# Heavy quarks in nuclear matter

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**Sixth Asia-Pacific Conference on Few-Body Problems in Physics**

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# Outline

- Motivation
- $J/\Psi$ in matter
- $\Lambda_c$ in matter
- Production of $\Lambda_c$
- D mesons in nuclei
- Production of D mesons
- SU(4) flavor symmetry in couplings

# Interaction of charm with matter

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

(origin of hadron masses & confinement)

- D-mesons in medium: chiral-symmetry restoration

- $J/\Psi$, $\eta_c$, D, $\Lambda_c \cdots$ : possibly bound to matter

- Quark-gluon plasma

Experiments underway:

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

# 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

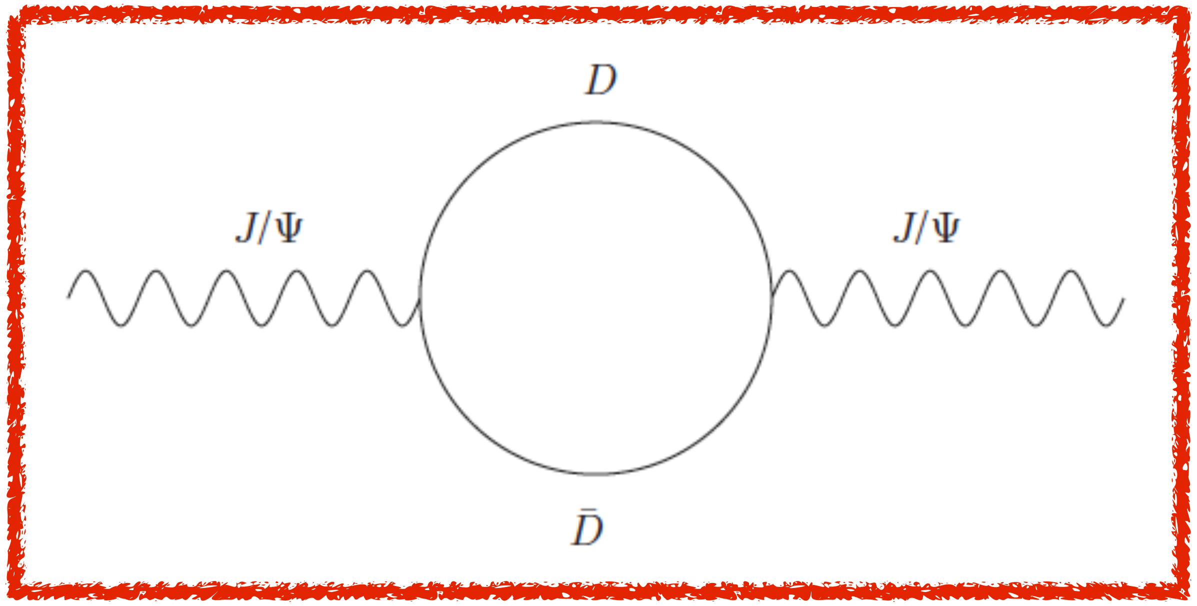
- No Pauli Principle – no short-range repulsion

- 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

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

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

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

# 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?

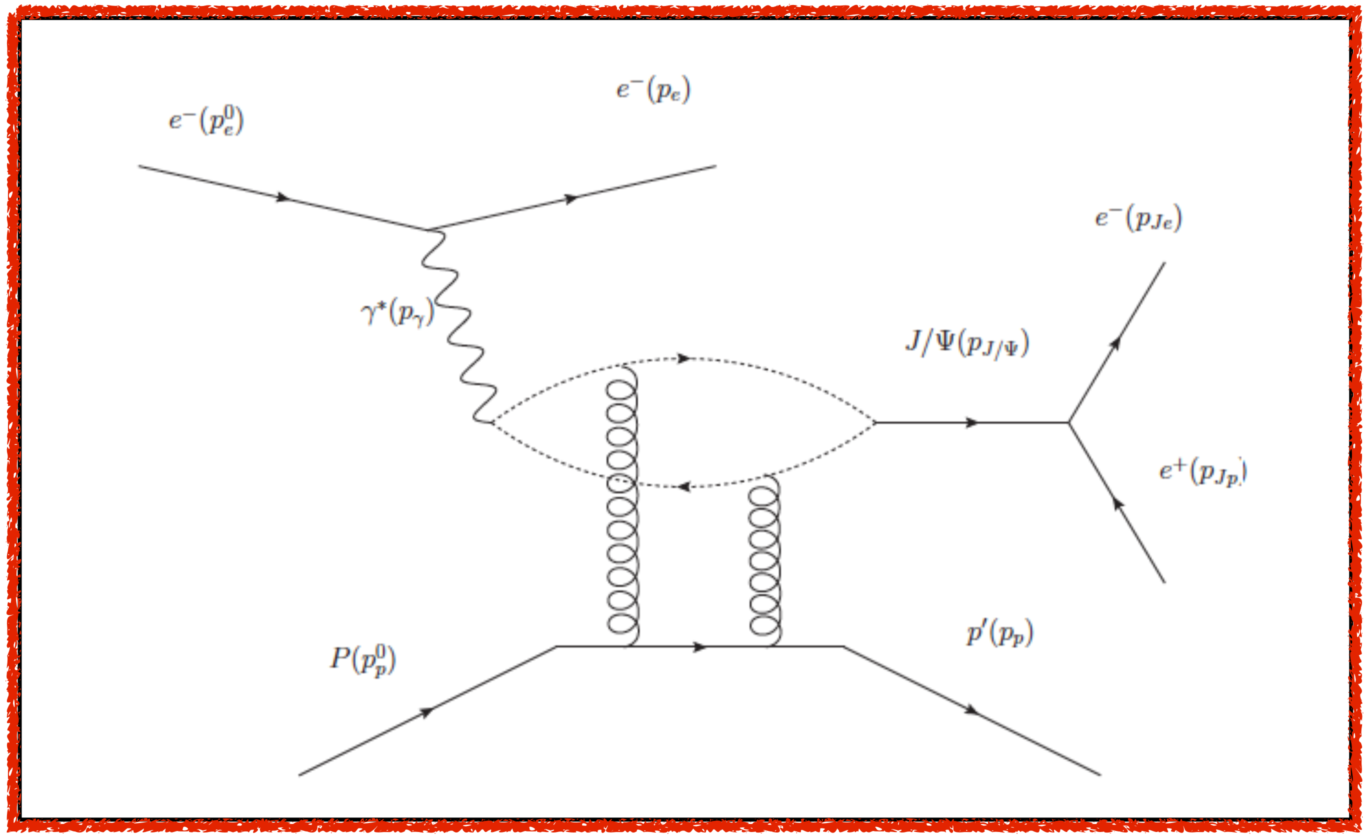
Condition for a bound state:

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

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

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

# ATHENNA* collaboration JLab @ 12 GeV




Z.-E. Meziani (Co-spokesperson/Contact)

*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) $J/\Psi$ moving, not at rest

5) . . .

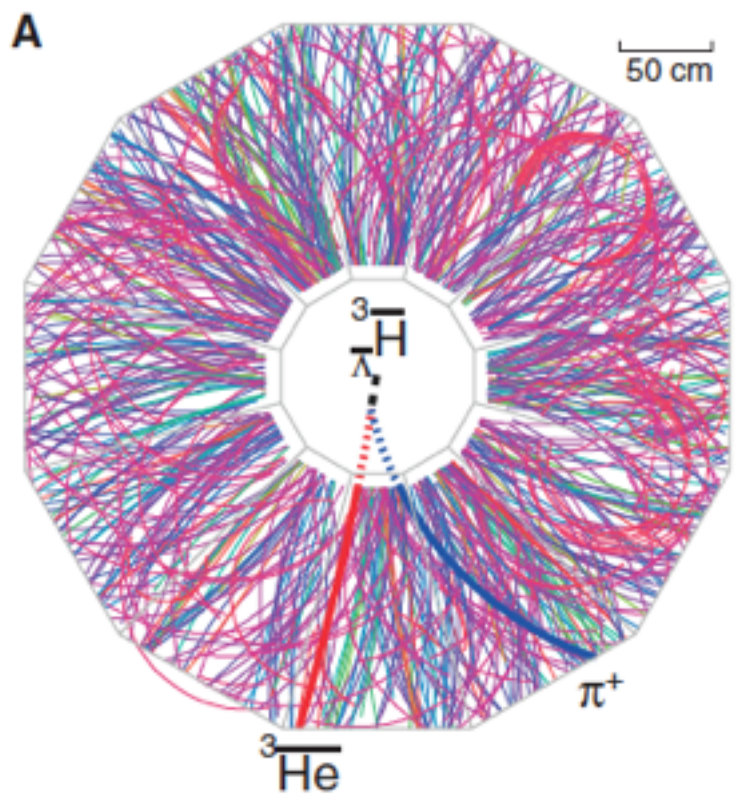
Next: 1) and 2)

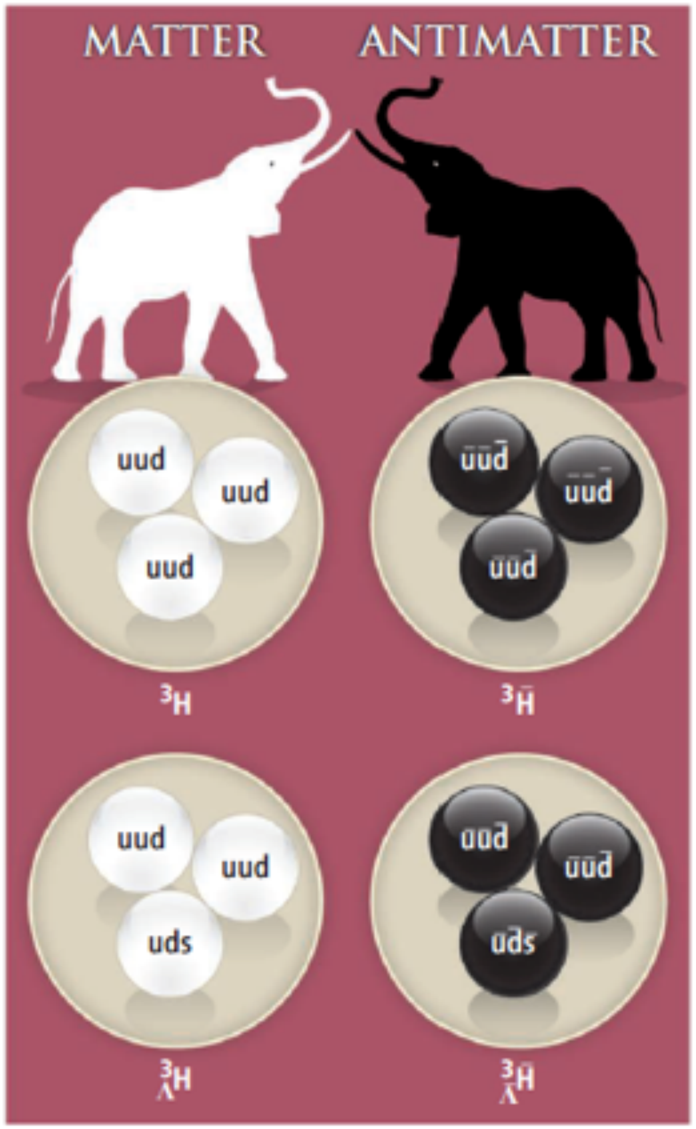
# How about J/Ψ+N bound state?

– coalescence in heavy-ion collisions at the LHC?

T.D. Cohen, Science **328**, 55 (2010)

**Observation of an Antimatter Hypernucleus**
The STAR Collaboration
*Science* **328**, 58 (2010);
DOI: 10.1126/science.1183980

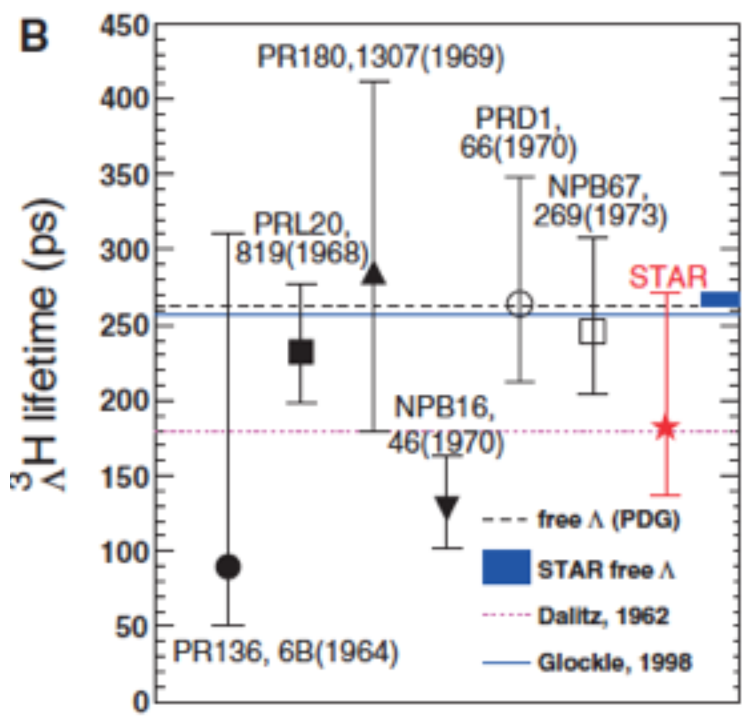


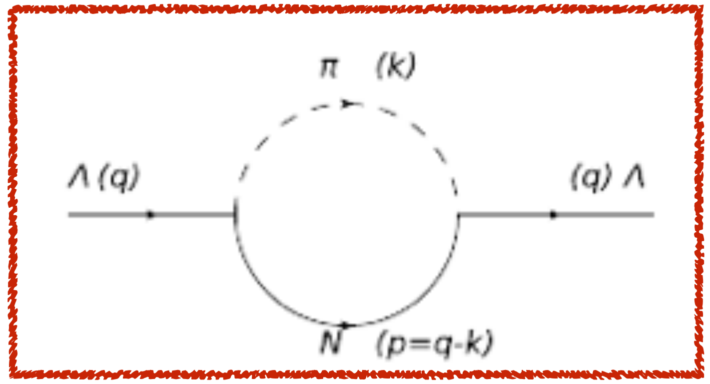

Chances of a J/Ψ meeting a nucleon should not be smaller than those for forming an antihypernucleus

# Propagation of $\Lambda$ in a hot pion gas

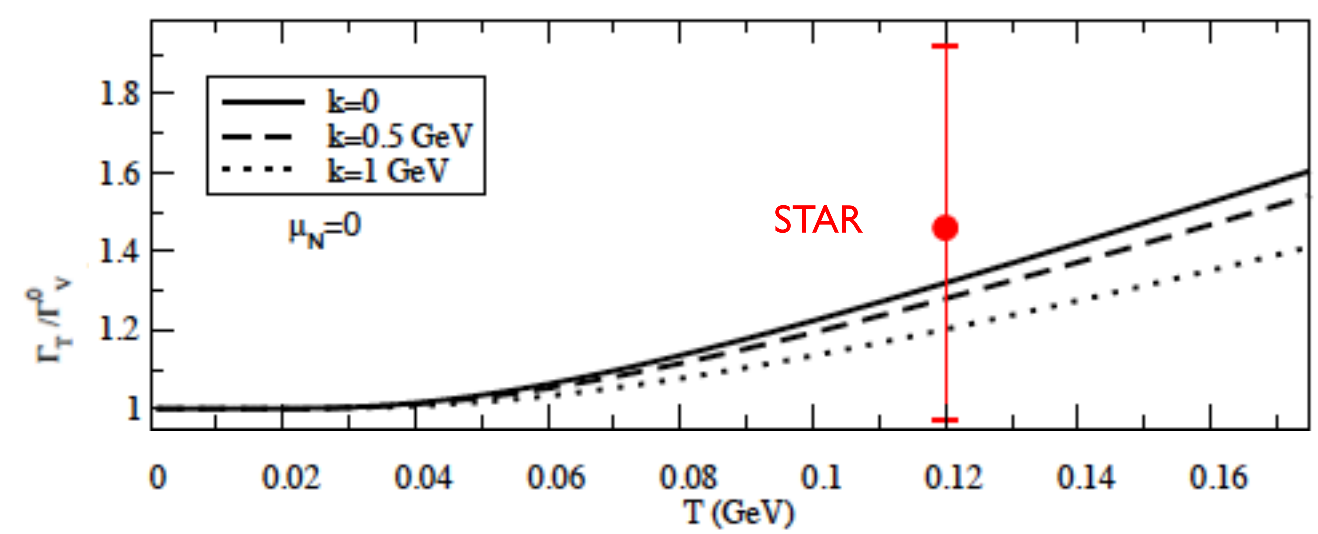
Observation of an Antimatter Hypernucleus
The STAR Collaboration
*Science* **328**, 58 (2010);
DOI: 10.1126/science.1183980




3-body calculation




$$\mathcal{L}^{W}_{\Lambda N\pi} = iG_F m_\pi^2 \bar{\psi}_N \left(A_\pi + B_\pi\gamma_5\right)\vec{\pi}\cdot\vec{\tau}\psi_\Lambda \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$



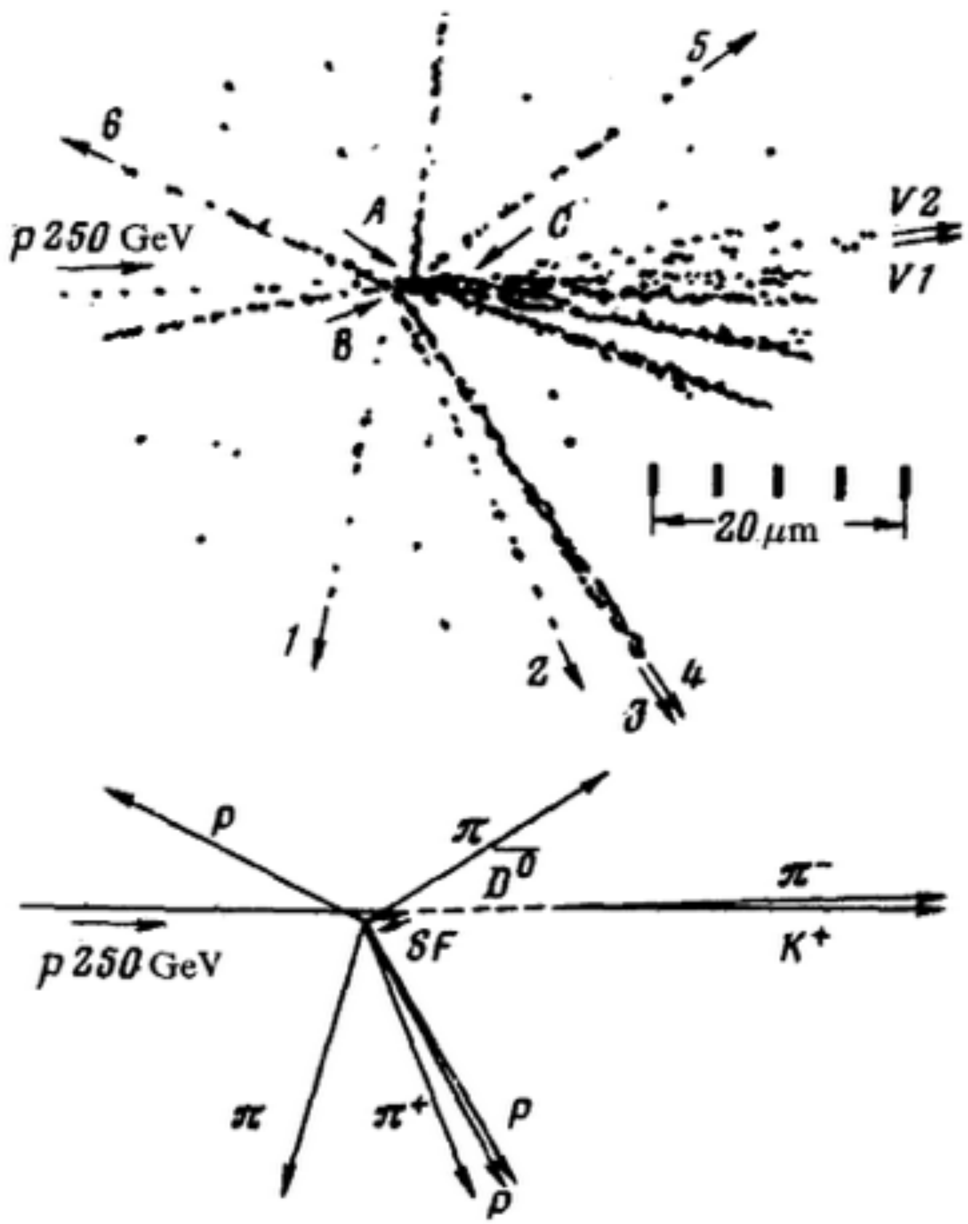

Additional effect:

Lifetime decreases because of Bose enhancement in the pion gas

S. Ghosh & GK (2014)

# 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 $c\overline{c}$ pair)

A search for Charmed Nuclei

u c t
d s b
quarks

Next flavor

**Charm**

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.

# Theory, QMC model:

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

**$\Lambda_c^+$ and $\Lambda_b$ 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 $\Lambda$ hypernuclei are taken from Ref. [28], where spin-orbit splittings for $\Lambda$ hypernuclei are not well determined by the experiments.

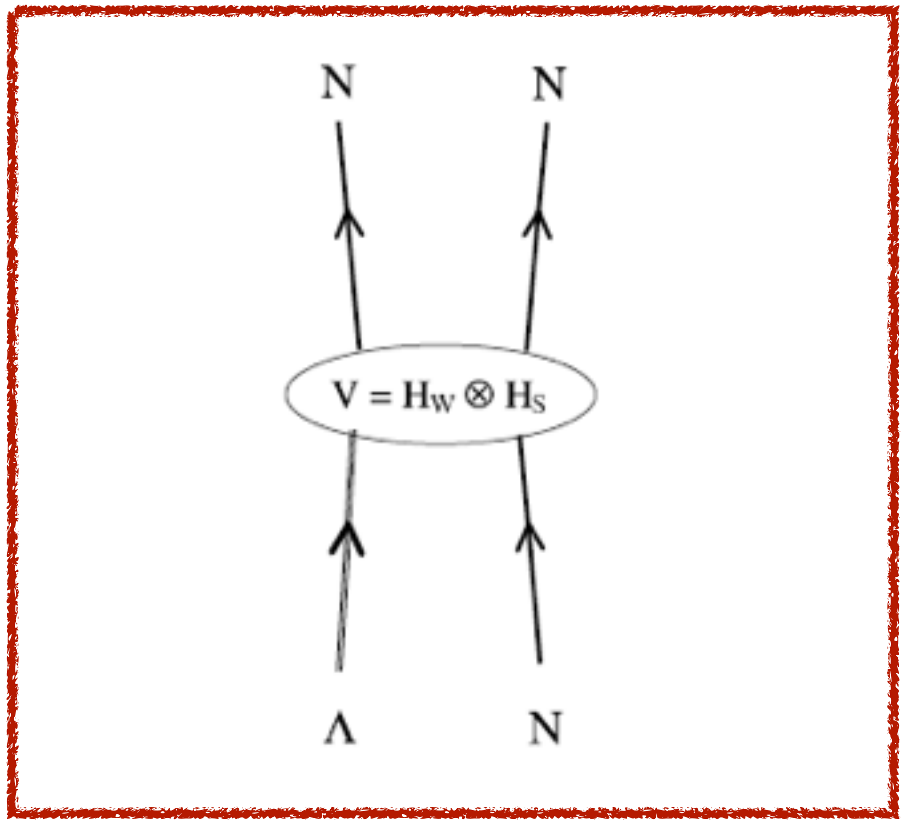
| | ${}^{16}_{\Lambda}$O (Expt.) | ${}^{17}_{\Lambda}$O | ${}^{17}_{\Lambda_c^+}$O | ${}^{17}_{\Lambda_b}$O | ${}^{40}_{\Lambda}$Ca (Expt.) | ${}^{41}_{\Lambda}$Ca | ${}^{41}_{\Lambda_c^+}$Ca | ${}^{41}_{\Lambda_b}$Ca | ${}^{49}_{\Lambda}$Ca | ${}^{49}_{\Lambda_c^+}$Ca | ${}^{49}_{\Lambda_b}$Ca |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $1s_{1/2}$ | −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



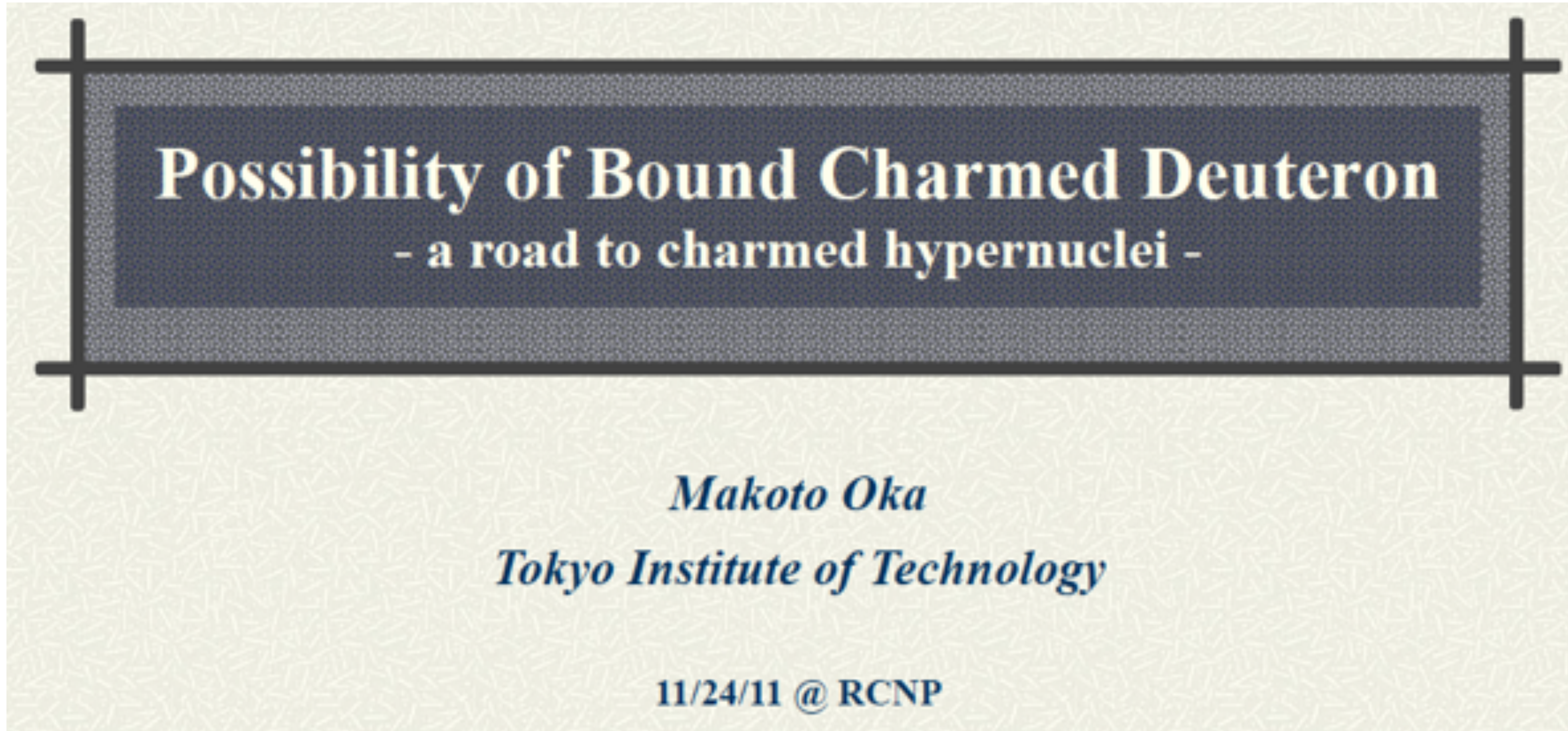

→

Happen only if bound

$$\Lambda + N \to N + N$$

$$\Lambda_c + N \to N + \Lambda$$

A.P. Galeao, GK, F. Krmpotic (2014)

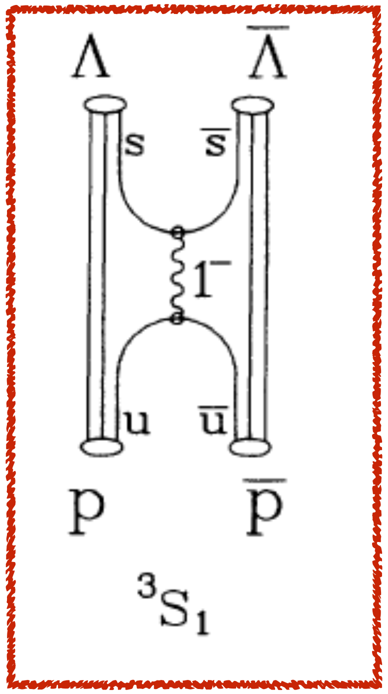



| $J^P$ | | $\Lambda_c N$ (S-wave) | $\Lambda_c N - \Sigma_c N - \Sigma_c^* N$ |
|---|---|---|---|
| $0^+$ | OPEP ($\Lambda$) | $\times$ | [1.367: 13.60, 1.38] |
| | OMEP ($\Lambda$) | [0.900: -1.24, 3.86] | [0.900: 13.60, 1.46] |
| | OMEP ($\alpha$) | [1.533: -0.25, 8.13] | [1.533: 13.57, 1.37] |
| $1^+$ | OPEP ($\Lambda$) | $\times$ | [1.353: 13.54, 1.40] |
| | OMEP ($\Lambda$) | [0.900: -1.24, 3.86] | [0.900: 13.49, 1.47] |
| | OMEP ($\alpha$) | [1.618: -0.80, 4.72] | [1.618: 13.47, 1.39] |

Table: Comparison among different cases. The meaning of the numbers are [cutoff $\Lambda_{\rm com}$ in GeV or dimensionless $\alpha$: B.E. in MeV, RMS radius in fm]. ($\Lambda = m_{meson} + \alpha\Lambda_{QCD}$)

# Production of $\Lambda_c$

$$\bar{p} + p \to \Lambda_c^+ + \Lambda_c^-$$

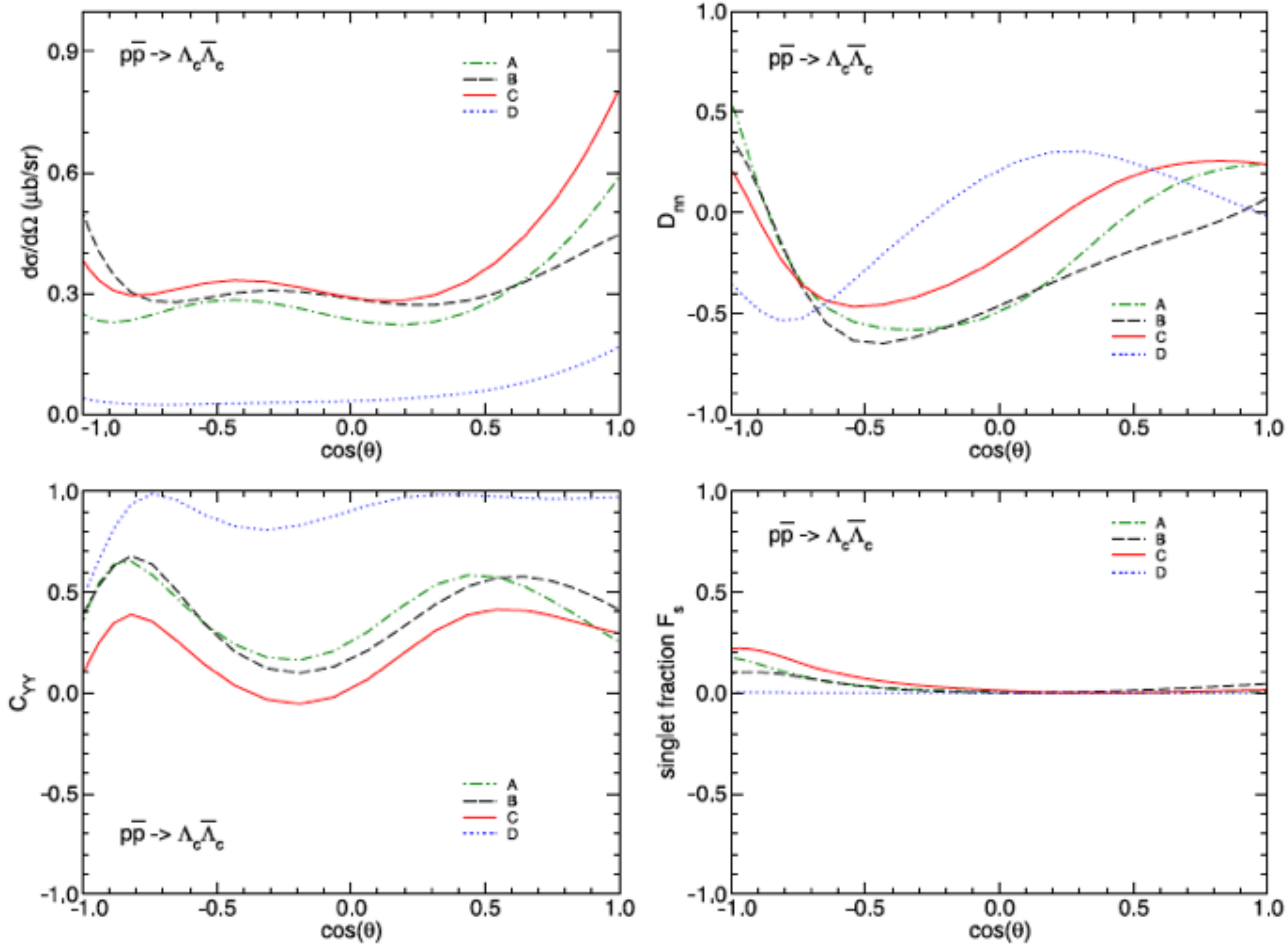



Meson-Exchange + quark model

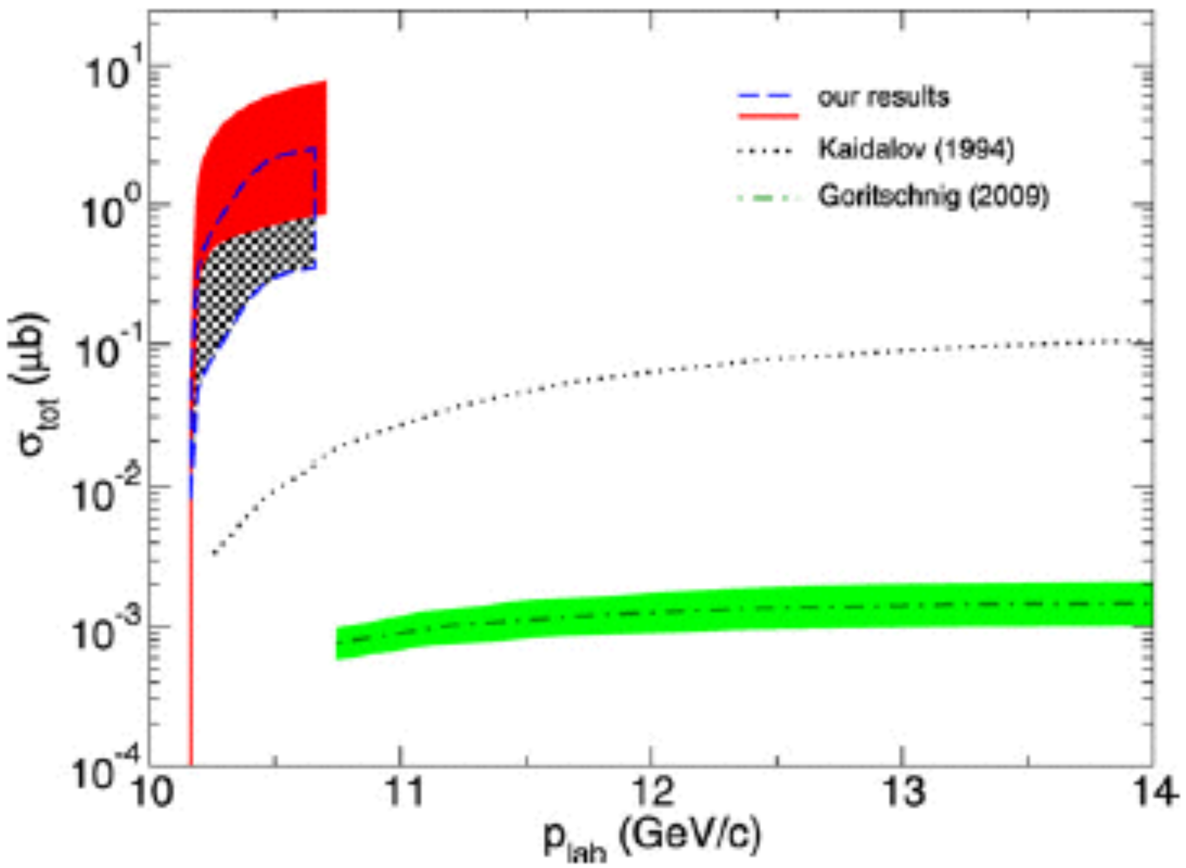
- ISI: Optical potential + G(NN) + SU(4)
- FSI: Optical potential ($\bar{\Lambda}\,\Lambda$) + SU(4)
- Transition: D,D* + SU(4) & QM

Model fits $\bar{\Lambda}\,\Lambda$ available data

J. Haidenbauer & GK PLB 687, 314 (2010)



$p\bar{p}$ -> $\Lambda_c\bar{\Lambda}_c$
A
B
C
D
dσ/dΩ (μb/sr)
cos(θ)
$D_{nn}$
$C_{YY}$
singlet fraction $F_s$



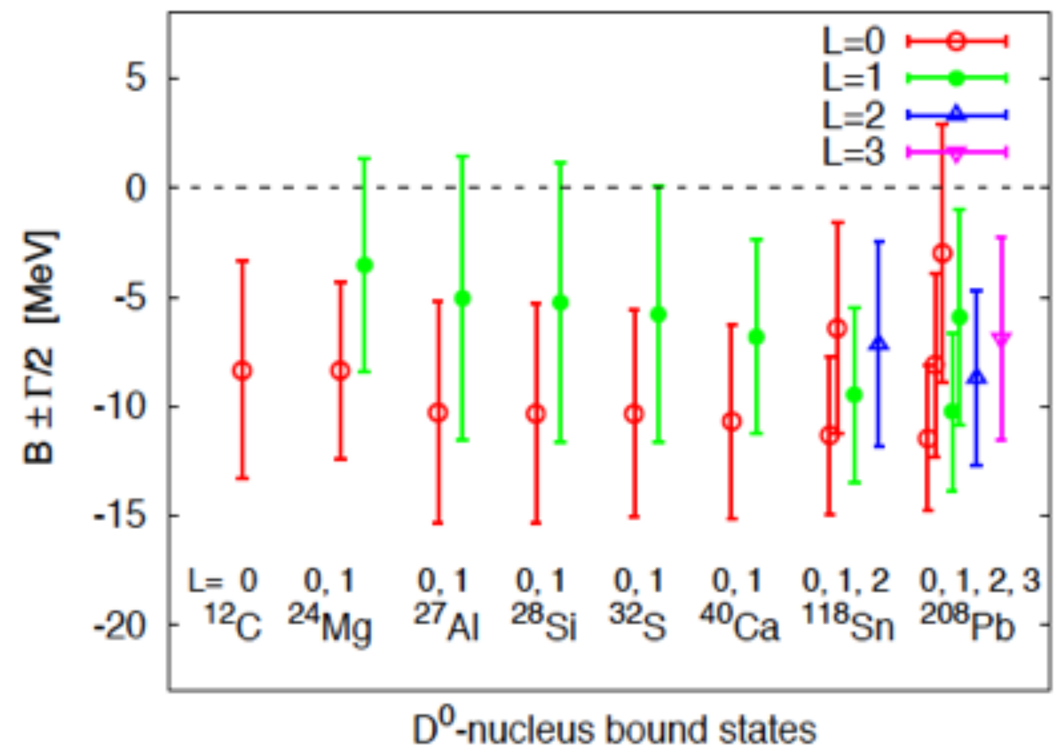

- 10-70 times smaller than $\bar{\Lambda}\Lambda$

- 100 - 1000 times larger than other models in the literature

# D-mesic nuclei

## $\bar{D}$ bound state energy in Pb

| state | $D^-$ 1.96 $*Vq\omega$ | $D^-$ $Vq\omega$ | $D^-$ $Vq\omega$ No Coulomb | $\bar{D}0$ 1.96 $*Vq\omega$ | $\bar{D}0$ $Vq\omega$ | D0 $Vq\omega$ |
|---|---|---|---|---|---|---|
| 1s | -10.6 | -35.2 | -11.2 | unbound | -25.4 | -96.2 |
| 1p | -10.2 | -32.1 | -10.0 | unbound | -23.1 | -93.0 |
| 2s | -7.7 | -30.0 | -6.6 | unbound | -19.7 | -88.5 |




QMC model:
K. Tsushima, D-H Lu, A. W. Thomas, K. Saito, R.H. Landau PRC 59, 2824 (1999).

HQSS Lagrangian:
C. Garcia-Recio, J. Nieves, L. Tolos, PLB 690, 369 (2010)

TO CONSTRAIN MODELS OF D MESONS IN MATTER

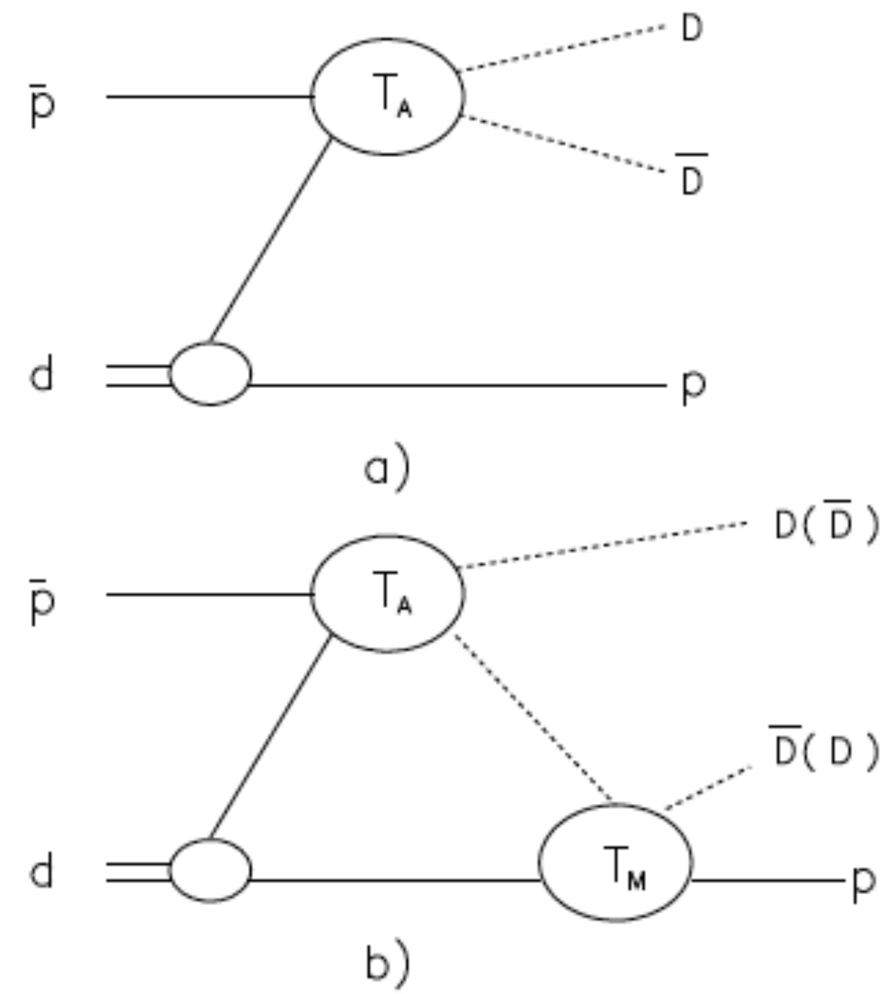
NEED EXPERIMENTS

- interactions
- production

# DN Experiment

## - antiproton annihilation on the deuteron*

P̄anda @ FAIR

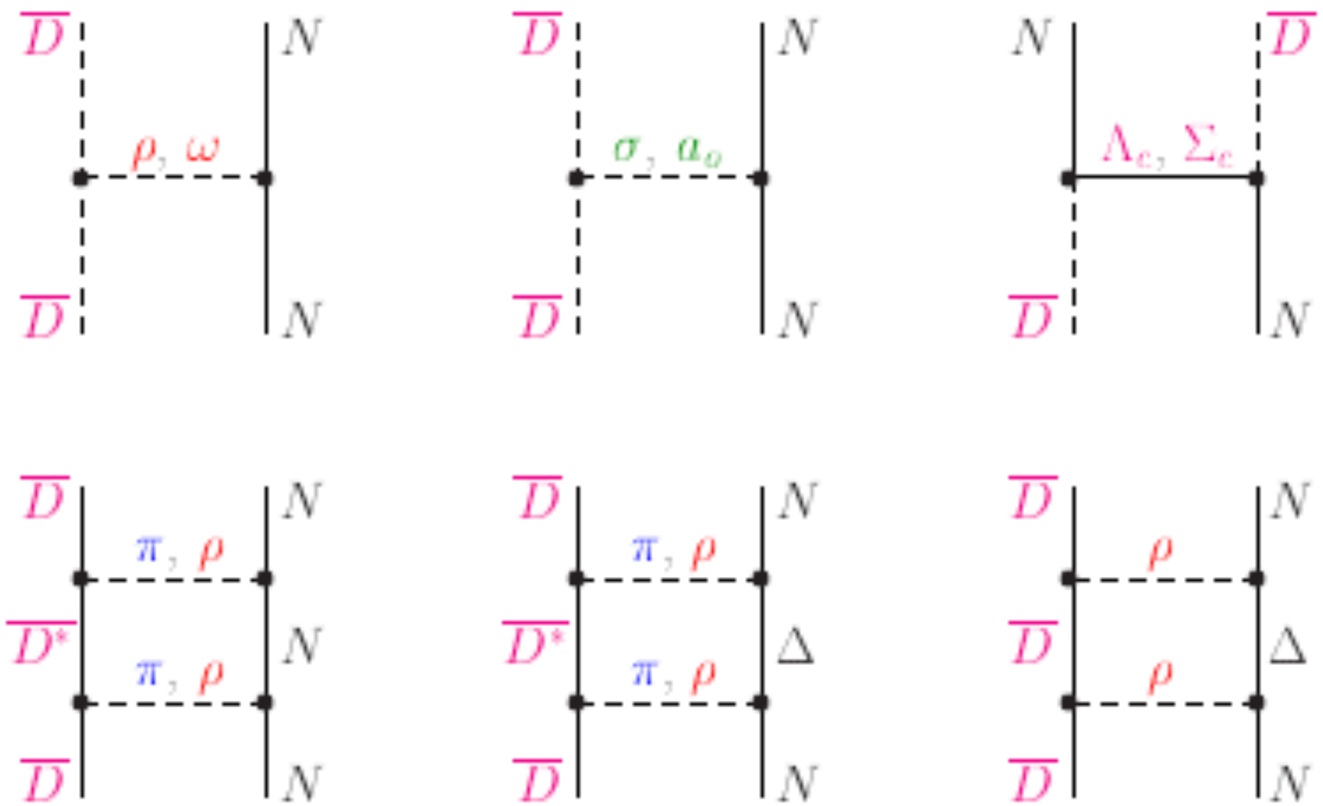



* J. Haidenbauer, G. Krein, U.-G. Meissner, A. Sibirtsev

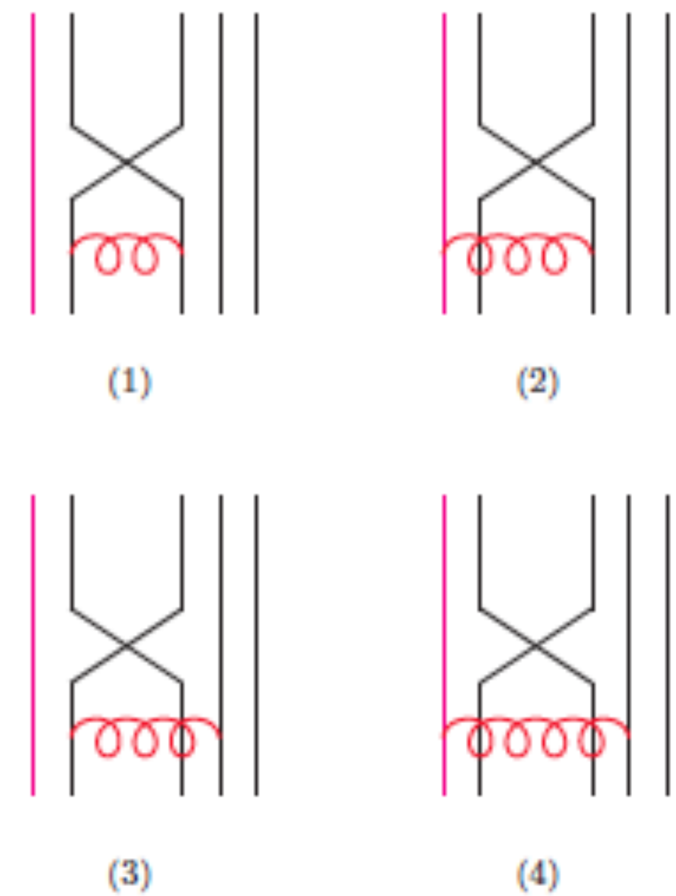

1) Eur. Phys. J. A 33, 107 (2007)

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

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




+

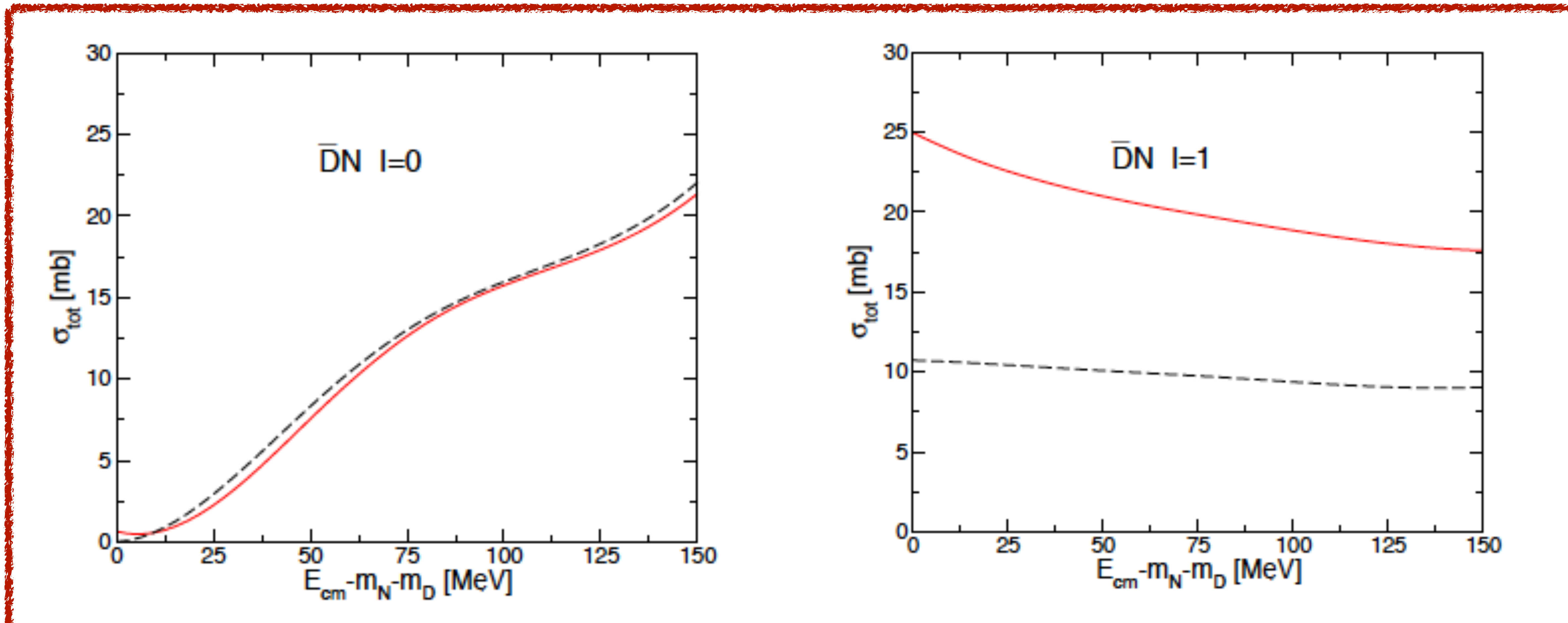



MEX: SU(4)-flavor symmetry for couplings, same cutoffs as KN

QEX: change quark masses (wave functions)

# 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)

# Production of D mesons

$$\bar{p} + p \to D + \bar{D}$$

Meson-Exchange + quark model

- ISI: Optical potential + G(NN) + SU(4)
- FSI: Meson exchange + SU(4)
- Transition: Baryon exch + SU(4) & QM

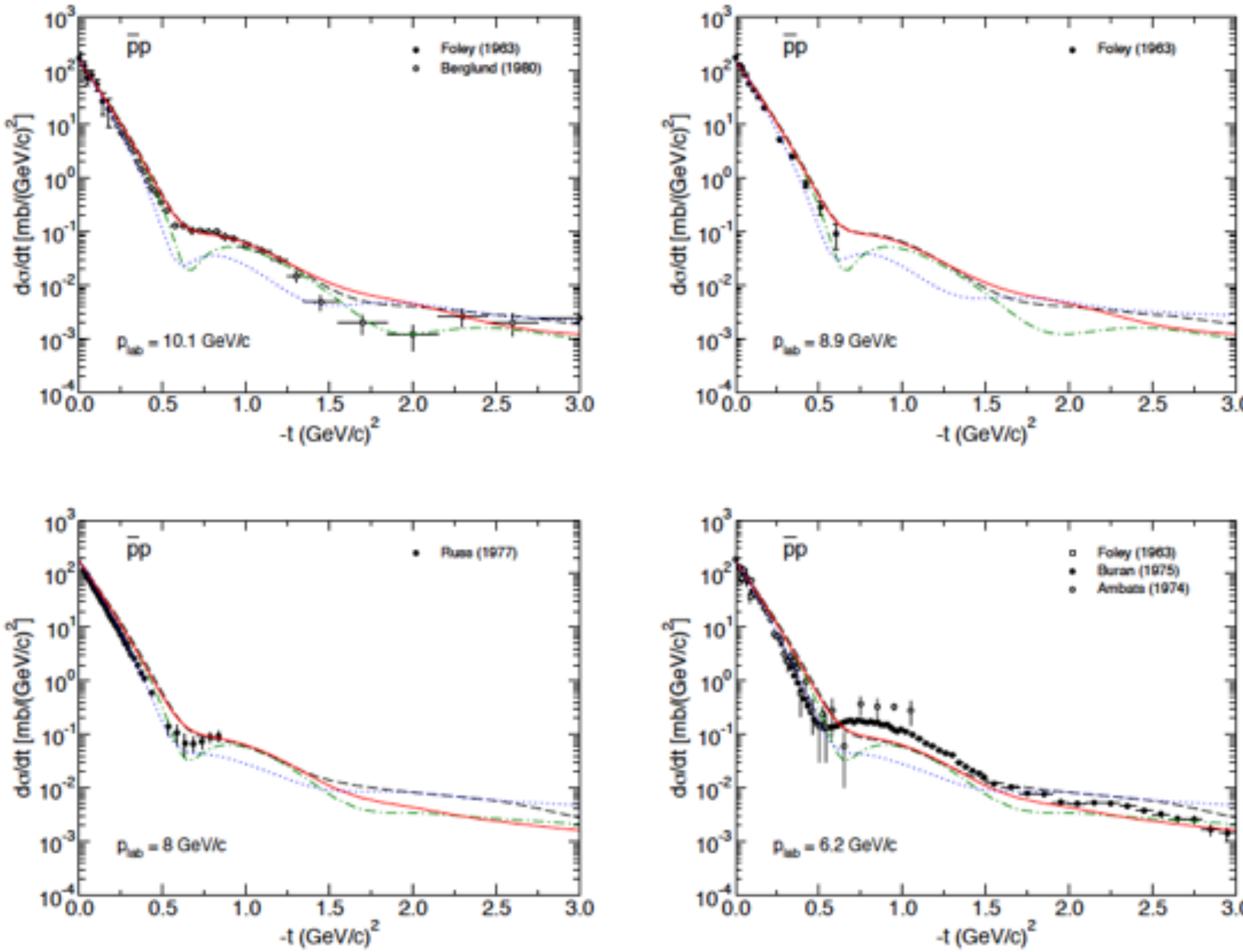
Model fits $K\bar{K}$ available data

J. Haidenbauer & GK (2014)

# Initial State Interactions

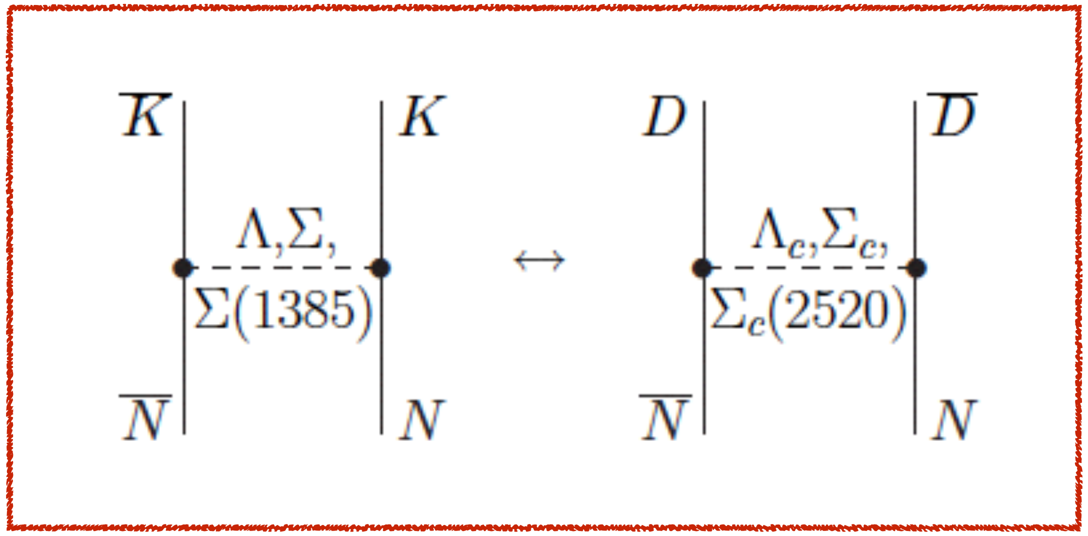
TABLE I: Total and integrated elastic $\bar{p}p$ cross sections and integrated charge-exchange ($\bar{p}p \rightarrow \bar{n}n$) cross sections in $mb$ for the four potentials considered in comparison to experimental values.

| | $p_{lab}$ (GeV/c) | A | A' | B | C | Experiment |
|---|---|---|---|---|---|---|
| $\sigma_{tot}$ | 6.65 | 56.6 | 59.1 | 57.0 | 56.9 | $59.5 \pm 0.5$ [40] |
| | 7.30 | 56.0 | 58.5 | 56.3 | 56.3 | $58.3 \pm 1.3$ [41] |
| | 9.10 | 54.7 | 56.9 | 54.7 | 54.8 | $57.51 \pm 0.73$ [42] |
| | 10.0 | 54.2 | 56.4 | 54.1 | 54.3 | $54.7 \pm 0.60$ [40] |
| | 12.0 | 53.5 | 55.6 | 53.3 | 53.4 | $51.7 \pm 0.80$ [44] |
| $\sigma_{el}$ | 6.0 | 15.9 | 15.1 | 16.7 | 15.9 | $15.6 \pm 0.8$ [50] |
| | 7.2 | 15.2 | 14.3 | 15.8 | 15.2 | $13.79 \pm 1.0$ [43] |
| | 8.0 | 14.9 | 14.0 | 15.4 | 14.8 | $12.88 \pm 0.1$ [48] |
| | 8.9 | 14.6 | 13.6 | 15.0 | 14.5 | $13.89 \pm 0.35$ [43] |
| | 10.0 | 14.4 | 13.4 | 14.6 | 14.2 | $14.6 \pm 3.3$ [43] |
| | 12.0 | 14.0 | 13.0 | 14.1 | 13.8 | $11.59 \pm 0.41$ [43] |
| | | | | | | $11.34 \pm 0.6$ [44] |
| $\sigma_{cex}$ | 6.0 | 0.50 | 0.57 | 0.55 | 0.78 | $0.563 \pm 0.082$ [45] |
| | 7.0 | 0.38 | 0.45 | 0.42 | 0.64 | $0.373 \pm 0.054$ [45] |
| | 7.76 | 0.32 | 0.37 | 0.36 | 0.57 | $0.380 \pm 0.042$ [46] |
| | 9.0 | 0.24 | 0.29 | 0.28 | 0.47 | $0.284 \pm 0.041$ [45] |

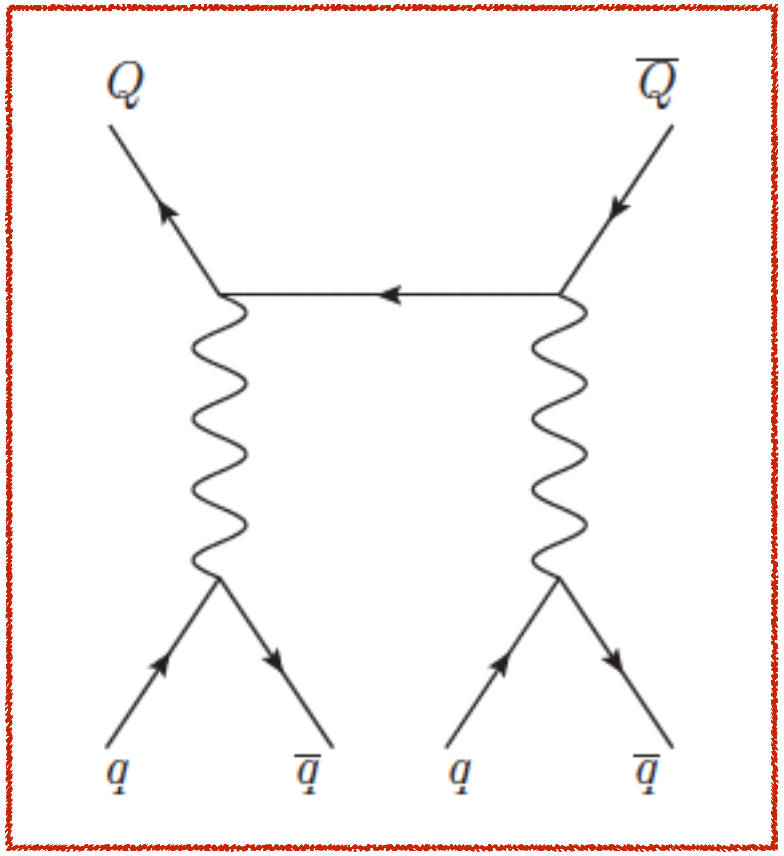


# Transition amplitudes

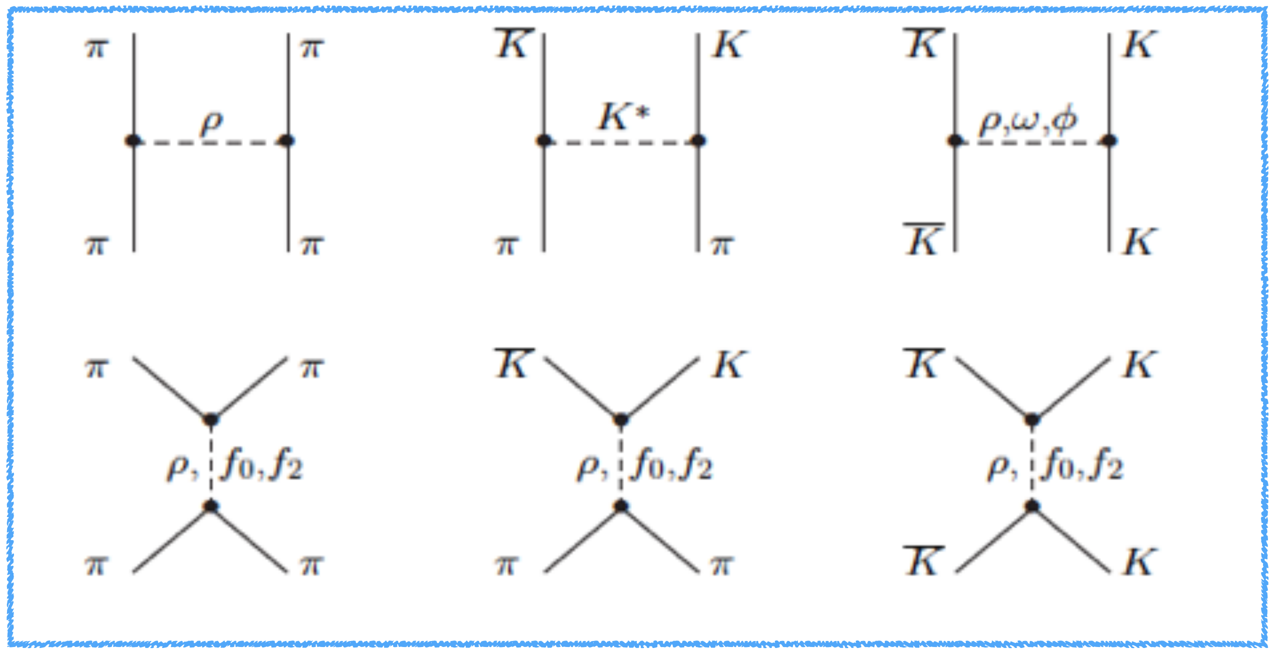
Baryon exchange

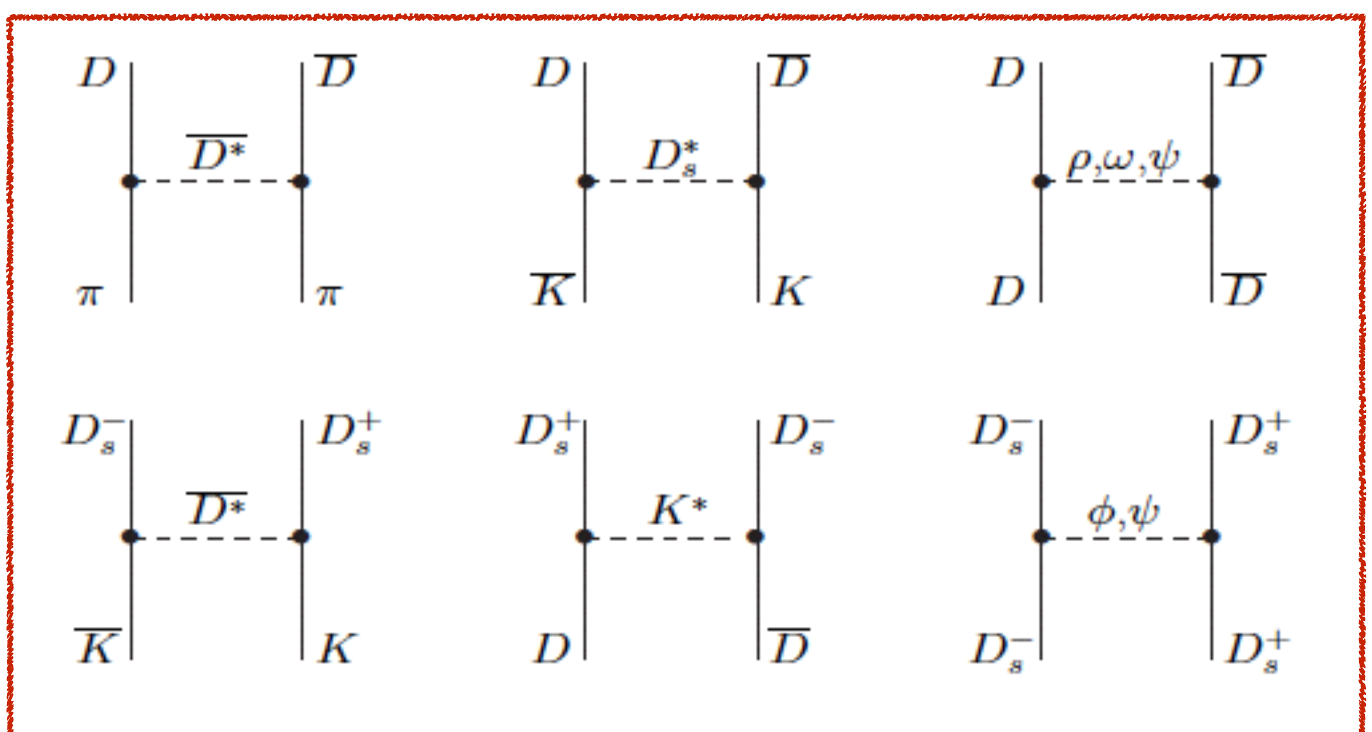



Quark model



# Final State Interactions



# Model describes $K\bar{K}$ data

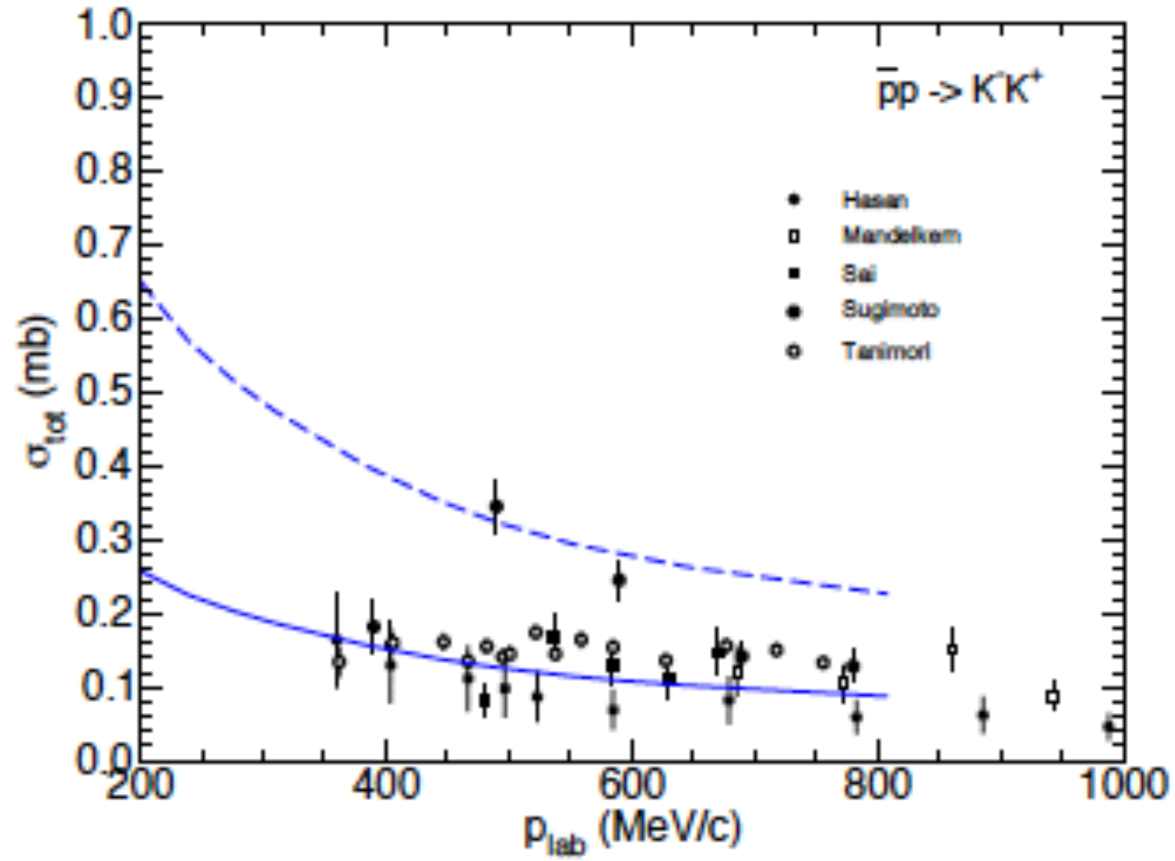



FIG. 5: Cross section for $\bar{p}p \to K^-K^+$ scattering as a function of $p_{lab}$. Results are based on the quark model. The curves correspond to different values for the effective coupling strength $\alpha_A/m_G^2$ – 0.12 (solid line) or 0.15 (dashed line) – see discussion in the text. Data are taken from Refs. [52–56].

# Final result

- Here: total cross sections

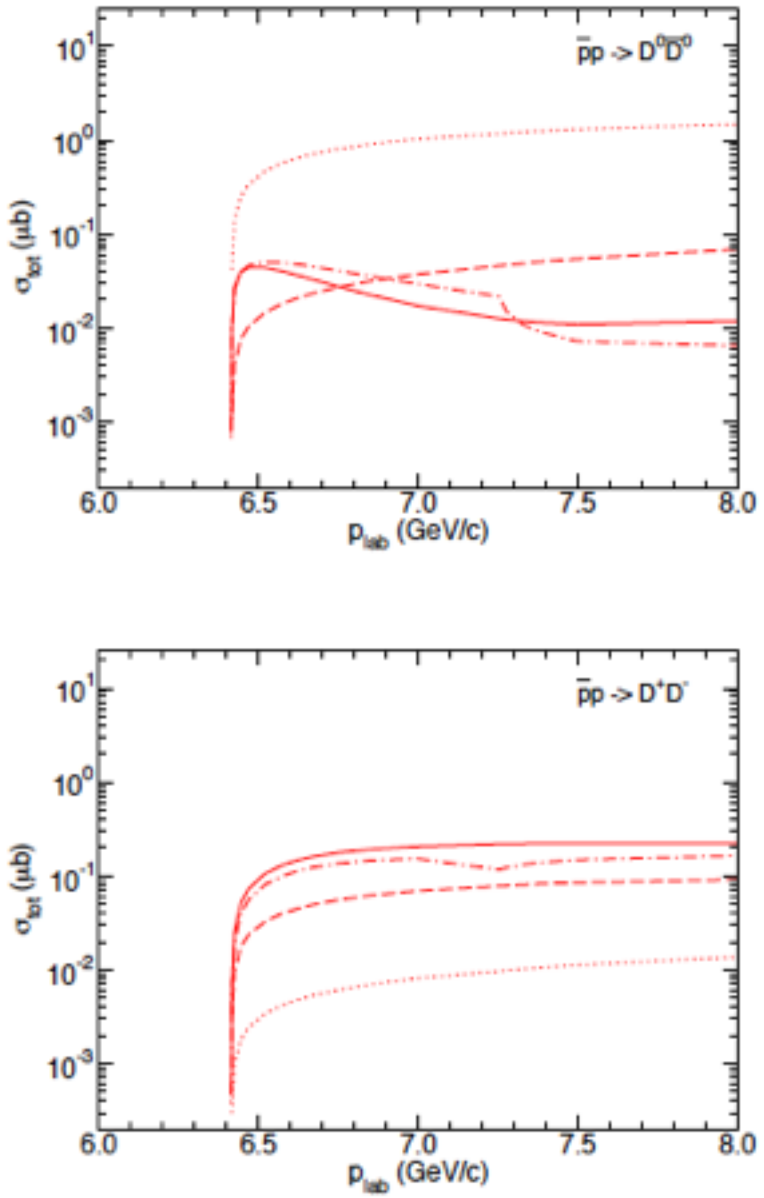



FIG. 10: Total reaction cross sections for $\bar{p}p \to D\bar{D}$ as a function of $p_{lab}$. Effects of the final state interaction. The dashed lines are results with the $\bar{N}N$ model A as ISI, but without FSI. Inclusion of the $D\bar{D}$ FSI yields the solid curves. Including in addition the coupling of $D\bar{D}$ to $D_s^+D_s^-$ leads to the dash-dotted lines. Results obtained in Born approximation are indicated by the dotted lines.

Quark model transition gives similar results

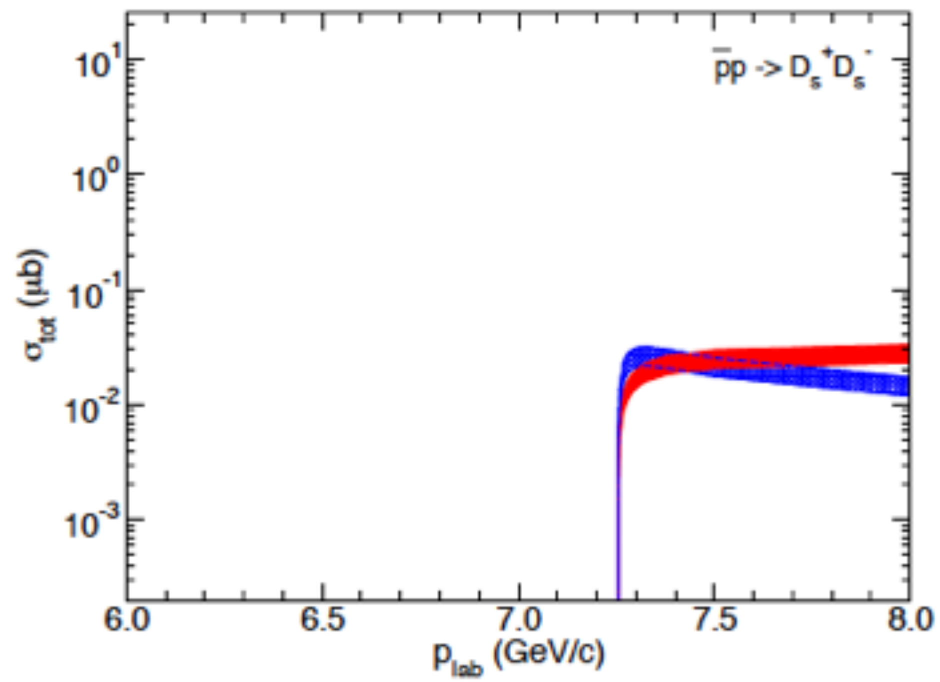
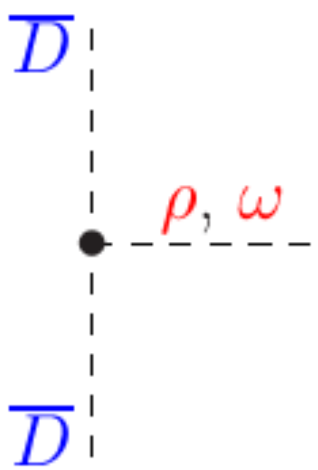
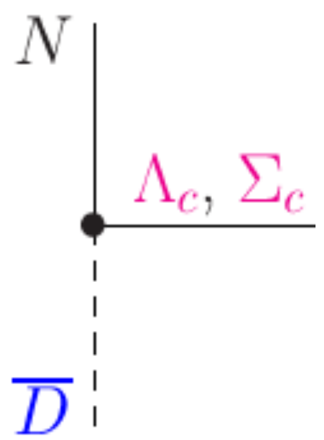



FIG. 11: Total reaction cross sections for $\bar{p}p \to D_s^+ D_s^-$ as a function of $p_{lab}$, based on baryon-exchange (shaded band) and the quark model (grid).

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

$$m_u < m_s \ll m_c$$




SU(4) symmetry:

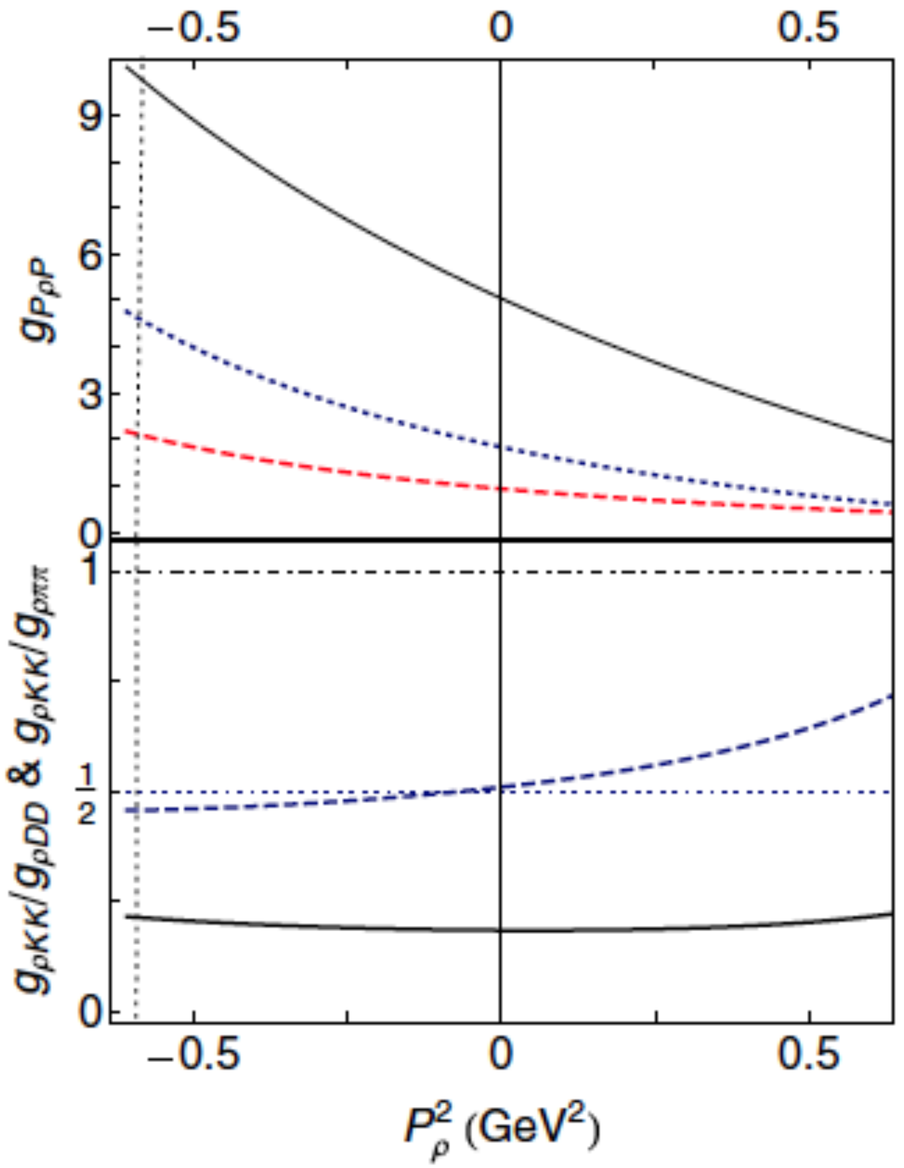
$$g_{\bar{D}\rho\bar{D}} = g_{K\rho K} = \frac{1}{2} g_{\pi\rho\pi}$$

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

# 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 (2014)

# 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%

# AdS/QCD hard wall model

$$\frac{g_{\rho\pi\pi}}{2g_{\rho KK}} = 1.08$$

$$\frac{g_{\rho\pi\pi}}{2g_{\rho DD}} = 1.78$$

$$\frac{g_{\rho KK}}{g_{\rho DD}} = 1.65$$

C. Miller, A. Bayona & GK (2014)

# 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)