QCD and applications to nuclear physics and matter in extreme conditions

Miguel Albaladejo (IFIC)

Workshop CSIC Strategic Theme
"Understanding the basic components of the Universe, its structure and evolution"
Madrid Feb. 22-23, 2023

PID2020-112777GB-I00

From the book…

CHAPTER 3

SOLVING QUANTUM CHROMO- DYNAMICS

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Juan Nieves (IFIC, CSIC – UV)
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Agustín Sabio Vera (IFT, CSIC – UAM)

Lacking an analytical solution of QCD, a multi-prong strategy has been implemented that includes a variety of tools:

1. the **perturbative treatment** whenever high-momentum scales are involved,
2. the construction of **effective field theories** that exploit symmetries in a maximal way,
3. and a **first-principles** formulation, based on the introduction of a space- time lattice, that allows, in particular, for a **numerical solution** [LQCD].

Notwithstanding, a formal solution to the theory continues to be a key challenge for the future both in physics and mathematics.

In this talk…

In Alberto's very nice previous talk we have already seen quite a lot about points 1 and 3. In this talk, I will focus more on point **EFTs** (point 2), and its application to **hadron spectroscopy** and **extreme conditions**, without forgetting their **mutual connection**.

Effective Field Theories

- QCD lagrangian built in terms of (degrees of freedom) quarks and gluons: $\mathcal{L}[q, \bar{q}, g]$
- Quarks are **confined** into colorless hadrons, which are ultimately the objects detected in experiments.
- EFTs: build QFT with hadrons ($\pi, K, \ldots, D, B, \ldots$) as degrees of freedom

Example 1: Chiral Perturbation Theory

- Light quarks are… light: $m_u \simeq m_d \simeq m_s \simeq 0$
- 8 Goldstone bosons SU(3): $\phi_i \to \pi, K, \eta$
- [Weinberg, PRL,17,616('66); Phys. A96,327 ('79)]]
  [Gasser, Leutwyler, AP,158,142('84); NP,B250,465('85)]
- LO lagrangians:

$$\mathcal{L}_2 = \frac{f^2}{4}\left\langle D_\mu U^\dagger D^\mu U \right\rangle + \frac{f^2}{4}\left\langle \chi^\dagger U + \chi U^\dagger \right\rangle$$

$$U[\phi] = \exp\left(i \sum_{i=1}^{8} \phi_i \lambda_i \right)$$

$$\chi = 2B_0 \mathrm{diag}\left(m_u, m_d, m_s\right) \simeq \mathrm{diag}\left(m_\pi^2, m_\pi^2, 2m_K^2 - m_\pi^2\right)$$

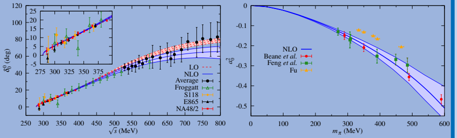
Symmetry **2022**, *14*, 1884. https://doi.org/10.3390/sym14091884

Article

Weinberg's Compositeness †

Ubirajara van Kolck [1,2]

[1] Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France; vankolck@ijclab.in2p3.fr
[2] Department of Physics, University of Arizona, Tucson, AZ 85721, USA
† Dedicated to the memory of Steven Weinberg, who always chose the right degrees of freedom.



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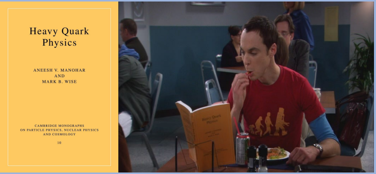
Example 2: HQSS + SU(3) flavour

- Heavy quarks are… heavy: $m_c, m_b \to \infty$
- $H_a^{(Q)} = \frac{1+\not{v}}{2}\left(P^{*(Q)}_{a\mu}\gamma^\mu - P_a^{(Q)}\gamma_5\right)$
- HQSS and $SU(3)$ light flavour symmetry: $H_a^{(Q)} \sim (Q\bar{u}, Q\bar{d}, Q\bar{s}) \sim \left(D^{(*)0}, D^{(*)+}, D_s^{(*)+}\right)$

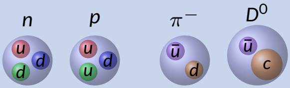


[Grinstein *et al.*, NP,B380('92); Alfiky *et al.*, PL,B640('06), …]

$H\bar{H} \longrightarrow H\bar{H}$ LO lagrangian:

$$\begin{aligned}\mathcal{L}_{4H} &= \frac{1}{4}\,\mathrm{Tr}\left[\bar{H}^{(Q)a}H_b^{(Q)}\gamma_\mu\right]\mathrm{Tr}\left[H^{(\bar{Q})c}\bar{H}_d^{(\bar{Q})}\gamma^\mu\right]\left(F_A\,\delta_a^{\,b}\delta_c^{\,d} + F_A^\lambda\,\vec{\lambda}_a^{\,b}\cdot\vec{\lambda}_c^{\,d}\right)\\ &+ \frac{1}{4}\,\mathrm{Tr}\left[\bar{H}^{(Q)a}H_b^{(Q)}\gamma_\mu\gamma_5\right]\mathrm{Tr}\left[H^{(\bar{Q})c}\bar{H}_d^{(\bar{Q})}\gamma^\mu\gamma_5\right]\left(F_B\,\delta_a^{\,b}\delta_c^{\,d} + F_B^\lambda\,\vec{\lambda}_a^{\,b}\cdot\vec{\lambda}_c^{\,d}\right),\end{aligned}$$

(Convential and exotic) Spectroscopy. The recent LHCb T_{cc}^{+} "tetraquark"



- Conventional hadrons:
  - Mesons: $q\bar{q}'$: $\pi^+ = u\bar{d}$, $D^0 = c\bar{u}$, ...
  - Baryons: $q_1q_2q_3$: $p = uud$, $n = udd$, ...

- Constituent **quark models** have succesfully described most of (but not all!) the hadrons discovered so far.
- Only possibilities? No, the only requirement is to be **color singlets**. There can be tetraquarks ($q_1q_2q_3q_4$), pentaquarks ($\bar{q}_1q_2q_3q_4$), hybrids ($\bar{q}_1q_2g$), glueballs (gg), **hadronic molecules** (MM', MB, BB'),...

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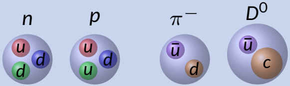

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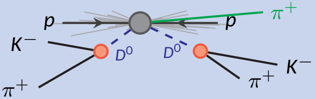
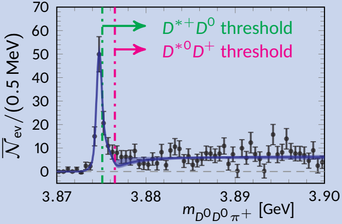
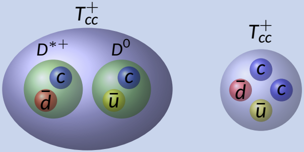
[LHCb: Nature Phys. 18, 751('22); Nature Commun., 13, 3351('22)]





- In 2021, the LHCb collaboration discovers T_{cc}^{+}, with quark content $cc\bar{u}\bar{d}$, and very close to $D^{*+}D^0$ threshold
- Even if something is **explicitly exotic**, you still have to understand how are quarks distributed inside the hadron.



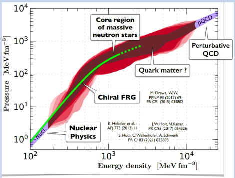
- [MA, PL,B829,137052('21); MA, Nieves, EPJ,C82,724('22)]
- Our analysis favours the **molecular** picture.
- Also, relevant to understand QCD confinement, and color combinations.

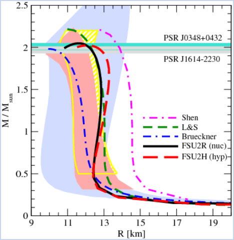
Nuclear and Astroparticle Physics Group @ ICE-CSIC (Barcelona)

Physics of **compact/dense stellar** objects from its hadron/nuclear constituents:

- Equation of state $P(\epsilon)$ of dense phases, including the interplay of dense matter with dark matter, to determine M and R:

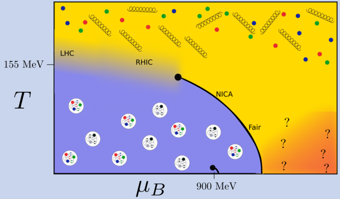
  [Tolos *et al.*, Ast.J., 834,3('17); Ast.Soc.Aus., 34,65('17)]





[W. Weise@HYP2022]

- Transport properties inside NS (hydrodynamical modes, rotational properties, and cooling)

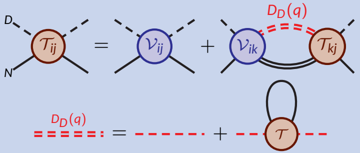


Matter at **extreme large temperatures**, as those occurring few microseconds after the Big Bang;

- Exploration of QCD phase diagram
- Properties of quarks and hadrons in hot and dense matter
- Effective descriptions of the dynamics of the hot quark-gluon plasma
- Studied in present particle accelerators, such as the LHC/CERN or RHIC/BNL.

$D^{(*)}$ and $\overline{D}^{(*)}$ in nuclear matter

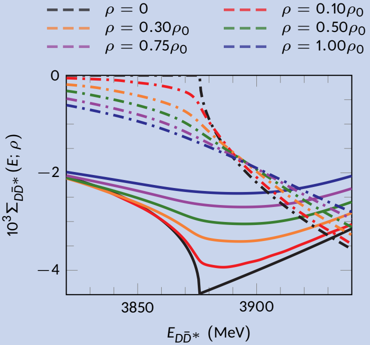
- Suppose you make your experiments **"inside" of a nuclear medium**, with nucleon density $\rho \lesssim \rho_0 \simeq 0.17\,\text{fm}^{-3}$



- $D^{(*)}$, $\bar{D}^{(*)}$ propagators in nuclear matter:

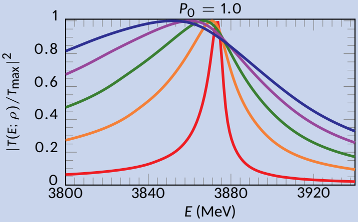
$$D_Y^{-1}(q) = q_0^2 - \vec{q}^2 - m_Y^2 - \Pi_Y(q^0, \vec{q})$$

- Self-consistent calculation:
  - $D^{(*)}$: Tolos *et al.*, PR,C80,065202('09)
  - $\bar{D}^{(*)}$: Garcia-Recio *et al.*, PR,C85,025203('12)

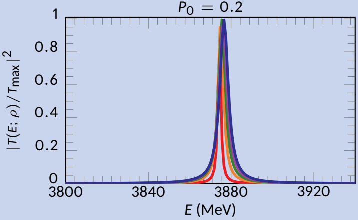


- [MA, Nieves, Tolos, PR,C104,035203('21)]
- With these modified propagators, one can compute $D\bar{D}^*$ loop functions in nuclear medium.
- **Threshold effect** washed out as ρ increases. $D^{(*)}$, $\bar{D}^{(*)}$ acquire in-medium widths.

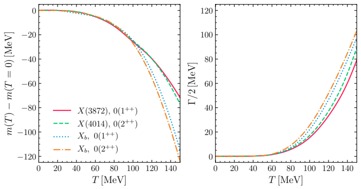
$D\bar{D}^*$ amplitudes and the $X(3872)$ peak (high and low P_0)



- For P_0 high ($\gtrsim 0.7$) large modifications induced by the nuclear medium
- Very large broadening (larger for larger P_0)
- $P_0 = 1$, $|T|^2$ peak shifted to the left
- $P_0 = 0.8$, $|T|^2$ peak shifted to the right



- For P_0 low, medium-induced modifications are small
- Broadening is small (smaller for smaller P_0)
- Some “pre-existence” of $X(3872)$, not directly associated with $D\bar{D}^*$, makes that the state does not wash out with increasing ρ



- Together with **density** modifications, one can also study the modifications due to **temperature** of $X(3872)$ [Montaña *et al.*, 2211.01896]

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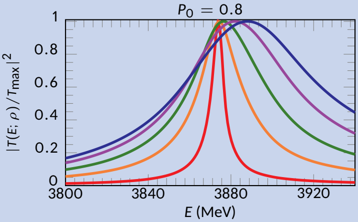

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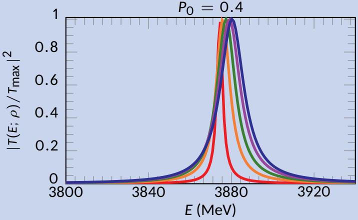

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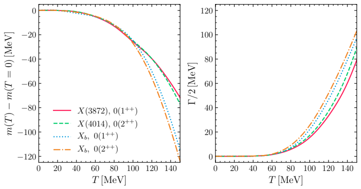

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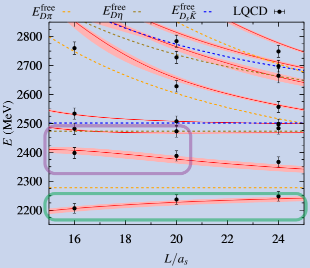
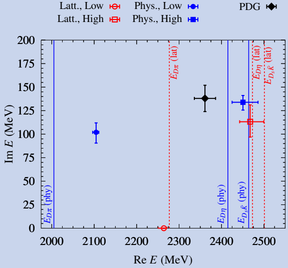
$D\pi$, $D\eta$, $D_s\bar{K}$ and $D^*(2300)$: Comparison with LQCD energy levels

Important connections between LQCD and EFTs!

[MA *et al.*, Phys. Lett. B **767**, 465 (2017)]



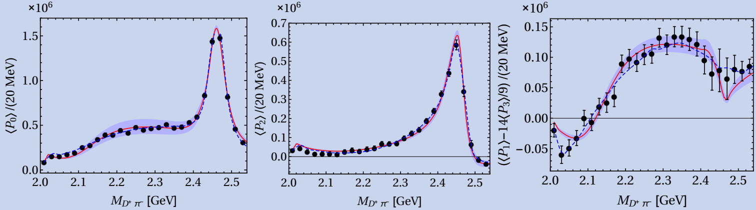


- $E_n(L)$ are provided for $D\pi$, $D\eta$, $D_s\bar{K}$ in a recent LQCD simulation.
  [G. Moir *et al.*, JHEP 1610, 011 (2016)]
- **Red Bands:** Our amplitude in a finite volume.
  [MA *et al.*, Phys. Lett. B **767**, 465 (2017)]
- **No fit** is performed (LECs previously determined)
- Level **below threshold**, associated with a **bound state**.
- **Second level** has large shifts w. r. t. thresholds, non-interacting energy levels.
- For lattice masses, we find a **bound state** and a **resonance**
- For physical masses:
  - The bound state evolves into a **resonance** above $D\pi$ threshold.
  - The resonance varies very little.
- PDG: only one resonance, "suspiciously" lying between both.
- We also study DK, $D_s\eta$, $(S, I) = (1, 0)$, $D^*_{s0}(2317)$ bound state: $M = 2315^{+18}_{-28}$ MeV.

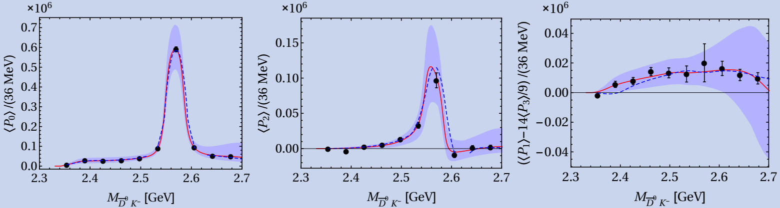
$D\pi$, $D\eta$, $D_s\bar{K}$ and $D^*(2300)$: Comparison with experimental data from LHCb

Du, MA, Fernández-Soler, Guo, Hanhart, Meißner, Nieves, Yao, PR,D98,094018('18)

- $B^- \to D^+\pi^-\pi^-$ [LHCb Collab., PR,D94,072001('16)]

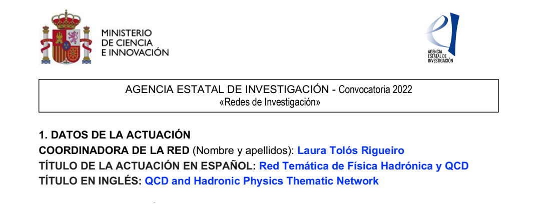


- $B_s^0 \to \bar{D}^0 K^- \pi^+$ [LHCb Collab., PR,D90,072003('14)]



- Rapid movement in $\langle P_{13}\rangle$ [no $D_2(2460)$] between 2.4 and 2.5 GeV. Related to $D\eta$ and $D_s\bar{K}$ openings.
- Recall: these are the amplitudes with **two states** in the $D_0^*(2300)$ region, and no fit of the T-matrix parameters is done.

QCD and Hadronic Physics Thematic Network



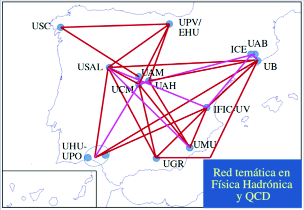
MINISTERIO DE CIENCIA E INNOVACIÓN

AGENCIA ESTATAL DE INVESTIGACIÓN

AGENCIA ESTATAL DE INVESTIGACIÓN - Convocatoria 2022
«Redes de Investigación»

1. DATOS DE LA ACTUACIÓN
COORDINADORA DE LA RED (Nombre y apellidos): Laura Tolós Rigueiro
TÍTULO DE LA ACTUACIÓN EN ESPAÑOL: Red Temática de Física Hadrónica y QCD
TÍTULO EN INGLÉS: QCD and Hadronic Physics Thematic Network

ħadQCDnet



- Application submitted to 2022 call for "Redes de Investigación"
- PI (coordinator): Laura Tolós (ICE)
- Several coPIs (representatives) are also from CSIC
- Many of the people in the proposal from CSIC too
- Joint application between more QCD- and hadron-oriented researchers
- Can be an important, strategic tool for this chapter of the challenge

Summary / prospectives

- Solving QCD is certainly a fundamental challenge
- Currently, in the non-perturbative regimes, we can provide approximate numerical calculations of the exact solution through LQCD simulations.
- Perturbative calculations with (rather complicated) loops, which are currently one of the bottlenecks in precision calculations, are being improved with new methods developed.
- EFTs, supplemented with non-perturbative (unitarity, crossing, ...) methods, are also living great advances, which are playing an important role in the field of hadron spectroscopy, where new resonances/particles/states are being constantly discovered in experiments (LHCb, BES,...)
- Many of these aspects can be applied together to increase our knowledge of strong interactions

Summary of summary

In the context of **"Understanding the basic components of the Universe, its structure and evolution"**, the problem of **"Solving Quantum Chromodynamics"** its a lively and exciting challenge, with many developments in several branches, which can also interact together to achieve this goal