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## Physics Letters B 4 69

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### $\frac{11}{10}$  Theoremses via current configurant  $\frac{1}{12}$  Photon mass via current confinement

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## <sup>19</sup> ARTICLE INFO ABSTRACT <sup>84</sup>

to current confinement.

20 and the state of <sup>21</sup> Article history: **A parity invariant theory, consisting of two massive Dirac fields, defined in three dimensional space–time, <sup>86</sup>** 22 Received 8 August 2016 **Exercise 2018** with the confinement of a certain current is studied. It is found that the electromagnetic field, when 87 23 Received in revised only to two years of coupled minimally to these Dirac fields, becomes massive owing to the current confinement. It is seen 88 24 Australia or that the origin of photon mass is not due to any kind of spontaneous symmetry breaking, but only due ag 25 Editor: B. Grinstein 90 26 **1912 The Authorm** Capaciter B.V. This is an open access article under the CC BY license  $\frac{1}{91}$  $\epsilon$ 27 *Keywords:* Europe 27 *Seywords:* Europe 27 *Seywords:* 27 *Seywords:* 27 *Seywords:* 28 *SCOAP3*. *Article history:* Received 8 August 2016 Received in revised form 10 May 2017 Accepted 31 May 2017 Available online xxxx *Keywords:*

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## **1. Introduction**

<sup>35</sup> ject of intense study since a couple of decades now. There are sev-<br>of non-compact QED was studied by Grignani et al. [18]. <sup>36</sup> eral reasons which make such field theories interesting. Firstly of-<br>In this paper, it is shown that an assumption of confinement of  $^{101}$ <sup>37</sup> ten the theories in lower dimensions are simpler than their higher a certain current gives rise to the photon mass. The theory con- $38$  dimensional counterparts. Secondly, it offers new structures like sider here consists of two species of free Dirac fermions living on  $103$ <sup>39</sup> possibility of gauge invariant mass term for gauge field in the form the plane, defined such that the theory is even under parity. These  $104$ <sup>40</sup> of Chern–Simons term in the action. Interestingly, it was recently fermions are minimally coupled to the photon field. It is found that  $105$ <sup>41</sup> found that planar QED with a tree level Chern–Simons term ad-<br>although the photons in the theory are massive, there is no spon-<sup>42</sup> mits a photon which is composite [\[1\].](#page--1-0) Theories with Chern–Simons taneous symmetry breaking. It is also shown that when such a  $107$ <sup>43</sup> term are found to play an important role in physics of quantum theory is defined over a manifold with finite boundary, then there  $108$ <sup>44</sup> Hall effect and anyonic superconductors  $[2-6]$ . Models which ex- exist massless particles living on the boundary. <sup>45</sup> hibit dynamical mass generation and spontaneous chiral symmetry  $\qquad$  In the following section the model is introduced and its various  $\qquad 110$ <sup>46</sup> breaking have been constructed and extensively studied [7–11]. In features are discussed. Section [3](#page--1-0) deals with the effective action  $111$ <sup>[4](#page--1-0)7</sup> recent years, with the discovery of graphene [12] and topological of photon and its mass. Section 4 deals with the case when the  $112$ <sup>48</sup> insulators [\[13\]](#page--1-0) there has been a renewed interest in the study of theory lives on a manifold with a finite boundary, followed by a  $113$ Field theories in three dimensional space time have been a subpossibility of gauge invariant mass term for gauge field in the form of Chern–Simons term in the action. Interestingly, it was recently found that planar QED with a tree level Chern–Simons term adterm are found to play an important role in physics of quantum hibit dynamical mass generation and spontaneous chiral symmetry breaking have been constructed and extensively studied [\[7–11\].](#page--1-0) In recent years, with the discovery of graphene [\[12\]](#page--1-0) and topological

<sup>50</sup> Colour confinement is one of the still not well understood as-<sup>51</sup> pect of QCD. One of the main hindrance is the fact that the low  $2$ . The model  $52$  energy dynamics in such theory becomes non-perturbative, which  $117$  $^{53}$  makes dealing with them difficult. To circumvent this difficulty,  $\hskip 1.6cm$  The Lagrangian describing two species of massive Dirac fermi-  $^{\rm 118}$ <sup>54</sup> there have been attempts to assume colour confinement from the consiliary on state of the mensional space-time reads: <sup>55</sup> beginning and work subsequently to see if one can get some idea<br> $\frac{120}{2}$ <sup>56</sup> about the dynamics of non-Abelian gauge fields [\[14–16\].](#page--1-0) In a re-  $Z_D = \psi_+(i\gamma_+^{\prime\prime} \partial_\mu - m)\psi_+ + \psi_-(i\gamma_-^{\prime\prime} \partial_\mu - m)\psi_-\,$ . (1) 121 <sup>57</sup> markable paper by Srinivasan and Rajasekaran, it was shown that **Here gamma matrices are defined for**  $\psi_0$  field as  $y^0 = \sigma_0 y^1 = \frac{122}{\sigma_0 y^2}$ 58 by assuming quark confinement it was possible to get QCD out of  $\frac{1}{2}$  and  $\frac{1}{2}$  for example matrices for  $\frac{1}{2}$  for  $\frac{1}{2$ 

63 128 <http://dx.doi.org/10.1016/j.physletb.2017.05.088>

32 **1. Introduction in the studied in the studied in theories defined in**  $\frac{97}{2}$  **ii** [\[16\].](#page--1-0) Confinement has also been studied in theories defined in  $\frac{97}{2}$ **133** 83 **1989 19** <sup>34</sup> Field theories in three dimensional space time have been a sub-<br>pact planar QED exhibits charge confinement [\[17\].](#page--1-0) While the case of non-compact QED was studied by Grignani et al. [\[18\].](#page--1-0)

In this paper, it is shown that an assumption of confinement of a certain current gives rise to the photon mass. The theory consider here consists of two species of free Dirac fermions living on taneous symmetry breaking. It is also shown that when such a exist massless particles living on the boundary.

49 114 lower dimensional field theories. theory lives on a manifold with a finite boundary, followed by a brief summary.

## **2. The model**

The Lagrangian describing two species of massive Dirac fermions living in  $2 + 1$  dimensional space–time reads:

$$
\mathcal{L}_D = \bar{\psi}_+ (i\gamma_+^{\mu} \partial_{\mu} - m)\psi_+ + \bar{\psi}_- (i\gamma_-^{\mu} \partial_{\mu} - m)\psi_-.
$$
 (1)

by assuming quark commentent it was possible to get QCD out of  $i\sigma_1$  and  $\gamma_+^2 = i\sigma_2$ . Gamma matrices for  $\psi_-$  field are also same <sub>124</sub> 60 **125 as**  $\psi_+$  except for  $\gamma^2$ , which is defined as  $\gamma_+^2 = -\gamma_-^2$ . This de-61 **126** E-mail addresses: vivekv@rri.res.in (V.M. Vyas), pprasanta@iiserkol.ac.in **126** liberate difference in choice of gamma matrices ensures that the 126 62 127 Lagrangian is even under parity. It is known that, unlike four Here, gamma matrices are defined for  $\psi_+$  field as  $\gamma_+^0 = \sigma_3$ ,  $\gamma_+^1 =$ 

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4 69 *ψ*±, one can work in <sup>a</sup> reducible representation by defining = dimensional space–time, in the three dimensional world parity

$$
\mathscr{L}_D = \bar{\Psi}(i\gamma^\mu \partial_\mu - m)\Psi,
$$

$$
\psi_{+}(r) \to e^{-i\theta} \psi_{+}(r), \ \psi_{-}(r) \to e^{-i\theta} \psi_{-}(r); \tag{2}
$$

$$
\psi_{+}(r) \to e^{-i\lambda} \psi_{+}(r), \ \psi_{-}(r) \to e^{i\lambda} \psi_{-}(r). \tag{3}
$$

<sup>20</sup> Here *θ* and *λ* are continuous real parameters. These being contin-<br>theory reads<sup>3</sup>  $^{21}$  uous symmetry operations, give rise to conserved currents as per  $^{112}$   $^{123}$   $^{136}$ 

$$
\partial_{\mu} (j_{+}^{\mu} + j_{-}^{\mu}) = 0 \text{ and } \partial_{\mu} (j_{+}^{\mu} - j_{-}^{\mu}) = 0, \tag{2}
$$

 $J^{\mu} = j^{\mu}_{+} + j^{\mu}_{-} = \bar{\Psi}\gamma^{\mu}\Psi$  transforms as a vector<sup>1</sup>:<br>  $J^{\mu} = j^{\mu}_{+} + j^{\mu}_{-} = \bar{\Psi}\gamma^{\mu}\Psi$  transforms as a vector<sup>1</sup>:  $\mathcal{P}$ <br>  $\mathcal{P}$   $\mathcal{P}$   $\mu(x, y, t)$   $\mathcal{P}^{-1} = \Lambda^{\mu}{}_{\nu}J^{\nu}(x, -y, t)$ , whereas  $\tilde{J}^{\mu} = j^{\mu}{}_{\mu} - j^{\mu}{}_{\nu} = \Lambda^{\mu}{}_{\nu}j^{\nu}(x, y, t)$  Here  $\eta$  and  $\bar{\eta}$  are external sources which are coupled to Fermi  $\mathcal{P}_1^{\prime\prime}$   $\mathcal{P}_2^{\prime\prime}$   $\mathcal{P}_3^{\prime\prime}$   $\mathcal{P}_4^{\prime\prime}$   $\mathcal{P}_5^{\prime\prime}$   $\mathcal{P}_6^{\prime\prime}$   $\mathcal{P}_7^{\prime\prime}$   $\mathcal{P}_8^{\prime\prime}$   $\mathcal{P}_9^{\prime\prime}$   $\mathcal{P}_9^{\prime\prime}$   $\mathcal{P}_9^{\prime\prime}$   $\mathcal{P}_9^{\prime\prime}$   $\mathcal{P}_9^{\prime\prime}$   $\mathcal{P}_9^{\prime\prime$  $\frac{29}{4}$   $\frac{1}{4}$  *y*<sup>1</sup> (0.3)  $\frac{1}{4}$ , the state of the proceed *before we* proceed with the details of the quantum theory, it is worth <sup>94</sup> 30  $\mathscr{L}$  *p*<sup>-</sup>(x, y, t) $\mathscr{L}$  = *p*<sup>-</sup>(x, -y, t). Since the physical photon field<br> **pointing out that if one function** in the above gener-<br>  $\epsilon$  **contains** *a i above gener-* $\frac{1}{21}$   $\frac{1}{4}$   $\frac{32}{24}$  *d'*<sub>*y*</sub> *d'*(*x*, -*y*, *t*), its coupling with the current  $j'_{+} + j'_{-}$  preserves dition  $\delta(j''_{+} - j''_{-})$ , since  $a_{\mu}$  appears linearly in the action. This clearly <sup>97</sup><br>as parity while making the symmetry  $-i\bar{\Psi}\gamma^{\mu}(\sigma_3 \otimes \sigma_3)\Psi$ , transforms as a pseudovector:  $\mathscr{P} \tilde{J}^{\mu}(x, y, t) \mathscr{P}^{-1} = \tilde{J}^{\mu}(x, -y, t)$ . Since the physical photon field transforms as a vector under parity operation:  $\mathscr{P}A^{\mu}(x, y, t)\mathscr{P}^{-1}$  =  $\Lambda^{\mu}{}_{\nu}A^{\nu}(x, -y, t)$ , its coupling with the current  $j^{\mu}_{+} + j^{\mu}_{-}$  preserves parity while making the symmetry transformation (2) local.

 $34$  In this paper, we are interested in looking at the physical conse-<br>34 is properly implementing the current configurant contraint <sup>35</sup> quences if the current  $j^{\mu}_{+} - j^{\mu}_{-}$  is confined. As pointed out by Kugo  $a_{\mu}$  is properly implementing the current confinement constraint.  $\frac{36}{10}$  and Office in the context of QCD, and further discussed at length<br>in Ref. [21] that the statement of colour charge confinement can<br>in Ref. [21] that the statement of colour charge confinement can 37 In Rei, [21], that the statement of colour charge commement can<br>38 be accurately stated as the absence of charge bearing states in theory should also be invariant under (3), that is  $\delta Z = 0$ , is not 38 be accurately stated as the absence of charge bearing states in<br>the physical sector of the Hilbert space: O . . . Inhus) – O In what unreasonable. Interestingly, it will be seen that this will give rise  $_{39}$  the physical sector of the Hilbert space:  $Q_{colour}$  *phys* $\rangle = 0$ . *In what*  $_{tot}$  *Mard* Takabashi identities amongst various n-point functions in 40 105 *follows, we shall work with a stronger condition than the Kugo–Ojima* 41 106 *condition, and demand that the physical space of the theory described by Lagrangian* [\(1\)](#page-0-0) should not have any states which carry  $(j''_+ - j''_-)$  current,<br>means  $\delta Z = 0$ , which can be written as:<br>means  $\delta Z = 0$ , which can be written as: *that is:*  $(j^{\mu}_+ - j^{\mu}_-)|phys\rangle = 0.^2$  *This shall be referred to as current con-<br>*  $f(x) = \int_0^x (j^{\mu}_+ - j^{\mu}_-) |phys\rangle = 0.^2$  *<i>This shall be referred to as current con-*44 109 finement condition *henceforth. Since we are demanding a priori that* 45 110 *this current confinement condition should hold, it ought to be under-*46 111 *stood as a constraint. There exists a well known powerful technique to* 47 112 *implement such a constraint using what is called the Lagrange multi-*48 113 *plier (auxiliary) field [\[22\].](#page--1-0) One postulates the existence of a Lagrange* 49 multiplier field which is such that its only appearance in the action is  $J^{(2)}(\Psi \pm \frac{1}{2}) \Psi + J^{(1)}(\frac{1}{2}) \Psi + J^{(2)}(\frac{1}{2}) \Psi + J^{(3)}(\frac{1}{2}) \Psi + J^{(4)}(\frac{1}{2}) \Psi + J^{(5)}(\frac{1}{2}) \Psi + J^{(6)}(\frac{1}{2}) \Psi + J^{(7)}(\frac{1}{2}) \Psi + J^{(8)}(\frac{1}{2}) \Psi + J^{(8)}$ 50 115 *via its coupling to the constraint condition. Thus the equation of motion* 51 116 *corresponding to this field, obtained by demanding that the functional*  $52$  variation of the action with respect to this field be zero, is simply the  $W(1) \pm W(1) \pm W(1) \pm W(1) \pm W(1)$ , equation (5) becomes. 53 118 *constraint condition. It is worth pointing out that such Lagrange multi-*54 plier fields have no dynamics of their own, in the sense that there are no  $\eta + (x) \frac{\pi}{8}$   $\frac{x}{\pi}$   $\frac{y}{\pi}$   $\frac{y}{\pi}$   $\frac{z}{\pi}$   $\frac{z}{\pi}$   $\frac{y}{\pi}$  (b) 119 55 120 *terms in the action comprising of spatial or temporal derivatives of these* 56 fields to begin with, and their sole purpose of existence is to ensure im-<br> $-p_1(x) \frac{\partial w}{\partial x} + p_2(x) \frac{\partial w}{\partial x} = 0.$  $57$  plementation of the constraint. Thus by enlarging the degree of freedom  $\delta \eta_+(x)$   $\delta \eta_-(x)$ 58 123 *in the theory by an additional field, one ensures that the constraint con-*59 124 *dition gets neatly embedded into the action, and hence into the dynamics* and Ojima in the context of QCD, and further discussed at length in Ref. [\[21\],](#page--1-0) that the statement of colour charge confinement can be accurately stated as the absence of charge bearing states in

 $\overline{1}$   $\Lambda$  is diagonal matrix  $\Lambda = diag(1, 1, -1)$ .

 $\frac{127}{2}$  127 13 ungunal matrix  $\Lambda = \text{diag}(1, 1, -1)$ .  $\frac{2}{63}$  The physical space here stands for the set of states in the vector space of the  $\frac{2}{3}$  The physical space here stands for the set of states in the vector space of the  $\frac{2}{3}$ 64 states are altogether absent, then the condition  $(j^{\mu}_+ - j^{\mu}_-) | phys \rangle = 0$  holds for the  $\frac{3}{3}$  Since the current in this theory couples directly to  $a_{\mu}$ , it is treated as a dynam-65 whole of Hilbert space and hence becomes an operator condition  $(j^{\mu}_+ - j^{\mu}_-) = 0$ . ical variable instead of  $\chi_{\mu}$ . Such a treatment is advocated by Hagen in Ref. [23]. 130 theory, which do not have negative norm [\[22\].](#page--1-0) In case when the negative normed

1 dimensional space–time, in the three dimensional world parity of the theory. In our case the Lagrange multiplier Bose field is α<sub>μ</sub>, which 66 <sup>2</sup> transformation is defined by reflecting one of the space axis, say is meant to implement the constraint  $(i^{\mu}_{+}-i^{\mu}_{-})$ , will only couple to it so  $67$ 3 68 Y axis, *(x, y)* → *(x,*−*y)*. Instead of working with two spinor fields *is meant to implement the constraint*  $(j^{\mu}_{+} - j^{\mu}_{-})$ *, will only couple to it so that the Lagrangian [\(1\)](#page-0-0) gets an additional term*:

$$
(\psi_+, \psi_-)^T, \text{ with } \beta = \gamma^0 = 1 \otimes \sigma_3, \ \alpha_1 = 1 \otimes \sigma_1 \text{ and } \alpha_2 = \sigma_3 \otimes \sigma_2, \qquad \mathcal{L} = \bar{\psi}_+ (i\gamma_+^{\mu} \partial_{\mu} - m)\psi_+ + \bar{\psi}_- (i\gamma_-^{\mu} \partial_{\mu} - m)\psi_- + a_{\mu} (j_+^{\mu} - j_-^{\mu}).
$$
  
\nso that the above Lagrangian now reads:

 $\mathcal{Z}_D = \Psi(l\mathcal{V}^T \mathcal{O}_\mu - m)\Psi,$ <br>  $\mathcal{V}^3 = \mathcal{V}^4(l\mathcal{V}^T \mathcal{O}_\mu - m)\Psi,$ <br>  $\mathcal{V}^4 = \mathcal{V}^4(l\mathcal{V}^T \mathcal{O}_\mu - m)\Psi,$ <sup>9</sup> where  $\gamma_{1,2} = \beta \alpha_{1,2}$ . Under parity operation, Ψ transforms as straint  $j^{\mu}_+ - j^{\mu}_- = 0$ . In order to preserve parity,  $a_{\mu}$  field has to be  $\frac{74}{75}$ <sup>10</sup>  $\mathscr{P}\Psi(x, y, t) \mathscr{P}^{-1} = (\sigma_1 \otimes 1)\Psi(x, -y, t)$ . It can be checked that un-<br>
a pseudovector owing to its coupling with pseudovector current. <sup>11</sup> der this peculiar parity transformation, above Lagrangian remains  $\frac{1}{2}$   $\frac{1}{10}$   $\frac{1}{10$ 12 even despite of having a mass term [\[19\].](#page--1-0)  $\alpha_{11} = \epsilon_{111} \frac{\partial^3 V}{\partial x^2}$  and can not have a contribution that can be writ-13 As it stands, apart from above mentioned parity transformation,  $\mu$  as a gradient of some scalar field. This asserts that q<sub>u</sub> can not 14 the Lagrangian of this theory is invariant under two independent be a gauge field since a gauge field under a gauge transformation <sup>15</sup> continuous rigid transformations:<br>transforms as a vector  $\partial_{\mu}$ ,  $\Delta$ , which is not consistent with the nseu-16<br>16 dovector nature of  $a_{\mu}$ . Further note that since  $a_{\mu}$  is curl of  $\chi_{\mu}$ , it  $17 \quad y|_{U_{\alpha}}(r) \rightarrow e^{-10y} |_{U_{\alpha}}(r) y|_{U_{\alpha}}(r) \rightarrow e^{-10y} |_{U_{\alpha}}(r)$  (2)  $(2)$  (2)  $(2)$  (3)  $(2)$  (3)  $(2)$  (4)  $(2)$  (4)  $(2)$  (4)  $(2)$  (4)  $(2)$  (4)  $(2)$  (4)  $(2)$  (4)  $(2)$  (4)  $(2)$  (4)  $(2)$  (4)  $(2)$  (4)  $(2)$  (4)  $($  $\psi_{+}(r) \to e^{-r\omega} \psi_{+}(r), \ \psi_{-}(r) \to e^{-r\omega} \psi_{-}(r);$  (2) immediately follows that its divergence vanishes:  $\partial_{\mu} a^{\mu} = 0.$  as *straint*  $j^{\mu}_{+} - j^{\mu}_{-} = 0$ . In order to preserve parity,  $a_{\mu}$  field has to be a pseudovector owing to its coupling with pseudovector current. Thus *aμ* can in general be written as curl of some vector field *χ*:  $a_{\mu} = \epsilon_{\mu\nu\lambda}\partial^{\nu}\chi^{\lambda}$ , and can not have a contribution that can be written as a gradient of some scalar field. This asserts that *aμ* can not be a gauge field, since a gauge field under a gauge transformation transforms as a vector  $\partial_{\mu} \Lambda$ , which is not consistent with the pseu-

 $\psi_+ (t) \to \epsilon \quad \psi_+ (t), \; \psi_- (t) \to \epsilon \quad \psi_- (t).$ <br>
erating functional is an object of central importance, which for this In functional integral formulation of quantum field theory, gentheory reads<sup>3</sup>:

$$
Z[\eta_{\pm}, \bar{\eta}_{\pm}] = N \int \mathcal{D}[\bar{\psi}_{\pm}, \psi_{\pm}, a_{\mu}] e^{iS},
$$
\n
$$
Z[\eta_{\pm}, \bar{\eta}_{\pm}] = N \int \mathcal{D}[\bar{\psi}_{\pm}, \psi_{\pm}, a_{\mu}] e^{iS},
$$
\n
$$
\frac{\partial u}{\partial t}(\bar{i}_{\pm}^{\mu} + \bar{i}^{\mu}) = 0 \text{ and } \frac{\partial u}{\partial t}(\bar{i}_{\pm}^{\mu} - \bar{i}^{\mu}) = 0.
$$

$$
\sum_{\substack{25 \ 26}}^{25} \text{ where } j^{\mu}(r) = \bar{\psi}(r)\gamma^{\mu}\psi(r).
$$
 It turns out that under parity, current  
\n
$$
\sum_{\substack{25 \ 26}}^{25} \text{ where } j^{\mu}(r) = \bar{\psi}(r)\gamma^{\mu}\psi(r).
$$
 It turns out that under parity, current  
\n
$$
\sum_{\substack{25 \ 26}}^{25} \text{ where } S = \int d^3x \left( \mathcal{L} + \bar{\eta}_{\pm}\psi_{\pm} + \bar{\psi}_{\pm}\eta_{\pm} \right).
$$

fields  $\bar{\psi}$  and  $\psi$  respectively.

33 98 *shows that in the quantum theory as well, the Lagrange multiplier field aμ is properly implementing the current confinement constraint.*

Since the Lagrangian  $(4)$  of the theory is invariant under transto Ward–Takahashi identities amongst various *n*-point functions in this theory and lead to non-trivial consequences. Demanding that *Z* be invariant under infinitesimal version of transformation (3) means  $\delta Z = 0$ , which can be written as:

$$
\int \mathscr{D}[\bar{\psi}_{\pm}, \psi_{\pm}, a_{\mu}] (\delta S) e^{iS} = 0.
$$

This can further be simplified to read:

$$
\int \mathscr{D}[\bar{\psi}_{\pm},\psi_{\pm},a_{\mu}] \left( \mp \bar{\eta}_{\pm}(x)\psi_{\pm}(x) \pm \bar{\psi}_{\pm}(x)\eta_{\pm}(x) \right) e^{iS} = 0. \quad (5)
$$

In terms of the generating functional of connected diagrams  $W[\bar{\eta}_{\pm}, \eta_{\pm}] = -i \ln Z[\bar{\eta}_{\pm}, \eta_{\pm}]$ , equation (5) becomes:

$$
\bar{\eta}_{+}(x)\frac{\delta W}{\delta \bar{\eta}_{+}(x)} - \bar{\eta}_{-}(x)\frac{\delta W}{\delta \bar{\eta}_{-}(x)}
$$
\n(6)

$$
-\eta_{+}(x)\frac{\delta W}{\delta \eta_{+}(x)}+\eta_{-}(x)\frac{\delta W}{\delta \eta_{-}(x)}=0.
$$

60  $M/E = 1 - \frac{\prod_{i=1}^{n} (1 - \frac{1}{2}) - \prod_{i=1}^{n} (1 - \frac{1}{2}) - \prod_{i=1}^{n} (1 - \frac{1}{2})}{\prod_{i=1}^{n} (1 - \frac{1}{2}) - \prod_{i=1}^{n} (1 - \frac{1}{2}) - \prod_{i=1}^{n} (1 - \frac{1}{2})}$ 60  $W[\bar{\eta}_{\pm}, \eta_{\pm}] = \Gamma[\bar{\psi}_{\pm}, \psi_{\pm}] + \int d^3x (\bar{\eta}_{\pm} \psi_{\pm} + \bar{\psi}_{\pm} \eta_{\pm})$ , so that equation 126<br>61  $\frac{126}{126}$ It is often convenient to work with the effective action  $\Gamma[\bar{\psi}_{\pm}, \psi_{\pm}]$ which is defined to be Legendre transform of  $W[\bar{\eta}_{\pm}, \eta_{\pm}]$ : (6) reads:

Since the current in this theory couples directly to  $a_{\mu}$ , it is treated as a dynamical variable instead of  $\chi_{\mu}$ . Such a treatment is advocated by Hagen in Ref. [\[23\].](#page--1-0)

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