Real-time Quantum-Inspired Algorithms for Anomaly Detection in Collider Triggers

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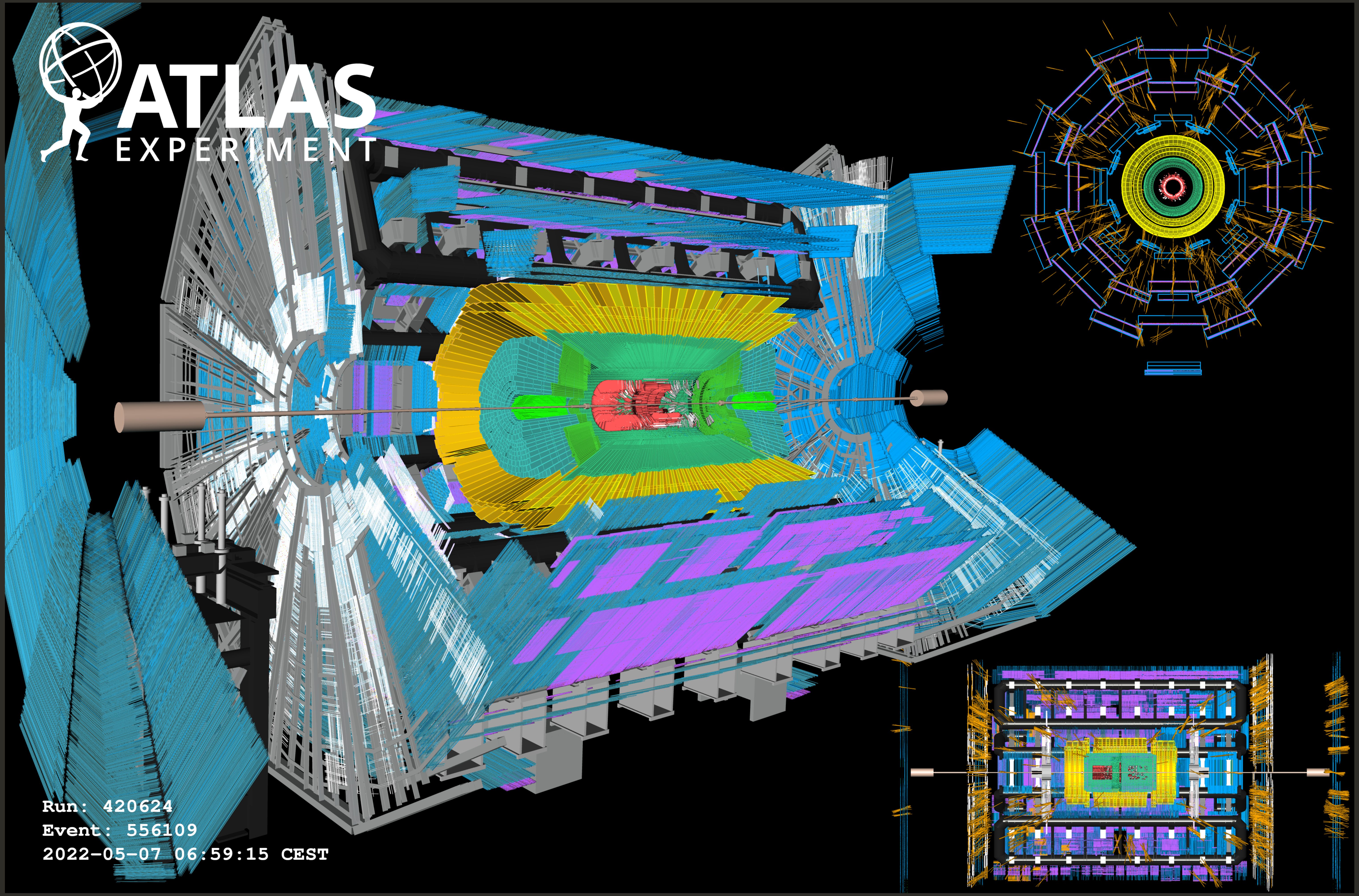
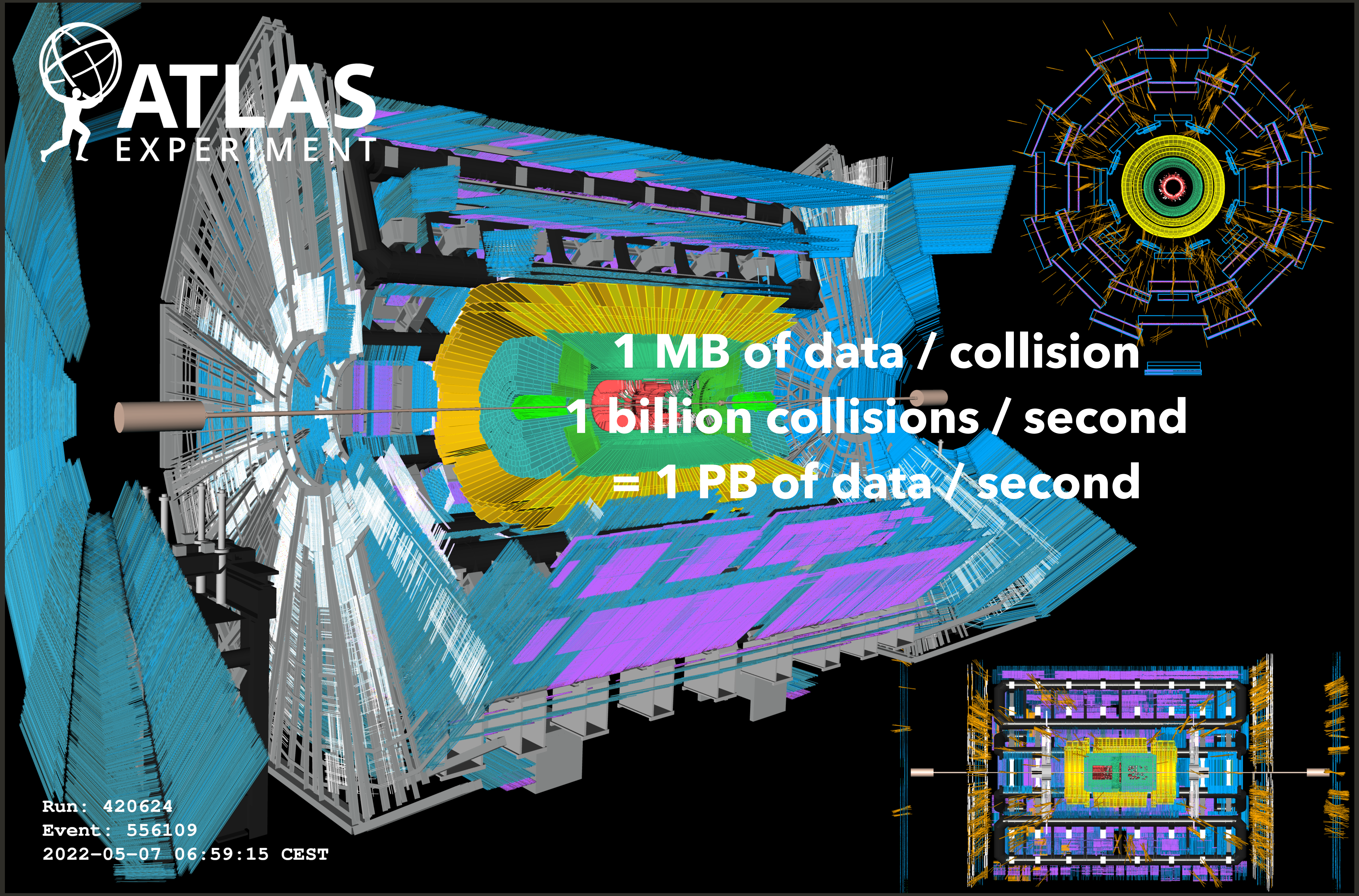
SLAC NATIONAL ACCELERATOR LABORATORY
Stanford University | U.S. DEPARTMENT OF ENERGY

Collider Triggers




ATLAS
EXPERIMENT
1 MB of data / collision
1 billion collisions / second
= 1 PB of data / second
Run: 420624
Event: 556109
2022-05-07 06:59:15 CEST

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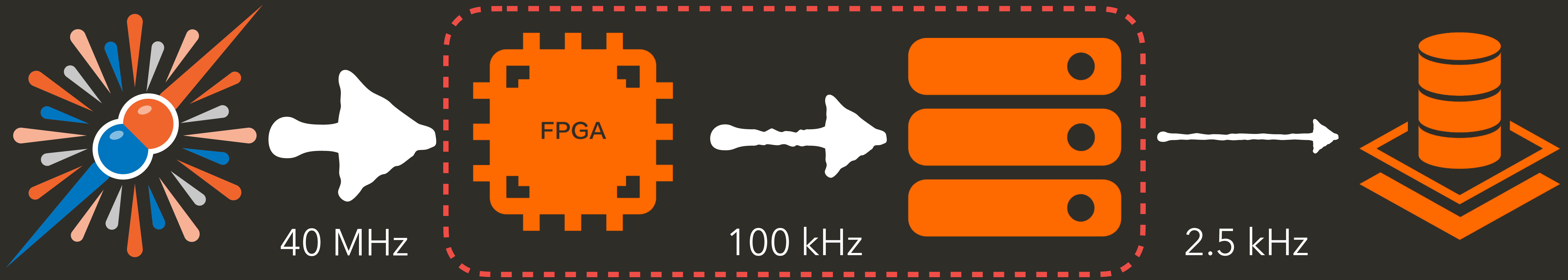

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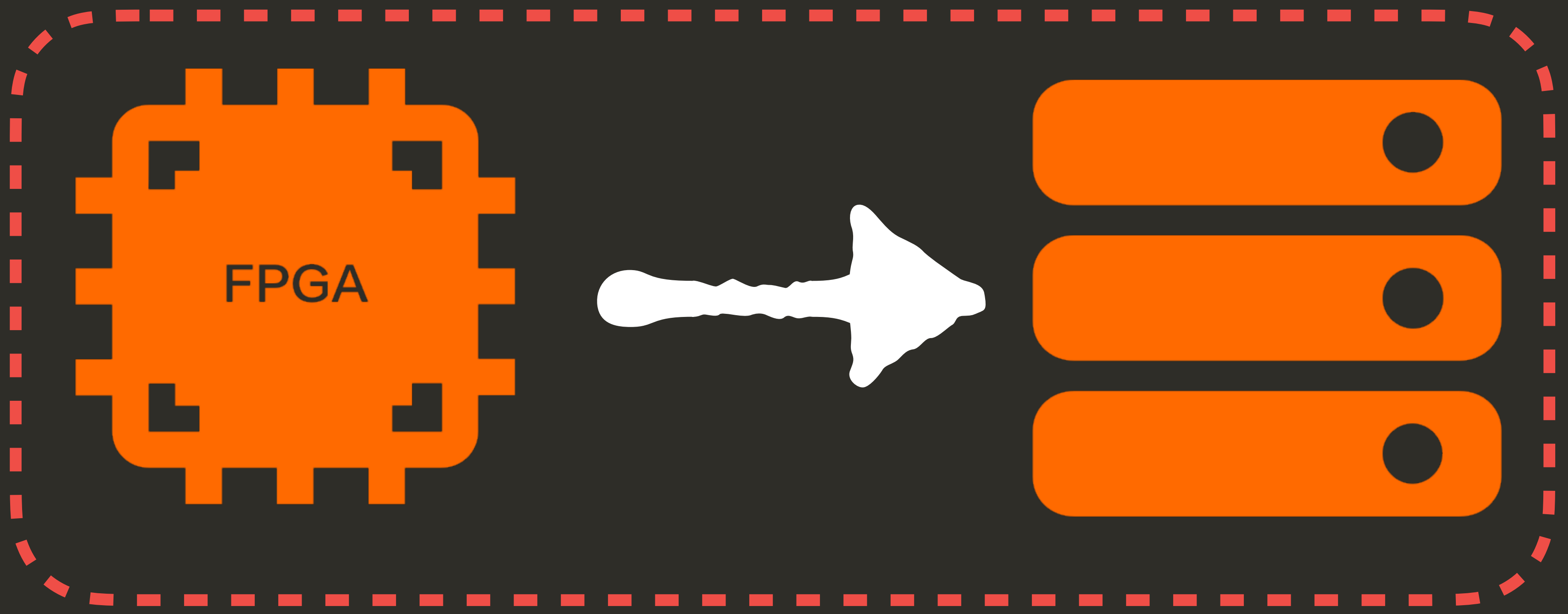
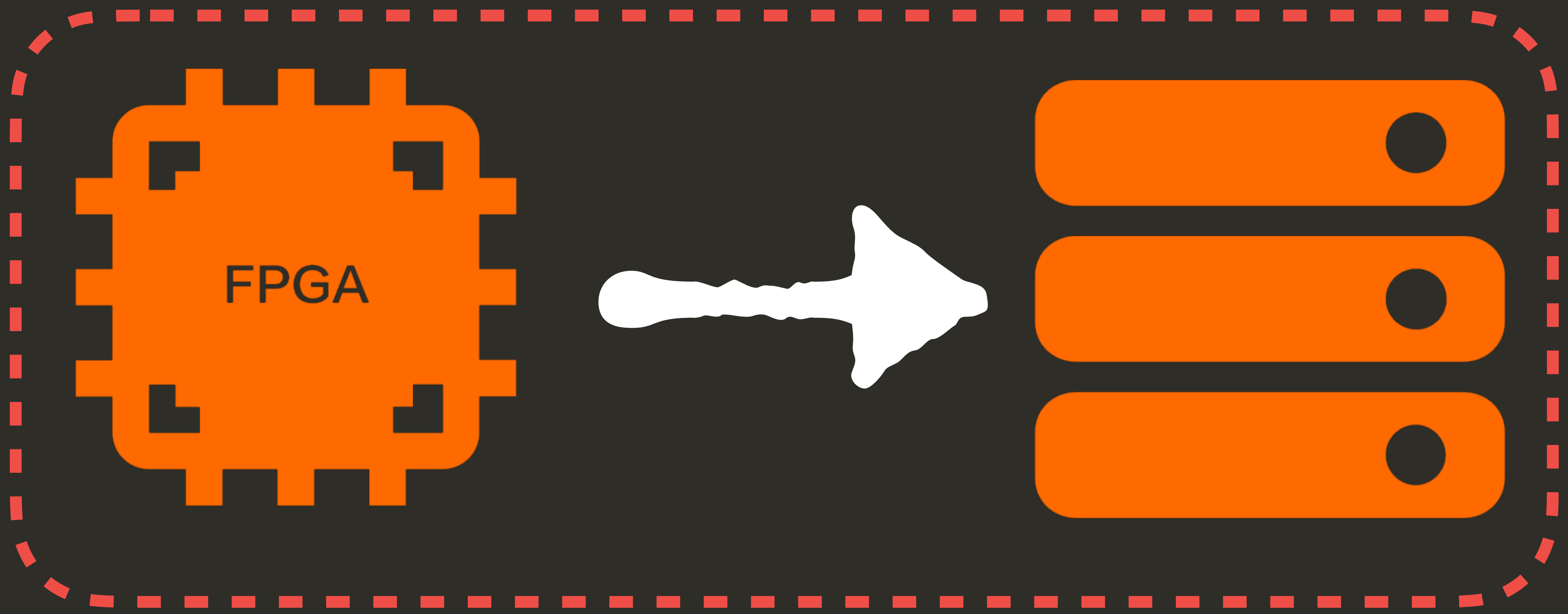


Energy-thresholded

Algorithms reflect our best **priors** of where interesting physics lives

Topology-specific



Algorithms reflect our best **priors** of where interesting physics lives

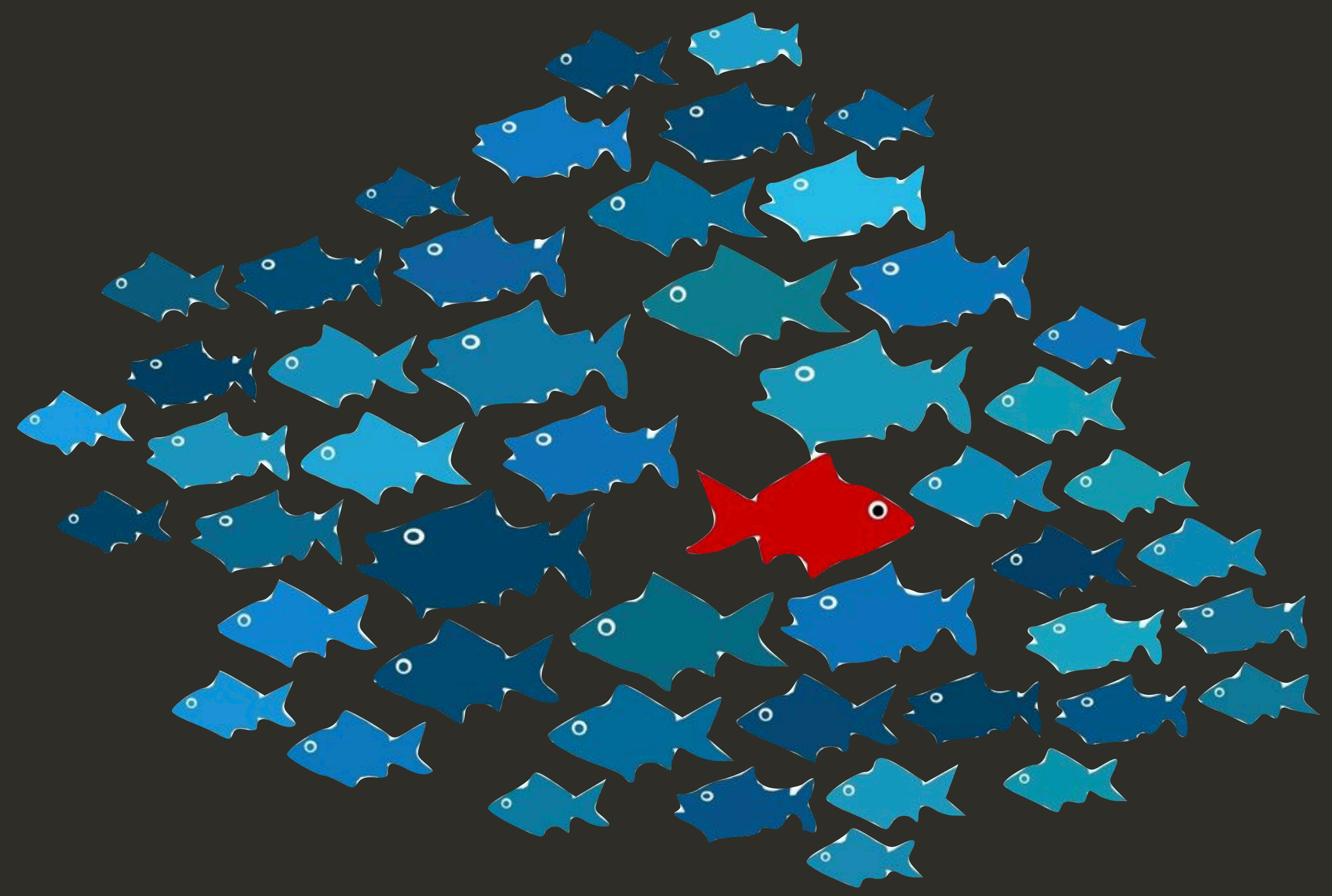
What if we are leaving BSM physics in the data we **do not** collect?

Energy-thresholded

Topology-specific

Instead of only using priors, we can learn directly from data what's **normal** and what's **anomalous**

Opens up a large phase space:
Uncovered? Unexpected? Unknown?



ML-enabled anomaly detection is now available and (reasonably) well-understood

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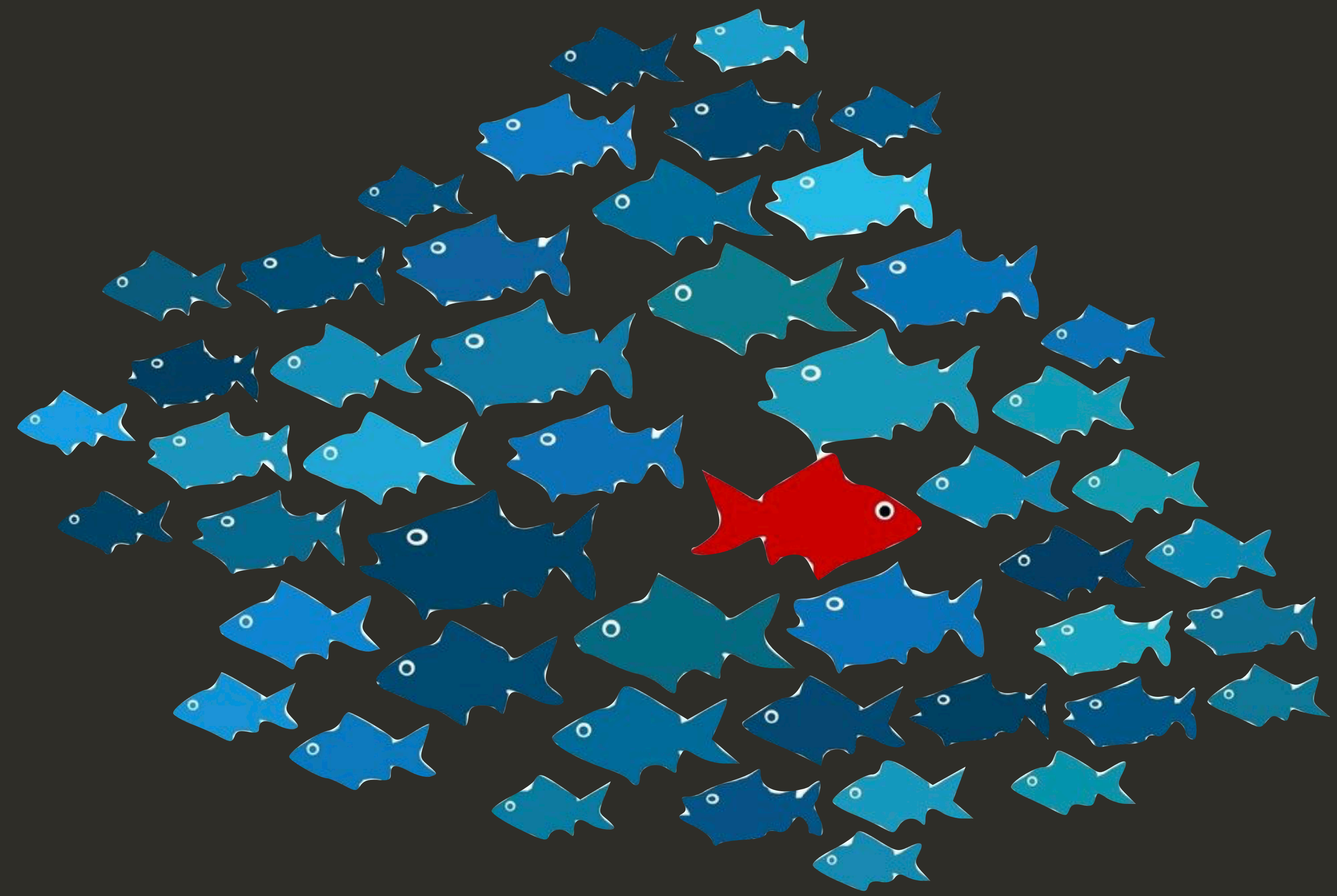


ML-enabled anomaly detection is now available and (reasonably) well-understood

We have accelerated neural networks to run in O(10 ns) latency on FPGAs
Already running in ATLAS and CMS, and have taken useful physics data!

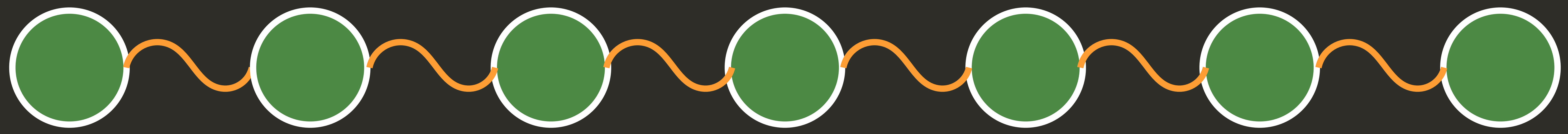
GELATO, ATLAS

AXOL1TL, CMS

CICADA, CMS

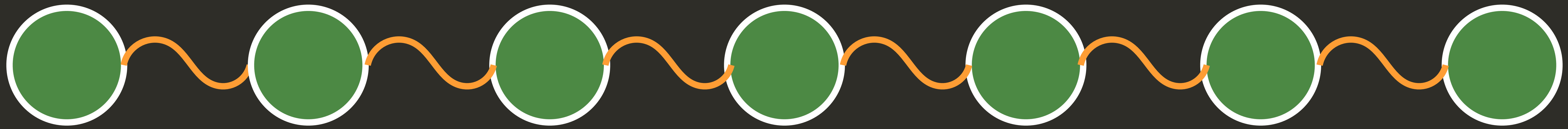
NOMAD, ATLAS

N-particle entangled quantum many-body system with some Hamiltonian



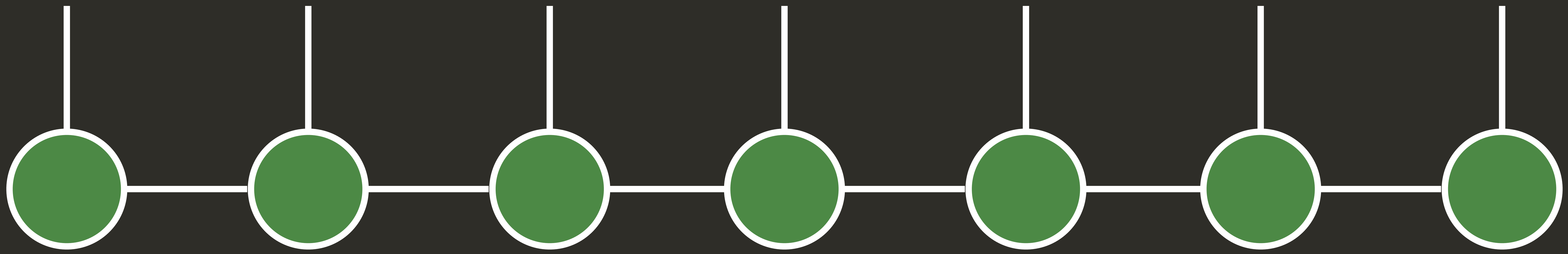
How to find its ground state energy? Model its low energy behavior?

N-particle entangled quantum many-body system with some Hamiltonian

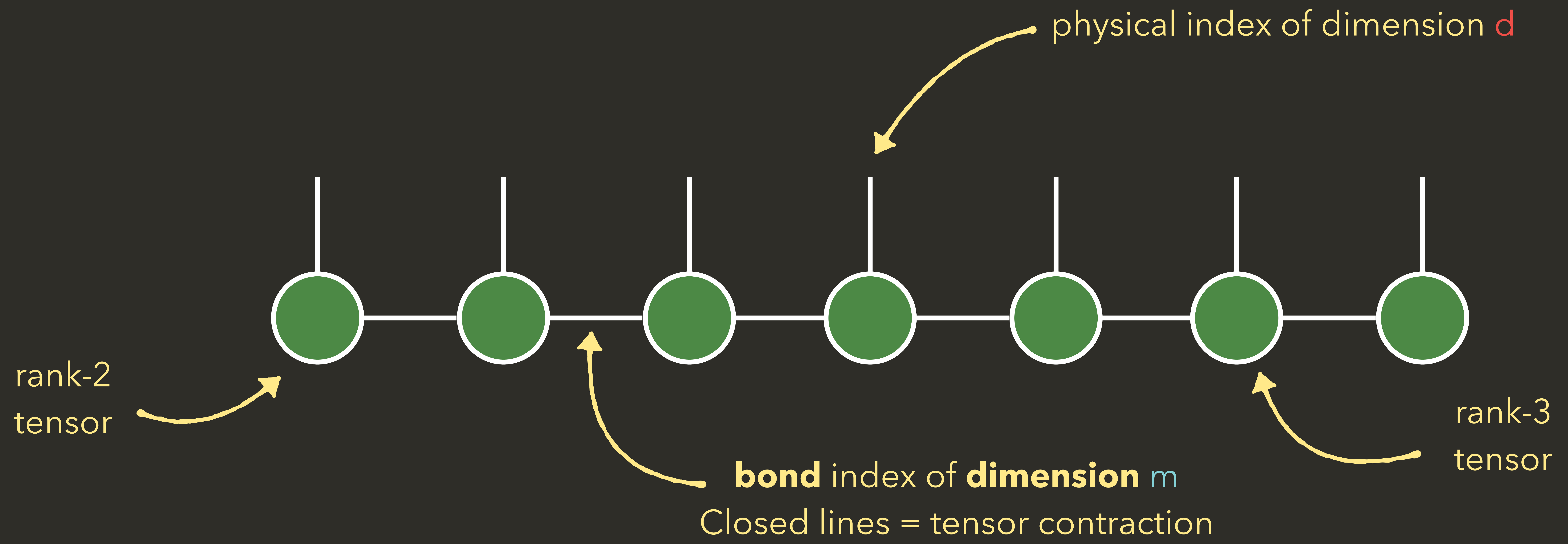


How to find its ground state energy? Model its low energy behavior?

DMRG formulation, devised by Steve White in 1992: Phys. Rev. Lett. 69, 2863

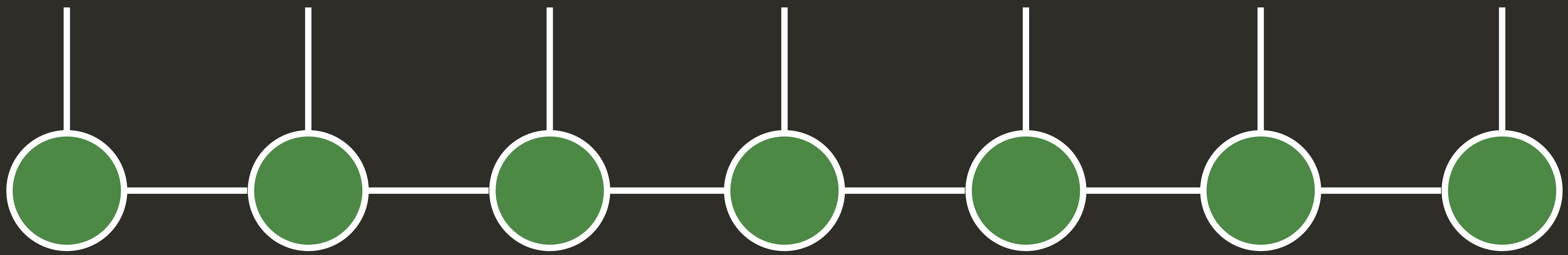


Matrix Product State


physical index of dimension d
rank-2
tensor
rank-3
tensor
bond index of **dimension** m
Closed lines = tensor contraction

Can we think of the particles produced in an LHC collision in terms of a highly entangled many body system?

If so, can tensor networks be used to model their behavior?
Can they learn long-range correlations?



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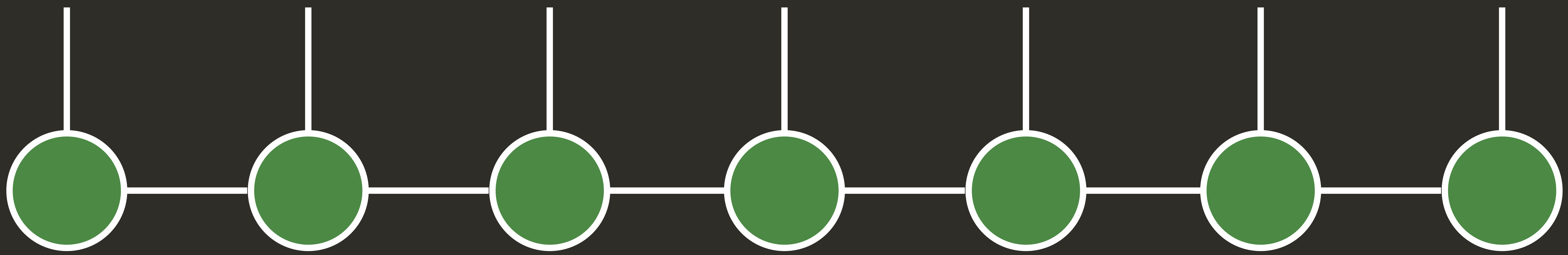
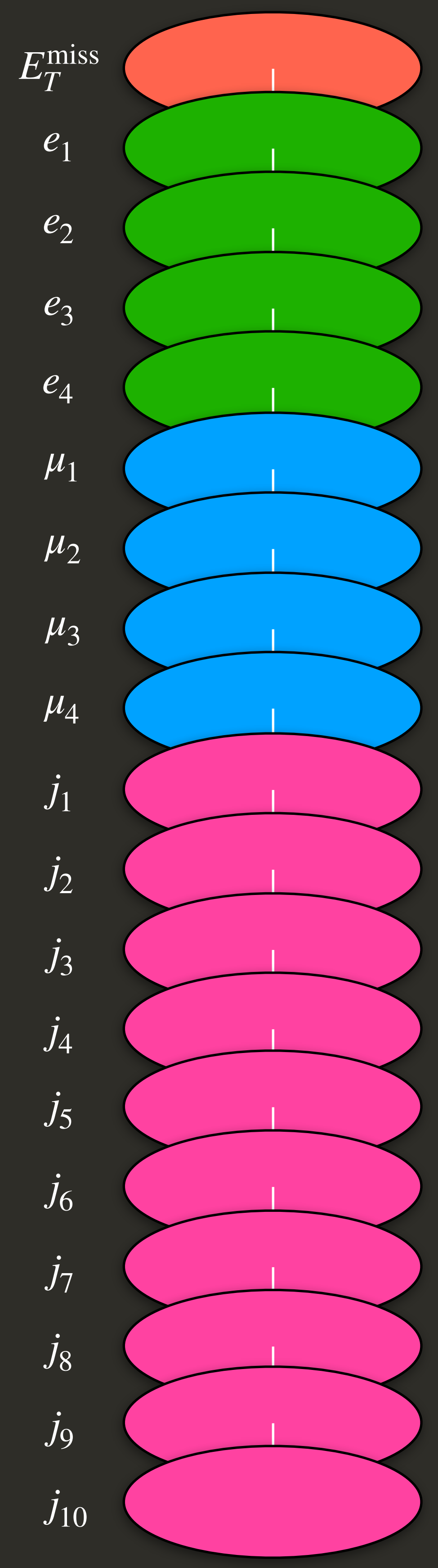


Underlying physics is highly complex, can we learn it directly from data?

Finally, can we detect anomalies by tagging out of behavior-events?

Summary of the ML workflow

Embedded Inputs

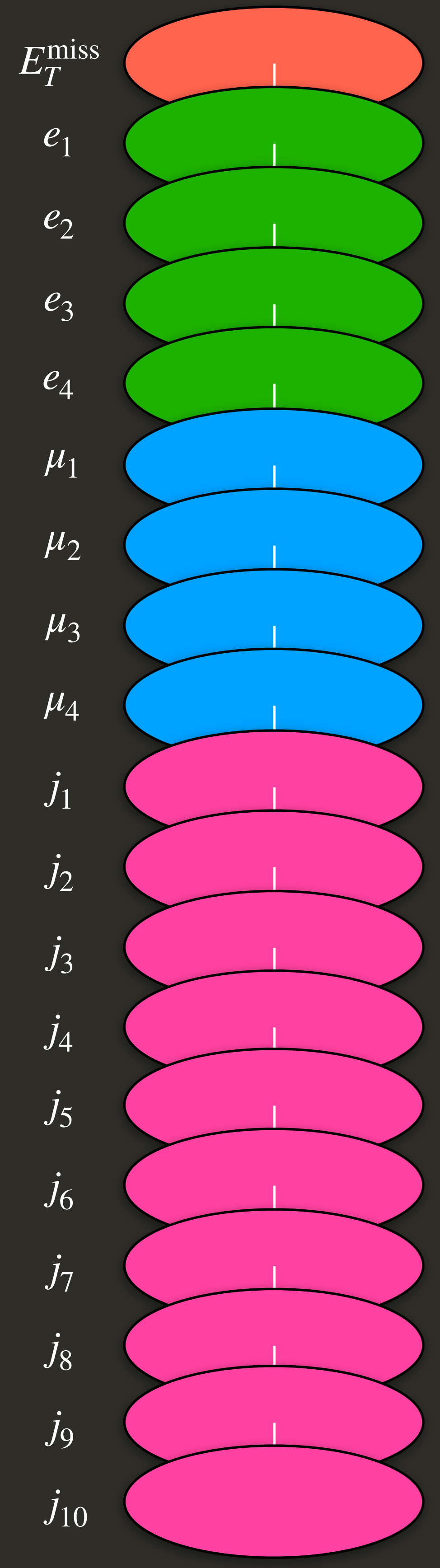


Encode particle 3-momenta into states
19 particles = 19 vector sites

Ordering of the sites matters!

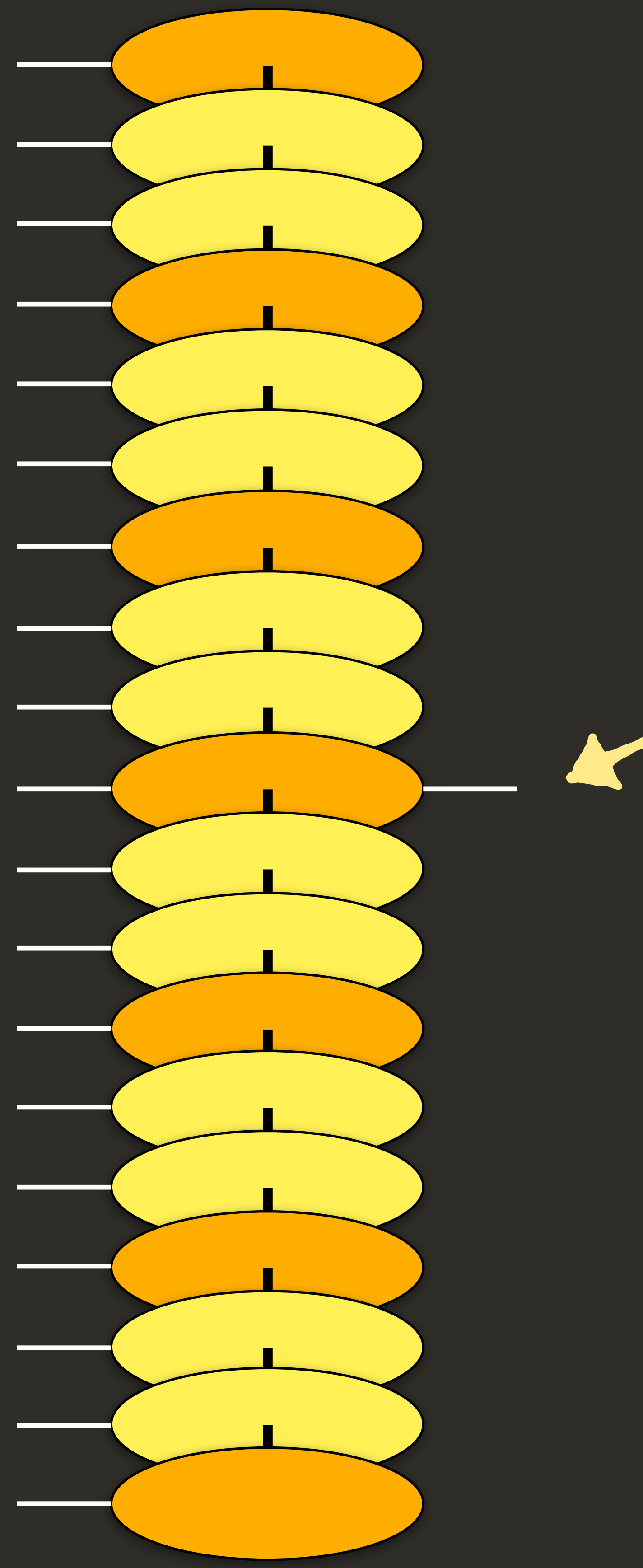
Summary of the ML workflow

Embedded Inputs



Takes a 19 site input MPS prepared per event

Operator / ML Model



Free parameters:
Elements of the TN are machine-learnt; trained unsupervised on background-only

Training target:
Compresses to a vector of a target norm

Anomaly score:
Deviations of the vector norm from the target

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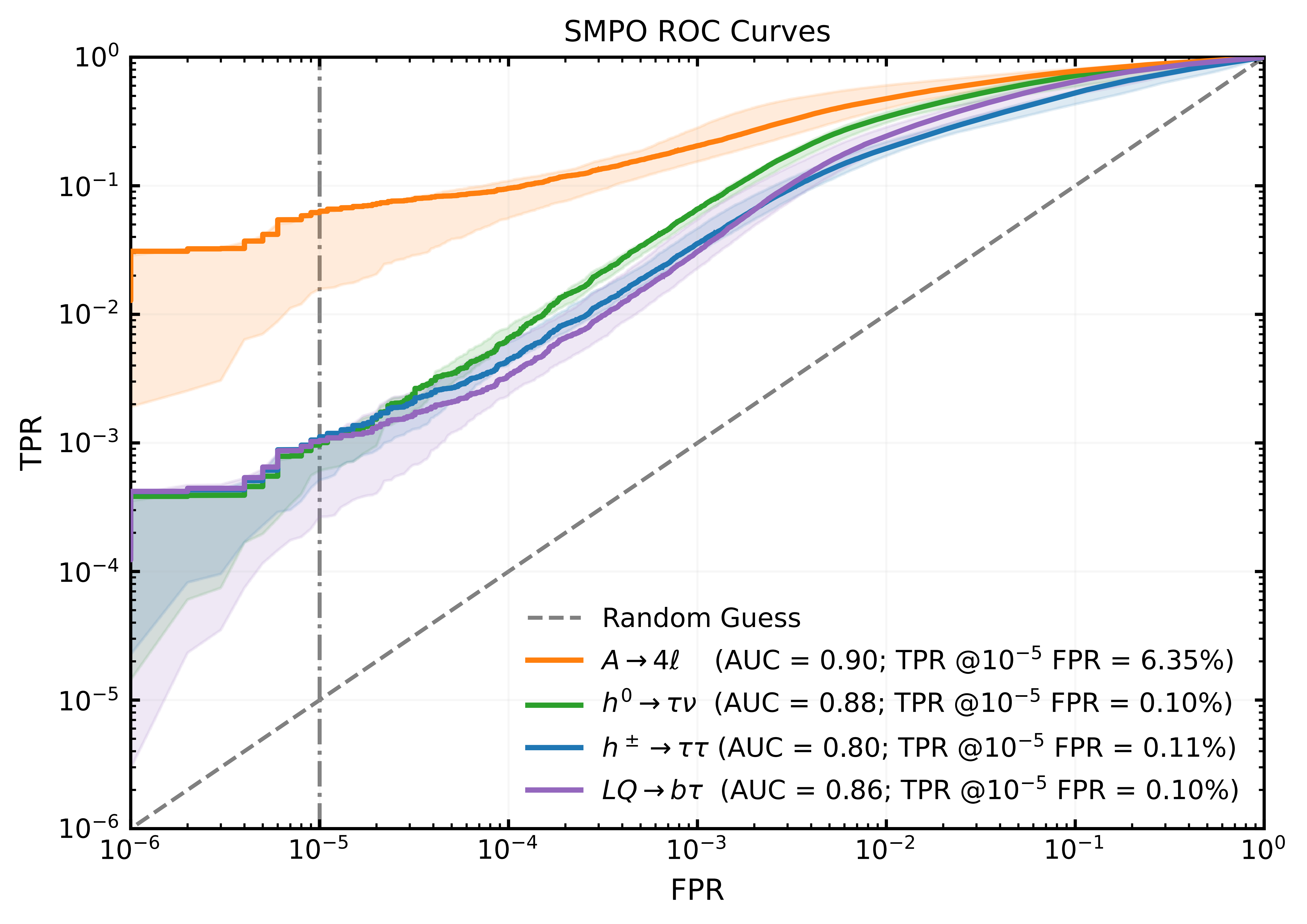
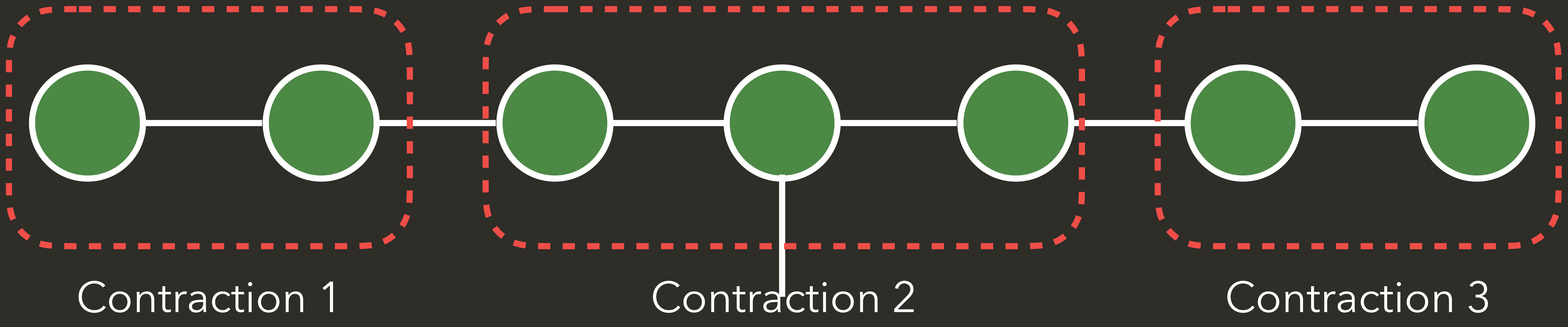


- Trained and tested on simulated data (ADC2021)
- 4 benchmark signals with distinct topologies
- NN baseline from Govorkova et al, [Nature MI 4, 154–161 (2022)]
- Tail performance comparable to NN architectures (AE, VAE, CNN-AE)
- Fully linear architecture with much fewer params (O(1k) vs O(10k))!

Tensor networks structurally offer high parallelization potential!



Di/tri-site tensor contractions can happen simultaneously; no far-site data dependence

Fewer parameters, shallow depth = fewer operations

When accelerated on an FPGA, we achieved a **0.37 μs latency**, well within collider trigger limits

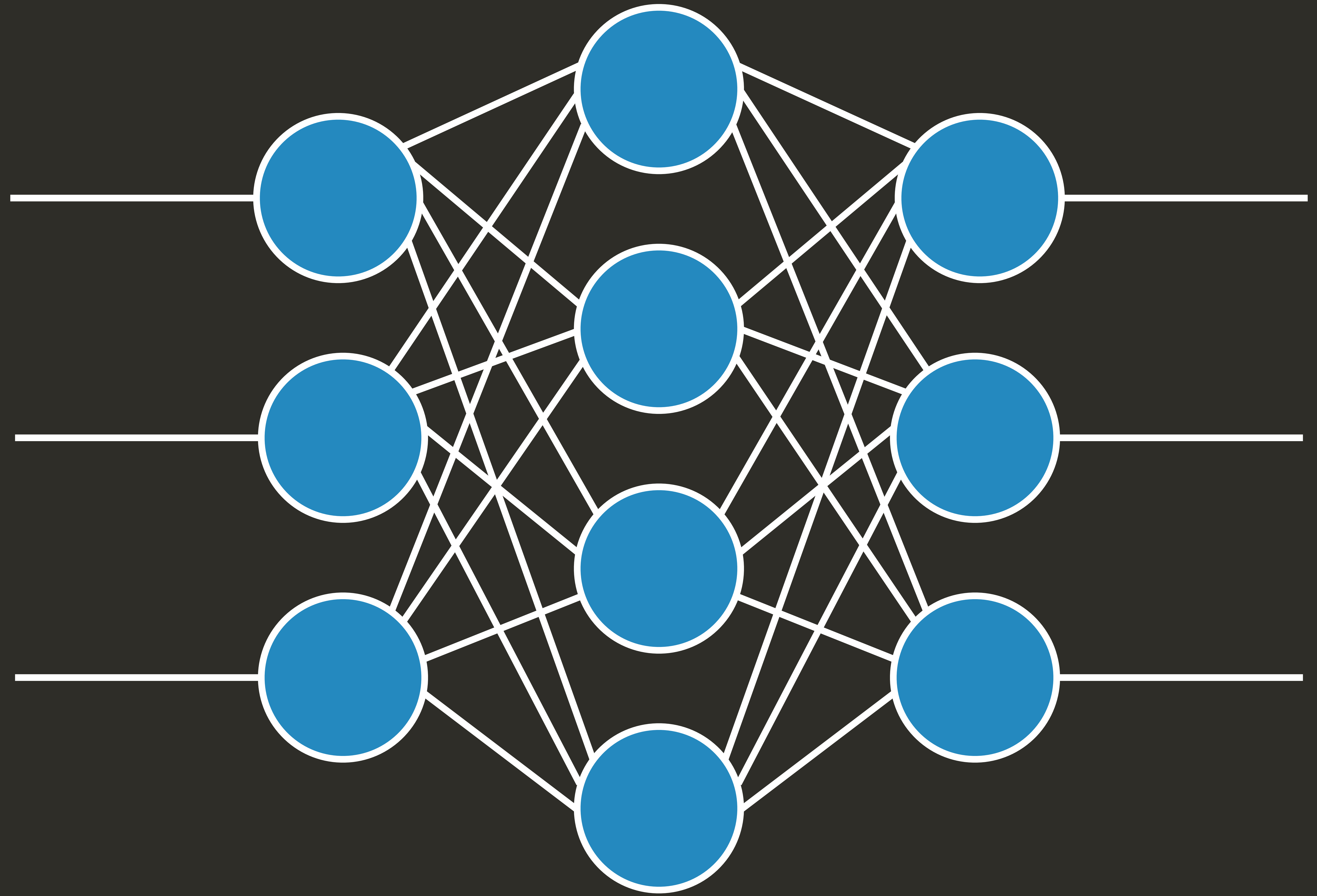
Summary

- Tensor network architectures offer a compelling alternative to SOTA NNs for real-time ML
- We adapted a TN structure for an anomaly detection task and showed comparable discrimination
- FPGA accelerated implementation deployed at sub-μs latency compatible with today's collider constraints

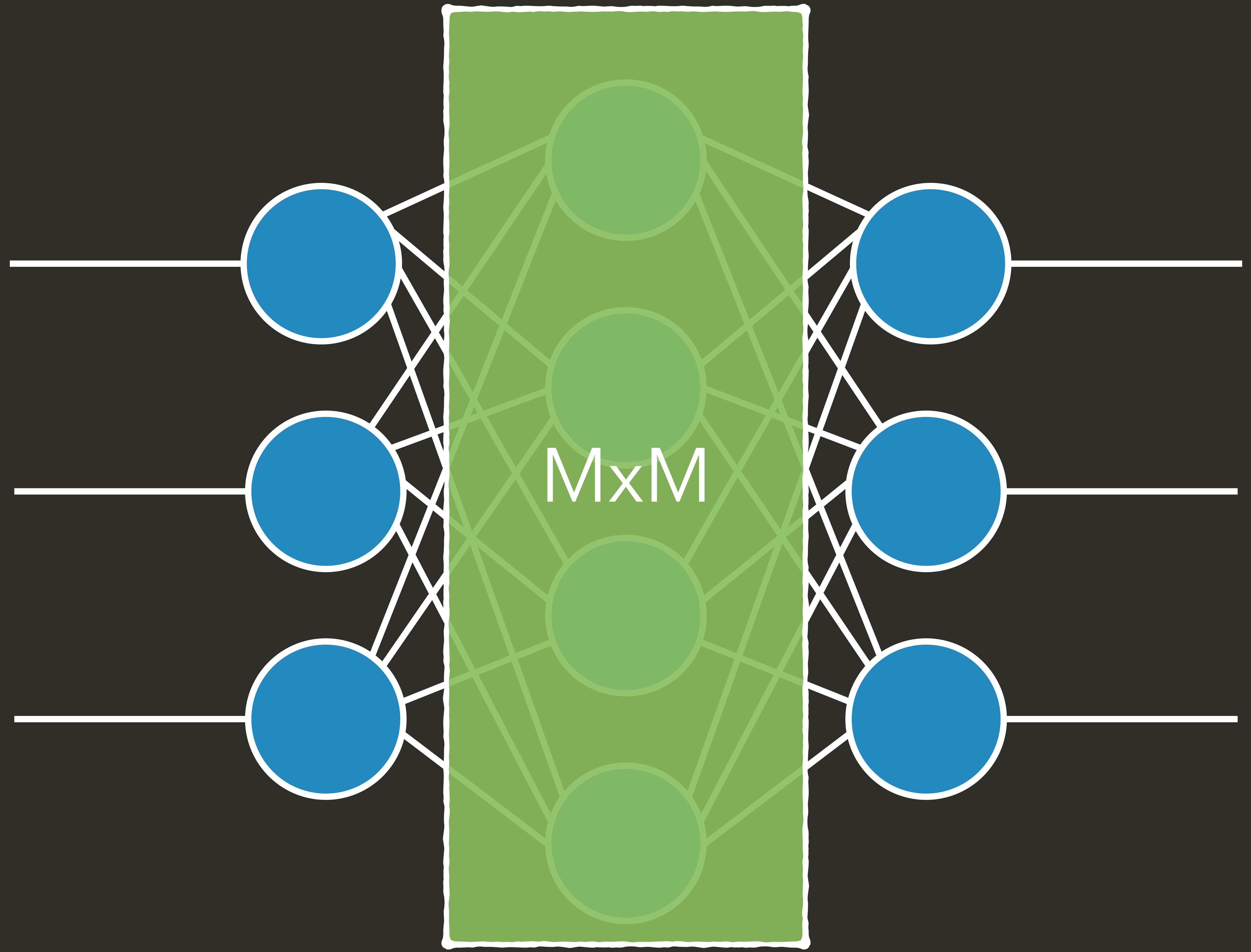
- Related work:
  - Cascade of TNs, FPGA acceleration techniques: arXiv:2603.26604 (this work)
  - Quantum autoencoder on FPGAs for AD at colliders: arXiv:2607.20302
  - TN pruning techniques for further (2x) FPGA resource reduction: paper in prep.

- The theoretical promise of quantum algorithms could be realized on classical data and classical hardware through tensor networks. Excited for what's next!

ADDITIONAL MATERIAL



$$y = Wx + b$$



$$y = Wx + b$$

parameters = M^2

Tensor Notation of Matrix - M_{ij}

$$M_{ij}, 0 \leq i, j < M$$

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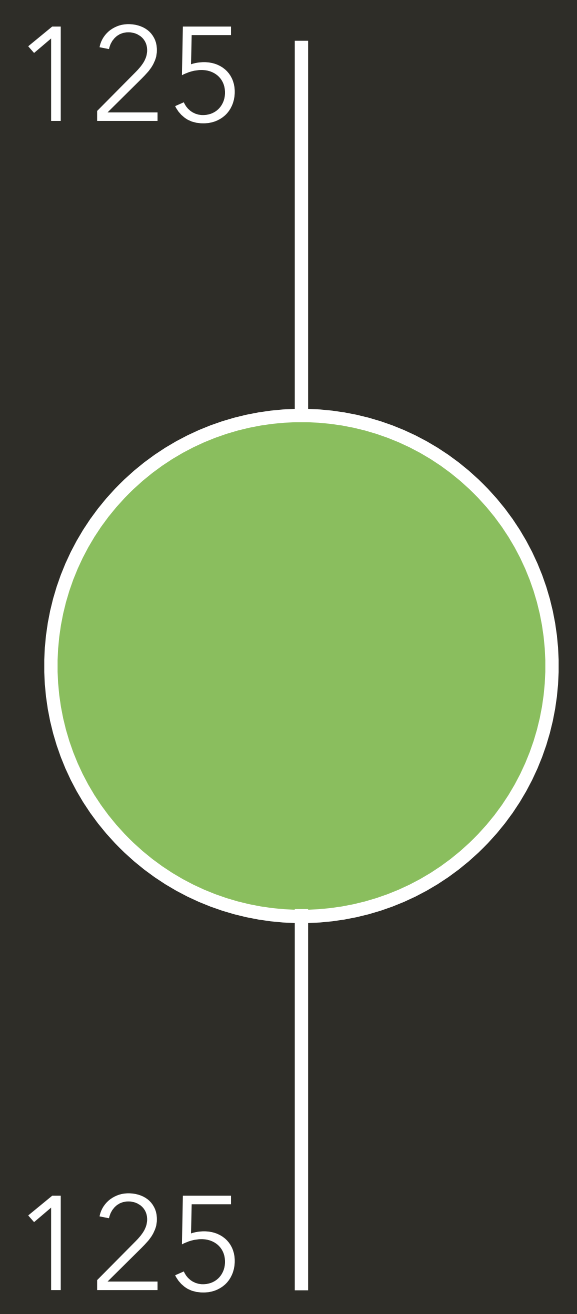
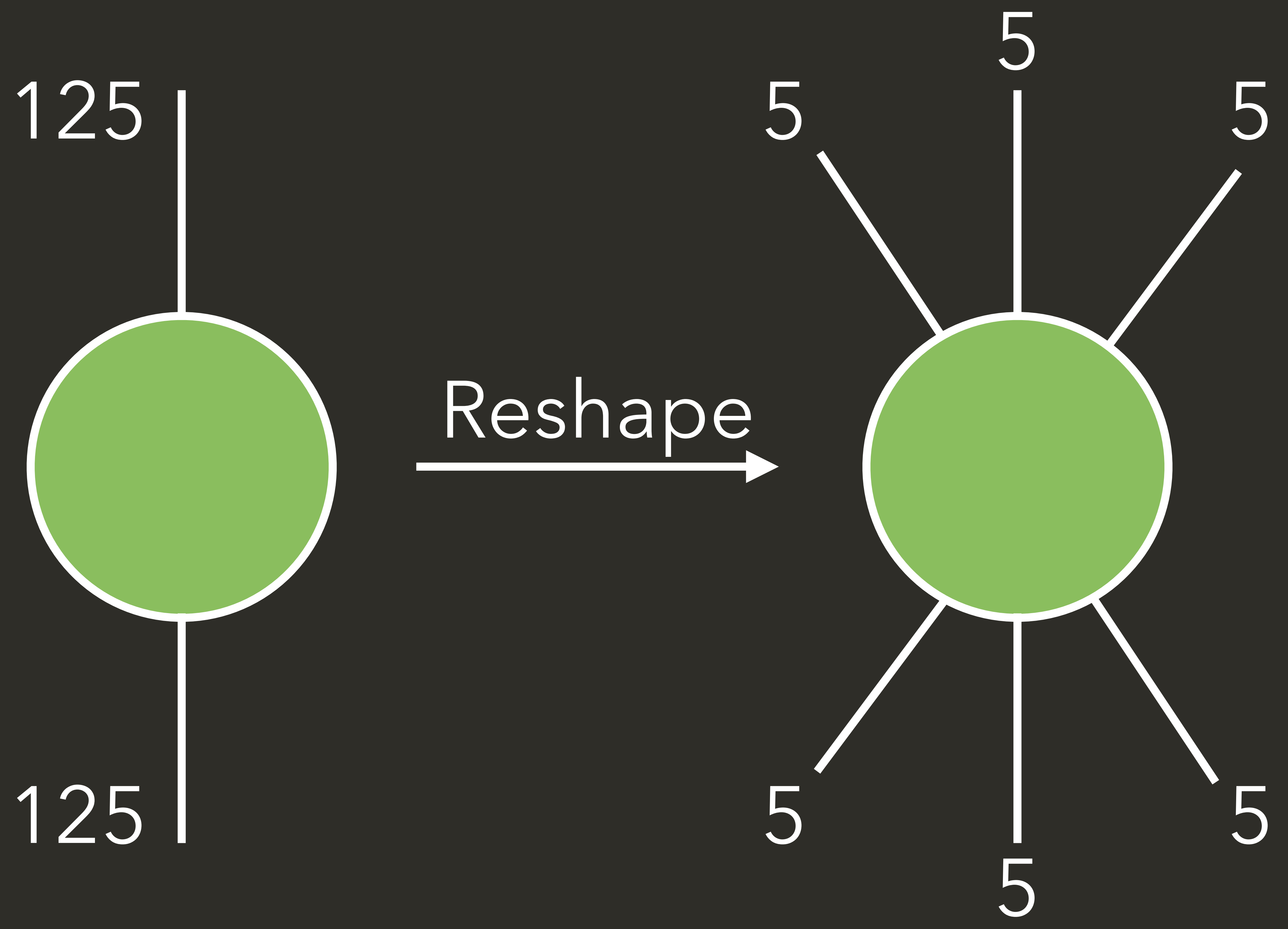
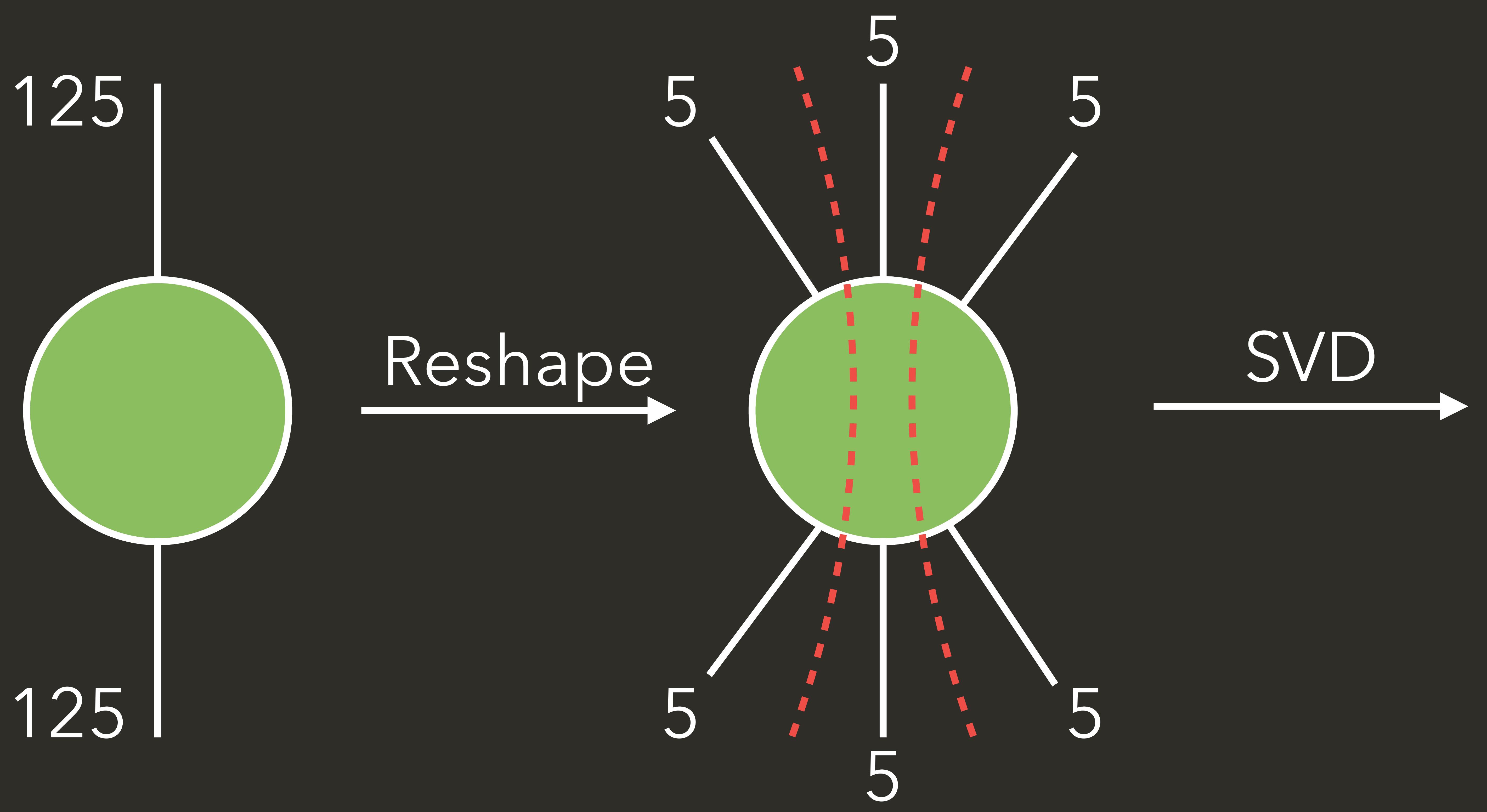
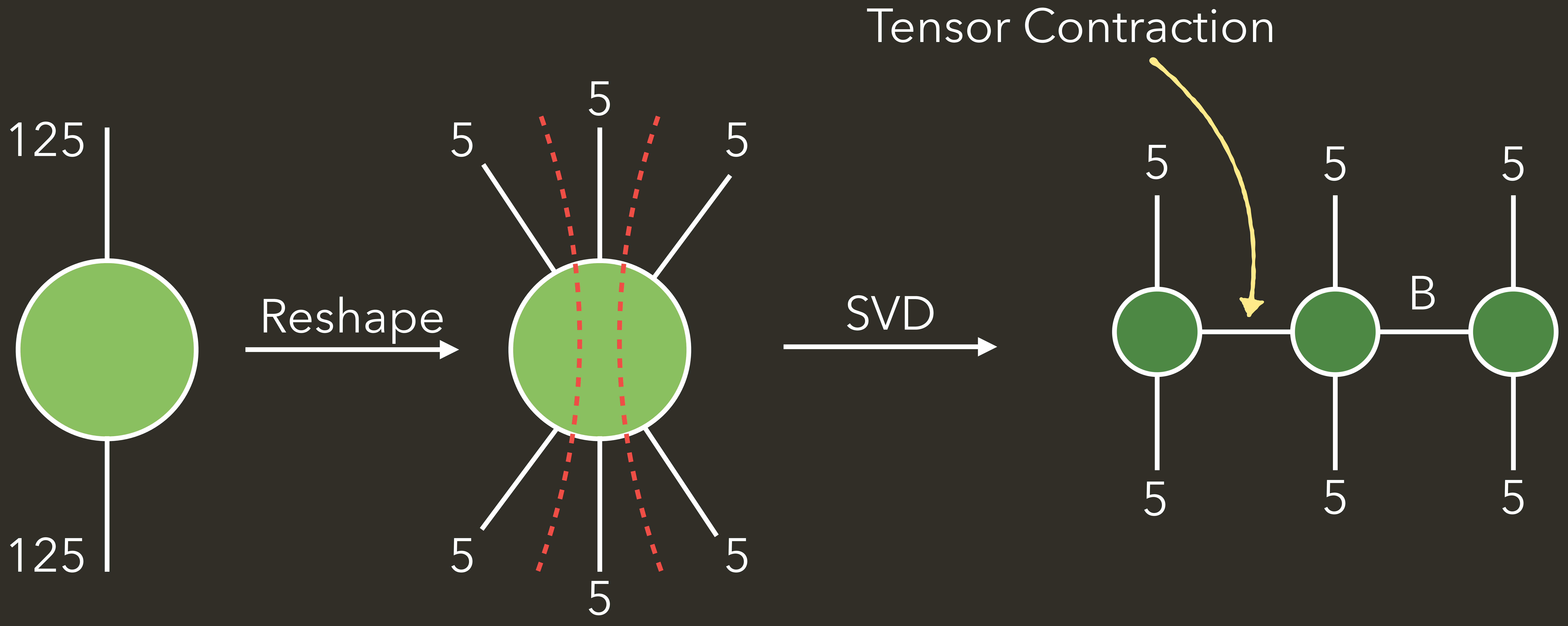



125
125
Reshape
5
5
5
5
5
5
5



SVD = Singular Value Decomposition



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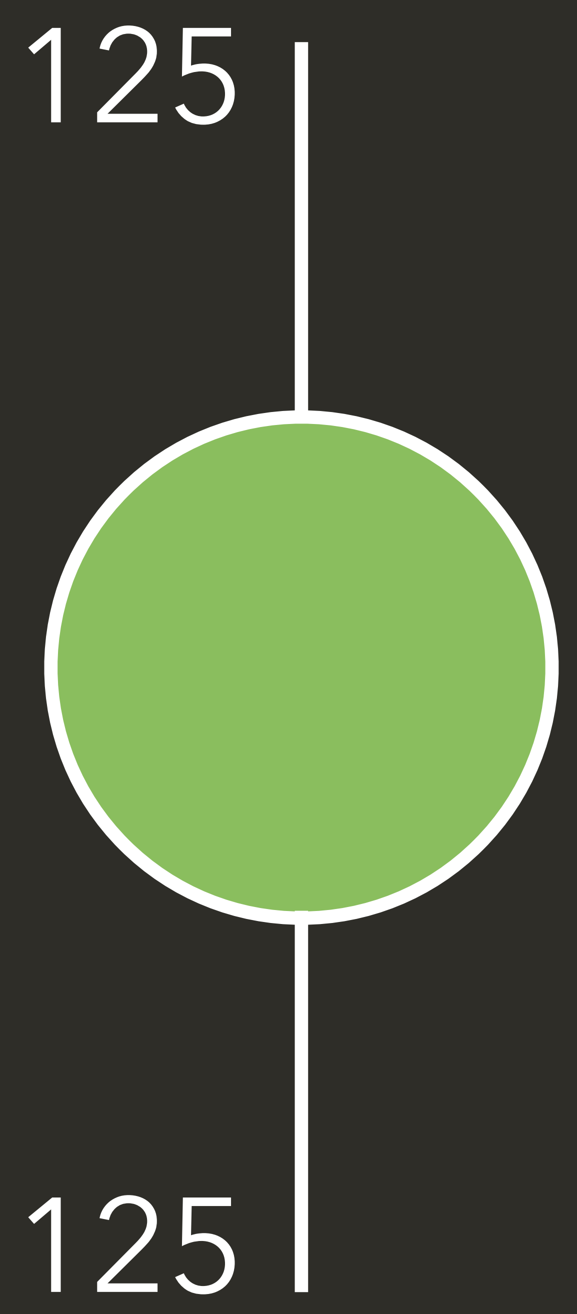
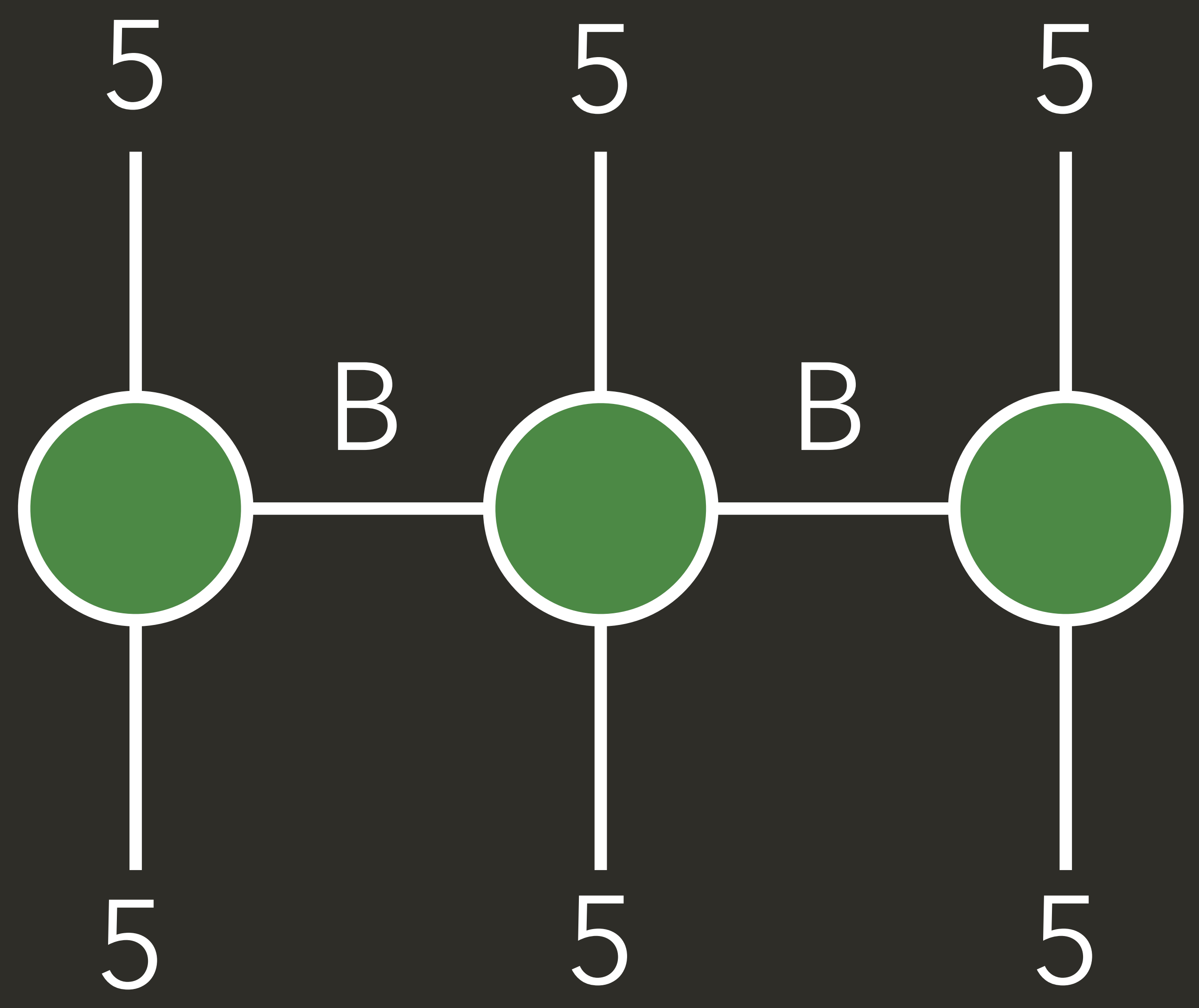


$125^2 = 15{,}625$

$5^6 = 15{,}625$



$3.5^2.B^2$

$B=5 \rightarrow 1875$

$B=8 \rightarrow 4800$

$B=10 \rightarrow 7500$