

# Effective field theory for long-range properties of bottomonium states



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XIIith Quark Confinement and the Hadron Spectrum

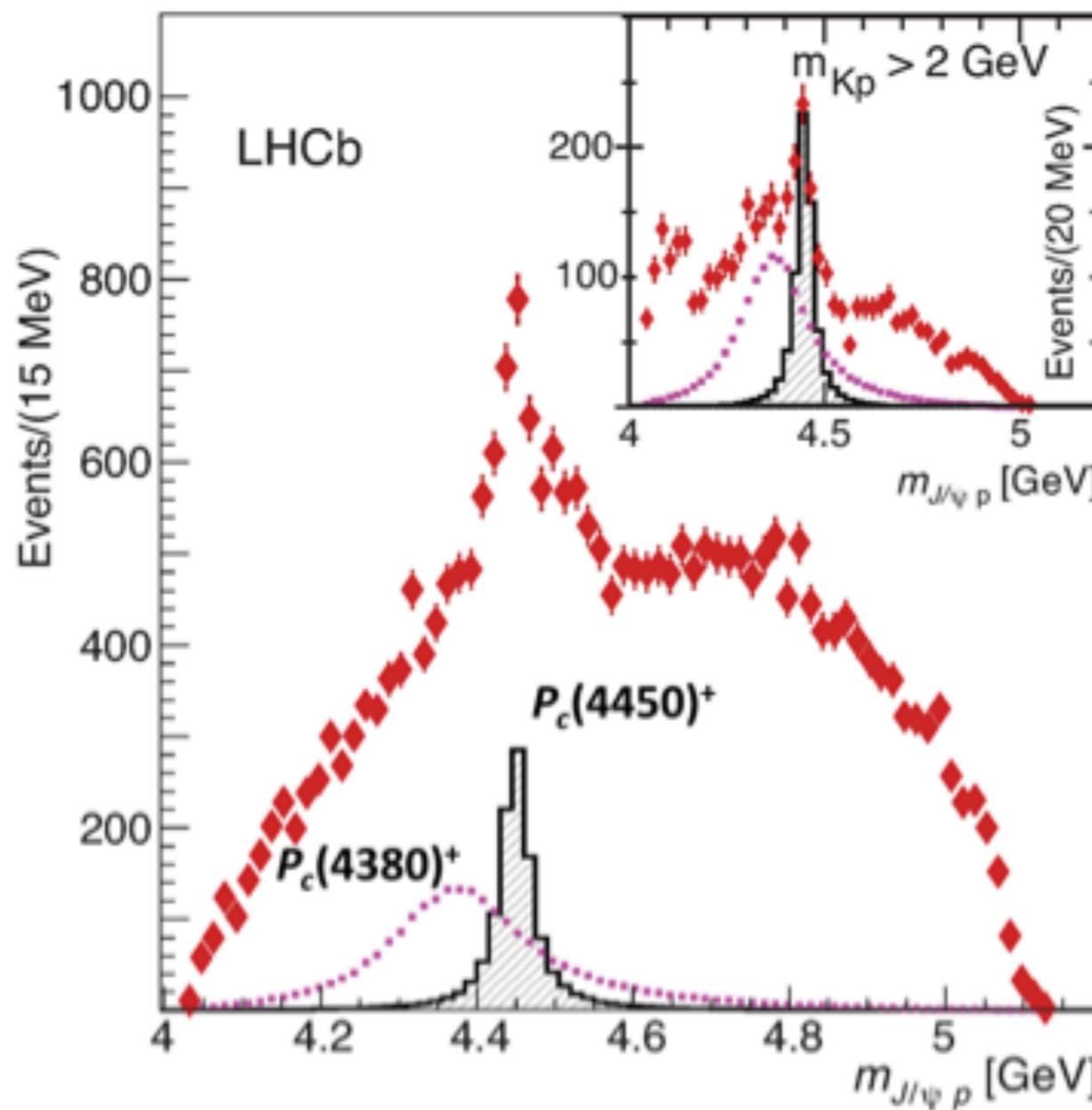
from 28 August 2016 to 4 September 2016  
Europe/Athens timezone

Work in collaboration with

- Nora Brambilla
- Jaume Tarrús-Castellà
- Antonio Vairo

# Motivation 1

# J/ $\Psi$ binding to proton?



2015



## Model-Independent Evidence for $J/\psi p$ Contributions to $\Lambda_b^0 \rightarrow J/\psi p K^-$ Decays

R. Aaij *et al.*\*

(LHCb Collaboration)

(Received 19 April 2016; published 18 August 2016)

The data sample of  $\Lambda_b^0 \rightarrow J/\psi p K^-$  decays acquired with the LHCb detector from 7 and 8 TeV  $p\bar{p}$  collisions, corresponding to an integrated luminosity of  $3 \text{ fb}^{-1}$ , is inspected for the presence of  $J/\psi p$  or  $J/\psi K^-$  contributions with minimal assumptions about  $K^- p$  contributions. It is demonstrated at more than nine standard deviations that  $\Lambda_b^0 \rightarrow J/\psi p K^-$  decays cannot be described with  $K^- p$  contributions alone, and that  $J/\psi p$  contributions play a dominant role in this incompatibility. These model-independent results support the previously obtained model-dependent evidence for  $P_c^+ \rightarrow J/\psi p$  charmonium-pentaquark states in the same data sample.

DOI: 10.1103/PhysRevLett.117.082002



## Evidence for Exotic Hadron Contributions to $\Lambda_b^0 \rightarrow J/\psi p\pi^-$ Decays

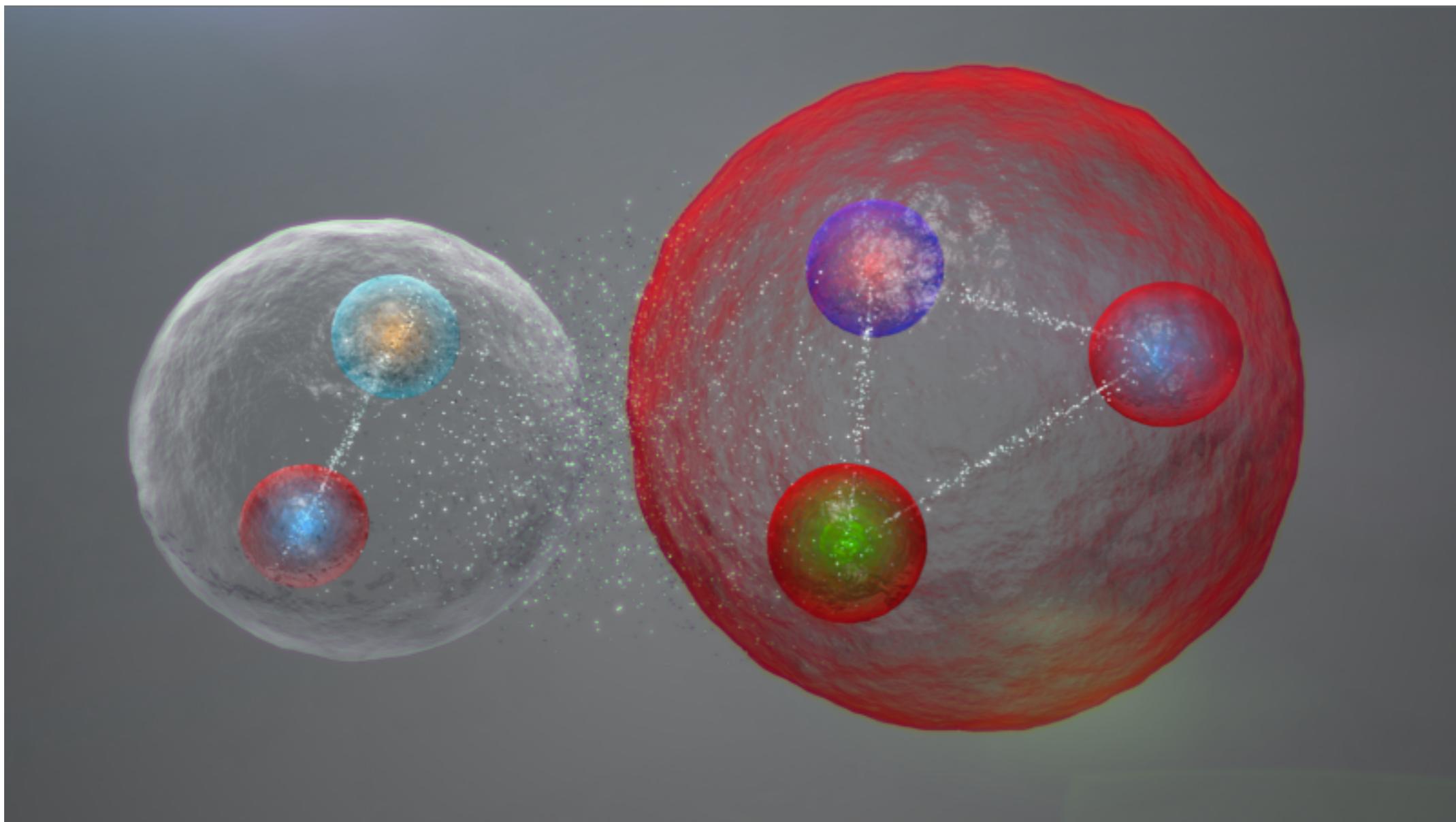
R. Aaij *et al.*<sup>\*</sup>

(LHCb Collaboration)

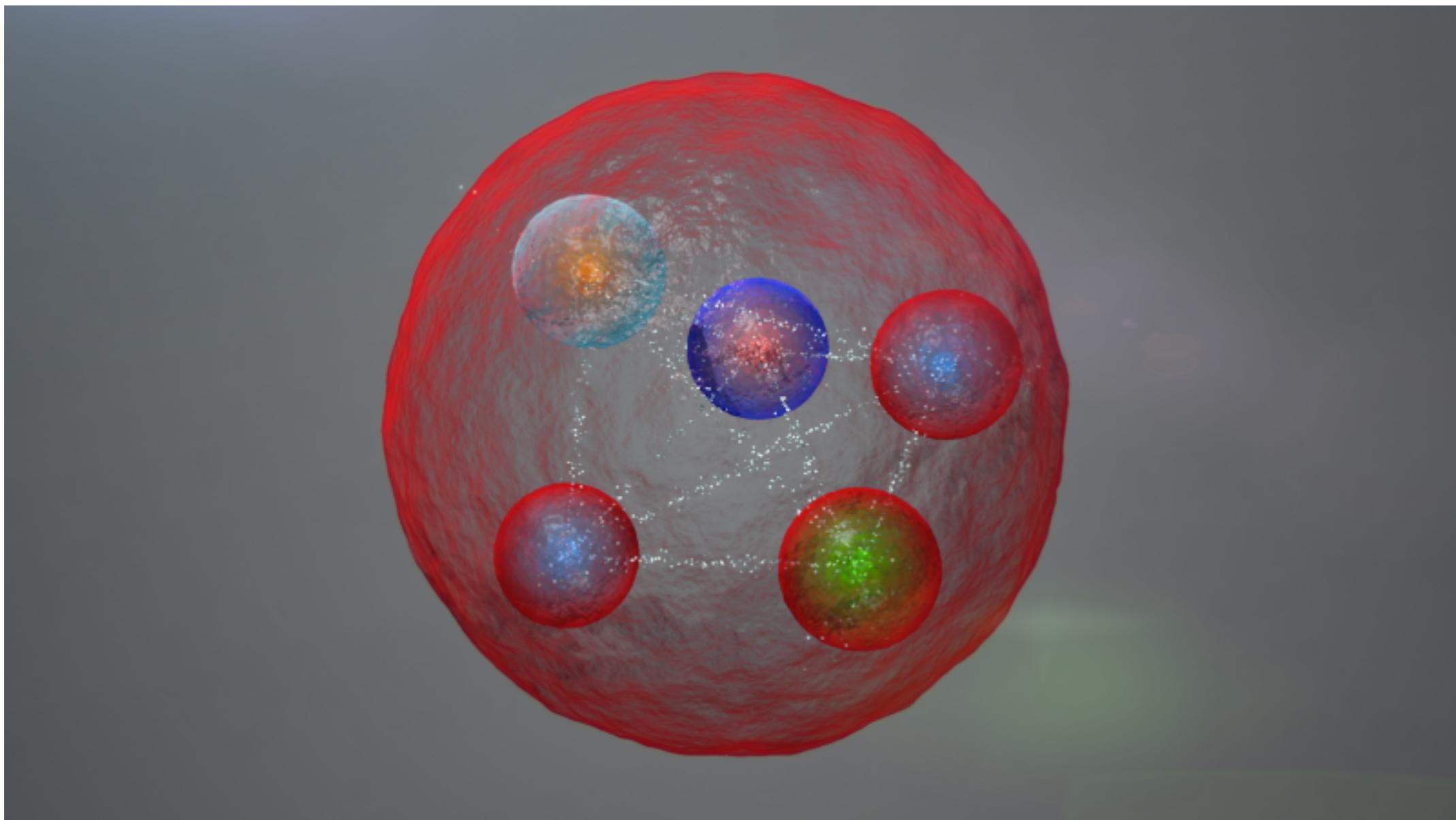
(Received 22 June 2016; published 18 August 2016; corrected 24 August 2016)

A full amplitude analysis of  $\Lambda_b^0 \rightarrow J/\psi p\pi^-$  decays is performed with a data sample acquired with the LHCb detector from 7 and 8 TeV  $p p$  collisions, corresponding to an integrated luminosity of  $3 \text{ fb}^{-1}$ . A significantly better description of the data is achieved when, in addition to the previously observed nucleon excitations  $N \rightarrow p\pi^-$ , either the  $P_c(4380)^+$  and  $P_c(4450)^+ \rightarrow J/\psi p$  states, previously observed in  $\Lambda_b^0 \rightarrow J/\psi pK^-$  decays, or the  $Z_c(4200)^- \rightarrow J/\psi\pi^-$  state, previously reported in  $B^0 \rightarrow J/\psi K^+\pi^-$  decays, or all three, are included in the amplitude models. The data support a model containing all three exotic states, with a significance of more than three standard deviations. Within uncertainties, the data are consistent with the  $P_c(4380)^+$  and  $P_c(4450)^+$  production rates expected from their previous observation taking account of Cabibbo suppression.

DOI: 10.1103/PhysRevLett.117.082003



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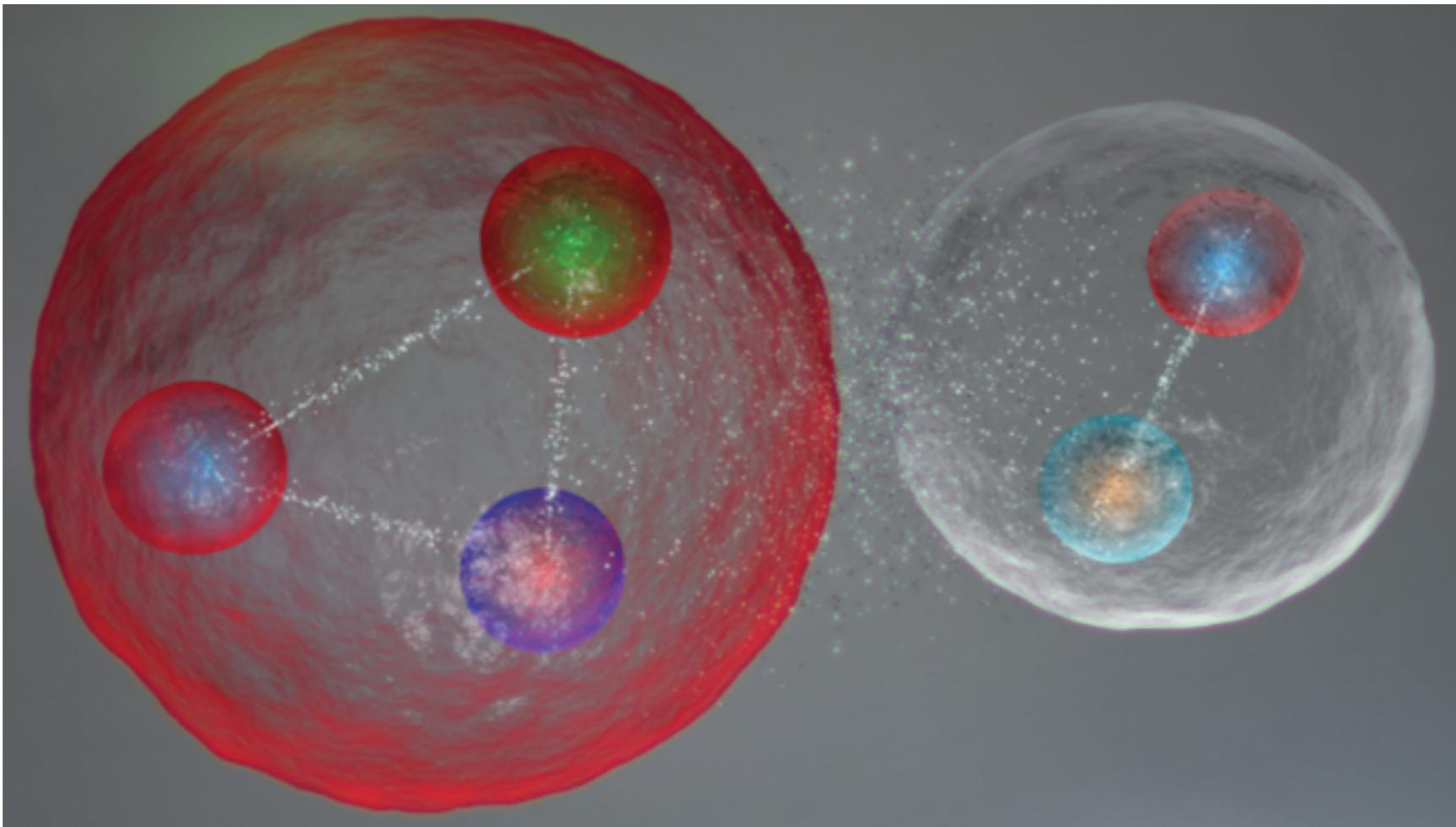
# Chromopolarizability & color van der Waals forces — an EFT perspective

Interactions between color neutral objects:

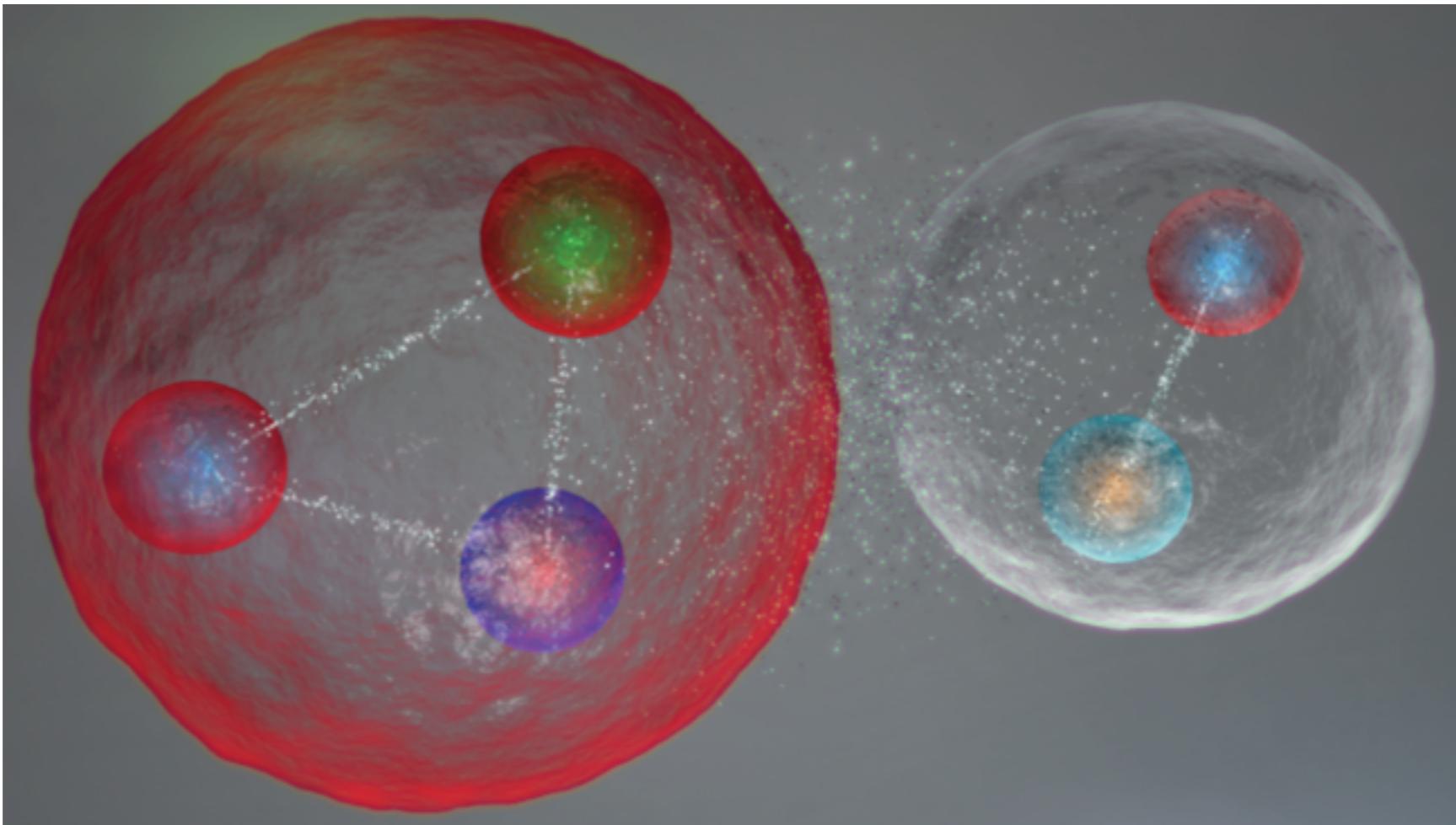
Via creation of instantaneous color dipole moments &  
gluon transitions in virtual color-octet intermediate state

— Polarizability —

Would like to treat this

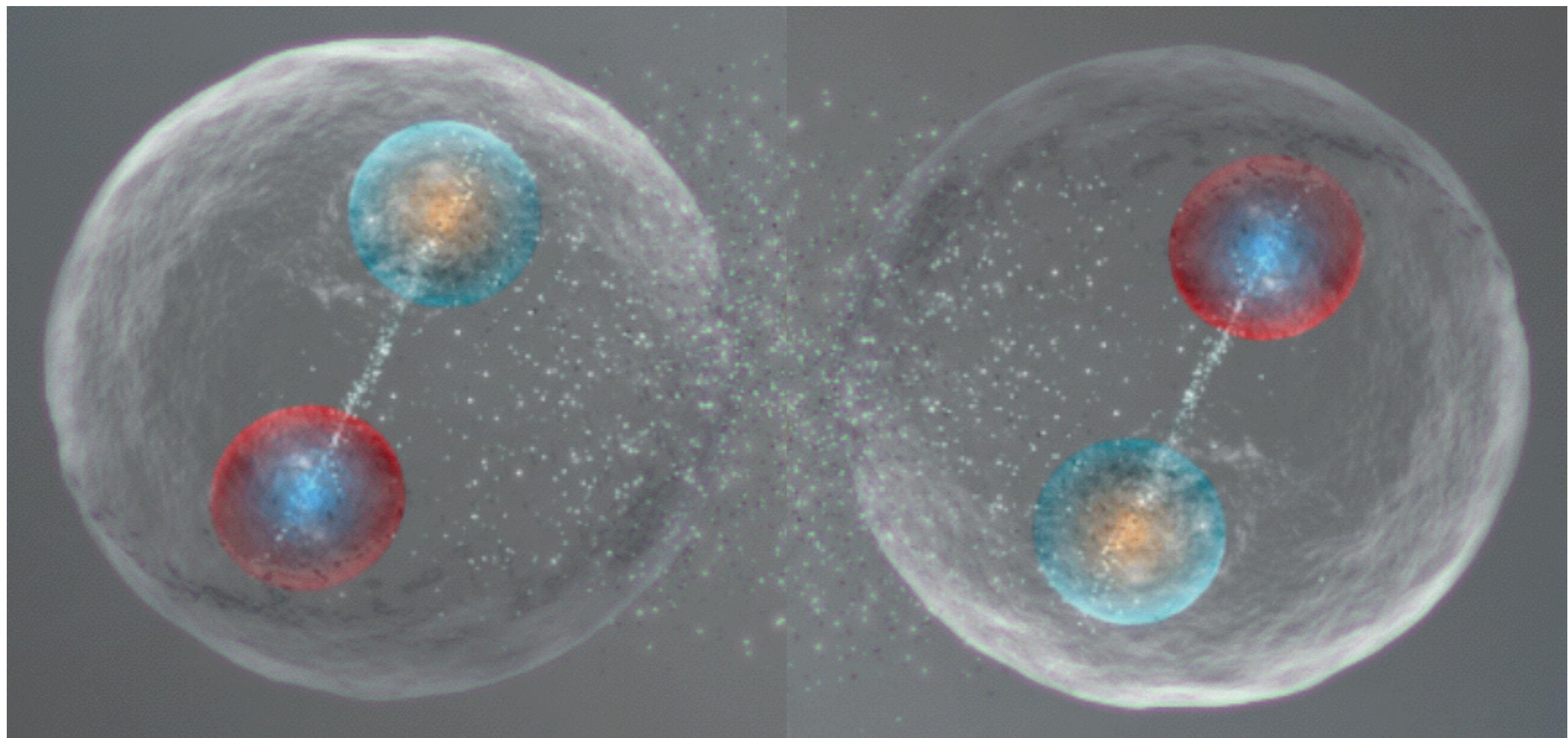


# Would like to treat this



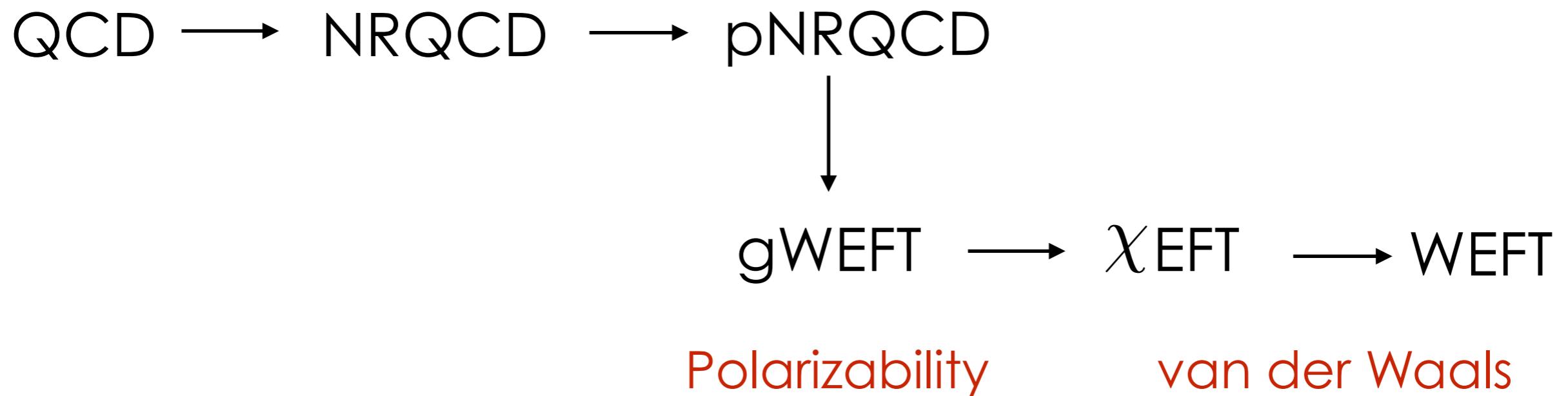
But will start with a simpler system ...

$$\eta_b - \bar{\eta}_b$$



# 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



# Scales

$m$ : bottom mass,       $v$ : relative velocity

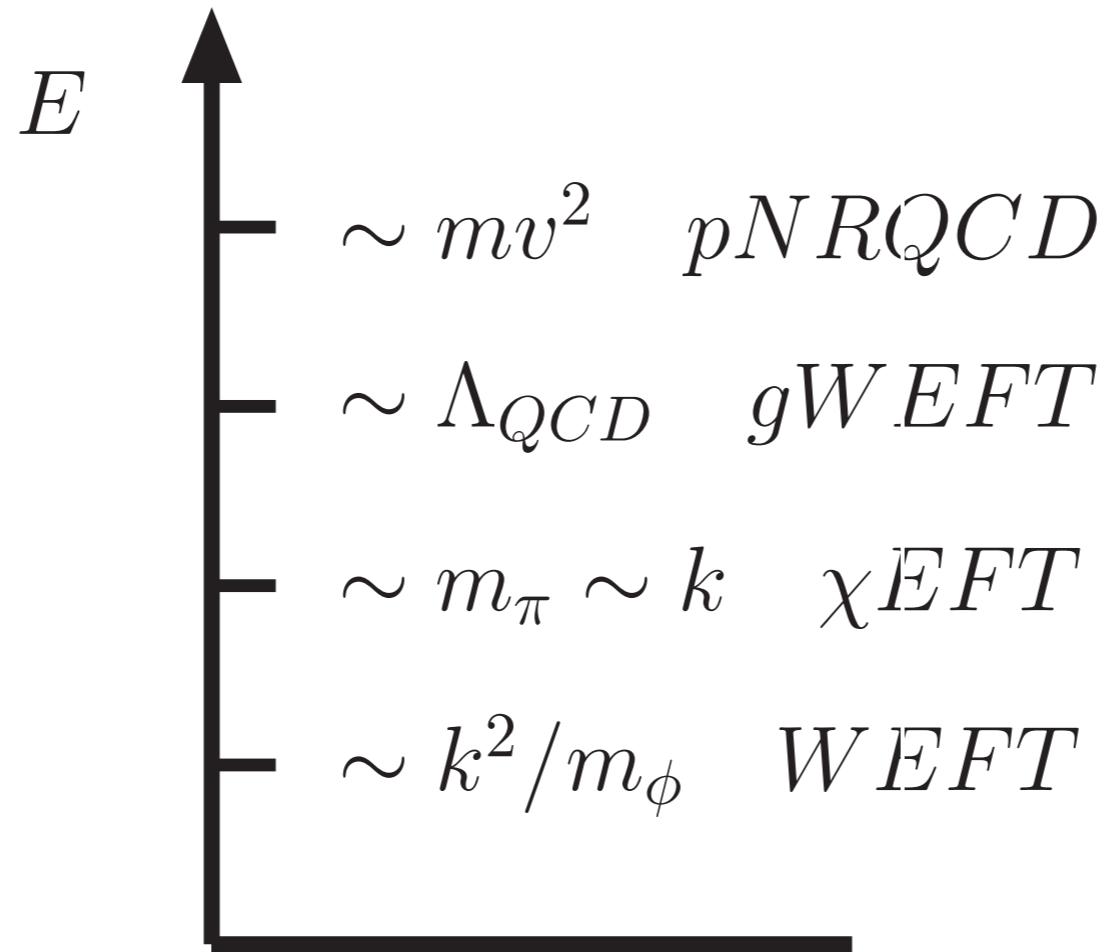
$$m \gg mv \gg mv^2 \gg \Lambda_{\text{QCD}}$$

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

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

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

gWEFT  $\longrightarrow$   $\chi$ EFT  $\longrightarrow$  WEFT



Hierarchies of scales and the corresponding EFTs

A potential worry  
— are the different hierarchies satisfied?

A potential worry

— are the different hierarchies satisfied?

Assume they are, see what are the consequences

- a self-consistent, systematic, modern approach
- some old (forgotten?) results reproduced
- corrected and completed early calculations

# pNRQCD\*

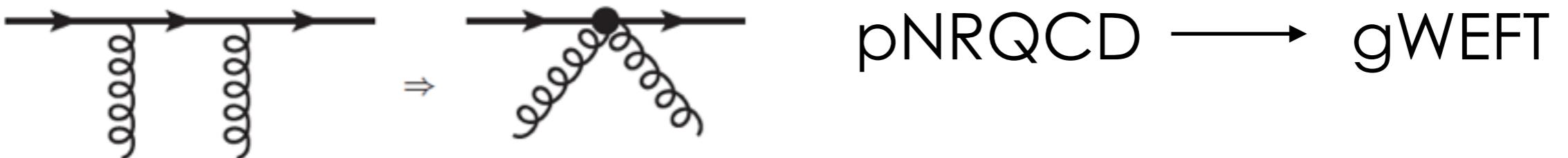
$$\begin{aligned} \mathcal{L}_{\text{pNRQCD}} = & \int d^3r \text{Tr} [S^\dagger (i\partial_0 - h_s) S + O^\dagger (iD_0 - h_o) O] \\ & + gV_A(r)\text{Tr} [O^\dagger \mathbf{r} \cdot \mathbf{E} S + S^\dagger \mathbf{r} \cdot \mathbf{E} O] + \frac{g}{2}V_B(r)\text{Tr} [O^\dagger \mathbf{r} \cdot \mathbf{E} O + O^\dagger O \mathbf{r} \cdot \mathbf{E}] \\ & + \mathcal{L}_{\text{light}} \end{aligned}$$

$$\begin{aligned} h_s &= -\frac{\nabla_{\mathbf{r}}^2}{m} - \frac{\nabla_{\mathbf{R}}^2}{4m} + V_s(r), & V_s(r) &= -C_F \frac{\alpha_s(r)}{r}, \\ h_o &= -\frac{\nabla_{\mathbf{r}}^2}{m} - \frac{D_{\mathbf{R}}^2}{4m} + V_o(r), & V_o(r) &= \left( \frac{C_A}{2} - C_F \right) \frac{\alpha_s(r)}{r}, \\ & & V_A(r) &= 1, \\ & & V_B(r) &= 1, \end{aligned}$$

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

\* 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)

# Chromopolarizability



$$L_{\text{gWEFT}} = \int d^3 R \left\{ \phi^\dagger(t, \mathbf{R}) \left[ i\partial_0 + E_\phi - \frac{\nabla_{\mathbf{R}}^2}{4m} + \frac{1}{2}\beta g^2 E_a^2 + \dots \right] \phi(t, \mathbf{R}) \right\} + \mathcal{L}_{\text{light}}$$

Chromopolarizability

$$\begin{aligned} \beta &= -\frac{2V_A^2 T_F}{3N_c} \langle \phi | \mathbf{r} \frac{1}{E_\phi - h_o} \mathbf{r} | \phi \rangle \\ &= -\frac{2V_A^2 T_F}{3N_c} \sum_l \int \frac{d^3 p}{(2\pi)^3} |\langle \phi | \mathbf{r} | \mathbf{p} l \rangle|^2 \frac{1}{E_\phi - \frac{p^2}{m}} \end{aligned}$$

# Wave functions

Bound-state

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

Continuum octet\*

$$|\langle \phi | \mathbf{r} | \mathbf{p} \rangle|^2 = \frac{512\pi^2\rho(\rho+2)^2a_0^6|\mathbf{p}|(1+\frac{\rho^2}{a_0^2|\mathbf{p}|^2})e^{\frac{4\rho}{a_0|\mathbf{p}|}\arctan(a_0|\mathbf{p}|)}}{(e^{\frac{2\pi\rho}{a_0|\mathbf{p}|}} - 1)(1 + a_0^2|\mathbf{p}|^2)^6}.$$
$$\rho = (N_c^2 - 1)^{-1}$$

\*N .Brambilla, M. A. Escobedo, J. Ghiglieri, and A. Vairo,  
J. High Energy Phys. 12 (2011) 116.

# Results: polarizability

$$\beta = 256 \frac{\rho(\rho+2)^2}{3N_c} \frac{1}{mE_\phi^2} I$$

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

$$I = \int_0^\infty dp p^3 \frac{(1 + \frac{\rho^2}{p^2}) e^{\frac{4\rho}{p} \arctan p}}{(e^{\frac{2\pi\rho}{p}} - 1)(1 + p^2)^7} \Big|_{N_c=3} = 0.01143.$$

Agrees with:

H. Leutwyler, Phys. Lett. **98B**, 447 (1981)

M. B. Voloshin, Yad. Fiz. **36**, 247 (1982)

# Results: polarizability

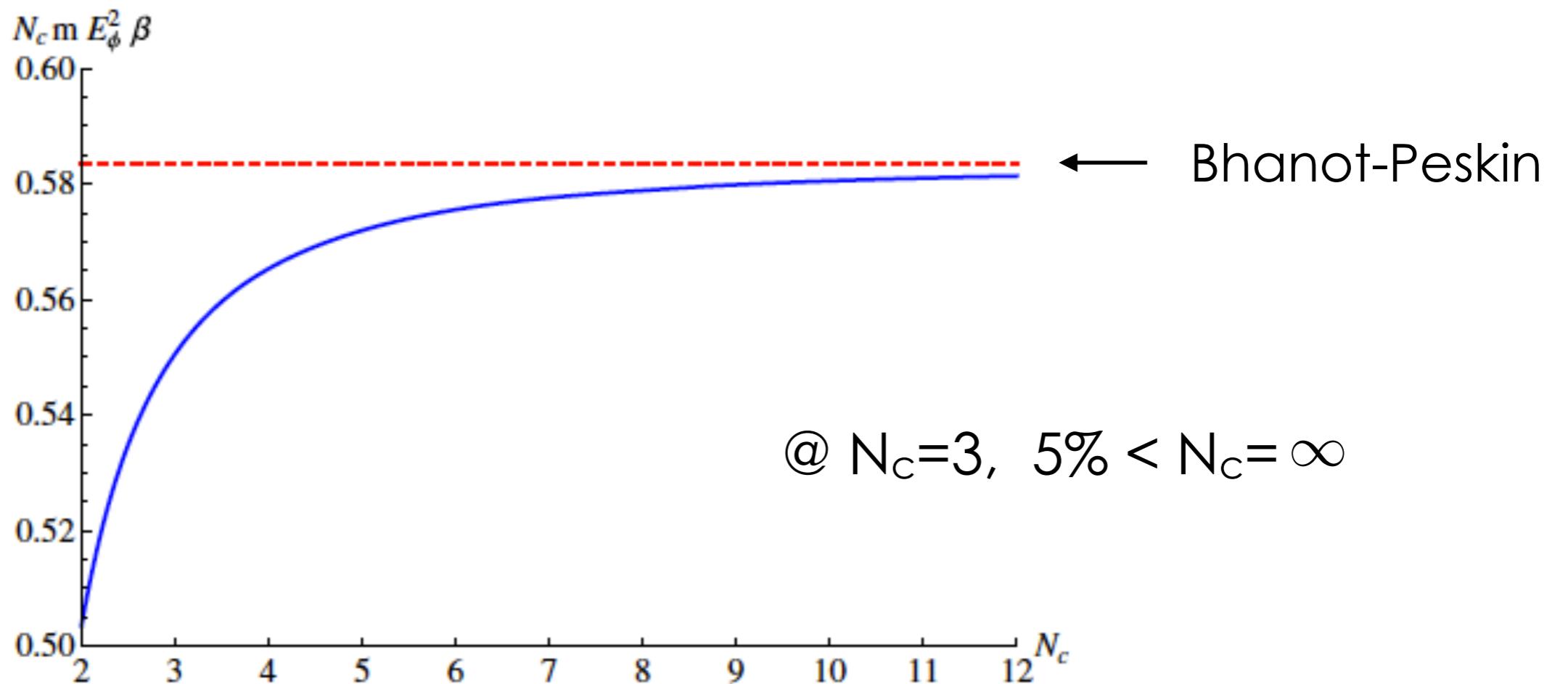


FIG. 3. The dependence of the polarizability on the number of colors. The dashed line at the constant value  $7/12$  corresponds to the large- $N_c$  limit computed in Ref. [13].

# Results: polarizability

$$E_\phi = -m \frac{(C_F \alpha_s)^2}{4} = -\frac{1}{ma_0^2}$$

$$m_\phi = 9.4454 \text{ GeV} \left\{ \begin{array}{l} \text{average of} \\ \eta_b \text{ & } \Upsilon_b(1S) \end{array} \right.$$

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

$$m = 5 \text{ GeV}$$

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

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

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

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

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

# Results: polarizability

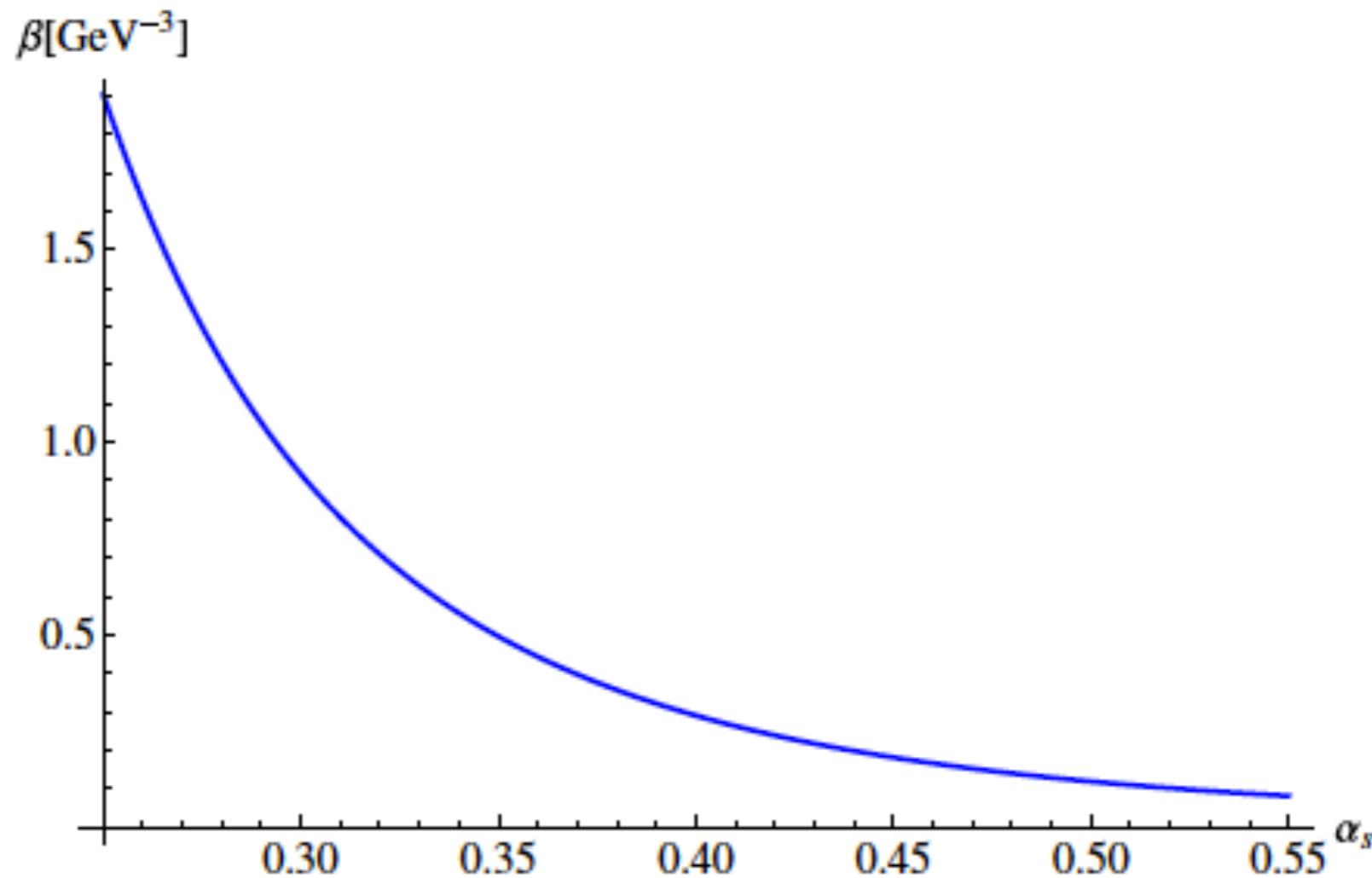
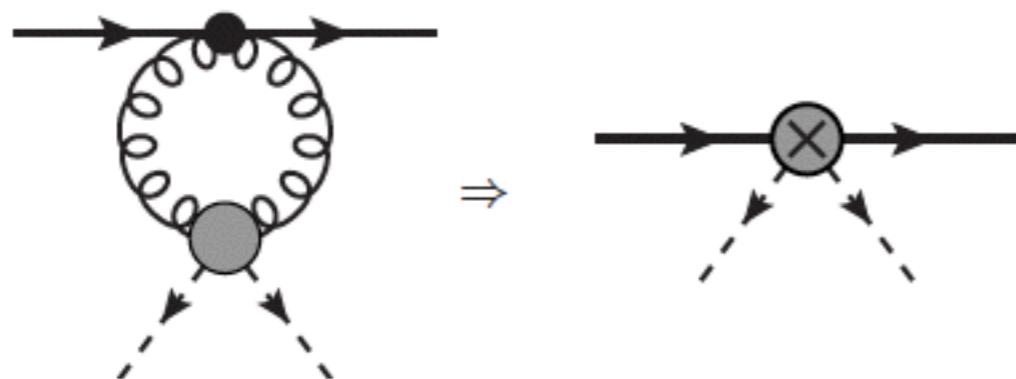


FIG. 4. Plot of  $\beta$  from Eq. (12) as a function of  $\alpha_s$  for  $m = 5 \text{ GeV}$ .

# van der Waals force

gWEFT  $\longrightarrow$   $\chi$ EFT



QCD trace  
anomaly

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

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

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

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

# Matching gWEFT $\longrightarrow$ $\chi$ EFT

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

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

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

$$\chi = 2B\hat{m}\mathbf{1} \quad F = F_\pi = 92.419 \text{ MeV}$$

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

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

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

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

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

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

# Chiral correction

## — bottomonium mass

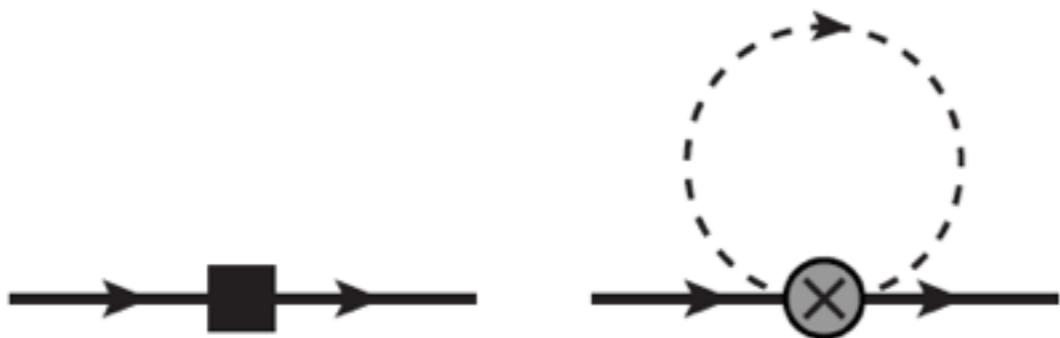
$$\begin{aligned}\delta m_\phi &= -F^2 c_m m_\pi^2 + \text{counterterms of } \mathcal{O}(m_\pi^4) \\ &\quad + \frac{3m_\pi^2}{8} (c_{d0} + 3c_{di} - 4c_m) A[m_\pi^2] + \frac{3m_\pi^4(c_{d0} - c_{di})}{256\pi^2}\end{aligned}$$

$$A[m_\pi^2] = \frac{m_\pi^2}{16\pi^2} \left( \lambda - \log \frac{m_\pi^2}{\nu^2} \right)$$

$$\lambda = \frac{2}{4-d} + 1 - \gamma_E + \log 4\pi$$

# Bottomonium mass

## — leading chiral log contribution



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

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

Corrected  
Grinstein & Rothstein PLB 385, 265 (1996)

# van der Waals force

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

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

Relative motion at energies lower than pion mass  
— integrate out the pion

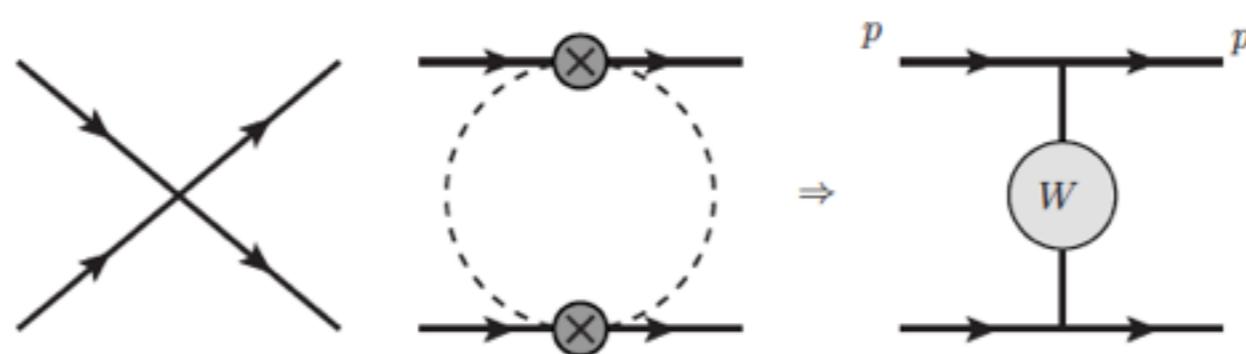
$$\chi\text{EFT} \longrightarrow \text{WEFT}$$

# Matching

$\chi$ EFT



WEFT



$$L_{\text{WEFT}}^\phi = \int d^3 \mathbf{R} \phi^\dagger(t, \mathbf{R}) \left( i\partial_0 + \frac{\nabla^2}{2m_\phi} \right) \phi(t, \mathbf{R})$$

$$L_{\text{WEFT}}^{\phi\phi} = -\frac{1}{2} \int d^3 \mathbf{R}_1 d^3 \mathbf{R}_2 \phi^\dagger \phi(t, \mathbf{R}_1) W(\mathbf{R}_1, \mathbf{R}_2) \phi^\dagger \phi(t, \mathbf{R}_2)$$

# vdW potential

$$\widetilde{W}(\mathbf{k}^2) = \text{contact terms}$$

$$-\frac{3}{8} \left( \mathbf{k}^2 c_{di} + 2m_\pi^2 (c_{di} - c_m) \right)^2 B [m_\pi^2, -\mathbf{k}^2]$$

$$-\frac{3}{2} (c_{d0} - c_{di}) \left( \mathbf{k}^2 c_{di} + 2m_\pi^2 (c_{di} - c_m) \right) C_1 [m_\pi^2, -\mathbf{k}^2]$$

$$-\frac{3}{2} (c_{d0} - c_{di})^2 C_2 [m_\pi^2, -\mathbf{k}^2]$$



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

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

$$\begin{aligned} C_2 \left[ m_\pi^2 - \mathbf{k}^2 \right] &= \frac{31\mathbf{k}^4 + 280\mathbf{k}^2 m_\pi^2 + 705m_\pi^4}{19200\pi^2} + \frac{1}{1280\pi^2} \left( (\mathbf{k}^4 + 10\mathbf{k}^2 m_\pi^2 + 30m_\pi^4) \right. \\ &\quad \times \left. \left( \lambda - \log \frac{m_\pi^2}{\nu^2} \right) + \mathbf{k}^4 \left( 1 + \frac{4m_\pi^2}{\mathbf{k}^2} \right)^{5/2} \log \left[ \frac{\sqrt{1 + \frac{4m_\pi^2}{\mathbf{k}^2}} - 1}{\sqrt{1 + \frac{4m_\pi^2}{\mathbf{k}^2}} + 1} \right] \right) \end{aligned}$$

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

$$\begin{aligned} C_2 \left[ m_\pi^2 - \mathbf{k}^2 \right] &= \frac{31\mathbf{k}^4 + 280\mathbf{k}^2 m_\pi^2 + 705m_\pi^4}{19200\pi^2} + \frac{1}{1280\pi^2} \left( (\mathbf{k}^4 + 10\mathbf{k}^2 m_\pi^2 + 30m_\pi^4) \right. \\ &\quad \times \left( \lambda - \log \frac{m_\pi^2}{\nu^2} \right) + \mathbf{k}^4 \left( 1 + \frac{4m_\pi^2}{\mathbf{k}^2} \right)^{5/2} \log \left[ \frac{\sqrt{1 + \frac{4m_\pi^2}{\mathbf{k}^2}} - 1}{\sqrt{1 + \frac{4m_\pi^2}{\mathbf{k}^2}} + 1} \right] \right) \end{aligned}$$

$$\begin{aligned} C_1 \left[ m_\pi^2 - \mathbf{k}^2 \right] &= \frac{5\mathbf{k}^2 + 24m_\pi^2}{576\pi^2} + \frac{1}{192\pi^2} \left( (\mathbf{k}^2 + 6m_\pi^2) \left( \lambda - \log \frac{m_\pi^2}{\nu^2} \right) \right. \\ &\quad \left. + \mathbf{k}^2 \left( 1 + \frac{4m_\pi^2}{\mathbf{k}^2} \right)^{3/2} \log \left[ \frac{\sqrt{1 + \frac{4m_\pi^2}{\mathbf{k}^2}} - 1}{\sqrt{1 + \frac{4m_\pi^2}{\mathbf{k}^2}} + 1} \right] \right) \end{aligned}$$

# Final result

## — vdW potential

$$\begin{aligned} W(r) &= \frac{1}{2\pi^2 r} \int_{2m_\pi}^{\infty} d\mu \mu e^{-\mu r} \operatorname{Im} [\widetilde{W}(\epsilon - i\mu)] \\ &= -\frac{3\pi\beta^2 m_\pi^2}{8b^2 r^5} \left[ \left( 4(\kappa_2 + 3)^2 (m_\pi r)^3 + (3\kappa_1^2 + 43\kappa_2^2 + 14\kappa_1\kappa_2) m_\pi r \right) K_1(2m_\pi r) \right. \\ &\quad \left. + 2(2(\kappa_2 + 3)(\kappa_1 + 5\kappa_2)(m_\pi r)^2 + (3\kappa_1^2 + 43\kappa_2^2 + 14\kappa_1\kappa_2)) K_2(2m_\pi r) \right] \end{aligned}$$



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

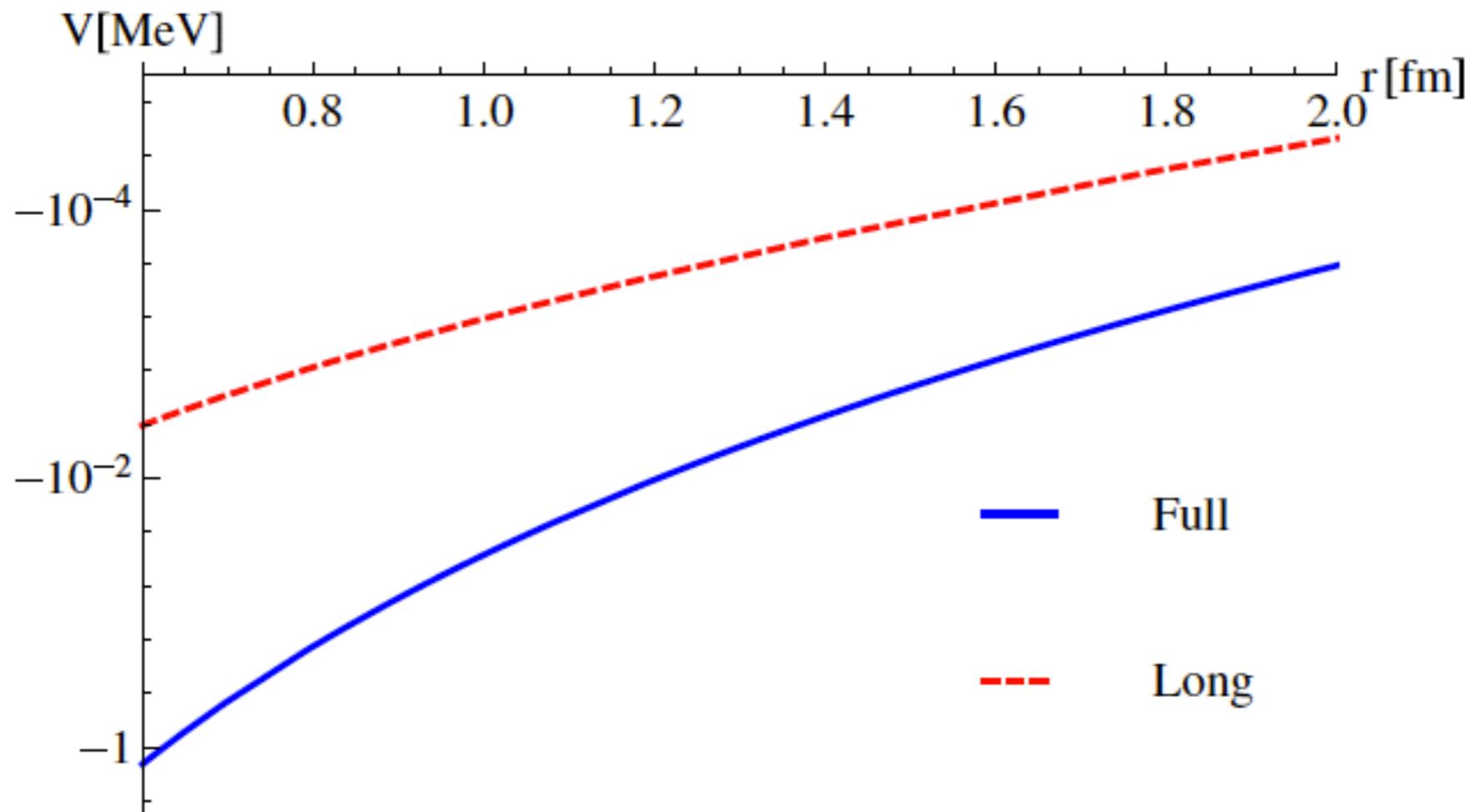


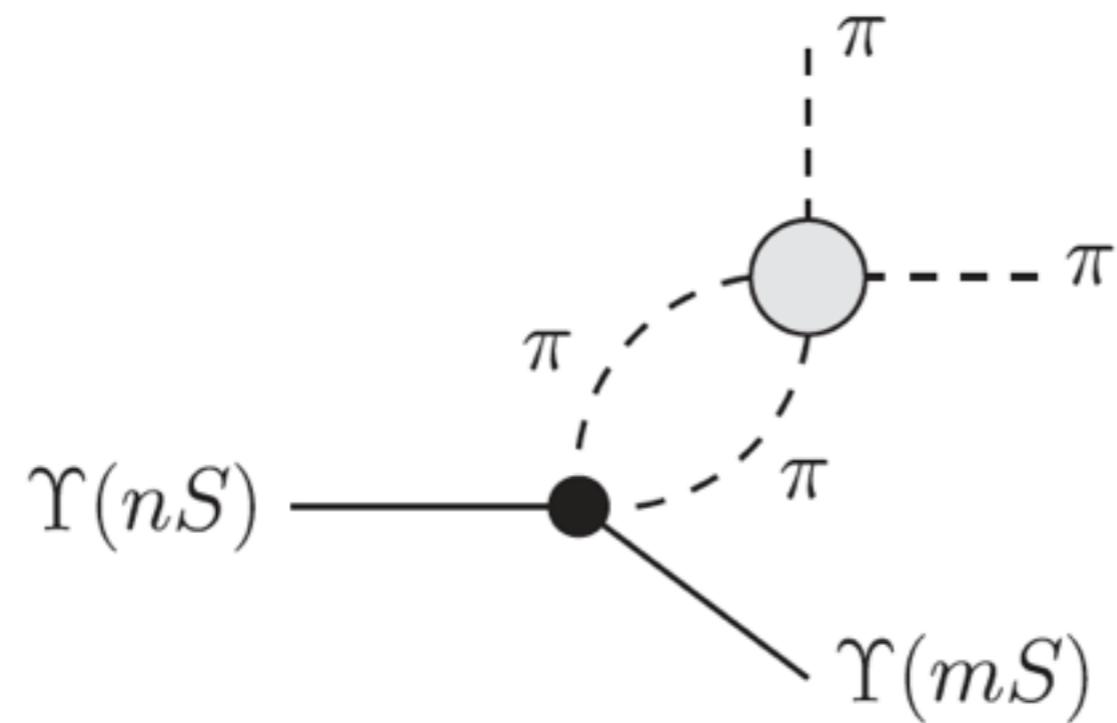
FIG. 9. Comparison of the van der Waals potential (40) (blue line) with its long-range expansion (41) (red line) for  $\beta = 0.92 \text{ GeV}^{-3}$  and other parameters like in Fig. 8.

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

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

# Extension of our study

— nondiagonal polarizabilities



# Motivation 2

# Charmonium binding in nuclei

- 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

$$BE \sim 10 - 20 \text{ MeV}$$

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

# J/ $\Psi$ binding to nuclei

Generically: two independent mechanisms

- van der Waals force - octet intermediate state, large  $N_c$

M.E. Luke, A.V. Manohar & M.J. Savage PLB 288, 355(1992)

- D,D\* meson-loop – color singlet intermediate state  
D mesons interact with the nuclear mean fields

S. H. Lee & C.M. Ko PRC 67, 038202 (2003)  
GK, A. W. Thomas & K. Tsushima PLB 697, 136 (2011)  
K. Tsushima, D.H. Lu, GK & A.W. Thomas PRC 83, 065208 (2011)

# J/ $\Psi$ single-particle energies in nuclei

## — from Klein-Gordon equation

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

# Quarkonium-nucleus bound states from lattice QCD

S. R. Beane,<sup>1</sup> E. Chang,<sup>1,2</sup> S. D. Cohen,<sup>2</sup> W. Detmold,<sup>3</sup> H.-W. Lin,<sup>1</sup> K. Orginos,<sup>4,5</sup> A. Parreño,<sup>6</sup> and M. J. Savage<sup>2</sup>  
 (NPLQCD Collaboration)

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

# 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.

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



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)
$p\bar{p}\eta_c$	37.8(1.1)(4.5)	41.5(1.0)(7.5)	41.5(7.6)
${}^3\text{He}\eta_c$	57.2(1.3)(8.3)	56.7(2.0)(9.4)	56.7(9.6)
${}^4\text{He}\eta_c$	70(02)(13)	56(06)(17)	56(18)
${}^4\text{He}J/\psi$	75.7(1.9)(9.4)	53(07)(18)	53(19)



# NPLQCD

Need crucial input  
— DN interaction

Need crucial input  
— DN interaction

— PANDA @ FAIR

Need crucial input  
— DN interaction

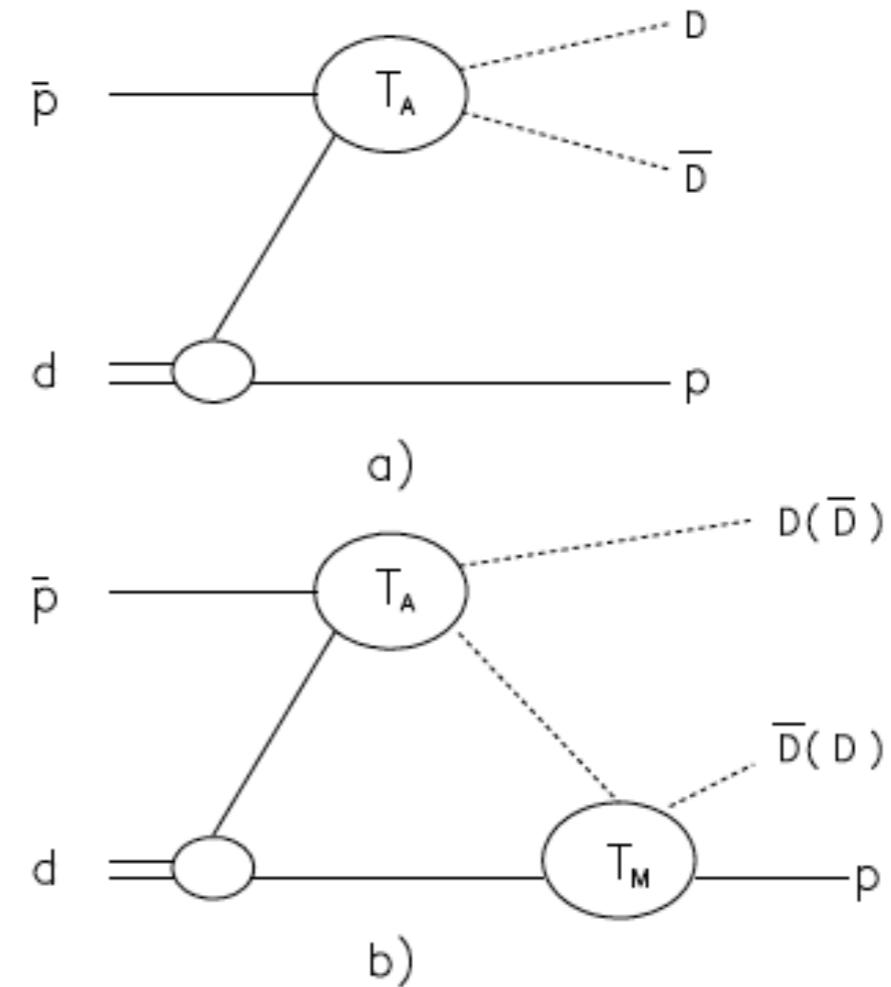
Ȑ PANDA @ FAIR



# DN Experiment

- antiproton annihilation on the deuteron\*

Pa<sup>n</sup>da @ FAIR



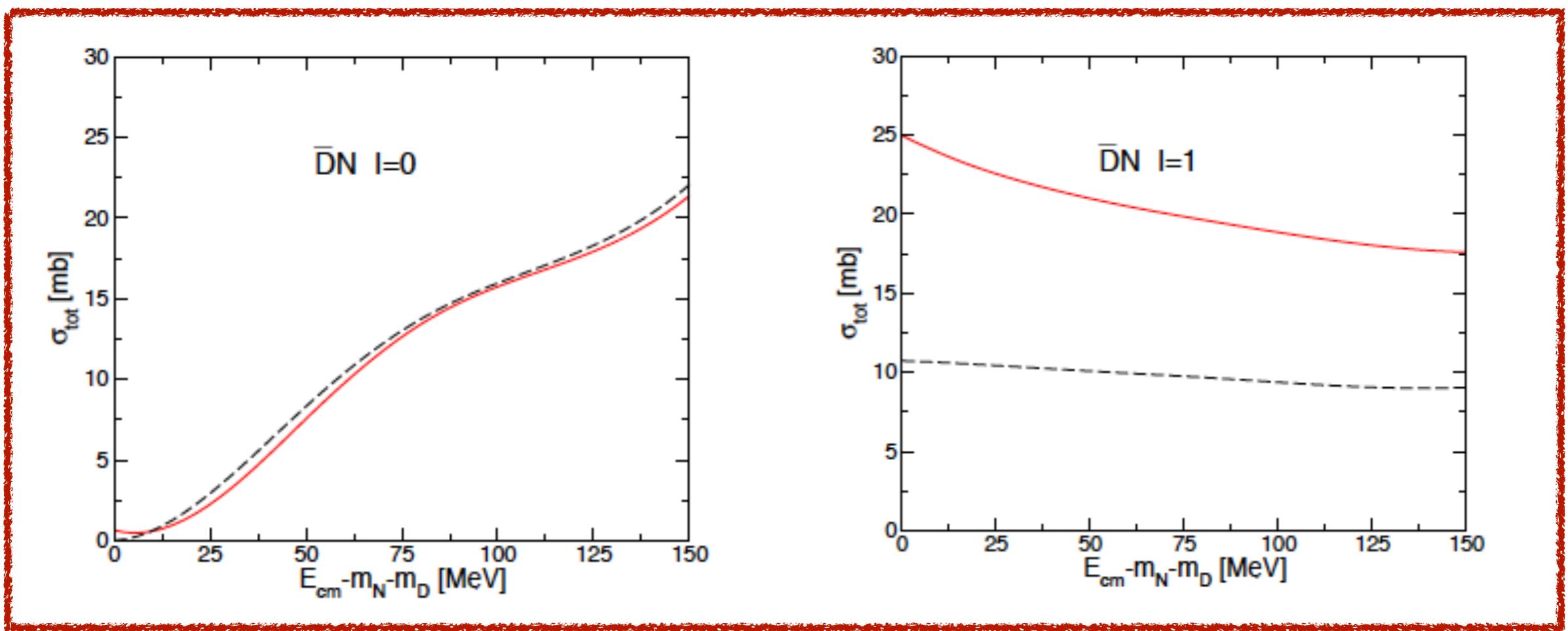
\* J. Haidenbauer, GK, U.-G. Meissner, A. Sibirtsev

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

# Perspectives

- Nonperturbative input from the lattice
- Phenomenology, need experiments, e.g. DN
- EFT for molecules, Born-Oppenheimer

# Funding

