4/3/17 Lecture 1 outline

• **Symmetries**. Noether's theorem. Examples, including rigid translations, rotations, general covariance, global $U(1)$s, gauge $U(1)$ and gauge invariance. Local symmetries and forces.

• A bit about QFT: usual rules of QM don't apply, particle creation and annihilation, quantize fields.

• Plot, with v/c and $\hbar/S$, with QFT in box. Started with Dirac, QM + relativity $\to$ antiparticles. E.g. $e^- + e^+ \to \gamma + \gamma$. Positron predicted in 1937, first observed in 1931.

• Periodic table of elements. Goal of "high energy" or "elementary particle physics" is to find the updated version, with basic building blocks of matter and interactions. From atoms to quarks and electrons.

• Subject in need of a better name. Elementary? Particles? Actually everything consists of quantum fields, e.g. quark field, electron field, photon field, etc. Observed particles (or waves) are ripples of these fields. Explains why all electrons are the same. Fields are specified by their gauge charges, including mass, spin, electric charge.

• Spin statistics and bosons and fermions. Particles vs waves.

• Energy scales. Atomic physics $\sim 1eV$, non-relativistic QM is a good approximation. Nuclear physics scale, e.g. MeV. Proton or neutron scale $\sim GeV$. Electroweak $\sim 100GeV$. LHC $\sim 10TeV = 10^{13}eV$.

• 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.

Lecture 1 ended here.

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