NEXUS Qubit Analysis: Jump Rates and Efficiencies

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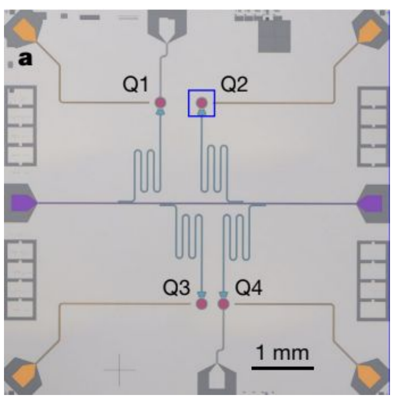
Superconducting Qubits

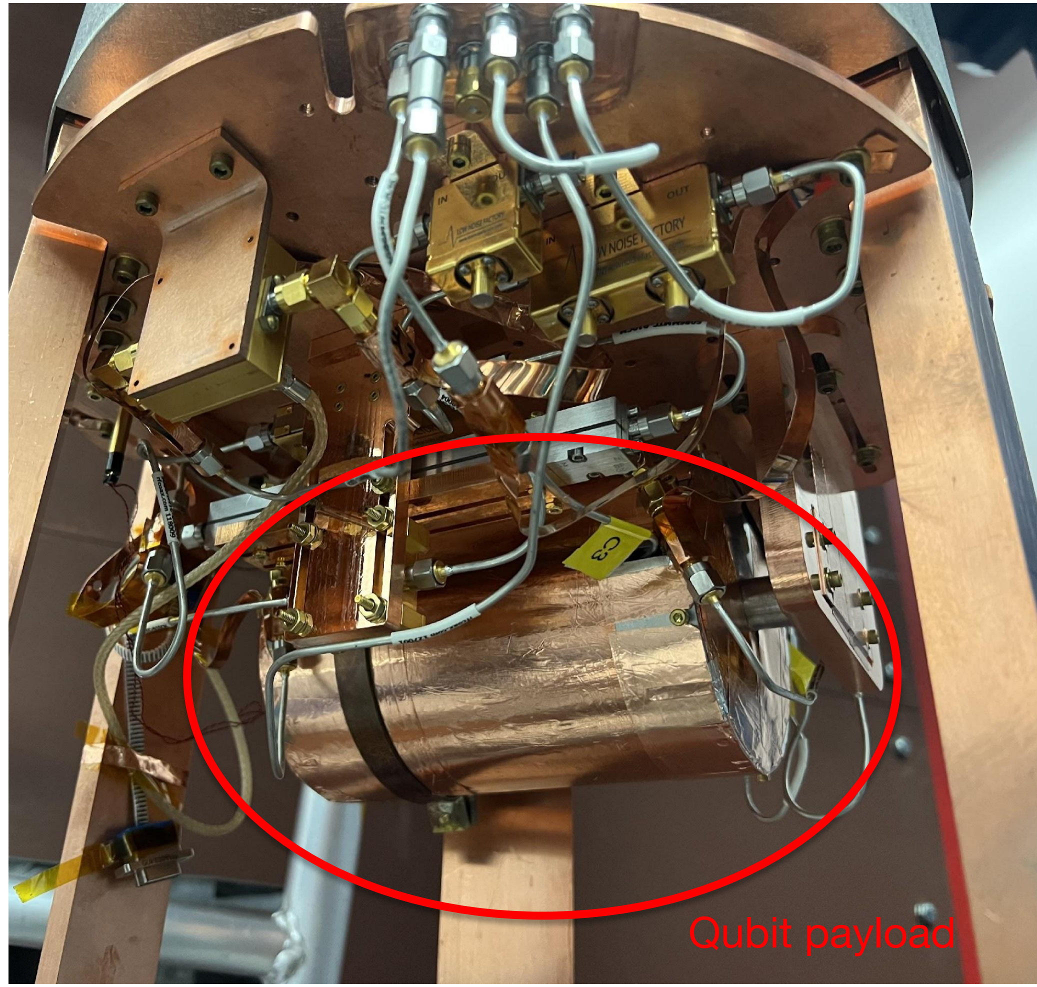
- Qubits: quantum bits with information encoded on it
- Qubit Error: When any of the above information is lost
  - Decoherence Errors
  - **Charge Burst Errors**

What are Qubit Errors?
What causes them?

McEwan et. al. 2021 shows that ionizing radiation and comic ray muons can cause qubit errors. (That's one reason we're doing this 100+ m underground)



Layout of the qubit chip currently being used in NEXUS; Image Credit: Wilen et. al. 2021



NEXUS Qubit Payload, along with other experiments in the NEXUS Dil Fridge (KIPMDS, etc.)

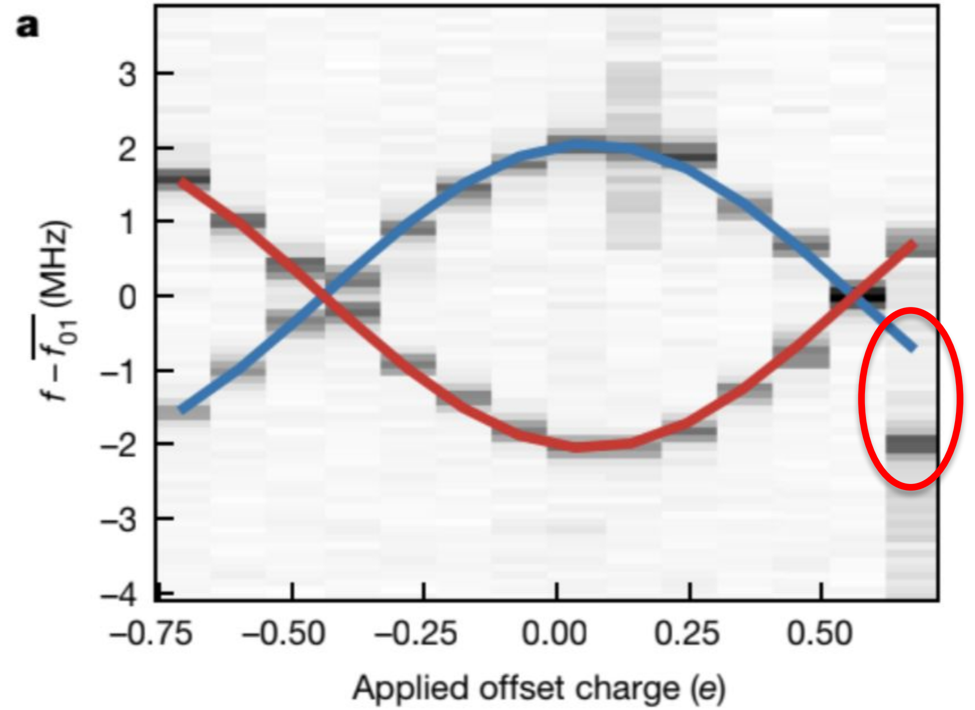
Qubit Jumps

A **charge jump** in a qubit is when a particle is incident on the chip, causing the qubit to decohere, resulting in a **jump** in offset charge.

Ex. A cosmic ray muon passes through a qubit, resulting in a phonon being released, which causes errors in nearby qubits.

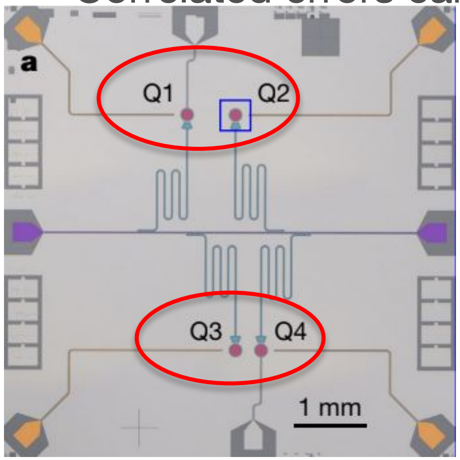
Correlated Qubit Error: when two qubits that are spatially nearby see errors that are correlated in time as well.

Correlated errors can not be solved with error correction.



Qubit spectroscopy versus charge the applied offset charge, the red and blue lines trace the qubit parity. A jump is seen in the rightmost column.

Image credit: Wilen et. al. 2021



Correlated Errors + Quantum Computing = **BAD**

Correlated Errors + Particle Detection = **GOOD**

What is the goal?

Article

Correlated charge noise and relaxation errors in superconducting qubits

Expanding on previous work and further quantifying it

Specifically…

- Analyzing and identifying the effect of ionizing radiation and cosmic ray muons on qubits using
  - 4 radiation configurations
    - Lead Shield Closed, No Source (SC)
    - Lead Shield Open, No Source (SO)
    - Lead Shield Closed, Barium – 133 Source
    - Lead Shield Closed, Cesium – 137 Source

Lower incident rate

Higher incident rate

NEXUS
Lead shield

Pt. by Pt. Jump Detection Code: χ^2 Analysis

1. Calculate χ^2 of each point in data (80 pts) with each point in template (608 pts)
2. Calculate the combined χ^2 for each point by summing the 608 points per point
3. Select minimum combined χ^2 for each point
4. When minimum combined χ^2 is above Least χ^2 Threshold, Jump is logged; combined χ^2 reset
    a. Phase before jump must be different by |Phase Dif. Limit| to phase after jump

$$\chi^2 = \left(\frac{x_{\text{data}} - x_{\text{template}}}{\sigma_{\text{template}}} \right)^2 \qquad \chi^2_{\text{combo}}[n,] = \frac{1}{n+1} \sum_{i=0}^{n} \chi^2[i,]$$

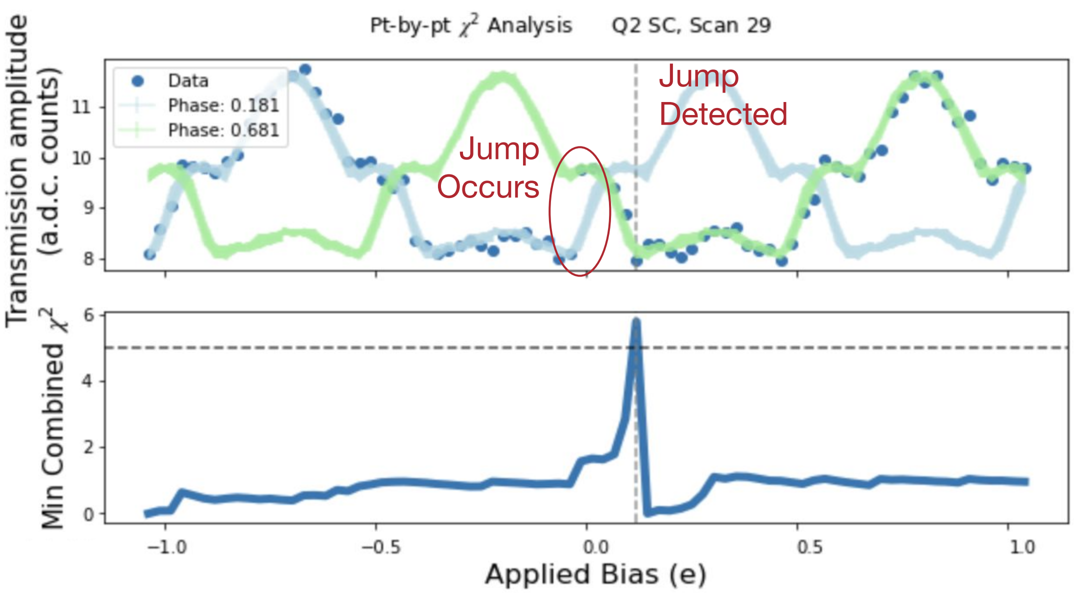
Pt. by Pt. Jump Detection Code: Parameters

Generating simulation data and running the jump finding code on it determines how to set different free parameters for each qubit

- Least χ^2 Threshold: Value of combined (rolling avg) least χ^2 that triggers jump finder
- Jump Num. Limit: Number of extended indices as buffer before jump can be detected from beginning of scan or last jump
- Phase Dif. Limit: Extended index difference that throws out 'non jumps' that were tagged (new phase isn't different enough)
- Backoff: Number of extended indices before a jump where window ends for calculating pre-jump phase
- Combined χ^2 Cut: If combined χ^2 is greater than this value, then a jump is confirmed to have happened in scan

Pt. by Pt. Jump Detection Code: Index Matching

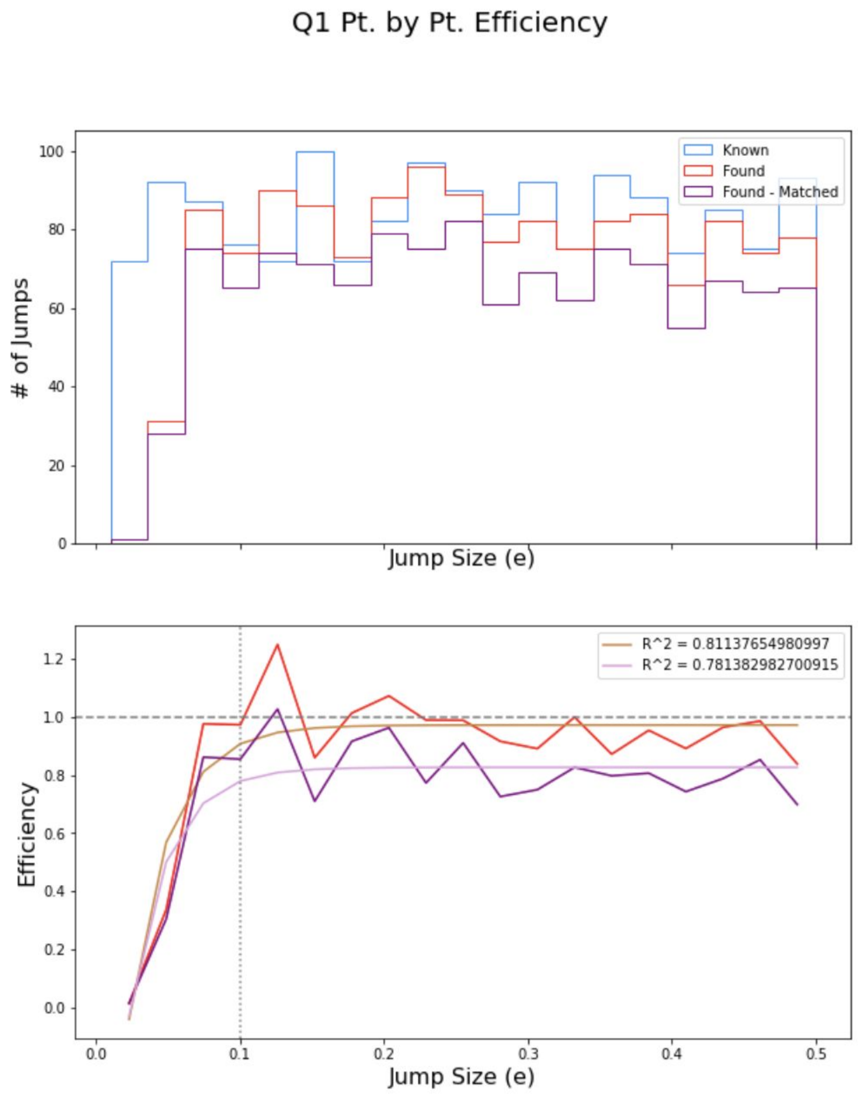
- In previous versions, jumps were considered correlated if they happened in two different qubits during the same scan (aka happened within nearly 6 minutes of each other)
- With Index matching, the code notes what index in a scan a jump is found; to match correlated jumps, the indices must be within a set window of each other
  - ex. if the window is 10 indices, then the window is ~45 seconds
  - Due to the combined χ^2 aspect, there is a slight delay for when jumps are found, which is reflected in the window size



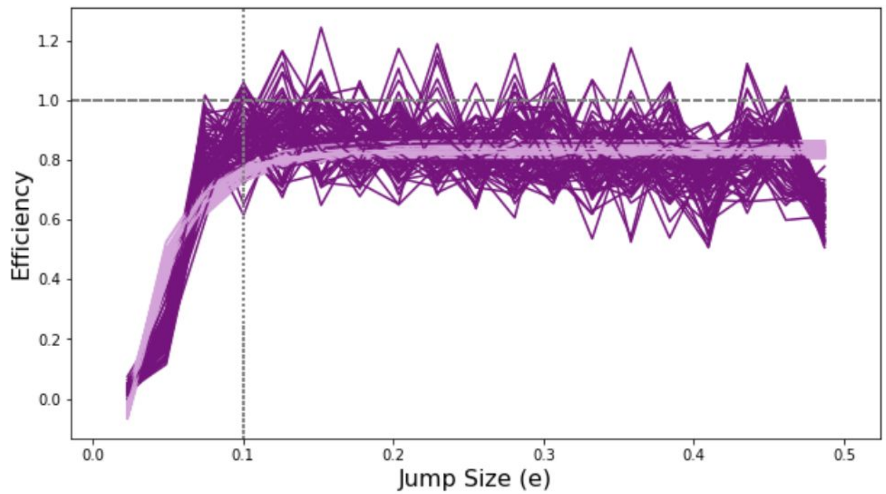
Fermilab

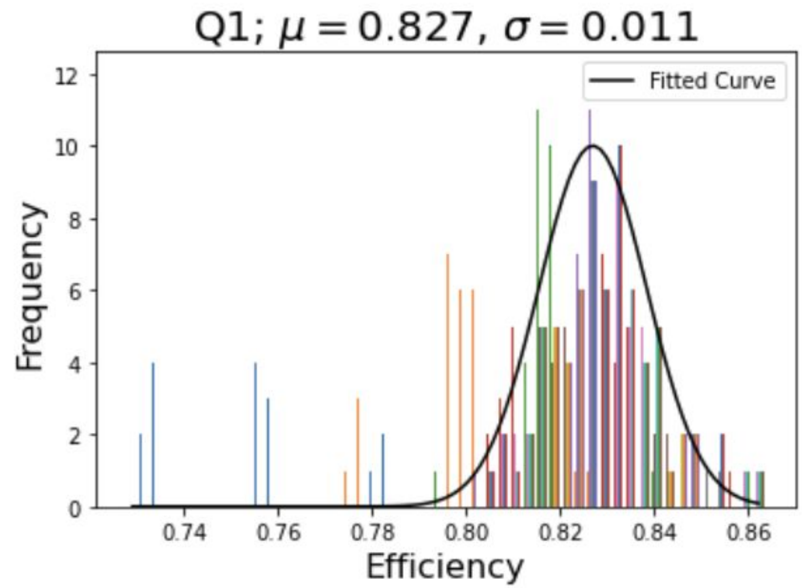
Getting Efficiencies with Simulated Data

- Efficiency = (# of found jumps / # of Known Jumps) per Jump Size
  - Parameters are selected by testing the parameter space and selecting the parameters with the highest efficiency.
  - A jump is considered correctly tagged if it is within X e of where it is injected **and** within Y e of the phase.
  - X and Y are qubit dependent
- An exponential is then fit to the efficiencies



Getting Efficiencies with Simulated Data





- The efficiencies are then calculated for a large set of simulated data, using the same parameters
- Interested in getting the efficiencies of jumps with a size greater than 0.1e
  - Make new array with that portion of the curve and plot histogram
  - Fit a gaussian to get μ and σ

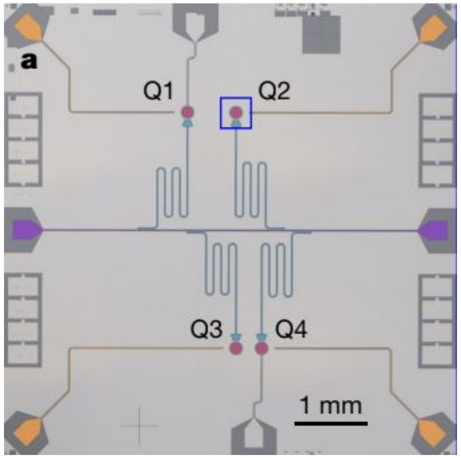
Qubit Rates (Efficiencies Incorporated)

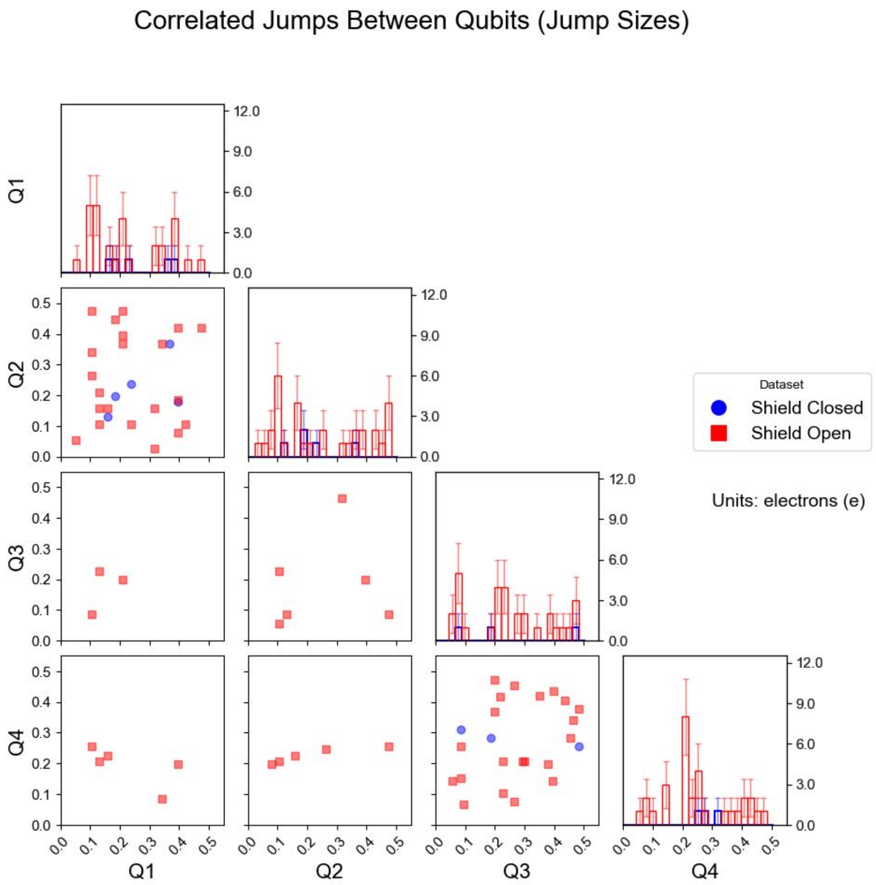
	Q1	Q2	Q3	Q4 SC	Q4 SO
Eff.	0.827 ± 0.01	0.794 ± 0.01	0.872 ± 0.03	0.723 ± 0.02	0.735 ± 0.05
Raw Rate (mHz)	0.1647	0.1520	0.1773	0.1267	0.4185
Rate adj. with Eff.	0.199	0.191	0.203	0.175	0.569

- Q1, Q2, and Q3 are all using SC (shield closed) templates for the respective qubit
- We use two templates for Q4 due to the quality of the data. The amplitudes of the SC data varies more than it does in other qubits; using this template leads to much lower efficiency. The SO (shield open) template is more representative of the data for the SO configuration, as well as the Ba and Cs configurations.

Correlated Qubit Rates (Efficiencies Incorporated)

- Q1 & Q2 Rates (jumps/hour)
  - SC: 0.23
  - SO: 0.88
- Q3 & Q4 Rates
  - SC: 0.14
  - SO: 0.88





Credit to Arianna

Summary

- Qubit Errors: Any loss of information

Correlated Errors + Quantum Computing = **BAD**

Correlated Errors + Particle Detection = **GOOD**

- Correlated Errors are good news in particle detectors as they indicate energy deposits

- How well does the jump detection code find jumps greater than 0.1 e?

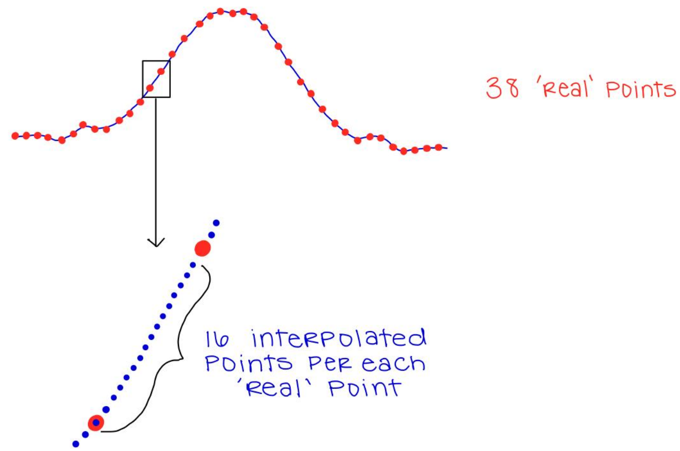
	Q1	**Q2**	**Q3**	**Q4 SC**	**Q4 SO**
Eff.	0.827 ± 0.01	0.794± 0.01	0.872 ± 0.03	0.723 ± 0.02	0.735 ± 0.05

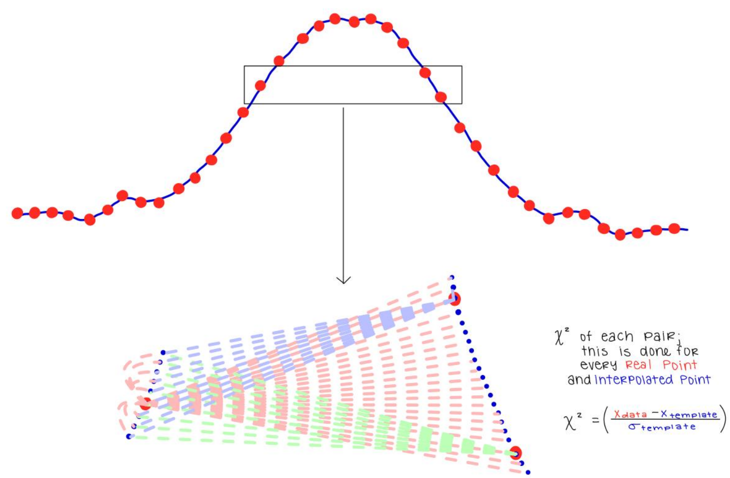
- Results Coming Soon !!

Works Cited

- O'Malley Dissertation 2016
- Wilen et. al. 2021
- McEwan et. al. 2021

Back Up


38 'Real' Points
16 interpolated
points per each
'Real' point


χ^2 of each pair;
this is done for
every Real Point
and Interpolated Point
$\chi^2 = \left(\frac{X_{data} - X_{template}}{\sigma_{template}}\right)$

1 column for each interpolated point

1 row for each real point →

$$\begin{bmatrix} 0 & \chi^2_{0\,0} & \chi^2_{0\,1} & \chi^2_{0\,2} & \chi^2_{0\,3} & \cdots & \chi^2_{0\,604} & \chi^2_{0\,605} & \chi^2_{0\,606} & \chi^2_{0\,607} \\ 1 & \chi^2_{1\,0} & \chi^2_{1\,1} & \chi^2_{1\,2} & \chi^2_{1\,3} & \cdots & \chi^2_{1\,604} & \chi^2_{1\,605} & \chi^2_{1\,606} & \chi^2_{1\,607} \\ 2 & \chi^2_{2\,0} & \chi^2_{2\,1} & \chi^2_{2\,2} & \chi^2_{2\,3} & \cdots & \chi^2_{2\,604} & \chi^2_{2\,605} & \chi^2_{2\,606} & \chi^2_{2\,607} \\ 3 & \chi^2_{3\,0} & \chi^2_{3\,1} & \chi^2_{3\,2} & \chi^2_{3\,3} & \cdots & \chi^2_{3\,604} & \chi^2_{3\,605} & \chi^2_{3\,606} & \chi^2_{3\,607} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ 76 & \chi^2_{76\,0} & \chi^2_{76\,1} & \chi^2_{76\,2} & \chi^2_{76\,3} & \cdots & \chi^2_{76\,604} & \chi^2_{76\,605} & \chi^2_{76\,606} & \chi^2_{76\,607} \\ 77 & \chi^2_{77\,0} & \chi^2_{77\,1} & \chi^2_{77\,2} & \chi^2_{77\,3} & \cdots & \chi^2_{77\,604} & \chi^2_{77\,605} & \chi^2_{77\,606} & \chi^2_{77\,607} \\ 78 & \chi^2_{78\,0} & \chi^2_{78\,1} & \chi^2_{78\,2} & \chi^2_{78\,3} & \cdots & \chi^2_{78\,604} & \chi^2_{78\,605} & \chi^2_{78\,606} & \chi^2_{78\,607} \\ 79 & \chi^2_{79\,0} & \chi^2_{79\,1} & \chi^2_{79\,2} & \chi^2_{79\,3} & \cdots & \chi^2_{79\,604} & \chi^2_{79\,605} & \chi^2_{79\,606} & \chi^2_{79\,607} \end{bmatrix}$$

χ^2 saved as 80 x 608 matrix

Get combined χ^2

$$\chi^2_{combo}[n] = \frac{1}{n+1} \sum_{i=0}^{n} \chi^2[i,]$$

$$\begin{bmatrix} 0 & \chi^2_{0\,0} & \chi^2_{0\,1} & \chi^2_{0\,2} & \chi^2_{0\,3} & \cdots & \chi^2_{0\,604} & \chi^2_{0\,605} & \chi^2_{0\,606} & \chi^2_{0\,607} \\ 1 & \chi^2_{1\,0} & \chi^2_{1\,1} & \chi^2_{1\,2} & \chi^2_{1\,3} & \cdots & \chi^2_{1\,604} & \chi^2_{1\,605} & \chi^2_{1\,606} & \chi^2_{1\,607} \\ 2 & \chi^2_{2\,0} & \chi^2_{2\,1} & \chi^2_{2\,2} & \chi^2_{2\,3} & \cdots & \chi^2_{2\,604} & \chi^2_{2\,605} & \chi^2_{2\,606} & \chi^2_{2\,607} \\ 3 & \chi^2_{3\,0} & \chi^2_{3\,1} & \chi^2_{3\,2} & \chi^2_{3\,3} & \cdots & \chi^2_{3\,604} & \chi^2_{3\,605} & \chi^2_{3\,606} & \chi^2_{3\,607} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ 76 & \chi^2_{76\,0} & \chi^2_{76\,1} & \chi^2_{76\,2} & \chi^2_{76\,3} & \cdots & \chi^2_{76\,604} & \chi^2_{76\,605} & \chi^2_{76\,606} & \chi^2_{76\,607} \\ 77 & \chi^2_{77\,0} & \chi^2_{77\,1} & \chi^2_{77\,2} & \chi^2_{77\,3} & \cdots & \chi^2_{77\,604} & \chi^2_{77\,605} & \chi^2_{77\,606} & \chi^2_{77\,607} \\ 78 & \chi^2_{78\,0} & \chi^2_{78\,1} & \chi^2_{78\,2} & \chi^2_{78\,3} & \cdots & \chi^2_{78\,604} & \chi^2_{78\,605} & \chi^2_{78\,606} & \chi^2_{78\,607} \\ 79 & \chi^2_{79\,0} & \chi^2_{79\,1} & \chi^2_{79\,2} & \chi^2_{79\,3} & \cdots & \chi^2_{79\,604} & \chi^2_{79\,605} & \chi^2_{79\,606} & \chi^2_{79\,607} \end{bmatrix}$$

← row 0 is the 0th row of χ^2 matrix

Intro to Quantum Computing at Fermilab

Dilution Refrigerators: cryogenic cooling device that cools materials down to the millikelvin scale

- LOUD
  - Oxford Proteox
- **NEXUS (Northwestern Experimental Underground Site)**
  - MINOS Cavern
- **QUIET (Quantum Underground Instrumentation Experimental Testbed)**
  - MINOS Cavern
  - Oxford Proteox

Newly commissioned QUIET cleanroom

What are we cooling down in the fridges?

Correlated Qubit Jumps

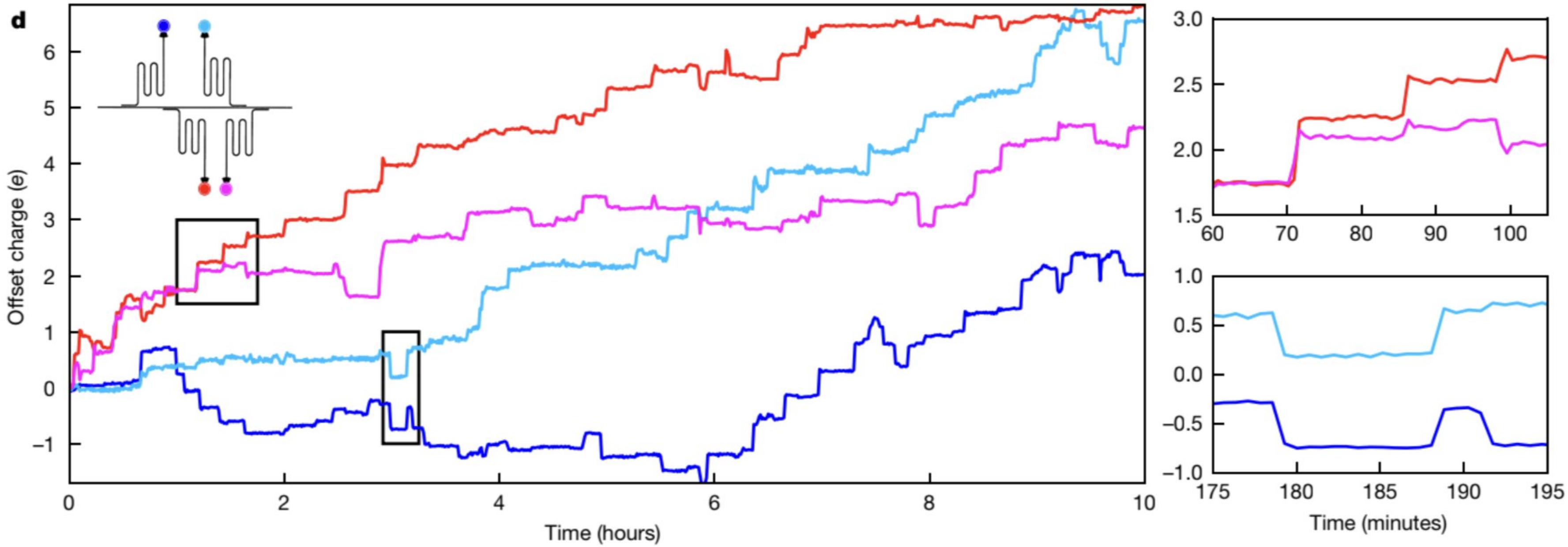


Image Credit: Wilen et. al. 2021