4/5/17 Lecture 2 outline

• Baryons, e.g. proton, neutron, other cousins, made up from 3 quarks.

• Mesons (Yukawa 1934) "holds nucleus together". Massive. Seen in cosmic rays. Now we know they're made up from 2 quarks.

Meson lifetimes, e.g. $\tau_{\pi^\pm} \sim 2.6 \times 10^{-8}s$, $\tau_{\pi^0} \sim 8.4 \times 10^{-17}s$.

• Muons (1946), seen in cosmic rays. Exactly like the electron, but much heavier. $m_e \sim .51MeV$, $m_\mu \sim 105.6MeV$, $\tau_\mu \sim 2.2 \times 10^{-6}$ seconds "long lived".

• Neutrinos. Massless or very light, neutral very weakly interacting. Pauli 1930 proposed it to recover energy and momentum conservation in beta decays.

• Beta decays: $n \to p^+ + e^- + \overline{\nu}$, and $\mu^- \to e^- + \nu_\mu + \bar{\nu}_e$. $\pi^- \to \mu^- + \overline{\nu}_\mu$.

• Strange particles, and new zoo of a new generation of particles.

All organized by the Standard Model.

• Relativity review: $x^{\mu'} = \Lambda^{\mu'}_\nu x^\nu$ and inverse. $ds^2 = ds'^2$ and metric. $ds^2 = c^2 d\tau^2$ for timelike. 4-vectors more generally. Examples: p^μ, k^μ, $u^\mu = dx^\mu/d\tau$, j^μ, $A^\mu = (\phi, \vec{A})$. Upper and lower indices, and 4-dot products, example of ∂_μ and conservation $\partial_\mu j^\mu = 0$. Invariance of d^4x and $j^0 d^3x$. (Some asides on $g_{\mu\nu}$ in GR vs $\eta_{\mu\nu}$ here.)

• $S = -mc^2 \int d\tau$ and L for relativistic particle. Relativistic charged particle $S \supset -(q/c) \int A_\mu dx^\mu$ and term in $L \supset -q\phi + (q/c)\vec{v} \cdot \vec{A}$. Canonical momentum $\vec{p} = \partial L/\partial \vec{v} = \gamma m\vec{v} - q\vec{A}/c$ and $H = \vec{p} \cdot \vec{v} - L = \gamma mc^2 - q\phi$ (magnetic fields do no work). But H should be expressed in terms of $\vec{p}$.

• QM: replace $\widehat{p}^\mu \to i\hbar\partial^\mu$ in position space. Consider the S.E.

• Punchline: in non-rel limit get $i\hbar D^0\psi = (\hbar^2/2m)\vec{D}^2\psi$, where $D^\mu \equiv (D^0, \vec{D}) = \partial^\mu - (q/i\hbar c)A^\mu$.

• Last time: Get $p^\mu \to p^\mu - (q/c)A^\mu$ when a charged particle is in an $\vec{E}$ and $\vec{B}$ field. For QM, $p^\mu \to i\hbar\partial^\mu$ in position space, so get e.g. $i\hbar D^0\psi = (-\hbar^2/2m)\vec{D}^2\psi$, where (punchline) $D^\mu \equiv (D^0, \vec{D}) = \partial^\mu - (q/i\hbar c)A^\mu$ is the covariant derivative.

• $S = \ldots - q/c \int A_\mu dx^\mu$ and gauge invariance.

• Gauge transformations $A_\mu \to A_\mu + \partial_\mu f(x)$, and local $U(1)$ phase rotation of $\psi \to e^{-iq/\hbar c}\psi$, with $D_\mu\psi \to e^{-iq/\hbar c}D_\mu\psi$.

• Path integral description of QM, solenoids and observability of flux inside. Dirac's magnetic monopoles and quantization rule.

• Klein Gordon theory, SHO, and charged Klein Gordon theory. Covariant derivatives and minimal substitution. Euler Lagrangian equations for field theory.

• $S = \int d^4x(-1/4)F_{\mu\nu}F^{\mu\nu} - j^\mu A_\mu/c$.

• Dirac equation and Lagrangian