Theory-driven quantum machine learning for colliders

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Durham University

Science & Technology Facilities Council

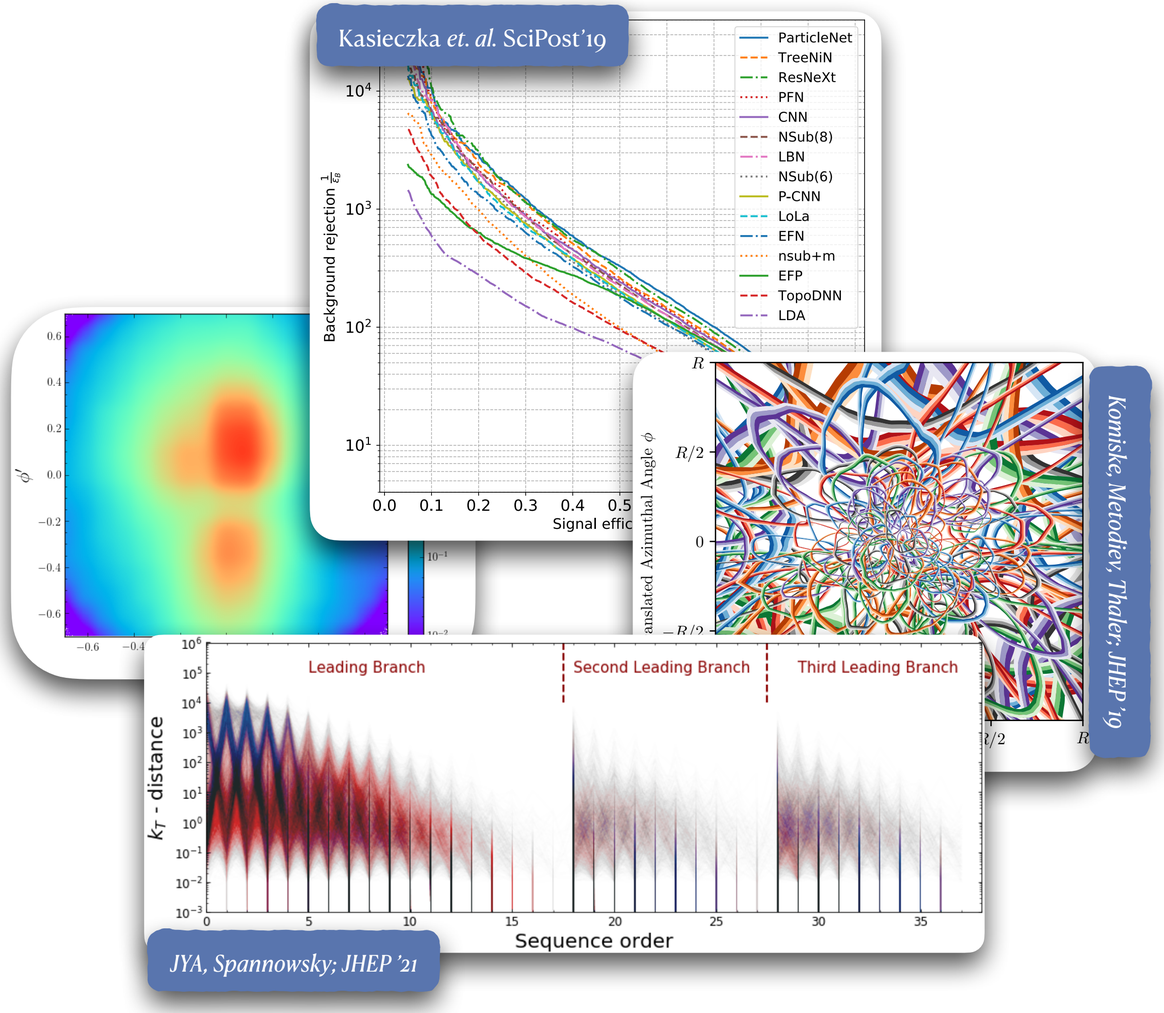
MCnet

IP3

Sales pitch of the talk!

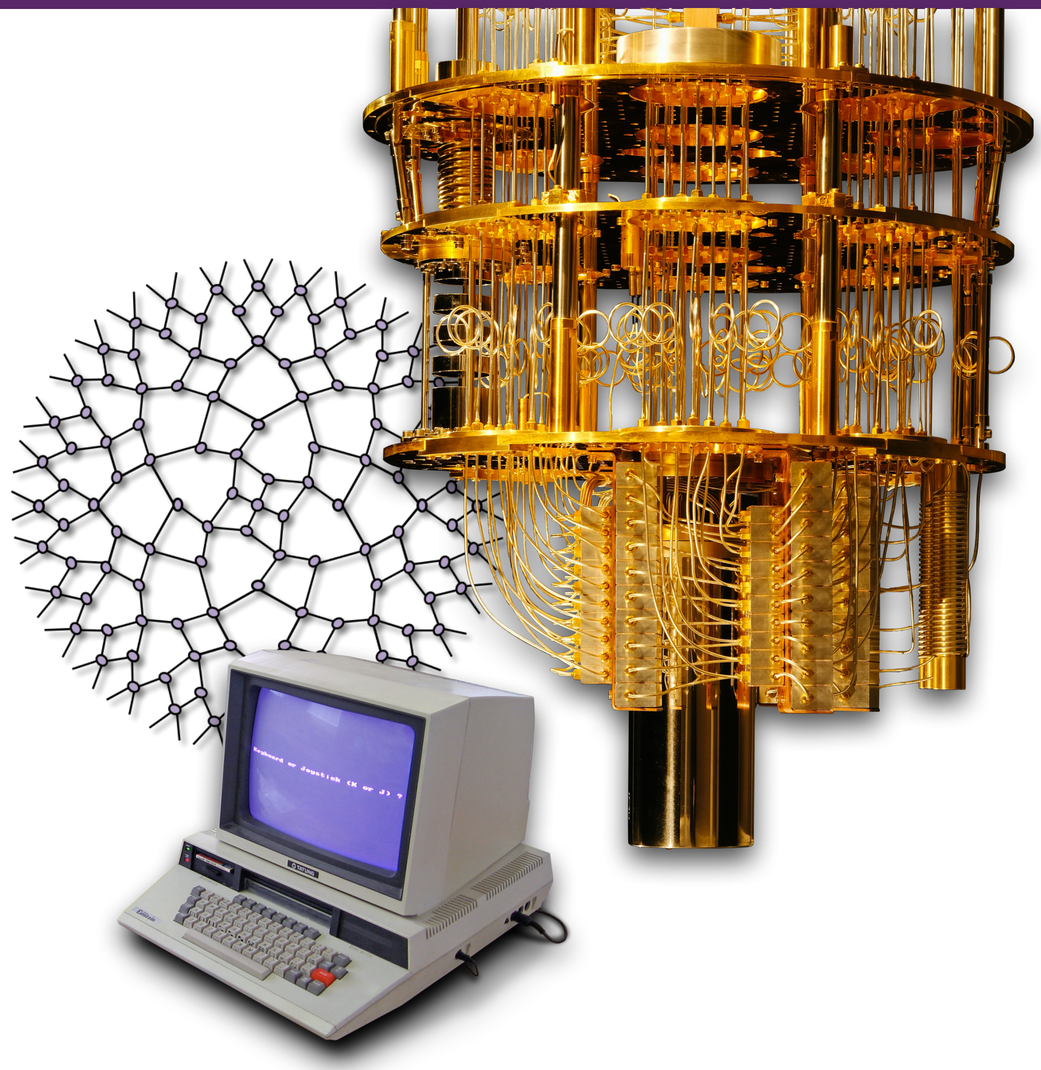
- We more or less know how to get a well-performing Neural Network to classify jets, generate LHC events, and even differentiate cats and dogs...
- What we don't know is what this network learns.
- Can we use Quantum Mechanics to have more insight into the learning process?
  - ✦ What has a model learned?
  - ✦ What is learning?
  - ✦ How do we develop "insightful" algorithms?
  - ✦ How to perform this on a Quantum device?

❖ Can an ML problem be formulated as a quantum many-body system?

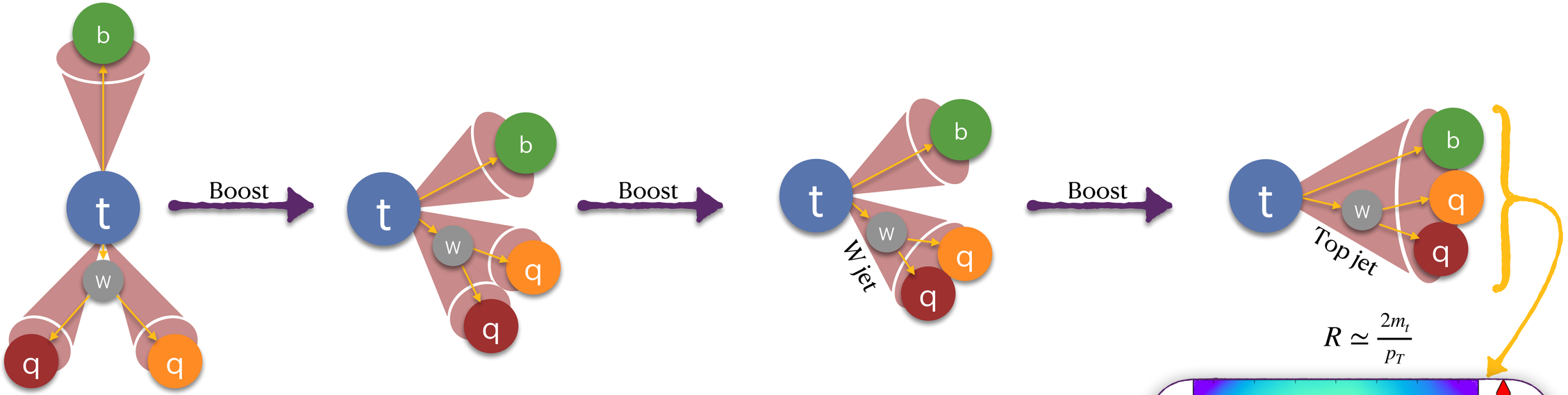


Outline

- Hamiltonian learning for anomaly detection
- Classification as a quantum many-body problem
- Conclusion



Hello world of HEP-ML: Top tagging



- With the increased boost factor, jets (top decay products) are getting more collimated.
- Hadronic top tagging tools: Mass grooming and filtering, Pruning, Trimming, Soft Drop Tagger, Mass Drop Tagger, HEPTopTagger, Machine Learning

JYA, Spannowsky; JHEP '21

Hamiltonian learning for anomaly detection

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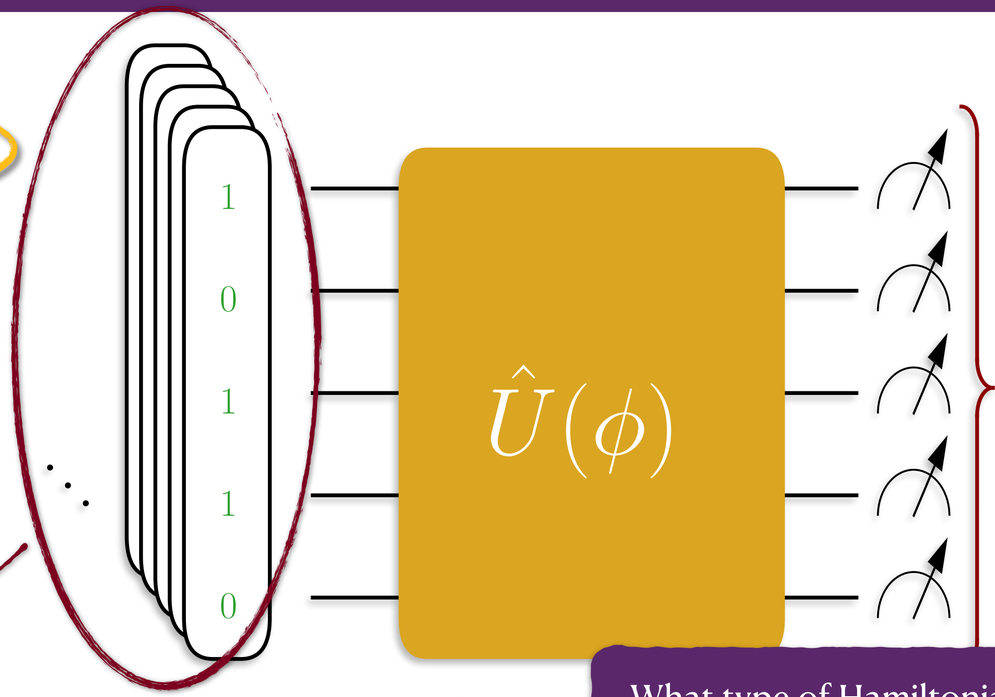
What has Hamiltonian to do with data?

JYA, Spannowsky; arXiv: 2211.03803

Quantum Circuit is a pure-state simulator!

A data point can be represented as a mixed state

$$\sigma_D = \sum_i p_i |\psi_i\rangle \ , \ |\psi_i\rangle := \text{pure states}$$



Hamiltonian captures the entropic probability distribution of the mixed state.

Bernoulli(p_i)

$$\frac{1}{N_{\text{sample}}} \sum_{\psi_i \in \Psi}^{N_{\text{sample}}} \left| \langle Z \rangle \langle Z \rangle \langle Z \rangle \langle Z \rangle \langle Z \rangle \langle Z \rangle \right|^2 \simeq \text{P(Data)}$$

$|\psi_i\rangle$

$|\langle \psi_i | Z | \psi_i \rangle|^2$

What type of Hamiltonian can we choose?

- Any field theory Hamiltonian, e.g. Ising model
- A generic Hamiltonian e.g. $\sum_{\langle i,j \rangle} (\alpha_{i,j} \sigma_i^+ \sigma_j^- + \text{h . c.})$
- But can these options capture the full complexity of the data? Can we get ambitious?

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What has Hamiltonian to do with data?

JYA, Spannowsky; arXiv: 2211.03803

Quantum Circuit is a pure-state simulator!

A data point can be represented as a mixed state

$$\sigma_D = \sum_i p_i |\psi_i\rangle \ , \ |\psi_i\rangle := \text{pure states}$$

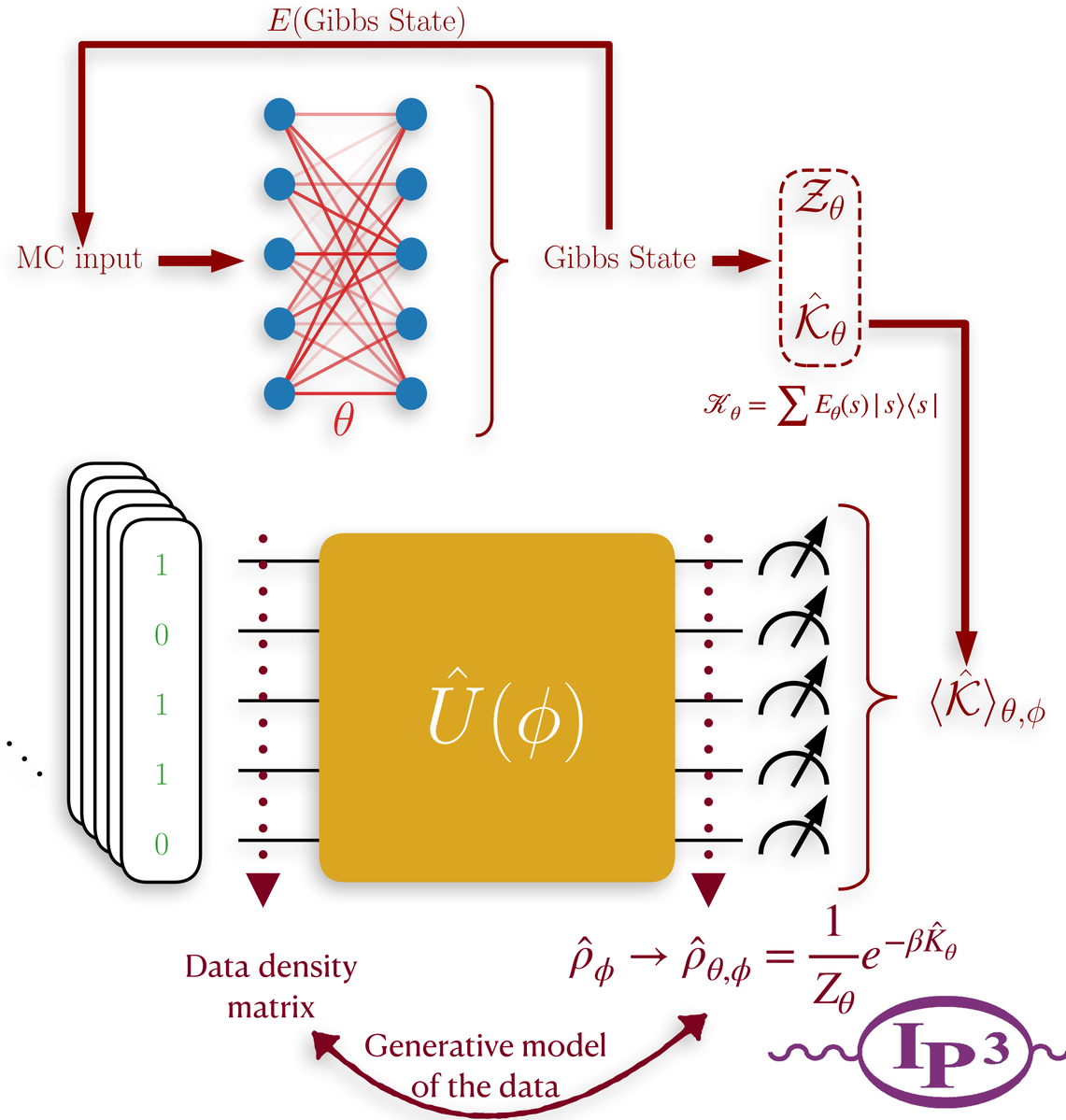
See Gibbs-Delbrück-Moliéve variational principle

$$F = E - TS = -k_\beta T \ln Z_\theta$$

$$\mathscr{L}_{\theta,\phi}(\sigma_D) = \beta \langle \hat{K} \rangle_{\theta,\phi} + k_\beta \ln Z_\theta \ \geq \ S(\sigma_D)$$

$k_\beta :=$ Boltzmann constant

$\beta :=$ Inverse temperature



What has Hamiltonian to do with data?

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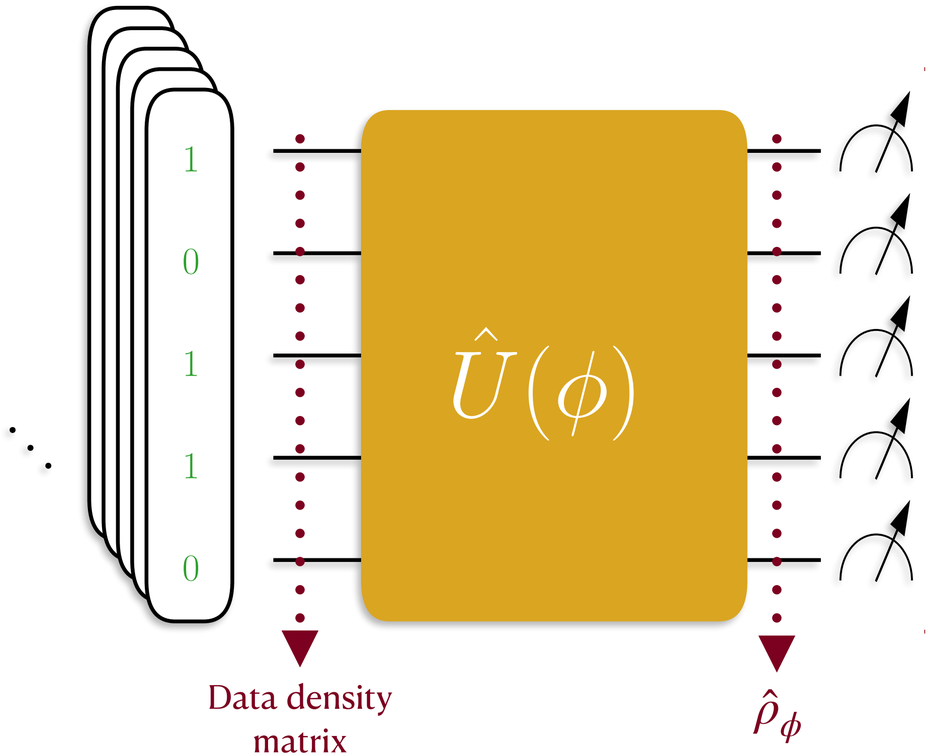
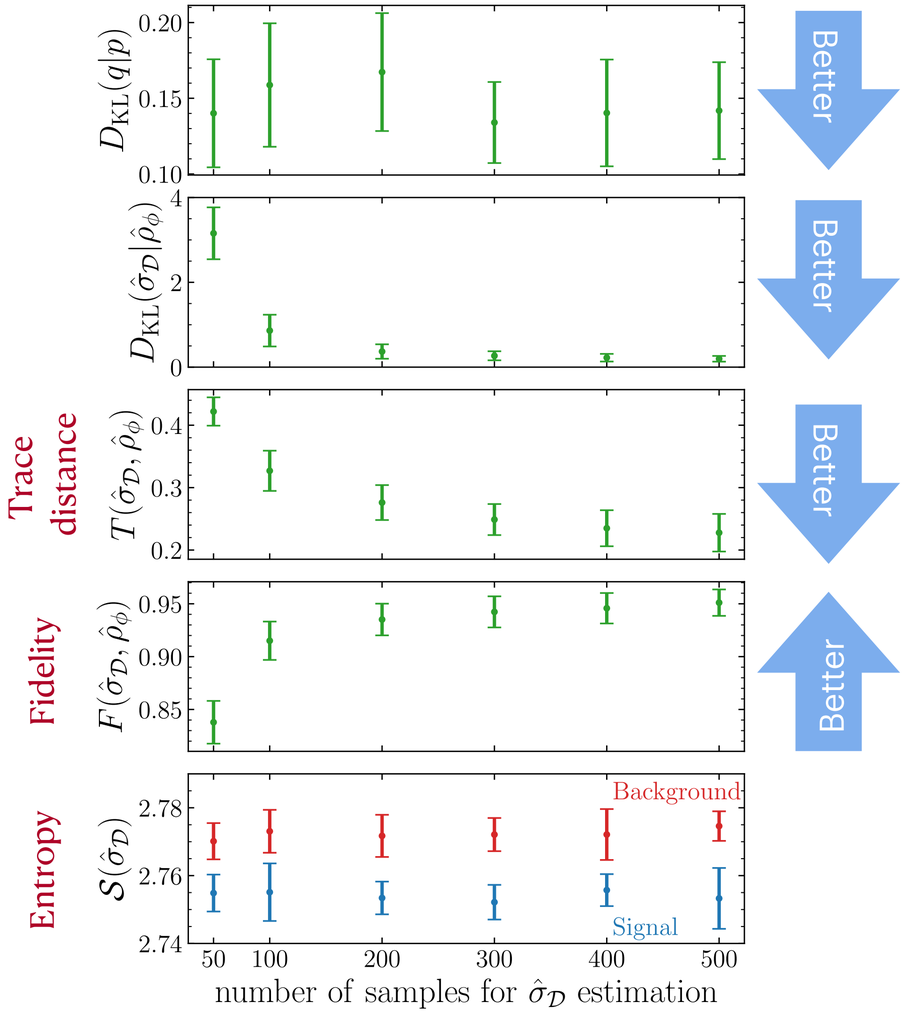


$$\mathscr{L}_{\theta,\phi}(\sigma_D) = \langle \hat{K} \rangle_{\theta,\phi} + \ln Z_\theta \;\geq\; S(\sigma_D)$$

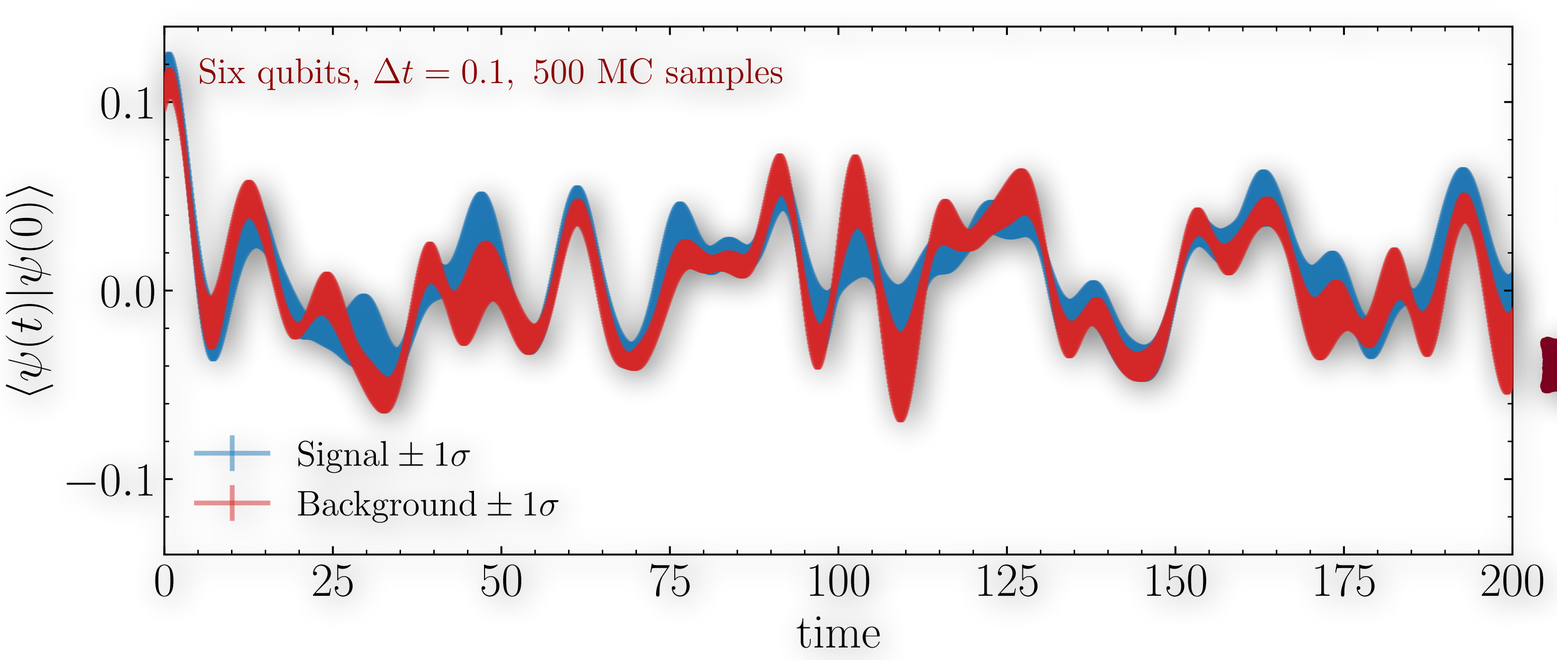
$$\arg\min_{\theta,\phi} \mathscr{L}_{\theta,\phi}(\sigma_D) \simeq S(\sigma_D)$$



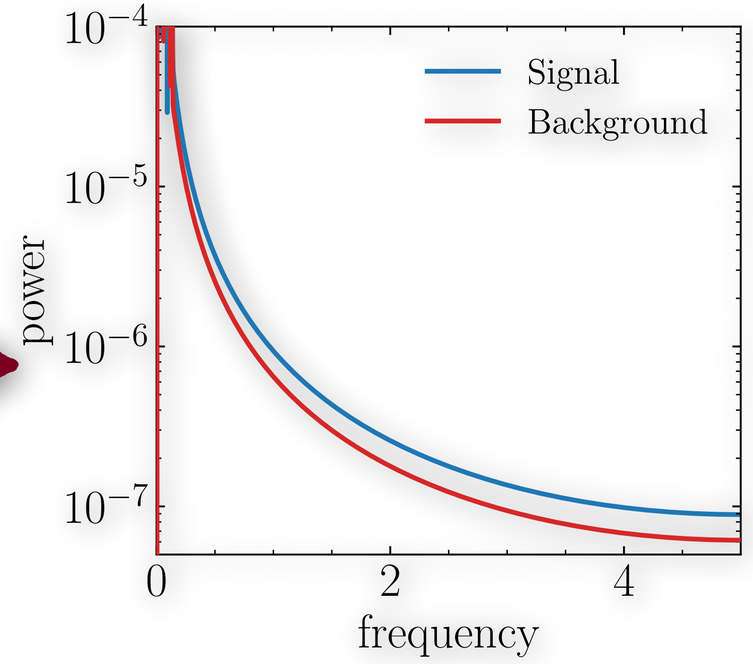
Hamiltonian as a discriminator!

JYA, Spannowsky; arXiv: 2211.03803

Trotter-Suzuki approximation $\longrightarrow$ $e^{-iT\hat{K}_\theta} = \prod^{N} e^{-i\Delta t\hat{K}_\theta}$



Fast Fourier Transform



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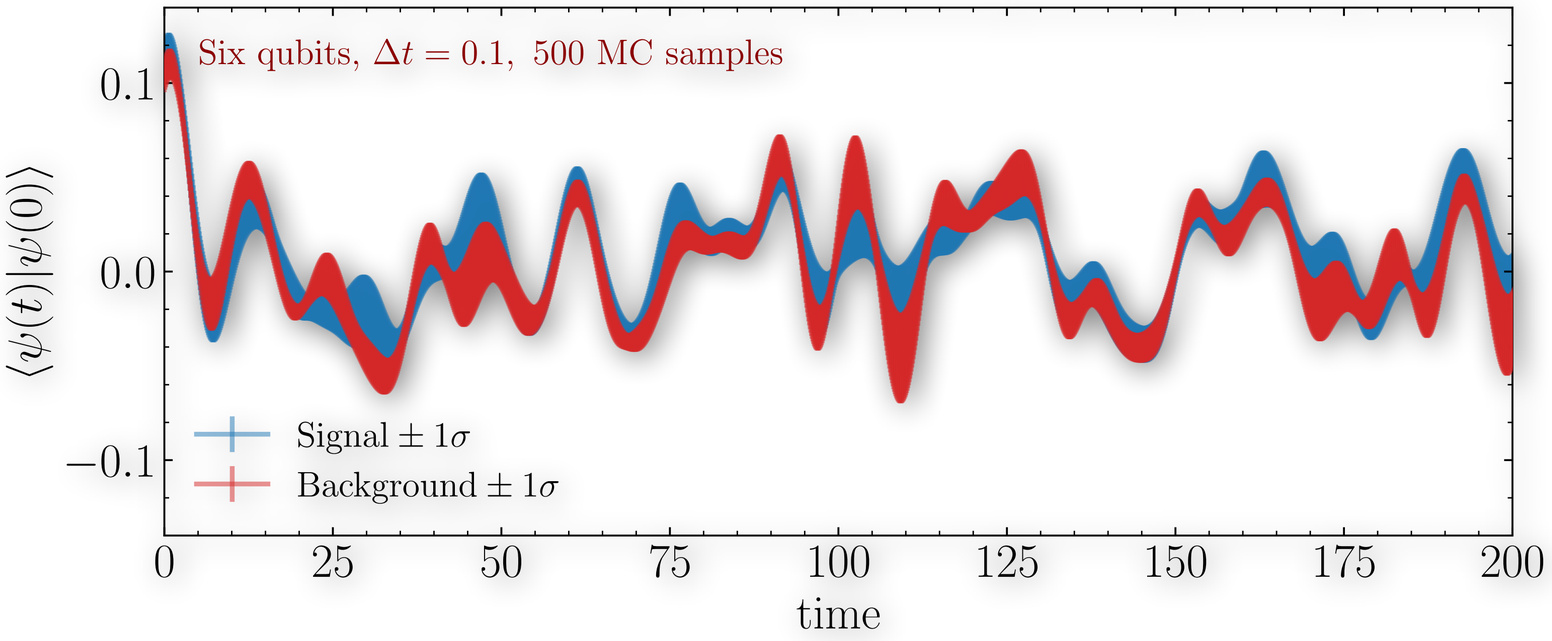
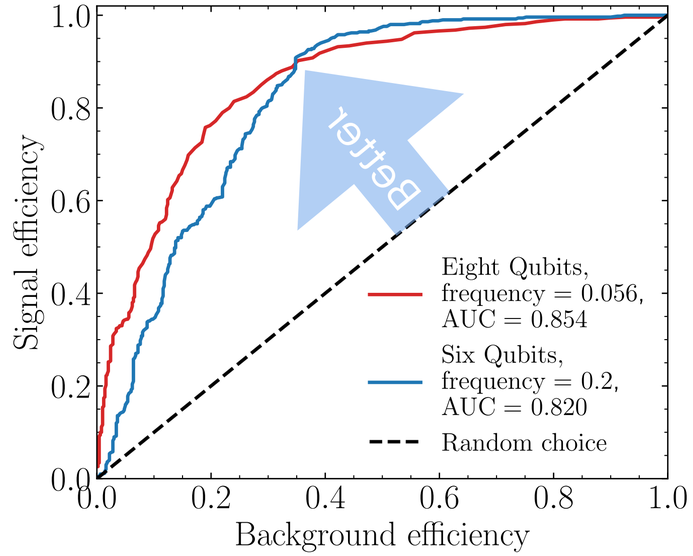
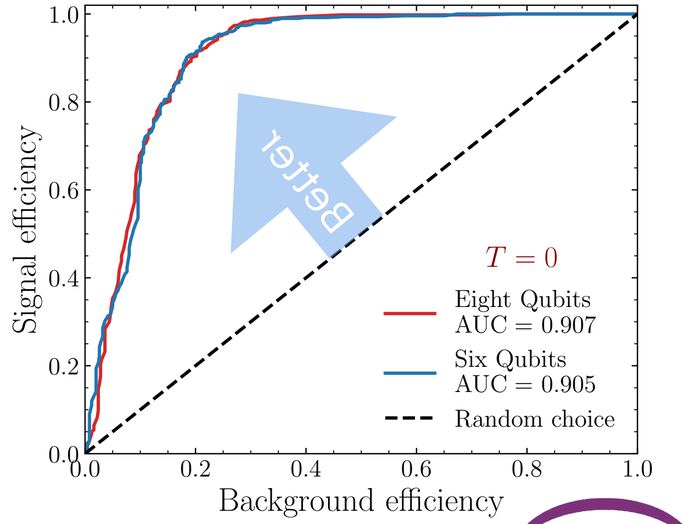
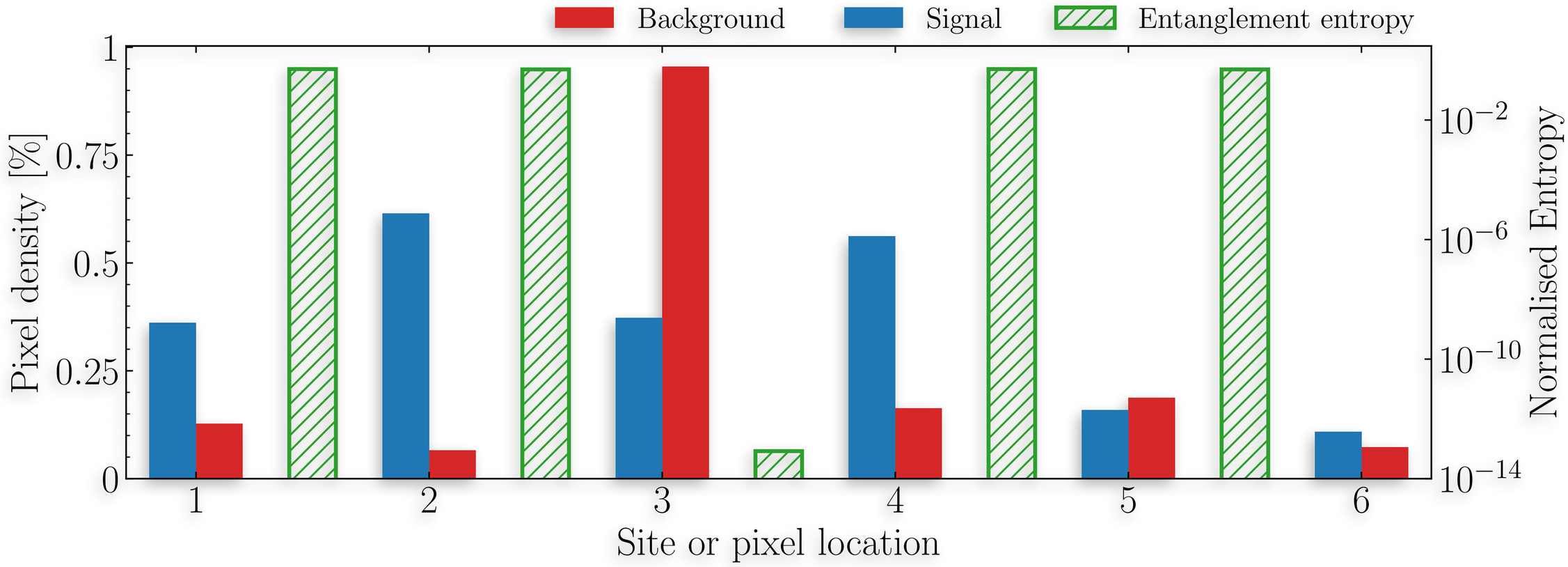






What did the Hamiltonian learn?



$$\mathcal{S}(\rho) = -\operatorname{Tr}[\rho \log \rho]$$

Classification as a quantum many-body problem

Tensor Networks: Origins

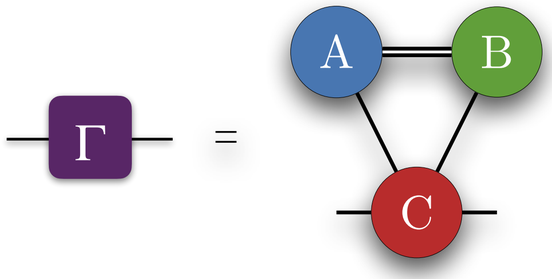
Tensor Diagram Notation

Scalar — Matrix, Λ^{ij}

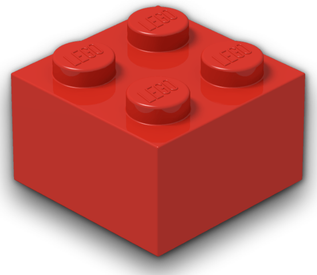
Vector, v^i — Rank 3 Tensor, Γ^{ijk}

$$|\Psi\rangle = \sum_{\phi_1,\ldots,\phi_n=0} \mathscr{W}_{\phi_1\ldots\phi_n} |\phi_1\rangle \otimes |\phi_2\rangle \otimes \ldots \otimes |\phi_n\rangle$$

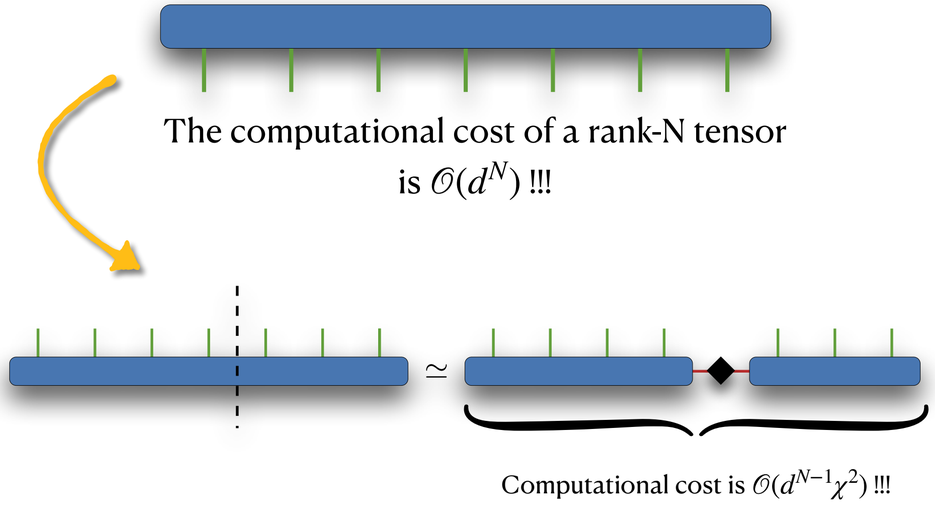
$$\forall |\phi_i\rangle \in \mathscr{H}^{\otimes 2^N} \quad \rightarrow \quad |\phi_i\rangle \in \{|\uparrow\rangle, |\downarrow\rangle\}$$



$$\Gamma^{ij} = A^{klm} B^{n}{}_{lm} C^{ij}{}_{kn}$$

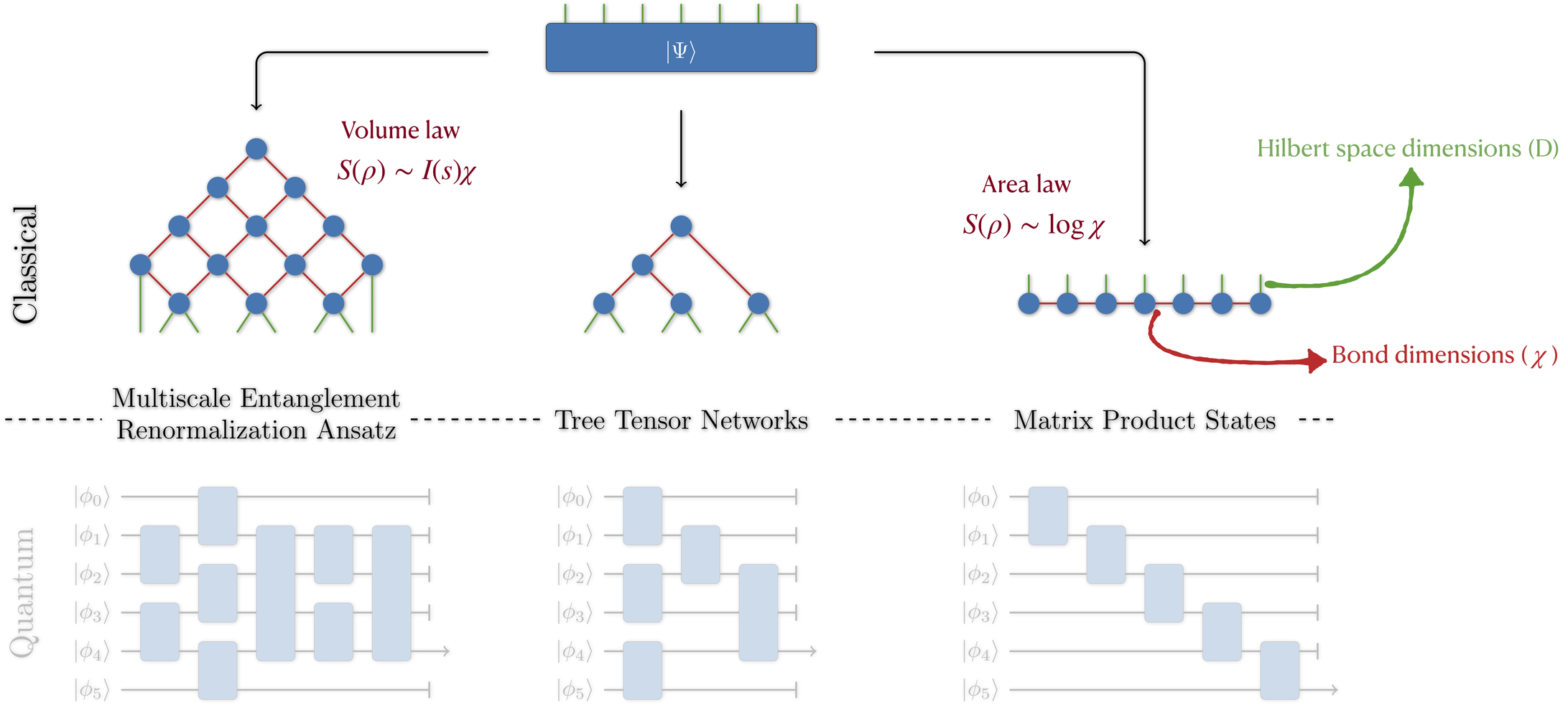


$$= L^{ijkl}{}_{\mu\nu\rho\theta}$$



Types of Tensor Networks (some of them)

$S(\rho) = \mathrm{Tr}[\rho \log \rho]$



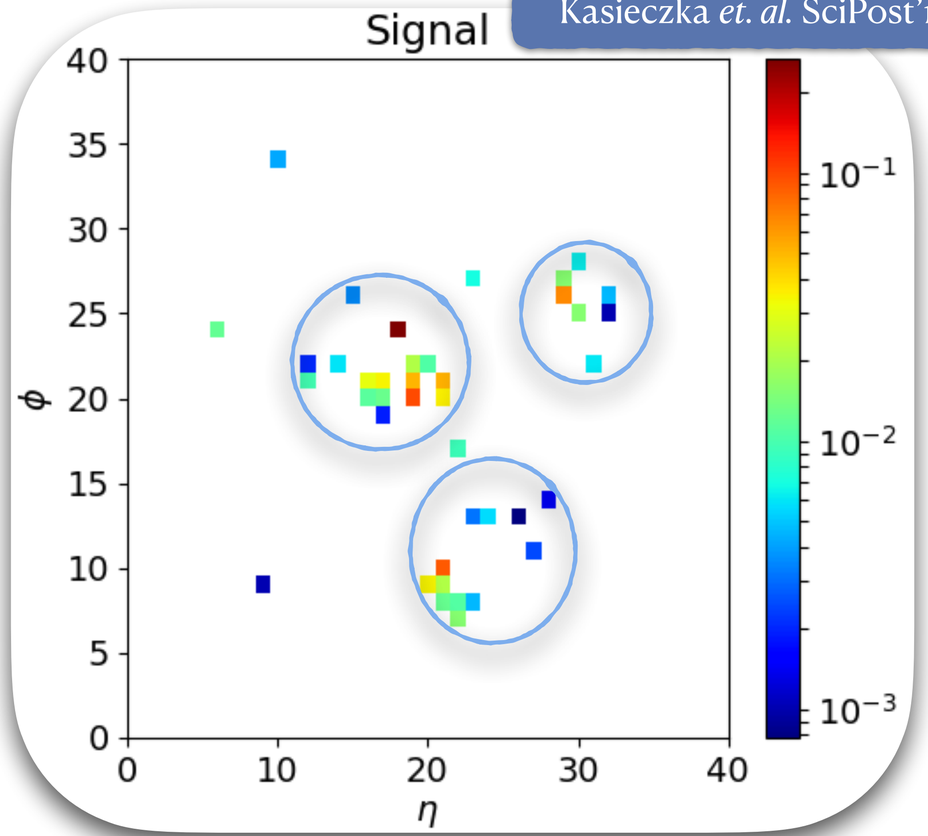
Not in this talk! See:

JYA, Spannowsky; PRA '22, arXiv: 2202.10471

Why TNs "might" perform well in such tasks?

- The correlation range of a node in an MPS is bounded by its bond dimension and distance between correlated sites.
- Tensor Networks can capture local "anomalies".
- We are dealing with sparse, locally correlated calorimeter pixels.

Kasieczka *et. al.* SciPost'19

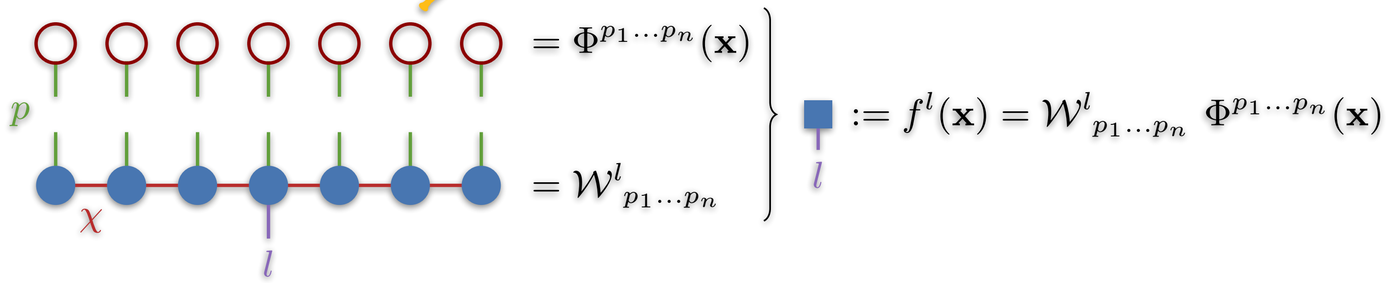


Matrix Product States for Classification

Sub-Outline

- How to embed the data?
- How to form a network?
- How to train the network?

$$\phi^i(\mathbf{x}) = R_{SU(N)}(\tilde{p}^i_T \pi/2)\ |0\rangle$$



$$p(x^{(i)};\theta) = \left| f^l(x^{(i)}) \right|^2$$

No activation function!!
Everything is linear!!

TNs intrinsically have "topological nonlinearity"

Stoudenmire, Schwab 1605.05775

Novikov, Trofimov, Oseledets; 1605.03795

$$\mathscr{L} = \frac{1}{N} \sum_{x \in \mathbf{x}^N} q^{\text{truth}}\ \log\left(p(x^{(i)};\theta)\right)$$

Or anything else you like to minimise...

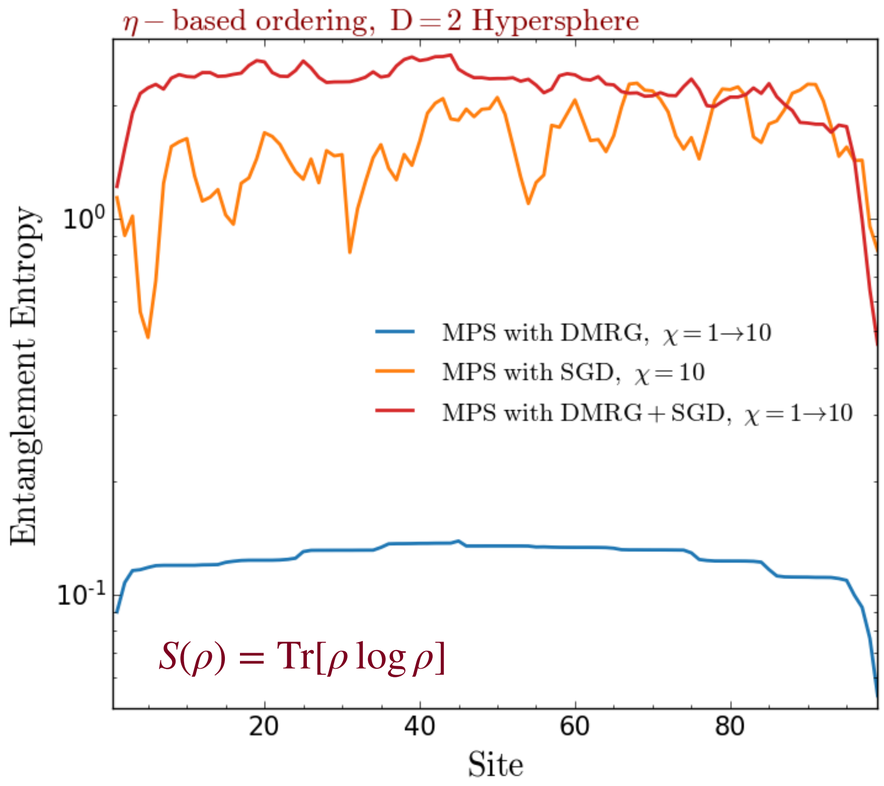
Traditionally NNs are trained with SGD, but MPS is trained with Density Matrix Renormalisation Group Algorithm

JYA, Spannowsky; JHEP '21, arXiv: 2106.08334

Why finding a quantitative measure is important?

JYA, Spannowsky; JHEP '21, arXiv: 2106.08334

- A 50% reduction in the number of pixels used and a 91% reduction in the number of parameters lead to the same classification quality!
- Understanding the network gives the ability to build better training algorithms.
- Scientific data is largely sparse; if we know where the information comes from, we can get rid of large amounts of data.
- Suppress the noise (and for pile-up mitigation to be confirmed)!



Conclusion

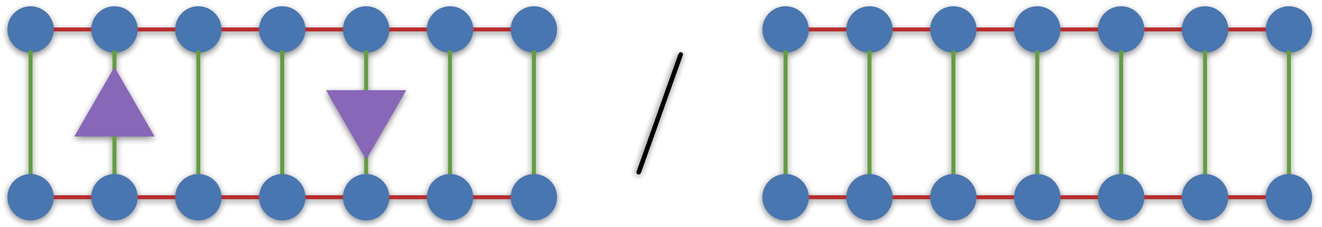
Conclusion

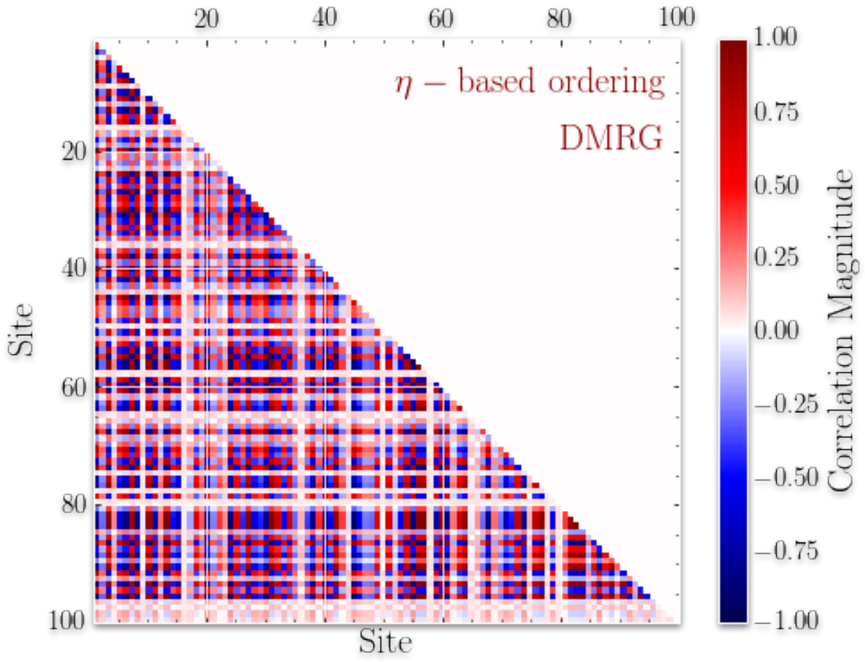
- The name of the game is optimisation. Techniques developed for field theory computations are easily transferable for ML applications!
- Designing quantifiable measures from the ansätze can allow us to improve training procedures and can be used for feature selection. (Thought: maybe helpful to lock on a symmetry during training?)
- Tensor Networks are the tool for the near future to understand quantum computing until the machinery is ready for more significant problems.

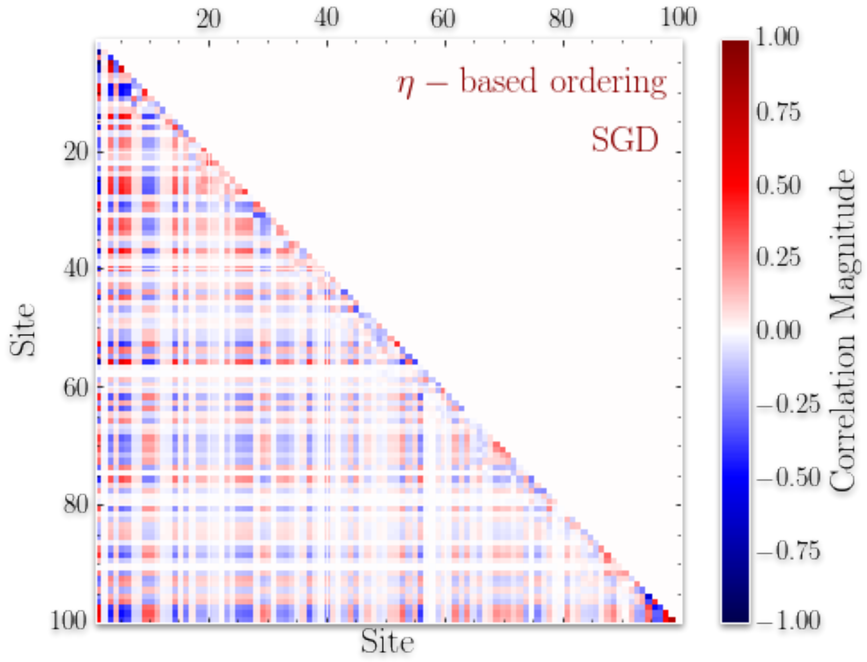
BACKUP

Correlations by SU(2) generators

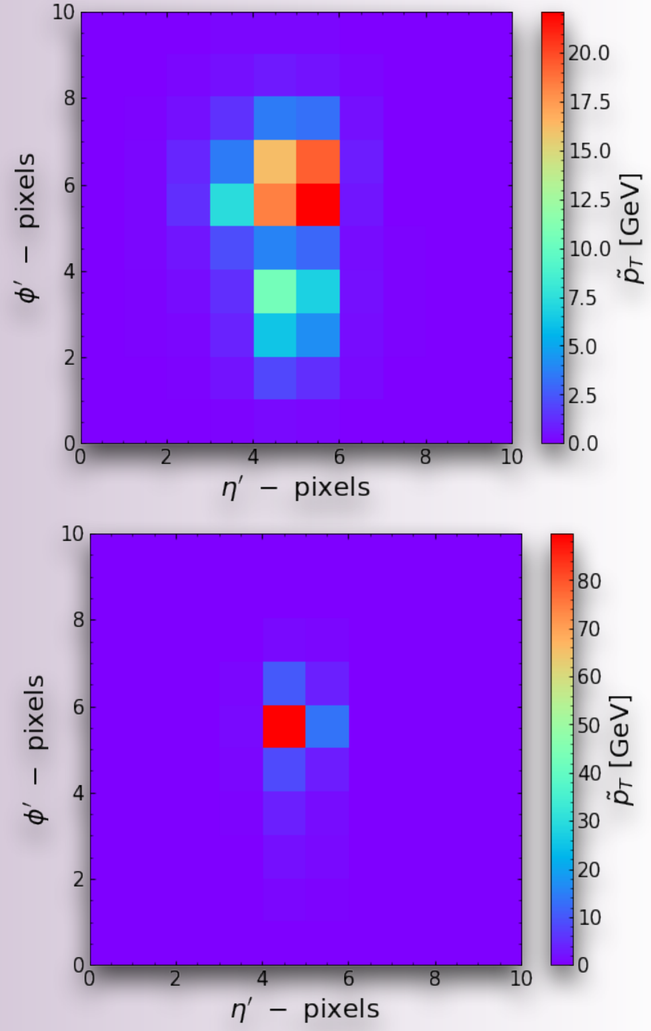
$$C_{ij}^{l} = \frac{\langle W^{l} | \mathcal{O}_i \mathcal{O}_j^{\dagger} | W^{l} \rangle}{\langle W^{l} | W^{l} \rangle} =$$







Top Tagging through MPS

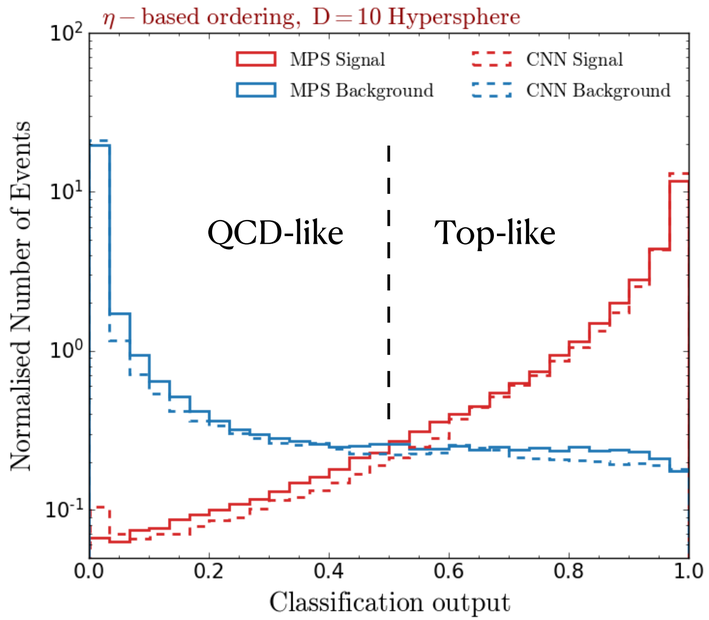


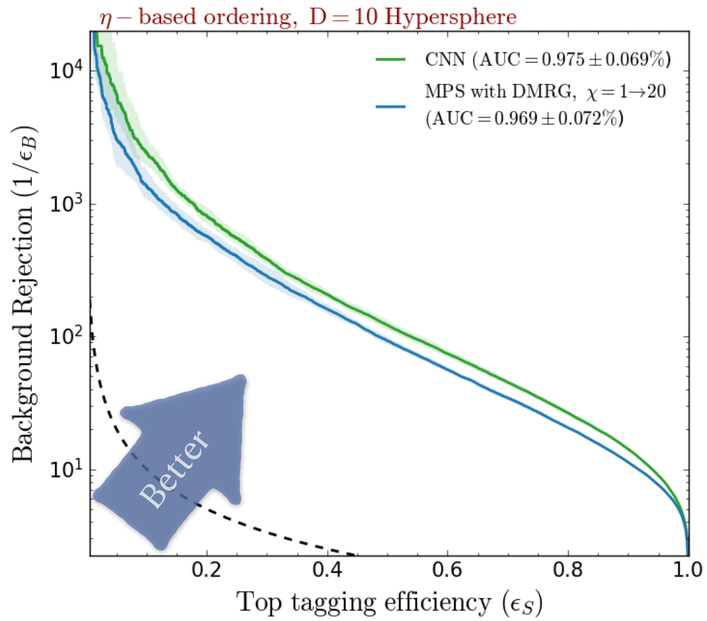
Assumptions & Requirements

- No prior entanglement/correlation between pixels
- Network is a Born Machine → square of the wave-function gives the probability of the classification.
- Maximum bond dimension that network can get is 20.

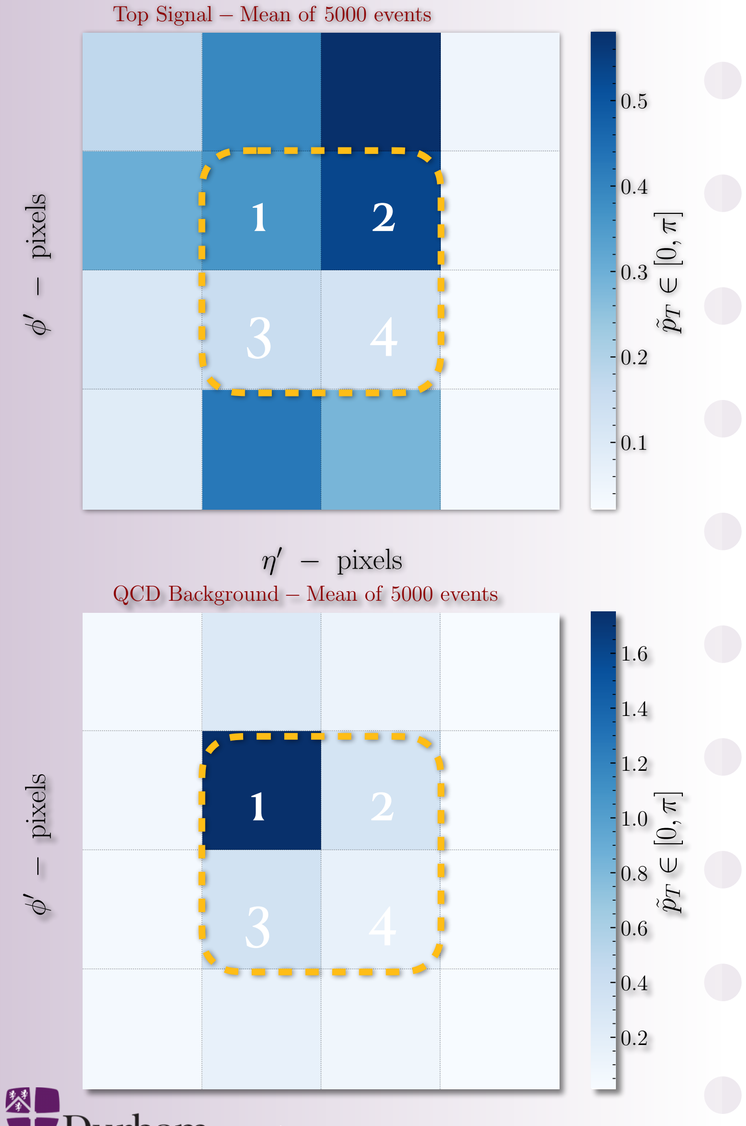
CNN architecture from:

JYA, Spannowsky; JHEP '21

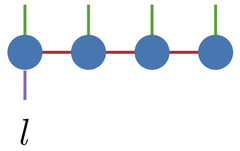


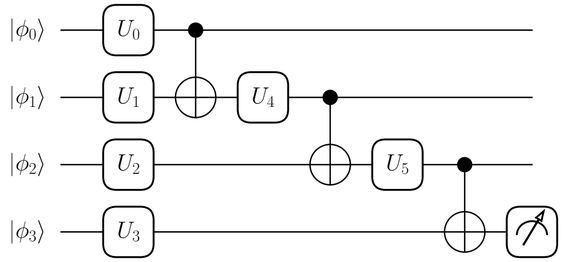


Experimenting with 4-Qubits

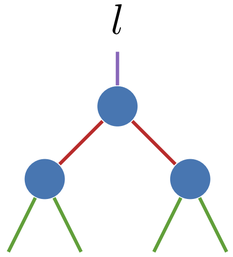


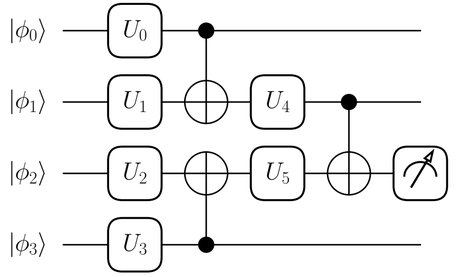
Matrix Product States



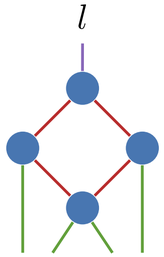


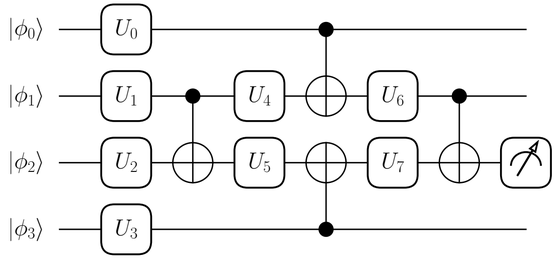
Tree Tensor Networks



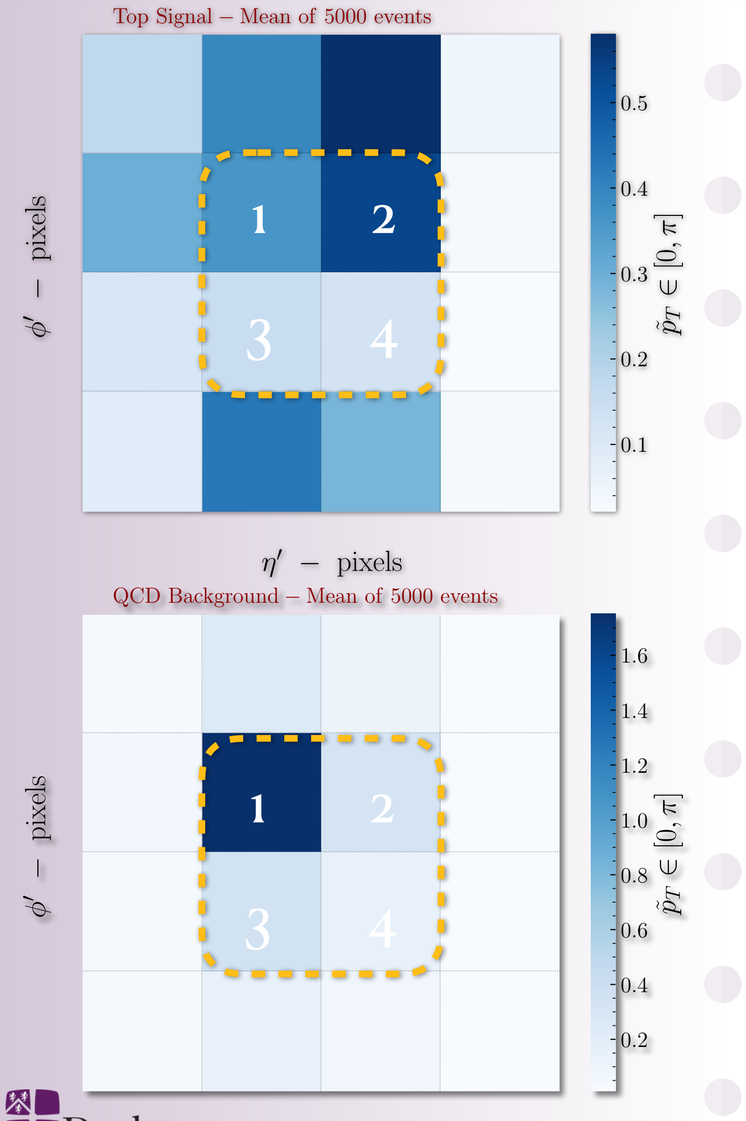


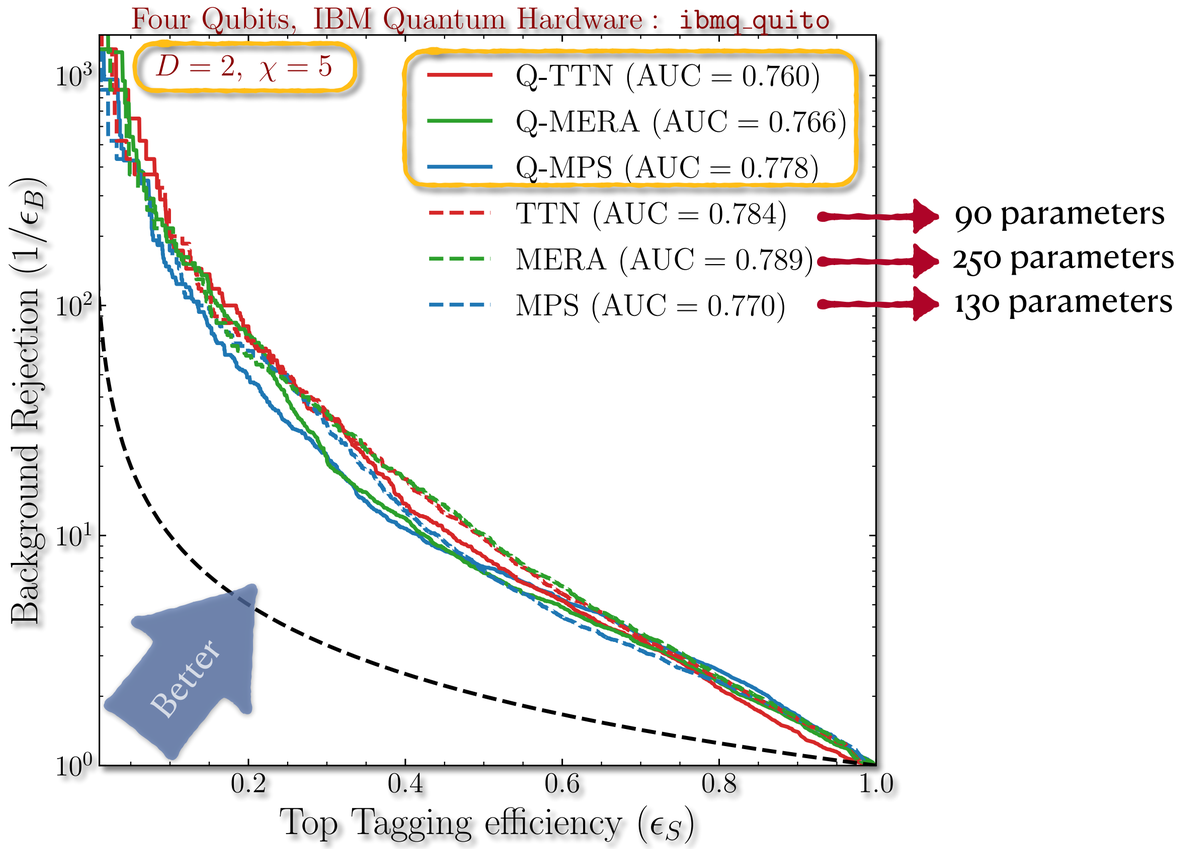
Multiscale Entanglement Renormalisation Ansatz



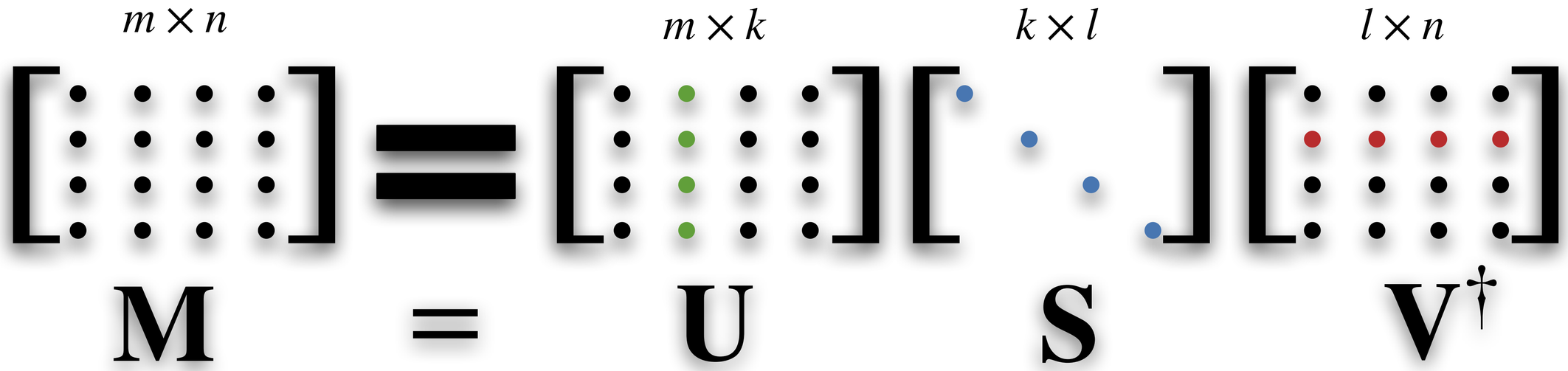


Experimenting with 4-Qubits





Singular Value Decomposition



Orthogonal singular column vectors

Positive definite singular values in descending order

Orthogonal singular row vectors

By changing the number of singular values one can change the accuracy of the decomposition!!!

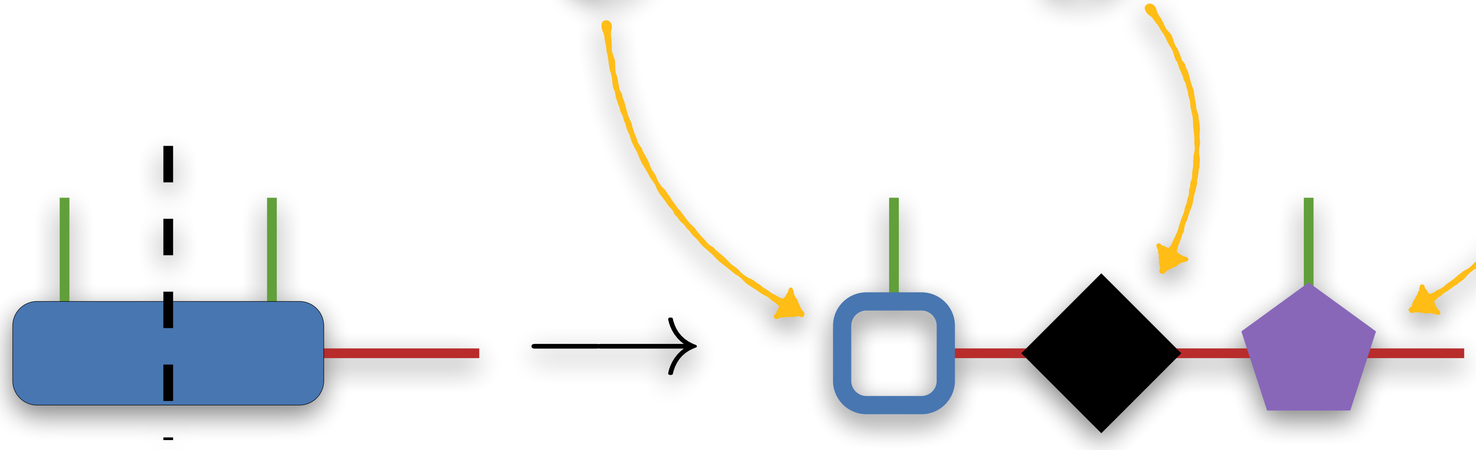
$$\mathbf{S} = \mathrm{diag}(\lambda_1, \lambda_2, \cdots, \lambda_n)$$

λ_i also known as Schmidt values

Singular Value Decomposition

$m \times n$ $m \times k$ $k \times l$ $l \times n$

$$\mathbf{M} = \mathbf{U}\,\mathbf{S}\,\mathbf{V}^{\dagger}$$



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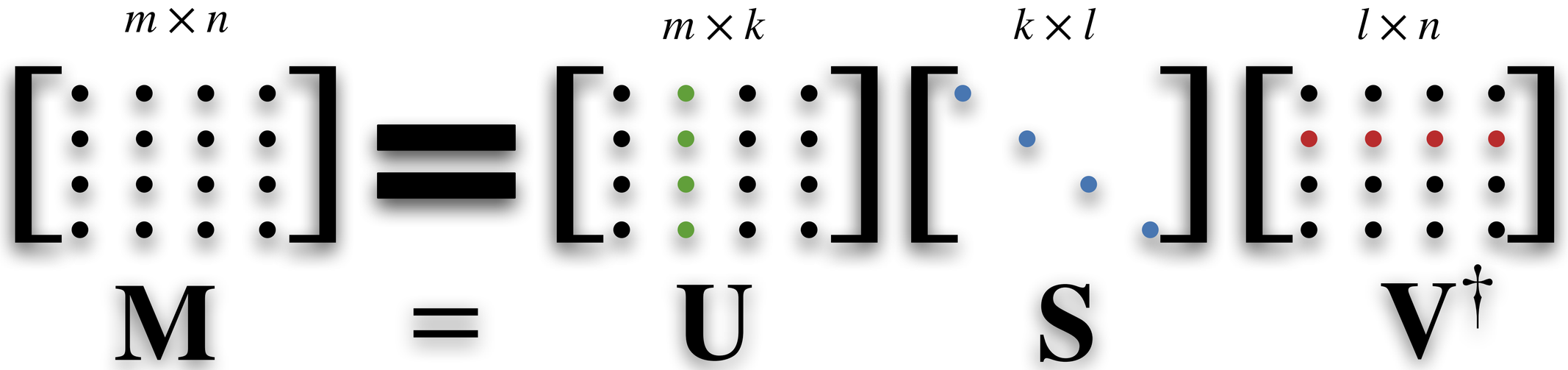

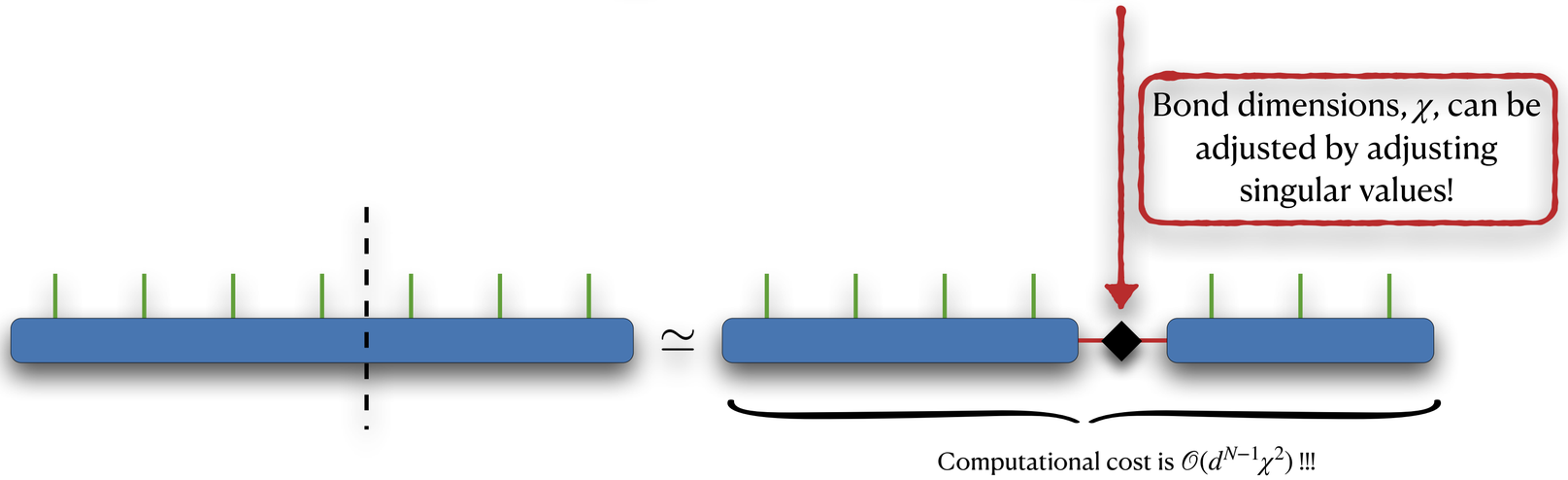

Matrix Product States for Classification

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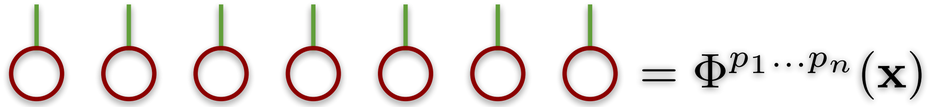
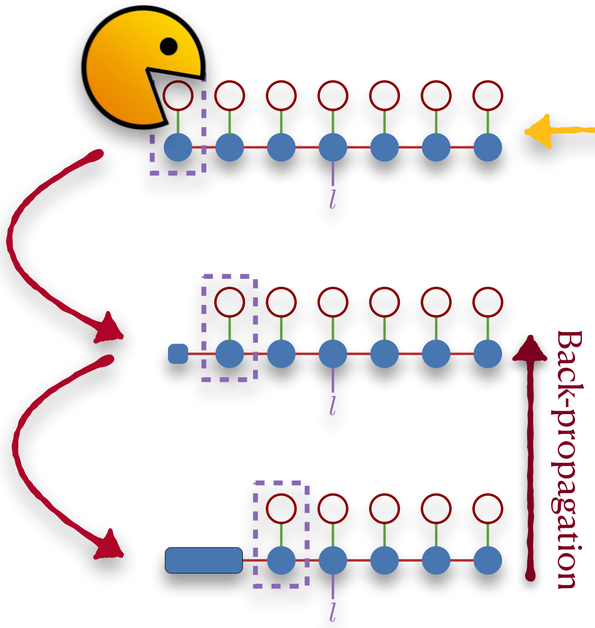
Data Embedding

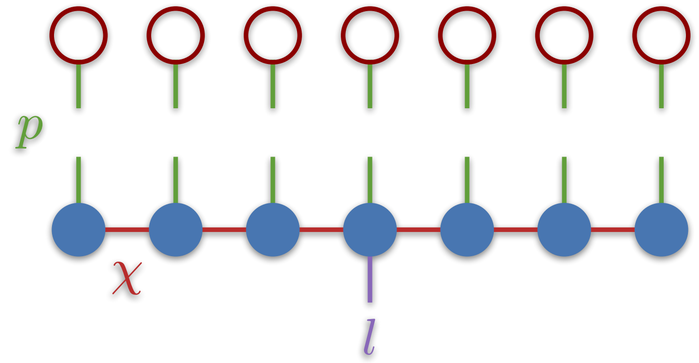
$$\Phi^{p_1 \cdots p_n}(\mathbf{x}) = \phi^{p_1}(x_1) \otimes \phi^{p_2}(x_2) \otimes \cdots \otimes \phi^{p_n}(x_n)$$

$$\phi^{p_i}(x_i) = \begin{bmatrix} \cos(x_i\ \pi/2) \\ \sin(x_i\ \pi/2) \end{bmatrix} \quad \text{or} \quad \phi^{p_i}(x_i) = \begin{bmatrix} 1 \\ x_i \\ x_i^2 \end{bmatrix} \quad \text{or} \quad \cdots$$

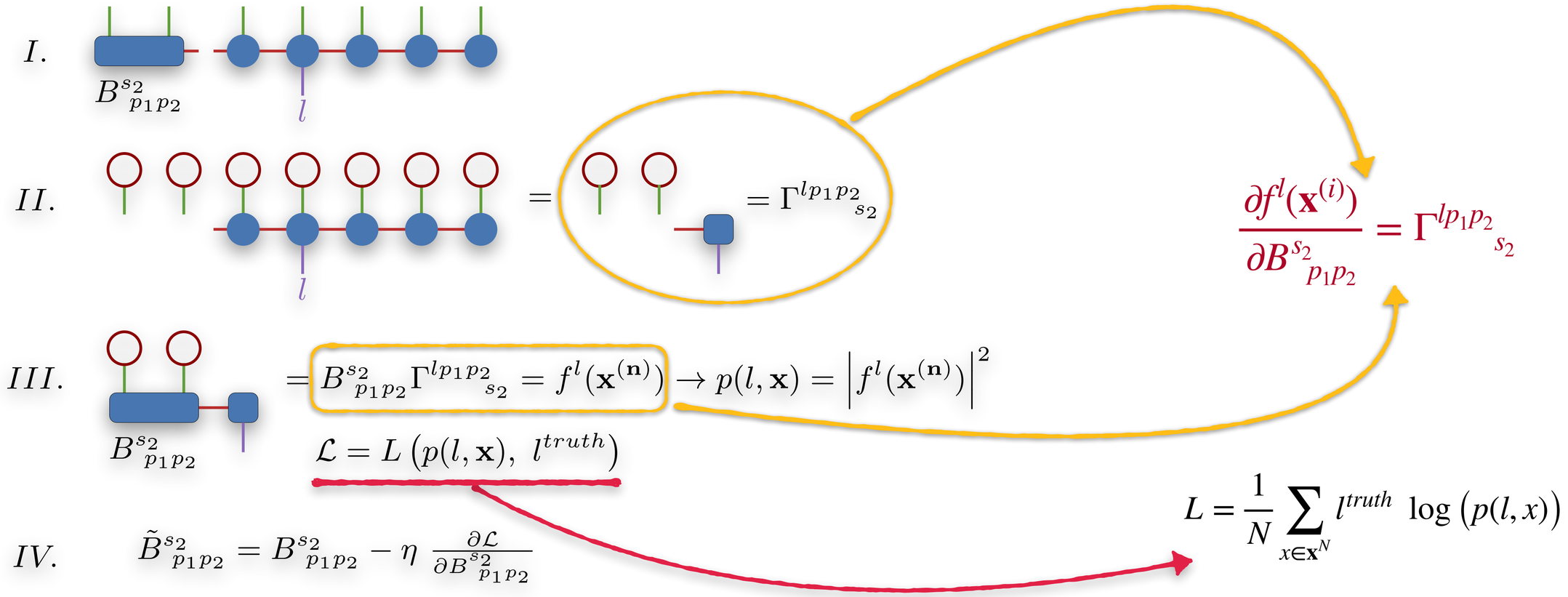




An efficient contraction algorithm is essential for training!



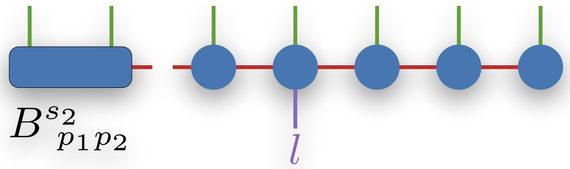
Density Matrix Renormalization Group Algorithm



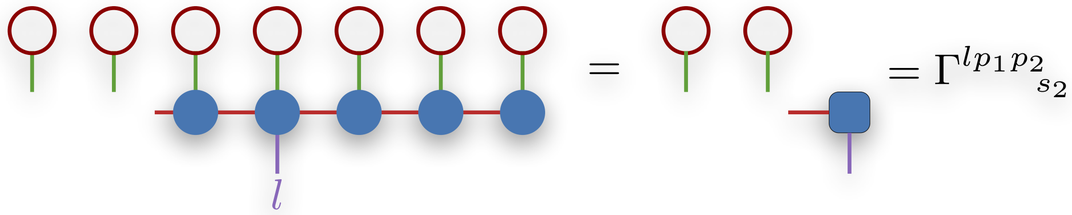
Initially proposed in: Stoudenmire, Schwab; '16

Density Matrix Renormalization Group Algorithm

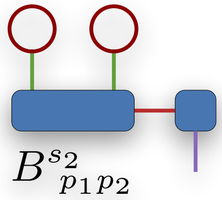
I.



II.



III.



$$= B^{s_2}_{p_1 p_2} \Gamma^{l p_1 p_2}{}_{s_2} = f^l(\mathbf{x}^{(\mathbf{n})}) \rightarrow p(l, \mathbf{x}) = \left| f^l(\mathbf{x}^{(\mathbf{n})}) \right|^2$$

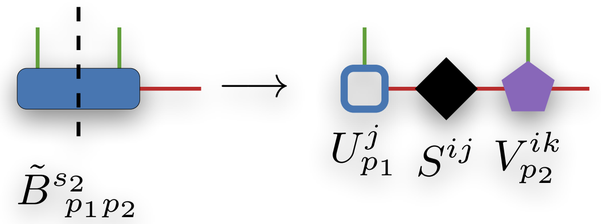
$$\mathcal{L} = L\left(p(l, \mathbf{x}),\ l^{truth}\right)$$

IV.

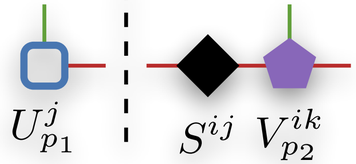
$$\tilde{B}^{s_2}_{p_1 p_2} = B^{s_2}_{p_1 p_2} - \eta \frac{\partial \mathcal{L}}{\partial B^{s_2}_{p_1 p_2}}$$

Adjust the bond dimension via SVD!

V.

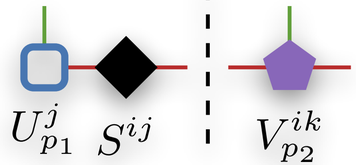


VI. Sweep direction to the right:



Node I Node II

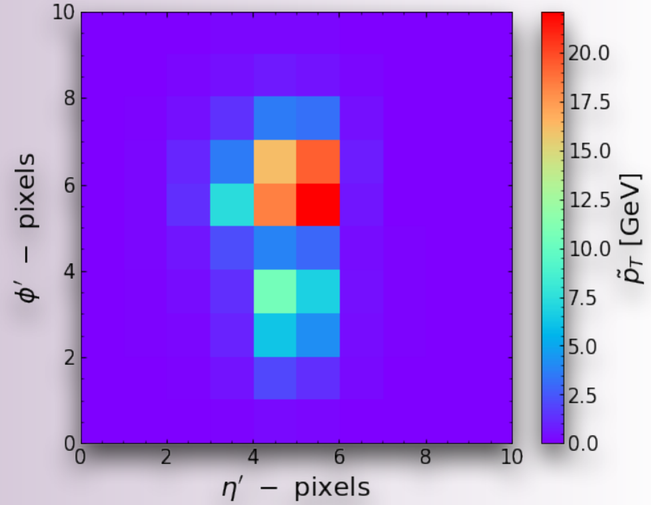
Sweep direction to the left:

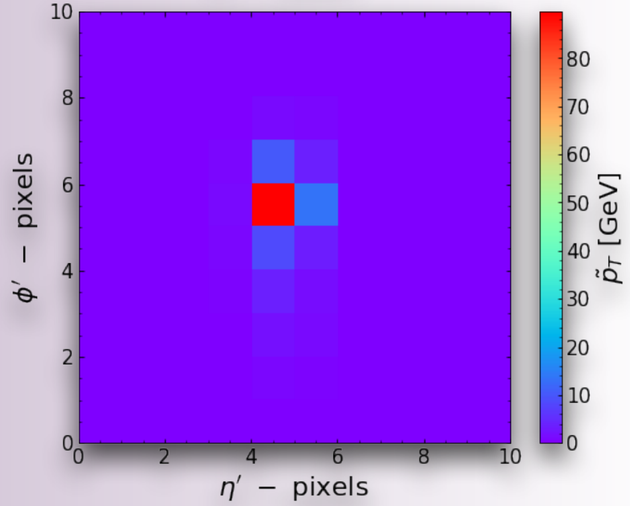


Node I Node II

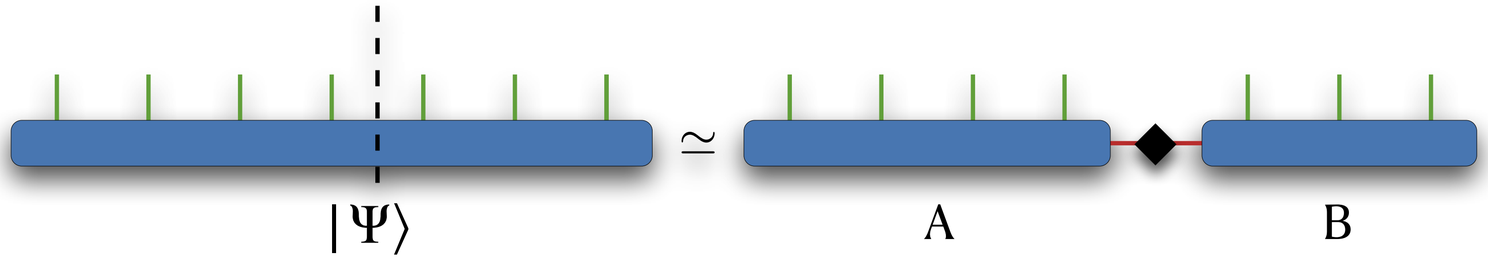
Initially proposed in: Stoudenmire, Schwab; '16

Top Tagging through MPS





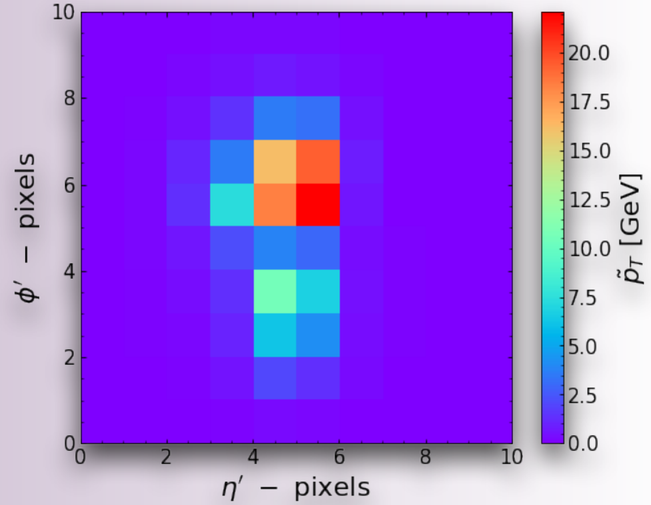
Entanglement Entropy & Schmidt Decompostion

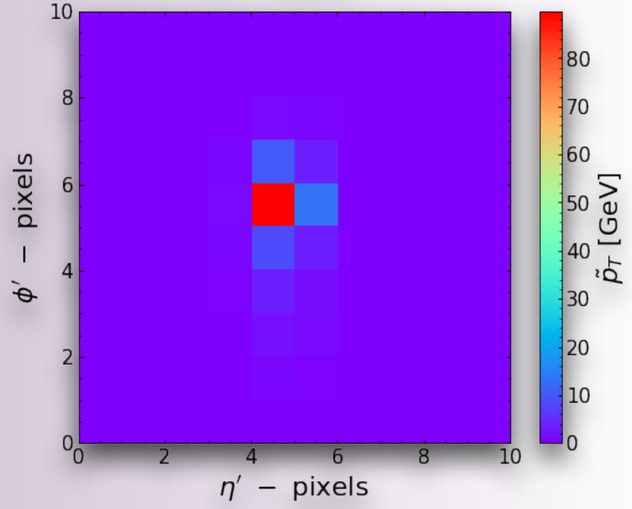


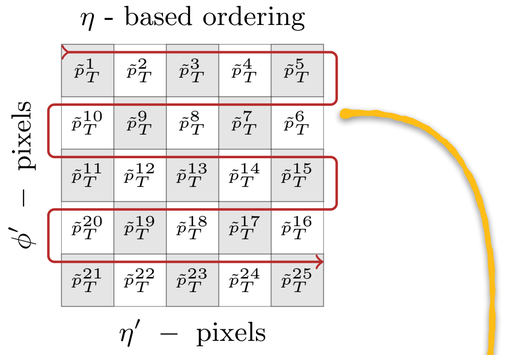
$$|\Psi\rangle_{AB} = \sum_{i}^{\chi} \lambda_\alpha |\alpha\rangle_A |\alpha\rangle_B \quad \rightarrow \quad \lambda_\alpha := \text{Schmidt values}$$

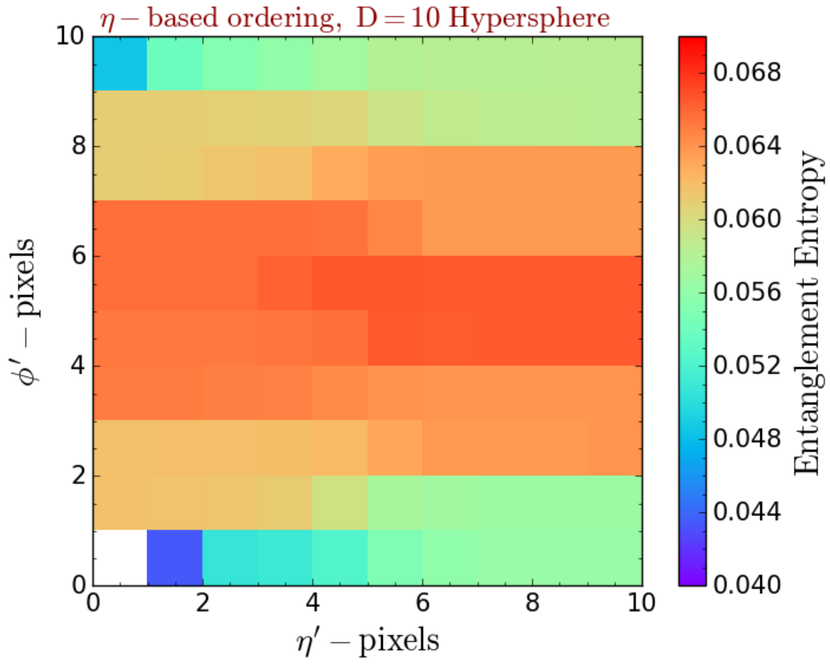
$$\mathcal{S} = -\sum_{i}^{\chi} \lambda_i^2 \log \lambda_i^2 \quad \rightarrow \quad \text{von Neumann entropy}$$

Top Tagging through MPS

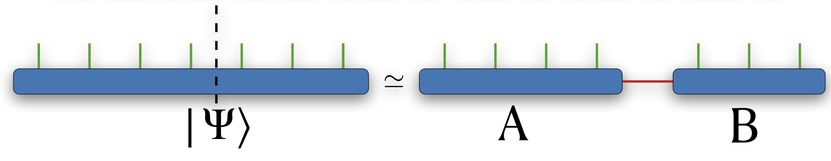






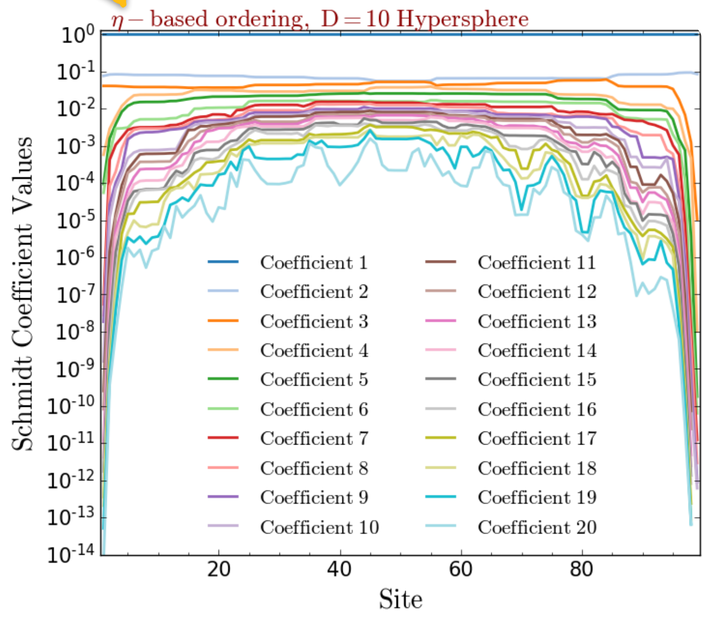


Entanglement Entropy & Schmidt Decompostion



$$|\Psi\rangle_{AB} = \sum_{i}^{\chi} \lambda_\alpha |\alpha\rangle_A |\alpha\rangle_B$$

$$\mathcal{S} = -\sum_{i}^{\chi} \lambda_i^2 \log \lambda_i^2$$



Fisher Information & Effective Dimensions