Continuous-Variable Quantum Machine Learning for High-Energy Physics: The 1-Particle 1-Qumode Framework

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Computational Challenges

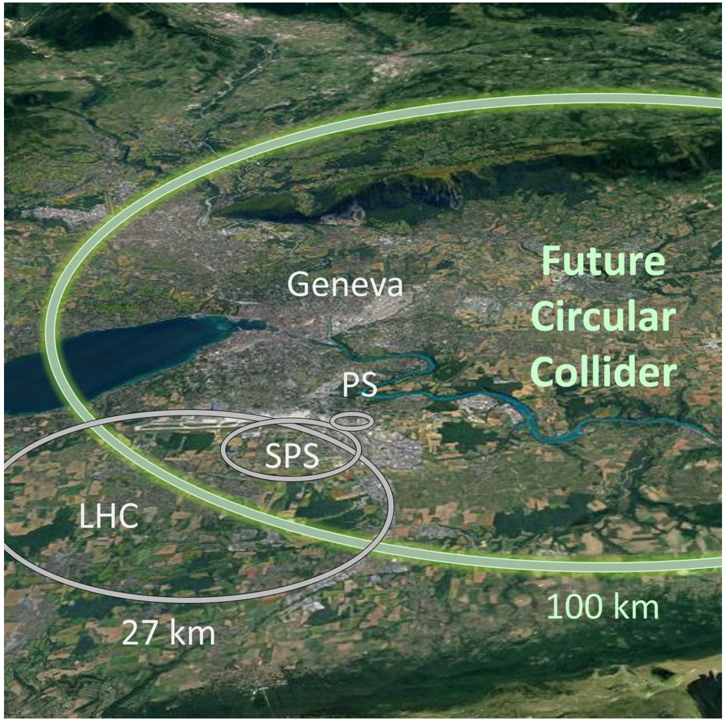
- Next-generation colliders → higher luminosities & data rates
- New techniques → QML
- CV-QML

  → natural compatibility with continuous data

  → highly non-trivial correlations

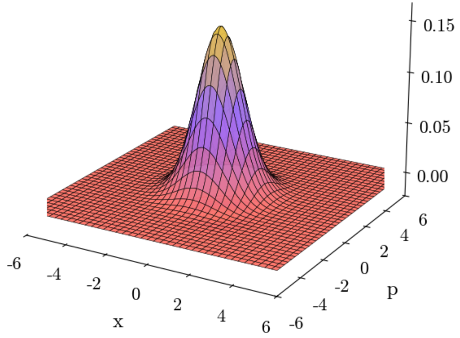
  → picosecond inference times*

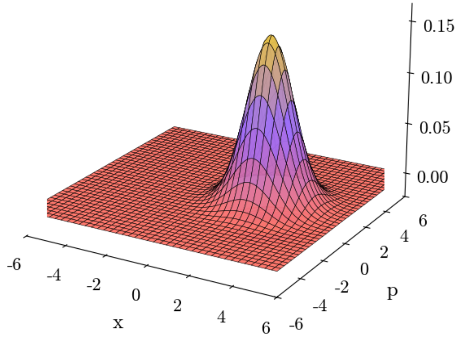
  → room temperature operation*



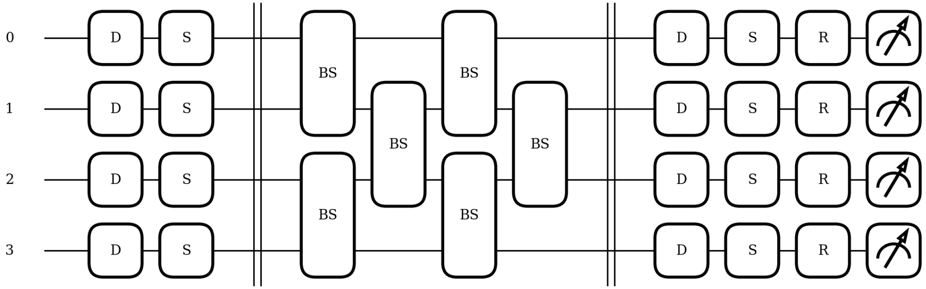
CV-QML

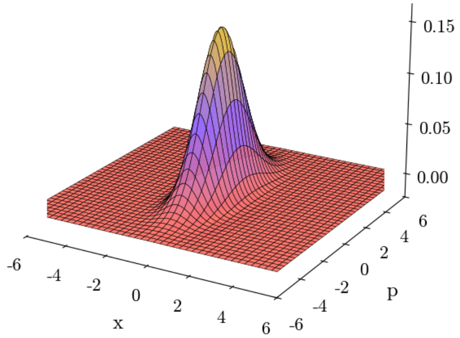
- Qumode → CV analogue of qubit
  → quantised continuous degree of freedom (QHO)
  → Fock states | x, p quadratures





- Circuits → unitary evolution of qumodes (wires)
  → displacement, squeezing, rotation, beamsplitters
  → homodyne, heterodyne, PNR





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Investigation

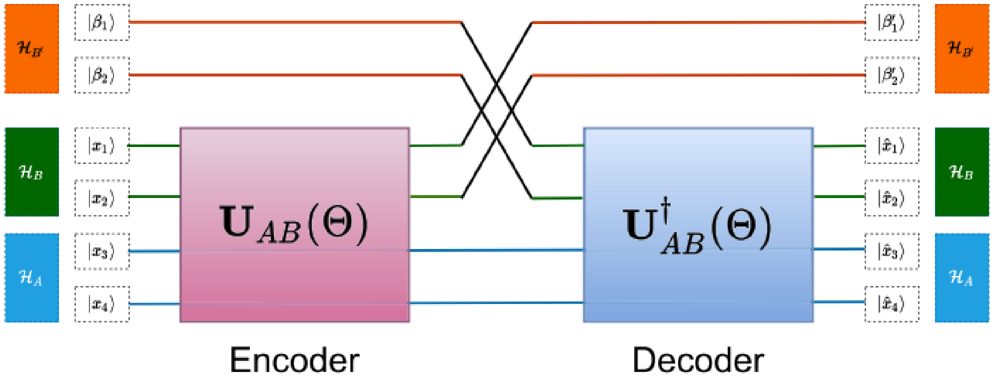
- Test → **anomaly detection** (CV autoencoder)
  → **jet classification** (CV classifier)
  → classical reference neural nets

- Data → heavy-flavour jets ($t\bar{t}$) vs qcd jets (Z → $\nu\bar{\nu}$ + jets)
  → eta, pt, phi (↓ pt_{frac})
  → 100 constituents x 230k jets

- Reason → benefits seen in similar tasks for qubit-based devices
  → CV devices offer additional strengths

CV Autoencoder

- Unitary → dimension preserving
- Latent + trash → latent + vacuum
- Encoder-only training
- Maximise trash-vacuum overlap



Source: Ngairangbam, Spannowsky, Takeuchi (2022), *Anomaly detection in high-energy physics using a quantum autoencoder*

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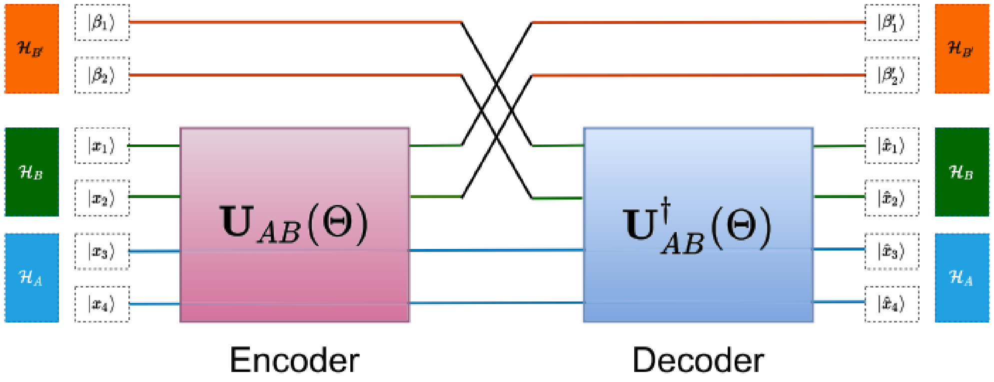

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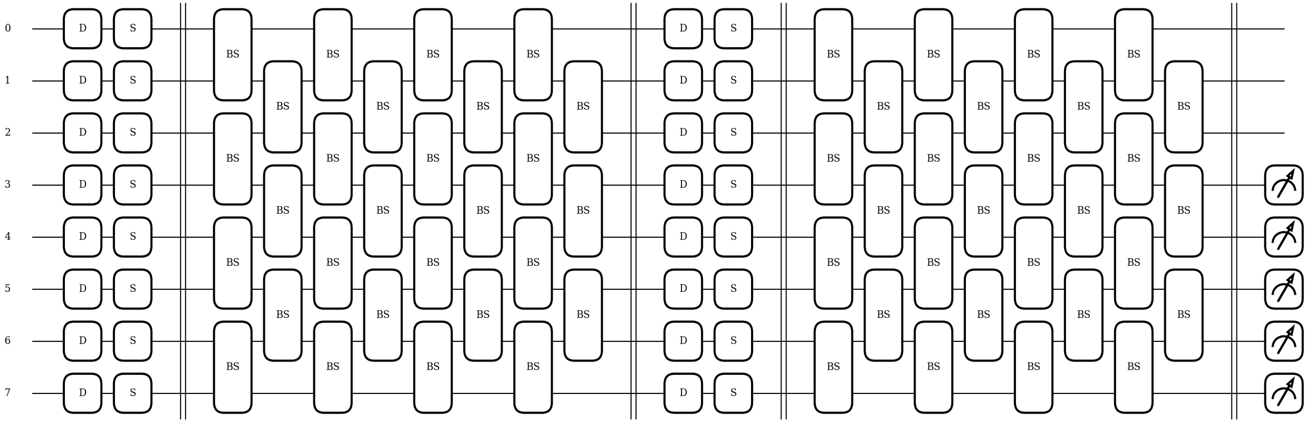
- Structure



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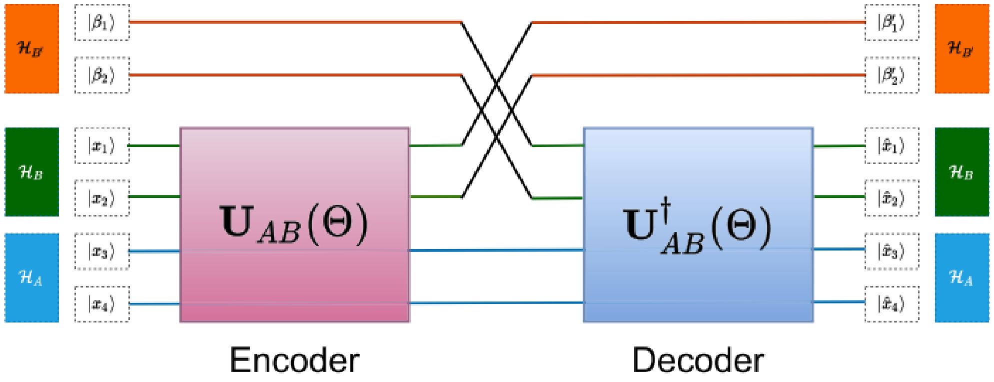

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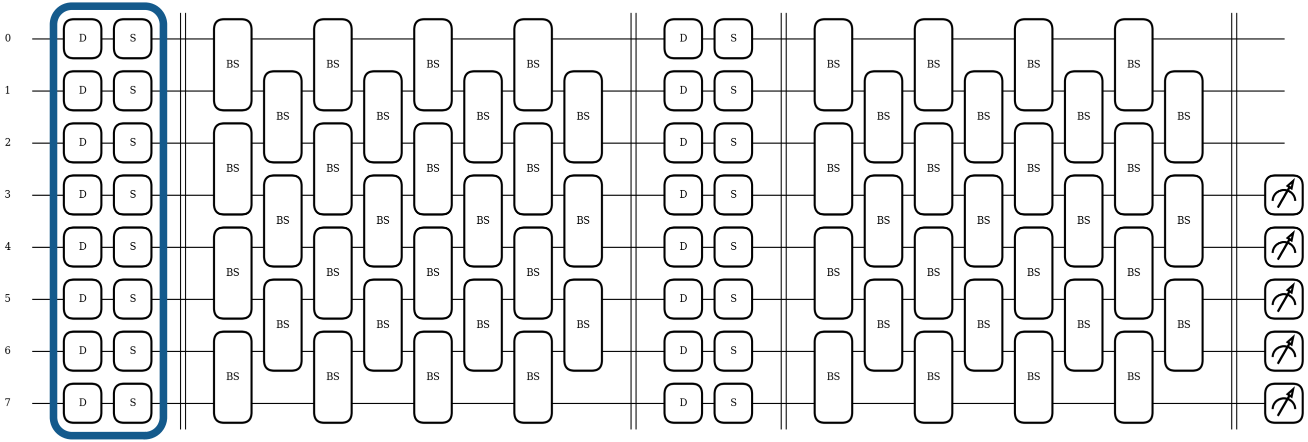
- Structure

  → 1P1Qm encoding



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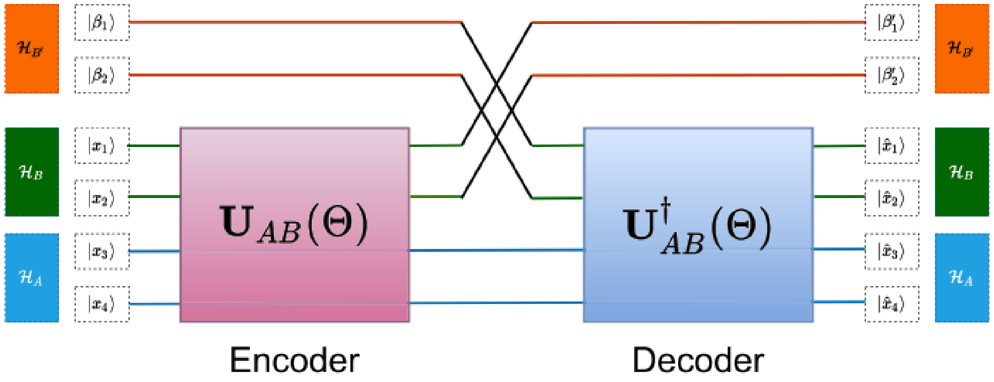

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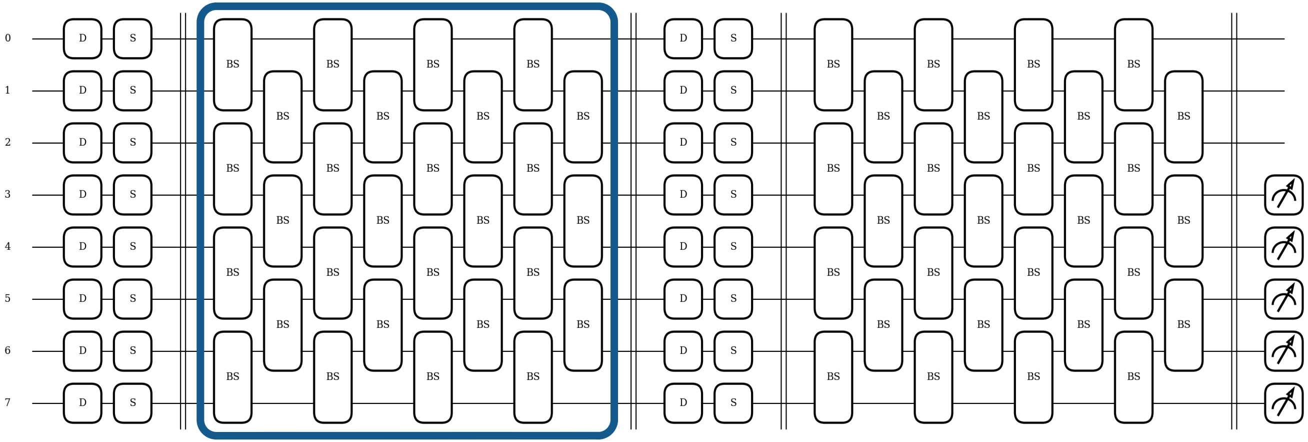
- Structure
  - → 1P1Qm encoding
  - → BS substrate



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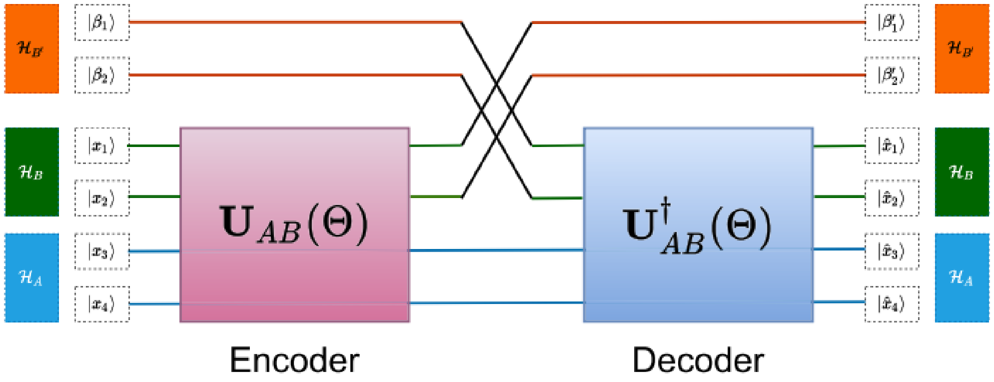

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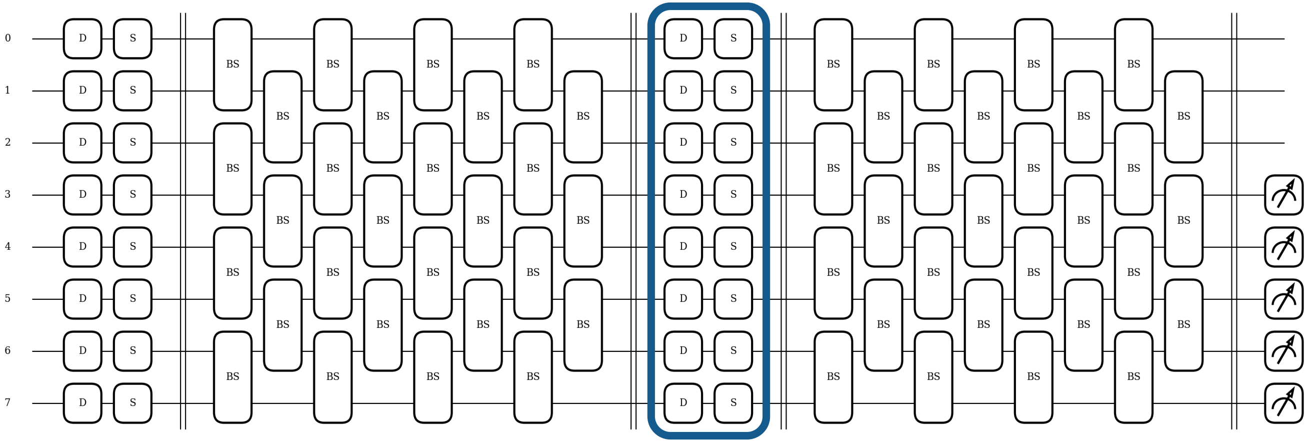
- Structure
  - → 1P1Qm encoding
  - → BS substrate
  - → Local gates



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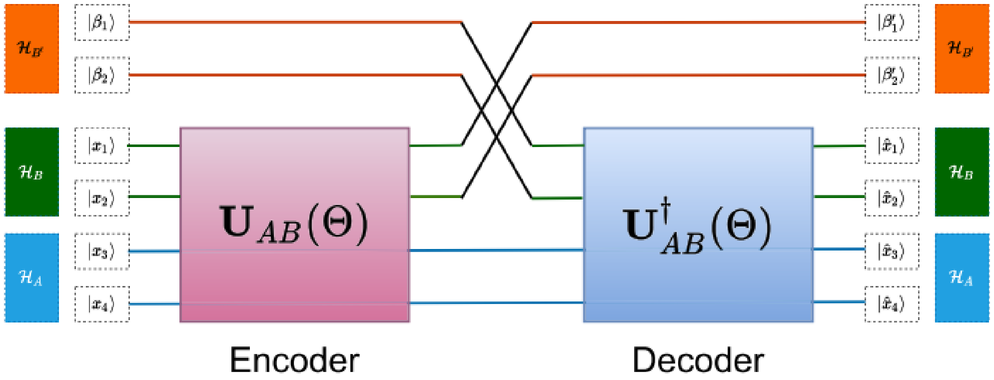

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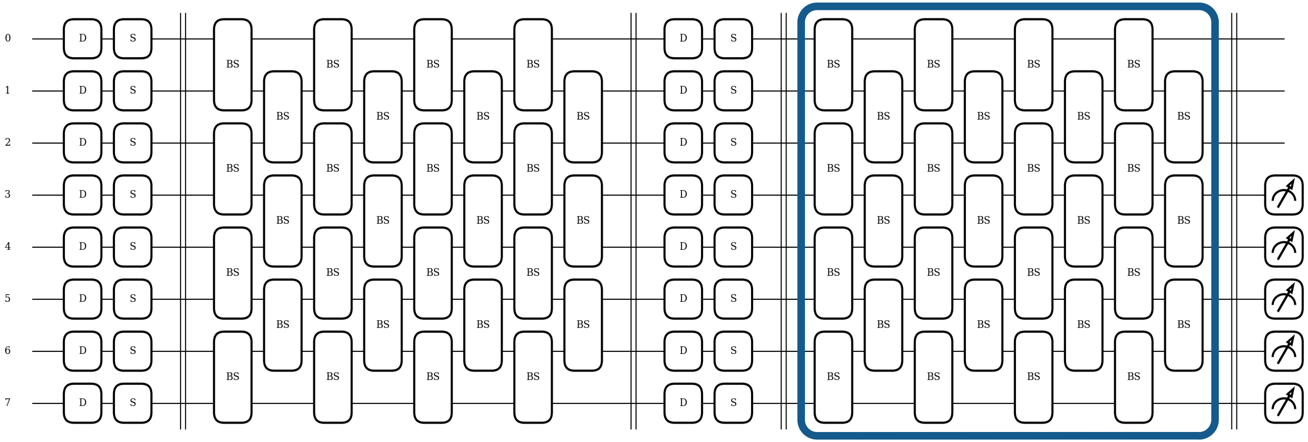

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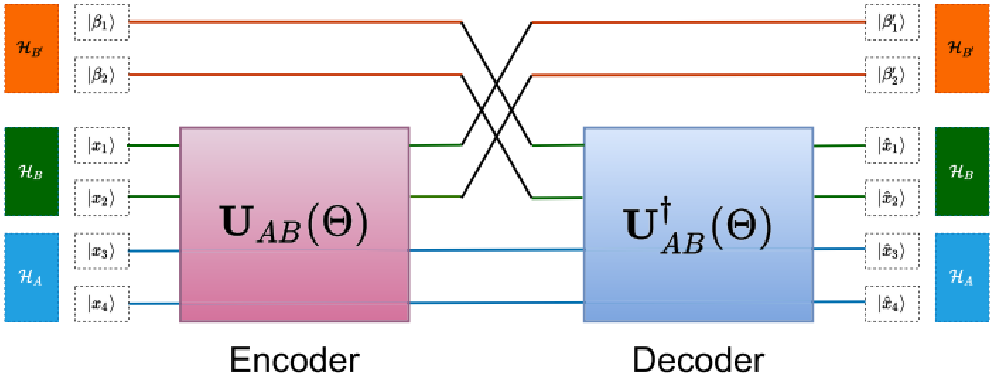

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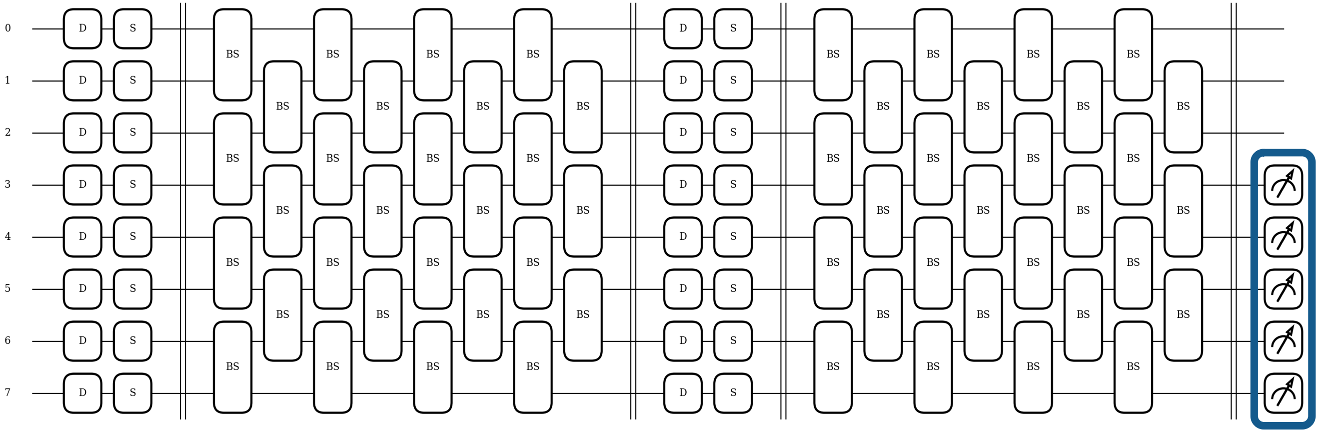
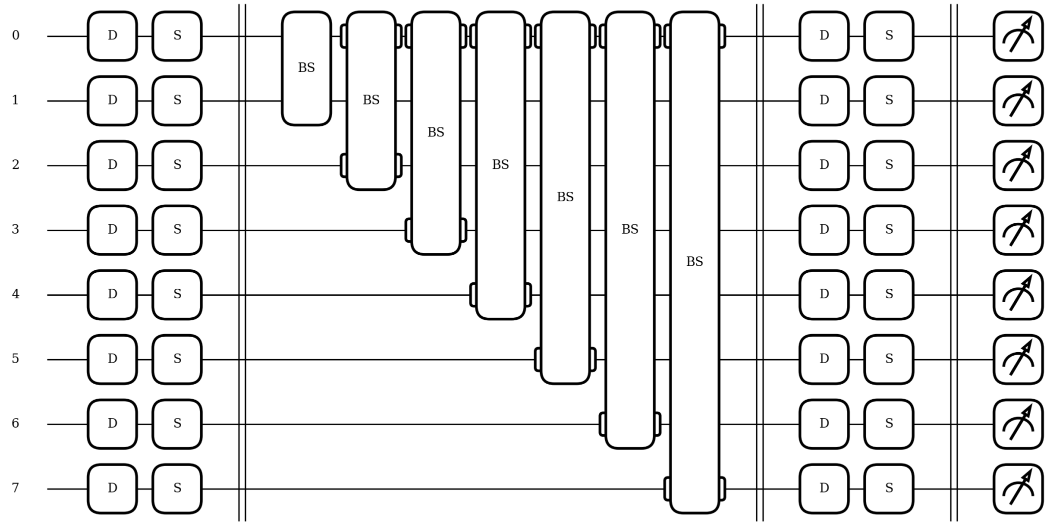
- Structure
  - → 1P1Qm encoding
  - → BS substrate
  - → Local gates
  - → BS substrate
  - → Measurement (trash)



CV Classifier

- Vacuum-fidelity
  → Background to vacuum
  → Signal away

- Structure



CV Classifier

- Vacuum-fidelity
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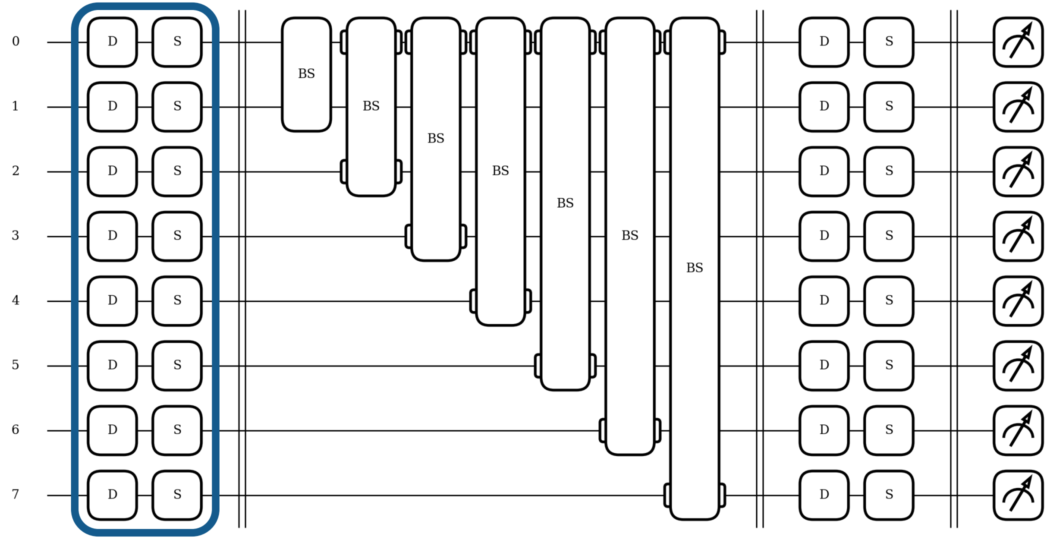
  → 1P1Qm encoding



CV Classifier

- Vacuum-fidelity
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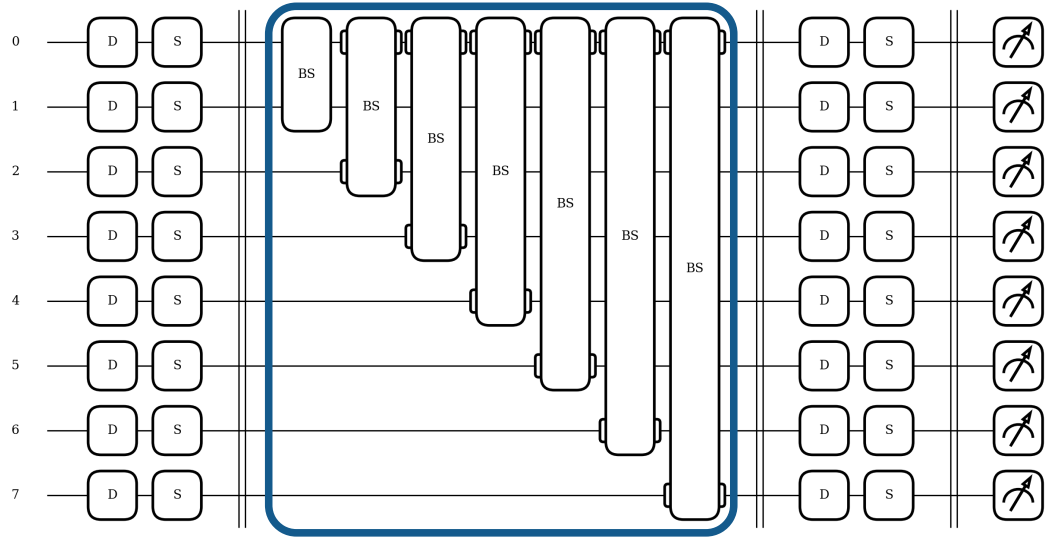

CV Classifier

- Vacuum-fidelity
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- Structure
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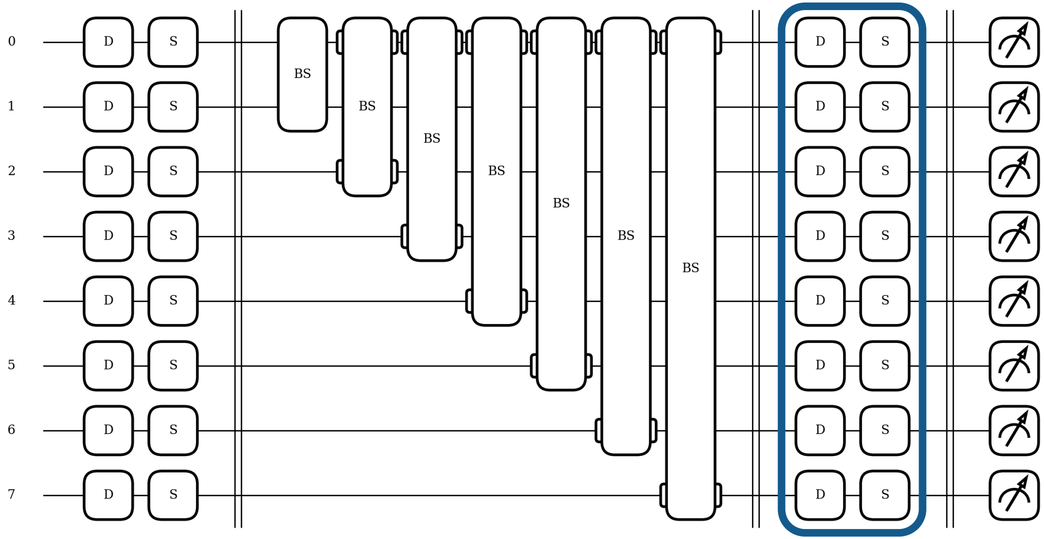
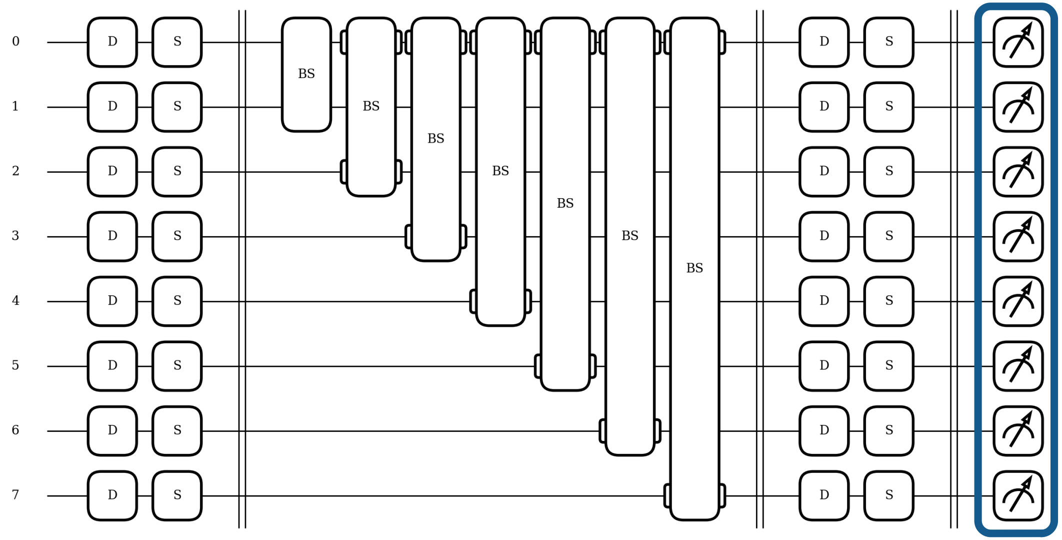
  → Local gates



CV Classifier

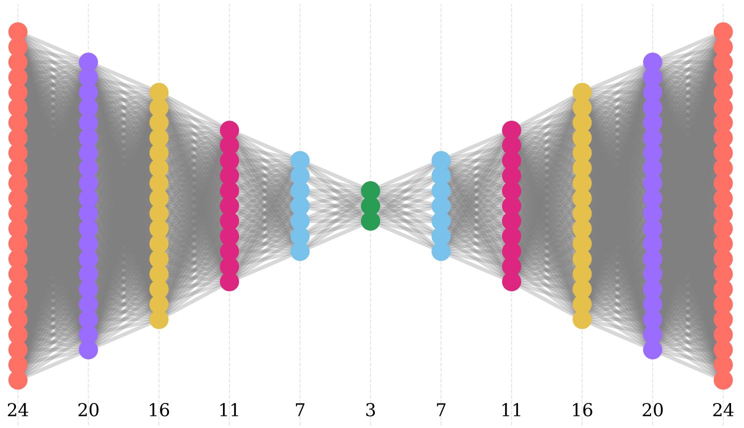
- Vacuum-fidelity
  - → Background to vacuum
  - → Signal away

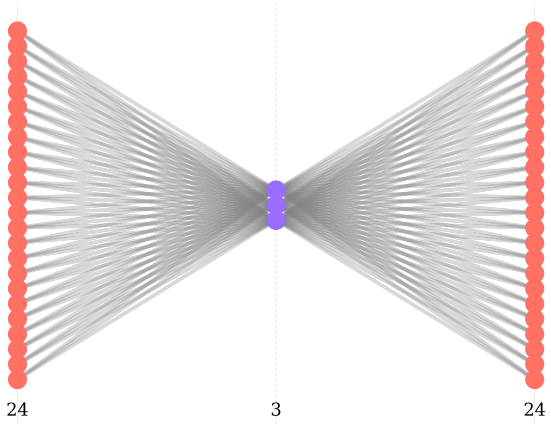
- Structure
  - → 1P1Qm encoding
  - → BS substrate
  - → Local gates
  - → Measurement (all)



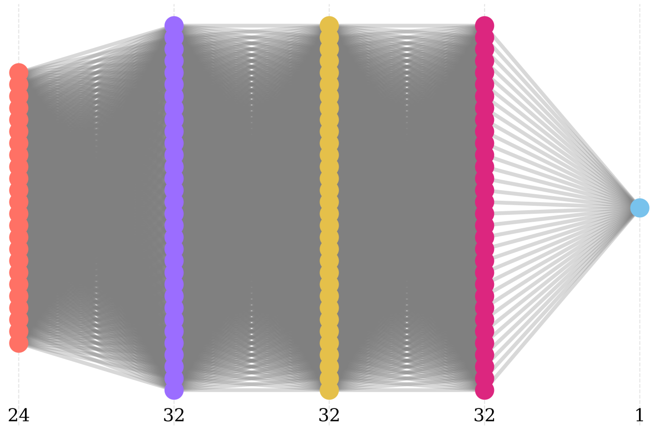
Classical Reference Models

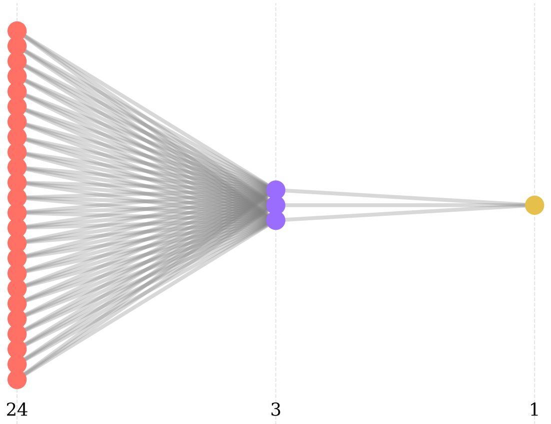
Autoencoder





Classifier





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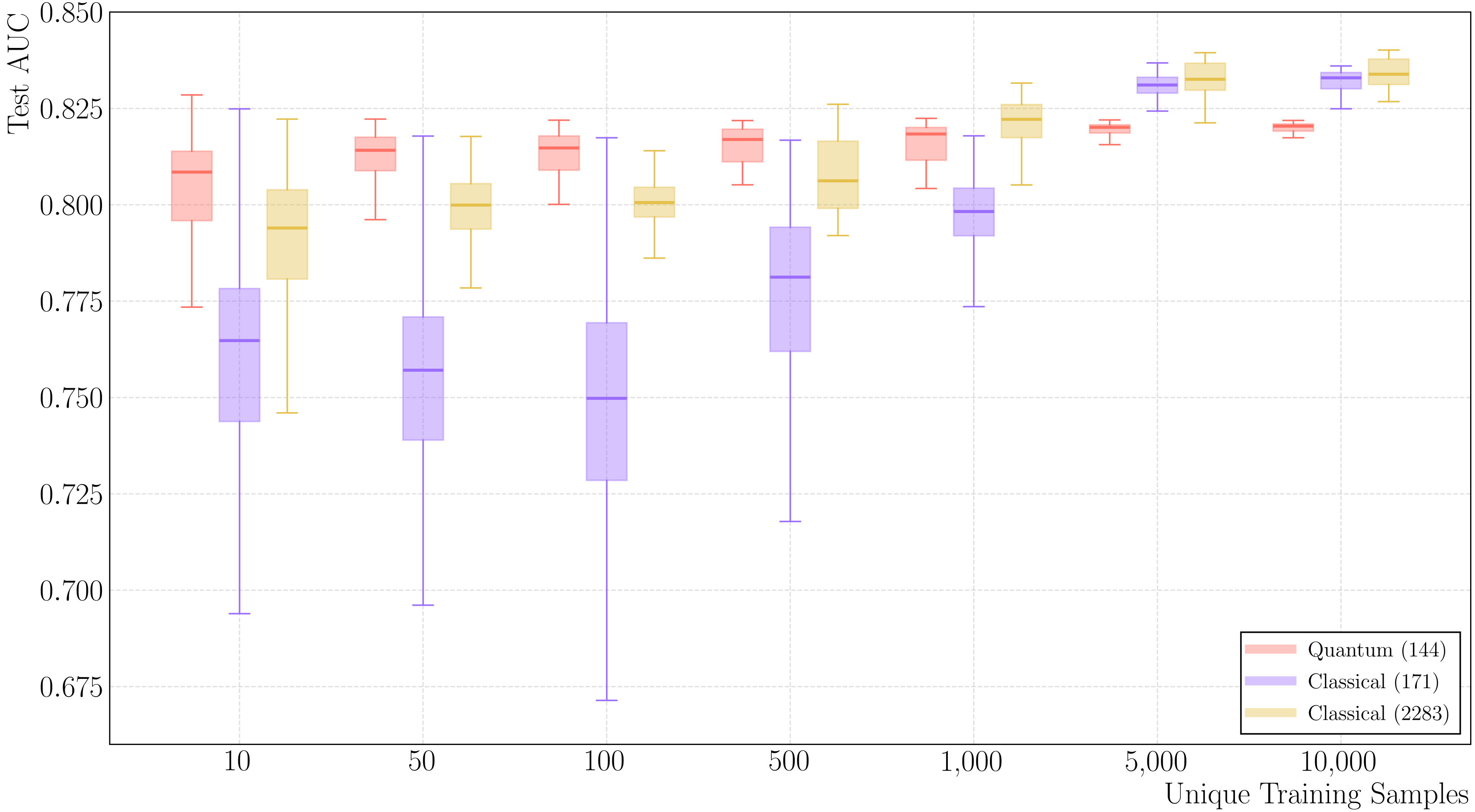
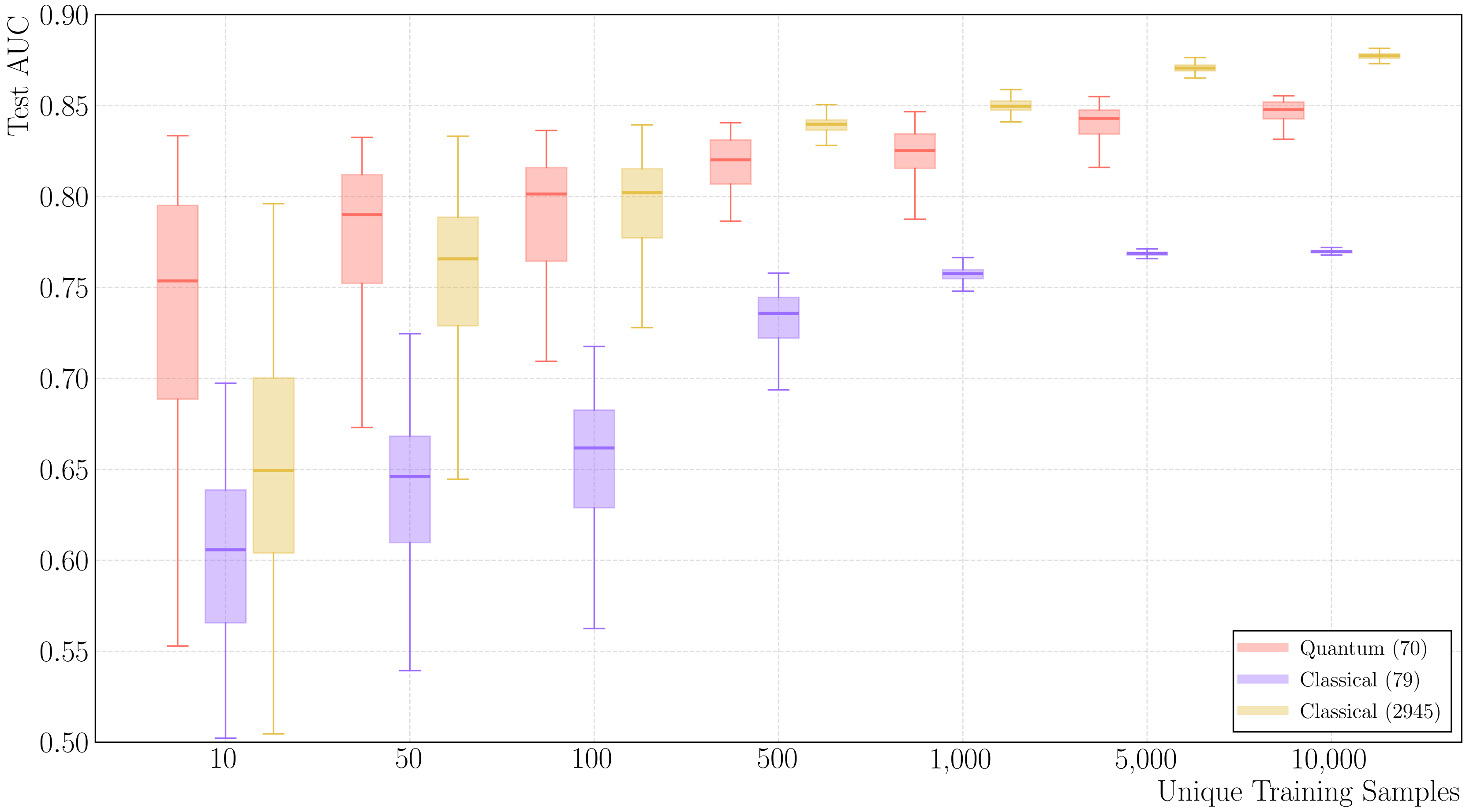
Quantum Vs Classical - Unsupervised



Quantum Vs Classical - Supervised



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Summary & Future

- Anomaly detection and classification
- CV-QML potential
  → Outperform classical reference models (low-data regime)
  → Substantially fewer parameters
- Future → measurement hardware → full picosecond/room temp inference
- Paper coming soon!