Fermilab Core HEP Competences: from Detectors, to Quantum Networks, to Dark Matter

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• The Quantum S&T program effort, outside of SQMS scope, resides in the Quantum Division (formerly known as FQI) within the new Emerging Technologies Directorate (ETD), and the Theory Division within the Particle Physics Directorate (PPD). Both ETD and PPD organizations provide effort towards SQMS activities.

• The Quantum Division houses the Quantum S&T “base” program, supported by competitive awards from DOE/HEP (QuantISED), DOE/ASCR, and private foundations, as well as Fermilab’s QSC scope.
Fermilab Core HEP Competences

- Advancing HEP science requires unprecedented sensitivities which goes beyond conventional HEP approaches
- Quantum S&T has the potential to deliver such sensitivity
- System engineering, detectors, electronics, fast timing, controls, etc.
Fermilab Core HEP Competences

• In addition our research might enable applications beyond HEP & new sensor capabilities

• Overarching goal is to realize distributed quantum sensors

• When realized quantum networks (QNETs) will enable impactful applications outside HEP

• SNSPD (QNETs sensor) is a powerful tools for discovery
Quantum Internet Vision

Quantum Computer Networking

Long-distance quantum coherence

Quantum-enhanced security

arxiv:2203.16979
arXiv:2311.01930
Quantum Sensors (SNSPD)

- Single photon (heat) triggers detector out of superconductor state
- Resistance quickly (ps) jumps to few kΩ → detector current into readout
- Highest performance single-photon detector, from UV to mid-infrared
- Operating temperature: 1-4 Kelvin

more on quantum sensors in A. Chou’s presentation
Quantum Communication Enabler: SNSPDs

SNSPD Has Achieved:

- > 90% system efficiency ✓
- Low dark count rate $1 \times 10^{-5}$Hz ✓
- Record time resolution ~3ps ✓

Korzh et al, Nature Photonics (2020)
Chiles et al, PRL (2022)
Quantum Networks: towards a Quantum Internet

Current focus: deploy a multi-node, multi-user metropolitan scale quantum network in the greater Chicago area.

Leveraging Fermilab competencies in precision timing, controls, network architecture, and systems integration

Long-term vision: enable security, sensor, and computing applications, following the DOE Quantum Internet Blueprint
Next Quantum Network Initiative

New DOE Project: **Advanced Quantum Networks (A-QNET)**

More Nodes; Longer distances; Higher Rates; Hybrid free-space to fiber
Large Collaborative Effort

More than 30 active members: students (grad&undergrad), postdocs, engineers
Entanglement-enabled Communication
Entanglement enabled Communication

- ALICE
- CHARLIE
- BOB

- INCOMING PHOTON
- BELL STATE MEASUREMENT
- CLASSICAL CHANNEL
- QUANTUM CHANNEL
- ENTANGLED PHOTON PAIR
- UNITARY TRANSFORMATION
- TELEPORTED PHOTON
In this paper we present an efficient BSM for time-bin qubits encoded into telecommunication wavelengths. Arguably, the best detectors today are based on the transition of a superconducting nanowire into the resistive state, and many benchmark results have been reported with these SNSPDs. This includes dead-times as small as 10 ns [19,20], and restricted BSMs with time-bin qubits to projections onto $|\psi^-\rangle$. This includes the demonstrations reported in [13–15] and [17].

Recent years have seen great progress in the development of single-photon detectors for single photon detectors (SPDs), which are widely used for quantum communication applications. The detectors cannot detect a subsequent photon. For example, for commercial InGaAs-based SPDs with dead-times of 2 ns and 10 ns and quantum detection efficiencies of 15%, into account, the highest efficiency of a BSM for time-bin qubits is currently thus only around 1%. This includes the demonstrations reported in [13–15] and [17].

For instance, when implementing a BSM for polarization qubits, a projection onto $\mathcal{B}_i$, so-called time-bin qubits. Time-bin qubits are particularly well suited for approaches to Bell state analysis uses a 50/50 beam splitter followed by single-photon detectors of the experimental setup. The results of our measurements are presented and discussed in section 3.

The remainder of this article is structured as follows. In section 2 we describe the single photon detectors employed to perform the measurements, and in section 3 we present the details of the experimental setup. The results of our measurements are presented and discussed in section 3.

**Challenge:** Increase detector efficiency with negligible dark count rate and excellent time resolution
Fermilab Quantum Network (FQNET)

- Multiple deployed QNodes at Fermilab (D0, FCC, IERC*) and at ANL
- Demonstrated Quantum Teleportation and Swapping with record high fidelities

Deployed infrastructure at D0-QNode

Including multiple EPS, SNSPDS, high-speed electronics and dedicated DAQ
FNAL/Caltech Quantum Networks

Use telecom (1536 nm) photon qubits

Cutting-edge optics, high-speed electronics and quantum sensors

Quantum Indistinguishability
FNAL/Caltech Quantum Networks

Entanglement Generation

Quantum Sensor: SNSPDs

Teleportation Monitoring
FNAL/Caltech Quantum Networks

The results: PRX QUANTUM 1, 020317 (2020)

Hong-Ou-Mandel Effect

Teleportation Fidelity

Record-high teleportation fidelity over 44 km of fiber

https://www.caltech.edu/about/news/quantum-internet-tested-caltech-and-fermilab
High precision timing (3 ps) synchronization

Classical resources needed for network operation

Coexistence of quantum and classical signal achieved
Fermilab Quantum Network

Complex protocols: **Entanglement Swapping**

Underpins long-distance quantum communication
Fermilab Quantum Network

Teleportation of entanglement!

Underpins long-distance quantum communication
Swapping Experimental Setup

Real world implementation

Challenging experiment with several cutting edge technologies
Entanglement Swapping

Preliminary experimental results

Hong-Ou-Mandel Effect

Swapping Visibility

4-fold HOM dip with high visibility

High swapping visibility (x-basis)
HEP Dark Matter Enabler

SNSPD R&D recently achieved:

- Ultra-low energy sensitivity (40 meV)
- Opens up unexplored DM regions
- Large area single device (> mm$^2$)
- Compatible with HEP needs
- Ultra-low dark counts rate
- Critical for HEP applications

**Ultra-low energy sensitivity**

First large area SNSPD operation

Dark count characterization
Deeper into the IR: New probes for fundamental physics

- sub-MeV DM
- sub-eV axions
- dark photons
- Exoplanet transit spectroscopy
Accelerate SNSPD R&D

DOE project for R&D towards large area, ultra-low energy sensitivity, and ultra-low dark count rate
Axions

- Axions solve the strong CP problem and a dark matter candidate
- Axion-photon coupling under B-field converts axion to photon
- Past experiments use resonant cavities to detect \( \sim \mu \text{eV} \) axions, but:
  - The cavities need to scan for unknown axion mass
  - Technologically and practically difficult to reach higher axion masses

See more details in A. Chou’s presentation
Axions Landscape

Large region of parameter space unexplored
Axions Landscape

New SNSPDs can probe new parameter space

BREAD experiment with SNSPD
All Pieces in Place for Pilot Experiment
Dark Photon Pilot Experiment

New SNSPDs can probe new parameter space

![Graph showing Dark photon mass and kinetic mixing with different experimental conditions such as 1 day, A = 0.7 m², 10 days, A = 10 m², 1000 days, A = 10 m², and 1000 days, DCR/100, A = 10 m².](image)
Unique Testing Capabilities at Fermilab

Unique infrastructure to test new SNSPDs

- Absolute efficiency characterization
- Dark count rate dependence on T
- Cosmic ray response
- New underground facilities

Christina Wang
New Lederman Fellow
SCGSR @ FNAL
SNSPD Vision for HEP S&T Applications

- sub-MeV DM
  - Cryogenic Scintillator readout

- Distributed quantum sensors
  - Long-distance quantum coherence
  - Telescopes (on Earth or in space)

Towards the quantum internet

- Ultra low-threshold millicharged particles

- Time-resolved astrophysics
  - Entangled states distributed over quantum networks can link detectors together coherently, improving sensitivity and directional resolution; a leading example is detection of wave-like dark matter.
List of Accomplishments (QNETs)

- Record high fidelity quantum teleportation. PRX Quantum 1, 020317
- Entanglement distribution between Argonne and Femi National Labs. IEEE JQE, 59,1-7
- High precision clock synchronization between Argonne and Femi National Labs. IEEE JQE, 59,1-7
- Design and Implementation of the IEQNET, in IEEE TQE, 3, 1-20
- Entanglement Swapping at Fermilab. Samantha Davis at APS 2023
- High fidelity entanglement swapping (teleportation of entanglement). In preparation
- The Illinois Express Quantum Network (IEQNET). DOE Award 2018-2023
- Advanced Quantum Networks (AQNET) for Scientific Discovery. DOE Award 2023-2026
List of Accomplishments (SNSPD R&D)

- Demonstration of **sub-3 ps** temporal resolution with a SNSPD. *Nature Photonics*, 14, 250–255 (2020)

- Free-space coupled SNSPD with **low dark counts** (world-best). *Optica* 8, 1586-1587 (2021)

- **Large active-area** superconducting microwire detector array with single-photon sensitivity in the near-infrared. *Appl. Phys. Lett.* 122, 243506 (2023)

- **First** in depth characterization of SNSPD **dark count rate for HEP experiments**. To be submitted to *Appl. Phys. Lett.*

- Impedance-matched differential superconducting nanowire detectors (first milestone towards ultra-low jitter). *arXiv*:2108.07962

- Accelerate SNSPD technology for HEP Discoveries. *DOE Award 2023-2026*