

Experimental methods in Hadron Spectroscopy

Light mesons with open and hidden strangeness PART2

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Hadronic processes for spectroscopic studies

Scattering experiments

- NN and πN scattering
 - pp at threshold
 - pp/ πp in the central region
 - peripheral pp/ πp interactions
- $\bar{N}N$ scattering in flight
- γN photoproduction

“At rest” experiments:

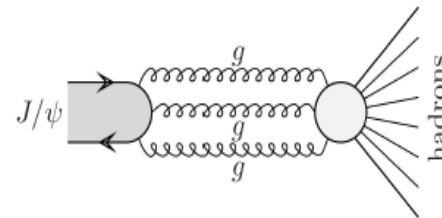
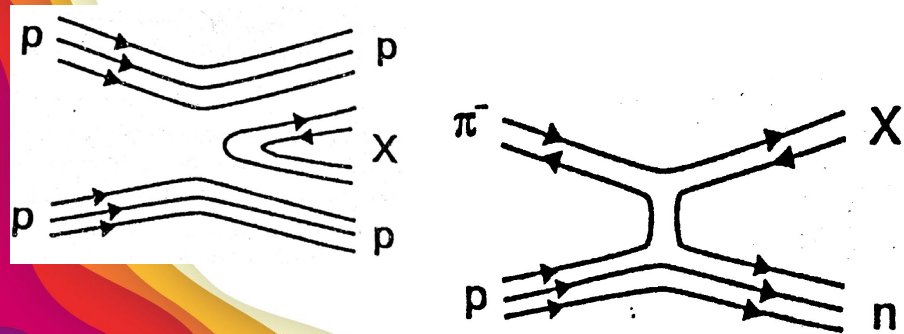
fixed quantum numbers for the initial states:

«Glue-rich» environments

- $\bar{N}N$ at rest
- e^+e^- collisions in quarkonium factories

- OZI suppressed decays mediated by 2-3 gluons:

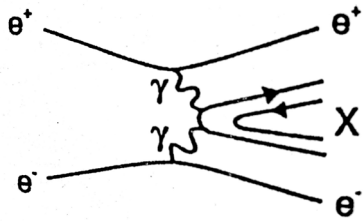
- $\phi(1020)$ decays
- J/ψ decays
- Y decays, ...



Reactions with electromagnetic probes: $\gamma\gamma$, ISR photons, virtual photons in e^- scattering

• $\gamma\gamma$ scattering: $e^+e^- \rightarrow \gamma\gamma \rightarrow e^+e^-X$

- The photons are radiated by both the leptons
 - Untagged: both are lost (real photons)
 - Tagged: one real photon is detected, the other may be off-shell if the momentum transfer is *small*
- **Vector meson dominance: real γ convert into $q\bar{q}$ pairs with $J^{PC}=1^{--}$: gluon production is suppressed**
 - Gluons do not carry electric charge: "antigluonball filter"
- **Yang theorem (selection rule): a massive spin 1 particle cannot decay into two massless spin 1 objects**
 - Vector particles cannot be produced in real $\gamma\gamma$ collisions
 - If *one* photon is virtual, vector meson production is allowed

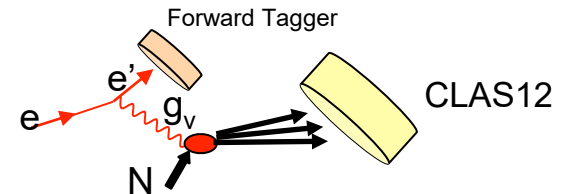


• ISR radiation: $e^+e^- \rightarrow e^+e^-\gamma$

- The photons is real, it can be detected or not (missing energy)
- Method to control and reduce the available energy in the center-of-mass
- *BaBar* + all experiments at B-factories

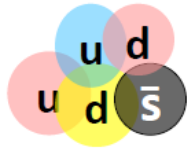
• Electro-production with virtual photon exchange $e^-N \rightarrow e^-N'X$

- If the diffused electron emerges at small angle (ideally at zero) the **transferred momentum Q^2 is *small*** and the **exchanged photon is *quasi-real***
 - "almost" a real photon beam (with high energy and polarization) which can conveniently excite the production of spin 1 mesons (VDM)
- Technique exploited at CLAS12 (MesonEx experiment)



Other non-standard mesons

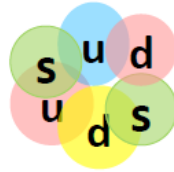
non- $q\bar{q}$ & non- qqq color-singlet combinations



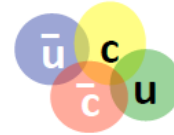
pentaquarks



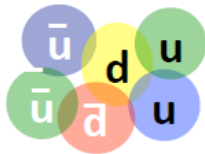
glueballs



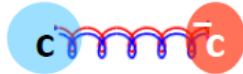
H-dibaryon



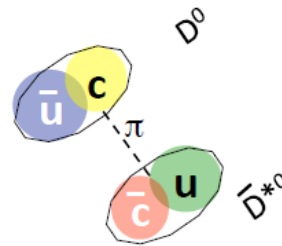
diquark-diantiquarks



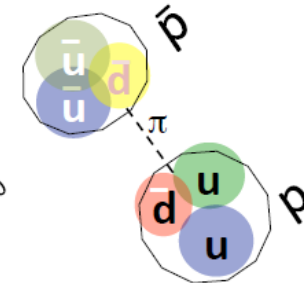
heptaquarks



hybrids



deusons



molecules

Their quantum numbers may be the same as for ordinary $q\bar{q}$ mesons, or they can be “exotic” and not permitted for $q\bar{q}$ (but allowed by QCD anyhow)

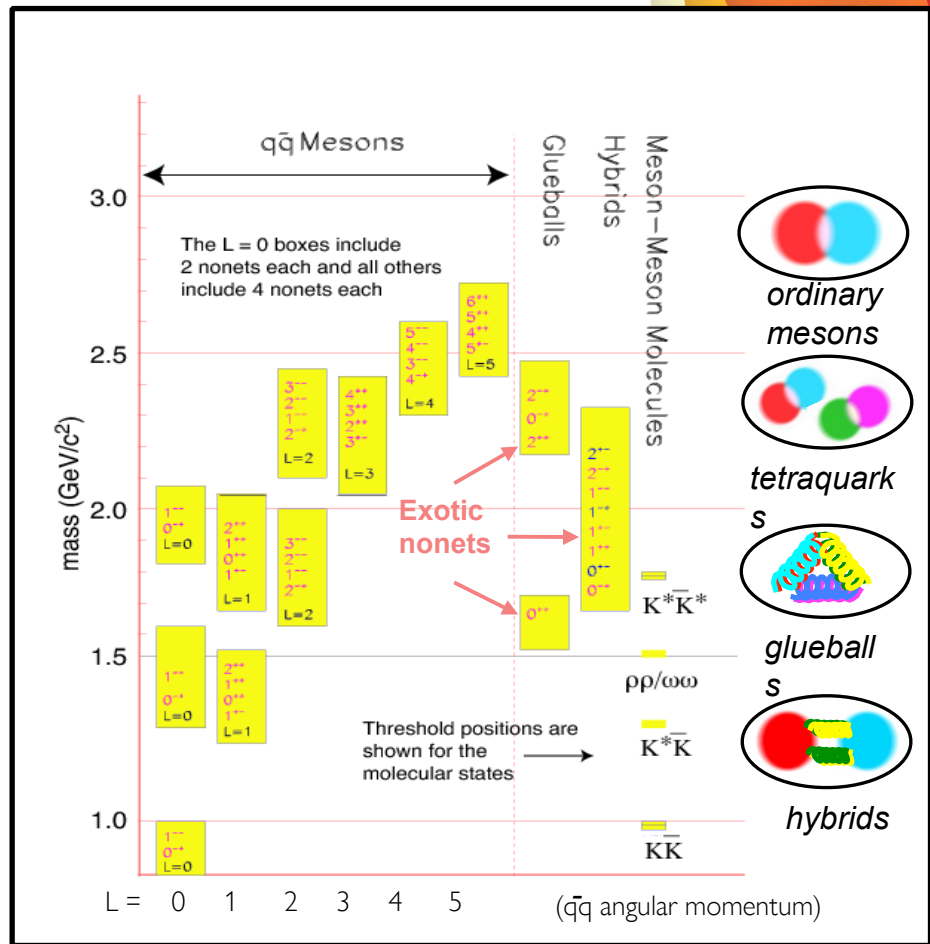
The meson spectrum + gluons: exotics

- The meson spectrum bears also the information about gluons, which bind quarks
- Which is the expected signature of gluonic degrees of freedom ?
 - Observation of extra states possibly with quantum numbers not allowed by CQM

New states with gluonic content:

- **Glueballs (ggg)**
- **Hybrids (qqg)**
- **Multiquark/molecular states**

■ **EXOTICS**



The scalar sector... a mess!

- Since half 90's: too many observed states to be fit into the scalar nonet: what are they? \Rightarrow **"isoscalar ($\pi\pi$) S-wave puzzle"**
- Three "confirmed" f_0 mesons (some of them *very* broad)+ a pair of suspect characters:
 - $f_0(400) \rightarrow$ " σ " ($\pi\pi$ S-wave), $f_0(980)$, $f_0(1300)$, $f_0(1590)$
 - $f_0(1500)$, $f_0(1370)$
 - $f_0(1370)$ is very broad (300 MeV) and easily identified with $f_0(1300)$
- Experimental facts:
 - The first radial excitation should be 200-300 MeV heavier than the ground state
 - If $f_0(1300)$ is the ground state $\Rightarrow f_0(1500)$ would be OK as hidden strange component
 - $f_0(1500)$ almost degenerate with $f_2'(1525)$ which is a sound D-wave $s\bar{s}$ candidate
 - **A good candidate for a glueball would be "flavor blind"**
 - Indications of signatures in several decay channels
 - Measured branching fractions: $\pi\pi : \eta\eta : \eta\eta' : \bar{K}K = 1. : 0.27 : 0.19 : < 0.1$
 - The branching ratio in $K\bar{K}$ is too low: due to mixing with ordinary mesons?

Two main open challenges persist:

- Determination of the **nature of $f_0(1500)$**

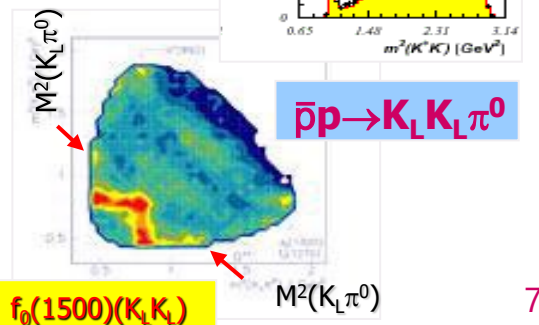
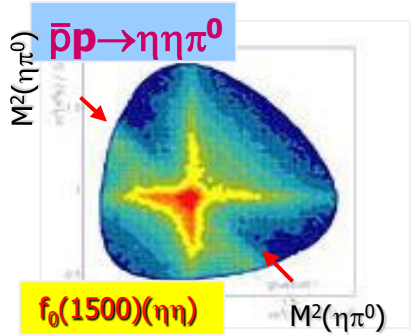
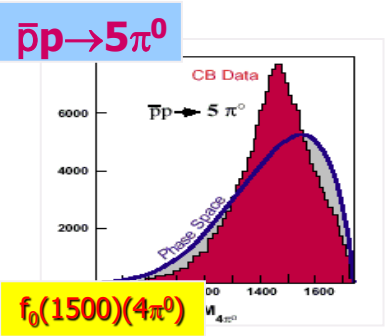
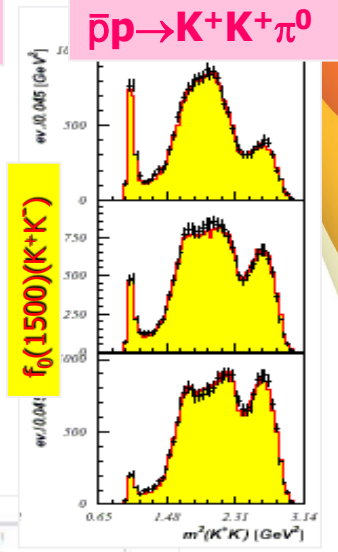
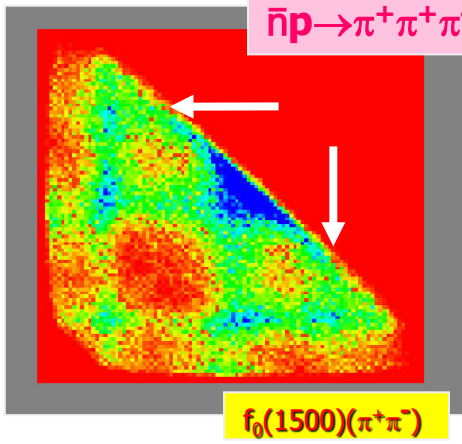
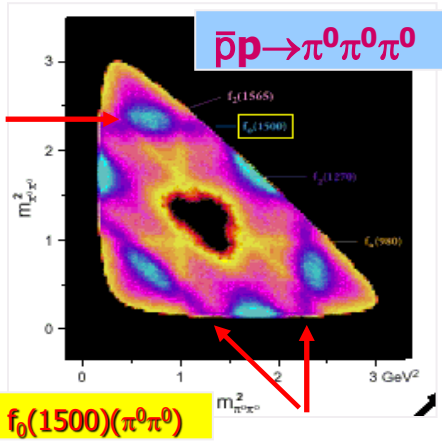
- Search for the **$s\bar{s}$ partner of $f_0(1300) \Rightarrow \kappa : f_0(980) ?$**

The search for the scalar glueball

- Lightest glueball candidate until the 00's: scalar state
- $f_0(1500)$ observed by **Crystal Barrel** and **OBELIX** in $\bar{N}N$ @LEAR-CERN

Glueballs are expected to be:

- Flavor blind
- Not coupled to $\gamma\gamma$



The pseudoscalar sector: excitations or supernumerary states?

- Two suspect states observed in 20 years (most recent results by LEP) in different reactions: $\eta(1405)$ and $\eta(1475)$
 - Are they really two states or different signatures of a single one ($\eta(1440)$)?
- Usually one η only is observed in low statistics experiments (with decay modes sometimes in tension)
- No observation in central hadroproduction reactions

● $\eta(1405)$: gluonium candidate

- **Dominant decay:** $a_0(980)\pi$, direct $\eta\pi\pi$, $K\bar{K}\pi$
- **Not observed in $\gamma\gamma$ collisions**
- **Large production in gluon rich environments**
 - J/ψ Radiative decays
 - Peripheral hadroproduction (BNL-E769, E852)
 - $\bar{p}p$ annihilation at rest in LH_2 target (S-wave enhancement)
- Estimated glue content $\sim 76\%$
- **Expectations contrary to LQCD:** lightest pseudoscalar glueball expected beyond 2 GeV

● $\eta(1475)$: $\bar{s}s$ 2S excitation? (first η' excitation)

- **Dominant decay:** $K^*\bar{K} + c.c.$
- **Observed in $\gamma\gamma$ collisions by L3**
- Not observed in $\eta\pi\pi$
- If this is the case: no available slot for $\eta(1405)$
- The width matches with the value expected for a radially excited $\bar{s}s$ state
- **Lack of observations in $K^*\bar{p}$**

Observed properties of $\eta(1440)$ consistent with expectations for a 2^1S_0 $\bar{s}s$ state in $K^*\bar{K}$

The axial sector: states decaying into $K\bar{K}\pi$

- Long standing problem since the 70's: superimposition of several pseudoscalar and axial states in the (1.3-1.5) GeV mass region \Rightarrow "E/1 puzzle"
- The $K\bar{K}\pi$ decay channel is **only possible for $J^{PC} = (\text{odd})^+ \text{ or } (\text{even})^-$**

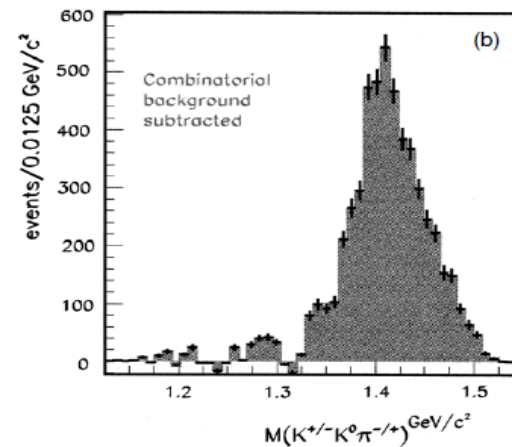
● Pseudoscalar states

- All of them decay to $a^0(980)\pi$, K^*K , direct $K\bar{K}\pi$
- $\eta(1275)$: First η' radial excitation?
- $\eta(1440)$ likely split in two states
 - $\eta(1440)$: gluonium ?
 - $\eta(1475)$

● Axial states 1^{++}

- $f_1(1285)$: does not decay in KK^*
- $f_1(1420)$: arguments to interpret it as hybrid $q\bar{q}g$, or 4-quark state, or $K^*\bar{K}$ molecule
- $f_1(1510)$: not established yet
- + isovector $a_1(1420)$ (COMPASS)

OBELIX, PL B462, 453 (1998)



$$p\bar{p} \rightarrow K^0 K^\pm \pi^\mp \pi^+ \pi^-$$

The isoscalar vector sector

- Below 2.1 GeV: 22 states are expected for $(\text{odd})^{--}$ strangeonium but only < 10 have been steadily established
- The strangeonium spectrum does not simply replicate the light meson spectrum ~ 250 MeV higher in mass
- Charmonium states are much easier to spot!
- Several observations are still controversial and structures are not identified
 - Large probability of mixing with open-flavor mesons (also charm) and possibly other exotic structures
 - Overlap of broad states
 - Sharing common decay channels
 - Couplings are channel-dependent
 - Not unique identification of strangeonia through decay to open-strangeness final states
- Large production of open-strangeness, OZI suppression for hidden-strangeness particles

Strangeonia and excitations

- Small $s\bar{s}$ production cross sections

- OZI suppressed processes

- Most effective reactions:

- **Hadronic reactions**

- Central production (CERN, Fermilab)
- Strangeness exchange reaction $K^-p \rightarrow \Lambda X$ (SLAC)
- π^-p peripheral collisions

- **e^+e^- collisions: pure $J^{PC} = 1^{--}$**

- Most recent results at higher energies
- Mixing between possible vector hybrids and quarkonia

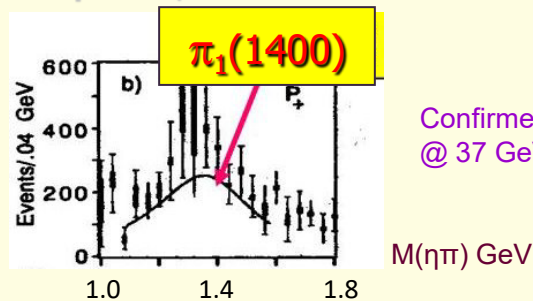
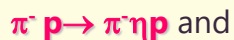
- **Diffraction photoproduction: $\gamma p \rightarrow Xp$**

- Excitation of $C=-1$ $s\bar{s}$ states: photon beam as a superimposition of vector mesons, with meaningful $s\bar{s}$ coupling
- Lack of intense enough sources (so far, at least)

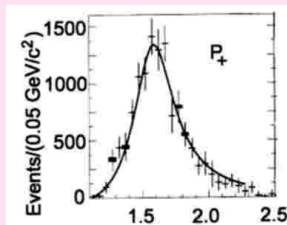
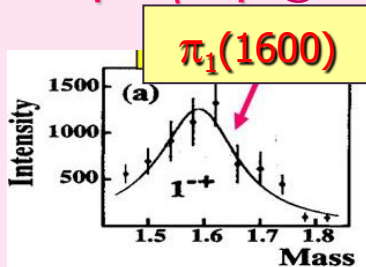
Possible 1^{-+} hybrid signatures: $\pi(1400)/\pi(1600)$

- $\pi(1400)$ first observed by E852 & Crystal Barrel in $\eta\pi$
 - Confirmed by VES

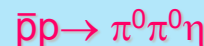
E852: Systematic study of the reactions



State reported in $\eta'\pi$ and $\rho\pi$ channels



CRYSTAL BARREL: $\bar{N}N$ annihilations at rest



The decays of σ and ρ into $\pi\pi$ and of $a_2(1320)$ into $\eta\pi$ do not describe the data correctly enough

- The presence of a $\pi_1(1400)$ meson decaying into $\eta\pi$ is needed

