ORIGIN OF PROTON MASS AND QUARKONIUM IN NUCLEI

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SPRACE

Emergent mass and its consequences in the Standard Model

Trento, September 17 - 21, 2018

Talk based on

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

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

GK
— ongoing work

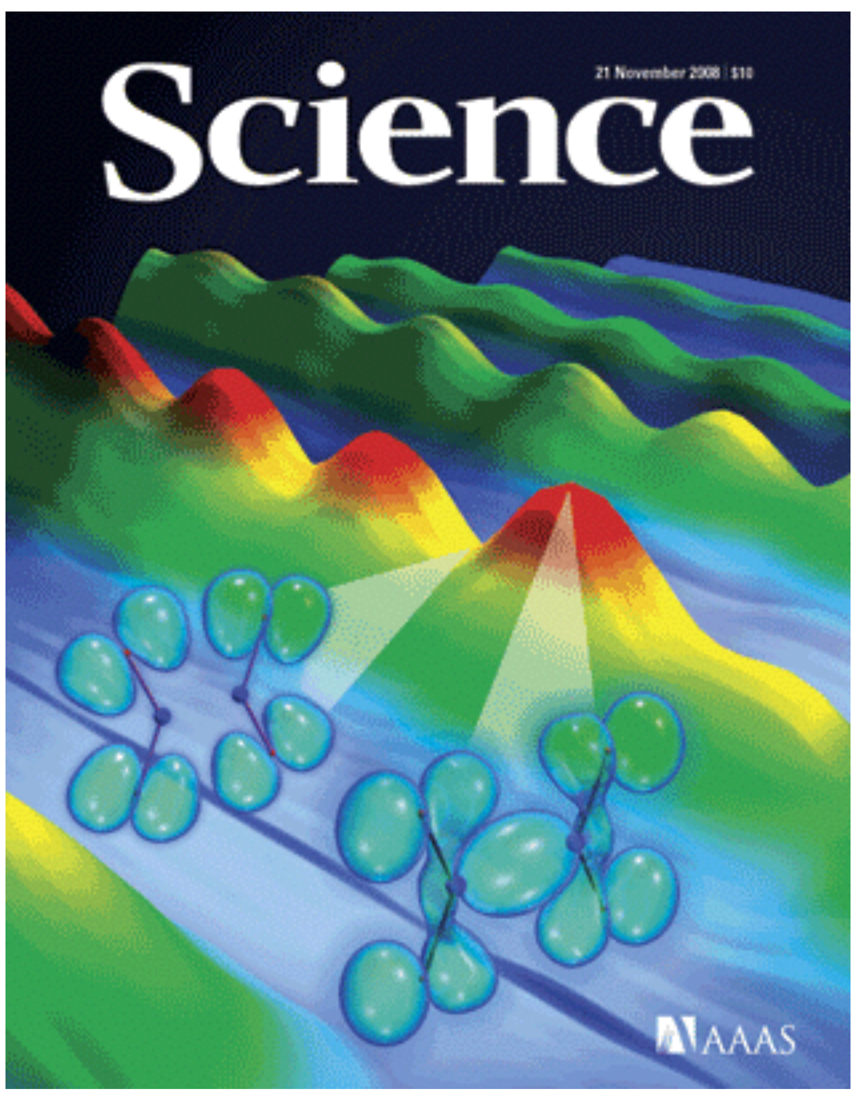
Science

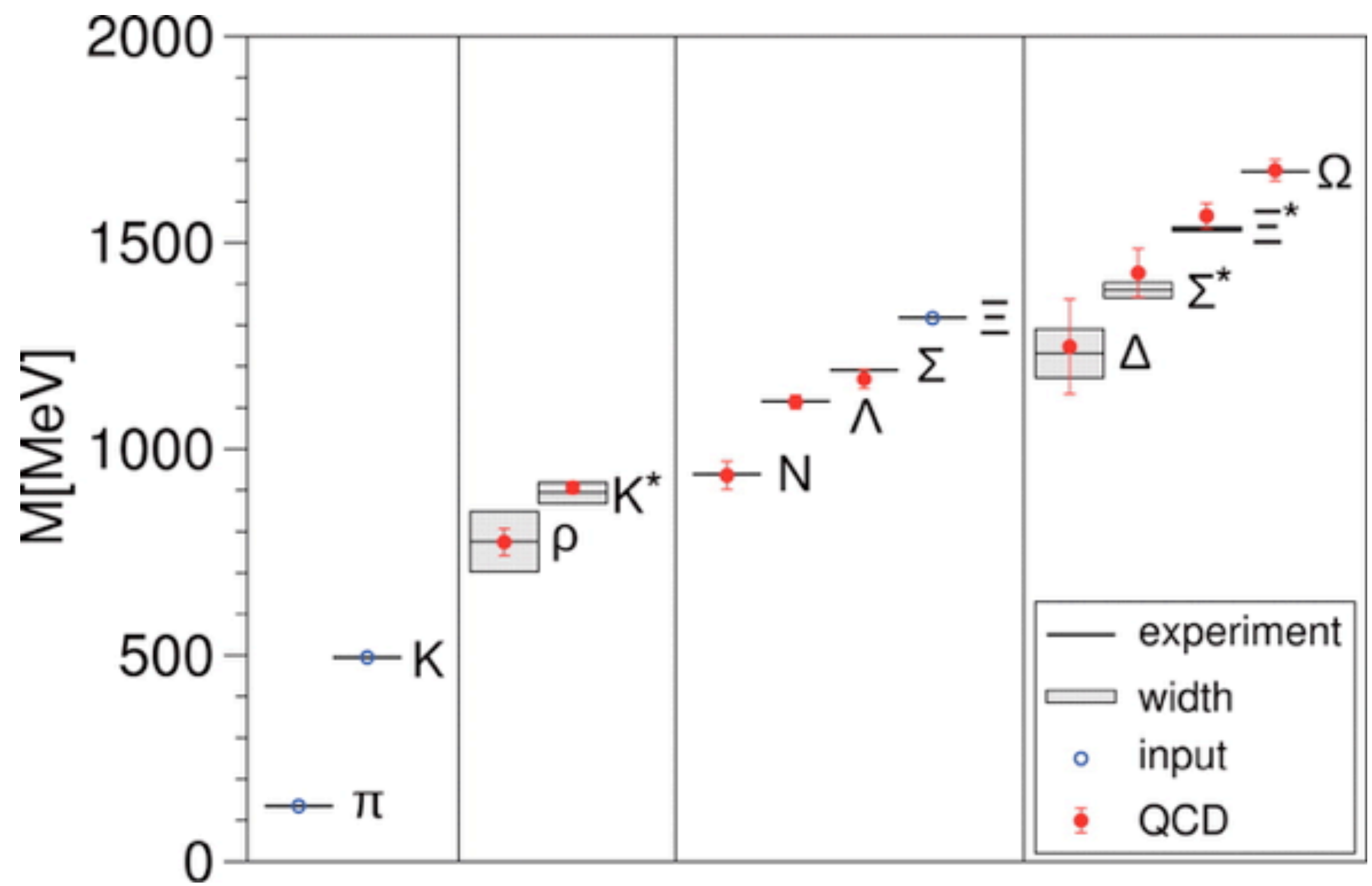
2008

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





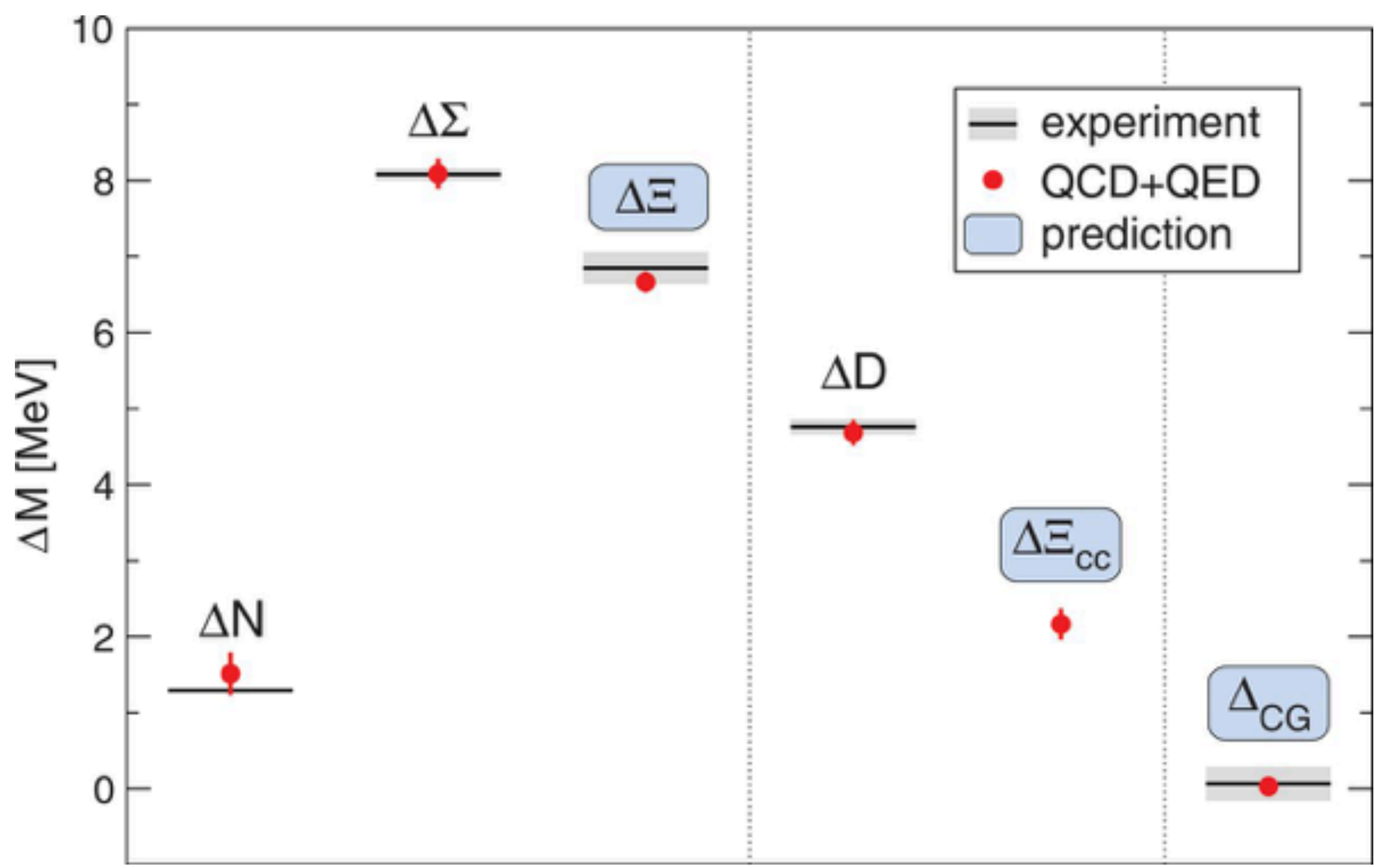
Science

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)

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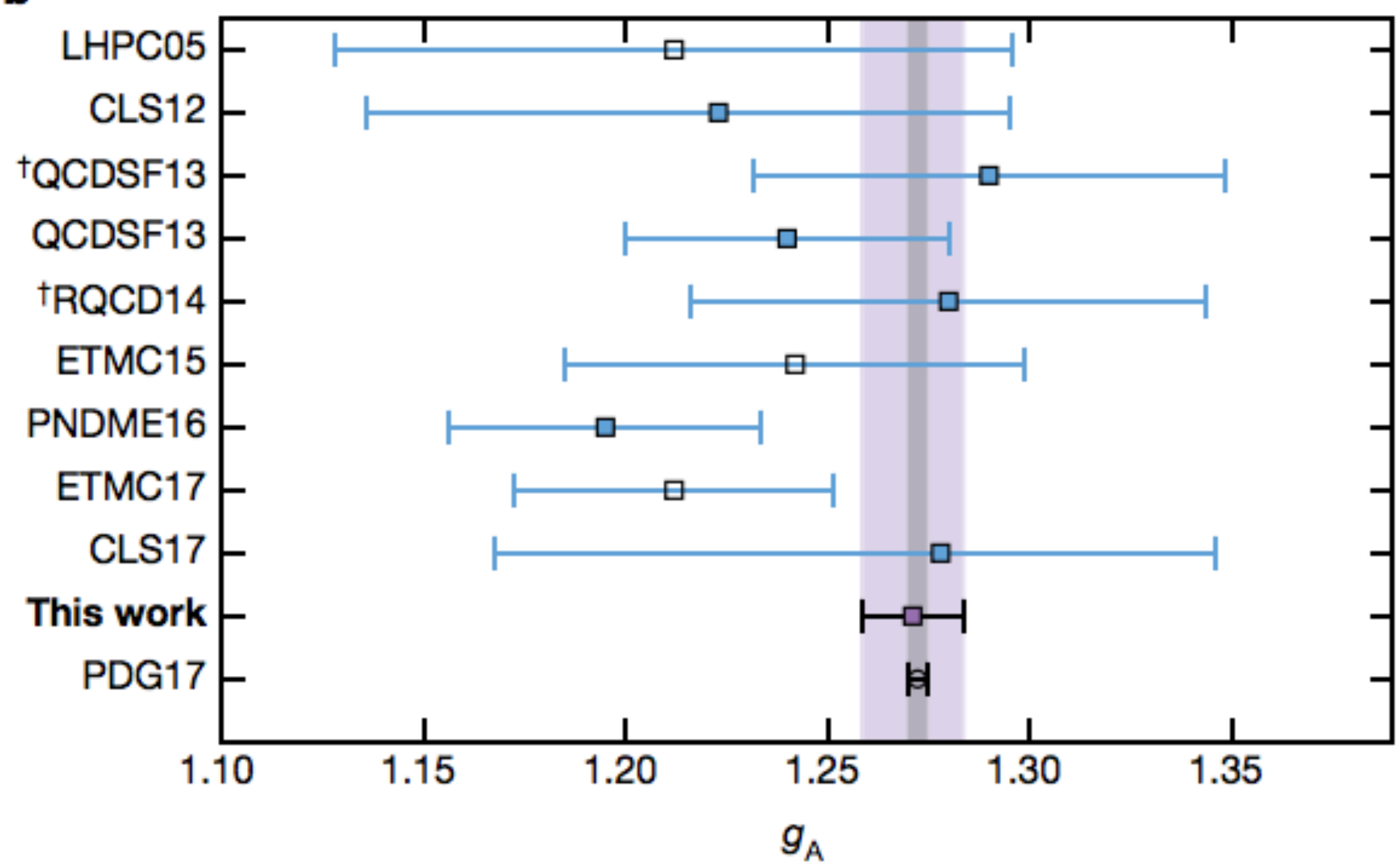


Computation of the masses

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

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

↑

Proton: sigma term
~ 50 MeV

Why is this interesting ?

Because

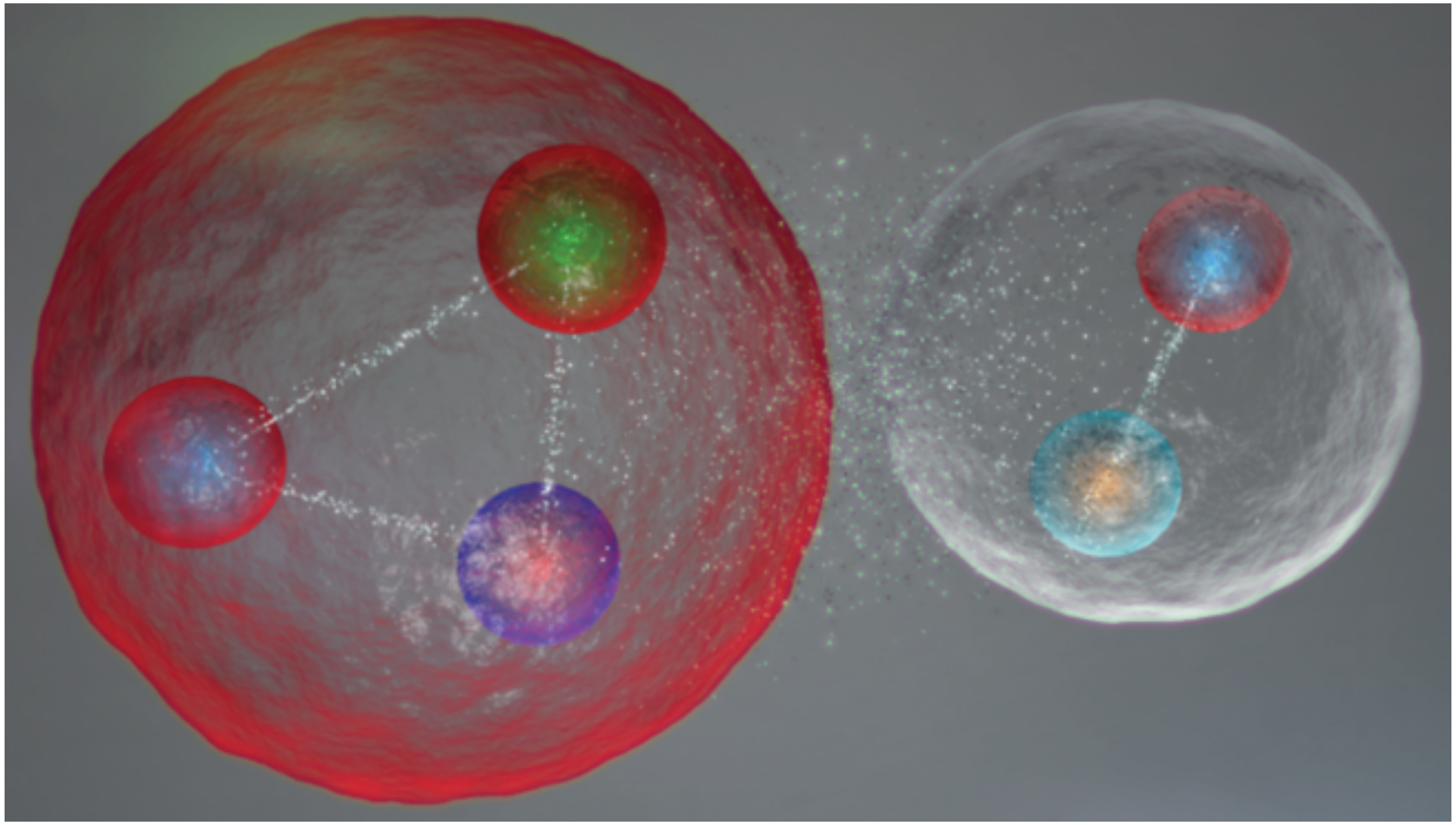
$$\langle h | g^2 G^a_{\mu\nu} G^{a\mu\nu} | h \rangle$$

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

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:

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

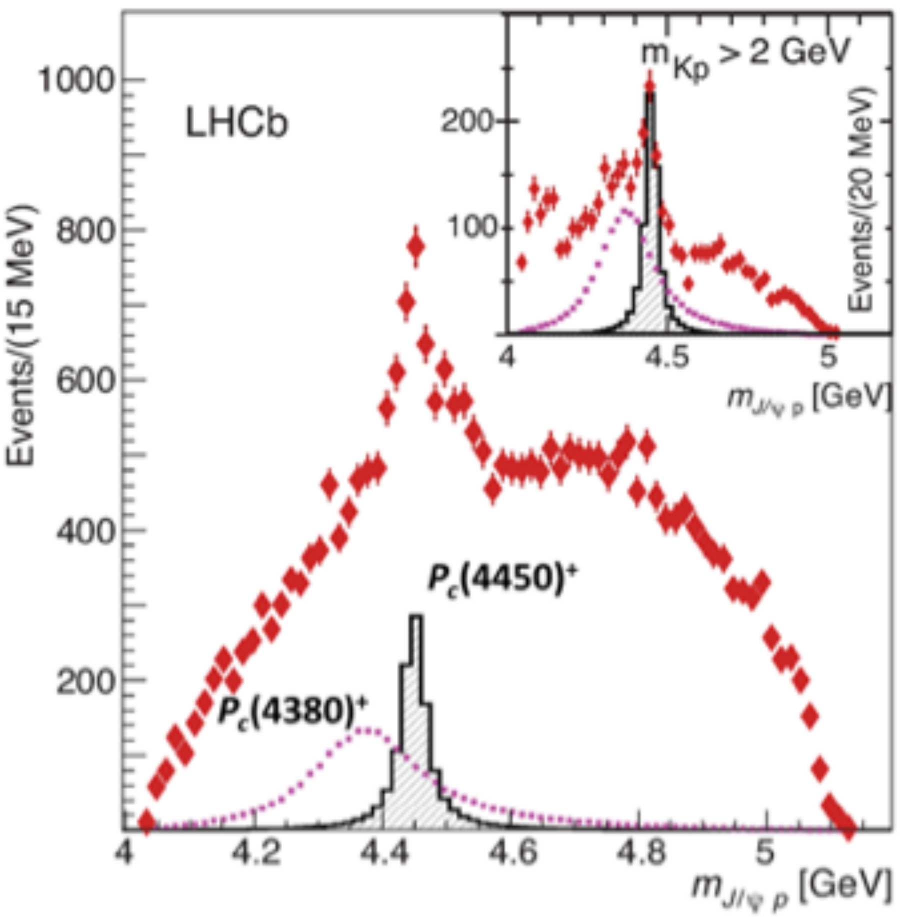
Bound from trace anomaly:

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

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

Quarkonium-nucleon

— also relevant for the LHCb pentaquark



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. …

Scales in nuclei

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

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

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

Recall that:

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

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

Scales in nuclei

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

⇩

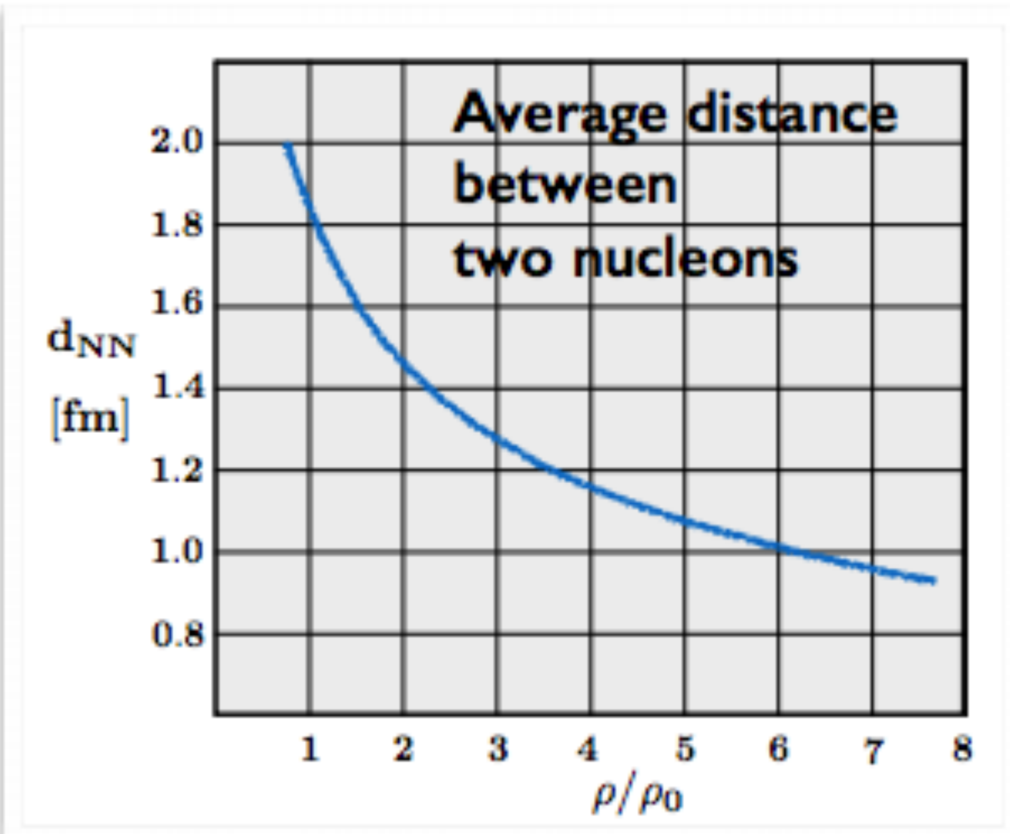
Little (or no) superposition of nucleons in nuclei

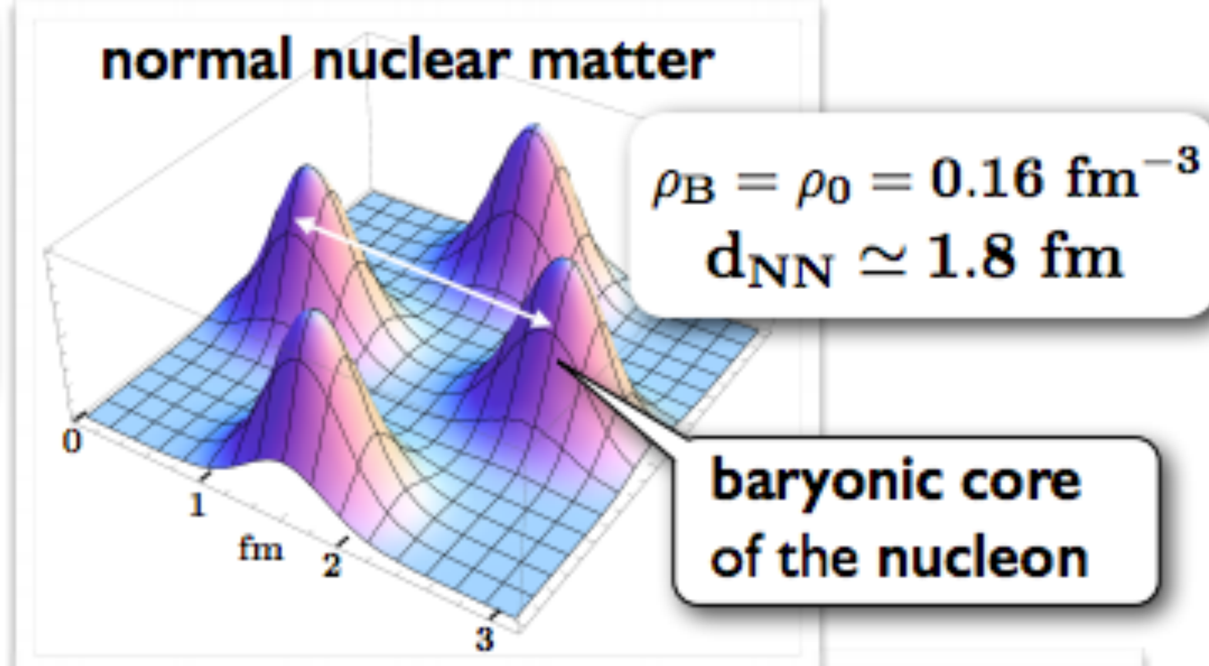
+ Pauli principle (among nucleons) ⇨

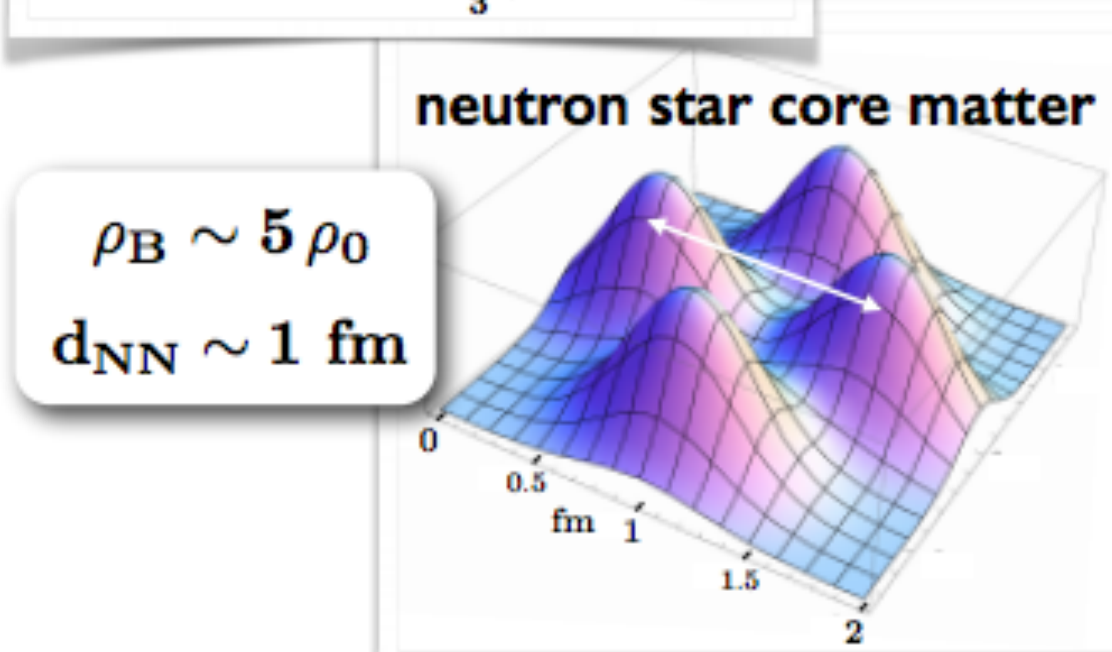
— Independent-particle model
— Mean-field model
— Nuclear shell model

Gomes, Walecka & Weisskopf

Densities and Distance Scales in Baryonic Matter







- (Multi-)pion fields in space between baryonic sources (ChEFT)
- Quark cores of nucleons overlap (percolate) at baryon densities $\rho_B > 5\,\rho_0$

Slide from W Weise

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 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:

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

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

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

Scattering length
— where from?

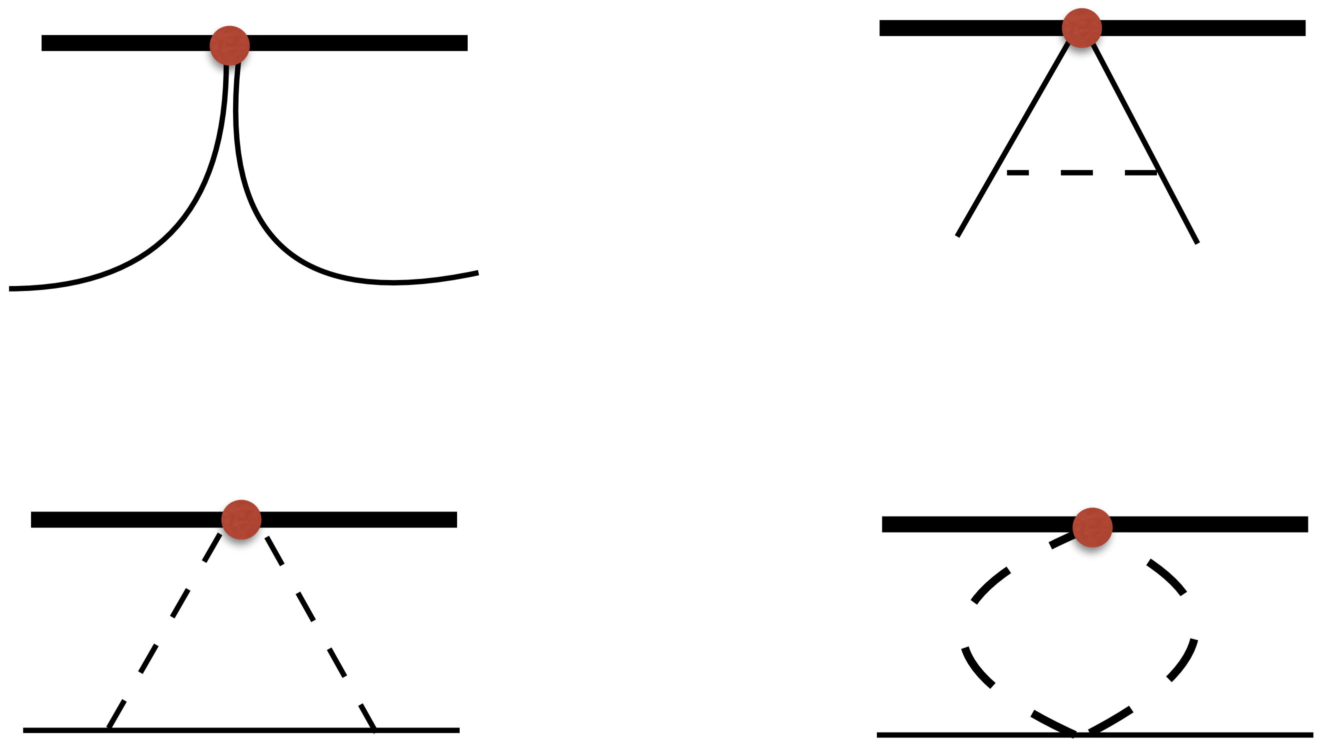
No experiment yet, look at lattice:

- — K Yokokawa, S Sasaki, T Hatsuda & A Hayashigata, PRD 74, 034504 (2006)
- — L Liu, H-W Lin & K Orginos, PoS (LATTICE) 2008, 112 (2008)
- — T Kawanai & S Sasaki, PoS (LATTICE2010) 2010, 156 (2010)
- — S R Beane, E Chang, SD Cohen, W Detmold, H-W Lin, K Orginos, A Parreño & MJ Savage, PRD 91, 114503 (2015)
- — M Alberti, G Bali, S Collins, F Knechtli, G Moir & W Söldner, PRD 95, 074501 (2017)
- — T Kawanai & S Sasaki, Phys. Rev. D 82, 091501 (2018)
- — T Sugiura, Y Ikeda & N Noriyoshi EPJ Web Conf 175, 05011 (2018)

Need extrapolation to physical pion masses

EFT for quarkonium-nucleon

Quarkonium polarizability + Chiral EFT



JT Castellà & GK
PRD **98**, 014029 (2018)

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

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

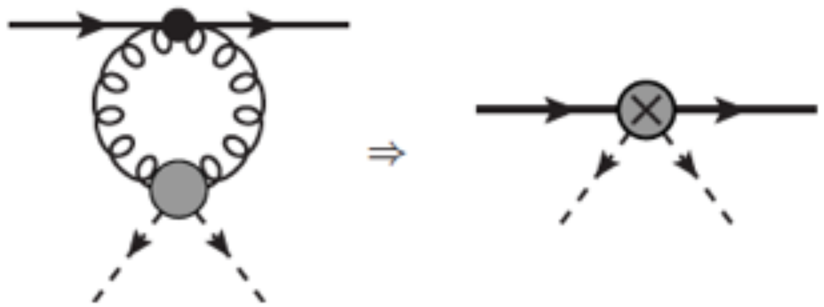
Nucleon-pion

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

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

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

Quarkonium-Pion



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

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

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

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

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

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

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

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

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

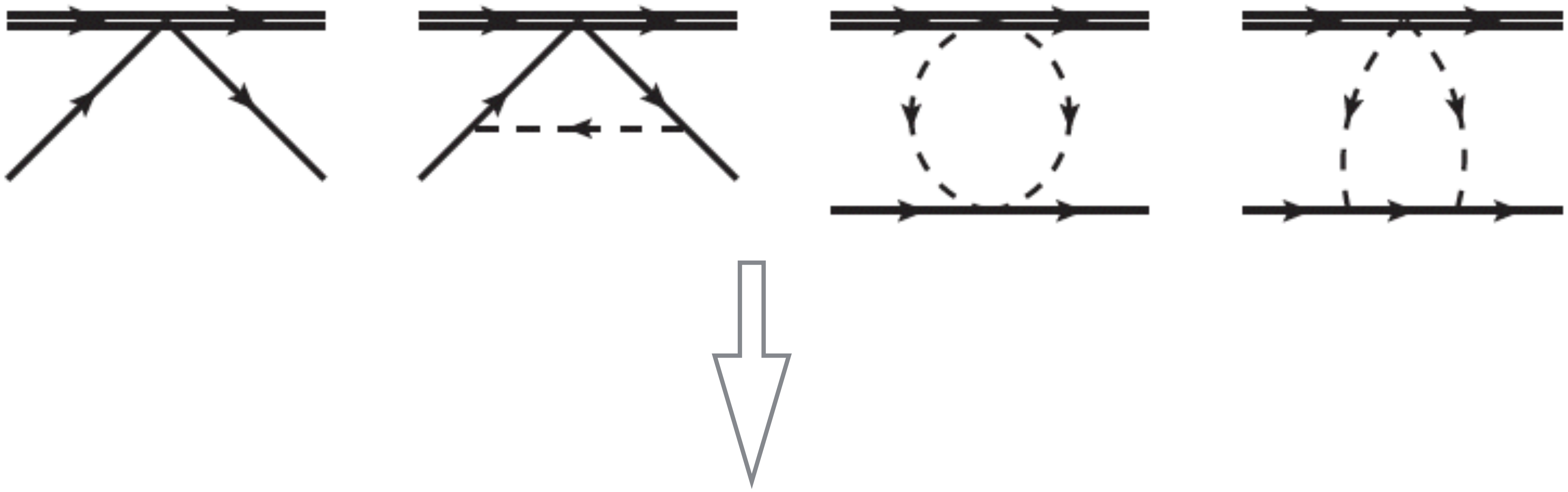
Integrate out the pion

Quarkonium-nucleon potential — pQNEFT

Integrate out the pion

$$
\begin{aligned}
\mathcal{L}^{\mathrm{pQNEFT}} =& N^\dagger \left(i\partial_0 + \frac{\boldsymbol{\nabla}^2}{2m_N} \right) N + \phi^\dagger \left(i\partial_0 + \frac{\boldsymbol{\nabla}^2}{2m_\phi} \right) \phi \\
& - C_0 N^\dagger N \phi^\dagger \phi - D_1 \boldsymbol{\nabla} \left(N^\dagger N \right) \cdot \boldsymbol{\nabla} \left(\phi^\dagger \phi \right) \\
& - D_2 \left(N^\dagger \overleftrightarrow{\boldsymbol{\nabla}} N \right) \cdot \left(\phi^\dagger \overleftrightarrow{\boldsymbol{\nabla}} \phi \right) - D_3 \boldsymbol{\nabla} N^\dagger \cdot \boldsymbol{\nabla} N \phi^\dagger \phi - D_4 N^\dagger N \boldsymbol{\nabla} \phi^\dagger \cdot \boldsymbol{\nabla} \phi \\
& - \int d^3r\, N^\dagger N(t, \boldsymbol{x}_1) V(\boldsymbol{x}_1 - \boldsymbol{x}_2) \phi^\dagger \phi(t, \boldsymbol{x}_2)
\end{aligned}
$$

Matching



Renormalization of couplings + van der Waals

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

Scattering amplitude (s-wave)

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

<u>Scattering length</u>

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

<u>Effective range</u>

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

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

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

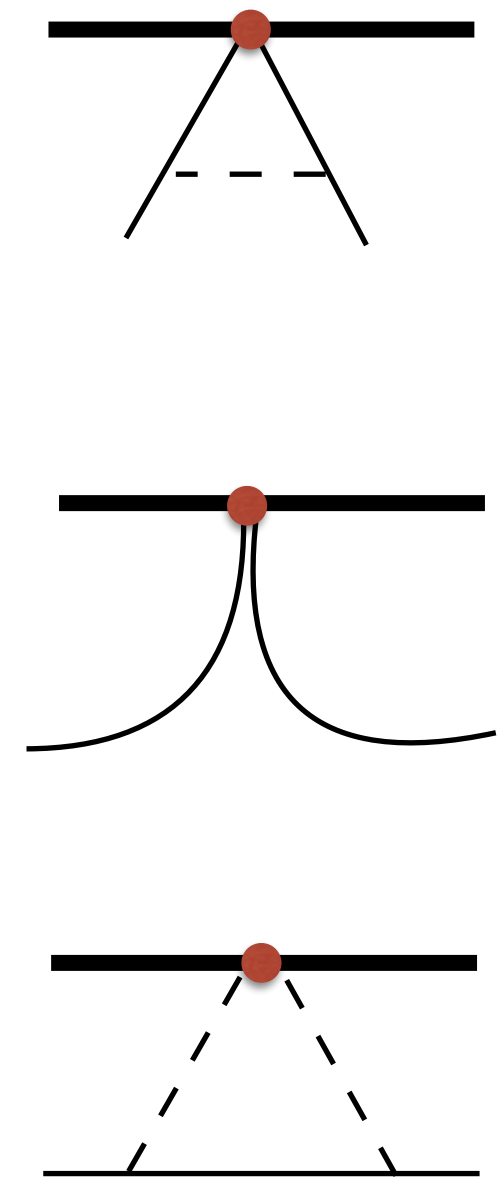
To extrapolate lattice data to physical quark masses, need:

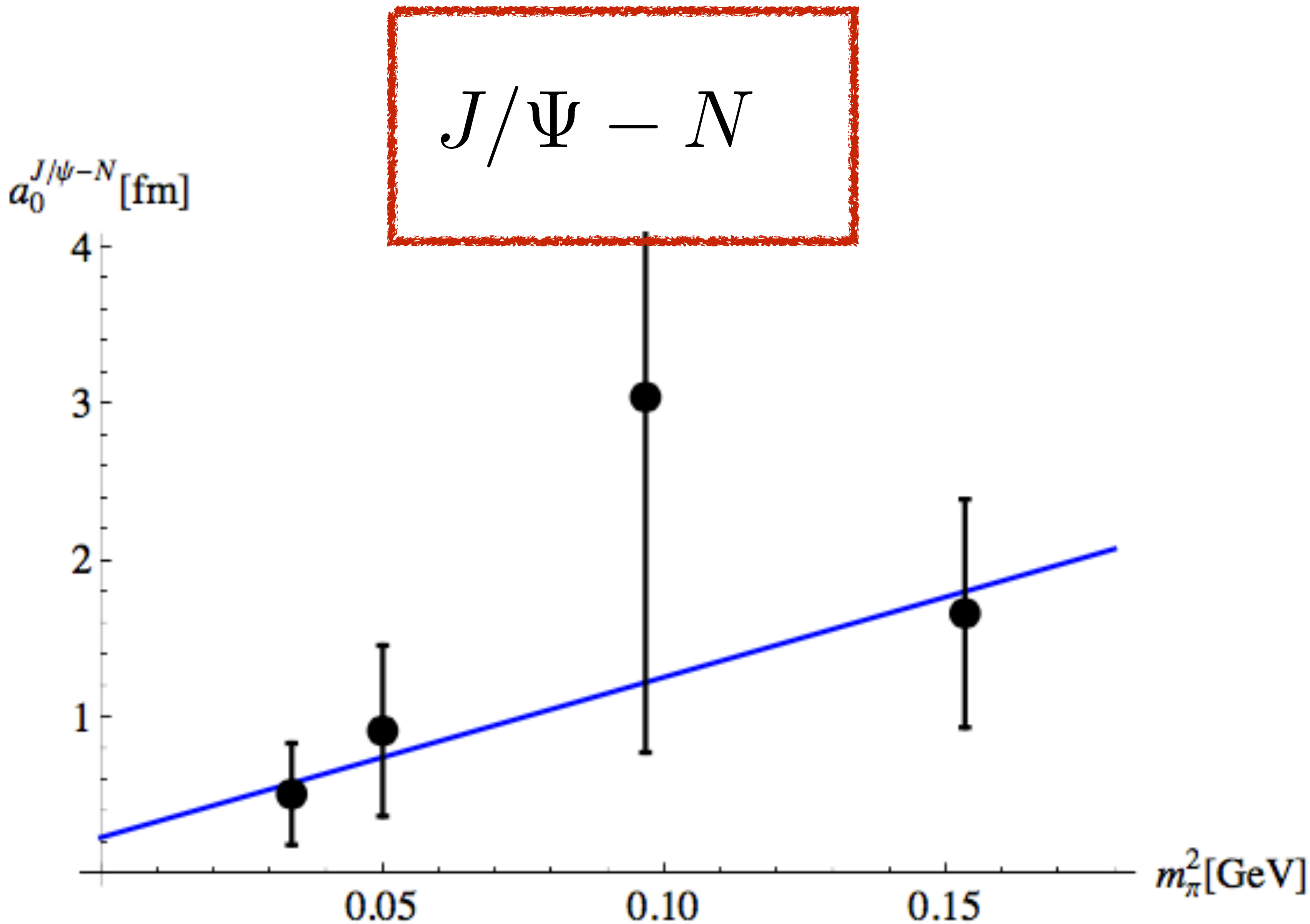
$$\begin{aligned} m_N &= \hat{m}_N - 4c_1 m_\pi^2 - \frac{3g_A^2 m_\pi^3}{32\pi F^2} \\ m_\phi &= \hat{m}_\phi - F^2 c_m m_\pi^2 \end{aligned}$$

Unknown contact couplings

— extrapolate from lattice data*

c_0, d_m, d_1, d_2





* L Liu, H-W Lin & K Orginos PoS (LATTICE) 2008, 112 (2008)

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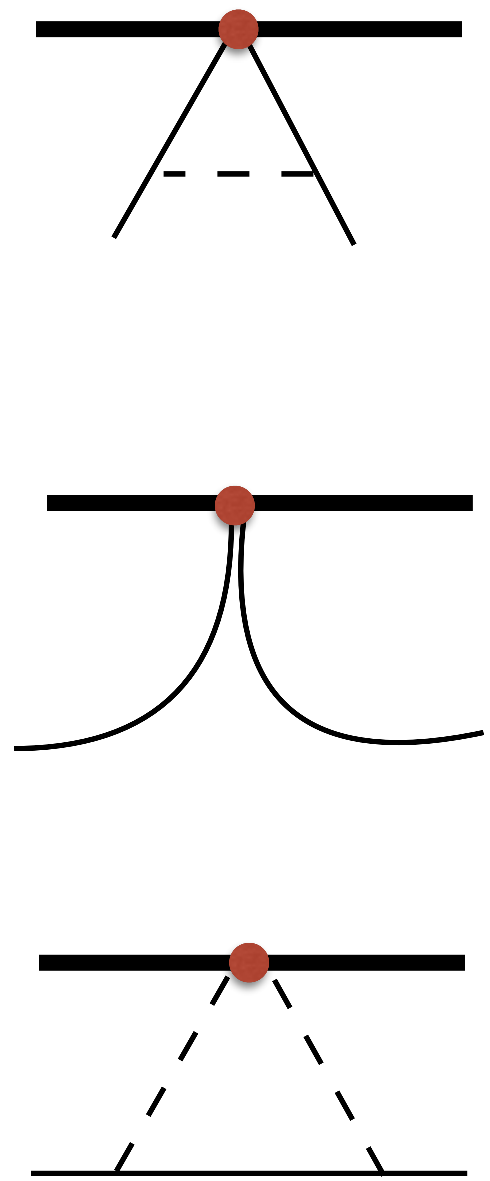
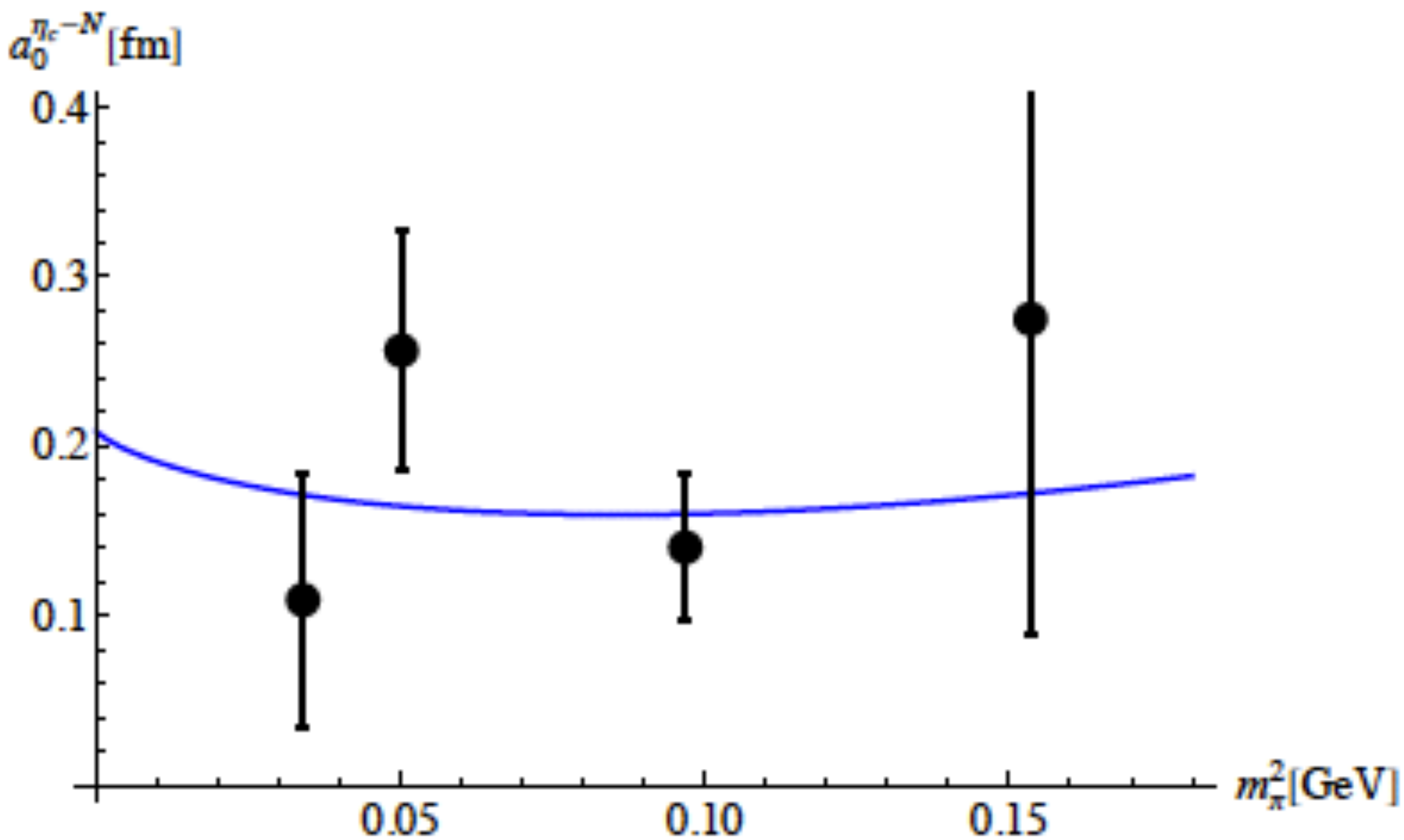


$$\eta_c - N$$

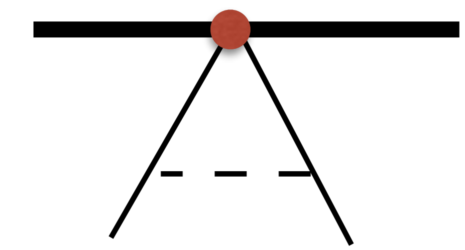


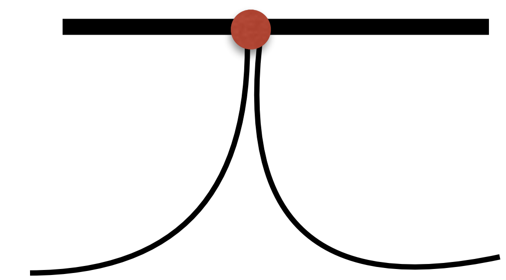
* L Liu, H-W Lin & K Orginos
PoS (LATTICE) 2008, 112 (2008)

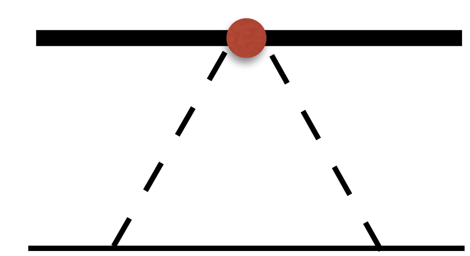
Values of contact couplings

— extrapolation from lattice data*

c_0, d_m, d_1, d_2







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	$-0.40(80)$	$-12(18)$	$-100(80)$

$$d_1 + d_2 = \begin{cases} 26\,\mathrm{GeV}^{-4} & \text{for} \quad J/\Psi \\ 13\,\mathrm{GeV}^{-4} & \text{for} \quad \eta_c \end{cases}$$

Lattice data

[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)

Fits of the polarizabilites from lattice data for potential*

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

$$\kappa_1 = 2 - 9\kappa/2$$

$$\psi' \to J/\psi\pi^+\pi^-$$

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

$$\kappa_2 = 2 + 3\kappa/2$$

$$\kappa = 0.186(9)$$

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

$$b = (11N_c - 2N_f)/3$$

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

Stable fit for
0.5 fm < r < 1.4 fm

*T Kawanai & S Sasaki
Phys. Rev. D82, 091501 (2018)

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↓ pNRQCD

$$\alpha_\psi \sim \frac{1}{m_Q E_\psi^2} \sim \frac{1}{m_Q^3 \alpha_s^4}$$

— substantially larger if $\alpha_s \ll 1$

*T Kawanai & S Sasaki
Phys. Rev. D82, 091501 (2018)

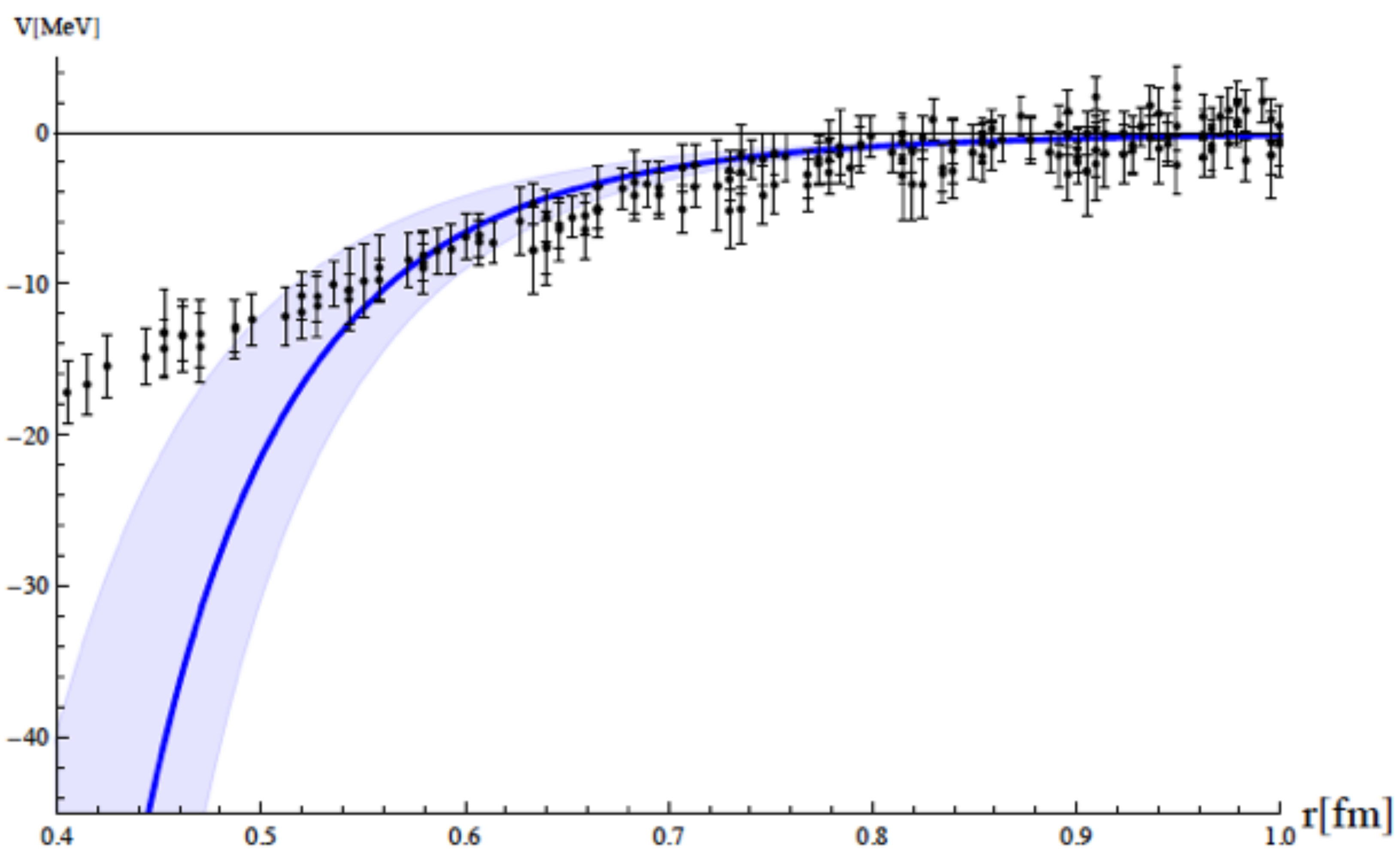
van de Waals potential

— compare with HAL lattice potential

Kanaway & Sasaki, PRD 82, 091501 (2010)

vdW force

$$J/\Psi - N$$

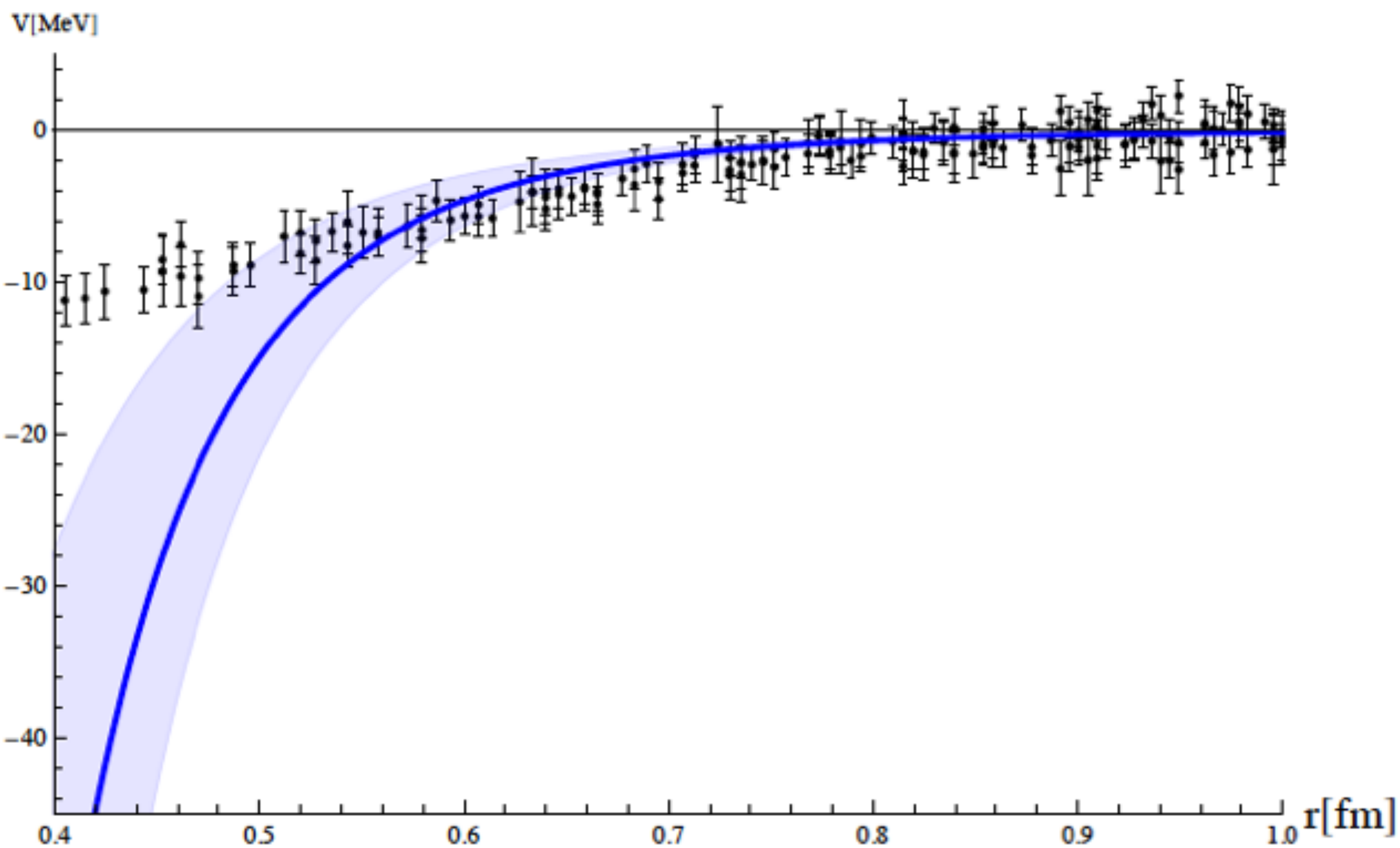


Lattice data

*T Kawanai & S Sasaki
Phys. Rev. D82, 091501 (2018)

vdW force

$$\eta_c - N$$



Lattice data

*T Kawanai & S Sasaki
Phys. Rev. D82, 091501 (2018)

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

Scattering amplitude (s-wave)

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

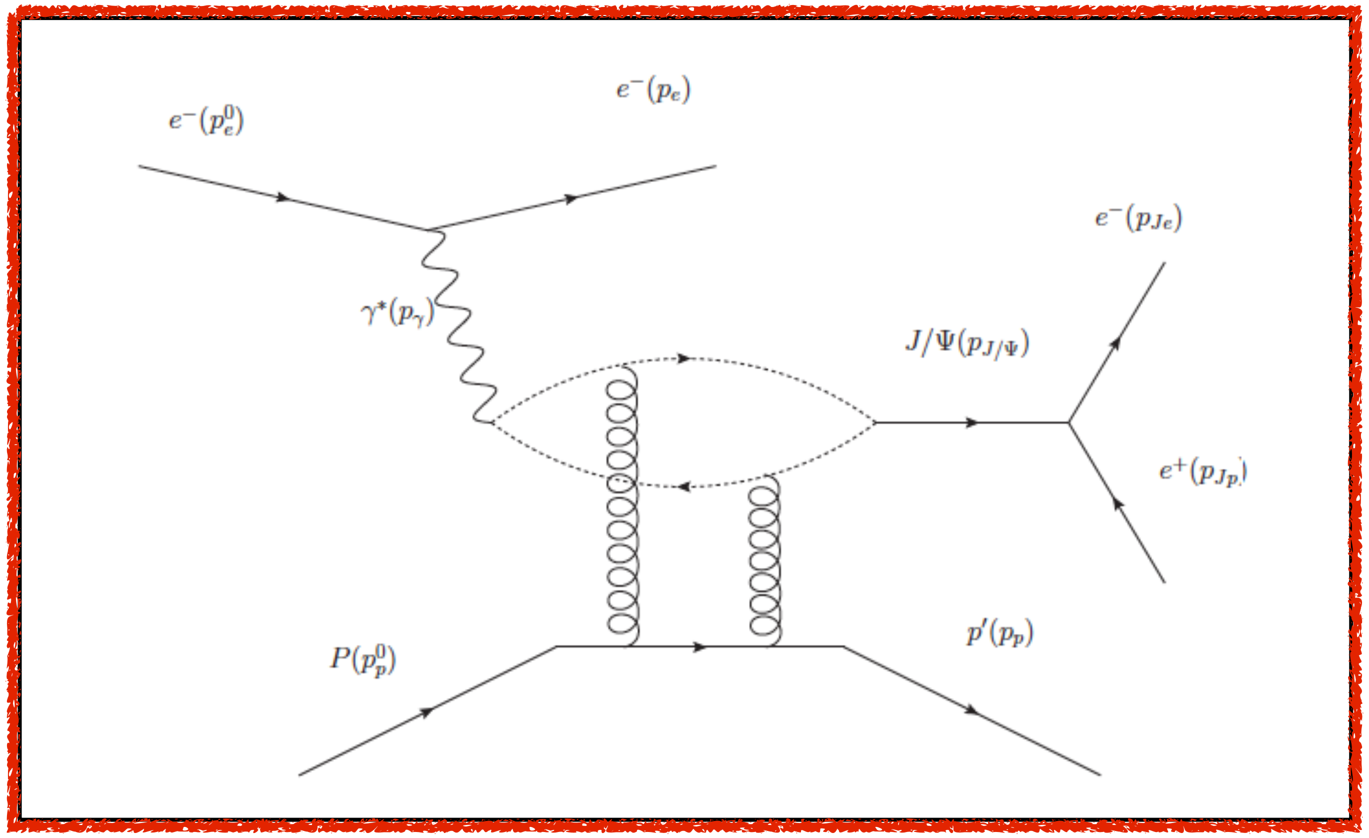
$$a_0 = \frac{\mu_{\phi N}}{2\pi} \left[c_0 + 4 d_m m_\pi^2 + \frac{9 g_A^2 m_\pi^2 c_0}{64\pi^2 F^2} \left(\log \frac{m_\pi^2}{\nu^2} + \frac{2}{3} \right) + \frac{3 g_A^2}{64\pi F^2} m_\pi^3 \left(5 c_{di} - 3 c_m \right) \right]$$

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

No quarkonium-nucleon bound states within the applicability of the present calculation:

$$|p_{\phi N}| \leq m_\pi$$

ATHENNA* @ JLab

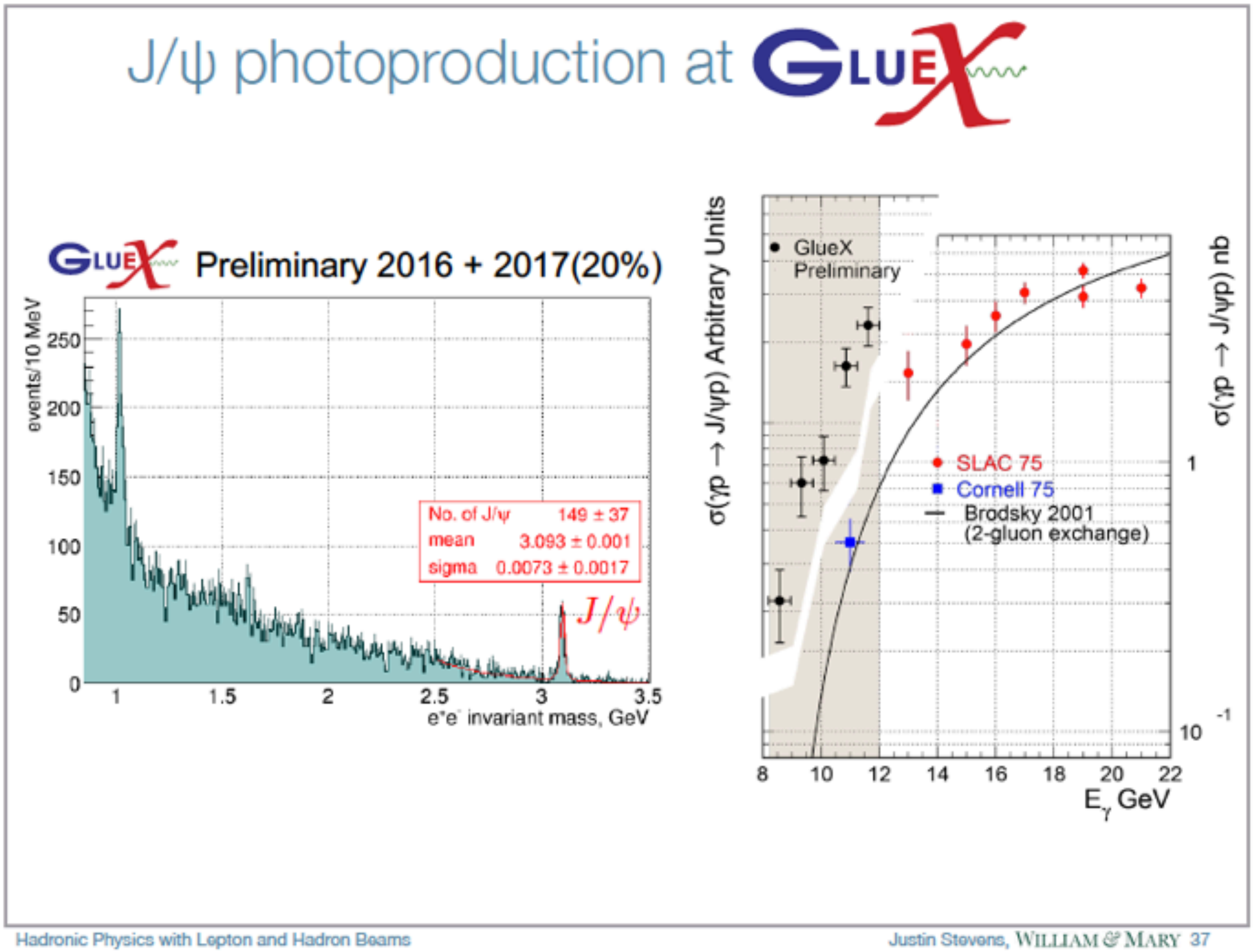


Hall A — E12-12-006
K. Hafidi, Z.-E. Meziani, N. Sparveris, Z.W. Zhao

*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.

GLUEX @ JLab


J/ψ photoproduction at GlueX
Preliminary 2016 + 2017(20%)
events/10 MeV
250
200
150
100
50
0
1
1.5
2
2.5
3
3.5
e⁺e⁻ invariant mass, GeV
No. of J/ψ 149 ± 37
mean 3.093 ± 0.001
sigma 0.0073 ± 0.0017
J/ψ
σ(γp → J/ψp) Arbitrary Units
GlueX Preliminary
SLAC 75
Cornell 75
Brodsky 2001 (2-gluon exchange)
σ(γp → J/ψp) nb
1
10⁻¹
8
10
12
14
16
18
20
22
Eγ GeV
Hadronic Physics with Lepton and Hadron Beams
Justin Stevens, WILLIAM & MARY 37

Is it possible to measure the van der Waals force?

Perhaps in a partial wave analysis (?)

S-wave:

$$\mathcal{A}_S(p) = -C_0 + iC_0\left(\frac{\mu p}{2\pi}C_0\right) - 2(D_1 + D_2)p^2 + C_0\left(\frac{\mu p}{2\pi}C_0\right)^2 + C_0\left(\frac{\mu p}{2\pi}C_0\right)^3 - V_S^{\mathrm{vdW}}(p)$$

P-wave:

$$\mathcal{A}_P(p) = -2(D_2 - D_1)p^2 - V_P^{\mathrm{vdW}}(p)$$

D-wave:

$$\mathcal{A}_D(p) = -V_D^{\mathrm{vdW}}(p)$$

$$\vec{p} = \vec{k} - \vec{k}'$$

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

YES, for sufficiently large nuclei

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-<u>nucleus</u> 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

J/Ψ in nuclei

— nuclear potentials

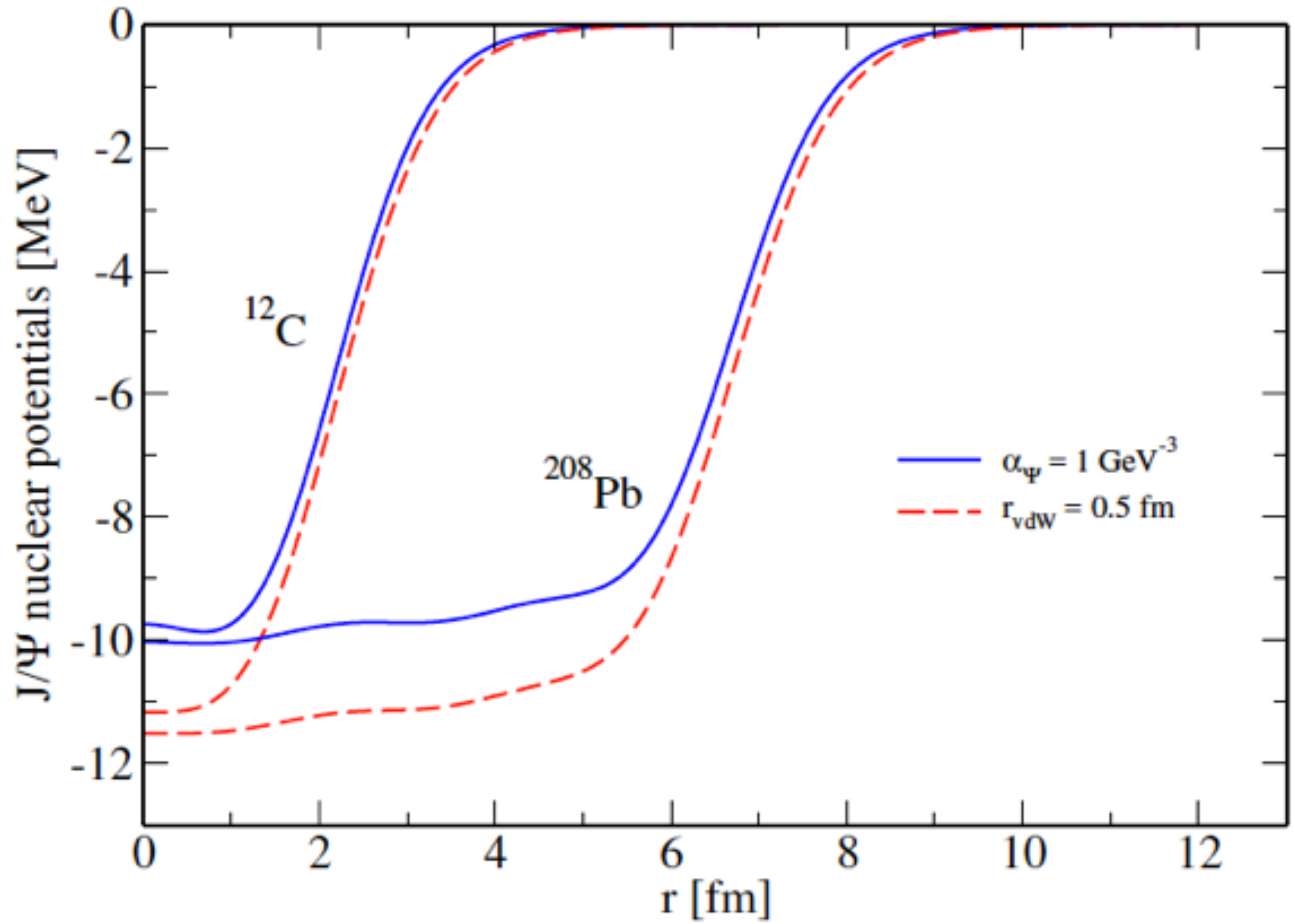


Figure 8: J/Ψ nuclear potentials $W^{\rm pol}_{J/\Psi A}(\vec{r})$ (solid line) for a polarizability $\alpha_{J/\Psi} = 1$ GeV^{-3} and $W^{\rm latt}_{J/\Psi A}(\vec{r})$ (dashed line) from a fit to the lattice data with a cutoff $r_{\rm vdW} = 0.5$ fm.

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

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

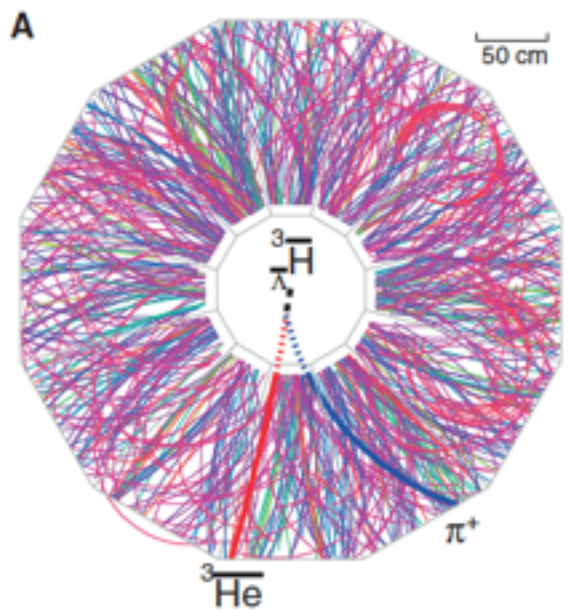
System	$24^3 \times 64$	$32^3 \times 64$	$L = \infty$
$N\eta_c$	17.9(0.4)(1.5)	19.8(0.7)(2.6)	19.8(2.6)
$d\eta_c$	39.3(1.3)(4.8)	42.4(1.1)(7.9)	42.4(7.9)
$pp\eta_c$	37.8(1.1)(4.5)	41.5(1.0)(7.5)	41.5(7.6)
^{3}Heη_c	57.2(1.3)(8.3)	56.7(2.0)(9.4)	56.7(9.6)
^{4}Heη_c	70(02)(13)	56(06)(17)	56(18)
^{4}HeJ/ψ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

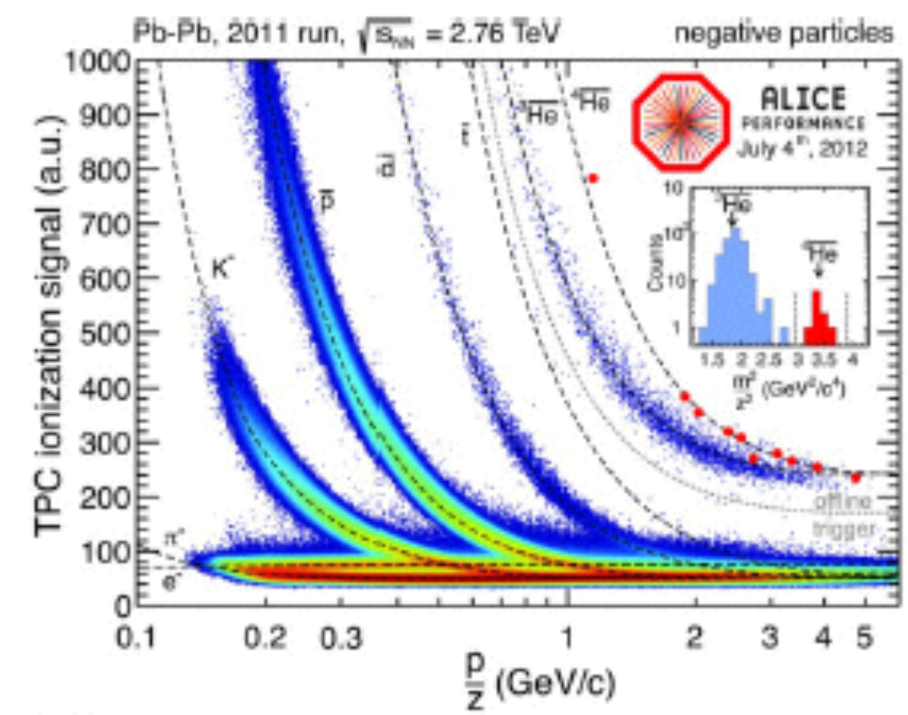
How About coalescence at the LHC?

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

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

Femtoscopy

— Measure two-particle correlation function

i.e. correlation of proton & quarkonium

For S-waves

$$C(k) \simeq 1 + \int_0^\infty 4\pi r^2\, dr\, S_{12}(\mathbf{r}) \left[|\psi(k,r)|^2 - |j_0(kr)|^2 \right]$$

Source, size R (“known")

$$S_{12}(\mathbf{r}) = \exp(-r^2/4R^2)/(2\sqrt{\pi}R)^3$$

Wave function of quarkonium-nucleon

Using asymptotic form of the wave function*

$$C(k) \simeq 1 + \frac{|f(k)|^2}{2R^2} F(r_0) + \frac{2\mathrm{Re} f(k)}{\sqrt{\pi} R} F_1(x) - \frac{\mathrm{Im} f(k)}{R} F_2(x)$$

$$f(k) = \frac{1}{-1/a_0 + 1/2\, r_0^2\, k^2 - ik}$$

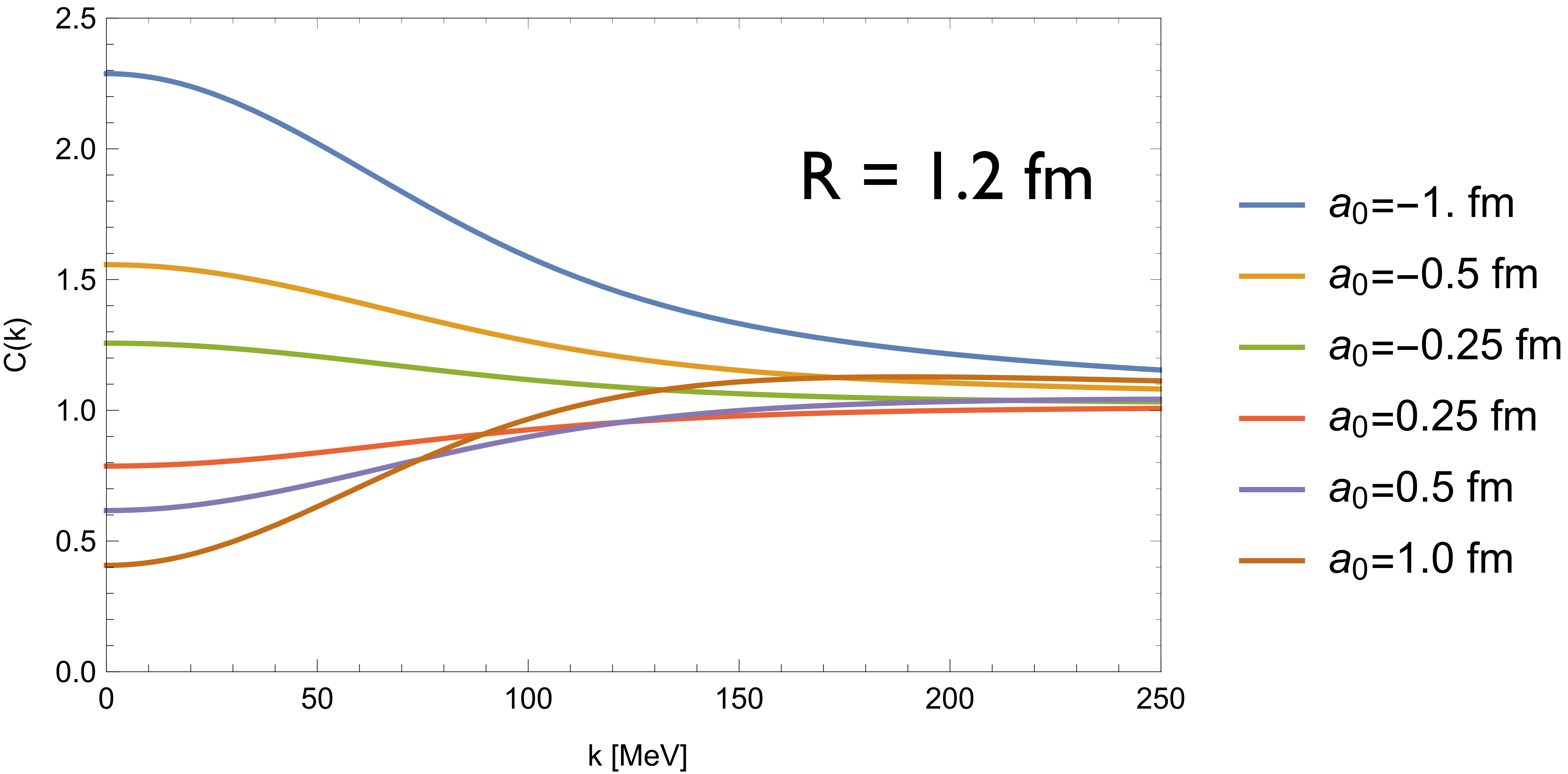
$$F(r_0) = 1 - r_0/(2\sqrt{\pi} R)$$

$$F_1(x) = \int_0^x dt\, e^{t^2 - x^2}/x$$

$$F_2(x) = (1 - e^{-x^2})/x$$

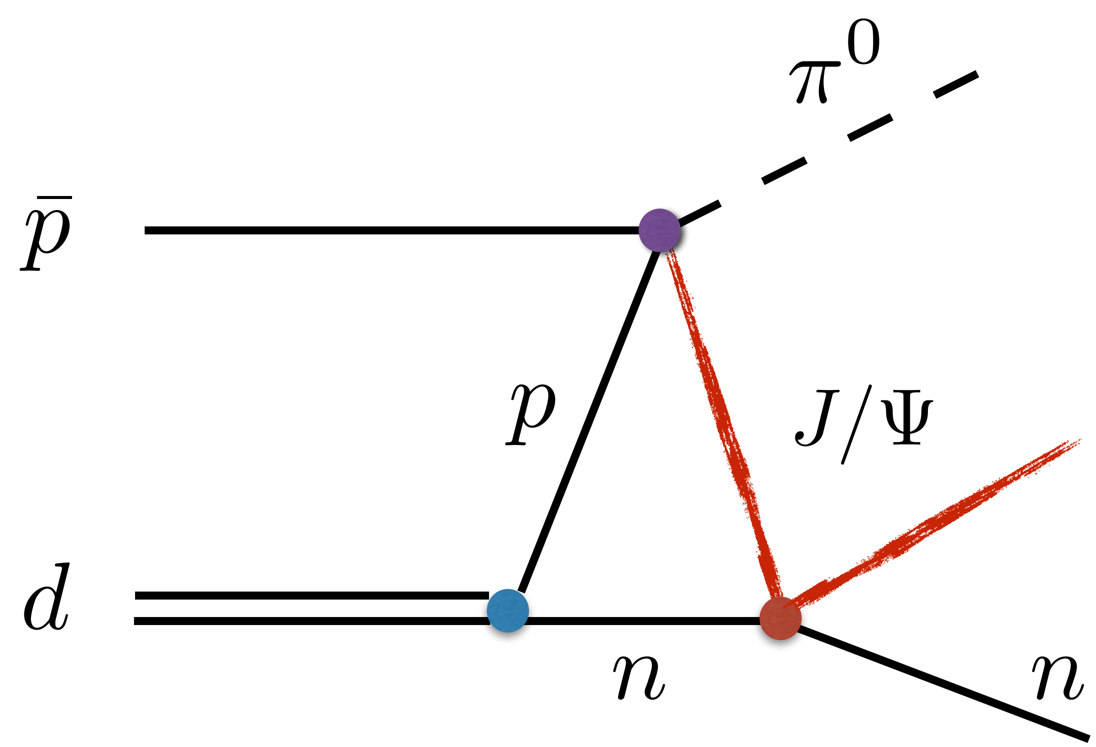
* R Lednicky et al, Sov J Nucl Phys 35, 770 (1982)
Phys Atom Nucl 61, 2950 (1998)

Clear sensitivity to the interaction



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

panda @ FAIR



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