# Displaced A' with SeaQuest

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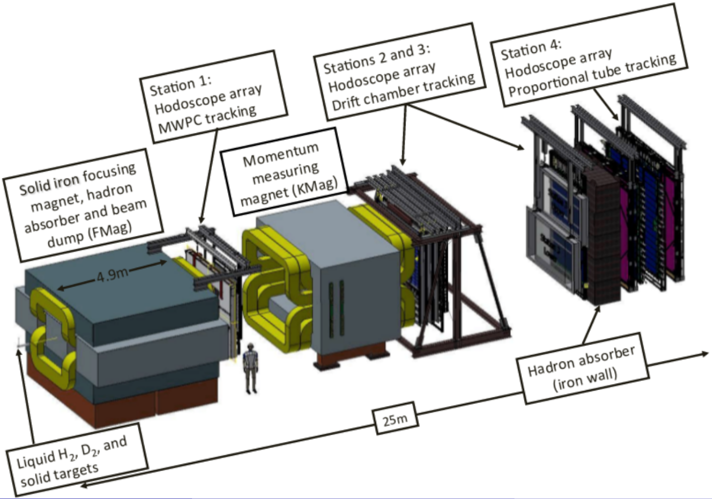
SeaQuest Collaboration

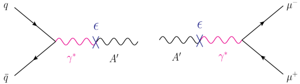
# The SeaQuest facility

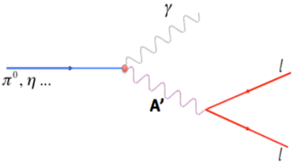
- Fixed target muon spectrometer, Fermilab 120 GeV proton beam
- Measurement of the nucleon sea quark distribution using Drell-Yan
- Parasitic searches for dark photons approved 2015

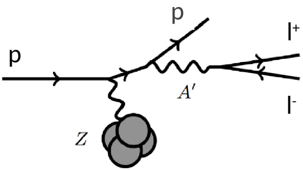


# Production and signatures at SeaQuest

- Three dominant production mechanisms: Drell-Yan, meson decay, proton bremsstrahlung
- Branching fraction to $\mu^+\mu^-$ is significant at all $m_{A'} > 2m_\mu$; decay length depends on $\epsilon$
- Two signatures: mass resonance and (at small $\epsilon$) displaced vertices

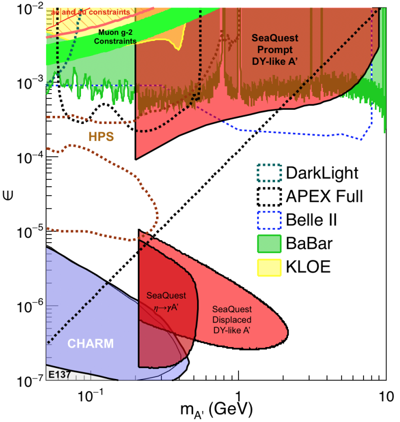


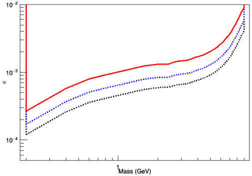



# SeaQuest reach

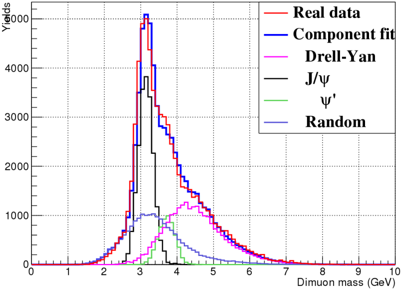
- Bump-hunt and vertexing reach; vertexing reach shows Drell-Yan and $\eta$-decay production separately
- Models and assumptions are from last year
- Reach contours with different beam times:
  - Red: 5 days (in the bag)
  - Blue: 1 month (possible in 2018)
  - Black: 4 months

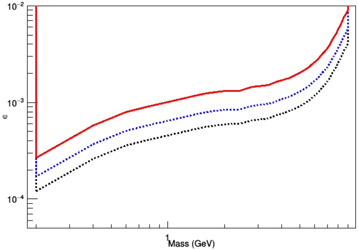


# SeaQuest searches for dark photons: prompt

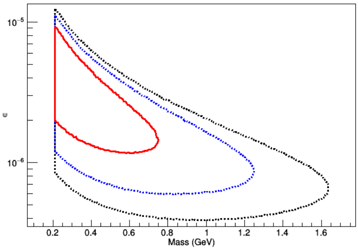
- Prompt dark photons (large $\epsilon$): look for a mass bump above the smooth background
- SeaQuest trigger excludes low masses due to trigger rate limitations; DAQ upgrade (completed this year) should improve the mass range
- Meson resonances will block parts of the mass range
- Mass resolution is limited by multiple scattering in the beam dump

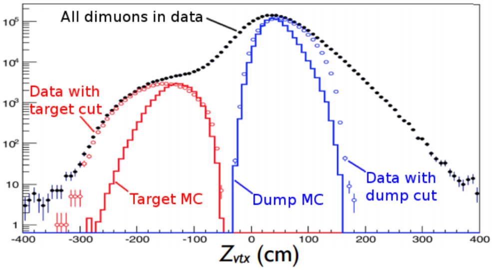


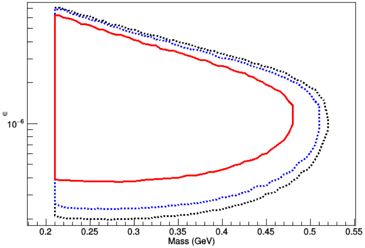



# SeaQuest searches for dark photons: displaced vertex

- Small $\epsilon$: look for dimuon vertices deep inside the beam dump
- Requires a new trigger for low-mass displaced vertices, which was commissioned this year
- Vertex tails have not been studied, particularly at low mass

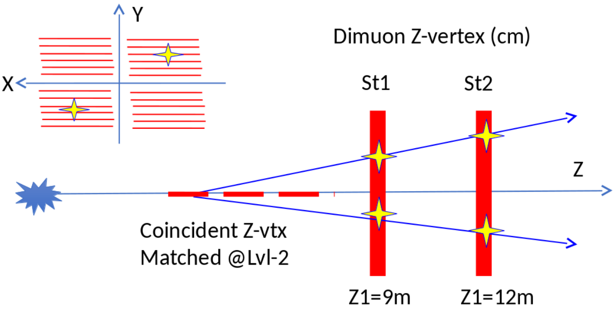


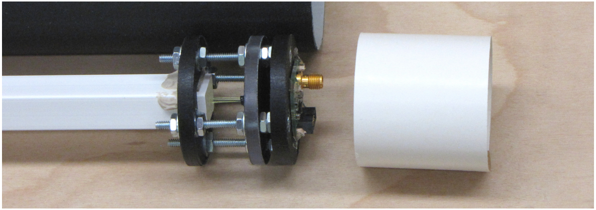
# Displaced vertex trigger

- Two stations of fine-grained scintillator hodoscopes measure track Y
- FPGA trigger extrapolates tracks to the beam plane and fires on pairs of tracks with matching Z



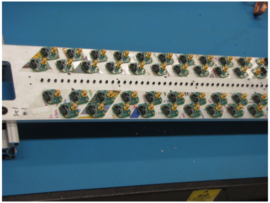
# Trigger hodoscopes

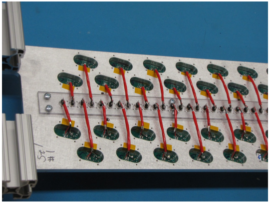
- Extruded scintillator bars detect charged particles, wavelength-shifting fibers collect light and transport it to SiPMs
- Station 1: four boxes, 80 $1 \times 1$ cm bars each
- Station 2: four boxes, 50 $2 \times 2$ cm bars each



# Readout and services

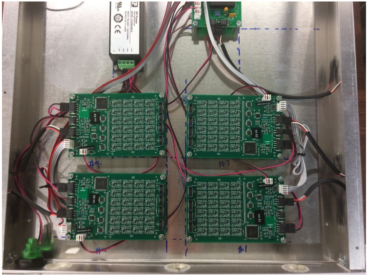
- Postage-stamp preamps read out the SiPMs and send signals to discriminators
- Power supplies provide independent control of every SiPM bias voltage
- Trigger decision made using CAEN V1495 FPGA boards





# Power supply

- SiPMs need individually controllable bias voltages (520 channels!); preamps need 6V
- SiPM bias board design contributed by Fermilab, modified to match our requirements
  - Each board takes bulk HV and LV supplies, regulates down 24 bias voltages and a single 6V supply
  - Voltage and current readbacks for all channels, plus temperature readout
- 24 “power boards” total, housed in 6 “power boxes”

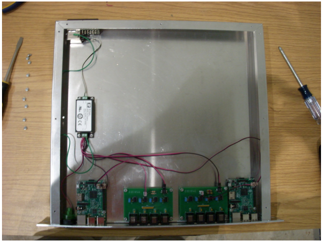


# Power supply: distribution

- “Distribution board” passes bias and 6V into the box

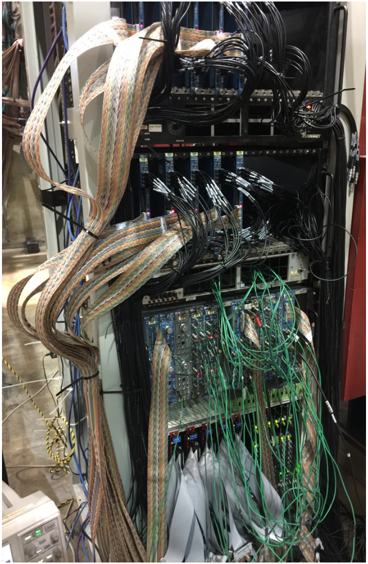
# Power supply: control

- Power boards are controlled using I2C protocol; we developed a system to control all 24 boards from a pair of Raspberry Pi computers
  - “Mux board” in each power box contains an I2C switch and an I2C buffer to drive a long Ethernet cable
  - Cables run to “master boards” with corresponding buffers; single “master box” holds Pis and master boards
- This solution keeps sensitive electronics away from the beam, and simplifies control software
- I2C is widely used and this scheme can be used to network any set of boards with I2C control



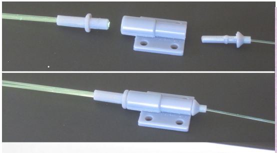
# Readout electronics: cabling

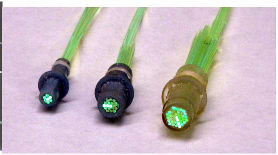
- Short coaxial cables connect preamp outputs to patch panel
- Long coaxial cables connect patch panel to CAMAC discriminators
- Ribbon cables connect discriminators to trigger boards and TDCs



# Calibration system

- LED calibration system tests/monitors function of all channels
- LED pulser boards generate narrow light pulses
- 3D-printed fiber couplers fan out a single pulser channel from a commercial connector to 19 bare fibers
- Fibers couple light into the scintillator bars



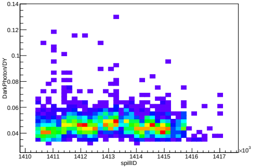


# Trigger FPGA development

- Dark photon trigger uses the CAEN V1495 FPGA board (same as E906 trigger)
  - Four “L1” V1495s, one for each quadrant, trigger on displaced single tracks in St-1, St-2, and E906 hodoscope H4
  - “L2” trigger is a coincidence between L1 boards with matching vertex Z
  - Dark photon trigger firmware is based on E906 firmware, with modifications
- Lookup table redesigned for dark photon trigger
- A full quadrant needs 80+50+8=138 inputs per V1495, E906 firmware only supports 96
  - Modified various parts of the E906 firmware (TDC, data format, interface to DAQ software) to allow for up to 160 inputs

# Installation and commissioning

- Trigger hodoscopes installed on the SeaQuest beamline this spring
- Detectors and trigger electronics tested and timed in
- Displaced vertex trigger rate is ∼5% of the SeaQuest Drell-Yan trigger, acceptable for parasitic running
- 5 days of good data taken with the displaced vertex trigger before accelerator shutdown


# Schedule and prospects

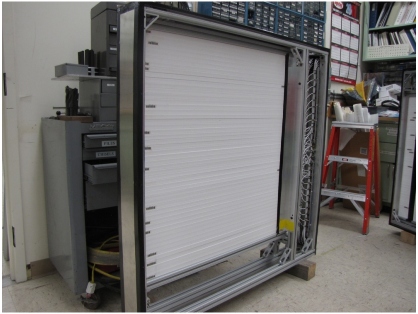
- This year's commissioning data is sufficient to understand the real backgrounds and sensitivity of the displaced vertex search
  - Expect updated reach estimates before next fall
  - Some physics reach may be possible with this data
- SeaQuest will run with polarized target (E1039) in 2018 and 2019: dark photon search will run parasitically
- Possible PID upgrade (using recycled PHENIX EMCal) may add sensitivity to dielectron decay channel

# Backup: Displaced vertex trigger hodoscopes

- Hardware delivered this year:
  - Hodoscope boxes and prototypes
  - Readout and calibration systems
  - Power supply system
  - FPGA trigger
- Installed and commissioned at Fermilab, and recorded physics data

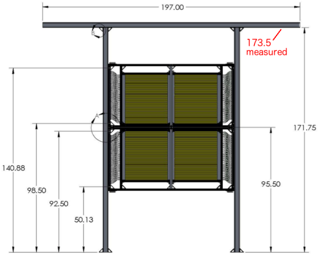
# Backup: Detector design

- Extruded scintillator bars detect charged particles, wavelength-shifting fibers collect light and transport it to the SiPMs
- Station 1: four boxes, 80 1-cm bars each
- Station 2: four boxes, 50 2-cm bars each



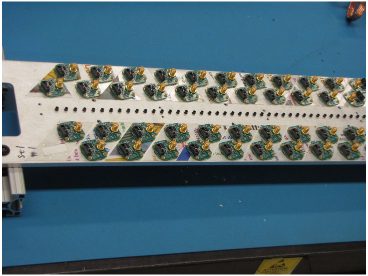
# Backup: Mechanical structure

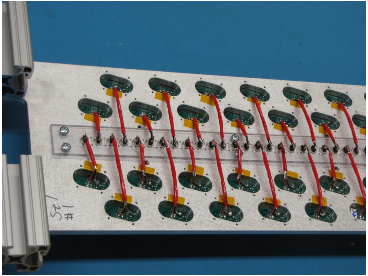
- Frame modified to minimize material in the detector acceptance
- Survey monuments for reproducible positioning
- Boxes are light-tight with patch panels for signals and voltages, ventilation flanges for air cooling (if necessary)
- Quadrants are bolted together using 80-20 hardware, then bolted to I-beams




# Backup: Readout electronics: preamps

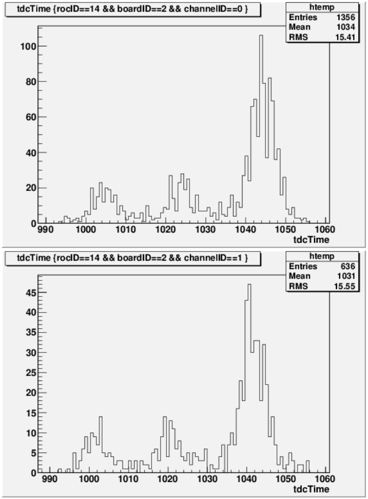
- “Postage stamp” x10 preamp design contributed by Fermilab, with modification to the pulse shaper
- Benchtop tests confirm gain degradation in magnetic field is acceptable
- SiPMs and preamps are mounted on “preamp plate”
- All components electrically isolated from plate to avoid noise pickup
- Twisted-pair pigtail connects SiPM to preamp

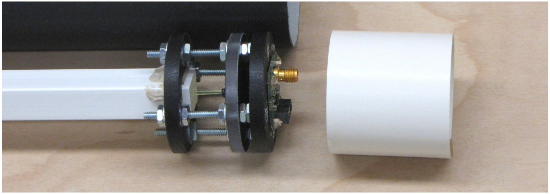




# Backup: Single-bar beam test

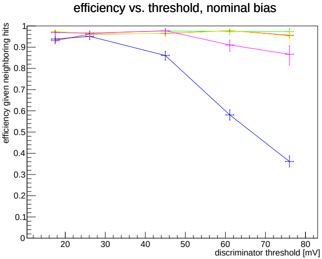
- Single-bar test units: 1-cm and 2-cm units built and tested on the beam at SeaQuest in March
- Plots on right (2-cm on top, 1-cm on bottom) show hit times relative to E906 Drell-Yan trigger
  - Small peaks are random particles from other beam buckets, big peak is in time with the trigger
- Proved the system works with real beam, in the real environment

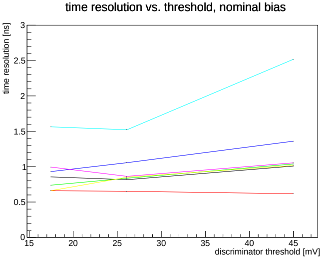


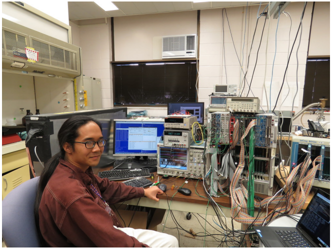



# Backup: Seven-bar cosmic test

- Instrumented the first seven bars of a St-2 hodoscope box, take data with a test setup of the E906 DAQ
- Understand efficiency and time resolution as a function of threshold, debug light collection issues, test different options for the long coaxial cables

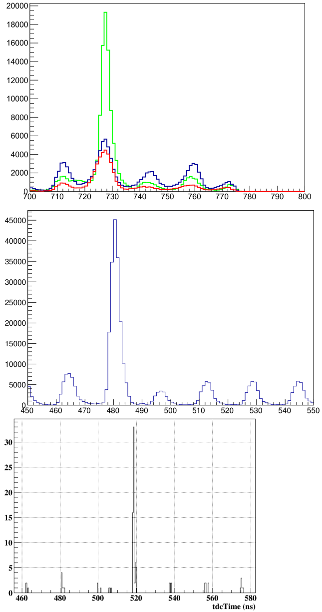


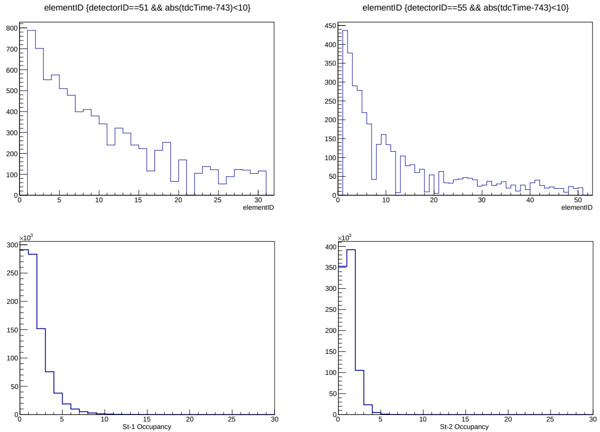
# Backup: Timing in

- Input delays must be adjusted to compensate for time-of-flight and cable delays
- All quadrant triggers must fire in time with each other, and the final dark photon trigger must have the same latency as the E906 DY trigger
- Top: hit times after delay adjustment (green: St1, blue: St2, red: H4)
- Middle: time distribution of one quadrant's trigger signal
- Bottom: time distribution of final dark photon trigger

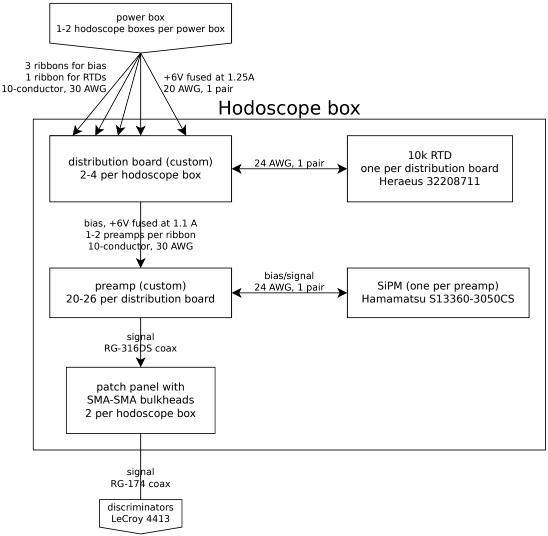


# Backup: Performance

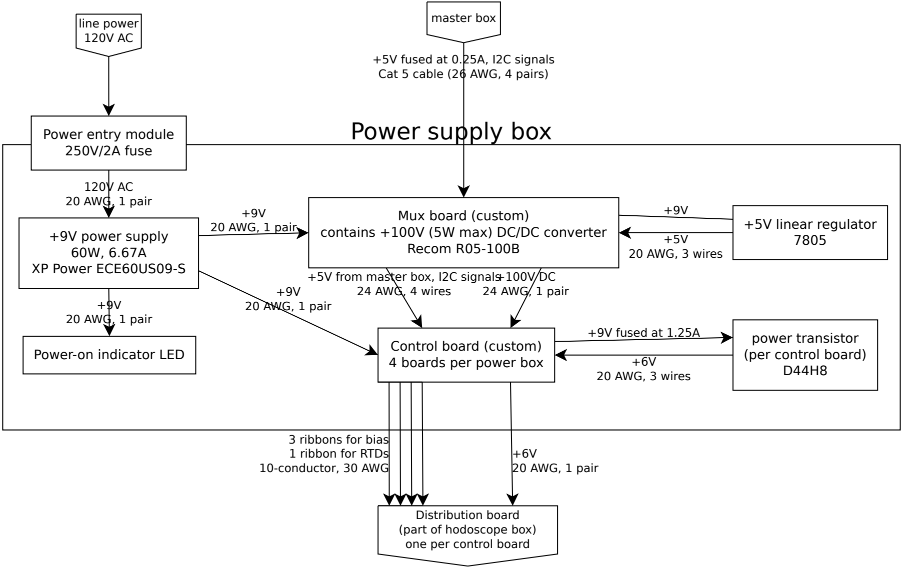
- St-1 on left, St-2 on right; hit rates on top, occupancy on bottom
  - Note: for commissioning, only 30/80 innermost St-1 bars were read out (outer bars do not correspond to displaced tracks)
- Consistent performance aside from a few bad channels



# Backup: hodoscope block diagram



# Backup: power box block diagram



# Backup: master box block diagram