Spectroscopy and scattering: applications (day 1)

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Deutsches Elektronen-Synchrotron DESY

Frontiers and Challenges in Lattice Gauge Theory
MITP Summer School 2025
July 21 to August 1, 2025

Quantum chromodynamics

Elementary quantum field theory describing the strong nuclear force.

- $SU(3)$ gauge symmetry, “colour”
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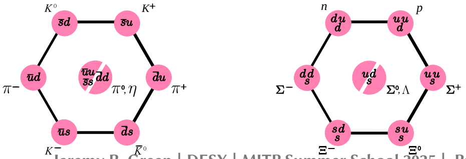
Useful to classify into multiplets of approximate flavour symmetry.
SU(3) octets: $J^P = 0^-$ mesons and $\frac{1}{2}^+$ baryons.



Decays of hadrons

Except for proton and some nuclei, hadrons are unstable. It matters how they decay.

- Weak, e.g. $n \longrightarrow pe^- \bar{\nu}$ ($\tau \approx 900$ s), $K^+ \longrightarrow \mu^+ \nu$ or $K^+ \longrightarrow \pi^+ \pi^0$ ($\tau \approx 10^{-8}$ s).
- Electromagnetic, e.g. $\pi^0 \longrightarrow \gamma\gamma$ ($\tau \approx 10^{-16}$ s), $\Sigma^0 \longrightarrow \Lambda\gamma$ ($\tau \approx 10^{-19}$ s).
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If yes, then name includes approximate mass: $\rho(770)$, $\Delta(1232)$, $f_0(500)$, etc.

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It is a resonance.
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This can change as quark masses are varied. If $2m_\pi > m_\rho$, then the ρ becomes stable.

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- T_{cc}^{+} $(cc\bar{u}\bar{d})$
- Z_c charged charmonium $(c\bar{c}u\bar{d})$
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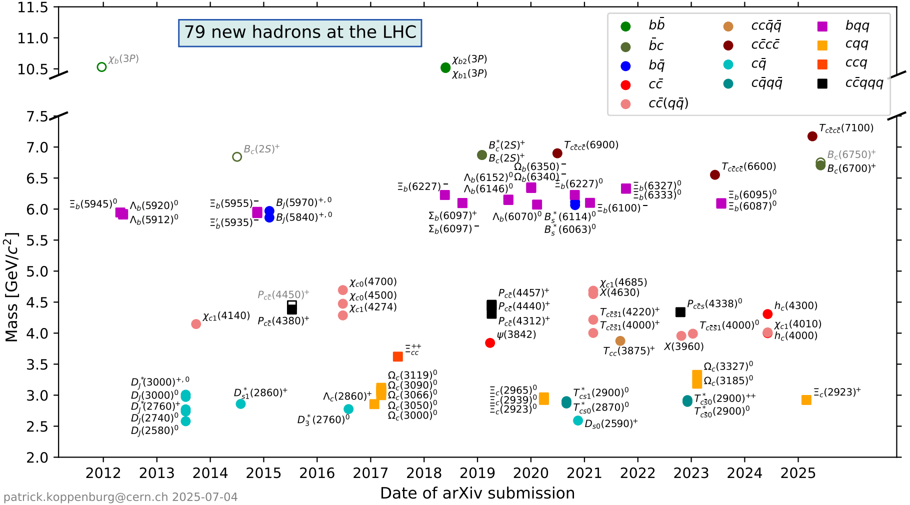
6 quarks $qqqqqq$ "hexaquark" dibaryon

- deuteron $(uuddd)$ "pn molecule" $B_d = 2.2$ MeV
- conjectured H dibaryon $(uuddss)$

Ordinary and exotic hadrons at the LHC



LHCb collaboration, P. Koppenburg, List of hadrons observed at the LHC, LHCb-FIGURE-2021-001, 2021, and recent updates.

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NN interaction (and NNN) leads to nuclei.

How fine tuned is the universe?

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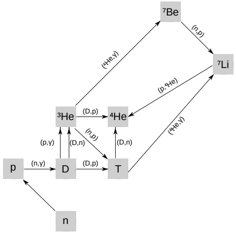

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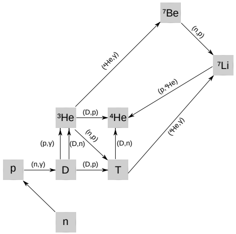

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How strongly does deuteron binding depend on quark masses?
Could pp or nn bind?

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Hyperon interactions with $S = -1$ or -2 less well known.

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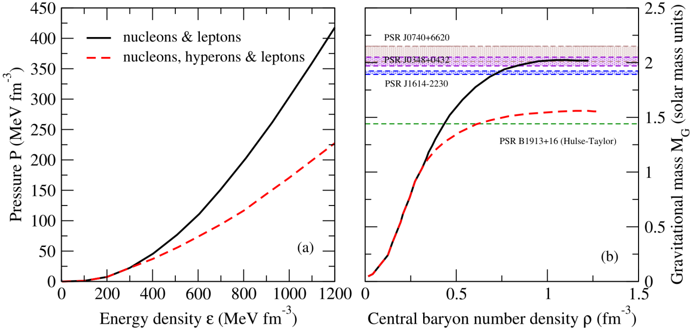

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Contradicted by detection of neutron stars with $M \approx 2M_{\odot}$.

I. Vidaña, EPJ Web Conf. **271**, 09001 (2022)

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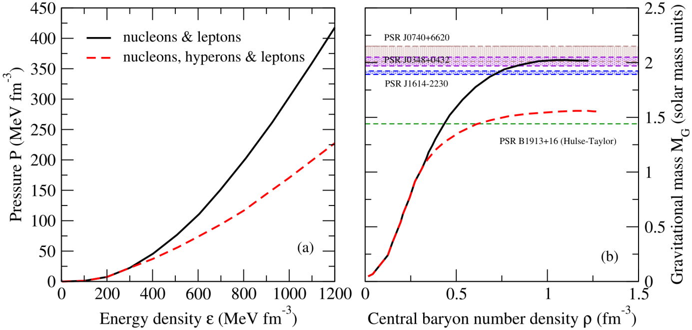

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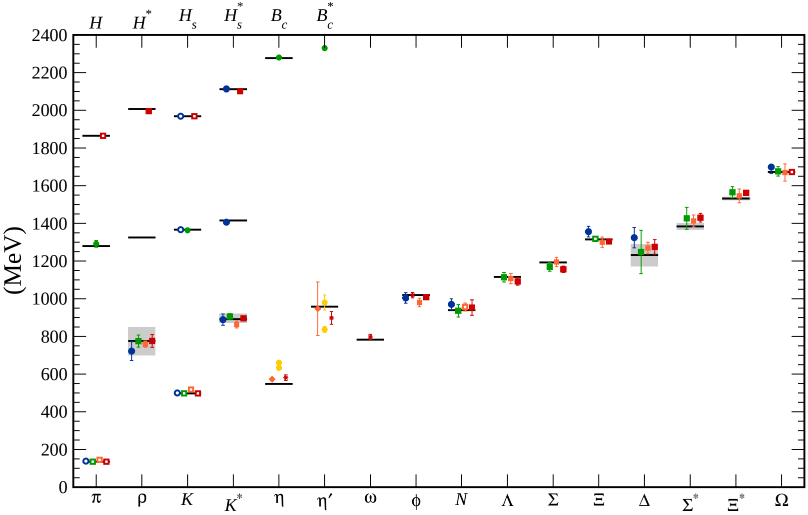
Do hyperon-hyperon (YY) or NNY interactions play a role?

Lattice QCD in 2012: stable hadrons



A. S. Kronfeld, Ann. Rev. Nucl. Part. Sci. **62**, 265–284 (2012) [1203.1204]

(B mesons shifted by -4 GeV.)

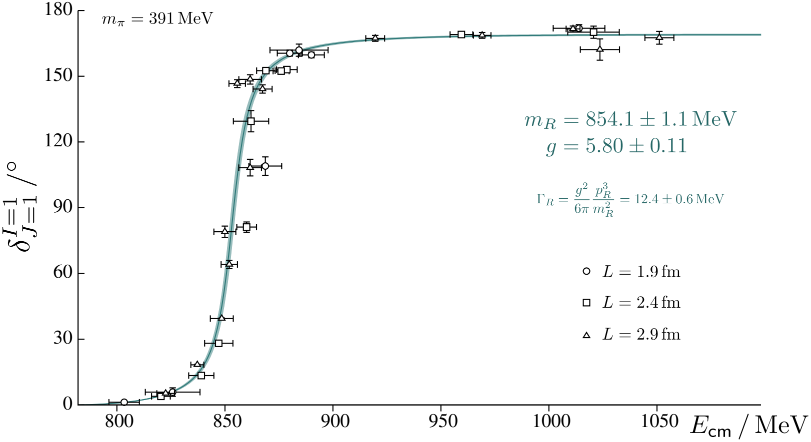
Calculations by different collaborations using different actions.

Some include $m_\pi \to m_\pi^{\text{phys}}$ and $a \to 0$ extrapolations.

Open symbols: inputs.

Grey bands: resonance widths from experiment.
Uncontrolled approximation on the lattice!

Lattice QCD in 2012: unstable hadron



ρ meson as resonance in p-wave $\pi\pi$ scattering.

Single lattice spacing, single pion mass.

J. J. Dudek, R. G. Edwards, C. E. Thomas (Hadron Spectrum Collaboration), Phys. Rev. D **87**, 034505 (2013); **90**, 099902(E) (2014) [1212.0830]

Chalkboard notes

Two-point correlation functions

- spectral decomposition
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- quantum numbers in rest frame and moving frames
- single-hadron interpolators
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Computing correlation functions

- example Wick contraction
- distillation