Meson Spectroscopy in the Light Quark Sector

Raffaella De Vita
INFN – Genova
Why Hadron Spectroscopy

• Most of the visible mass of the universe is due to hadrons, in particular to the protons and neutrons that form the atomic nucleus

• Hadrons have an internal structure being made of quarks: known quark configurations are baryons, made of three quarks and mesons, made of quark-antiquark pairs

• Quark masses account only for a small fraction of the nucleon mass: $\sim 1\%$
  - $m_q \sim 10 \text{ MeV}$
  - $m_N \sim 1000 \text{ MeV}$
while the remaining fraction is due to the force that binds the quarks: QCD

• QCD with its rules and constraints determines the mass and spectrum of hadrons and makes the world as we know it
• Studying the hadron properties and the rules of QCD is crucial to reach a deep understanding of the structure of matter

• Hadrons are color neutral systems made of quarks and gluons but…
  – What is the internal structure and what are the internal degrees of freedom of hadrons?
  – What is the role of gluons?
  – What is the origin of quark confinement?
  – Are 3-quarks and quark-antiquark the only possible configurations

• **Meson spectroscopy is a key tool to investigate these issues**
Meson Spectroscopy

Mesons are the simplest quark bound states, i.e. the best benchmark to understand how quarks interact to form hadrons

Historically, the study of meson properties led to some of the most relevant discoveries in particles physics

- in 1947 the discovery of the pion by Powell, Occhialini and Lattes
- in the same year, the discovery of strange particles by Rochester and Butler
- the interpretation of the $\phi$ decay to KK by Zweig and others in 1963
- the discovery of the $J/\psi$ in 1974
- ...

After many years, meson spectroscopy remains a very active field and a precious source of information for the understanding of quark-gluon interaction
Goal of modern meson spectroscopy is to answer these fundamental questions of QCD, studying the spectrum of mesons and searching for exotic states.

**Light quark mesons (uds):**
- sensitive to chiral symmetry breaking and vacuum condensate effects
- probe the strong force at larger distances (confinement)

**Heavy quark mesons (cbt):**
- can be describe with non-relativistic potential models
- probe the strong force at smaller distances where short-range color interaction dominates

D. Leinweber: LQCD visualization of the QCD vacuum

S. B. Bali et al., PRD56 (1997)
First indications on the meson spectrum are given by the Constituent Quark Model:

- Quark-antiquark pairs with total spin $S=0,1$ and orbital angular momentum $L$
- SU(3) flavor symmetry
- A nonet of states with the same quantum numbers, $J^{PC}$, for each value of $L$ and $S$

- Great success in describing the lower mass states
- A number of predicted states is not experimentally observed and assignments are uncertain:
  - failure of the model?
  - limitations in the experimental techniques?
  - …
Beyond the quark model... Exotics

QCD tells us that bound states have to be color neutral but does not prohibit the existence of states with unconventional quark-gluon configurations as tetraquarks, glueballs or hybrids.

- Several phenomenological models predict the existence of such states and give indications of masses and decays.
- Supporting evidence is provided by Lattice QCD calculations.
- Experimental evidence has been searched in many laboratories:
  - $X(3872)$ observed at B-factories interpreted as tetraquarks.
  - Indication of hybrids below 2 GeV reported by several experiments.
  - ... 

- If unambiguously confirmed, these states would provide the means to further investigate aspects of QCD as confinement and gluonic excitations.
Predictions of the meson spectrum from Lattice QCD are now available

- **Good reproduction of the regular meson spectrum**
- **Indication of the existence of states with high gluonic content**

**normal mesons**

isovector mesons, $m_\pi \sim 700$ MeV
Many experiments in the world have studied and are studying the meson spectrum in the light-quark sector using different production processes:

- **Proton-antiproton annihilation:**
  Crystal Barrel at CERN, Panda at GSI, ...

- **$e^+ e^-$ annihilation:**
  LEP, Babar at SLAC, Belle at KEK, KLOE at Frascati, CLEO at Cornell, BES at Beijing, KLOE-II, Belle II at SuperKEKB, ...

- **Proton-proton scattering:**
  WA experiments at CERN, GAMS at Protvino, LHC, ...

- **Pion beams on fixed target:**
  E852 at BNL, VES at Protvino, COMPASS at Cern, ...

- **Photoproduction experiments:**
  CLAS at Jefferson Lab, GlueX and CLAS12 at Jefferson Lab
Scalar Mesons

Scalars are fundamental states because they represent the Higgs sector of strong interaction:

- same quantum numbers of the QCD vacuum
- responsible for chiral symmetry breaking

- The scalar meson nonet should be composed by $a_0(l=1), K^*(l=1/2), f_0$ and $f_0'(l=0)$, with the $a_0$ as lightest state and the $f_0'$ showing a large strange content
- At present, given the $l=1$ and $l=1/2$ states that have been identified, there is an excess of $l=0$ states
The $f_0(980)$ meson

The $f_0(980)$ is one of the lowest mass scalar and isosinglet candidate of the first nonet:

- Unusual mass hierarchy of the multiplet ($f_0(980)$ almost degenerate with $a_0(980)$) and decays led to propose these states as TETRAQUARKs

Detailed measurement of the S wave around the resonance mass needed to determine the nature of this state

- High precision data from BES, KLOE, BABAR, CLAS and others now available can shed light on this puzzle
Higher mass scalars

Abundance of I=0 states with unexpected decay patterns between 1.3 and 2 GeV led to speculate about the presence of a glueball in this sector

- $f_0(1370)$
- $f_0(1500)$
- $f_0(1710)$
- $f_0(2100)$

... Lower two states seen first by Crystal Barrel
Higher mass states seen by WA102 and BES
Discrepancies between different experimental observations
High statistics/high precision data needed!

New high statistics data set from BESIII in Beijing:
- clear structures in the $\eta\eta$ mass spectrum from $J/\psi$ radiative decays
- full partial wave analysis to isolate S wave contribution
- $f_0(1710)$ and $f_0(2100)$ are dominant scalars
- $f_0(1500)$ exists (8.2 $\sigma$)
- $f_0(1710)$ and $f_0(2100)$ strength ~10x larger than $f_0(1500)$

Additional data expected in the near future from this and other experiments can lead to a full understanding of the scalar sector

Search for Hybrids

* Ideal benchmark to study quark-quark interaction and excitations of the glue
* Existence of hybrids states is supported by several theoretical models and by lattice QCD calculations
* Recent studies indicate the lightest states could have mass below 2 GeV and “exotic” quantum numbers $J^{PC}=1^{-+}$

Most debated experimental evidence is related to the so-called $\pi_1(1600)$:
- observed in several decay modes ($\rho \pi$, $\eta'\pi$, $f_1\pi$, $b_1\pi$) including decays to $L=1$-$L=0$ meson pairs as predicted by the flux tube model
- observations reported by different experiments (E852, VES, COMPASS) but with different production mechanisms
- presence of resonant signal still requires confirmation
The exotic $\pi_1(1600)$

Exotic signal reported by BNL-E852 experiment in the analysis of the 3 pion final state

Opposite findings reported by the CLAS Collaboration in photo-production

Significant intensity in the $1^{-+}$ wave with clear phase motion with respect to the $2^{-+}$

$$M = (1.593 \pm 0.080^{+0.029}_{-0.047}) GeV$$

$$\Gamma = (0.168 \pm 0.020^{+0.150}_{-0.012}) GeV$$
Experimental investigation continues at COMPASS at CERN SPS with 192 GeV pion beam on nuclear targets

- Positive observation reported from the analysis of 2004 pilot run on lead
  
  \[ M = (1.660 \pm 0.010^{+0.064}_{-0.064}) \text{GeV} \]
  \[ \Gamma = (0.269 \pm 0.021^{+0.042}_{-0.064}) \text{GeV} \]

- Analysis of 2008 run (96 M events) will allow better control of background processes
- High quality results expected
Many experiments in the world have studied and are studying the meson spectrum in the light-quark sector using different production processes:

- **proton-antiproton annihilation:**
  Crystal Barrel at CERN, Panda at GSI, ...

- **$e^+ e^-$ annihilation:**
  LEP, Babar at SLAC, Belle at KEK, CLEO at Cornell, KLOE at Frascati, BES at Beijing, KLOE-II, Belle II at SuperKEKB, ...

- **proton-proton scattering:**
  WA experiments at CERN, GAMS at Protvino, LHC, ...

- **pion beams on fixed target:**
  E852 at BNL, VES at Protvino, COMPASS at Cern, ...

- **photoproduction experiments:**
  CLAS at Jefferson Lab, GlueX and CLAS12 at Jefferson Lab
Continuous Electron Beam Accelerator Facility (CEBAF):
• a superconducting electron machine based on two linacs in racetrack configuration
• presently being upgraded to 12 GeV

High electron polarization
Beam Power: 1 MW
Beam Current: 90 µA
Max Energy Hall A-C: 10.9 GeV
Max Energy Hall D: 12 GeV
Meson spectroscopy is one of the main topics that will be studied with the Jlab 12 GeV upgrade. Key elements are:

- High intensity tagged photon beams
- Detectors with large acceptance and good particle identification capabilities
The GlueX Experiment

Hermetic detection of charged and neutral particles in solenoid magnet:
- Photon beam produced by coherent Bremsstrahlung on diamond radiator
- Initial Flux $10^7$ g/s
- 18,000 FADCs
- 4,000 pipeline TDCs
- 20 KHz L1 trigger
- 300 MB/s to tape

D. Lawrence’s talk
The CLAS12 Experiment

Quasi-real photoproduction on proton target:
- Detection of multiparticle final state from meson decay in the large acceptance spectrometer CLAS12
- Detection of the scattered electron for the tagging of the quasi-real photon in the novel Forward Tagger

Physics goals:
- Detailed mapping of the meson spectrum up to 2.5 GeV
- Investigation of strangeonium and strangeness rich states
- Search for exotics

Electromagnetic calorimeter (PbWO)
Micromegas Tracker
Scintillation Hodoscope
Meson spectroscopy is a key field for the understanding of fundamental questions in hadronic physics as what is the origin of the nucleon mass and what is the role of gluons.

Primary focus of the research activity in this field is to establish the quark-antiquark bound state spectrum and search for exotic configurations.

Experiments all over the world are collecting high statistics high precision data, providing new insight in the meson spectrum.

The new experimental data with the support of recent theoretical developments can lead physicists to solve one of the most intriguing puzzles in hadronic physics.