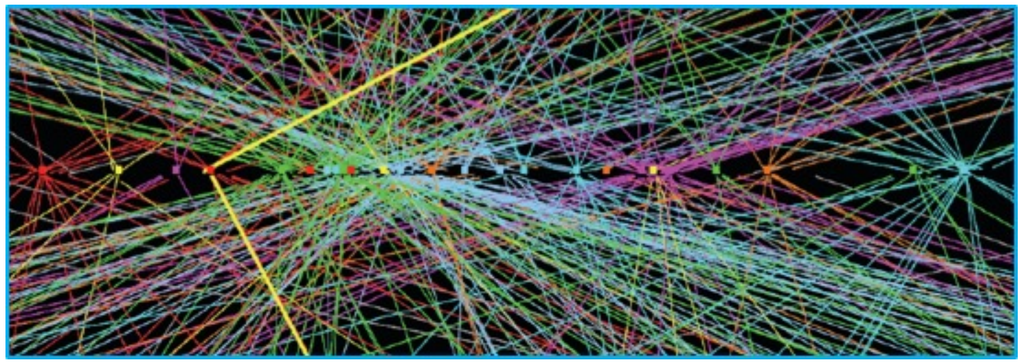
Reconstruction at the HL-LHC

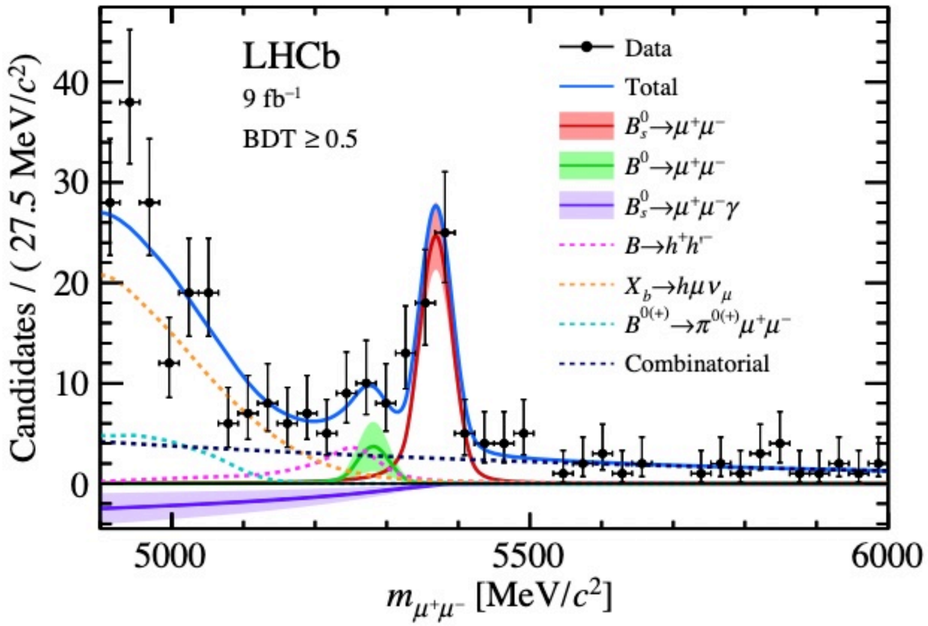
FASTER kickoff @Nikhef, 31 Jan 2024

Maastricht University

More data…

- Main physics output is statistically limited
- Increase luminosity -> simultaneous collisions -> busy events
- ‘Precision’ vs ‘Statistics’





… in LHCb run 3

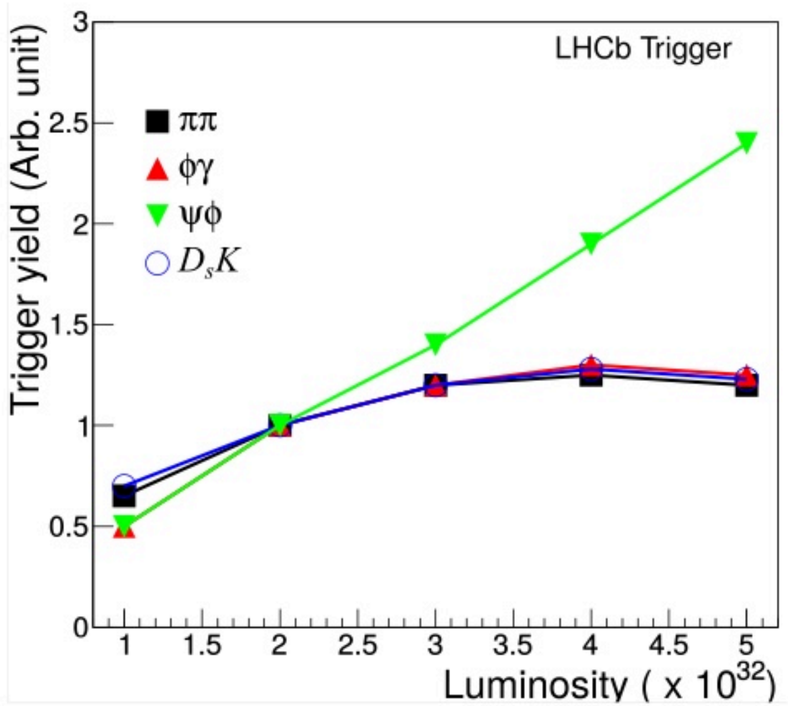
⟶ Redesign most detectors for 5x higher occupancy

⟶ Real-time data filter (‘trigger’): L0 + Hlt1 + Hlt2

Run 1&2 bottleneck: L0 hardware (FPGA) trigger (40 MHz —> 1 MHz)

- Very low-level information used to make tough decisions:
  ⟶ energy in ECAL cells: $E_T > 3\ (3.7)$ GeV [450 (150) kHz]
  ⟶ muon hits: $p_T > 1.76\ (1.6)$ GeV/c [400 kHz]

- Run 2: *directly* take **40 MHz** to software: **GPUs** (‘Allen’ project)
  ⟶ Reconstruct tracks, vertices, in parallel scheme, **in real time**
  ⟶ Make more informed decisions, greatly increase efficiency
  ⟶ Reduce rate from 2 TB/s —> 10 GB/s



http://dx.doi.org/10.1088/1742-6596/762/1/012046
https://doi.org/10.1007/s41781-020-00039-7

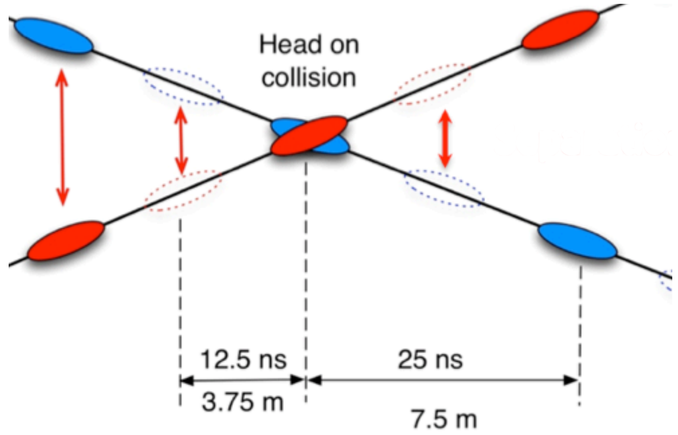
… at the HL-LHC?

Up to 50x higher occupancy for some experiments

→ How to deal with reconstruction in real time? And keep precision?

→ While reducing our carbon footprint?

→ Use the time spread during proton bunch overlaps



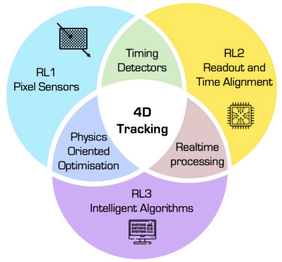
FASTER

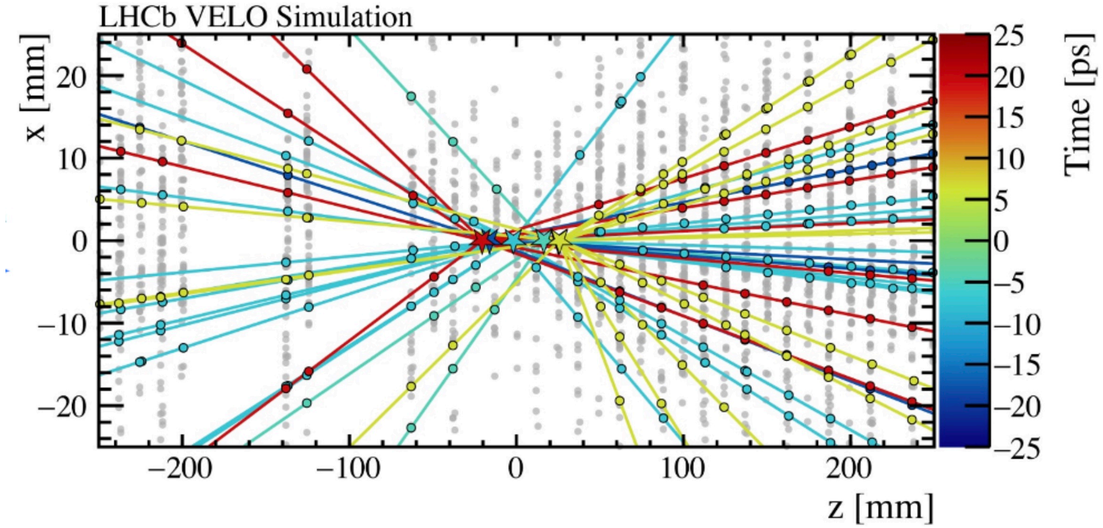
WP1 WP1

→ Develop 4D sensors/readout with picosecond timing

→ Develop algorithms (/ infrastructure) to benefit

WP3





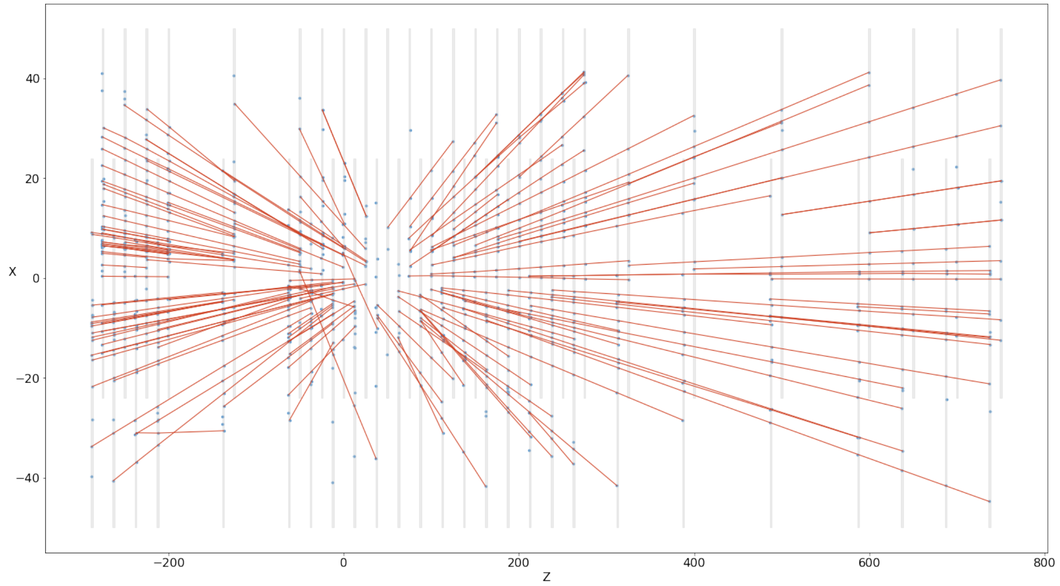
Track reconstruction

Pattern Recognition

“Find all the hits that belong to one track”

⟶ Clustering, Hough transforms, seeding&following, …

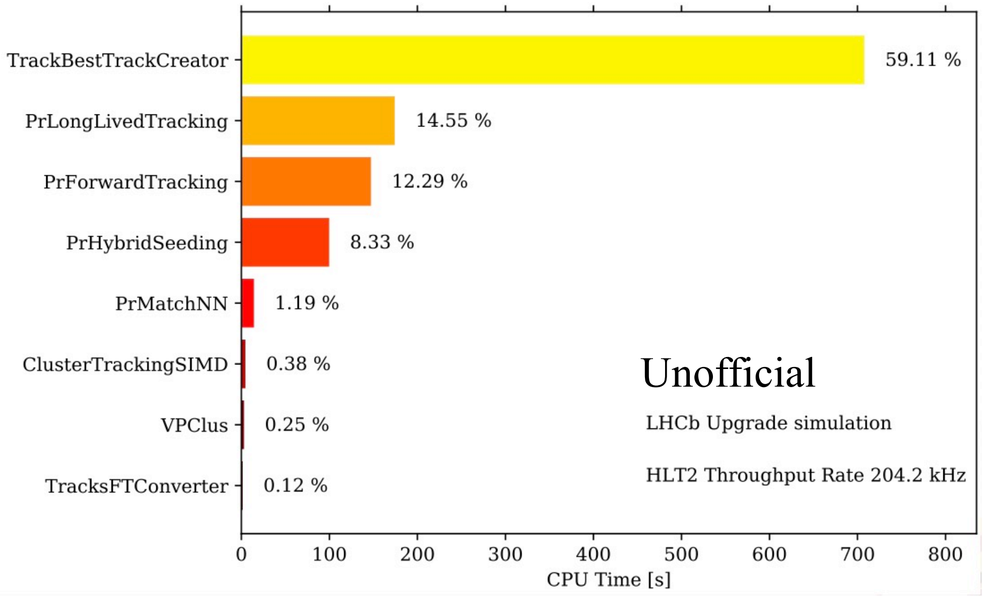
⟶ Scales with N_{hits}^{2-3} -> polynomial growth



Track Fitting

”Obtain the best track parameters given the hits”

⟶ Usual approach: (extended) Kalman Filter

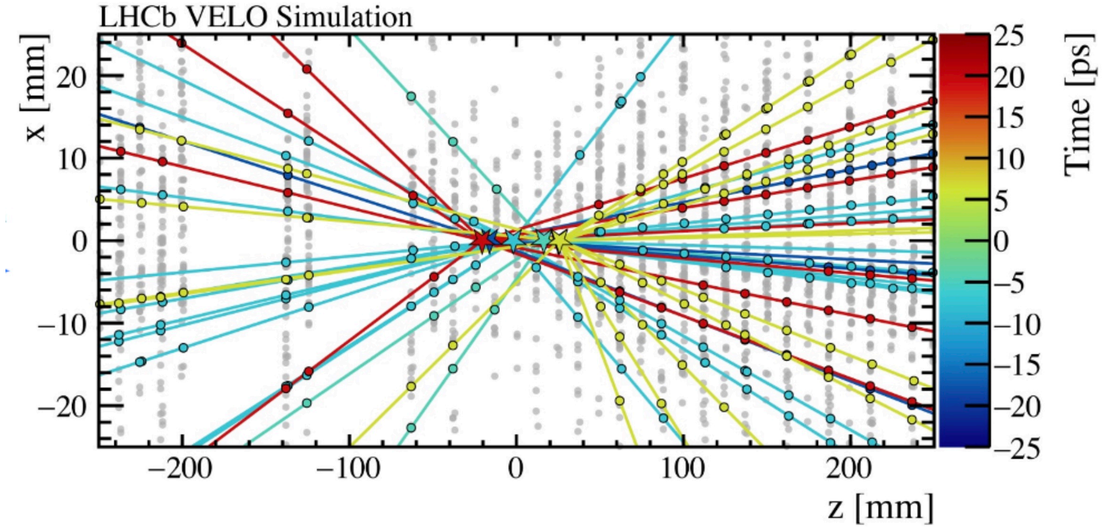


FASTER WP3

“Our proposal is to develop new, more efficient, and

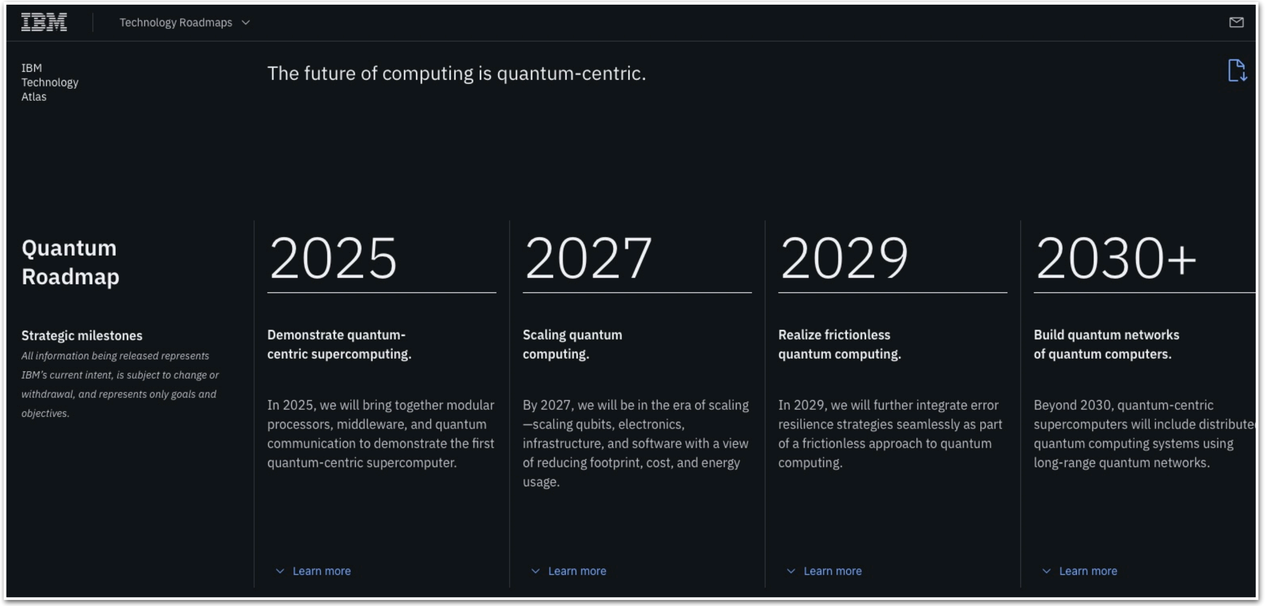
better scaling algorithms utilizing the timing information of 4D tracking detectors”

- Splitting up the data in ‘time slices’ -> reduction of complexity
- Adding time to the states of the Kalman filter
- Exploring further applications of parallelisation on GPUs
- Pre-processing (e.g. sorting/clustering) hits in front-end electronics
- Novel algorithm design for specific use cases
- WP3.2: Explore the use of quantum algorithms



Why quantum?

- Quantum states embed 2^N states simultaneously —> exponential speedup?*
- A lot of investments being made, ‘promising’ quantum roadmap, rapid developments
- Interest at CERN via QTI / OpenLab
- Landscape in Netherlands —> so far focus on hardware
  —> Niche for dev software / applications
  —> Connect with other entities (e.g. QuSoft)
- Unknown territory for particle physics computing
- Exciting!



Why not quantum?

Concern / criticism about feasibility exists

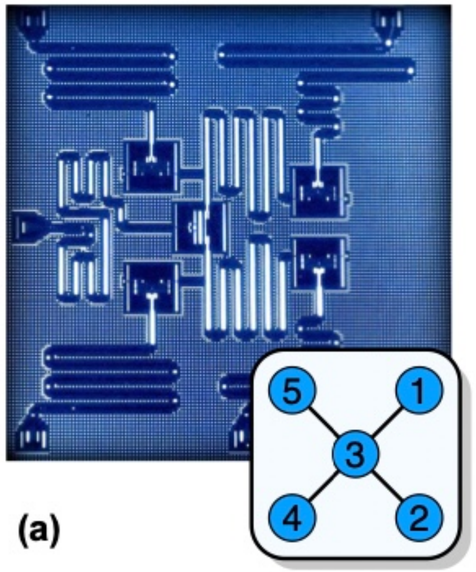
- Current systems only O(50) qubits.
  (Shor's supremacy: 2048 + 1024 needed)
  —> scaling up comes with topology issues

- For any sizeable computation, errors / decoherence destroys states,
  Coherence time 60 us, 2-qubit gate time 300 ns
  —> need error-corrected qubits

- Needs clever algorithm design to actually benefit from speedup
  —> Only a handful of examples exist today (e.g. Quantum Phase Estimation)

- Suitable for high-throughput needs?
  —> state preparation, readout 'probabilistic'

—> UM/FASTER/NWO: Worth exploring as 'blue sky research'.



https://arxiv.org/abs/2312.17570
https://arxiv.org/pdf/1702.01852.pdf

Maastricht

- 2019: Interest from Computer Science department (DKE / DACS)
  —> 2022: PhD on quantum MCTS, Vincenzo Lipardi

Gravitational Waves & Fundamental Physics (GWFP): *'QC for track reconstruction'*

- 2021: IBM postdoc Miriam Lucio Martinez, QUBO/QAOA
- 2022: SURF grant for 1 year PhD, Davide Nicotra, HHL
- 2023: FASTER grant for 1 PhD, Xenofon Chiotopoulos, 'QC for tracking'
  —> MSc 'quantum technologies'

Projects - Harrow-Hassadim-Lloyd

Started by Davide combined with SURF / Ariana Torres

LHCb Velo toy: straight lines, simplified problem

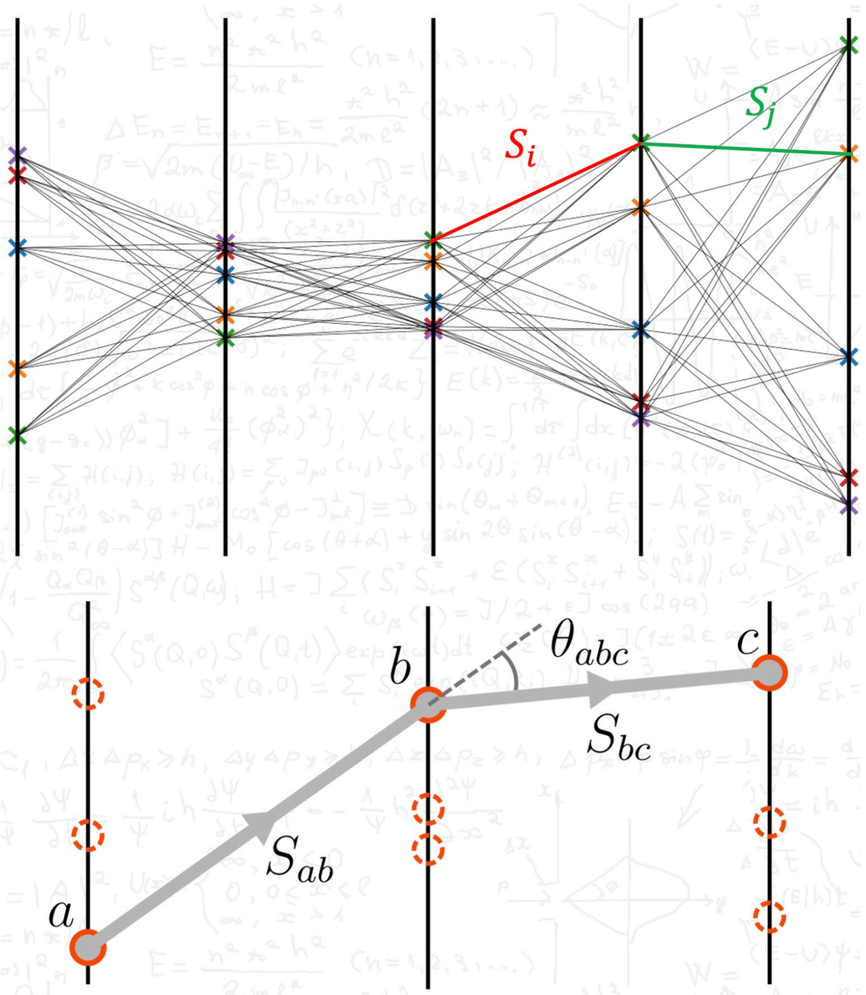
- Build global hamiltonian connecting hit pairs (doublets)

  —> penalise large angles

$$\mathcal{H} = -\frac{1}{2}\sum_{ij} A_{ij} S_i S_j + \sum_i b_i S_i \quad S_i \in \{0,1\}$$

- Turn into matrix inversion problem for A_{ij}
- Solve with HHL (Hamiltonian simulation + QPE)

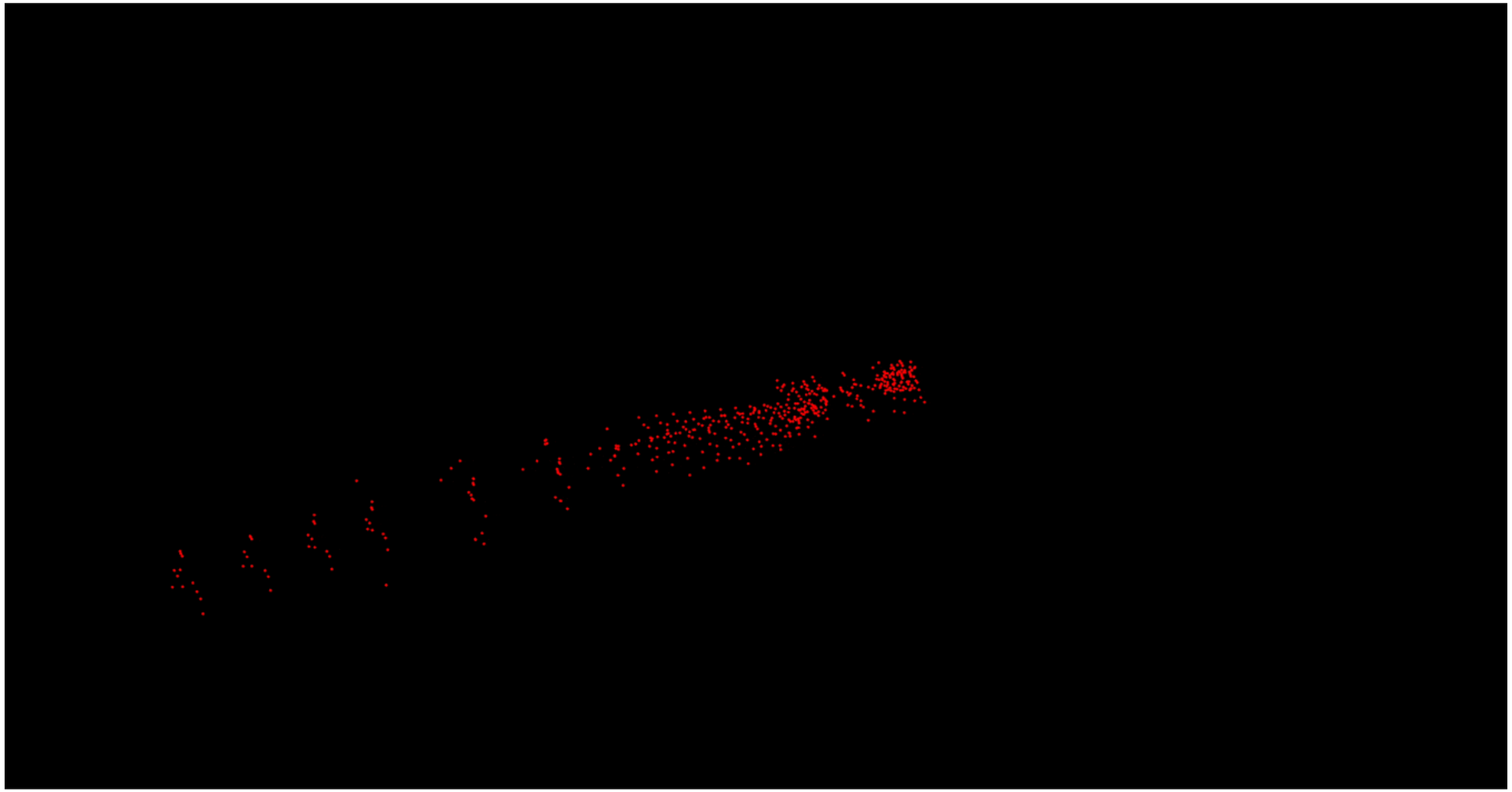
Classical: O(N)
Quantum: O(log N)

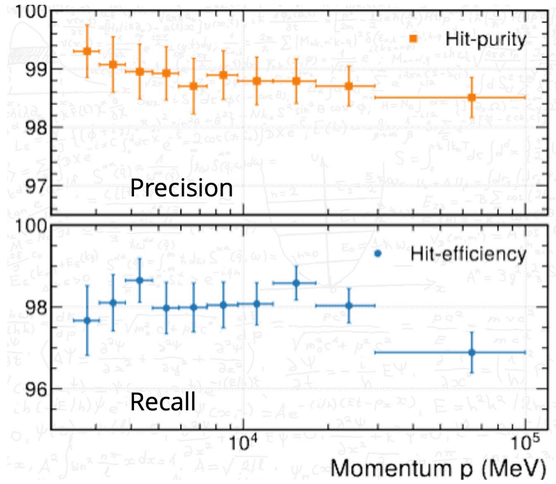


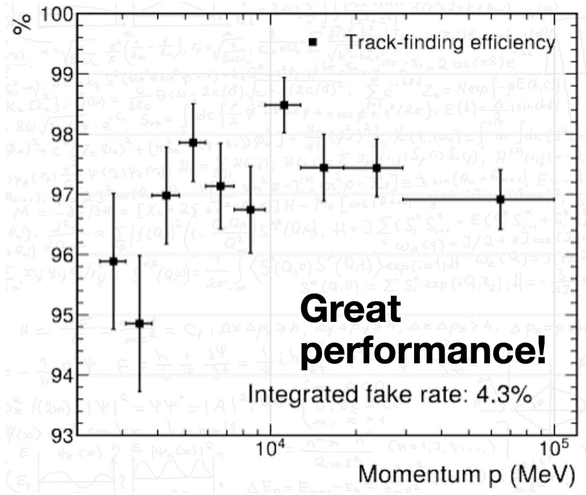
https://iopscience.iop.org/article/10.1088/1748-0221/18/11/P11028

Projects - HHL

Classical - it works!







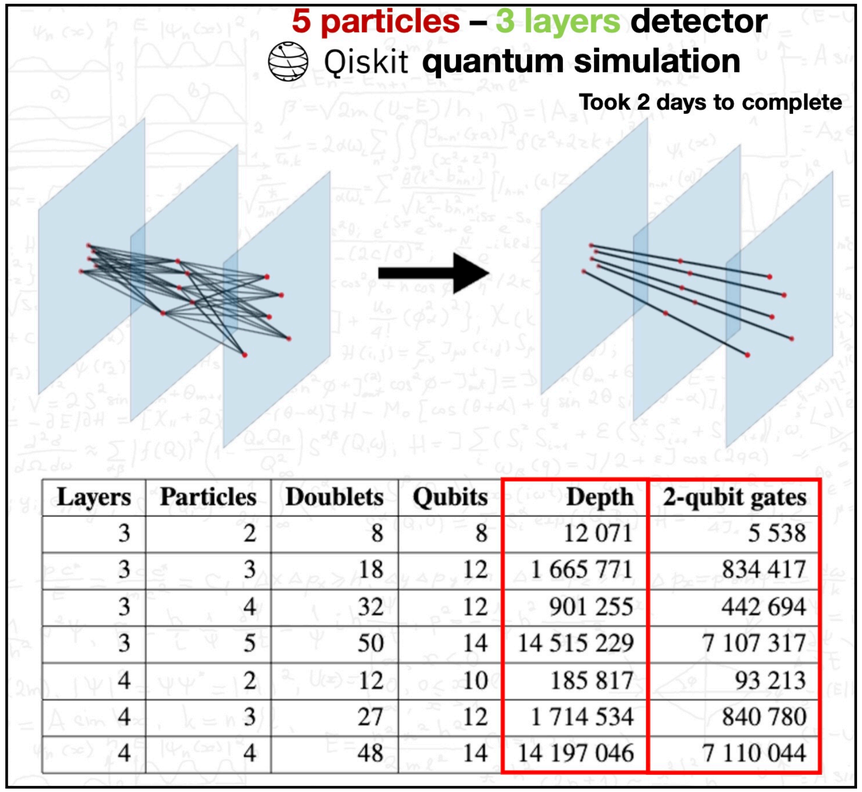
Projects - HHL

Quantum - it works*

- Correct solutions on simplified problem always obtained!

- Badly optimised implementation of HHL in Qiskit —> extreme circuit depth
  —> Make use of extremely sparse matrix!

- Readout of states: currently tomography —> destroys speedup
  —> How to get relevant information out?



Layers	Particles	Doublets	Qubits	Depth	2-qubit gates
3	2	8	8	12 071	5 538
3	3	18	12	1 665 771	834 417
3	4	32	12	901 255	442 694
3	5	50	14	14 515 229	7 107 317
4	2	12	10	185 817	93 213
4	3	27	12	1 714 534	840 780
4	4	48	14	14 197 046	7 110 044

https://iopscience.iop.org/article/10.1088/1748-0221/18/11/P11028

Projects - Continuation

Xenofon

- Improve Hamiltonian simulation for sparse matrices
  —> investigate decomposition, Suzuki trotter
  —> 350x reduction in two-qubit gates
- Readout problem
  —> We don’t “need” all the doublets, just the tracks.
  —> Hough transforming the z of ‘closest point of track to beamline’ should give peaks in vertex position?
- Variational methods, adiabatic quantum computing, …

Support and new ideas via

- SURF platform for various hardware (IBM silicon, D-Wave, Ions? photonic?)
- Experts at TU Eindhoven (Michiel Hochstenbach, Oliver Tse)
- Experts at QuSoft (KarelJan Schoutens)

—> Connect to FASTER WP3.1, FASTER WP2

Changes in organisation

- Daniel Campora left

  —> Kurt Driessens (Asso. Prof. in ML @ DACS) stepped in

- Harry Buhrman from QuSoft left

  —> Looking for strategic replacement

Conclusion

FASTER gives us the opportunity to explore quantum algorithms for particle physics

—> New ideas about pattern recognition

—> Contributions to the field of quantum computing

—> New connections / funding opportunities for Nikhef

Is it the answer for HL-LHC?

—> would need a breakthrough