LHC-Théorie – Heavy exotics at LHC


Jean-Marc Richard

Laboratoire de Physique Subatomique et Cosmologie
Université Joseph Fourier–IN2P3–CNRS–INPG
Grenoble, France

West-Cost LHC Theory, November 21, 2008
Table of contents

1 Introduction
2 Recent work by my colleagues
3 Stable or narrow multiquark states?
4 Dodecatoplet \((t^6\bar{t}^6)\)
   - First speculations
   - Revised estimates
5 Double charm exotics
   - Favourable symmetry breaking
   - Improved four-body calculation
6 Conclusions
Introduction

LHC-Théorie

- Many activities in France related to LHC (Orsay, Paris, Annecy, etc.)
- Small network including Lyon and Grenoble to coordinate studies related to LHC
- We: Aldo Deandrea, Sacha Davidson et al. (Lyon), Michaël Klasen, Sabine Kraml, Ingo Schienbein, JMR (Grenoble) + postdocs + thesis students + visitors
- Aim at developing collaboration West-Cost–Lyon–Grenoble meeting
- Some recent work by my colleagues
- Remark on the dodecatoplet $t^6\bar{t}^6$
- New calculation of $(QQ\bar{q}\bar{q})$ with better treatment of confinement.
Recent or ongoing work by my colleagues

- Sabine Kraml, several recent papers on NMSSM, unification, and participation in several working groups,
- Carole Weydert (thesis with Klasen) is studying the production of charged Higgs in minimal extensions of SM, and beyond.
- Aldo Deandrea, MSSM, ILC working group, flavor physics at LHC, hadron physics ($\eta \rightarrow 3\pi^0, \ldots$)
- Sacha Davidson, Flavor physics at LHC plus many other things,
- Ingo Schienbein et al. studied the hadroproduction of $D$ and $B$ mesons, for which a serious disagreement existed between data (too high) and predictions (too low). While data ↘, theoretical estimates ↗. In these processes involving heavy quarks, the difficulty was to keep the mass terms and resum the Logs.
- Another work by Ingo dealt with NuTeV results. See next slide, his results reproducing quite well the results, with less shadowing and less antishadowing than in most previous works. These PDF enter a number of processes at LHC. See next slide.
**Hadroproduction of D and B mesons** [see arXiv:0807.2215]

- **dσ/dp_T (nb/GeV)**: $p\bar{p} \rightarrow D^{+}X$ GM-VFNS \[\sqrt{S} = 1.96 \text{ TeV}\] $-1 \leq y \leq 1$

- **dσ/dp_T (nb/GeV)**: $p\bar{p} \rightarrow B^{+}X$ GM-VFNS \[\sqrt{S} = 1.96 \text{ TeV}\] $-1 \leq y \leq 1$

**PDFs and nuclear corrections for the LHC** [see arXiv:0807.2215]

- **$R_{F_{p}}$ vs $x$**
  - $A=56$, $Z=26$
  - $Q^2=5 \text{ GeV}^2$
  - $R_{F_{p}}$
  - fit A2
  - KP
  - SLAC/NMC
  - HKN07 (NLO)
Production of $\gamma$, $Z$, $Z'$

Work by Klasen, Ledroit, Morel, Fuks, etc.
Theoretical estimates using fixed order and resummation vs. more conventional approaches using fixed order, MC+ parton shower, etc.
Comparison PYTHIA, MC@NLO, joint resummation

1 TeV $Z'$; PYTHIA (LO/LL$^+$), MC@NLO (NLO/LL), resummation (NLO/NLL).

Mass-spectrum normalized to leading order:

* PYTHIA (*power shower*): mass-spectrum multiplied by a $K$-factor of 1.26.
* Good agreement between MC@NLO and resummation.

Transverse-momentum distribution:

* PYTHIA spectrum much too soft, peak not well predicted.
* Good agreement between MC@NLO and resummation.
Stable or narrow multiquark states?

- Many scenarios for multiquark (meta) stability,
- Coherences in the chromomagnetic operator \( \sigma_i \cdot \sigma_j \tilde{\lambda}_i \cdot \tilde{\lambda}_j \)
- \( H(\text{uuddss}) < (\text{uds}) + (\text{uds}) \) [Jaffe] not found, or \( P(\bar{Q}qqqq) < (\bar{Q}q) + (qqq) \) [Lipkin, Gignoux et al.] not seen!
- Chiral dynamics Late light pentaquark not confirmed!
- Nuclear forces \( X(3872) \) predicted as \( D\bar{D}^* \) “molecule”. Perhaps other examples.
- Other speculations will become accessible to experimental tests, in particular at LHC.
- Below: brief discussion of \( t^n \bar{t}^m \) toplets and \( (QQ\bar{q}\bar{q}) \) with charm or beauty = 2.
Dodecatoplet \( (t^6\bar{t}^6) \)

- Higgs exchange
  \[
  -\alpha_H \frac{\exp(-\mu_H r)}{r}, \quad \text{with} \quad \alpha_H = \frac{g_t^2}{4\pi} \quad \text{and} \quad g_t \sim 1.
  \]

- Does it bind \( t^n\bar{t}^m \)? (Frogatt, H.B. Nielsen)
- Up to \( n \leq 6 \) and \( m \leq 6 \), behave as bosons.
- Optimistic estimate by Nielsen and Frogatt, who neglected the Debye factor!
- Corrected by a Hartree (self consistent effective one-particle potential) by Shuryak et al. → upper variational bound on ground state energy
- In fact, the calculation of the self-Yukawian boson system already available in the literature (Pacheco et al.) and a lower bound is also possible.
**Dodecatoplet \((t^6\bar{t}^6)\)**

- If Higgs exchange alone, by scaling, the only parameter is
  \[ G = m_t \alpha_H / \mu_H \]
- for 2-body, no binding for \( G \leq 1.68 \) (Blatt and Jackson, 1949),
  i.e., \( \mu_H \leq 8.2 \text{ GeV} \) for \( \alpha_H = 1/(4\pi) \).
- For \((t^6\bar{t}^6)\), estimate \( \mu_H \lesssim 29 \text{ GeV} \) By Shuriak, and \( \mu_H \lesssim 31 \text{ GeV} \) from Pacheco et al.
- Perhaps slightly heavier with a better variational calculation,
- From the lower-bound on the ground-state energy, the critical mass [again for \( \alpha_H = 1/(4\pi) \)], cannot exceed \( \mu_H^{(c)} = 49 \text{ GeV} \).
- If \( \alpha_H \) bigger, \( \mu_H^{(c)} \) inversely proportional.
- Higher \( t^n\bar{t}^m \) not excluded (with Fermi statistics). Remember clusters of \(^3\text{He} \) atoms: \( (^3\text{He})^n \) bound for \( n \gtrsim 35 \)!
Limits on the $t^6\bar{t}^6$ energy
Double charm exotics

Favourable symmetry breaking

- Starts from \((QQ\bar{q}\bar{q}) = (M, M, m, m)\) with \(M = m\)
- Increase \(M\) and decrease \(m\), while \(M^{-1} + m^{-1} = \text{Constant}\)
- Then \(E(QQ\bar{q}\bar{q})\) decrease while \(E(\text{threshold}) = \text{constant}\)
- Thus for \(M/m\) large enough, stability [Ader et al., Heller et al., Brink et al., Lipkin, Nussinov, Rosina et al., Semay et al., etc.]
- But the “critical” \(M/m\) likely to require more that charm = 2 in “current” models

Better treatment of confinement

- Coulomb (one-gluon exchange) has a colour factor \(\tilde{\lambda}_i.\tilde{\lambda}_j\)
- The same factor \(\tilde{\lambda}_i.\tilde{\lambda}_j\) also applied to confinement in early models!
- Hence \(\sigma r_{12}\) (quarkonium) becomes \(\sigma [r_{12} + r_{23} + r_{31}]\) for baryons
- But there is no justification!
Steiner-tree model of confinement-1

- The linear $q - \bar{q}$ potential of mesons interpreted as minimising the gluon energy in the flux tube limit.
- Artru, Dosch, Merkuriev, etc., proposed a better ansatz, often verified and rediscovered (strong coupling, adiabatic bag model (Kuti et al.), flux tube (Kogut et al.), lattice QCD, etc.).
- The $q - q - q$ potential of baryons is with the junction optimised, i.e., fulfilling the conditions of the well-known Fermat-Torricelli problem.
Steiner-tree model of confinement-2

Generalisation to tetraquarks [e.g., Sugunama et al., Lattice QCD]

\[ V_4 = \min(V_f, V_S) \]

combination of

- **flip-flop** \( V_f \) (already used in its quadratic version by Lenz et al.)

\[ V_f = \lambda \min(r_{13} + r_{24}, r_{23} + r_{14}) \]

- **Steiner-tree** \( V_S \)

\[ V_S = \lambda \min_{k, \ell}(r_{1k} + r_{2k} + r_{k\ell} + r_{\ell3} + r_{\ell4}) \cdot \]

- This QCD-inspired potential is more favourable and should reasonably lead to stable \((cc\bar{q}\bar{q})\) states, to found together with double-charm baryons \((QQq)\)
The Steiner tree model of tetraquarks

As an illustration, we consider two variants of a purely linear potential

1. The additive model

\[ H_1 = \sum_i \frac{\mathbf{p}^2}{2m_i} - \frac{3}{16} \sum_{i<j} \tilde{\lambda}_i^{(c)} \tilde{\lambda}_j^{(c)} r_{ij} \]

2. The Steiner-tree model

\[ H_2 = \sum_i \frac{\mathbf{p}^2}{2m_i} + V_4 \]

- \( H_1 \) does not bind for masses \((m, m, m, m)\) but for masses \((M, M, m, m)\), if \(M/m \gtrsim 5\)
- J. Carlson and V.R. Pandharipande concluded that \( H_2 \) does not bind, but
- they used too simple trial wave functions for the 4-body problem, and did not consider unequal masses.
Numerical study
Vijande, Valcarce and R. revisited the calculation of Carlson at al. with a basis of correlated Gaussians (matrix elements painfully calculated numerically), and obtained stability for $(QQ\bar{q}\bar{q})$ even for $M/m = 1$, and better stability for $M/m \gg 1$.

Rigorous study
Hyam Rubinstein (Melbourne) and JMR demonstrated binding in the limit of very large $M/m$

Proof

\[
H_2 \leq \left[ \frac{p_x^2}{M} + \frac{\sqrt{3}}{2} |x| \right] + \left[ \frac{p_y^2}{m} + \frac{\sqrt{3}}{2} |y| \right] + \left[ \frac{p_z^2}{2\mu} + |z| \right]
\]

which is exactly solvable.
Tetraquarks in the minimal-path model-2

The inequality comes from a standard reduction pattern of Steiner trees (Melznak’s circles or torroïdal domain associated to subsets of points)

A flavour of the proof. In the 3-body case, Steiner tree linked to Napoleon’s theorem.

\[ JA + JB + JC = CC' \]

where \( C' \) makes an external equilateral triangle associated to the side \( AB \).

Well-known property of the Fermat-Torricelli problem.

\( C' \) belongs to the torroïdal domain associated to \( AB \)

\[ JA + JB + JC = CC' \]
Tetraquarks in the minimal-path model-3

The analogue for the planar tetraquark is

\[ V_S = JA + JB + JK + KC + KD = EF \]

The minimal network linking \((A, B, C, D)\) is the maximal distance between \(\{E, E'\}\) and \(\{F, F'\}\), which are the torroidal domains associated to \((A, B)\) and \((C, D)\) (= points completing an equilateral tr.)
Tetraquarks in the minimal-path model-4

In space, still

\[ V_S = JA + JB + JK + KC + KD = EF \]

where

- \( E \in C_{AB} \) = torroïdal domain of quarks \( AB \), (equilateral circle)
- \( F \in C_{CD} \) = torroïdal domain of antiquarks \( CD \),
- \( V_S \) is the maximal distance between the circles \( C_{AB} \) and \( C_{CD} \), which is less than the distance between the centres and the sum of radii.
Conclusions

- Intense activity of my colleagues for LHC,
- \((t^6\bar{t}^6)\) probably unbound,
- **Better models of confinement** beyond naive additive models, plus Fermat, Torricelli, Steiner, Melznak and even Napoleon, suggest **double-flavour exotics** to be found at LHC
- The hadron family already rich, but likely to welcome new members,