Entanglement in pair creation

From string breaking to strong electric fields

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C2QA

Plan

"Real-time non-perturbative dynamics of jet production in Schwinger model: quantum entanglement and vacuum modification"

with D. Frenklakh, K. Ikeda, D. Kharzeev, V. Korepin, S. Shi, K. Yu, arXiv:2301.11991

"Entropy Suppression through Quantum Interference in Electric Pulses"

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Motivation

Real-time dynamics $1+1$ models

Learn about physics

Opportunity for co-design quantum comp.

Schwinger model

Electromagnetism in 1 dimension

Schwinger model

Electromagnetism in 1 dimension

Full fledged quantum field theory

Simulable in the near future (?)

Solved in some limit ($m \to 0$)

Schwinger model

Electromagnetism in 1 dimension

$\nabla E = \rho$

Full fledged quantum field theory

Confines $V(x) \propto x$

Simulable in the near future (?)

Highly non-trivial vacuum

Solved in some limit ($m \to 0$)

Schwinger model

Electromagnetism in 1 dimension

$\nabla E = \rho$

Full fledged quantum field theory

Confines $V(x) \propto x$

Simulable in the near future (?)

Highly non-trivial vacuum

Solved in some limit ($m \to 0$)

Use-case/testbed $\longleftrightarrow$ Learn new physics (dynamics)

Word of caution

Not QCD, only toy model ($1D$, no dynamical gluons)

$\downarrow$

Need to ask reasonable questions

Only qualitative predictions

Dynamical string breaking

Look at dynamical string breaking

En.$\sim m + m + \alpha l_1$

Dynamical string breaking

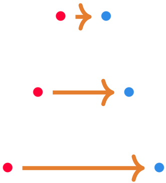
Look at dynamical string breaking

En.$\sim$ $m + m + \alpha l_1$

En.$\sim$ $m + m + \alpha l_2$

Dynamical string breaking

Look at dynamical string breaking



$$\text{En.} \sim m + m + \alpha l_1$$

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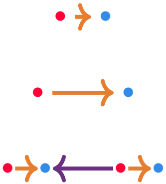
$$\text{En.} \sim m + m + \alpha l_3$$

Dynamical string breaking

Look at dynamical string breaking



$$\text{En.} \sim m + m + \alpha l_1$$

$$\text{En.} \sim m + m + \alpha l_2$$

$$\cancel{\text{En.} \sim m + m + \alpha l_3}$$

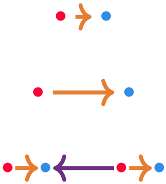
$$\downarrow$$

$$\text{En.} \sim m + m + m + m$$

when $\alpha l_3 > 2m$

Dynamical string breaking

Look at dynamical string breaking



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when $\alpha l_3 > 2m$

Screen field by creating particles!

Dynamical string breaking

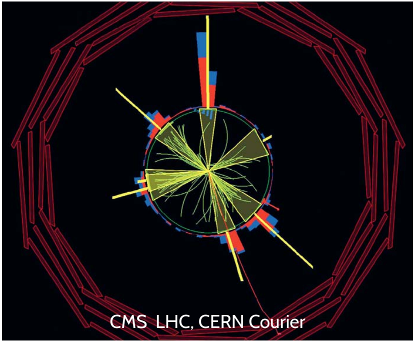
Look at dynamical string breaking

En.$\sim m + m + \alpha l_1$

En.$\sim m + m + \alpha l_2$

Screen field by creating particles!

Motivation: QCD jets



Our set-up

$$H(t) = \int \mathrm{d}x \left[\frac{1}{2} E^2 + \hat{\bar{\psi}} \left(-i\gamma^1 \partial_1 + g A^1 \gamma_1 + m \right) \hat{\psi} + j^1_{ext}(t) A_1 \right]$$

Our set-up

$$H(t) = \int \mathrm{d}x \left[\frac{1}{2} \underset{\text{Electric field}}{E^2} + \hat{\bar{\psi}} \left(-i\gamma^1 \partial_1 + gA^1 \gamma_1 + m \right) \hat{\psi} + j^1_{ext}(t) A_1 \right]$$

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$$H(t) = \int \mathrm{d}x \left[\frac{1}{2} \overbrace{E^2}^{\text{Electric field}} + \hat{\bar{\psi}} \left(-i\gamma^1 \partial_1 + g \underbrace{A^1}_{\text{Vector potential}} \gamma_1 + m \right) \hat{\psi} + j^1_{ext}(t) \underbrace{A_1}_{\text{Vector potential}} \right]$$

Our set-up

Electric field

Vector potential

$$H(t) = \int \mathrm{d}x \left[\frac{1}{2} E^2 + \hat{\bar{\psi}} \left(-i\gamma^1 \partial_1 + g A^1 \gamma_1 + m \right) \hat{\psi} + j^1_{ext}(t) A_1 \right]$$

Fermion

Our set-up

Electric field

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Fermion

External charges: $j^1_{ext}(t) = g \left(\delta(x+t) + \delta(x-t) \right) \theta(t)$

2 point charges moving apart at speed of light

Our set-up

Electric field

Vector potential

$$H(t) = \int \mathrm{d}x \left[\frac{1}{2}E^2 + \hat{\bar{\psi}}\left(-i\gamma^1\partial_1 + gA^1\gamma_1 + m\right)\hat{\psi} + j^1_{ext}(t)A_1\right]$$

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Idea:
- Find $|vac\rangle_{t<0}$
- Compute $|\psi(t)\rangle = e^{-i\int_0^t \mathrm{d}t' H(t')}|vac\rangle_{t<0}$

Our set-up

Electric field

Vector potential

$$H(t) = \int \mathrm{d}x \left[\frac{1}{2} E^2 + \hat{\bar{\psi}} \left(-i\gamma^1 \partial_1 + gA^1 \gamma_1 + m \right) \hat{\psi} + j^1_{ext}(t) A_1 \right]$$

Fermion

External charges: $j^1_{ext}(t) = g\left(\delta(x+t) + \delta(x-t)\right)\theta(t)$

2 point charges moving apart at speed of light

Idea: • Find $|vac\rangle_{t<0}$

• Compute $|\psi(t)\rangle = e^{-i\int_0^t \mathrm{d}t' H(t')} |vac\rangle_{t<0}$

see also [74, Casher, Kogut, Susskind], [12,13, Kharzeev, Loshaj], [14, Berges, Hebenstreit]

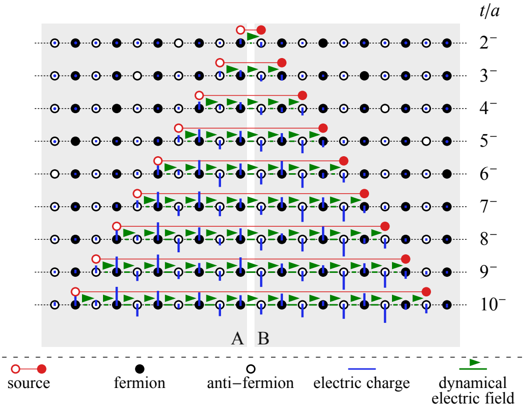
In practice

- Staggered fermions χ_n
- Integrate out E: $\partial_1 E = \rho + \rho_{ext}$
- (Map to non-local spin chain)

$$H(t) = H_{\pm} + H_{ZZ} + H_Z(t)$$
$$H_{\pm} = \frac{1}{4a} \sum_{n=1}^{N-1} (X_n X_{n+1} + Y_n Y_{n+1})$$
$$H_{ZZ} = \frac{ag^2}{4} \sum_{n=1}^{N-1} \sum_{m=1}^{n} \sum_{k=1}^{m-1} Z_m Z_k, \;\; H_Z = \sum_{n=1}^{N} f(n) Z_n$$

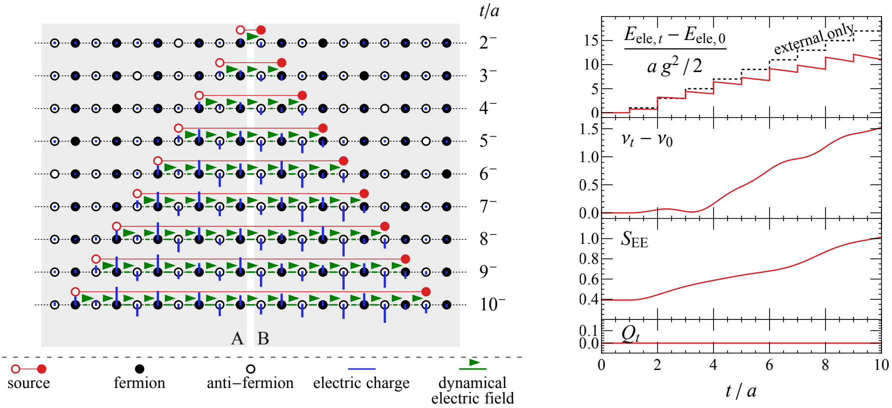
- Use exact diagonalization
- Compute observables $\bar{O}(t) = \langle \psi(t) | O | \psi(t) \rangle$

Results, $m = 0.25, g = 0.5, a = 1$



Results, $m = 0.25, g = 0.5, a = 1$

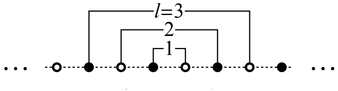
ν : $\langle\bar{\psi}\psi\rangle$, $\quad S_{EE}$: entanglement entropy A/B



Is entanglement manifest in correlations $\leftrightarrow$ measurable?

Correlation

1) Look at $\langle \Delta\nu_{N/2+l+1}(t)\Delta\nu_{N/2-l}(t)\rangle, \quad \Delta\nu_n = \bar{\psi}\psi|_n(t) - \bar{\nu}$



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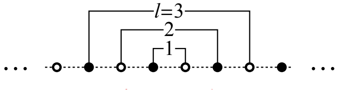
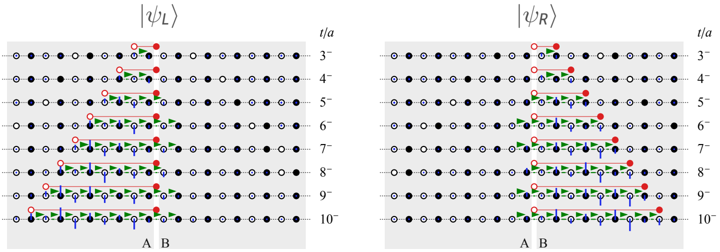


2) Compare to uncorrelated reference case



Correlation

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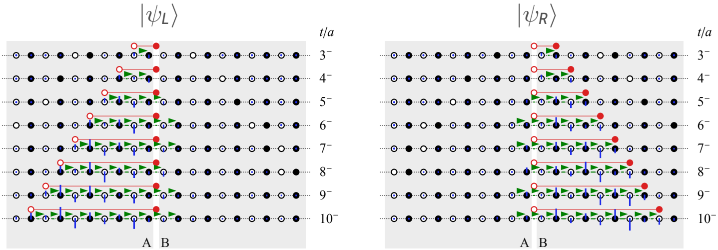
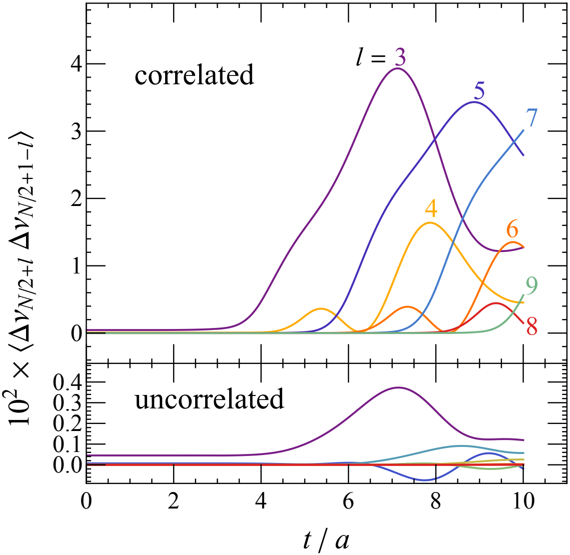


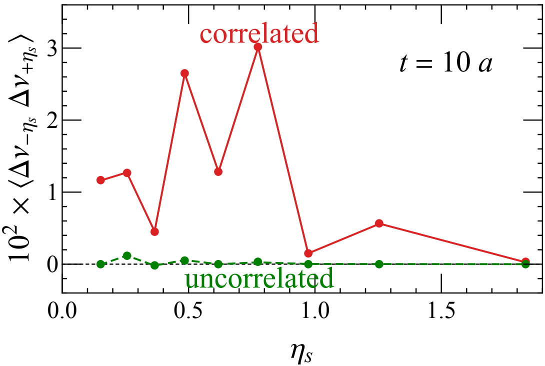
$$|\psi_{ref}\rangle = |\psi_L\rangle + e^{i\phi}|\psi_R\rangle$$

Random uniform phase

$$\langle\langle\psi_{ref}|O|\psi_{ref}\rangle\rangle \equiv \int \langle\psi_{ref}|O|\psi_{ref}\rangle \frac{\mathrm{d}\varphi}{2\pi} = \frac{\langle\psi_{\mathrm{L}}|O|\psi_{\mathrm{L}}\rangle}{2} + \frac{\langle\psi_{\mathrm{R}}|O|\psi_{\mathrm{R}}\rangle}{2}$$


correlated
l = 3
5
7
4
6
9
8
uncorrelated
$10^2 \times \langle \Delta\nu_{N/2+l}\, \Delta\nu_{N/2+1-l} \rangle$
$t\,/\,a$
0
1
2
3
4
0.0
0.1
0.2
0.3
0.4
0
2
4
6
8
10

For exp. $\to$ spatial rapidity $\eta_s \equiv \mathrm{arctanh}\frac{x}{t}$



Next steps

Finite temperature

Thermalization/ETH

Tensor networks

Summary

- Schwinger model can still teach us some physics
- Direct observation of quantum properties of string breaking
- Suggests enhanced correlations at low/mid rapidities in jet production

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Motivation

Entanglement

Distinctive feature of quantum world

Ressource for quantum comp.

Question: Effect of quantum interferences on entanglement?

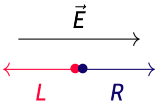
Set-up

Pair creation in strong electric fields (Schwinger effect)

- Creation of entangled pair of particles
- Typical 2-levels system

Mechanism: Similar to string breaking.

$E \cdot L \approx 2m \rightarrow$ energetically favorable to create particles



Entanglement in momentum space

n_k: Probability to create particle with momentum k

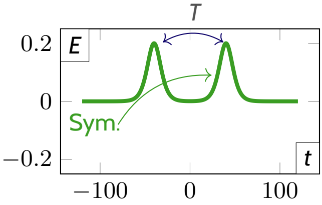
Left/right entanglement [AF, Kharzeev, 2021] :

$$S = -\int \frac{\mathrm{d}k}{2\pi} \left[(1-n_k)\log(1-n_k) + n_k \log(n_k)\right]$$

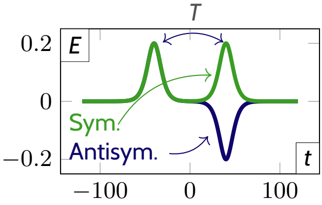
$$\mathcal{N} = -\int \frac{\mathrm{d}k}{2\pi} n_k$$

Gibbs entropy!

Interferences

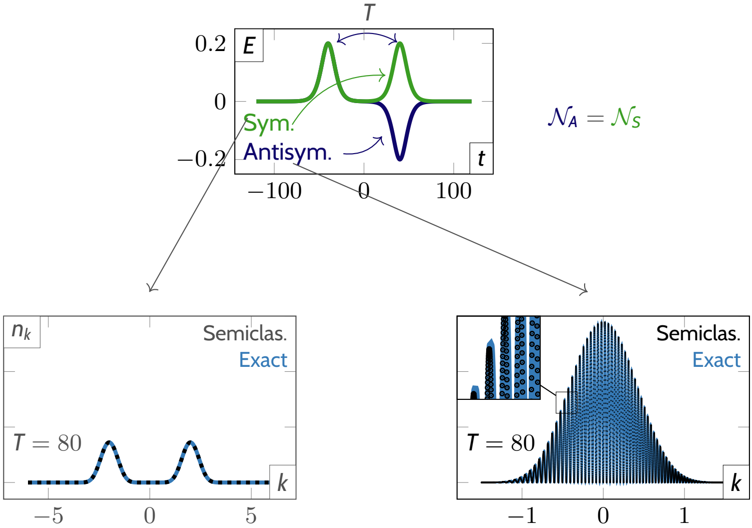


Interferences



$$\mathcal{N}_A = \mathcal{N}_S$$

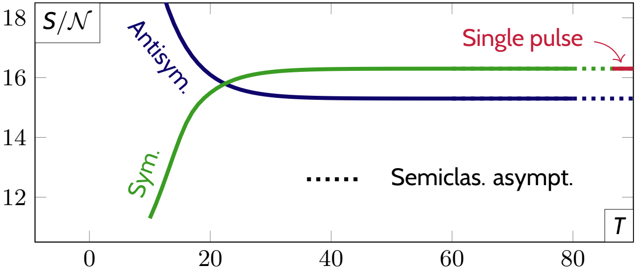
Interferences



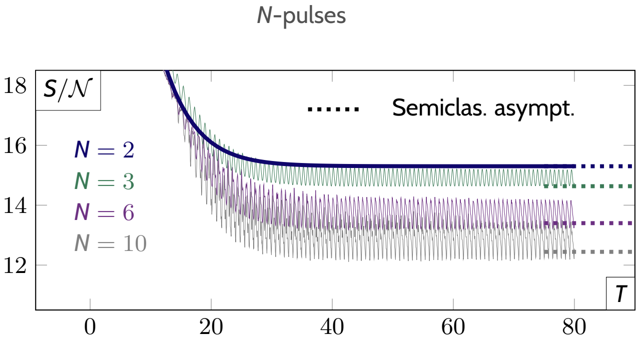
$\mathcal{N}_A = \mathcal{N}_S$

Entanglement suppression

Two-pulses



Entanglement suppression



Summary # 2

- Interference effects can suppress entropy production

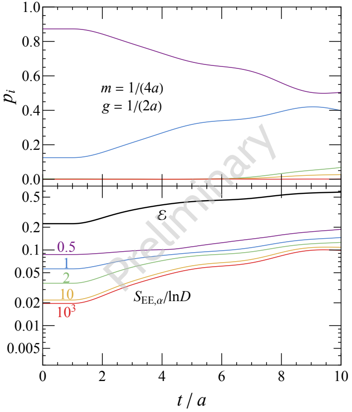
- Potential applications to sensing/hardware?

Thank you!

Trailer #1: entanglement spectrum

Entanglement spectrum: $\{p_i\}$, e-values of ρ_A

$$S_{\text{Rényi},\alpha} \equiv \frac{\ln \operatorname{tr}(\rho_A^\alpha)}{1-\alpha} \qquad\qquad \mathcal{E} \equiv \frac{1-\operatorname{tr}\rho_A^2}{1-1/D} = \frac{1-\sum_{i=1}^D p_i^2}{1-1/D}\,.$$



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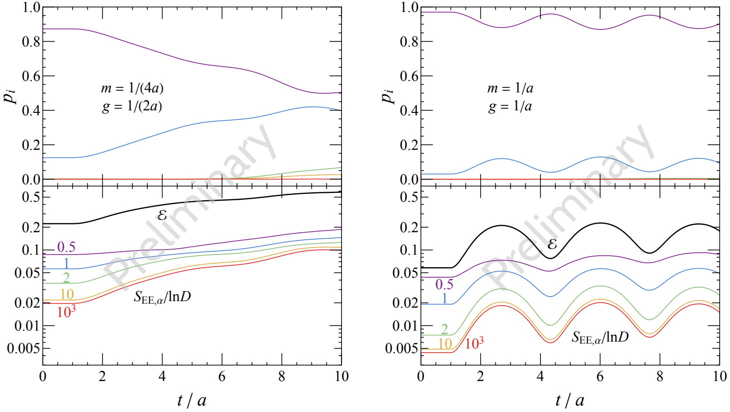
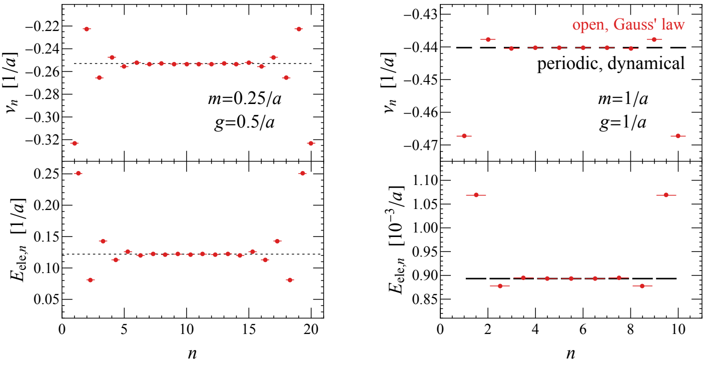
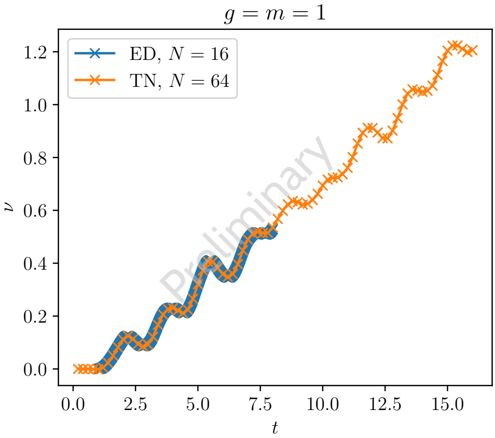


Trailer #1: entanglement spectrum

Boundary effects



Trailer #2: TN



$g = m = 1$
ED, $N = 16$
TN, $N = 64$
Preliminary
ν
t
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0.0
2.5
5.0
7.5
10.0
12.5
15.0