

**Polymer parametrized field theory**

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Free scalar field theory on 2-dimensional flat spacetime, cast in diffeomorphism invariant guise by treating the inertial coordinates of the spacetime as dynamical variables, is quantized using loop quantum gravity (LQG) type “polymer” representations for the matter field and the inertial variables. The quantum constraints are solved via group averaging techniques and, analogous to the case of spatial geometry in LQG, the smooth (flat) spacetime geometry is replaced by a discrete quantum structure. An overcomplete set of Dirac observables, consisting of (a) (exponentials of) the standard free scalar field creation-annihilation modes and (b) canonical transformations corresponding to conformal isometries, are represented as operators on the physical Hilbert space. None of these constructions suffer from any of the “triangulation”-dependent choices which arise in treatments of LQG. In contrast to the standard Fock quantization, the non-Fock nature of the representation ensures that the group of conformal isometries as well as that of the gauge transformations generated by the constraints are represented in an anomaly free manner. Semiclassical states can be analyzed at the gauge invariant level. It is shown that “physical weaves” necessarily underlie such states and that such states display semiclassicality with respect to, at most, a countable subset of the (uncountably large) set of observables of type (a). The model thus offers a fertile testing ground for proposed definitions of quantum dynamics as well as semiclassical states in LQG.

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**I. INTRODUCTION**

This work is devoted to an application of canonical loop quantum gravity (LQG) techniques to the quantization of a generally covariant, field theoretic toy model which goes by the name of parametrized field theory (PFT). PFT is just free field theory on flat spacetime, cast in a diffeomorphism invariant disguise. It offers an elegant description of free scalar field evolution on *arbitrary* (and in general curved) foliations of the background spacetime by treating the “embedding variables” which describe the foliation as dynamical variables to be varied in the action in addition to the scalar field. Specifically, let  $X^A = (T, X)$  denote inertial coordinates on 2 dimensional flat spacetime. In PFT,  $X^A$  are parametrized by a new set of arbitrary coordinates  $x^\alpha = (t, x)$  such that for fixed  $t$ , the embedding variables  $X^A(t, x)$  define a spacelike Cauchy slice of flat spacetime. General covariance of PFT ensues from the arbitrary choice of  $x^\alpha$  and implies that in its canonical description, evolution from one slice of an arbitrary foliation to another is generated by constraints. While 2 dimensional PFT has been quantized in a Fock representation for the matter fields in Refs. [1,2], here we are interested in the

construction of an LQG type representation for both the embedding as well as the matter fields, along the lines of Ref. [3]. The usefulness of this exercise for canonical LQG can only be gauged in the context of the current status of the field, a brief discussion of which we now turn to.

LQG is a non-perturbative approach to quantum gravity which, in its canonical version, attempts to construct a Dirac quantization of a Hamiltonian description of gravity in terms of a spatial  $SU(2)$  connection, and its conjugate electric field. The strength of this approach is that it constitutes, for the most part, an extremely conservative development and application of canonical quantization techniques to gravity (see for e.g. the reviews [4–7]). This conservative union of the principles of quantum mechanics with those of classical gravity has yielded many beautiful results such as a satisfactory treatment of spatial diffeomorphisms [8,9], discrete spatial geometry [10–12], a calculation of black hole entropy [13,14], and a uniqueness theorem for its underlying representation [15,16]. However, a necessity for radical ideas has arisen in the treatment of quantum dynamics [17,18] as well as in that of semiclassical issues [19–21].

The key obstruction to a completely conservative treatment stems from the fact that in LQG only certain non-local functionals of the connection, namely, the holonomies around spatial loops, can be promoted to quantum

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operators rather than the connection itself.<sup>1</sup> As a result, all questions of interest (including that of the quantum dynamics defined by the Hamiltonian constraint which is a *local* function of the connection and triad) need to be phrased in terms of holonomy operators. Since holonomy operators associated with close by loops have actions unrelated by any sort of continuity, this leads to a situation where a *choice* of a subset of the (uncountable) set of all holonomy operators (or equivalently, the spatial loops labelling them) becomes necessary. We shall loosely refer to such choices as “triangulation” choices since, often, the family of loops is chosen to lie on some set of triangulations of the spatial manifold. Since there seems to be no natural choice independent of the intuition of the researcher, this leads to proposals which may be seen as radical or ad hoc depending on one’s taste.

In order to test these proposals it is necessary to have a “perfect” toy model in which an LQG type of quantization can be constructed which is free from any triangulation ambiguities. What is needed is a generally covariant, *field theoretic* (with an infinite number of true degrees of freedom, since many of the difficulties can be traced to the field theoretic nature of gravity) system in which all steps of an LQG type quantization procedure can be carried out in a triangulation independent manner. As we show in this work, just such a model is provided by 2 dimensional parametrized field theory on  $S^1 \times R$ . Specifically, we construct, in a triangulation independent manner: an appropriate kinematic “holonomy” algebra and its LQG type “polymer” representation on a kinematic Hilbert space  $\mathcal{H}_{\text{kin}}$ , a representation on  $\mathcal{H}_{\text{kin}}$  of both (the finite transformations generated by) the constraints and an overcomplete set of gauge invariant observables, the group averaging map [9,22] and the physical state space  $\mathcal{H}_{\text{phys}}$  which naturally inherits a representation of the Dirac observables from that on  $\mathcal{H}_{\text{kin}}$ .

The above quantization of PFT offers an arena in which proposals for quantum dynamics developed for LQG may be tested against the manifestly triangulation/regularization free group averaging techniques used in this work. Further, semiclassical issues can be examined at the physical state level since both  $\mathcal{H}_{\text{phys}}$  and representation of an overcomplete set of Dirac observables thereon, are available. This is in contrast to LQG wherein most current proposals are defined on  $\mathcal{H}_{\text{kin}}$  with the hope that they may still be useful at the physical state level. Again, since the quantization here admits a representation of Dirac observables on  $\mathcal{H}_{\text{kin}}$  as well as  $\mathcal{H}_{\text{phys}}$ , it offers a useful testing ground for proposed constructions of semiclassical

<sup>1</sup>The reason for this is the lack of regularity in the action of the holonomy operators: while, classically, the connection at a point can be obtained from the holonomy of a loop containing the point in the limit that the loop is infinitesimally small, the limit of the corresponding operators does not exist in the LQG representation.

states in LQG. Finally, since PFT also admits the usual Fock space quantization of the scalar field [1,2], this can be compared with the “polymer” quantization presented here. This comparison is useful for similar “graviton from LQG” issues [23] in canonical LQG.

The layout of the paper is as follows. Section II contains a brief review of classical PFT on  $S^1 \times R$ . Details may be found in [24]. In Sec. III,  $\mathcal{H}_{\text{kin}}$  is constructed as the tensor product of Hilbert spaces for the matter and embedding sectors, each of which supports a polymer representation of suitably defined LQG- type operators. It is shown that  $\mathcal{H}_{\text{kin}}$  also supports a unitary representation of the finite canonical transformations generated by the constraints. In Sec. IV an overcomplete set of gauge invariant (Dirac) observables corresponding to (a) exponentials of the standard mode functions of the free scalar field on flat spacetime and (b) conformal isometries, are promoted to operators on  $\mathcal{H}_{\text{kin}}$ . These operators commute with those corresponding to finite gauge transformations. In Sec. V, the physical state space,  $\mathcal{H}_{\text{phys}}$ , is constructed through group averaging techniques [9,22]. Ambiguities in the group averaging map are systematically reduced by requiring commutativity with the Dirac observables and superselection sectors are described, each of which provide a cyclic, *non-separable* representation of the algebra generated by the gauge invariant operators of Sec. IV. Section VI is devoted to a preliminary discussion of semiclassical issues. It is shown that, at most, only a countable subset of the overcomplete (and uncountable) set of Dirac observables of type (a) can be approximated by semiclassical states in  $\mathcal{H}_{\text{phys}}$ . Further, it is shown that any such state must be characterized by a suitably defined “physical” weave. Two issues (connected with the  $S^1$  spatial topology and the treatment of zero modes) are addressed in Sec. VII. Section VIII contains a discussion of our results as well as of open issues.

In the interests of brevity, we shall refrain from providing detailed proofs where such proofs are straightforward. Some lemmas are proved in the Appendices A and B. The dimensions of various quantities and our choice of units are displayed in Appendix C.

## II. CLASSICAL PFT ON $S^1 \times R$

We provide a brief review of classical 2 dimensional PFT. In sections II A and II B we shall implicitly assume that the spatial topology is that of a circle. The consequences of this nontrivial spatial topology on the formalism will be made explicit in Sec. II C.

### A. The action for PFT

The action for a free scalar field  $f$  on a fixed flat 2-dimensional spacetime in terms of global inertial coordinates  $X^A$ ,  $A = 0, 1$  is

$$S_0[f] = -\frac{1}{2} \int d^2X \eta^{AB} \partial_A f \partial_B f, \quad (1)$$

where the Minkowski metric in inertial coordinates,  $\eta_{AB}$ , is diagonal with entries  $(-1, 1)$ . If instead, we use coordinates  $x^\alpha$ ,  $\alpha = 0, 1$  (so that  $X^A$  are “parametrized” by  $x^\alpha$ ,  $X^A = X^A(x^\alpha)$ ), we have

$$S_0[f] = -\frac{1}{2} \int d^2x \sqrt{\eta} \eta^{\alpha\beta} \partial_\alpha f \partial_\beta f, \quad (2)$$

where  $\eta_{\alpha\beta} = \eta_{AB} \partial_\alpha X^A \partial_\beta X^B$  and  $\eta$  denotes the determinant of  $\eta_{\alpha\beta}$ . The action for PFT is obtained by considering the right-hand side of (2) as a functional, not only of  $\phi$ , but also of  $X^A(x)$  i.e.  $X^A(x)$  are considered as 2 new scalar fields to be varied in the action [ $\eta_{\alpha\beta}$  is a function of  $X^A(x)$ ]. Thus

$$S_{\text{PFT}}[f, X^A] = -\frac{1}{2} \int d^2x \sqrt{\eta(X)} \eta^{\alpha\beta}(X) \partial_\alpha f \partial_\beta f. \quad (3)$$

Note that  $S_{\text{PFT}}$  is a diffeomorphism invariant functional of the scalar fields  $f(x)$ ,  $X^A(x)$ . Variation of  $f$  yields the equation of motion  $\partial_\alpha (\sqrt{\eta} \eta^{\alpha\beta} \partial_\beta f) = 0$ , which is just the flat spacetime equation  $\eta^{AB} \partial_A \partial_B f = 0$  written in the coordinates  $x^\alpha$ . On varying  $X^A$ , one obtains equations which are satisfied if  $\eta^{AB} \partial_A \partial_B f = 0$ . This implies that  $X^A(x)$  are undetermined functions (subject to the condition that determinant of  $\partial_\alpha X^A$  is non-vanishing). This 2 functions-worth of gauge is a reflection of the 2 dimensional diffeomorphism invariance of  $S_{\text{PFT}}$ . Clearly the dynamical content of  $S_{\text{PFT}}$  is the same as that of  $S_0$ ; it is only that the diffeomorphism invariance of  $S_{\text{PFT}}$  naturally allows a description of the standard free field dynamics dictated by  $S_0$  on *arbitrary* foliations of the fixed flat spacetime.

### B. Hamiltonian formulation of PFT

In the previous subsection,  $X^A(x)$  had a dual interpretation—one as dynamical variables to be varied in the action, and the other as inertial coordinates on a flat spacetime. In what follows we shall freely go between these two interpretations.

We set  $x^0 = t$  and  $\{x^\alpha\} = \{t, x\}$ . We restrict attention to  $X^A(x^\alpha)$  such that for any fixed  $t$ ,  $X^A(t, x^\alpha)$  describe an embedded spacelike hypersurface in the 2-dimensional flat spacetime (it is for this reason that  $X^A(x)$  are called embedding variables in the literature). This means that, for fixed  $t$ , the functions  $X^A(x)$  must be such that the symmetric form  $q_{ab}$  defined by

$$q_{ab}(x) := \eta_{AB} \frac{\partial X^A(x)}{\partial x^a} \frac{\partial X^B(x)}{\partial x^b} \quad (4)$$

is a 1-dimensional Riemannian metric. This follows from the fact that  $q_{ab}(x)$  is the induced metric on the hypersurface in the flat spacetime defined by  $X^A(x)$  at fixed  $t$ .

A  $1 + 1$  decomposition of  $S_{\text{PFT}}$  with respect to the time “ $t$ ,” leads to its Hamiltonian form:

$$S_{\text{PFT}}[f, X^A; \pi, \Pi_A; N^A] = \int dt \int d^2x (\Pi_A \dot{X}^A + \pi_f \dot{f} - N^A H_A). \quad (5)$$

Here  $\pi_f$  is the momentum conjugate to the scalar field  $f$ ,  $\Pi_A$  is the momenta conjugate to the embedding variables  $X^A$ ,  $N^A$  are Lagrange multipliers for the first class constraints  $H_A$ . It turns out that the motions on phase space generated by the “smeared” constraints,  $\int d^2x (N^A H_A)$  correspond to scalar field evolution along arbitrary foliations of the flat spacetime, each choice of foliation being in correspondence with a choice of multipliers  $N^A$ . Since the constraints are first class they also generate gauge transformations and, as in general relativity, the notions of gauge and evolution are intertwined.

Since free scalar field theory in 2 dimensions finds its simplest expression in terms of left and right movers, it is useful to make a point canonical transformation to light cone embedding variables  $X^\pm(x) := T(x) \pm X(x)$  (here we have set  $X^0 = T$ ,  $X^1 = X$ ). Denoting the conjugate embedding momenta by  $\Pi_\pm(x)$ , and setting  $H_\pm = H_0 \pm H_1$ , the action takes the form

$$S = \int dt \int dx [\pi_f \dot{f} + \Pi_+ \dot{X}^+ + \Pi_- \dot{X}^- - N^+ H_+ - N^- H_-], \quad (6)$$

where  $N^\pm$  are the new Lagrange multipliers appropriate to  $H_\pm$ . Explicitly, the constraints  $H_\pm$  are given by

$$H_\pm(x) = [\Pi_\pm(x) X^{\pm'}(x) \pm \frac{1}{4} (\pi_f \pm f')(x) (\pi_f \pm f')(x)]. \quad (7)$$

Note that while  $X^\pm(x)$ ,  $f(x)$  transform as scalars under spatial coordinate transformations,  $\Pi_\pm$ ,  $\pi_f$ ,  $N^\pm$  transform as scalar densities (or equivalently as spatial vector fields).

The Poisson brackets between various fields are given by

$$\{f(x), \pi_f(x')\} = \delta(x, x'), \quad \{X^\pm(x), \Pi_\pm(x')\} = \delta(x, x'), \quad (8)$$

and the remaining brackets are zero. Here  $\delta(x, x')$  is the delta function on  $S^1$ .

To complete the transition to variables closely related to the left and right movers of free scalar field theory [24], we perform a canonical transformation on the matter variables.  $(f, \pi_f) \rightarrow (Y^+, Y^-)$ . Here  $Y^\pm(x) = \pi_f(x) \pm f'(x)$  (strictly speaking this transformation is not invertible when the spatial topology is  $S^1$  due to the existence of zero modes; we shall return to this issue in Sec. III). The Poisson brackets between the scalar densities,  $Y^\pm$ , are given by

$$\begin{aligned} \{Y^\pm(x), Y^\pm(x')\} &= \pm[\partial_x \delta(x, x') - \partial_{x'} \delta(x', x)] \\ \{Y^\mp(x), Y^\pm(x')\} &= 0. \end{aligned} \quad (9)$$

The constraints are now

$$H^\pm(x) = [\Pi_\pm(x)X^\pm(x) \pm \frac{1}{4}Y^\pm(x)^2]. \quad (10)$$

and the constraint algebra is

$$\begin{aligned} \{H_\pm[N^\pm], H_\pm[M^\pm]\} &= H_\pm[\mathcal{L}_{N^\pm}M^\pm] \\ \{H_\pm[N^\pm], H_\mp[M^\mp]\} &= 0 \end{aligned} \quad (11)$$

Here  $\mathcal{L}_N$  denotes the Lie derivative with respect to the 1-dimensional spatial vector field with component  $N(x)$  in the coordinate system “ $x$ .” The action of the constraints on the phase space variables can be expressed as follows. Let  $\Phi^\pm = (Y^\pm, \Pi_\pm)$ , we have

$$\begin{aligned} \{\Phi^\pm(x), H_\pm[N^\pm]\} &= \mathcal{L}_{N^\pm} \Phi^\pm(x) \\ \{\Phi^\mp(x), H_\pm[N^\pm]\} &= 0, \end{aligned} \quad (12)$$

Thus, on the set of variables  $\Phi^\pm$ , infinitesimal gauge transformations act as diffeomorphisms on  $S^1$ , and there is a split of the constraints and the phase space variables into commuting “+” and “-” parts which correspond to the usual right and left moving sectors of free scalar field theory. The action of the constraints on the embedding variables  $X^\pm(x)$  preserves this split:

$$\{X^\pm(x), H_\pm[N^\pm]\} = N^\pm(X^\pm)', \quad (13)$$

$$\{X^\mp(x), H_\pm[N^\pm]\} = 0. \quad (14)$$

Indeed, the above equations seem to indicate that infinitesimal gauge transformations, once again, act as diffeomorphisms on  $S^1$ ; however, as we shall see in the next subsection, this interpretation is not strictly true for Eqs. (13) and (14) due to the nonexistence of global, single valued coordinates on  $S^1$ .

### C. Consequences of spatial topology = $S^1$

#### 1. Conditions on the canonical variables

$S^1$  does not admit a global single valued coordinate system. However, at the cost of introducing appropriate periodic/quasiperiodic boundary conditions on the fields we may choose  $x$  to be the standard angular coordinate,  $x \in [0, 2\pi]$  with the identification  $x = 0 \sim x = 2\pi$ . The Minkowskian coordinates  $X^A = (T, X)$  in the action (1) are chosen so that  $T \in (-\infty, \infty)$ ,  $X \in (-\infty, \infty)$  with the identifications  $X \sim X + 2\pi$ . The above specifications on  $x, X$  imply the following conditions on the canonical embedding variables and the Lagrange multipliers:

- (i)  $X^\pm(2\pi) - X^\pm(0) = \pm 2\pi$ .
- (ii) Any two sets of embedding data  $(X_1^+(x), X_1^-(x))$  and  $(X_2^+(x), X_2^-(x))$  are to be identified if there exists an integer  $m$  such that  $X_1^+(x) = X_2^+(x) + 2m\pi \forall x \in [0, 2\pi]$  and  $X_1^-(x) = X_2^-(x) - 2m\pi \forall x \in [0, 2\pi]$ .

- (iii)  $\Pi_\pm(x), N^\pm(x)$  and their spatial derivatives to all orders, as well as the spatial derivatives to all orders of the embedding coordinates  $X^\pm(x)$  are periodic on  $[0, 2\pi]$  with period  $2\pi$ . This follows from the 1 + 1 Hamiltonian decomposition of (3) and the fact that  $\frac{\partial X^A}{\partial x^\alpha}$  in Eq. (4) is single valued on  $S^1 \times R$ .

An additional “nondegeneracy” condition arises from (4):

- (iv)  $\pm(X^\pm)' > 0$ .

Since  $f$  in (1) is a single valued function on  $S^1 \times R$ , it follows that the matter phase space variables  $(f, \pi_f)$  and their spatial derivatives to all orders are also periodic functions on  $[0, 2\pi]$ . Note also that the delta function  $\delta(x, y)$  in (8) and (9) is periodic in both its arguments.

#### 2. Finite gauge transformations

Whereas Eq. (12) implies that finite gauge transformations act on  $(\Pi_\pm, Y^\pm)$  as spatial diffeomorphisms on  $S^1$ , as remarked earlier the case of the embedding variables  $X^\pm$  is more subtle as  $X^\pm$  are not single valued fields on  $S^1$  by virtue of (i), Sec. II C 1. Therefore, evolution of  $X^\pm$  under the flow generated by the constraints is better understood in terms of transformations on the universal cover of  $S^1$  as follows.

Unwind  $S^1$  to its universal cover  $\mathbf{R}$ . Quasiperiodic boundary conditions obeyed by the embeddings suggest that their extension to  $\mathbf{R}$  satisfies:

$$X_{\text{ext}}^\pm(x \pm 2n\pi) := X^\pm(x) \pm 2n\pi \quad (15)$$

where  $x \in [0, 2\pi]$  and  $n \in \mathbf{Z}$ . The vector fields  $N^\pm(x)$  on  $S^1$  extend to periodic vector fields  $N_{\text{ext}}^\pm$  on  $\mathbf{R}$  so that  $N_{\text{ext}}^\pm(x + 2n\pi) = N^\pm(x)$ ,  $x \in [0, 2\pi]$ . Let the 1 parameter family of (periodic) diffeomorphisms of  $\mathbf{R}$  generated by  $N_{\text{ext}}^\pm$  be denoted by  $\phi[N_{\text{ext}}^\pm, t]$ . And let  $\phi[N_{\text{ext}}^\pm, t](x) \in \mathbf{R}$  be the image of  $x \in [0, 2\pi]$  under  $\phi[N_{\text{ext}}^\pm, t]$ . Then it is straightforward to check that the finite transformations generated by the constraints on  $X^\pm(x)$  are labeled by  $\phi[N_{\text{ext}}^\pm, t]$  and act as follows:

$$\begin{aligned} (\alpha_{\phi[N_{\text{ext}}^\pm, t]} X^\pm)(x) &= X_{\text{ext}}^\pm(\phi[N_{\text{ext}}^\pm, t](x)) \quad \forall x \in [0, 2\pi] \\ (\alpha_{\phi[N_{\text{ext}}^\mp, t]} X^\mp)(x) &= X^\mp(x) \quad \forall x \in [0, 2\pi] \end{aligned} \quad (16)$$

Here  $\alpha_{\phi[N_{\text{ext}}^\pm, t]}$  is the flow generated by Hamiltonian vector field of  $H_\pm[N^\pm]$ .

It is also straightforward to see that the action of finite gauge transformations on the phase space variables  $\Phi^\pm \in \{Y^\pm, \Pi_\pm\}$  can be equally well written in terms of the action of the periodic diffeomorphisms  $\phi[N_{\text{ext}}^\pm, t]$  on the periodic extensions  $\Phi_{\text{ext}}^\pm$  as

$$\begin{aligned} (\alpha_{\phi[N_{\text{ext}}^\pm, t]} \Phi^\pm)(x) &= \Phi_{\text{ext}}^\pm(\phi[N_{\text{ext}}^\pm, t](x)) \quad \forall x \in [0, 2\pi] \\ (\alpha_{\phi[N_{\text{ext}}^\mp, t]} \Phi^\mp)(x) &= \Phi^\mp(x) \quad \forall x \in [0, 2\pi] \end{aligned} \quad (17)$$

Here  $\Phi_{\text{ext}}^\pm(x + 2n\pi) = \Phi^\pm(x) \quad \forall x \in [0, 2\pi], n \in \mathbf{Z}$ .

Since  $\phi[N_{\text{ext}}^\pm, t]$ ,  $\forall(N_{\text{ext}}^\pm, t)$  range over all periodic diffeomorphisms of  $\mathbf{R}$  connected to identity, we label every finite gauge transformation by a pair of such diffeomorphisms  $(\phi^+, \phi^-)$  so that the Hamiltonian flows generated by  $H_\pm$  are denoted by  $\alpha_{\phi^\pm}$ . To summarize: Let  $\Psi^\pm(x) \in (X^\pm(x), \Pi_\pm(x), Y^\pm(x))$  and let its appropriate quasiperiodic/periodic extension on  $\mathbf{R}$  be  $\Psi_{\text{ext}}^\pm$ . Then we have that,  $\forall x \in [0, 2\pi]$ ,

$$(\alpha_{\phi^\pm} \Psi^\pm)(x) = \Psi_{\text{ext}}^\pm(\phi^\pm(x)) \quad (\alpha_{\phi^\pm} \Psi^\mp)(x) = \Psi^\mp(x). \quad (18)$$

Eqs. (18) imply a left representation of the group of periodic diffeomorphisms of  $\mathbf{R}$  by the Hamiltonian flows corresponding to finite gauge transformations:

$$\alpha_{\phi_1^\pm} \alpha_{\phi_2^\pm} = \alpha_{\phi_1^\pm \circ \phi_2^\pm} \quad (19)$$

$$\alpha_{\phi_1^\pm} \alpha_{\phi_2^\mp} = \alpha_{\phi_2^\mp \circ \phi_1^\pm}. \quad (20)$$

We emphasize that the extended fields are only formal constructs which are useful for interpreting gauge transformations in terms periodic diffeomorphisms of  $\mathbf{R}$ . The spatial slice is always  $S^1$  coordinatized by  $x \in [0, 2\pi]$  with boundary points identified.

#### D. Dirac observables

Since finite gauge transformations act as periodic diffeomorphisms of  $\mathbf{R}$ , it follows, directly, that the integral over  $x \in [0, 2\pi]$  of any periodic scalar density constructed solely from the phase space variables, is an observable.

An analysis of the Hamiltonian equations [24] shows that the relation between solutions  $f(X^+, X^-)$  of the flat spacetime wave equation and canonical data  $(Y^\pm, X^\pm)$  on the constraint surface is

$$\pm 2 \frac{\partial f}{\partial X^\pm} = \frac{Y^\pm}{(X^\pm)}. \quad (21)$$

Here  $f$  is evaluated at the spacetime point  $(X^+, X^-)$  defined by the canonical data. Recall that any solution  $f(X^+, X^-)$  to the free scalar field equation is of the form

$$f(X^+, X^-) = \frac{\mathbf{q}}{\sqrt{2\pi}} + \frac{\mathbf{p}}{\sqrt{2\pi}} \frac{(X^+ + X^-)}{2} + \sum_{n=1}^{\infty} \frac{i}{4\pi n} \times (\mathbf{a}_{(+)\mathbf{n}} e^{-inX^+} + \mathbf{a}_{(-)\mathbf{n}} e^{-inX^-} - \text{c.c.}), \quad (22)$$

where c.c. stands for ‘‘complex conjugate.’’ Equations (21) and (22) yield an interpretation for the Dirac observables constructed below.

#### 1. Mode functions

From (21) and (22) and the remarks above, it follows that

$$a_{(\pm)\mathbf{n}} = \int_{S^1} dx Y^\pm(x) e^{inX^\pm(x)}, \quad \mathbf{n} \in \mathbf{Z}, \quad \mathbf{n} > 0 \quad (23)$$

(and their complex conjugates,  $a_{(\pm)\mathbf{n}}^*$ ) are Dirac observables which correspond to the mode functions  $\mathbf{a}_{(\pm)\mathbf{n}}$  of Eq. (22). These observables form the (Poisson) algebra,

$$\{a_{(\pm)\mathbf{n}}, a_{(\pm)\mathbf{m}}^*\} = -4\pi in \delta_{\mathbf{n},\mathbf{m}}, \quad \{a_{(\pm)\mathbf{n}}, a_{(\pm)\mathbf{m}}\} = 0, \\ \{a_{(\pm)\mathbf{n}}^*, a_{(\pm)\mathbf{m}}^*\} = 0. \quad (24)$$

The Dirac observables corresponding to right-moving sector  $(a_{(+)\mathbf{m}}, a_{(+)\mathbf{n}}^*)$  Poisson commute with the observables corresponding to the left moving sector  $(a_{(-)\mathbf{m}}, a_{(-)\mathbf{n}}^*)$ .

#### 2. Zero modes

The quantities  $\mathbf{q}$ ,  $\mathbf{p}$  in Eq. (22) are referred to as zero modes of the scalar field and are also realizable as Dirac observables which are canonically conjugate to each other [24]. Indeed, it is straightforward to see from (21) and (22), that  $\mathbf{p}$  corresponds to  $p := \int_{S^1} dx Y^+(x) = \int_{S^1} dx Y^-(x)$ . However, the degree of freedom corresponding to  $\mathbf{q}$  is absent in the phase space coordinates  $(X^\pm, \Pi_\pm, Y^\pm)$  as a result of  $Y^\pm$  only containing derivatives of  $f$  [see Eq. (21)].

Our aim in this work is to construct a triangulation independent polymer quantization of a generally covariant field theoretic model. Issues related to the construction of zero modes [which are anyway mechanical (as opposed to field theoretic) degrees of freedom] as Dirac observables serve to distract from this aim. Hence we shall switch off the zero modes by setting  $\mathbf{q} = \mathbf{p} = 0$ . Since  $\mathbf{q}$  and  $\mathbf{p}$  are canonically conjugate, this can be done consistently. In the free scalar field action (1) this corresponds to limiting the space of all scalar fields by the conditions  $\mathbf{q} = \frac{1}{\sqrt{2\pi}} \times \int_{S^1} dX f(T=0, X) = 0$  and  $\mathbf{p} = \frac{1}{\sqrt{2\pi}} \int_{S^1} dX \frac{\partial f(T,X)}{\partial T} = 0$ . In the canonical description of PFT in terms of  $(\Pi_\pm, X^\pm, Y^\pm)$ , since  $\mathbf{q}$  does not appear, we only need to set the quantity

$$p := \frac{1}{\sqrt{2\pi}} \int_{S^1} dx Y^+(x) = \frac{1}{\sqrt{2\pi}} \int_{S^1} dx Y^-(x) = 0. \quad (25)$$

Since, as can easily be checked,  $p$  commutes with  $(\Pi_\pm, X^\pm, Y^\pm)$  as well as the constraints (10), it is consistent to impose (25).

To summarize: The system we consider in this work is PFT on  $S^1 \times R$  with the zero modes switched off. The phase space variables are  $(\Pi_\pm, X^\pm, Y^\pm)$  subject to the conditions of Sec. II C 1. The symplectic structure is given by (8) and (9) and the constraints by (10). The degrees of freedom of the theory reside entirely in the mode coefficients  $\mathbf{a}_{(\pm)\mathbf{n}}$ ,  $\mathbf{a}_{(\pm)\mathbf{n}}^*$  (22) which are expressed as the functions  $a_{(\pm)\mathbf{n}}$ ,  $a_{(\pm)\mathbf{n}}^*$  on phase space via (23).

### 3. Conformal isometries

Free scalar field theory in 1 + 1 dimensions (1) is conformally invariant. It turns out that the generators of conformal isometries in free scalar field theory are expressible as Dirac observables in PFT (for details, see Ref. [24]). Consider the conformal isometry generated by the conformal Killing field  $\vec{U}$  on the Minkowskian cylinder. Let  $\vec{U}$  have the components  $(U^+(X^+), U^-(X^-))$  in the  $(X^+, X^-)$  coordinate system.  $U^\pm$  are periodic functions of  $X^\pm$  by virtue of the fact that  $\vec{U}$  is smooth vector field on the flat spacetime  $S^1 \times R$ . These components of  $\vec{U}$  naturally correspond to the functions  $(U^+(X^+(x)), U^-(X^-(x)))$  on the phase space of PFT. The Dirac observable in PFT corresponding to the generator of conformal transformations in free scalar field theory associated with  $\vec{U}$  is given by

$$\Pi_\pm[U^\pm] = \int_{S^1} \Pi_\pm(x) U^\pm(X^\pm(x)). \quad (26)$$

These observables generate a Poisson algebra isomorphic to that of the commutator algebra of conformal Killing fields:

$$\begin{aligned} \{\Pi_\pm[U^\pm], \Pi_\pm[V^\pm]\} &= \Pi[[V, U]^\pm] \\ \{\Pi_\pm[U^\pm], \Pi_\mp[V^\mp]\} &= 0. \end{aligned} \quad (27)$$

Here  $[V, U]^\pm$  refer to the  $\pm$  components of the commutator of the spacetime vector fields  $\vec{U}, \vec{V}$ , i.e.  $[V, U]^\pm = V^\pm \frac{\partial U^\pm}{\partial X^\pm} - U^\pm \frac{\partial V^\pm}{\partial X^\pm}$ .  $[V, U]^\pm$  define functions of the embedding variables  $X^\pm(x)$  in the manner described above.

Note that these observables are weakly equivalent, via the constraints (10) to quadratic combinations of the mode functions [24]. In the standard Fock representation of quantum theory (see for e.g. Ref. [1]), these quadratic combinations are nothing but the generators of the Virasoro algebra.

As we shall see, the polymer quantization of PFT provides a representation for the finite canonical transformations generated by  $\Pi^\pm[U^\pm]$ . For future reference, it is straightforward to check that the Hamiltonian flow,  $\alpha_{(\Pi_\pm[U^\pm], t)}$  generated by  $\Pi_\pm[U^\pm]$  leaves the matter sector of phase space untouched and acts on the embedding variables  $X^\pm$  as

$$\alpha_{(\Pi_\pm[U^\pm], t)} X^\pm(x) = (\phi_{(\vec{U}, t)} X^\pm)(x). \quad (28)$$

Here  $\phi_{(\vec{U}, t)}$  denotes the one parameter family of conformal isometries generated by the conformal Killing field  $\vec{U}$  on spacetime.  $\phi_{(\vec{U}, t)}$  maps the spacetime point  $(X^+, X^-)$  to  $\phi_{(\vec{U}, t)} X^\pm$  and hence maps the spatial slice defined by the canonical data  $X^\pm(x)$  to the new slice (and hence the new canonical data)  $(\phi_{(\vec{U}, t)} X^\pm)(x)$ .  $\phi_{(\vec{U}, t)}$  ranges over all conformal isometries connected to identity. Any such conformal isometry  $\phi_c$  is specified by a pair of functions  $\phi_c^\pm$  so that  $\phi_c(X^+, X^-) := (\phi_c^+(X^+), \phi_c^-(X^-))$ . Invertibility of  $\phi_c$  together with connectedness with identity implies that

$$\frac{d\phi_c^\pm}{dX^\pm} > 0, \quad (29)$$

and the cylindrical topology of spacetime implies that

$$\phi_c^\pm(X^\pm \pm 2\pi) = \phi_c^\pm(X^\pm) \pm 2\pi. \quad (30)$$

Thus, we may denote the Hamiltonian flows which generate conformal isometries by  $\alpha_{\phi_c}$  or, without loss of generality, by  $\alpha_{\phi_c^\pm}$  with  $\alpha_{\phi_c^\pm}$  acting trivially on the  $\mp$  sector.

To summarize:  $\alpha_{\phi_c^\pm}$  leave the matter variables untouched, so that

$$\alpha_{\phi_c^\pm} Y^\pm(x) = Y^\pm(x), \quad \alpha_{\phi_c^\pm} Y^\mp(x) = Y^\mp(x), \quad (31)$$

and act on  $X^\pm(x)$  as

$$\alpha_{\phi_c^\pm} X^\pm(x) = \phi_c^\pm(X^\pm(x)), \quad \alpha_{\phi_c^\pm} X^\mp(x) = X^\mp(x). \quad (32)$$

Further, since  $\Pi_\pm[U^\pm]$  are observables which commute strongly with the constraints, the corresponding Hamiltonian flows are gauge invariant. This translates to the condition that for all

$$\alpha_{\phi_c^\pm} \circ \alpha_{\phi^+} = \alpha_{\phi^+} \circ \alpha_{\phi_c^\pm} \quad \alpha_{\phi_c^\pm} \circ \alpha_{\phi^-} = \alpha_{\phi^-} \circ \alpha_{\phi_c^\pm} \quad (33)$$

where as before  $\phi^\pm$  label finite gauge transformations.

## III. POLYMER QUANTUM KINEMATICS

### A. Preliminaries

As in LQG, the polymer quantization is based on suitably defined ‘‘holonomies’’ and the polymer Hilbert space is spanned by suitably defined ‘‘charge-network’’ states. In view of the correspondence between finite gauge transformations and periodic diffeomorphisms of  $\mathbf{R}$ , it is useful to define periodic and quasiperiodic extensions of charge-network labels. Hence we define the following.

*Definition 1:* A charge-network  $s$  is specified by the labels  $(\gamma(s), (j_{e_1}, \dots, j_{e_n}))$  consisting of a graph  $\gamma(s)$  (by which we mean a finite collection of closed, nonoverlapping (except in boundary points) intervals which cover  $[0, 2\pi]$ ) and ‘‘charges’’  $j_e \in \mathbf{R}$  assigned to each interval  $e$ . (Note that  $j_e = 0$  is allowed.) Equivalence classes of charge networks are defined as follows. The graph  $\gamma'$  is said to be finer than graph  $\gamma$  iff every edge of  $\gamma$  is identical to, or composed of, edges in  $\gamma'$ . The charge network  $s'$  is said to be finer than  $s$  iff (a)  $\gamma(s')$  is finer than  $\gamma(s)$  (b) the charge labels of identical edges in  $\gamma(s), \gamma(s')$  are identical and the charge labels of the edges of  $\gamma(s')$  which compose to yield an edge of  $\gamma(s)$  are identical and equal to that of their union in  $\gamma(s)$ . Two charge networks are equivalent if there exists a charge network finer than both. Hence we can represent each equivalence class by a unique representative

$s$  such that no two adjacent edges have the same charge. However, unless otherwise mentioned,  $s$  will not necessarily denote this unique choice.

*Definition 2:* The periodic extension of the charge network  $s$  to  $\mathbf{R}$  is denoted by  $s_{\text{ext}}$  and defined as follows.

Given a graph  $\gamma$  as in Definition 1 above,  $T_N(\gamma)$  denotes the translation of  $\gamma$  by  $2N\pi$ , i.e.  $T_N(\gamma)$  lies in  $[2N\pi, 2(N+1)\pi]$ . We define the *extension* of  $\gamma$  to  $\mathbf{R}$  as  $\gamma_{\text{ext}} = \cup_{N \in \mathbf{Z}} T_N(\gamma)$ . The *restriction* of  $\gamma_{\text{ext}}$  to any interval  $I \subset \mathbf{R}$  is denoted by  $\gamma_{\text{ext}}|_I$  so that  $\gamma_{\text{ext}}|_{[0, 2\pi]} = \gamma$ .

Given a charge network  $s = (\gamma(s), (j_{e_1}, \dots, j_{e_n}))$ ,  $s_{\text{ext}}$  is specified by the graph  $\gamma(s_{\text{ext}}) := \gamma(s)_{\text{ext}}$  ( $\gamma(s)_{\text{ext}}$  denotes the extension of  $\gamma(s)$  to  $\mathbf{R}$ ) and charge labels for each edge of  $\gamma(s_{\text{ext}})$  which are such that  $T_N(\gamma(s)) \subset \gamma(s_{\text{ext}})$  has the same set of charges which are on  $\gamma$ . Thus

- (1) On any closed interval  $I_N = [2N\pi, 2(N+1)\pi]$ ,  $N \in \mathbf{Z}$ ,  $\gamma(s_{\text{ext}})|_{I_N}$  is naturally isomorphic to  $\gamma(s)$ .
- (2) The set of charges on  $\gamma(s_{\text{ext}})|_{I_N}$  is  $(j_{e_1}, \dots, j_{e_n})$ .

We refer to  $s_{\text{ext}}|_{[0, 2\pi]}$  as the restriction of  $s_{\text{ext}}$  to  $[0, 2\pi]$  so that  $s_{\text{ext}}|_{[0, 2\pi]} = s$ .

*Definition 3:* The quasiperiodic extension of the charge network  $s$  to  $\mathbf{R}$  is denoted by  $\bar{s}_{\text{ext}}$  and defined as follows. Given a charge network  $s = (\gamma(s), (j_{e_1}, \dots, j_{e_n}))$ ,  $\bar{s}_{\text{ext}}$  is specified by the graph  $\gamma(\bar{s}_{\text{ext}}) := \gamma(s)_{\text{ext}}$  and charge labels for each edge of  $\gamma(\bar{s}_{\text{ext}})$  which are such that  $T_N(\gamma(s)) \subset \gamma(\bar{s}_{\text{ext}})$  has the set of charges which are on  $\gamma$  augmented by  $2N\pi$ . Thus

- (1) On any closed interval  $I_N = [2N\pi, 2(N+1)\pi]$ ,  $N \in \mathbf{Z}$ ,  $\gamma(\bar{s}_{\text{ext}})|_{I_N}$  is naturally isomorphic to  $\gamma(s)$ .
- (2) The set of charges on  $\gamma(\bar{s}_{\text{ext}})|_{I_N}$  is  $(j_{e_1} + 2N\pi, \dots, j_{e_n} + 2N\pi)$ .

*Definition 4:* The action of periodic diffeomorphisms with period  $2\pi$  on  $\gamma_{\text{ext}}$ ,  $s_{\text{ext}}$ ,  $\bar{s}_{\text{ext}}$  may be defined as follows. Any periodic diffeomorphism  $\phi$  of  $\mathbf{R}$  commutes with the  $2\pi$  translations,  $T_N$ . Hence its natural action  $\phi(\gamma_{\text{ext}})$  on the extension  $\gamma_{\text{ext}}$  of graph  $\gamma$  preserves periodicity i.e.  $(\phi(\gamma_{\text{ext}})|_{[0, 2\pi]})_{\text{ext}} = \phi(\gamma_{\text{ext}})$ . Let the edge  $\phi(e) \in \phi(\gamma_{\text{ext}})$  be the image, by  $\phi$  of the edge  $e \in \gamma_{\text{ext}}$ . The action of  $\phi$  on the extensions  $s_{\text{ext}}$ ,  $\bar{s}_{\text{ext}}$  is defined by

- (i) mapping the underlying graph  $\gamma(s)_{\text{ext}}$  to  $\phi(\gamma(s)_{\text{ext}})$
- (ii) labeling the edge  $\phi(e) \in \phi(\gamma(s)_{\text{ext}})$  by the same charge as the edge  $e \in \gamma(s)_{\text{ext}}$  so that  $k_{\phi(e)} = k_e$ .

Denote the resulting periodic/quasiperiodic charge networks on  $\mathbf{R}$  by  $\phi(s_{\text{ext}})/\phi(\bar{s}_{\text{ext}})$

## B. Embedding sector

### 1. The \*-algebra

The elementary variables which generate the \*-Poisson algebra are,  $X^+(x)$ ,  $T_{s^+}[\Pi_+]$ ,  $X^-(x)$ ,  $T_{s^-}[\Pi_-]$ . Here  $T_{s^\pm}[\Pi_\pm]$  are the holonomy-type functions associated with the charge networks  $s^\pm$ , and are given by

$$T_{s^\pm}[\Pi_\pm] = \prod_{e^\pm \in \gamma(s^\pm)} \exp\left[-ik_{e^\pm}^\pm \int_{e^\pm} \Pi_\pm\right]. \quad (34)$$

The only nontrivial Poisson brackets are

$$\begin{aligned} \{X^\pm(x), T_{s^\pm}[\Pi_\pm]\} &= -ik_{e^\pm}^\pm T_{s^\pm}[\Pi_\pm] \\ \text{if } x \in \text{Interior}(e^\pm) &= -\frac{i}{2}(k_{e_{I^\pm}^\pm}^\pm + k_{e_{(I^\pm+1)^\pm}^\pm}^\pm) T_{s^\pm}^E[\Pi_\pm] \\ \text{if } x \in e_{I^\pm}^\pm \cap e_{(I^\pm+1)^\pm}^\pm & 1 \leq I^\pm \leq (n^\pm - 1) \\ \{X^\pm(0), T_{s^\pm}[\Pi_\pm]\} &= \{X^\pm(2\pi), T_{s^\pm}[\Pi_\pm]\} \\ &= -\frac{i}{2}(k_{e_1^\pm}^\pm + k_{e_{n^\pm}^\pm}^\pm) T_{s^\pm}[\Pi_\pm], \end{aligned} \quad (35)$$

where the last Poisson bracket uses the periodicity of the delta function. The \*-relations are given by

$$\begin{aligned} (X^\pm(x))^* &= X^\pm(x) \quad \forall x \in [0, 2\pi] \\ T_{s^\pm}[\Pi_\pm]^* &= T_{-s^\pm}[\Pi_\pm], -s^\pm \\ &= (\gamma(s^\pm), (-k_{e_1^\pm}^\pm, \dots, -k_{e_{n^\pm}^\pm}^\pm)) \end{aligned} \quad (36)$$

The action of finite gauge transformations on these elementary functions is as follows (we only analyze the right-moving sector; the analysis of the left-moving sector is identical).

From Eq. (18) we have

$$\alpha_{\phi^+} T_{s^+}[\Pi_+] = T_{s^+}[(\phi^+)_* \Pi_+]. \quad (37)$$

It is straightforward to check, using the periodicity of  $\phi^+$ ,  $\Pi_+$ ,  $s_{\text{ext}}^+$  and the various definitions in Sec. III A that

$$T_{s^+}[(\phi^+)_* \Pi_+] = T_{\phi^+(s_{\text{ext}}^+)|_{[0, 2\pi]}}[\Pi_+]. \quad (38)$$

Finite gauge transformations act on  $X^\pm$  as in Eqs. (16) and (18). To summarize, under finite gauge transformations the generators of the Poisson algebra transform as

$$\begin{aligned} \alpha_{\phi^\pm}(X^\pm(x)) &= X_{\text{ext}}^\pm((\phi^\pm)(x)) = X^\pm(y^\pm) \pm 2\pi N^\pm \\ \text{if } (\phi^\pm)(x) &= y^\pm + 2\pi N^\pm y^\pm \in [0, 2\pi] \\ \alpha_{\phi^\mp}(X^\pm(x)) &= X^\pm(x) \\ \alpha_{\phi^\pm}(T_{s^\pm}[\Pi_\pm]) &= T_{\phi^\pm(s_{\text{ext}}^\pm)|_{[0, 2\pi]}}[\Pi_\pm] \\ \alpha_{\phi^\mp}(T_{s^\pm}[\Pi_\pm]) &= T_{s^\pm}[\Pi_\pm] \end{aligned} \quad (39)$$

### 2. Representation of the \*-algebra

Denote the kinematic Hilbert space for the  $\pm$  embedding sectors by  $\mathcal{H}_E^\pm$ .  $\mathcal{H}_E^\pm$  is the closure of the span of the orthonormal basis of embedding ‘‘charge-network states’’. Each such state is labeled by a charge network  $s^\pm$  and denoted by  $T_{s^\pm}$ .<sup>2</sup> The inner product is

$$\langle T_{s^\pm}, T_{s'^\pm} \rangle = \delta_{s^\pm, s'^\pm} \quad (40)$$

where  $\delta_{s^\pm, s'^\pm}$  is a Kronecker delta function which is unity

<sup>2</sup>More precisely, the labeling is by the equivalence class of  $s^\pm$  as in Definition 1, Sec. III A

when the two charge networks are equivalent and vanishes otherwise.

The “ $\pm$ ” sector operators corresponding to the elementary functions of the previous section are denoted by  $\hat{X}^\pm(x)$ ,  $\hat{T}_{s^\pm}$ .  $\hat{T}_{s^\pm}$  acts on the charge-network states as

$$\hat{T}_{s^\pm T_{s'^\pm}} := T_{s^\pm + s'^\pm}, \quad (41)$$

where  $s^\pm + s'^\pm$  is the charge network obtained by choosing its underlying graph to be finer than  $\gamma(s^\pm)$ ,  $\gamma(s'^\pm)$  dividing  $\gamma(s^\pm)$ ,  $\gamma(s'^\pm)$  and assigning charge  $k_{e^\pm}^\pm + k_{e'^\pm}^\pm$  to  $e^\pm \cap e'^\pm$  where  $e^\pm \in \gamma(s^\pm)$ ,  $e'^\pm \in \gamma(s'^\pm)$ .

The action of  $\hat{X}^\pm(x)$  is

$$\hat{X}^\pm(x)T_{s^\pm} := \lambda_{x,s^\pm}T_{s^\pm}, \quad (42)$$

where, for  $\gamma(s^\pm)$  with  $n^\pm$  edges,

$$\lambda_{x,s^\pm} := \hbar k_{e^\pm}^\pm T_{s^\pm} \quad \text{if } x \in \text{Interior}(e_{I^\pm}^\pm),$$

$$1 \leq I^\pm \leq n^\pm := \frac{\hbar}{2}(k_{e_{I^\pm}^\pm}^\pm + k_{e_{(I^\pm+1)^\pm}^\pm}^\pm)T_{s^\pm} \quad (43)$$

$$\text{if } x \in e_{I^\pm}^\pm \cap e_{(I^\pm+1)^\pm}^\pm, 1 \leq I^\pm \leq (n^\pm - 1)$$

$$:= \frac{\hbar}{2} \left( k_{e_{n^\pm}^\pm}^\pm \mp \frac{2\pi}{\hbar} + k_{e_1^\pm}^\pm \right) T_{s^\pm} \quad \text{if } x = 0$$

$$:= \frac{\hbar}{2} \left( k_{e_1^\pm}^\pm \pm \frac{2\pi}{\hbar} + k_{e_{n^\pm}^\pm}^\pm \right) T_{s^\pm} \quad \text{if } x = 2\pi \quad (44)$$

The last two equations, (44), implement the boundary condition  $X^\pm(2\pi) - X^\pm(0) = \pm 2\pi$  [see (i) of Sec. II C 1.]

It is straightforward to check that Eqs. (41)–(44) provide a representation of the Poisson bracket algebra (35) so that quantum commutators equal  $i\hbar$  times the Poisson brackets. It is also straightforward to verify that the \*-relations (36) on  $\hat{X}^\pm(x)$ ,  $\hat{T}_{s^\pm}$  are implemented by the inner product (40) so that  $\hat{X}^\pm(x)$  are self-adjoint and  $\hat{T}_{s^\pm}$  are unitary.

### 3. Unitary representation of finite gauge transformations

Since the Hamiltonian flows of  $\alpha_{\phi^\pm}$  (18) are real, the corresponding quantum operators  $\hat{U}(\phi^\pm)$  must be unitary. Equations (18) and (19), imply that this unitary representation must satisfy

$$\hat{U}^\pm(\phi_1^\pm)\hat{U}^\pm(\phi_2^\pm) = \hat{U}^\pm(\phi_1^\pm \circ \phi_2^\pm)$$

$$\hat{U}^\pm(\phi^\pm)\hat{X}^\pm(x)\hat{U}^\pm(\phi^\pm)^{-1} = \hat{X}^\pm(y^\pm) \pm 2\pi N^\pm \quad (45)$$

$$\hat{U}^\pm(\phi^\pm)\hat{T}_{s^\pm}\hat{U}^\pm(\phi^\pm)^{-1} = \hat{T}_{\phi^\pm(s^\pm)_{\text{ext}}|_{[0,2\pi]}}$$

where  $\phi^\pm(x) = y^\pm + 2\pi N^\pm$ , with  $y^\pm \in [0, 2\pi]$  and  $N^\pm \in \mathbf{Z}$ .

We define the action of  $\hat{U}(\phi^\pm)$  to be

$$(\phi^\pm)T_{s^\pm} := T_{\phi(\bar{s}_{\text{ext}}^\pm)|_{[0,2\pi]}} \quad \hat{U}^\mp(\phi^\mp)T_{s^\pm} := T_{s^\pm}. \quad (46)$$

The appearance of the quasiperiodic extensions  $\bar{s}_{\text{ext}}^\pm$  of the charge networks  $s^\pm$  (see Definition 3, Sec. III A) in the first

equation above may be anticipated from the quasiperiodic nature of the embedding variables  $X^\pm(x)$  (15). Unitarity of  $\hat{U}^\pm(\phi^\pm)$  follows straightforwardly:

$$\langle \hat{U}^\pm(\phi^\pm)T_{s_1^\pm}, \hat{U}^\pm(\phi^\pm)T_{s_2^\pm} \rangle = \langle T_{\phi(\bar{s}_{\text{ext}}^\pm)|_{[0,2\pi]}} T_{\phi(\bar{s}_{\text{ext}}^\pm)|_{[0,2\pi]}} \rangle$$

$$= \delta_{\phi^\pm(\bar{s}_{\text{ext}}^\pm)|_{[0,2\pi]}, \phi^\pm(\bar{s}_{\text{ext}}^\pm)|_{[0,2\pi]}}$$

$$\forall \phi^\pm = \delta_{s_1^\pm, s_2^\pm} \quad (47)$$

where we have used the fact that two charge networks are equal on  $[0, 2\pi]$  iff their extensions are equal.

From Eq. (46) and Definitions 3,4 of Sec. III A, it follows that

$$\hat{U}^\pm(\phi_1^\pm)\hat{U}^\pm(\phi_2^\pm)T_{s^\pm} = T_{\phi_1^\pm(\overline{\phi_2^\pm(\bar{s}_{\text{ext}}^\pm)|_{[0,2\pi]}})_{\text{ext}}|_{[0,2\pi]}}$$

$$= T_{\phi_1^\pm(\phi_2^\pm(\bar{s}_{\text{ext}}^\pm))|_{[0,2\pi]}}$$

$$= T_{(\phi_1^\pm \circ \phi_2^\pm)(\bar{s}_{\text{ext}}^\pm)|_{[0,2\pi]}}$$

$$= \hat{U}^\pm(\phi_1^\pm \circ \phi_2^\pm)T_{s^\pm}, \quad (48)$$

thus verifying the first relation in (45).

Next, we turn to the second relation of (45). We sketch the proof for the “+” sector; the proof for the “−” sector is on similar lines. From (42) and (46) we have that

$$\hat{U}^+(\phi^+)\hat{X}^+(x)\hat{U}^+(\phi^+)^{-1}T_{s^+}$$

$$= \hat{U}^+(\phi^+)\hat{X}^+(x)T_{(\phi^+)^{-1}(\bar{s}_{\text{ext}}^+)|_{[0,2\pi]}} = \lambda_{x,(\phi^+)^{-1}(\bar{s}_{\text{ext}}^+)|_{[0,2\pi]}}T_{s^+}. \quad (49)$$

It is straightforward to see that

$$\lambda_{x,(\phi^+)^{-1}(\bar{s}_{\text{ext}}^+)|_{[0,2\pi]}} = \lambda_{y^+,s^+} + 2\pi N^+, \quad (50)$$

which via Eq. (42) obtains the desired result.

Finally, we turn to the last relation of (45). Once again, we sketch the proof for the “+” sector; the “−” sector proof follows analogously. We want to show that

$$\hat{U}^+(\phi^+)\hat{T}_{s^+}\hat{U}^+((\phi^+)^{-1}) = \hat{T}_{\phi^+(s_{\text{ext}}^+)|_{[0,2\pi]}}. \quad (51)$$

Since charge-network states form an orthonormal basis in the Hilbert space, it follows that (51) is equivalent to the condition that  $\forall s_1^+, s_2^+$

$$\langle T_{(\phi^+)^{-1}(\bar{s}_1^+)_{\text{ext}}|_{[0,2\pi]}} | \hat{T}_{s^+} | T_{(\phi^+)^{-1}(\bar{s}_2^+)_{\text{ext}}|_{[0,2\pi]}} \rangle$$

$$= \langle T_{s_1^+} | \hat{T}_{\phi^+(s_{\text{ext}}^+)|_{[0,2\pi]}} | T_{s_2^+} \rangle, \quad (52)$$

which from Eq. (41) is, in turn, equivalent to the equation

$$\delta_{(\phi^+)^{-1}(\bar{s}_1^+)_{\text{ext}}|_{[0,2\pi]}, s_1^+ + (\phi^+)^{-1}(\bar{s}_2^+)_{\text{ext}}|_{[0,2\pi]}} = \delta_{s_1^+, \phi^+(s_{\text{ext}}^+)|_{[0,2\pi]} + s_2^+}. \quad (53)$$

However, (suppressing the “+” superscript), we have that



$$\begin{aligned}
\delta \phi^{-1}(\bar{s}_1)_{\text{ext}}|_{[0,2\pi]} + \phi^{-1}(\bar{s}_2)_{\text{ext}}|_{[0,2\pi]} &= \delta \phi^{-1}(\bar{s}_1)_{\text{ext}} + \phi^{-1}(\bar{s}_2)_{\text{ext}} \\
&= \delta(\bar{s}_1)_{\text{ext}} \phi(s_{\text{ext}}) + (\bar{s}_2)_{\text{ext}} \\
&= \delta(s_1)_{\text{ext}} \phi(s_{\text{ext}}) + (s_2)_{\text{ext}} \\
&= \delta_{s_1, \phi(s_{\text{ext}})|_{[0,2\pi]} + s_2}
\end{aligned} \quad (54)$$

thus proving (51).

### C. Matter sector

#### 1. The \*-algebra

The \*-algebra is generated by the operators corresponding to the classical holonomies  $W_{s^\pm}[Y^\pm]$  which are defined as

$$W_{s^\pm}[Y^\pm] = \exp\left[ i \sum_{e^\pm \in E(\gamma(s^\pm))} l_{e^\pm}^\pm \int_{e^\pm} Y^\pm \right]. \quad (55)$$

Here  $s^\pm := \{\gamma(s^\pm), (l_{e_1^\pm}^\pm, \dots, l_{e_{m^\pm}^\pm}^\pm)\}$  are charge networks.

The algebra for the holonomy operators is the analog of the Weyl algebra for linear quantum fields. Similar to that case, we need to first evaluate the Poisson brackets,  $\{\sum_{e^\pm} l_{e^\pm}^\pm \int_{e^\pm} Y^\pm, \sum_{e'^\pm} l_{e'^\pm}^\pm \int_{e'^\pm} Y^\pm\}$ , between the exponents of pairs of classical holonomies and then use the Baker-Campbell-Hausdorff lemma [25] to define the algebra on the holonomy operators in quantum theory.

Let  $\kappa_e$  be the characteristic function associated with a closed interval  $e$  and denote the beginning and final points of  $e$  by  $b(e)$  and  $f(e)$  so that

$$\begin{aligned}
\kappa_e(x) &= 1 \quad \text{if } x \in \text{Interior}(e) \\
&= \frac{1}{2} \quad \text{if } x = b(e) \quad \text{or} \quad f(e)
\end{aligned} \quad (56)$$

$$\begin{aligned}
&= \frac{1}{2} \quad \text{if } x = 0 \quad \text{and} \quad f(e) = 2\pi \\
&= \frac{1}{2} \quad \text{if } x = 2\pi \quad \text{and} \quad b(e) = 0.
\end{aligned} \quad (57)$$

Here, Eqs. (57) follow from the periodicity of the delta function. From Eq. (9) it follows that

$$\begin{aligned}
\left\{ \int_{e^\pm} Y^\pm, \int_{e'^\pm} Y^\pm \right\} &= \pm \alpha(e^\pm, e'^\pm) \\
&:= \pm (\kappa_{e'^\pm}|_{\partial_{e^\pm}} - \kappa_{e^\pm}|_{\partial_{e'^\pm}}),
\end{aligned} \quad (58)$$

where  $\partial_e$  refers to the boundary of  $e$  and

$$\kappa_e|_{\partial_{e'}} := \kappa_e(f(e')) - \kappa_e(b(e')), \quad (59)$$

so that

$$\begin{aligned}
&\left\{ \sum_{e^\pm} l_{e^\pm}^\pm \int_{e^\pm} Y^\pm, \sum_{e'^\pm} l_{e'^\pm}^\pm \int_{e'^\pm} Y^\pm \right\} \\
&= \pm \sum_{e^\pm, e'^\pm} l_{e^\pm}^\pm l_{e'^\pm}^\pm \alpha(e^\pm, e'^\pm).
\end{aligned} \quad (60)$$

It follows that the “Weyl algebra” of holonomy operators is

$$\begin{aligned}
\hat{W}(s^\pm) \hat{W}(s'^\pm) &= \exp\left[ \mp \frac{i\hbar}{2} \alpha(s^\pm, s'^\pm) \right] \hat{W}(s^\pm + s'^\pm), \\
\hat{W}(s^\pm)^* &= \hat{W}(-s^\pm),
\end{aligned} \quad (61)$$

where

$$\alpha(s^\pm, s'^\pm) := \sum_{e^\pm \in \gamma(s^\pm)} \sum_{e'^\pm \in \gamma(s'^\pm)} l_{e^\pm}^\pm l_{e'^\pm}^\pm \alpha(e^\pm, e'^\pm), \quad (62)$$

with  $\alpha(e, e')$  defined through Eqs. (58) and (59). From the second equation of (9), it follows that the “+” and “−” holonomy operators commute, so that, once again, these sectors can be treated independently.

#### 2. Representation of the \*-algebra

It is convenient to define the quantum theory through the Gelfand- Naimark-Segal (GNS) construction [26]. The explicit operator action on the basis of charge-network states is provided after we present the GNS state.

We define the GNS states  $\omega_M^\pm$  on the  $\pm$  holonomy algebras by specifying their action on the holonomy operators as follows:

$$\omega_M^\pm(\hat{W}(s^\pm)) = \delta_{s^\pm, \circ}. \quad (63)$$

Here “ $\circ$ ” is the trivial charge network which may be represented by graph  $\gamma(\circ)$  consisting of the single edge  $e = [0, 2\pi]$  with vanishing charge  $l_e^\pm = 0$ . The Kronecker delta function  $\delta_{s^\pm, \circ}$  is unity iff  $s^\pm = \circ$  and vanishes otherwise. It follows from the GNS construction that the corresponding GNS Hilbert spaces  $\mathcal{H}_M^\pm$  are spanned by charge-network states denoted by  $W(s^\pm)$ . The inner product is

$$\langle W(s^\pm), W(s'^\pm) \rangle_\pm = \delta_{s^\pm, s'^\pm} \quad (64)$$

and the action of the holonomy operators is

$$\hat{W}(s^\pm) W(s'^\pm) = \exp\left[ \mp \frac{i\hbar \alpha(s^\pm, s'^\pm)}{2} \right] W(s^\pm + s'^\pm). \quad (65)$$

Here, as for the embedding sector,  $s^\pm + s'^\pm$  is defined as in (41).<sup>3</sup>

It is straightforward to check, explicitly, that Eq. (65) provides a representation for the first equation of (61). Verification of the second equation of (61) is equivalent to showing that  $\forall s^\pm, s'^\pm, s''^\pm$ ,

$$\langle W(s'^\pm), (\hat{W}(s^\pm))^\dagger W(s''^\pm) \rangle_\pm = \langle W(s'^\pm), \hat{W}(-s^\pm) W(s''^\pm) \rangle_\pm. \quad (66)$$

Equation (66) follows straightforwardly from (64) and (65). One needs to use the identity  $\delta_{s^\pm, -s'^\pm + s''^\pm} =$

<sup>3</sup>While our notation uses charge-network labels, the operators  $\hat{W}(s^\pm)$  and states  $W(s^\pm)$  only depend on the equivalence classes of labels. See also footnote 2 in this regard.

$\delta_{s^\pm + s'^\pm, s''^\pm}$  and the easily verifiable fact that  $\alpha(s^\pm, s'^\pm)$  is bilinear and antisymmetric in its arguments.

### 3. Unitary representation of finite gauge transformations

Since  $Y^\pm$  are periodic scalar densities, under finite gauge transformations their holonomies transform in a similar manner to those of the embedding momenta. Specifically, Eq. (18) in conjunction with the periodicity of  $\phi^\pm, Y^\pm, s_{\text{ext}}^\pm$  and the various definitions of section III A, imply that

$$\alpha_{\phi^\pm} W_{s^\pm}[Y^\pm] := W_{(\phi^\pm)(s_{\text{ext}}^\pm)|_{[0,2\pi]}}[Y^\pm]. \quad (67)$$

It is straightforward to see [either explicitly from Eq. (62) or abstractly using the fact that the periodicity of  $\phi^\pm, Y^\pm, s_{\text{ext}}^\pm$  implies that one is effectively restricting attention to diffeomorphisms, graphs, charge networks and holonomies on  $S^1$ ] that

$$\alpha(s^\pm, s'^\pm) = \alpha(\phi^\pm(s_{\text{ext}}^\pm)|_{[0,2\pi]}, \phi^\pm(s'_{\text{ext}})|_{[0,2\pi]}). \quad (68)$$

Equations (65) and (68) imply that the Hamiltonian flow of (67) induces an automorphism of the Weyl algebra of holonomies. Note also that Eq. (63) is invariant under the action of this automorphism. This directly implies that the group of finite gauge transformations is unitarily represented in the quantum theory. Let these unitary operators be denoted, as in the embedding sector, by  $\hat{U}^\pm(\phi^\pm)$ . Their explicit action on the charge-network basis can be defined from the GNS construction to be

$$\hat{U}^\pm(\phi^\pm)W(s^\pm) := W((\phi^\pm)(s_{\text{ext}}^\pm)|_{[0,2\pi]}). \quad (69)$$

### D. The kinematic Hilbert space

The kinematic Hilbert space  $\mathcal{H}_{\text{kin}}^\pm$  is the product of the Hilbert spaces  $\mathcal{H}_{\text{kin}}^\pm$  with

$$\mathcal{H}_{\text{kin}}^\pm = (\mathcal{H}_E^\pm \otimes \mathcal{H}_M^\pm) \quad (70)$$

so that

$$\mathcal{H}_{\text{kin}} = (\mathcal{H}_E^+ \otimes \mathcal{H}_M^+) \otimes (\mathcal{H}_E^- \otimes \mathcal{H}_M^-). \quad (71)$$

$\mathcal{H}_{\text{kin}}^\pm$  is spanned by an orthonormal basis of equivalence classes of charge-network states of the form  $T_{s^\pm} \otimes W(s'^\pm)$  with  $s^\pm = \{\gamma(s^\pm), (k_{e_1^\pm}, \dots, k_{e_{n^\pm}^\pm})\}$ ,  $s'^\pm = \{\gamma(s'^\pm), (l_{e_1'^\pm}, \dots, l_{e_{m'^\pm}^\pm})\}$ .

The results of the previous subsections show that  $\mathcal{H}_{\text{kin}}$  supports a \*-representation of the \*-algebras for the matter and embedding degrees of freedom, as well as a unitary representation of finite gauge transformations.

Consider, as above, the state  $T_{s^\pm} \otimes W(s'^\pm)$ . The equivalence relation between charge networks is defined in Definition 1, Sec. III A. Using this equivalence, it is straightforward to see that we can always choose  $s^\pm, s'^\pm$  such that  $\gamma(s^\pm) = \gamma(s'^\pm)$ . Then each edge  $e^\pm$  of  $\gamma(s^\pm)$  is labeled by a pair of real charges  $(k_e^\pm, l_e^\pm)$ . Note that such a choice of graph and charge pairs is not unique. However, it

is easy to see that a unique choice can be made if we require that the pairs of charges,  $(k_{e^\pm}, l_{e^\pm})$ , are such that no two consecutive edges are labeled by the same pair of charges. We shall denote this unique labeling by  $\mathbf{s}^\pm$  so that

$$\mathbf{s}^\pm := \{\gamma(\mathbf{s}^\pm), (k_{e_1^\pm}, l_{e_1^\pm}), \dots, (k_{e_{n^\pm}^\pm}, l_{e_{n^\pm}^\pm})\}, \quad (72)$$

with

$$k_{e_{t^\pm}^\pm} \neq k_{e_{(t^\pm+1)}^\pm} \quad \text{or/and} \quad l_{e_{t^\pm}^\pm} \neq l_{e_{(t^\pm+1)}^\pm}. \quad (73)$$

The corresponding charge-network state is denoted by  $|\mathbf{s}^\pm\rangle$  so that

$$|\mathbf{s}^\pm\rangle = T_{s^\pm} \otimes W(s'^\pm) \quad (74)$$

with  $\mathbf{s}^\pm$  defined from  $s^\pm, s'^\pm$  in the manner discussed above. It follows from (46) and (69) that  $\hat{U}^\pm(\phi^\pm)$  maps  $|\mathbf{s}^\pm\rangle$  to a new charge-network state. We denote the new (unique) charge-network label by  $\mathbf{s}_{\phi^\pm}^\pm$  so that

$$|\mathbf{s}_{\phi^\pm}^\pm\rangle := \hat{U}^\pm(\phi^\pm)|\mathbf{s}^\pm\rangle. \quad (75)$$

## IV. UNITARY REPRESENTATION OF DIRAC OBSERVABLES

### A. Exponentials of mode functions

Whereas  $a_{(\pm)n}$  (23) depend on  $Y^\pm(x)$ , the basic operators of quantum theory are the holonomies  $\hat{W}(s^\pm)$ . As in LQG, the representation of the holonomy operators on  $\mathcal{H}_{\text{kin}}$  is not regular enough to allow a definition of  $\hat{Y}^\pm(x)$  via a ‘‘shrinking of edges’’ procedure [3]. For example, let  $s^\pm(t)$  be a 1 parameter family of charge networks such that  $\gamma(s^\pm(t))$  has non-vanishing unit charge on only one of its edges. Let this edge contain  $x$  and let its coordinate length be  $t$ . Whereas, classically,  $Y^\pm(x) = \lim_{t \rightarrow 0} \frac{W(s^\pm(t)) - 1}{it}$ , it is easy to check that, as in LQG, the corresponding operators are not weakly continuous in  $t$  and the limit cannot be defined on the charge-network basis. This leads to a regularization dependence in the definition of  $\hat{a}_{(\pm)n}$  [3]. However, as we show below, suitably defined exponential functions of  $a_{(\pm)n}, a_{(\pm)n}^*$  can be promoted to quantum operators in a regularization/triangulation independent manner. Let  $q_n, p_n$  be the real and imaginary parts of  $a_{(\pm)n}$  so that

$$\begin{aligned} q_{(\pm)n} &= \int_{S^1} Y^\pm(x) \cos(nX^\pm(x)), \\ p_{(\pm)n} &= \int_{S^1} Y^\pm(x) \sin(nX^\pm(x)), \end{aligned} \quad (76)$$

and consider the functions

$$\begin{aligned} e^{i\alpha q_{(\pm)n}} &= e^{i\alpha \int_{S^1} Y^\pm(x) \cos(nX^\pm(x))} \\ e^{i\beta p_{(\pm)n}} &= e^{i\beta \int_{S^1} Y^\pm(x) \sin(nX^\pm(x))} \end{aligned} \quad (77)$$

where  $\alpha, \beta \in \mathbf{R}$ . These functions can be promoted to quantum operators as follows.

Let  $f(X^\pm)$  be a smooth periodic *real* function of  $X^\pm$ . Then  $O_f^\pm := \int_{S^1} Y^\pm(x) f(X^\pm(x))$  are functions on the phase space of PFT. Next, restrict attention to the embedding sector Hilbert space  $\mathcal{H}_E^\pm$  and consider the operator valued (on  $\mathcal{H}_E^\pm$ ) function on the matter phase space,  $O_f^\pm := \int_{S^1} Y^\pm(x) f(\hat{X}^\pm(x))$ . Since charge-network states are eigenstates of the embedding operator, we have that

$$O_f^\pm T_{s^\pm} = \left( \sum_{i=1}^{n^\pm} f(\hbar k_{e_i^\pm}^\pm) \int_{e_i^\pm} Y^\pm(x) \right) T_{s^\pm}, \quad (78)$$

where  $s^\pm = \{\gamma(s^\pm), (k_{e_1^\pm}^\pm, \dots, k_{e_{n^\pm}^\pm}^\pm)\}$  and that

$$\begin{aligned} e^{iO_f^\pm} T_{s^\pm} &= e^{i \sum_{i=1}^{n^\pm} f(\hbar k_{e_i^\pm}^\pm) \int_{e_i^\pm} Y^\pm(x)} T_{s^\pm}, \\ &= W(s_f^\pm) [Y^\pm] T_{s^\pm}, \end{aligned} \quad (79)$$

where  $s_f^\pm := \{\gamma(s^\pm), (f(\hbar k_{e_1^\pm}^\pm), \dots, f(\hbar k_{e_{n^\pm}^\pm}^\pm))\}$ . Equation (79)

implies that we can define the operators  $\widehat{\text{exp}iO_f^\pm}$  corresponding to the functions  $\text{exp}iO_f^\pm$  via their action on the charge-network states  $T_{s^\pm} \otimes W(s'^\pm) \in \mathcal{H}^\pm$ :

$$(\widehat{\text{exp}iO_f^\pm}) T_{s^\pm} \otimes W(s'^\pm) := T_{s^\pm} \otimes \widehat{W}(s_f^\pm) W(s'^\pm). \quad (80)$$

Clearly, this is a manifestly regularization/triangulation independent definition. Moreover, since  $s_f^\pm$  is constructed from the embedding part of the charge network, and since  $f$  is periodic, it is straightforward to check that  $e^{iO_f^\pm}$  commute with the unitary operators corresponding to finite gauge transformations. Hence  $e^{iO_f^\pm}$  are Dirac observables in quantum theory. It is also easy to check that

$$(\widehat{\text{exp}iO_f^\pm})^\dagger = (\widehat{\text{exp}iO_f^\pm})^{-1} = (\widehat{\text{exp}iO_{-f}^\pm}) \quad (81)$$

so that the classical reality conditions are implemented.

By setting  $f$  to be the appropriate cosine (sine) function times  $\alpha$  ( $\beta$ ), we obtain the operators corresponding to the functions in Eq. (77). Clearly, these operators ( $\forall \alpha, \beta \in \mathbf{R}, n > 0$ ) form an over-complete set of Dirac observables.

## B. Conformal isometries

Regularization dependence also manifests in attempts to promote the generators of conformal isometries,  $\Pi^\pm[U^\pm]$  [see Eq. (26)], to operators on  $\mathcal{H}_{\text{kin}}$ . Choosing exponentials of these observables only partially alleviates this problem since (unlike the case of  $a_{(\pm)n}$ ) the resulting operator suffers from operator ordering problems stemming from the fact that  $\{\Pi_\pm(x), U^\pm(X^\pm(x))\} \neq 0$ . Therefore, we focus on the Hamiltonian flows corresponding to finite conformal isometries.

The action of the Hamiltonian flows (corresponding to conformal isometries),  $\alpha_{\phi_c^\pm}$ , on  $(X^\pm(x), Y^\pm(x))$  has been detailed in Sec. IID 3. It remains to specify their action on the embedding momenta,  $\Pi_\pm(x)$ . The information in this specification can equally well be seeded in the action of  $\alpha_{\phi_c^\pm}$  on the Hamiltonian flows  $\alpha_{\phi_c^\pm}$  corresponding to finite gauge transformations by virtue of the facts that (a) the constraints (10) are linear in the embedding momenta and (b) this linear dependence is invertible by virtue of the non-degeneracy condition (iv) of section IIC 1. Thus  $\alpha_{\phi_c^\pm}$  are completely specified through Eqs. (31)–(33). Accordingly, we seek a unitary representation of  $\alpha_{\phi_c^\pm}$  by operators  $\hat{V}(\phi_c^\pm)$  such that  $\hat{V}^\pm(\phi_c^\pm)$  act trivially on the matter sector, commute with the operators  $\hat{U}^+(\phi^+)$  and  $\hat{U}^-(\phi^-)$  which implement gauge transformations, and transform  $\hat{X}^\pm(x)$  through

$$\hat{V}^\pm(\phi_c^\pm) \hat{X}^\pm(x) (\hat{V}^\pm)^\dagger(\phi_c^\pm) = \phi_c^\pm(\hat{X}^\pm(x)), \quad (82)$$

while leaving  $\hat{X}^\mp(x)$  invariant.

We define  $\hat{V}^\pm(\phi_c^\pm)$  to act trivially on the matter Hilbert spaces  $\mathcal{H}_M^+$ ,  $\mathcal{H}_M^-$  and on the  $\mp$  embedding Hilbert space  $\mathcal{H}_E^\mp$ . The action of  $\hat{V}^\pm(\phi_c^\pm)$  on  $\mathcal{H}_E^\pm$  is defined as follows. Let  $s = \{\gamma(s)(k_{e_1^\pm}^\pm, \dots, k_{e_n^\pm}^\pm)\}$  be a charge network. Define the charge networks  $\phi_c^+(s^+)$ ,  $\phi_c^-(s^-)$  by

$$\phi_c^\pm(s^\pm) := \{\gamma(s^\pm), (\phi_c^\pm(k_{e_1^\pm}^\pm), \dots, \phi_c^\pm(k_{e_n^\pm}^\pm))\}. \quad (83)$$

Then the action of  $\hat{V}(\phi_c^\pm)$  on the charge-network state  $T_{s^\pm} \in \mathcal{H}_E^\pm$  is defined to be

$$\hat{V}^\pm[\phi_c^\pm] T_{s^\pm} = T_{(\phi_c^\pm)^{-1}(s^\pm)}. \quad (84)$$

To reiterate, in the notation (83) we have that  $(\phi_c^\pm)^{-1} \times (s^\pm) = \{\gamma(s^\pm), ((\phi_c^\pm)^{-1}(k_{e_1^\pm}^\pm), \dots, (\phi_c^\pm)^{-1}(k_{e_n^\pm}^\pm))\}$ .

From Eq. (84), the invertibility of the functions  $\phi_c^\pm$  [which follows from Eq. (29)] and the inner product (40), it follows that  $\langle \hat{V}^\pm[\phi_c^\pm] T_{s^\pm} | \hat{V}^\pm[\phi_c^\pm] T_{s'^\pm} \rangle = \langle T_{s^\pm} | T_{s'^\pm} \rangle \forall s^\pm, s'^\pm$ , thus showing unitarity. It is also straightforward to check, using the quasiperiodicity of the functions  $\phi_c^\pm$  (30), that  $\hat{V}^\pm[\phi_c^\pm]$  commutes with  $\hat{U}(\phi^\pm)$ . By definition  $\hat{V}^\pm[\phi_c^\pm]$  commutes with  $\hat{U}(\phi^\mp)$  and with the matter holonomies. Finally, it is easy to check that Eq. (82) holds when applied on any charge-network state. Thus, our definition of  $\hat{V}^\pm[\phi_c^\pm]$  provides a satisfactory definition of conformal isometries in quantum theory.

Note also that Eq. (84) implies that

$$\hat{V}^\pm[\phi_{1c}^\pm] \hat{V}^\pm[\phi_{2c}^\pm] = \hat{V}^\pm[\phi_{2c}^\pm \circ \phi_{1c}^\pm], \quad (85)$$

so that our definition of  $\hat{V}^\pm[\phi_c^\pm]$  implies an anomaly free representation (by right multiplication) of the group of conformal isometries.

## V. PHYSICAL STATE SPACE BY GROUP AVERAGING

Only gauge invariant states are physical so that physical states  $\Psi$  must satisfy the condition  $\hat{U}^\pm(\phi^\pm)\Psi = \Psi, \forall \phi^\pm$ . A formal solution to this condition is to fix some  $|\psi\rangle \in \mathcal{H}_{\text{kin}}$  and set  $\Psi = \sum |\psi'\rangle$  where the sum is over all distinct  $|\psi'\rangle$  which are gauge related to  $\psi$ . A mathematically precise implementation of this idea places the gauge invariant states in the dual representation (corresponding to a formal sum over bras rather than kets) and goes by the name of group averaging. The ‘‘group’’ is that of gauge transformations and the ‘‘averaging’’ corresponds to the construction of a gauge invariant state from a kinematical one by giving meaning to the formal sum over gauge related states. Specifically (for details see Ref. [9]), the physical Hilbert space can be constructed if there exists an antilinear map  $\eta$  from a dense subspace  $\mathcal{D}$  of the kinematical Hilbert space  $\mathcal{H}_{\text{kin}}$ , to its algebraic dual  $\mathcal{D}^*$ , subject to certain requirements. The algebraic dual of  $\mathcal{D}$  is defined to be the space of linear mappings from  $\mathcal{D}$  to the complex numbers. The requirements which  $\eta$  needs to satisfy are as follows. Let  $\psi_1, \psi_2 \in \mathcal{D}$ , let  $\hat{A}$  be a Dirac observable of interest and let  $\phi^\pm$  be a gauge transformation with  $\hat{U}^\pm(\phi^\pm)$  being its unitary implementation on  $\mathcal{H}_{\text{kin}}$ . Let  $\eta(\psi_1) \in \mathcal{D}^*$  denote the image of  $\psi_1$  by  $\eta$  and let  $\eta(\psi_1)[\psi_2]$  denote the complex number obtained by the action of  $\eta(\psi_1)$  on  $\psi_2$ . Then for all  $\psi_1, \psi_2, \hat{A}, \phi$  we require that

- (1)  $\eta(\psi_1)[\psi_2] = \eta(\psi_1)[\hat{U}(\phi)\psi_2]$
- (2)  $\eta(\psi_1)[\psi_2] = (\eta(\psi_2)[\psi_1])^*, \eta(\psi_1)[\psi_1] \geq 0$ .
- (3)  $\eta(\psi_1)[\hat{A}\psi_2] = \eta(\hat{A}\psi_1)[\psi_2]$ .

Here, we choose  $\mathcal{D}$  to be the finite span of charge-network states. Clearly due to the split of ‘‘+’’ and ‘‘-’’ structures, we may consider averaging maps  $\eta^\pm$  on the dense sets  $\mathcal{D}^\pm \subset \mathcal{H}_{\text{kin}}^\pm$  separately. Here  $\mathcal{D}^\pm$  is the finite span of states of the form  $|\mathbf{s}^\pm\rangle$  (see Sec. III D for the notation used here and below). Define the action of  $\eta^\pm$  on  $|\mathbf{s}^\pm\rangle$  as

$$\begin{aligned} \eta^\pm(|\mathbf{s}^\pm\rangle) &= \eta_{[\mathbf{s}^\pm]} \sum_{\mathbf{s}'^\pm \in [\mathbf{s}^\pm]} \langle \mathbf{s}'^\pm | \\ &= \eta_{[\mathbf{s}^\pm]} \sum_{\phi^\pm \in \text{Diff}_{[\mathbf{s}^\pm]}^P \mathbf{R}} \langle \mathbf{s}_{\phi^\pm}^\pm |, \end{aligned} \quad (86)$$

where  $[\mathbf{s}^\pm] = \{\mathbf{s}'^\pm | \mathbf{s}'^\pm = \mathbf{s}_{\phi^\pm}^\pm \text{ for some } \phi^\pm\}$ ,  $\text{Diff}_{[\mathbf{s}^\pm]}^P \mathbf{R}$  is a set of gauge transformations such that for each  $\mathbf{s}'^\pm \in [\mathbf{s}^\pm]$  there is precisely one gauge transformation in the set which maps  $\mathbf{s}^\pm$  to  $\mathbf{s}'^\pm$  and  $\eta_{[\mathbf{s}^\pm]}$  is a positive real number depending only on the gauge orbit  $[\mathbf{s}^\pm]$ . The right-hand side of Eq. (86) inherits an action on states in  $\mathcal{D}$  from that of each of its summands. Because of the inner product (40) and (64), only a finite number of terms in the sum contribute so that  $\eta^\pm(|\mathbf{s}^\pm\rangle)$  is indeed in  $\mathcal{D}^*$ . It is straightforward to see that  $\eta^\pm$  satisfies the requirements (1), (2) and that a positive definite inner product  $\langle, \rangle_{\text{phys}}$  on the space

$\eta^\pm(\mathcal{D}^\pm)$  can be defined through

$$\langle \eta^\pm(|\mathbf{s}_1^\pm\rangle), \eta^\pm(|\mathbf{s}_2^\pm\rangle) \rangle_{\text{phys}} = \eta^\pm(|\mathbf{s}_1^\pm\rangle)[|\mathbf{s}_2^\pm\rangle]. \quad (87)$$

If in addition, (3) is also satisfied by  $\eta^\pm$ , the group averaging technique guarantees that the above inner product automatically implements the adjointness conditions on the Dirac observables (which act by dual action on  $\mathcal{D}^{\pm*}$ )<sup>4</sup> of Sec. IV, by virtue of the fact that these conditions are implemented on  $\mathcal{H}_{\text{kin}}$ .

In Sec. V B we use the requirement (3) to constrain the positive real numbers  $\eta_{[\mathbf{s}^\pm]}$  and thus bring down the enormous ambiguity in the inner product (87). While the analysis can be done, in principle, for all of  $\eta^\pm[\mathcal{D}^\pm]$ , we shall, for simplicity, restrict attention to a certain subspace of  $\mathcal{D}^\pm$  which is left invariant by finite gauge transformations as well as the Dirac observables of Sec. IV. In Sec. V A we define this ‘‘superselected’’ subspace. Finally, in Sec. V C we display a cyclic representation of the operator algebra generated by the Dirac observables in conjunction with the gauge transformations.

### A. The chosen subspace of $\mathcal{D}$

Consider the charge-network state  $T_{s^\pm} \otimes W_{s'^\pm}$ . Let  $\gamma(s^\pm)$  have  $n^\pm$  edges and let the embedding charges on these edges be such that

- (a)  $\pm k_{e_{I^\pm}}^\pm \geq \pm k_{e_{(I^\pm-1)}}^\pm \quad I^\pm = 2, \dots, n^\pm$ .
- (b)  $\pm(k_{e_{n^\pm}}^\pm - k_{e_1}^\pm) \leq \frac{2\pi}{\hbar}$ .

These conditions are physically motivated. Conditions (a), (b) are the quantum analogs of the classical nondegeneracy condition (iv) of Sec. II C 1. when  $x \in (0, 2\pi)$ , and when  $x \in \{0, 2\pi\}$ , respectively.

Henceforth we shall restrict attention to charge-network states subject to (a) and (b). Note that these conditions define a superselection sector of  $\mathcal{D}$  with respect to gauge transformations as well as the observables of Sec. IV. We will refer to this subspace as  $\mathcal{D}_{(a)(b)}$ .

### B. Commutativity of $\eta^\pm$ with Dirac observables

We focus on the ‘‘+’’ case and suppress the ‘‘+’’ superscripts wherever possible. The ‘‘-’’ case follows analogously. We aim to restrict  $\eta_{[\mathbf{s}]}$  by subjecting it to condition

(3) above. We choose  $\hat{A} := e^{iO_f^+}$  [recall, from Sec. IV A, that  $O_f^+ := \int_{S^1} Y^+(x)f(X^+(x))$ ]. Thus we require that  $\forall \mathbf{s}$ ,

$$e^{i \int \widehat{Y^+ f(X^+)}} \eta(|\mathbf{s}\rangle) = \eta\left(e^{i \int \widehat{Y^+ f(X^+)}} |\mathbf{s}\rangle\right). \quad (88)$$

As in Eq. (74) we set  $|\mathbf{s}^\pm\rangle = T_{s^\pm} \otimes W(s'^\pm)$ . The equivalence relation between charge-network labels allows us,

<sup>4</sup>Given  $\Psi^\pm \in \mathcal{D}^{\pm*}$ ,  $\psi^\pm \in \mathcal{D}^\pm$  and  $\hat{A}_\pm$  such that  $\hat{A}_\pm^\dagger \psi^\pm \in \mathcal{D}^\pm$ , define  $\hat{A}_\pm \Psi^\pm$  through  $\hat{A}_\pm \Psi^\pm[\psi^\pm] := \Psi^\pm[\hat{A}_\pm^\dagger \psi^\pm]$ . This is the dual action.

without loss of generality, to choose  $\gamma(\mathbf{s}) = \gamma(s) = \gamma(s')$ . Equations (62), (65), and (80) imply that

$$e^i \int \widehat{Y^{+f(X^+)}} |\mathbf{s}\rangle = \widehat{W}_{s_f} |\mathbf{s}\rangle := e^{-(i\hbar\alpha(s_f, s')/2)} |\mathbf{s}(f)\rangle, \quad (89)$$

where

$$\mathbf{s} = \{\gamma(\mathbf{s}), ((k_{e_1}, l_{e_1}), \dots, (k_{e_n}, l_{e_n}))\}, \quad (90)$$

$$s' = \{\gamma(\mathbf{s}), (l_{e_1}, \dots, l_{e_n})\}, \quad (91)$$

$$s_f = \{\gamma(\mathbf{s}), (f(\hbar k_{e_1}), \dots, f(\hbar k_{e_n}))\}, \quad (92)$$

$$\mathbf{s}(f) = \{\gamma(\mathbf{s}), ((k_{e_1}, l_{e_1} + f(\hbar k_{e_1})), \dots, (k_{e_n}, l_{e_n} + f(\hbar k_{e_n})))\}, \quad (93)$$

$$\alpha(s_f, s') = \sum_{I=1}^n f(\hbar k_{e_I}) [l_{e_{I+1}} - l_{e_{I-1}}], \quad (94)$$

$$e_0 := e_n, \quad e_{n+1} := e_1.$$

Recall (see Sec. III D) that  $\mathbf{s}$  denotes the unique labelling such that no two consecutive edges of  $\gamma(\mathbf{s})$  have the same pair of charges. It is straightforward to see from Eq. (94) that for  $I = 1, \dots, n-1$ ,

$$k_{e_I} \neq k_{e_{I+1}} \quad \text{or/and} \quad l_{e_I} \neq l_{e_{I+1}} \Rightarrow k_{e_I} \neq k_{e_{I+1}} \quad (95)$$

or/and  $l_{e_I} + f(\hbar k_{e_I}) \neq l_{e_{I+1}} + f(\hbar k_{e_{I+1}})$ .

Thus, consistent with the use of bold face notation (see Sec. III D),  $\mathbf{s}(f)$  is also the unique labeling such that no two consecutive edges of its underlying graph [also chosen to be  $\gamma(\mathbf{s})$ ] have the same pair of charges.

From footnote 4 (68) and (89), the fact that  $e^i \int \widehat{Y^{+f(X^+)}}$  commutes with gauge transformations, and (86), it follows that the left-hand side of (88) is

$$e^i \int \widehat{Y^{+f(X^+)}} \eta(|\mathbf{s}\rangle) = \eta_{[\mathbf{s}]} e^{(i\hbar\alpha(s_f, s')/2)} \sum_{\phi \in \text{Diff}_{[\mathbf{s}]}^P \mathbf{R}} \langle \mathbf{s}(f) | \phi \rangle. \quad (96)$$

and that the right-hand side of (88) is

$$\eta(e^i \int \widehat{Y^{+f(X^+)}} |\mathbf{s}\rangle) = \eta_{[\mathbf{s}(f)]} e^{(i\hbar\alpha(s_f, s')/2)} \sum_{\phi \in \text{Diff}_{[\mathbf{s}(f)]}^P \mathbf{R}} \langle \mathbf{s}(f) | \phi \rangle \quad (97)$$

where  $|\mathbf{s}(f) | \phi \rangle := \widehat{U}(\phi) |\mathbf{s}(f)\rangle$ . Thus we need to impose

$$\eta_{[\mathbf{s}]} \sum_{\phi \in \text{Diff}_{[\mathbf{s}]}^P \mathbf{R}} \langle \mathbf{s}(f) | \phi \rangle = \eta_{[\mathbf{s}(f)]} \sum_{\phi \in \text{Diff}_{[\mathbf{s}(f)]}^P \mathbf{R}} \langle \mathbf{s}(f) | \phi \rangle \quad (98)$$

It is easy to see that we may choose

$$\text{Diff}_{[\mathbf{s}]}^P \mathbf{R} = \text{Diff}_{[\mathbf{s}(f)]}^P \mathbf{R}. \quad (99)$$

This immediately follows from the fact that

$$\widehat{U}(\phi) e^{iO_f^+} |\mathbf{s}\rangle \neq e^{iO_f^+} |\mathbf{s}\rangle \quad \text{iff} \quad \widehat{U}(\phi) |\mathbf{s}\rangle \neq |\mathbf{s}\rangle. \quad (100)$$

Equation (100) follows, in turn, from the invertibility of  $e^{iO_f^+}$  (81) and its commutativity with  $\widehat{U}(\phi)$ . Equations (98) and (99) imply that

$$\eta_{[\mathbf{s}]} = \eta_{[\mathbf{s}(f)]}. \quad (101)$$

Next, we analyze the consequences of the restriction (101). There are 2 cases:

Case 1:  $[\mathbf{s}]$  is such that there exists some  $\mathbf{s} \in [\mathbf{s}]$ ,  $\mathbf{s} = \{\gamma(\mathbf{s}), ((k_{e_1}, l_{e_1}), \dots, (k_{e_n}, l_{e_n}))\}$  with

$$k_{e_1} < k_{e_2} < \dots < k_{e_n}, \quad (k_{e_n} - k_{e_1}) < 2\pi. \quad (102)$$

Case 2: The complement of Case 1.

We have analyzed both cases. The analysis for Case 2 is quite involved and, in the interests of pedagogy, we do not present it here. We shall focus only on Case 1 in this paper. Accordingly, consider  $\mathbf{s}$  as in Case 1. We define  $\tilde{\mathbf{s}}$  to be the *embedding* charge-network label which is obtained by dropping the matter charge labels from  $\mathbf{s}$  so that  $\gamma(\tilde{\mathbf{s}}) = \gamma(\mathbf{s})$  with the edges of  $\gamma(\tilde{\mathbf{s}})$  carrying the same embedding charges as in  $\mathbf{s}$ . Since  $\mathbf{s}$ ,  $\mathbf{s}(f)$  have the same embedding charges and the same underlying graph, we could equally well have obtained  $\tilde{\mathbf{s}}$  by dropping the matter charge labels from  $\mathbf{s}(f)$ . Thus, using the ‘‘ $\tilde{\phantom{x}}$ ’’ notation, we have that

$$\tilde{\mathbf{s}} = \tilde{\mathbf{s}}(f) = (\gamma(\mathbf{s}), (k_{e_1}, \dots, k_{e_n})). \quad (103)$$

Next, note that we can always choose  $f$  such that  $f(\hbar k_{e_I}) = -l_{e_I}$ ,  $I = 1, \dots, n$  so that  $\mathbf{s}(f)$  has vanishing matter charges. Clearly the property that all matter charges vanish is a gauge invariant statement. This fact together with Eq. (103) implies that the set  $[\mathbf{s}(f)]$  (with  $f$  chosen as above) is isomorphic to the set of *embedding* charge networks which are gauge equivalent to  $\tilde{\mathbf{s}}$ . Denoting the latter set by  $[\tilde{\mathbf{s}}]$  we have, from Eq. (101) that  $\eta_{[\mathbf{s}]}$  can only depend on the set  $[\tilde{\mathbf{s}}]$ . We denote this dependence through the notation

$$\eta_{[\tilde{\mathbf{s}}]} := \eta_{[\mathbf{s}]}. \quad (104)$$

An identical analysis holds for the conformal isometry operators  $\widehat{V}(\phi_c)$ . Equation (84) implies that

$$\widehat{V}(\phi_c) |\mathbf{s}\rangle =: |\phi_c^{-1}(\mathbf{s})\rangle. \quad (105)$$

$\mathbf{s}$  is given by Eqs. (90) and (102), and

$$\phi_c^{-1}(\mathbf{s}) = \{\gamma(\mathbf{s}), ((\phi_c^{-1}(k_{e_1}), l_{e_1}), \dots, (\phi_c^{-1}(k_{e_n}), l_{e_n}))\}. \quad (106)$$

The invertibility of  $\phi_c$  and its quasiperiodicity imply that  $\phi_c^{-1}(\mathbf{s})$  is the unique labeling such that no two consecutive edges have the same pairs of charges, and that the condition (102) is preserved by the action of  $\widehat{V}(\phi_c)$ .

Condition (3) implies that, in obvious notation,

$$\begin{aligned} \eta_{[s]} \sum_{\phi \in \text{Diff}_{[s]}^p \mathbf{R}} &< \phi_c^{-1}(\mathbf{s}) | \hat{U}^\dagger(\phi) \\ &= \eta_{[\phi_c^{-1}(\mathbf{s})]} \sum_{\phi \in \text{Diff}_{[\phi_c^{-1}(\mathbf{s})]}^p \mathbf{R}} < \phi_c^{-1}(\mathbf{s}) | \hat{U}^\dagger(\phi). \end{aligned} \quad (107)$$

An argument identical to that in (100) implies that  $\text{Diff}_{[s]}^p \mathbf{R} = \text{Diff}_{[\phi_c^{-1}(\mathbf{s})]}^p \mathbf{R}$  so that

$$\eta_{[s]} = \eta_{[\phi_c^{-1}(\mathbf{s})]}. \quad (108)$$

Clearly, given any pair of charge networks  $\mathbf{s}_1, \mathbf{s}_2$  as in Case 1, with  $\gamma(\mathbf{s}_1) = \gamma(\mathbf{s}_2)$  and with identical matter charges, there exists some  $\phi_c$  such that  $|\mathbf{s}_2\rangle = \hat{V}(\phi_c)|\mathbf{s}_1\rangle$ . This, in conjunction with Eqs. (104) and (108), implies that  $\eta_{[s]}$  can only depend on the set of graphs  $[\gamma(\mathbf{s})]$  which are obtained by the action of gauge transformations on  $\gamma(\mathbf{s})$ . Specifically,

$$[\gamma(\mathbf{s})] = \{\gamma' \text{ s.t. } \exists \phi \text{ s.t. } \gamma'_{\text{ext}} = \phi(\gamma_{\text{ext}})\} \quad \gamma := \gamma(\mathbf{s}), \quad (109)$$

where we have used the notation defined in Sec. III A. We denote this dependence of  $\eta_{[s]}$  through the notation

$$\eta_{[s]} = \eta_{[\gamma(\mathbf{s})]}. \quad (110)$$

This completes our analysis of the rigging map.

### C. Cyclic representation

We focus on the “+” sector of the algebra of operators and the “+” sector of the state space. As in Sec. VB we suppress “+” superscripts. The analysis for the “−” case follows analogously. Cyclicity is defined with respect to an algebra of operators. Here the putative generators of the algebra are the Dirac observables of Sec. IV and the finite gauge transformations. As we shall see in Sec. VI, neither does the commutator of two of the observables of Sec. IVA yield a representation of the corresponding Poisson brackets nor does their product yield a representation of the appropriate Weyl algebra. As shown in Sec. VI, the connection with classical theory is state dependent and only holds for semiclassical states (this is roughly similar to what happens for area operators in LQG [27]). Given this situation, we define the operator algebra in terms of the concrete representation on  $\mathcal{H}_{\text{kin}}$  (or  $\mathcal{H}_{\text{phys}}$ ) of the relevant operators rather than in terms of abstract representations of classical structures.

Since the operators of Sec. IV as well as those for finite gauge transformations are unitary (and hence bounded), the finite span of their products is well defined on  $\mathcal{H}_{\text{kin}}$  so that it is possible to define the algebra of operators generated by these elementary ones in terms of the action of elements of this algebra on  $\mathcal{H}_{\text{kin}}$ . We denote this algebra of operators as  $\mathcal{A}_{D,G}^{\text{kin}}$ . In a similar manner, consider the algebra of operators generated by the action of the Dirac

observables of Sec. IV on  $\mathcal{H}_{\text{phys}}$ . Denote this algebra by  $\mathcal{A}_D^{\text{phys}}$ .

Fix a graph  $\gamma$ . Let  $\mathbf{s}_\gamma$  be the set of charge networks such that  $\forall \mathbf{s} \in \mathbf{s}_\gamma, \gamma(\mathbf{s}) = \gamma$  and  $\mathbf{s}$  satisfies condition (102) on its embedding charges. Let  $[\mathbf{s}_\gamma]$  be the set of charge networks which are gauge related to elements of  $\mathbf{s}_\gamma$  i.e.  $\forall \mathbf{s}' \in [\mathbf{s}_\gamma] \exists$  some gauge transformation  $\phi$  and some  $\mathbf{s} \in \mathbf{s}_\gamma$  such that  $\mathbf{s}' = \mathbf{s}_\phi$ . Finally, let  $\mathcal{H}_{[\gamma]}$  be the (Cauchy completion of the) finite span  $\mathcal{D}_{[\gamma]} (\subset \mathcal{D}_{(a)(b)})$  of charge-network states  $|\mathbf{s}'\rangle, \mathbf{s}' \in [\mathbf{s}_\gamma]$ .

The analysis of the preceding section shows that:

- (1)  $\mathcal{H}_{[\gamma]} \subset \mathcal{H}_{\text{kin}}$  provides a cyclic representation of the algebra  $\mathcal{A}_{D,G}^{\text{kin}}$ . Any charge-network state in  $\mathcal{H}_{[\gamma]}$  is a cyclic state.
- (2) Group averaging of states in  $\mathcal{D}_{[\gamma]}$  yields a cyclic representation of the algebra  $\mathcal{A}_D^{\text{phys}}$  i.e.  $\mathcal{A}_D^{\text{phys}}$  is represented cyclically on  $\mathcal{H}_{[\gamma],\text{phys}} \subset \mathcal{H}_{\text{phys}}$  where  $\mathcal{H}_{[\gamma],\text{phys}}$  is the Cauchy completion (in the physical inner product) of  $\eta(\mathcal{D}_{[\gamma]})$ . The group average of any charge-network state in  $\mathcal{D}_{[\gamma]}$  is a cyclic state.

Note that both  $\mathcal{H}_{[\gamma]}$  and  $\mathcal{H}_{[\gamma],\text{phys}}$  are *nonseparable*.

## VI. SEMICLASSICAL ISSUES

An exhaustive analysis of semiclassical states is outside the scope of this paper. Instead, we focus on two issues related to semiclassicality. In Sec. VIA we show that semiclassical states must be based on suitably defined “weaves.” In Sec. VIB we show that semiclassicality can be exhibited with respect to, at most, a countable number of the mode function operators of Sec. IVA.

### A. Semiclassicality and weaves

Recall that in LQG, states which exhibit semiclassical behavior for spatial geometry operators are based on graphs called weaves [28]. Here the (flat) spacetime geometry is encoded in the behavior of the  $\hat{X}^\pm(x)$  operators. Hence we define the notion of a weave as follows. The embedding charge network  $s^\pm = \{\gamma(s^\pm), (k_{e_\mp}^\pm, \dots, k_{e_N^\pm}^\pm)\}$  will be called a *weave* iff the embedding charges satisfy (a), (b) of Sec. VA together with  $k_{e_N^\pm}^\pm - k_{e_1^\pm}^\pm \approx \pm 2\pi$  and iff  $N \gg 1$ . This is, of course, not a precise definition since  $k_{e_N^\pm}^\pm - k_{e_1^\pm}^\pm \approx 2\pi$  and  $N \gg 1$ . are not precise statements. Nevertheless this “working” definition will suffice for our purposes.

Let  $\psi^\pm \in \mathcal{H}_{\text{kin}}^\pm$  exhibit semiclassicality with respect to the  $\pm$  sector observables of Sec. IVA. Further, let  $\psi^\pm$  be an eigenstate of  $\hat{X}^\pm(x)$  (we shall relax this assumption later) so that  $\psi^\pm = T_{s^\pm} \otimes \psi_M^\pm, \psi_M^\pm \in \mathcal{H}_M^\pm$ . The analysis below is for the + sector and can be trivially extended to the − sector. In what follows we suppress the + superscript. From Eq. (80) it follows straightforwardly that

$$\langle [e^{i\alpha q_m}, e^{i\beta p_m}] \rangle = -2i \sin\left(\frac{\alpha\beta\hbar}{2} f_{s,m}\right) \langle e^{i\alpha q_m + i\beta p_m} \rangle, \quad (111)$$

where

$$f_{s,m} := \sum_{l=1}^N \cos(\hbar m k_{e_l}) (\sin(\hbar m k_{e_{l+1}}) - \sin(\hbar m k_{e_l})), \quad (112)$$

where  $k_{e_{N+1}} := k_{e_1}$ . In order to write (112) in a more useful form, we define the following:

$$\Delta k_{e_l} := k_{e_{l+1}} - k_{e_l}, \quad I = 1, \dots, N-1 \quad (113)$$

$$\Delta k_{e_N} := k_{e_1} - k_{e_N} + \frac{2\pi}{\hbar}. \quad (114)$$

Rearranging terms in (112) and using standard trigonometric identities we obtain that

$$f_{s,m} = \sum_{l=1}^N \sin(\hbar m \Delta k_{e_l}). \quad (115)$$

Since  $\psi$  is semiclassical we assume that, for some classical data  $(q_m, p_m)$ ,

$$\langle e^{i\alpha q_m + i\beta p_m} \rangle \approx e^{i\alpha q_m + i\beta p_m}, \quad (116)$$

and we require that as  $\hbar \rightarrow 0$

$$\langle [e^{i\alpha q_m}, e^{i\beta p_m}] \rangle \rightarrow i\hbar \{e^{i\alpha q_m}, e^{i\beta p_m}\} \quad (117)$$

where the Poisson bracket evaluates to

$$\{e^{i\alpha q_m}, e^{i\beta p_m}\} = -\alpha\beta 2\pi m e^{i\alpha q_m + i\beta p_m}. \quad (118)$$

Equations (111)–(118) imply that to leading order in  $\hbar$

$$f_{s,m=1} \approx 2\pi. \quad (119)$$

Note that the eigenvalues of the embedding operators are in terms of

$$k_I := \hbar k_{e_I} \quad (120)$$

so that in the  $\hbar \rightarrow 0$  (classical) limit,  $k_I$  does not vanish (except when  $k_{e_I} = 0$ ). Hence, we investigate the conditions imposed on  $s$  by the requirement

$$\left| 2\pi - \sum_{l=1}^N \sin(\Delta k_l) \right| < \epsilon, \quad \epsilon \ll 1. \quad (121)$$

where, similar to (113) we have defined

$$\Delta k_I := k_{I+1} - k_I, \quad I = 1, \dots, N-1 \quad (122)$$

$$\Delta k_N := k_1 - k_N + 2\pi. \quad (123)$$

Note that conditions (a), (b) of Sec. VA imply that

$$\Delta k_I \geq 0, \quad \sum_{l=1}^N \Delta k_l = 2\pi. \quad (124)$$

Intuitively, since  $|\frac{\sin x}{x}| \leq 1$  and  $= 1$  at  $x = 0$ , Eqs. (121) and (124), lead us to expect that  $\Delta k_I$ ,  $I = 1, \dots, N$  should be small. That this is indeed the case is shown in lemmas 1–3 in the appendix. Clearly, the fact that  $\Delta k_I \rightarrow 0$  as  $\epsilon \rightarrow 0$  (see appendix) implies that  $s$  is a weave. Thus, we have shown that any kinematic semiclassical state which is an eigenstate of the embedding operators must be based on a weave.

Next, consider an arbitrary kinematic state  $|\psi\rangle = \sum a_i |s_i\rangle \otimes |\psi_{iM}\rangle$  where  $a_i$  are complex coefficients,  $|s_i\rangle$  are an orthonormal set of embedding charge-network states and  $|\psi_{iM}\rangle \in \mathcal{H}_M$ . In order that this state satisfies Eq. (117), it turns out that  $|\psi\rangle$  must be peaked around  $s_i$  such that  $s_i$  are weaves. This is shown in lemma 4 of the appendix. Finally, consider an arbitrary physical state. Such a state is a linear combination of averages over embedding eigenstates. Lemma 5 shows that such a state is peaked around averages of embedding eigenstates which are based on weaves.

## B. Semiclassicality and mode function operators:

### A no-go result

We show that no states exist which are semiclassical with respect to the uncountable set of operators  $\{e^{i\alpha q_m}, e^{i\beta p_m}, |\alpha - \alpha_0| < \epsilon, |\beta - \beta_0| < \delta\}$  for any fixed  $m$ ,  $\alpha_0$ ,  $\beta_0$  and any  $\epsilon, \delta > 0$ . First, consider states  $|\psi\rangle$  which are embedding eigenstates so that  $|\psi\rangle = |s\rangle \otimes |\psi_M\rangle$ . Here  $s$  is an embedding charge network and  $|\psi_M\rangle \in \mathcal{H}_M$  can be expanded as  $|\psi_M\rangle = \sum_r b_r |s'_r\rangle$  where  $\{|s'_r\rangle\}$  is a countable set of orthonormal matter charge networks.

The operators  $e^{i\alpha q_m}, e^{i\beta p_m}$  act by changing the matter charge labels by sines and cosines of ( $m$  times) the embedding charges [see (80)]. Consider the set  $L$  of all matter charges on  $s_r, \forall r$  and construct the set  $\Delta L$  of differences between all pairs of elements of  $L$  i.e.  $\Delta L := \{l - l' \mid l, l' \in L\}$ . Let  $k_e, e \subset \gamma(s)$  be such that  $\cos m\hbar k_e \neq 0$ . Then, in any neighborhood of  $\alpha_0$  we can choose uncountably many  $\alpha$  such that  $\alpha \cos m\hbar k_e \notin \Delta L$ . Clearly for such  $\alpha$  we have that  $\langle e^{i\alpha q_m} \rangle = 0$ . If  $\cos m\hbar k_e = 0$  we can repeat the same argument with  $\sin m\hbar k_e$  and conclude that  $\langle e^{i\beta p_m} \rangle = 0$  for uncountable many  $\beta$  near  $\beta_0$ . Clearly, such behavior is far from semiclassical. This argument can be suitably generalised for arbitrary states in  $\mathcal{H}_{\text{kin}}$  as well as in  $\mathcal{H}_{\text{phys}}$ . The relevant material is in lemma 6 and lemma 7 of Appendix B.

## VII. TWO OPEN ISSUES AND THEIR RESOLUTION

Before we conclude this paper, a couple of points remain which we have not yet addressed. First, it still remains to enforce (ii), Sec. IIC 1 in order to ensure that the spatial topology is a circle. Second, we need to take care of the

zero modes by imposing Eq. (25) in quantum theory and show that the results of Sec. VI continue to hold after this is done. We address these points in Secs. VII A and VII B below.

### A. Identifying $2\pi$ shifted embeddings

Although the spatial inertial coordinate  $X$  ranges over  $(-\infty, \infty)$ , we need to identify  $X \sim X + 2\pi$  in accordance with the discussion in Sec. II C 1. Condition (ii), Sec. II C 1 states that two embeddings  $(X_1, T_1), (X_2, T_2)$  are equivalent if the following conditions are satisfied:

$$\begin{aligned} X_1^+(x) &= X_2^+(x) + 2m\pi \quad \forall x \in [0, 2\pi], \\ X_1^-(x) &= X_2^-(x) - 2m\pi \quad \forall x \in [0, 2\pi]. \end{aligned} \quad (125)$$

We now show that this equivalence has already been taken care of at the physical state-space level. Let

$$\begin{aligned} \mathbf{s}^+ &= \{\gamma(\mathbf{s}^+), (k_{e_1^+}, \dots, k_{e_N^+}), (l_{e_1^+}, \dots, l_{e_N^+})\} \\ \mathbf{s}^- &= \{\gamma(\mathbf{s}^-), (k_{e_1^-}, \dots, k_{e_M^-}), (l_{e_1^-}, \dots, l_{e_M^-})\} \end{aligned} \quad (126)$$

The identification (126) in the classical theory implies the following equivalence condition in quantum theory:

$$|\mathbf{s}^+\rangle \otimes |\mathbf{s}^-\rangle \sim |\mathbf{s}_{2\pi m}^+\rangle \otimes |\mathbf{s}_{-2\pi m}^-\rangle \quad (127)$$

where,

$$\begin{aligned} \mathbf{s}_{2\pi m}^+ &= \{\gamma(\mathbf{s}^+), (k_{e_1^+} + 2m\pi, \dots, k_{e_N^+} + 2m\pi), (l_{e_1^+}, \dots, l_{e_N^+})\}, \\ \mathbf{s}_{-2\pi m}^- &= \{\gamma(\mathbf{s}^-), (k_{e_1^-} - 2m\pi, \dots, k_{e_M^-} - 2m\pi), (l_{e_1^-}, \dots, l_{e_M^-})\}. \end{aligned} \quad (128)$$

Next, note that for any integer  $m$ , there exist gauge transformations  $\phi_{(m)}^\pm$  such that  $\phi_{(m)}^\pm \cdot \mathbf{s}^\pm = \{\gamma(\mathbf{s}^\pm), (k_{e_1^\pm} \pm 2m\pi, \dots, k_{e_N^\pm} \pm 2m\pi), (l_{e_1^\pm}, \dots, l_{e_N^\pm})\}$ . Thus  $|\mathbf{s}^\pm\rangle$  and  $|\mathbf{s}_{\pm 2\pi m}^\pm\rangle$  are gauge related so that

$$\eta^\pm(|\mathbf{s}^\pm\rangle) = \eta^\pm(|\mathbf{s}_{\pm 2\pi m}^\pm\rangle), \quad (129)$$

$$\Rightarrow \eta^+(|\mathbf{s}^+\rangle) \otimes \eta^-(|\mathbf{s}^-\rangle) = \eta^+(|\mathbf{s}_{2\pi m}^+\rangle) \otimes \eta^-(|\mathbf{s}_{-2\pi m}^-\rangle). \quad (130)$$

Equation (130) shows that the identification of  $2\pi$ -shifted embeddings is *subsumed* by the identification of embeddings related by gauge transformations.

### B. Taking care of the zero mode in quantum theory

In Sec. VII B 1 we impose the condition  $p = 0$  [see Eq. (25)] by appropriate group averaging. In Sec. VII B 2 we show that this does not alter the conclusions of Sec. VI

### 1. Imposition of $p = 0$ by averaging

The conditions  $\int_{S^1} Y^\pm = 0$  of Eq. (25) are equivalent to the conditions  $e^{i\lambda^\pm} \int_{S^1} Y^\pm = 1, \forall \lambda^\pm$ . The latter can be imposed by group averaging with respect to the operators  $e^{i\lambda^\pm} \int_{S^1} Y^\pm$ . Let  $s_{\lambda^\pm}^\pm$  be matter charge networks with a single edge  $e^\pm = [0, 2\pi]$  labeled by the charge  $\lambda^\pm$  i.e.  $s_{\lambda^\pm}^\pm = \{\gamma(s_{\lambda^\pm}^\pm) = [0, 2\pi], l_{e^\pm}^\pm = \lambda^\pm\}$ . Clearly, we have that  $e^{i\lambda^\pm} \int_{S^1} Y^\pm = \hat{W}(s_{\lambda^\pm}^\pm)$ . Note that  $\hat{W}(s_{\lambda^\pm}^\pm)$  commutes with all the gauge transformations as well as observables of Sec. IV. Since we have already averaged over the group of gauge transformations, the map  $\tilde{\eta}^\pm$  which implements (25) is defined from the space  $\eta^\pm(\mathcal{D}_{(a)(b)}^\pm)$  to its algebraic dual  $\eta^\pm(\mathcal{D}_{(a)(b)}^\pm)^*$ . Recall that  $\mathcal{D}_{(a)(b)}^\pm$  (defined in Sec. VA) is the finite span of charge networks subject to the conditions (a), (b) of Sec. VA. Before defining  $\tilde{\eta}^\pm$ , note that

$$\hat{W}(s_{\lambda^\pm}^\pm)|\mathbf{s}^\pm\rangle =: |\mathbf{s}_{\lambda^\pm}^\pm\rangle, \quad (131)$$

where  $\mathbf{s}_{\lambda^\pm}^\pm$  is obtained from  $\mathbf{s}^\pm = \{\gamma(\mathbf{s}^\pm), (k_{e_1^\pm}, \dots, k_{e_N^\pm}), (l_{e_1^\pm}, \dots, l_{e_N^\pm})\}$  by adding  $\lambda^\pm$  to all the matter charges. We now define

$$\tilde{\eta}^\pm(\eta^\pm(|\mathbf{s}^\pm\rangle)) = \tilde{\eta}_{[[\mathbf{s}^\pm]]_0} \eta_{[\mathbf{s}^\pm]} \left( \bigoplus_{\lambda^\pm \in \mathbf{R}} \sum_{\phi^\pm \in \text{Diff}_{[\gamma(\mathbf{s}^\pm)]}^P \mathbf{R}} \langle (\mathbf{s}_{\phi^\pm}^\pm)_{\lambda^\pm} | \cdot \right) \quad (132)$$

The equivalence class  $[[\mathbf{s}^\pm]]_0$  is defined via following relation.  $[[\mathbf{s}^\pm]]_0 \sim [[\mathbf{s}_1^\pm]]_0$  if for any  $\{\gamma(\mathbf{s}^\pm), (k_{e_1^\pm}, \dots, k_{e_N^\pm}), (l_{e_1^\pm}, \dots, l_{e_N^\pm})\} \in [\mathbf{s}^\pm]$ ,  $\exists \{(\gamma(\mathbf{s}_1^\pm), (k_{e_1^\pm}, \dots, k_{e_N^\pm}), (l_{e_1^\pm} + \lambda^\pm, \dots, l_{e_N^\pm} + \lambda^\pm)) \in [\mathbf{s}_1^\pm]$  for some  $\lambda^\pm \in \mathbf{R}$ .

Once again the ambiguity in the rigging map contained in  $\tilde{\eta}_{[[\mathbf{s}^\pm]]_0}$  can be reduced by demanding that  $\tilde{\eta}^\pm$  commutes with the observables. It can be checked that for the superselected sector of  $\mathcal{H}_{\text{phys}}$  defined in Sec. VB, we have  $\tilde{\eta}_{[[\mathbf{s}]]_0} = \tilde{\eta}_{[\gamma]}$ , where as in Sec. VB and VC we have once again suppressed  $\pm$  superscripts and where  $[\gamma]$  is defined as in Sec. VC. Setting  $\tilde{\eta}_{[\gamma(\mathbf{s})]} := \tilde{\eta}_{[\gamma]} \eta_{[\gamma]}$ , we have that the inner product on  $\tilde{\eta}^\pm(\mathcal{D}_{\text{phys}}^{\pm,ss})$  is given by

$$\langle \tilde{\eta}(\eta(|\mathbf{s}\rangle)) | \tilde{\eta}(\eta(|\mathbf{s}_1\rangle)) \rangle = \tilde{\eta}_{[\gamma(\mathbf{s})]} \bigoplus_{\lambda} (\eta(|\mathbf{s}\rangle)) [|\mathbf{s}_{1,\lambda}\rangle]. \quad (133)$$

### 2. Semiclassical issues

Since the zero mode operator  $\hat{W}(s_{\lambda^\pm}^\pm)$  leaves the embedding part of the states in  $\mathcal{H}_{\text{kin}}$  and  $\mathcal{H}_{\text{phys}}$  untouched, it is easy to see that the proofs of Sec. VI A and appendix A still apply after the zero mode averaging is done. Thus, semiclassical states which satisfy the  $p = 0$  constraint are necessarily based on weaves.



It is also straightforward to see that the results of Sec. VIB apply after zero mode group averaging. While the line of argument is roughly similar to that in Sec. VIB and appendix B, there are some differences. In the interests of brevity, we provide only a skeleton of the argument below. As usual we shall suppress the  $\pm$  superscripts.

The averaging with respect to  $\bar{\eta}$  slightly complicates matters because there is an additional sum over matter charge networks wherein matter charges associated with charge-network states are all incremented by the same amount. As a result, it is necessary to consider pairs of edges subject to conditions on their embedding charges. This is in contrast to the role of single edges (with cosines or sines of ( $\hbar$  times) their embedding charges being non-vanishing) in the arguments of Sec. VIA and appendix B. Specifically, consider a state decomposition defined in terms of embedding charge networks  $s_j$  as in Eqs. (A5) and (A18). Separate the values taken by the index  $j$  into a set  $C_1$  and its complement,  $C_2$ , where  $j \in C_1$  iff for fixed  $m$ , there exist a pair of edges  $e_I(j), e_J(j) \in \gamma(s_j)$  such that  $\text{cosm}\hbar k_{e_I(j)} \neq \text{cosm}\hbar k_{e_J(j)}$ .

Next, with a slight abuse of notation, for each  $j \in C_1$  fix a pair of edges  $e_I(j), e_J(j) \in \gamma(s_j)$  such that  $\text{cosm}\hbar k_{e_I(j)} \neq \text{cosm}\hbar k_{e_J(j)}$ . As in appendix B, define  $\Delta L$  to be the set of differences of all matter charges which occur in the expansions (A5), (A18), and (B1). Also define  $\Delta^2 L$  to be the set of all differences between pairs of elements of  $\Delta L$ . For each  $j \in C_1$  define  $\Delta^2 L_j$  to be the set of elements obtained by dividing each element of  $\Delta^2 L$  by  $\text{cosm}\hbar k_{e_I(j)} - \text{cosm}\hbar k_{e_J(j)}$ . Let  $\Delta^2 L_{C_1} := \cup_{j \in C_1} \Delta^2 L_j$ . The set  $\Delta^2 L_{C_1}$  is countable so that there are uncountably many  $\alpha$  in any neighborhood of  $\alpha_0$  such that  $\alpha \notin \Delta^2 L_{C_1}$ . It can then be checked that  $\langle e^{i\alpha q_m} \rangle$  obtains contributions only from terms labeled by  $j \in C_2$ .

Finally, we show that such terms are of negligible measure. Note that for  $j \in C_2$  we have that  $\text{cosm}\hbar k_{e_I(j)} = \text{cosm}\hbar k_{e_J(j)}$  for any pair of edges  $e_I(j), e_J(j) \in \gamma(s_j)$ . It is then straightforward to see that for such  $j$ , the function  $f_{s_j, m}$  [defined by Eqs. (112) and (A11)] vanishes identically. Then the arguments of Sec. VIA and appendix A imply that the contribution from  $j \in C_2$  must be negligible for semiclassicality to hold.

Similar arguments can be made for  $\langle e^{i\beta p_m} \rangle$  by replacing cosines with sines in the above argument.

## VII. DISCUSSION OF RESULTS AND OPEN ISSUES

In this work, we constructed a quantization of PFT similar to that used in LQG. Our constructions are based on Ref. [3]. Quantum states are in correspondence with graphs (i.e. collections of edges) in the spatial manifold. The edges of these graphs are labeled by a set of real valued embedding and matter charges. These charge-network states are analogs of the spin network states in LQG.

There, however, the labels are integer valued. Such a labeling is also, in principle, possible here. Had the holonomies of Sec. III been based on charge networks with embedding charges which were integer multiples of  $\frac{2\pi}{L}$  for some fixed integer  $L$  and matter charges which were also integer multiples of some appropriate dimensionful unit, such holonomies would still separate points in phase space by virtue of the fact that they were based on arbitrary graphs (this is similar to what happens in LQG). Such a choice would lead to states with integer valued charges. However it is not clear if (a large enough subset of) the Dirac observables of Sec. IV preserve the space spanned by these integer-charge-network states. It would be useful to investigate this issue in detail.

The polymer quantization of the embedding variables replaces the classical (flat) spacetime continuum with a discrete structure consisting of a countable set of points. This can be seen as follows. The canonical data  $X^\pm(x)$  is a map from  $S^1$  into the flat spacetime  $(S^1 \times R, \eta)$  and embeds the former into the latter as a spatial Cauchy slice. Any gauge transformation generated by the constraints maps this data to new embedding data which, in turn, define a new Cauchy slice in the flat spacetime. In particular, the action of the one parameter family of gauge transformations generated by smearing the constraints with some choice of ‘‘lapse-shift’’ type functions  $N^A$  (see Sec. II) generates a foliation of  $(S^1 \times R, \eta)$ . Consider the image set in  $(S^1 \times R, \eta)$  of the set of all embeddings which are gauge related to a given one. From the above discussion it follows that this image set is exactly the flat spacetime  $(S^1 \times R, \eta)$  itself. Next, consider the corresponding quantum structures. Any charge-network state is an eigenstate of  $\hat{X}^\pm(x)$ . Consider a charge-network state,  $|s^+\rangle \otimes |s^-\rangle$  with  $|s^\pm\rangle = T_{s^\pm} \otimes W_{s^\pm}$ , where  $s^\pm$  satisfy the conditions (a), (b) of section VA. From Eqs. (42)–(44) it follows that the set of eigenvalues  $\lambda_{x, s^\pm}$  for all  $x \in [0, 2\pi]$  describes a finite set of points on a spacelike Cauchy surface in  $(S^1 \times R, \eta)$ . These points have light cone coordinates  $(X^+, X^-) = (\lambda_{x, s^+}, \lambda_{x, s^-})$ . The action of any gauge transformation on such a charge-network state yields another charge-network state whose eigenvalues lie, once again, on a Cauchy slice in  $(S^1 \times R, \eta)$ . From Eq. (46) it follows that the set of eigenvalues for all possible gauge related charge-network states is countable and defines a corresponding set of points in  $(S^1 \times R, \eta)$ . The gauge invariant state obtained by group averaging a charge-network state is a sum over all distinct gauge equivalent states and hence contains the elements of this discrete structure. The discrete structure is a good approximant of the continuum spacetime  $(S^1 \times R, \eta)$  for charge networks with a large number of embedding charges i.e. for weave states. Thus, it is not surprising that semiclassicality requires states to be based on weaves as in Sec. VIA and appendix A.

In contrast to the embedding charges, the matter charges do not have a direct physical interpretation because charge-

network states are not eigenstates of the matter holonomies. As a tentative, provisional interpretation we choose to think of them, rather imprecisely, as measuring excitations of the matter. Since, on the constraint surface, the classical data  $(X^\pm(x), Y^\pm(x))$  correspond to free scalar field data  $Y^\pm(x)$  on the slice  $(X^+(x), X^-(x))$  in flat spacetime, we interpret a charge-network state  $|s^+\rangle \otimes |s^-\rangle \in \mathcal{H}_{\text{kin}}$  as specifying excitations of matter on the discretized “quantum” slice specified by the embedding charges. The action of a gauge transformation on a charge-network state can then be interpreted as evolving the matter excitations on the “initial” quantum slice specified by this state to the new one specified by the gauge related charge-network state. Since the physical state obtained as the group average of a charge-network state contains all distinct gauge related states, it follows that such a physical state may be interpreted, roughly, as a “history.” It may be useful to attempt an interpretation of physical states in LQG along these lines.

An overcomplete set of Dirac observables corresponding to exponential functions of the standard annihilation-creation modes of free scalar field theory are represented as (unitary) operators in the polymer representation. Note that in contrast to the assumption of Ref. [9], here the commutator between two such operators does not close as in the case of Weyl algebras. Indeed, as shown in Sec. VIA, the commutator only approximates the corresponding Poisson bracket for semiclassical states based on weaves. This underlines the fact that in a general covariant theory involving spacetime geometry, classical structures are typically not approximated in the  $\hbar \rightarrow 0$  limit unless it is possible to coarse grain/smoothen away the underlying discreteness of the quantum spacetime. Nevertheless the action of the basic Dirac observables is well defined and there is no obstruction to the quantization procedure.

The results of Sec. VIB imply that semiclassical analysis requires a choice of a countable subset of these observables. One possibility is to choose, for each  $n$ , a pair  $\alpha, \beta \ll \frac{1}{\sqrt{\hbar}}$  and define the approximants to  $\hat{q}_n, \hat{p}_n$  by  $\frac{e^{i\alpha q_n} - e^{-i\alpha q_n}}{2i\alpha}, \frac{e^{i\beta p_n} - e^{-i\beta p_n}}{2i\beta}$ . However, there is no natural choice of  $\alpha, \beta$  and so, while the quantization constructed in this paper is free of the “triangularization” choices which occur in the definition of the quantum dynamics of LQG, an element of choice does appear when semiclassical issues are confronted. Note, however, that the results of Sec. VIA indicate that any physical semiclassical state necessarily has an associated (gauge invariant) structure, namely, that of a weave.<sup>5</sup> The “spacing” of the weave (i.e.  $\hbar \Delta k_j$  of Sec. VIA and the Appendix A) provides a natural scale for  $\alpha, \beta$ . Thus, our viewpoint is that since choices of

<sup>5</sup>Note that in contrast to the weaves of Ref. [28] which approximate a spatial geometry, here it is the (flat) spacetime geometry which is being approximated by virtue of the discussion in the second paragraph of this section.

Dirac observables can be tied (however tenuously) to structures already present in the semiclassical states, ambiguities (if present) in definitions of the quantum dynamics are more worrying because quantum dynamics is defined for all states, not only semiclassical ones.

While the general covariance of PFT is encoded in the gauge transformations generated by the constraints, the conformal invariance of the underlying free scalar field theory is reflected in the canonical transformations which correspond to the Dirac observables of Sec. IID3. The results of Secs. III and IV B show that the group of gauge transformations as well as that of conformal isometries are represented in an anomaly-free manner. While the anomaly-free nature of the former is necessary for the consistency of the quantum theory, it is possible, in principle, for the latter to admit anomalies. Indeed this is exactly what happens in the representation of PFT constructed in Refs. [1,2]. While the algebra of gauge transformations is anomaly-free, the physical Hilbert space representation is equivalent to the standard free field Fock representation and the algebra of the generators of conformal isometries displays the standard Virasoro central extension. Motivated by the results of Refs. [1,2,29], we believe that the anomaly manifests as result of the Poincare invariance of the Fock representation i.e. as a result of the existence of the Poincare invariant vacuum. From this point of view the absence of anomalies in the group of gauge transformations as well as the group of conformal isometries in the polymer quantization is related to the absence of a Poincare invariant state (Poincare transformations are a subset of the conformal isometry group and it is easy to see that no kinematic or physical state is Poincare invariant). We shall return to the issue of Poincare invariance towards the end of this section.

Next we turn to the discussion of the efficacy of polymer PFT as a toy model for LQG. We believe that the quantization provided here is a useful testing ground for proposed definitions of quantum dynamics in canonical LQG. It would be of interest to construct the quantum dynamics of the model along the lines of Ref. [17] and compare the resulting physical Hilbert space with the one considered here. Proposals for examining semiclassical issues [20,21] may also be tested here. One of the outstanding problems in LQG [23,30] is the relation between states in LQG and the Fock states of perturbative gravity. Since PFT admits a Fock quantization [1,2] equivalent to the standard flat spacetime free scalar field Fock representation, one may enquire as to how Fock states arise from the polymer Hilbert space. Since the results of Sec. VIB suggest that the operators corresponding to exponentials of mode functions do not possess the requisite continuity for the annihilation-creation modes themselves to be defined as operators, it is difficult to identify Fock states in terms of their properties with respect to the action of the annihilation-creation operators. However, as a first step,

it may be possible to identify candidate states corresponding to the Fock vacuum by using the Poincare invariance of the latter. Specifically, since the operators corresponding to finite Poincare transformations are available (as a subset of the conformal isometry operators of Sec. IV), one could try and group average with respect to these operators.

Another open issue pertains to the representation appropriate to the case of noncompact spatial topology. The quantization here explicitly incorporates the compact spatial topology  $S^1$ . Here, the unit of length has been chosen so that the circumference of the  $T = \text{const}$  circle is  $2\pi$ . By allowing the circle to have an arbitrarily large circumference, it may be possible to transit to polymer PFT on  $R \times R$  and compare the resulting quantization with the infinite tensor product proposal of Thiemann *et al.* [31,32].

### APPENDIX A: LEMMAS CONCERNING SEMICLASSICALITY AND WEAVES

*Lemma 1:* If  $\Delta k_J \geq \pi$  [see (120) and (122)] for some  $J$ ,  $1 \leq J \leq N$  then  $-1 \leq f_{s,m=1} \leq \pi$ .

*Proof:* Let  $\Delta k_J \geq \pi$ . Equations (124) imply that

$$\sum_{I \neq J} \Delta k_I \leq \pi, \quad (\text{A1})$$

and, hence, that

$$\Delta k_I|_{I \neq J} \leq \pi. \quad (\text{A2})$$

This in conjunction with the fact that  $|\frac{\sin x}{x}| \leq 1$  implies that

$$\sum_{I=1}^N \sin \Delta k_I \leq \sum_{I \neq J} \Delta k_I + \sin \Delta k_J \leq \pi. \quad (\text{A3})$$

From Eq. (A2) and  $\Delta k_J \geq \pi$ , we have that

$$\sum_{I=1}^N \sin \Delta k_I \geq -1. \quad (\text{A4})$$

The lemma follows immediately from Eqs. (A3) and (A4) and the definition (115) of  $f_{s,m=1}$

*Lemma 2:* If  $\Delta k_I \leq \pi$ ,  $I = 1, \dots, N$  [see (120) and (122)] then  $0 \leq f_{s,m=1} \leq 2\pi$ .

*Proof:* This follows immediately from the fact that  $|\frac{\sin x}{x}| \leq 1$  in conjunction with Eqs. (124) and the definition (115) of  $f_{s,m=1}$ .

*Lemma 3:* Equation (121) implies that as  $\epsilon \rightarrow 0$ ,  $\Delta k_I \rightarrow 0$ ,  $I = 1, \dots, N$  and  $N \rightarrow \infty$ .

*Proof:* From lemma 1 and Eq. (121) it follows that for sufficiently small  $\epsilon$ , it must be the case that  $\Delta k_I \leq \pi$ ,  $I = 1, \dots, N$ .

Next, let  $\alpha$  be the minimum value of the bounded, continuous function  $\frac{\sin \theta}{\theta}$  in the interval  $[0, \frac{\pi}{2}]$  (here  $\frac{\sin \theta}{\theta}|_{\theta=0} := 1$ ). Define the function  $f(x) := x - \sin x - \frac{\alpha}{6}x^3$ . It is easy to check that  $\frac{df}{dx} \geq 0$ ,  $x \in [0, \pi]$  and that  $f(x=0) = 0$ . This implies that  $x - \sin x \geq \frac{\alpha}{6}x^3$ ,  $x \in$

$[0, \pi]$ . This in conjunction with Eqs. (121) and (124) implies that  $\sum_{I=1}^N (\Delta k_I)^3 < \frac{6\epsilon}{\alpha}$  so that  $\Delta k_I \rightarrow 0$ ,  $I = 1, \dots, N$  as  $\epsilon \rightarrow 0$ . This in turn, together with (124), implies that  $N \rightarrow \infty$  as  $\epsilon \rightarrow 0$ .

*Lemma 4:* Any normalized  $|\psi\rangle \in \mathcal{H}_{\text{kin}}$  admits the expansion:

$$|\psi\rangle = \sum_j a_j |s_j, \psi_{jM}\rangle, \quad |s_j, \psi_{jM}\rangle := |s_j\rangle \otimes |\psi_{jM}\rangle, \quad (\text{A5})$$

$$\langle s_i | s_j \rangle = \delta_{ij}, \quad s_j = \{\gamma(s_j), (k_{e_1}^j, \dots, k_{e_{n_j}}^j)\} \quad (\text{A6})$$

$$\langle \psi_{jM} | \psi_{jM} \rangle = 1, \quad (\text{A7})$$

$$\sum_j |a_j|^2 = 1. \quad (\text{A8})$$

Here  $s_j$  are embedding charge labels,  $e_I^j$ ,  $I = 1, \dots, n_j$  are the edges of the graph underlying  $s_j$ ,  $a_j$  are complex coefficients and  $|\psi_{jM}\rangle \in \mathcal{H}_M$ .

If  $|\psi\rangle$  is semiclassical then the coefficients  $a_j$  are such that  $|\psi\rangle$  is peaked around  $s_j$  such that  $s_j$  are weaves.

*Proof:* The proof closely mirrors the arguments of Sec. VIA. Semiclassicality implies that to leading order in  $\hbar$ ,

$$\begin{aligned} \langle \psi | [e^{i\alpha q_m}, e^{i\beta p_m}] | \psi \rangle &\approx i\hbar \{e^{i\alpha q_m}, e^{i\beta p_m}\} \\ &= -i\hbar \alpha \beta 2\pi m e^{i\alpha q_m + i\beta p_m} \end{aligned} \quad (\text{A9})$$

Using Eqs. (80), (A5), and (A9) we have that

$$\begin{aligned} \sum_j |a_j|^2 2 \sin\left(\frac{\alpha\beta\hbar}{2} f_{s_j,m}\right) \langle s_j, \psi_{jM} | e^{i\alpha q_m + i\beta p_m} | s_j, \psi_{jM} \rangle \\ \approx \hbar \alpha \beta 2\pi m e^{i\alpha q_m + i\beta p_m} \end{aligned} \quad (\text{A10})$$

where

$$f_{s_j,m} = \sum_{I=1}^{n_j} \sin m \Delta k_I^j, \quad (\text{A11})$$

and  $\Delta k_I^j := k_{I+1}^j - k_I^j$  for  $1 \leq I \leq n_j - 1$ ,  $\Delta k_{n_j}^j := k_1^j - k_{n_j}^j + 2\pi$  and we have set  $k_{e_j}^j := \hbar k_{e_j}$ . From lemmas 1 and 2 it follows that

$$-1 \leq f_{s_j,m=1} \leq 2\pi \quad \forall j. \quad (\text{A12})$$

Since  $f_{s_j,m=1}$  is bounded, Eq. (A10) implies that to leading order in  $\hbar$ , we have that

$$\sum_j |a_j|^2 f_{s_j,m=1} \langle s_j, \psi_{jM} | e^{i\alpha q_1 + i\beta p_1} | s_j, \psi_{jM} \rangle e^{-i\alpha q_1 - i\beta p_1} \approx 2\pi \quad (\text{A13})$$

Denote the left-hand side of Eq. (A13) by LHS. Equation (A13) implies that

$$|\text{LHS} - 2\pi| \leq \delta, \quad \delta \ll 1. \quad (\text{A14})$$

Taking absolute values of both sides of Eq. (A13) and using (A8) and (A12) and the fact that  $e^{i\alpha q_m + i\beta p_m}$  is a bounded operator of norm 1, we have that

$$2\pi \geq \sum_j |a_j|^2 |f_{s_j, m=1}| \geq |\text{LHS}|. \quad (\text{A15})$$

From (A14) and (A15) we have that  $\delta \geq |2\pi - \text{LHS}| \geq 2\pi - |\text{LHS}| \geq 2\pi - \sum_j |a_j|^2 |f_{s_j, m=1}|$ , so that

$$\sum_j |a_j|^2 |f_{s_j, m=1}| \geq 2\pi - \delta. \quad (\text{A16})$$

Let  $J_<$  be the set of all  $j$  such that  $|f_{s_j, m=1}| \leq 2\pi - \delta^{1/2}$  and let  $\sum_{j \in J_<} |a_j|^2 = P_<$ . Then (A12) and (A16) imply that  $P_<(2\pi - \delta^{1/2}) + (1 - P_<)2\pi \geq 2\pi - \delta$  so that  $P_< \leq \delta^{1/2}$ . Thus as  $\delta \rightarrow 0$ , almost all  $j$  are such that  $|f_{s_j, m=1}| \geq 2\pi - \epsilon$ , where we have set  $\epsilon := \delta^{1/2}$ . Using (A12), this, in turn, implies that for small enough  $\epsilon$ ,

$$f_{s_j, m=1} \geq 2\pi - \epsilon. \quad (\text{A17})$$

This brings us back to Eq. (119) with  $s = s_j$ ,  $m = 1$ . The analysis subsequent to that equation implies that such  $s_j$  must be a weave.

*Lemma 5:* Let  $|\psi\rangle \in \mathcal{H}_{\text{phys}}$  be semiclassical. Then  $|\psi\rangle$  is peaked at group averages of embedding eigenstates which are based on weaves.

*Proof:* Recall that  $|\psi\rangle$  is in the completion of  $\eta(\mathcal{D})$  where  $\mathcal{D}$  is the finite span of charge-network states. It is then straightforward to see that any such  $|\psi\rangle$  admits the expansion:

$$|\psi\rangle = \sum_j a_j \eta(|s_j\rangle \otimes |\psi_{jM}\rangle), \quad (\text{A18})$$

such that

$$\eta(|s_i\rangle \otimes |\psi_{iM}\rangle)[|s_j\rangle \otimes |\psi_{jM}\rangle] = \delta_{ij}, \quad (\text{A19})$$

and  $|s_i\rangle, |s_j\rangle$  are not gauge related if  $i \neq j$  i.e. for  $i \neq j$  and  $\forall \phi$ ,

$$|s_i\rangle \neq \hat{U}(\phi)|s_j\rangle. \quad (\text{A20})$$

Here  $s_j$  is an embedding charge-network label,  $\phi$  is a gauge transformation and  $|\psi_{jM}\rangle \in \mathcal{H}_M$ . We shall use the notation of lemma 4 for the edges and charge labels of  $s_j$ . Note that  $|\psi_{jM}\rangle$  is such that  $\eta(|s_j\rangle \otimes |\psi_{jM}\rangle) \in \mathcal{H}_{\text{phys}}$  as implied by (A19). Using (87), the normalization  $\langle \psi | \psi \rangle_{\text{phys}} = 1$  implies that

$$\sum_j |a_j|^2 = 1 \quad (\text{A21})$$

Semiclassicality implies that, to leading order in  $\hbar$ ,

$$\langle \psi | [e^{i\alpha q_m}, e^{i\beta p_m}] | \psi \rangle_{\text{phys}} \approx +i\hbar\alpha\beta 2\pi m e^{i\alpha q_m + i\beta p_m}, \quad (\text{A22})$$

where the “+” sign in the right-hand side is due to the fact that operators act on  $\mathcal{H}_{\text{phys}}$  by dual action (see footnote 4). Using Eqs. (80) and (A20) we have that

$$\sum_j |a_j|^2 2i \sin\left(\frac{\alpha\beta\hbar}{2} f_{s_j, m}\right) \langle \eta(|s_j\rangle \otimes |\psi_{jM}\rangle), e^{i\alpha q_m + i\beta p_m} \eta(|s_j\rangle \otimes |\psi_{jM}\rangle) \rangle_{\text{phys}} \approx i\hbar\alpha\beta 2\pi m e^{i\alpha q_m + i\beta p_m}. \quad (\text{A23})$$

Here  $f_{s_j, m}$  is defined as in lemma 4.<sup>6</sup> This is the analog of Eq. (A10) of lemma 4. The analysis of lemma 4 subsequent to that equation applies here identically thus proving lemma 5.

## APPENDIX B: LEMMAS CONCERNING THE NO GO RESULT OF SECTION VI B

*Lemma 6:* No states  $|\psi\rangle \in \mathcal{H}_{\text{kin}}$  exist which are semiclassical with respect to the uncountable set of operators  $\{e^{i\alpha q_m}, e^{i\beta p_m}, |\alpha - \alpha_0| < \epsilon, |\beta - \beta_0| < \delta\}$  for any fixed  $m, \alpha_0, \beta_0$  and any  $\epsilon, \delta > 0$ .

*Proof:* As in lemma 4 of Appendix A, any  $|\psi\rangle \in \mathcal{H}_{\text{kin}}$  admits the expansion (A5)–(A8). Additionally we may expand  $|\psi_{jM}\rangle$  in terms of matter charge networks so that for any fixed  $j$ ,

$$|\psi_{jM}\rangle = \sum_{r^j} b_{r^j} |s'_{r^j}\rangle \quad (\text{B1})$$

$$\langle s'_{r_1^j} | s'_{r_2^j} \rangle = \delta_{r_1^j, r_2^j} \quad (\text{B2})$$

where  $r^j$  varies over a countable set (as, of course, does  $j$ ),  $b_{r^j}$  are complex coefficients and  $s'_{r^j}$  are matter charge networks.

Let  $C$  be the set of all  $j$  such that  $\gamma(s_j)$  has at least one edge  $e(j)$  with embedding charge  $k_{e(j)}$  such that  $\text{cosm}\hbar k_{e(j)} \neq 0$ . For every  $j \in C$  choose an edge  $e^j \subset \gamma(s_j)$  with embedding charge  $k_{e^j}$  such that

$$c_j := \text{cosm}\hbar k_{e^j} \neq 0. \quad (\text{B3})$$

Let  $S$  be the set of all  $j$  such that  $j \notin C$ . Clearly, for each  $j \in S$  we can fix an edge  $e^j \in \gamma(s_j)$  such that its charge label  $k_{e^j}$  satisfies

$$s_j := \text{sinm}\hbar k_{e^j} \neq 0. \quad (\text{B4})$$

Next, let  $L$  be the set of all matter charges which occur in  $s'_{r^j} \forall j, r$ . Let  $\Delta L$  be the set of differences between all pairs

<sup>6</sup>It is straightforward to check that  $f_{s_j, m}$  in (A11) is a gauge invariant function of  $s_j$  i.e.  $f_{s_j, m} = f_{s'_j, m} \forall s'_j$  such that  $\exists$  a gauge transformation  $\phi$  such that  $|s'_j\rangle = \hat{U}(\phi)|s_j\rangle$ .

of elements of  $L$  i.e.  $\Delta L = \{l - l' \forall l, l' \in L\}$ . For every  $j_C \in C$ ,  $j_S \in S$ , define the sets  $\Delta L_{j_C}$ ,  $\Delta L_{j_S}$  whose elements are obtained by dividing elements of  $\Delta L$  by  $c_{j_C}$ ,  $s_{j_S}$  [see (B3) and (B4)] i.e.  $\Delta L_{j_C} := \left\{ \frac{x}{c_{j_C}} \forall x \in \Delta L \right\}$ ,  $\Delta L_{j_S} := \left\{ \frac{x}{s_{j_S}} \forall x \in \Delta L \right\}$ . Finally, let  $\Delta L_C := \cup_{j_C \in C} \Delta L_{j_C}$ ,  $\Delta L_S := \cup_{j_S \in S} \Delta L_{j_S}$ .

Note that  $\Delta L_C$ ,  $\Delta L_S$  are both countable sets. It follows that in any neighborhood of  $\alpha_0$ ,  $\beta_0$  there exist uncountably many  $\alpha$ ,  $\beta$  such that  $\alpha \notin \Delta L_C$ ,  $\beta \notin \Delta L_S$ . Then from (80) and the fact that  $e^{i\beta p_m}$  is an operator of unit norm, it follows that for such  $\alpha$ ,  $\beta$ ,

$$|\langle \psi | e^{i\alpha q_m} | \psi \rangle| = \sum_{j \in S} |a_j|^2, \quad (\text{B5})$$

$$|\langle \psi | e^{i\beta p_m} | \psi \rangle| \leq \sum_{j \in C} |a_j|^2 = 1 - \sum_{j \in S} |a_j|^2. \quad (\text{B6})$$

Semiclassicality requires that both (B5) and (B6) be close to unity. Clearly, this is not possible.

*Lemma 7:* No states  $|\psi\rangle \in \mathcal{H}_{\text{phys}}$  exist which are semiclassical with respect to the uncountable set of operators  $\{e^{i\alpha q_m}, e^{i\beta p_m}, |\alpha - \alpha_0| < \epsilon, |\beta - \beta_0| < \delta\}$  for any fixed  $m$ ,  $\alpha_0$ ,  $\beta_0$  and any  $\epsilon$ ,  $\delta > 0$ .

*Proof:* As in lemma 5, Appendix A, any  $|\psi\rangle \in \mathcal{H}_{\text{phys}}$  admits the expansion (A18)–(A20). Further  $|\psi_{j_M}\rangle$  can be expanded as in Eq. (B1)–(B3) of lemma 6. Note that the antilinearity of  $\eta$  implies that we may rewrite Eq. (A18) as

$$|\psi\rangle = \eta \left( \sum_j a_j^* |s_j\rangle \otimes |\psi_{j_M}\rangle \right). \quad (\text{B7})$$

Next, let us construct the sets  $\Delta L_C$ ,  $\Delta L_S$  (as defined in

lemma 6) for the state  $\sum_j a_j^* |s_j\rangle \otimes |\psi_{j_M}\rangle \in \mathcal{H}_{\text{kin}}$ . It follows straightforwardly from the periodicity of the cosine and sine functions in conjunction with the action of gauge transformations (75) that we may choose the sets  $\Delta L_C$ ,  $\Delta L_S$  in such a way that they are identical for any (kinematic) state which is gauge related to the state  $\sum_j a_j^* |s_j\rangle \otimes |\psi_{j_M}\rangle$ . Thus the sets  $\Delta L_C$ ,  $\Delta L_S$  can be chosen so as to depend only on the physical state  $|\psi\rangle$ , and it is straightforward to see that, as in lemma 6, if we choose  $\alpha \notin \Delta L_C$ ,  $\beta \notin \Delta L_S$ , we obtain Eqs. (B5) and (B6) with  $|\psi\rangle$  as in (B7). This proves the lemma.

### APPENDIX C: CHOICE OF UNITS

In this appendix we summarize dimensions of various operators and parameters of the theory. We have set the speed of light  $c$  to be unity.

$$\begin{aligned} [S_0] &= ML = [\hbar] \\ [f] &= M^{1/2} L^{1/2}, [\pi_f] = M^{1/2} L^{-(1/2)} \\ [X^\pm] &= L, [\Pi_\pm] = ML^{-1} \\ [q_{(\pm)n}] &= M^{1/2} L^{1/2} = [p_{(\pm)n}] \end{aligned} \quad (\text{C1})$$

where  $[n] = L^{-1}$ .

The dimensions of the above fields naturally imply the dimensions of the various charges and parameters involved in the theory.

$$\begin{aligned} [k_e] &= M^{-1}, \quad [l_e] = M^{-(1/2)} L^{-(1/2)} \\ [\alpha] &= M^{-(1/2)} L^{-(1/2)} \end{aligned} \quad (\text{C2})$$

where the parameter  $\alpha$  occurs in the exponentiated observables defined in (77). Throughout this paper, we have fixed the units such that length of the  $T = \text{const}$  circle is  $2\pi$ . Thus the only arbitrary scale in the theory is the mass scale.

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