(New) physics from lower dimensions

Adrien Florio

Brookhaven National Laboratory

C²QA

QuantFunc 2024

Line world

Relativistic field theories in $1+1$ dimensions

↙ ↘

Opportunity for co-design quantum comp.

Learn about physics

Schwinger model $\leftrightarrow$ Electro~~magnetism~~ in $1+1D$

Model: $S = \int \mathrm{d}x\mathrm{d}t \left[\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \bar{\psi}\left(\not{D} + m\right)\psi\right]$

Electric field

Vector potential

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

Fermion

Gauss law: $\partial_x E = \bar{\psi}\gamma^0\psi$ Temp. gauge: $A_0 = 0$

Properties:

- **Confinement:** $\partial_x E = \delta(x) \leftrightarrow E(x) = \Theta(x) \leftrightarrow$ linearly rising confining force
- **Chiral anomaly:** $\partial_\mu j_5^\mu|_{m=0} = \frac{1}{4\pi}\epsilon_{\mu\nu}F^{\mu\nu} = \frac{1}{2\pi}E$
- **Chiral condensate:** $\langle\bar{\psi}\psi\rangle \neq 0$
- **Duality:** $m = 0 \rightarrow$ free *massive* boson, $m \neq 0$ interacting massive boson

Schwinger model $\leftrightarrow$ Electro~~magnetism~~ in $1+1D$

Model: $S = \int \mathrm{d}x\mathrm{d}t \left[\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \bar{\psi}\left(\not{D} + m\right)\psi\right]$

Electric field

Vector potential

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

Fermion

Gauss law: $\partial_x E = \bar{\psi}\gamma^0\psi$ Temp. gauge: $A_0 = 0$

Properties:

- **Confinement:** $\partial_x E = \delta(x) \leftrightarrow E(x) = \Theta(x) \leftrightarrow$ linearly rising confining force
- **Chiral anomaly:** $\partial_\mu j_5^\mu|_{m=0} = \frac{1}{4\pi}\epsilon_{\mu\nu}F^{\mu\nu} = \frac{1}{2\pi}E$
- **Chiral condensate:** $\langle\bar{\psi}\psi\rangle \neq 0$
- **Duality:** $m = 0 \to$ free *massive* boson, $m \neq 0$ interacting massive boson

Schwinger model $\leftrightarrow$ Electro~~magnetism~~ in $1+1D$

Model: $S = \int \mathrm{d}x\mathrm{d}t \left[\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \bar{\psi}\left(\not{D} + m\right)\psi\right]$

Electric field

Vector potential

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

Fermion

Gauss law: $\partial_x E = \bar{\psi}\gamma^0\psi$ Temp. gauge: $A_0 = 0$

No dynamical gauge fields

Properties:

- **Confinement:** $\partial_x E = \delta(x) \leftrightarrow E(x) = \Theta(x) \leftrightarrow$ linearly rising confining force
- **Chiral anomaly:** $\partial_\mu j_5^\mu|_{m=0} = \frac{1}{4\pi}\epsilon_{\mu\nu}F^{\mu\nu} = \frac{1}{2\pi}E$
- **Chiral condensate:** $\langle\bar{\psi}\psi\rangle \neq 0$
- **Duality:** $m = 0 \rightarrow$ free *massive* boson, $m \neq 0$ interacting massive boson

New physics 1D relativistic models

Many works: non-exhaustive list

- Schwinger effect: [Buyens, Haegeman, Hebenstreit, Verstraete, Van Acoleyen, '16]
- θ-vacuum: [Zache, Mueller, Schneider, Jendrzejewski, Berges, Hauke, '18]
- Open-system: [de Jong, Lee, Mulligan, Ploskon, Ringer, Yao, '21]
- Abelian-Higgs: [Chanda, Lewenstein, Zakrzewski, Tagliacozzo, '21]
- Schwinger model scattering: [Belyansky, Whitsitt, Mueller, Fahimniya, Bennewitz, Davoudi, Gorshkov, '23][Papaesfstathiou, Knolle, Bañuls, '24]
- Chiral magnetic wave Schwinger model: [Ikeda, Kharzeev, Shi, '23]
- Spin correlations: [Barata, Gong, Venugopalan, '23]
- Hadrons in $1+1$ QCD: [Rigobello, Magnifico, Silvi, Montangero, '23]
- QZD: [AF, Weichselbaum, Valgushev, Pisarski, '23]
- $\ldots$

Today:

	Entanglement	Dynamics
	[AF, PRD,'24]	[AF, Frenklakh, Ikeda, Kharzeev, Korepin, Shi, Yu, PRL '23 and arXiv:2404.00087]

Entanglement in QFT

Entanglement structure of fields

Effect on nuclear matter?

Relation to confinement?

Entanglement in QFT

Entanglement structure of fields

Effect on nuclear matter?

Relation to confinement?

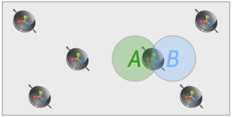
See also [Klebanov, Kutasov, Murugan, '07] in holography

Entanglement in QFT

Entanglement structure of fields

Effect on nuclear matter?

Relation to confinement?



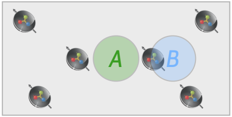
See also [Klebanov, Kutasov, Murugan, '07] in holography

Entanglement in QFT

Entanglement structure of fields

Effect on nuclear matter?

Relation to confinement?



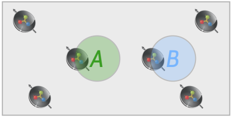
See also [Klebanov, Kutasov, Murugan, '07] in holography

Entanglement in QFT

Entanglement structure of fields

Effect on nuclear matter?

Relation to confinement?



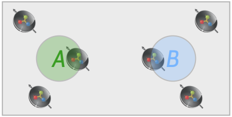
See also [Klebanov, Kutasov, Murugan, '07] in holography

Entanglement in QFT

Entanglement structure of fields

Effect on nuclear matter?

Relation to confinement?



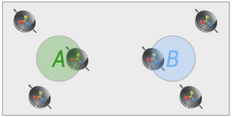
See also [Klebanov, Kutasov, Murugan, '07] in holography

Entanglement in QFT

Entanglement structure of fields

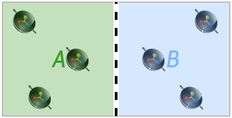
Effect on nuclear matter?

Relation to confinement?



- Bi-partition:

$\rho_{AB} = |\psi\rangle\langle\psi|$ pure state



Ent. entropy: $S = -\mathrm{Tr}(\rho_A \ln \rho_A)$

$\rho_A = -\mathrm{Tr}_B(\rho_{AB})$

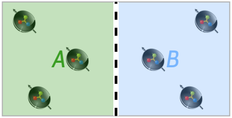
- Sub-regions:

$\rho_{AB} = \mathrm{Tr}_C\,(|\psi\rangle\langle\psi|)$ mixed state

?

- Bi-partition:

$$\rho_{AB} = |\psi\rangle\langle\psi| \text{ pure state}$$



Ent. entropy: $S = -\mathrm{Tr}(\rho_A \ln \rho_A)$

$$\rho_A = -\mathrm{Tr}_B(\rho_{AB})$$

- Sub-regions:

$$\rho_{AB} = \mathrm{Tr}_C\left(|\psi\rangle\langle\psi|\right) \text{ mixed state}$$

?

E^F E^D

Formation / distillable entanglement

$\sim$

How many Bell pairs

to form the

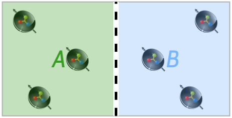
/

can be extracted from

the state

- Bi-partition:

$\rho_{AB} = |\psi\rangle\langle\psi|$ pure state



Ent. entropy: $S = -\mathrm{Tr}(\rho_A \ln \rho_A)$

$\rho_A = -\mathrm{Tr}_B(\rho_{AB})$

- Sub-regions:

$\rho_{AB} = \mathrm{Tr}_C\,(|\psi\rangle\langle\psi|)$ mixed state

?

$|Bell\rangle = \frac{1}{\sqrt{2}}\left(|01\rangle + |10\rangle\right)$, 1 "e-bit"

E^F E^D

Formation / distillable entanglement

$\sim$

How many Bell pairs

to form the

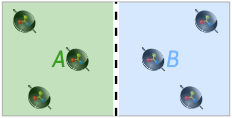
/

can be extracted from

the state

- Bi-partition:

$\rho_{AB} = |\psi\rangle\langle\psi|$ pure state



Ent. entropy: $S = -\mathrm{Tr}(\rho_A \ln \rho_A)$

$\rho_A = -\mathrm{Tr}_B(\rho_{AB})$

- Sub-regions:

$\rho_{AB} = \mathrm{Tr}_C\left(|\psi\rangle\langle\psi|\right)$ mixed state

?

$|Bell\rangle = \frac{1}{\sqrt{2}}\left(|01\rangle + |10\rangle\right)$, 1 "e-bit"

E^F E^D

Formation / distillable entanglement

$\sim$

How many Bell pairs

to form the

/

can be extracted from

the state

Pure state: $E^F = E^D \leftrightarrow$ Ent. entropy

Mixed state: $E^F \neq E^D$!

$|Bell\rangle = \frac{1}{\sqrt{2}}\left(|01\rangle + |10\rangle\right)$, 1 “e-bit”

E^F E^D

Formation / distillable entanglement

$\sim$

How many Bell pairs

to form the

/

can be extracted from

the state

Pure state: $E^F = E^D \leftrightarrow$ Ent. entropy

Mixed state: $E^F \neq E^D$!

E_D hard to compute, but...

$\epsilon_{\mathcal{N}}$: logarithmic negativity

1) $\epsilon_{\mathcal{N}} \neq 0 \implies \rho_{AB}$ not separable

2) $E_D \leq \epsilon_{\mathcal{N}}$

Computable in practice

$|Bell\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle)$, 1 “e-bit”

E^F E^D

Formation / distillable entanglement

$\sim$

How many Bell pairs

to form the

/

can be extracted from

the state

Pure state: $E^F = E^D \leftrightarrow$ Ent. entropy

Mixed state: $E^F \neq E^D$!

E_D hard to compute, but...

$\epsilon_{\mathcal{N}}$: logarithmic negativity

1) $\epsilon_{\mathcal{N}} \neq 0 \implies \rho_{AB}$ not separable

2) $E_D \leq \epsilon_{\mathcal{N}}$

Computable in practice

Peres-Horodecki criterion:

$\rho = \rho_A \otimes \rho_B \implies \rho^{\mathrm{T}_A} \equiv \rho_A^{\mathrm{T}} \otimes \rho_B$ is a density matrix

$\implies |\rho^{\mathrm{T}_A}|_1 = 1$

$|\rho^{\mathrm{T}_A}|_1 < 1 \implies \rho \neq \rho_A \otimes \rho_B$

$|Bell\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle)$, 1 "e-bit"

E^F E^D

Formation / distillable entanglement

$\sim$

How many Bell pairs

to form the

/

can be extracted from

the state

Pure state: $E^F = E^D \leftrightarrow$ Ent. entropy

Mixed state: $E^F \neq E^D$!

E_D hard to compute, but...

$\epsilon_{\mathcal{N}}$: logarithmic negativity

1) $\epsilon_{\mathcal{N}} \neq 0 \implies \rho_{AB}$ not separable

2) $E_D \leq \epsilon_{\mathcal{N}}$

Computable in practice

Peres-Horodecki criterion:

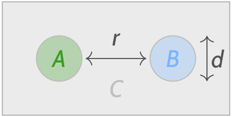
$\rho = \rho_A \otimes \rho_B \implies \rho^{T_A} \equiv \rho_A^T \otimes \rho_B$
is a density matrix
$\implies |\rho^{T_A}|_1 = 1$

$|\rho^{T_A}|_1 < 1 \implies \rho \neq \rho_A \otimes \rho_B$

$\epsilon_{\mathcal{N}} = \log |\rho_{AB}^{T_A}|_1$

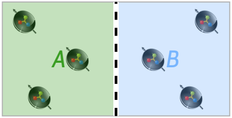
- Sub-regions:

  $\rho_{AB} = \mathrm{Tr}_C(|\psi\rangle\langle\psi|)$ mixed state



- Bi-partition:

  $\rho_{AB} = |\psi\rangle\langle\psi|$ pure state

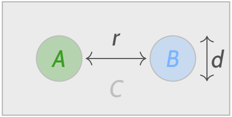


Log. negativity $\epsilon_{\mathcal{N}}$:

Some known QFT results

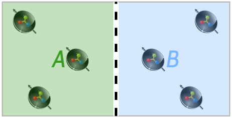
- Sub-regions:

  $\rho_{AB} = \mathrm{Tr}_C\left(|\psi\rangle\langle\psi|\right)$ mixed state



- Bi-partition:

  $\rho_{AB} = |\psi\rangle\langle\psi|$ pure state



Log. negativity $\epsilon_{\mathcal{N}}$:

Exponential decay $\sim e^{-\beta r/d}$ for

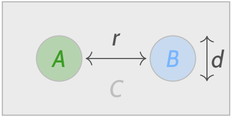
- Free massless boson
- Bosonic CFTs

See [Klco, Savage, PRL 2021] and refs. therein

Some known QFT results

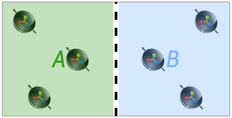
- Sub-regions:

  $\rho_{AB} = \mathrm{Tr}_C\left(|\psi\rangle\langle\psi|\right)$ mixed state



- Bi-partition:

  $\rho_{AB} = |\psi\rangle\langle\psi|$ pure state



Log. negativity $\epsilon_{\mathcal{N}}$:

Exponential decay $\sim e^{-\beta r/d}$ for

- Free massless boson
- Bosonic CFTs

See [Klco, Savage, PRL 2021] and refs. therein

vs

Power law decay $\sim (r/d)^{-\alpha}$ for

- (Some?) fermionic CFTs

[Parez, Witczak-Krempa, PRR 2024]

Some known QFT results

Log. negativity $\epsilon_{\mathcal{N}}$:

Exponential decay $\sim e^{-\beta r/d}$ for

- Free massless boson
- Bosonic CFTs

See [Klco, Savage, PRL 2021] and refs. therein

vs

Power law decay $\sim (r/d)^{-\alpha}$ for

- (Some?) fermionic CFTs

[Parez, Witczak-Krempa, PRR 2024]

Fermions more entangled than bosons?

Detect quark to meson transition?

Some known QFT results

Log. negativity $\epsilon_{\mathcal{N}}$:

Exponential decay $\sim e^{-\beta r/d}$ for

- Free massless boson
- Bosonic CFTs

See [Klco, Savage, PRL 2021] and refs. therein

vs

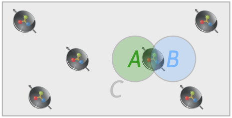
Power law decay $\sim (r/d)^{-\alpha}$ for

- (Some?) fermionic CFTs

[Parez, Witczak-Krempa, PRR 2024]

Fermions more entangled than bosons?

Detect quark to meson transition?



Some known QFT results

Log. negativity $\epsilon_{\mathcal{N}}$:

Exponential decay $\sim e^{-\beta r/d}$ for

- Free massless boson
- Bosonic CFTs

See [Klco, Savage, PRL 2021] and refs. therein

vs

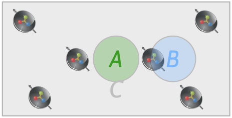
Power law decay $\sim (r/d)^{-\alpha}$ for

- (Some?) fermionic CFTs

[Parez, Witczak-Krempa, PRR 2024]

Fermions more entangled than bosons?

Detect quark to meson transition?



Some known QFT results

Log. negativity $\epsilon_{\mathcal{N}}$:

Exponential decay $\sim e^{-\beta r/d}$ for

- Free massless boson
- Bosonic CFTs

See [Klco, Savage, PRL 2021] and refs. therein

vs

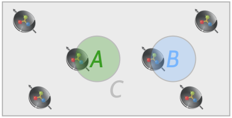
Power law decay $\sim (r/d)^{-\alpha}$ for

- (Some?) fermionic CFTs

[Parez, Witczak-Krempa, PRR 2024]

Fermions more entangled than bosons?

Detect quark to meson transition?



Some known QFT results

Log. negativity $\epsilon_{\mathcal{N}}$:

Exponential decay $\sim e^{-\beta r/d}$ for

- Free massless boson
- Bosonic CFTs

See [Klco, Savage, PRL 2021] and refs. therein

vs

Power law decay $\sim (r/d)^{-\alpha}$ for

- (Some?) fermionic CFTs

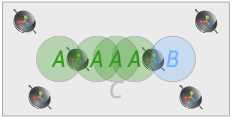
[Parez, Witczak-Krempa, PRR 2024]

Fermions more entangled than bosons?

Detect quark to meson transition?

Fermions more entangled than bosons?

Detect quark to meson transition?

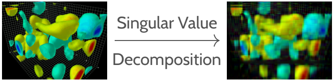


Setup: Schwinger model

- Discretize (solve Gauss law, only fermions)
- Find ground state $|\psi_{GS}\rangle$
  - Tensor network (DMRG)

  ITensors library:

  [Fishman, White, Stoudenmire, SciPost, 2022]

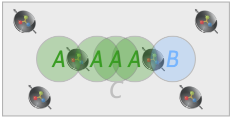


- Compute $\epsilon_{\mathcal{N}^{2f}}(r) \equiv \epsilon_{\mathcal{N}}(r, a)$

  “Two-fermion negativity”

Fermions more entangled than bosons?

Detect quark to meson transition?

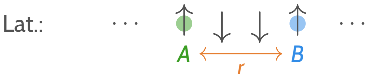


Setup: Schwinger model

- Discretize (solve Gauss law, only fermions)
- Find ground state $|\psi_{GS}\rangle$
  - Tensor network (DMRG)
    ITensors library:
    [Fishman, White, Stoudenmire, SciPost, 2022]

- Compute $\epsilon_{\mathcal{N}^{2f}}(r) \equiv \epsilon_{\mathcal{N}}(r, a)$

  "Two-fermion negativity"

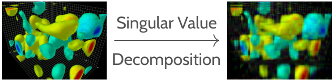


Setup: Schwinger model

- Discretize (solve Gauss law, only fermions)
- Find ground state $|\psi_{GS}\rangle$
  - Tensor network (DMRG)

  ITensors library:

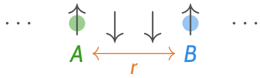
  [Fishman, White, Stoudenmire, SciPost, 2022]



- Compute $\epsilon_{\mathcal{N}^{2f}}(r) \equiv \epsilon_{\mathcal{N}}(r, a)$

"Two-fermion negativity"

Lat.:



Two-fermion negativity

- Closed expression for $\epsilon_{\mathcal{N}}^{2f}$ in terms of 1pt and 2pt functions

[Parez, Witczak-Krempa, PRR 2024]

- Continuum expression !

$$\epsilon_{\mathcal{N}^{2f}}/a^2 \to 16|D^F(r)|^2$$

D^F : Full propagator $\langle\psi_{GS}|\frac{1}{\not{D}}|\psi_{GS}\rangle$

- D^F known for $m_f = 0$ Schwinger model [Casher, Kogut, Susskind, '73]

Setup: Schwinger model

- Discretize (solve Gauss law, only fermions)
- Find ground state $|\psi_{GS}\rangle$
  - Tensor network (DMRG)

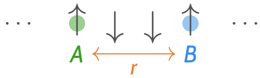
  ITensors library:

  [Fishman, White, Stoudenmire, SciPost, 2022]

- Compute $\epsilon_{\mathcal{N}^{2f}}(r) \equiv \epsilon_{\mathcal{N}}(r, a)$

  "Two-fermion negativity"

Lat.:



Two-fermion negativity

- Closed expression for $\epsilon^{2f}_{\mathcal{N}}$ in terms of 1pt and 2pt functions

  [Parez, Witczak-Krempa, PRR 2024]

- Continuum expression !

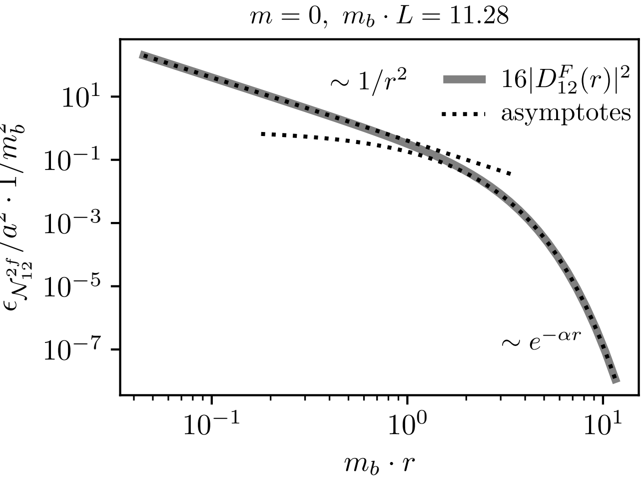
  $\epsilon_{\mathcal{N}^{2f}}/a^2 \to 16|D^F(r)|^2$

  D^F : Full propagator $\langle\psi_{GS}|\frac{1}{\not{D}}|\psi_{GS}\rangle$

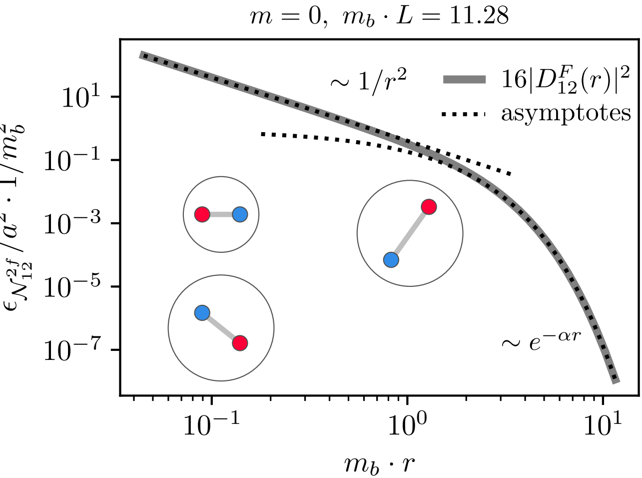
- D^F known for $m_f = 0$ Schwinger model [Casher, Kogut, Susskind, '73]

See [AF, PRD 2024] for details

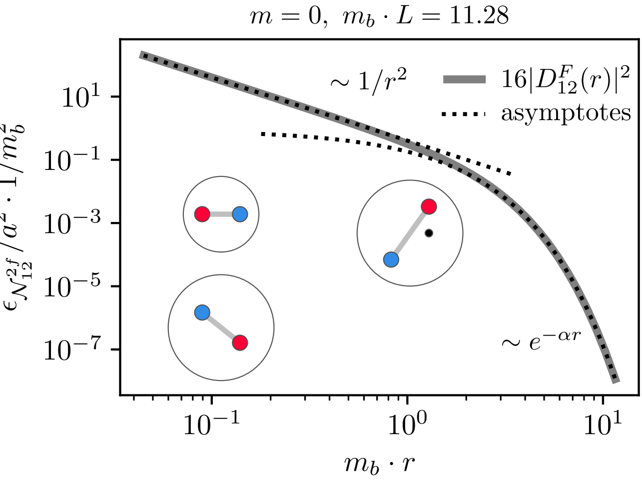
Massless case



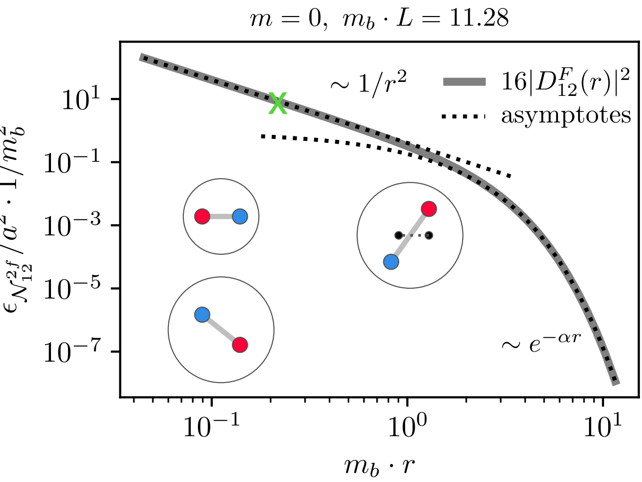
Massless case



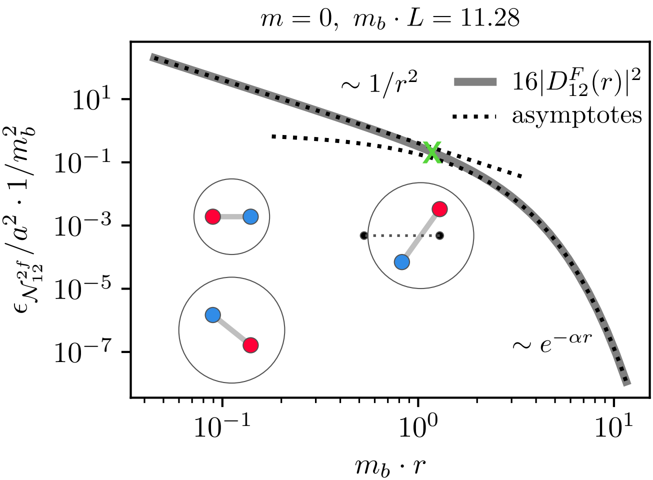
Massless case



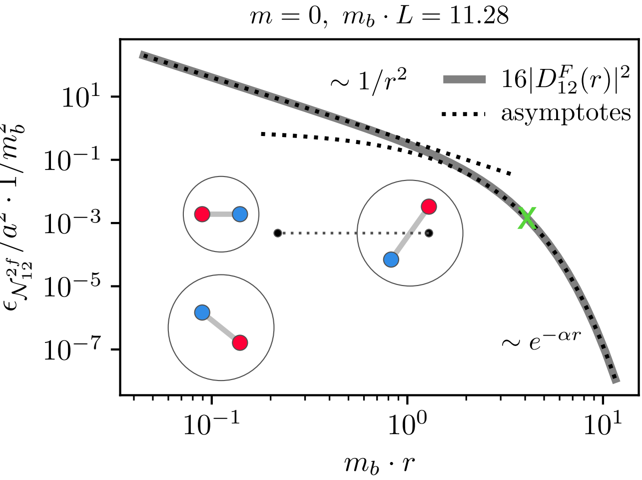
Massless case



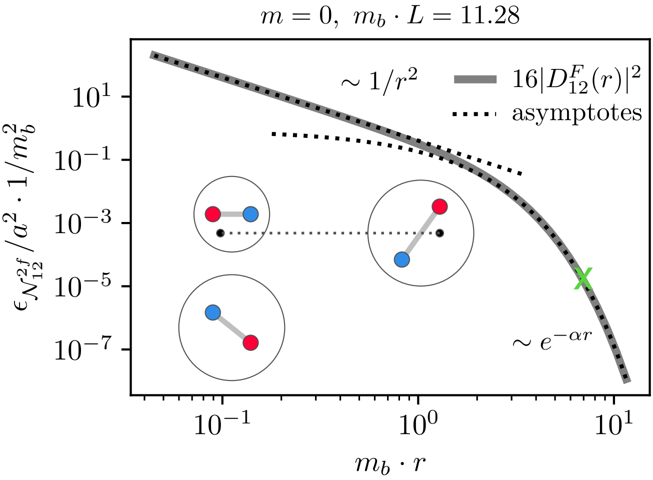
Massless case



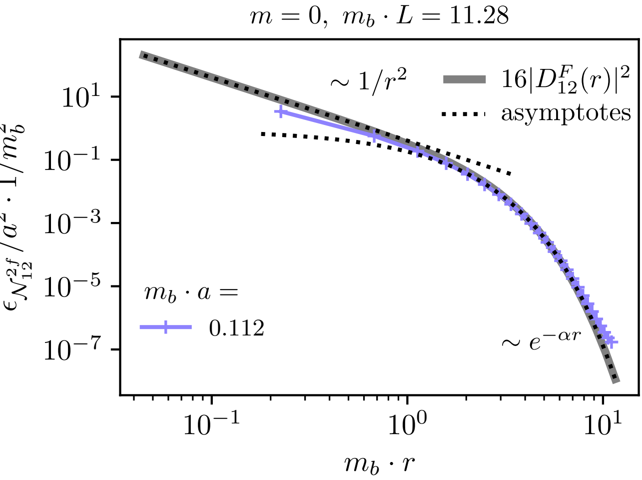
Massless case



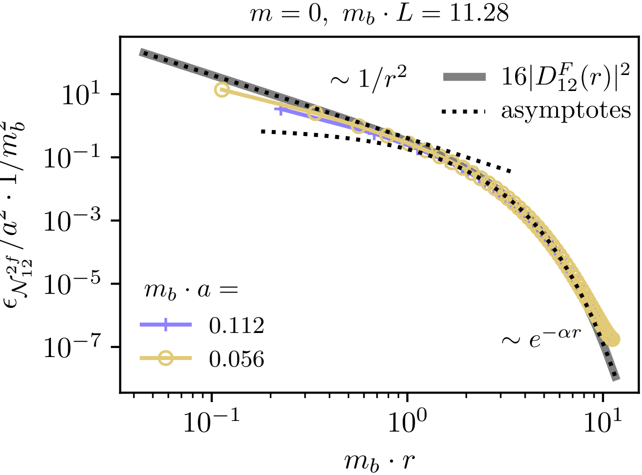
Massless case



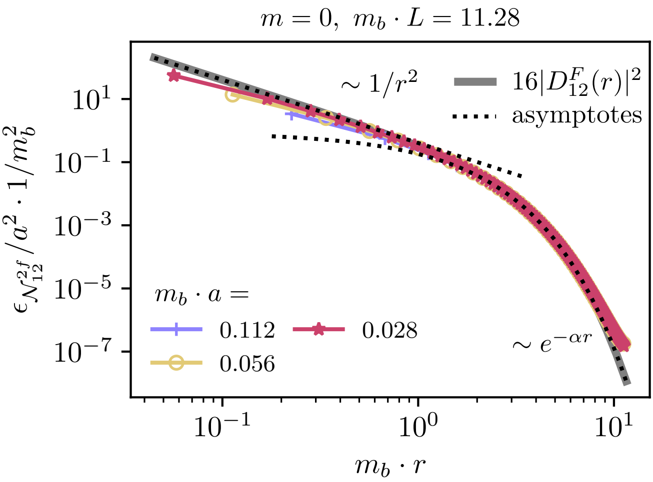
Massless case



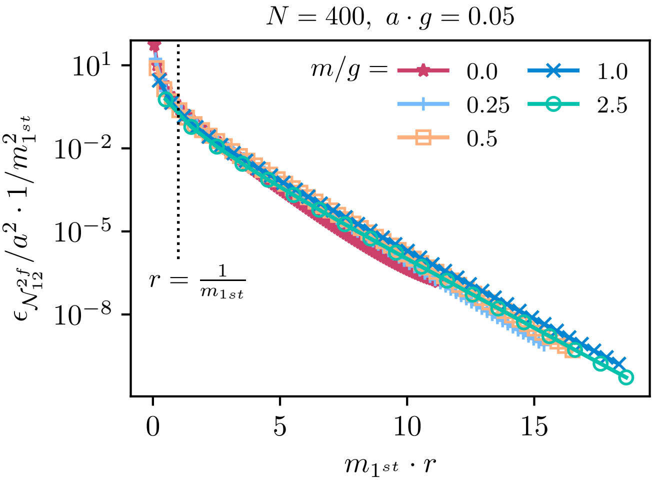
Massless case



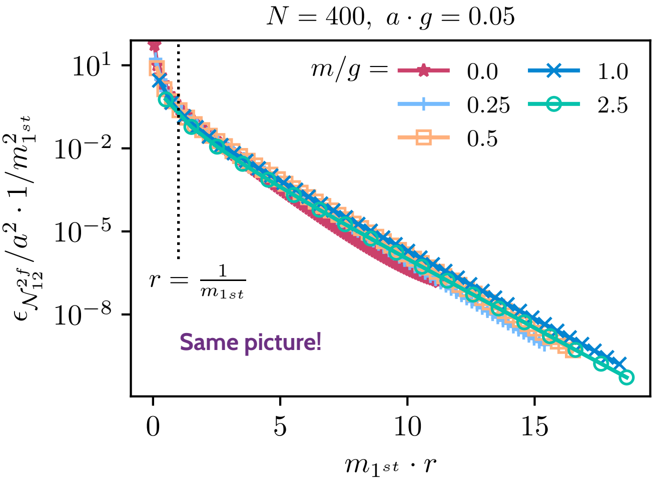
Massless case



Massive case



Massive case



Today:

Entanglement [AF, PRD,'24]

↕

Confinement

Dynamics [AF, Frenklakh, Ikeda, Kharzeev, Korepin, Shi, Yu, PRL '23 and arXiv:2404.00087]

Outlooks:

- More complicated models
- Higher dimensions
- Monte carlo?

  Checkout for entanglement entropy: [Buividovich, Polikarpov, '08] [Bulgarelli, Panero, '23]

Today:

Entanglement

[AF, PRD,'24]

↕

Confinement

Dynamics

[AF, Frenklakh, Ikeda, Kharzeev, Korepin, Shi, Yu, PRL '23 and arXiv:2404.00087]

String breaking in the Schwinger model

Look at string breaking

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

String breaking in the Schwinger model

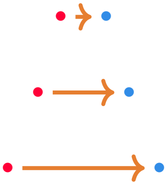
Look at string breaking

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

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

String breaking in the Schwinger model

Look at string breaking



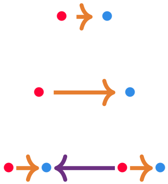
En.$\sim m + m + \alpha l_1$

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

En.$\sim m + m + \alpha l_3$

String breaking in the Schwinger model

Look at string breaking



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

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

~~En.$\sim m + m + \alpha l_3$~~

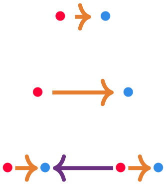
$\downarrow$

En.$\sim m + m + m + m$

when $\alpha l_3 > 2m$

String breaking in the Schwinger model

Look at string breaking



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

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

~~En. $\sim m + m + \alpha l_3$~~

$\downarrow$

En. $\sim m + m + m + m$

when $\alpha l_3 > 2m$

Screen field by creating particles!

String breaking in the Schwinger model

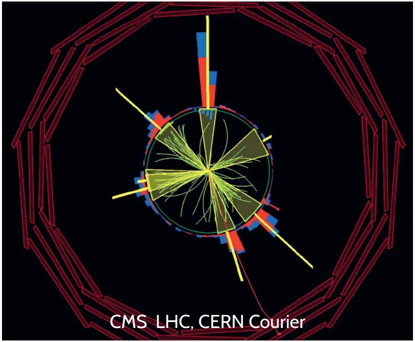
Look at string breaking

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

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

Screen field by creating particles!

Motivation: QCD jets



Set-up

Electric field — Vector potential

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

Fermion

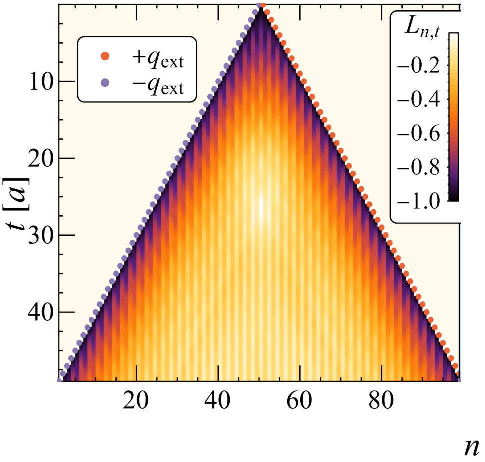
External charges: $j^1_{ext}(t) = g \left(\delta(x+t) + \delta(x-t) \right) \theta(t)$

2 point charges moving apart at speed of light

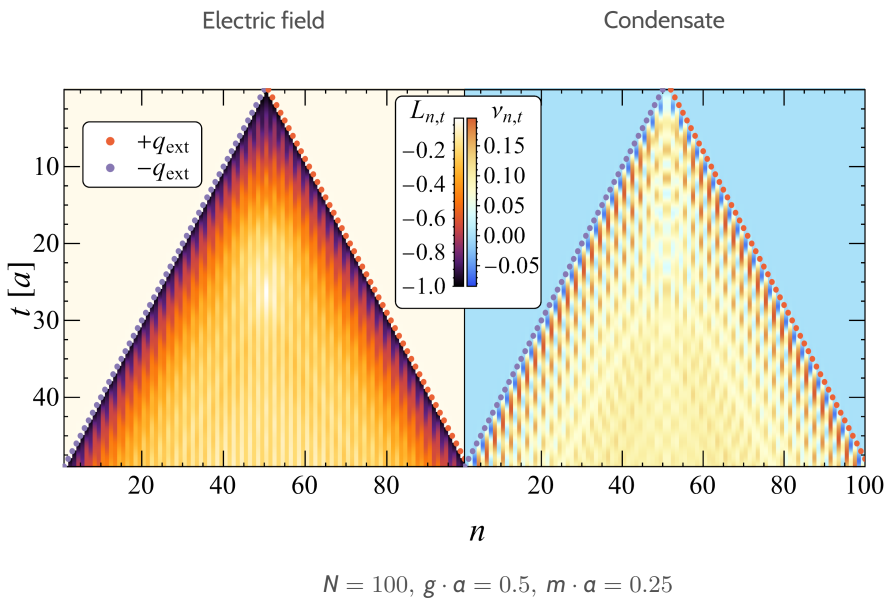
Idea:
- Find $|vac\rangle_{t<0}$
- Compute $|\psi(t)\rangle = e^{-i \int_0^t \mathrm{d}t' H(t')} |vac\rangle_{t<0}$

see also [Casher, Kogut, Susskind, '74], [Kharzeev, Loshaj, '12, '13], [Berges, Hebenstreit, '14], [Batini, Kuhn, Berges, Floerchinger, '24]

Electric field

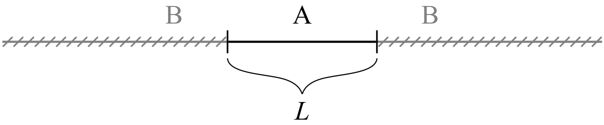


$N = 100,\ g \cdot a = 0.5,\ m \cdot a = 0.25$

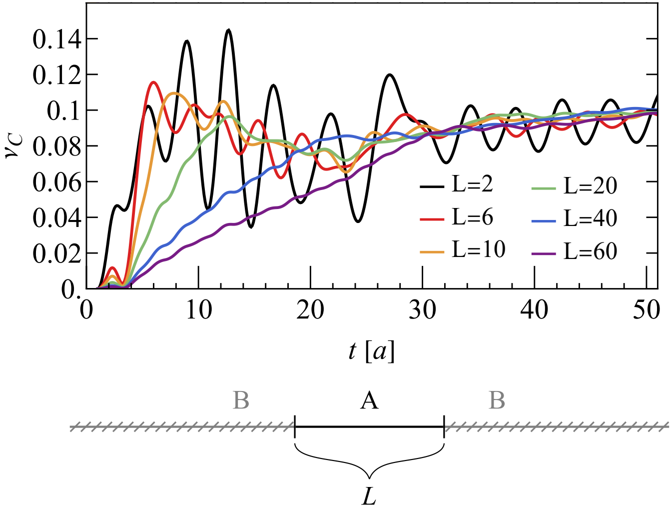


Electric field
Condensate
$+q_{\text{ext}}$
$-q_{\text{ext}}$
$L_{n,t}$
$\nu_{n,t}$
$t\ [a]$
n
$N = 100,\ g \cdot a = 0.5,\ m \cdot a = 0.25$

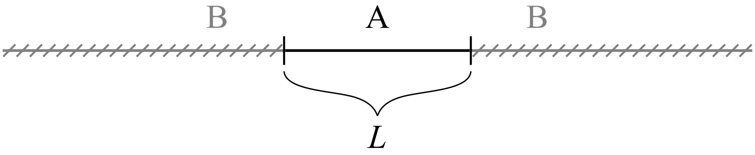
Relaxation of condensate



Relaxation of condensate



Area and volume law of entanglement



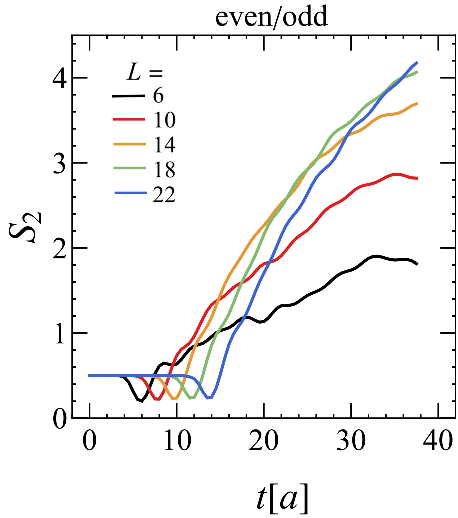
Gapped ground states: area law

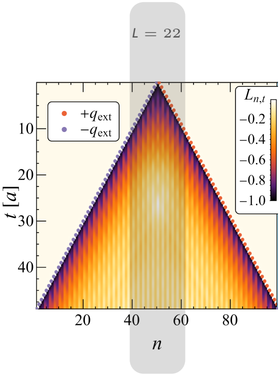
Thermal states: volume law

Ent. entropy: $S = -\mathrm{Tr}\left(\rho_A \ln \rho_A\right)$ ✓

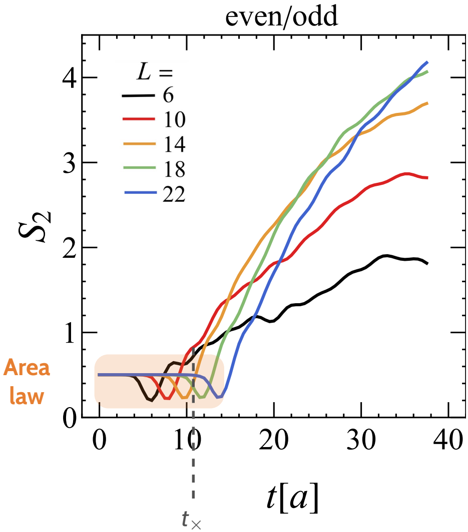
Renyi entropy: $S_2 = -\ln\left(\mathrm{Tr}\left(\rho_A^2\right)\right)$ ✓

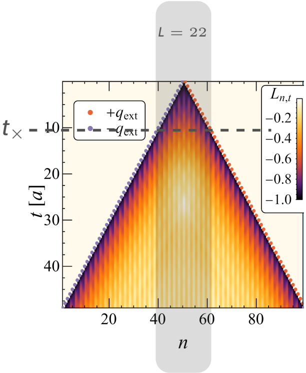
Area and volume law of entanglement



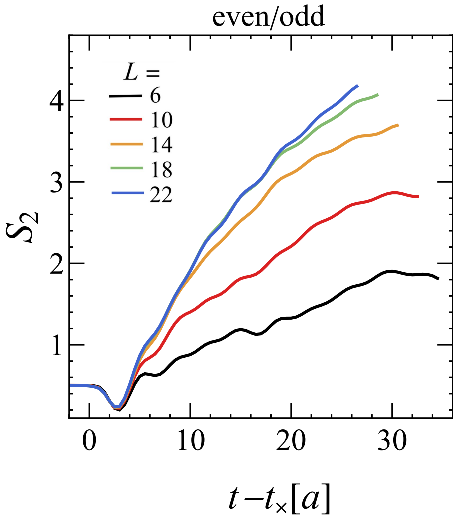


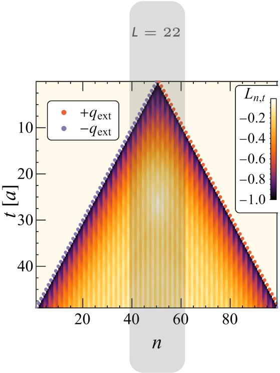
Area and volume law of entanglement



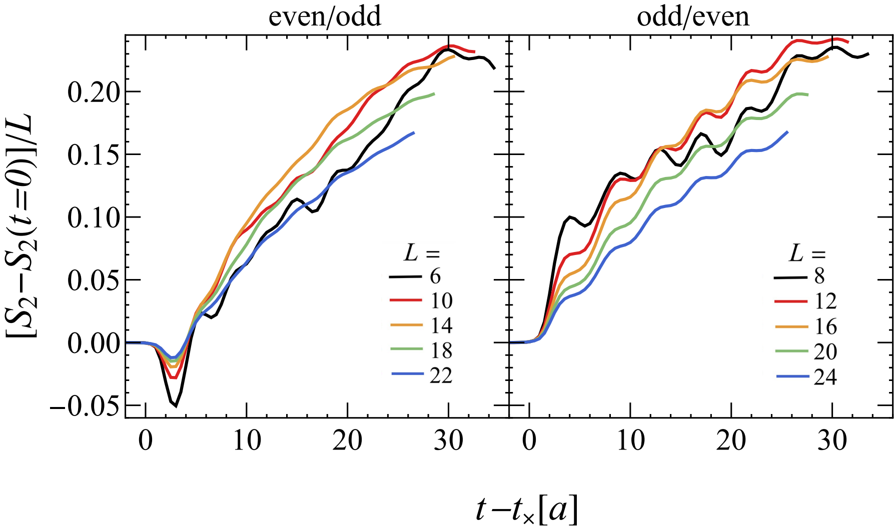


Area and volume law of entanglement

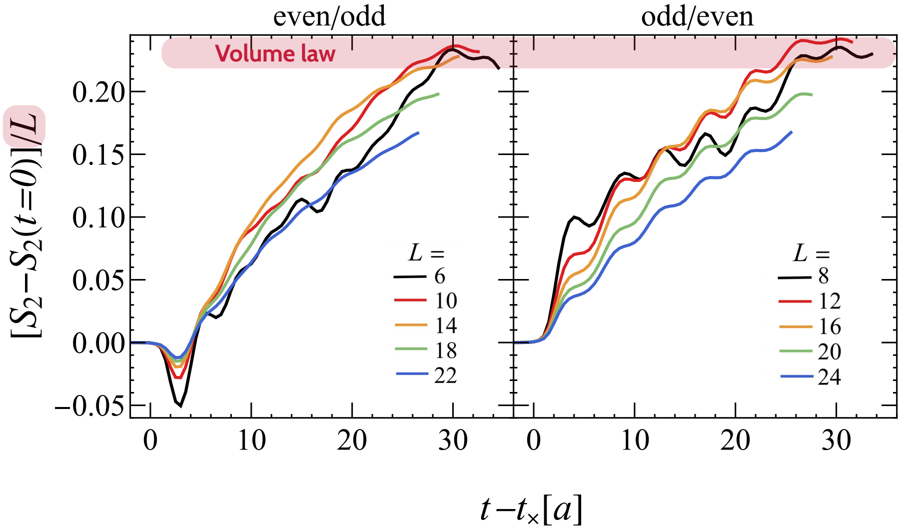




Area and volume law of entanglement



Area and volume law of entanglement



Also...

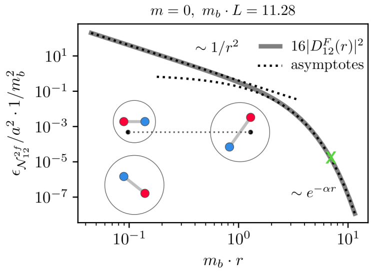
- Detecting entanglement through correlations
- Entanglement generation
- ...

Take-home

- The Schwinger model can still teach us some physics
- Entanglement structures can give new insights into relativistic field theories (confinement?)
- Direct observation of quantum properties of string breaking and onset of thermalization
- Be creative with low-dimensional models!

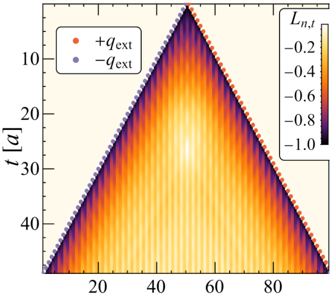
Take-home

- The Schwinger model can still teach us some physics
- Entanglement structures can give new insights into relativistic field theories (confinement?)
- Direct observation of quantum properties of string breaking and onset of thermalization
- Be creative with low-dimensional models!



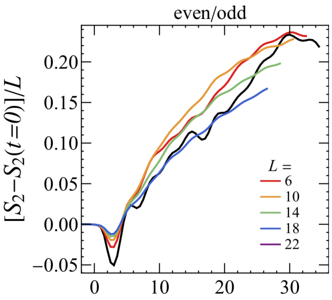
Take-home

- The Schwinger model can still teach us some physics
- Entanglement structures can give new insights into relativistic field theories (confinement?)
- Direct observation of quantum properties of string breaking and onset of thermalization
- Be creative with low-dimensional models!



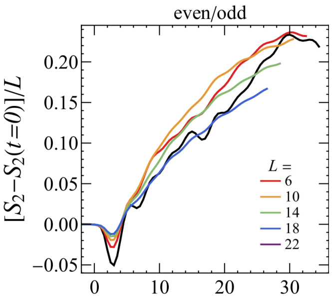
Take-home

- The Schwinger model can still teach us some physics
- Entanglement structures can give new insights into relativistic field theories (confinement?)
- Direct observation of quantum properties of string breaking and onset of thermalization
- Be creative with low-dimensional models!



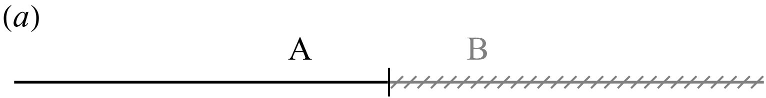
Take-home

- The Schwinger model can still teach us some physics
- Entanglement structures can give new insights into relativistic field theories (confinement?)
- Direct observation of quantum properties of string breaking and onset of thermalization
- Be creative with low-dimensional models!



“QCD Dynamics” by DALL·E 3

Mid-lattice entanglement spectrum



Schmidt decomposition: $\rho_A = \sum_\alpha \lambda_\alpha |\lambda_\alpha\rangle\langle\lambda_\alpha|$

Mid-lattice entanglement spectrum