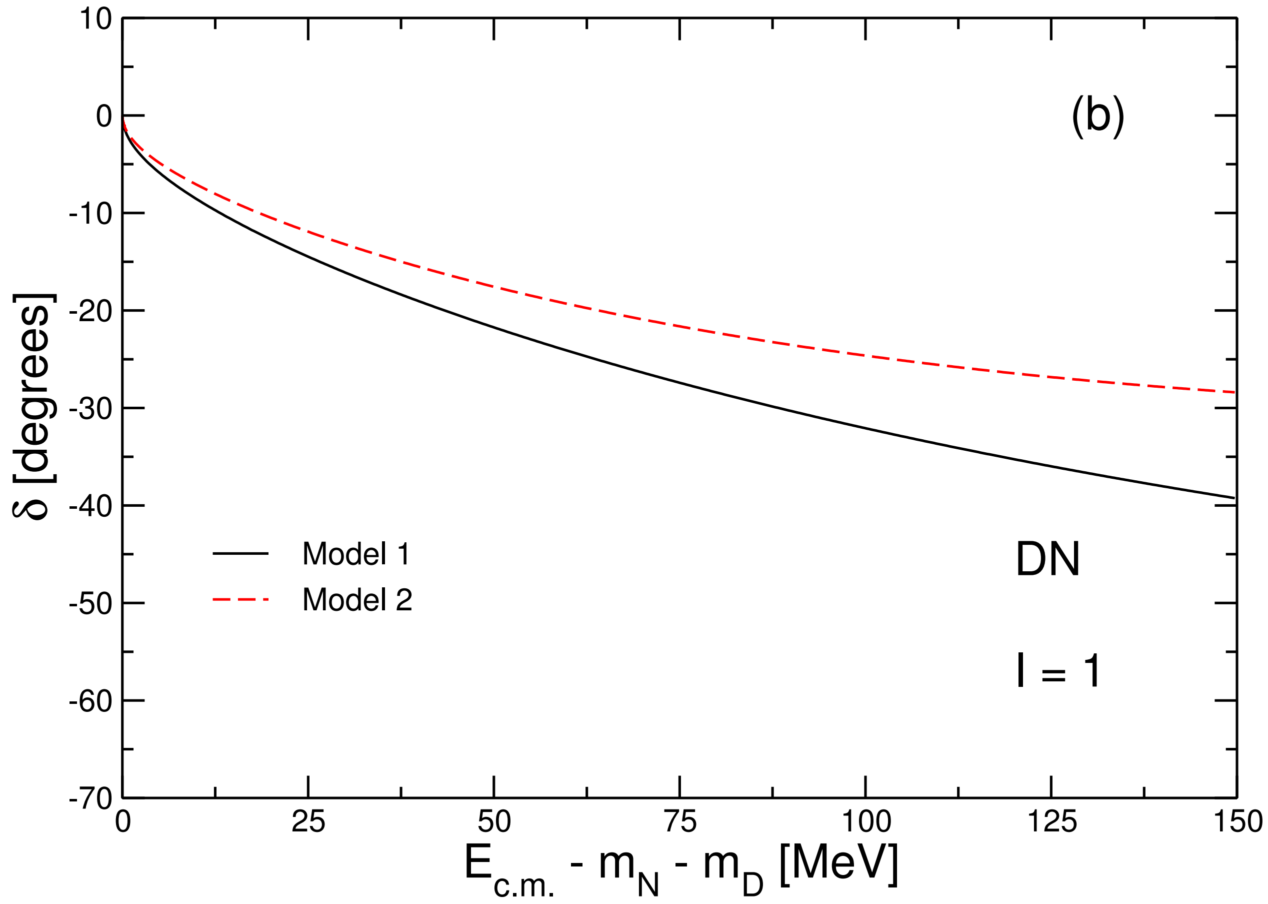


Phase shifts

KN

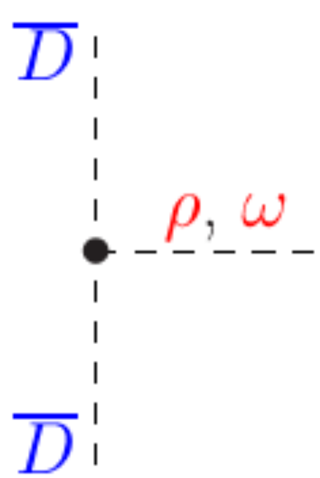


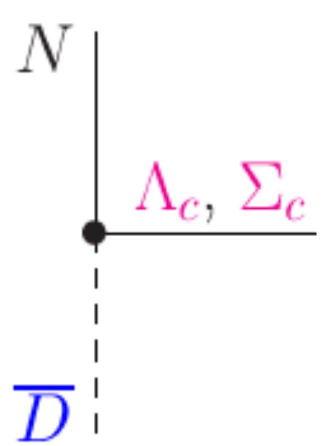
$\bar{D}N$



How good is SU(4) flavor symmetry for couplings ?

$$m_u < m_s \ll m_c$$





SU(4) symmetry:

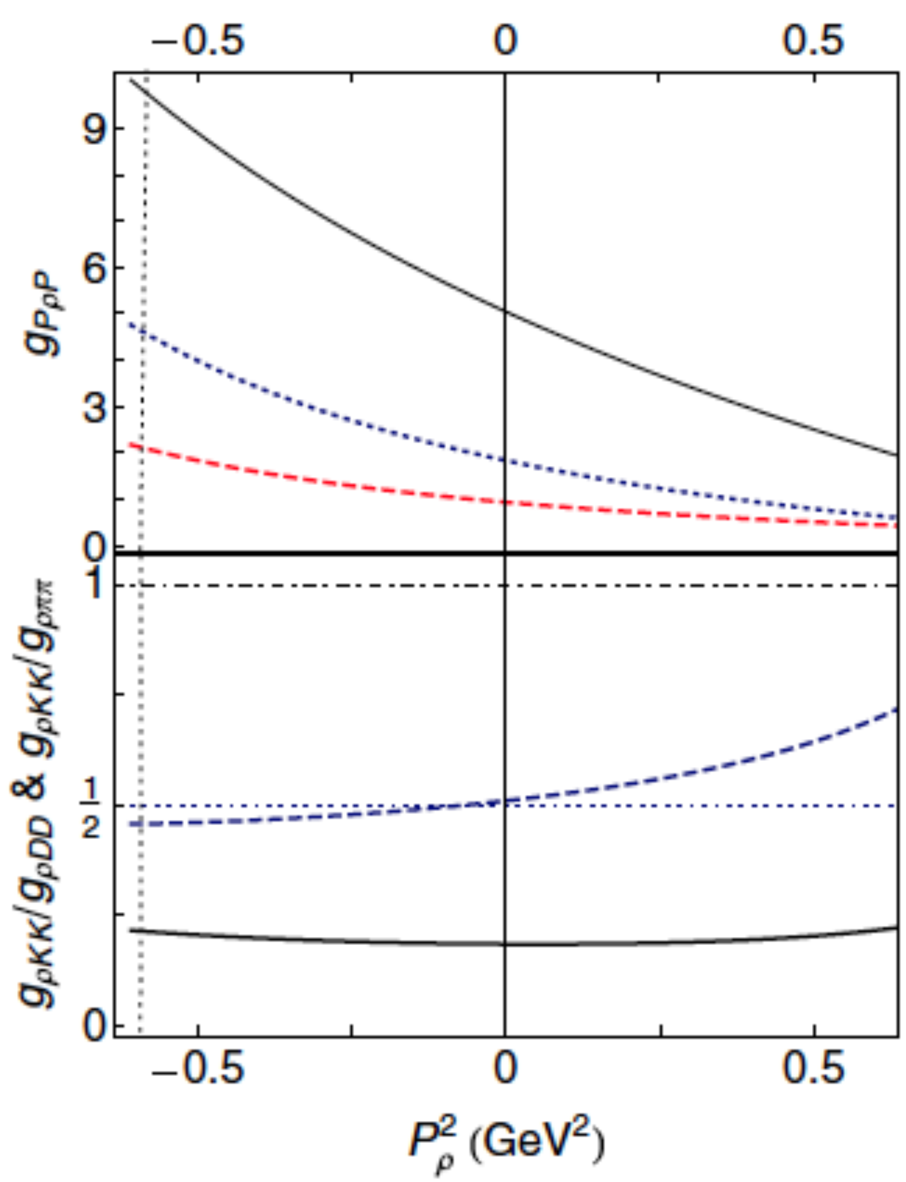
$$g_{\bar{D}\rho\bar{D}} = g_{K\rho K} = \frac{1}{2} g_{\pi\rho\pi}$$

$$g_{N\Lambda_c\bar{D}} = g_{N\Lambda K} = g_{NN\pi}$$

Coupling constants & Form factors

Dyson-Schwinger & Bethe-Salpeter equations:

- rainbow ladder, no free parameters (heavily constrained spectrum and e.w. decay constants)



$g_{K\rho K}/g_{D\rho D}$ ~ 1/4 → 400% violation

$g_{K\rho K}/g_{\pi\rho\pi}$ ~ 1/2 → SU(4) OK

COUPLING LARGE, BUT FORM FACTORS ARE SOFT

- DN X-SECTION ONLY 5 TIMES LARGER THAN SU(4)

B. El Bennich, GK, L. Chang, C.D. Roberts, D.J. Wilson, PRD 85, 031502 (2012)

On the other hand:

- nonrelativistic quark model + $^3P_0$ decay

	$g_{\rho\pi\pi} / 2g_{\rho KK}$	$g_{\rho\pi\pi} / 2g_{\rho DD}$	$g_{\rho KK} / g_{\rho DD}$
SU(4) symmetric	*1*	*1*	*1*
SU(4) broken	*1.05*	*1.28*	*1.22*

SU(4) BREAKING: AT THE LEVEL OF 20% – 30%

C. E. Fontoura, GK, J. Haidenbauer (2013)

Nonrelativistic quark model + $^3P_0$ decay

	$\frac{g_{NN\pi}}{g_{N\Lambda_s K}}$	$\frac{g_{NN\pi}}{g_{N\Lambda_c \bar{D}}}$	$\frac{g_{N\Lambda_s K}}{g_{N\Lambda_c \bar{D}}}$
SU(4) symmetric	1	1	1
SU(4) broken	1.07	1.20	1.12

SU(4) BREAKING: AT THE LEVEL OF 10% – 15%

QCD sum rules[1] & Lattice[2]

– looked at SU(4) symmetry breaking within the charm sector only

$$g_{\rho DD} = g_{\rho D^* D^*} = g_{\pi D^* D}$$

1) M.E. Bracco, M. Chiapparini, F.S. Navarra, M. Nielsen, Prog. Part. Nucl. Phys. 67, 1019 (2012)
2) K.U. Can, G. Erkol, M. Oka, T. Takahashi, Phys. Lett. B 719 , 103 (2013)

QCD sum rules

Table 8
SU(4) relations between the coupling constants (on the left column) and their violation (in percentage on the right column) found in QCDSR.

SU(4) relation	Violation
$g_{J/\psi DD} = g_{J/\psi D^* D^*}$	(7%)
$g_{\rho DD^*} = \frac{\sqrt{6}}{2} g_{J/\psi DD^*}$	(12%)
$g_{\rho DD} = \frac{\sqrt{6}}{4} g_{J/\psi DD}$	(17%)
$g_{\pi D^* D^*} = \frac{\sqrt{6}}{2} g_{J/\psi DD^*}$	(20%)
$g_{D^* D^* \rho} = \frac{\sqrt{6}}{4} g_{J/\psi D^* D^*}$	(20%)
$g_{DD\rho} = \frac{\sqrt{6}}{4} g_{J/\psi D^* D^*}$	(21%)
$g_{\rho D^* D^*} = \frac{\sqrt{6}}{4} g_{J/\psi DD}$	(25%)
$g_{\pi D^* D^*} = g_{\rho DD^*}$	(29%)
$g_{\rho DD} = g_{\rho D^* D^*}$	(36%)
$g_{D^* D\pi} = g_{D^* D^* \rho}$	(52%)
$g_{D^* D\pi} = \frac{\sqrt{6}}{4} g_{J/\psi D^* D^*}$	(62%)
$g_{D^* D\pi} = \frac{\sqrt{6}}{4} g_{J/\psi DD}$	(64%)
$g_{D^* D\pi} = g_{DD\rho}$	(70%)

M.E. Bracco, M. Chiapparini, F.S. Navarra, M. Nielsen, Prog. Part. Nucl. Phys. 67, 1019 (2012)

Lattice

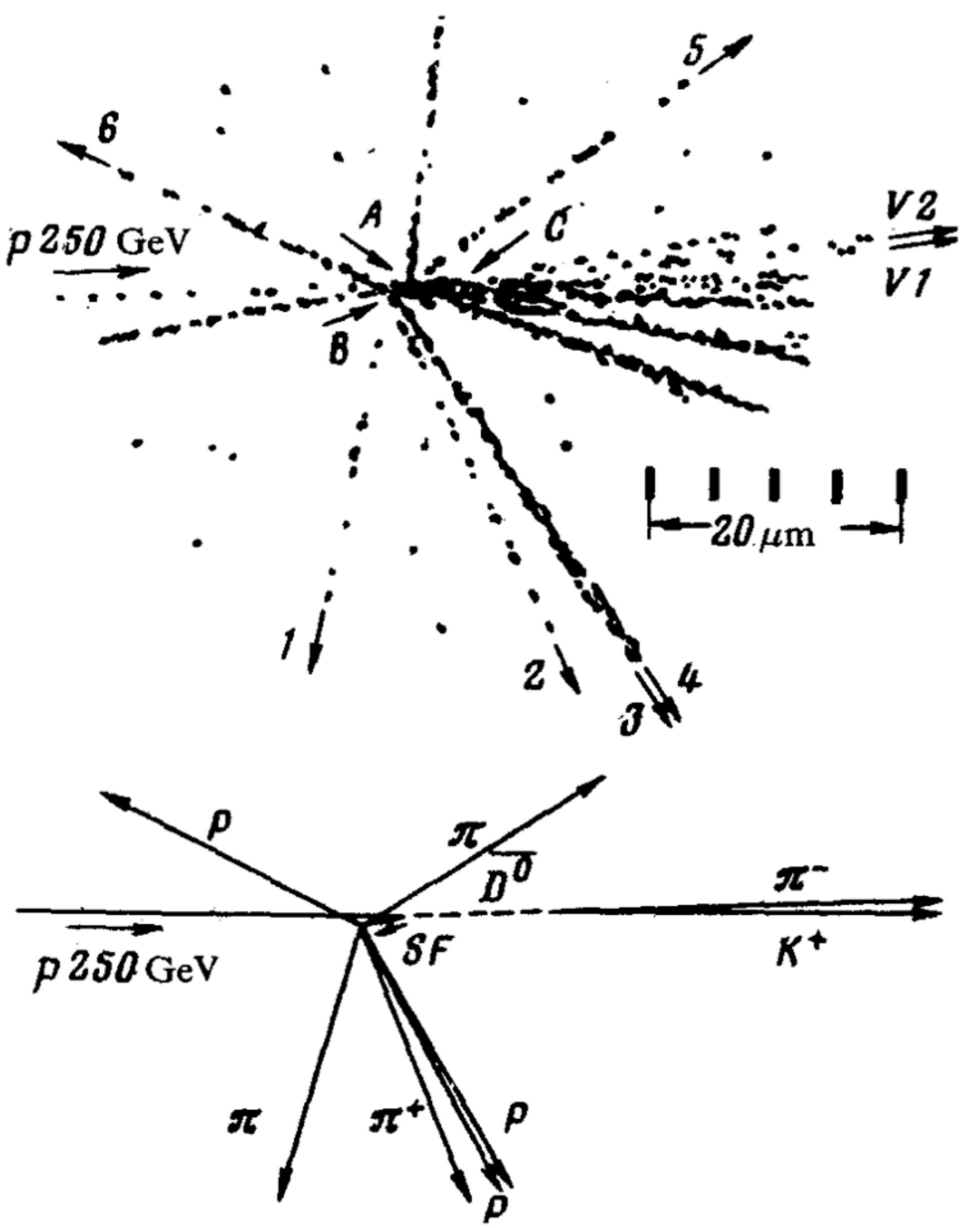
$$g_{D^*D\pi} = 16.23(1.71)$$

$$g_{DD\rho} = 4.84(34)$$

$$g_{D^*D^*\rho} = 5.94(56)$$

K.U. Can, G. Erkol, M. Oka, T. Takahashi, Phys. Lett. B 719 , 103 (2013)

Perspectives
- supernuclei (or charm hypernuclei)

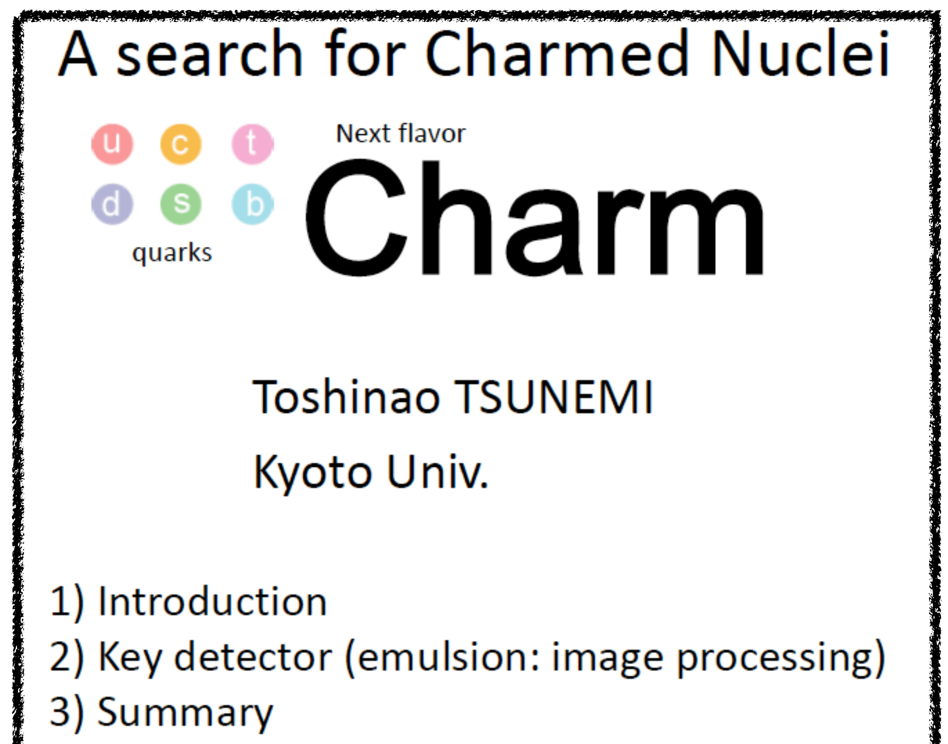


Yu. A. Batusov et al., JETP Lett. 33, 56 (1981)

A: primary vertex

B: vertex decay of a supernucleus decay

C: decay of $\overline{\mathrm{D}}^0$ (signal of $c\bar{c}$ pair)


A search for Charmed Nuclei

Next flavor

Charm

u c t
d s b
quarks

Toshinao TSUNEMI

Kyoto Univ.

1) Introduction
2) Key detector (emulsion: image processing)
3) Summary

- An experiment of searching for Super nuclei(charm) is being prepared at J-PARC experiment.
- Emulsion is a key detector.

Recent theory

PHYSICAL REVIEW C **67**, 015211 (2003)

Λ_c^+ and Λ_b hypernuclei

K. Tsushima[1,*] and F. C. Khanna[2,†]

TABLE I. Single-particle energies (in MeV) for $^{17}_{j}$O, $^{41}_{j}$Ca, and $^{49}_{j}$Ca ($j=\Lambda,\Lambda_c^+,\Lambda_b$). Single-particle energy levels are calculated up to the same highest states as that of the core neutrons. Results for the hypernuclei are taken from Ref. [10]. Experimental data for Λ hypernuclei are taken from Ref. [28], where spin-orbit splittings for Λ hypernuclei are not well determined by the experiments.

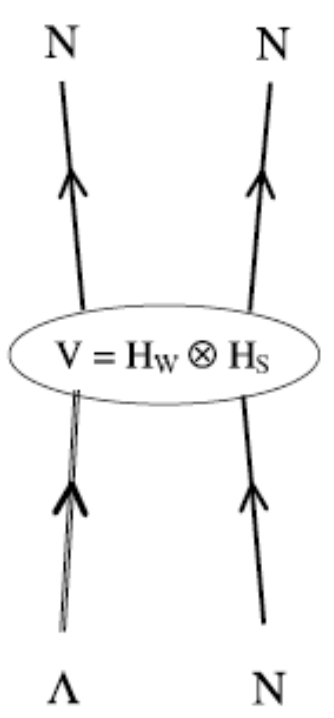
	$^{16}_{\Lambda}$O (Expt.)	$^{17}_{\Lambda}$O	$^{17}_{\Lambda_c^+}$O	$^{17}_{\Lambda_b}$O	$^{40}_{\Lambda}$Ca (Expt.)	$^{41}_{\Lambda}$Ca	$^{41}_{\Lambda_c^+}$Ca	$^{41}_{\Lambda_b}$Ca	$^{49}_{\Lambda}$Ca	$^{49}_{\Lambda_c^+}$Ca	$^{49}_{\Lambda_b}$Ca
$1s_{1/2}$	−12.5	−14.1	−12.8	−19.6	−20.0	−19.5	−12.8	−23.0	−21.0	−14.3	−24.4
$1p_{3/2}$	−2.5	−5.1	−7.3	−16.5	−12.0	−12.3	−9.2	−20.9	−13.9	−10.6	−22.2
$1p_{1/2}$	($1p_{3/2}$)	−5.0	−7.3	−16.5	($1p_{3/2}$)	−12.3	−9.1	−20.9	−13.8	−10.6	−22.2
$1d_{5/2}$						−4.7	−4.8	−18.4	−6.5	−6.5	−19.5
$2s_{1/2}$						−3.5	−3.4	−17.4	−5.4	−5.3	−18.8
$1d_{3/2}$						−4.6	−4.8	−18.4	−6.4	−6.4	−19.5
$1f_{7/2}$									—	−2.0	−16.8

Nonmesonic decays of charm hypernuclei*

L: weak vertex

+

R: strong vertex



$$\Lambda_c + N \rightarrow N + N$$

$$\Lambda_c + N \rightarrow N + \Lambda$$

*A.P. Galeao, GK, F. Krmpotic