Co-Design of Quantum Hardware and Algorithms in Nuclear and High Energy Physics

Maja Franz[1], Pía Zurita[2], Markus Diefenthaler[3], Wolfgang Mauerer[1,4]

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Overview of Quantum Algorithms for NHEP

“Low-Level” Algorithms

- Grover’s & Shor’s algorithms
- Provable speedup / error correction required

Quantum Simulation

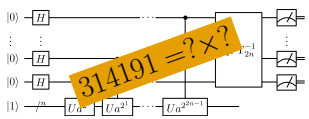
- Mimic system using simplified model
- Classically likely intractable

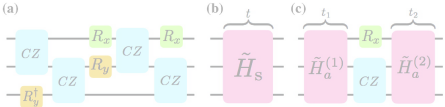
Unorthodox Approaches

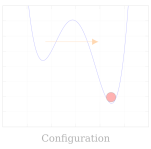
- Quantum annealing, adiabatic quantum computing
- (Gaussian) Boson sampling, etc.

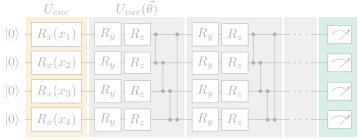
NISQ Algorithms

- Variational algorithms: Hybrid quantum-classical
- Less resources / potential speedups









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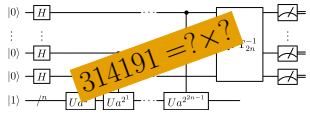

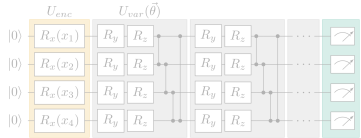

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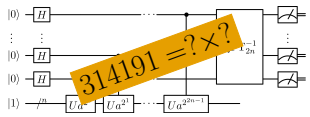

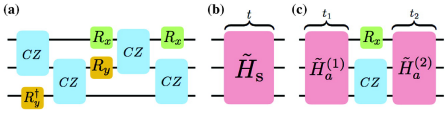

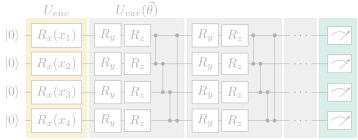

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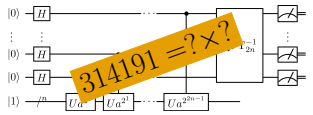
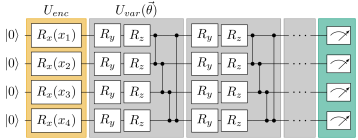
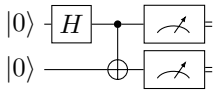




Overview of Quantum HW (high level)

Transmon	Ion Traps	Neutral Atoms
IBM, Google, rigetti	IONQ, AQT, QUANTINUUM, Honeywell	PASQAL, atom computing, ColdQuanta

⇒ Strong coupling to hardware properties



$\Leftrightarrow$

```
// prepare Bell state

OPENQASM 2.0;
include "qelib1.inc";

qreg q[2];
creg c[2];
reset q[0];
reset q[1];
h q[0];
cx q[0], q[1];
```

Co-Design Parameters

	Transmons	Trapped Ions	Neutral Atoms
#Qubits	50-127	23	~100
Single qubit gate time	ns	μs	μs
Two qubit gate time	ns	μs	~ns
T1 time	> 100 μs	10-100 s	~ms - s
T2 time	~100 μs	0.2-1 s	~ms - s
Single qubit gate error	~0.1 %	0.01-1 %	< 0.5 %
Two qubit gate error	0.1-2.5 %	< 0.5 %	< 3 %
Temperature requirements	~0 K	Room temperature[1]	Room temperature[1]
Qubit coupling density	< 10 %	100 %	10-20 %

[1] conditions apply

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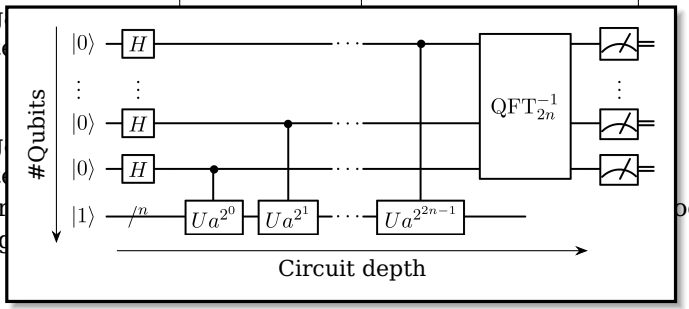

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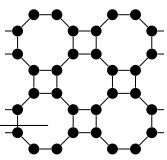

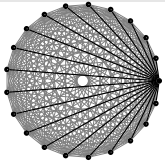

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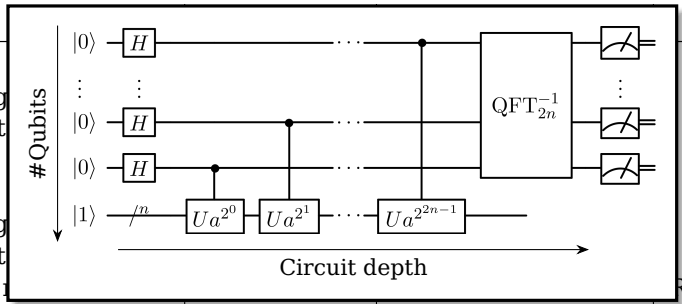

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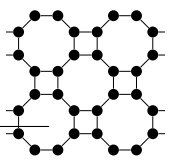

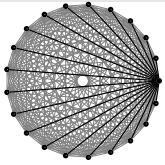

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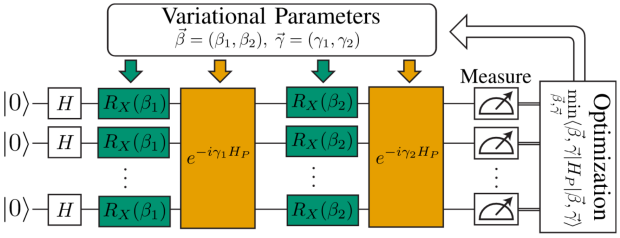
Quantum Approximate Optimisation Algorithm (QAOA)

- Approximation of Adiabatic Evolution
- Goal: Find groundstate of hamiltonian H_p
- Instead of a continuous time evolution: Discretise in p timesteps
- $p \uparrow \Leftrightarrow$ approximation quality $\uparrow$



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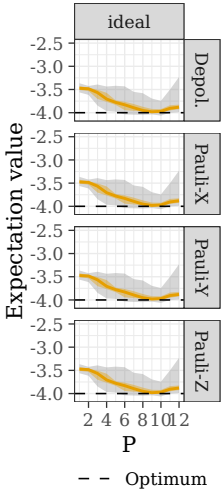
Influence of Noise on Optimisation (QAOA)



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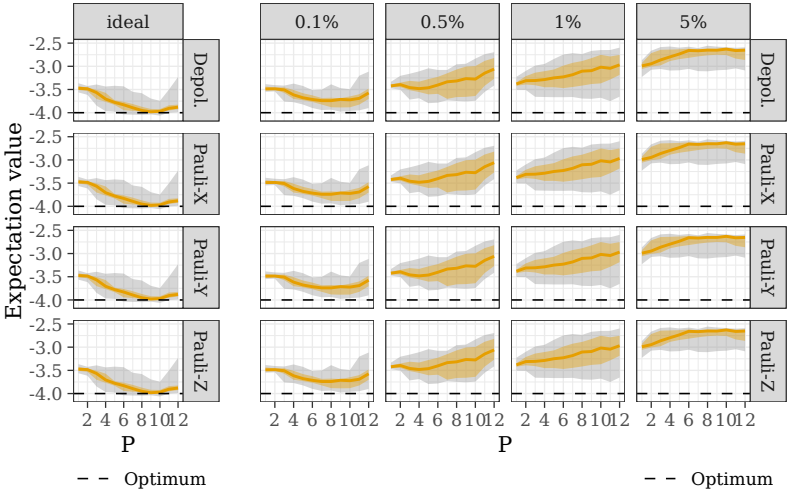

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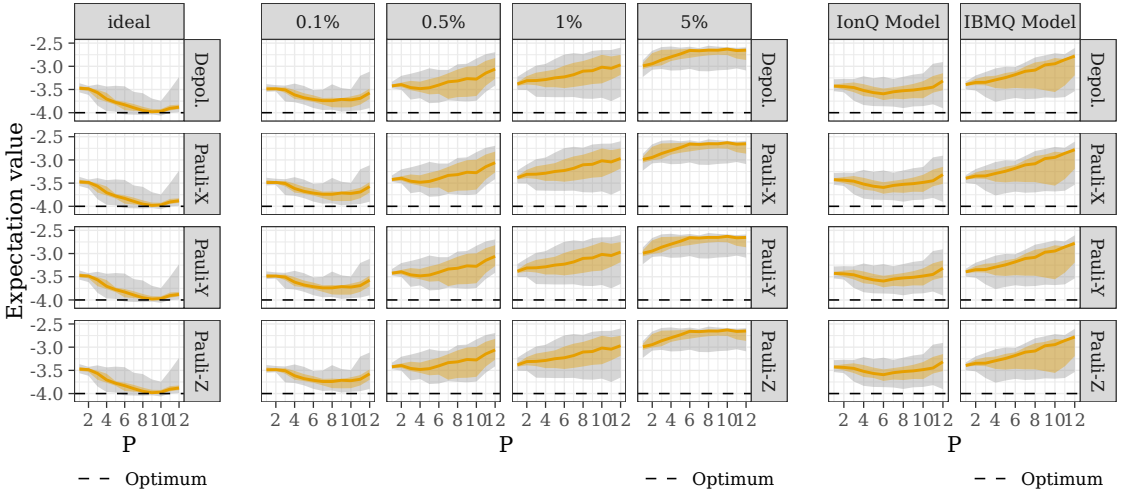
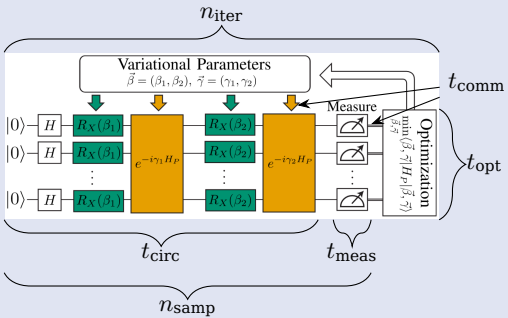


Influence Factors



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Latency and Jitter and Integration

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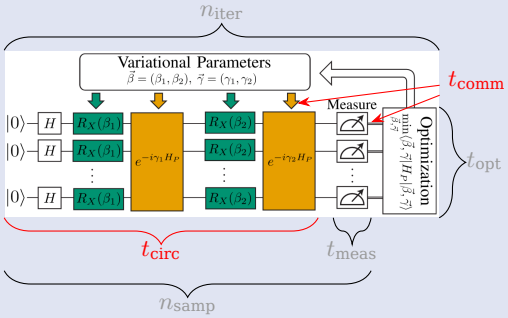

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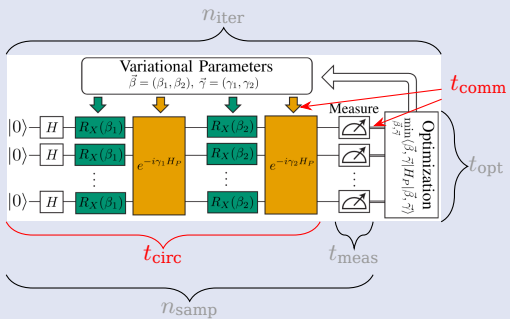

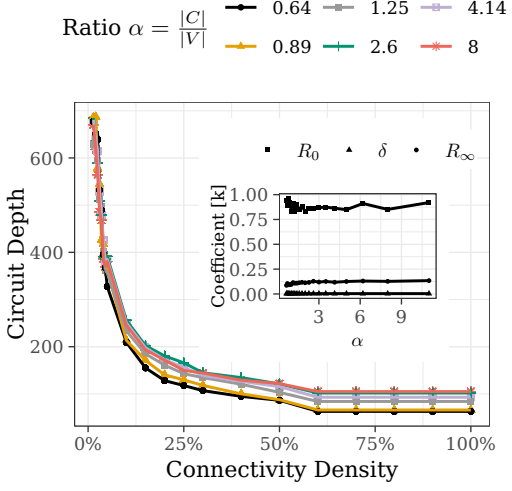

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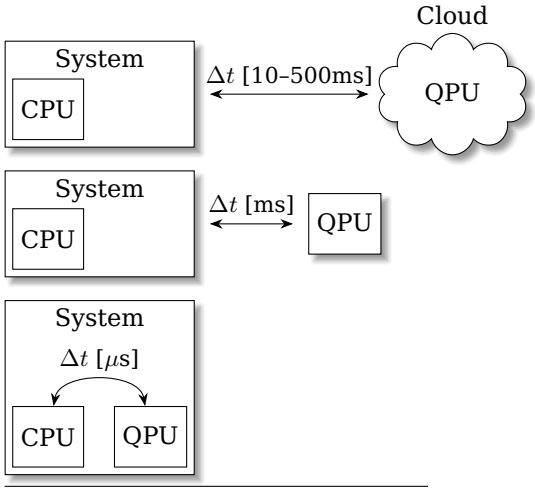

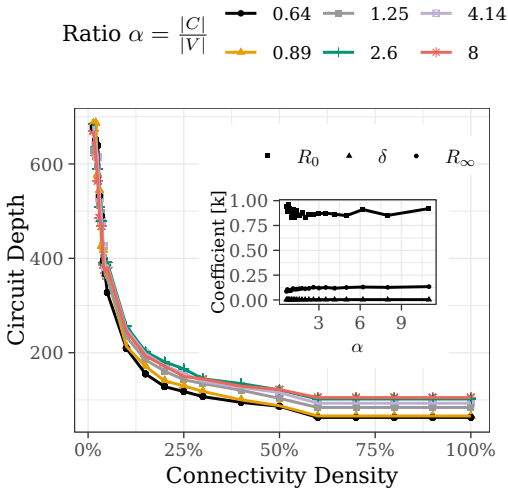

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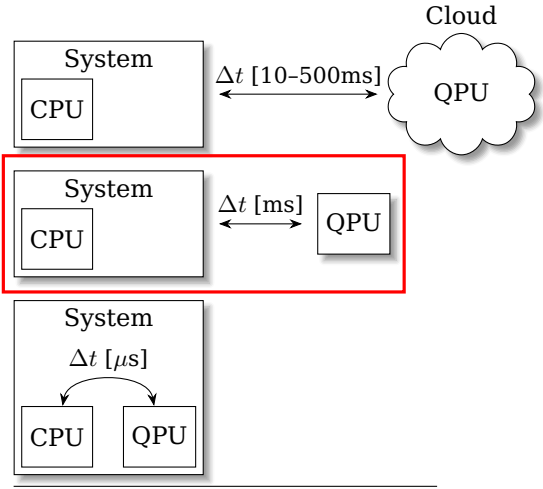

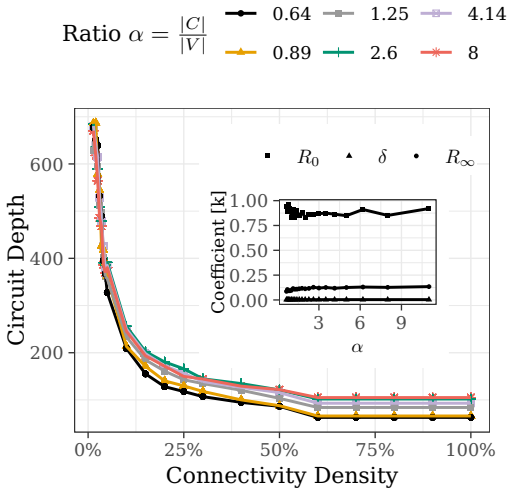

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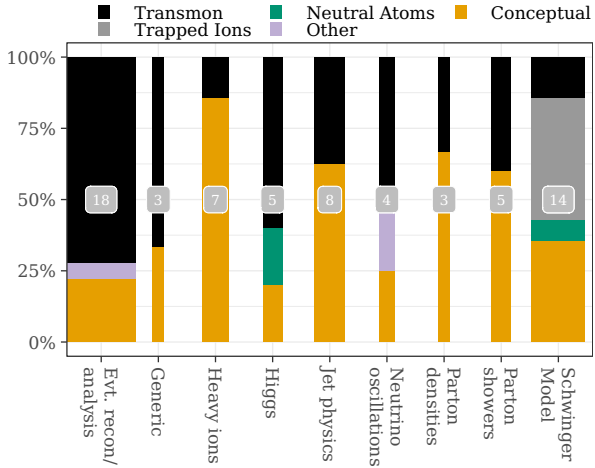
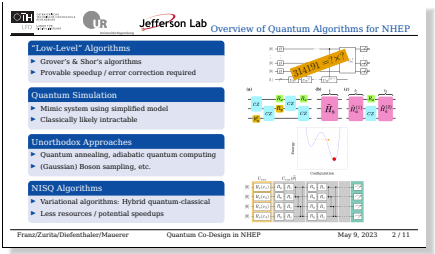
H. Safi, K. Wintersperger, W. Mauerer: Influence of HW-SW-Co-Design on Quantum Computing Scalability; Proc. IEEE Quantum Software Week (2023)

Summary

- HW-SW: Non-trivial, crucial interaction → Co-Design promising
- Interdisciplinary exchange QC/NHEP
- Promising directions:
  - Physical Simulation
  - Optimisation: Large-Scale Systems, Real-Time Control
  - Model Sampling



Thank you!


Overview of Quantum Algorithms for NHEP
"Low-Level" Algorithms
Grover's & Shor's algorithms
Provable speedup / error correction required
Quantum Simulation
Mimic system using simplified model
Classically likely intractable
Unorthodox Approaches
Quantum annealing, adiabatic quantum computing
(Gaussian) Boson sampling, etc.
NISQ Algorithms
Variational algorithms: Hybrid quantum-classical
Less resources / potential speedups
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Quantum Co-Design in NHEP
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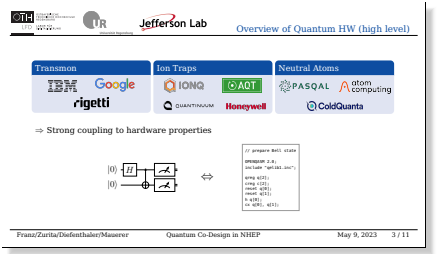
Overview of Quantum HW (high level)
Transmon
Ion Traps
Neutral Atoms
rigetti
IONQ
AQT
PASQAL
atom computing
QUANTINUUM
Honeywell
ColdQuanta
⇒ Strong coupling to hardware properties
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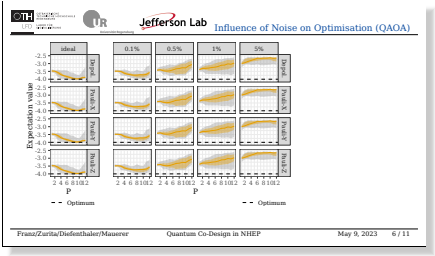
Influence of Noise on Optimisation (QAOA)
ideal
0.1%
0.5%
1%
5%
Expectation value
Depol
Bit-flip X
Phase-flip X
Bit-flip Z
p
Optimum
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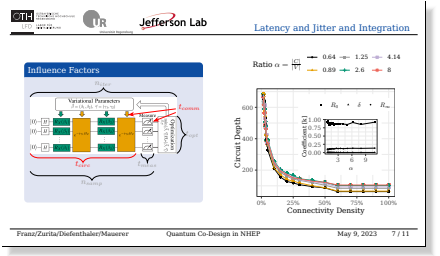
Latency and Jitter and Integration
Influence Factors
Variational Parameters
Measure
Reset
Feedback
Circuit Depth
Connectivity Density
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Latency and Execution Time