Charmonium in matter

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Motivation

Interaction of charm with ordinary matter is important for several reasons

- Understanding of nuclear force at QCD level
- Nonperturbative QCD
- Quark-gluon plasma: e.g. J/Ψ suppression
- D-mesons in medium: chiral-symmetry restoration
- J/Ψ, η_c, $\cdots$: possibly bound to ordinary matter

Dedicated experiments underway:

JLab @ 12 GeV, Panda & CBM @ Fair

VOLUME 64, NUMBER 9 PHYSICAL REVIEW LETTERS 26 FEBRUARY 1990

Nuclear-Bound Quarkonium

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Guy F. de Téramond
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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.

VOLUME 65, NUMBER 7 PHYSICAL REVIEW LETTERS 13 AUGUST 1990

Color van der Waals Force Acting in Heavy-Ion Scattering at Low Energies

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(Received 6 December 1989; revised manuscript received 19 March 1990)

The influence of the color van der Waals force in the elastic scattering of ^{208}Pb on ^{208}Pb at sub-barrier energies is studied. The conspicuous changes in the Mott oscillation found here are suggested as a possible experimental test.

PACS numbers: 25.70.Cd, 21.30.+y

Several theoretical investigations have considered the possible existence of strong color van der Waals forces between hadrons.[1-6] Just as the usual electromagnetic van der Waals (VDW) force between neutral atoms arises from two-photon exchange, the color VDW force is suggested by several theorists to come about from two-gluon and multigluon exchanges between color-singlet hadrons. There are, of course, important differences between the QCD and the color VDW forces. The most notable of these differences are related to confinement (in the MIT bag model this force does not exist) and the nonlinear structure of the Yang-Mills gluon fields. Although the overwhelming majority of particle physicsts do not believe in the existence of the color VDW force, it is still important to set experimental limits on these forces. Estimates of the strength of the

or (1b)], where A_i is the atomic number of nucleus i. We therefore propose to look for the color VDW force in the low-energy scattering of $^{208}\mathrm{Pb}+{}^{208}\mathrm{Pb}$. By low energy we mean low enough to avoid the action of the strong short-range nuclear interaction. At these energies, the Coulomb repulsion completely dominates the scattering and consequently the cross section is structureless and almost entirely Rutherford. Small perturbations such as the color VDW force have to be looked for in quantum interference effects which would arise from, e.g., the identity of the projectile and the target. Thus our choice of $^{208}\mathrm{Pb}+{}^{208}\mathrm{Pb}$. We proceed now to describe our calculation.

We first remind the reader that other small effects, besides the VDW interaction, have to be taken into account. These include QED vacuum polarization V_{VP}

VOLUME 71, NUMBER 16 PHYSICAL REVIEW LETTERS 18 OCTOBER 1993

Search for Color van der Waals Force in ^{208}Pb+^{208}Pb Mott Scattering

A. C. C. Villari,[2] W. Mittig,[1] A. Lépine-Szily,[1,2] R. Lichtenthäler Filho,[2] G. Auger,[1] L. Bianchi,[1] R. Beunard,[1] J. M. Casandjian,[2] J. L.Ciffre,[1] A. Cunsolo,[3] A. Foti,[3] L. Gaudard,[1] C. L. Lima,[2] E. Plagnol,[1] Y. Schutz,[1] R. H. Siemssen,[1,4] and J. P. Wieleczko[1]
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(Received 15 April 1992)

In a high precision experiment, Mott scattering of the ^{208}Pb +^{208}Pb system was measured at $E_{\mathrm{lab}} = 873.40$ MeV and 1129.74 MeV with kinematic coincidences for angle pairs around $\theta_{\mathrm{lab}} = 30°$, 60° and $\theta_{\mathrm{lab}} = 45°$, 45°. The observed Mott oscillations exhibit an angular shift with respect to pure Mott scattering. A comparison with the angular shift produced by a color van der Waals force including nuclear polarizability, vacuum polarization, relativistic effects, and electronic screening provides a new upper limit for the strength of this force. Influence of atomic effects other than screening were identified for the first time.

PACS numbers: 25.70.Bc, 24.85.+p

Precision measurements of sub-Coulomb-barrier scattering have been used successfully in the past to study the influence of vacuum polarization and relativistic effects. These have been clearly observed in the ^{16}O + ^{208}Pb [1] and ^{12}C + ^{12}C [2] elastic scattering and were found to be consistent with standard QED. The use of Mott scattering was found [2,3] to be especially sensitive to detect small effects via the angular shifts in the oscillatory Mott scattering pattern.

The possibility of the existence of long range forces compared to Mott scattering of low-Z nuclei. Moreover, the large masses involved will lead to an "amplification" of the effects of the possible color van der Waals force. Effects of strong Coulomb fields in the scattering of two heavy nuclei have an additional interest in view of the unresolved problem of the discrete positron lines observed at GSI [11]. More generally, precision data could serve as a stringent test for the known and higher order QED effects.

The interference term of the Mott differential cross

Charmonium binding in nuclear matter

– an exotic nuclear bound state

- 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

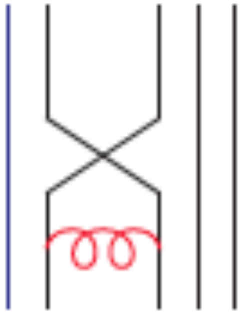
BE (η_c to A = 9 nucleus) ~ 180 MeV*

~ 20 times BE (nucleon in Fe) !

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

Short range repulsion

Quark-gluon exchange + Pauli exclusion principle



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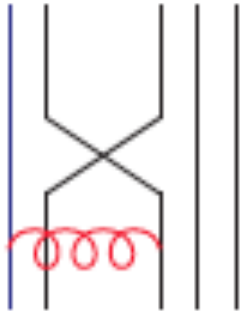

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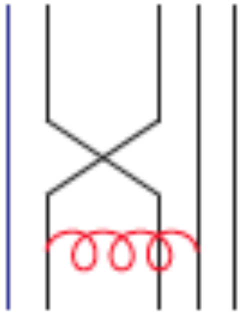

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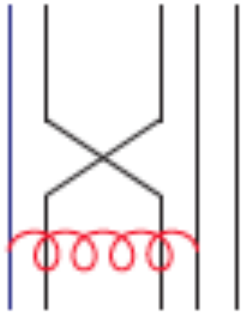


(4)

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 interact with the nuclear mean fields

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

Second-order Stark effect

J/Ψ as a small color-electric dipole

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

$\psi(k)$: charmonium wave function

ρ_B : nuclear density

m_c, m_N : masses charm quark and nucleon

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

Numerical results:

$$\langle \alpha_s E^2/\pi \rangle_N = 0.5\,\mathrm{GeV}^2$$

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

ψ : Gaussian

$\langle r^2 \rangle$: from Cornell potential model

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

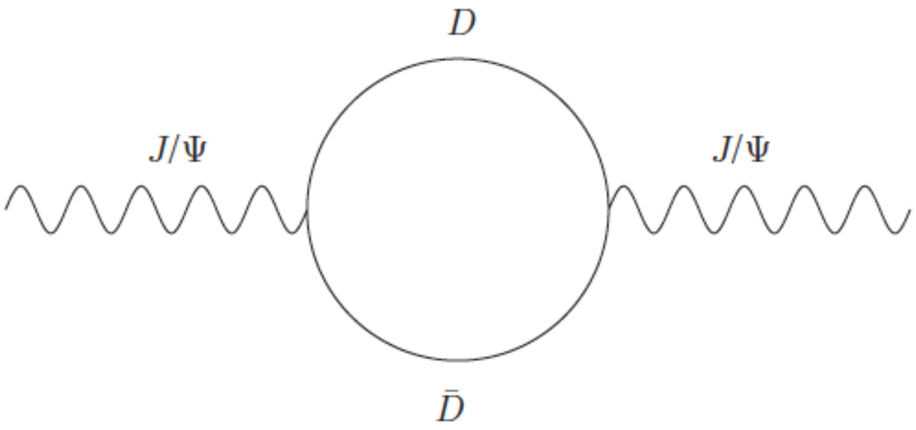
at normal nuclear
matter density

Sibirtsev & Voloshin, PRD 71, 076005 (2005)

$J/\Psi\ N$ cross section > 17 mb

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

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

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

- used gauged Lagrangian
- found almost no binding

– SU(4) flavor symmetry

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

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

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

Potential of J/Ψ in nuclear matter

$$U_\psi(\rho_B) \equiv m_\psi^* - m_\psi$$

- J/Ψ self-energy:

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

$\Delta_D, \Delta_{\bar{D}}$: D-meson propagators

$F(q^2)$: form factor

- J/Ψ masses:

$$\boxed{\begin{aligned} m_\psi^2 &= \left(m_\psi^{(0)}\right)^2 + \Sigma_\psi^{D\bar{D}}(k^2 = m_\psi^2) \\ m_\psi^{*2} &= \left(m_\psi^{(0)}\right)^2 + \Sigma_\psi^{*D\bar{D}}(k^2 = m_\psi^2) \end{aligned}}$$

Structure of the mesons

– form factors

Form factor for the loop calculation:

$$F(q^2) = \begin{cases} u_D^2(q^2) \\ u_{D^*}^2(q^2) \\ u_D(q^2)u_{D^*}(q^2) \end{cases}$$

Quark model ($^3P_0$ quark-pair creation, Gaussian w.f.):

$$u_D(q^2) = e^{-q^2/4(\beta_D^2+2\beta_\psi^2)}$$

Phenomenological (dipole):

$$u_D(q^2) = \left[\frac{\Lambda^2 + m_\psi^2}{\Lambda^2 + 4(q^2 + m_D^2)}\right]^2$$

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

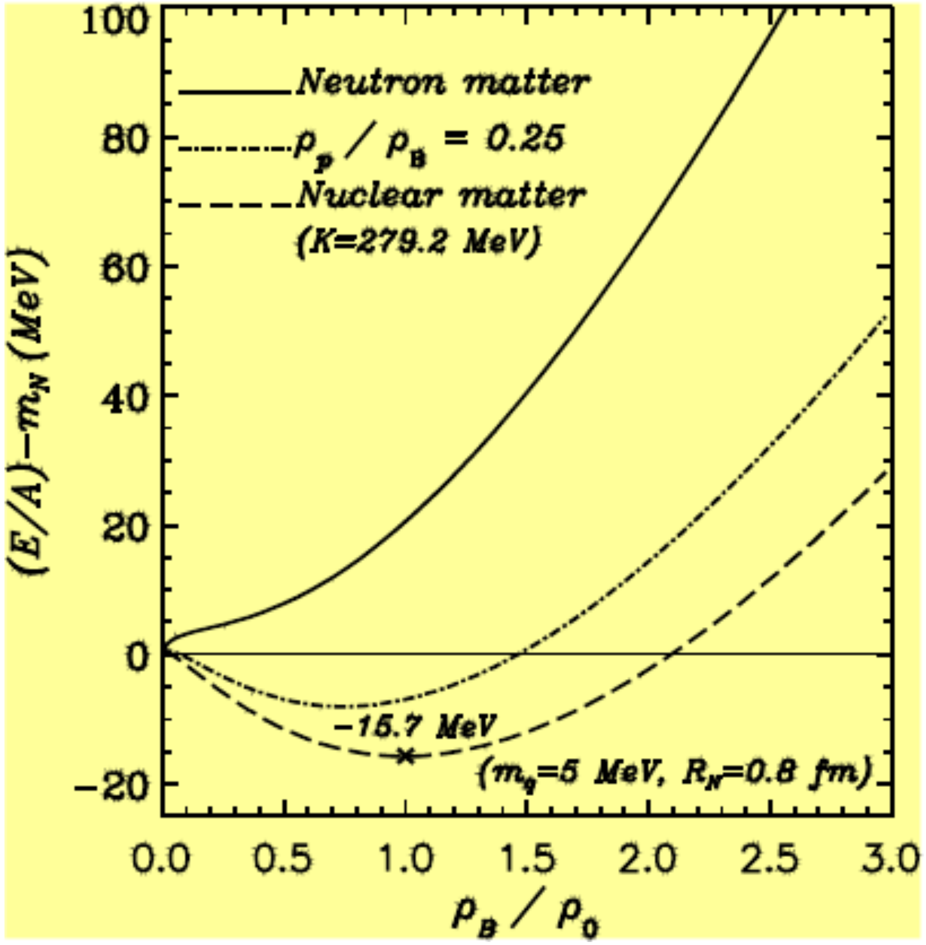
Single quark wavefunction in the bag

$$[i\gamma\cdot\partial-(m_q-g^q_\sigma\,\sigma)+g^q_\omega\,\gamma\cdot\omega]\,\psi_q=0$$

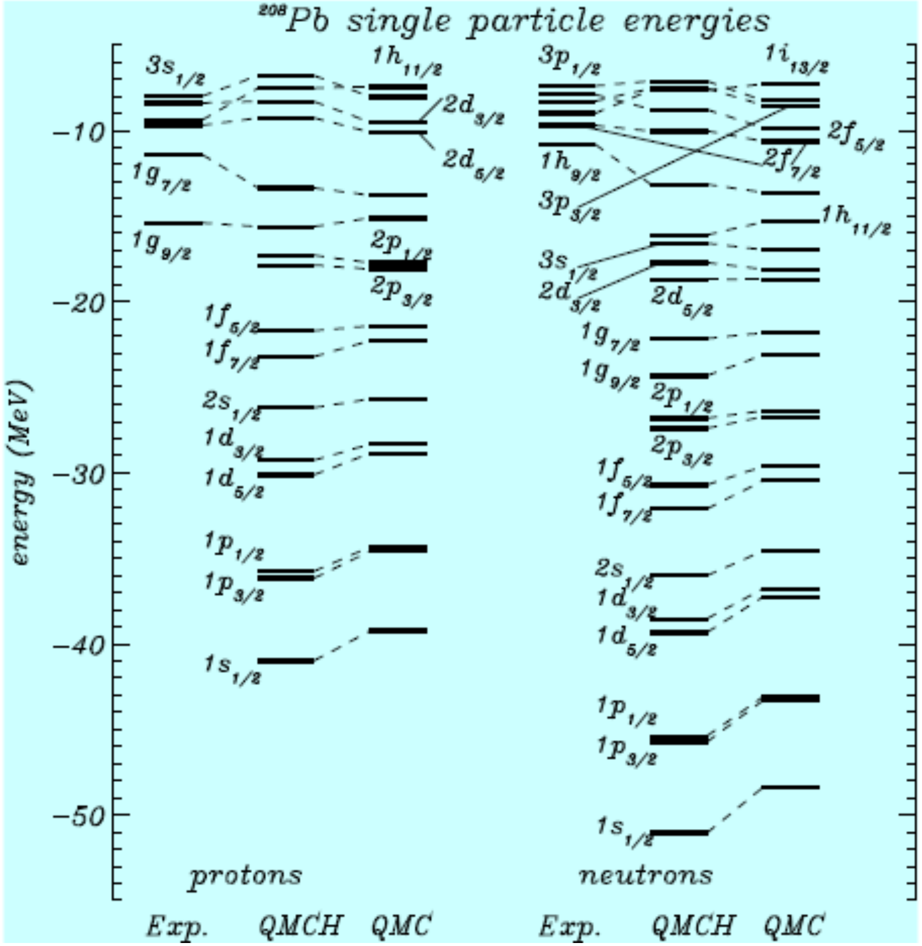
* P.A.M. Guichon, PLB 200, 235 (1988)
K. Saito, K. Tsushima & A.W. Thomas, Prog. Part. Nucl. Phys. 58, 1 (2007)

Gross properties of nuclear matter & nuclei

Nuclear matter



Lead nucleus



K. Tsushima, …

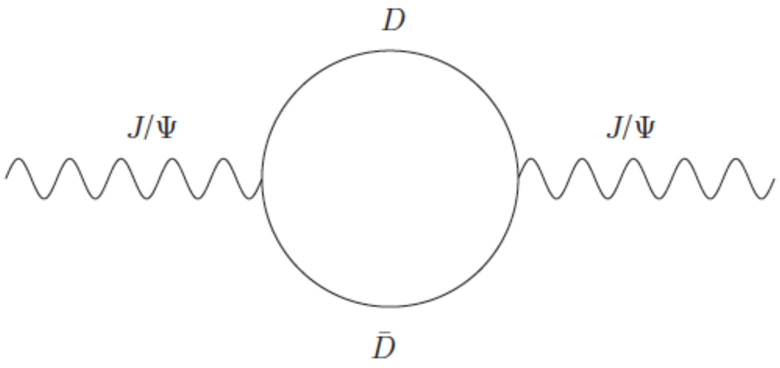
DD,DD* & D*D* contributions

Parameters: $g_{DD\psi}$ & cutoff Λ_D

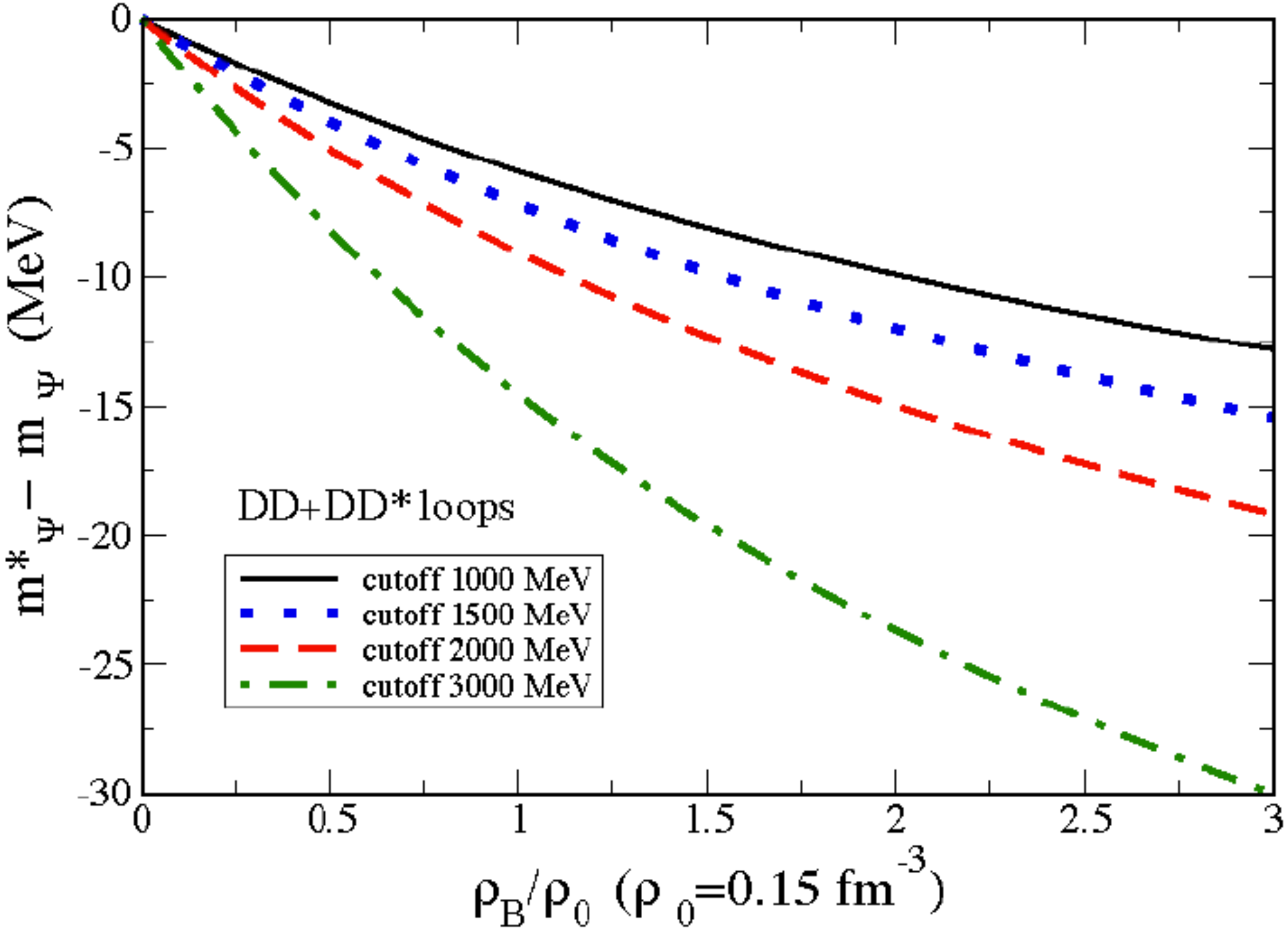
Couplings: VECTOR-MESON DOMINANCE

Matinyan & Müller, PRC 58, 2994(1998)
Lin & Ko, PRC 62, 034903 (2000)
Liu, Ko & Lin, PRC 65, 015203 (2002)

Λ_D	$m^*_{J/\Psi}$	DD	DD^*	D^*D^*	Δm
1000	3081	−3	−2	−11	−16
1500	3079	−3.5	−2.5	−12	−18
2000	3077	−4	−3	−13	−20
3000	3072	−6.5	−5	−12.5	−24



J/Ψ in nuclear matter



Can J/Ψ be bound to a nucleus?

Condition for a bound state

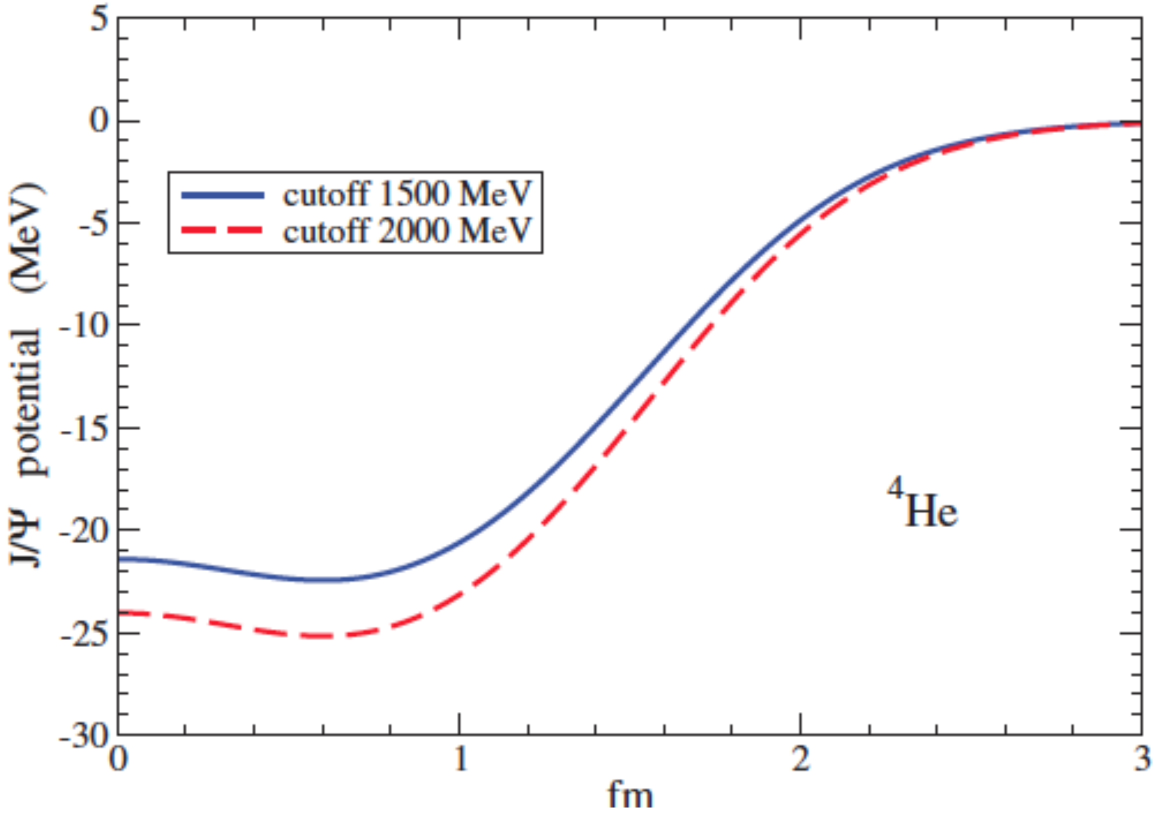
- spherical "square-well" radius *R*, depth V_0

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

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

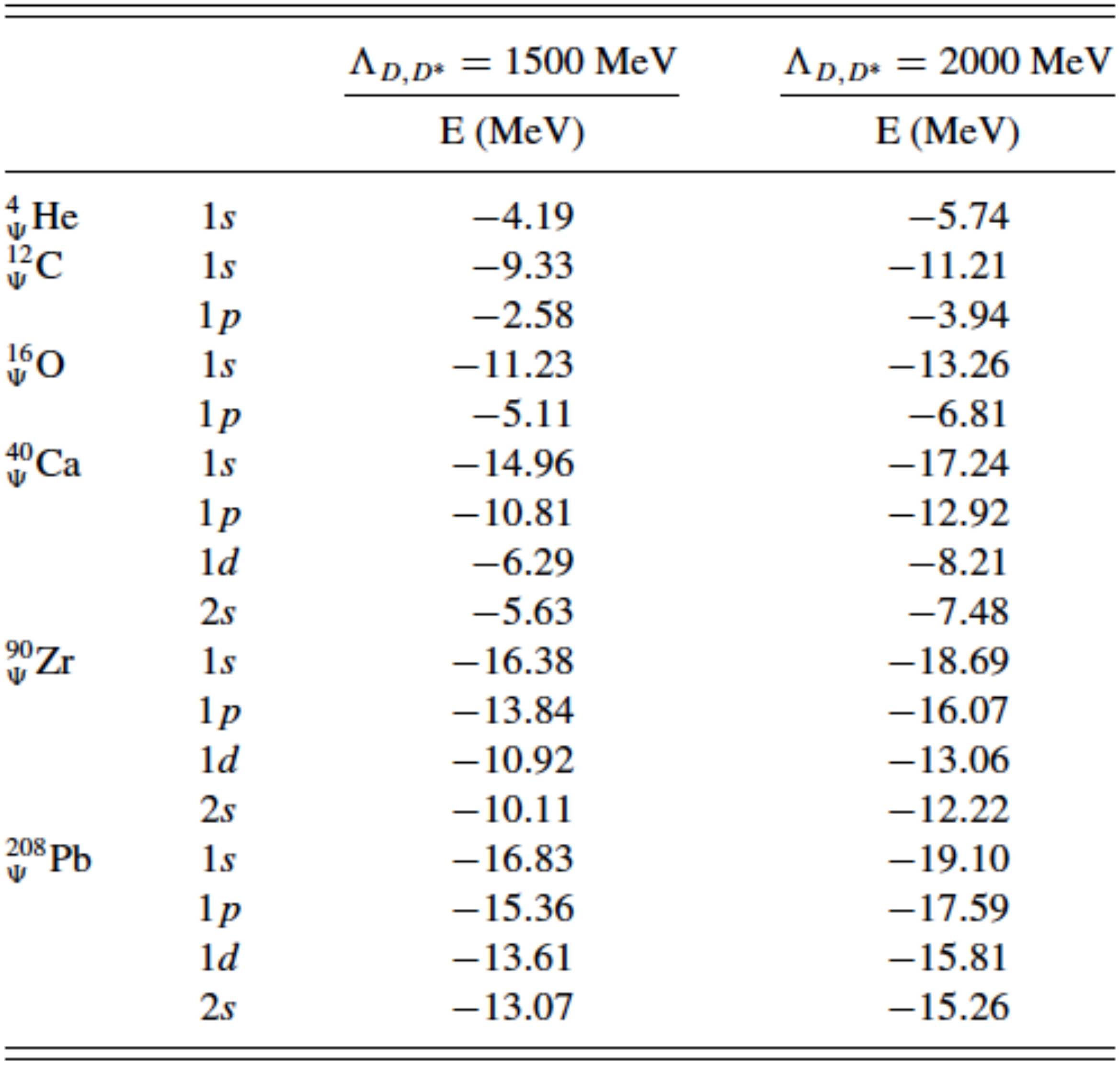
J/Ψ potential in ^{4}He

- Use local-density approximation
- Experimental nuclear density distributions



J/Ψ single–particle energies in nuclei

– solving a Klein-Gordon equation



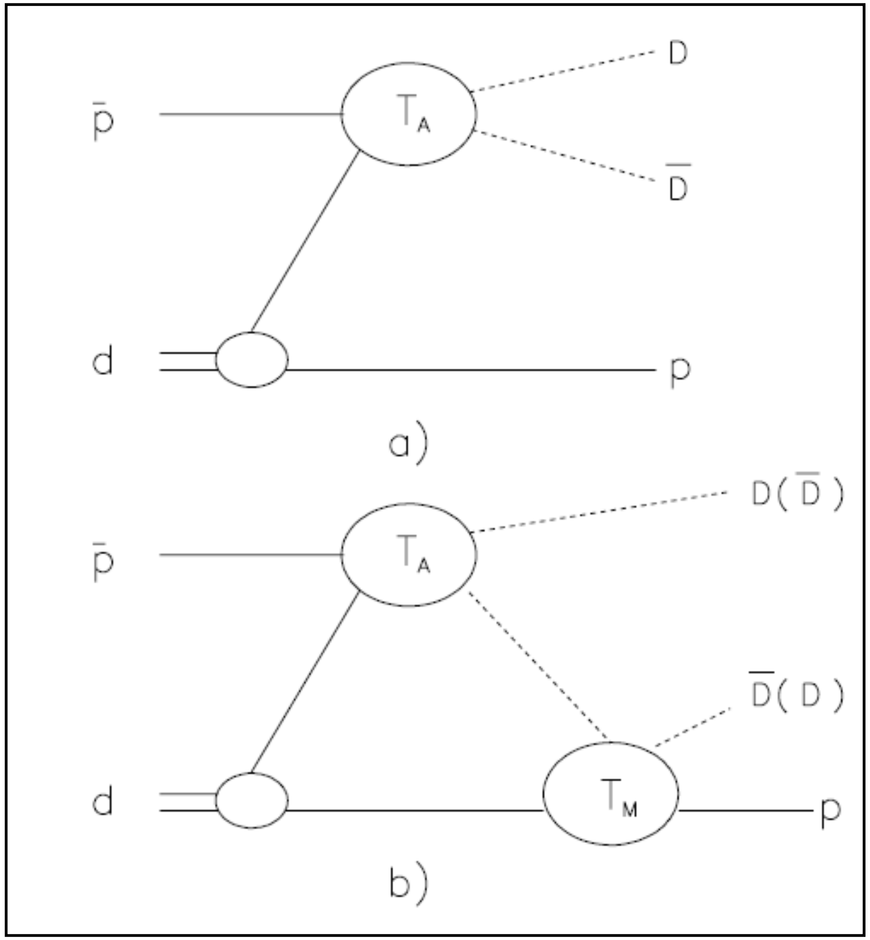
		$\Lambda_{D,D^*} = 1500$ MeV	$\Lambda_{D,D^*} = 2000$ MeV
		E (MeV)	E (MeV)
$^{4}_{\Psi}$He	1s	−4.19	−5.74
$^{12}_{\Psi}$C	1s	−9.33	−11.21
	1p	−2.58	−3.94
$^{16}_{\Psi}$O	1s	−11.23	−13.26
	1p	−5.11	−6.81
$^{40}_{\Psi}$Ca	1s	−14.96	−17.24
	1p	−10.81	−12.92
	1d	−6.29	−8.21
	2s	−5.63	−7.48
$^{90}_{\Psi}$Zr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

Issues:

- J/Ψ moving, not at rest
- Width of D mesons
- Interaction of D mesons with nucleons
- SU(4) flavor symmetry

Antiproton annihilation on the deuteron

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



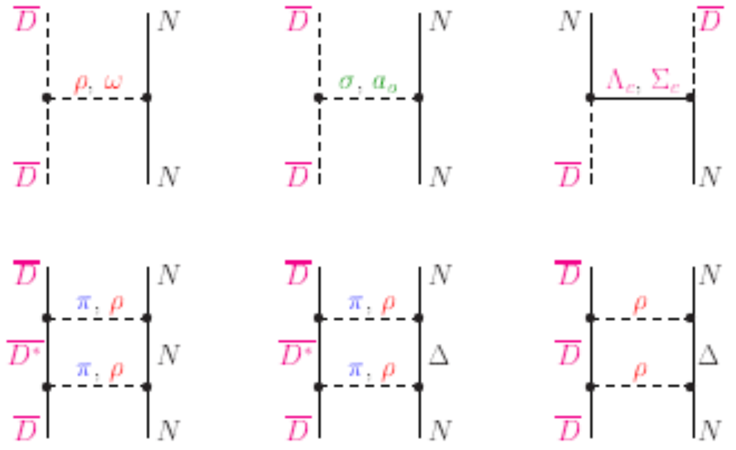
J. Haidenbauer, G. Krein, U.-G. Meissner, A. Sibirtsev

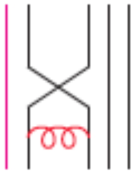
1) Eur. Phys. J. A 33, 107 (2007)

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

$\overline{D}N$ interaction

- meson + quark exchange





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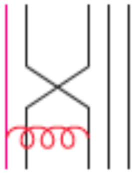

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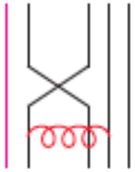

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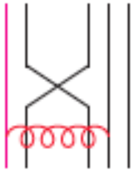

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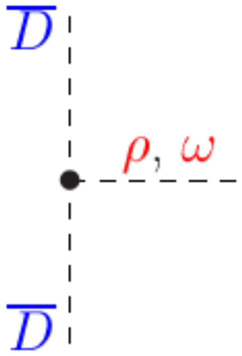
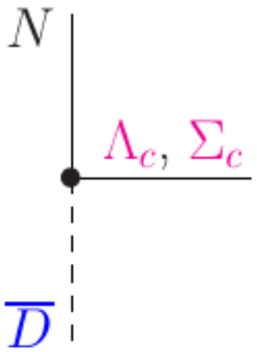
SU(4) flavor symmetry for couplings

$$m_u < m_s \ll m_c$$





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

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

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

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

Transition matrix element

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

$h_{fi} = gF(q^2)$: COUPLING X FORM-FACTOR

Wave functions

- constituent quark model

Hamiltonian:

$$H = m_1 + \frac{p_1^2}{2m_1} + m_2 + \frac{p_2^2}{2m_2} + F_1 \cdot F_2 \left[\frac{\alpha_c}{r} - \frac{3b}{4} r - \frac{8\pi\alpha_h}{3m_1 m_2} \left(\frac{\sigma^3}{\pi^3} e^{-\sigma^2 r_{12}} \right) S_1 \cdot S_2 - C \right]$$

Solve matrix problem: expand w.f. finite HO basis

$$H|\Phi\rangle = E|\Phi\rangle, \qquad |\Phi\rangle = \sum_n \Phi_n |n\rangle$$

$\langle r|n\rangle = e^{-n\beta^2 r^2/2},$ β : variational parameter

Meson 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

– nonrelativistic quark model + $^3P_0$

$F(q^2)$ at $q^2 = 0$

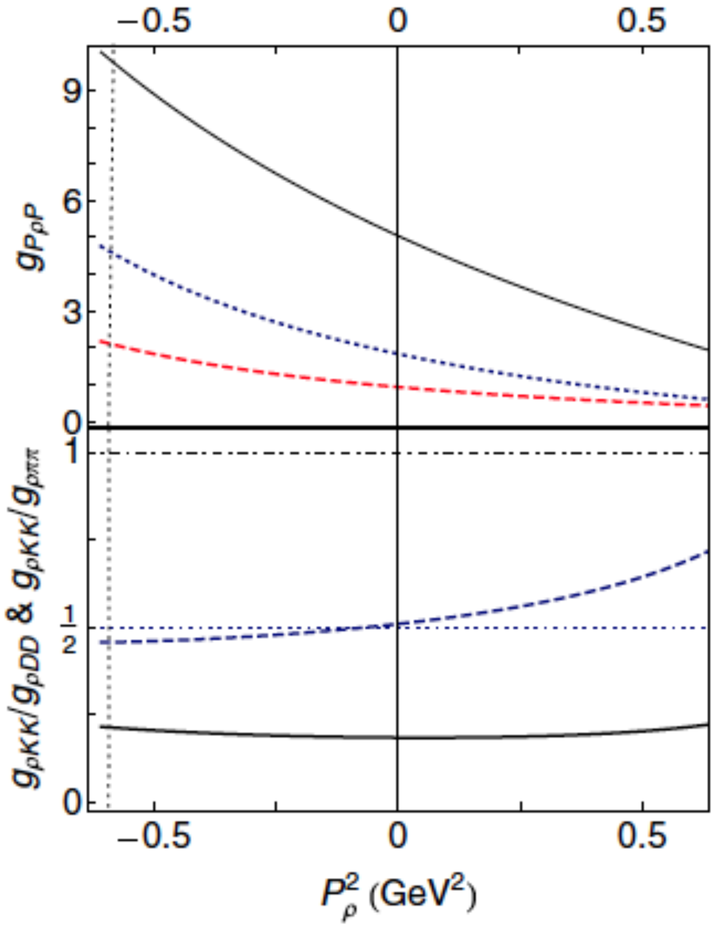
	$g_{\rho\pi\pi} / 2g_{\rho KK}$	$g_{\rho\pi\pi} / 2g_{\rho DD}$	$g_{\rho KK} / g_{\rho DD}$
SU(4) symmetric	*1*	*1*	*1*
SU(4) broken	*1.05*	*1.28*	*1.22*

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

C. E. Fontoura, GK, J. Haidenbauer

SU(4) flavor symmetry for couplings

– Dyson-Schwinger + Bethe-Salpeter equations



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

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

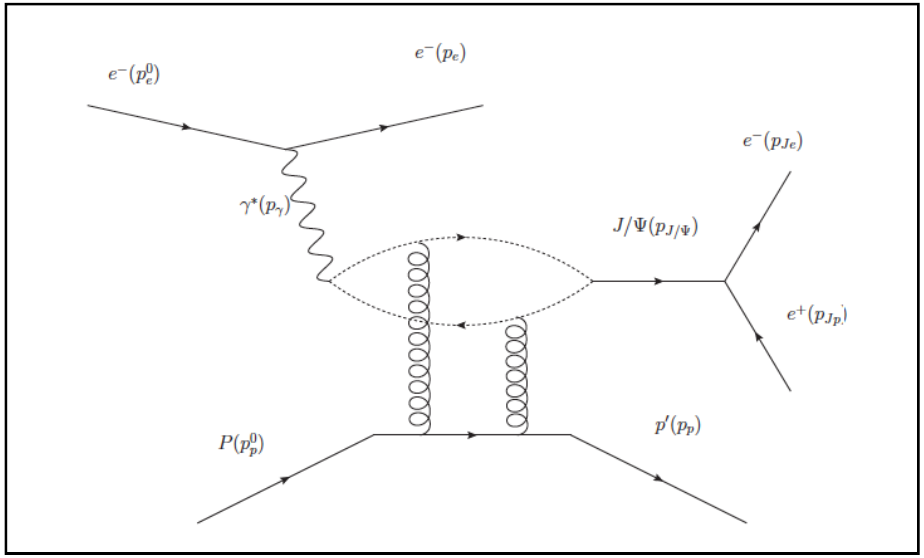
COUPLING LARGE, BUT FORM FACTORS ARE SOFT

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

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

Perspectives

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

Near Threshold Electroproduction of J/Ψ at 11 GeV

May 10, 2012

the ATHENNA Collaboration [1]

(A new experiment proposal to JLab-PAC39)

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[1] **A** J/Ψ **TH**reshold **E**lectroproduction on the **N**ucleon and **N**uclei **A**nalysis

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