Computing hybrid static potentials at short quark-antiquark separations from fine lattices in SU(3) Yang-Mills theory

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in collaboration with Marc Wagner

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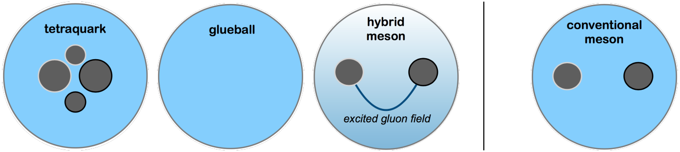
Non-quark model mesons



- active field of research, both theoretically and experimentally

[E. Braaten, C. Langmack, D. H. Smith, Phys. Rev. Lett. 112 (2014), 222001 [arXiv:1401.7351 [hep-ph]]

[C. A. Meyer, E. S. Swanson, Prog. Part. Nucl. Phys. 82 (2015), 21-58 [arXiv:1502.07276 [hep-ph]]]

[E. S. Swanson, AIP Conf. Proc. 1735 (2016) no.1, 020013 [arXiv:1512.04853 [hep-ph]]]

[S. L. Olsen, T. Skwarnicki,D. Zieminska, Rev. Mod. Phys. 90 (2018) no.1, 015003 [arXiv:1708.04012 [hep-ph]]]

[N. Brambilla, S. Eidelman, C. Hanhart, A. Nefediev, C. P. Shen, C. E. Thomas, A. Vairo, C. Z. Yuan, Phys. Rept. 873 (2020), 1-154 [arXiv:1907.07583 [hep-ex]]]

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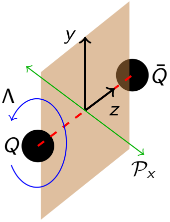
Heavy hybrid meson

Heavy quark and antiquark surrounded by an excited gluon field
$\rightarrow$ *hybrid static potential*

Hybrid static potentials

= gluonic static energy between quark and antiquark in a distance r



Quantum numbers Λ_η^ϵ $\quad e.g.\ \Sigma_g^+, \Pi_u, \Sigma_u^-$

$\Lambda = \Sigma, \Pi, ..$ orbital angular momentum along quark separation axis L_z

$\eta = u, g$ combination of parity and charge conjugation $P \circ C$

$\epsilon = +, -$ spatial inversion P_x

- excited gluon field contributes to the quantum numbers of the meson

$\Rightarrow$ exotic meson quantum numbers J^{PC} possible

$$P = (-1)^{L+1+\Lambda}$$
$$C = \eta\epsilon(-1)^{L+S+\Lambda}$$

Λ_η^ϵ	L	J^{PC} $S=0$	J^{PC} $S=1$
Σ_u^-	0	0^{++}	1^{+-}
	1	1^{--}	$\{0,\mathbf{1},2\}^{-+}$
	2	2^{++}	$\{1,\mathbf{2},3\}^{+-}$
Π_u^-	1	1^{++}	$\{\mathbf{0},1,\mathbf{2}\}^{+-}$
	2	2^{--}	$\{\mathbf{1},2,\mathbf{3}\}^{-+}$
Π_u^+	1	1^{--}	$\{0,\mathbf{1},2\}^{-+}$
	2	2^{++}	$\{1,\mathbf{2},3\}^{+-}$

Hybrid static potentials

- Computation of spectra of $\bar{b}b$ and $\bar{c}c$ hybrid mesons in the Born-Oppenheimer approximation

[S. Perantonis and C. Michael, Nuclear Physics B 347 no. 3, (1990) 854 – 868]

[K. J. Juge, J. Kuti and C. J. Morningstar, Nucl. Phys. Proc. Suppl. 63, 326 (1998) [hep-lat/9709131]]

[E. Braaten, C. Langmack and D. H. Smith, Phys. Rev. D 90, 014044 (2014) [arXiv:1402.0438 [hep-ph]]]

[R. Oncala and J. Soto, Phys. Rev. D96 no. 1, (2017) 014004, arXiv:1702.03900 [hep-ph]]

[S. Capitani, O. Philipsen, C. Reisinger, C. Riehl and M. Wagner, Phys. Rev. D 99, no. 3, 034502 (2019) [arXiv:1811.11046 [hep-lat]]]

- Matching coefficients for potential Non-Relativistic QCD

[M. Berwein, N. Brambilla, J. Tarrus Castella and A. Vairo, Phys. Rev. D 92, 114019 (2015) [arXiv:1510.04299 [hep-ph]]]

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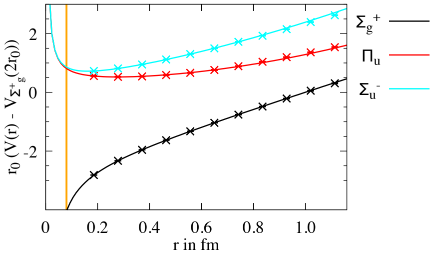


$\rightarrow$ so far based on lattice data at $r \gtrsim 0.16\,\text{fm}$

$\Rightarrow$ New $SU(3)$ lattice results at r as small as $0.08\,\text{fm}$

Simulations at small lattice spacings

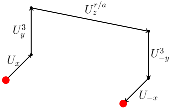
β	6.00	6.284	6.451	6.594
a	$0.093\,\text{fm}$	$0.060\,\text{fm}$	$0.048\,\text{fm}$	$0.040\,\text{fm}$

[S. Necco and R. Sommer, Nucl. Phys. B 622 (2002) 328–346, arXiv:hep-lat/0108008.]

- $SU(3)$ gauge field configurations generated with a Monte Carlo heatbath algorithm and standard Wilson plaquette action
- Isotropic lattices with volume $T \times L^3 \approx (2.4\,\text{fm}) \times (1.2\,\text{fm})^3$
- Multilevel algorithm [M. Lüscher and P. Weisz, JHEP 09 (2001), 010 [arXiv:hep-lat/0108014 [hep-lat]]
- Optimized hybrid static potential creation operators

  [S. Capitani, O. Philipsen, C. Reisinger, C. Riehl and M. Wagner, Phys. Rev. D 99, no. 3, 034502 (2019)

  [arXiv:1811.11046 [hep-lat]]]



- *APE*-smearing of spatial links optimized at each lattice spacing
- Tree-level improved separations $r \to r_{\text{improved}}$

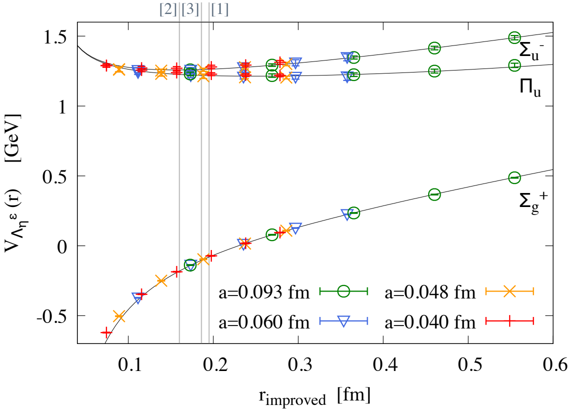
Lattice results for hybrid static potentials

- new $SU(3)$ lattice data at separations as small as $r \approxeq 0.08$ fm
- previous lattice data at separations $r \gtrapprox 0.16$ fm

[1] [K. J. Juge, J. Kuti and C. J. Morningstar, Nucl. Phys. Proc. Suppl. 63, 326 (1998) [hep-lat/9709131]]

[2] [G. S. Bali and A. Pineda, Phys. Rev., D69, 094001 (2004), arXiv:hep-ph/0310130 [hep-ph]]

[3] [S. Capitani, O. Philipsen, C. Reisinger, C. Riehl and M. Wagner, Phys. Rev. D 99, no. 3, 034502 (2019) [arXiv:1811.11046 [hep-lat]]



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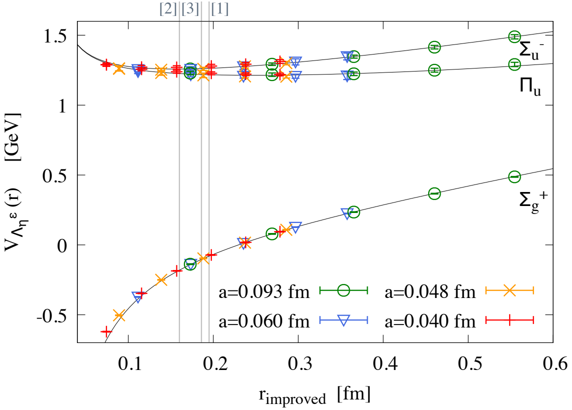
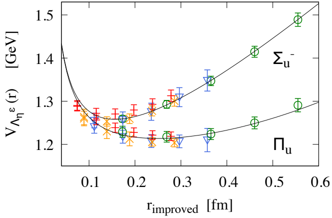




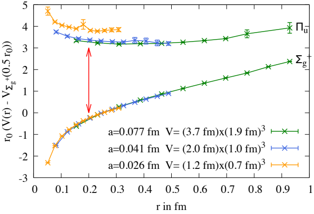
$$V_{\Pi_u/\Sigma_u^-}(r) = \frac{a}{r} + b + \mathcal{O}(r^2)$$

[M. Berwein, N. Brambilla, J. Tarrus Castella and A. Vairo, Phys. Rev. D 92, 114019 (2015) [arXiv:1510.04299 [hep-ph]]]

Excluding possible systematic errors

- Finite volume effects
  - sizable spatial volume dependence of the ordinary static potential and hybrid static potentials, when the volume is smaller than $\approx (1.0\,\mathrm{fm})^3$

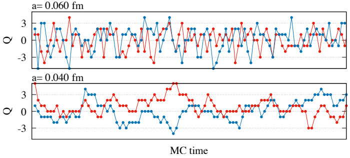
  $\rightarrow$ for $L^3 \approx (1.2\,\mathrm{fm})^3$ already negligible compared to statistical errors



- Topological freezing

  = Rare tunneling between topological sectors when approaching continuum (lattice spacing $a \rightarrow 0$)

  $\rightarrow$ topological charge distribution is still sampled correctly by the algorithm at all lattice spacings



Possible glueball decay at small separations

- For sufficiently small r: energy difference $V_{\Lambda_\eta^\epsilon} - V_{\Sigma_g^+}$ is large enough such that the hybrid flux tube can dissolve into a glueball and the Σ_g^+ flux tube

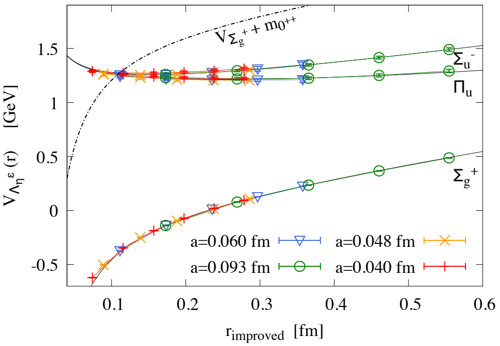


Figure: Minimal energy for a decay into the lightest glueball 0^{++}.

- Σ_u^-: decay into lightest 0^{++} - glueball not allowed due to symmetry

Summary & Outlook

Summary

- $SU(3)$ lattice results for ordinary and hybrid static potentials Σ_g^+, Π_u and Σ_u^- at four small lattice spacings $a = 0.040\,\text{fm} \ldots 0.093\,\text{fm}$
- Excluded systematic errors from topological freezing and finite volume effects
- Glueball decay at small separations
  - Decay of Σ_u^- into $0^{++} + \Sigma_g^+$ not allowed

Outlook

- Higher hybrid static potentials at small separations
- Computation of heavy hybrid meson spectrum based on new lattice results at small r

Thank you!