HADRON PHYSICS
FROM NUCLEI TO QUARKS AND GLUONS

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OUR GROUP: LISBOA, ÉVORA, GRAZ, NEWPORT NEWS

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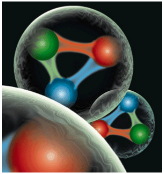
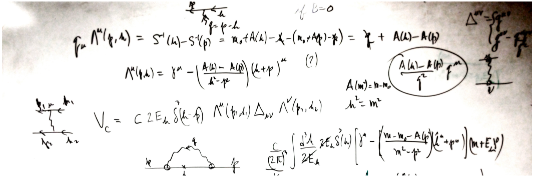
WHAT WE DO & WANT TO KNOW

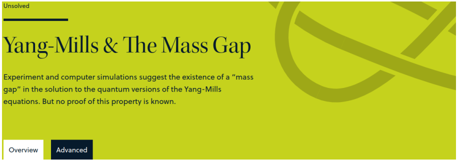
We investigate the **strong force** using quantum field theory





The 2 big questions:

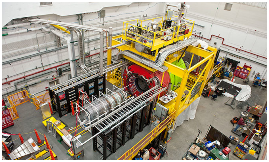
- Where does **98% of the mass** of ordinary matter come from?
- Origin of **confinement**?
  (*Millennium Prize Problem*: US \$1 million by Clay Mathematics Institute)



KEY EXPERIMENTS AND LABS

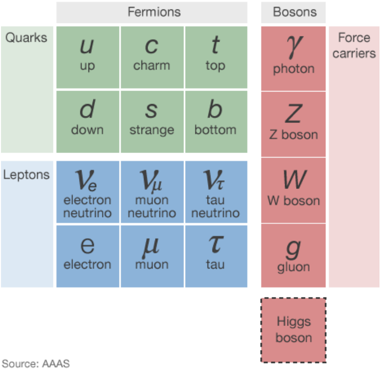
ALICE, LHCb, COMPASS (CERN), Switzerland
BaBar (Slac), USA
BELLE (KeK), Japan
BES Collab., China
CLEO (Cornell), USA
Hall-A and Hall-D (GlueX) (JLab), USA
J-PARC, Japan
NICA, Russia
PANDA (FAIR-GSI), Germany
RHIC, future EIC (Brookhaven NL), USA

Jefferson Lab

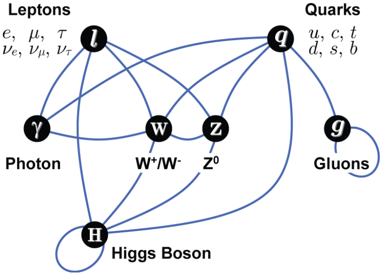


THE STANDARD MODEL

- **forces** (gauge bosons): electromagnetic (γ), weak ($W^{\pm}, Z^0$) and strong ($g_1 \dots g_8$)
- **matter** (fermions): quarks and leptons



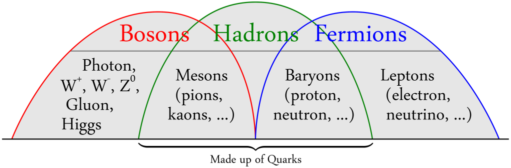
Source: AAAS



- leptons interact via $\gamma, W^{\pm}, Z^0$
- quarks interact via $\gamma, W^{\pm}, Z^0, g_1, \dots\dots g_8$
  $\Rightarrow$ only elementary particles that interact with all fundamental forces

STRONGLY-INTERACTING MATTER IN THE UNIVERSE

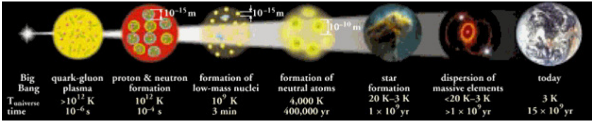
- quarks interacting strongly form bound states: **Hadrons**



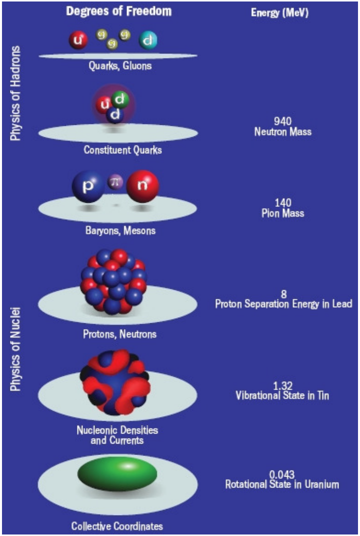
- residual interquark forces ≡ nuclear force (mesons) between neutrons & protons → bind to form **nuclei**
- scale of hadron physics

$\sim 1\ \mathrm{fm} = 0.000\,000\,000\,000\,001\ \mathrm{m}$!

Evolution of the Universe



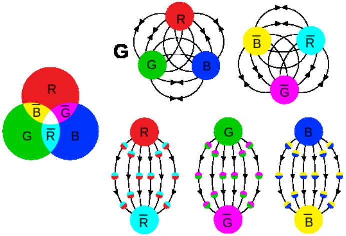
Strong interaction at different scales



Courtesy of SciDAC Review magazine

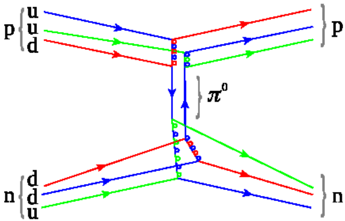
QUARK MODEL AND QCD

- mesons: quark-antiquark, baryons: 3 quarks
- Δ^{++}: 3-quark wave function $\psi_{3q} = \psi_{\text{space}}\psi_{\text{spin}}\psi_{\text{flavour}}$ not antisymmetric $\Rightarrow$ need additional degree of freedom: **color** charge **Red**, **Green**, **Blue**: **R+G+B=White**
- hadrons only observed as white, colour-neutral (colour singlets)



$\Rightarrow$ **Quantum ChromoDynamics (QCD)** as fundamental theory of strong interaction

- Nuclear force $\equiv q\bar{q}$ exchange



QUARK MODEL HADRONS

Particle Data Group (2023)

$q\bar{q}$ mesons

LIGHT UNFLAVORED ($S = C = B = 0$)

	$I^G(J^{PC})$		$I^G(J^{PC})$
• $\pi^\pm$	$1^-(0^-)$	• $\rho_3(1690)$	$1^+(3^{--})$
• π^0	$1^-(0^{-+})$	• $\rho(1700)$	$1^+(1^{--})$
• η	$0^+(0^{-+})$	• $a_2(1700)$	$1^-(2^{++})$
• $f_0(500)$	$0^+(0^{++})$	$a_0(1710)$	$1^-(0^{++})$
• $\rho(770)$	$1^+(1^{--})$	• $f_0(1710)$	$0^+(0^{++})$
• $\omega(782)$	$0^-(1^{--})$	$X(1750)$	$?^-(1^{--})$
• $\eta'(958)$	$0^+(0^{-+})$	$\eta(1760)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$	$f_0(1770)$	$0^+(0^{++})$
• $a_0(980)$	$1^-(0^{++})$	• $\pi(1800)$	$1^-(0^{-+})$
• $\phi(1020)$	$0^-(1^{--})$	$f_2(1810)$	$0^+(2^{++})$
• $h_1(1170)$	$0^-(1^{+-})$	$X(1835)$	$?^?(0^{-+})$
• $b_1(1235)$	$1^+(1^{+-})$	• $\phi_3(1850)$	$0^-(3^{--})$
• $a_1(1260)$	$1^-(1^{++})$	$\eta_1(1855)$	$0^+(1^{-+})$
• $f_2(1270)$	$0^+(2^{++})$	• $\eta_2(1870)$	$0^+(2^{-+})$
• $f_1(1285)$	$0^+(1^{++})$	• $\pi_2(1880)$	$1^-(2^{-+})$
• $\eta(1295)$	$0^+(0^{-+})$	$\rho(1900)$	$1^+(1^{--})$
• $\pi(1300)$	$1^-(0^{-+})$	$f_2(1910)$	$0^+(2^{++})$
• $a_2(1320)$	$1^-(2^{++})$	$a_0(1950)$	$1^-(0^{++})$
• $f_0(1370)$	$0^+(0^{++})$	• $f_2(1950)$	$0^+(2^{++})$
• $\pi_1(1400)$	$1^-(1^{-+})$	• $a_4(1970)$	$1^-(4^{++})$
• $\eta(1405)$	$0^+(0^{-+})$	$\rho_3(1990)$	$1^+(3^{--})$
• $h_1(1415)$	$0^-(1^{+-})$	$\pi_2(2005)$	$1^-(2^{-+})$
• $f_1(1420)$	$0^+(1^{++})$	• $f_2(2010)$	$0^+(2^{++})$
• $\omega(1420)$	$0^-(1^{--})$	• $f_0(2020)$	$0^+(0^{++})$
$f_2(1430)$	$0^+(2^{++})$	• $f_4(2050)$	$0^+(4^{++})$
• $a_0(1450)$	$1^-(0^{++})$	$\pi_2(2100)$	$1^-(2^{-+})$
• $\rho(1450)$	$1^+(1^{--})$	$f_0(2100)$	$0^+(0^{++})$
• $\eta(1475)$	$0^+(0^{-+})$	$f_2(2150)$	$0^+(2^{++})$
• $f_0(1500)$	$0^+(0^{++})$	$\rho(2150)$	$1^+(1^{--})$
$f_1(1510)$	$0^+(1^{++})$	• $\phi(2170)$	$0^-(1^{--})$
• $f_2'(1525)$	$0^+(2^{++})$	$f_0(2200)$	$0^+(0^{++})$
$f_2(1565)$	$0^+(2^{++})$	$f_J(2220)$	$0^+(2^{++}$ or $4^{++})$
$\rho(1570)$	$1^+(1^{--})$	$\eta(2225)$	$0^+(0^{-+})$
$h_1(1595)$	$0^-(1^{+-})$	$\rho_3(2250)$	$1^+(3^{--})$
• $\pi_1(1600)$	$1^-(1^{-+})$	• $f_2(2300)$	$0^+(2^{++})$
• $a_1(1640)$	$1^-(1^{++})$	$f_4(2300)$	$0^+(4^{++})$
$f_2(1640)$	$0^+(2^{++})$	$f_0(2330)$	$0^+(0^{++})$
• $\eta_2(1645)$	$0^+(2^{-+})$	• $f_2(2340)$	$0^+(2^{++})$
• $\omega(1650)$	$0^-(1^{--})$	$\rho_5(2350)$	$1^+(5^{--})$
• $\omega_3(1670)$	$0^-(3^{--})$	$X(2370)$	$?^?(?^{??})$
• $\pi_2(1670)$	$1^-(2^{-+})$	$f_0(2470)$	$0^+(0^{++})$
• $\phi(1680)$	$0^-(1^{--})$	$f_6(2510)$	$0^+(6^{++})$

STRANGE ($S = \pm1$, $C = B = 0$)

	$I(J^P)$
• $K^\pm$	$1/2(0^-)$
• K^0	$1/2(0^-)$
• K^0_S	$1/2(0^-)$
• K^0_L	$1/2(0^-)$
• $K_0^*(700)$	$1/2(0^+)$
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K_0^*(1430)$	$1/2(0^+)$
• $K_2^*(1430)$	$1/2(2^+)$
• $K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
$K(1630)$	$1/2(?^?)$
• $K_1(1650)$	$1/2(1^+)$
• $K^*(1680)$	$1/2(1^-)$
• $K_2(1770)$	$1/2(2^-)$
• $K_3^*(1780)$	$1/2(3^-)$
• $K_2(1820)$	$1/2(2^-)$
$K(1830)$	$1/2(0^-)$
$K_0^*(1950)$	$1/2(0^+)$
• $K_2^*(1980)$	$1/2(2^+)$
• $K_4^*(2045)$	$1/2(4^+)$
$K_2(2250)$	$1/2(2^-)$
$K_3(2320)$	$1/2(3^+)$
$K_5^*(2380)$	$1/2(5^-)$
$K_4(2500)$	$1/2(4^-)$
$K(3100)$	$?^?(?^{??})$

CHARMED ($C = \pm1$)

	$I(J^P)$
• $D^\pm$	$1/2(0^-)$
• D^0	$1/2(0^-)$
• $D^*(2007)^0$	$1/2(1^-)$
• $D^*(2010)^\pm$	$1/2(1^-)$
• $D_0^*(2300)$	$1/2(0^+)$
• $D_1(2420)$	$1/2(1^+)$
• $D_1(2430)^0$	$1/2(1^+)$
• $D_2^*(2460)$	$1/2(2^+)$
$D_0(2550)^0$	$1/2(0^-)$
$D_1^*(2600)^0$	$1/2(1^-)$
$D^*(2640)^\pm$	$1/2(?^?)$
$D_2(2740)^0$	$1/2(2^-)$
• $D_3^*(2750)$	$1/2(3^-)$
$D_1^*(2760)^0$	$1/2(1^-)$
$D(3000)^0$	$1/2(?^?)$

CHARMED, STRANGE ($C = \pm1$, $S = \pm1$)

	$I(J^P)$
• $D_s^\pm$	$0(0^-)$
• $D_s^{*\pm}$	$0(?^?)$
• $D_{s0}^*(2317)^\pm$	$0(0^+)$
• $D_{s1}(2460)^\pm$	$0(1^+)$
• $D_{s1}(2536)^\pm$	$0(1^+)$
• $D_{s2}^*(2573)$	$0(2^+)$
$D_{s0}(2590)^+$	$0(0^-)$
• $D_{s1}^*(2700)^\pm$	$0(1^-)$
$D_{s1}^*(2860)^\pm$	$0(1^-)$
• $D_{s3}^*(2860)^\pm$	$0(3^-)$
$D_{sJ}(3040)^\pm$	$0(?^?)$

BOTTOM ($B = \pm1$)

	$I(J^P)$
• $B^\pm$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• $B^\pm/B^0$ ADMIXTURE	
• $B^\pm/B^0/B^0_s/b$-baryon ADMIXTURE	
V_{cb} and V_{ub} CKM Matrix Elements	
• B^*	$1/2(1^-)$
• $B_1(5721)$	$1/2(1^+)$
$B_J^*(5732)$	$?(?^?)$
• $B_2^*(5747)$	$1/2(2^+)$
$B_J(5840)$	$1/2(?^?)$
• $B_J(5970)$	$1/2(?^?)$

BOTTOM, STRANGE ($B = \pm1$, $S = \mp1$)

	$I(J^P)$
• B^0_s	$0(0^-)$
• B^*_s	$0(1^-)$
• $B_{s1}(5830)^0$	$0(1^+)$
• $B_{s2}^*(5840)^0$	$0(2^+)$
$B_{sJ}^*(5850)$	$?(?^?)$
$B_{sJ}(6063)^0$	$0(?^?)$
$B_{sJ}(6114)^0$	$0(?^?)$

BOTTOM, CHARMED ($B = C = \pm1$)

	$I(J^P)$
• B_c^+	$0(0^-)$
• $B_c(2S)^\pm$	$0(0^-)$

$c\bar{c}$

	$I^G(J^{PC})$
• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
• $h_c(1P)$	$0^-(1^{+-})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
• $\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$0^-(1^{--})$
• $\psi_2(3823)$	$0^-(2^{--})$
• $\psi_3(3842)$	$0^-(3^{--})$
$\chi_{c0}(3860)$	$0^+(0^{++})$
• $\chi_{c1}(3872)$	$0^+(1^{++})$
• $\chi_{c0}(3915)$	$0^+(0^{++})$

$c\bar{c}$ continued

	$I^G(J^{PC})$
• $\chi_{c2}(3930)$	$0^+(2^{++})$
$X(3940)$	$?^?(?^{??})$
• $\psi(4040)$	$0^-(1^{--})$
• $\chi_{c1}(4140)$	$0^+(1^{++})$
• $\psi(4160)$	$0^-(1^{--})$
$X(4160)$	$?^?(?^{??})$
• $\psi(4230)$	$0^-(1^{--})$
• $\chi_{c1}(4274)$	$0^+(1^{++})$
$X(4350)$	$0^+(?^{?+})$
• $\psi(4360)$	$0^-(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$
$\chi_{c0}(4500)$	$0^+(0^{++})$
$X(4630)$	$0^+(?^{?+})$
• $\psi(4660)$	$0^-(1^{--})$
$\chi_{c1}(4685)$	$0^+(1^{++})$
$\chi_{c0}(4700)$	$0^+(0^{++})$

$b\bar{b}$

	$I^G(J^{PC})$
• $\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $h_b(1P)$	$0^-(1^{+-})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
$\eta_b(2S)$	$0^+(0^{-+})$
• $\Upsilon(2S)$	$0^-(1^{--})$
• $\Upsilon_2(1D)$	$0^-(2^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$
• $\chi_{b1}(2P)$	$0^+(1^{++})$
• $h_b(2P)$	$0^-(1^{+-})$
• $\chi_{b2}(2P)$	$0^+(2^{++})$
• $\Upsilon(3S)$	$0^-(1^{--})$
• $\chi_{b1}(3P)$	$0^+(1^{++})$
• $\chi_{b2}(3P)$	$0^+(2^{++})$
• $\Upsilon(4S)$	$0^-(1^{--})$
$\Upsilon(10753)$	$?^?(1^{--})$
• $\Upsilon(10860)$	$0^-(1^{--})$
• $\Upsilon(11020)$	$0^-(1^{--})$

OTHER

	$I^G(J^{PC})$
$X_0(2900)$	$?(0^+)$
$X_1(2900)$	$?(1^-)$
$T_{cc}(3875)^+$	$?(?^?)$
• $Z_c(3900)$	$1^+(1^{+-})$
$Z_{cs}(4000)$	$1/2(1^+)$
• $X(4020)^\pm$	$1^+(?^{?-})$
$X(4050)^\pm$	$1^-(?^{?+})$
$X(4055)^\pm$	$1^+(?^{?-})$
$X(4100)^\pm$	$1^-(?^{??})$
$Z_c(4200)$	$1^+(1^{+-})$
$Z_{cs}(4220)^+$	$1/2(1^+)$
$R_{c0}(4240)$	$1^+(0^{--})$
$X(4250)^\pm$	$1^-(?^{?+})$
• $Z_c(4430)$	$1^+(1^{+-})$
$X(5568)^\pm$	$?(?^?)$
$X(6900)$	$?^{??}$
• $Z_b(10610)$	$1^+(1^{+-})$
• $Z_b(10650)$	$1^+(1^{+-})$
Further States	

qqq baryons

p	$1/2^+$	****
n	$1/2^+$	****
$N(1440)$	$1/2^+$	****
$N(1520)$	$3/2^-$	****
$N(1535)$	$1/2^-$	****
$N(1650)$	$1/2^-$	****
$N(1675)$	$5/2^-$	****
$N(1680)$	$5/2^+$	****
$N(1700)$	$3/2^-$	***
$N(1710)$	$1/2^+$	****
$N(1720)$	$3/2^+$	****
$N(1860)$	$5/2^+$	**
$N(1875)$	$3/2^-$	***
$N(1880)$	$1/2^+$	***
$N(1895)$	$1/2^-$	****
$N(1900)$	$3/2^+$	****
$N(1990)$	$7/2^+$	**
$N(2000)$	$5/2^+$	**
$N(2040)$	$3/2^+$	*
$N(2060)$	$5/2^-$	***
$N(2100)$	$1/2^+$	***
$N(2120)$	$3/2^-$	***
$N(2190)$	$7/2^-$	****
$N(2220)$	$9/2^+$	****
$N(2250)$	$9/2^-$	****
$N(2300)$	$1/2^+$	**
$N(2570)$	$5/2^-$	**
$N(2600)$	$11/2^-$	***
$N(2700)$	$13/2^+$	**

$\Delta(1232)$	$3/2^+$	****
$\Delta(1600)$	$3/2^+$	****
$\Delta(1620)$	$1/2^-$	****
$\Delta(1700)$	$3/2^-$	****
$\Delta(1750)$	$1/2^+$	*
$\Delta(1900)$	$1/2^-$	***
$\Delta(1905)$	$5/2^+$	****
$\Delta(1910)$	$1/2^+$	****
$\Delta(1920)$	$3/2^+$	***
$\Delta(1930)$	$5/2^-$	***
$\Delta(1940)$	$3/2^-$	**
$\Delta(1950)$	$7/2^+$	****
$\Delta(2000)$	$5/2^+$	**
$\Delta(2150)$	$1/2^-$	*
$\Delta(2200)$	$7/2^-$	***
$\Delta(2300)$	$9/2^+$	**
$\Delta(2350)$	$5/2^-$	*
$\Delta(2390)$	$7/2^+$	*
$\Delta(2400)$	$9/2^-$	**
$\Delta(2420)$	$11/2^+$	****
$\Delta(2750)$	$13/2^-$	**
$\Delta(2950)$	$15/2^+$	**
Λ	$1/2^+$	****
$\Lambda(1380)$	$1/2^-$	**
$\Lambda(1405)$	$1/2^-$	****
$\Lambda(1520)$	$3/2^-$	****
$\Lambda(1600)$	$1/2^+$	****
$\Lambda(1670)$	$1/2^-$	****
$\Lambda(1690)$	$3/2^-$	****
$\Lambda(1710)$	$1/2^+$	*
$\Lambda(1800)$	$1/2^-$	***
$\Lambda(1810)$	$1/2^+$	***
$\Lambda(1820)$	$5/2^+$	****
$\Lambda(1830)$	$5/2^-$	****
$\Lambda(1890)$	$3/2^+$	****
$\Lambda(2000)$	$1/2^-$	*
$\Lambda(2050)$	$3/2^-$	*
$\Lambda(2070)$	$3/2^+$	*
$\Lambda(2080)$	$5/2^-$	*
$\Lambda(2085)$	$7/2^+$	**
$\Lambda(2100)$	$7/2^-$	****
$\Lambda(2110)$	$5/2^+$	***
$\Lambda(2325)$	$3/2^-$	*
$\Lambda(2350)$	$9/2^+$	***
$\Lambda(2585)$		*

Σ^+	$1/2^+$	****
Σ^0	$1/2^+$	****
Σ^-	$1/2^+$	****
$\Sigma(1385)$	$3/2^+$	****
$\Sigma(1580)$	$3/2^-$	*
$\Sigma(1620)$	$1/2^-$	*
$\Sigma(1660)$	$1/2^+$	***
$\Sigma(1670)$	$3/2^-$	****
$\Sigma(1750)$	$1/2^-$	***
$\Sigma(1775)$	$5/2^-$	****
$\Sigma(1780)$	$3/2^+$	*
$\Sigma(1880)$	$1/2^+$	**
$\Sigma(1900)$	$1/2^-$	**
$\Sigma(1910)$	$3/2^-$	***
$\Sigma(1915)$	$5/2^+$	****
$\Sigma(1940)$	$3/2^+$	*
$\Sigma(2010)$	$3/2^-$	*
$\Sigma(2030)$	$7/2^+$	****
$\Sigma(2070)$	$5/2^+$	*
$\Sigma(2080)$	$3/2^+$	*
$\Sigma(2100)$	$7/2^-$	*
$\Sigma(2110)$	$1/2^-$	*
$\Sigma(2230)$	$3/2^+$	*
$\Sigma(2250)$		**
$\Sigma(2455)$		*
$\Sigma(2620)$		*
$\Sigma(3000)$		*
$\Sigma(3170)$		*
Ξ^0	$1/2^+$	****
Ξ^-	$1/2^+$	****
$\Xi(1530)$	$3/2^+$	****
$\Xi(1620)$		*
$\Xi(1690)$		***
$\Xi(1820)$	$3/2^-$	***
$\Xi(1950)$		***
$\Xi(2030)$	$\geq \frac{5}{2}?$	***
$\Xi(2120)$		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*
Ω^-	$3/2^+$	****
$\Omega(2012)^-$	$?^-$	***
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**

Λ_c^+	$1/2^+$	****
$\Lambda_c(2595)^+$	$1/2^-$	***
$\Lambda_c(2625)^+$	$3/2^-$	***
$\Lambda_c(2765)^+$		*
$\Lambda_c(2860)^+$	$3/2^+$	***
$\Lambda_c(2880)^+$	$5/2^+$	***
$\Lambda_c(2940)^+$	$3/2^-$	***
$\Sigma_c(2455)$	$1/2^+$	****
$\Sigma_c(2520)$	$3/2^+$	***
$\Sigma_c(2800)$		***
Ξ_c^+	$1/2^+$	***
Ξ_c^0	$1/2^+$	****
$\Xi_c'^+$	$1/2^+$	***
$\Xi_c'^0$	$1/2^+$	***
$\Xi_c(2645)$	$3/2^+$	***
$\Xi_c(2790)$	$1/2^-$	***
$\Xi_c(2815)$	$3/2^-$	***
$\Xi_c(2923)$		**
$\Xi_c(2930)$		**
$\Xi_c(2970)$	$1/2^+$	***
$\Xi_c(3055)$		***
$\Xi_c(3080)$		***
$\Xi_c(3123)$		*
Ω_c^0	$1/2^+$	***
$\Omega_c(2770)^0$	$3/2^+$	***
$\Omega_c(3000)^0$		***
$\Omega_c(3050)^0$		***
$\Omega_c(3065)^0$		***
$\Omega_c(3090)^0$		***
$\Omega_c(3120)^0$		***
Ξ_{cc}^+		*
Ξ_{cc}^{++}		***

Λ_b^0	$1/2^+$	***
$\Lambda_b(5912)^0$	$1/2^-$	***
$\Lambda_b(5920)^0$	$3/2^-$	***
$\Lambda_b(6070)^0$	$1/2^+$	***
$\Lambda_b(6146)^0$	$3/2^+$	***
$\Lambda_b(6152)^0$	$5/2^+$	***
Σ_b	$1/2^+$	***
Σ_b^*	$3/2^+$	***
$\Sigma_b(6097)^+$		***
$\Sigma_b(6097)^-$		***
Ξ_b^-	$1/2^+$	***
Ξ_b^0	$1/2^+$	***
$\Xi_b'(5935)^-$	$1/2^+$	***
$\Xi_b(5945)^0$	$3/2^+$	***
$\Xi_b(5955)^-$	$3/2^+$	***
$\Xi_b(6100)^-$	$3/2^-$	***
$\Xi_b(6227)^-$		***
$\Xi_b(6227)^0$		***
$\Xi_b(6327)^0$		***
$\Xi_b(6333)^0$		***
Ω_b^-	$1/2^+$	***
$\Omega_b(6316)^-$		***
$\Omega_b(6330)^-$		***
$\Omega_b(6340)^-$		***
$\Omega_b(6350)^-$		***
$P_c(4312)^+$		*
$P_c(4380)^+$		*
$P_c(4440)^+$		*
$P_c(4457)^+$		*

CLASSIFICATION (MESONS, NON-RELATIVISTICALLY)

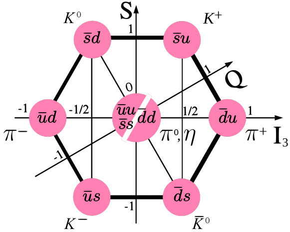
- **total angular momentum** $\vec{J} = \vec{L} + \vec{S}$, orbital $\vec{L} = \vec{r} \times \vec{p}$, spin $\vec{S} = \vec{s}_q + \vec{s}_{\bar{q}}$
  $|L - S| \leq J \leq L + S = 0, 1, 2, \ldots, \quad S = 0, 1$
- **parity** $\mathcal{P} = \underbrace{(-1)^L}_{\text{angular}} \underbrace{(-1)}_{\text{intrinsic}} = (-1)^{L+1}$
- **charge conjugation** $\mathcal{C} = \underbrace{(-1)^L}_{\text{angular}} \underbrace{(-1)^{S+1}}_{\text{spin}} \underbrace{(-1)}_{q \leftrightarrow \bar{q}} = (-1)^{L+S}$
- G**-parity** $\mathcal{G} = (-1)^{I+L+S}$

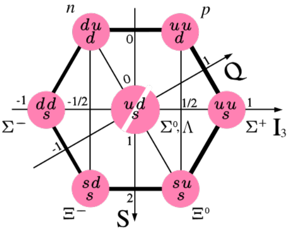
Meson		$J^{\mathcal{PC}}$	L	S	$^{2S+1}L_J$
Pseudoscalar	P	0^{-+}	0	0	$^1S_0$
Scalar	S	0^{++}	1	1	$^3P_0$
Vector	V	1^{--}	0, 2	1	$^3S_1$, $^3D_1$
Pseudovector	A^-	1^{+-}	1	0	$^1P_1$
Axial-Vector	A^+	1^{++}	1	1	$^3P_1$
Tensor	T	2^{-+}	2	0	$^1D_2$
Tensor	T	2^{--}	2	1	$^3D_2$
Tensor	T	2^{++}	1, 3	1	$^3P_2$, $^3F_2$

- example 1: Pseudoscalar, $\mathcal{P} = - \Rightarrow L = 0, \cancel{2}, \cancel{4} \ldots, J = 0 \Leftrightarrow S = 0, \cancel{1} \Leftrightarrow \mathcal{C} = +$
- example 2: Vector, $\mathcal{P} = - \Rightarrow L = 0, 2, \cancel{4} \ldots, J = 1 \Leftrightarrow S = \cancel{0}, 1 \Leftrightarrow \mathcal{C} = -$

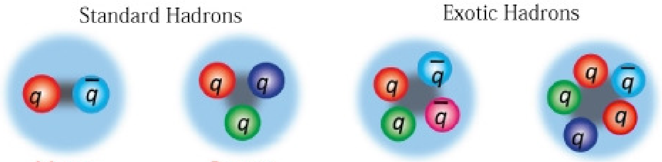
FLAVOR MULTIPLETS AND EXOTICS

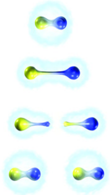
- form $q\bar{q}$ and qqq combinations from u, d, and s (anti-)quarks $\Rightarrow$ **flavour multiplets**
  e.g. pseudoscalar meson ($J = 0$) nonet and baryon ($J = \frac{1}{2}$) octet



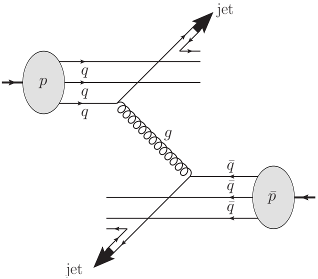


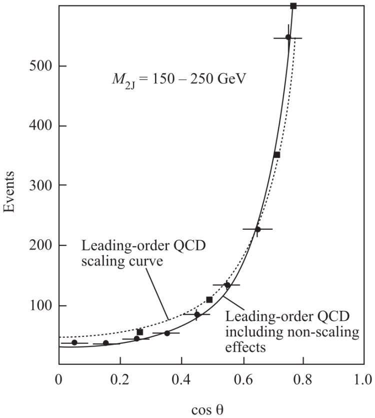
- other color-singlet combinations: **exotic** mesons and baryons
  tetraquarks ($qq\bar{q}\bar{q}$) ($\exists$ candidates),
  pentaquarks ($qqqq\bar{q}$) (**discovered** 2015 by LHCb @ CERN), etc...





- Try separate $q\bar{q}$
  BUT $\exists$ **confinement**: a single quark not observed as free isolated particle!
  $\rightarrow$ potential energy large enough to create $q\bar{q}$
  $\rightarrow$ hadronize
- p-$\bar{p}$ scattering $\rightarrow$ collimated **jets** of hadrons
  angular distribution of 2-jet-events $\sim$ "$\sin^{-4}\theta/2$-formula"
  $\Rightarrow V \sim 1/r \equiv$ massless boson – the **gluon**!





QCD LAGRANGEAN

$$\mathcal{L}_{\text{QCD}} = \underbrace{\bar{\psi} i \gamma^{\mu} (\partial_{\mu} - i g A_{\mu}^{a} t^{a}) \psi}_{\not{D}\text{-term; quark-gluon}} \underbrace{- m_0 \bar{\psi} \psi}_{\text{quark mass term}} \underbrace{- \frac{1}{4} F_{\mu\nu}^{a} F^{a\mu\nu}}_{\text{gluon kinetic term}}$$

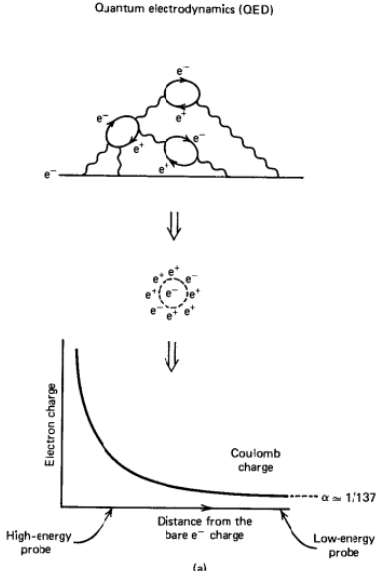
- spinor for color-triplet quarks

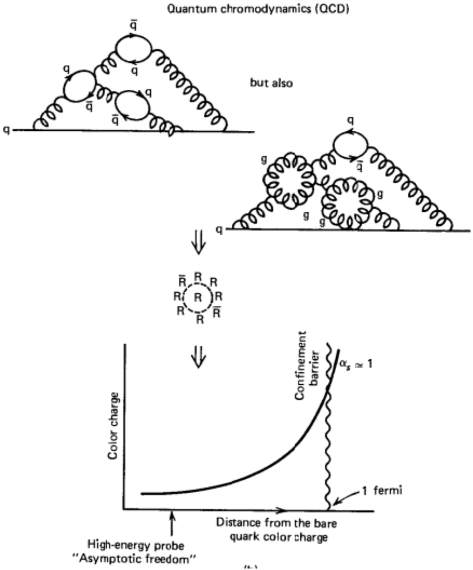
$$\psi = \begin{pmatrix} q_R \\ q_G \\ q_B \end{pmatrix}$$

- A_{μ}^{a} are 8 gluon fields ($a = 1, \ldots, 8$)
- **non-Abelian** field-strength tensor $F_{\mu\nu}^{a} = \partial_{\nu} A_{\mu}^{a} - \partial_{\mu} A_{\nu}^{a} + g f^{abc} A_{\mu}^{b} A_{\nu}^{c}$

three- and four-gluon **self interactions**!

CHARGE SCREENING: QED vs. QCD



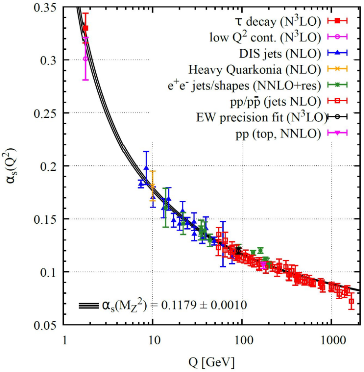


taken from Halzen, Martin, Quarks and Leptons, 1984

RUNNING COUPLING

- Anti-screening in QCD ⇒ strong "running" coupling $\alpha_s \equiv g^2/4\pi$ becomes small at short distances (large momentum transfer)
- at high energies, quarks behave as free particles: **asymptotic freedom** ⇒ perturbation theory ✓

  Gross, Wilczek and Politzer PRL 30, 1973; 't Hooft, 1972
- at short distances: quarks exchange massless gluons ⇒ **Coulomb**-type $1/r$-term present in static QCD potential for heavy quarks



- at large distance coupling becomes strong: cannot isolate quark ⇔ **Confinement**!

LINEAR CONFINEMENT

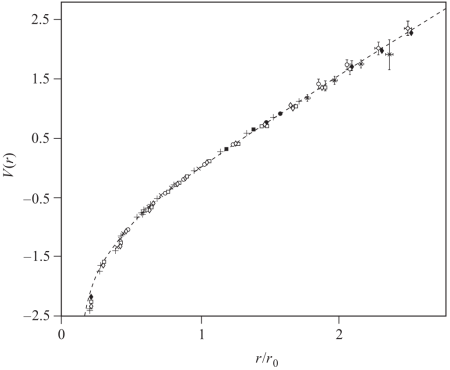
- confinement cannot be obtained from finite number of gluon exchanges ⇒ **non-perturbative** treatment necessary: e.g. lattice QCD, continuum models
- (non-relativistic) 'Cornell' $q\bar{q}$ potential

  EICHTEN *et al* PRD 17, 1978,0 and 21, 1980; RICHARDSON PLB 82, 1979

  $V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \sigma r + C$

  color factor $\frac{4}{3}$ ↪ *Hands-on Hadrons I*

- ✓ **good** quantum mechanical description of $c\bar{c}$ and $b\bar{b}$
  ↪ *Hands-on Hadrons II*
- $\sigma = 0.85$ GeV/fm: ≃ constant force of **14 tonnes!**
- light mesons require **relativistic** treatment
  e.g. "relativized" quark models:
  GODFREY, ISGUR PRD 32, 1985
  ✓ **good** description of meson spectrum
  × **not** Poincaré covariant
  × **not** based on quantum field theory



ALLTON *et al*, UKQCD Collab., PRD 65, 2002

QUARK AND PION MASSES

- confinement: single quark not observed as free isolated particle
  $\Rightarrow$ how to define their mass?
- nucleon mass $m_{\mathrm{N}} = 939$ MeV
  $\Rightarrow$ effective (constituent) quark mass $m_{u,d} \approx 300$ MeV
- questions

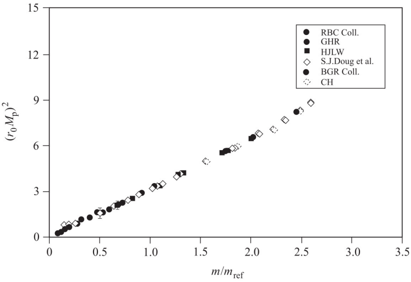
1. observe: pion $\pi^{\pm}$ (139 MeV) much lighter than the proton (938 MeV);
   Why is the pion so light?

2. (current) quark masses of Standard Model and $\mathcal{L}_{\mathrm{QCD}}$
   $m_u \approx 2$ MeV, $m_d \approx 5$ MeV
   Particle Data Group 2023
   current quarks $\overset{\textbf{connection?}}{\longleftrightarrow}$ constituent quarks?
   98% of $m_{\mathrm{N}} \Leftrightarrow$ most of the mass of ordinary matter in Universe!
   What mass-generating mechanism can explain this?

CHIRAL-SYMMETRY BREAKING

- If $m_u = m_d = 0$: $\mathcal{L}_{\text{QCD}}$ satisfies chiral symmetry
  $\Rightarrow$ there should be parity doublets in baryon spectrum
  BUT: **no parity doublets** observed!
  $\Leftrightarrow$ chiral symmetry must be **broken!**
- **spontaneous chiral-symmetry breaking**:
  - bulk of constituent quark masses **generated** by the strong interaction
  - appearance of 3 **massless Goldstone** bosons $\simeq$ 3 **pions** π^+, π^-, π^0

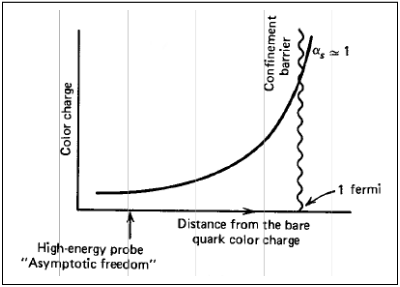
- m_u and m_d small
  $\Rightarrow$ physical pions anomalously light
- $m_\pi^2 \propto (m_u + m_d)$
  GASSER, LEUTWYLER, Phys.Rep. 87, 1982



GIUSTI, LATTICE 2002, hep-lat/0211009

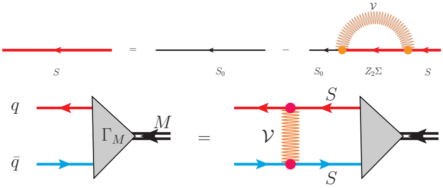
DESCRIPTION OF HADRONS

- strong coupling ‘constant’ α_s large at large distances
  $\Rightarrow$ perturbation theory **fails** ×
  scale $\sim$ **1 fm** $\sim$ size of hadron
- QCD bound-state problem **not yet** solved ×

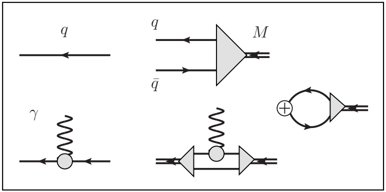


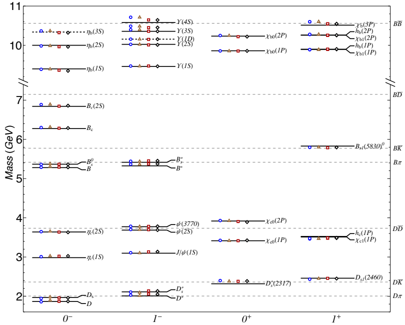
$\Rightarrow$ need effective non-perturbative tools based on QFT:

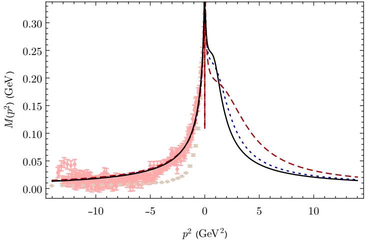
- **Covariant Spectator Theory** based on Gross equation
  F. Gross PR 186, 1969
- **Dyson-Schwinger** and **Bethe-Salpeter** equations

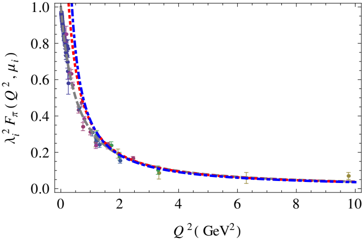


CURRENT RESEARCH









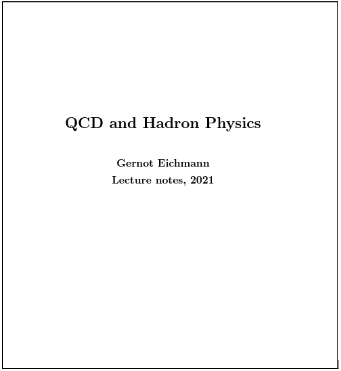
$\Rightarrow$ Learn about nature of **strong force** and **confinement**!

FURTHER INFORMATION

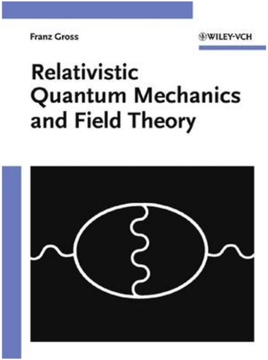
MEFT courses at Instituto Superior Técnico:

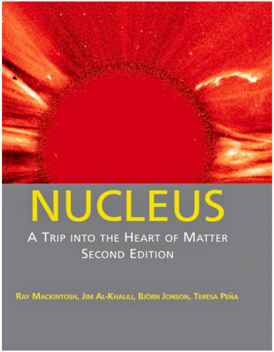
- **QCD and Hadron Physics** (2nd period)
  E.B., L. Apolinário (LIP)
- **Nuclear Physics** (1st period)
  E.B., T. Peña, A. Stadler, R. Silva (CTN), N. Catarino (CTN)

Literature for further reading:


QCD and Hadron Physics

Gernot Eichmann
Lecture notes, 2021





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https://doi.org/10.1140/epjc/s10052-023-11949-2

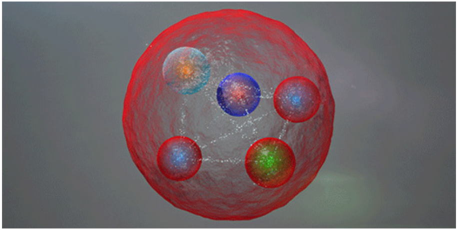
THE EUROPEAN PHYSICAL JOURNAL C

Review

50 Years of quantum chromodynamics

Introduction and Review

Pentaquark discovery in 2016!



THANK YOU!