Quantum Track Reconstruction Algorithms for non-HEP applications

Kristiane Novotny

TIME SAVING · KNOWLEDGE OVERVIEW · UNEXPECTED INSIGHTS

Outline

Particle and airplane track reconstructions

Quantum Graph Neural Network approach

Summary

★ **Particle and airplane track reconstructions**

- Motivation
- Aim of track reconstruction with airplanes
- Similarities

★ **Quantum Graph Neural Network approach**

- Hybrid Network Structure
- Tests with Circuits

★ **Summary**

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Motivation - Algorithms pave their way into society

Similarities
- Dedicated flight paths
- Difference: particle physics would like to have collisions, aviation industry not

Huge amount of data
- Huge amount of data expected during HL-LHC run
- Huge amount of data coming from air traffic (increase of regulations for drones and aircrafts)

Object Identification
- Possibility of Identifying airplanes via unique transponder
- Identification of hits possible in detectors

R&D study topic
- Collaboration between gluoNNet, CERN openlab, METU, researchers from DESY and Caltech
- Use of novel techniques, such as Quantum computing

Aim of track reconstruction with airplanes

Improvement of flight safety

- Better prediction of emergency situations
- Emergency situations recommendations
- Incident tracking

Anomaly detection

- Detection of unusual behaviour based on flight paths
- Identification of areas of unusual behaviour (e.g., crisis regions, regions affected by weather)

Environmental aspects

- Recommendation of best possible flight path according to data
- Reduction of carbon footprint

Improvement of cost & efficiency

- Reduction of fuel consumption
- Improvement of airport capacity
- Huge amount of data to be expected (e.g. increasing use of drones and ADS-B sender)

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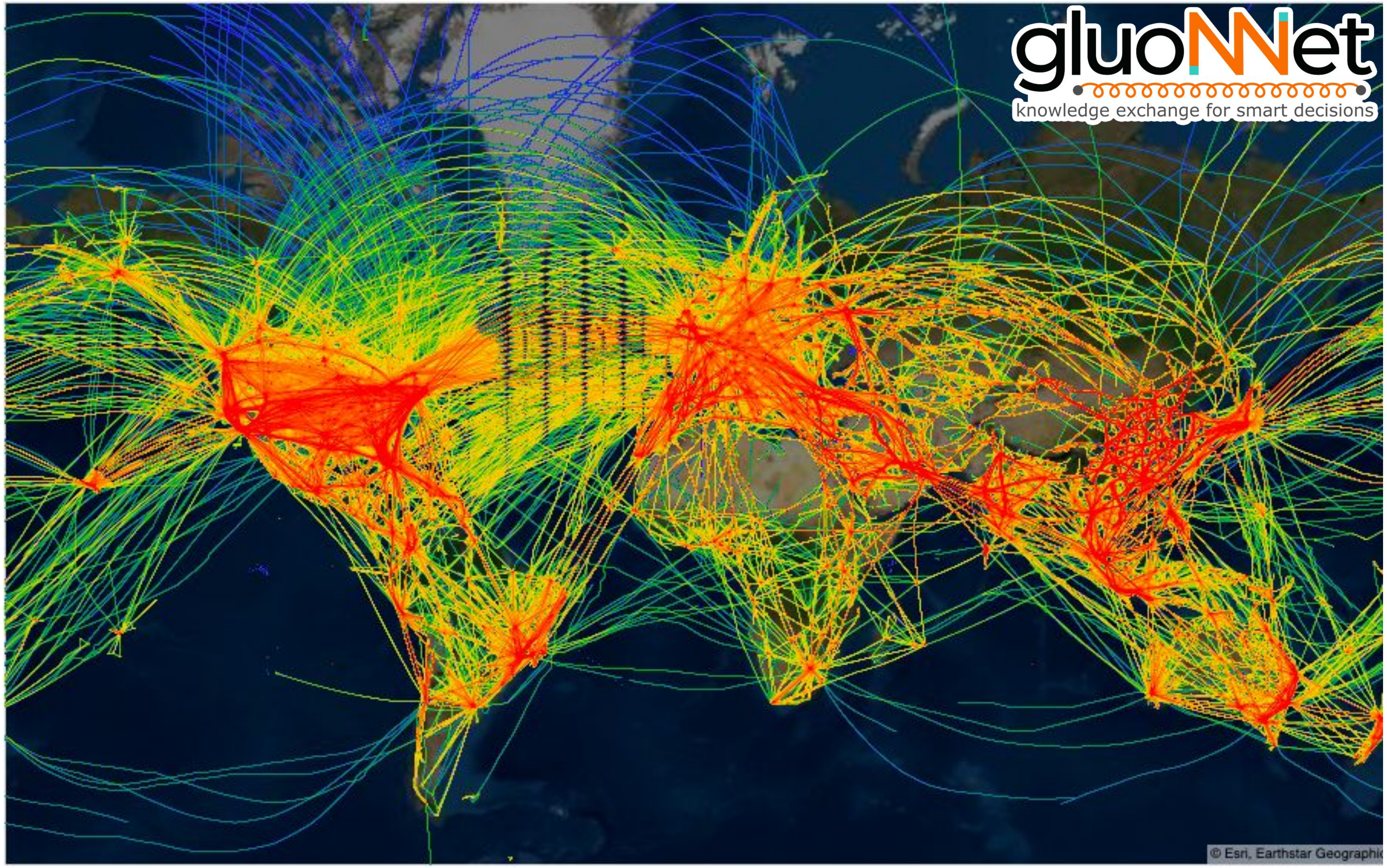
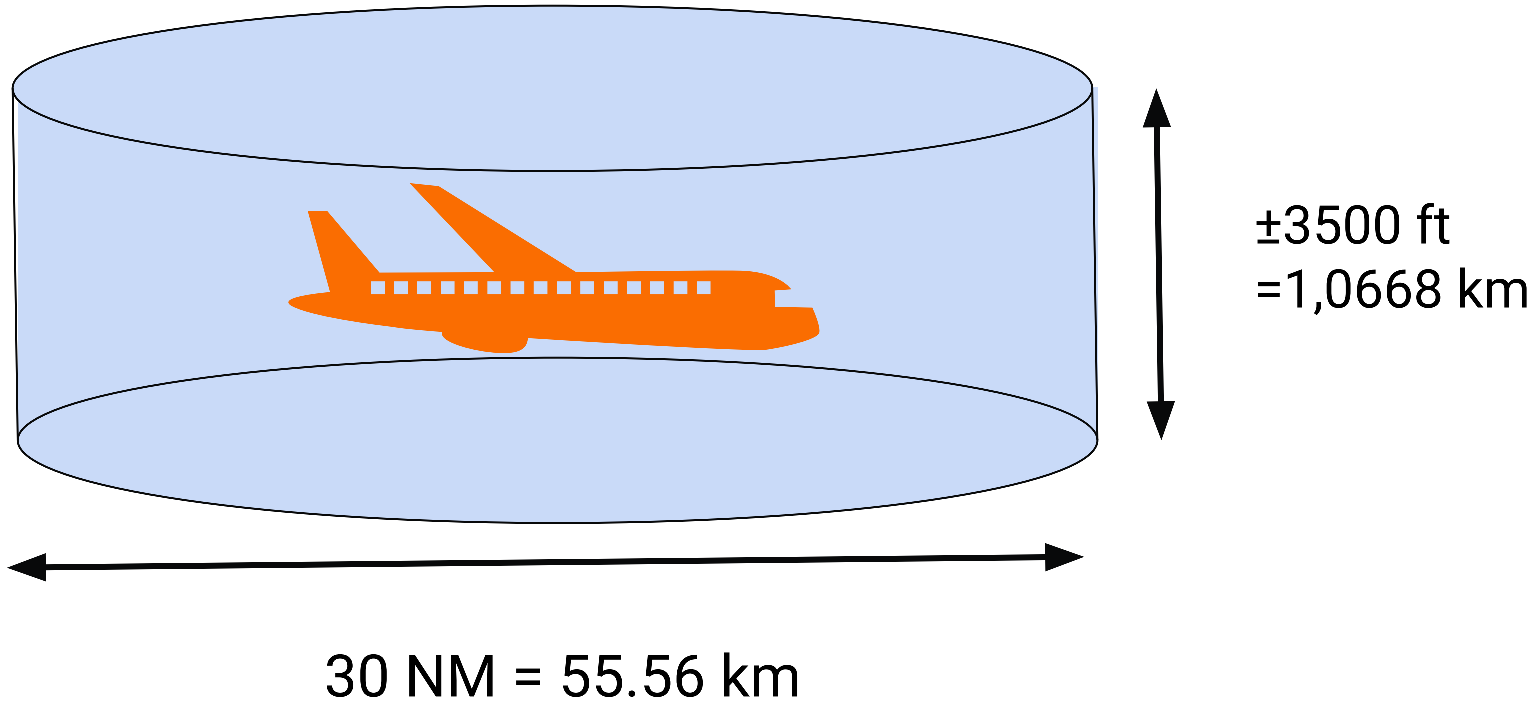
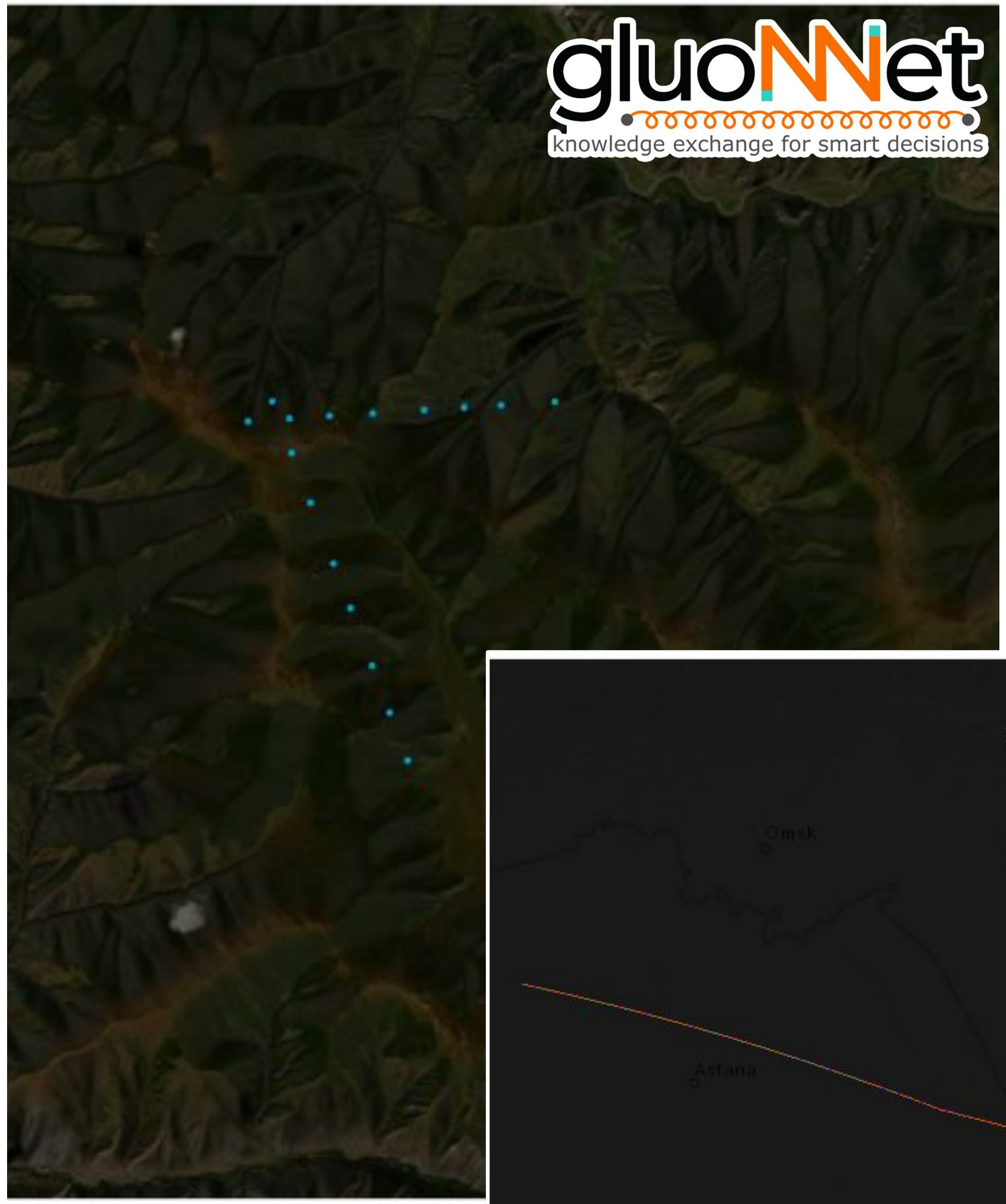
Air traffic during one day in April 2019



TCAS Analysis April 2019 16.04.2019



- TCAS = Traffic Collision Avoidance System
- TCAS is a collision warning system recommending the optimal flight path for avoiding a collision
  - mandatory after crash of two airplanes
- TCAS alerts are raised within a “Hockey puck” having a diameter of 55.56 km and a height of 1 km during cruise.
- During April 2019: 0.015% of total data corresponded to TCAS events



TCAS Analysis USA April 2019 01-30.04.2019

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Similarities in particle and airplane track reconstructions

Particle physics

- Detector hit
- Event Id
- Particle Id
- Edge
- Node

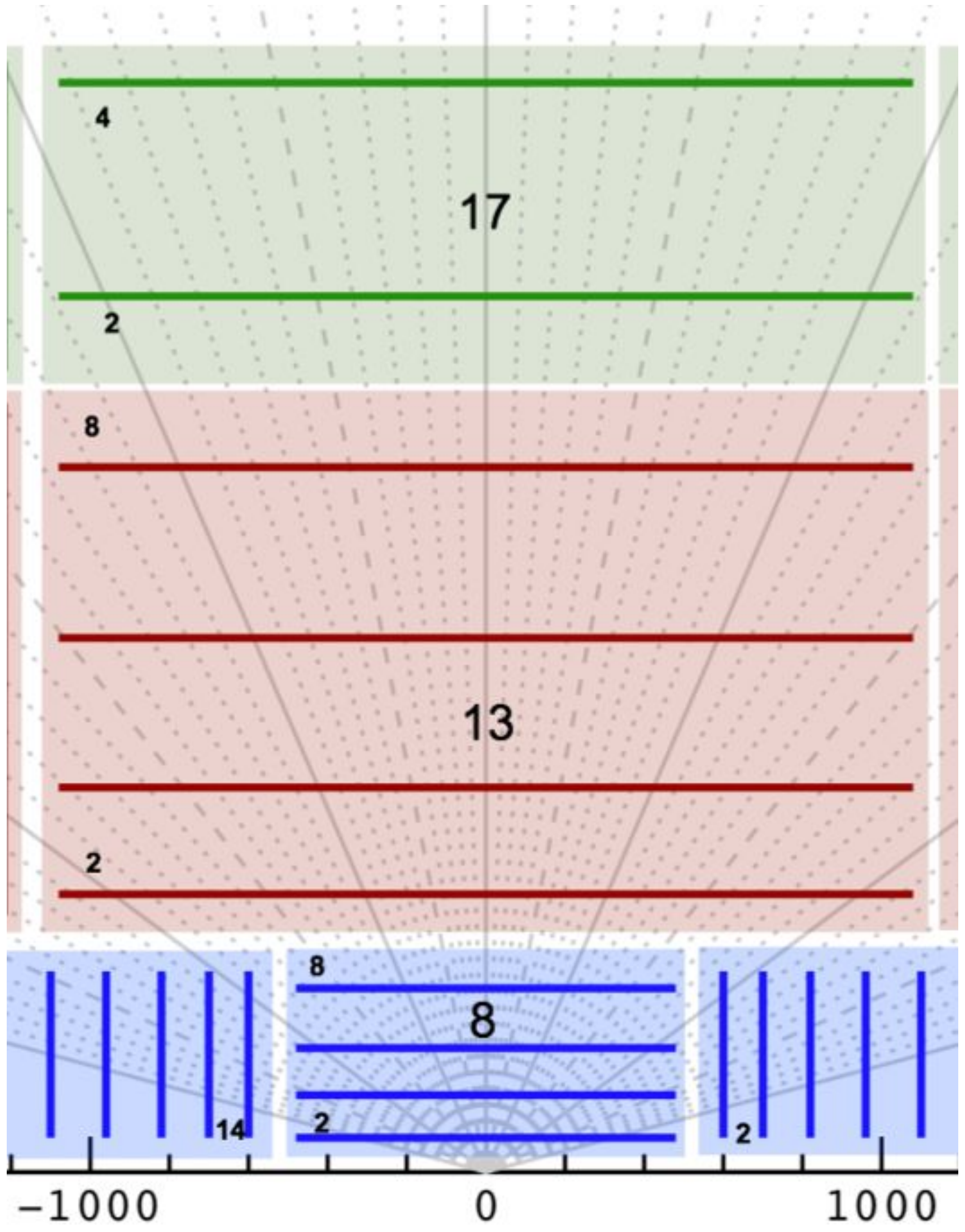
Airplanes

- Timestamp with position
- Id of airplane transponder
- Airplane type (e.g., A380, Boeing 737)
- Distance between two airplanes
- Airplane

TrackML challenge data as benchmark check for performance

https://www.kaggle.com/c/trackml-particle-identification/overview

- Ingested data for better comparison between underlying circuits and architecture of the network
- Focus on Barrel region



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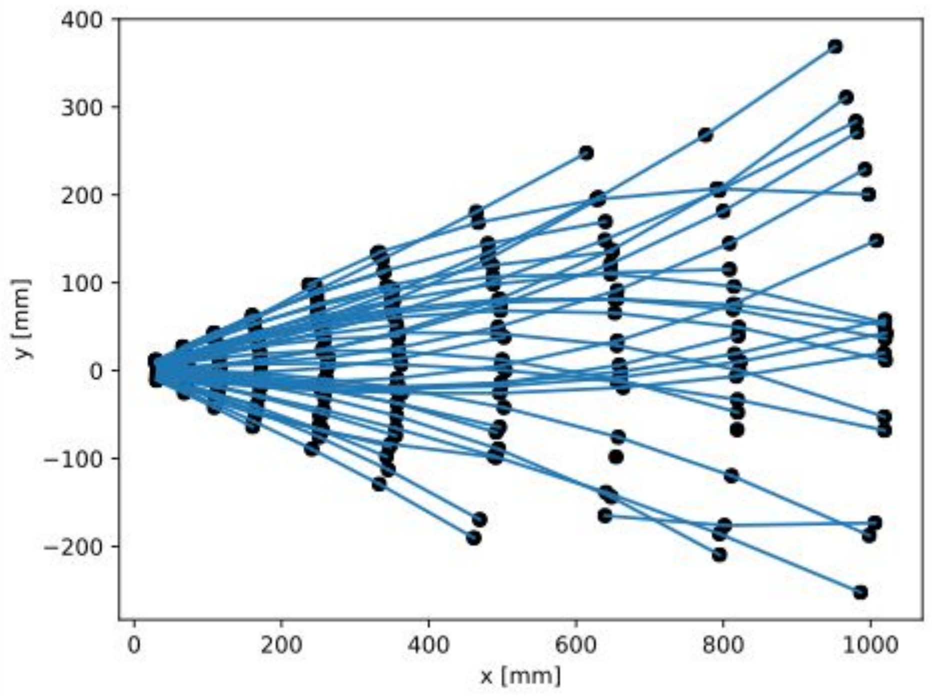
TrackML challenge data as benchmark check for performance

- 100 events are considered due to huge amount of processing time (15 qubits)
- 1 % of total TrackML events
- Division of events into 8 segments in η and two segments in z direction
- lower line: test of quality of data

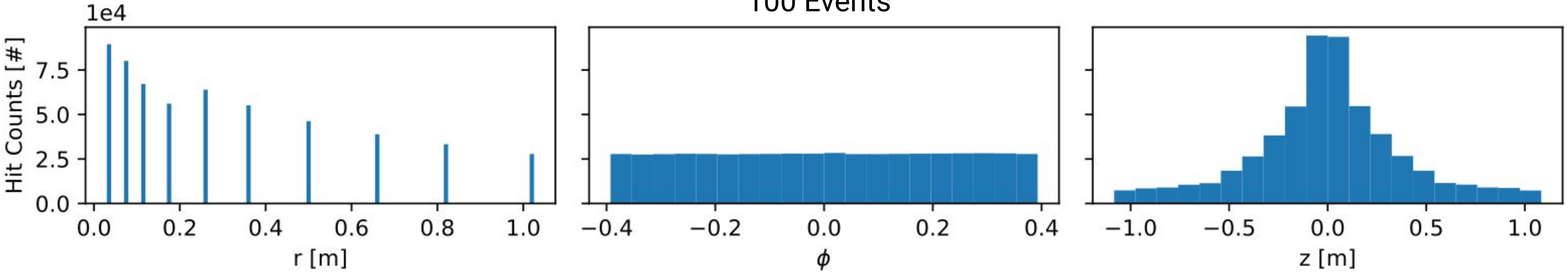
Applied cuts

$\|pT\|$	> 1 GeV
$\Delta\phi/\Delta r$	< 0.0006
z_0	< 100 mm
η	[-5, 5]

Example Graph



100 Events



plots by C. Tüysüz

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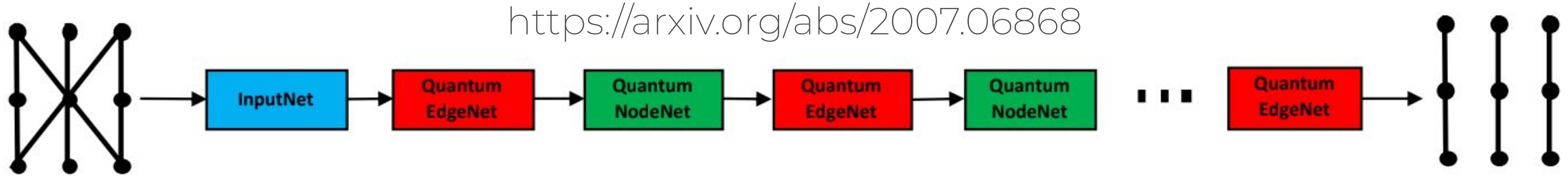
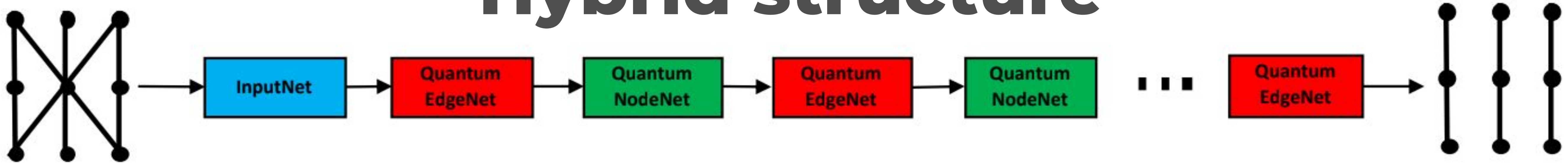
Quantum Graph Neural Network approach

https://arxiv.org/abs/2007.06868



- Joint collaboration between CERN openlab, Middle East Technical University of Ankara, and researchers of DESY and Caltech
- Study if its possible to reconstruct particle tracks using quantum computing techniques
  - Currently, classical machine learning techniques are sufficient for the amount of data in both particle physics and aviation
  - situation might change due to HL-LHC and possible FCC in particle physics and due to the increase of drone usage in aviation
- Hybrid model of classical GNN with quantum circuits
- Study with different circuits
- Application outside HEP: Integration of flight data
- Applications to other areas of society possible, e.g. poster by S. Hamm, ID 981 for sustainable finance or by D. Dobos/A.Martini, for analysing financial transactions to end violence against children

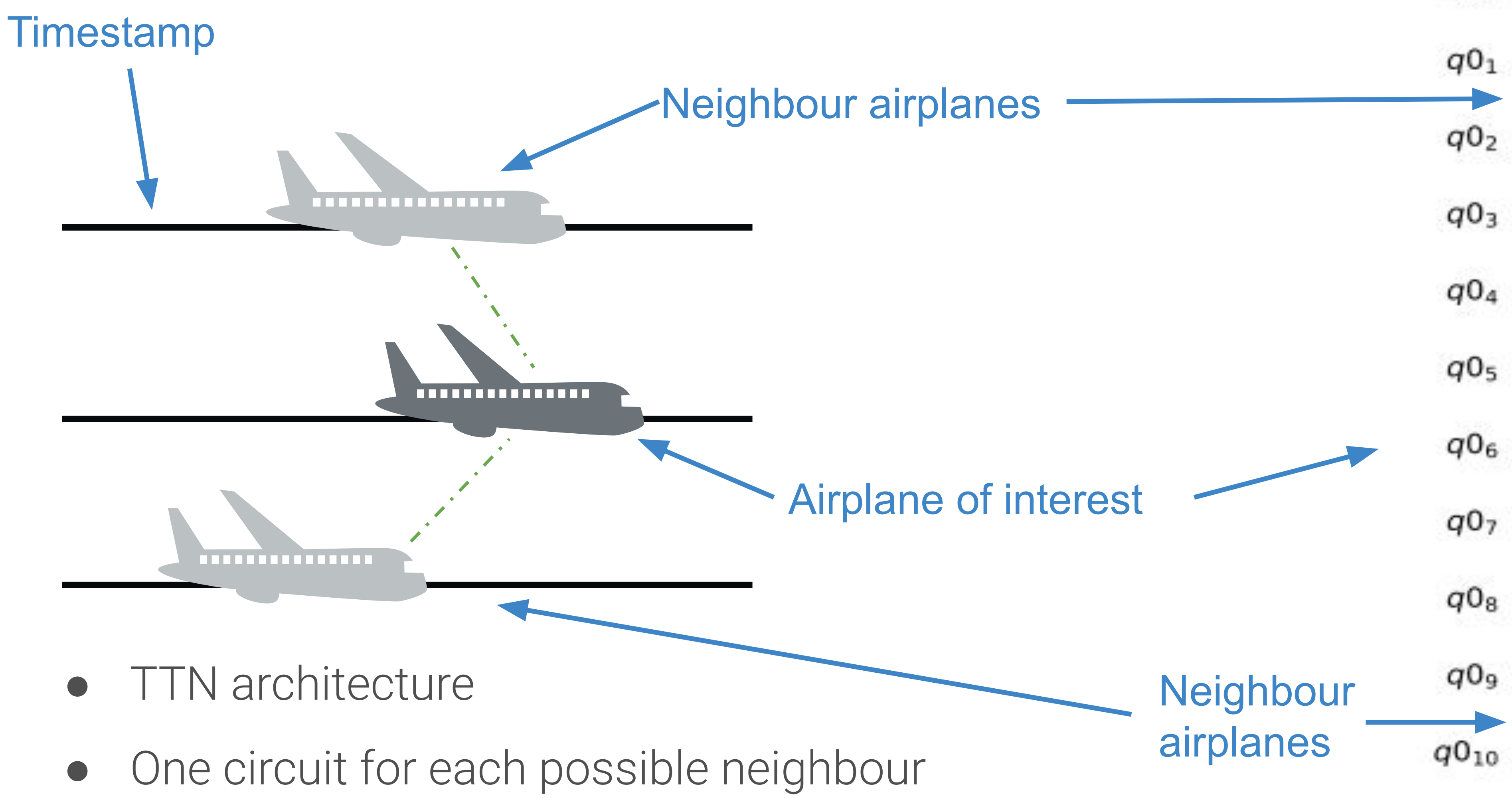
Quantum Graph Neural Network
Hybrid structure

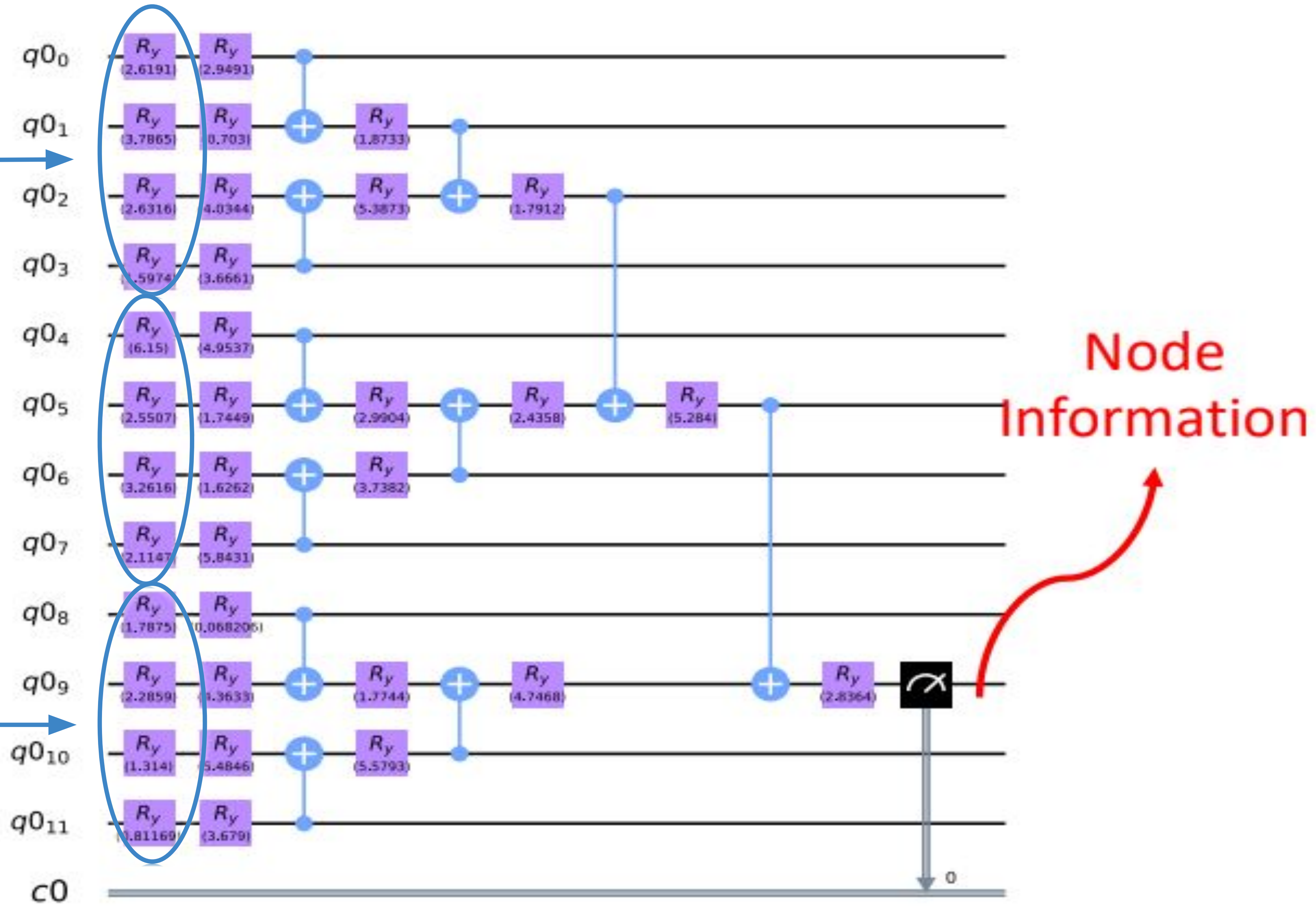


- Application of Input Neural Network
- Iterative application of Quantum Node Net and Quantum Edge Net
- Quantum Edge Net:
  - Classical Edge net: Reduction of Input Number of hidden dimensions to number of circuit parameters
  - Number of qubits corresponds to dimensions of Output layer
  - Application of arbitrary Quantum Circuit
  - Output ingested to Quantum Node Net
- Quantum Node Net:
  - Classical Node Net: Reduction of Input Number of hidden dimensions to number of circuit parameters
  - Application of arbitrary Quantum Circuit
  - Number of qubits corresponds to dimensions of Output layer
  - Output ingested to Quantum Edge Net

Quantum Neural Network approach
Node Neural Network
- current architecture

https://arxiv.org/abs/2007.06868





- TTN architecture
- One circuit for each possible neighbour
- Exact training due to knowledge of exact distance
- Good understanding of risk for collisions

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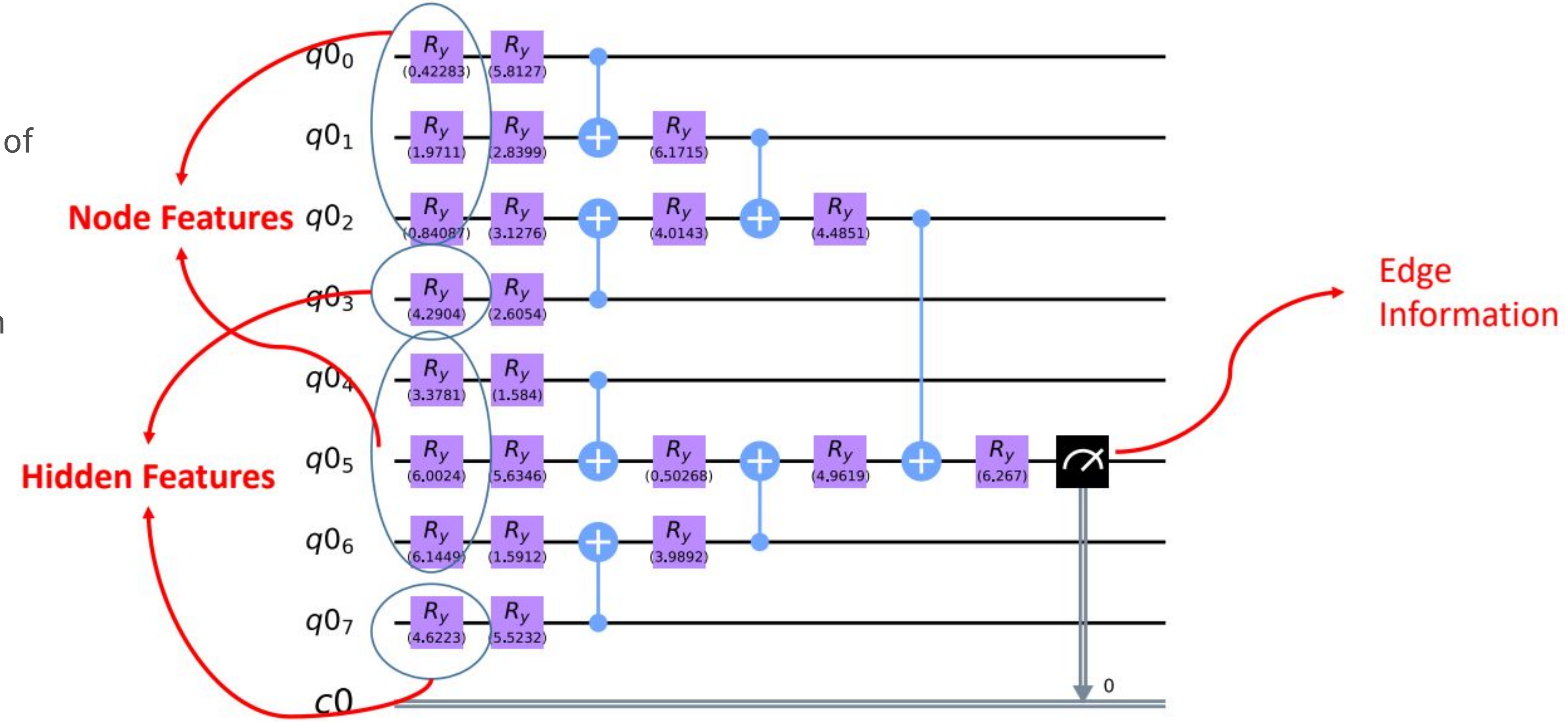
Quantum Neural Network approach
Edge Neural Network
- current architecture

https://arxiv.org/abs/2007.06868

- Additional qubits for increase of hidden dimension
- Classically: Hidden features correspond to hidden layers in Neural Net



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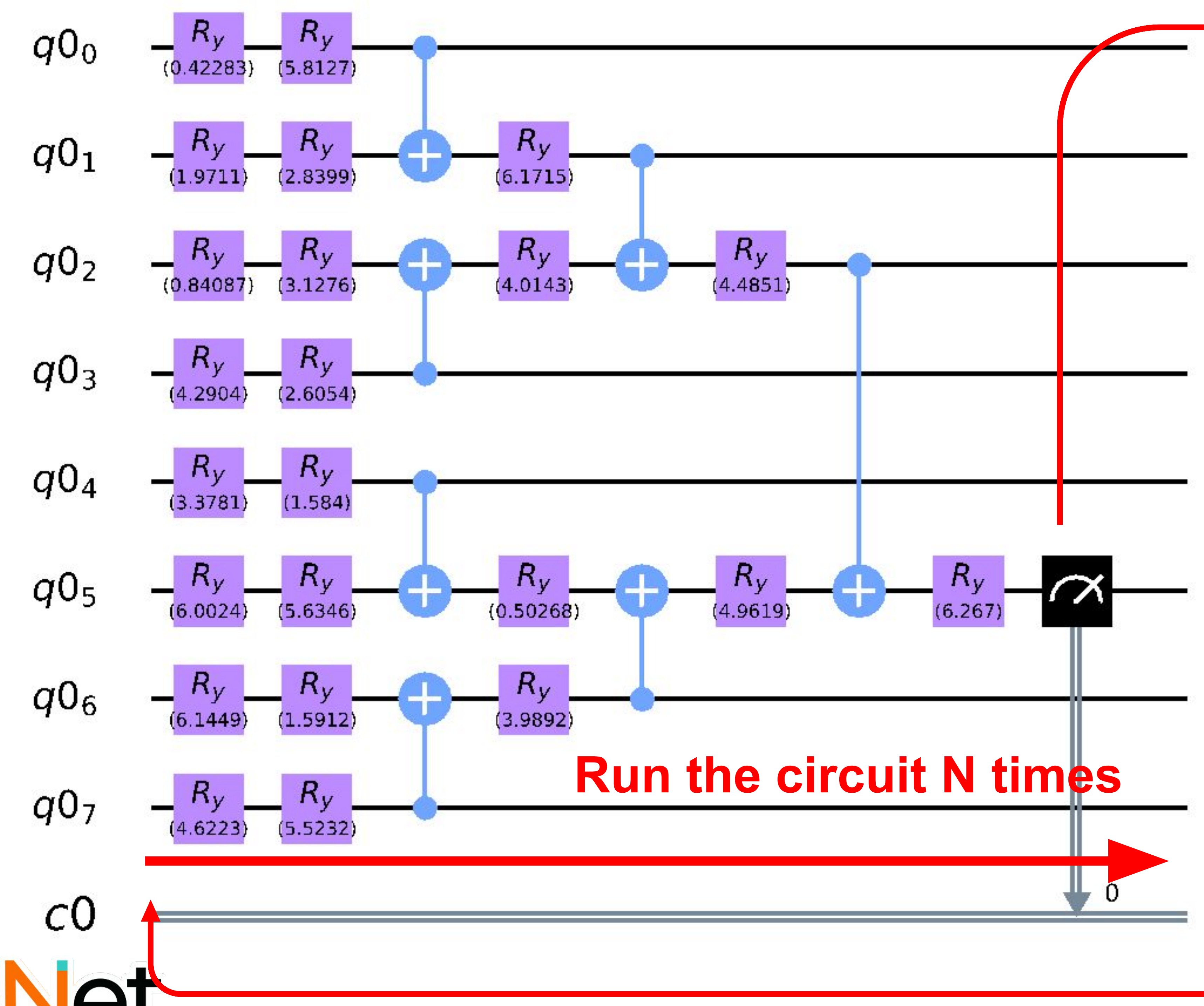
Quantum Neural Network approach
Network training

https://arxiv.org/abs/2007.08285



Averaging of measurement outcomes: edge probability.

Calculation of error from ground truth data.

Calculate the gradients of the parameters using parameter shift rule.

Update parameters $\boldsymbol{\theta} = \boldsymbol{\theta} - \eta \nabla_{\theta} \mathcal{J}(\theta)$

Repeat

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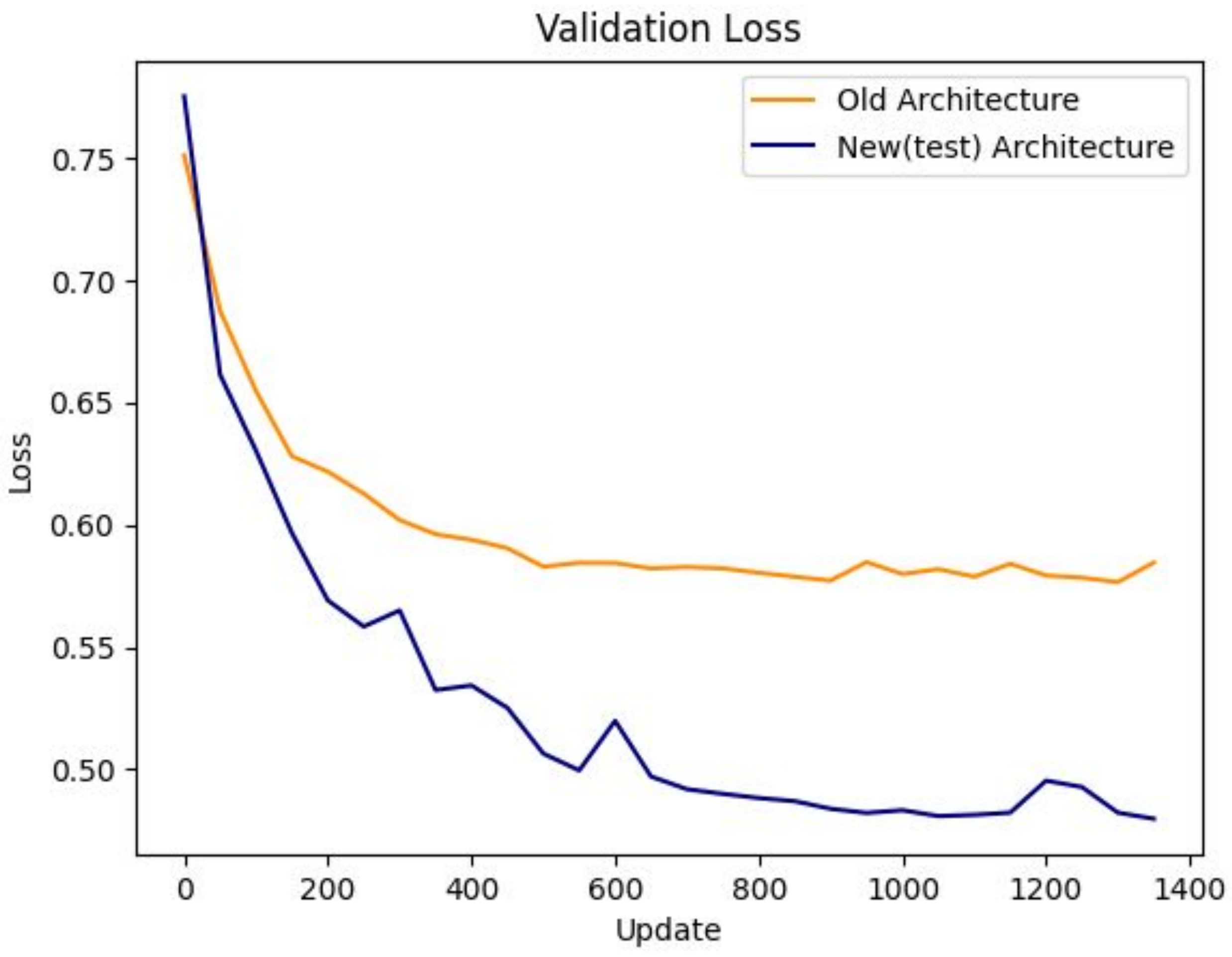
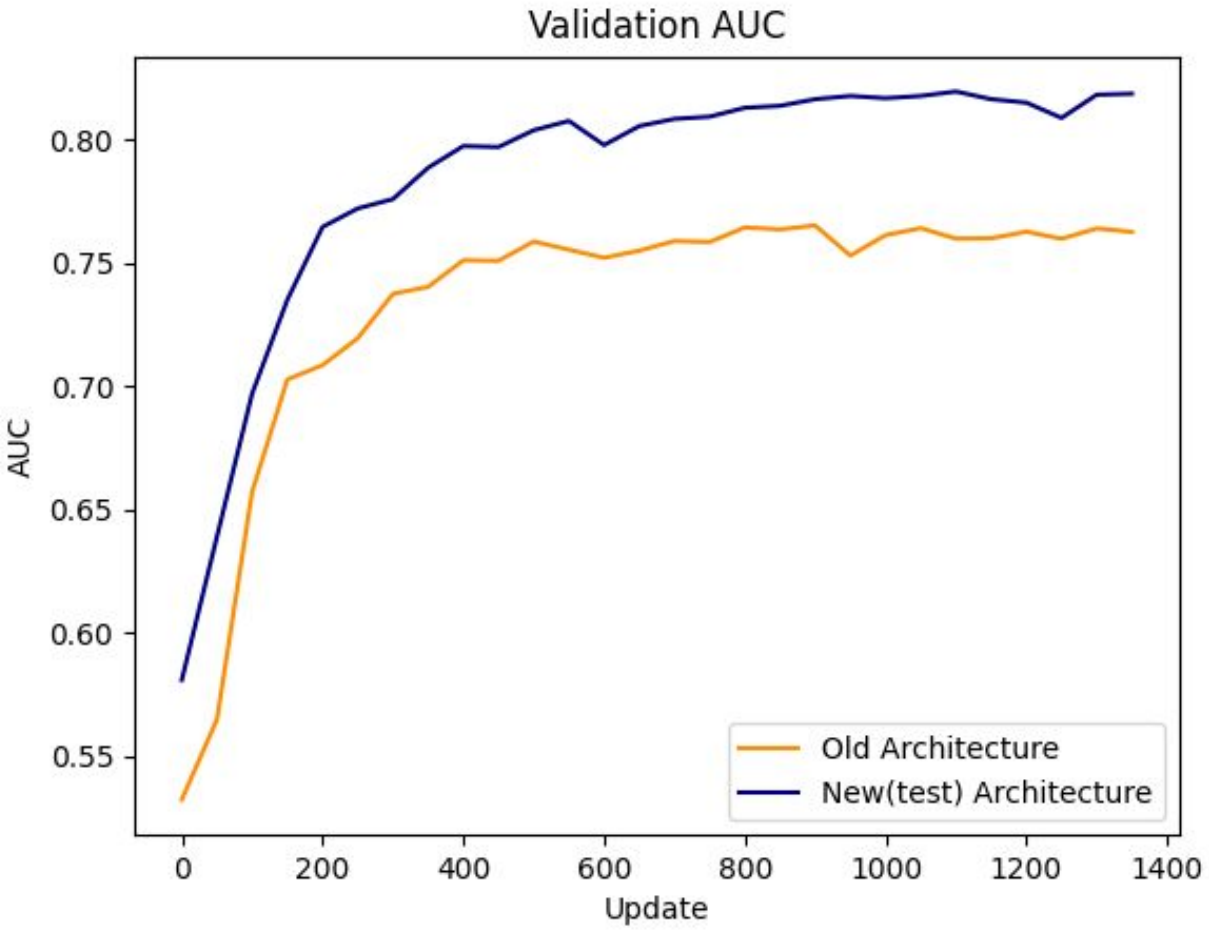
Quantum Neural Network approach
Network training





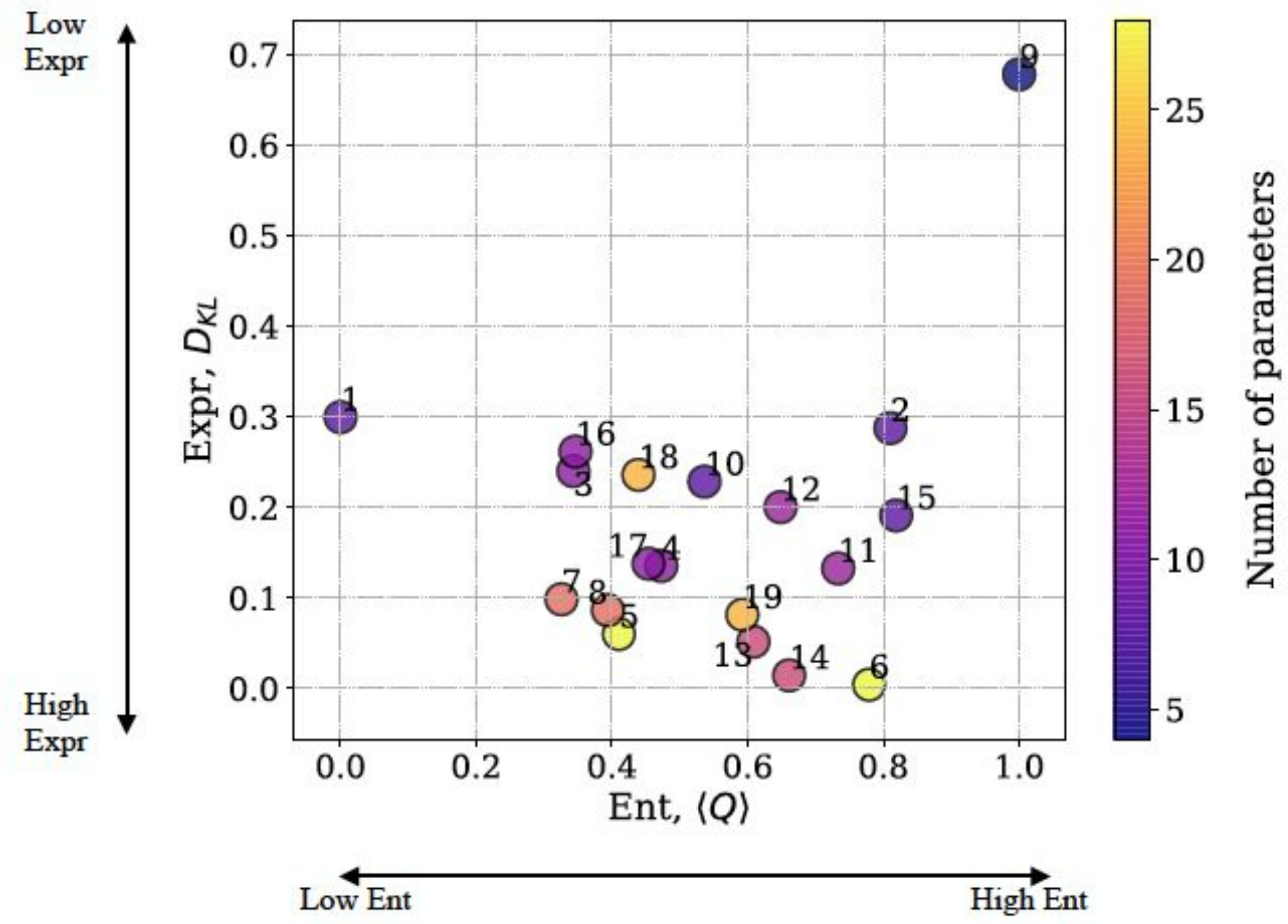
- orange: old version
- blue: new version, only one (direct) measurement
- AUC: measure for accuracy of different thresholds, perfect score for AUC = 1.0
- single epoch

- Training set: 1400 subgraphs, Validation set: 200 subgraphs, optimizer: ADAM,
  - learning rate for orange= 0.03,
  - learning rate for blue= 0.005
- Network requires smaller learning rate without having quantum circuit parameters

plots by C. Tüysüz

Current work

Circuit performance



https://arxiv.org/abs/1905.10876

High expressibility can lead to a performance increase

- Test performed with 4 qubits
- Use of circuits #6, #11, #14, #15 of https://arxiv.org/abs/1905.10876
- MERA and TTN with 4 qubits
- 5 Epochs used
- Learning rate is small - not surprising for a GNN https://arxiv.org/pdf/2003.00982.pdf
  - Gated GCN Needs at least 66 epochs for Node Classification and 96 epochs for graph classification (p.6, Tab.2)
- Goal: Extension to at least 8 qubits

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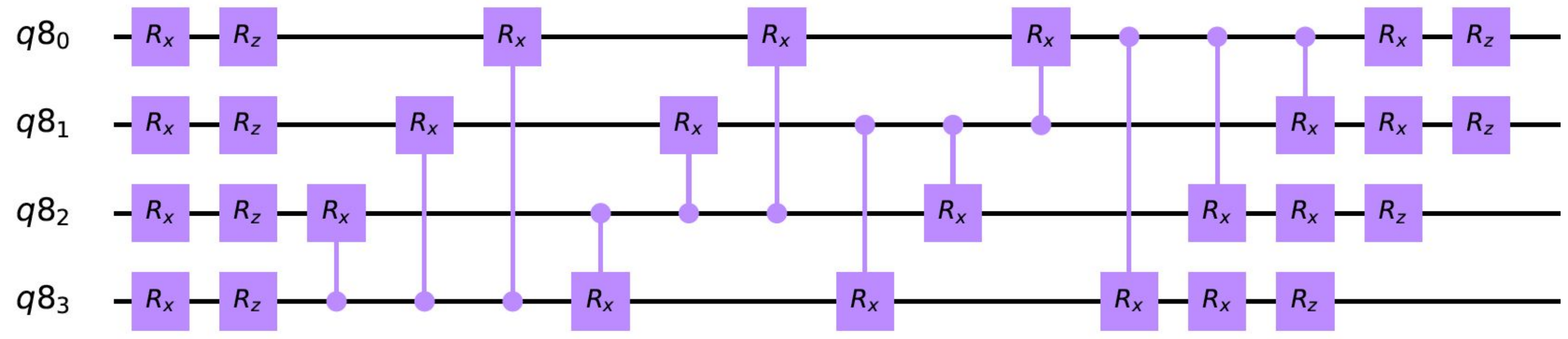

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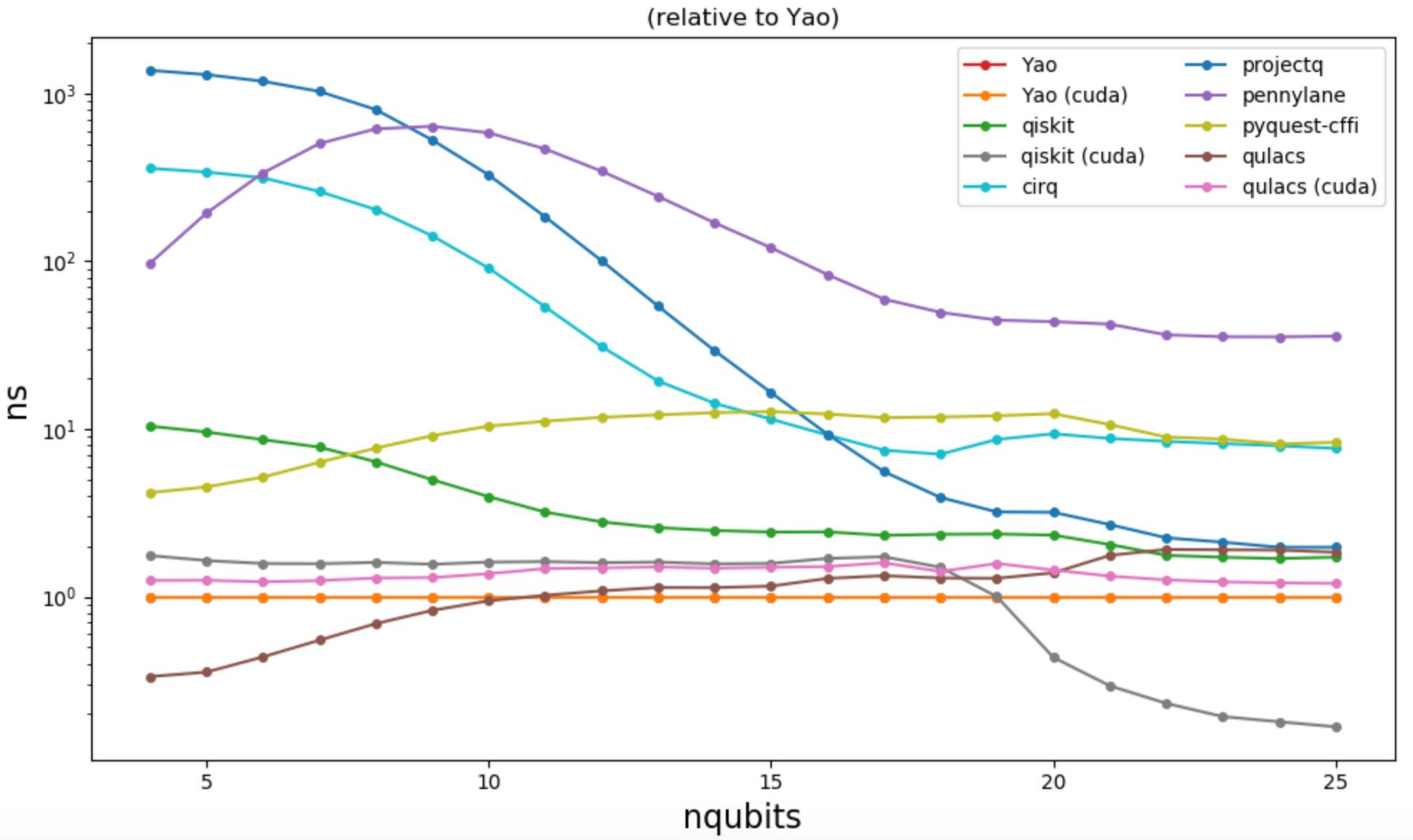
Next steps

- Variation of data sets
- Extension to more qubits
  - Using Pennylane's Qiskit backend for more than 15 qubits
- Parallelization of existing code
  - Feed of edges is sequential at the moment, but order does not matter
  - different quantum circuits could run parallel
  - Using PyTorch, dask and prefect
- Application of other quantum circuits



https://github.com/Roger-luo/quantum-benchmarks/blob/master/RESULTS.md

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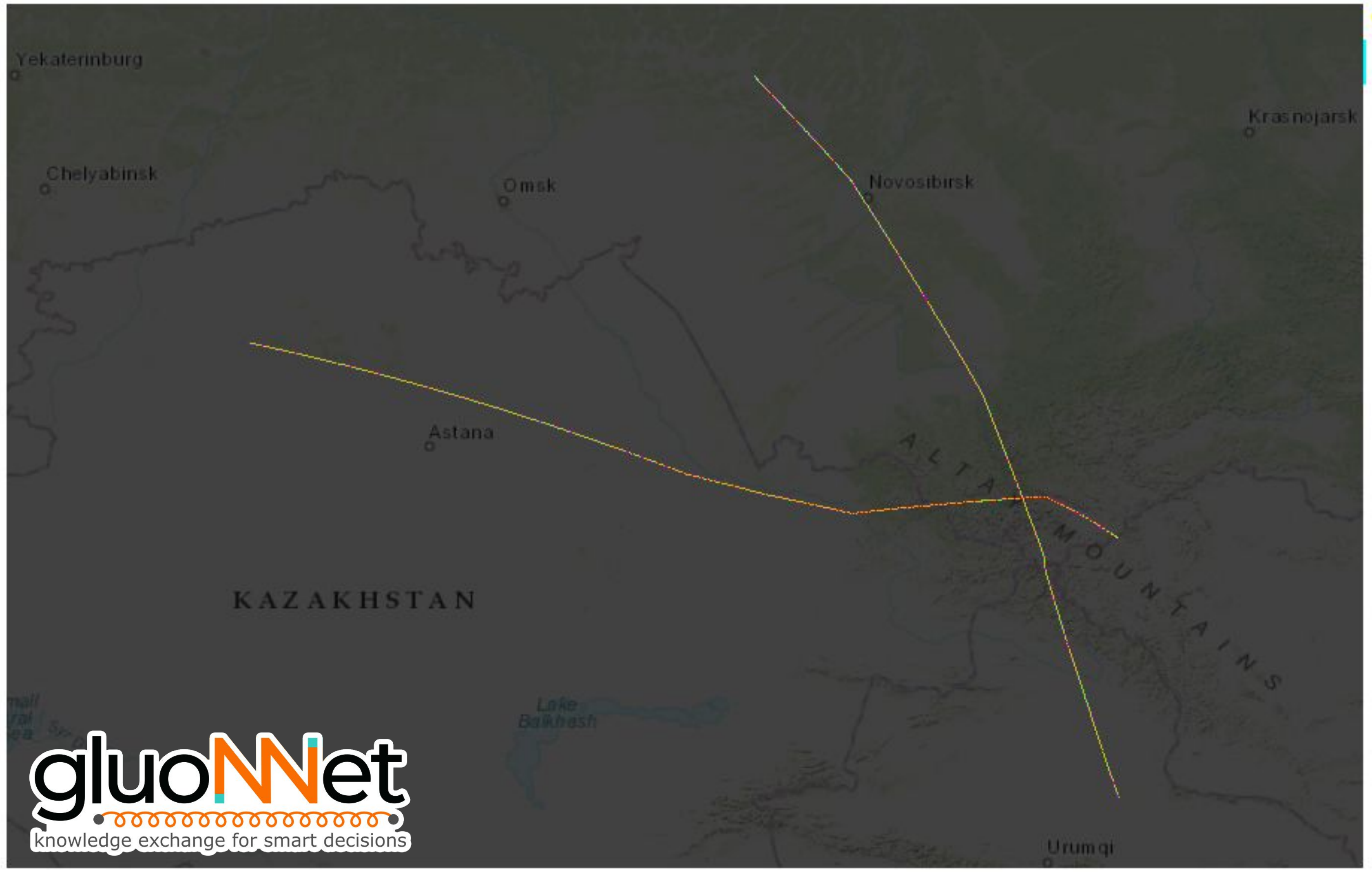
TCAS - Aviation case

- More challenging than particle track reconstruction
  - collisions of particles happened and are “snap-shot”s
  - airplane’s position is updated every 5 seconds
  - need of a procedural update of QGNN for every position



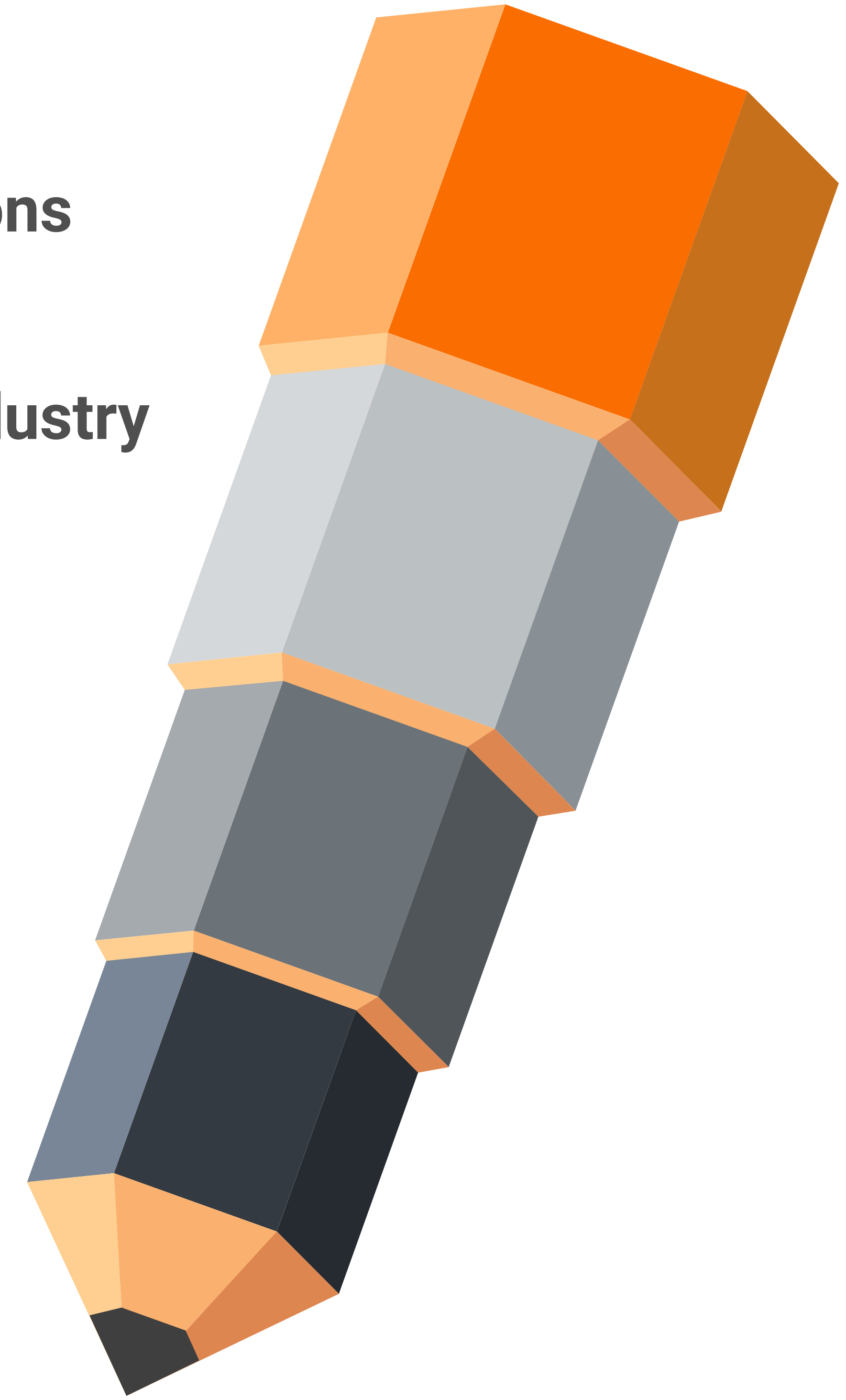
Summary

★ **Airplane track reconstructions are an intriguing similar to particle track reconstructions**

★ **Variety of needs in aviation industry can be addressed, but not limited to aviation industry**

★ **Quantum Graph Neural Networks**

- Hybrid structure of QGNN
- Tests running
- Next steps
  - Parallelisation of code
  - Variation of backends
  - Variation of circuits
  - Training with flight data is ongoing



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Thank you!

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Zoom link for discussion after the session

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Backup

Circuits used

https://arxiv.org/abs/1905.10876

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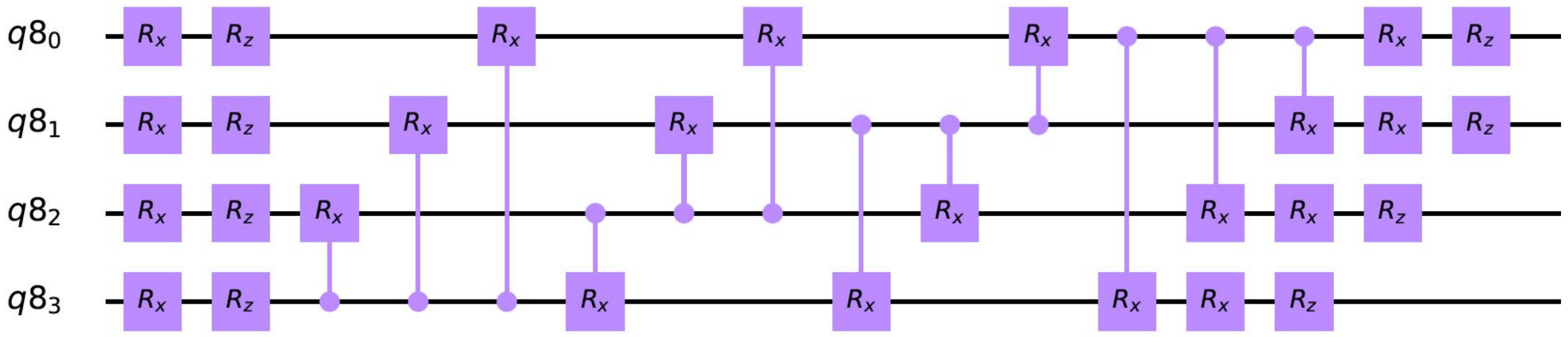

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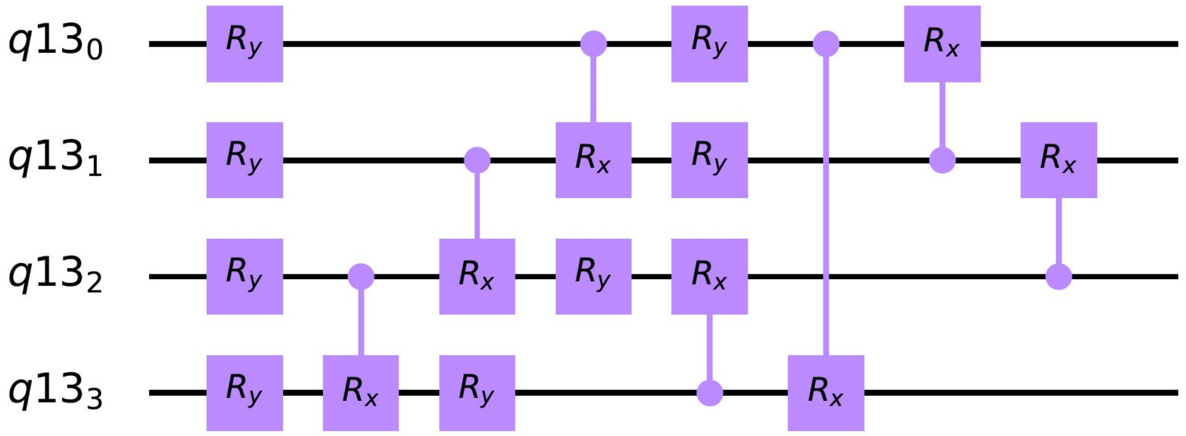

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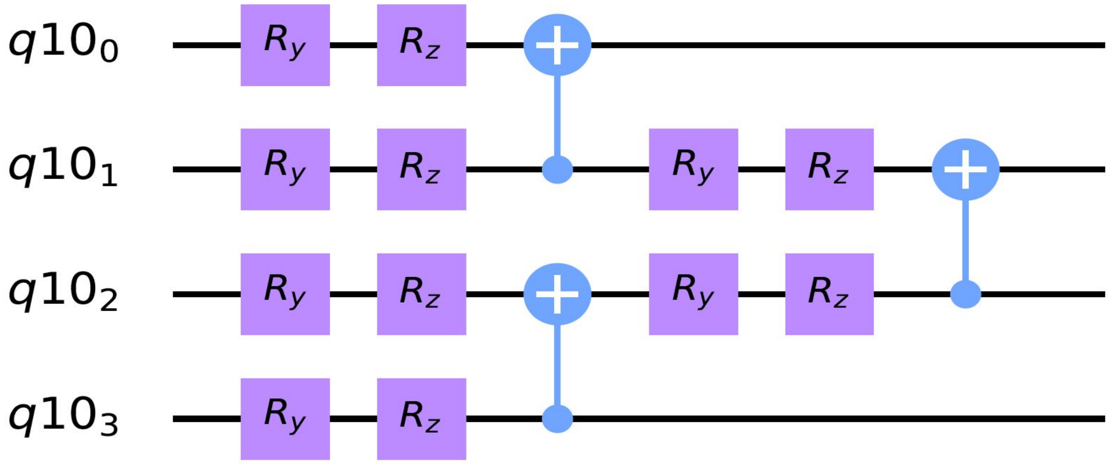

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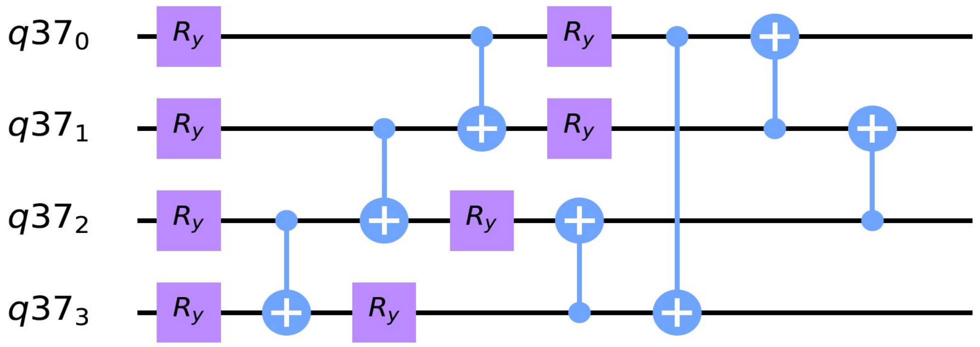
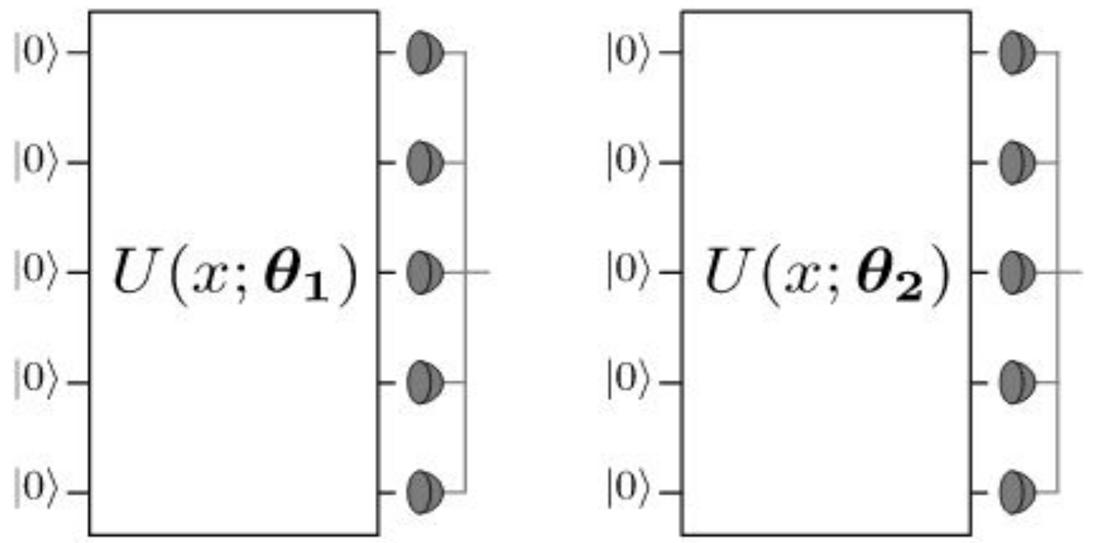


Gradient of a Quantum Circuit

- Composition of two circuits
- Pennylane supports an automatic differentiation between quantum circuits

$$\nabla_\theta f(x;\boldsymbol{\theta}) \quad = \quad f(x;\boldsymbol{\theta}_1) \quad - \quad f(x;\boldsymbol{\theta}_2)$$



https://pennylane.ai/