Quarkonium-nucleus bound states

— Chromopolarizability and color van der Waals forces

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INT Workshop INT-15-60W

Modern Exotic Hadrons
November 2-13, 2015

Outline

— Motivation

— From models (1990) to a lattice simulation (2015)

— Other interesting bound states: D–nuclei, $D^*\Delta$

— Experimental perspective

— EFT approach: polarizability & van der Waals forces

— Perspectives

Collaborators

- A. Ballon-Bayona
- N. Brambilla
- B. El Bennich
- T. Carames
- L. Chang
- C.E. Fontoura
- J. Haidenbauer
- D. Liu
- U.-G. Meissner
- C. Miller
- C.D. Roberts
- A. Sibirtsev
- A.W. Thomas
- J. Tarrús-Castellá
- L. Tolos
- K. Tsushima
- A. Vairo
- A. Valcarce
- D. Wilson

Charm in matter

— Understanding of the nuclear force, role of glue

— J/Ψ, η_C, ··· : color polarizability, van der Waals force

— D-mesons in medium: chiral-symmetry restoration

— Charm hypernuclei

— Quark-gluon plasma

Experiments ongoing and underway:

LHC, RHIC, JLab @ 12 GeV, JPARC, Fair, NICA

Charmonium 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)

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.

PACS numbers: 21.90.+f, 12.40.−y, 21.30.+y, 25.10.+s

Variational calculation of binding energy

$$V_{(c\bar{c})N}(r) = -\frac{\alpha}{r}e^{-\mu r}$$

TABLE I. Binding energies $\epsilon = |\langle H\rangle|$ of the η_c to various nuclei, for unscreened and partially screened potentials; all masses are given in GeV. The data for $\langle R_A^2\rangle^{1/2}$ (in GeV^{-1}) are from Ref. 10.

				Unscreened			Partially screened		
A	$\langle R_A^2\rangle^{1/2}$	μ	$m_{\rm red}$	α	γ	$\langle H\rangle$	α	γ	$\langle H\rangle$
1	3.9	0.60	0.715	0.59		> 0	0.42		> 0
2	10.7	0.23	1.15	0.172		> 0	0.122		> 0
3	9.5	0.26	1.45	0.327	0.40	−0.019	0.231	0.24	−0.003
4	8.2	0.30	1.66	0.585	0.92	−0.143	0.414	0.62	−0.051
6	11.2	0.22	1.95	0.470	0.89	−0.128	0.332	0.61	−0.050
9	11.2	0.22	2.20	0.705	1.53	−0.407	0.499	1.07	−0.179

Possible production processes

TABLE II. Kinematics for the production of η_c-nucleus bound states. All quantities are given in GeV.

Process	ϵ	$p_{\text{c.m.}}$	p_l^{lab}
$\gamma\,{}^3\text{He} \to ({}^3\text{He}\,\eta_c)$	0.020	2.20	4.52
$pd \to ({}^3\text{He}\,\eta_c)$	0.020	2.48	7.64
$\bar{p}\,{}^4\text{He} \to ({}^3\text{H}\,\eta_c)$	0.020	1.48	2.30
$\gamma\,{}^4\text{He} \to ({}^4\text{He}\,\eta_c)$	0.120	2.24	3.96
$n\,{}^3\text{He} \to ({}^4\text{He}\,\eta_c)$	0.120	2.60	6.09
$dd \to ({}^4\text{He}\,\eta_c)$	0.120	2.71	9.51

VOLUME 67, NUMBER 16 PHYSICAL REVIEW LETTERS 14 OCTOBER 1991

Comment on "Nuclear-Bound Quarkonium"

David A. Wasson
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Smearing of the interaction over the nuclear volume

$$V_{(c\bar{c})A}(r) = \int d^3r'\, V_{(c\bar{c})N}(r - r')\rho_A(r')$$

$$\int d^3r'\, \rho_A(r') = A$$

A	ϵ [MeV]	$\langle r^2 \rangle^{1/2}$ [fm]
3	- 0.8	3.5
4	- 5.0	1.9
12	- 13	1.7
40	- 19	2.0
200	- 27	3.1

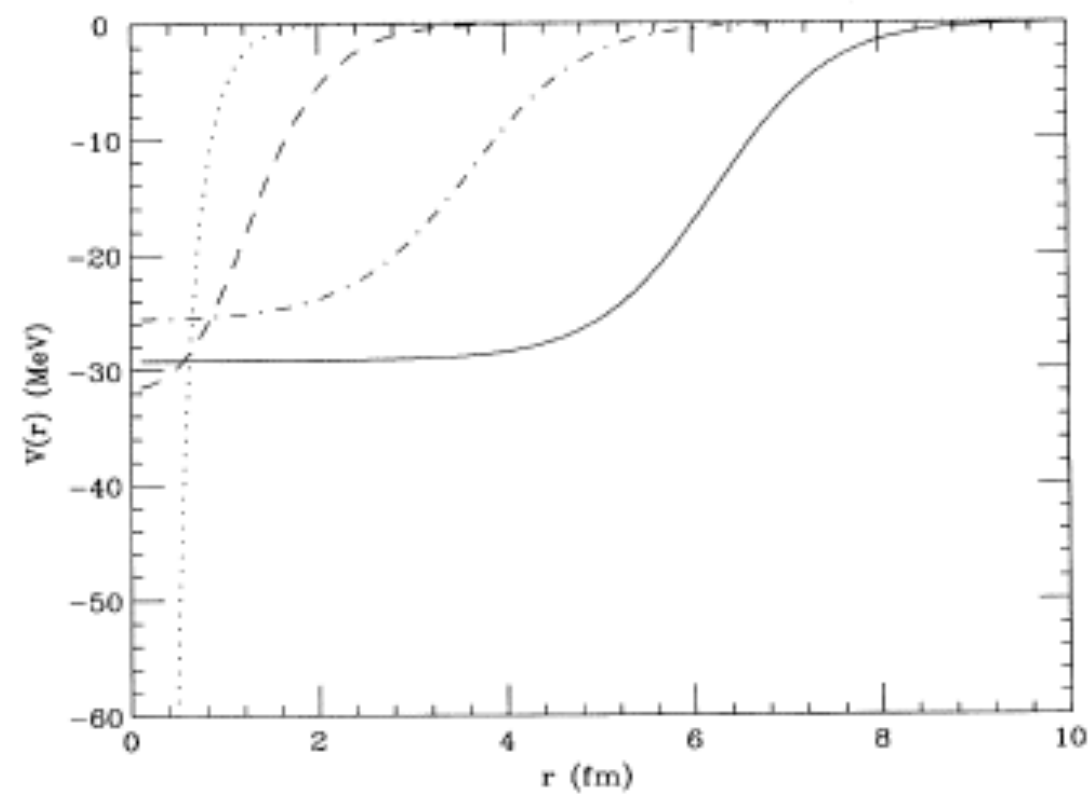


FIG. 1. Effective charmonium-nucleus potentials for various A. The dotted line is the $A=1$ result given by Eq. (1) and the dashed line is the $A=4$, the dash-dotted line is the $A=40$, and the solid line is the $A=200$ results predicted by Eq. (2).

Physics Letters B 288 (1992) 355–359
North-Holland

PHYSICS LETTERS B

A QCD calculation of the interaction of quarkonium with nuclei

Michael Luke, Aneesh V. Manohar and Martin J. Savage
Department of Physics 0319, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0319, USA

Binding to nuclear matter

$$\Upsilon, \eta_c \quad : \quad \epsilon \simeq -2 \ \text{ to } \ -4\,\text{MeV}$$

$$\left.\begin{array}{lll} J/\Psi & : & \epsilon \simeq -8 \ \text{ to } \ -11\,\text{MeV} \\ \psi'(2s) & : & \epsilon \simeq 700\,\text{MeV} \end{array}\right\} \text{less reliable}$$

J/Ψ binding to nuclei

Generically: two independent mechanisms

— Second order stark effect – octet intermediate state

van der Waals force

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

D mesons interact with the nuclear mean fields

Bhanot-Peskin theory

— van der Waals force (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

Note: intermediate state is noninteracting

Numerical results

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

ψ : Gaussian

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

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

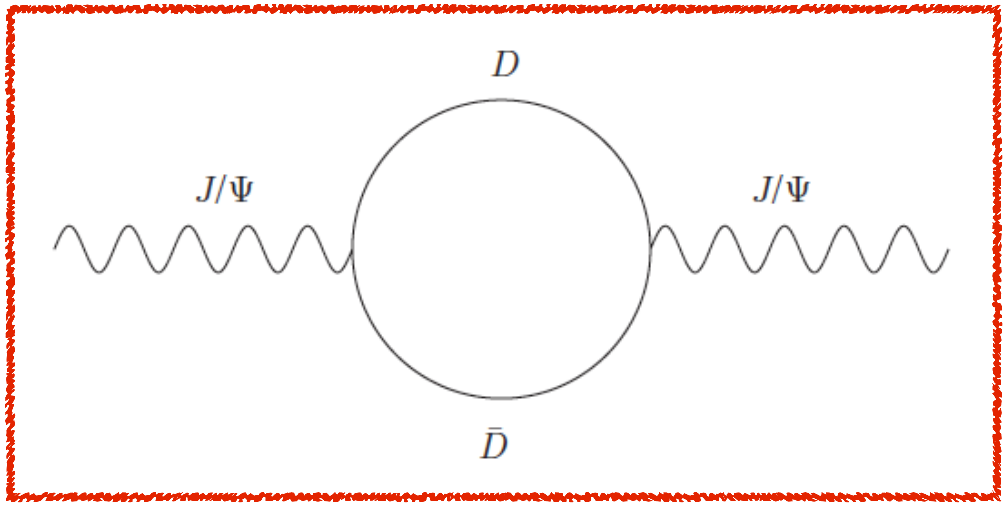
at normal nuclear matter density

Sibirtsev & Voloshin, PRD 71, 076005 (2005)

J/Ψ 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 medium dependence of D masses

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]

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Received 17 July 1997
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 $\pi^+ d \to J/\psi\, pp$.

PHYSICAL REVIEW C **77**, 055206 (2008)

Hadron loops: General theorems and application to charmonium

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(Received 7 December 2007; published 14 May 2008)

TABLE III. Mass shifts (in MeV) and $c\bar{c}$ probabilities for low-lying charmonium states due to couplings to two-meson continua. This one-loop estimate sets the unperturbed bare masses to the experimental values and assumes ${}^3P_0$ model and SHO wave function parameters $\gamma = 0.35$ and $\beta = 0.5$ GeV and quark mass ratios $r_n = m_n/m_c = 0.33/1.5$ and $r_s = m_s/m_c = 0.55/1.5$.

Bare $c\bar{c}$ state		Mass shifts by channel, ΔM_i (MeV)							$P_{c\bar{c}}$
Multiplet	State	DD	DD^*	D^*D^*	D_sD_s	$D_sD_s^*$	$D_s^*D_s^*$	Total	
1S	$J/\psi(1^3S_1)$	−23	−83	−132	−21	−76	−123	−457	0.69
	$\eta_c(1^1S_0)$	0	−114	−105	0	−106	−98	−423	0.73
2S	$\psi'(2^3S_1)$	−27	−84	−126	−19	−70	−113	−440	0.51
	$\eta_c'(2^1S_0)$	0	−118	−103	0	−102	−94	−416	0.61
1P	$\chi_2(1^3P_2)$	−40	−105	−144	−33	−88	−111	−521	0.49
	$\chi_1(1^3P_1)$	0	−127	−148	0	−90	−130	−496	0.52
	$\chi_0(1^3P_0)$	−57	0	−196	−34	0	−172	−459	0.58
	$h_c(1^1P_1)$	0	−149	−130	0	−118	−107	−504	0.52

D,D* in medium

Light quarks in D mesons

— quark condensate changes for nonzero temperature and baryon density

— quark-model: masses of the D mesons change

Quark condensate at finite T
— model independent result*

For low temperatures:

$$\frac{\langle \bar{q}q \rangle_T}{\langle \bar{q}q \rangle} = 1 - \frac{\Sigma_\pi}{m_\pi^2 f_\pi^2}\, \rho_s^\pi(T)$$

$$\simeq 1 - \frac{T^2}{8 f_\pi^2}$$

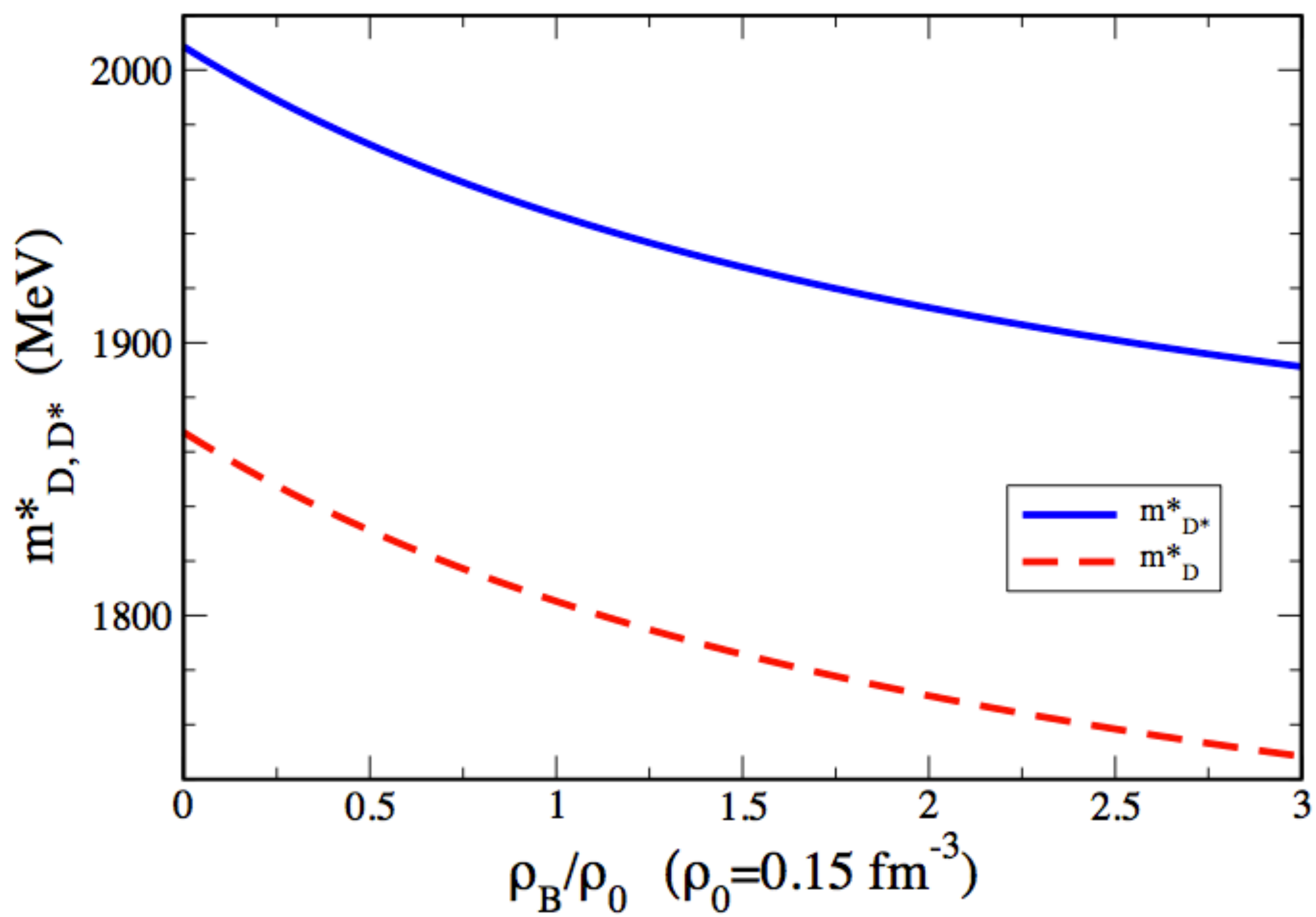
$$\Sigma_\pi = m_q \frac{dm_\pi}{dm_q}$$

$\rho_s^\pi(T)$: scalar density of pions in medium

* Gerber & Leutwyler (1989)

D,D* in medium

— QMC model

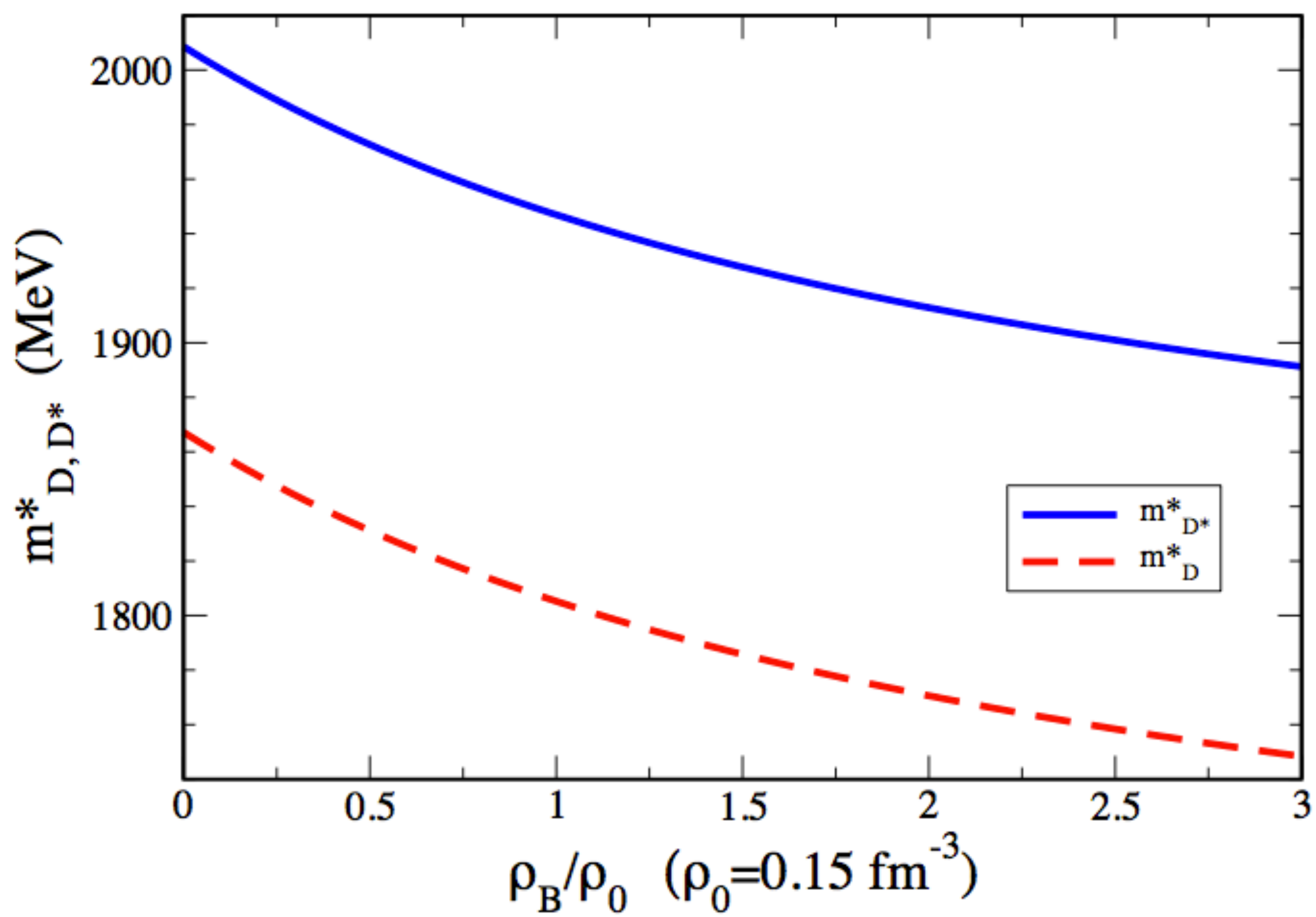


Low temperature and density:

K. Saito, K. Tsushima & A.W. Thomas, Prog. Part. Nucl. Phys. 58, 1 (2007)

D,D* in medium

— QMC model



Low temperature and density:

$$\langle \bar{q}q \rangle \simeq \left(1 - \frac{T^2}{8f_\pi^2} - 0.3\frac{\rho}{\rho_0}\right) \langle \bar{q}q \rangle_{\mathrm{vac}}$$

K. Saito, K. Tsushima & A.W. Thomas, Prog. Part. Nucl. Phys. 58, 1 (2007)

Effective Lagrangians

– SU(4) flavor symmetry for coupplings

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

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

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

J/Ψ in nuclear matter

J/Ψ self-energy:

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

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

$F(q^2)$: form factors, extension of the mesons

Effective potential:

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

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

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

Structure of the mesons
— form factors

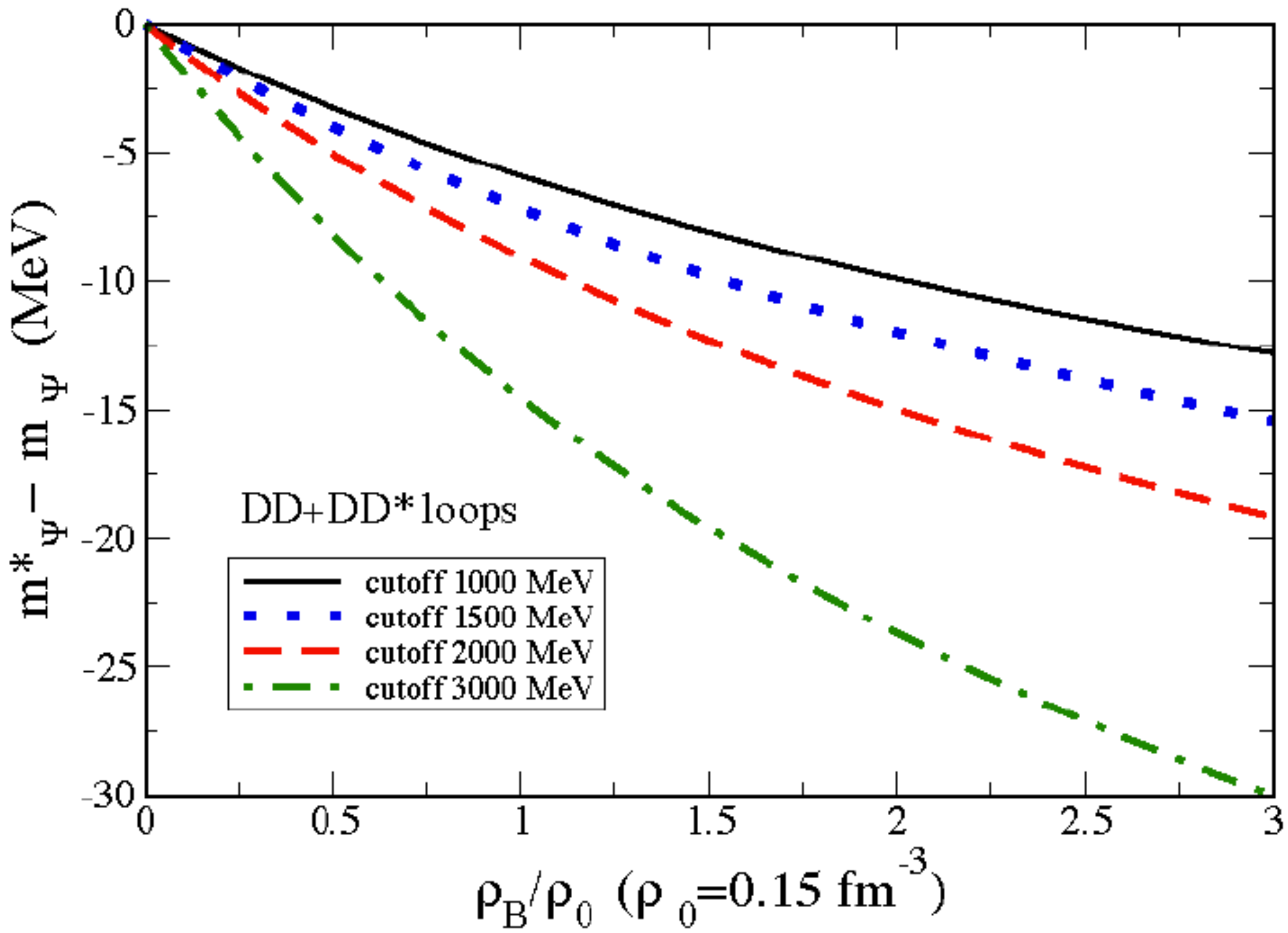
$^3P_0$ — model (E. Swanson)

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

Phenomenological

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

J/Ψ in nuclear matter



GK, A. W. Thomas & K. Tsushima PLB 697, 136 (2011)

J/Ψ single-particle energies in nuclei

— from 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

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

PHYSICAL REVIEW D **91,** 114503 (2015)

Quarkonium-nucleus bound states from lattice QCD

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(Received 9 November 2014; published 11 June 2015)

Quarkonium-nucleus systems are composed of two interacting hadronic states without common valence quarks, which interact primarily through multigluon exchanges, realizing a color van der Waals force. We present lattice QCD calculations of the interactions of strange and charm quarkonia with light nuclei. Both the strangeonium-nucleus and charmonium-nucleus systems are found to be relatively deeply bound when the masses of the three light quarks are set equal to that of the physical strange quark. Extrapolation of these results to the physical light-quark masses suggests that the binding energy of charmonium to nuclear matter is $B_{\mathrm{phys}}^{\mathrm{NM}} \lesssim 40$ MeV.

DOI: 10.1103/PhysRevD.91.114503 PACS numbers: 11.15.Ha, 12.38.Gc, 13.40.Gp

Models

TABLE I. Estimates for the binding energies of charmonium to light nuclei and nuclear matter (in MeV) from selected models. A "$*$" indicates the system is predicted to be unbound, while entries with center dots indicate that the system was not addressed.

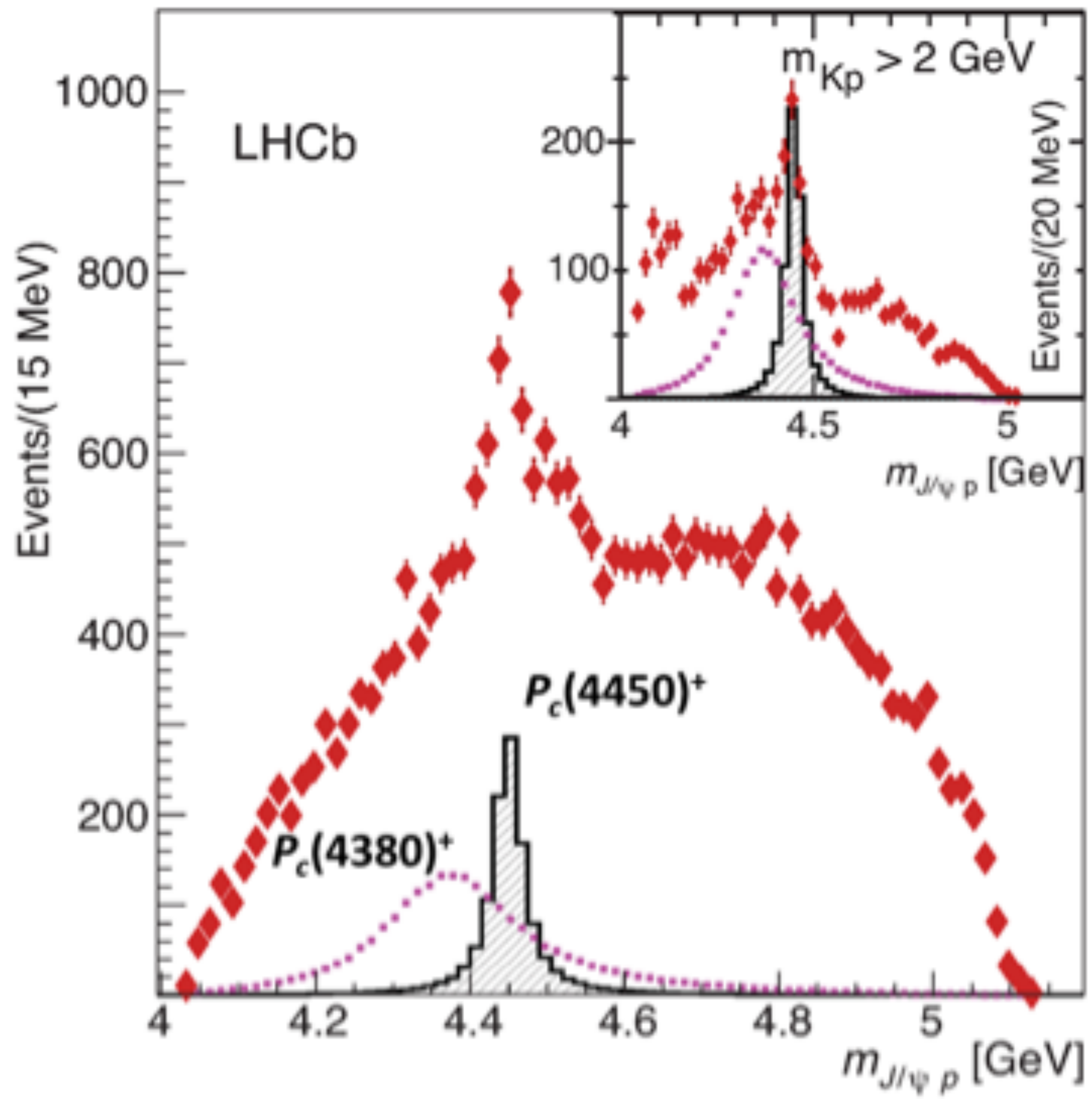
	Binding energy (MeV)			Binding energy (MeV)	
Ref.	^{3}He η_c	^{4}He η_c	NM η_c	^{4}He J/ψ	NM J/ψ
[1]	19	140	$*$		
[2]	0.8	5	27		
[3]			10		10
[5]	$*$	$*$	9		
[6]					5
[7]				5	18
[8]				15.7	

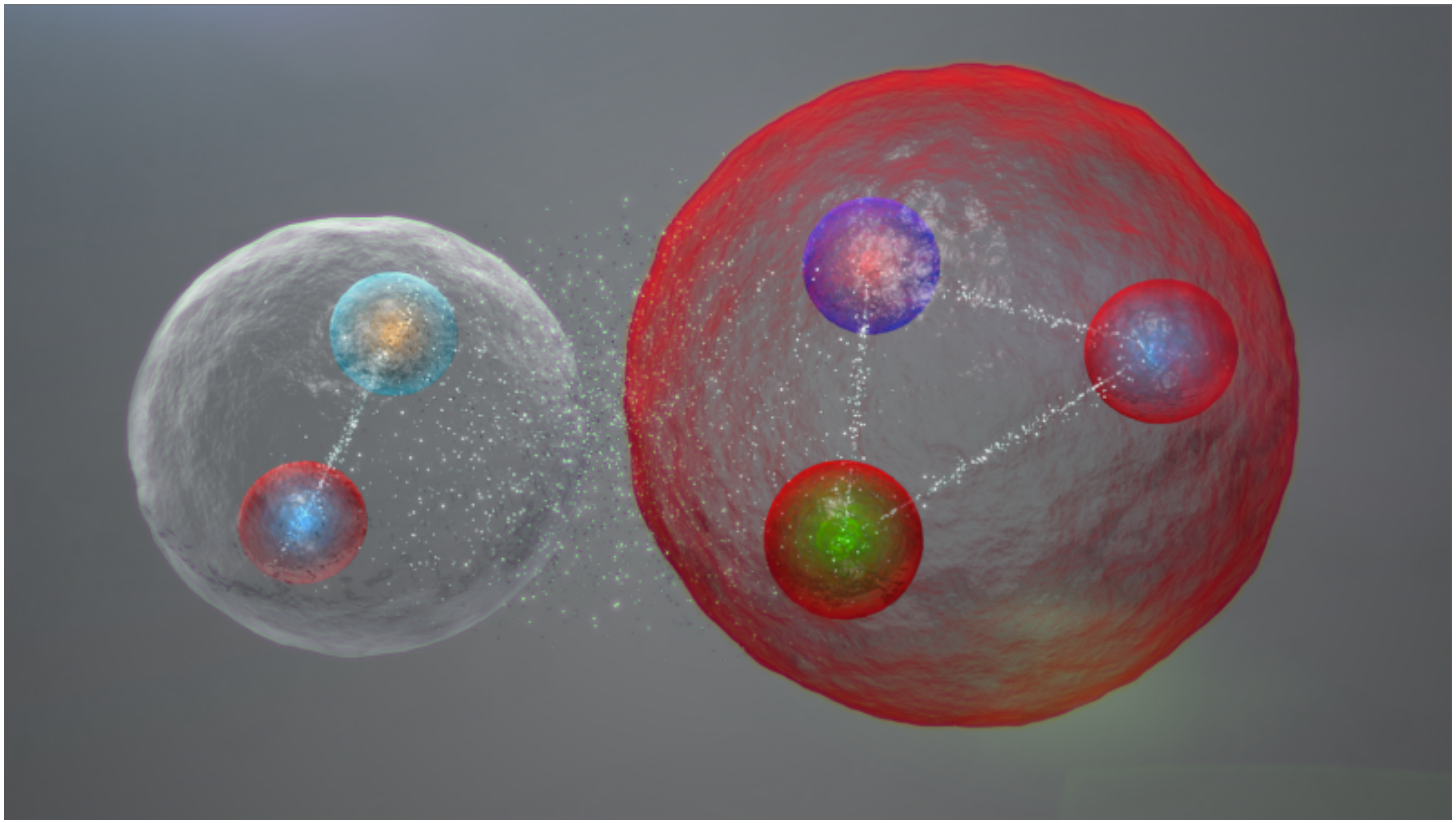
NPLQCD

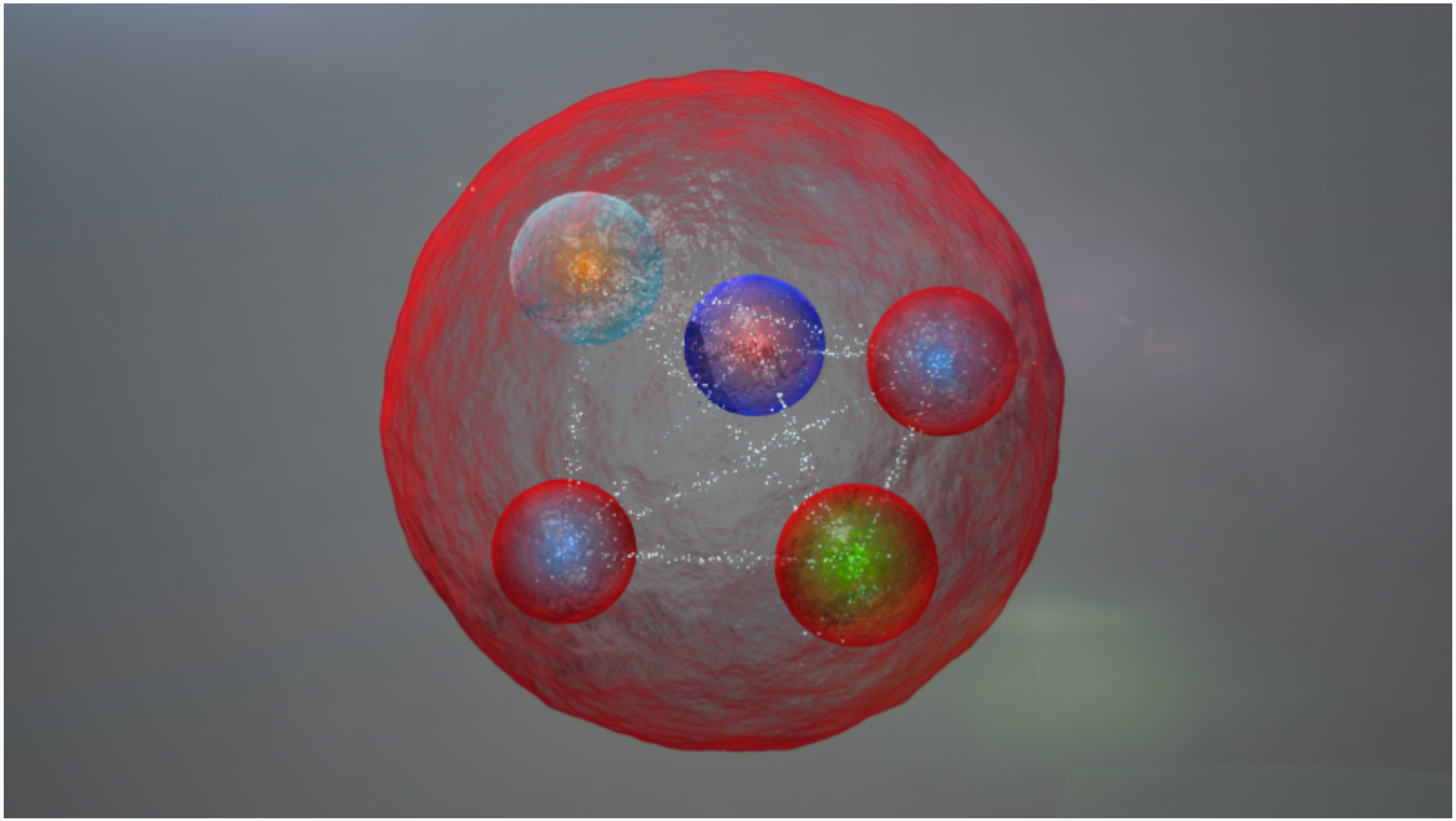
TABLE V. The binding energies (in MeV) of charmonium-nucleus systems calculated on the $L = 24$ and 32 ensembles. The rightmost column shows the infinite-volume estimate, which, without results on the $L = 48$ ensemble, is taken to be the binding calculated on the $L = 32$ ensemble. The first and second sets of parentheses shows the statistical and quadrature-combined statistical plus systematic uncertainties, respectively.

System	$24^3 \times 64$	$32^3 \times 64$	$L = \infty$
$N\eta_c$	17.9(0.4)(1.5)	19.8(0.7)(2.6)	19.8(2.6)
$d\eta_c$	39.3(1.3)(4.8)	42.4(1.1)(7.9)	42.4(7.9)
$pp\eta_c$	37.8(1.1)(4.5)	41.5(1.0)(7.5)	41.5(7.6)
^{3}Heη_c	57.2(1.3)(8.3)	56.7(2.0)(9.4)	56.7(9.6)
^{4}Heη_c	70(02)(13)	56(06)(17)	56(18)
^{4}HeJ/ψ	75.7(1.9)(9.4)	53(07)(18)	53(19)

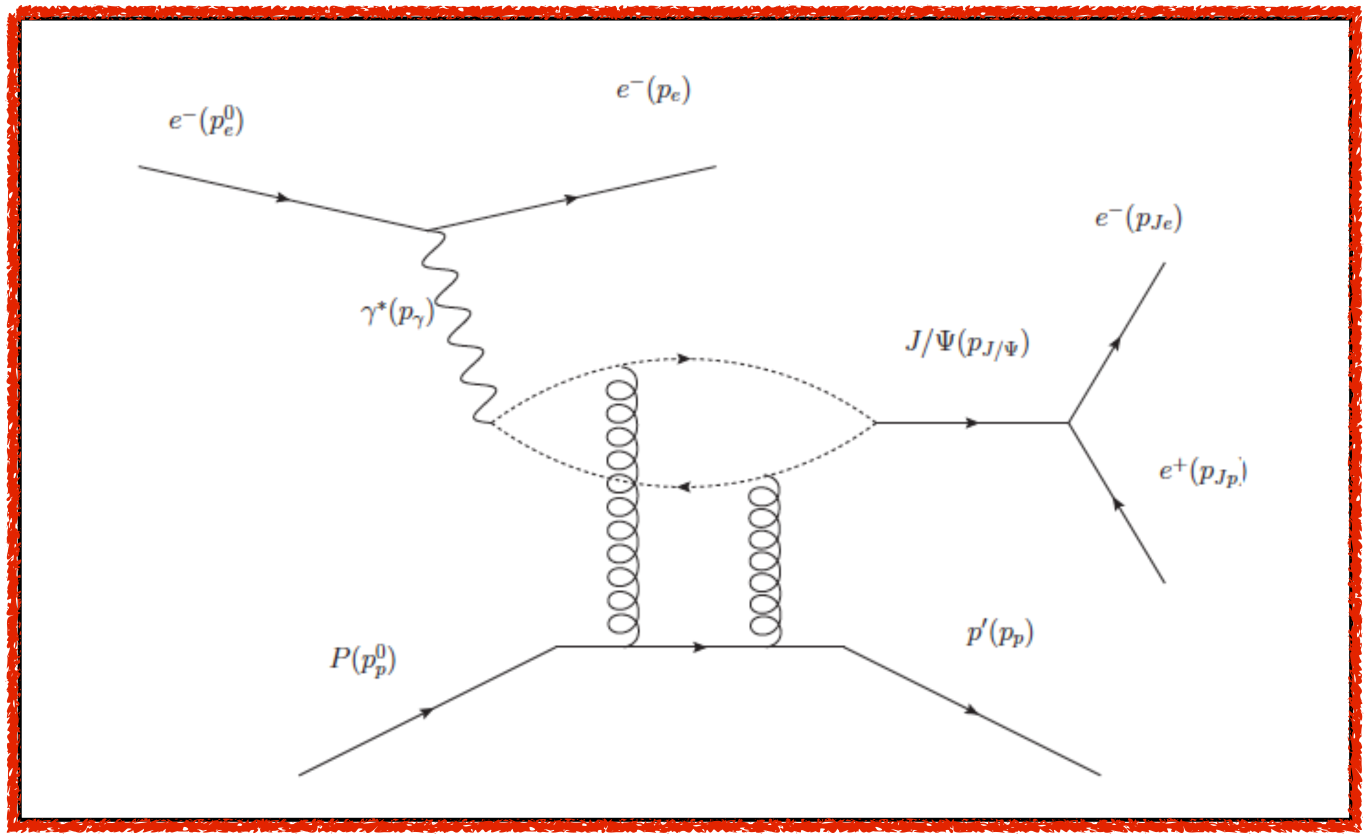
J/Ψ binding to proton?







ATHENNA* collaboration JLab @ 12 GeV



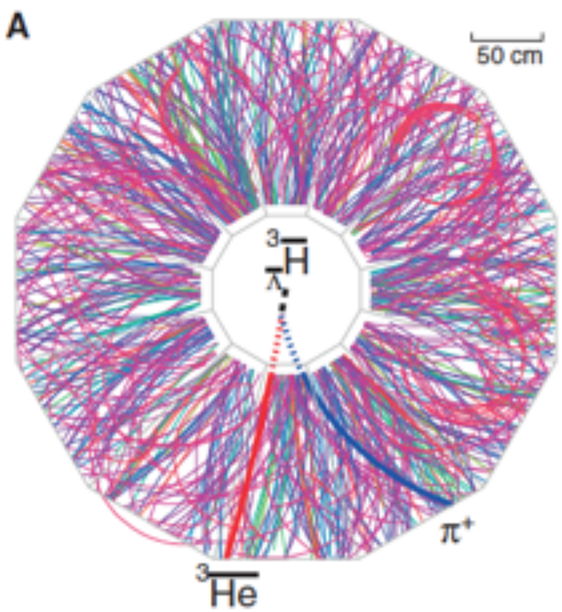
Z.-E. Meziani (Co-spokesperson/Contact)
N. Sparveris (Co-spokesperson)
Z. W. Zhao (Co-spokesperson)

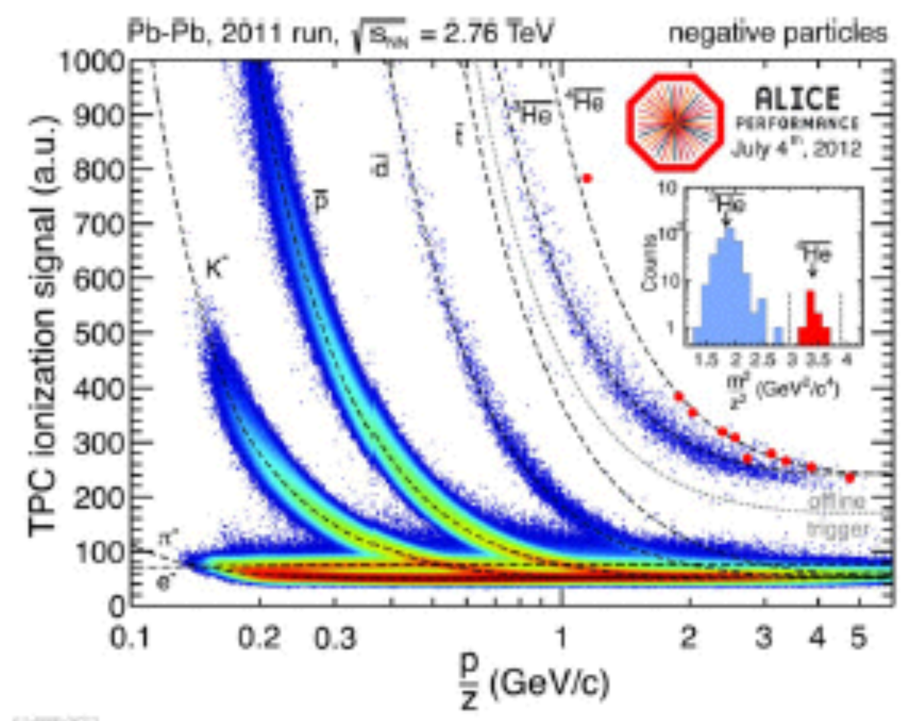
*A J/Ψ THreshold Electroproduction on the Nucleon and Nuclei Analysis

How About coalescence at the LHC?

— Chances of a charmed hadron meeting one or two nucleons not smaller than of two antinucleons and one antihyperon meeting to form an antihypernucleus

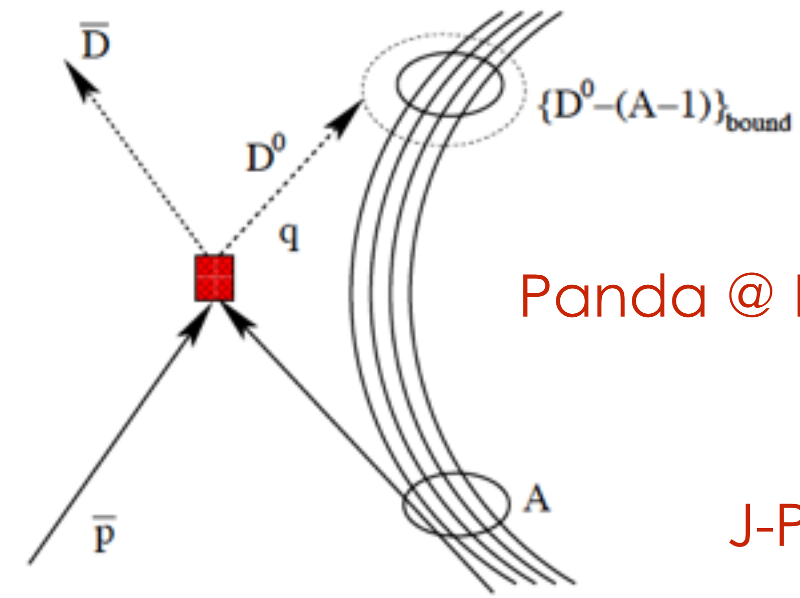
Observation of an Antimatter Hypernucleus
The STAR Collaboration
Science **328**, 58 (2010);
DOI: 10.1126/science.1183980





Need to detect in coincidence the decay products

D-mesons
— bound to nuclei



Panda @ FAIR

J-PARC

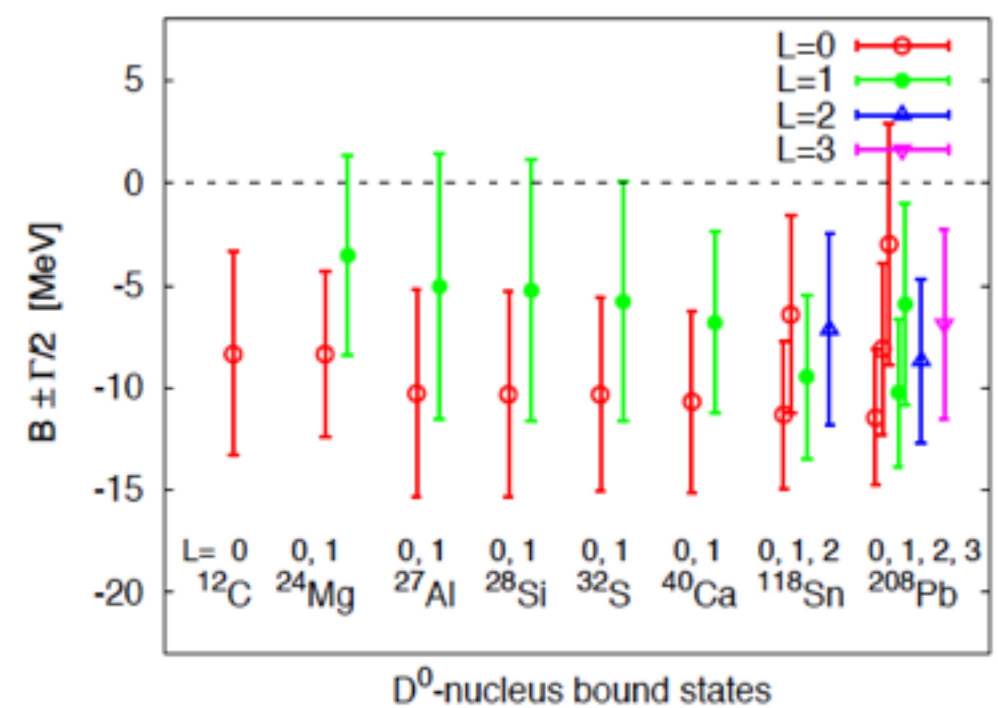
Quark-meson-coupling model
- Hartree MFT*, scalar + vector mean fields

D̄ bound state energy in Pb

state	D^- 1.96 *Vqω	D^- Vqω	D^- Vqω No Coulomb	$\bar{D}0$ 1.96 *Vqω	$\bar{D}0$ Vqω	D0 Vqω
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

Review
K. Saito et al. PPNP (2007)

EFT HQSS
- MFT, coupled channels



Review
L. Tolos, Int. J. Mod. Phys. E (2013)

*Fock terms do not change much size of mean fields
GK, K. Tsushima, T. Thomas

DN, DΔ states

Chiral quark model*

— constituent quarks

— confining potential

— OGE, OPE, OSE

Coupled channels - T. Caramés, A. Valcarce (2012)

	$T=0$	$T=1$	$T=2$
$J=1/2$	$N\bar{D}-N\bar{D}^*$	$N\bar{D}-N\bar{D}^*-\Delta\bar{D}^*$	$\Delta\bar{D}^*$
$J=3/2$	$N\bar{D}^*$	$N\bar{D}^*-\Delta\bar{D}-\Delta\bar{D}^*$	$\Delta\bar{D}-\Delta\bar{D}^*$
$J=5/2$		$\Delta\bar{D}^*$	$\Delta\bar{D}^*$

— In vacuum: very few DN bound states (Caramés & Valcarce)

— In medium: many become bound, combined effect of coupled channels and change of condensate

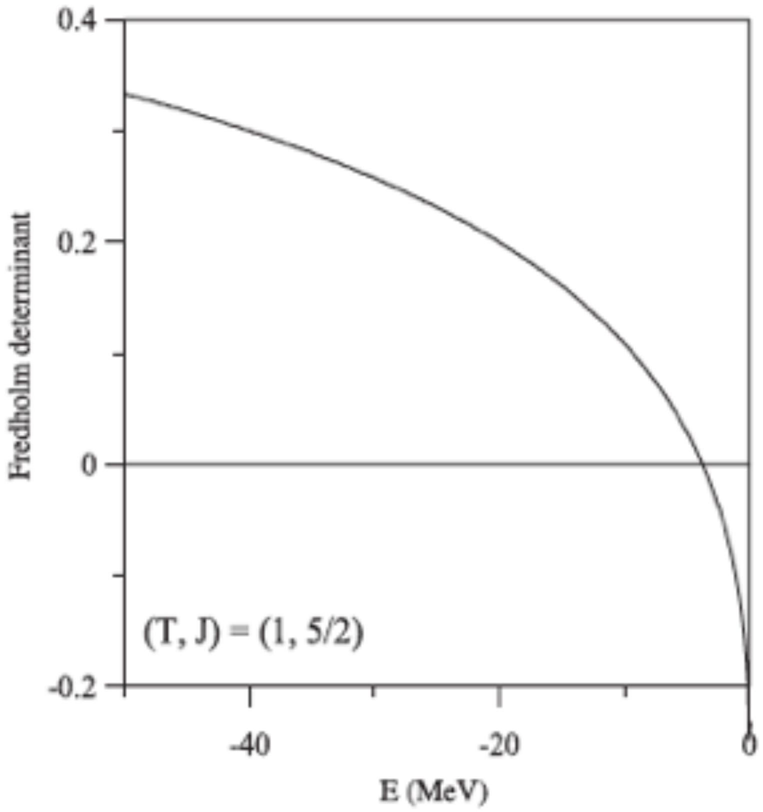
T. Caramés, C. E. Fontoura, GK, K. Tsushima, A. Valcarce (2015)

*J. Vijande, F. Fernandez, A. Valcarce (2005)

J. Segovia, A. M. Yasser, D. R. Entem, F. Fernandez (2008)

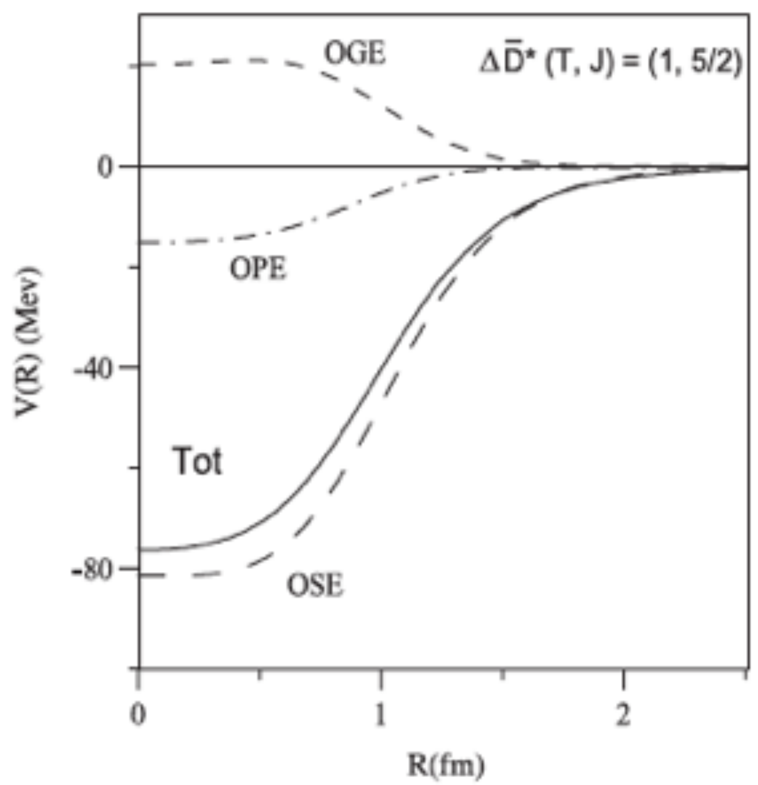
$\bar{D}^*\Delta$ - an interesting molecular state

— $(T,J^P) = (1,5/2^-)$



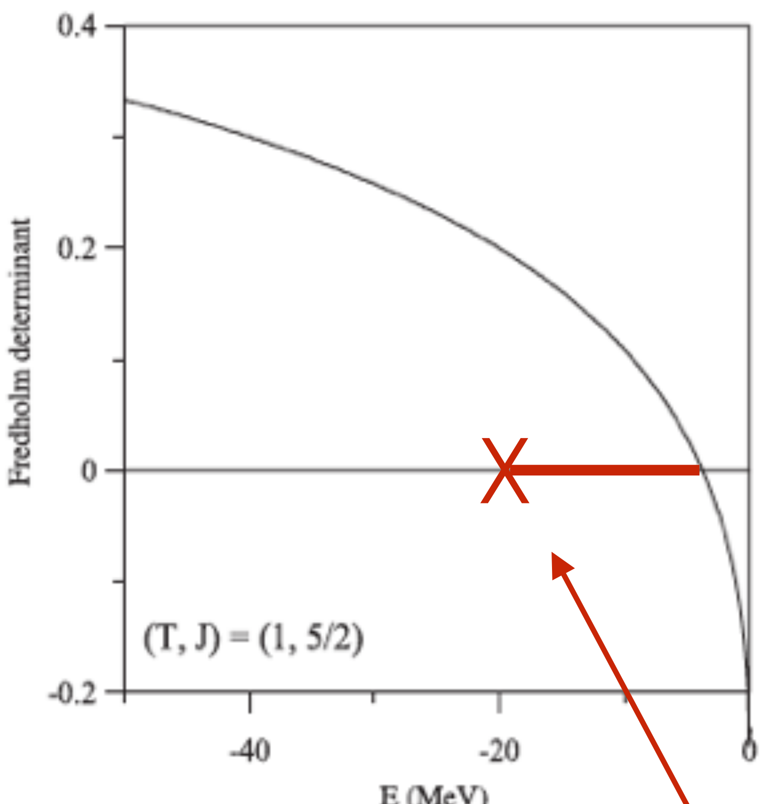
OSE dominates

OGE & OPE cancel



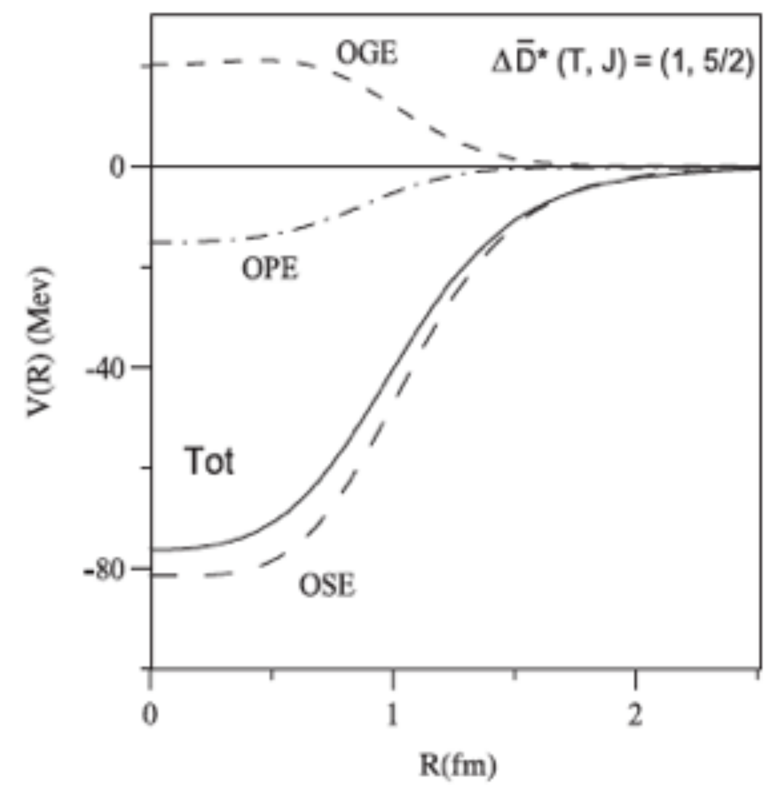
$\bar{D}^*\Delta$ - an interesting molecular state

— $(T,J^P) = (1,5/2^-)$



OSE dominates

OGE & OPE cancel



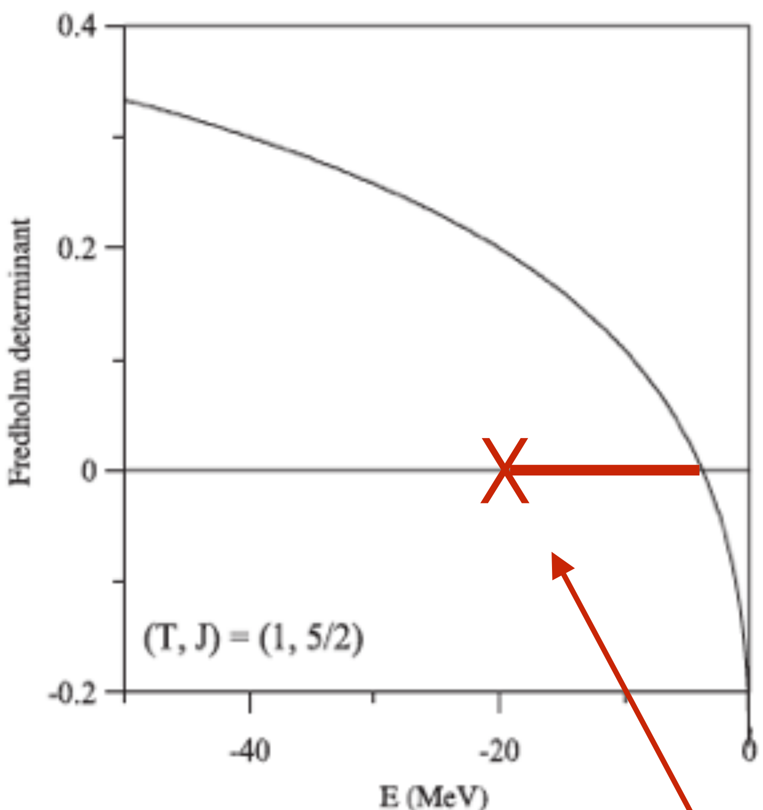
Drop of the condensate

— OGE & OPE still cancel each other

— OSE, extended range, larger binding

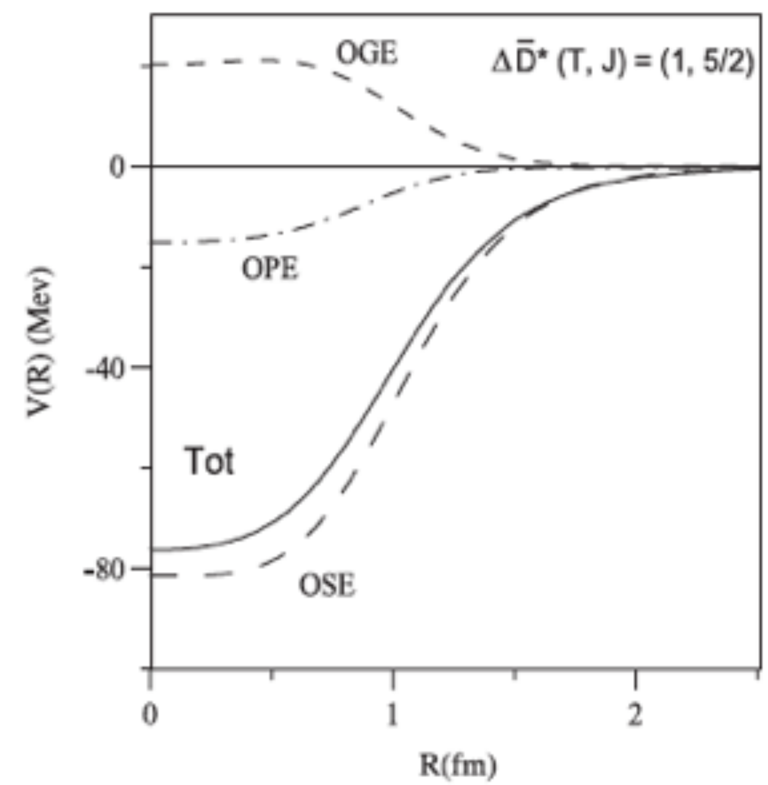
$\bar{D}^*\Delta$ - an interesting molecular state

— $(T, J^P) = (1, 5/2^-)$



OSE dominates

OGE & OPE cancel



Drop of the condensate

— OGE & OPE still cancel each other

— OSE, extended range, larger binding

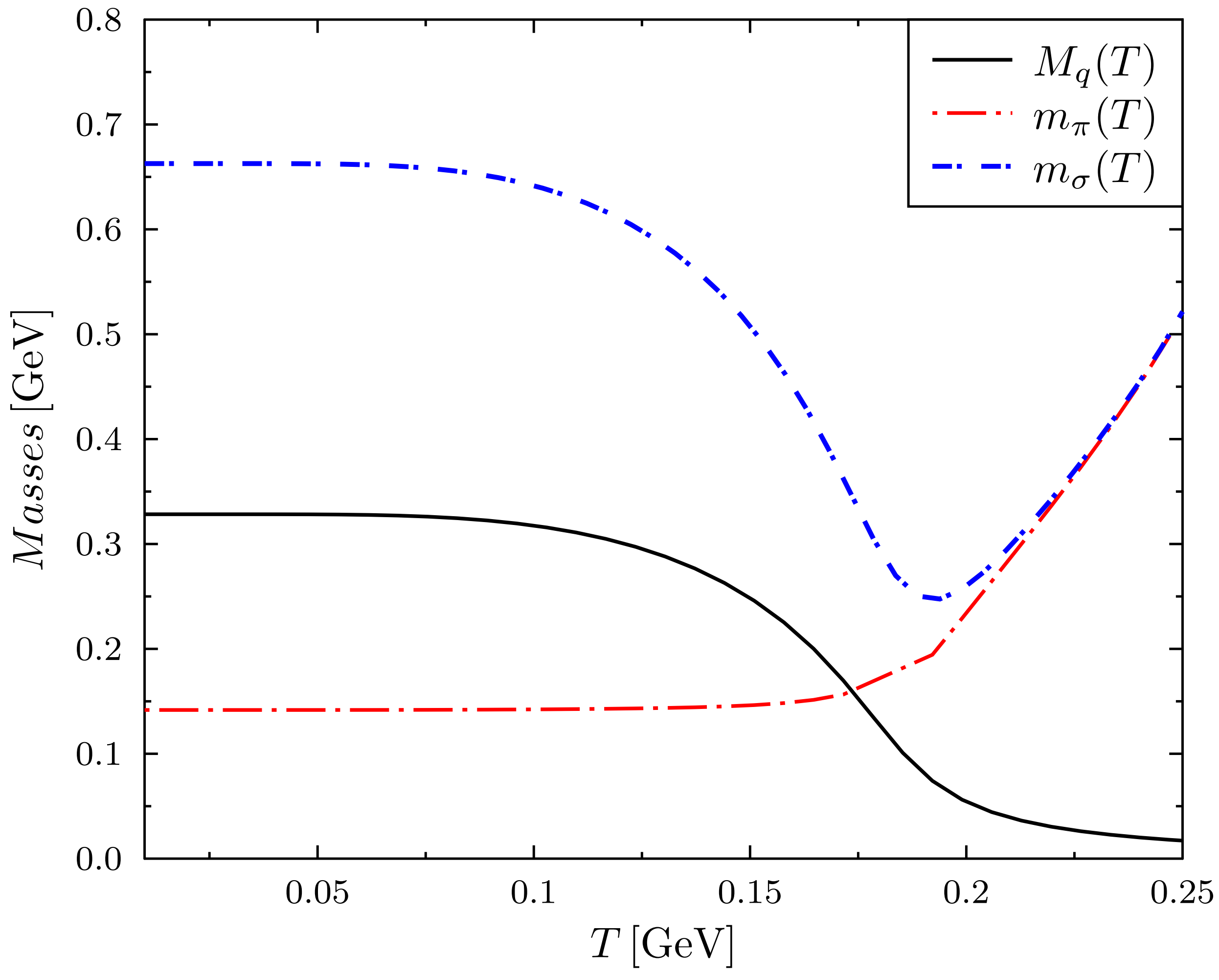
Also, $\Lambda_C(2940)^+$ as a D*N bound state

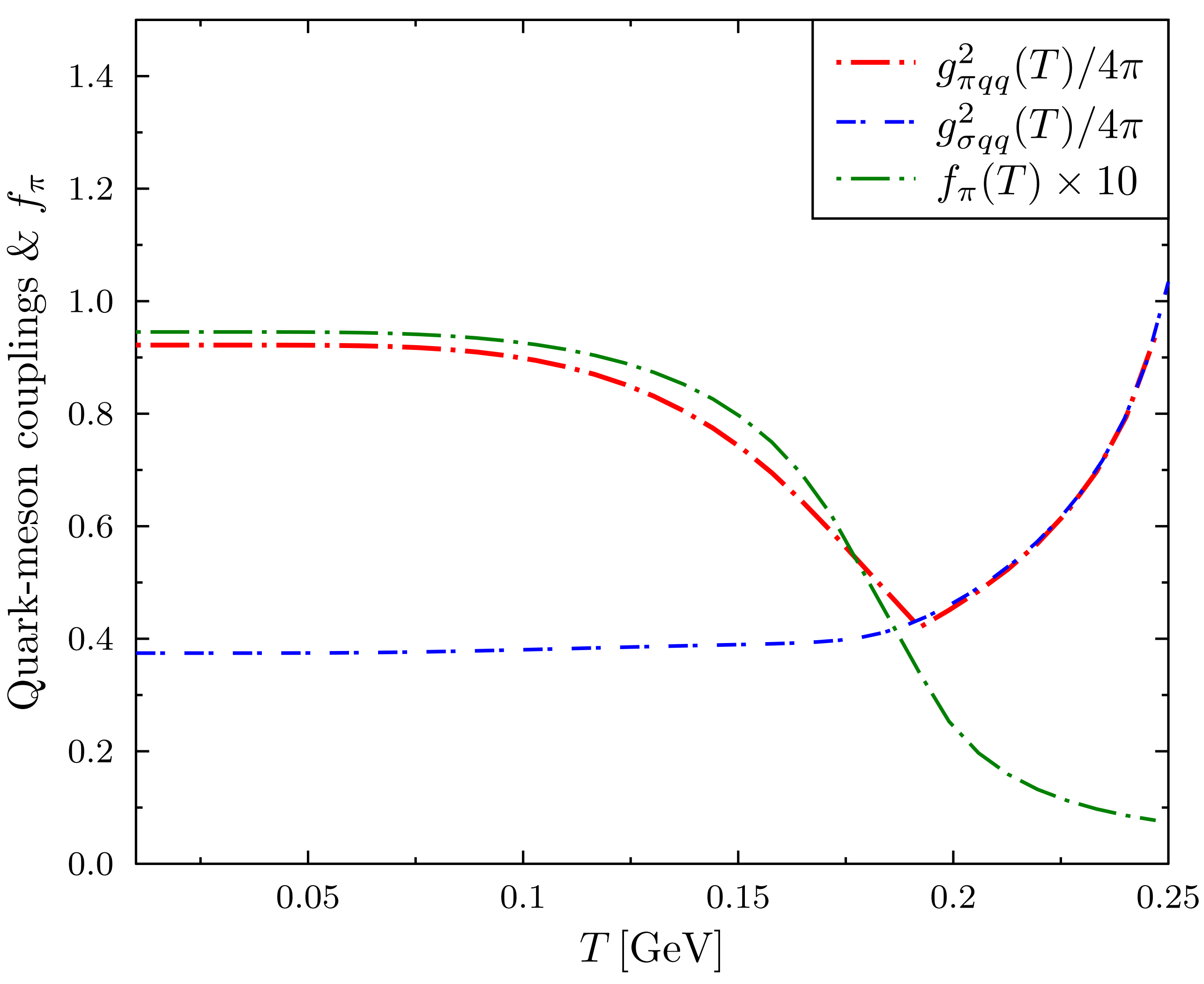
P. G. Ortega, D. Entem, F. Fernandez (2013)

$\bar{D}^*\Delta$ - in medium

— $(T,J^P) = (1,5/2^-)$

Input for the chiral quark model - NJL model



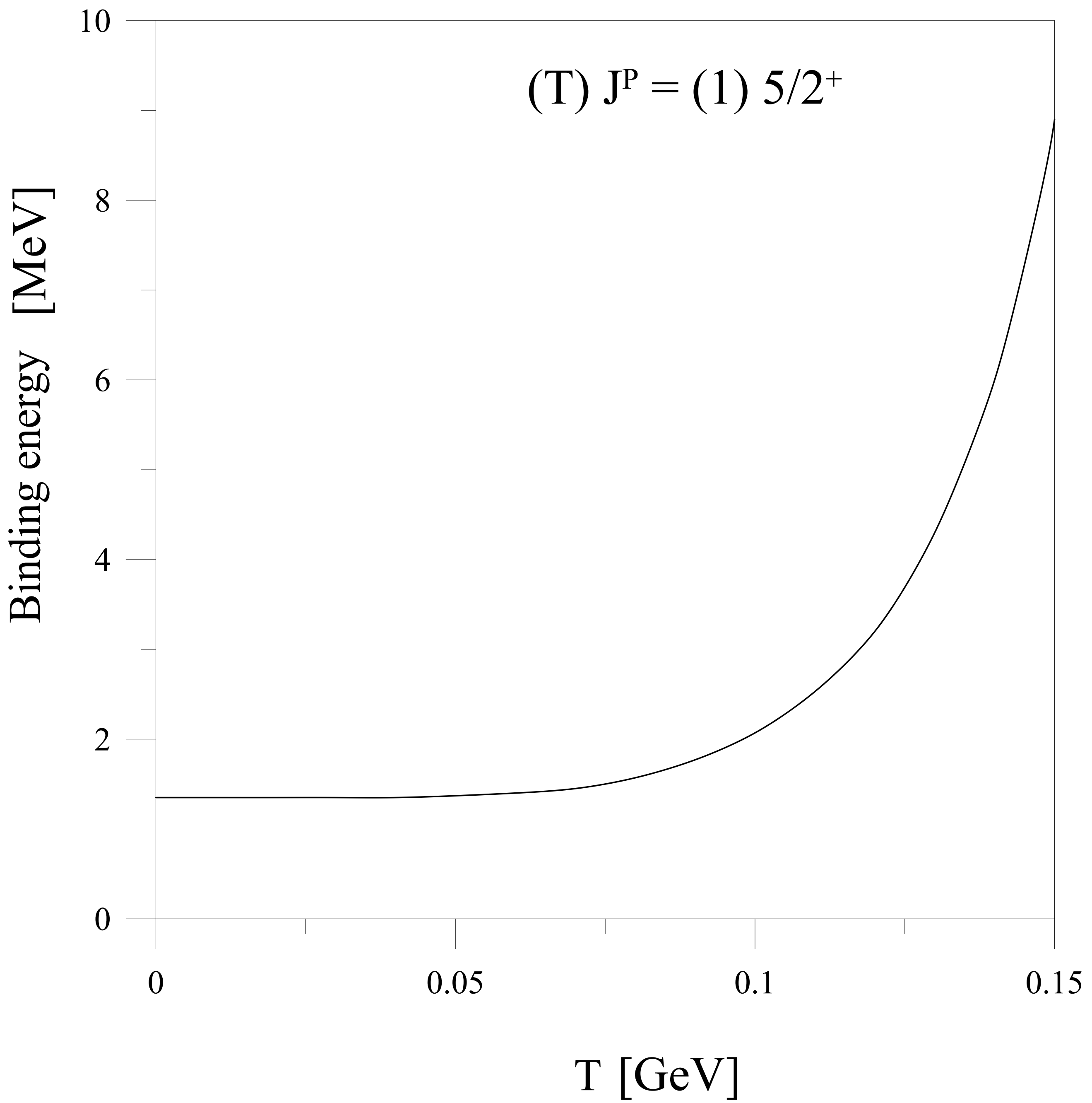


T. Caramés, C. E. Fontoura, GK, K. Tsushima, A. Valcarce (2015)

$\bar{D}^*\Delta$ - in medium

— $(T, J^P) = (1, 5/2^-)$

Binding energy



Need crucial input

— DN interaction

Need crucial input

— DN interaction

P̄ANDA @ FAIR

Need crucial input

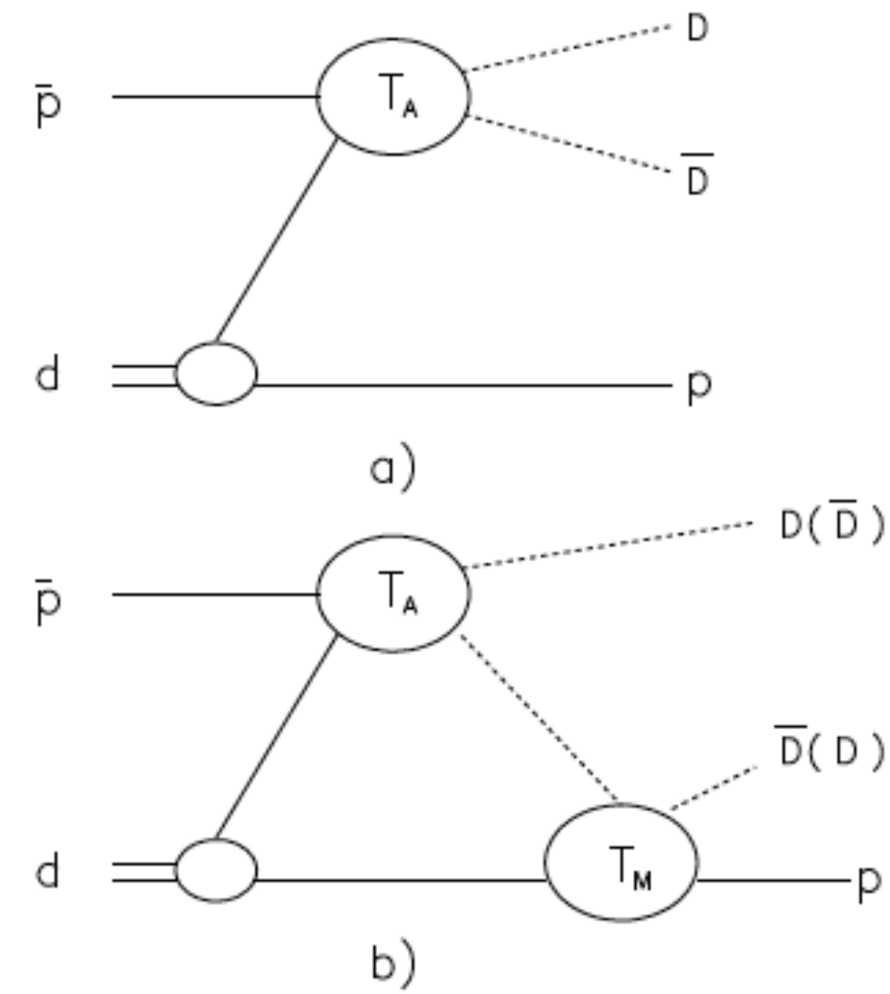
— DN interaction

P̄ANDA @ FAIR

DN Experiment

- antiproton annihilation on the deuteron*

P̄anda @ FAIR



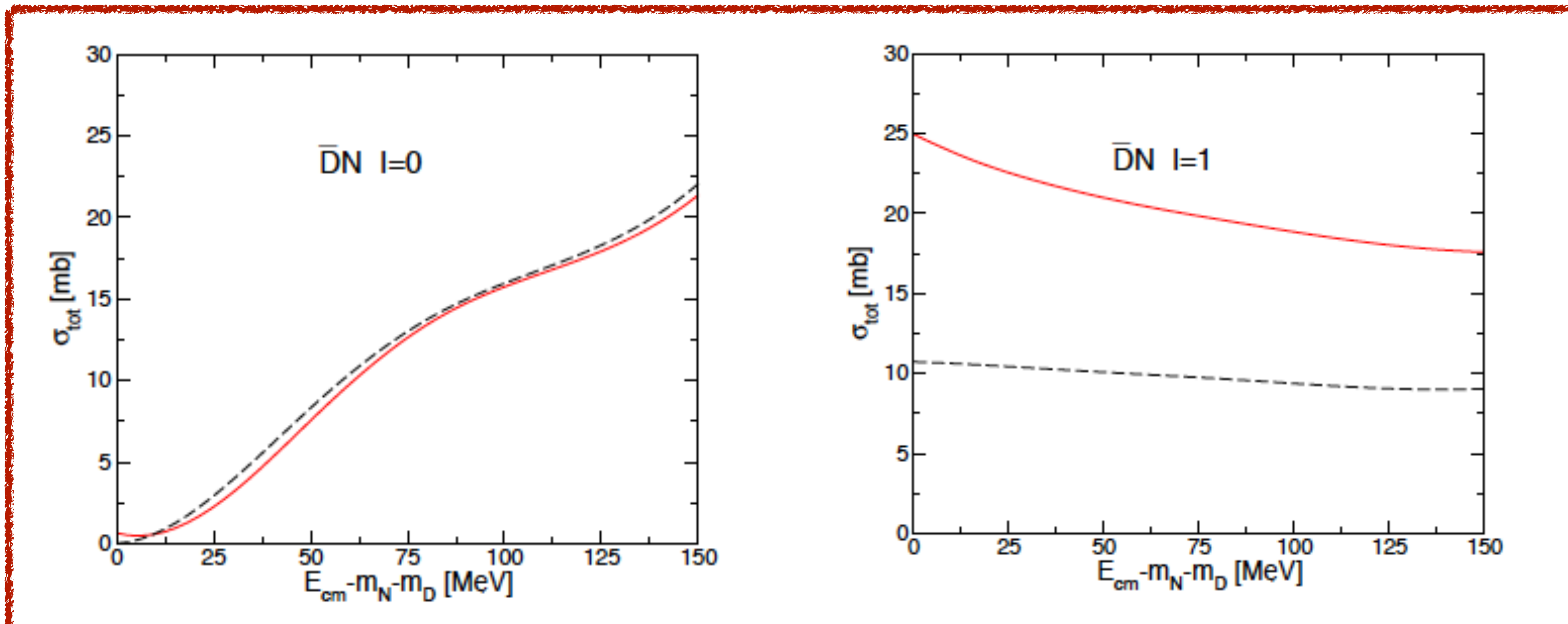
* J. Haidenbauer, GK, U.-G. Meissner, A. Sibirtsev

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

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

Predictions for the PANDA measurement

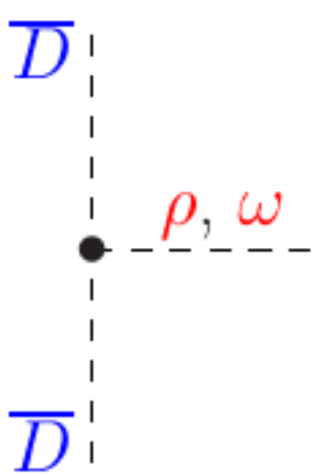
Use SU(4) symmetry for couplings:

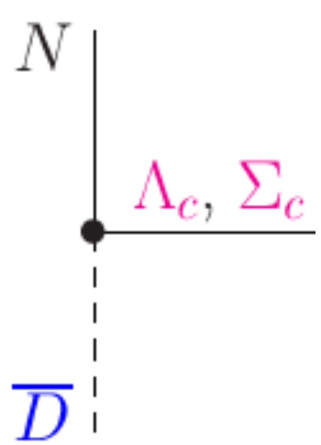


Similar magnitude to KN

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

$$m_u < m_s \ll m_c$$





SU(4) symmetry:

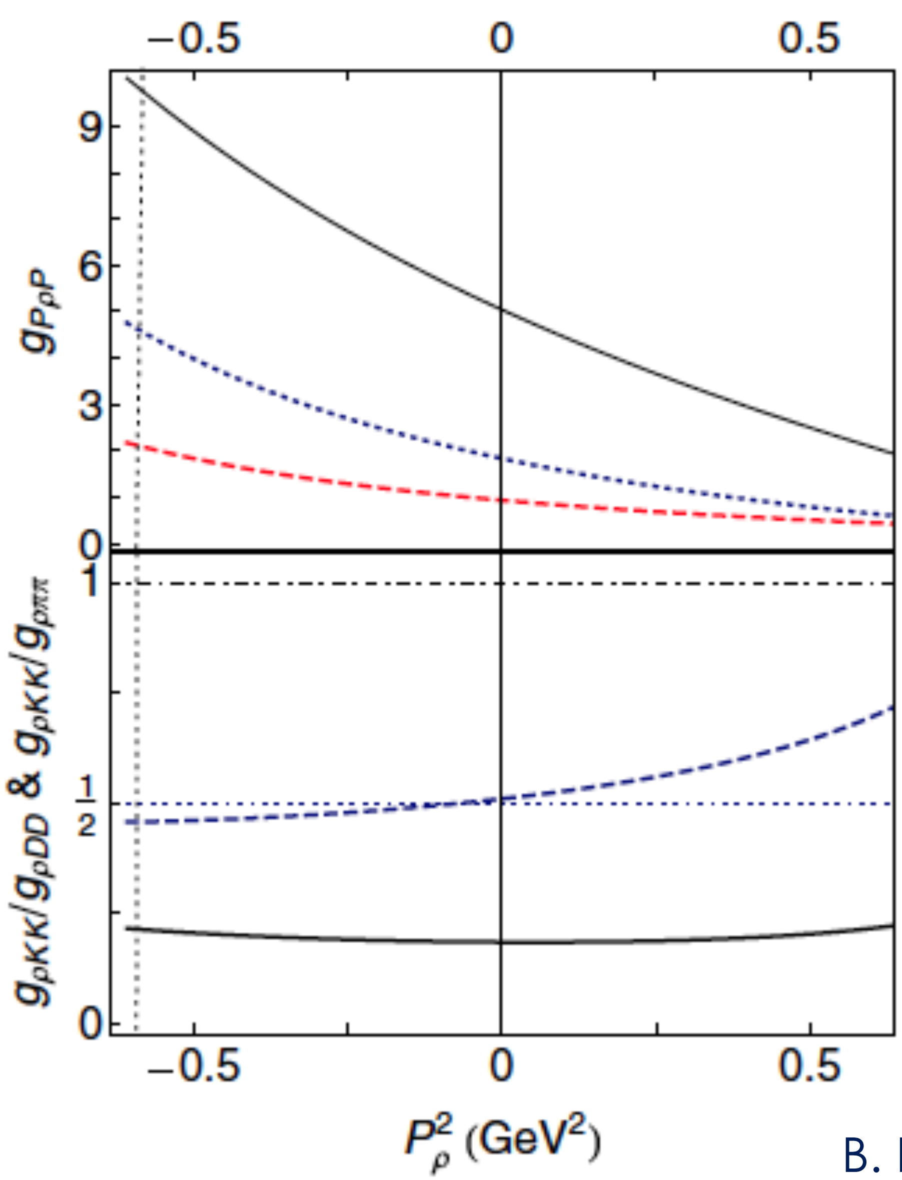
$$g_{\bar{D}\rho\bar{D}} = g_{K\rho K} = \frac{1}{2} g_{\pi\rho\pi}$$

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

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:

— 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 (2015)

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 (2015)

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%)
$g_{\rho D D^*} = \frac{\sqrt{6}}{2} g_{J/\psi D D^*}$	(12%)
$g_{\rho DD} = \frac{\sqrt{6}}{4} g_{J/\psi DD}$	(17%)
$g_{\pi D^* D^*} = \frac{\sqrt{6}}{2} g_{J/\psi D D^*}$	(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%)
$g_{\pi D^* D^*} = g_{\rho D D^*}$	(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%)

Lattice

Extrapolation to physical pion mass from

$$m_\pi : 700,\ 570,\ 410,\ 300\,\mathrm{MeV}$$

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

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

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

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

Chromopolarizability & color van der Waals forces

— an EFT perspective

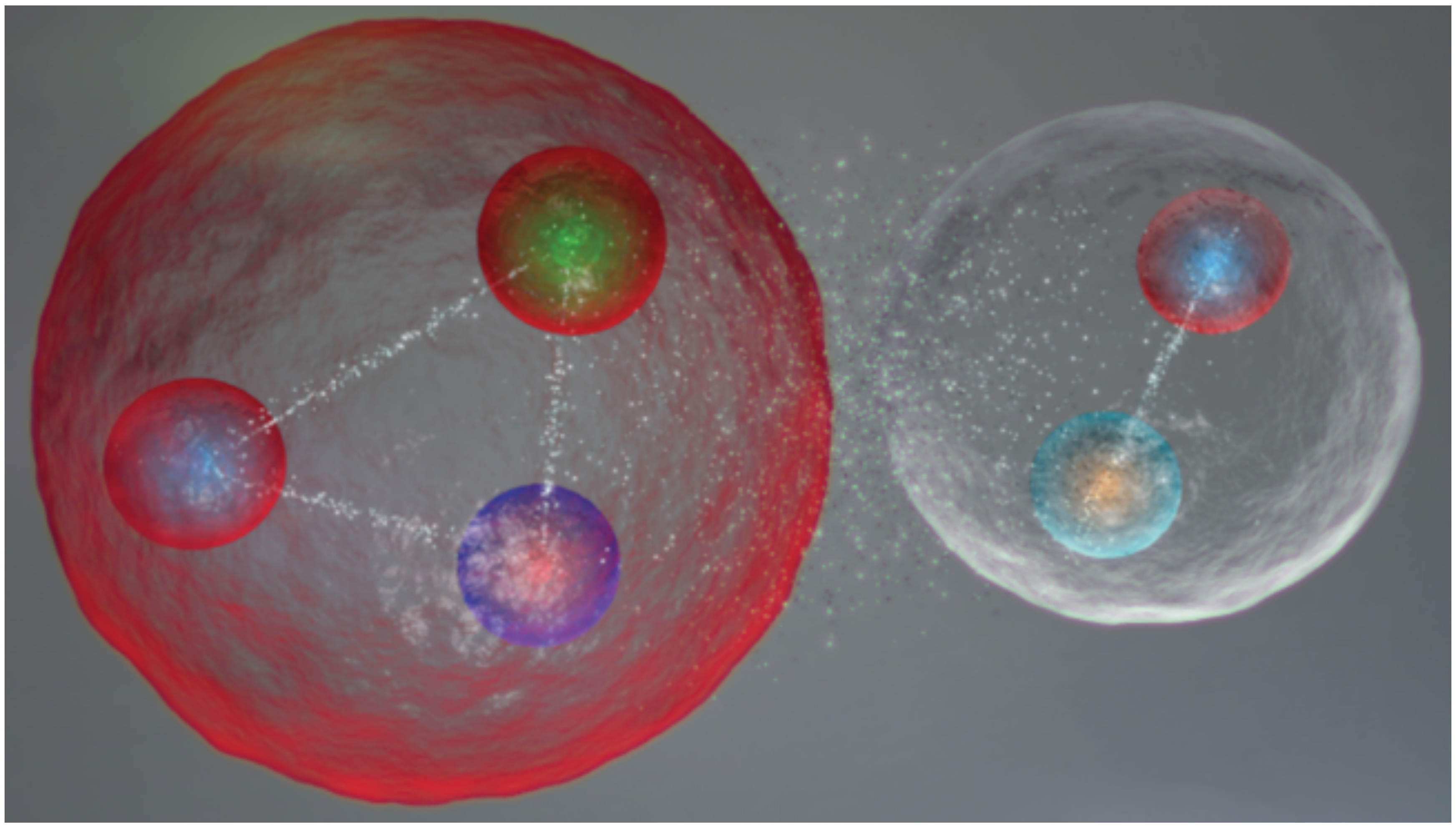
Interactions between color neutral objects:

Via creation of instantaneous color dipole moments & gluon transitions in virtual color-octet intermediate state

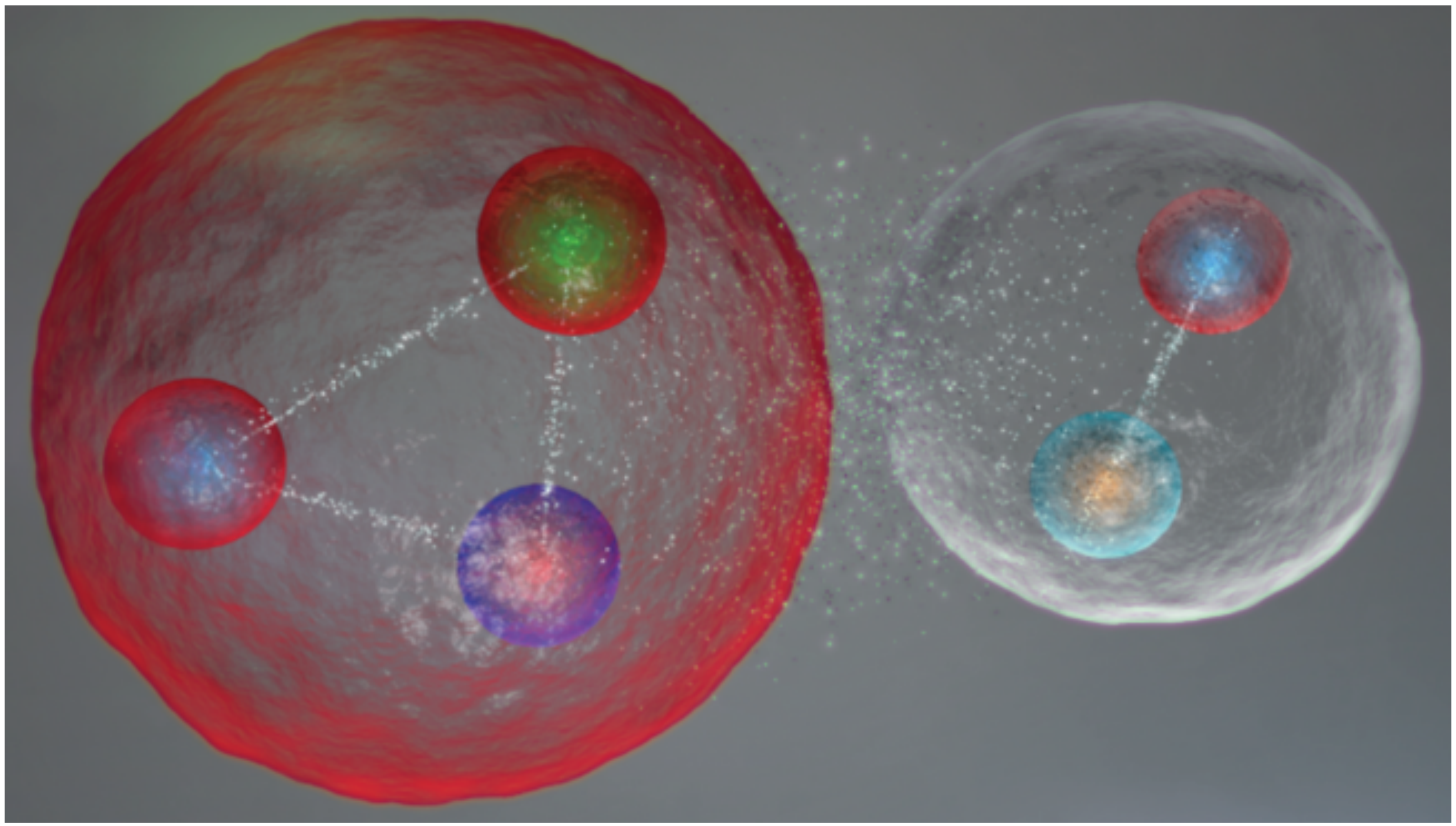
— Polarizability—

N. Brambilla, GK, J. Tarrús-Castellà, A. Vairo, arXiv:1510.05895

Would like to treat this

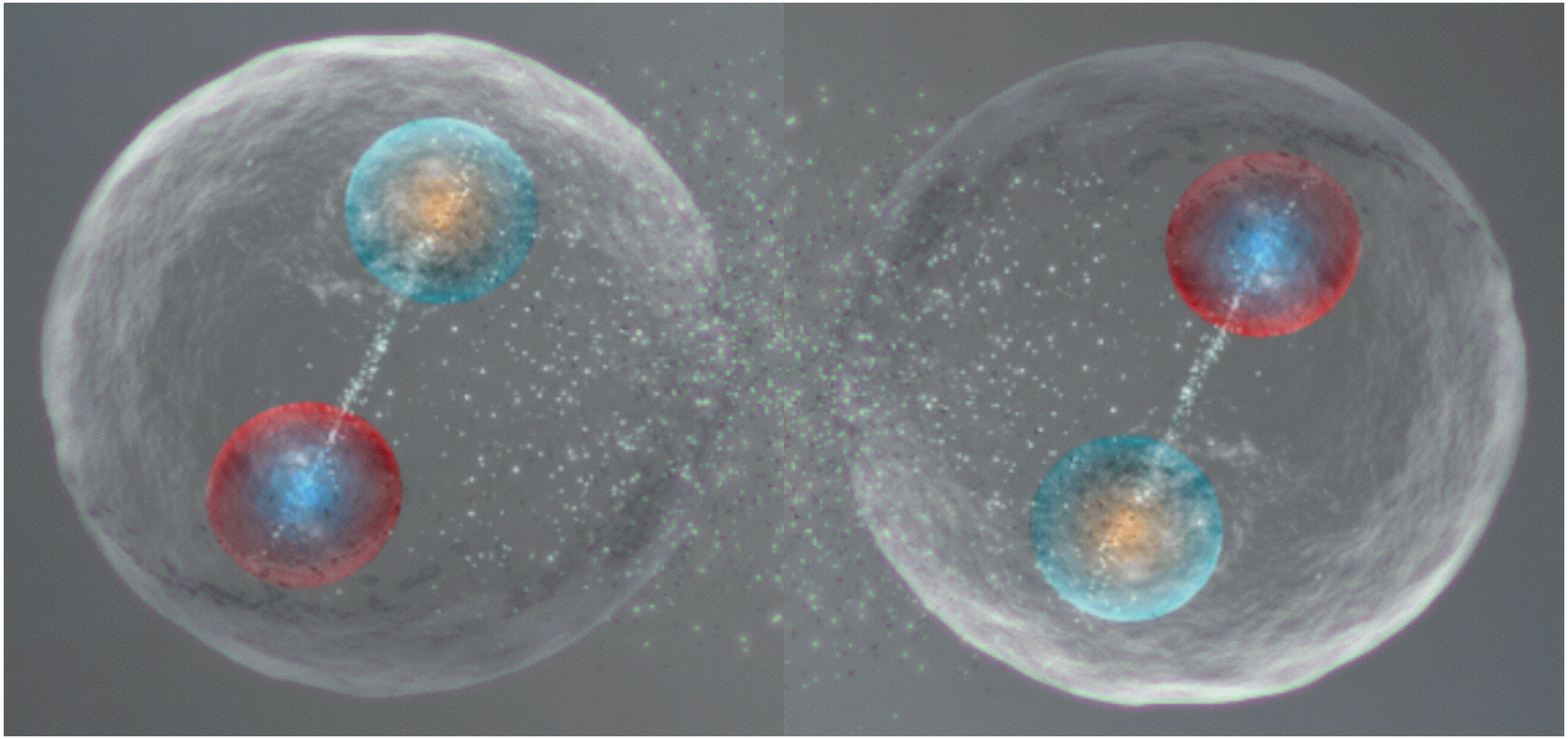


Would like to treat this



But will start with a simpler system …

$$\eta_b - \eta_b$$



EFT approch

— Chromopolarizability of 1S bottomonium;
use pNRQC (potential Nonrelativistic QCD)

— van der Waals force between two bottomonia;
use QCD trace anomaly to match pNRQC to a chiral EFT

QCD → NRQCD → pNRQCD

↓

gWEFT → χEFT → WEFT

Polarizability   van der Waals

Scales

m: bottom mass, v: relative velocity

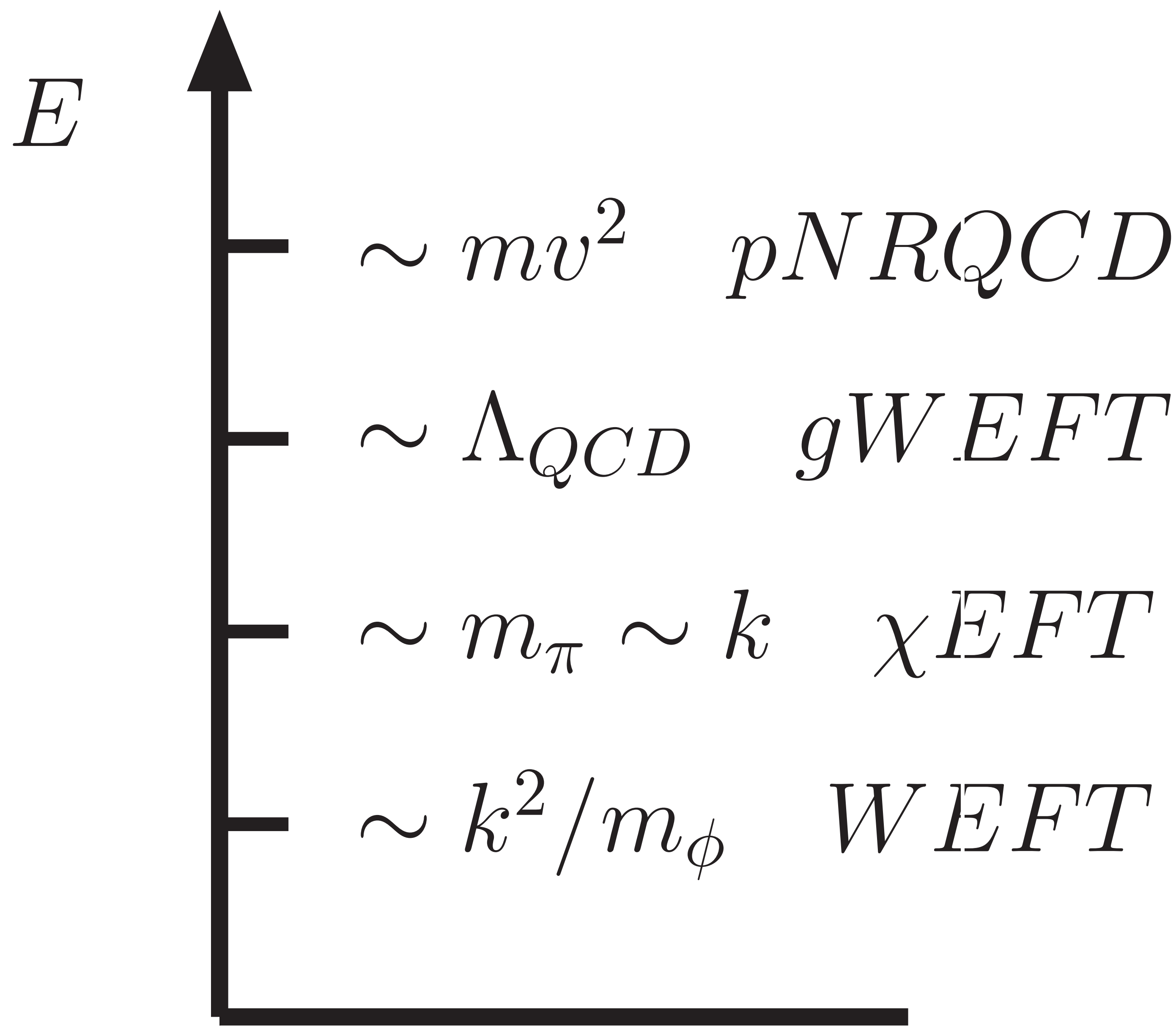
$$m \gg mv \gg mv^2 \gg \Lambda_{\rm QCD}$$

QCD $\longrightarrow$ NRQCD $\longrightarrow$ pNRQCD $\longrightarrow$ gWEFT

m_ϕ: mass bottomonium, $r_{\phi\phi} \sim 1/m_\pi$: relative distance

$$\mathbf{k}^2_{\phi\phi}/m_\phi = m_\pi^2/m_\phi \ll m_\pi$$

gWEFT $\longrightarrow$ EFT $\longrightarrow$ WEFT



Hierarchy of scales and the corresponding EFTs

pNRQCD

$$\mathcal{L}_{\rm pNRQCD} = \int d^3r \, {\rm Tr} \left[S^\dagger \left(i\partial_0 - h_s \right) S + O^\dagger \left(iD_0 - h_o \right) O \right]$$

$$+ g V_A(r) {\rm Tr} \left[O^\dagger \boldsymbol{r} \cdot \boldsymbol{E} S + S^\dagger \boldsymbol{r} \cdot \boldsymbol{E} O \right] + \frac{g}{2} V_B(r) {\rm Tr} \left[O^\dagger \boldsymbol{r} \cdot \boldsymbol{E} O + O^\dagger O \boldsymbol{r} \cdot \boldsymbol{E} \right]$$

$$+ \mathcal{L}_{\rm light}$$

$$h_s = -\frac{\boldsymbol{\nabla}_r^2}{m} - \frac{\boldsymbol{\nabla}_R^2}{4m} + V_s(r) \, ,$$

$$h_o = -\frac{\boldsymbol{\nabla}_r^2}{m} - \frac{\boldsymbol{D}_R^2}{4m} + V_o(r) \, ,$$

$$V_s(r) = -C_F \frac{\alpha_s(r)}{r} \, ,$$

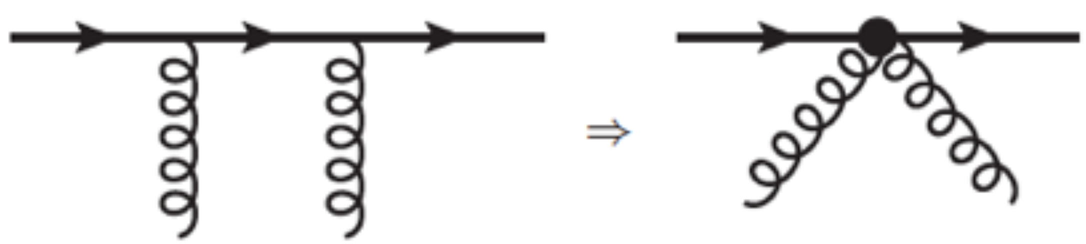
$$V_o(r) = \left(\frac{C_A}{2} - C_F \right) \frac{\alpha_s(r)}{r} \, ,$$

$$V_A(r) = 1 \, ,$$

$$V_B(r) = 1 \, ,$$

$C_A = N_c = 3$, $C_F = (N_c^2 - 1)/(2N_c)$ and $T_F = 1/2$

Chromopolarizability



pNRQCD $\longrightarrow$ gWEFT

$$L_{\mathrm{gWEFT}} = \int d^3\boldsymbol{R} \left\{ \phi^\dagger(t,\boldsymbol{R}) \left[i\partial_0 + E_\phi - \frac{\boldsymbol{\nabla}_{\boldsymbol{R}}^2}{4m} + \frac{1}{2}\beta g^2 \boldsymbol{E}_a^2 + \cdots \right] \phi(t,\boldsymbol{R}) \right\} + \mathcal{L}_{\mathrm{light}}$$

Chromopolarizability

$$\beta = -\frac{2V_A^2 T_F}{3N_c} \langle \phi | \boldsymbol{r} \frac{1}{E_\phi - h_o} \boldsymbol{r} | \phi \rangle$$

$$= -\frac{2V_A^2 T_F}{3N_c} \sum_l \int \frac{d^3p}{(2\pi)^3} |\langle \phi | \boldsymbol{r} | \boldsymbol{p}\, l \rangle|^2 \frac{1}{E_\phi - \frac{p^2}{4m}}$$

Wave functions

Bound-state

$$\langle \boldsymbol{r}|\phi\rangle = \frac{1}{\sqrt{\pi a_0^3}} e^{-r/a_0} \qquad a_0 = 1/(m\alpha_s)$$

Continuum octet*

$$\langle \boldsymbol{r}|\boldsymbol{p}\,1\rangle = e^{i(\pi/2-\delta_1)}\sqrt{2\pi}\boldsymbol{p}\cdot\boldsymbol{r}\sqrt{\frac{\rho\left(1+\frac{\rho^2}{a_0^2|\boldsymbol{p}|^2}\right)}{a_0|\boldsymbol{p}|\left(e^{\frac{2\pi\rho}{a_0|\boldsymbol{p}|}}-1\right)}}e^{i|\boldsymbol{p}||\boldsymbol{r}|}\,{}_1F_1\left(2+i\frac{\rho}{a_0|\boldsymbol{p}|};\,4;\,-2|\boldsymbol{p}||\boldsymbol{r}|\right)$$

$$\rho = (N_c^2-1)^{-1}$$

*N. Brambilla, M.A. Escobedo, J. Ghiglieri, A. Vairo JHEP 1112, 116 (2011)

Result
— sensitivity to bottom mass

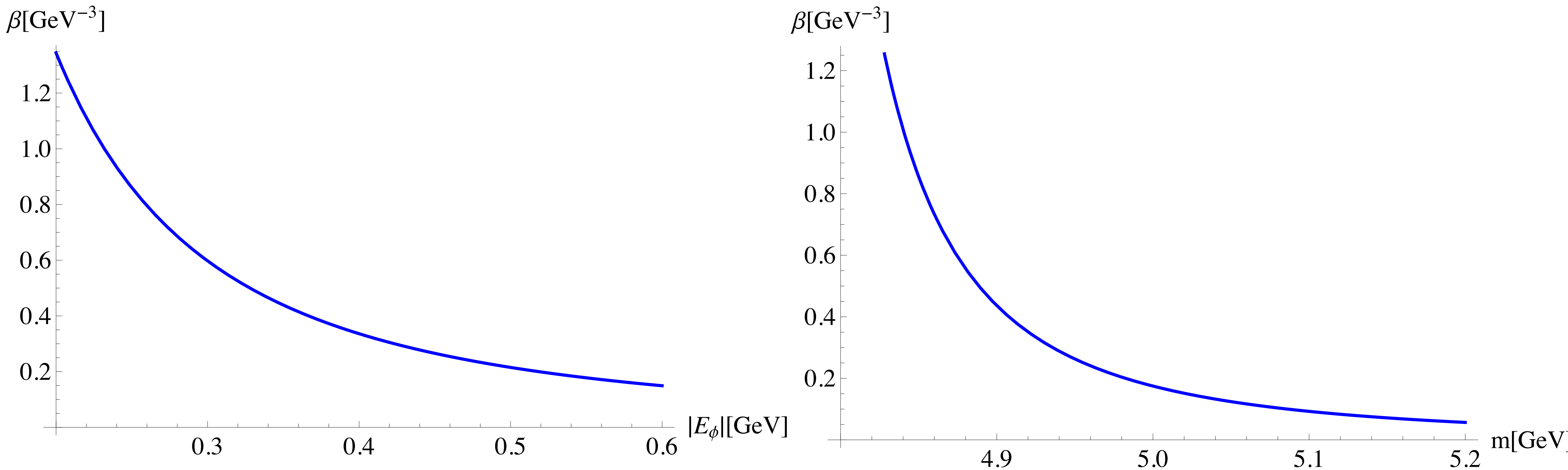


Figure 3. Plot of β from eq. (19). Left panel: plot as a function of the ϕ binding energy for $m = 5$ GeV. Right panel: plot as a function of the bottom mass fixing the binding energy as $E_\phi = m_\phi - 2m$.

Numerical results

$m = 5\ \mathrm{GeV}$ $m_\phi = 9.4454\ \mathrm{GeV}$ { average of η_b & $\Upsilon_b(1S)$

$$E_\phi = m_\phi - 2m = -0.555\,\mathrm{GeV}$$

$$\alpha_s = \sqrt{\frac{4|E_\phi|}{C_F^2 m}} \approx 0.5$$

$$\beta = 0.175\ \mathrm{GeV}^{-3}$$

$\Upsilon(2S) \to \Upsilon(1S)\pi\pi$

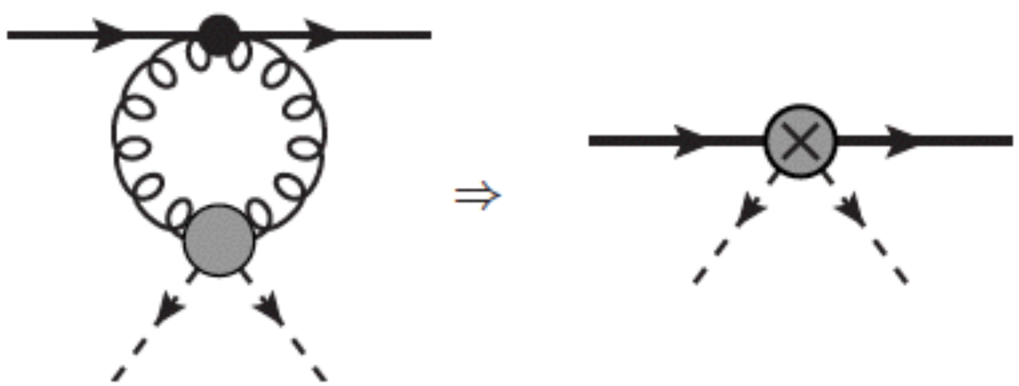
$\beta_{\Upsilon-\Upsilon'} = 0.66\ \mathrm{GeV}^{-3}$

M.B. Voloshin, Mod. Phys. Lett A 19, 665 (2004)

We can obtain this value if we use $m = 4.863\ \mathrm{GeV}$

van der Waals force

gWEFT ⟶ χEFT ⟶ WEFT



QCD trace anomaly

$$g^2\langle\pi^+(p_1)\pi^-(p_2)|E_a^2|0\rangle = \frac{8\pi^2}{3b}\left((p_1+p_2)^2\kappa_1 + m_\pi^2\kappa_2\right)$$

$$\kappa_1 = 1-9\kappa/4,\ \kappa_2 = 1-9\kappa/2$$

$$b = \frac{11}{3}N_c - \frac{2}{3}N_f$$

$$\kappa = 0.186 \pm 0.003 \pm 0.006 \longleftarrow \psi' \to J/\psi\pi^+\pi^-$$

Matching gWEFT $\longrightarrow$ χEFT

$$\mathcal{L}^{\phi}_{\chi\mathrm{EFT}} = \phi^\dagger \left(i\partial_0 - \frac{\boldsymbol{\nabla}^2}{2m_\phi} \right) \phi$$

$$U = e^{i\phi/F} = u^2 \,, \quad \phi = \begin{pmatrix} \pi^0 & \sqrt{2}\pi^+ \\ \sqrt{2}\pi^- & -\pi^0 \end{pmatrix}$$

$$\mathcal{L}^{\pi}_{\chi\mathrm{EFT}} = \frac{F^2}{4} \left(\langle \partial_\mu U \partial^\mu U^\dagger \rangle + \langle \chi^\dagger U + \chi U^\dagger \rangle \right)$$

$$\chi = 2B\hat{m}\mathbf{1} \qquad F = F_\pi = 92.419\,\mathrm{MeV}$$

$$\mathcal{L}^{\phi-\pi}_{\chi\mathrm{EFT}} = \phi^\dagger \phi \frac{F^2}{4} \left(c_{d0} \langle \partial_0 U \partial_0 U^\dagger \rangle + c_{di} \langle \partial_i U \partial^i U^\dagger \rangle + c_m \langle \chi^\dagger U + \chi U^\dagger \rangle \right)$$

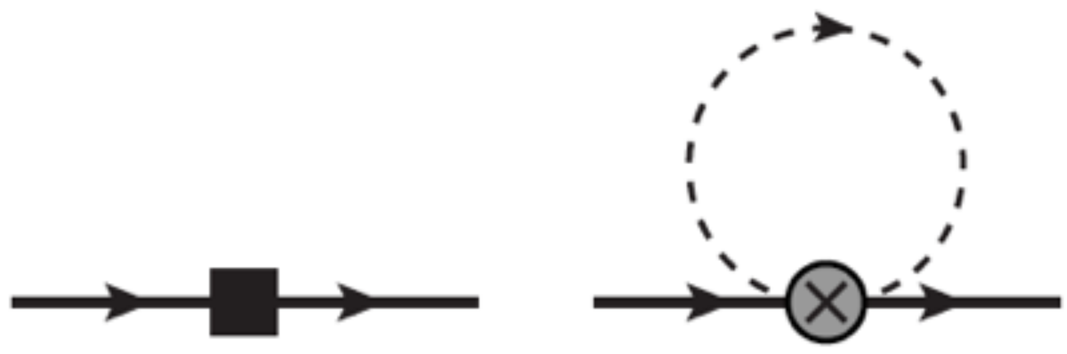
$$\mathcal{A} = \frac{4\pi^2\beta}{b} \left(\kappa_1 p_1^0 p_2^0 - \kappa_2 p_1^i p_2^i + 3m_\pi^2 \right)$$

$$\mathcal{A} = -c_{d0} p_1^0 p_2^0 + c_{di} p_1^i p_2^i - c_m m_\pi^2$$

$$c_{d0} = -\frac{4\pi^2\beta}{b}\kappa_1 \qquad c_{di} = -\frac{4\pi^2\beta}{b}\kappa_2 \qquad c_m = -\frac{12\pi^2\beta}{b}$$

Chiral correction bottomonium mass

— leading chiral log



$$\delta m_\phi\big|_{\rm chiral\,log} = -\frac{15}{8}\frac{\beta}{b} m_\pi^4 \log\frac{m_\pi^2}{\nu^2}$$

van der Waals force

$r_{\phi\phi} \sim 1/m_\pi$ $\qquad$ $\mathbf{k}^2_{\phi\phi}/m_\phi = m_\pi^2/m_\phi \ll m_\pi$

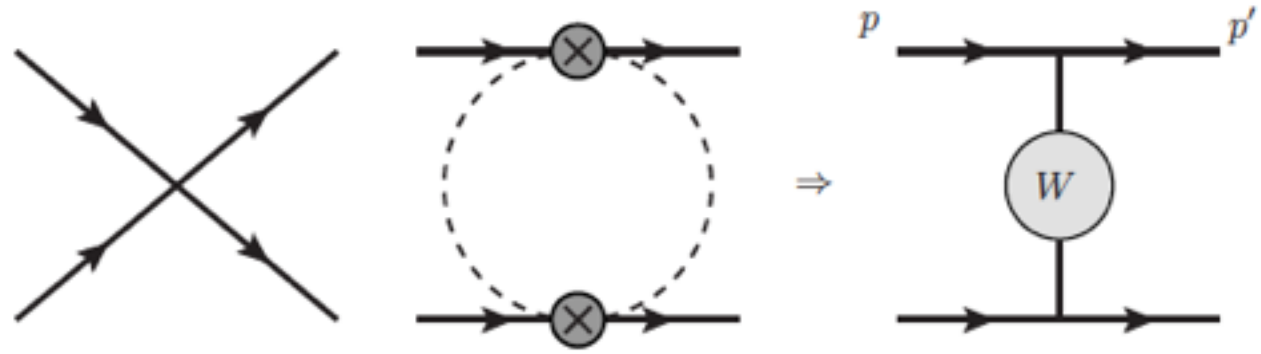
Relative motion at energies lower than pion mass

— integrate out the pion

χEFT $\longrightarrow$ WEFT

Matching

χEFT ⟶ WEFT



$$\mathcal{L}^{\phi}_{\mathrm{WEFT}} = \phi^\dagger \left(i\partial_0 - \frac{\boldsymbol{\nabla}^2}{2m_\phi} \right) \phi \,,$$

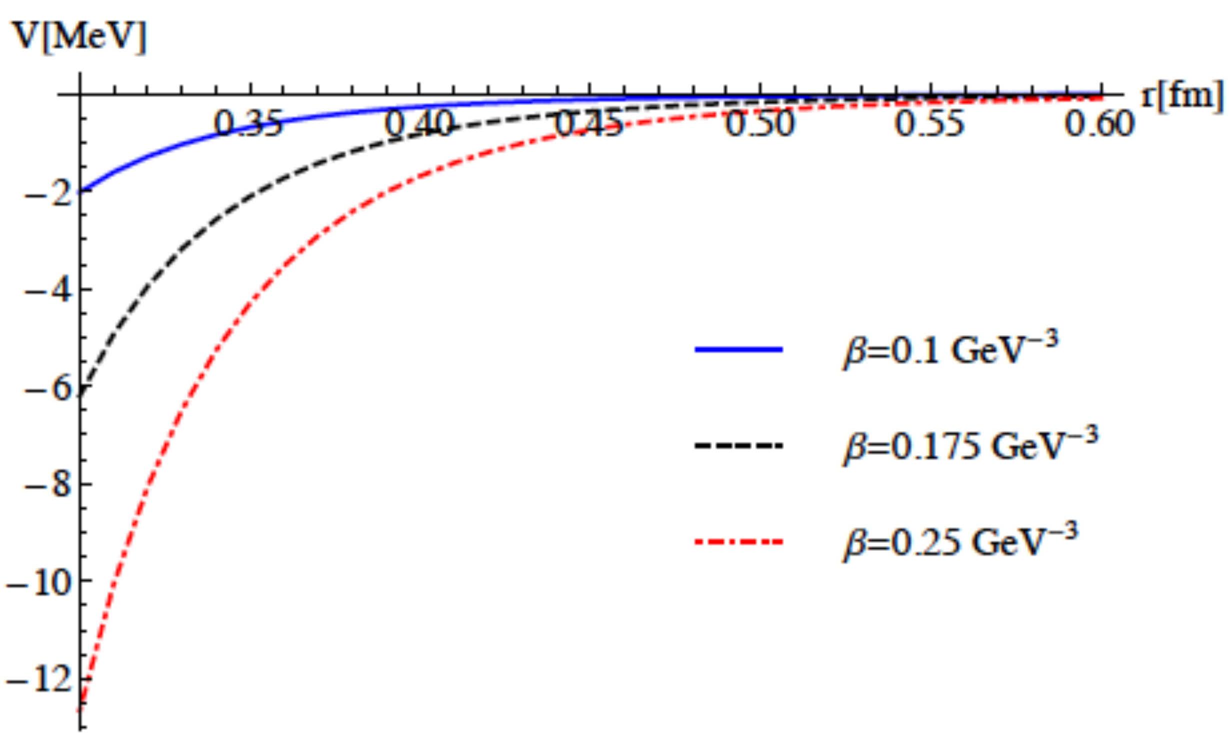
$$L^{\phi\phi}_{\mathrm{WEFT}} = -\int d^3\boldsymbol{R}_1 d^3\boldsymbol{R}_2\, \phi^\dagger\phi(t,\boldsymbol{R}_1)\, W(\boldsymbol{R}_1 - \boldsymbol{R}_2)\, \phi^\dagger\phi(t,\boldsymbol{R}_2)$$

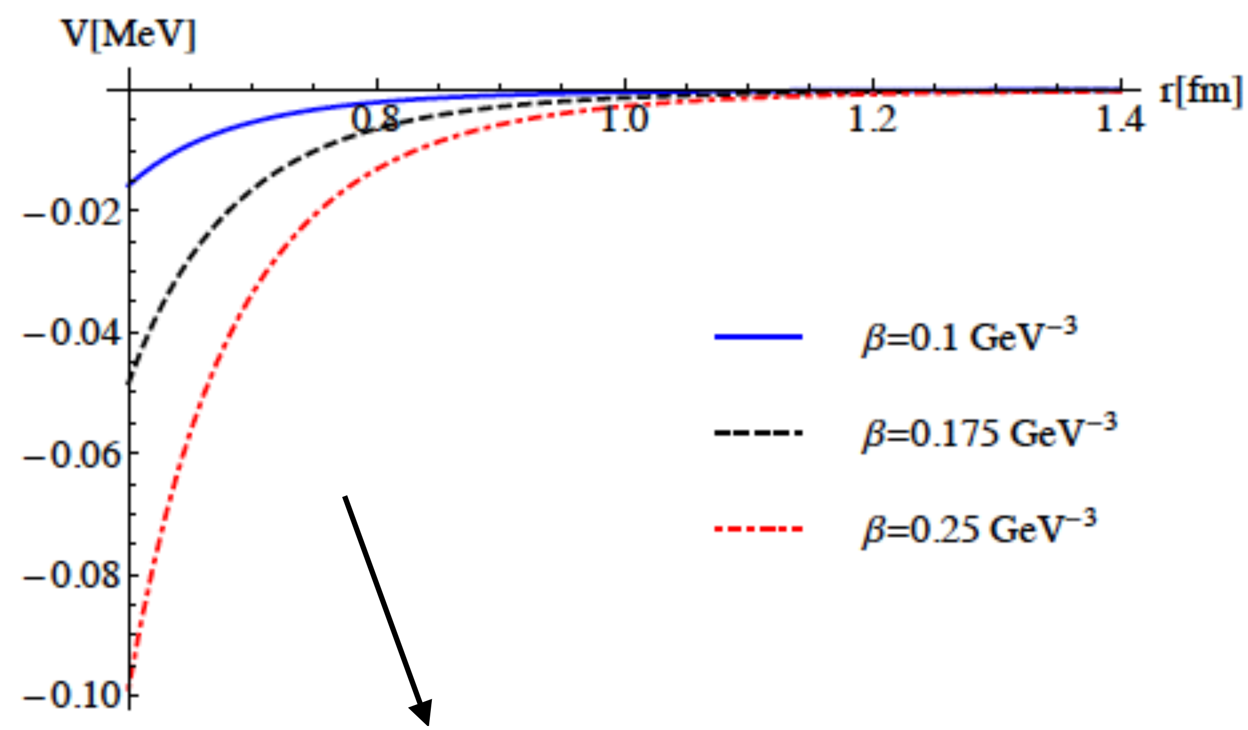
Long-range part:

$$W(r) = -\frac{3\pi\beta^2 m_\pi^2}{8b^2 r^5}\left[\left(4\left(\kappa_2+3\right)^2 \left(m_\pi r\right)^3 + \left(3\kappa_1^2 + 43\kappa_2^2 + 14\kappa_1\kappa_2\right) m_\pi r\right) K_1(2m_\pi r)\right.$$

$$\left. +2\left(2\left(\kappa_2+3\right)\left(\kappa_1+5\kappa_2\right)\left(m_\pi r\right)^2 + \left(3\kappa_1^2+43\kappa_2^2+14\kappa_1\kappa_2\right)\right) K_2(2m_\pi r)\right]$$

Numerical result





$$W(r) = -\frac{3(3+\kappa_2)^2\pi^{3/2}\beta^2}{4b^2}\frac{m_\pi^{9/2}}{r^{5/2}}e^{-2m_\pi r}$$

Possible bound state?

$$E_{\phi\phi} \sim 1\,\mathrm{MeV}$$

Perspectives

— EFT for molecules, Born-Oppenheimer

— Help from the lattice

— Need experiments, e.g. DN

Funding

FAPESP
SÃO PAULO RESEARCH FOUNDATION

BAYLAT

CNPq
Conselho Nacional de Desenvolvimento Científico e Tecnológico