NUCLEAR-BOUND HEAVY-FLAVOR HADRONS

IFT - UNESP
INSTITUTO DE FÍSICA TEÓRICA

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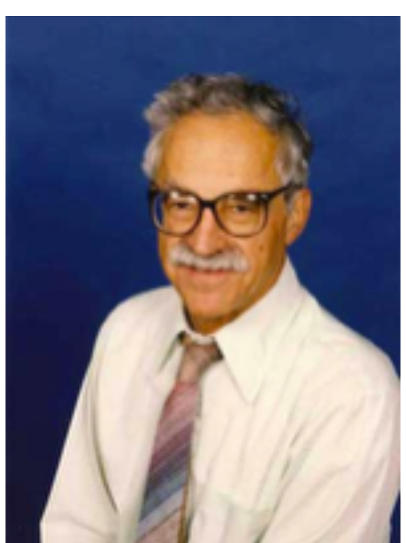
SPRACE



INT Symposium

Symmetry in Subatomic Physic: In Memory of Ernest Henley

September 10-11, 2018

Subject too broad — decided to focus on a single heavy hadron

HEAVY QUARKONIA

Talk based on

GK, AW Thomas & K Tsushima
— Prog Part Nucl Phys **100**, 161 (2018)

JT Castellà & GK
— Phys Rev D **98**, 014029 (2018)

Ernie was a humble person

— thought it would be appropriate to talk
on something nothing really ambitious

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Understand matter that amounts to 5%
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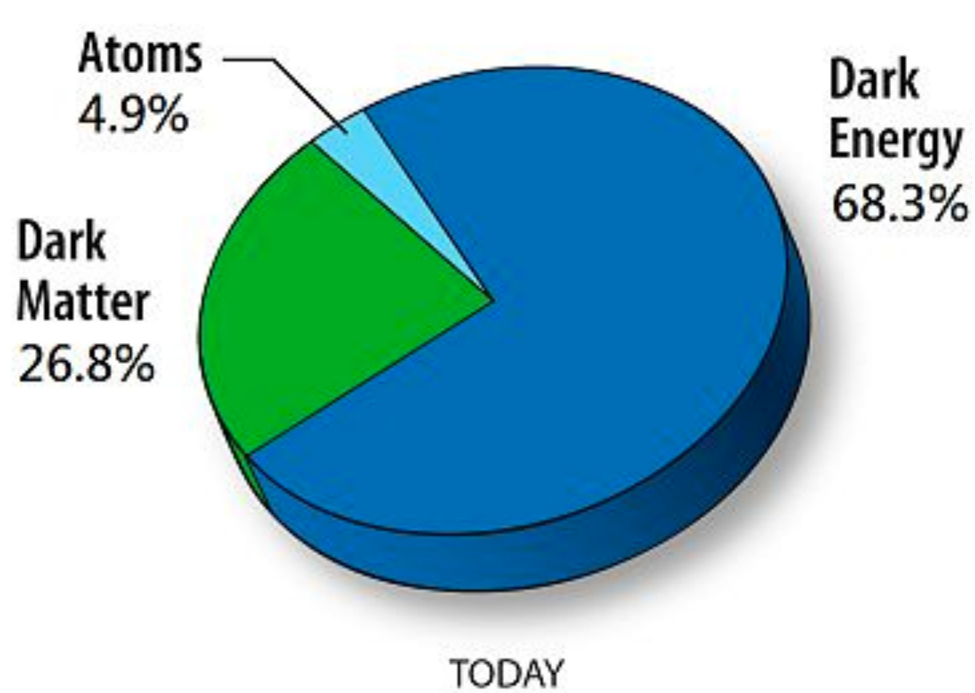

Actually, to make justice to his modesty

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Focus on understanding the proton mass

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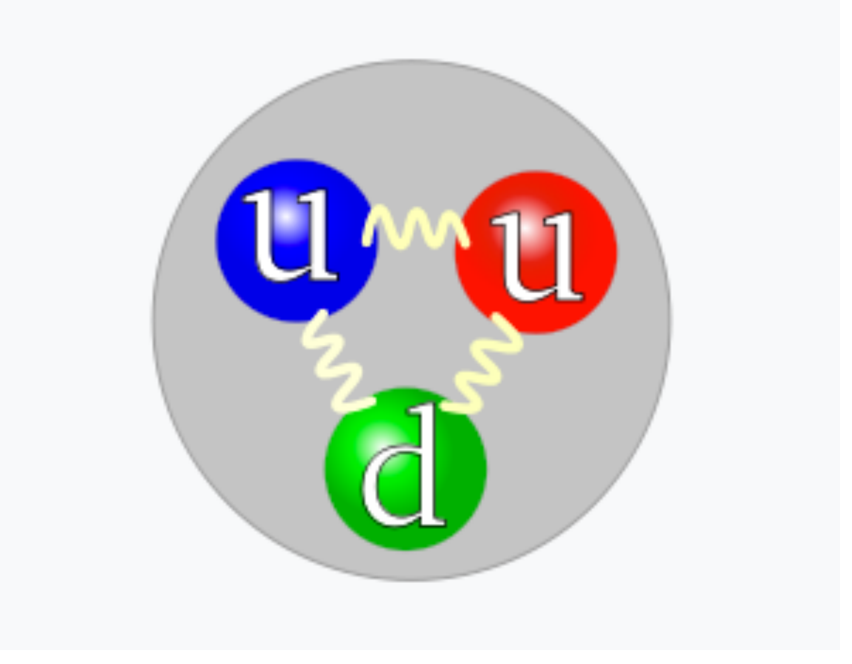
Focus on understanding the proton mass



Starting point ?

Seems to be

Q C D

Quantum Chromodynamics

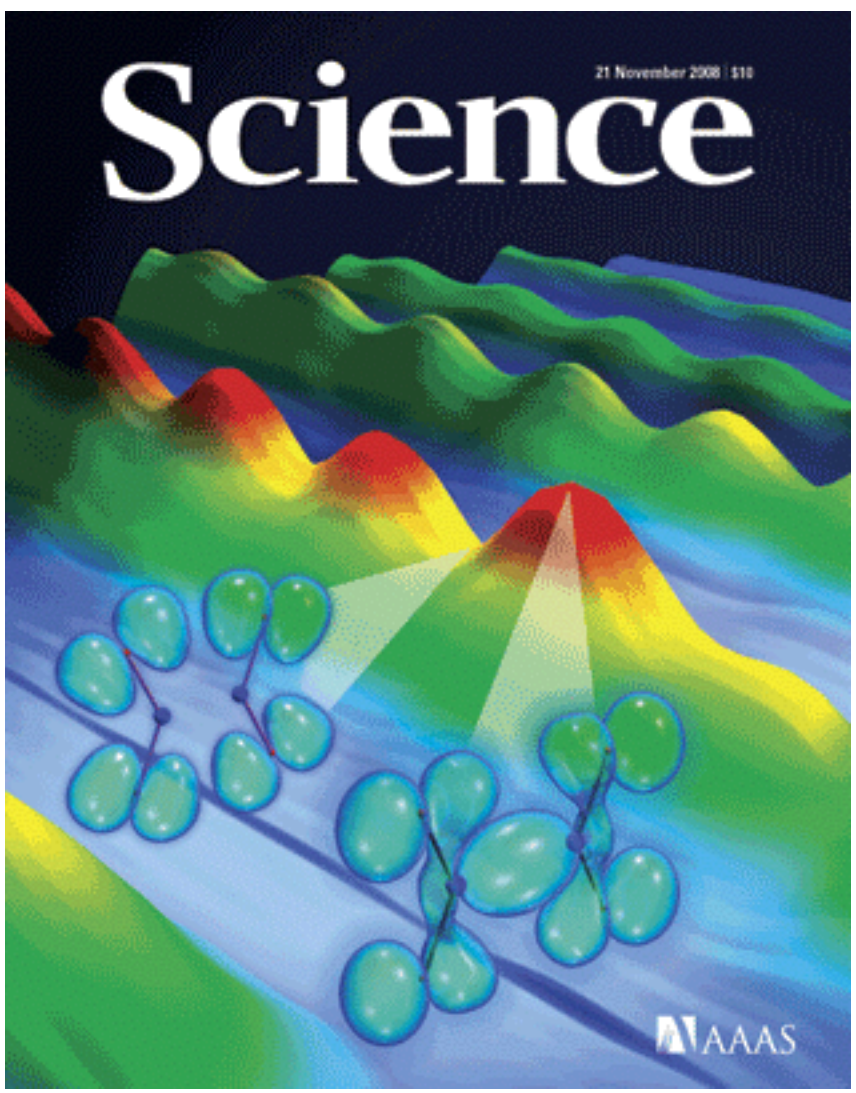
Science

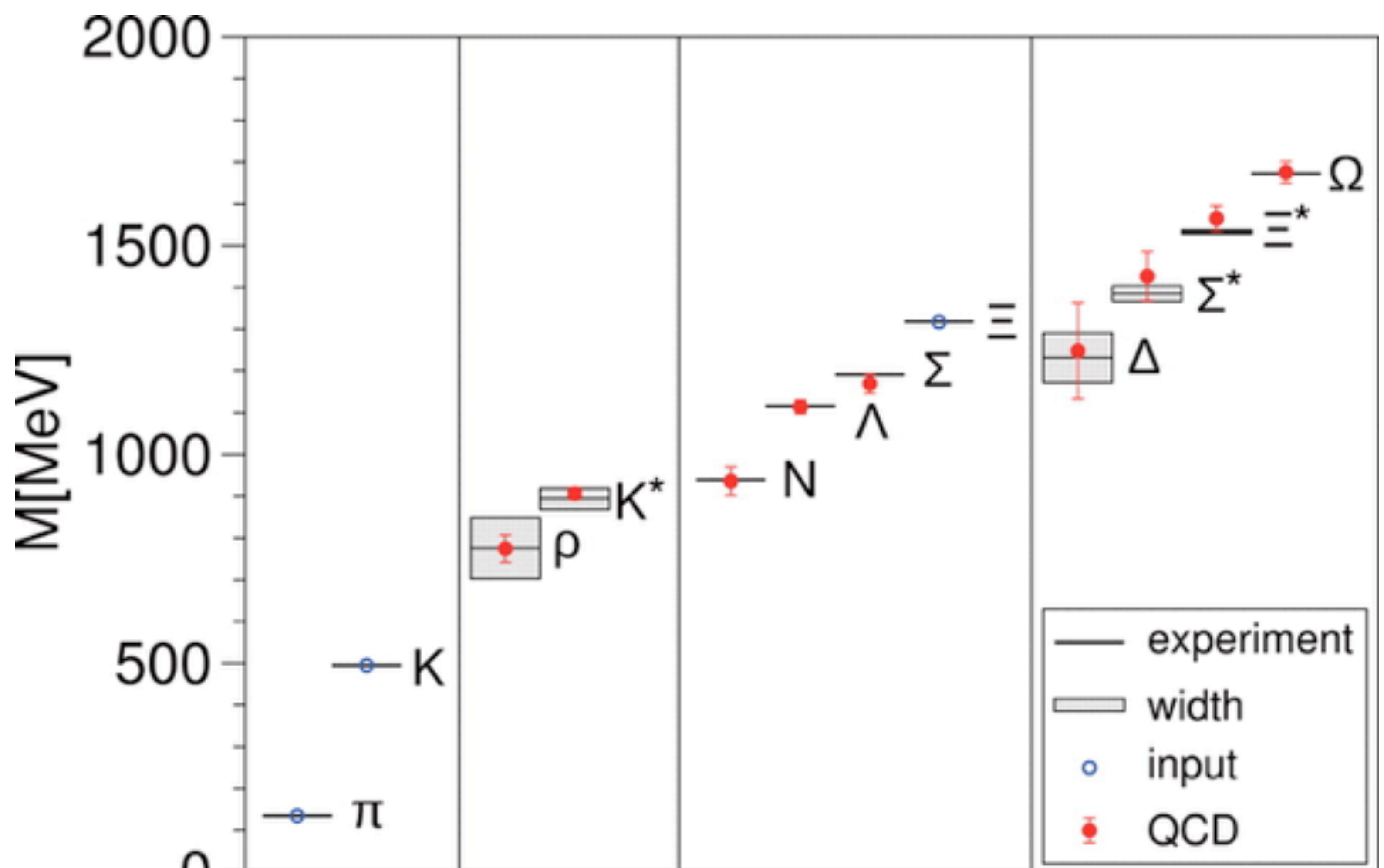
2008

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





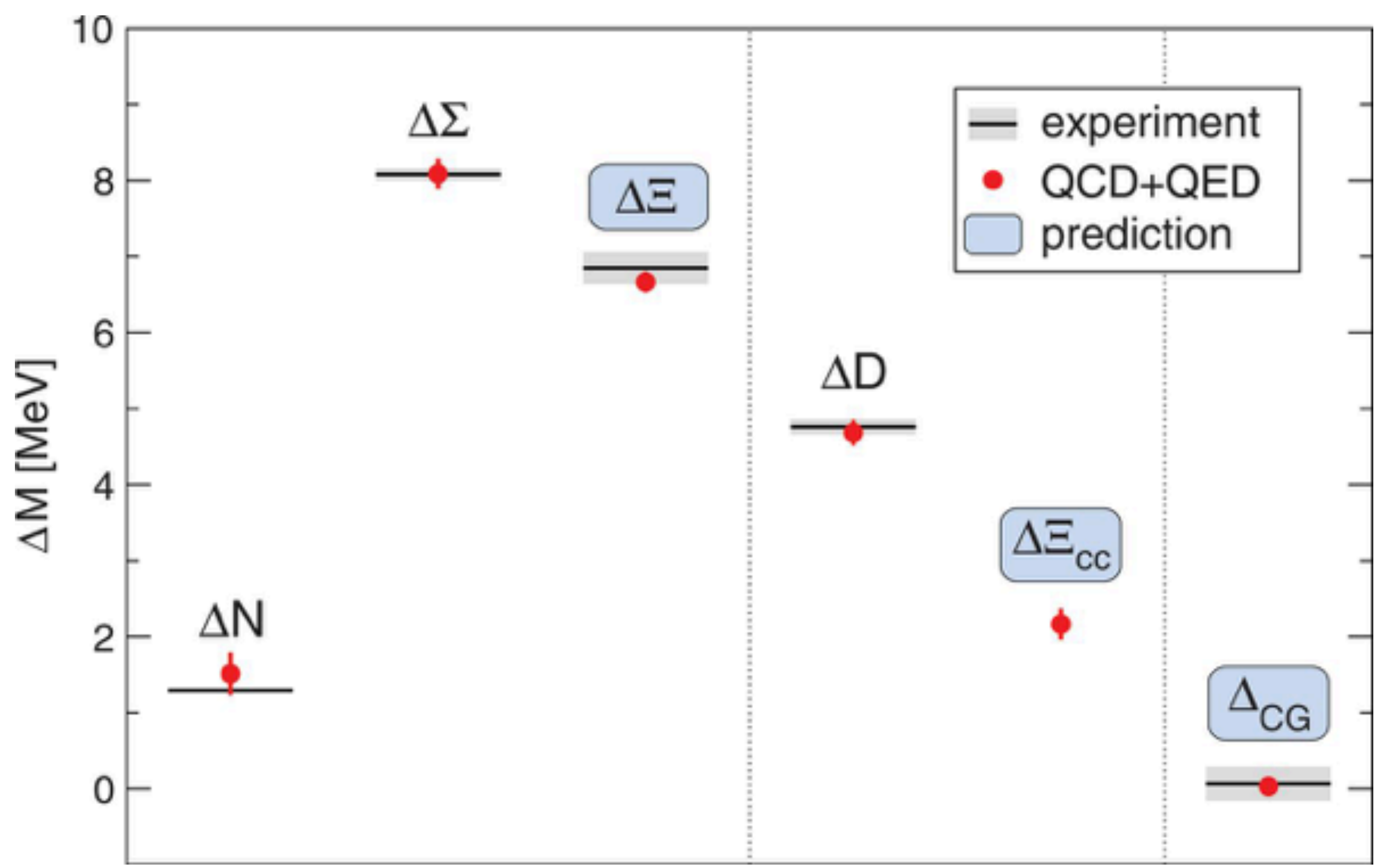
Science

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

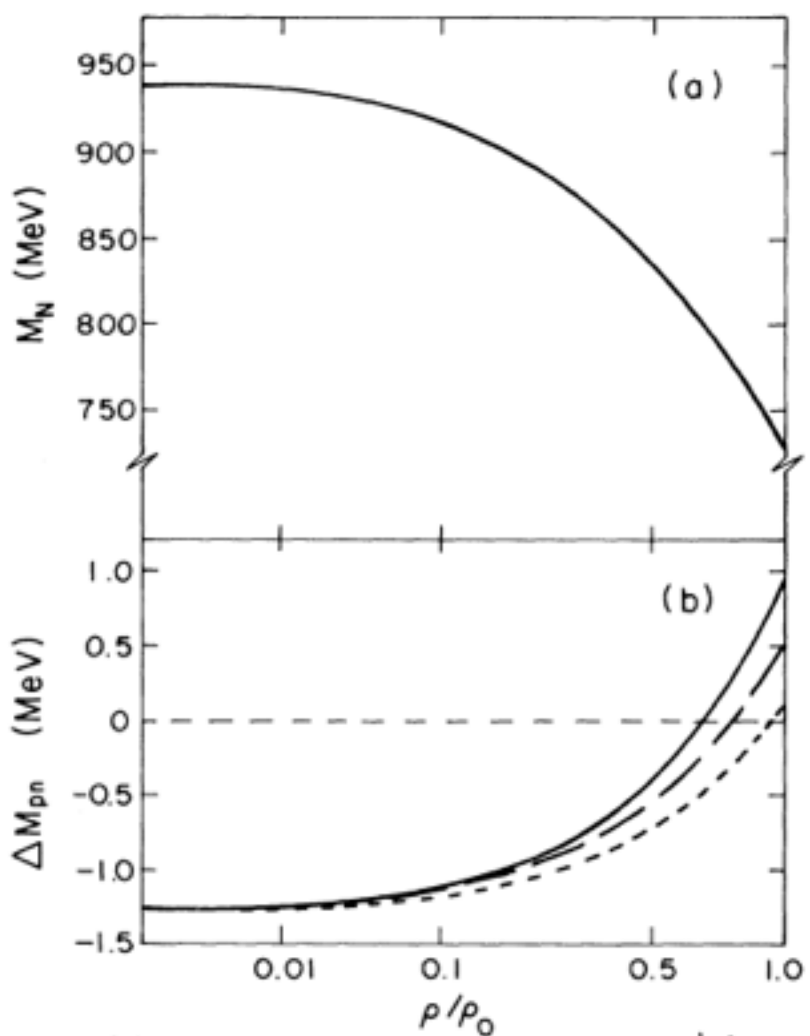
Science **347** (6229), 1452-1455.
DOI: 10.1126/science.1257050



Nambu–Jona-Lasinio Model and Charge Independence

E. M. Henley and G. Krein[(a)]
Institute for Nuclear Theory, Department of Physics, FM-15, University of Washington, Seattle, Washington 98195
(Received 28 September 1988)

For different up and down current quark masses, charge independence follows in the Nambu–Jona-Lasinio model from chiral-symmetry breaking; however, chiral symmetry is restored at high densities. The dependence of the constituent quark masses and the neutron-proton mass difference on the density are examined. The effect of the up-down-quark mass difference on the neutron-proton mass difference is large and in the right direction to explain the Nolen-Schiffer anomaly.



The proton mass gets closer to the neutron mass in medium

Computation of the masses

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 ?

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:

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

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

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

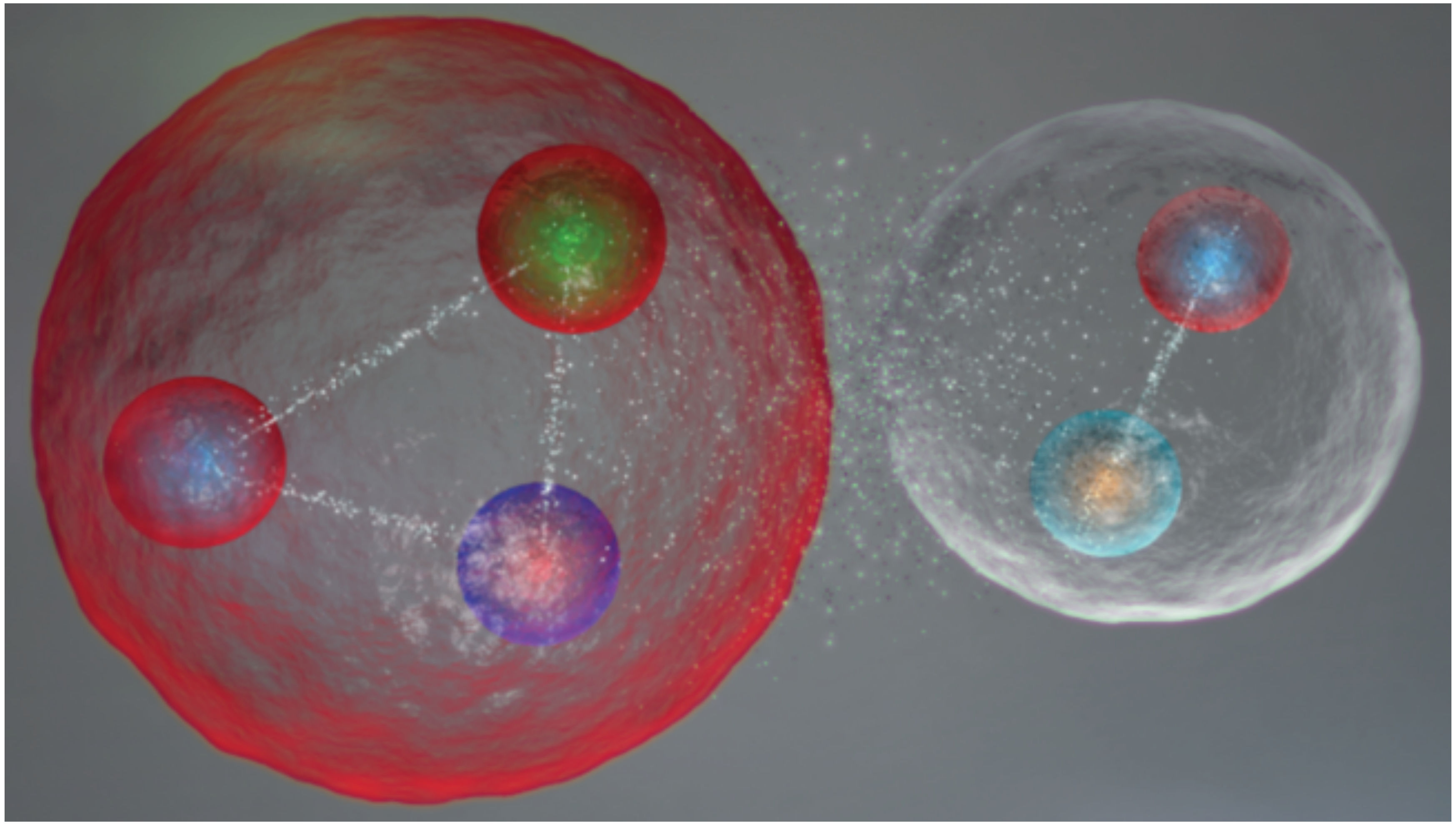
$$\langle h|g^2 G^a_{\mu\nu} G^{a\mu\nu}|h\rangle$$

contributes to threshold quarkonium-nucleon scattering

Bhanot & Peskin, Kaidalov & Volkovitsky, Voloshin et al,

Kharzeev, Hoodbhoy, Brodsky et al., Luke et al, Swanson, …

Quarkonium-nucleon



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

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:

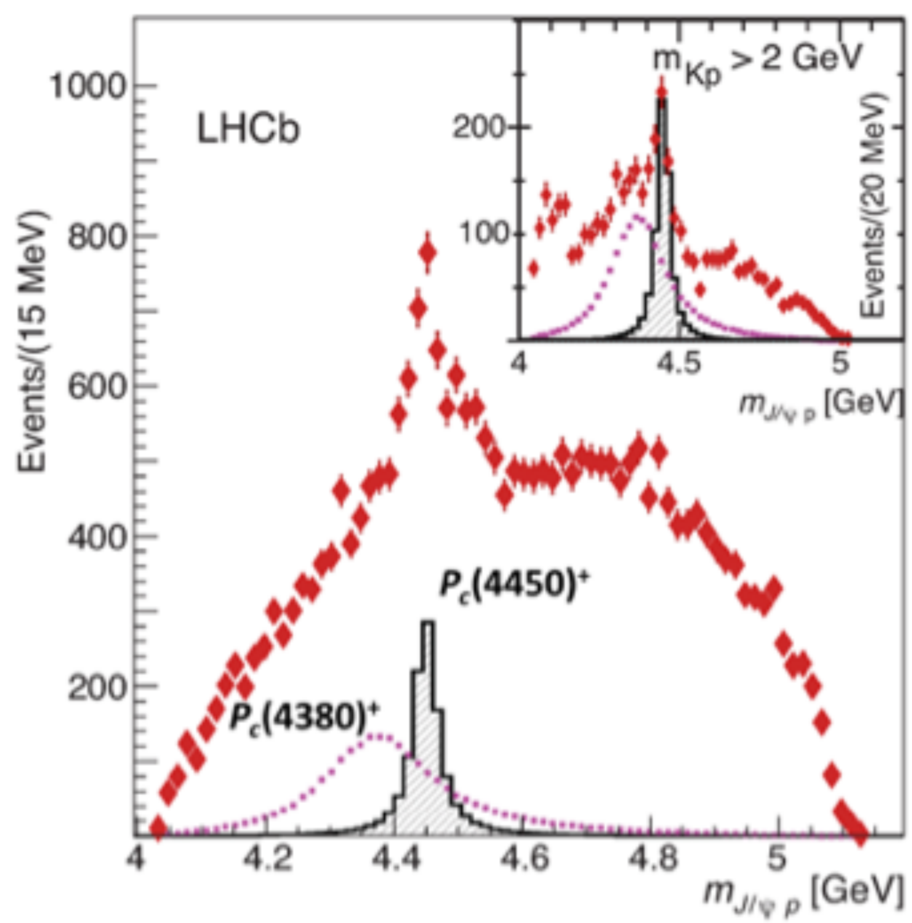
$$a_{\varphi N} = -\left(\frac{\mu_{\varphi N}}{2\pi}\right) \mathcal{A}_{\varphi N} = -\left(\frac{\mu_{\varphi N}}{4\pi}\right) \alpha_\varphi \langle N| \left(g\vec{E}\right)^2 |N\rangle$$

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



Why quarkonium in nuclei?

— scattering amplitude is enhanced

— new exotic nuclear state

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

Brodsky, Schmidt & de Teramond, Ko et al., Brodsky & Miller, Weise et al., Kharzeev, Sibirtseev & Voloshin. …

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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Quarkonium behaves as a small color dipole immersed in a uniform gluon field

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

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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 experiment, no need for a nuclear model

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:

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

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

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

J/Ψ in nuclei

— nuclear potentials

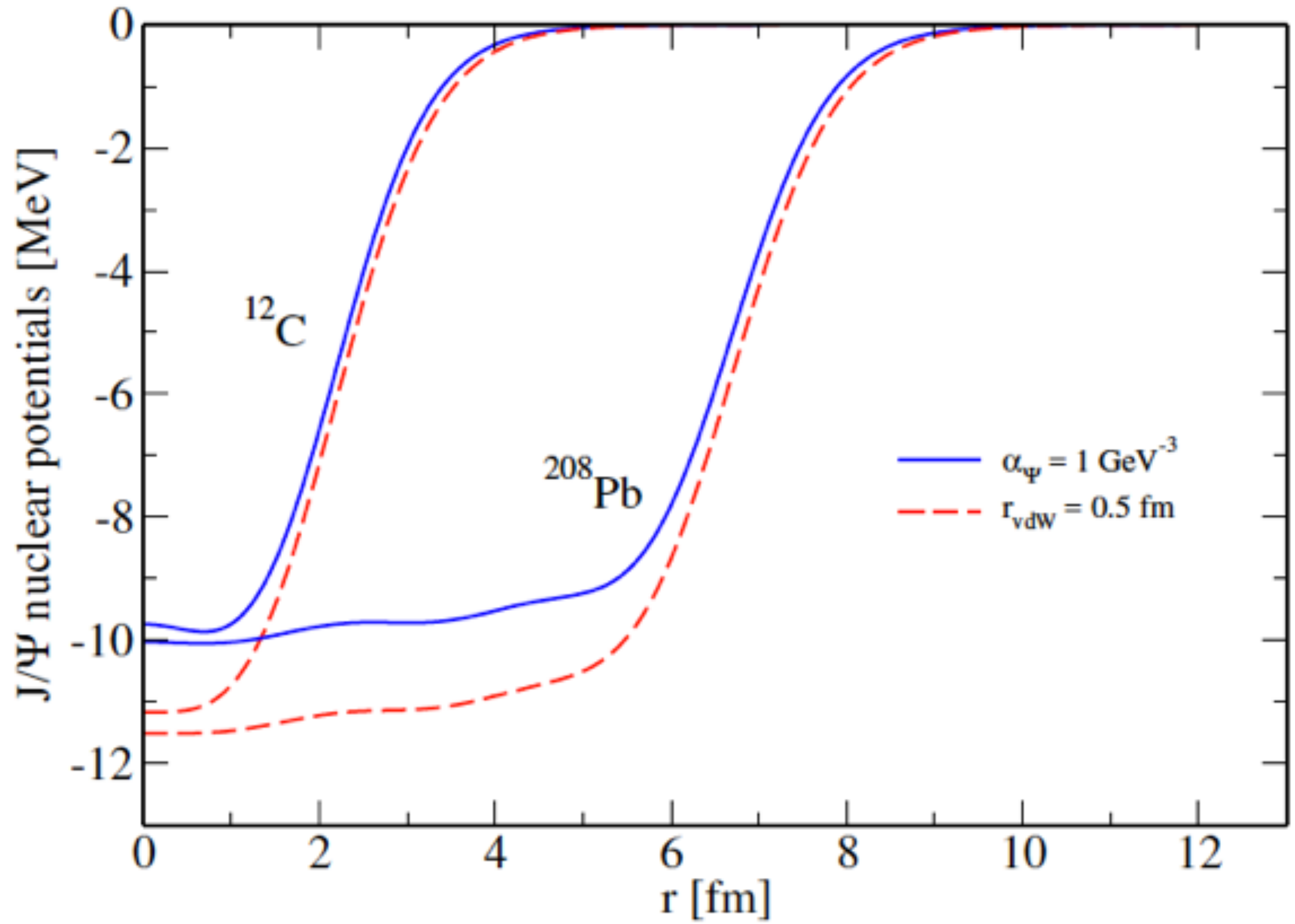

Figure 8: J/Ψ nuclear potentials $W^{\mathrm{pol}}_{J/\Psi A}(\vec{r})$ (solid line) for a polarizability $\alpha_{J/\Psi} = 1$ GeV^{-3} and $W^{\mathrm{latt}}_{J/\Psi A}(\vec{r})$ (dashed line) from a fit to the lattice data with a cutoff $r_{\mathrm{vdW}} = 0.5$ fm.

J/Ψ 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
			$\alpha_{J/\Psi} = 1\ \mathrm{GeV}^{-3}$ ← $a_{J/\Psi N} = -0.18\ \mathrm{fm}$				
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
			$\alpha_{J/\Psi} = 2\ \mathrm{GeV}^{-3}$ ← $a_{J/\Psi N} = -0.36\ \mathrm{fm}$				
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

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]
(NPLQCD Collaboration)

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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

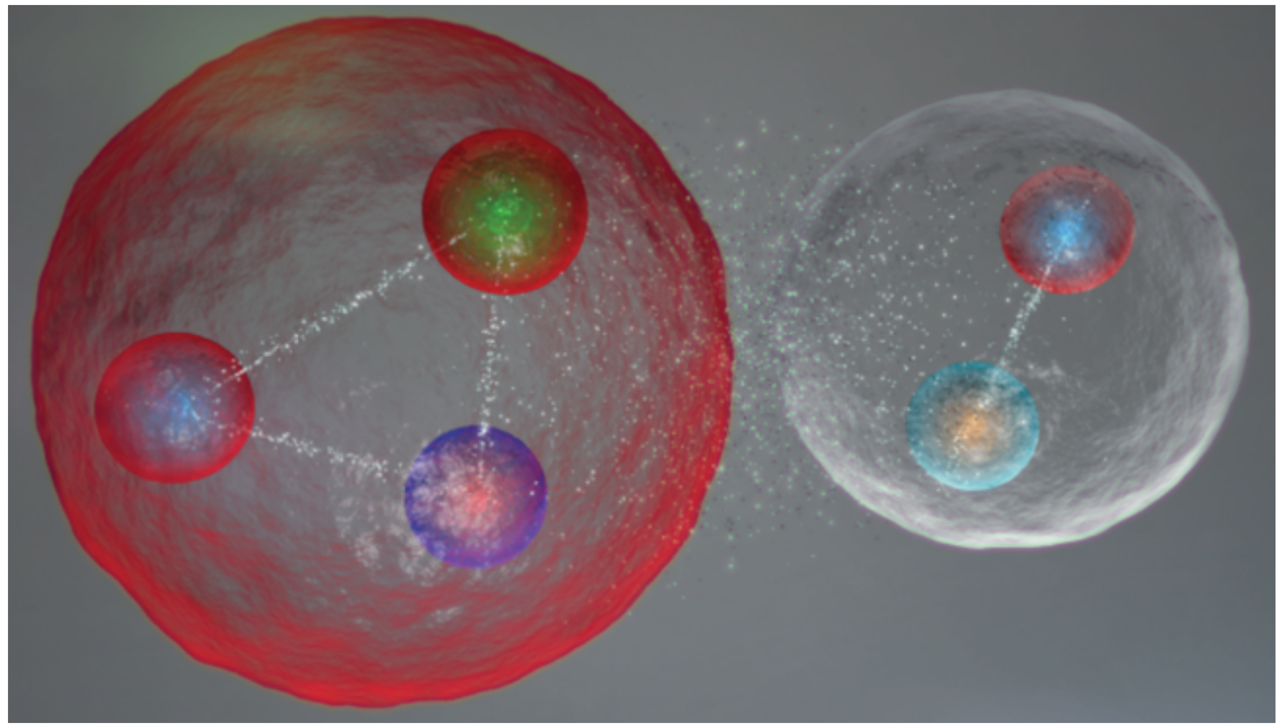
TABLE I. Estimates for the binding energies of charmonium to light nuclei and nuclear matter (in MeV) from selected models. A "*" indicates the system is predicted to be unbound, while entries with center dots indicate that the system was not addressed.

	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.

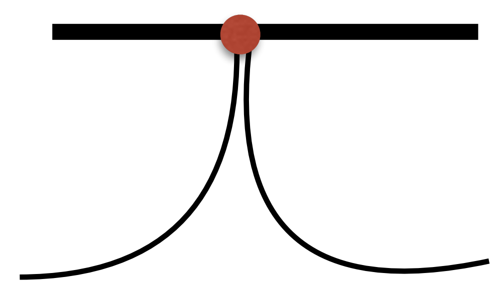
System	$24^3 \times 64$	$32^3 \times 64$	$L = \infty$
$N\eta_c$	17.9(0.4)(1.5)	19.8(0.7)(2.6)	19.8(2.6)
$d\eta_c$	39.3(1.3)(4.8)	42.4(1.1)(7.9)	42.4(7.9)
$pp\eta_c$	37.8(1.1)(4.5)	41.5(1.0)(7.5)	41.5(7.6)
^{3}Heη_c	57.2(1.3)(8.3)	56.7(2.0)(9.4)	56.7(9.6)
^{4}Heη_c	70(02)(13)	56(06)(17)	56(18)
^{4}HeJ/ψ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



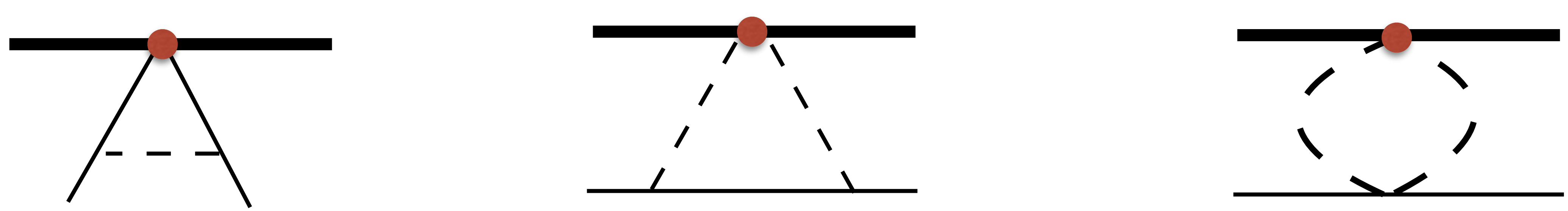
Can one do better?

Quarkonium-nucleon*

Lattice



Chiral EFT



J.T. Castellà, GK
PRD (2018), 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

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

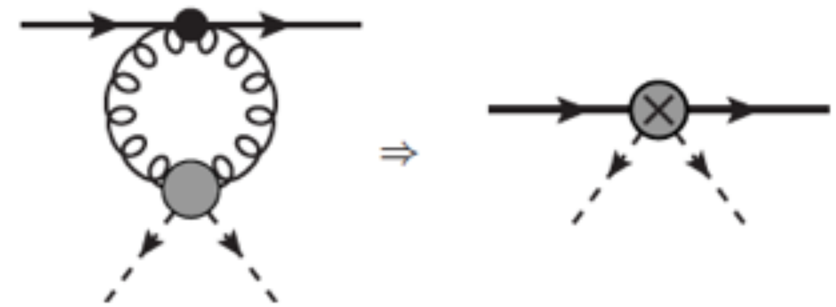
Nucleon-pion

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

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

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

Quarkonium-Pion



$$\mathcal{L}^{\phi-\pi} = \frac{F^2}{4}\phi^\dagger\phi\left(c_{d0}\langle u_0 u_0\rangle + c_{di}\langle u_i u^i\rangle + c_m\langle\chi_+\rangle\right)$$

$$c_{d0} = -\frac{4\pi^2\alpha_\phi}{b}\kappa_1$$

$$c_{di} = -\frac{4\pi^2\alpha_\phi}{b}\kappa_2$$

$$c_m = -\frac{12\pi^2\alpha_\phi}{b}$$

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

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

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

Chromopolarizability

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

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

Quarkonium-nucleon potential — pQNEFT

Integrate out the pion

$$
\begin{aligned}
\mathcal{L}^{\mathrm{pQNEFT}} =& N^\dagger\left(i\partial_0+\frac{\boldsymbol{\nabla}^2}{2m_N}\right)N+\phi^\dagger\left(i\partial_0+\frac{\boldsymbol{\nabla}^2}{2m_\phi}\right)\phi \\
&-C_0 N^\dagger N\phi^\dagger\phi-D_1\boldsymbol{\nabla}\left(N^\dagger N\right)\cdot\boldsymbol{\nabla}\left(\phi^\dagger\phi\right) \\
&-D_2\left(N^\dagger\overleftrightarrow{\boldsymbol{\nabla}}N\right)\cdot\left(\phi^\dagger\overleftrightarrow{\boldsymbol{\nabla}}\phi\right)-D_3\boldsymbol{\nabla}N^\dagger\cdot\boldsymbol{\nabla}N\phi^\dagger\phi-D_4N^\dagger N\boldsymbol{\nabla}\phi^\dagger\cdot\boldsymbol{\nabla}\phi \\
&-\int d^3r\,N^\dagger N(t,\boldsymbol{x}_1)V(\boldsymbol{x}_1-\boldsymbol{x}_2)\phi^\dagger\phi(t,\boldsymbol{x}_2)
\end{aligned}
$$

Matching

Renormalization of couplings + van der Waals

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

Long-distance part of QN potential — vdW force

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

$$\left. + c_m m_\pi^2 r^2 \left(1 + m_\pi r\right)^2\right\}$$

No free parameters here:

— trace anomaly

— chiral physics

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

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

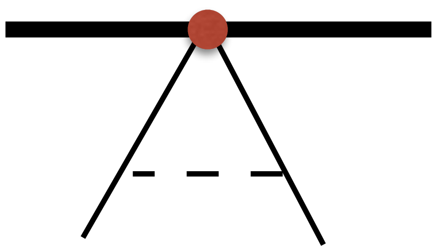
$$V(r) = \frac{3g_A^2 m_\pi^4 \left(c_{di} + c_m\right)}{128\pi^2 F^2} \frac{e^{-2m_\pi r}}{r^2}$$

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}]
[27]	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	$-0.39(14)$	$-17(6)$	
[29]		η_c	$-0.25(5)$	$-8(2)$	Quenched
		J/ψ	$-0.35(6)$	$-12(3)$	
[28]		η_c	$-0.18(9)$	$-9.7(1.2)$	14.7(4.8)
		J/ψ	$-0.40(80)$	$-12(18)$	$-100(80)$
[12]		$\alpha_{J/\Psi}$ [GeV^{-3}]			
		2	-0.37	-16.5	
		0.24	-0.05	-2.0	

Lattice:

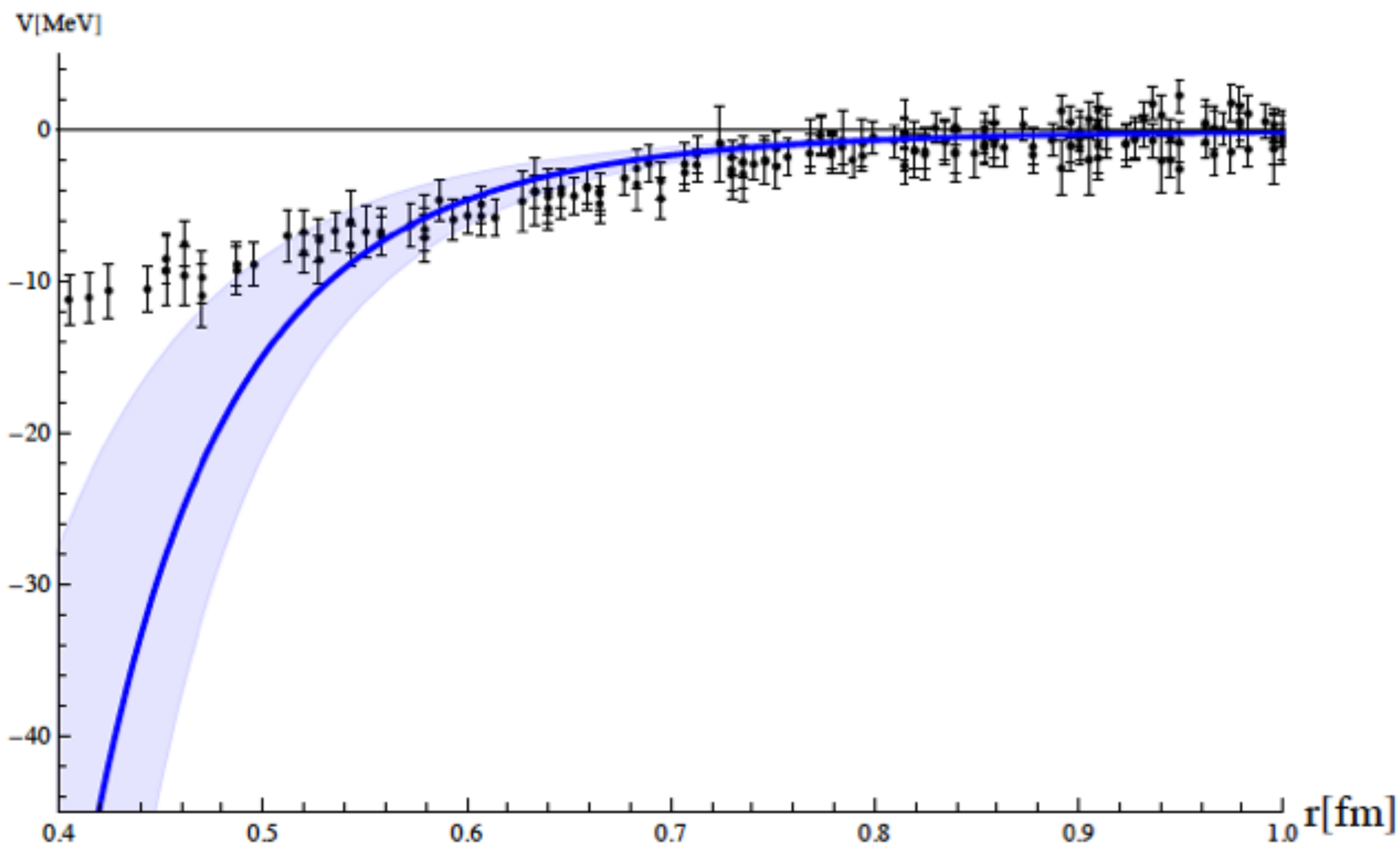
[27] Yokokawa et al PRD 74, 034504 (2006)
[28] Liu et al PoS (LATTICE) 2008, 112 (2008)
[29] Kanaway & Sasaki PoS (LATTICE) 2010, 156 (2010)

Comparing long distance part with HAL lattice potential

Kanaway & Sasaki, PRD 82, 091501 (2010)

vdW force

$\eta_c - N$

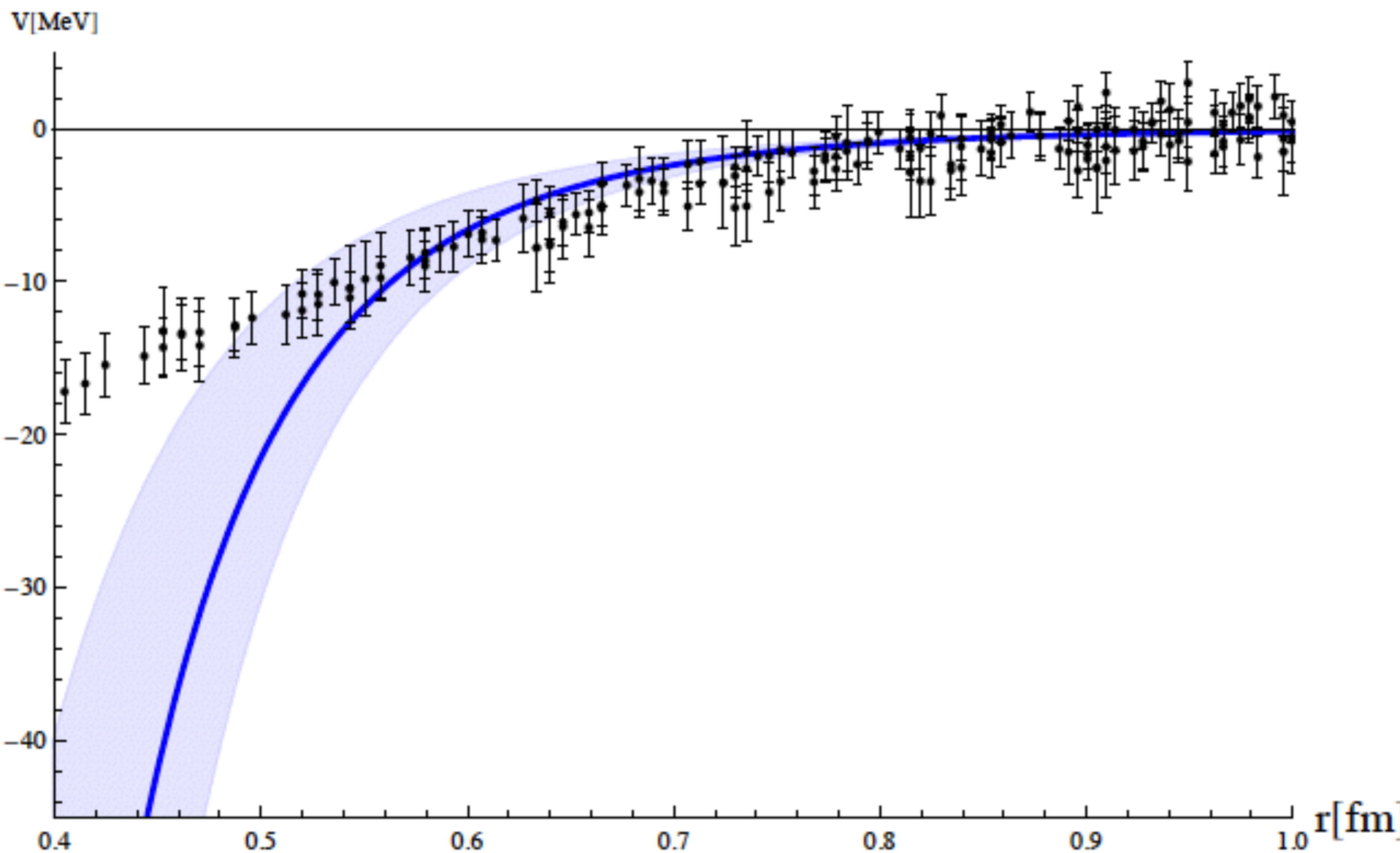


Lattice:

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.

Change of notation

$$\alpha_\varphi \to \beta_\varphi$$

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

Scattering amplitude (s-wave)

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

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

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

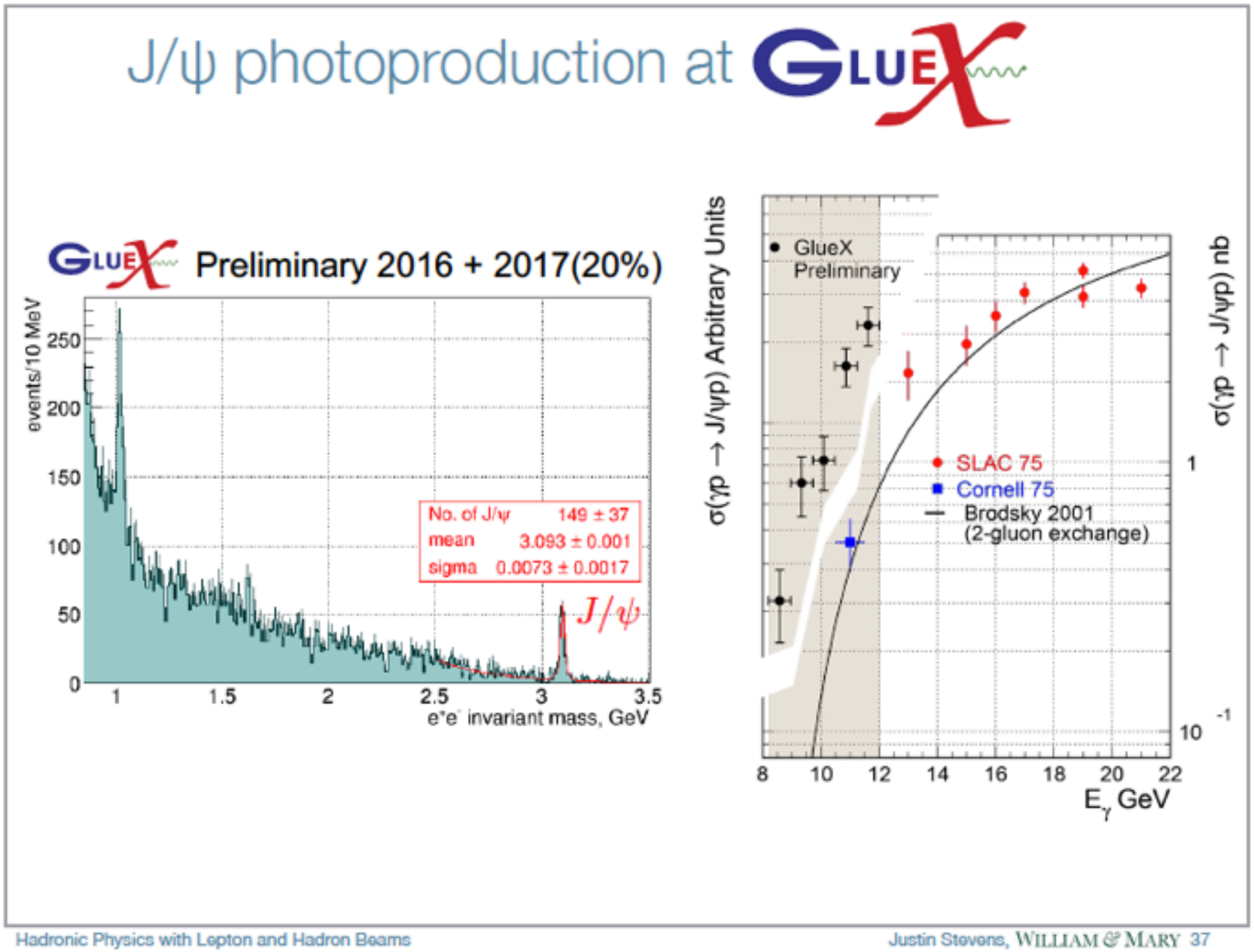
No quarkonium-nucleon bound states within the applicability of the present calculation: $|p_{\phi N}| \leq m_\pi$

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

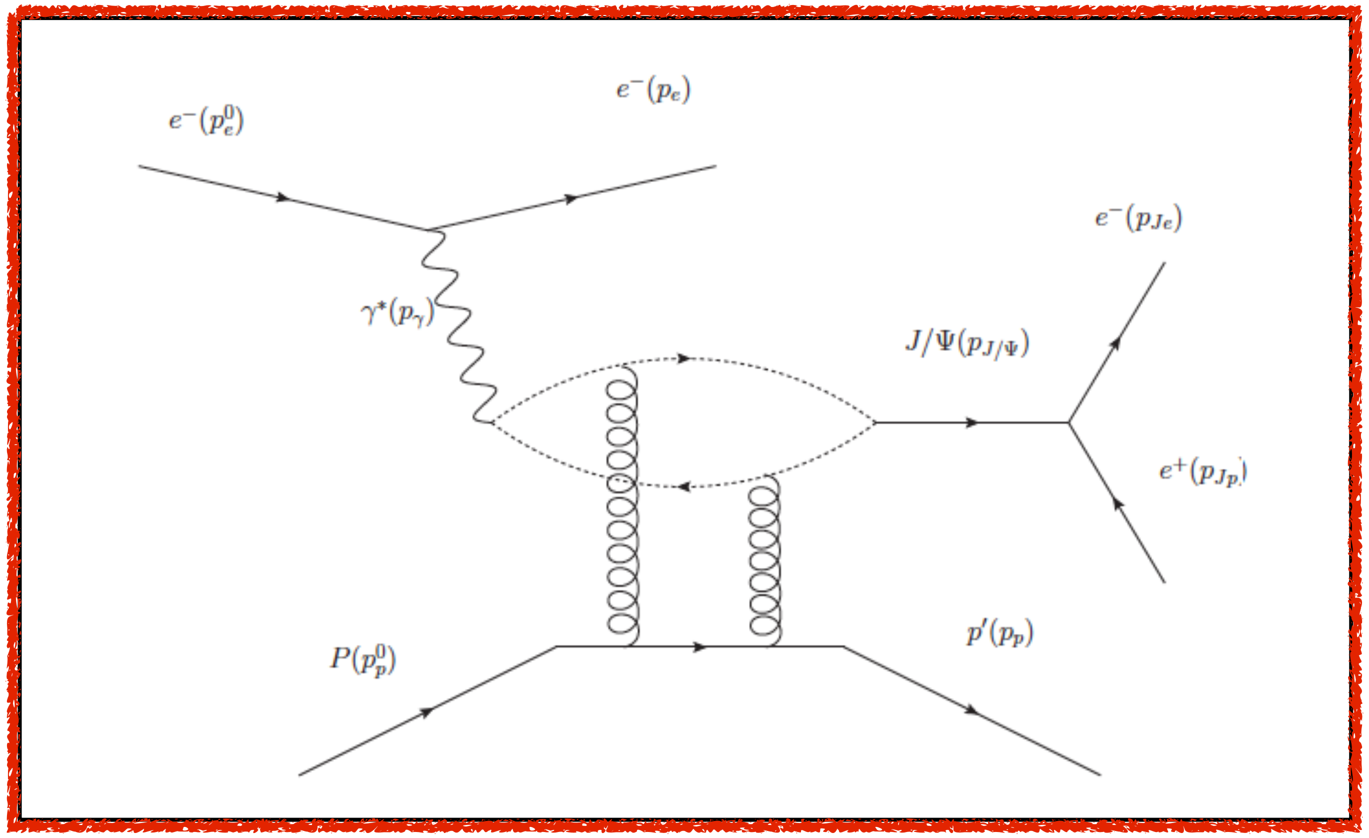
YES, for sufficiently large nuclei

Experiments

— JLab



ATHENNA* collaboration JLab @ 12 GeV



Hall A — E12-12-006

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

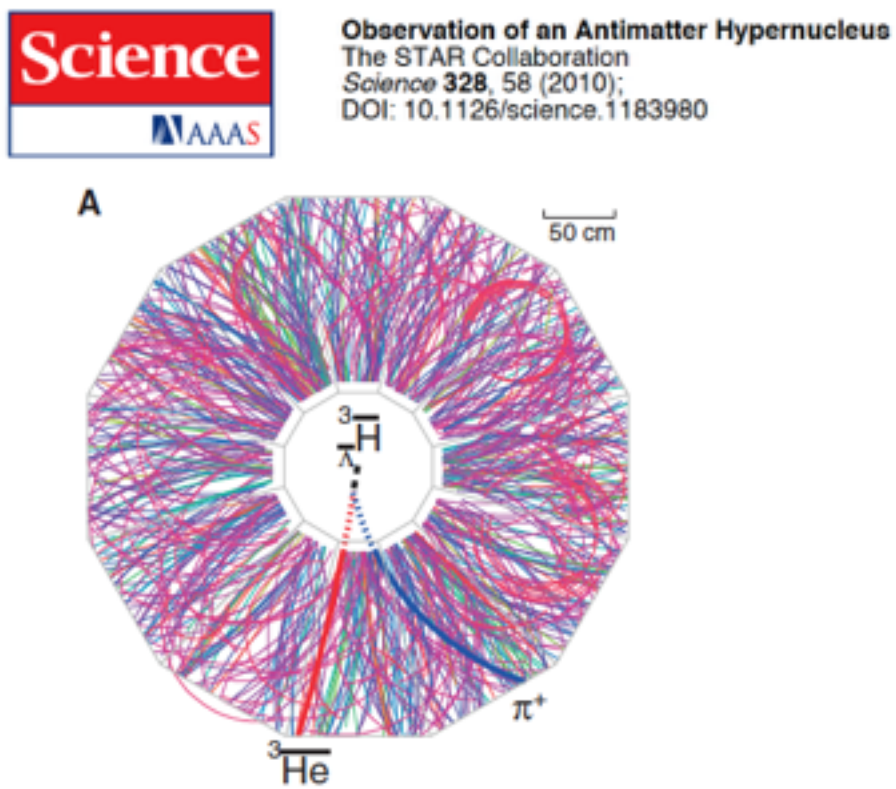
*A J/Ψ THreshold Electroproduction on the Nucleon and Nuclei Analysis

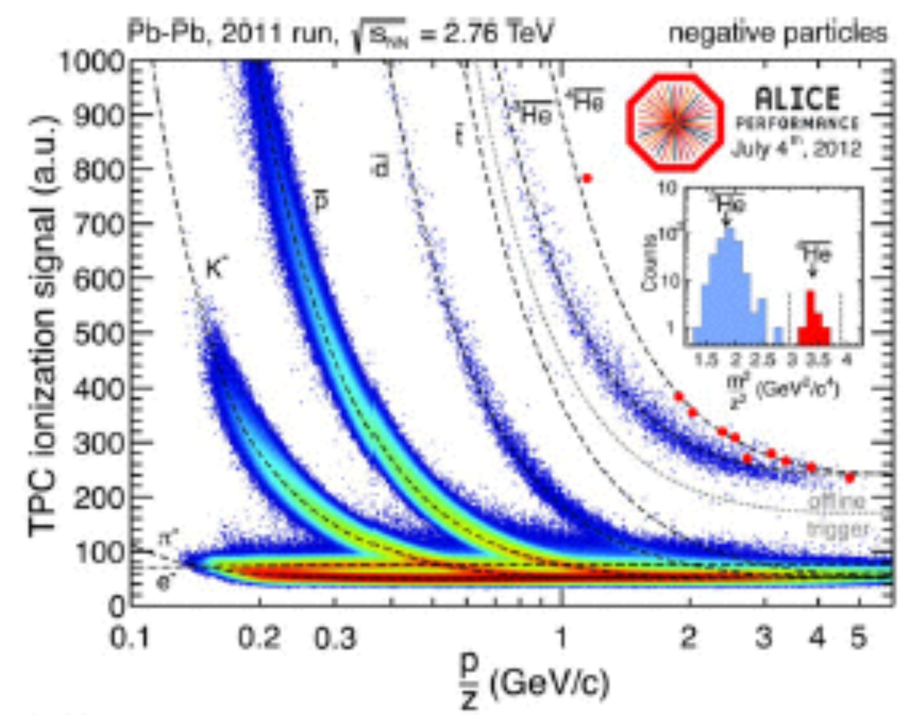
Hall C — E-12-16-007 (Pentaquarks)

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

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

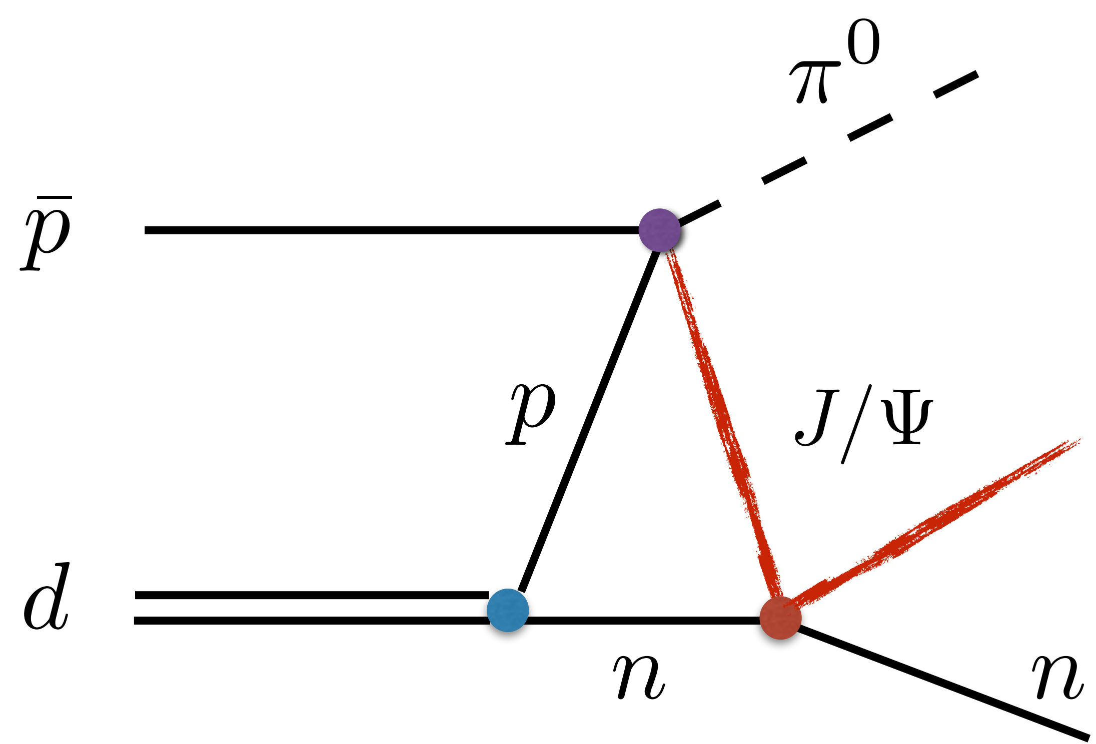




Need to detect in coincidence
the decay products

Antiproton annihilation on deuteron, J/Ψ re-scattering on spectator nucleon

@ FAIR



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