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Non-conventional mesons @ PANDA

Fairness 2014 – Vietri sul Mare

Francesco Giacosa

25/9/2014

Outline

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The Lagrangian of QCD and its symmetries

What is a meson? Conventional mesons and nonconventional mesons

PANDA: what it will search

Some selected results of the eLSM: the scalar and the pseudoscalar glueballs.

Non-quarkonium candidates: X,Y,Z states and other ambiguous states

Summary

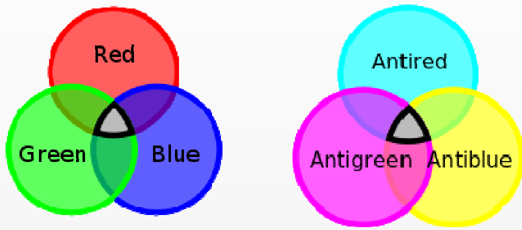
The Lagrangian of QCD and its symmetries

Born	Giuseppe Lodovico Lagrangia 25 January 1736 Turin
Died	10 April 1813 (aged 77) Paris

Francesco Giacosa

The QCD Lagrangian

Quark: u,d,s and c,b,t R,G,B



$$q_i = \begin{pmatrix} q_i^R \\ q_i^G \\ q_i^B \end{pmatrix};\ i = u,d,s\ ,...$$

8 type of gluons ($R\bar{G}$,$B\bar{G}$,…)

$$\mathcal{L}_{QCD} = \sum_{i=1}^{N_f} \overline{q}_i (i\gamma^\mu D_\mu - m_i) q_i - \frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu}$$

$$A_\mu^a\ ;\ \ a = 1,...,8$$

Feynman diagrams of QCD

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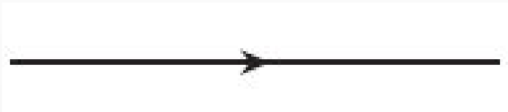
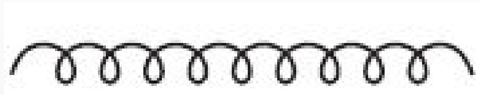
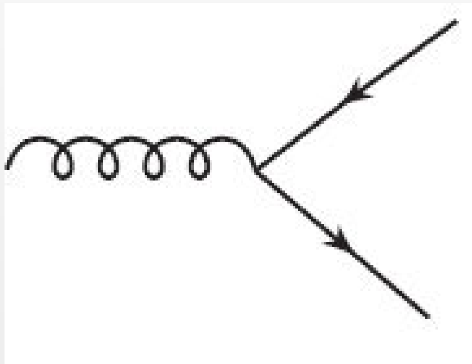
$$\mathcal{L}_{QCD} = \sum_{i=1}^{N_f} \overline{q}_i (i\gamma^\mu D_\mu - m_i) q_i - \frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu}$$



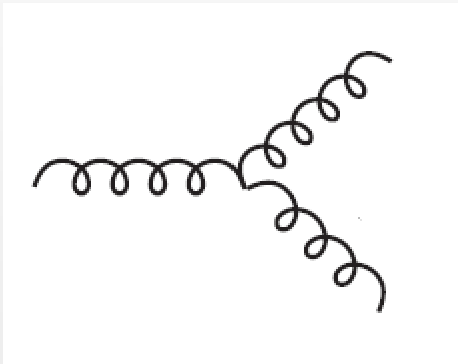
Quark



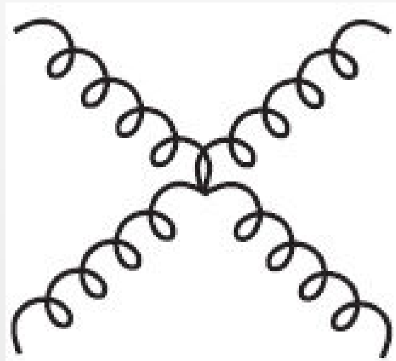
Gluon



Gluon-quark-antiquark vertex



3-gluon vertex



4-gluon vertex

Trace anomaly: the emergence of a dimension

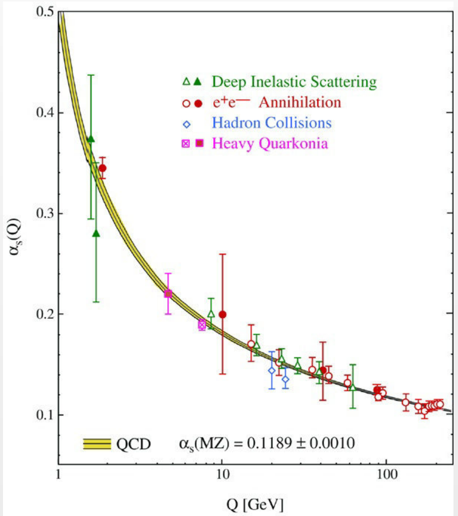
Chiral limit: $m_i = 0$

$x^\mu \to x'^\mu = \lambda^{-1} x^\mu$ is a classical symmetry broken by quantum fluctuations (trace anomaly)

$$g_0 \overset{\text{Renormierung}}{\longrightarrow} g(\mu)$$

Dimensional transmutation $\Lambda_{YM} \approx 250 \text{ MeV}$

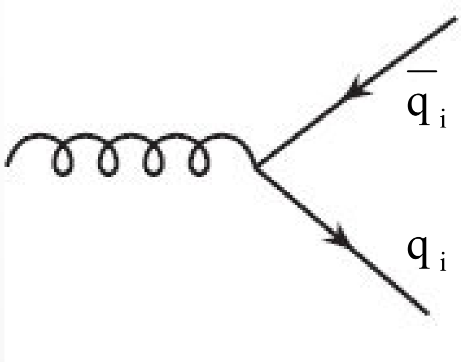
$$\alpha_S(\mu = Q) = \frac{g^2(Q)}{4\pi}$$



Effective gluon mass: $m_{gluon} = 0 \to m^*_{gluon} \approx 500 - 800 \text{ MeV}$

Gluon condensate: $\langle G^a_{\mu\nu} G^{a,\mu\nu} \rangle \neq 0$

Flavor symmetry



Gluon-quark-antiquark vertex.

It is democratic! The gluon couples to each flavor with the same strength

$$q_i \rightarrow U_{ij} q_j$$

$$U \in U(3)_V \rightarrow U^+ U = 1$$

Chiral symmetry

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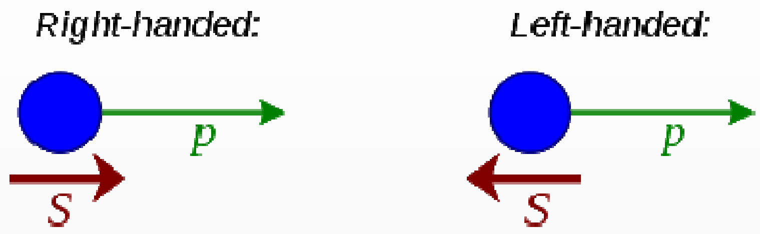
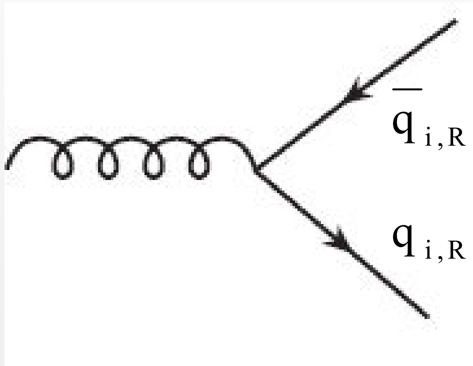
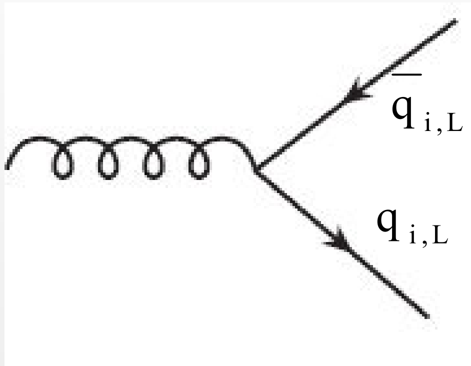






$$q_i = q_{i,R} + q_{i,L}$$

$$q_{i,R} = \frac{1}{2}(1+\gamma^5)q_i$$

$$q_{i,L} = \frac{1}{2}(1-\gamma^5)q_i$$

$$\mathrm{q_i} = \mathrm{q_{i,R}} + \mathrm{q_{i,L}} \rightarrow \mathrm{U^R_{ij} q_{j,R}} + \mathrm{U^L_{ij} q_{j,L}}$$

$$U(3)_R \times U(3)_L = U(1)_{R+L} \times U(1)_{R-L} \times SU(3)_R \times SU(3)_L$$

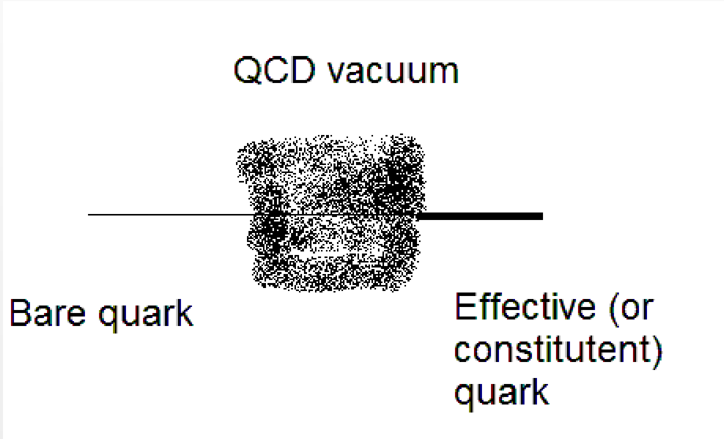
In the chiral limit (m_i=0) chiral symmetry is exact

Spontaneous breaking of chiral symmetry

$$U(3)_R \times U(3)_L = U(1)_{R+L} \times U(1)_{R-L} \times SU(3)_R \times SU(3)_L$$

$$\mathrm{SSB:}\ \mathrm{SU(3)_R \times SU(3)_L \rightarrow SU(3)_{V=R+L}}$$

Chiral symmetry → Flavor symmetry



$$\left\langle \bar{q}_i q_i \right\rangle = \left\langle \bar{q}_{i,R} q_{i,L} + \bar{q}_{i,L} q_{i,R} \right\rangle \neq 0$$

$$\mathrm{m} \approx \mathrm{m_u} \approx \mathrm{m_d} \approx 5\ \mathrm{MeV} \rightarrow \mathrm{m}^* \approx 300\ \mathrm{MeV}$$

$$\mathrm{m}_{\rho-\mathrm{meson}} \approx 2\mathrm{m}^*$$

$$\mathrm{m}_{\mathrm{proton}} \approx 3\mathrm{m}^*$$

Symmetries of QCD: summary

SU(3)$_{\text{color}}$: exact. Confinement: you never see color, but only white states.

Dilatation invariance: holds only at a classical level and in the chiral limit. Broken by quantum fluctuations (trace anomaly) and by small quark masses

SU(3)$_R$xSU(3)$_L$: holds in the chiral limit, but is broken by nonzero quark masses. Moreover, it is spontaneously broken to U(3)$_{V=R+L}$

U(1)$_{A=R-L}$: holds at a classical level, but is also broken by quantum fluctuations (chiral anomaly)

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What is a meson?

Hadrons

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No ‚colored‘ state has been seen.

Confinement: physical states are white and are called hadrons.

Hadrons can be:

Mesons: bosonic hadrons

Baryons: fermionic hadrons

Meson

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Definition(s):

1) A meson is a strongly interacting particle with integer spin.

2) A meson is a strongly interacting particle with zero baryon number.

A meson is not necessarily a quark-antiquark state

Conventional mesons

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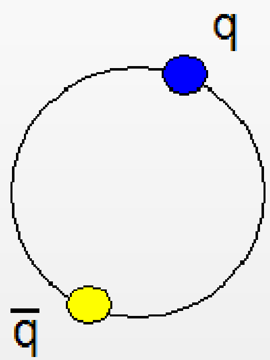
Quark: u,d,s,… R,G,B

Quark-antiquark bound states: conventional mesons



$$\left| color \right\rangle = \sqrt{1/3}\,(\bar{R}R + \bar{B}B + \bar{G}G)$$

Non-conventional mesons

1) Glueballs

2) Hybrids

3) Tetraquarks

4) Molecular states (dynamical generation)

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Short digression: is wikipedia correct?

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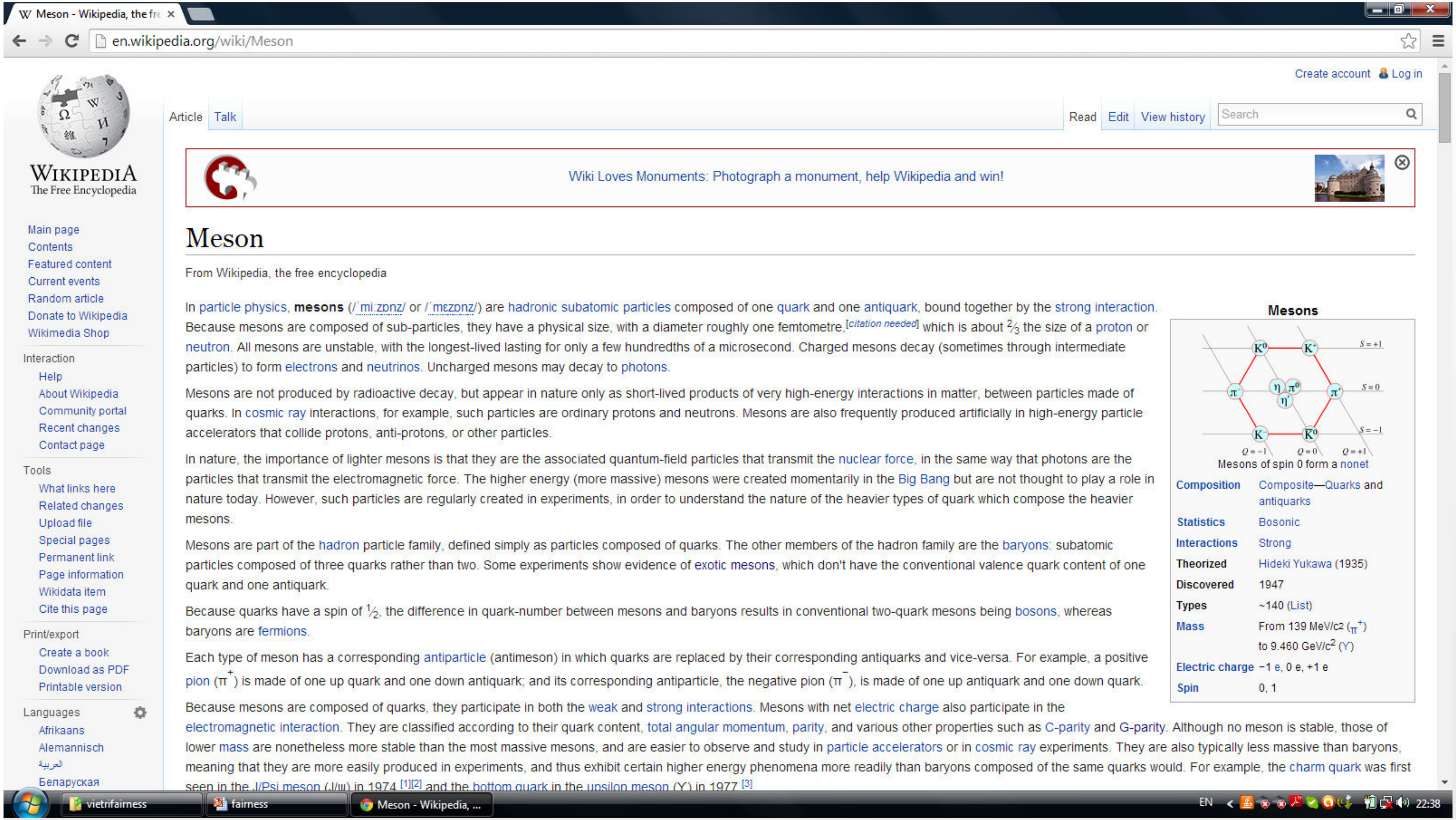
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Meson

From Wikipedia, the free encyclopedia

In particle physics, **mesons** (/ˈmiːzɒnz/ or /ˈmɛzɒnz/) are hadronic subatomic particles composed of one quark and one antiquark, bound together by the strong interaction. Because mesons are composed of sub-particles, they have a physical size, with a diameter roughly one femtometre,[citation needed] which is about $\frac{2}{3}$ the size of a proton or neutron. All mesons are unstable, with the longest-lived lasting for only a few hundredths of a microsecond. Charged mesons decay (sometimes through intermediate particles) to form electrons and neutrinos. Uncharged mesons may decay to photons.

Mesons are not produced by radioactive decay, but appear in nature only as short-lived products of very high-energy interactions in matter, between particles made of quarks. In cosmic ray interactions, for example, such particles are ordinary protons and neutrons. Mesons are also frequently produced artificially in high-energy particle accelerators that collide protons, anti-protons, or other particles.

In nature, the importance of lighter mesons is that they are the associated quantum-field particles that transmit the nuclear force, in the same way that photons are the particles that transmit the electromagnetic force. The higher energy (more massive) mesons were created momentarily in the Big Bang but are not thought to play a role in nature today. However, such particles are regularly created in experiments, in order to understand the nature of the heavier types of quark which compose the heavier mesons.

Mesons are part of the hadron particle family, defined simply as particles composed of quarks. The other members of the hadron family are the baryons: subatomic particles composed of three quarks rather than two. Some experiments show evidence of exotic mesons, which don't have the conventional valence quark content of one quark and one antiquark.

Because quarks have a spin of $\frac{1}{2}$, the difference in quark-number between mesons and baryons results in conventional two-quark mesons being bosons, whereas baryons are fermions.

Each type of meson has a corresponding antiparticle (antimeson) in which quarks are replaced by their corresponding antiquarks and vice-versa. For example, a positive pion (π^+) is made of one up quark and one down antiquark; and its corresponding antiparticle, the negative pion (π^-), is made of one up antiquark and one down quark.

Because mesons are composed of quarks, they participate in both the weak and strong interactions. Mesons with net electric charge also participate in the electromagnetic interaction. They are classified according to their quark content, total angular momentum, parity, and various other properties such as C-parity and G-parity. Although no meson is stable, those of lower mass are nonetheless more stable than the most massive mesons, and are easier to observe and study in particle accelerators or in cosmic ray experiments. They are also typically less massive than baryons, meaning that they are more easily produced in experiments, and thus exhibit certain higher energy phenomena more readily than baryons composed of the same quarks would. For example, the charm quark was first seen in the J/Psi meson (J/ψ) in 1974 [1][2] and the bottom quark in the upsilon meson (ϒ) in 1977 [3]

Mesons

Mesons of spin 0 form a nonet

Composition	Composite—Quarks and antiquarks
Statistics	Bosonic
Interactions	Strong
Theorized	Hideki Yukawa (1935)
Discovered	1947
Types	~140 (List)
Mass	From 139 MeV/c2 (π^+) to 9.460 GeV/c^2 (ϒ)
Electric charge	−1 e, 0 e, +1 e
Spin	0, 1

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Meson – Wikipedia

de.wikipedia.org/wiki/Meson

Meson

Mesonen (von griechisch: τὸ μέσον (tó méson) „das Mittlere"; deutet auf seine mittelschwere Masse hin) sind instabile subatomare Teilchen. Aufgebaut aus einem Quark-Antiquark-Paar, bilden sie eine der zwei Gruppen von Hadronen. Von der zweiten Hadronengruppe, den Baryonen, unterscheiden sich Mesonen durch ihren ganzzahligen Spin; sie sind somit Bosonen.

Mesonen entstehen in hochenergetischen Teilchenkollisionen (z. B. in der kosmischen Strahlung oder in Teilchenbeschleuniger-Experimenten) und zerfallen in Sekundenbruchteilen. Sie werden nach der Art der enthaltenen Quarks, ihrem Spin und ihrer Parität klassifiziert. Mittels ihrer Quarks nehmen Mesonen an der starken und schwachen Wechselwirkung sowie der Gravitation teil; elektrisch geladene Mesonen unterliegen zusätzlich der elektromagnetischen Wechselwirkung.

Inhaltsverzeichnis [Verbergen]

Eigenschaften [Bearbeiten]

Das Quarkmodell erlaubt eine konsistente Beschreibung aller beobachteten Mesonen als Bindungszustand eines Quarks mit dem Antiteilchen eines Quarks (Antiquark). Als zusammengesetzte Teilchen sind Mesonen somit keine fundamentalen Elementarteilchen.

Mesonen haben einen ganzzahligen (Gesamt-)Spin, die leichtesten J=0 (**skalare** oder **pseudoskalare Mesonen**) oder J=1 (**Vektormesonen** oder **Pseudovektor-Mesonen**). Dies lässt sich im Quarkmodell damit erklären, dass die beiden Quarks, die ein Meson bilden, jeweils einen Spin von 1/2 haben und ihre Spins antiparallel oder parallel stehen können. Zusätzlich können Mesonen auch innere Anregungszustände besitzen, die durch einen Bahndrehimpuls > 0 beschrieben werden, sowie radiale Anregungen. Hierdurch steigt ihre Energie an, so dass sie andere Eigenschaften (Spin, Zerfallsprodukte, …) als die Mesonen im Grundzustand besitzen.

Alle Mesonen sind instabil. Sie zerfallen in leichtere Hadronen (meist andere, leichtere Mesonen) und/oder in Leptonen. Mesonen ohne Ladung und Flavor-Quantenzahlen können auch elektromagnetisch in

Mesone - Wikipedia

it.wikipedia.org/wiki/Mesone

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Mesone

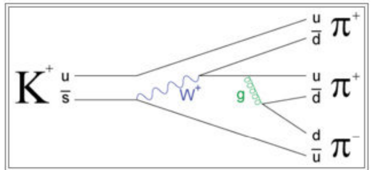
Da Wikipedia, l'enciclopedia libera.

In fisica delle particelle, i **mesoni** sono un gruppo di particelle subatomiche composte da un quark e un antiquark legati dalla forza forte.

I mesoni sono instabili e decadono tipicamente in fotoni o in leptoni, come gli elettroni e i neutrini.

Il primo mesone venne teorizzato nel 1935 da Hideki Yukawa come mediatore dell'interazione forte fra nucleoni[1] e fu poi identificato sperimentalmente nel 1947 nei raggi cosmici con il pione.[2]

Il termine mesone nacque storicamente per indicare particelle con massa intermedia fra l'elettrone e il protone.



Il decadimento di un kaone (K^+) in tre pioni ($2\,\pi^+$, 1 π^-) è un processo che coinvolge sia le interazioni deboli che quelle forti.

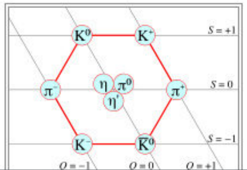
Le *interazioni deboli* : l'antiquark strange ($\bar{s}$) del kaone trasmuta in un antiquark up ($\bar{u}$) tramite l'emissione di un bosone W^+, il quale decade consequenzialmente in un antiquark down ($\bar{d}$) e un quark up (u).

Le *interazioni forti* : un quark up (u) emette un gluone (g) che decade in un quark down (d) e un antiquark down ($\bar{d}$).

Indice [nascondi]

Caratteristiche [modifica | modifica sorgente]

I mesoni fanno parte della famiglia degli adroni e avendo spin intero sono bosoni. I mesoni più leggeri agiscono a livello effettivo come particelle che mediano la forza fra i nucleoni a brevi distanze e più in generale svolgono un ruolo nei processi di interazione forte. Poiché sono composti da quark, interagiscono con altre particelle sia tramite la forza debole che quella forte. I mesoni che hanno una carica elettrica netta partecipano anche all'interazione elettromagnetica a grandi distanze.



I mesoni sono classificati secondo il loro contenuto in quark, il momento angolare totale, la parità e la coniugazione di carica. In base al contenuto di quark e alla simmetria di flavor, i mesoni sono divisi in multipletti di masse quasi degeneri. Ad esempio i tre pioni con carica elettrica positiva, negativa e neutra individuano un tripletto di isospin in cui le masse differiscono solo di circa il 3%.

Mezony – Wikipedia, woln

pl.wikipedia.org/wiki/Mezony

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Mezony [edytuj]

Mezony – cząstki elementarne należące do hadronów, o liczbie barionowej B=0 oraz spinach całkowitych. Mezony zbudowane są z par kwark-antykwark, co jest związane z tym, że wypadkowy ładunek kolorowy cząstki musi być równy zeru (antykwark posiada antykolor kwarku). Wewnętrzna geometria mezonu może być określona poprzez geometrię Bolai-Łobaczewskiego i przypuszczalnie ma, tak jak grawitacja, naturę geometryczną.

Historycznie nazwa mezon dotyczyła cząstek o masie pośredniej (po grecku *mesos* – pośredni) między masą elektronu a masą protonu. Obecnie do mezonów zalicza się także wiele rezonansów o masach większych od masy protonu.

Do metatrwałych (trwałych ze względu na oddziaływanie silne) mezonów należą mezony π (piony), K (kaony), η, D i B, a do rezonansów mezonowych mezony ρ, ω, φ, J/ψ i Υ, przy czym zgodnie z regułą OZI lekkie stany mezonów ψ i Υ są jednak stosunkowo trwałe[1].

Wszystkie metatrwałe mezony mają spin 0 i parzystość – chociaż dla B nie jest to pewne.

Jądro atomowe, interpretowane jako stany związane barionów, istnieje wskutek wymiany mezonów między barionami.

Spis treści [ukryj]

Historia [edytuj | edytuj kod]

W 1935 Hideki Yukawa opublikował teorię silnych oddziaływań jądrowych, która przewidywała istnienie cząstek o masie pośredniej między protonem a elektronem. Proponowano dla nich takie nazwy, jak *barytron*, *yukon*, *mesotron*, *meson*[2]. W 1936 Carl David Anderson odkrył cząstkę o odpowiedniej masie, dzisiaj nazywaną mionem, ale jej własności nie odpowiadały przewidywaniom teorii. Przewidywaną cząstkę, dziś nazywaną [m]ezonem π albo pionem, odkrył Cecil Frank Powell.

Nazewnictwo [edytuj | edytuj kod]

Mezony pozbawione zapachu – różne możliwości i odpowiednie symbole są podane w tabeli:

pl.wikipedia.org/w/index.php?title=Mezony&oldid=39605145

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W Mesón - Wikipedia, la enc ×

es.wikipedia.org/wiki/Mesón

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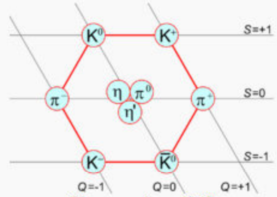
Mesón

En física de partículas, un **mesón** (del griego antiguo *μεσος (mesos) = medio*) es un bosón que responde a la interacción nuclear fuerte, esto es, un hadrón con un espín entero.

En el Modelo estándar, los mesones son partículas compuestas en un estado quark-antiquark. Se cree que todos los mesones conocidos consisten en un par quark-antiquark (los así llamados quarks de valencia) más un "mar" de pares quark-antiquark y gluones virtuales. Está en progreso la búsqueda de mesones exóticos que tienen constituyentes diferentes. Los quarks de valencia pueden existir en una superposición de estados de sabor; por ejemplo, el pion neutro no es ni un par arriba-antiarriba ni un par abajo-antiabajo, sino una superposición cuántica igual de ambos. Los mesones pseudoescalares (con espín 0) tienen la menor energía en reposo, donde el quark y antiquark tienen espines opuestos, y luego el mesón vectorial (vector meson) (con espín 1), donde el quark y antiquark tienen espines paralelos. Ambos presentan versiones de mayor energía donde el espín está incrementado por el momento angular orbital. Todos los mesones son inestables.

Originalmente, se predijo que los mesones eran los portadores de la fuerza que une al protón y al neutrón, de ahí su nombre. Cuando fue descubierto, el muon se asignó a esta familia de masa similar y fue bautizado como "mesón mu", sin embargo no mostró interacción fuerte con la materia nuclear: es en realidad un leptón. El pion fue el primer mesón auténtico en ser descubierto.

En 1949 Hideki Yukawa fue galardonado con el Premio Nobel de física por predecir la existencia del mesón. Originalmente lo llamo 'mesontrón', pero fue corregido por Werner Heisenberg (su padre fue profesor en griego de la Universidad de Múnich), quien indicó que no había un 'tr' en la palabra griega 'mesos'.



Mesones de espín 0

Composición	Compuesta - Quarks y antiquarks
Familia	Bosón
Grupo	Hadrón
Interacción	Nuclear fuerte
Teorizada	Hideki Yukawa (1935)
Descubierta	1946
Tipos	~140 (Lista)
Masa	Entre 139 MeV/c^2 (π+) y 9,460 MeV/c^2 (Υ)
Carga eléctrica	−1 e, 0 e, +1 e
Espín	0, 1

Índice [ocultar]

Descubrimiento y desarrollo [editar]

La existencia de los mesones fue propuesta por el físico nuclear japonés Hideki Yukawa en 1935. Su idea era que existían una serie de partículas más pesadas que el electrón

vietrifairness fairness Mesón - Wikipedia, ... EN 22:39

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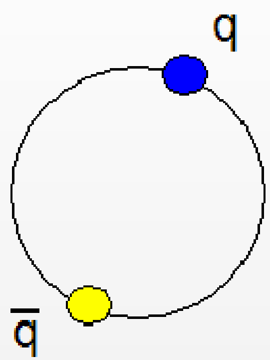
Conclusion: read the spanish wiki

in the preparation of your PhD exam!

Back to conventional mesons

Surely, with quark-antiquark states we can understand a lot of QCD, but definitely not everything.

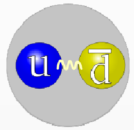


$$\vec{L},\vec{S} \Rightarrow P=-(-1)^{L} \qquad C=(-1)^{L+S}$$

$$\vec{L},\vec{S} \Rightarrow \vec{J}=\vec{L}+\vec{S} \qquad J^{PC}$$

$L = S = 0 \rightarrow J^{PC} = 0^{-+}$ pseudoscalar mesons

$$\left|\pi^{+}\right\rangle = \left|u\bar{d}\right\rangle \left|space: L=0\right\rangle \left|spin: S=0\right\rangle \left|\bar{R}R + \bar{B}B + \bar{G}G\right\rangle$$



$$\left|\pi^{-}\right\rangle = \left|d\bar{u}\right\rangle \left|space: L=0\right\rangle \left|spin: S=0\right\rangle \left|\bar{R}R + \bar{B}B + \bar{G}G\right\rangle$$

$$\left|\pi^{0}\right\rangle = \left|u\bar{u} - d\bar{d}\right\rangle \left|space: L=0\right\rangle \left|spin: S=0\right\rangle \left|\bar{R}R + \bar{B}B + \bar{G}G\right\rangle$$

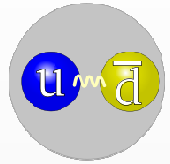
$$\left|K^{+}\right\rangle = \left|u\bar{s}\right\rangle \left|space: L=0\right\rangle \left|spin: S=0\right\rangle \left|\bar{R}R + \bar{B}B + \bar{G}G\right\rangle$$

...

$$\left|D^{0}\right\rangle = \left|u\bar{c}\right\rangle \left|space: L=0\right\rangle \left|spin: S=0\right\rangle \left|\bar{R}R + \bar{B}B + \bar{G}G\right\rangle$$

...

$L=0\ ,\ S=1 \rightarrow J^{PC}=1^{--}$ vector mesons



$$\left|\rho^{+}\right\rangle = \left|u\bar{d}\right\rangle \left|space : L=0\right\rangle \left|spin : S=1\right\rangle \left|\bar{R}R+\bar{B}B+\bar{G}G\right\rangle$$

...

$$\left|K^{*}(892)^{+}\right\rangle = \left|u\bar{s}\right\rangle \left|space : L=0\right\rangle \left|spin : S=1\right\rangle \left|\bar{R}R+\bar{B}B+\bar{G}G\right\rangle$$

...

$$\left|D^{*0}\right\rangle = \left|u\bar{c}\right\rangle \left|space : L=0\right\rangle \left|spin : S=1\right\rangle \left|\bar{R}R+\bar{B}B+\bar{G}G\right\rangle$$

...

$$\left|j/\Psi\right\rangle = \left|c\bar{c}\right\rangle \left|space : L=0\right\rangle \left|spin : S=1\right\rangle \left|\bar{R}R+\bar{B}B+\bar{G}G\right\rangle$$

$$L = S = 1 \rightarrow J^{PC} = 0^{++} \quad \text{scalar mesons}$$

$$\left|\sigma\right\rangle = \left|u\bar{u} + d\bar{d}\right\rangle \left|\text{space}: L = 1\right\rangle \left|\text{spin}: S = 1\right\rangle \left|\bar{R}R + \bar{B}B + \bar{G}G\right\rangle$$

corresponds to the resonance $f_0(1370)$.

...

...

$$\left|\chi_{c0}(1S)\right\rangle = \left|c\bar{c}\right\rangle \left|\text{space}: L = 1\right\rangle \left|\text{spin}: S = 1\right\rangle \left|\bar{R}R + \bar{B}B + \bar{G}G\right\rangle$$

Spontaneous symmetry breaking at the meson level

$$\pi = \pi^0 \equiv \sqrt{1/2}(\bar{u}u - \bar{d}d) \text{ neutral pion}$$

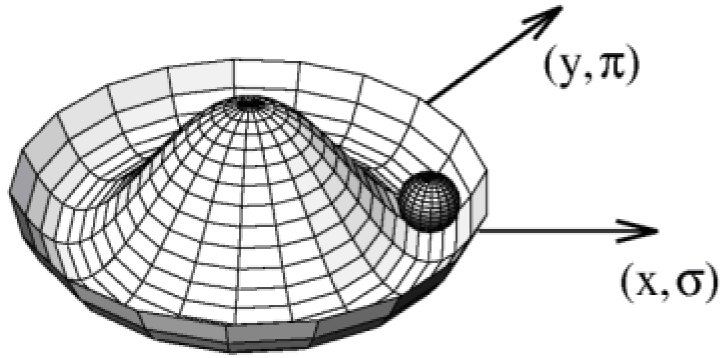
$$\sigma \equiv \sqrt{1/2}(\bar{u}u + \bar{d}d) \equiv f_0(1370)$$

Chiral transformation: $\sigma \leftrightarrow \pi$

$$V = \frac{m_0^2}{2}\left(\sigma^2 + \pi^2\right) + \frac{\lambda}{4}\left(\sigma^2 + \pi^2\right)^2$$

$m_0^2 < 0 \quad \rightarrow$ Mexican hat

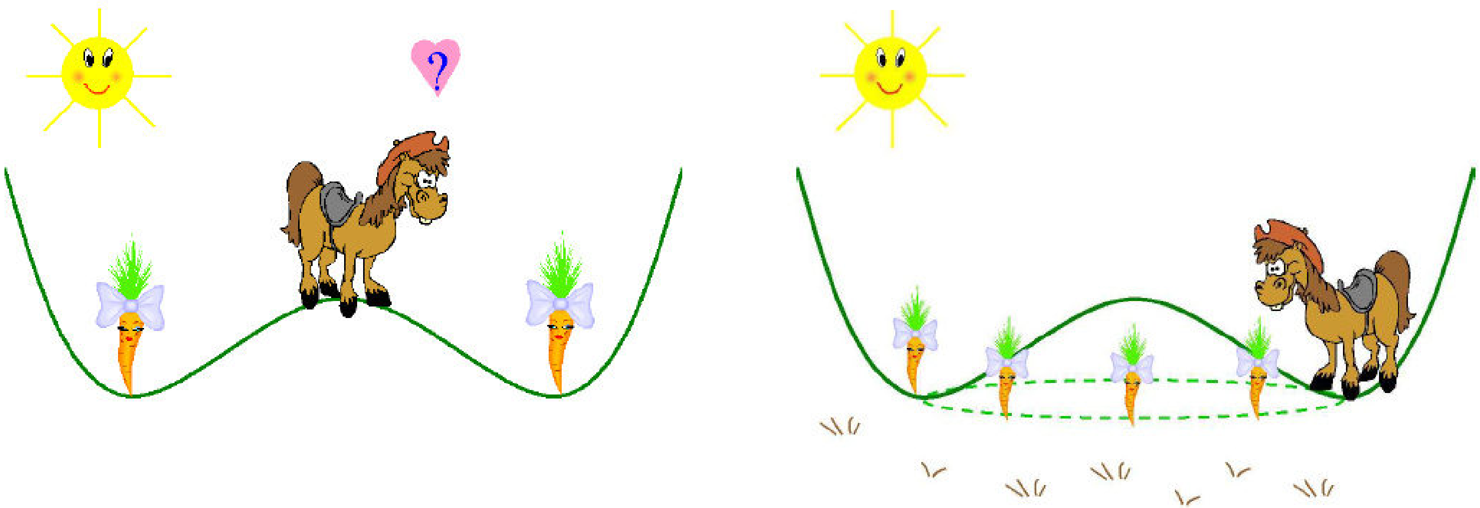
SSB: $\langle \sigma \rangle \propto \left\langle u\bar{u} + d\bar{d} \right\rangle \neq 0$



The donkey of Buridan

Jean Buridan (in Latin, *Johannes Buridanus*) (ca. 1300 – after 1358)

Spontaneous Symmetry Breaking



Although Nicolás likes the symmetric food configuration, he must break the symmetry deciding which carrot is more appealing. In three dimensions, there is a continuous valley where Nicolás can move from one carrot to the next without effort.

Exotic quantum numbers

Not all quantum numbers are permitted for a quark-antiquark states.

$$J^{PC} = 0^{+-}\ ,\ 1^{-+}\ ,\ 2^{+-}, \ldots$$

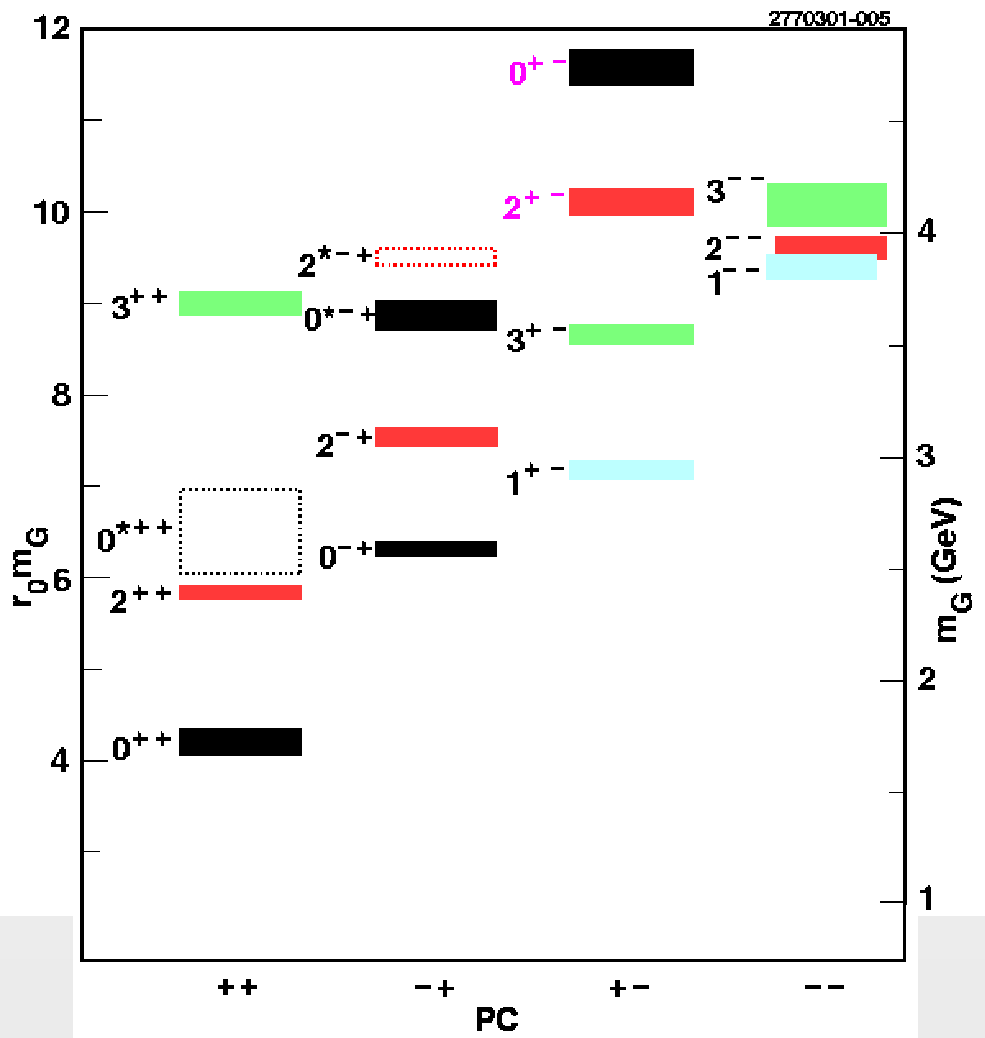
are exotic quantum numbers.

In PDG: $\pi_1(1400)$ and $\pi_1(1600)$ have $J^{PC} = 1^{-+}$. These states are not quarkonia.

Short ex.: show that it is so!

$$P = -(-1)^{L}$$
$$C = (-1)^{L+S}$$
$$\vec{J} = \vec{L} + \vec{S}$$

Glueball spectrum from quenched lattice QCD



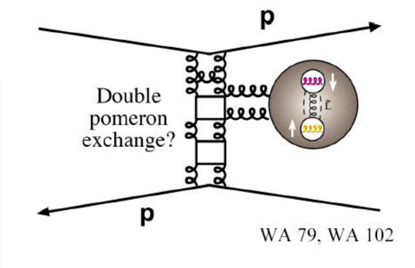
PANDA experiment at FAIR

Francesco Giacosa

Hadronic experiments

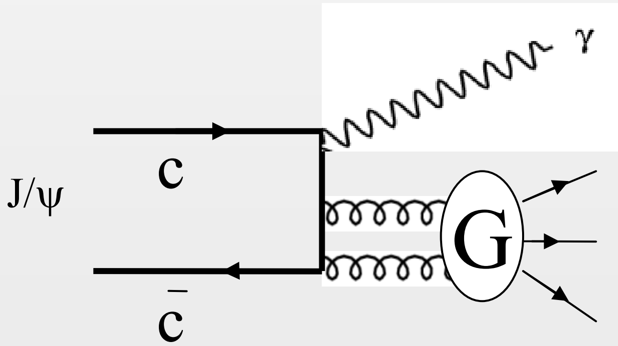
Proton-proton

(WA79,WA102,LHC)

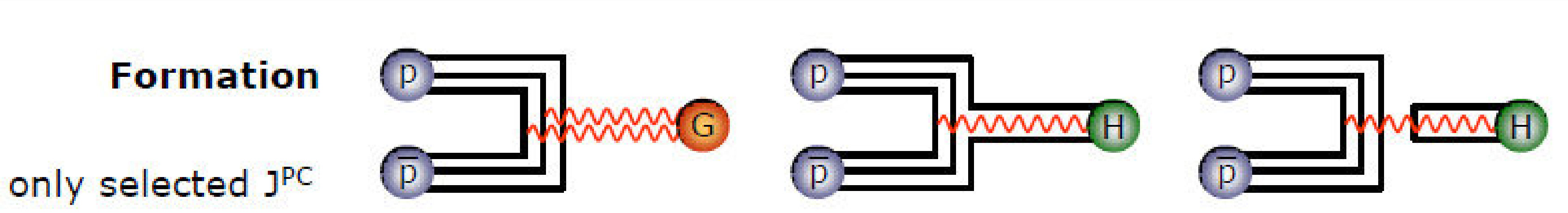


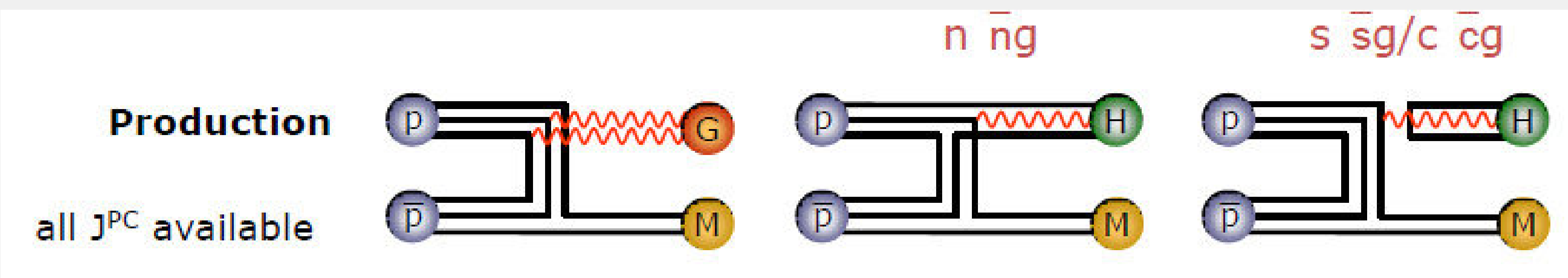
Electron-positron

(Belle, Babar,BES,KLOE,…)

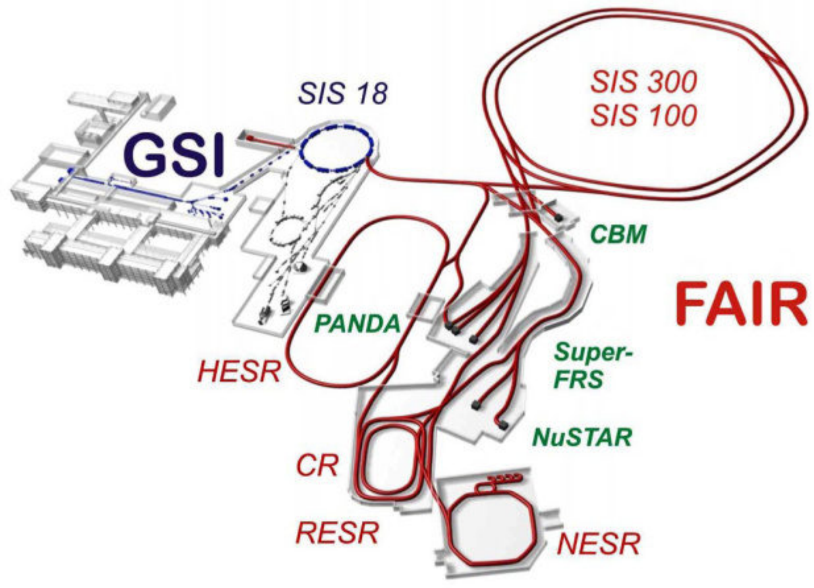


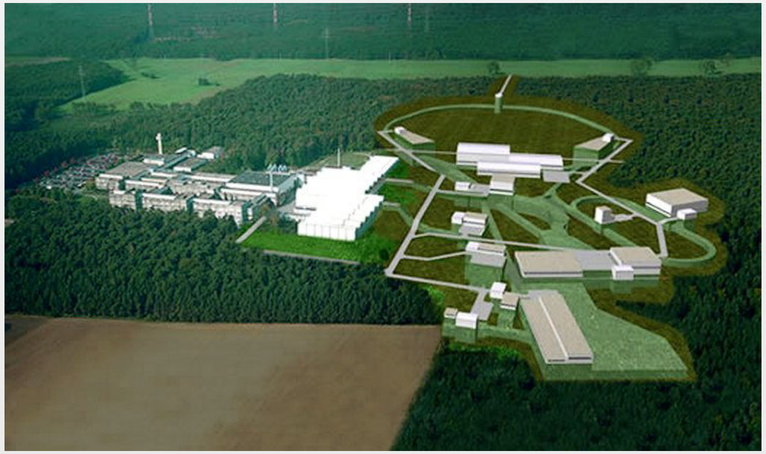
Proton-antiproton
(Lear,Fermilab, and in the future: Panda)

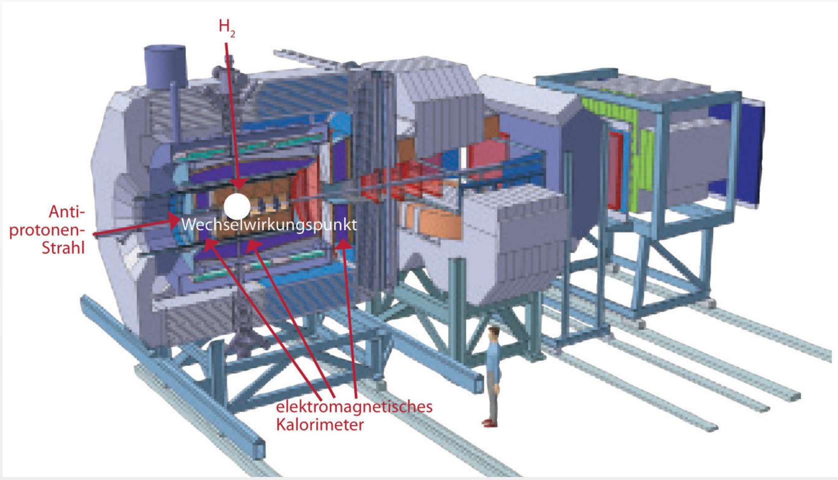




The PANDA experiment







Formation process: the energy range at PANDA

$$\bar{p} + p \rightarrow X$$

…then X decays in something else (pions,kaons,…)

Antiproton moves, proton at rest

$$E_{\bar{p}} = \sqrt{\vec{q}^{\,2} + m_p^2}$$

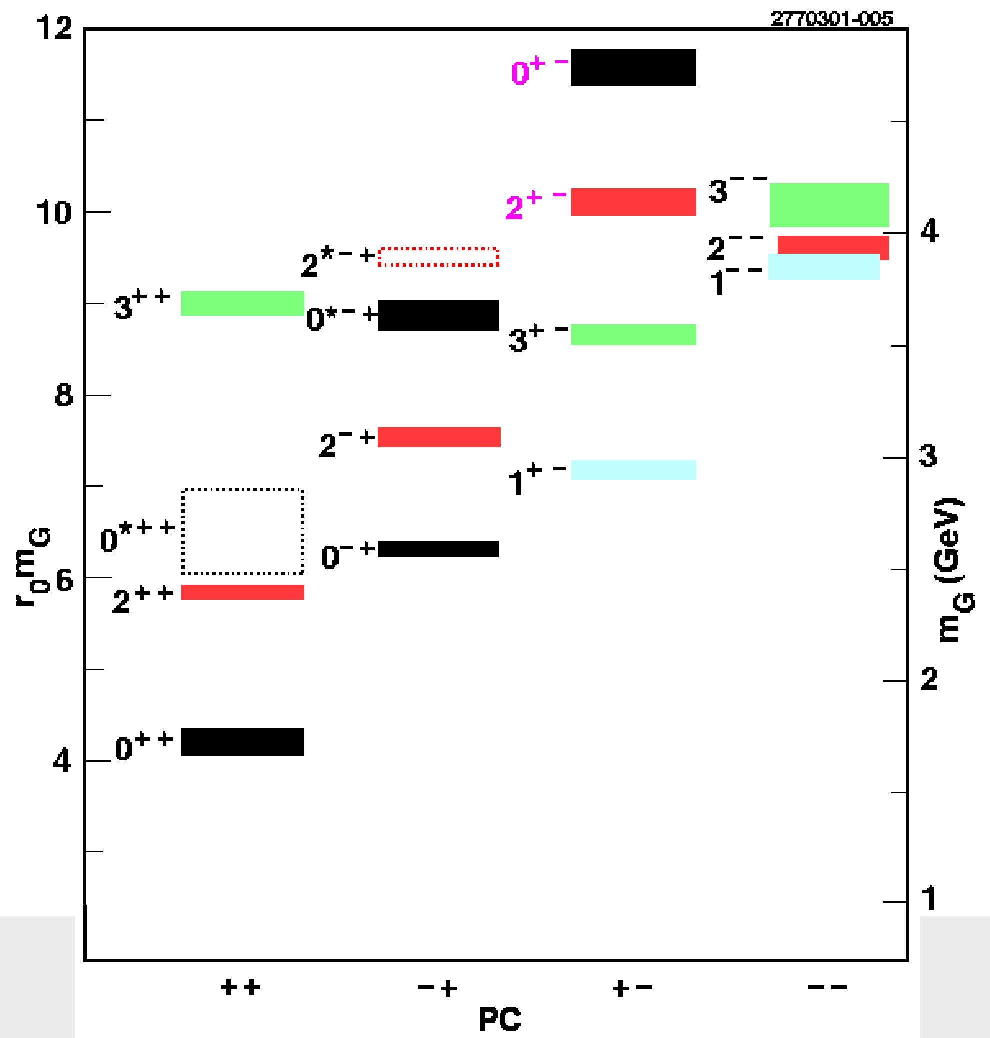
$$m_X = \sqrt{2m_p(m_p + E_{\bar{p}})}$$

Short ex (2): show that it is so!

$$\text{Using } |\vec{q}| = 1.5 - 10 \text{ GeV}: \ m_X = 2.25 - 4.53 \text{ GeV}$$

Which glueballs will be formed?

Interesting objects: Oddballs.
These are glueballs with exotic quantum numbers.



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Selected results of the eLSM

Talks of:

Anja Habersetzer (Nf =2 and spectral functions)
Peter Kovacs (Nf=3 and nonzero temperature)
Walaa Eshraim (Nf=4: charmed mesons)

Fields of the eLSM

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- Quark-antiquark mesons: scalar, pseudoscalar, vector and axial-vector quarkonia.

- Additional mesons: The scalar and the pseudoscalar glueballs

- Baryons: nucleon doublet and its partner

  (in the so-called mirror assignment)

Criteria

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We construct the Lagrangian of the so-called Extended Linear Sigma Model (ELSM) according to:

dilatation symmetry

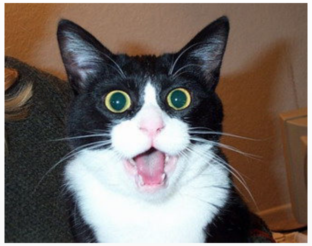
and

chiral invariance.

The breaking of the dilatation symmetry is only included in the „gluonic part“…(scalar glueball and axial anomaly) through a dilaton field

Moreover, invariance under C and P is also taken into account.

Model of QCD – eLSM with scalar Glueball



$$\begin{aligned}\mathcal{L} \;=\;& \frac{1}{2}(\partial_\mu G)^2 - \frac{1}{4}\frac{m_G^2}{\Lambda^2}\left(G^4 \ln\left|\frac{G}{\Lambda}\right| - \frac{G^4}{4}\right) + \mathrm{Tr}\left[(D^\mu\Phi)^\dagger(D_\mu\Phi)\right] \\ & - m_0^2\left(\frac{G}{G_0}\right)^2 \mathrm{Tr}\left[\Phi^\dagger\Phi\right] - \lambda_1(\mathrm{Tr}\left[\Phi^\dagger\Phi\right])^2 - \lambda_2 \mathrm{Tr}\left[(\Phi^\dagger\Phi)^2\right] \\ & + \left(\frac{G}{G_0}\right)^2 \mathrm{Tr}\left[\left(\frac{m_1^2}{2} + \Delta\right)\left((L^\mu)^2 + (R^\mu)^2\right)\right] \\ & - \frac{1}{4}\mathrm{Tr}\left[(L^{\mu\nu})^2 + (R^{\mu\nu})^2\right] + \mathrm{Tr}\left[H\left(\Phi^\dagger + \Phi\right)\right] \\ & + c_1[\det(\Phi) - \det(\Phi^\dagger)]^2 + \frac{h_1}{2}\mathrm{Tr}[\Phi^\dagger\Phi]\mathrm{Tr}[L_\mu L^\mu + R_\mu R^\mu] \\ & + h_2 \mathrm{Tr}[\Phi^\dagger L_\mu L^\mu \Phi + \Phi R_\mu R^\mu \Phi^\dagger] + 2h_3 \mathrm{Tr}[\Phi R_\mu \Phi^\dagger L^\mu]\end{aligned}$$

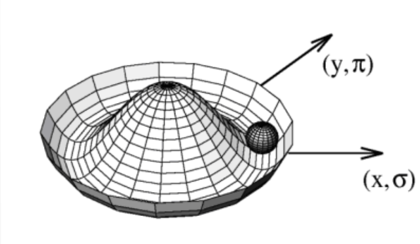
$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} \frac{(\sigma_N + a_0^0) + i(\eta_N + \pi^0)}{\sqrt{2}} & a_0^+ + i\pi^+ & K_0^{\star +} + iK^+ \\ a_0^- + i\pi^- & \frac{(\sigma_N - a_0^0) + i(\eta_N - \pi^0)}{\sqrt{2}} & K_0^{\star 0} + iK^0 \\ K_0^{\star -} + iK^- & \bar{K}_0^{\star 0} + i\bar{K}^0 & \sigma_S + i\eta_S \end{pmatrix}$$

$$L^\mu, R^\mu = \frac{1}{\sqrt{2}}\begin{pmatrix} \frac{\omega_N \pm \rho^0}{\sqrt{2}} \pm \frac{f_{1N} \pm a_1^0}{\sqrt{2}} & \rho^+ \pm a_1^+ & K^{\star +} \pm K_1^+ \\ \rho^- \pm a_1^- & \frac{\omega_N \mp \rho^0}{\sqrt{2}} \pm \frac{f_{1N} \mp a_1^0}{\sqrt{2}} & K^{\star 0} \pm K_1^0 \\ K^{\star -} \pm K_1^- & \bar{K}^{\star 0} \pm i\bar{K}_1^0 & \omega_S \pm f_{1S} \end{pmatrix}$$

S. Janowski, D. Parganlija, F. Giacosa, D. H. Rischke, **Phys. Rev. D84, 054007 (2011**)
D. Parganlija, P. Kovacs, G. Wolf , F. Giacosa, D. H. Rischke, **Phys.Rev. D87 (2013) 014011**
W. I. Eshraim, F.G., D.H. Rischke, arXiv: 1405.5861

Technical remarks

Spontaneous Symmetry Breaking (SSB) implies:



$$\sigma_N \to \sigma_N + \phi_N \;,\; \sigma_S \to \sigma_S + \phi_S$$

Explicit symmetry breaking terms:

$$H = diag\{h_1, h_2, h_3\} \text{ with } h_i \propto m_i \qquad m_\pi^2 \propto (m_u + m_d)\langle \bar{q}q \rangle$$

$$\delta = diag\{\delta_1, \delta_2, \delta_3\} \text{ with } \delta_i \propto m_i^2$$

Parameter c: axial anomaly and eta-prime mass

But: only a finite number of terms is allowed!

We can calculate: masses, decays, and scattering lengths.

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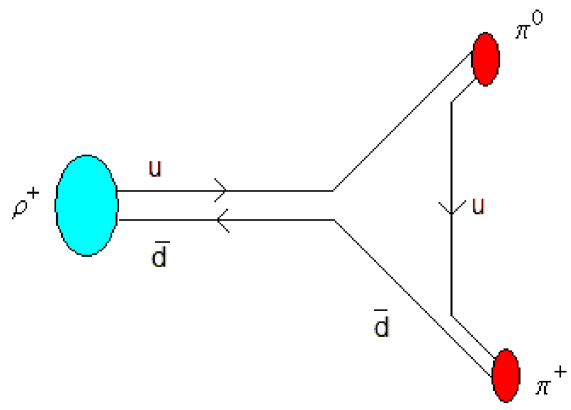
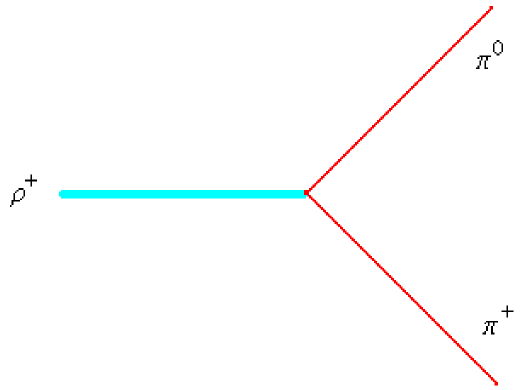
Example: ρ-meson decay into pions

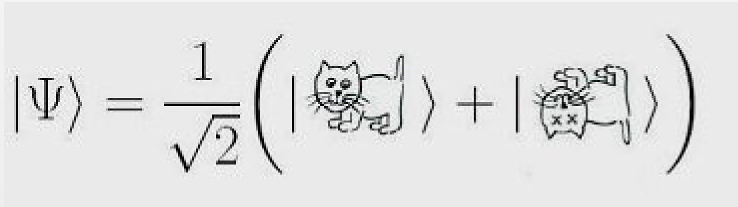
Microscopic



eLSM

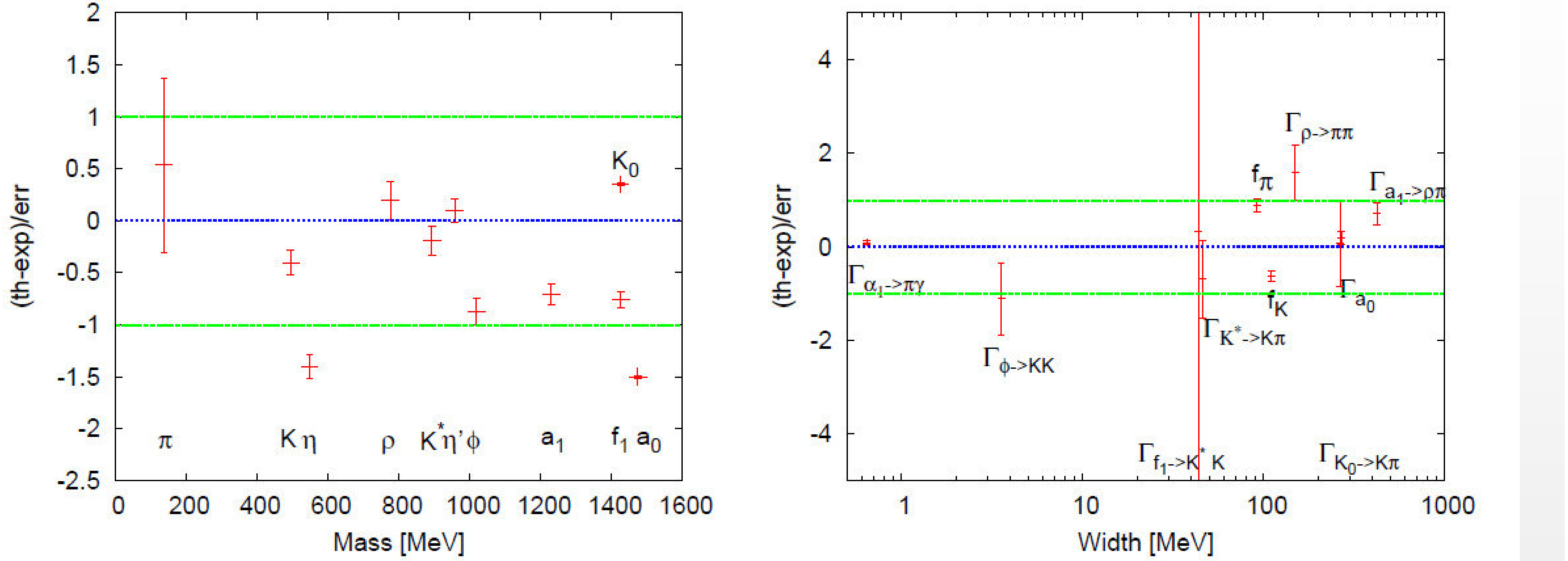


Decay processes: do not forget that…



Schrödingers Katze

Results of the fit (11 parameters, 21 exp. quantities)



arXiv:1208.0585

Overall phenomenology is good.

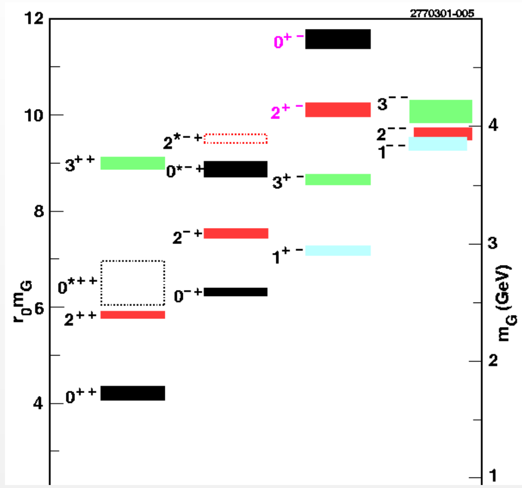
Scalar mesons $a_0(1450)$ and $K_0(1430)$ above 1 GeV and are quark-antiquark states.

Importance of the (axial-)vector mesons

The scalar glueball

The calculation of the full mixing problem in the I=J=0 sector shows that:

$$\begin{pmatrix} f_0(1370) \\ f_0(1500) \\ f_0(1710) \end{pmatrix} = \begin{pmatrix} 0.91 & -0.24 & 0.33 \\ 0.30 & 0.94 & -0.17 \\ -0.27 & 0.26 & 0.93 \end{pmatrix} \begin{pmatrix} \sigma_N \equiv \bar{n}n = \sqrt{1/2}(\bar{u}u + \bar{d}d) \\ \sigma_S \equiv \bar{s}s \\ G \equiv gg \end{pmatrix}$$



Ergo: $f_0(1710)$ is predominantly a glueball!
…and $f_0(1370)$ is the chiral partner of the pion

Details in S. Janowski, F.G, D. H. Rischke, arXiv: 1408.4921

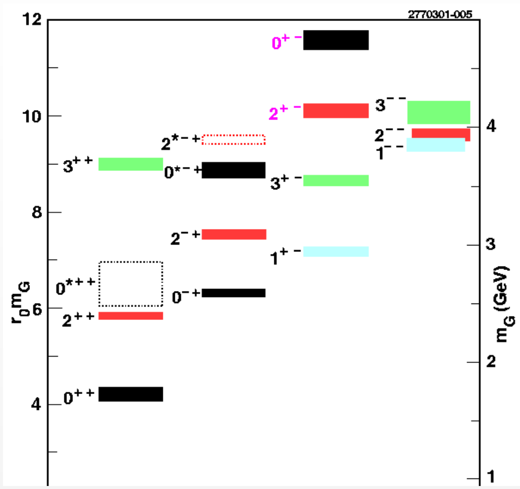
In PANDA: production processes with these states.

The pseudoscalar glueball

$$\mathcal{L}^{int}_{\tilde{G}\text{-mesons}} = ic_{\tilde{G}\Phi}\tilde{G}\left(\det\Phi - \det\Phi^{\dagger}\right)$$

Quantity	Value
$\Gamma_{\tilde{G}\to KK\eta}/\Gamma^{tot}_{\tilde{G}}$	0.049
$\Gamma_{\tilde{G}\to KK\eta'}/\Gamma^{tot}_{\tilde{G}}$	0.019
$\Gamma_{\tilde{G}\to\eta\eta\eta}/\Gamma^{tot}_{\tilde{G}}$	0.016
$\Gamma_{\tilde{G}\to\eta\eta\eta'}/\Gamma^{tot}_{\tilde{G}}$	0.0017
$\Gamma_{\tilde{G}\to\eta\eta'\eta'}/\Gamma^{tot}_{\tilde{G}}$	0.00013
$\Gamma_{\tilde{G}\to KK\pi}/\Gamma^{tot}_{\tilde{G}}$	0.46
$\Gamma_{\tilde{G}\to\eta\pi\pi}/\Gamma^{tot}_{\tilde{G}}$	0.16
$\Gamma_{\tilde{G}\to\eta'\pi\pi}/\Gamma^{tot}_{\tilde{G}}$	0.094

Quantity	Value
$\Gamma_{\tilde{G}\to KK_S}/\Gamma^{tot}_{\tilde{G}}$	0.059
$\Gamma_{\tilde{G}\to a_0\pi}/\Gamma^{tot}_{\tilde{G}}$	0.083
$\Gamma_{\tilde{G}\to\eta\sigma_N}/\Gamma^{tot}_{\tilde{G}}$	0.028
$\Gamma_{\tilde{G}\to\eta\sigma_S}/\Gamma^{tot}_{\tilde{G}}$	0.012
$\Gamma_{\tilde{G}\to\eta'\sigma_N}/\Gamma^{tot}_{\tilde{G}}$	0.019



$$\Gamma_{\tilde{G}\to\pi\pi\pi} = 0$$

PANDA will produce a pseudoscalar glueball (if existent).

Details in:

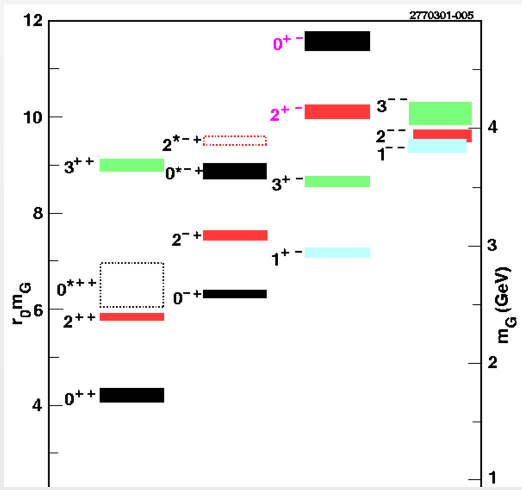
W. Eshraim, S. Janowski, F.G., D. Rischke, **Phys.Rev. D87 (2013) 054036. arxiv: 1208.6474** .
W. Eschraim, S. Janowski, K. Neuschwander, A. Peters, F.G., **Acta Phys. Pol. B**, Prc. Suppl. 5/4, **arxiv: 1209.3976**

Other glueballs

Calculation of branching ratios for the other glueball states.

Ongoing studies: vector, tensor, and pseudotensor glueballs.

…but before 2018 we will do all of them…



Not only glueballs: other interesting states…
that indeed surely exist ☺

X,Y,Z states

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X(3872). $M_X = 3871.52 \pm 0.2$ MeV, $\Gamma = 1.3 \pm 0.6$ MeV, $J^{PC} = 1^{++}$

Various works (see Brambilla et al, EPJ C (2011) 71):

tetraquark or molecular states the most probable intepretations.

(Mass too light when compared to)

„Perfect“ for PANDA research program: direct formation.

My personal opinion: a D-D* molecular state which arises due to mesonic loops.

Y(4260) $M_Y = 4263 \pm 5$ MeV, $\Gamma = 108 \pm 14$ MeV, $J^{PC} = 1^{--}$

Formation at PANDA.

$Z(4430)^+$ $M_Z = 443 \pm 24$ MeV, $\Gamma = 107^{+113}_{-71}$ MeV, $J^{PC} = ?$

Production at PANDA. Surely not a quark-antiquark state.

… … …

$D^*_{S0}(2317)$

$D^*_{S0}(2317)$: too light to be a $c\bar{s}$, $\bar{c}s$ quarkonium.

$J^P = 0^+$, Mass $= 2317.8 \pm 0.6$ MeV

In arXiv: 1405.5861 we find that the quarkonium state:

$M_{D^*_{S0}} = 2.47$ GeV $> M_{D^*_0}$ (which is a $u\bar{c}$,... state and has a mass of 2318 MeV)

$\Gamma_{D^*_{S0}}$ very large

It is a good candidate to be a molecular state / dynamically generated state…

Lust but not least: the light scalar states

$$a_0(980) \quad k(800) \quad f_0(980) \quad f_0(500)$$

$$J^{PC} = 0^{++}$$

$f_0(500)$ important at nonzero density (nuclear matter) and at nonzero temperature (for the correct phase transition).

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The light scalars can be interpeted as tetraquark state

A tetraquark is the bound state of two diquarks

An example of „good diquark" is:

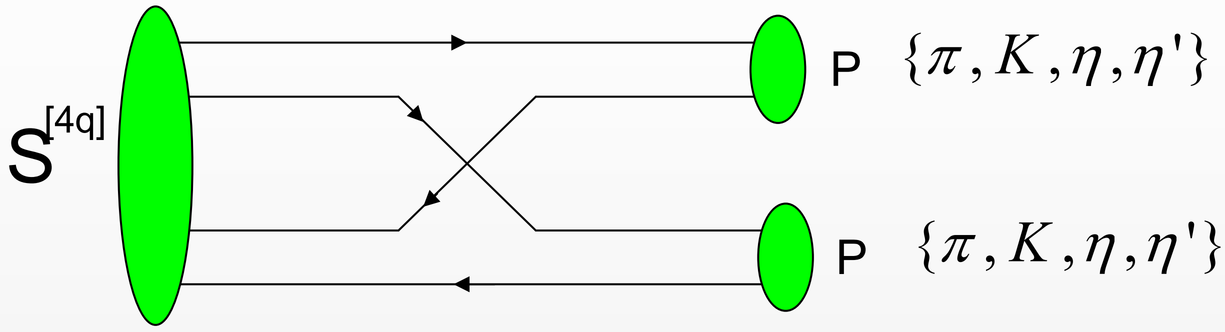
$$\left|qq\right\rangle = \left|Space : L = 0\right\rangle \left|Spin : (\uparrow\downarrow - \downarrow\uparrow)\right\rangle \left|f : (ud - du)\right\rangle \left|c : (RB - BR)\right\rangle$$

Example: $a_0^+(980) = -[\bar{d},\bar{s}][u,s]$ (and not $u\bar{d}$)

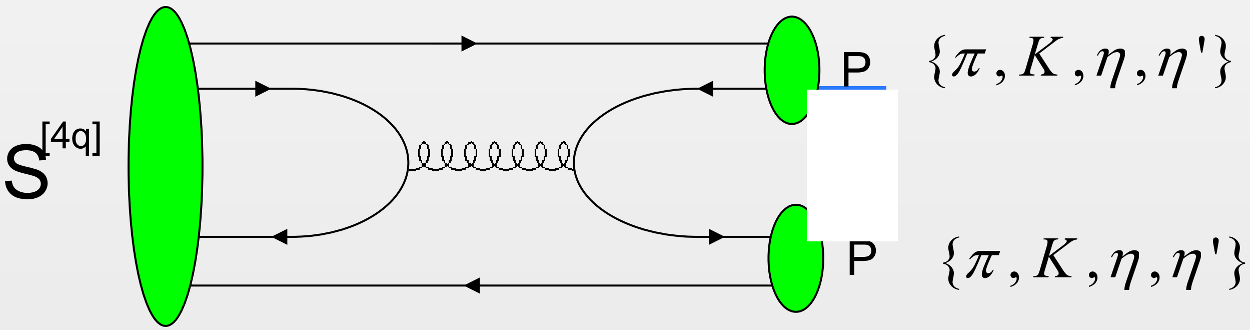
$J^{PC}=0^{++}$	M < 1 GeV	Tetraquark interpretation
$I=1$	$a_0(980)$	$[u,s][\bar{d},\bar{s}],\ [\bar{u},\bar{s}][d,s],$ $([u,s][\bar{u},\bar{s}]-[d,s][\bar{d},\bar{s}])$
$I=\frac{1}{2}$	$k(800)$	$[u,d][\bar{d},\bar{s}],\ [\bar{u},\bar{d}][d,s],$ $[u,d][\bar{u},\bar{s}],\ [\bar{u},\bar{d}][u,s]$
$I=0$	$f_0(500)$	$\approx[\bar{u},\bar{d}][u,d]$
	$f_0(980)$	$\approx([u,s][\bar{u},\bar{s}]+[d,s][\bar{d},\bar{s}])$

Strong decays of a tetraquark state:

Previous works and motivations



Dominant



Subdominant

Jaffe-orig: Jaffe, Phys. Rev. D 15 (1977),

Maiani: Maiani et al, Phys. Rev. Lett. (2004)

Bugg-06: D. V. Bugg, EPJC47 (2006)

Systematic evaluation of amplitudes:

My work: F.G., Phys. Rev. D 74 (2006)

Summary

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Confinement: hadrons

Mesons: not only quark-antiquark states

PANDA experiment will be able to form non-conventional states, most notably glueballs, but also the X,Y states

…it will also produce many ambiguous states and help to understand them…

We (in particular theorists) definitely need the PANDA experiment

…we still have some time for further predictions…

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Thank You