"The spectroscopy program at EIC and future accelerators"
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Low-energy interactions of heavy quarkonium with matter:

pentaquarks, tetraquarks, and chromoelectric polarizabilities*

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Outline

- **motivation**
  – quarkonium bound in light hadron: hadrocharmonium
- **effective interaction of quarkonia with hadrons**
  – chromoelectric polarizabilities
  – chromoelectric field strength
- **hadrocharmonia**
  – pentaquarks and tetraquarks
  – predictions and tests
- **lattice QCD**
  – $\alpha(1S)$ and $\alpha(2S)$
  – possibility of pentaquarks
- **EIC**
  – what can we study?
  – building bridges

* supported by NSF

Motivation

- hypothetical process:
  – capture of (small-size) quarkonium in (large-size) light hadron or nucleus

- in principle remote(!) analogy to:
  – "muon capture" in muonic atoms

- if this was possible(?) for charmonia:
  opportunity to study slow charmonia in matter!

- in practice the life time of J/ψ with 7×10^{-21} s short for:
  – producing charmonium (typically at high energies)
  – slowing down charmonium in nuclear matter
  – waiting for bound state to form

- more promising: take advantage of weak decays
  – e.g. $\boldsymbol{\Lambda_b^0 \longrightarrow J/\Psi\, p\, K^-}$ branching ratio $(3.2^{+0.6}_{-0.5}) \times 10^{-4}$
  – explore configurations of $J/\psi\, p$ with low relative momentum
  – done at LHCb

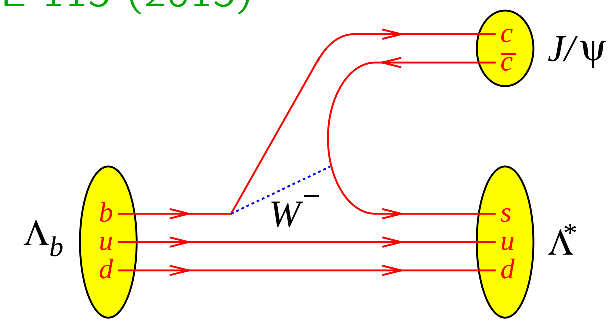
hidden-charm pentaquarks in $\Lambda_b^0 \longrightarrow J/\psi\, p\, K^-$ at LHCb

- "kinematical configuration" possible
  where $\bar{c}c$ slow with respect to nucleon
  $\Rightarrow$ "enough time" to form resonance

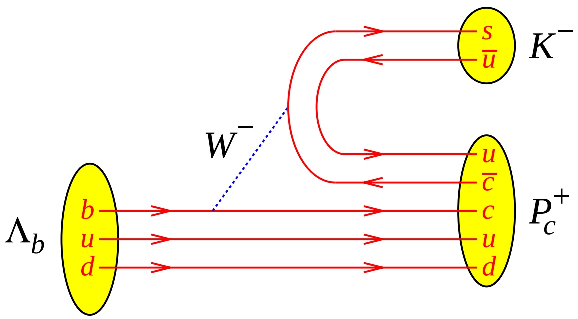
Λ_b^0	$m = 5.6$ GeV,	$\tau = 1.5$ ps
J/Ψ	$m = 3.1$ GeV,	$\Gamma = 93$ keV, $\Gamma_{\mu^+\mu^-} = 6\,\%$
Λ^*	$m \geq 1.4$ GeV,	subsequently $\Lambda^* \to K^- p$

- observed! Aaij *et al.* PRL 115 (2015)

$\longrightarrow J/\Psi\, \Lambda^*$



$\longrightarrow K^-\, P_c^+$



state	m [MeV]	Γ [MeV]	Γ_{rel}	mode	J^P
$P_c^+(4380)$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$(4.1 \pm 0.5 \pm 1.1)\,\%$	$J/\psi\, p$	$\frac{3}{2}^{\mp}$ or $\frac{5}{2}^{+}$
$P_c^+(4450)$	$4450 \pm 2 \pm 3$	$39 \pm 5 \pm 19$	$(8.4 \pm 0.7 \pm 4.2)\,\%$	$J/\psi\, p$	$\frac{5}{2}^{\pm}$ or $\frac{3}{2}^{-}$

observation of resonances in J/ψ-nucleon-spectrum

- resonances in $J/\psi\, p$-spectrum in decay mode $\Lambda_b^0 \longrightarrow J/\psi\, p\, K^-$ at LHCb
  Aaij *et al.* PRL 115, 072001 (2015)
- $p\, K^-$-resonant or nonresonant contributions
  cannot explain it Aaij *et al.* PRL 117, 082002 (2016)
- analysis of $\Lambda_b \to J/\psi\, p\, \pi^-$ decay mode provides support for existence of pentaquark states
  Aaij *et al.* PRL 117, 082003 (2016)
- preparing independent confirmation e.g. in
  photoproduction at JLab, Hall-C proposal Meziani et al, PR12-16-007, arXiv:1609.00676 [hep-ex]
  πp collisions in J-PARC charm spectroscopy program S.H.Kim, H.C.Kim, A.Hosaka, PLB763 (2016) 358

theoretical approaches (non-exhaustive list)

- loosely bound ("molecular") charmed baryon-meson states: Chen, Liu, Li, Zhu, PRL 115, 132002 (2015); Chen, Chen, Liu, Steele, Zhu, PRL 115, 172001 (2015); Roca, Nieves, Oset, PRD 92, 094003 (2015); J.He, PLB 753, 547 (2016), Yamaguchi, Santopinto PRD96 (2017) 014018
- bound states of light and heavy diquarks including c-quarks: Maiani, Polosa, Riquer, PLB 749, 289 (2015); Anisovich, Matveev, Nyiri, Sarantsev, Semenova, arXiv:1507.07652; Lebed, PLB 749, 454 (2015); Li, He, He, J. High Energy Phys. 12 (2015) 128
- possibility of open-color bound states explored:
  Mironov, Morozov, JETP Lett. 102, 271 (2015)
- credible explanation for broader $P_c(4380)$: threshold cusp effect Meißner, Oller, PLB 751, 59 (2015); Mikhasenko, arXiv:1507.06552; Guo, Meißner, Wang, Yang, PRD D 92, 071502 (2015)
- appealing approach to $\boldsymbol{P_c(4450)}$ **= hadrocharmonium** Eides, Petrov, Polyakov, PRD 93, 054039 (2016); Perevalova, Polyakov, Schweitzer, PRD 94, 054024 (2016); Eides, Petrov, Polyakov, EPJ C78, 36 (2018)

hadrocharmonia

- **effective interaction**

$\bar{c}c$-system small in heavy quark limit $\ll R_{\text{nucleon}}$
$\Rightarrow$ non-relativistic multipole expansion Gottfried, PRL 40 (1978) 598

baryon-quarkonium interaction dominated by emission of
2 virtual chromoelectric dipole gluons in a color singlet state

$$V_{\text{eff}} = -\frac{1}{2}\,\alpha\,\vec{E}^2$$ Voloshin, Yad. Fiz. **36**, 247 (1982)

- **ingredients:**

$\boldsymbol{\alpha}$ = chromoelectric polarizability property of quarkonium

$\vec{E}^2$ = chromoelectric field strength in nucleon

chromoelectric polarizability α

- describes effective interaction of a hadron with soft gluonic fields
  - in principle, property of each hadron (immersed in a gluonic back ground field)

- analogous to electric polarizability of neutral atom in electric field
  - induced dipole moments
  - van der Waals interactions
  - exact result: $\alpha_{\text{H-atom}} = \frac{9}{2} R^3_{\text{Bohr}}$

- practical importance for quarkonia
  - $R_{\text{quarkonium}} \to 0$ in heavy quark limit $m_Q \to \infty$

- plays important role for many applications
  - hadrocharmonia
  - interaction of slow charmonia with nuclear medium
  - hadronic transitions between charmonium resonances
  - photo/hadro-production of charmonia, charmed hadrons

- perturbative QCD calculation for α of quarkonia
  - heavy quark + large N_c limit (Coulomb system): $\alpha(nS)_{\text{pert}} = \dfrac{16\pi n^2 c_n}{3 g_c^2 N_c^2}\, a_0^3\,, \quad a_0 = \dfrac{16\pi}{g_c^2 N_c m_Q}$

    $c_1 = 7/4,\ c_2 = 251/8,\ c_n = (5/16)n^2(7n^2 - 3)$ for $n \geq 3$

    Peskin, Bhanot & Peskin (1979)

  - practical estimates for charmonia can vary (depending how one evaluates):

    $\alpha(1S)_{\text{pert}} \approx 0.2\,\text{GeV}^{-3}$ $\quad\alpha(2S)_{\text{pert}} \approx 14\,\text{GeV}^{-3}$ Eides, Petrov, Polyakov, PRD 93 (2016)
    $\alpha(1S)_{\text{pert}} \approx 4.1\,\text{GeV}^{-3}$ $\quad\alpha(2S)_{\text{pert}} \approx 296\,\text{GeV}^{-3}$ J. Ferretti, Phys.Lett.B782 (2018) 702

    discrepancy: estimate "Bohr radius" a_0 = size of a hadron in perturbative QCD(?)

  - use transitional polarizability to "test" perturbative calculation:

    $\alpha(2S \to 1S)_{\text{pert}} = -\dfrac{51200\sqrt{2}\pi}{1287 g_c^2 N_c^2}$ perturbative calculation Peskin (1979)

    $\alpha(2S \to 1S)_{\text{pert}} \approx -0.6\,\text{GeV}^{-3}$ from Eides, Petrov, Polyakov, PRD 93 (2016)

    $|\alpha(2S \to 1S)|_{\text{pheno}} \approx 2\,\text{GeV}^{-3}$ analysis of $\psi' \to J/\psi\,\pi\,\pi$ decays Voloshin (2008)

  - perturbative QCD results: rough guideline (to be used with caution)

chromoelectric field strength $\vec{E}^2$

- explore trace anomaly

$$\vec{E}^2 = g_c^2 \left(\frac{8\pi^2}{b g_s^2} T^\mu{}_\mu + T_{00}^G \right)$$

$b = \frac{11}{3} N_c - \frac{2}{3} N_F$ leading coeff. of β-function

g_s strong coupling at low (nucleon) scale $\lesssim 1$ GeV

$g_c =$ strong coupling at scale of heavy quark ($g_c \neq g_s$)

$T_{00}^G = \xi T_{00}$ with $\xi =$ fraction of gluon contribution to M_N

$T^\mu{}_\mu = T^{00} + T^{ii}$, stress tensor $T^{ij} = \left(\frac{r^i r^j}{r^2} - \frac{1}{3} \delta^{ij} \right) s(r) + \delta^{ij} p(r)$

- universal effective potential

$$V_{\text{eff}} = -\frac{1}{2} \alpha \frac{8\pi^2}{b} \frac{g_c^2}{g_s^2} \left[\nu T_{00}(r) + 3p(r) \right], \quad \nu = 1 + \xi_s \frac{b g_s^2}{8\pi^2}$$

$\nu \approx 1.5$ estimate by Eides et al, op. cit.
Novikov, Shifman, Z.Phys.C8, 43 (1981)
X. D. Ji, Phys.Rev.Lett. **74**, 1071 (1995)

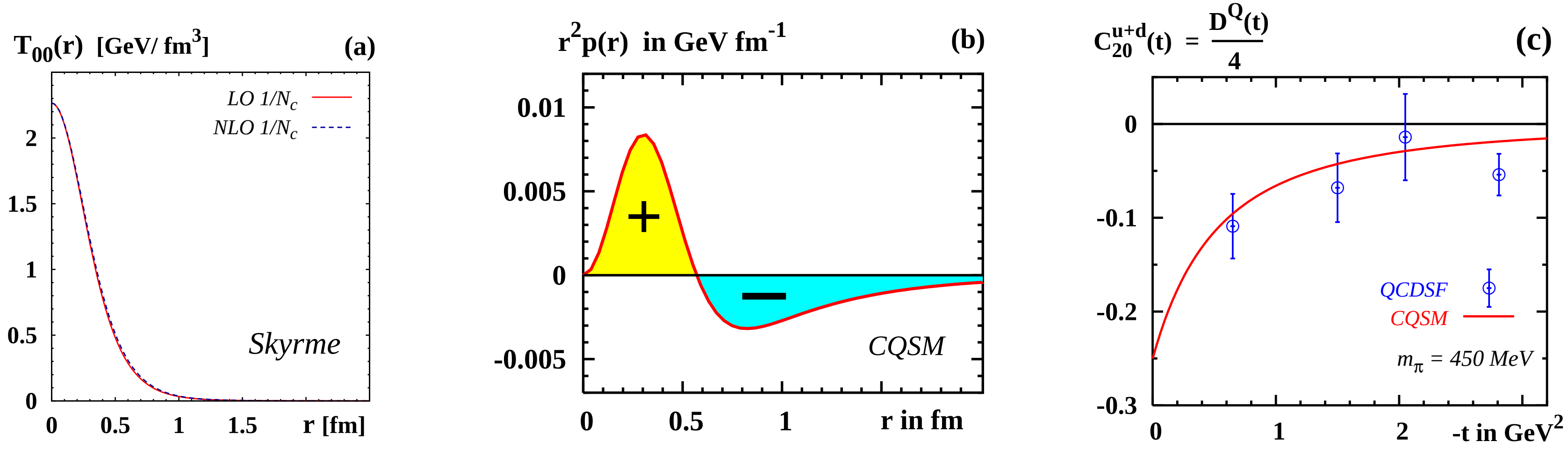
- nonperturbative nucleon properties:

$T_{00}(r)$ energy density: $\int \mathrm{d}^3 r \, T_{00}(r) = M_N$
$p(r)$ pressure distribution: $\int \mathrm{d}r \, r^2 p(r) = 0$

densities of energy-momentum tensor
Polyakov, PLB 555, 57 (2003)
for a review see Polyakov and Schweitzer, Int.J.Mod.Phys.A 33 (2018) 1830025

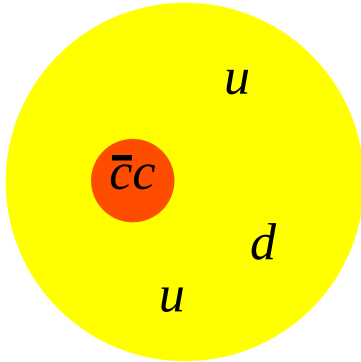
- for $T_{00}(r)$, $p(r)$ needed: non-perturbative computations or experiment

chiral quark soliton model Goeke et al, PRD 75, 094021 (2007)
Skyrme model Cebulla et al, NPA 794, 87 (2007)
lattice Hägler et al PRD 68, 034505 (2003);
Shanahan, Detmold, arXiv:1810.07589



future: EMT form factors from hard exclusive reactions
via generalized parton distribution functions (GPDs)
very first insights from phenomelogy/experiment:
Kresimir Kumerički, Dieter Müller, arXiv:1512.09014;
Burkert, Elouadrhiri, Girod, Nature 557 (2018) 396.

- **compute quarkonium-nucleon bound state**



solve $\left(-\frac{\vec{\nabla}^2}{2\mu} + V_{\text{eff}}(r)\right)\psi = E_{\text{bind}}\,\psi$

$\mu =$ reduced quarkonium-baryon mass

- **results:**

nucleon and J/ψ form no bound state

nucleon and $\psi(2S)$ form 2 bound states
for $\alpha(2S) \approx 17\ \text{GeV}^{-3}$
nearly degenerate masses around 4450 MeV
$L = 0$ channel, $J^P = \frac{1}{2}^-, \frac{3}{2}^-$ compatible with LHCb
mass-splitting $\mathcal{O}(10)$ MeV (suppressed in heavy quark limit)

decay: width of $\psi(2S)$ ca. 200keV (practically stable)
"wait" for $2S \to 1S$ transition in background gluon field
governed by V_{eff} with $|\boldsymbol{\alpha}(\mathbf{2S} \to \mathbf{1S})| \sim \mathbf{2GeV^{-3}} \ll \alpha(2S) \approx 17\ \text{GeV}^{-3}$ $\Rightarrow$ "takes" time!
narrow width $\Gamma = |\alpha(2S \to 1S)|^2 \times \cdots =$ few tens of MeV $\Rightarrow$ compatible with LHCb
narrow $P_c(4450)$ $= \psi(2S)$-nucleon bound state, broad $P_c(4380)$ not

- **approach can be tested**

  predictions for bound states of $\psi(2S)$ with Δ

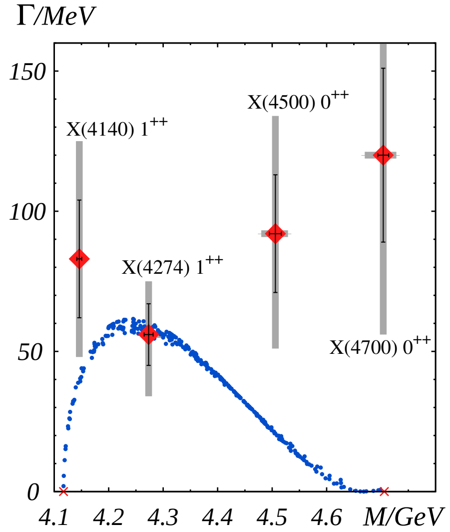
  Perevalova, Polyakov, Schweitzer, PRD 94, 054024 (2016)

  predictions for bound states of $\psi(2S)$ with hyperons

  Eides, Petrov, Polyakov, EPJ C78, 36 (2018)

  $X(4274)$ resonance in $J/\psi\,\phi$ system Aaij et al, PRD 95 (2017) 012002
  candidate for $\psi(2S)$-ϕ hadrocharmonium (tetraquark $\bar{c}c\bar{s}s$)
  concluded despite knowing nothing about ϕ-meson EMT densities
  characteristic relation of mass-width in hadrocharmonium picture

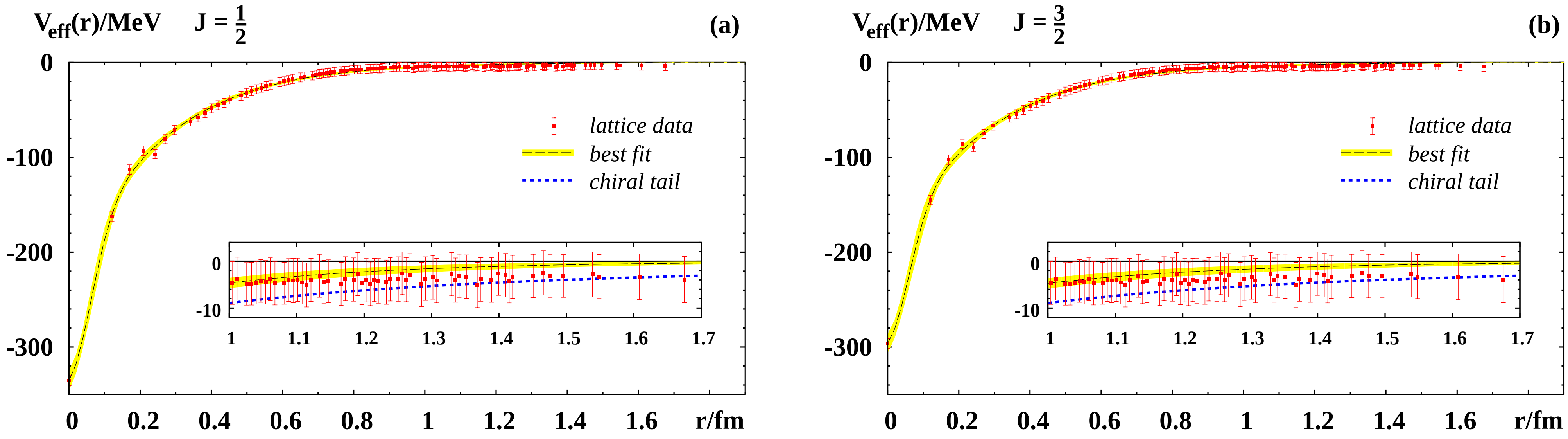
  Panteleeva, Perevalova, Polyakov, Schweitzer, arXiv:1802.09029



- so far:

  compatible with experiment
  compatible with lattice study
  (next slide)

lattice study of nucleon J/ψ potential



lattice: 2+1 light Wilson clover quarks, $16^3 \times 32$, $a = 0.1209$fm, $m_\pi = 875$ MeV
T.Sugiura, Y.Ikeda, N.Ishii, arXiv:1711.11219 [hep-lat]

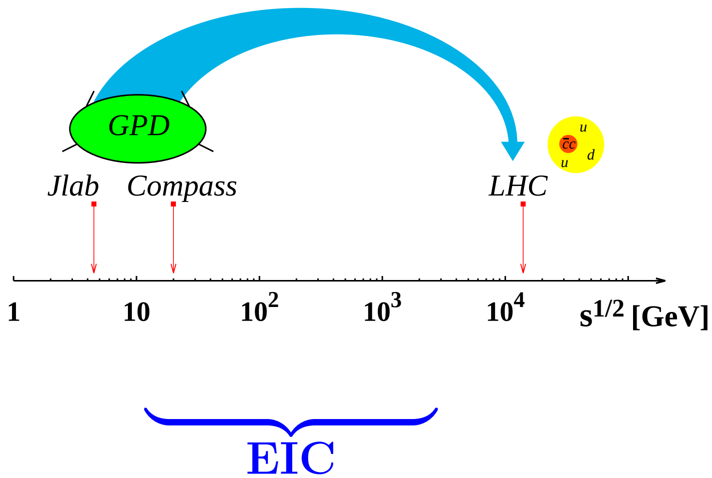
- $J = \frac{1}{2}$ and $\frac{3}{2}$ channels agree (except for 1 bin at $r = 0$) $\Rightarrow$ $1/m_Q$ corrections small
- normalization $\int \mathrm{d}^3 r\, V_{\rm eff}(r) = -\,\alpha(1S)\,\dfrac{4\pi^2}{b}\,\dfrac{g_c^2}{g_s^2}\,\nu\, M_N$
- **nonperturbative determination of $\alpha(1S) = (1.6 \pm 0.8)\,\mathrm{GeV}^{-3}$**
- $P_c(4450) = \psi(2S)$-nucleon bound state for $\dfrac{\alpha(2S)}{\alpha(1S)} = (15 \pm 1)$
  Polyakov, Schweitzer PRD98 (2018) 034030
- similar values can be estimated from J/ψ-nucleon scattering wave-lengths
  Ferretti, Santopinto arXiv:1806.02489

what can EIC contribute?

- measurements of hard-exclusive reactions
  generalized parton distributions (GPDs) $\to$ EMT densities

- interaction of slow J/ψ, $\psi(2S)$ with nuclear matter
  cross section determined by $\alpha(1S)$, $\alpha(2S)$

- direct production of pentaquarks $P_c(4450)$
  test hadrocharmonium picture



Thank you!