Born-Oppenheimer Potentials for Quarkonium Hybrid Mesons

Fareed Alasiri [1] Eric Braaten [1] Abhishek Mohapatra [2]

[1]The Ohio State University

[2]Technical University of Munich

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Exotic hadrons

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- Non-traditional states like mesons and baryons.
- XYZ hadrons.
- X(3872): The first exotic state discovered in 2003 by Belle.
- Dozens of exotic hadrons have been discovered since then.
- The challenge is building a theoretical framework to understand and predict their existence.

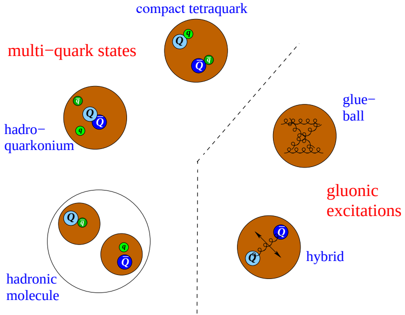


Figure: [arXiv:1907.07583]

The Born-Oppenheimer Potentials

Juge, Kuti, Morningstar (JKM) (hep-ph/9902336)
Brambilla, Pineda, Soto, Vairo (hep-ph/9907240).

- A fundamental understanding of exotic hadrons based on QCD presents a challenge.
- The Born-Oppenheimer approximation for QCD was pioneered by Juge, Kuti and Morningstar.
- The B-O approximation was developed by Brambilla *et al.* into an effective field theory named pNRQCD which was later called BOEFT.
- BOEFT can address all these states with inputs from Lattice QCD on the B-O potentials.

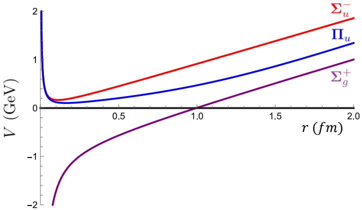
BO quantum numbers

- QCD symmetries: SO(3), $\mathcal{P}$ and $\mathcal{C}$ parity.
- Quantum numbers: $\mathcal{J}^{PC}$.
- QCD color sources separated by $\vec{r}$ break SO(3) into SO(2) generated by $\vec{J} \cdot \vec{r}$.
- It breaks $\mathcal{P}$ and $\mathcal{C}$ into $\mathcal{CP}$.
- $V_\Lambda(r)$: Λ labelled by cylindrical symmetry ($D_{\infty h}$) representation.
  - $\left|\vec{J} \cdot \vec{r}\right| \equiv \lambda = 0, 1, 2, ...$ or $(\Sigma, \Pi, \Delta, ...)$.
  - CP parity: $\eta = +1$ (g), -1 (u)
  - Reflection symmetry about a plane containing static sources: $\epsilon = \pm 1$
- All together: Λ_η^ϵ.

Short distance behaviour

$r \to 0$

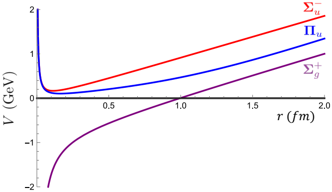
- QCD symmetries restored.
- Gluelumps with definite J^{PC} quantum numbers.
- Potentials: Perturbative (expanded in powers of $\alpha_s(1/r)$) + Nonperturbative corrections (expanded in powers of r).



Long distance behaviour

$r \to \infty$

- Potentials form multiplets at large r whose differences decrease as $1/r$.
- The difference between potentials within a multiplet decreases as higher powers of $1/r$.
- consistent with relativistic string excitation: $V_N(r) = \sqrt{\sigma^2 r^2 + 2\pi\left(N - \frac{1}{12}\right)\sigma}$.



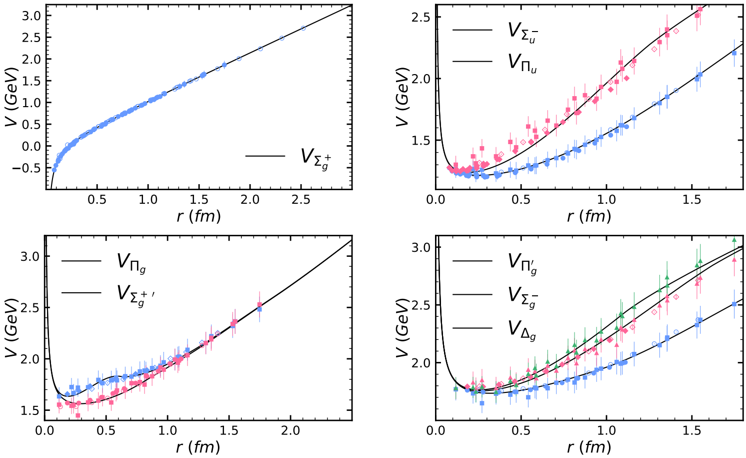
Setting the scale

Juge, Kuti Morningstar (JKM) (arXiv:2207.09365);
Schlosser Wagner (SW) (arXiv:2111.00741);
Capitani, Philipsen, Reisinger, Riehl Wagner (CPRRW) (arXiv:1811.11046);
Bicudo, Cardoso Sharifian (arXiv:2105.12159);
Sharifian, Cardoso, Bicudo (arXiv:2303.15152).

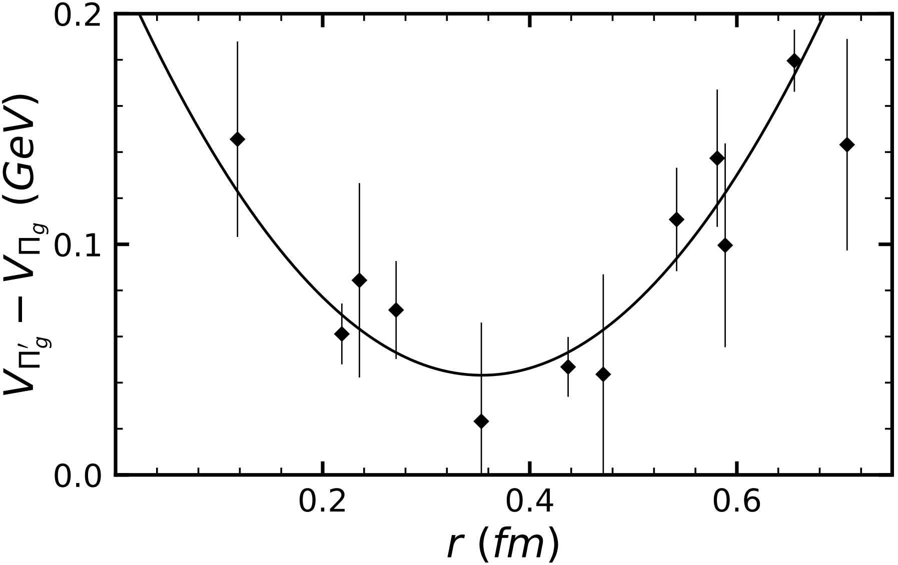
Scaling and shifting data

- Good scale:
  - Well-defined.
  - Low numerical effort.
  - Small systematic uncertainty.
- String tension: $V_{\Sigma_g^+}(r) \longrightarrow \sigma r \quad \text{as } r \to \infty.$
- Sommer scale (hep-lat/9310022):
  - Definition: $r^2 \frac{dV_{\Sigma_g^+}(r)}{d(r)}|_{r=r_0} = 1.65.$
  - replace the string tension for pure gauge theories.

Potentials with fits



Avoided crossing



Summary

- Exotic hadrons and quick look into the BOEFT and its quantum numbers.
- Short and long distance behavior of B-O potentials.
- The Sommer scale.
- Fitted data.
- Avoided crossing.