Yoshio Nishina
1890-1951

Hideki Yukawa
1907-1981

Sin-itiro Tomonaga
1906-1979
Ryogo Kubo 1920 - 1995
At Berkeley
Yukawa, Lawrence, Mrs. Yukawa, Serber
Brief history of particle physics since the 1930s

Neutron, positron
Cyclotron (Lawrence)
Beta decay theory
Meson theory (Yukawa)
Muon (second lepton)
*Pion (first meson)
QED and renormalization
*Non-Abelian gauge fields
*Various hadrons ($\rho, \omega$, etc.) and flavor symmetry
*Parity violation with $V - A$ weak interaction
*Chiral symmetry
*Spontaneous symmetry breaking and mass generation
*Quark model
Regge trajectories of hadrons
*Electroweak unification
Quark color and QCD
The standard model
  SU(3)xSU(2)xU(1) gauge fields,
  3 generations of quarks and leptons
Gregor Wentzel 1898-1978
Search for hadron internal symmetries

Flavor symmetry
  Isotopic spin SU(2) for (p,n), (π±, π⁰)
  SU(3) octet hadrons

Chiral symmetry (handedness)
  V - A weak interaction
  symmetry broken by fermion mass
  almost conserved axial vector current
  (PCAC, σ model)

Vector meson (ρ,ω) dominance ansatz

Colored quarks and color SU(3) gauge field (QCD)
The collective modes

Langmuir plasma
\[ \omega_P^2 = \frac{e^2 \rho}{m} \]
Debye screening
\[ e^{-\mu r/r}, \mu = \omega_P / \nu_T \]
Bohm and Pines
longitudinal and transverse
collective modes
Tomonaga effective theory for 1-D fermionic systems

London theory of superconductivity
\[ j = (1/\Lambda) \mathbf{A}, \quad 1/\Lambda = \omega_P \]

Simple transcription
\[ H = \int \psi^\dagger p^2/(2m) \psi + 1/2 \int \int' (\psi^\dagger \psi) V(\psi^\dagger \psi)' \]
\[ \psi, \psi^\dagger \to \rho^{1/2} \exp(\pm i \theta), \quad [\theta, \rho] = i \]
BCS theory
Cooper pairing and gap formation around the Fermi surface

Bogoliubov-Valatin quasiparticles
\[ \Psi = \alpha \psi_\uparrow + \beta \psi_\downarrow \] 
\[ H_{BV} = \Psi^\dagger (\tau_3 \epsilon + \tau_1 \Delta) \Psi, \quad \Psi = (\psi_\uparrow, \psi_\downarrow) \]

Collective modes
\[ \pi \sim \Psi_{\tau_2}^\dagger \pi, \quad m = 0 \quad \text{(NG)} \]
\[ \sigma \sim \Psi_{\tau_1}^\dagger \sigma, \quad m = 2\Delta \quad \text{(Higgs)} \]

London relation
\[ J = A/\Lambda \]

Conserved current
\[ J = \Psi^\dagger (p - \tau_3 eA) \Psi - \nabla \pi \]
\[ \rho = \Psi_{\tau_3}^\dagger \rho - (1/v^2) \pi \]
\[ v^2 = v_F^2/3 \]
\[ \partial \rho / \partial t + \nabla \cdot J = 0 \]
Chiral problem and nucleon mass generation

Chiral invariants

- vector, axial vector, (scalar, pseudoscalar)

→ SSB of chiral symmetry by mass scalar

\[ H_N = \Psi^\dagger (\rho_1 \sigma \cdot p + \rho_3 M + g \rho_2 \pi) \Psi \]

Chiral (axial) current

\[ j_{A \mu} = \Psi^\dagger (\rho_1, \sigma) \Psi, \]
\[ \partial \cdot j_A = -2M \Psi^\dagger \rho_2 \Psi, \]
\[ J_{A \mu} = j_{A \mu} - f \partial_\mu \pi \]
\[ f = 2M/g \] (Goldberger-Treiman)
\[ \partial \cdot J = f m_{\pi}^2 \] PCAC

Collective modes (mesons)

\[ \pi \quad \text{mass} \sim 0 \]
\[ \sigma \quad \text{mass} \ 2M \]

Quark model \( M_N \rightarrow M_q \ (\sim M_N/3) \)
General mass relations

<table>
<thead>
<tr>
<th>NG fermion “Higgs”</th>
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<tbody>
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<td>0     1     2</td>
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\( ^3 \text{He B} \)

\( \sigma \cdot p \)

\( \sigma \times p \)

\( \sigma_i p_k \)

\( \frac{2}{5}(2/5)^{1/2} \quad 1 \quad 2(3/5)^{1/2} \quad J=2 \)

\( m_1^2 + m_3^2 = 4m_2^2 \)

Quarks and Higgs mass relations?