Hadron Phenomenology and QCDs DSEs

Lecture 2: *The NJL model – from current to constituent quarks*

Ian Cloët

University of Adelaide & Argonne National Laboratory

Collaborators

Wolfgang Bentz – Tokai University

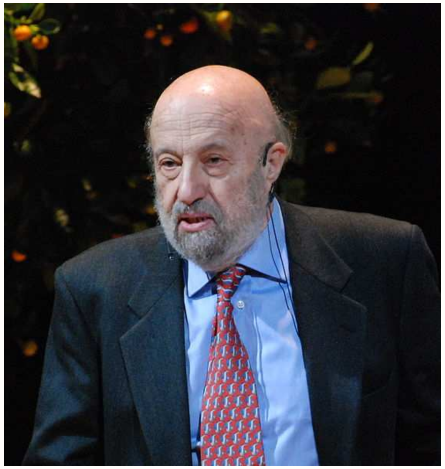
Craig Roberts – Argonne National Laboratory

Anthony Thomas – University of Adelaide

David Wilson – Argonne National Laboratory

USC Summer Academy on Non-Perturbative Physics, July–August 2012

The Nambu–Jona-Lasinio Model

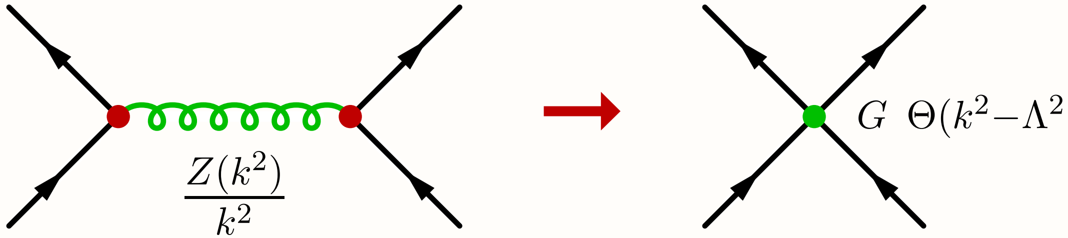


- The Nambu–Jona-Lasinio (NJL) Model was invented in 1961 by *Yoichiro Nambu* and *Giovanni Jona-Lasinio* while at The University of Chicago
  - was inspired by the BCS theory of superconductivity
  - was originally a theory of elementary nucleons
  - rediscovered in the 80s as an effective quark theory
- It is a relativistic quantum field theory, that is relatively easy to work with, and is very successful in the description of hadrons, nuclear matter, etc
- Nambu won half the 2008 Nobel prize in physics in part for the NJL model:

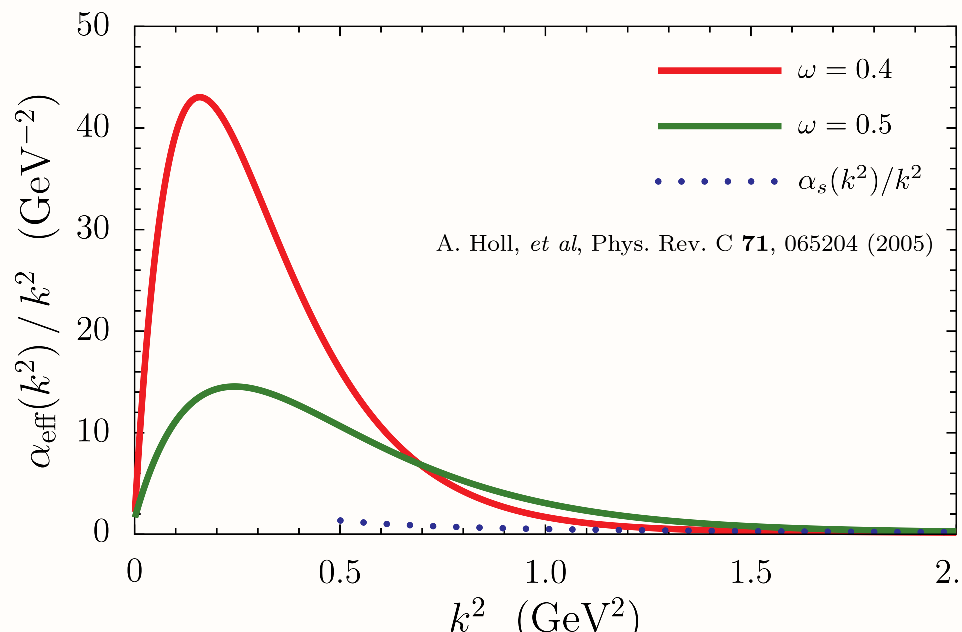
  "*for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics*" [Nobel Committee]

NJL Model

- NJL model is interpreted as low energy chiral effective theory of QCD



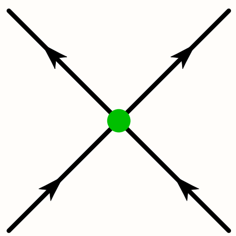
- Can be motivated by infrared enhancement of quark–gluon interaction
  e.g. DSEs and Lattice QCD



- Investigate the role of quark degrees of freedom
- NJL has same flavour symmetries as QCD
- NJL is non-renormalizable $\Longrightarrow$ cannot remove regularization parameter
- We will contrast NJL results with full DSE results

NJL Lagrangian

- In general the NJL Lagrangian has the form



$$\mathcal{L}_{NJL} = \mathcal{L}_0 + \mathcal{L}_I = \overline{\psi}\left(i\not{\partial} - m\right)\psi + \sum\nolimits_\alpha G_\alpha \left(\overline{\psi}\,\Gamma_\alpha\,\psi\right)^2$$

  - ✦ Γ_α represents a product of Dirac, colour and flavour matrices

- What about $\mathcal{L}_I$? – effective theories should maintain symmetries of QCD
- In chiral limit QCD Lagrangian has symmetries

$$\mathcal{S}_{QCD} = SU(3)_c \otimes SU(N_f)_V \otimes SU(N_f)_A \otimes U(1)_V \otimes U(1)_A \otimes \mathcal{C} \otimes \mathcal{P} \otimes \mathcal{T}$$

  - ✦ $SU(N_f)_A$ is broken dynamically – DCSB
  - ✦ $U(1)_A$ is broken in the anomalous mode – $U(1)$ problem – massive η'

- NJL interaction Lagrangian must respect the symmetries

$$\mathcal{S}_{NJL} = SU(3)_c \otimes SU(N_f)_V \otimes SU(N_f)_A \otimes U(1)_V \otimes \mathcal{C} \otimes \mathcal{P} \otimes \mathcal{T}$$

  - ✦ in NJL $SU(3)_c$ will be considered a global gauge symmetry
  - ✦ $U(1)_A$ is often broken explicitly $\Longrightarrow m_{\eta'} \neq 0$

NJL Lagrangian (2)

$$\mathcal{S}_{NJL} = SU(3)_c \otimes SU(N_f)_V \otimes SU(N_f)_A \otimes U(1)_V \otimes \mathcal{C} \otimes \mathcal{P} \otimes \mathcal{T}$$

- The NJL Lagrangian should be symmetric under the transformations

$$\begin{aligned}
SU(N_f)_V: &\quad \psi \longrightarrow e^{-i\,\boldsymbol{t}\cdot\boldsymbol{\theta_V}}\,\psi & \bar{\psi} \longrightarrow \bar{\psi}\,e^{i\,\boldsymbol{t}\cdot\boldsymbol{\theta_V}} \\
SU(N_f)_A: &\quad \psi \longrightarrow e^{-i\,\gamma_5\,\boldsymbol{t}\cdot\boldsymbol{\theta_A}}\,\psi & \bar{\psi} \longrightarrow \bar{\psi}\,e^{-i\,\gamma_5\,\boldsymbol{t}\cdot\boldsymbol{\theta_A}} \\
U(1)_V: &\quad \psi \longrightarrow e^{-i\,\theta}\,\psi & \bar{\psi} \longrightarrow \bar{\psi}\,e^{i\,\theta} \\
U(1)_A: &\quad \psi \longrightarrow e^{-i\,\gamma_5\,\theta}\,\psi & \bar{\psi} \longrightarrow \bar{\psi}\,e^{-i\,\gamma_5\,\theta}
\end{aligned}$$

- Nambu and Jona-Lasinio choose the Lagrangian

$$\mathcal{L} = \bar{\psi}\,(i\partial\!\!\!/ - m)\,\psi + G_\pi\left[(\bar{\psi}\psi)^2 - (\bar{\psi}\,\gamma_5\boldsymbol{\tau}\,\psi)^2\right]$$

- Can choose any combination of these $4-$fermion interactions

$$\begin{array}{lllll}
(\bar{\psi}\psi)^2, & (\bar{\psi}\,\gamma_5\,\psi)^2, & (\bar{\psi}\,\gamma^\mu\,\psi)^2 & (\bar{\psi}\,\gamma^\mu\gamma_5\,\psi)^2, & (\bar{\psi}\,i\sigma^{\mu\nu}\,\psi)^2, \\
(\bar{\psi}\,\boldsymbol{t}\,\psi)^2, & (\bar{\psi}\,\gamma_5\,\boldsymbol{t}\,\psi)^2, & (\bar{\psi}\,\gamma^\mu\,\boldsymbol{t}\,\psi)^2, & (\bar{\psi}\,\gamma^\mu\gamma_5\,\boldsymbol{t}\,\psi)^2, & (\bar{\psi}\,i\sigma^{\mu\nu}\,\boldsymbol{t}\,\psi)^2.
\end{array}$$

NJL Lagrangian (3)

- The most general $N_f = 2$ NJL Lagrangian that respects the symmetries is

$$\mathcal{L} = \bar{\psi}\,(i\partial\!\!\!/ - m)\,\psi + G_\pi\left[(\bar{\psi}\psi)^2 - (\bar{\psi}\,\gamma_5\boldsymbol{\tau}\,\psi)^2\right] + G_\omega\,(\bar{\psi}\,\gamma^\mu\,\psi)^2 + G_\rho\left[(\bar{\psi}\,\gamma^\mu\boldsymbol{\tau}\,\psi)^2 + (\bar{\psi}\,\gamma^\mu\gamma_5\boldsymbol{\tau}\,\psi)^2\right]$$
$$+G_h\,(\bar{\psi}\,\gamma^\mu\gamma_5\,\psi)^2 + G_\eta\left[(\bar{\psi}\,\gamma_5\,\psi)^2 - (\bar{\psi}\,\boldsymbol{\tau}\,\psi)^2\right] + G_T\left[(\bar{\psi}\,i\sigma^{\mu\nu}\psi)^2 - (\bar{\psi}\,i\sigma^{\mu\nu}\boldsymbol{\tau}\,\psi)^2\right]$$

- ✦ $\mathcal{L}_I$ is $U(1)_A$ invariant if: $G_\pi = -G_\eta$ & $G_T = 0$

$$\begin{array}{rcccl}
\bar{\psi}\psi & \longleftrightarrow & \sigma & \longleftrightarrow & (J^P, T) = (0^+, 0) \\
\bar{\psi}\,\gamma_5\boldsymbol{\tau}\,\psi & \longleftrightarrow & \pi & \longleftrightarrow & (J^P, T) = (0^-, 1) \\
\bar{\psi}\,\gamma^\mu\,\psi & \longleftrightarrow & \omega & \longleftrightarrow & (J^P, T) = (1^-, 0) \\
\bar{\psi}\,\gamma^\mu\boldsymbol{\tau}\,\psi & \longleftrightarrow & \rho & \longleftrightarrow & (J^P, T) = (1^-, 1) \\
\bar{\psi}\,\gamma^\mu\gamma_5\,\psi & \longleftrightarrow & f_1, h_1 & \longleftrightarrow & (J^P, T) = (1^+, 0) \\
\bar{\psi}\,\gamma^\mu\gamma_5\boldsymbol{\tau}\,\psi & \longleftrightarrow & a_1 & \longleftrightarrow & (J^P, T) = (1^+, 1) \\
\bar{\psi}\boldsymbol{\tau}\psi & \longleftrightarrow & a_0 & \longleftrightarrow & (J^P, T) = (0^+, 1) \\
\bar{\psi}\,\gamma_5\,\psi & \longleftrightarrow & \eta, \eta' & \longleftrightarrow & (J^P, T) = (0^-, 0)
\end{array}$$

NJL Lagrangian (4)

- The most general $N_f = 2$ NJL Lagrangian that respects the symmetries is

$$\mathcal{L}_I = \tfrac{1}{2}\,G_\pi\left[(\bar\psi\psi)^2 - (\bar\psi\,\gamma_5\boldsymbol{\tau}\,\psi)^2\right] - \tfrac{1}{2}\,G_\omega\,(\bar\psi\,\gamma^\mu\,\psi)^2 - \tfrac{1}{2}\,G_\rho\left[(\bar\psi\,\gamma^\mu\boldsymbol{\tau}\,\psi)^2 - (\bar\psi\,\gamma^\mu\gamma_5\boldsymbol{\tau}\,\psi)^2\right]$$
$$+\tfrac{1}{2}\,G_f\,(\bar\psi\,\gamma^\mu\gamma_5\,\psi)^2 - \tfrac{1}{2}\,G_\eta\left[(\bar\psi\,\gamma_5\,\psi)^2 - (\bar\psi\,\boldsymbol{\tau}\,\psi)^2\right] - \tfrac{1}{2}\,G_T\left[(\bar\psi\,i\sigma^{\mu\nu}\psi)^2 - (\bar\psi\,i\sigma^{\mu\nu}\boldsymbol{\tau}\,\psi)^2\right]$$

  - ✦ $\mathcal{L}_I$ is $U(1)_A$ invariant if: $G_\pi = -G_\eta$ & $G_T = 0$

- The most general $N_f = 3$ NJL Lagrangian that respects the symmetries is

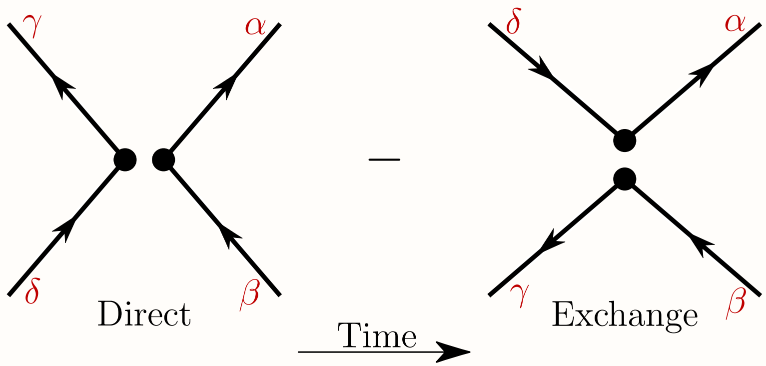
$$\mathcal{L}_I = G_\pi\left[\tfrac{1}{6}\,(\bar\psi\psi)^2 + (\bar\psi\,\boldsymbol{t}\,\psi)^2 - \tfrac{1}{6}\,(\bar\psi\,\gamma_5\,\psi)^2 - (\bar\psi\,\gamma_5\,\boldsymbol{t}\,\psi)^2\right]$$
$$-\frac{1}{2}\,G_\rho\left[(\bar\psi\,\gamma^\mu\,\boldsymbol{t}\,\psi)^2 + (\bar\psi\,\gamma^\mu\gamma_5\,\boldsymbol{t}\,\psi)^2\right] - \frac{1}{2}\,G_\omega\,(\bar\psi\,\gamma^\mu\,\psi)^2 - \frac{1}{2}\,G_f\,(\bar\psi\,\gamma^\mu\gamma_5\,\psi)^2$$

- Enlarging the $SU(N_f)_V \otimes SU(N_f)_A$ chiral group from $N_f = 2$ to $N_f = 3$ reduces the number of coupling from six to four
- The $N_f = 3$ Lagrangian is automatically $U(1)_A$ invariant
  - ✦ $U(1)_A$ is then often broken by the 't Hooft term – a 6-quark interaction

$$\mathcal{L}_I^{(6)} = K\left[\det\left(\bar\psi(1+\gamma_5)\psi\right) + \det\left(\bar\psi(1-\gamma_5)\psi\right)\right]$$

NJL Interaction Kernel

- Using Wick's theorem and the NJL Lagrangian their are 2 diagrams for the interaction between a quark and an anti-quark



$$2i\,G\left[\Omega^i_{\alpha\beta}\overline{\Omega}^i_{\gamma\delta} - \Omega^i_{\alpha\delta}\overline{\Omega}^i_{\gamma\beta}\right]$$

- Using Fierz transformations can express each *exchange term* as a sum of *direct terms*
- The $SU(2)$ NJL interaction kernel then takes the form

$$K_{\alpha\beta,\gamma\delta} = 2i\,G_\pi\left[(\mathbb{1})_{\alpha\beta}\,(\mathbb{1})_{\gamma\delta} - (\gamma_5\boldsymbol{\tau})_{\alpha\beta}\,(\gamma_5\boldsymbol{\tau})_{\gamma\delta}\right] - 2i\,G_\omega\,(\gamma_\mu)_{\alpha\beta}\,(\gamma^\mu)_{\gamma\delta}$$
$$- 2i\,G_\rho\left[(\gamma_\mu\boldsymbol{\tau})_{\alpha\beta}\,(\gamma^\mu\boldsymbol{\tau})_{\gamma\delta} + (\gamma_\mu\gamma_5\boldsymbol{\tau})_{\alpha\beta}\,(\gamma^\mu\gamma_5\boldsymbol{\tau})_{\gamma\delta}\right] + \ldots$$

- This kernel enters the NJL gap and meson Bethe-Salpeter equations

Regularization Schemes

- The NJL model is non-renormalizable $\Longrightarrow$ cannot remove regularization
  - ✦ regularization parameter(s) play a dynamical role

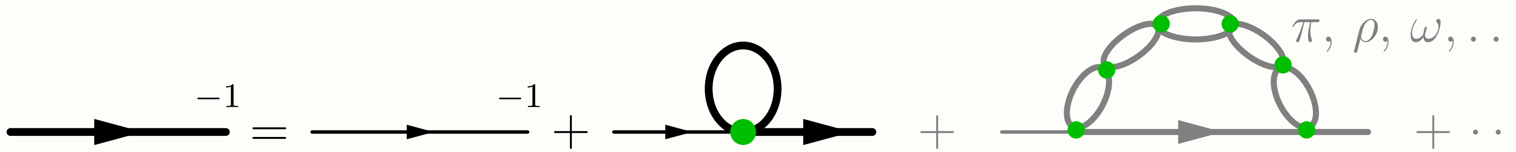
- Popular choices are:
  - ✦ 3-momentum cutoff: $\vec{p}^2 < \Lambda^2$
  - ✦ 4-momentum cutoff $p_E^2 < \Lambda^2$
  - ✦ Pauli-Villars, etc

- We will use the proper-time regularization scheme

$$\frac{1}{X^n} = \frac{1}{(n-1)!}\int_0^\infty d\tau\ \tau^{n-1}\, e^{-\tau\, X} \ \to\ \frac{1}{(n-1)!}\int_{1/\Lambda_{UV}^2}^{1/\Lambda_{IR}^2} d\tau\ \tau^{n-1}\, e^{-\tau\, X}$$

  - ✦ only Λ_{UV} is need to render the theory finite
  - ✦ however, as we shall see, Λ_{IR} plays a very important role; it prevents quarks going on their mass shell and hence simulates confinement

NJL Gap Equation



- The NJL gap equation has the form

$$S^{-1}(k) = S_0^{-1}(k) - \Sigma(k) = [\not{k} - m] - \sum_j \int \frac{d^4\ell}{(2\pi)^4} \mathrm{Tr}\left[S(\ell)\,\overline{\Omega}^j\right]\Omega^j$$

- The only piece of the interaction kernel that contributes is:

$$K^{\sigma}_{\alpha\beta,\gamma\delta} = 2i\,G_\pi\,(\mathbb{1})_{\gamma\delta}\,(\mathbb{1})_{\alpha\beta}$$

- Solving this equation give a quark propagator of the form

$$S^{-1}(k) = \not{k} - M + i\varepsilon$$

- The constituent quark mass satisfies the equation

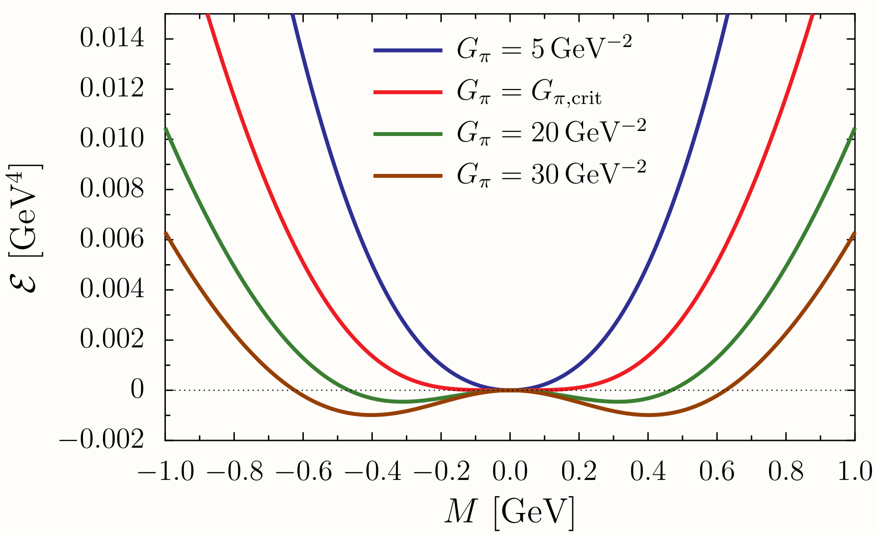
$$M = m + 48i\,G_\pi\,M \int \frac{d^4\ell}{(2\pi)^4}\,\frac{1}{\ell^2 - M^2 + i\varepsilon} = m + M\,\frac{3\,G_\pi}{\pi^2}\int d\tau\,\frac{e^{-\tau M^2}}{\tau^2}$$

NJL Gap Equation (2)

$$M = m + M\,\frac{3\,G_\pi}{\pi^2}\int d\tau\;\frac{e^{-\tau\,M^2}}{\tau^2}$$

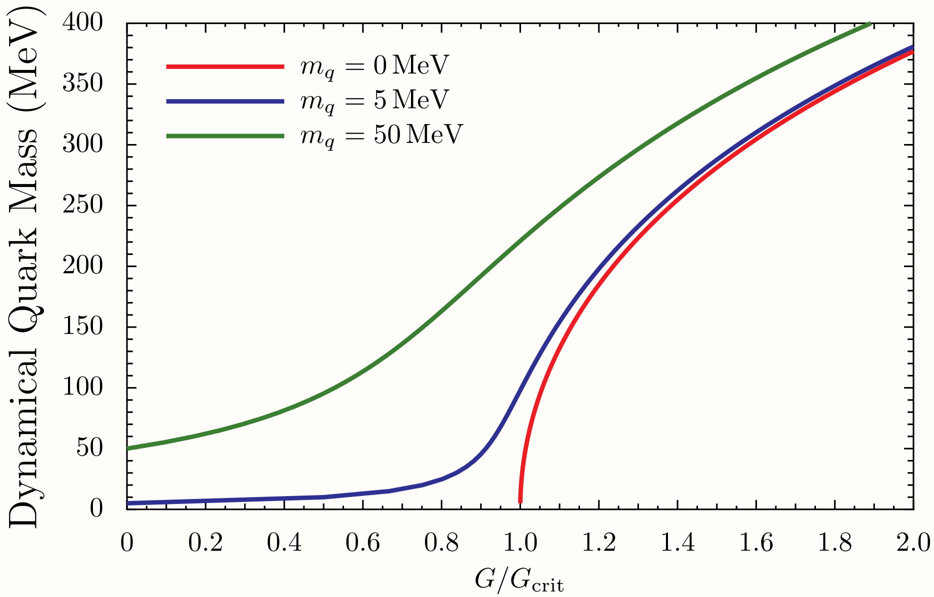
- For the case $m = 0$ the gap equation has two solutions:
  - ✦ trivial solution: $M = 0$ & non-trivial solution: $M \neq 0$
- Which solution does nature choose, that is, which solution minimizes the energy. Compare vacuum energy density, $\mathcal{E}$, for each case

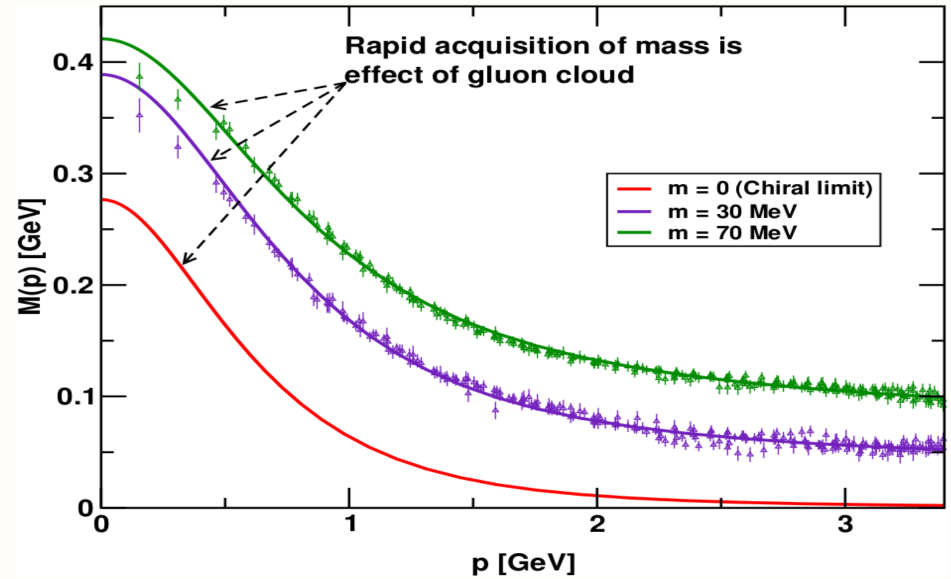
$$\mathcal{E}(M) - \mathcal{E}(M=0) = -\frac{3}{4\pi^2}\int d\tau\,\frac{1}{\tau^3}\left(e^{-\tau M^2} - 1\right) + \frac{M^2}{4\,G_\pi}$$



- For $G_\pi > G_{\pi,\text{crit}}$ the lowest energy solution has $M \neq 0$
- Therefore for $G_\pi > G_{\pi,\text{crit}}$ NJL has DCSB
- DCSB $\Longleftrightarrow$ generates mass from nothing

NJL & DSE gap equations





- NJL constituent mass is given by: $M = m - 2\,G_\pi \left<\bar{\psi}\psi\right>$
- Chiral condensate is defined by

$$\left<\bar{\psi}\psi\right> \equiv \lim_{x\to y} \mathrm{Tr}\left[-iS(x-y)\right] = -\int \frac{d^4k}{(2\pi)^4}\,\mathrm{Tr}\left[i\,S(k)\right]$$

- Mass is generated via interaction with vacuum
- Dynamically generated quark masses $\iff$ $\left<\bar{\psi}\psi\right> \neq 0$
- Difference in mass functions should have observable consequences!

Confinement in NJL model

- In general the NJL model is not confining; quark propagator is simply

$$S(k) = \frac{1}{\not{k} - M + i\varepsilon} = \frac{\not{k} + M}{k^2 - M^2 + i\varepsilon}$$

  - ✦ quark propagator has a pole $\Longrightarrow$ quarks are part of physical spectrum

- However the proper-time scheme is unique

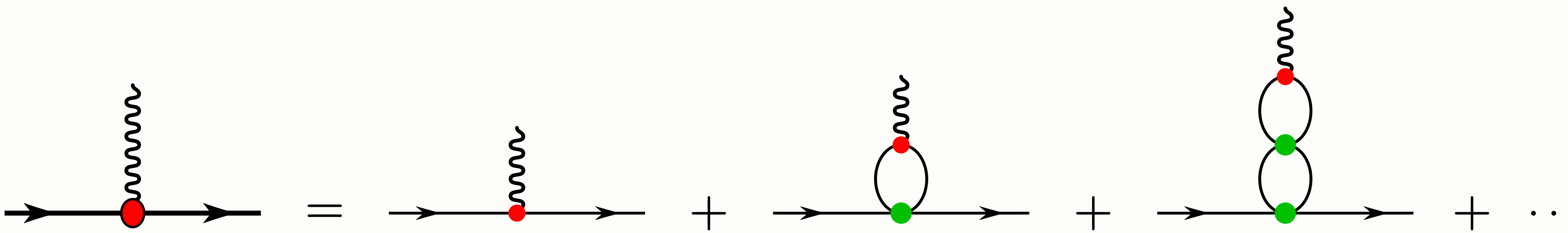
$$S(k) = \int_0^\infty d\tau\, (\not{k} + M)\, e^{-\tau\left(k^2 - M^2\right)} \to \underbrace{\frac{\left[e^{-\Lambda_{UV}(k^2-M^2)} - e^{-\Lambda_{IR}(k^2-M^2)}\right]}{k^2 - M^2}}_{\equiv Z(k^2)} [\not{k} + M]$$

- quark propagator does not have a pole: $Z(k^2) \stackrel{k^2 \to M^2}{=} \Lambda_{IR} - \Lambda_{UV} \neq \infty$

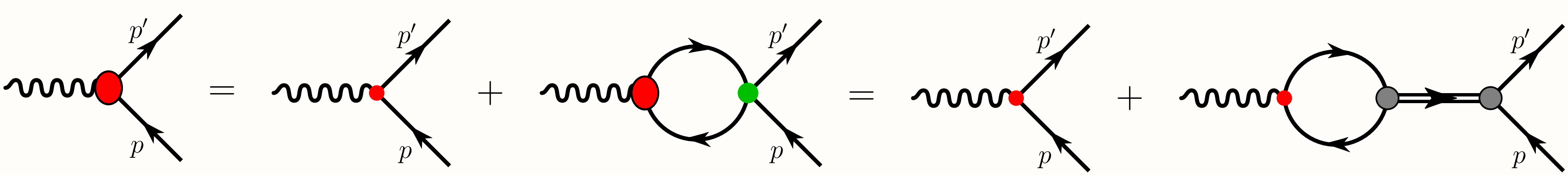
- Are confinement and DCSB related?
  - ✦ NJL model is proof that DCSB can exist without confinement
  - ✦ however their is no example of model with confinement and no DCSB!

From Current to Constituent Quarks

- Both the DSE and NJL gap equations take current quarks and dress them non-perturbatively so that they become constituent quarks
- Constituent quarks are extended non-trivial quasi-particles
- Consider an arbitrary current interacting with the current quarks



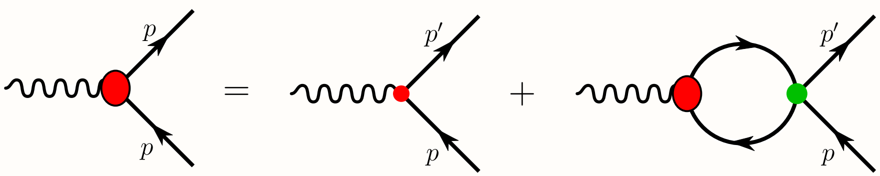
- This series can be represented by an integral equation

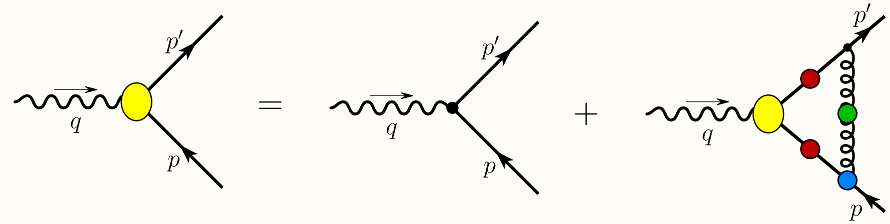


✦ *This is the inhomogeneous Bethe-Salpeter equation (BSE)*

Constituent Quark EM Form Factors

- The quark-photon vertex is given by the Bethe-Salpeter equation – where the driving term is an external vector current: $\gamma^\mu \left(\frac{1}{6} + \frac{\tau_3}{2}\right)$





- Lorentz covariance implies that the quark–photon vertex has the structure

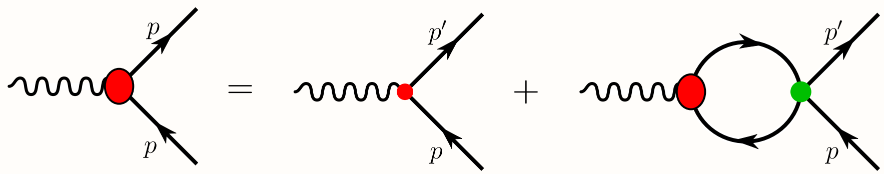
$$\Gamma^\mu_{\gamma qq}(p', p) = \sum_{i=1}^{12} \lambda_i^\mu \; f_i(p'^2, p^2, q^2) = \Gamma^\mu_L(p', p) + \Gamma^\mu_T(p', p)$$

- In QCD the properties of the quark–photon vertex are governed by the quark propagator and the quark–gluon vertex
- Ward-Takahashi identity constrains Γ^μ_L piece of quark–photon vertex

$$q_\mu \, \Gamma^\mu_{\gamma qq} = q_\mu \, \Gamma^\mu_L = \hat{Q} \left[S^{-1}(p') - S^{-1}(p)\right], \qquad q_\mu \, \Gamma^\mu_T = 0$$

- This BSE is difficult to solve in DSE framework, however in the NJL model it is straight forward

NJL Constituent Quark Form Factors



$$K_{\alpha\beta,\gamma\delta} = -\,2i\,G_\omega\,(\gamma_\mu)_{\alpha\beta}\,(\gamma^\mu)_{\gamma\delta} - 2i\,G_\rho\,(\gamma_\mu\boldsymbol{\tau})_{\alpha\beta}\,(\gamma^\mu\boldsymbol{\tau})_{\gamma\delta}$$

- In general the quark–photon vertex has form

$$\Gamma^\mu_{\gamma qq}(p',p) = \frac{1}{6}\,\Lambda^\mu_\omega(p',p) + \frac{\tau_3}{2}\,\Lambda^\mu_\rho(p',p).$$

- Recall Ward–Takahashi identity $\left[S^{-1}(p) = \not{p} - M + i\varepsilon\right]$

$$q_\mu\,\Gamma^\mu_{\gamma qq}(p',p) = \left(\frac{1}{6} + \frac{\tau_3}{2}\right)\left[S^{-1}(p') - S^{-1}(p)\right] \xrightarrow{NJL} \left(\frac{1}{6} + \frac{\tau_3}{2}\right)\not{q}$$

- NJL the vertex must be of form $\Lambda^\mu_{\omega,\rho} = \gamma^\mu +$ transverse terms
- Solving the NJL inhomogeneous BSE for the quark–photon vertex gives

$$\Lambda^\mu_\omega(p',p) = \gamma^\mu + \left(\gamma^\mu - \frac{q^\mu\not{q}}{q^2}\right)\hat{F}_{1\omega}(q^2), \quad \Lambda^\mu_\rho(p',p) = \gamma^\mu + \left(\gamma^\mu - \frac{q^\mu\not{q}}{q^2}\right)\hat{F}_{1\rho}(q^2)$$

NJL Results

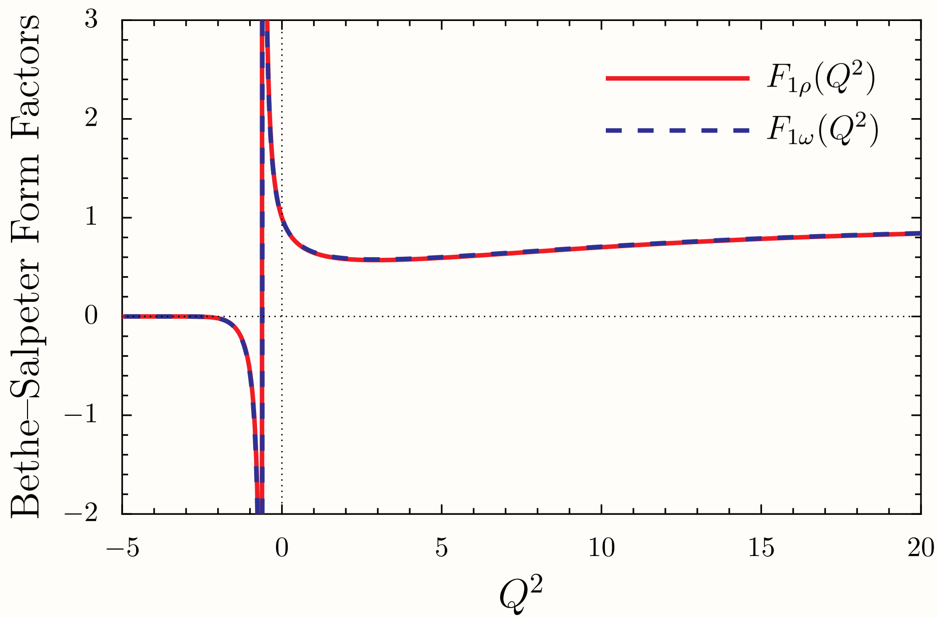
- Putting the quark-photon vertex on-shell gives

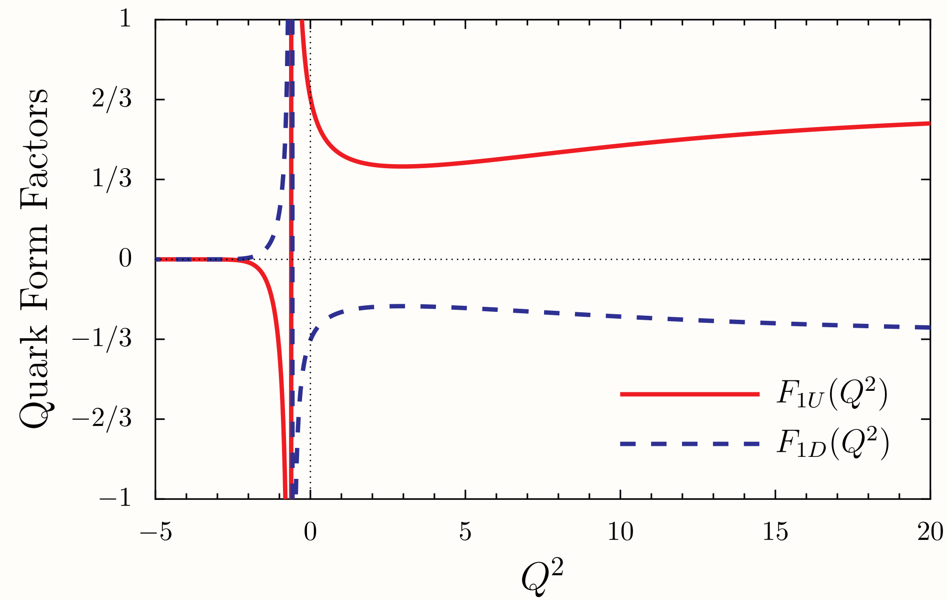
$$\langle J^\mu \rangle = \bar{u}(p')\,\Gamma^{\mu}_{\gamma qq}\,u(p) = \gamma^\mu\,\tfrac{1}{6}[1+\hat{F}_{1\omega}] + \gamma^\mu\,\tfrac{\tau_3}{2}[1+\hat{F}_{1\rho}] \equiv \gamma^\mu\left[\tfrac{1}{6}\,F_{1\omega} + \tfrac{\tau_3}{2}\,F_{1\rho}\right]$$

- The up and down constituent quark form factors are given by $[Q^2 = -q^2]$

$$F_{1U}(Q^2) = \tfrac{1}{6}\,F_{1\omega}(Q^2) + \tfrac{1}{2}\,F_{1\rho}(Q^2) \quad \& \quad F_{1D}(Q^2) = \tfrac{1}{6}\,F_{1\omega}(Q^2) - \tfrac{1}{2}\,F_{1\rho}(Q^2)$$

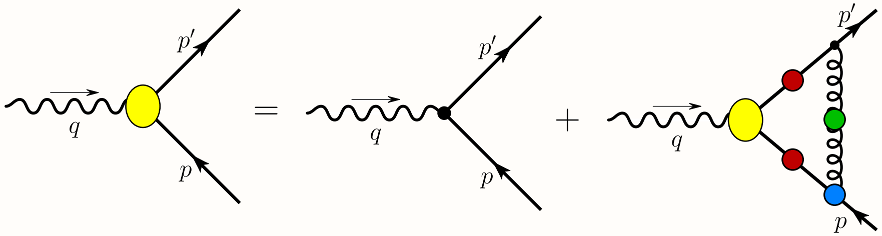
- Timelike poles at: $F_{1\omega}(Q^2 = -m_\omega^2)$ & $F_{1\rho}(Q^2 = -m_\rho^2)$





$$F_{1\omega}(Q^2) = \frac{1}{1+2\,G_\omega\,\Pi_{VV}(Q^2)} \quad \& \quad F_{1\rho}(Q^2) = \frac{1}{1+2\,G_\rho\,\Pi_{VV}(Q^2)}$$

DSE Quark Form Factors



$$q_\mu \, \Gamma^\mu_{\gamma qq}(p', p) = \hat{Q}\left[S^{-1}(p') - S^{-1}(p)\right]$$

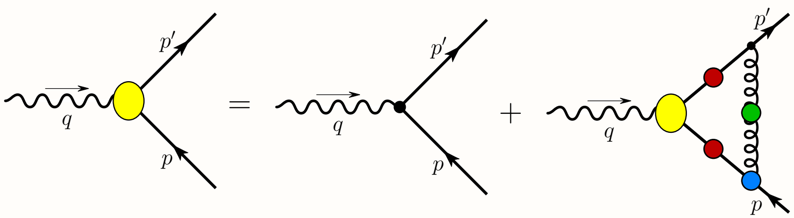
- The longitudinal piece of the quark-photon vertex, $\Gamma^\mu_{\gamma qq} = \Gamma^\mu_L + \Gamma^\mu_T$, is completely determined by the quark propagator
- This result is encapsulated in the Ball-Chiu vertex

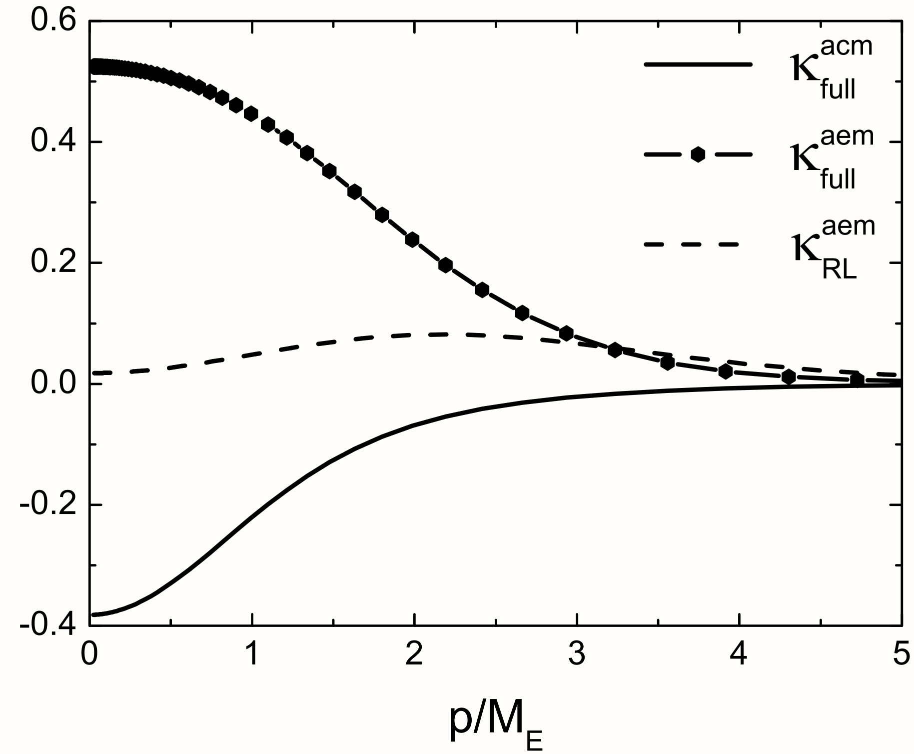
$$\Gamma^\mu_{BC} = \frac{A(p'^2)+A(p^2)}{2}\,\gamma^\mu - \frac{A(p'^2)-A(p^2)}{p'^2-p^2} i(p'+p)^\mu + \frac{1}{2}\frac{A(p'^2)-A(p^2)}{p'^2-p^2}(\not{p}'+\not{p})(p'+p)^\mu$$

- Recall: $S^{-1}(p) = i\not{p}\,A(p^2) + B(p^2)$ – it is then straight forward to show Γ^μ_{BC} satisfies the WTI
- The nature of the quark-photon vertex is largely controlled by the structure of the quark-gluon vertex
  - ✦ different quark-gluon vertices can give very similar quark-propagators
  - ✦ therefore transverse piece of $\Gamma^\mu_{\gamma qq}$ sensitive to the quark-gluon vertex
- Recall rainbow ladder: $\Gamma^{a,\mu}_{gqq} = \frac{\lambda^a}{2}\,\gamma^\mu$

DSE Quark Anomalous Magnetic Moment

- Include $\sigma^{\mu\nu} q_\nu \, \tau_5(p', p)$ [anomalous chromomagnetic] term in quark–gluon vertex: $\Gamma^{a,\mu}_{gqq}(p', p) = \frac{\lambda^a}{2} \, [\gamma^\mu + \sigma^{\mu\nu} q_\nu \, \tau_5(p', p)]$
  - ✦ beyond rainbow ladder – has been absent from previous calculations
- Generates anomalous electromagnetic term in quark–photon vertex
- Confined quarks $\Longrightarrow$ no mass shell – anomalous mm ill defined
  - ✦ however associate with $i\sigma^{\mu\nu} q_\nu$ piece of quark–photon vertex





- L. Chang, Y. -X. Liu, C. D. Roberts, Phys. Rev. Lett. **106**, 072001 (2011).
- Investigate effect on nucleon form factors

Table of Contents