# Mesons beyond the quark-antiquark picture: glueballs, hybrids, tetraquarks - part 1 -

55 Cracow School of Theoretical Physics

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Francesco Giacosa

# Outline

The Lagrangian of QCD and its symmetries

What is a meson?

Conventional mesons and nonconventional mesons

Experiments

Panoramic of candidates of non-connventional mesons

Summary

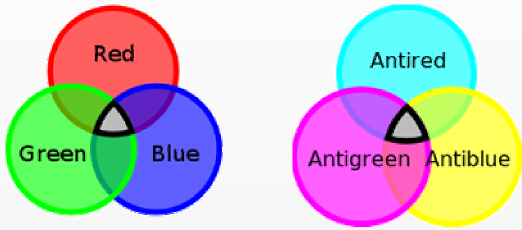
# The Lagrangian of QCD and its symmetries

| | |
|---|---|
| **Born** | Giuseppe Lodovico Lagrangia<br>25 January 1736<br>Turin |
| **Died** | 10 April 1813 (aged 77)<br>Paris |

Francesco Giacosa

# The QCD Lagrangian

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




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

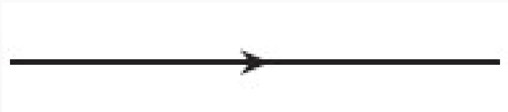
8 type of gluons ($R\bar{G}$,$B\bar{G}$,…)

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

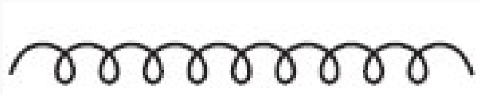
$$A_\mu^a \; ; \; a = 1,...,8$$

# Feynman diagrams of QCD

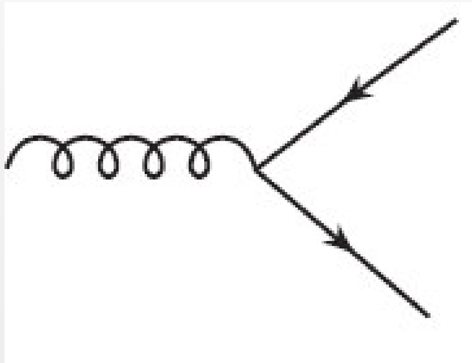
$$\mathcal{L}_{QCD} = \sum_{i=1}^{N_f} \overline{q}_i (i\gamma^\mu D_\mu - m_i) q_i - \frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu}$$



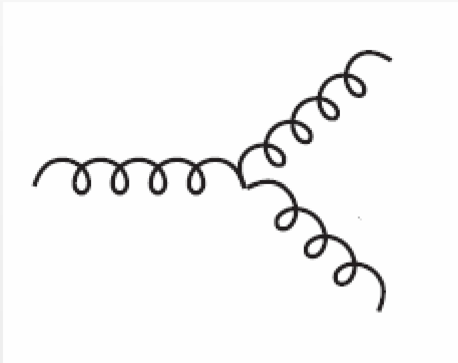
Quark



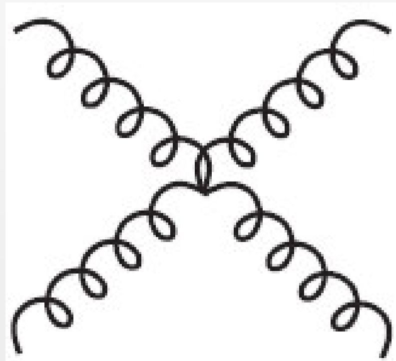
Gluon



Gluon-quark-antiquark vertex



3-gluon vertex



4-gluon vertex

# Trace anomaly: the emergence of a dimension

## Chiral limit: $m_i = 0$

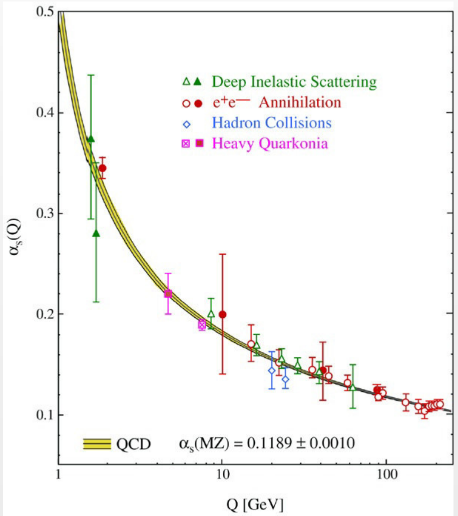
$$x^\mu \to x'^\mu = \lambda^{-1} x^\mu$$

is a classical symmetry broken by quantum fluctuations (trace anomaly)

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

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

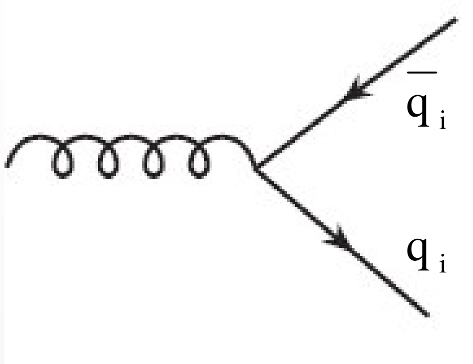
$$\alpha_S(\mu = Q) = \frac{g^2(Q)}{4\pi}$$




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

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

# Flavor symmetry



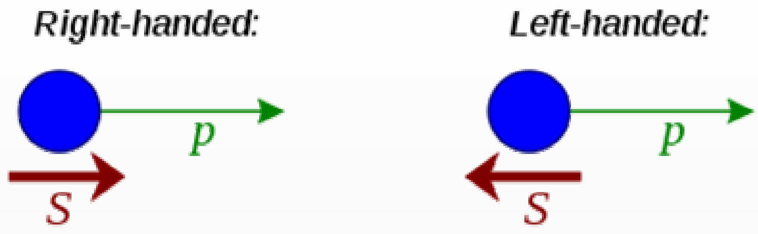

Gluon-quark-antiquark vertex.

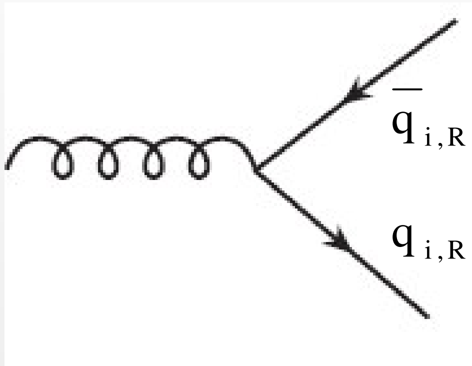
It is democratic! The gluon couples to each flavor with the same strength

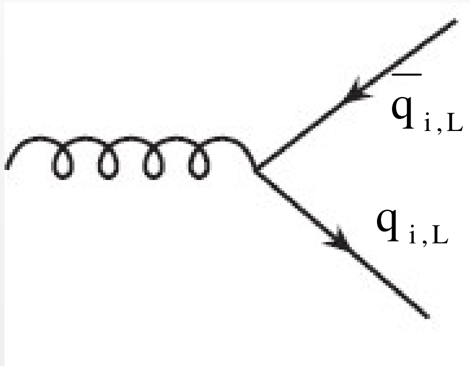
$$q_i \to U_{ij} q_j$$

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

# Chiral symmetry




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

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

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

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

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

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

# Spontaneous breaking of chiral symmetry

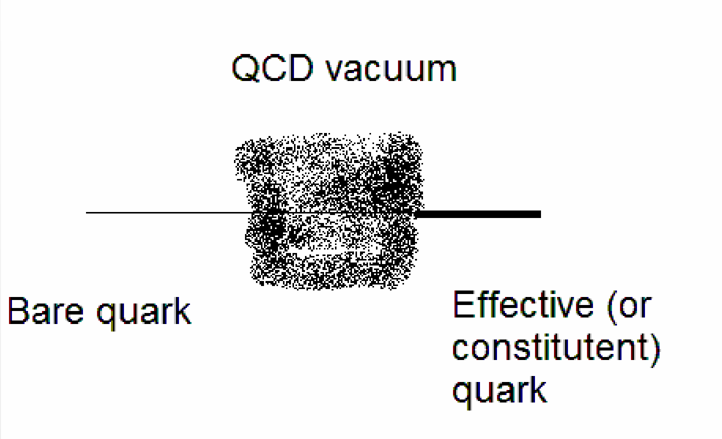
$$U(3)_R \times U(3)_L = U(1)_{R+L} \times U(1)_{R-L} \times SU(3)_R \times SU(3)_L$$

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

Chiral symmetry → Flavor symmetry

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

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




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

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

# Symmetries of QCD: summary

**$SU(3)_{color}$:** 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

**$SU(3)_R x SU(3)_L$**: 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)

# What is a meson?

# Hadrons

No ‚colored‘ state has been seen.

Confinement: physical states are white and are called hadrons.

Hadrons can be:

Mesons: bosonic hadrons

Baryons: fermionic hadrons

# Definition of mesons: WIkipedia???

Uniwersytet
Humanistyczno - Przyrodniczy
Jana Kochanowskiego w Kielcach

en.wikipedia.org/wiki/Meson

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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 ⅔ 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

**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 ($\pi^+$) |

it.wikipedia.org/wiki/Mesone

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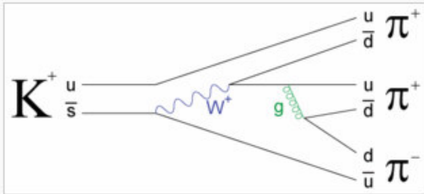
# Mesone

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. Sono particelle 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 ($2\ \pi^+$, $1\ \pi^-$) 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).

Uniwersytet Humanistyczno - Przyrodniczy Jana Kochanowskiego w Kielcach

Genova, bussano alla po | Il tradimento? È scritto | Meton – Wikipedia

de.wikipedia.org/wiki/Meson

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# Meson

**Mesonen** (von griechisch: τὸ μέσον (tó méson) „das Mittlere“) 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.

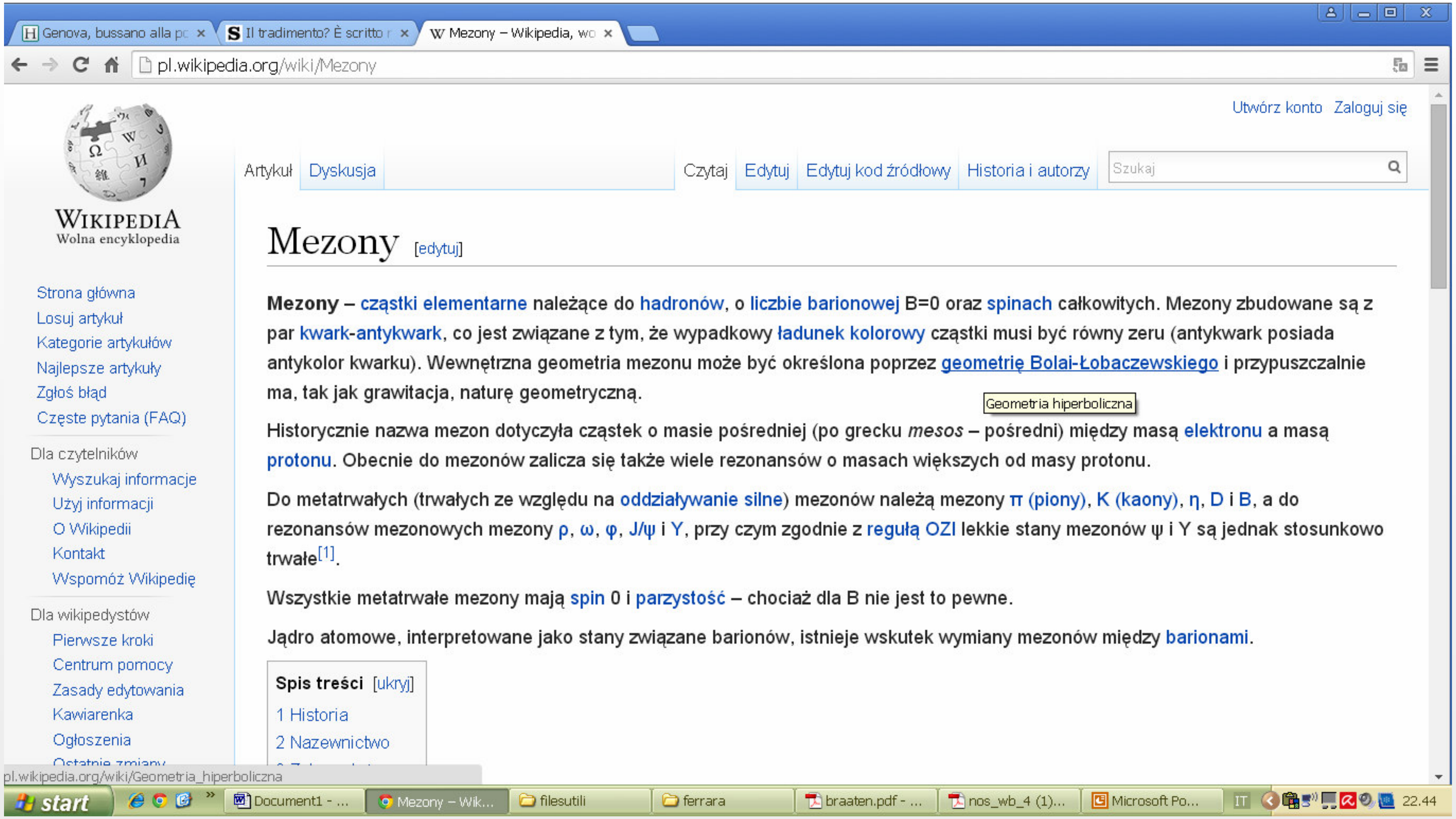
Der Name „Meson“ wurde wegen der mittelschweren Masse des zuerst entdeckten Mesons, des Pions, zwischen Elektron und Proton gewählt.

Mesonen entstehen in hochenergetischen Teilchenkollisionen (z. B. in der kosmischen Strahlung oder in Experimenten der Hochenergiephysik) 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]



start | Document1 - ... | Meson – Wiki... | filesutili | ferrara | braaten.pdf - ... | nos_wb_4 (1)... | Microsoft Po... | IT | 22.41



# 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]

Uniwersytet Humanistyczno - Przyrodniczy Jana Kochanowskiego w Kielcach

es.wikipedia.org/wiki/Mesón

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# Mesón

En física de partículas, un **mesón** (del griego antiguo μέσος *mésos* 'que está en 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

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$^2$ ($\pi$+) y 9,460 MeV/c$^2$ ($\Upsilon$) |

# Meson

Definition(s):

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

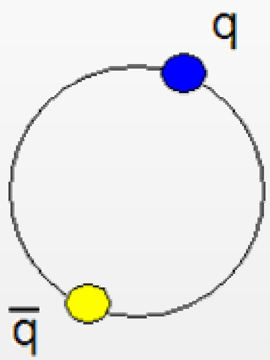
2) A meson is a strongly interacting particle with zero baryon number.

A meson is not necessarily a quark-antiquark state

# Conventional mesons

Quark: u,d,s,… R,G,B

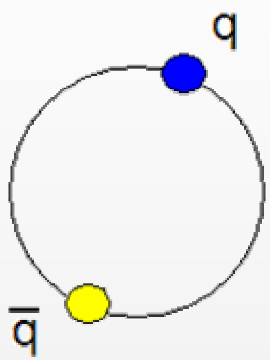
Quark-antiquark bound states: conventional mesons




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

# Conventional mesons/2

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




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

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

# Exotic quantum numbers

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

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

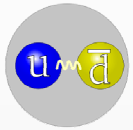
are exotic quantum numbers.

Short ex: show it is so!

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

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

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




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

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

Flavor symmetry: the 3 pions have the same mass.

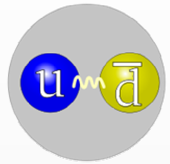
$$\left|K^{+}\right\rangle = \left|u\bar{s}\right\rangle \left|space: L=0\right\rangle \left|spin: S=0\right\rangle \left|\bar{R}R+\bar{B}B+\bar{G}G\right\rangle$$

...

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

...

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




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

...

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

...

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

...

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

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

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

corresponds to the resonance $f_0(1370)$.

...

...

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

# PDG quark-antiquark listing/1

**Table 15.2:** Suggested $q\overline{q}$ quark-model assignments for some of the observed light mesons. Mesons in bold face are included in the Meson Summary Table. The wave functions $f$ and $f'$ are given in the text. The singlet-octet mixing angles from the quadratic and linear mass formulae are also given for the well established nonets. The classification of the $0^{++}$ mesons is tentative: The light scalars $a_0(980)$, $f_0(980)$, and $f_0(500)$ are often considered as meson-meson resonances or four-quark states, and are omitted from the table. Not shown either is the $f_0(1500)$ which is hard to accommodate in the nonet. The isoscalar $0^{++}$ mesons are expected to mix. See the "Note on Scalar Mesons" in the Meson Listings for details and alternative schemes.

| $n\,^{2s+1}\ell_J$ | $J^{PC}$ | I = 1 $u\overline{d}$, $\overline{u}d$, $\frac{1}{\sqrt{2}}(d\overline{d}-u\overline{u})$ | I = $\frac{1}{2}$ $u\overline{s}$, $d\overline{s}$; $\overline{d}s$, $-\overline{u}s$ | I = 0 $f'$ | I = 0 $f$ | $\theta_{\text{quad}}$ [°] | $\theta_{\text{lin}}$ [°] |
|---|---|---|---|---|---|---|---|
| $1\,^1S_0$ | $0^{-+}$ | $\pi$ | $K$ | $\eta$ | $\eta'(958)$ | −11.4 | −24.5 |
| $1\,^3S_1$ | $1^{--}$ | $\rho(770)$ | $K^*(892)$ | $\phi(1020)$ | $\omega(782)$ | 39.1 | 36.4 |
| $1\,^1P_1$ | $1^{+-}$ | $b_1(1235)$ | $K_{1B}$ † | $h_1(1380)$ | $h_1(1170)$ | | |
| $1\,^3P_0$ | $0^{++}$ | $a_0(1450)$ | $K_0^*(1430)$ | $f_0(1710)$ | $f_0(1370)$ | | |
| $1\,^3P_1$ | $1^{++}$ | $a_1(1260)$ | $K_{1A}$ † | $f_1(1420)$ | $f_1(1285)$ | | |
| $1\,^3P_2$ | $2^{++}$ | $a_2(1320)$ | $K_2^*(1430)$ | $f_2'(1525)$ | $f_2(1270)$ | 32.1 | 30.5 |
| $1\,^1D_2$ | $2^{-+}$ | $\pi_2(1670)$ | $K_2(1770)$ † | $\eta_2(1870)$ | $\eta_2(1645)$ | | |
| $1\,^3D_1$ | $1^{--}$ | $\rho(1700)$ | $K^*(1680)$ | | $\omega(1650)$ | | |
| $1\,^3D_2$ | $2^{--}$ | | $K_2(1820)$ | | | | |
| $1\,^3D_3$ | $3^{--}$ | $\rho_3(1690)$ | $K_3^*(1780)$ | $\phi_3(1850)$ | $\omega_3(1670)$ | 31.8 | 30.8 |
| $1\,^3F_4$ | $4^{++}$ | $a_4(2040)$ | $K_4^*(2045)$ | | $f_4(2050)$ | | |
| $1\,^3G_5$ | $5^{--}$ | $\rho_5(2350)$ | $K_5^*(2380)$ | | | | |
| $1\,^3H_6$ | $6^{++}$ | $a_6(2450)$ | | | $f_6(2510)$ | | |
| $2\,^1S_0$ | $0^{-+}$ | $\pi(1300)$ | $K(1460)$ | $\eta(1475)$ | $\eta(1295)$ | | |
| $2\,^3S_1$ | $1^{--}$ | $\rho(1450)$ | $K^*(1410)$ | $\phi(1680)$ | $\omega(1420)$ | | |

† The $1^{+\pm}$ and $2^{-\pm}$ isospin $\frac{1}{2}$ states mix. In particular, the $K_{1A}$ and $K_{1B}$ are nearly equal (45°) mixtures of the $K_1(1270)$ and $K_1(1400)$. The physical vector mesons listed under $1^3D_1$ and $2^3S_1$ may be mixtures of $1^3D_1$ and $2^3S_1$, or even have hybrid components.

# PDG quark-antiquark listing/2

Uniwersytet Humanistyczno - Przyrodniczy Jana Kochanowskiego w Kielcach

**Table 15.3:** $q\bar{q}$ quark-model assignments for the observed heavy mesons with established $J^{PC}$. Mesons in bold face are included in the Meson Summary Table.

| $n\,^{2s+1}\ell_J$ | $J^{PC}$ | I = 0 $c\bar{c}$ | I = 0 $b\bar{b}$ | I = $\frac{1}{2}$ $c\bar{u}$, $c\bar{d}$; $\bar{c}u$, $\bar{c}d$ | I = 0 $c\bar{s}$; $\bar{c}s$ | I = $\frac{1}{2}$ $b\bar{u}$, $b\bar{d}$; $\bar{b}u$, $\bar{b}d$ | I = 0 $b\bar{s}$; $\bar{b}s$ | I = 0 $b\bar{c}$; $\bar{b}c$ |
|---|---|---|---|---|---|---|---|---|
| $1\,^1S_0$ | $0^{-+}$ | $\eta_c(1S)$ | $\eta_b(1S)$ | $D$ | $D_s^{\pm}$ | $B$ | $B_s^0$ | $B_c^{\pm}$ |
| $1\,^3S_1$ | $1^{--}$ | $J/\psi(1S)$ | $\Upsilon(1S)$ | $D^*$ | $D_s^{*\pm}$ | $B^*$ | $B_s^*$ | |
| $1\,^1P_1$ | $1^{+-}$ | $h_c(1P)$ | $h_b(1P)$ | $D_1(2420)$ | $D_{s1}(2536)^{\pm}$ | $B_1(5721)$ | $B_{s1}(5830)^0$ | |
| $1\,^3P_0$ | $0^{++}$ | $\chi_{c0}(1P)$ | $\chi_{b0}(1P)$ | $D_0^*(2400)$ | $D_{s0}^*(2317)^{\pm\dagger}$ | | | |
| $1\,^3P_1$ | $1^{++}$ | $\chi_{c1}(1P)$ | $\chi_{b1}(1P)$ | $D_1(2430)$ | $D_{s1}(2460)^{\pm\dagger}$ | | | |
| $1\,^3P_2$ | $2^{++}$ | $\chi_{c2}(1P)$ | $\chi_{b2}(1P)$ | $D_2^*(2460)$ | $D_{s2}^*(2573)^{\pm}$ | $B_2^*(5747)$ | $B_{s2}^*(5840)^0$ | |
| $1\,^3D_1$ | $1^{--}$ | $\psi(3770)$ | | | $D_{s1}^*(2700)^{\pm}$ | | | |
| $2\,^1S_0$ | $0^{-+}$ | $\eta_c(2S)$ | | $D(2550)$ | | | | |
| $2\,^3S_1$ | $1^{--}$ | $\psi(2S)$ | $\Upsilon(2S)$ | | | | | |
| $2\,^1P_1$ | $1^{+-}$ | | $h_b(2P)$ | | | | | |
| $2\,^3P_{0,1,2}$ | $0^{++},1^{++},2^{++}$ | $\chi_{c2}(2P)$ | $\chi_{b\,0,1,2}(2P)$ | | | | | |

† The masses of these states are considerably smaller than most theoretical predictions. They have also been considered as four-quark states The open flavor states in the $1^{+-}$ and $1^{++}$ rows are mixtures of the $1^{+\pm}$ states.

# Chiral models: the basic idea

# Spontaneous symmetry breaking at the meson level

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

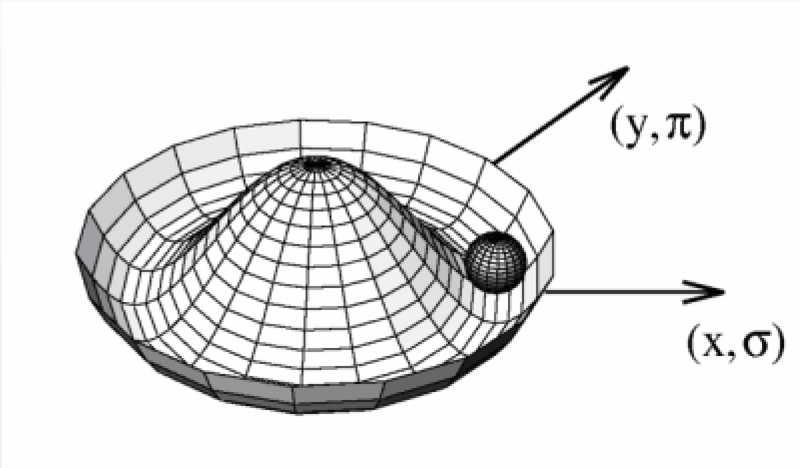
$$\sigma \equiv \sqrt{1/2}(\bar{u}u + \bar{d}d) \equiv f_0(1370)$$

Chiral transformation: $\sigma \leftrightarrow \pi$

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

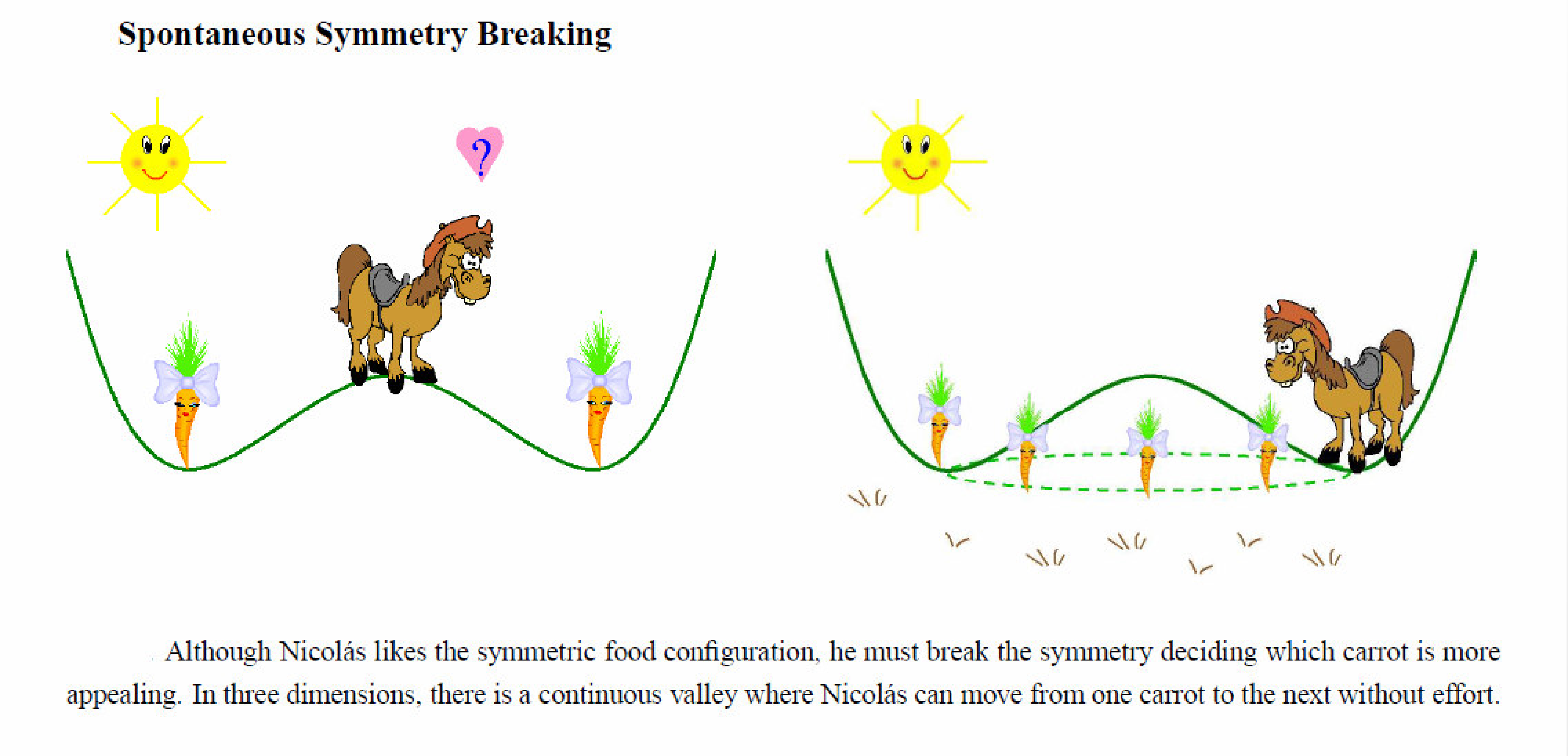
$m_0^2 < 0 \quad \rightarrow$ Mexican hat

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)




Picture taken from A. Pich, arXiv:0705.4264 [hep-ph],
Cern-Claf Lecture on 'The Standard model of electroweak interactions '

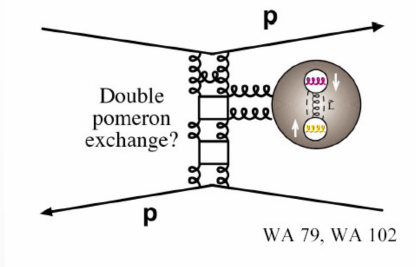
# Hadronic Experiments

Francesco Giacosa

# Hadronic experiments

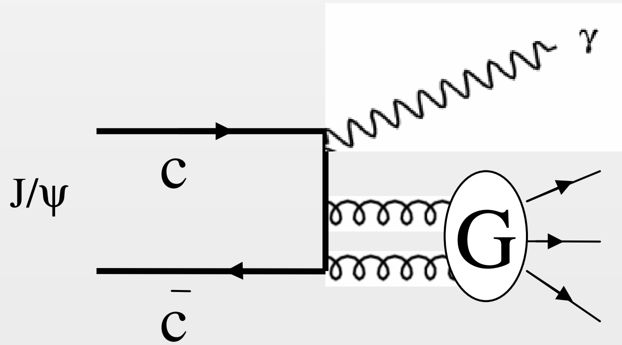
Proton-proton

(WA79,WA102,LHC)

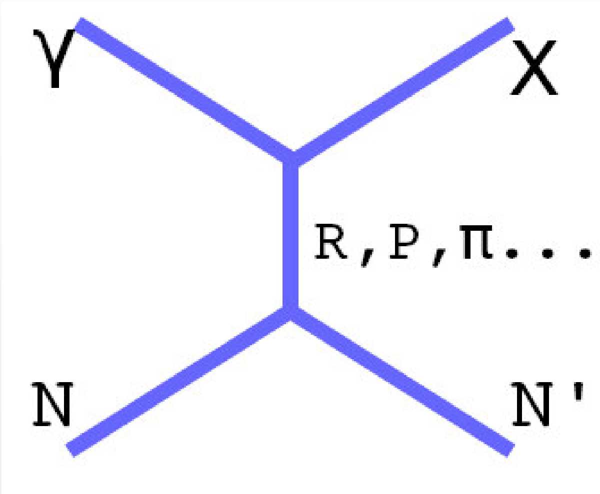



Electron-positron

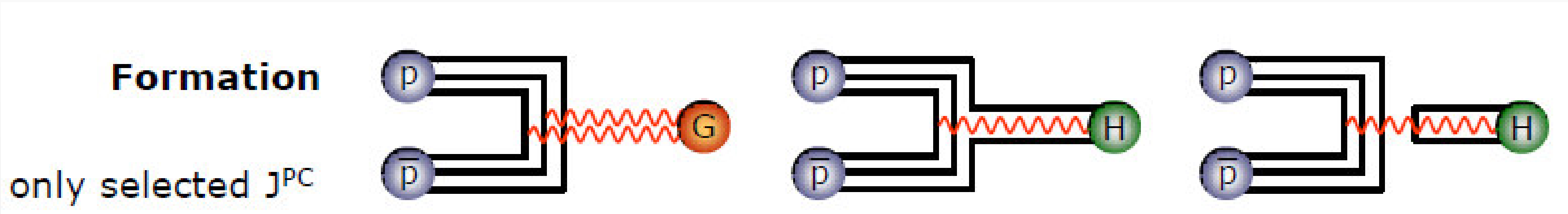
(Belle, Babar,BES,KLOE,…)

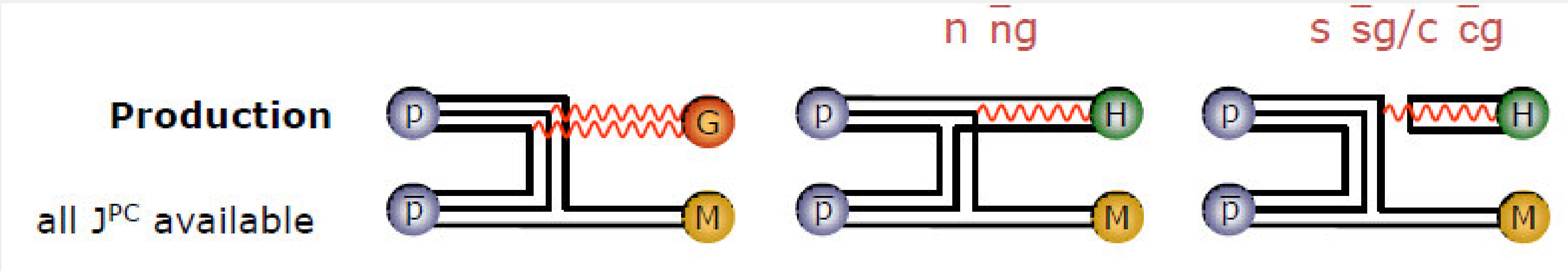


Photoproduction: Compass at Cern
GlueX AND CLAS12 AT Jlab (start soon)

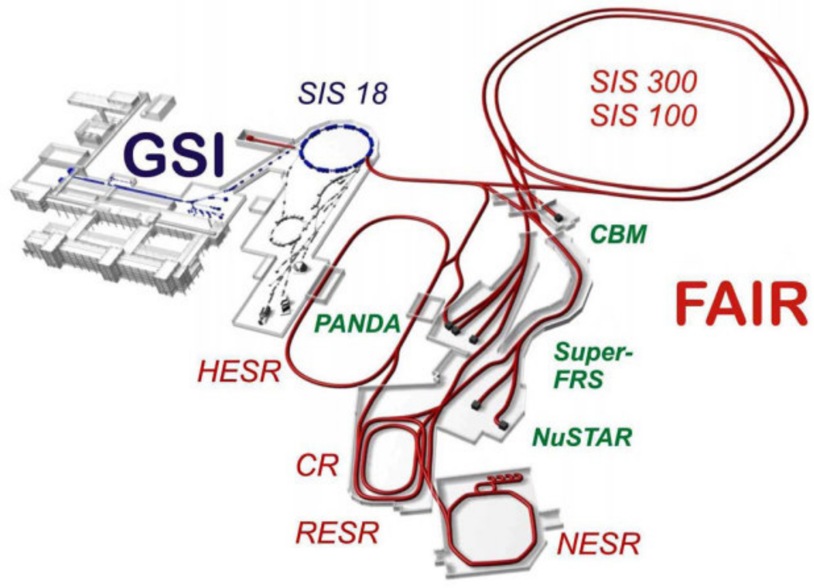


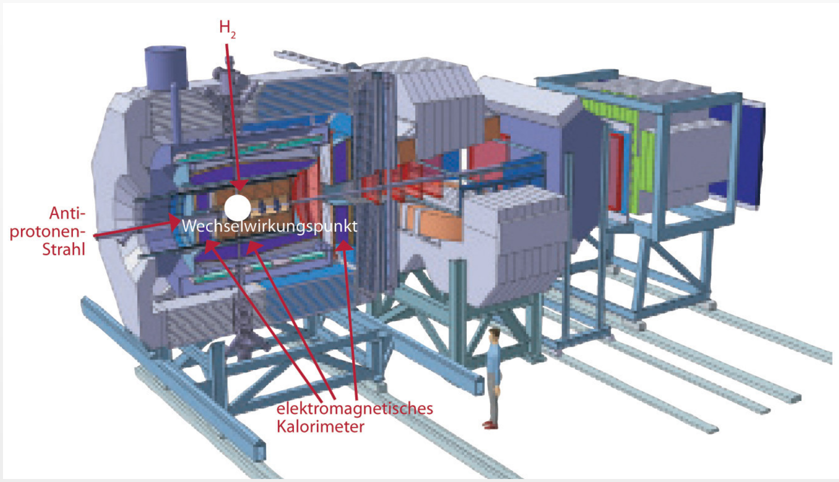
# Proton-antiproton
# (Lear,Fermilab, and in the future: Panda)

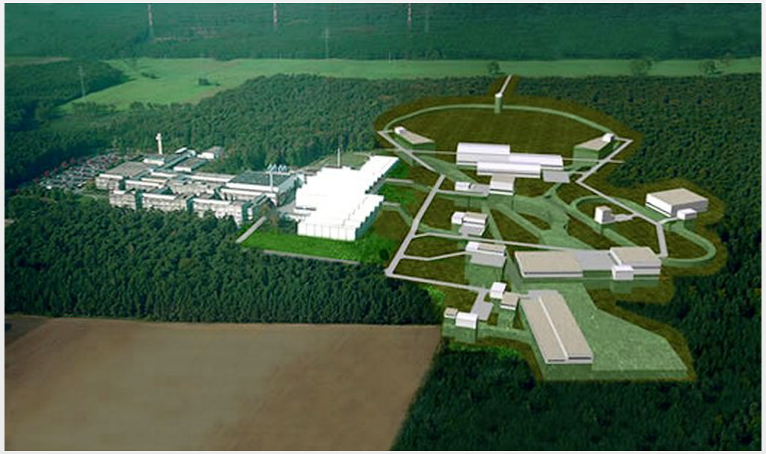


# The PANDA experiment



# Formation process: the energy range in PANDA

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

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

Antiproton moves, proton at rest

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

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

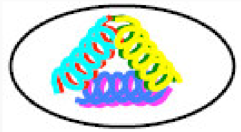
Short ex: show that it is so!

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

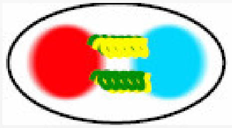
# Theoretical expectations

# Non-conventional mesons: theoretical expectations

1) Glueballs



2) Hybrids



Compact diquark-antidiquar states

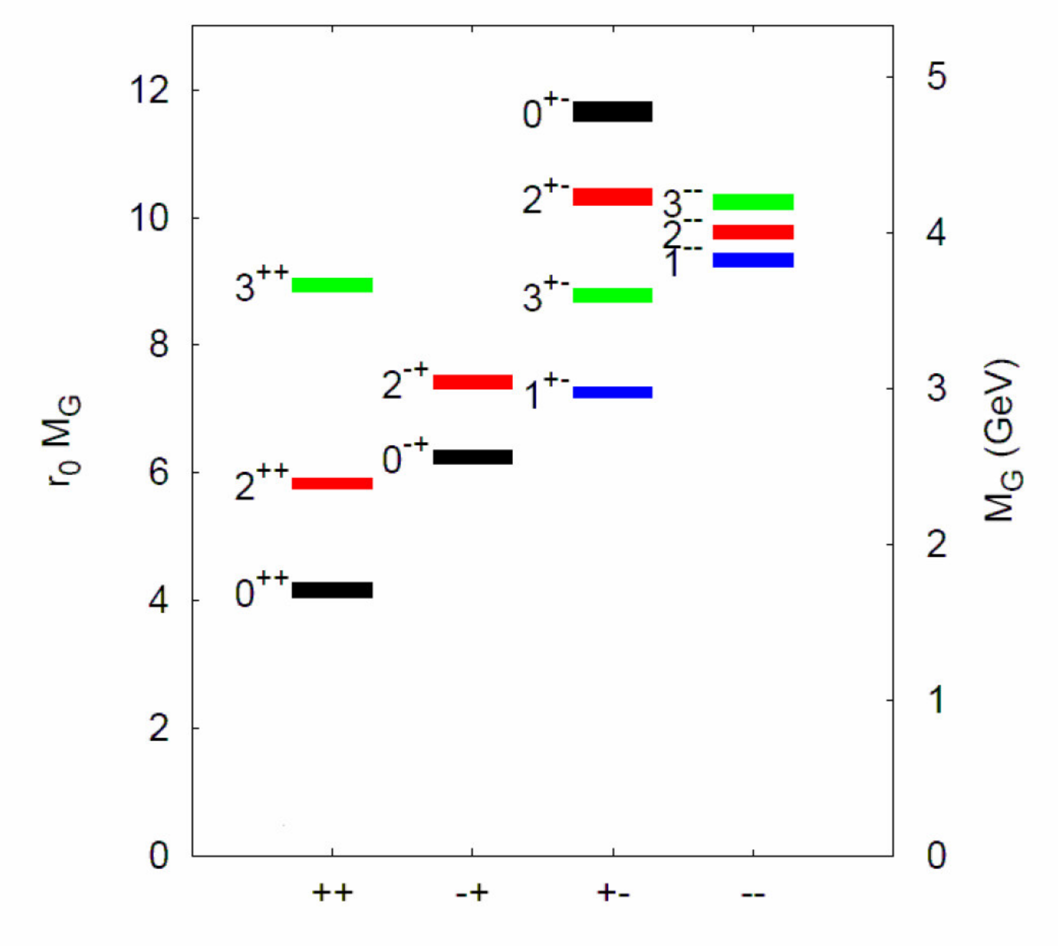
3) Four-quark states

Molecular states (a type of dynamical generation)

Companion poles (another type of dynamical generation)

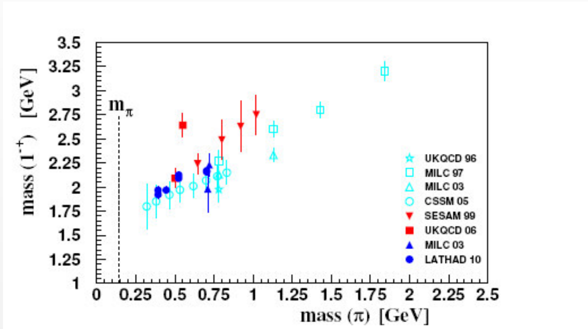
# Glueball spectrum from quenched lattice QCD

The missing pieces of the mesonic spectrum:
the glueballs. Where are they?



Hybrid mesons: lattice predictions for 1^-+ hybrids at about 2 GeV

See for instance the review:
C. Meyer and E. Swanson, Hybrid Mesons,''
Prog.\ Part.\ Nucl.\ Phys.\ {\bf 82} (2015) 21
[arXiv:1502.07276 [hep-ph]].




(Many) tetraquark states are predicted in various models.
Actually even too many…

See for instance:
D. Ebert et al, Excited heavy tetraquarks with hidden charm,
Eur. Phys. J. C 58 (2008) 399 [arXiv:0808.3912 [hep-ph]].

# Non-quarkonium candidates: light sector

# The light scalar mesons

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

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

They (most probably!) are not quark-antiquark states!!!

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 |
|---|---|---|
| $I=1$ | $a_0(980)$ | $[u,s][\bar{d},\bar{s}],\ [\bar{u},\bar{s}][d,s],$ $([u,s][\bar{u},\bar{s}]-[d,s][\bar{d},\bar{s}])$ |
| $I=\frac{1}{2}$ | $k(800)$ | $[u,d][\bar{d},\bar{s}],\ [\bar{u},\bar{d}][d,s],$ $[u,d][\bar{u},\bar{s}],\ [\bar{u},\bar{d}][u,s]$ |
| $I=0$ | $f_0(500)$ $f_0(980)$ | $\approx[\bar{u},\bar{d}][u,d]$ $\approx([u,s][\bar{u},\bar{s}]+[d,s][\bar{d},\bar{s}])$ |

| $J^{PC} = 0^{++}$ | M < 1 GeV | Molecular interpretation |
|---|---|---|
| $I = 1$ | $a_0(980)$ | KK bound-state |
| $I = \frac{1}{2}$ | $k(800)$ | πK bound-state |
| $I = 0$ | $f_0(500)$<br>$f_0(980)$ | ππ bound-state<br>KK bound-state |

# Scalars above 1 GeV and scalar glueball candidate

$f_0(1370)$ is compatible with a quark-antiquark substructure.

Yet, a large glueball component is expected in $f_0(1500)$ and/or in $f_0(1710)$.

Latest studies actually point toward $f_0(1710)$ as being predominantly gluonic.

# Pseudoscalar glueball: candidates

Up to now we do not know where it is. A light pseudoscalar glueball was not found yet. Here also the candidates are not so easily found.

η(1405) and η(1475)

(but much lighter than the lattice value of 2.6 GeV)

X(2370) (BES)

# Tensor glueball: candidate

Here it is fog…

The resonance $f_J(2220)$ could be a candidate, if J=2 will be confirmed.

# Two states with exotic quantum number

$$J^{PC} = 1^{-+}$$

$\Pi_1(1400)$

$\Pi_1(1600)$

What are they?
They cannot be quark-antiquark states, but they could be hybrid
(but mass too low w.r.t. lattice)

or they could be four-quark states

# Pseudoscalar glueball

Up to now we do not know where it is. A light pseudoscalar glueball was not found yet. Here also the candidates are not so easily found.

η(1405) and η(1475)

(but much lighter than the lattice value of 2.6 GeV)

X(2370) (BES)

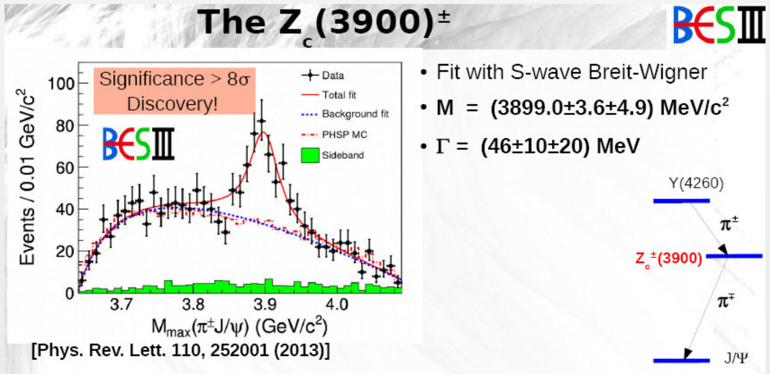
# Non-quarkonium candidates: charmonium sector

# X,Y states

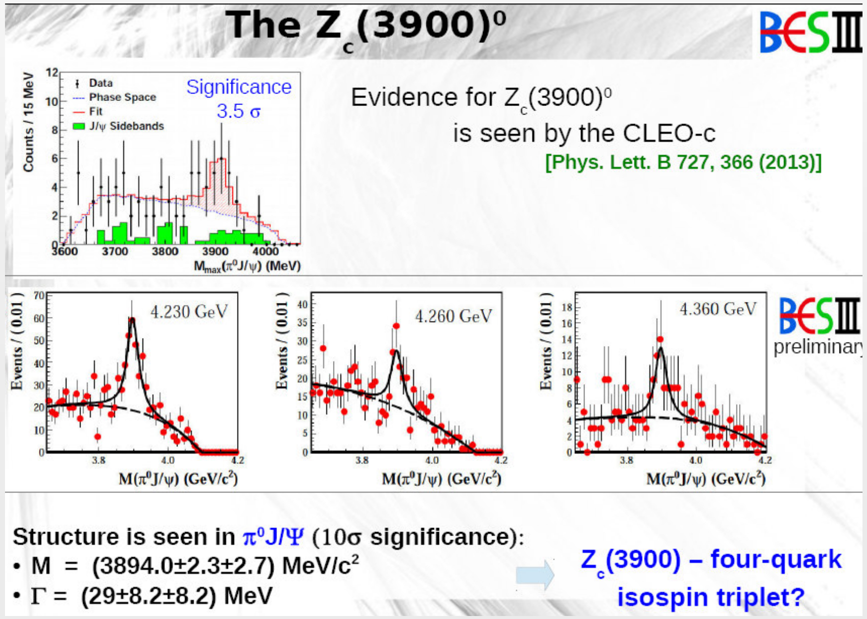
| State | $M$ (MeV) | $\Gamma$ (MeV) | $J^{PC}$ | Decay modes | 1st observation |
|---|---|---|---|---|---|
| $X(3823)$ | $3823.1\pm1.9$ | $<24$ | $?^{?-}$ | $\chi_{c1}\gamma$ | Belle 2013 |
| $X(3872)$ | $3871.68\pm0.17$ | $<1.2$ | $1^{++}$ | $J/\psi\,\pi^+\pi^-$, $J/\psi\,\pi^+\pi^-\pi^0$<br>$D^0\bar{D}^0\pi^0$, $D^0\bar{D}^0\gamma$<br>$J/\psi\,\gamma$, $\psi(2S)\,\gamma$ | Belle 2003 |
| $X(3915)$ | $3917.5\pm1.9$ | $20\pm5$ | $0^{++}$ | $J/\psi\,\omega$, $(\gamma\gamma)$ | Belle 2004 |
| $\chi_{c2}(2P)$ | $3927.2\pm2.6$ | $24\pm6$ | $2^{++}$ | $D\bar{D}$, $(\gamma\gamma)$ | Belle 2005 |
| $X(3940)$ | $3942^{+9}_{-8}$ | $37^{+27}_{-17}$ | $?^{?+}$ | $D^*\bar{D}$, $D\bar{D}^*$ | Belle 2007 |
| $G(3900)$ | $3943\pm21$ | $52\pm11$ | $1^{--}$ | $D\bar{D}$, $(e^+e^-)$ | *BABAR* 2007 |
| $Y(4008)$ | $4008^{+121}_{-49}$ | $226\pm97$ | $1^{--}$ | $J/\psi\,\pi^+\pi^-$, $(e^+e^-)$ | Belle 2007 |
| $Y(4140)$ | $4144.5\pm2.6$ | $15^{+11}_{-7}$ | $?^{?+}$ | $J/\psi\,\phi$ | CDF 2009 |
| $X(4160)$ | $4156^{+29}_{-25}$ | $139^{+113}_{-65}$ | $?^{?+}$ | $D^*\bar{D}^*$ | Belle 2007 |
| $Y(4220)$ | $4216\pm7$ | $39\pm17$ | $1^{--}$ | $h_c(1P)\,\pi^+\pi^-$, $(e^+e^-)$ | BESIII 2013 |
| $Y(4260)$ | $4263^{+8}_{-9}$ | $95\pm14$ | $1^{--}$ | $J/\psi\,\pi^+\pi^-$, $J/\psi\,\pi^0\pi^0$<br>$Z_c(3900)\,\pi$, $(e^+e^-)$ | *BABAR* 2005 |
| $Y(4274)$ | $4274.4^{+8.4}_{-6.7}$ | $32^{+22}_{-15}$ | $?^{?+}$ | $J/\psi\,\phi$ | CDF 2010 |
| $X(4350)$ | $4350.6^{+4.6}_{-5.1}$ | $13.3^{+18.4}_{-10.0}$ | $0/2^{++}$ | $J/\psi\,\phi$, $(\gamma\gamma)$ | Belle 2009 |
| $Y(4360)$ | $4361\pm13$ | $74\pm18$ | $1^{--}$ | $\psi(2S)\,\pi^+\pi^-$, $(e^+e^-)$ | *BABAR* 2007 |
| $X(4630)$ | $4634^{+9}_{-11}$ | $92^{+41}_{-32}$ | $1^{--}$ | $\Lambda_c^+\Lambda_c^-$, $(e^+e^-)$ | Belle 2007 |
| $Y(4660)$ | $4664\pm12$ | $48\pm15$ | $1^{--}$ | $\psi(2S)\,\pi^+\pi^-$, $(e^+e^-)$ | Belle 2007 |

# Z states

| State | $M$ (MeV) | $\Gamma$ (MeV) | $J^{PC}$ | Decay modes | 1[st] observation |
|---|---|---|---|---|---|
| $Z_c^+(3885)$ | $3883.9 \pm 4.5$ | $24.8 \pm 11.5$ | $1^{+?}$ | $D^{*+}\bar{D}^0,\ D^+\bar{D}^{*0}$ | BESIII 2013 |
| $Z_c^+(3900)$ | $3898 \pm 5$ | $51 \pm 19$ | $?^{?-}$ | $J/\psi\,\pi^+$ | BESIII 2013 |
| $Z_c^+(4020)$ | $4022.9 \pm 2.8$ | $7.9 \pm 3.7$ | $?^{?-}$ | $h_c(1P)\,\pi^+,\ D^{*+}\bar{D}^{*0}$ | BESIII 2013 |
| $Z_1^+(4050)$ | $4051^{+24}_{-43}$ | $82^{+51}_{-55}$ | $?^{?+}$ | $\chi_{c1}(1P)\,\pi^+$ | Belle 2008 |
| $Z_2^+(4250)$ | $4248^{+185}_{-\ 45}$ | $177^{+321}_{-\ 72}$ | $?^{?+}$ | $\chi_{c1}(1P)\,\pi^+$ | Belle 2008 |
| $Z^+(4430)$ | $4443^{+24}_{-18}$ | $107^{+113}_{-\ 71}$ | $1^{+-}$ | $\psi(2S)\,\pi^+$ | Belle 2007 |




From M. Kavatsyuk for BES, eQCD 2015



# X(3872)

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 quark-antiquark predictions)

Possibilities: tetraquark? a D-D* molecular state? It could arise due to mesonic loops as a companion pole. The starting seed state is a regular charm-anticharm object. Loops do the rest.

# Other unclarified states: open-charm sector

# $D^*_{s0}(2317)$

$D^*_{s0}(2317)$: too light to be a $c\bar{s}$ , $\bar{c}s$ quarkonium.

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

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

In arXiv: 1405.5861 we find that the quarkonium state
of 2.47 GeV and a very large width. Loop effects and companion pole?

# Summary

Confinement: hadrons

Mesons: not only quark-antiquark states.

Glueballs: the still missing link. They are yet to be found.

States beyond quark-antiquark: light scalar mesons amd related topics.

Region of charm-anticharm states: experimental proof of non-quarkonium states, but different models exist.

Thank You