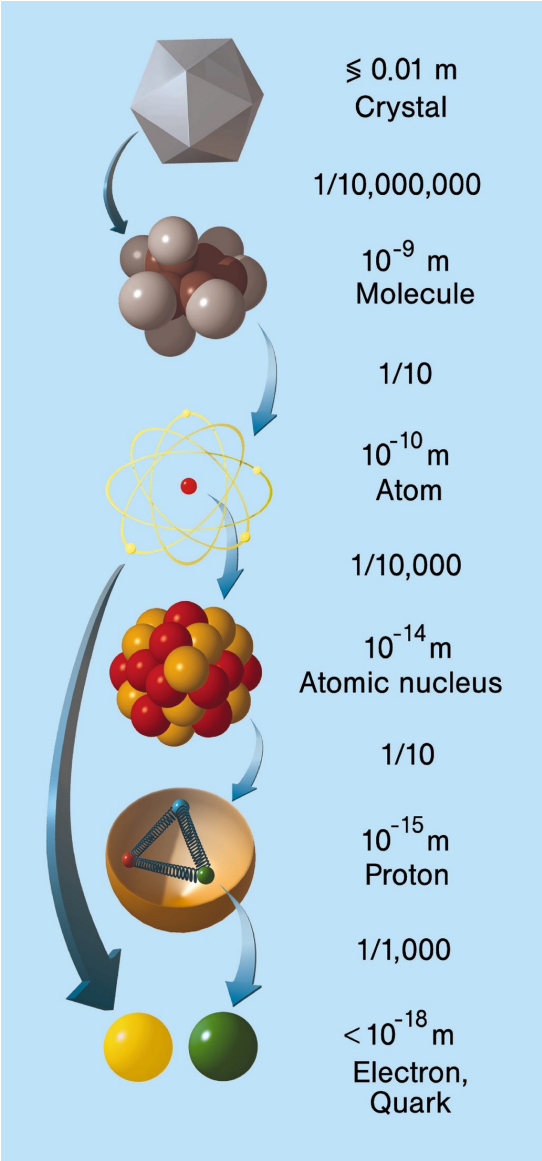
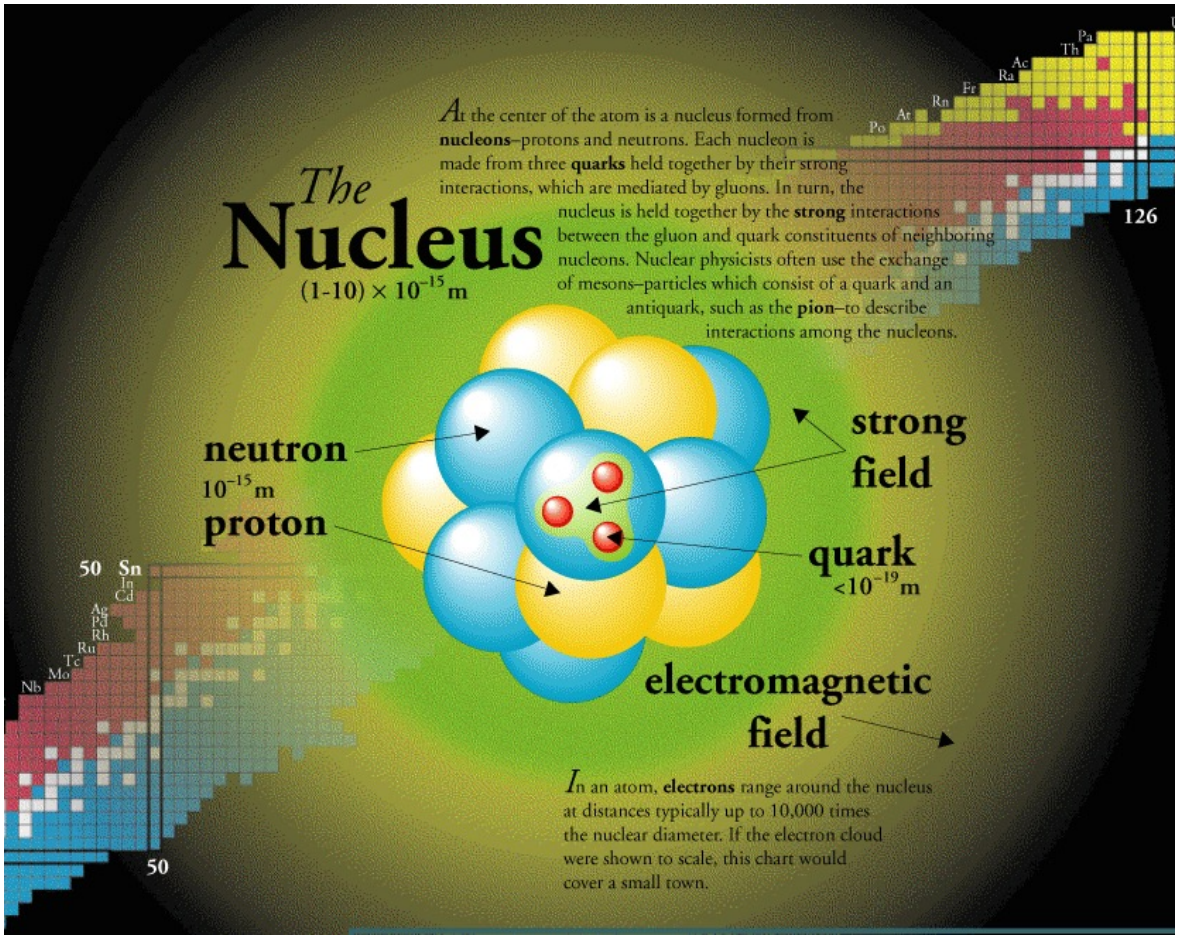
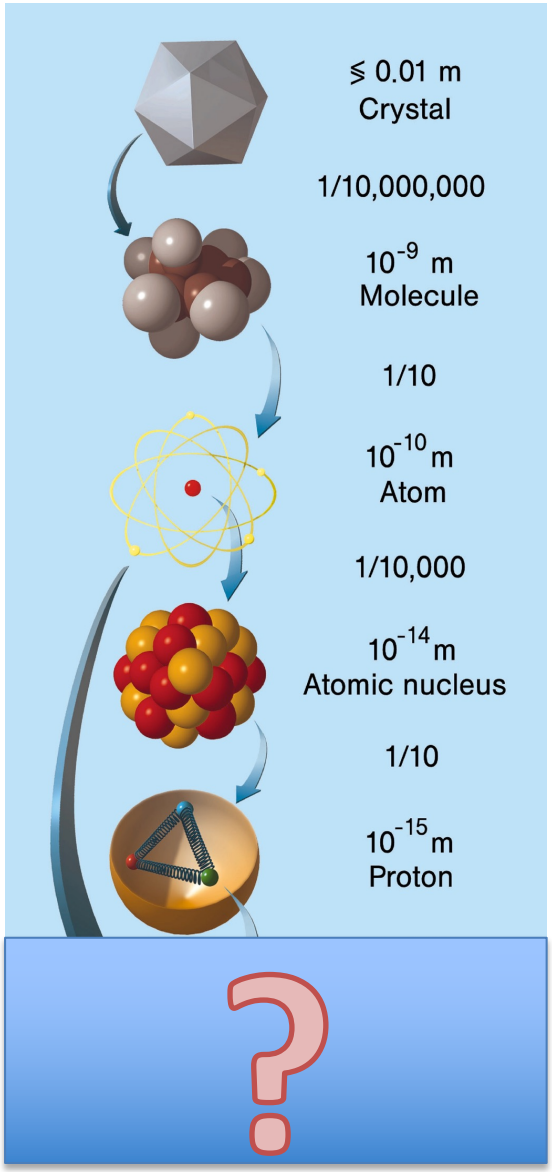
Quarks
and Hadron Structure

The Structure of Matter

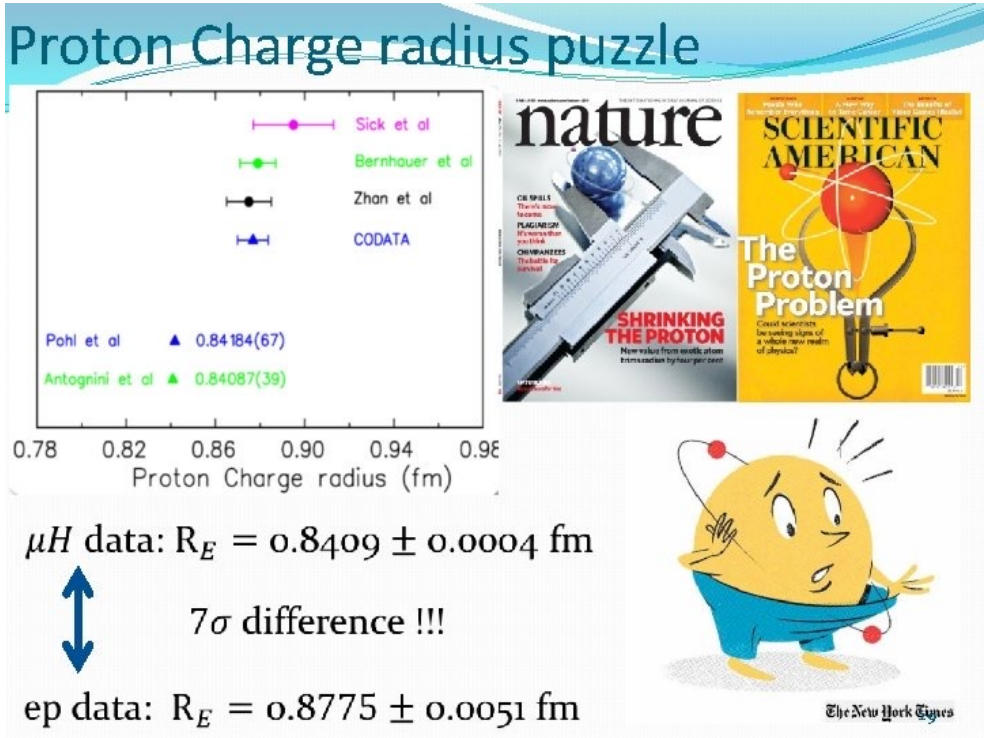




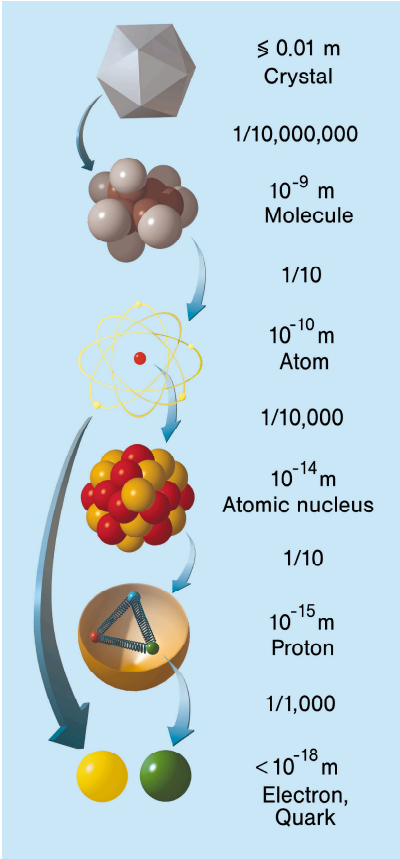
The Structure of Matter



The NucleON (and other hadronic matter)



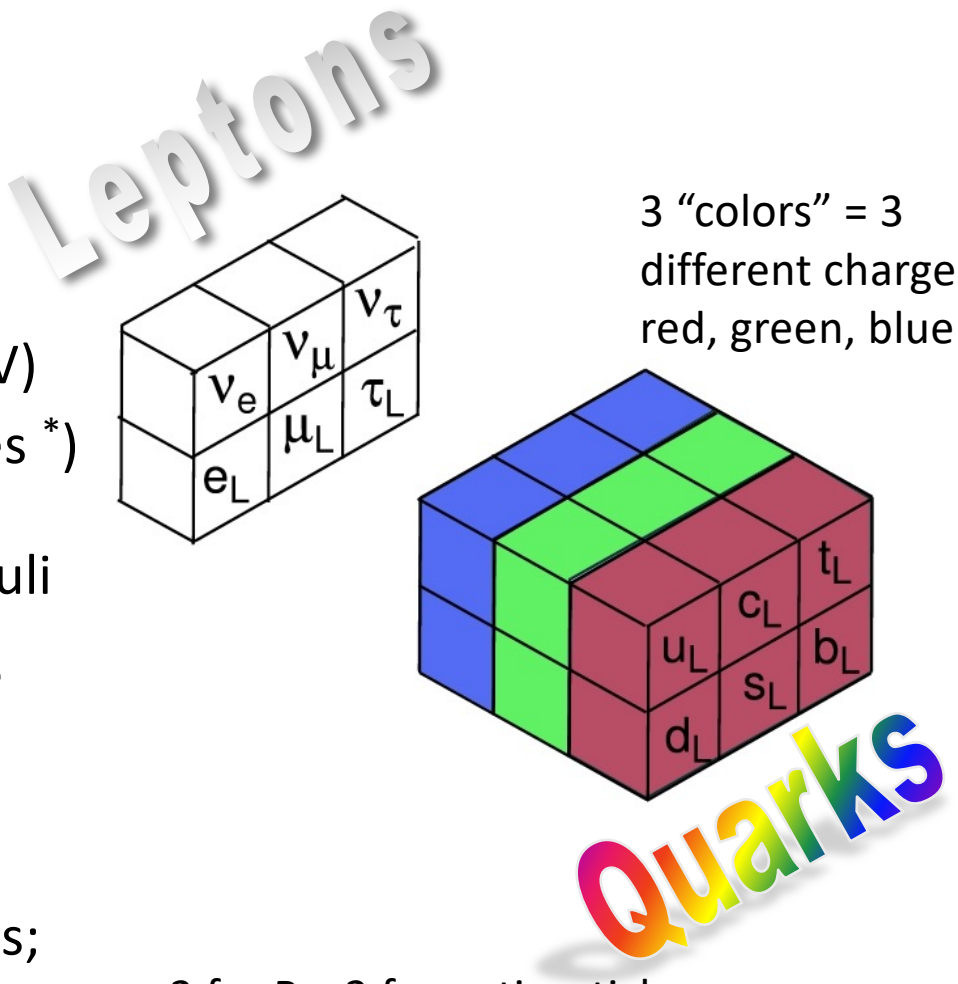
Elementary Particle Physics



- Everything (matter, waves,…) is ultimately composed of smallest units - particles!
- Have already encountered some particles: Protons, neutrons, electrons, positrons, neutrinos, photons,…
- First 2 are not fundamental - they are made from quarks which are truly point-like (as far as we know)
- Study particles at huge accelerators using big detectors; compare with fundamental theory

Matter Particles

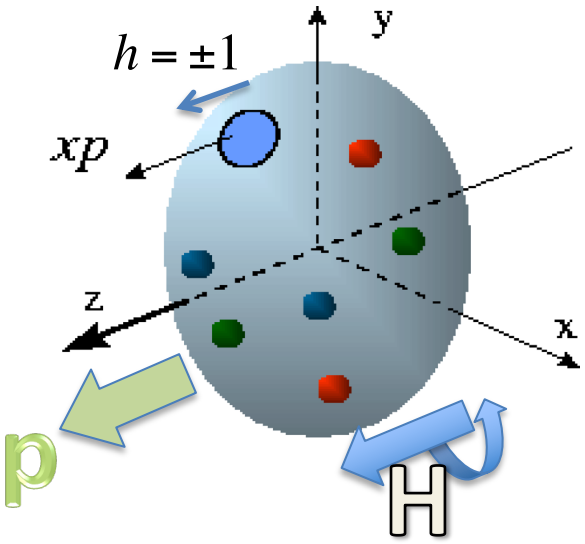
- Make up visible matter
- Pointlike (<10^{-18} m), Fundamental *)
- Have mass (from < ½ eV to 178,000,000,000 eV = 178 GeV)
- Distinct from their antiparticles *)
- Fermions (Spin ½) ⇒ they "defend" their space (Pauli Principle) and can only be created in particle-antiparticle pairs
- Can be "virtual", but make up matter being (nearly) "real"
- "stable" (against strong decays; lifetimes from ∞ to 10^{-24} s)



*) Until further notice

Inclusive lepton scattering

Parton model: DIS can access



$$q(x;Q^2), \langle h \cdot H \rangle q(x;Q^2)$$

Traditional "1-D" Parton Distributions (PDFs) (integrated over many variables)

Callan-Gross

Wandzura-Wilczek

$$F_1(x) = \tfrac{1}{2}\sum_i e_i^2 q_i(x) \quad \left(\text{and } F_2(x) \approx 2xF_1(x)\right)$$

$$g_1(x) = \tfrac{1}{2}\sum_i e_i^2 \Delta q_i(x) \quad \left(\text{and } g_2(x) \approx -g_1(x) + \int_x^1 \frac{g_1(y)}{y} dy\right)$$

At finite Q^2: pQCD evolution ($q(x,Q^2)$, $\Delta q(x,Q^2)$ ⇒ DGLAP equations), and gluon radiation

$$g_1(x,Q^2)_{pQCD} = \frac{1}{2}\sum_q^{N_f} e_q^2 [(\Delta q + \Delta\bar{q}) \otimes (1 + \frac{\alpha_s(Q^2)}{2\pi}\delta C_q) + \frac{\alpha_s(Q^2)}{2\pi}\Delta G \otimes \frac{\delta C_G}{N_f}]$$

⇒ access to gluons. $\delta C_q, \delta C_G$ – *Wilson* coefficient functions

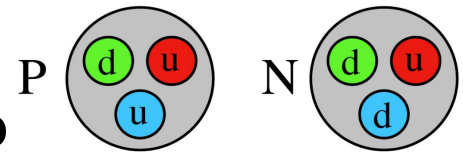
SIDIS: Tag the flavor of the struck quark with the leading FS hadron ⇒ separate $q_i(x,Q^2)$, $\Delta q_i(x,Q^2)$

Jefferson Lab kinematics: $Q^2 \approx M^2$ ⇒ target mass effects, higher twist contributions and resonance excitations

- Non-zero $R = \frac{F_2}{2xF_1}\left(\frac{4M^2x^2}{Q^2}+1\right)-1$, $g_2^{HT}(x) = g_2(x) - g_2^{WW}(x)$
- Further Q^2-dependence (power series in $\frac{1}{Q^n}$)

Hadronic Particle Zoo

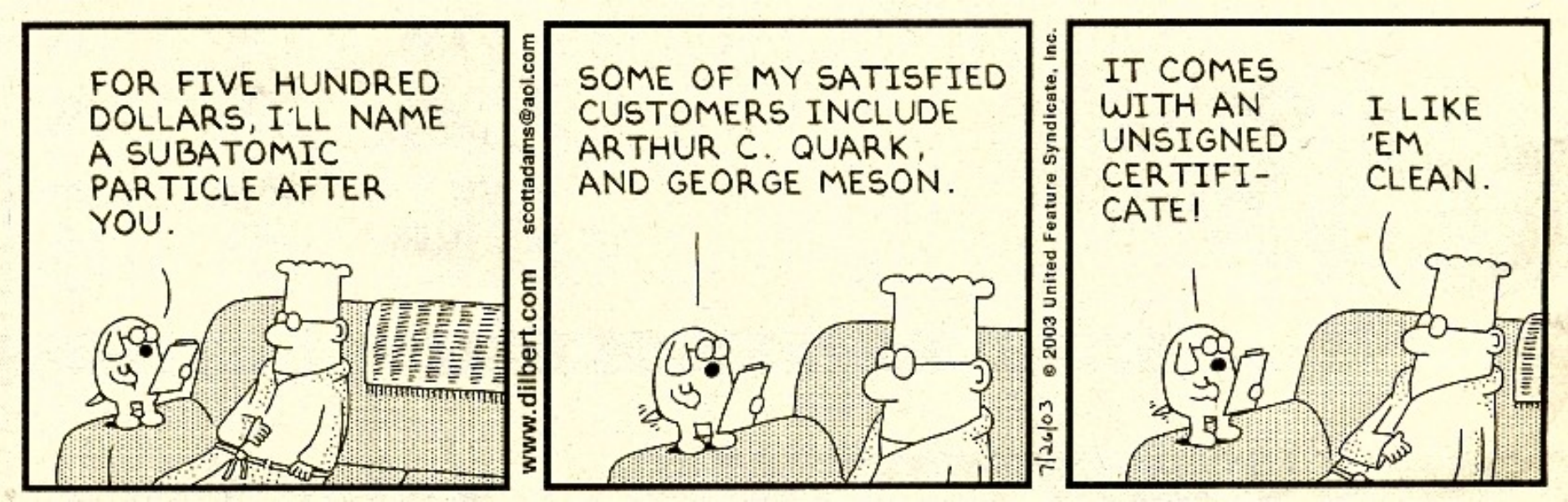
- what can one build from quarks?



HADRONS

Family Name	Particle Name	Particle Symbol	Antiparticle Symbol	Composition	Mass	Electric Charge	Lifetime in Seconds
baryon	proton	p or p^+	$\bar{p}$	uud	1,836	+1	stable
	neutron	n or n^0	$\bar{n}$	udd	1,839	0	887
	lambda	Λ^0	$\bar{\Lambda}^0$	uds	2,183	0	2.6×10^{-10}
	lambda-c	Λ_c^+	$\bar{\Lambda}_c^-$	udc	4,471	+1	2.1×10^{-13}
	lambda-b	Λ_b^0	$\bar{\Lambda}_b^0$	udb	11,000	0	1.1×10^{-12}
	sigma	Σ^+	$\bar{\Sigma}^+$	uus	2,328	+1	0.8×10^{-10}
		Σ^0	$\bar{\Sigma}^0$	$\frac{(ud \pm du)s}{\sqrt{2}}$	2,334	0	7.4×10^{-20}
		Σ^-	$\bar{\Sigma}^-$	dds	2,343	−1	1.5×10^{-10}
	xi	Ξ^0	$\bar{\Xi}^0$	uss	2,573	0	2.9×10^{-10}
		Ξ^-	$\bar{\Xi}^+$	dss	2,585	−1	1.6×10^{-10}
	xi-c	Ξ_c^0	$\bar{\Xi}_c^0$	dsc	4,834	0	9.8×10^{-14}
		Ξ_c^+	$\bar{\Xi}_c^-$	usc	4,826	+1	3.5×10^{-13}
	omega	Ω^-	Ω^+	sss	3,272	−1	0.8×10^{-10}
	omega-c	Ω_c^0	$\bar{\Omega}_c^0$	ssc	5,292	0	6.4×10^{-14}
meson	pion	π^+	π^-	$u\bar{d}$	273	+1	2.6×10^{-8}
		π^0	π^0	$\frac{(u\bar{u}-d\bar{d})}{\sqrt{2}}$	264	0	8.4×10^{-17}
	kaon*	K^+	K^-	$u\bar{s}$	966	+1	1.2×10^{-8}
		K^0	$\bar{K}^0$	$d\bar{s}$	974	0	8.9×10^{-11} 5.2×10^{-8}
	J/psi	J or Ψ	J or Ψ	$c\bar{c}$	6,060	0	1.0×10^{-20}
	omega	ω	ω	$\frac{(u\bar{u}+d\bar{d})}{\sqrt{2}}$	1,532	0	6.6×10^{-23}
	eta	η	η	$\frac{(u\bar{u}+d\bar{d})}{\sqrt{2}}$	1,071	0	3.5×10^{-22}
	eta-c	η_c	η_c	$c\bar{c}$	5,832	0	3.1×10^{-22}
	B	B^0	$\bar{B}^0$	$d\bar{b}$	10,331	0	1.6×10^{-12}
		B^+	B^-	$u\bar{b}$	10,331	+1	1.6×10^{-12}
	B-s	B_s^0	$\bar{B}_s^0$	$s\bar{b}$	10,507	0	1.6×10^{-12}
	D	D_0	$\bar{D}_0$	$c\bar{u}$	3,649	0	4.2×10^{-13}
		D^+	D^-	$c\bar{d}$	3,658	+1	1.1×10^{-12}
	D-s	D_s^+	D_s^-	$c\bar{s}$	3,852	+1	4.7×10^{-13}
	chi	χ_c^0	χ_c^0	$c\bar{c}$	6,687	0	3.0×10^{-22}
	psi	Ψ_c^0	Ψ_c^0	$c\bar{c}$	7,213	0	1.5×10^{-20}
	upsilon	Υ	Υ	$b\bar{b}$	18,513	0	8.0×10^{-21}

*The neutral kaon is composed of two particles; the average lifetime of each particle is given.



See also **http://particleadventure.org**