ORIGIN OF THE MOST VISIBLE MATTER IN THE UNIVERSE

IFT - UNESP
INSTITUTO DE FÍSICA TEÓRICA - UNESP

Gastão Krein
Instituto de Física Teórica, São Paulo

SPRACE

1st Meeting of LIA - Subatomic Physics: from theory to applications

12-13 June 2018
Instituto Tecnologico de Aeronautica

This talk based on:

G.K., A.W. Thomas & K. Tsushima

— Prog. Part. Nucl. Phys. 100, 161 (2018)

N. Brambilla, G.K., J. Tarrús-Castellà & A. Vairo

— Phys. Rev. D 93, 054002 (2016)

J. Tarrús-Castellà & G.K.

— arXiv: 1803.05412

Motivation

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We want to understand matter that
amounts to 5% of the mass of the universe

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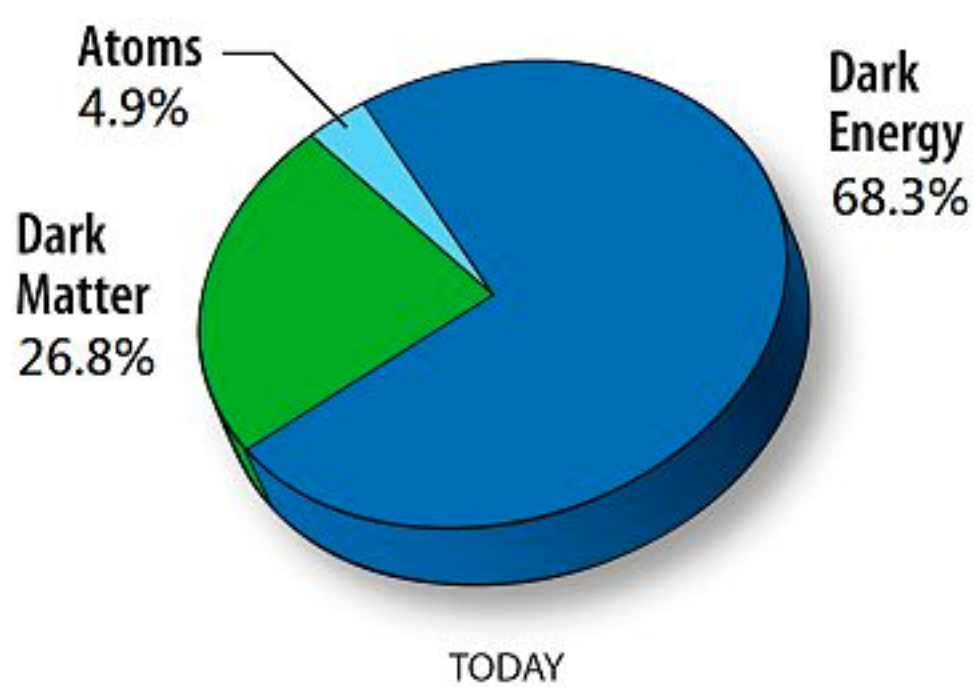

Actually we are even less ambitious than that

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We want to understand the proton mass

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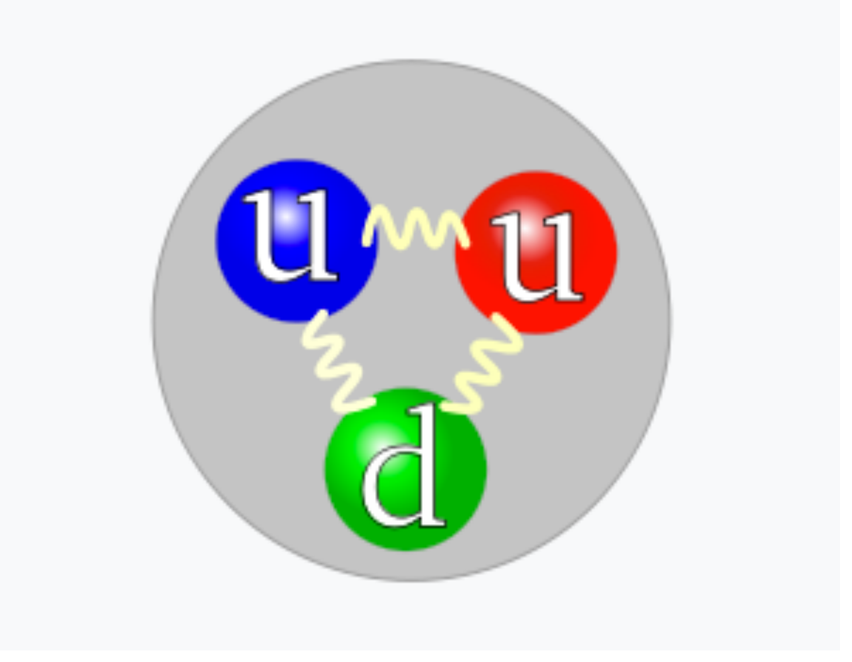


Starting point ?

Seems to be

Q C D

Quantum Chromodynamics

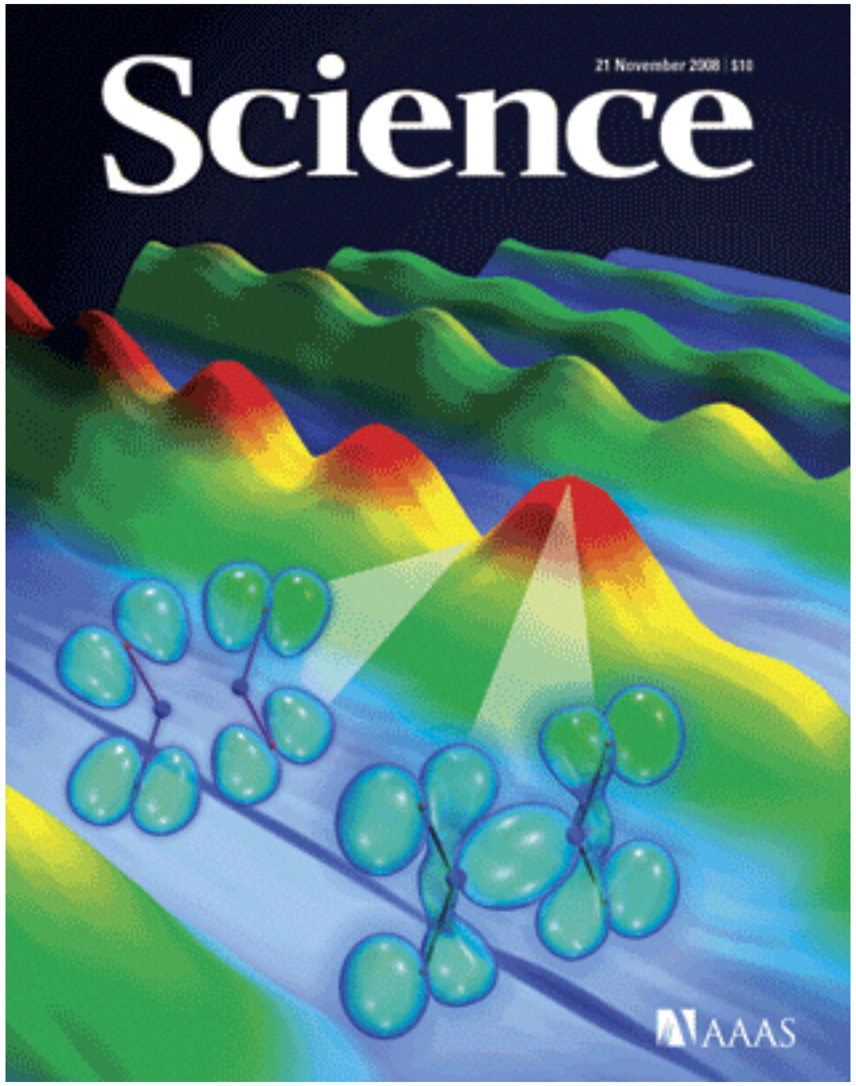
Science

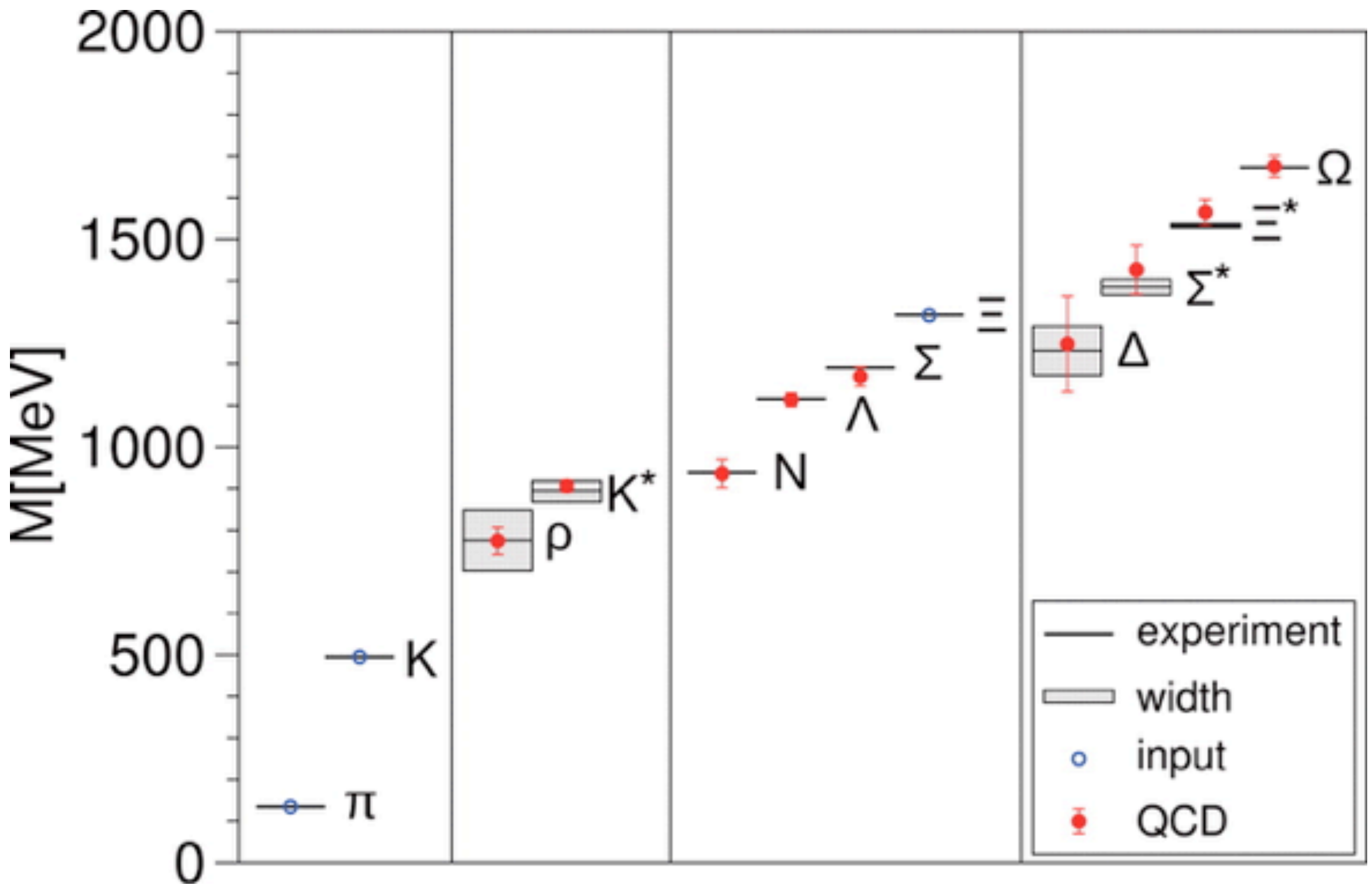
2008

Ab Initio Determination of Light Hadron Masses

S. Dürr, Z. Fodor, J. Frison, C. Hoelbling, R. Hoffmann, S. D. Katz, S. Krieg, T. Kurth, L. Lellouch, T. Lippert, K. K. Szabo and G. Vulvert

Science **322** (5905), 1224-1227.
DOI: 10.1126/science.1163233





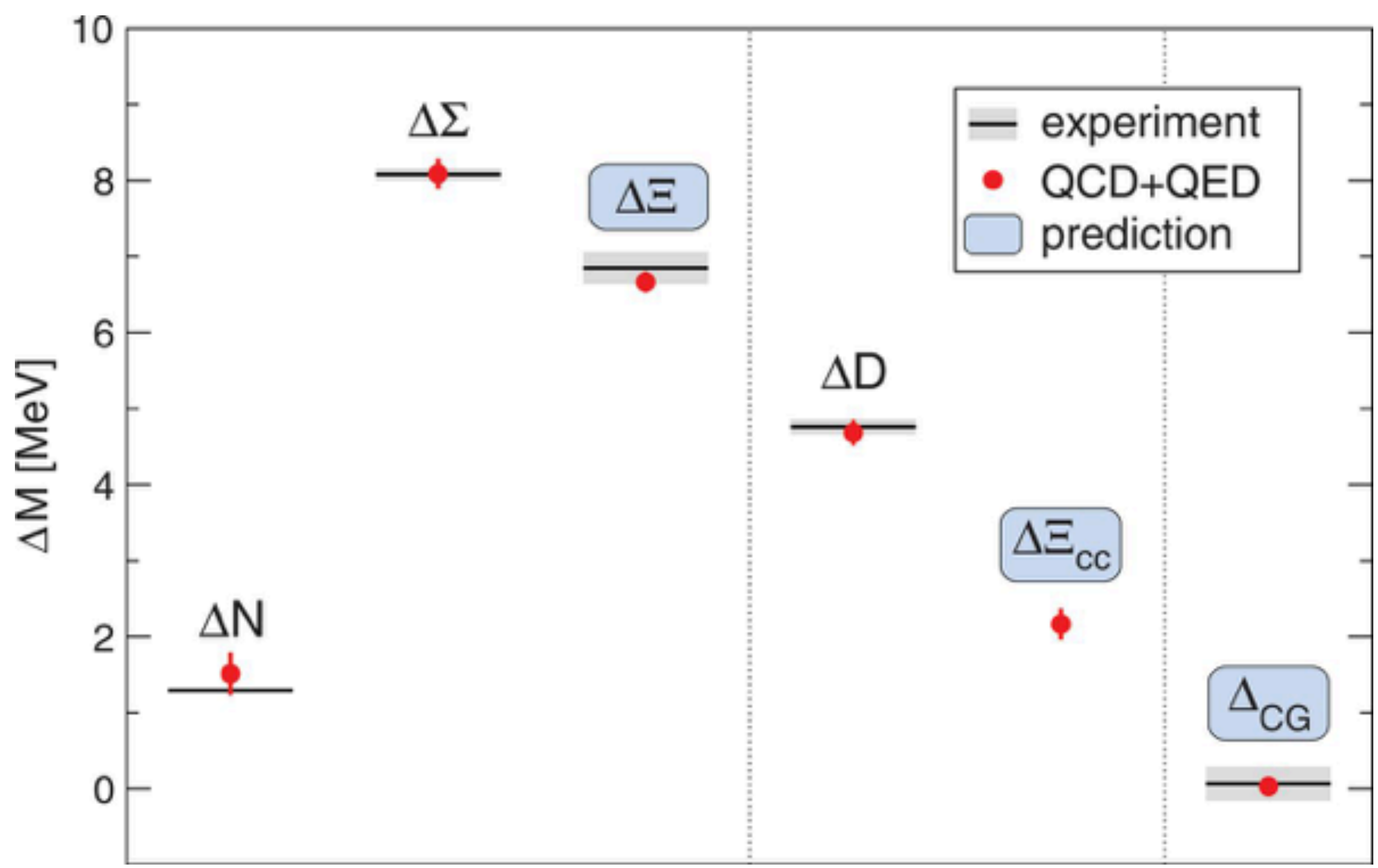
Science

2015

Ab initio calculation of the neutron-proton mass difference

Sz. Borsanyi, S. Durr, Z. Fodor, C. Hoelbling, S. D. Katz, S. Krieg, L. Lellouch, T. Lippert, A. Portelli, K. K. Szabo and B. C. Toth

Science **347** (6229), 1452-1455.
DOI: 10.1126/science.1257050



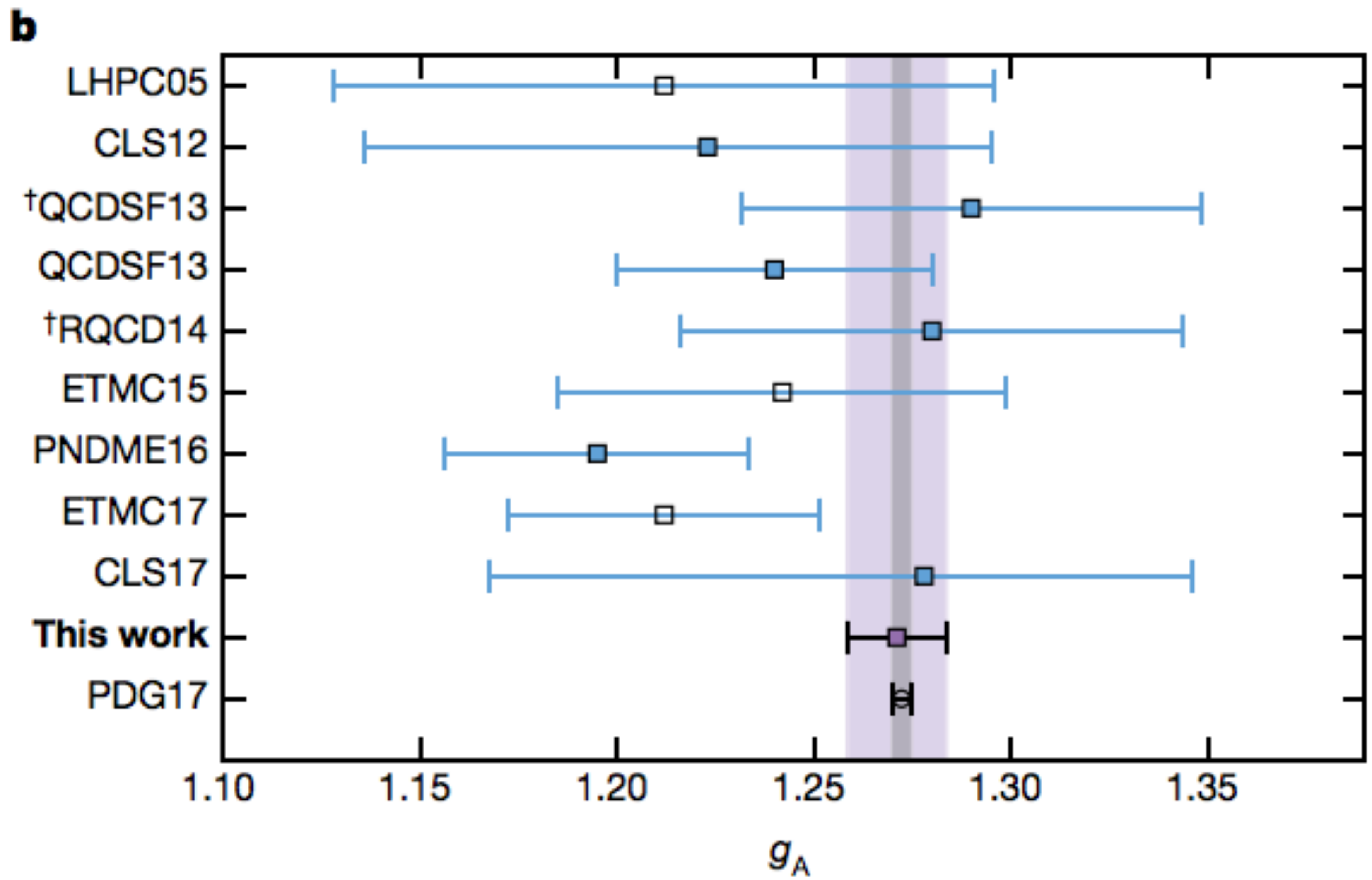
nature
International journal of science

2018

A per-cent-level determination of the nucleon axial coupling from quantum chromodynamics

C. C. Chang, A. N. Nicholson, E. Rinaldi, E. Berkowitz, N. Garron, D. A. Brantley, H. Monge-Camacho, C. J. Monahan, C. Bouchard, M. A. Clark, B. Joó, T. Kurth, K. Orginos, P. Vranas & A. Walker-Loud

Nature **558**, 91–94 (2018)



Computing from first principles!

Computation of the masses

$h(x):$ hadron interpolating field, e.g. $\pi^+(x) = \overline{u}(x)\gamma_5 d(x)$

$$\langle h(x)h(x+T)\rangle = \frac{\int \left[\mathcal{D}\psi\bar{\psi}A_\mu\right]\ h(x)h(x+T)\, e^{-\int d^4x\,\mathcal{L}_{\rm QCD}}}{\int \left[\mathcal{D}\psi\bar{\psi}A_\mu\right]\ e^{-\int d^4x\,\mathcal{L}_{\rm QCD}}}$$

$$\lim_{T\to\infty}\langle h(x)h(x+T)\rangle \sim e^{-M_h\,T}$$

Great, Impressive …

Great, Impressive …

BUT, how precisely those numbers

come out from

the QCD Lagrangian ?

Big questions

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— how precisely are masses generated from almost nothing?

— why are quarks and gluons not seen in isolation?

— dozens of new hadrons (X,Y,Z) have been discovered in the last 10 years. What they are?

Big questions

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Our ignorance is profound!

Trace anomaly

Take $m_q = 0$ & $m_Q = \infty$

$$x^\mu \to x'^\mu = \lambda\, x^\mu$$

$$q(x) \to q'(x) = \lambda^{3/2}\, q(\lambda x) \qquad A_\mu(x) \to A'_\mu(x) = \lambda\, A_\mu(\lambda x)$$

$$S'_{\rm QCD} = \int d^4x\, \lambda^4\, \mathcal{L}_{\rm QCD}(\lambda x) = \int d^4x'\, \mathcal{L}_{\rm QCD}(x') = S_{\rm QCD}$$

Classical action is invariant

Hadron masses

$|h\rangle$: hadron state $\qquad m_h = \langle h | T^\mu_\mu(x) | h \rangle$

From classical Lagrangian:

$$\frac{\delta S_{\mathrm{QCD}}}{\delta \lambda} = -\int d^4x \, T^\mu_\mu(x) = 0$$

$$\boxed{\langle h | T^\mu_\mu | h \rangle = m_h \to 0}$$

Quantum theory

$$g = g(\mu)$$

$$\delta S_{\rm QCD} = \delta \left(-\frac{1}{4\pi\alpha_s}\frac{1}{4}\int d^4x\, \overline{G}^a_{\mu\nu}(x)\overline{G}^{a\mu\nu}(x) \right) = -\frac{2\beta(\alpha_s)}{\alpha_s} S_{\rm QCD}\,\delta\lambda$$

$$T^\mu_\mu(x) = \frac{2\beta(\alpha_s)}{\alpha_s}\frac{1}{4} G^a_{\mu\nu}(x) G^{a\mu\nu}(x) = -\frac{1}{2} b_0 \alpha_s G^a_{\mu\nu}(x) G^{a\mu\nu}(x)$$

$$= -\frac{9}{32\pi^2} g^2 G^a_{\mu\nu}(x) G^{a\mu\nu}(x)$$

— this is the trace anomaly
— no scale invariance
— trace of $T^{\mu\nu}$ is nonzero

$$m_h = -\frac{9}{32\pi^2} \langle h | g^2 G^a_{\mu\nu} G^{a\mu\nu} | h \rangle$$

The entire mass comes from gluons

Contribution from quark masses

$$m_h = \frac{\beta(\alpha_s)}{2\alpha_s} G^a_{\mu\nu}(x) G^{a\mu\nu}(x) + \langle h|\overline{q}\, m_q\, q|h\rangle$$

small

Why is this interesting ?

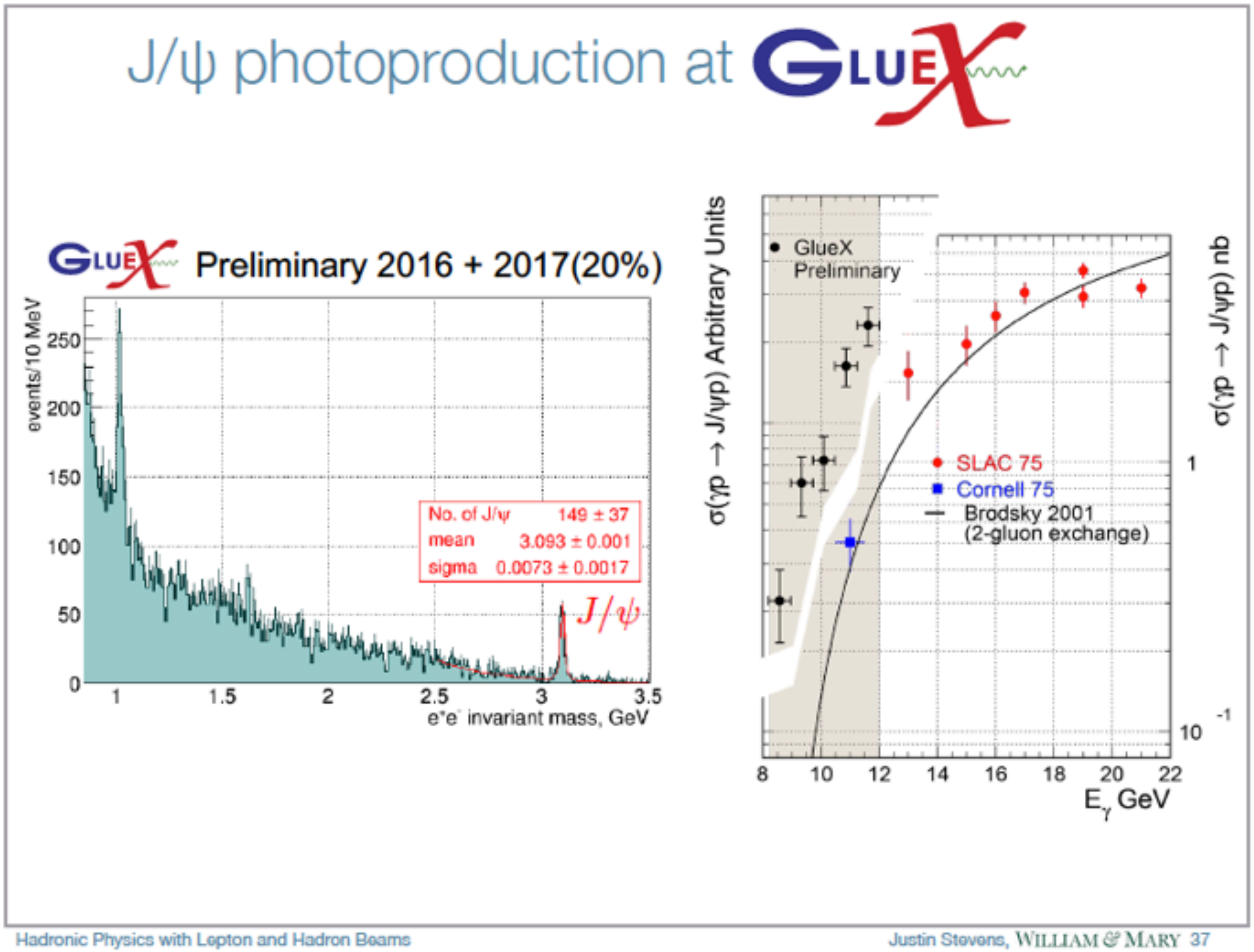
Because

$$\langle h|g^2 G^a_{\mu\nu} G^{a\mu\nu}|h\rangle$$

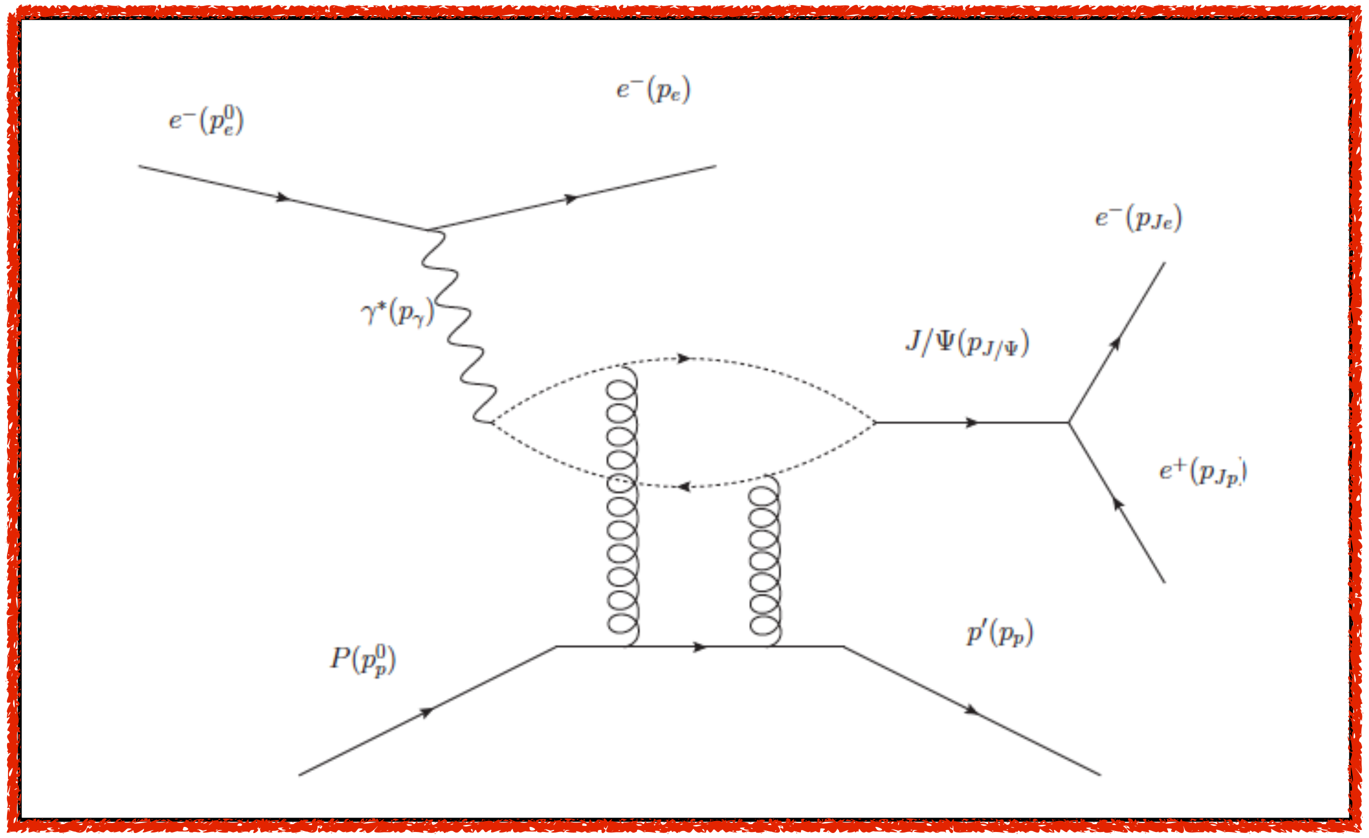
contributes to threshold
quarkonium-nucleon scattering

Experiments

— JLab



ATHENNA* collaboration JLab @ 12 GeV



Hall A — E12-12-006

K. Hafidi, Z.-E. Meziani, N. Sparveris, Z.W. Zhao

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

Hall C — E-12-16-007 (Pentaquarks)

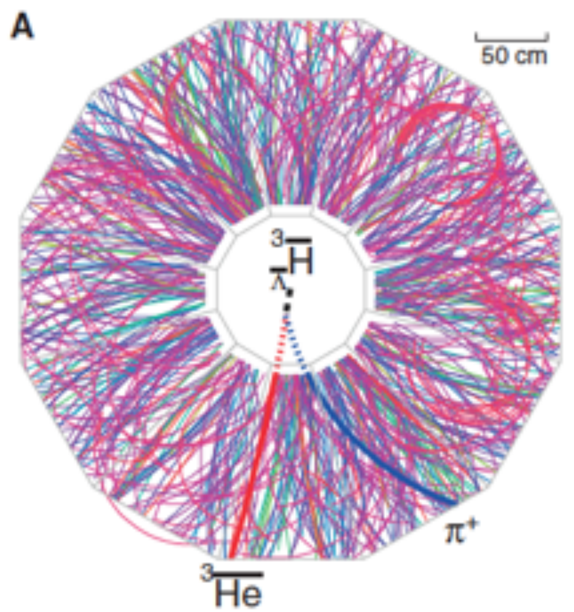
Z.-E. Meziani, S. Joosten, et al.

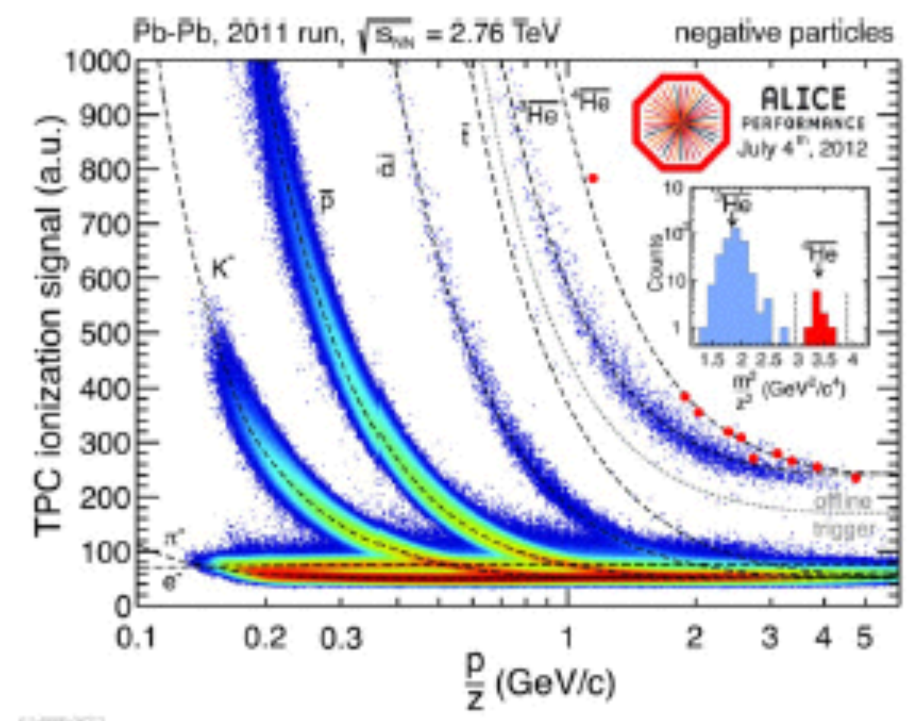
Coalescence at the LHC

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

Science AAAS

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

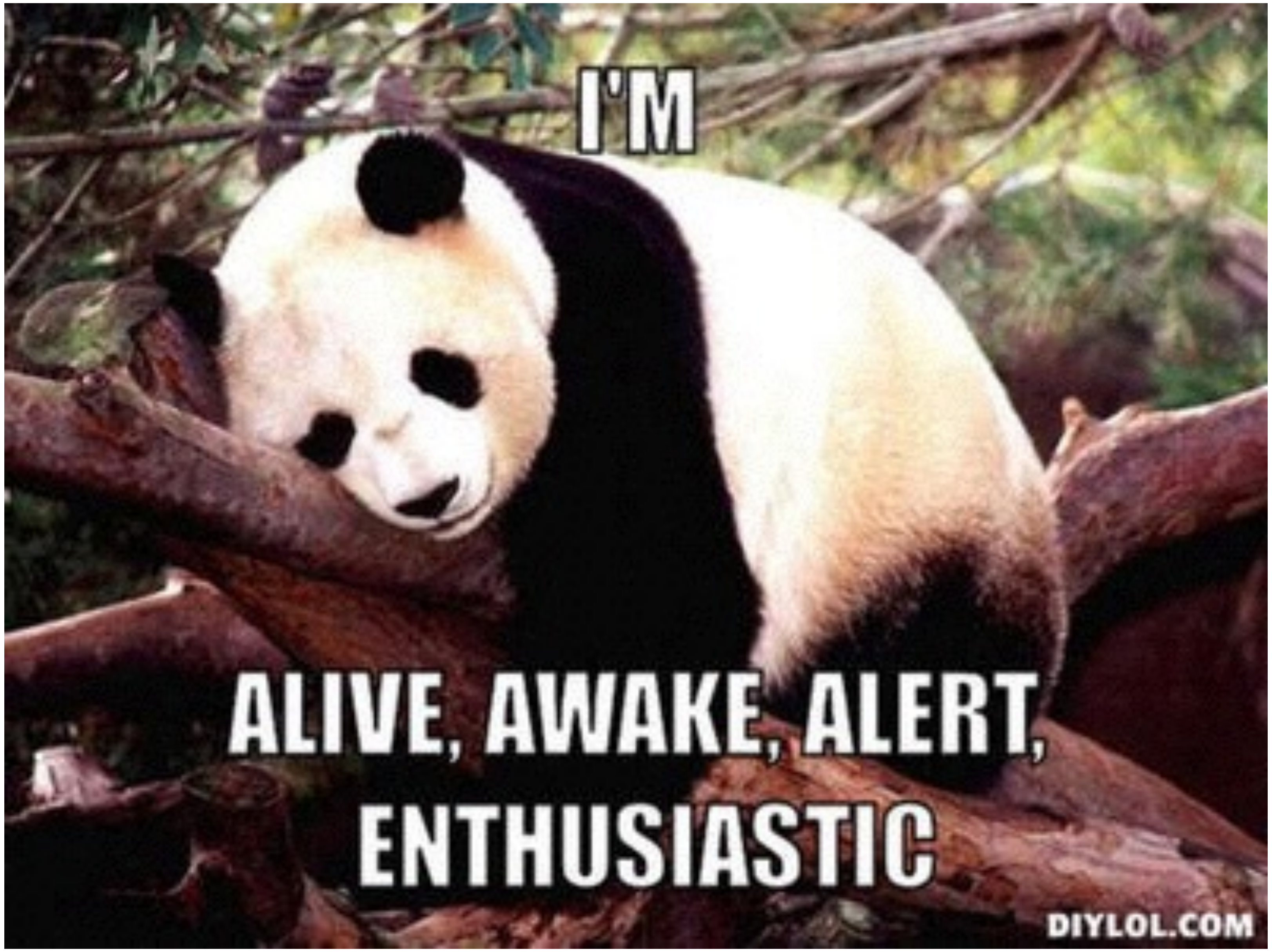




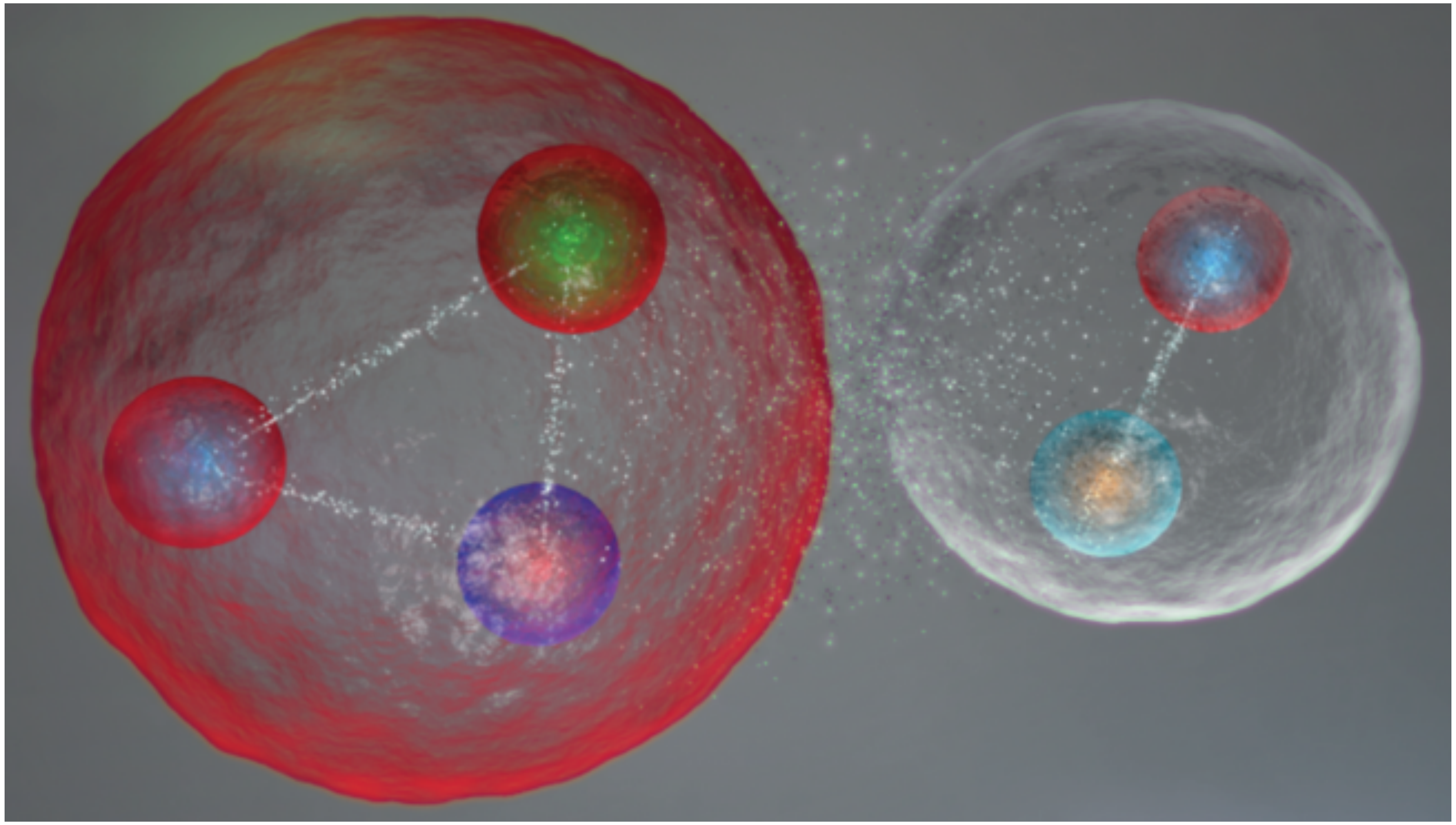
Need to detect in coincidence
the decay products

Experiments

P̄ANDA @ FAIR



Quarkonium-nucleon



Quarkonium: $\phi(s\bar{s}),\ \ \eta_c(c\bar{c}),\ \ J/\Psi(c\bar{c}),\ \ \eta_b(b\bar{b}),\ \ \Upsilon(b\bar{b})$

Quarkonium-nucleon scattering

$$\varphi = \phi(s\bar{s}), \quad \eta_c(c\bar{c}), \quad J/\Psi(c\bar{c}), \quad \eta_b(b\bar{b}), \quad \Upsilon(b\bar{b})$$

Forward amplitude

$$\mathcal{A}_{\varphi N} = \frac{1}{2}\alpha_\varphi \langle N| \left(g\vec{E}\right)^2 |N\rangle$$

α_φ : color polarizability

(property of the quarkonium)

$$\mathcal{A}_{\varphi N} = \frac{1}{2}\alpha_\varphi \langle N| \left(g\vec{E}\right)^2 |N\rangle$$

Measure scattering length:

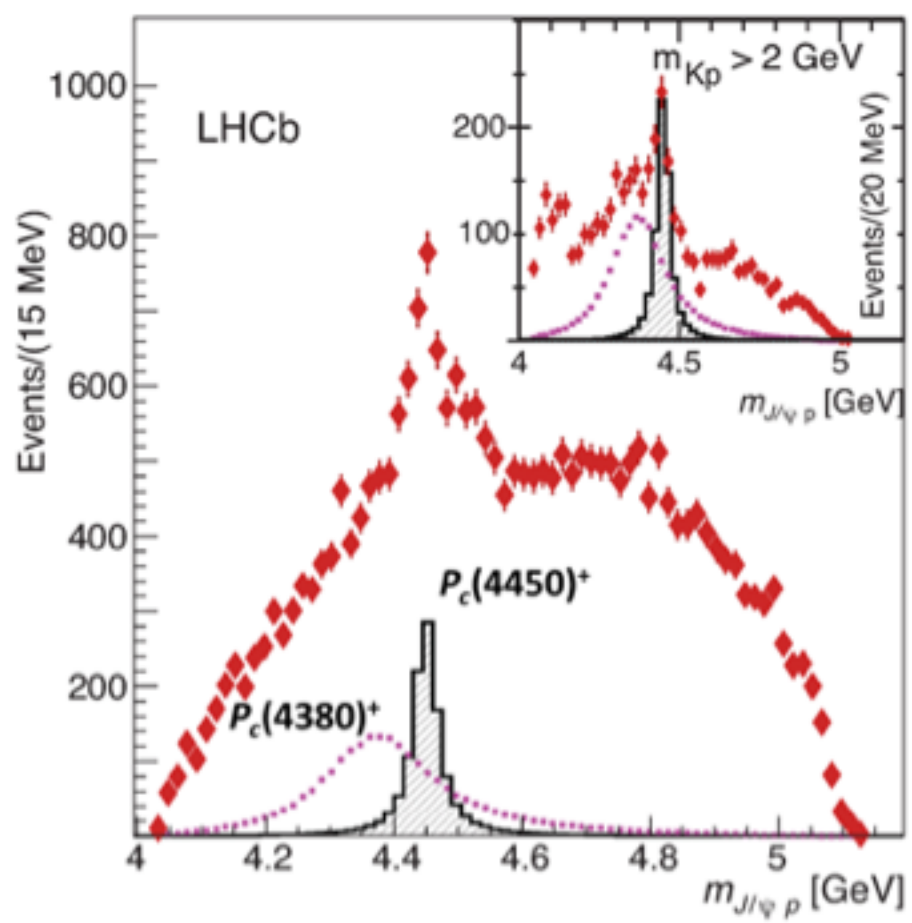
$$a_{\varphi N} = -\left(\frac{\mu_{\varphi N}}{2\pi}\right) \mathcal{A}_{\varphi N} = -\left(\frac{\mu_{\varphi N}}{4\pi}\right) \alpha_\varphi \langle N| \left(g\vec{E}\right)^2 |N\rangle$$

Bound from trace anomaly:

$$\langle N| \left[\left(g\vec{E}\right)^2 - \left(g\vec{B}\right)^2\right] |N\rangle = -\frac{1}{2}\langle N|g^2 G^a_{\mu\nu} G^{a\mu\nu}|N\rangle = \frac{16\pi^2}{9} m_N \leq \langle N| \left(g\vec{E}\right)^2 |N\rangle$$

$$a_{\varphi N} \leq -\left(\frac{\mu_{\varphi N}}{4\pi}\right) \frac{16\pi^2}{9} m_N \alpha_\varphi = -\frac{4\pi m_N}{9} \mu_{\varphi N} \alpha_\varphi$$

Renewed interest in quarkonium-nucleon



Quarkonium in nuclei:

— scattering amplitude is enhanced

— formation of a new exotic nuclear state

— adds a new flavor axis in the
nuclear e.o.s.

Scales in nuclei

$\rho \sim \rho_0 = 0.16\ \mathrm{fm}^{-3}$ baryon density (center nucleus)

$d_{\mathrm{av}} \sim \rho^{-1/3} \sim 1.8\ \mathrm{fm}$ internucleon distance

$\langle T_{\mathrm{N}} \rangle \sim \frac{3}{5}\frac{k_F^2}{2m_N} \sim 20\,\mathrm{MeV} \ll \Lambda_{\mathrm{QCD}}$ nucleon kinetic energy

<u>Recall that:</u>

$r_{\mathrm{N}} \sim \sqrt{\langle r_{\mathrm{ch}}^2 \rangle} \simeq 0.88\ \mathrm{fm} \sim \Lambda_{\mathrm{QCD}}^{-1}$ nucleon (charge) radius in free space

$r_{\mathrm{NN}}^{\mathrm{hard-core}} \sim 0.2\,\mathrm{fm}$ hard-core NN force

Scales in nuclei

$d_{\rm av} \sim 2\, r_{\rm N}$ + hard-core NN force

⇩

Little (or no) superposition of nucleons in nuclei

+ Pauli principle (among nucleons) ⇨

— Independent-particle model
— Mean-field model
— Nuclear shell model

Gomes, Walecka & Weisskopf

Low-momentum quarkonium in a nucleus

— Quarkonium interacts with light quarks in nucleons by exchanging gluons with wavelengths

$$\lambda \sim r_N$$

— Size of quarkonium

$$r_{J/\Psi} \sim 0.35\,\mathrm{fm}$$

$$\lambda \geq 2\, r_{J/\Psi}$$ ⇒ Quarkonium behaves as a small color dipole immersed in a uniform gluon field

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Embbeding quakonium-nucleon into a Nonrelativistic nuclear many-body problem

$$H = H_N + H_{\varphi N}$$

$$H_{\varphi N} = \int d^3r\, \varphi^\dagger(t,\vec{r}) \left(-\frac{1}{2m_\varphi}\nabla^2\right) \varphi(t,\vec{r})$$

$$+ \int d^3r d^3r'\, N^\dagger(t,\vec{r})\varphi^\dagger(t,\vec{r}\,')\, W_{\varphi N}(\vec{r}-\vec{r}\,')\, \varphi(t,\vec{r}\,') N(t,\vec{r})$$

↑

quarkonium-nucleon

G.K., A.W. Thomas & K.Tsushima, PPNP 100, 161 (2018)

Hartree-Fock equation
— for quarkonium in a nucleus

$$-\frac{1}{2m_\varphi}\nabla^2\varphi_\alpha(\vec{r}) + W_{\varphi A}(\vec{r})\varphi_\alpha(\vec{r}) = \epsilon_\alpha\varphi_\alpha(\vec{r})$$

$$W_{\varphi A}(\vec{r}) = \int d^3r'\, W_{\varphi N}(\vec{r}-\vec{r}')\,\rho_A(\vec{r}')$$

quarkonium-nucleus potential

$$\rho_A(\vec{r}) = \langle A|N^\dagger(\vec{r})N(\vec{r})|A\rangle = \sum_{n=1}^{A} N_n^*(\vec{r})N_n(\vec{r})$$

nuclear density functional

Neglecting back reaction of quarkonium on nucleons, take density from a model or experiment

Need quarkonium-nucleon potential

$$W_{\varphi A}(\vec{r}) = \int d^3r'\, W_{\varphi N}(\vec{r} - \vec{r}')\, \rho_A(\vec{r}')$$

From the forward amplitude:

$$W^{\rm pol}_{\varphi N}(\vec{r}) = \frac{4\pi}{2\mu_{\varphi N}}\, a_{\varphi N}\, \delta(\vec{r}) = -\frac{8\pi^2}{9} m_N \alpha_\varphi\, \delta(\vec{r})$$

$$W^{\rm pol}_{\varphi A}(\vec{r}) = \frac{4\pi}{2\mu_{\varphi N}}\, a_{\varphi N}\, \rho_A(\vec{r}) = -\frac{8\pi^2}{9} m_N \alpha_\varphi\, \rho_A(\vec{r})$$

$$k\ \mathrm{cotan}\,\delta(k) = -\frac{1}{a} + \frac{1}{2} r_e k^2 + \cdots$$

J/Ψ in nuclei

— nuclear potentials

Nuclear density from QMC model:
P.A.M. Guichon et al.

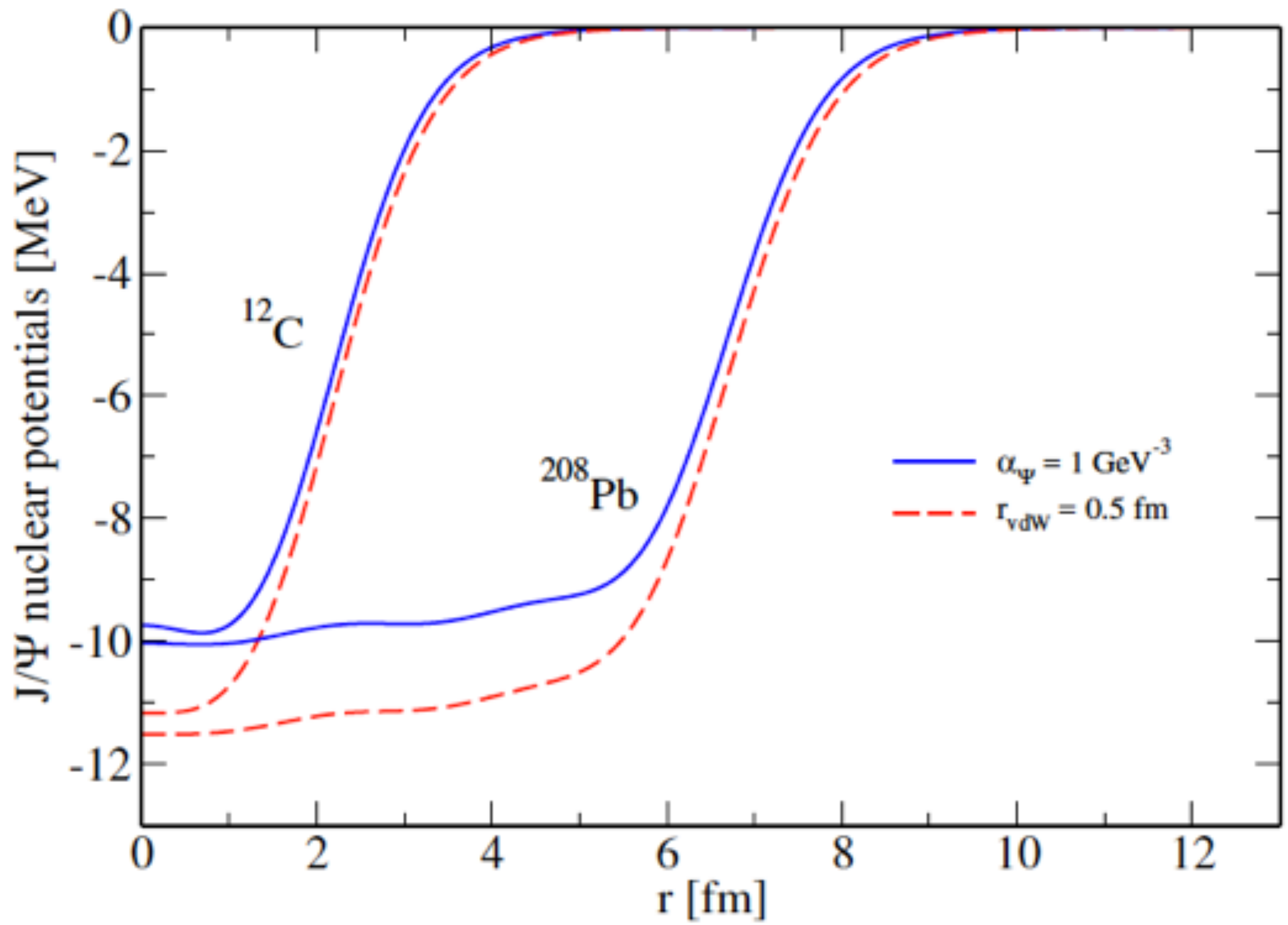


Figure 8: J/Ψ nuclear potentials $W^{\text{pol}}_{J/\Psi A}(\vec{r})$ (solid line) for a polarizability $\alpha_{J/\Psi} = 1\ \text{GeV}^{-3}$ and $W^{\text{latt}}_{J/\Psi A}(\vec{r})$ (dashed line) from a fit to the lattice data with a cutoff $r_{\text{vdW}} = 0.5$ fm.

Quarkonium in nuclei

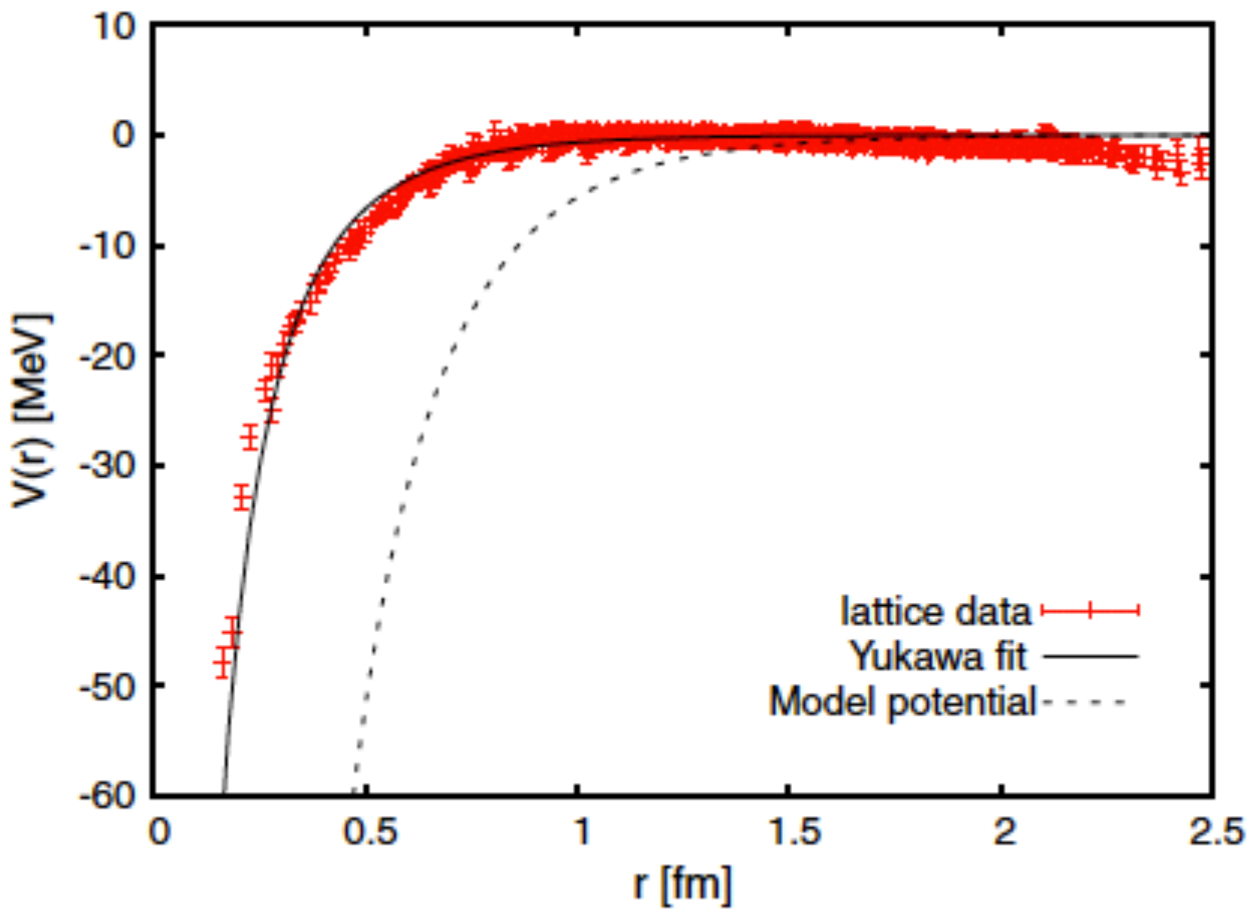
— use scattering length only

Table 7: Predictions for J/Ψ single-particle energies in several nuclei obtained with the polarization potential $W^{\rm pol}_{J/\Psi A}(\vec{r})$, defined in Eq. (105).

	${}^{4}_{J/\Psi}$He	${}^{12}_{J/\Psi}$C	${}^{16}_{J/\Psi}$O	${}^{40}_{J/\Psi}$Ca	${}^{48}_{J/\Psi}$Ca	${}^{90}_{J/\Psi}$Zr	${}^{208}_{J/\Psi}$Pb
			$\alpha_{J/\Psi} = 1$ GeV^{-3} $\leftarrow a_{J/\Psi N} = -0.18\,\mathrm{fm}$				
1s	n	-3.36	-4.41	-6.77	-6.84	-7.91	-8.38
1p	n	n	-0.39	-3.47	-3.95	-5.71	-7.05
2s	n	n	n	-0.26	-0.59	-2.70	-5.01
2p	n	n	n	n	n	-0.21	-2.94
3s	n	n	n	n	n	n	-0.70
			$\alpha_{J/\Psi} = 2$ GeV^{-3} $\leftarrow a_{J/\Psi N} = -0.36\,\mathrm{fm}$				
1s	-4.49	-10.76	-12.62	-16.41	-16.16	-17.70	-17.27
1p	n	-3.98	-6.54	-11.95	-12.44	-14.95	-16.30
2s	n	n	-0.54	-6.74	-7.50	-11.07	-13.95
2p	n	n	n	-1.62	-2.52	-7.33	-11.41
3s	n	n	n	n	n	-2.71	-8.28

Lattice*

— quenched, m_π = 640 MeV



Yukawa fit

$$V_{N\eta_c} = -\gamma \, \frac{e^{-\alpha\, r}}{r}$$

$$\gamma = 0.1$$
$$\alpha = 3\ \mathrm{fm}^{-1}$$

T. Kawanay & S. Sasaki, PRD 82, 091501 (2010)

Pion mass dependence

— quenched x unquenched

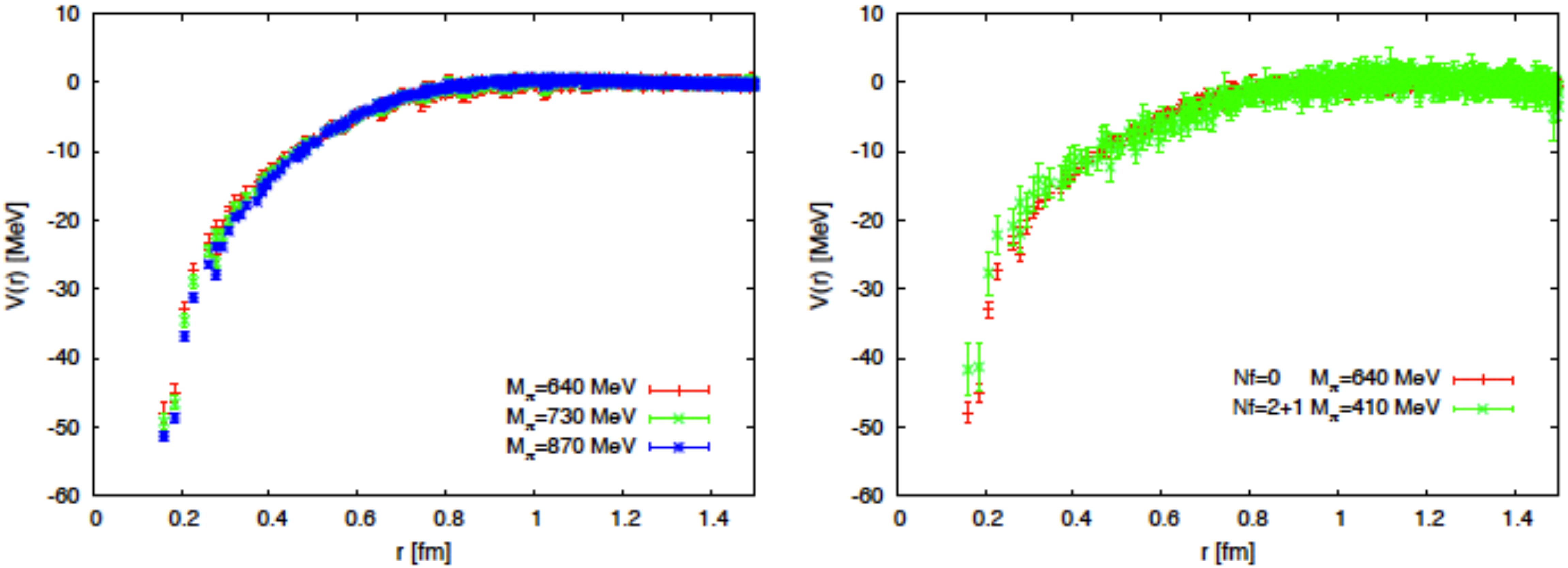


Figure 2: The quark-mass dependence of the η_c-N potential (left) and a comparison between quenched and dynamical simulations (right)

T. Kawanay & S. Sasaki, Pos (Lattice) 2010, 156 (2010)

Scattering length & effective range

— unquenched

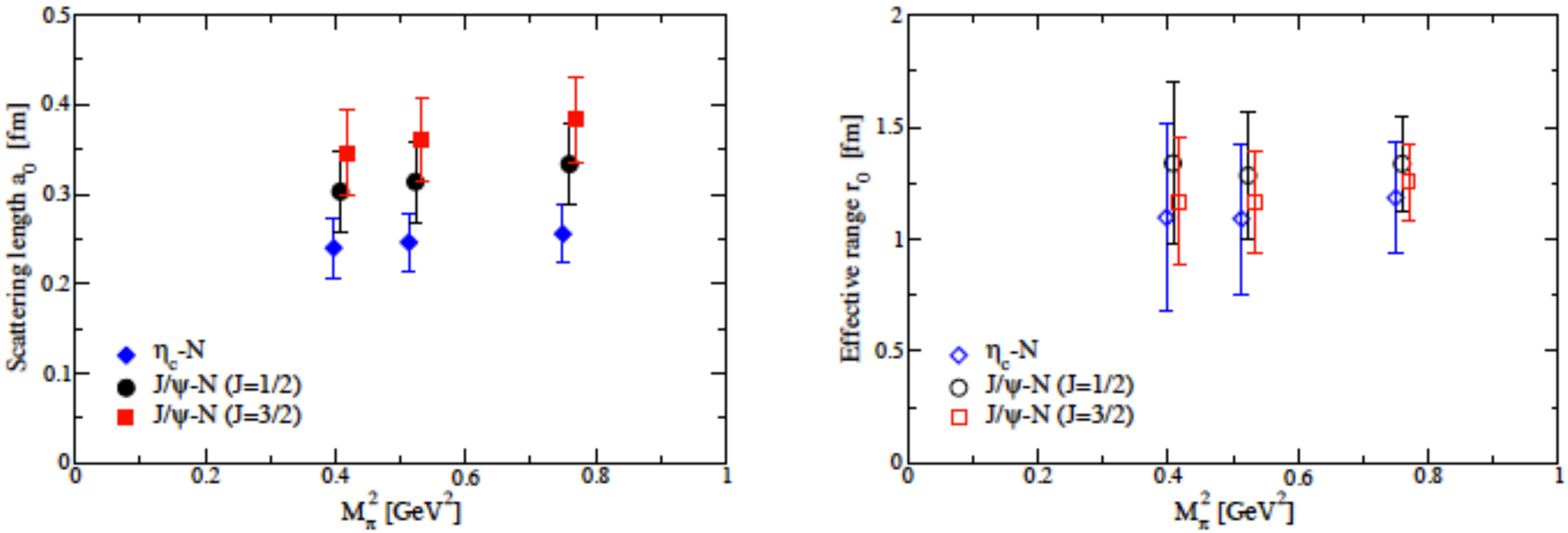


Figure 5: The scattering length a_0 (left) and effective range r_0 (right) as a function of M_π^2. The squared (diamond) symbols have been moved slightly in the plus (minus) x-direction.

T. Kawanay & S. Sasaki, Pos (Lattice) 2010, 156 (2010)

Fit to lattice results

Reproduce scattering length,
leave effective range free

$$W^{\mathrm{latt}}_{\varphi N}(r) = -W_0\left[1 - f(r, r_{\mathrm{vdW}})\right] + V^{\mathrm{fit}}_{\eta_c N}(r)\, f(r, r_{\mathrm{vdW}})$$

$$f(r, r_{\mathrm{vdW}}) = \frac{1}{1 + (r_{\mathrm{vdW}}/r)^{10}}.$$

$$W^{\mathrm{latt}}_{\varphi A}(\vec{r}) = \int d^3r'\, W^{\mathrm{latt}}_{\varphi N}(\vec{r} - \vec{r}\,')\rho_A(\vec{r}\,').$$

Fit to lattice results

$$(a_{J/\Psi N})_{\text{SAV}} \sim 0.35 \text{ fm} > a_{\eta_c N} \sim 0.25 \text{ fm}$$

$$r_e \sim 1.0 \text{ fm}$$

	$\eta_c N$		$J/\Psi N$	
r_{vdW}	W_0	r_e	W_0	r_e
0.3	252	1.4	288	1.2
0.5	74	1.7	95	1.4

J/Ψ in nuclei

— nuclear potentials

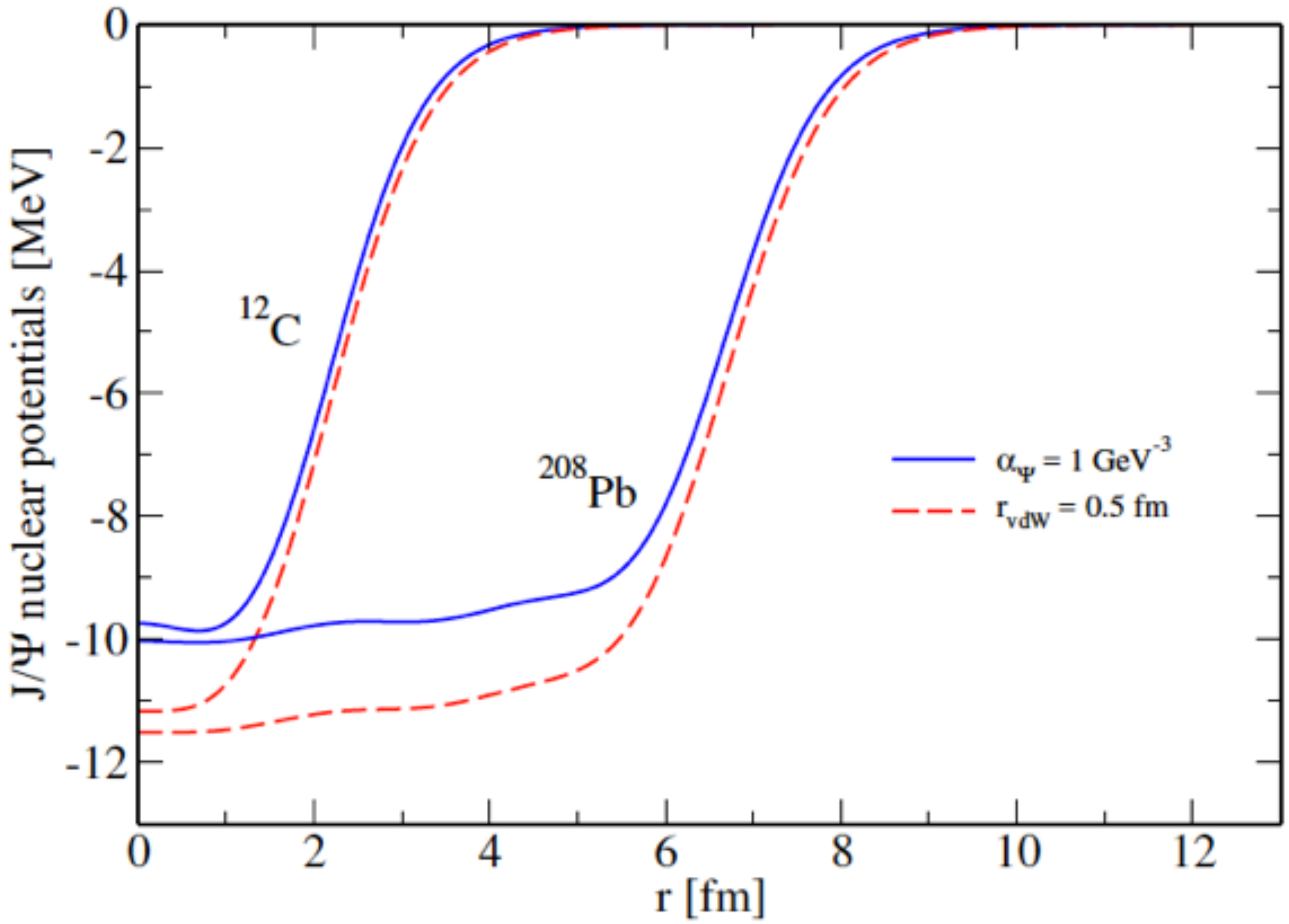


Figure 8: J/Ψ nuclear potentials $W^{\mathrm{pol}}_{J/\Psi A}(\vec{r})$ (solid line) for a polarizability $\alpha_{J/\Psi} = 1\ \mathrm{GeV}^{-3}$ and $W^{\mathrm{latt}}_{J/\Psi A}(\vec{r})$ (dashed line) from a fit to the lattice data with a cutoff $r_{\mathrm{vdW}} = 0.5$ fm.

Quarkonium in nuclei

— use of lattice potential

Table 8: Single-particle energies of η_c and J/Ψ in selected nuclei. The $\eta_c N$ and $J/\Psi N$ potentials fit the lattice scattering lengths and incorporate the Yuakwa tail from the fit from lattice data.

	${}^{16}_{\eta_c}$O	${}^{40}_{\eta_c}$Ca	${}^{90}_{\eta_c}$Zr	${}^{290}_{\eta_c}$Pb	${}^{16}_{J/\Psi}$O	${}^{40}_{J/\Psi}$Ca	${}^{90}_{J/\Psi}$Zr	${}^{290}_{J/\Psi}$Pb
				$r_{\rm vdW} = 0.3$ fm				
1s	-2.92	-5.15	-6.32	-6.88	-3.62	-5.92	-7.10	-7.62
1p	n	-2.06	-4.17	-5.55	n	-2.74	-4.93	-6.29
2s	n	n	-1.40	-3.53	n	n	-2.06	-4.29
2p	n	n	n	-1.50	n	n	n	-2.30
				$r_{\rm vdW} = 0.5$ fm				
1s	-3.62	-5.99	-7.23	-7.79	-5.23	-7.95	-9.24	-9.74
1p	n	-2.72	-4.99	-6.41	-0.87	-4.41	-6.90	-8.33
2s	n	n	-2.04	-4.33	n	-0.82	-3.71	-6.20
2p	n	n	n	-2.28	n	n	-0.92	-4.03

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

Quarkonium-nucleus bound states from lattice QCD

S. R. Beane,[1] E. Chang,[1,2] S. D. Cohen,[2] W. Detmold,[3] H.-W. Lin,[1] K. Orginos,[4,5] A. Parreño,[6] and M. J. Savage[2]
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[5]*Jefferson Laboratory, 12000 Jefferson Avenue, Newport News, Virginia 23606, USA*
[6]*Departament d'Estructura i Constituents de la Matèria and Institut de Ciències del Cosmos, Universitat de Barcelona, Martí i Franquès 1, Barcelona, 08028, Spain*

(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 $B_{\rm phys}^{\rm NM} \lesssim 40$ MeV.

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

Models

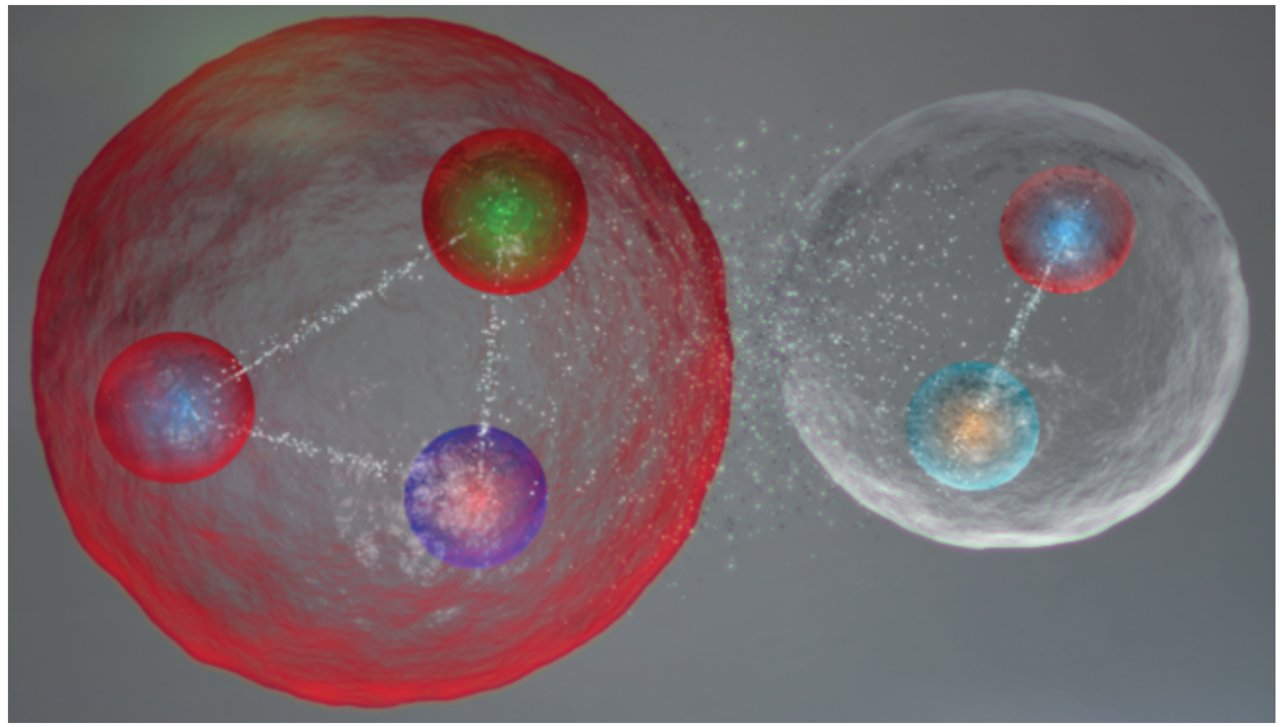
TABLE I. Estimates for the binding energies of charmonium to light nuclei and nuclear matter (in MeV) from selected models. A "$*$" indicates the system is predicted to be unbound, while entries with center dots indicate that the system was not addressed.

	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

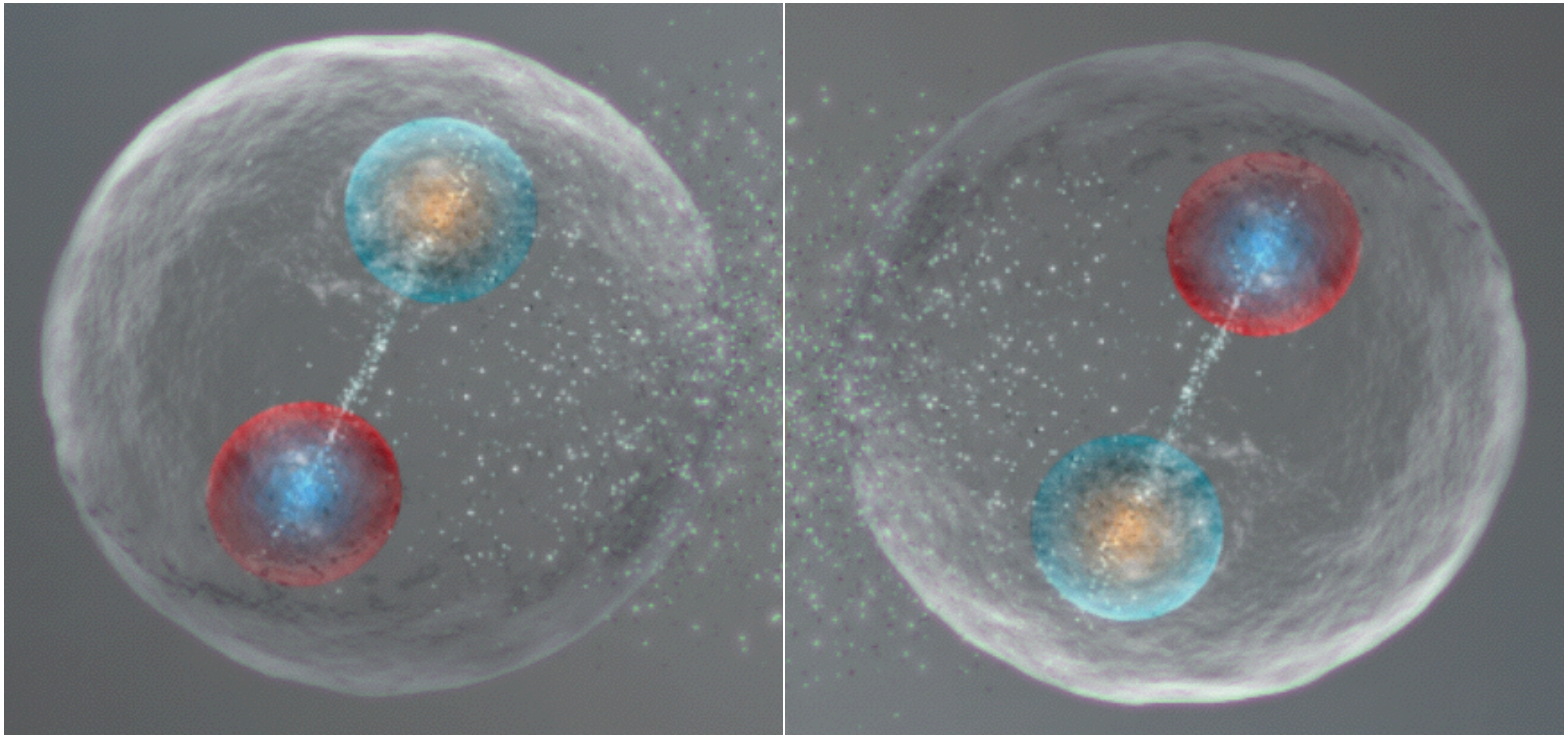
TABLE V. The binding energies (in MeV) of charmonium-nucleus systems calculated on the $L = 24$ and 32 ensembles. The rightmost column shows the infinite-volume estimate, which, without results on the $L = 48$ ensemble, is taken to be the binding calculated on the $L = 32$ ensemble. The first and second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



Can one do better?

$$\eta_b - \eta_b$$



N. Brambilla, GK, J. Tarrús-Castellà, A. Vairo, PRD 93, 054002 (2016)

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—

EFT approach

— 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

pNRQCD ↓ gWEFT ⟶ χEFT ⟶ WEFT

Polarizability (gWEFT)

van der Waals (χEFT ⟶ WEFT)

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 $\longrightarrow$ χEFT $\longrightarrow$ WEFT

pNRQCD*

— obtain e.g. bound states

S,*O*: singlet, octet $Q\overline{Q}$ states

$$\mathcal{L}_{\rm pNRQCD} = \mathcal{L}_{\rm light} + \int d^3r \left\{ {\rm Tr}\left[{\rm S}^\dagger\left(i\partial_0 - h_{\rm s}\right){\rm S} + {\rm O}^\dagger\left(iD_0 - h_{\rm o}\right){\rm O}\right] \right.$$
$$\left. + gV_A(r)\,{\rm Tr}\left[{\rm O}^\dagger(\vec{r}\cdot\vec{E}){\rm S} + {\rm S}^\dagger(\vec{r}\cdot\vec{E}){\rm O}\right] + \frac{g}{2}V_B(r)\,{\rm Tr}\left[{\rm O}^\dagger(\vec{r}\cdot\vec{E}){\rm O} + {\rm O}^\dagger{\rm O}(\vec{r}\cdot\vec{E})\right]\right\}$$

$$h_{\rm s} = -\frac{\nabla_r^2}{m_Q} - \frac{\nabla_R^2}{4m_Q} + V_{\rm s}(r)$$

$$h_{\rm o} = -\frac{\nabla_r^2}{m_Q} - \frac{D_R^2}{4m_Q} + V_{\rm o}(r)$$

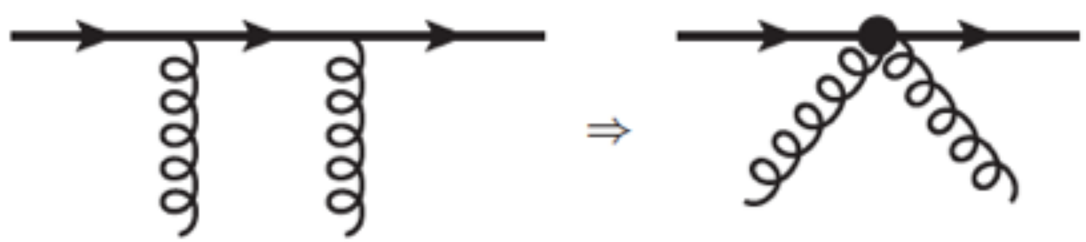
$$V_s(r) = -C_F\frac{\alpha_s(r)}{r}\,,$$
$$V_o(r) = \left(\frac{C_A}{2} - C_F\right)\frac{\alpha_s(r)}{r}\,,$$
$$V_A(r) = 1\,,$$
$$V_B(r) = 1\,,$$

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

* A. Pineda and J. Soto, Nucl. Phys. B, Proc. Suppl. 64, 428 (1998)
N. Brambilla, A. Pineda, J. Soto, and A. Vairo, Nucl. Phys. B 566, 275 (2000)

gWEFT
— hadronization, chromopolarizability

pNRQCD ⟶ gWEFT



$$\mathcal{L}_{\rm gWEFT} = \mathcal{L}_{\rm light} + \varphi^\dagger(t,\vec{R})\left(i\partial_0 - E_\varphi + \frac{\nabla^2_{\vec{R}}}{4m} + \frac{1}{2}\alpha_\varphi g^2 \vec{E}^2 + \cdots\right)\varphi(t,\vec{R})$$

Chromopolarizability

$$\alpha_\varphi = -\frac{2V_A^2 T_F}{3N_c}\langle\varphi|r^i\frac{1}{E_\varphi - h_o}r^i|\varphi\rangle$$

Results: polarizability

$$E_\varphi = -m_Q \frac{(C_F \alpha_s)^2}{4} = -\frac{1}{m_Q a_0}$$

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

$m = 5$ GeV

$\alpha_s(1 \text{ GeV}) \approx 0.5$

$\alpha_s(1.5 \text{ GeV}) \approx 0.35$

$\alpha_{\eta_b} = 0.50^{+0.42}_{-0.38} \text{ GeV}^{-3}$

$\alpha_s(2 \text{ GeV}) \approx 0.3$

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

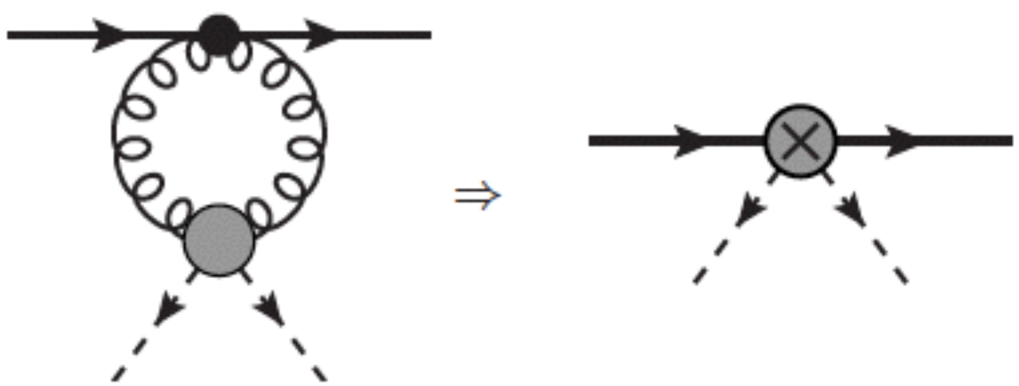
$\beta_{\Upsilon-\Upsilon'} = 0.66 \text{ GeV}^{-3}$

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

van der Waals force

gWEFT ⟶ χEFT

Nonperturbative matching



QCD trace anomaly

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

$$\kappa_1 = 1 - 9\kappa/4,\ \kappa_2 = 1 - 9\kappa/2 \qquad b = \frac{11}{3}N_c - \frac{2}{3}N_f$$

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

Matching gWEFT $\longrightarrow$ χEFT

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

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

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

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

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

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

van der Waals force

$r_{\phi\phi} \sim 1/m_\pi$

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

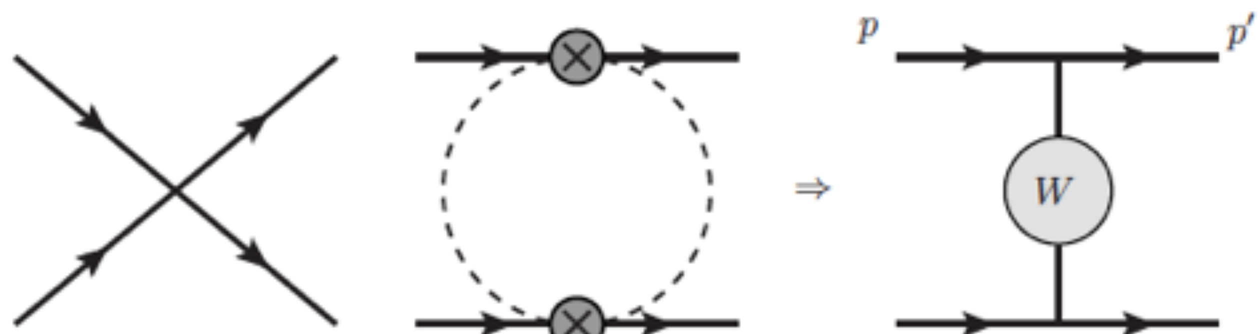
Relative motion at energies lower than pion mass

— integrate out the pion

χEFT $\longrightarrow$ WEFT

Matching

χEFT ⟶ WEFT



$$L_{\varphi\varphi} = \int d^3R\, \varphi^\dagger(t,\vec{R}) \left(i\partial_0 + \frac{\nabla^2}{2m_\varphi} \right) \varphi(t,\vec{R})$$
$$-\frac{1}{2}\int d^3R d^3R'\, \varphi^\dagger(t,\vec{R})\varphi^\dagger(t,\vec{R}')\, W_{\varphi\varphi}(\vec{R},\vec{R}')\, \varphi(t,\vec{R}')\varphi(t,\vec{R})$$

vdW potential

$$
\begin{aligned}
\widetilde{W}(\mathbf{k}^2) \quad = \quad & \text{contact terms} \\
& -\frac{3}{8}\left(\mathbf{k}^2 c_{di} + 2m_\pi^2\left(c_{di} - c_m\right)\right)^2 B\left[m_\pi^2, -\mathbf{k}^2\right] \\
& -\frac{3}{2}\left(c_{d0} - c_{di}\right)\left(\mathbf{k}^2 c_{di} + 2m_\pi^2\left(c_{di} - c_m\right)\right) C_1\left[m_\pi^2, -\mathbf{k}^2\right] \\
& -\frac{3}{2}\left(c_{d0} - c_{di}\right)^2 C_2\left[m_\pi^2, -\mathbf{k}^2\right]
\end{aligned}
$$

$$B\left[m_\pi^2\,,-\mathbf{k}^2\right] = \frac{1}{16\pi^2}\left(\lambda + 1 - \log\frac{m_\pi^2}{\nu^2} + \sqrt{1+\frac{4m_\pi^2}{\mathbf{k}^2}}\log\left[\frac{\sqrt{1+\frac{4m_\pi^2}{\mathbf{k}^2}}-1}{\sqrt{1+\frac{4m_\pi^2}{\mathbf{k}^2}}+1}\right]\right)$$

$$B\left[m_\pi^2\,,-\mathbf{k}^2\right] = \frac{1}{16\pi^2}\left(\lambda + 1 - \log\frac{m_\pi^2}{\nu^2} + \sqrt{1+\frac{4m_\pi^2}{\mathbf{k}^2}}\,\log\left[\frac{\sqrt{1+\frac{4m_\pi^2}{\mathbf{k}^2}}-1}{\sqrt{1+\frac{4m_\pi^2}{\mathbf{k}^2}}+1}\right]\right)$$

$$C_2\left[m_\pi^2\;-\mathbf{k}^2\right] \;=\; \frac{31\mathbf{k}^4+280\mathbf{k}^2 m_\pi^2+705m_\pi^4}{19200\pi^2}+\frac{1}{1280\pi^2}\Bigg(\left(\mathbf{k}^4+10\mathbf{k}^2m_\pi^2+30m_\pi^4\right)$$

$$\times\left(\lambda-\log\frac{m_\pi^2}{\nu^2}\right)+\mathbf{k}^4\left(1+\frac{4m_\pi^2}{\mathbf{k}^2}\right)^{5/2}\log\left[\frac{\sqrt{1+\frac{4m_\pi^2}{\mathbf{k}^2}}-1}{\sqrt{1+\frac{4m_\pi^2}{\mathbf{k}^2}}+1}\right]\Bigg)$$

$$B\left[m_\pi^2\,,-\mathbf{k}^2\right] = \frac{1}{16\pi^2}\left(\lambda + 1 - \log\frac{m_\pi^2}{\nu^2} + \sqrt{1+\frac{4m_\pi^2}{\mathbf{k}^2}}\,\log\left[\frac{\sqrt{1+\frac{4m_\pi^2}{\mathbf{k}^2}}-1}{\sqrt{1+\frac{4m_\pi^2}{\mathbf{k}^2}}+1}\right]\right)$$

$$C_2\left[m_\pi^2\ -\mathbf{k}^2\right] \quad = \quad \frac{31\mathbf{k}^4 + 280\mathbf{k}^2 m_\pi^2 + 705 m_\pi^4}{19200\pi^2} + \frac{1}{1280\pi^2}\left(\left(\mathbf{k}^4 + 10\mathbf{k}^2 m_\pi^2 + 30 m_\pi^4\right)\right.$$

$$\left.\times\left(\lambda - \log\frac{m_\pi^2}{\nu^2}\right) + \mathbf{k}^4\left(1+\frac{4m_\pi^2}{\mathbf{k}^2}\right)^{5/2}\log\left[\frac{\sqrt{1+\frac{4m_\pi^2}{\mathbf{k}^2}}-1}{\sqrt{1+\frac{4m_\pi^2}{\mathbf{k}^2}}+1}\right]\right)$$

$$C_1\left[m_\pi^2\ -\mathbf{k}^2\right] \quad = \quad \frac{5\mathbf{k}^2 + 24 m_\pi^2}{576\pi^2} + \frac{1}{192\pi^2}\left(\left(\mathbf{k}^2 + 6m_\pi^2\right)\left(\lambda - \log\frac{m_\pi^2}{\nu^2}\right)\right.$$

$$\left. + \mathbf{k}^2\left(1+\frac{4m_\pi^2}{\mathbf{k}^2}\right)^{3/2}\log\left[\frac{\sqrt{1+\frac{4m_\pi^2}{\mathbf{k}^2}}-1}{\sqrt{1+\frac{4m_\pi^2}{\mathbf{k}^2}}+1}\right]\right)$$

vdW potential

$$W(r) = \frac{1}{2\pi^2 r}\int_{2m_\pi}^{\infty} d\mu\, \mu\, e^{-\mu r}\,\mathrm{Im}\left[\widetilde{W}(\epsilon - i\mu)\right]$$

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

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

↓ asymptotic

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

Completed the calculation of
H. Fujii and D. Kharzeev, PRD 60, 114039 (1999)

Numerical result

— vdW potential

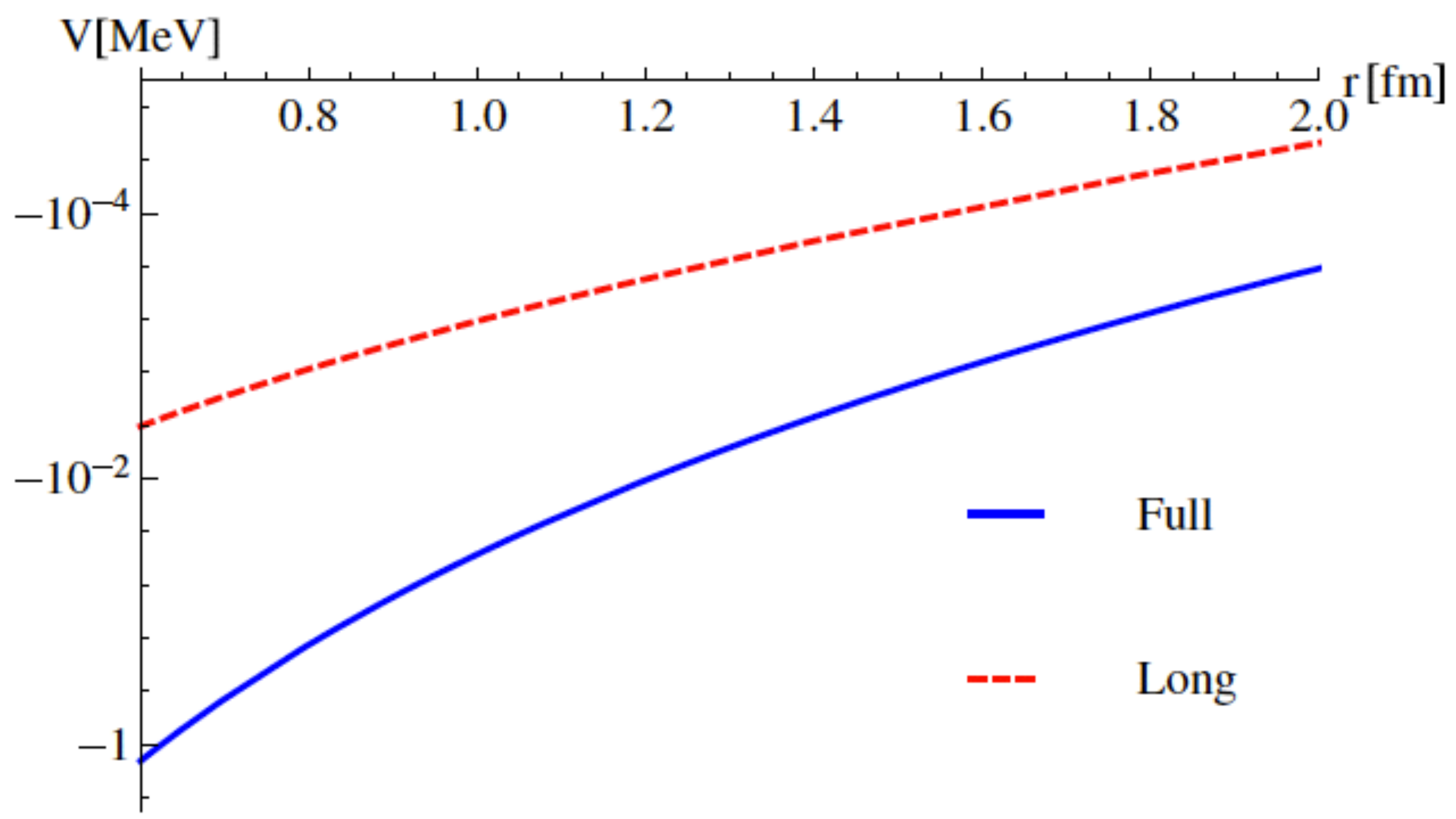


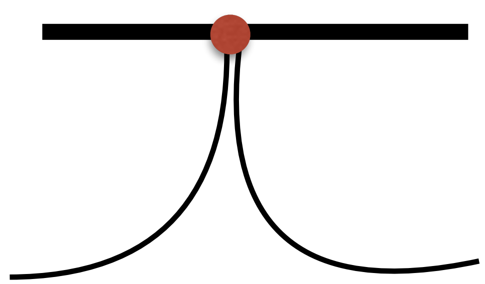
FIG. 9. Comparison of the van der Waals potential (40) (blue line) with its long-range expansion (41) (red line) for $\beta = 0.92\ \mathrm{GeV}^{-3}$ and other parameters like in Fig. 8.

Are there $\eta_b \, \eta_b$ bound-states?

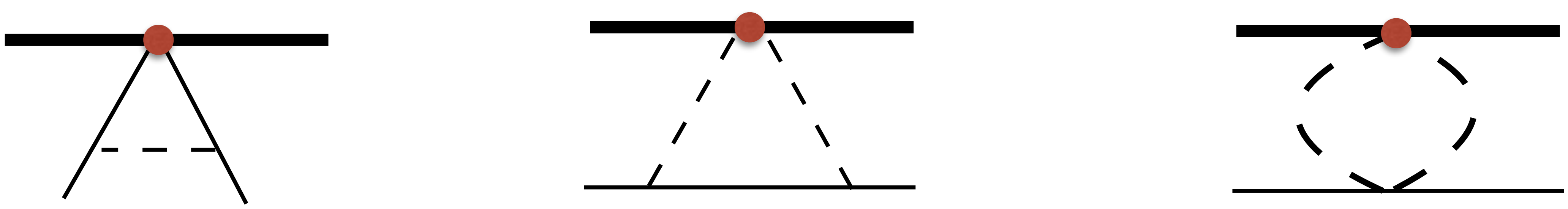
— It is likely, but depends somewhat
on the medium- and short-range pieces

Quarkonium-nucleon*

Lattice



Chiral EFT



J.T. Castellà, GK
arXiv: 1803.05412

Degrees of freedom & Scales & Power counting

DOF: nucleons, quarkonia, pions

Scales: $E_N, E_\phi \sim m_\pi \ll \Lambda_\chi \sim 1\mathrm{GeV}$

Power counting: terms of the effective Lagrangian organized in powers of $\frac{m_\pi}{\Lambda_\chi}$

(~ Weinberg for NN)

Loops: dimensional regularization

Quarkonium-nucleon EFT — QNEFT

Quarkonium

$$\mathcal{L}^{\phi} = \phi^{\dagger}\left(i\partial_0 + \frac{\boldsymbol{\nabla}^2}{2\hat{m}_{\phi}}\right)\phi$$

Nucleon-pion

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

$$\mathcal{L}^{N} = N^{\dagger}\left(iD_0 + \frac{\boldsymbol{D}^2}{2\hat{m}_N}\right)N - \frac{g_A}{2}N^{\dagger}\boldsymbol{u}\cdot\boldsymbol{\sigma}N$$

$$u_{\mu} = i\left\{u^{\dagger}, \partial_{\mu}u\right\} \qquad D_{\mu}N = \partial_{\mu}N + \Gamma_{\mu}N \qquad \Gamma_{\mu} = \tfrac{1}{2}\left[u^{\dagger}, \partial_{\mu}u\right]$$

Quarkonium-nucleon EFT
— QNEFT

Quarkonium-Nucleon

$$\mathcal{L}^{\phi-N} = - c_0 N^\dagger N \phi^\dagger \phi - d_m \langle \chi_+ \rangle N^\dagger N \phi^\dagger \phi - d_1 \boldsymbol{\nabla} \left(N^\dagger N \right) \cdot \boldsymbol{\nabla} \left(\phi^\dagger \phi \right)$$

$$- d_2 \left(N^\dagger \overleftrightarrow{\boldsymbol{D}} N \right) \cdot \left(\phi^\dagger \overleftrightarrow{\boldsymbol{\nabla}} \phi \right) - d_3 \boldsymbol{D} N^\dagger \cdot \boldsymbol{D} N \phi^\dagger \phi$$

$$- d_4 N^\dagger N \boldsymbol{\nabla} \phi^\dagger \cdot \boldsymbol{\nabla} \phi$$

$\chi_\pm = u^\dagger \chi u^\dagger \pm u \chi^\dagger u$ $\qquad \chi = 2B\hat{m}\mathbb{1}$ $\qquad m_u = m_d \equiv \hat{m}$

Low-energy quarkonium-nucleon dynamics

Quarkonium-nucleon dynamics,
e.g bound to nucleus occurs at energies

$$E_{\phi N} \sim \frac{k_{\phi N}^2}{2\mu_{\phi N}} < \frac{m_\pi^2}{\Lambda_\chi} \ll m_\pi$$

Integrate out the pion

Low-energy quarkonium-nucleon dynamics

$$\langle T_{\rm N}\rangle \sim \frac{3}{5}\frac{k_F^2}{2m_N} \sim 20\,{\rm MeV} \ll \Lambda_{\rm QCD}$$

Quarkonium-nucleon dynamics,
e.g bound to nucleus occurs at energies

$$E_{\phi N} \sim \frac{k_{\phi N}^2}{2\mu_{\phi N}} < \frac{m_\pi^2}{\Lambda_\chi} \ll m_\pi$$

Integrate out the pion

Low-energy quarkonium-nucleon dynamics

$$\langle T_{\rm N} \rangle \sim \frac{3}{5}\frac{k_F^2}{2m_N} \sim 20\,\mathrm{MeV} \ll \Lambda_{\rm QCD}$$

Quarkonium-nucleon dynamics,
e.g bound to nucleus occurs at energies

$$E_{\phi N} \sim \frac{k_{\phi N}^2}{2\mu_{\phi N}} < \frac{m_\pi^2}{\Lambda_\chi} \ll m_\pi$$

Integrate out the pion

Quarkonium-nucleon potential — pQNEFT

Integrate out the pion

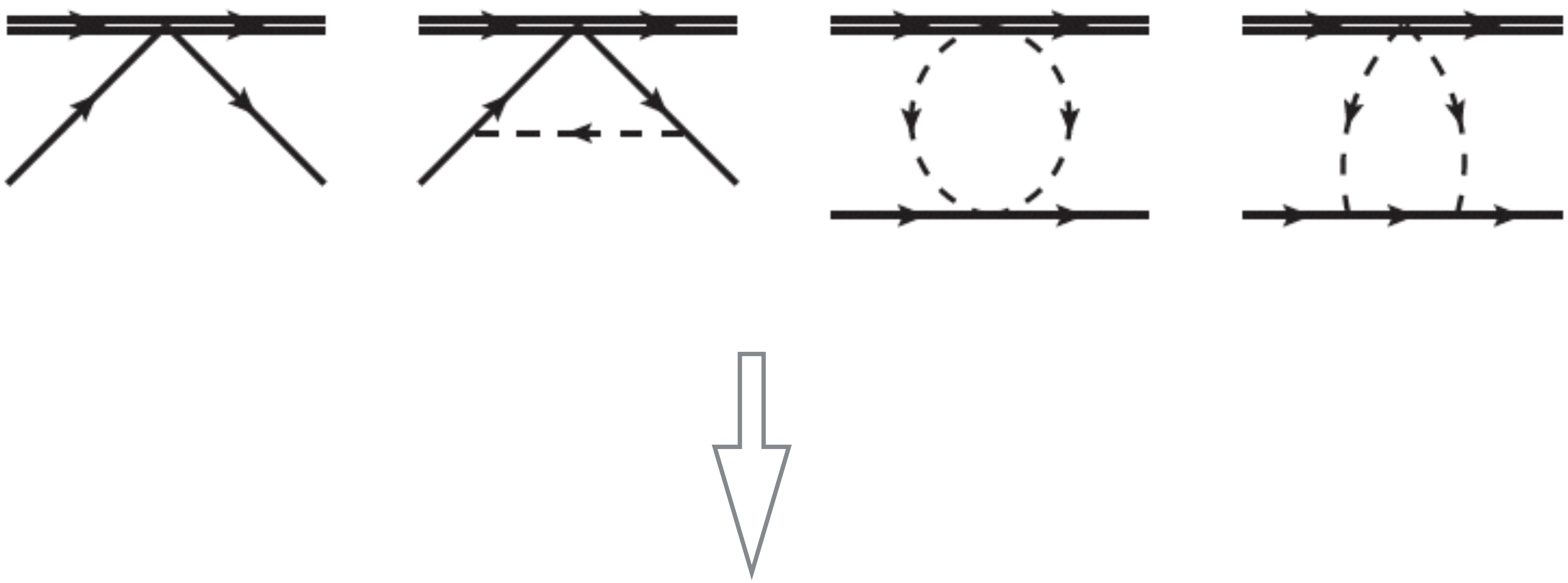
$$\mathcal{L}^{\mathrm{pQNEFT}} = N^\dagger\left(i\partial_0 + \frac{\boldsymbol{\nabla}^2}{2m_N}\right)N + \phi^\dagger\left(i\partial_0 + \frac{\boldsymbol{\nabla}^2}{2m_\phi}\right)\phi$$

$$- C_0 N^\dagger N \phi^\dagger \phi - D_1 \boldsymbol{\nabla}\left(N^\dagger N\right)\cdot\boldsymbol{\nabla}\left(\phi^\dagger\phi\right)$$

$$- D_2\left(N^\dagger \overleftrightarrow{\boldsymbol{\nabla}} N\right)\cdot\left(\phi^\dagger \overleftrightarrow{\boldsymbol{\nabla}}\phi\right) - D_3 \boldsymbol{\nabla} N^\dagger \cdot \boldsymbol{\nabla} N \phi^\dagger \phi - D_4 N^\dagger N \boldsymbol{\nabla}\phi^\dagger \cdot \boldsymbol{\nabla}\phi$$

$$- \int d^3r\, N^\dagger N(t, \boldsymbol{x}_1) V(\boldsymbol{x}_1 - \boldsymbol{x}_2)\phi^\dagger\phi(t, \boldsymbol{x}_2)$$

Matching



renormalization of couplings + van der Waals

Renormalized couplings

$$
\begin{aligned}
C_0 &= c_0 + 4m_\pi^2 d_m + \frac{9g_A^2 m_\pi^2 c_0}{64\pi^2 F^2}\left(\log\frac{m_\pi^2}{\nu^2} + \frac{2}{3}\right) + \frac{3g_A^2 m_\pi^3}{64\pi F^2}\left(5c_{di} - 3c_m\right) \\
D_1 &= d_1 + \frac{g_A^2 m_\pi}{256\pi F^2}\left(23c_{di} - 5c_m\right) \\
D_j &= d_j \quad \text{for} \quad j = 2, 3\,\text{and}\,4
\end{aligned}
$$

Long-distance part of QN potential — vdW force

$$V(r) = \frac{3g_A^2 m_\pi^3}{128\pi^2 F^2 r^6}\, e^{-2m_\pi r} \{c_{di}\,[6 + m_\pi r(2 + m_\pi r)(6 + m_\pi r(2 + m_\pi r))]$$

$$+c_m m_\pi^2 r^2\,(1 + m_\pi r)^2\}$$

No free parameters here:

— trace anomaly

— chiral physics

First, model-independent derivation of a quarkonium-nucleon van der Waals force

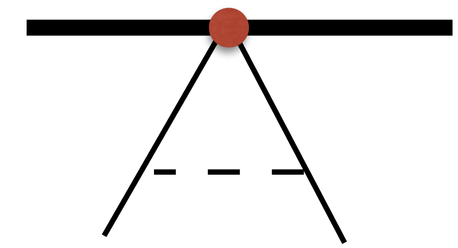
For $r \gg \frac{1}{2m_\pi}$:

$$V(r) = \frac{3g_A^2 m_\pi^4 \left(c_{di} + c_m\right)}{128\pi^2 F^2} \frac{e^{-2m_\pi r}}{r^2}$$

To extrapolate lattice data to physical quark masses, need:

$$\begin{aligned} m_N &= \hat{m}_N - 4c_1 m_\pi^2 - \frac{3g_A^2 m_\pi^3}{32\pi F^2} \\ m_\phi &= \hat{m}_\phi - F^2 c_m m_\pi^2 \end{aligned}$$

Unknown contact couplings — get them from lattice QCD

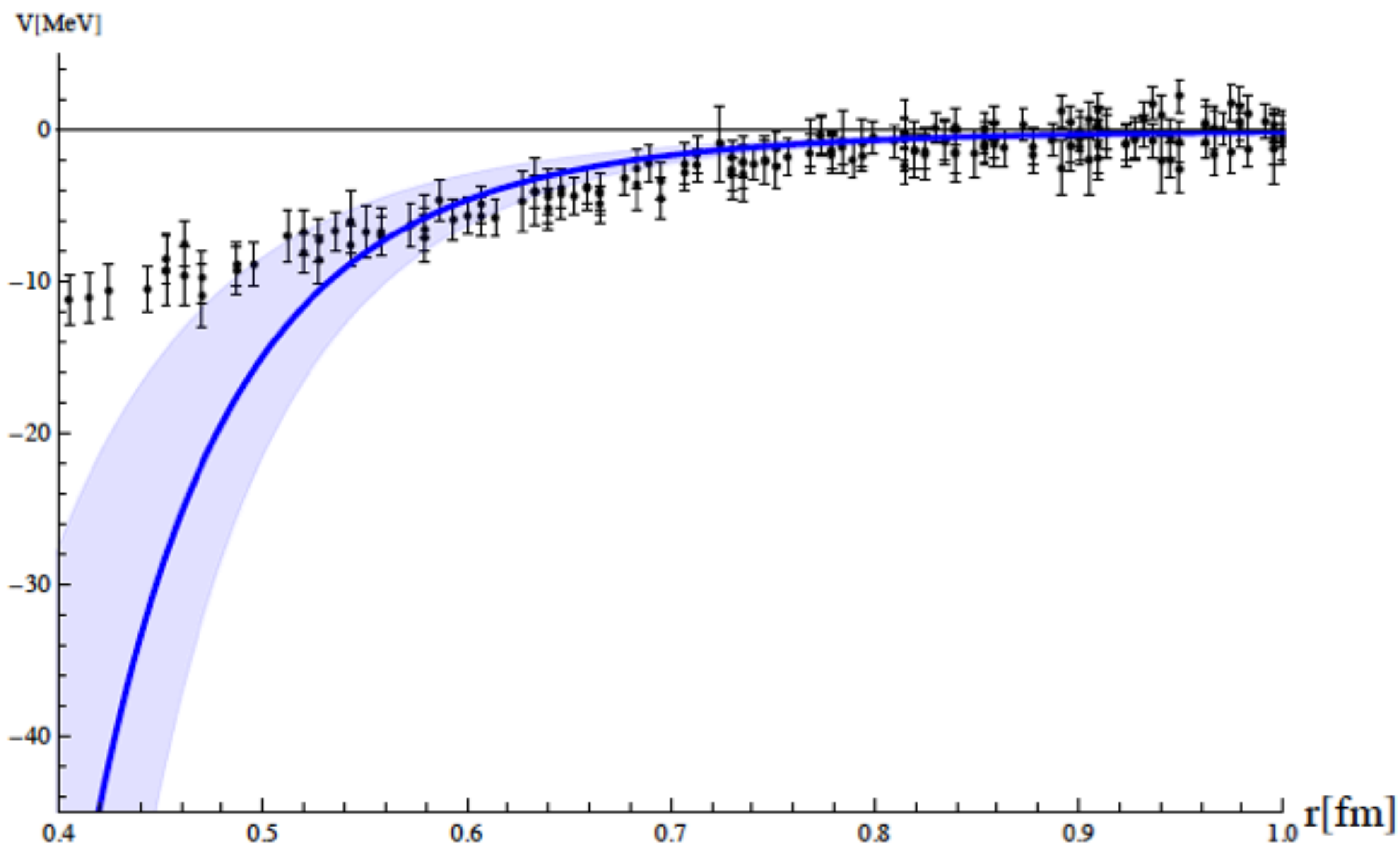


Reference		Channel	a_0 [fm]	c_0 [GeV^{-2}]	d_m [GeV^{-2}]
[23]	PSF	η_c	$-0.70(66)$	$-31(29)$	Quenched
		J/ψ	$-0.71(48)$	$-31(21)$	
	LLE	η_c	$-0.39(14)$	$-17(6)$	
		J/ψ	$-0.39(14)$	$-17(6)$	
[25]		η_c	$-0.25(5)$	$-8(2)$	Quenched
		J/ψ	$-0.35(6)$	$-12(3)$	
[24]		η_c	$-0.18(9)$	$-9.7(1.2)$	14.7(4.8)
		J/ψ	$-0.40(80)$	$-12(18)$	$-100(80)$
[16]		β [GeV^{-3}]			
		2	-0.37	-16.5	
		0.24	-0.05	-2.0	

Comparing long distance part with HAL lattice potential

vdW force

$$\eta_c - N$$

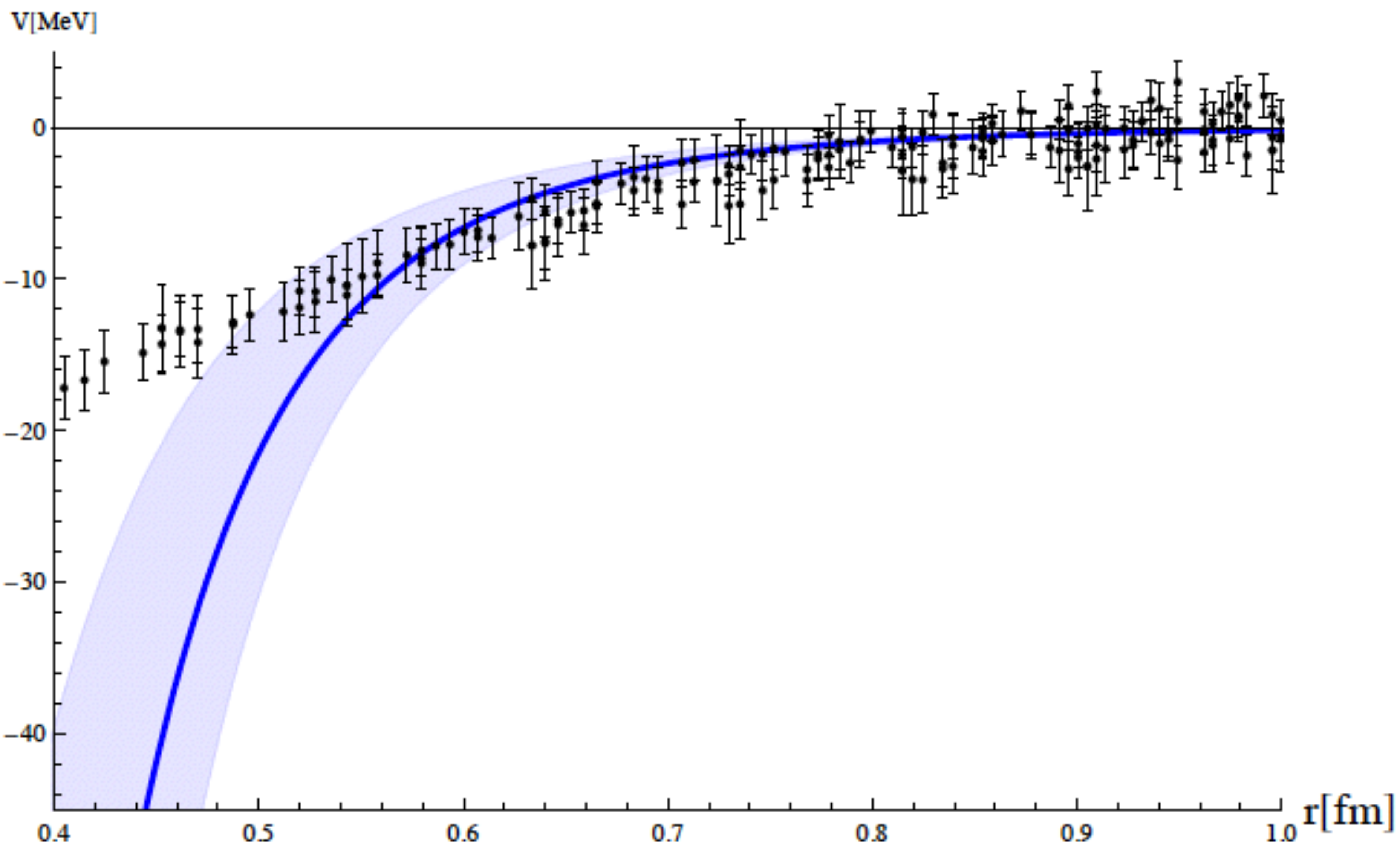


Lattice:

T. Kawanay & S. Sasaki, Pos (Lattice) 2010, 156 (2010)

vdW force

$$J/\Psi - N$$



Lattice:

T. Kawanay & S. Sasaki, Pos (Lattice) 2010, 156 (2010)

Fits of the polarizabilites

	c_{d0} [GeV^{-3}]	c_{di} [GeV^{-3}]	c_m [GeV^{-3}]
$\beta_{\eta_c} = 0.17$ GeV^{-3}	-0.83	-1.71	-2.24
$\beta_{J/\psi} = 0.24$ GeV^{-3}	-1.17	-2.42	-3.16

Table II. Values of the pion-quarkonium couplings according to the expressions in Eq. (5) for the values of the polarizabilities, in Eq. (29), obtained from the fit of the potential to the lattice data of Ref. Kawanai:2010ev.

Are there quarkonium-nucleon bound states at this order in pQNEFT?

Scattering amplitude (s-wave)

$$\mathcal{A} = \frac{2\pi}{\mu_{\phi N}} \frac{1}{p\cot\delta - ip} = \frac{2\pi}{\mu_{\phi N}} \frac{1}{-\frac{1}{a_0} + \frac{1}{2} r_0 p^2 + \dots}$$

$$a_0 = \frac{\mu_{\phi N}}{2\pi} \left[c_0 + 4 d_m m_\pi^2 + \frac{9 g_A^2 m_\pi^2 c_0}{64\pi^2 F^2} \left(\log\frac{m_\pi^2}{\nu^2} + \frac{2}{3} \right) + \frac{3 g_A^2}{64\pi F^2} m_\pi^3 \left(5 c_{di} - 3 c_m\right) \right]$$

$$r_0 = \frac{8\pi}{\mu_{\phi N} c_0^2} \left[(d_1 + d_2) + \frac{g_A^2}{256\pi F^2} m_\pi \left(23 c_{di} - 5 c_m\right) \right]$$

No quarkonium-nucleon bound states within the applicability of the present calculation: $|p_{\phi N}| \leq m_\pi$

Are there quarkonium-nucleus bound states at this order in pQNEFT?

YES, for sufficiently large nuclei

Potential for collaborations with colleagues in France

— Jaume Carbonell

— Jean-Marc Richard*

— Pierre Guichon*

— Bira van Kolck*

— Matthieu Tissier

— Hervé Moutarde

— Julien Surreau

* present talk

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