Positron Annihilation into
Dark Matter Experiment

Searching for the Dark Photon with the PADME Experiment

35th International Physics Congress of the
Turkish Physical Society
Bodrum, Turkey, September 4-8 2019

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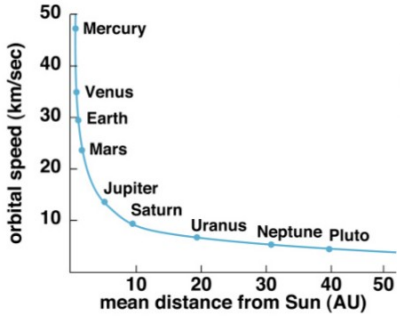
For the PADME Collaboration

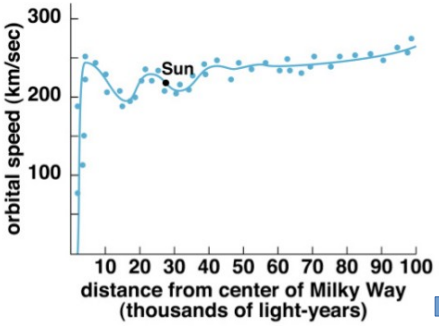
Supported by BG-NSF grant DN08-14/14.12.2016

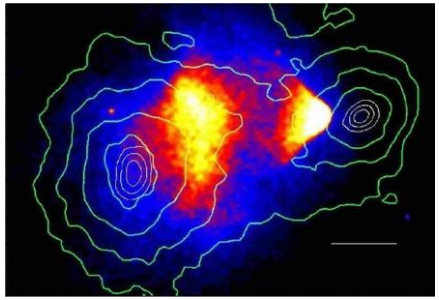
Dark Matter: Evidence and Models

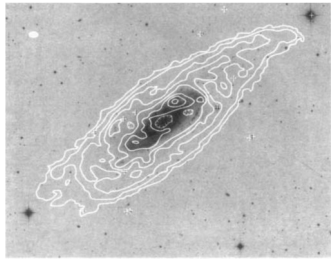
Positron Annihilation into Dark Matter Experiment

- Evidence
  - Galactic rotation curves
  - Cluster velocity distributions
  - Gravitational lensing
  - Intergalactic hot gas
- Possible Explanations
  - MAssive Compact Halo Objects
  - MOdified Newtonian Dynamics $GMm/r^2 = m\mu(a/a_0)*a$
  - New physics: Weakly Interacting Massive Particle models





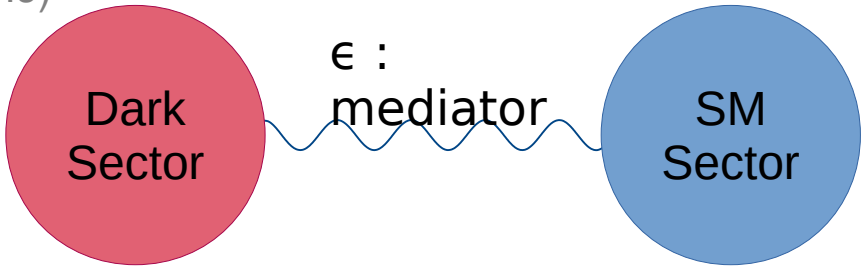




A DM Model: The Dark Sector

Positron Annihilation into Dark Matter Experiment

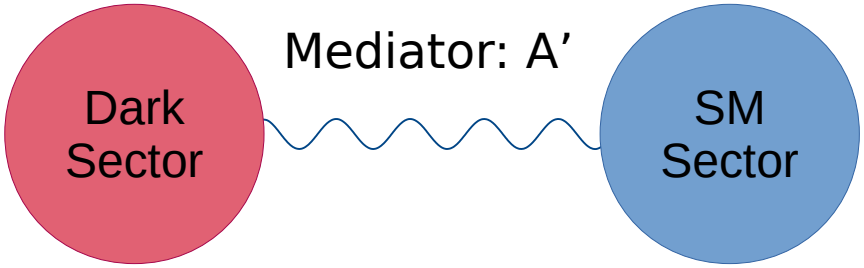
- A Dark Sector (DS) of particles neutral to SM with new “hidden” interactions
- Portals are possible mediator particles of different forms (scalars, fermions, vectors, axions) interacting weakly with the two sectors
- The DM can be the mediator, or a DS particle coupled to a portal via hidden interaction; different DM portals can co-exist
- Reasons to consider it:
  - Wide range of mass and coupling ranges allowed
  - Can explain other physics problems:muon g-2 anomaly, ^{8}Be anomaly, etc.
  - The vector portal DS model is among the most tractable models, theoretically and experimentally

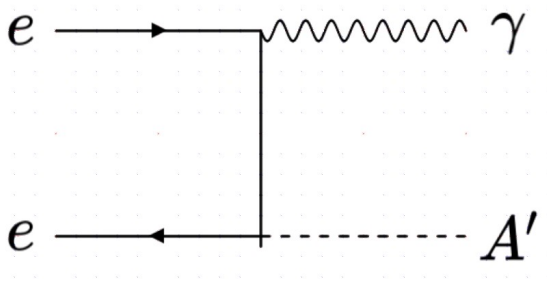


The Minimal DS Model: The Dark Photon

Positron Annihilation into Dark Matter Experiment

- Minimal extension of the SM:
- DS adding single additional U(1) Symmetry
- A single vector mediator particle coupled to the two sectors: the DP
- Can appear anywhere alongside ordinary photons, e.g. annihilation, bremsstrahlung, etc.
- Can address g-2, abundance of antimatter in cosmic rays, DM scattering signals
- If DP is the lightest DS particle, the model is dependent only on two parameters :
  - Coupling constant
  - Mediator mass



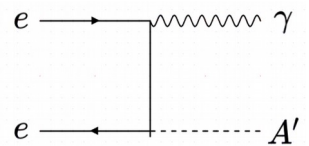


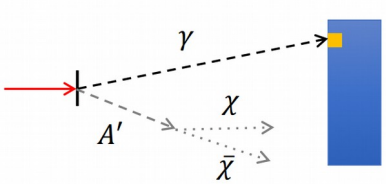
The Dark Photon: A Search with PADME

Positron Annihilation into Dark Matter Experiment

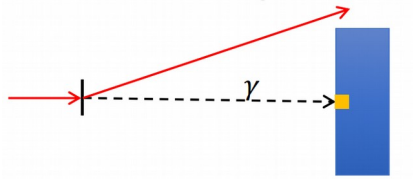
- Missing mass method for decays to the invisible state from measurements of initial and final state:
  $M^2_{miss} = (p_{e+} + p_{e-} - p_\gamma)^2$
- Positron initial state is determined by the accelerator properties
- A' is a product of e^+e^- collisions from positron beam on a thin, low-Z target, tuned for optimal annihilation and bremsstrahlung cross-sections
- Background elimination is key to detecting the signal

Invisible decays:

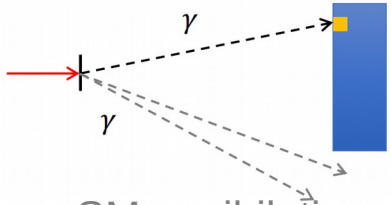




Background sources:



Bremsstrahlung



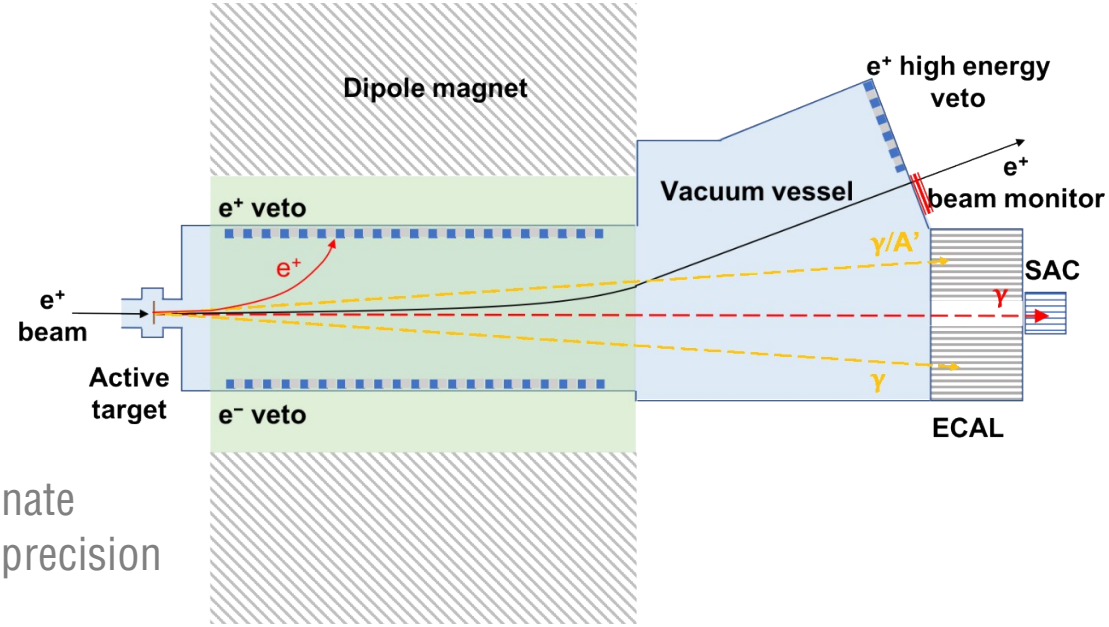
SM annihilation

Positron beam!

The PADME Experiment: An Overview

Positron Annihilation into Dark Matter Experiment

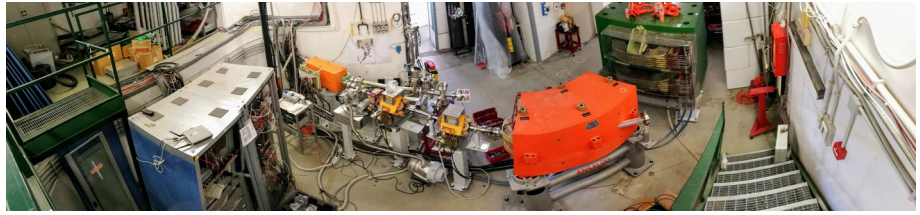
- Positron beam arrives from BTF@DAΦNE
- Positron bunch strikes active target
- Magnetic field deflects positrons and electrons onto the charged particle detectors
- Calorimeters detect gamma emissions from annihilation and bremsstrahlung events
- Charged particle veto provide timing and e^+ momentum data, allowing to discriminate background and to measure final state with precision
- Reconstruction of the data allows a search for the invisible decay events



Positron Source: BTF@DAΦNE

Positron Annihilation into Dark Matter Experiment

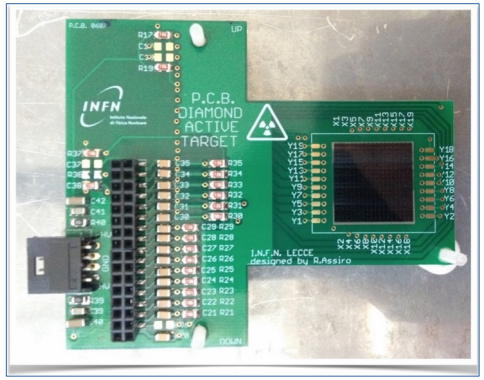
- Energy
  - 550MeV
  - Under 1% energy dispersion
- 49 bunches per second (50 Hz, one shot used for testing)
- ~$25*10^3$ positrons/bunch
- Pulse length from 10ns to 200ns (optimized for PADME)
- Beam quality: σ_{xy} ~1mm, divergence ~1mrad
- Able to provide the number of PoT we ask for: $4*10^{13}$

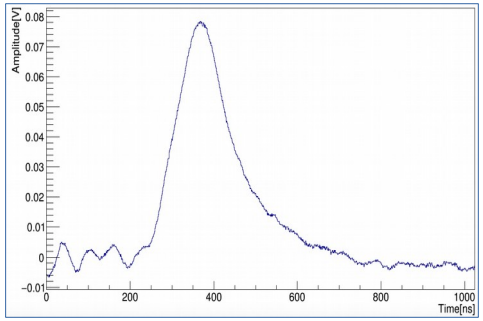


The PADME Detectors: The Active Target

Positron Annihilation into Dark Matter Experiment

- Role:
  - Annihilation target
  - Provides single-bunch X and Y beam profiles
  - Provides information about the beam multiplicity
- Characteristics:
  - Diamond target, low Z-number improves signal/background ratio
  - Area: 20x20mm^2, thickness: 100um
  - Double-sided graphite strips as Ohmic electrodes
    - 1mm pitch, 0.15mm inter-strip distance, ~2.5kΩ
  - Constructed by the Padme team from the University of Salento/INFN Lecce
- Front-end electronics
  - Diamond target inner board, placed between two IDEAS boards
  - 16 channel AMADEUS chips provide readouts for 16X+16Y stripes

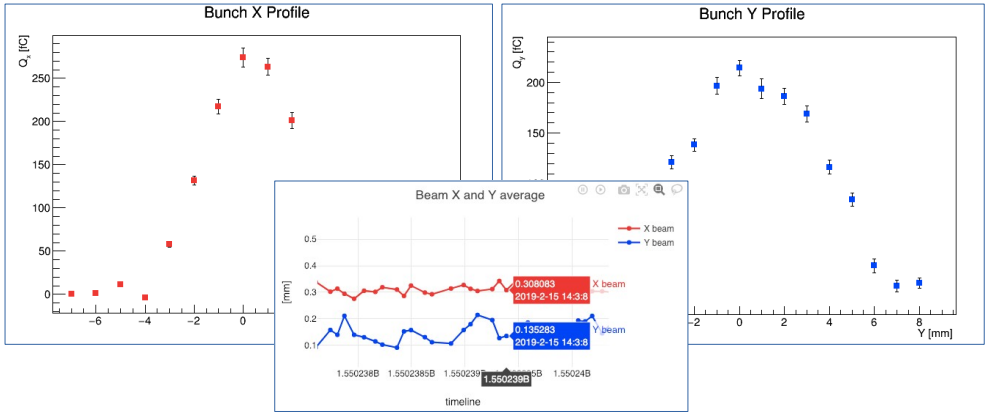


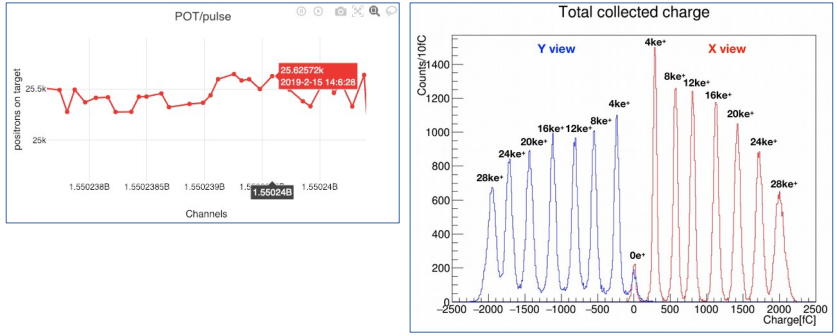


Active Target: Performance

Positron Annihilation into Dark Matter Experiment

- Bunch profile measurements:
  - X, Y measurements with good resolution (σ ~0.062mm) and linearity of response
  - Time-based measurements to track the initial state through the course of the experiment
- Other bunch measurements
  - Provides estimates of the number of positrons on target per bunch (multiplicity)

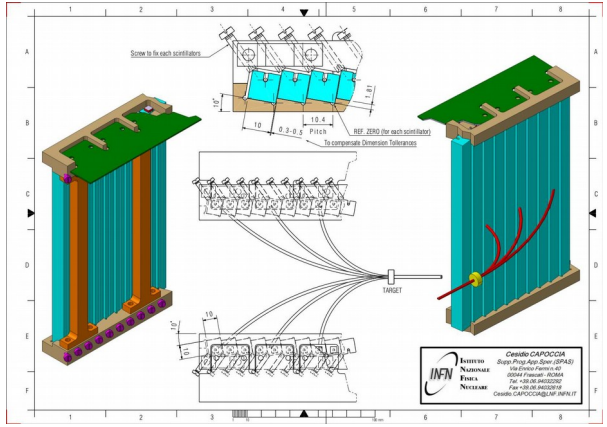


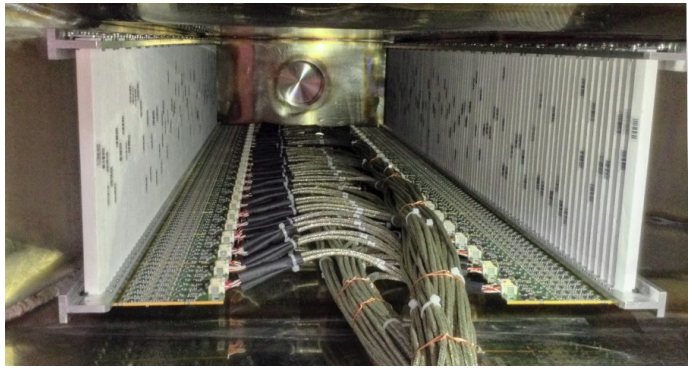


The PADME Detectors: Charged particle veto

Positron Annihilation into Dark Matter Experiment

- Role:
  - Bremsstrahlung background suppression
  - Registration of visible decays
- Requirements:
  - Momentum resolution: 5MeV or better
  - Time resolution: 1ns or better
- Characteristics
  - Plastic scintillators 10x10x178mm^3, glued-in WLS fiber
  - 96 in e^- veto, 90 in e^+ veto, 16 in HEP veto
  - Built by the Sofia University team
- Readout Electronics
  - SiPM front-end electronics inside vacuum chamber
  - Hamamatsu S13360 3x3mm^2 25um cells
  - Power supply/analog readout modules
  - Designed and built at LNF

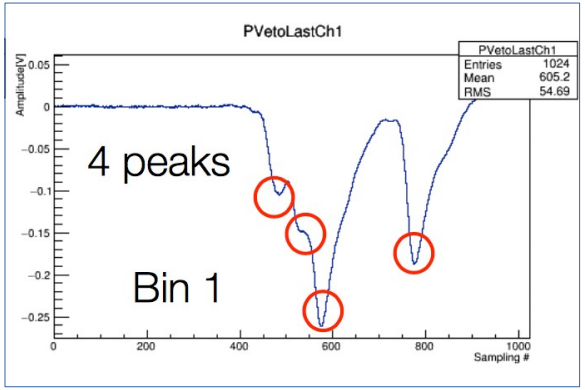


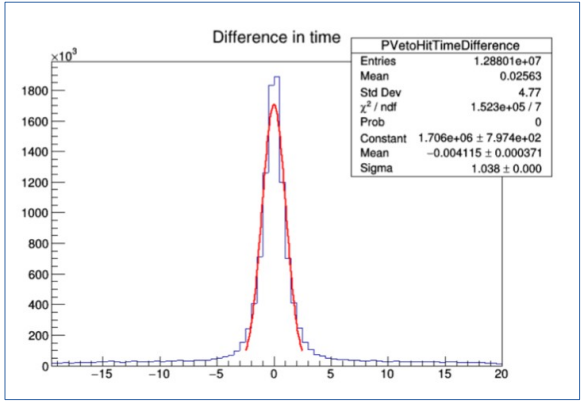


Charged Particle Veto: Performance

Positron Annihilation into Dark Matter Experiment

- Impulse resolution
  - Satisfactory results were shown to be achievable from the detector simulation studies
  - The simulation results were confirmed during initial testing before experiment commissioning to be within the required values
- Time resolution
  - Provisional data analysis shows that time resolutions of 750ps or better are achievable
  - Limited study of correlations between detectors indicate good results, but there is vast room for improvement.

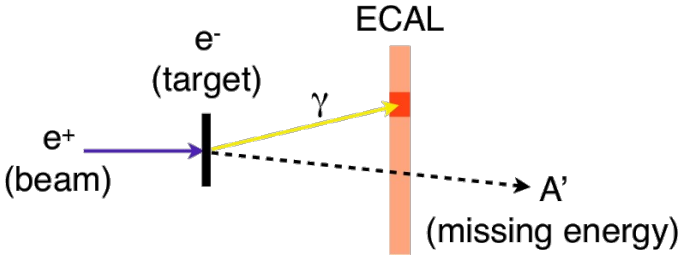


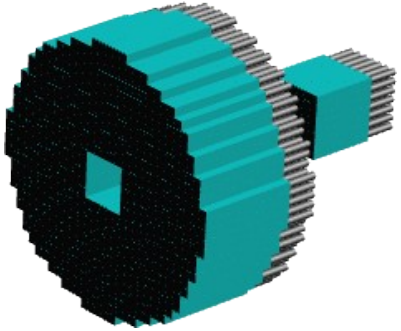


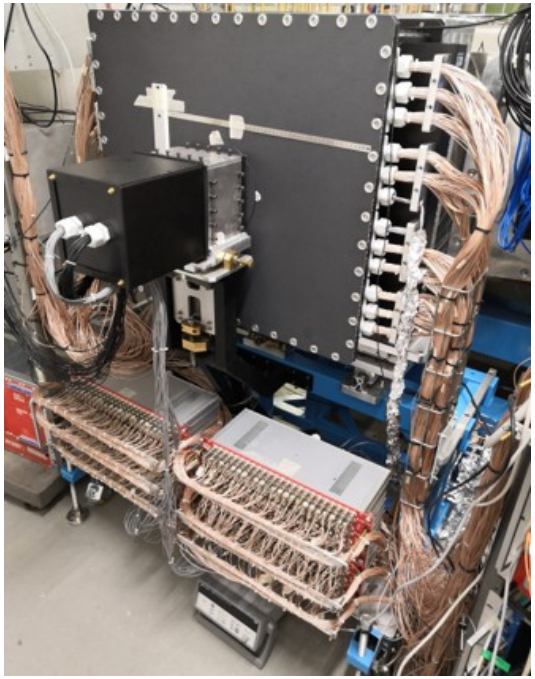
The PADME Detectors: EM Calorimeters

Positron Annihilation into Dark Matter Experiment

- Role:
  - Main detector for annihilation events
  - Suppression of bremsstrahlung background
- Requirements
  - $\sigma_E \simeq (1\text{-}2)\%/\sqrt{E(\text{GeV})}$
  - Cluster time resolution < 2 ns
  - Angular resolution < 2 mrad
  - Angular coverage: 20~93 mrad
  - Angular acceptance: 26~83 mrad
- Fast, central Cherenkov calorimeter for brems.



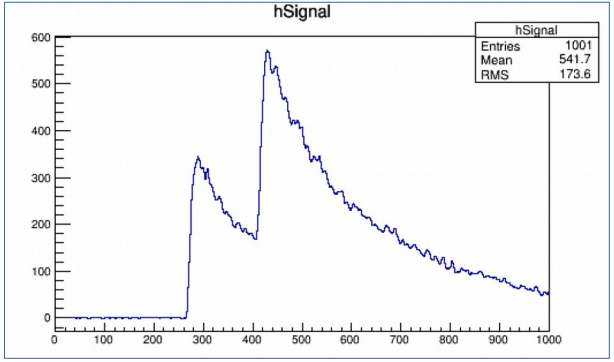


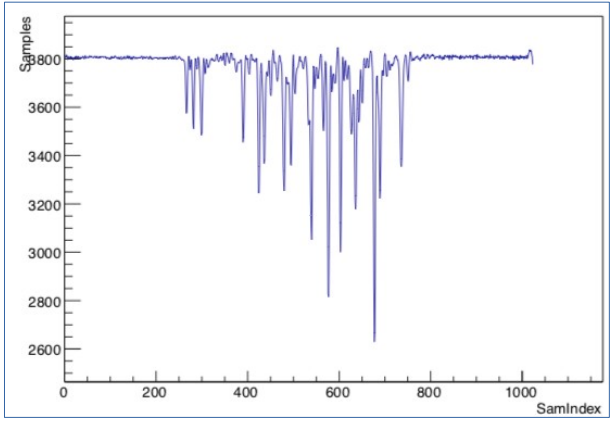


EM Calorimeters: Details and Performance

Positron Annihilation into Dark Matter Experiment

- ECal - High energy resolution calorimeter
  - 616 BGO crystals 21x21x230 mm^3
  - PMT Readout with HZC XP1911
  - Radius of 29 cm at 3.45 from target
  - Central hole (105x105 mm^2) for SAC
- SAC - Small angle calorimeter
  - 25 Cherenkov PbF_2 crystals 30x30x140 mm^3
  - 50 cm behind the ECal
  - PMT Readout with Hamamatsu R13478UV
  - Angular coverage: 0~20 mrad

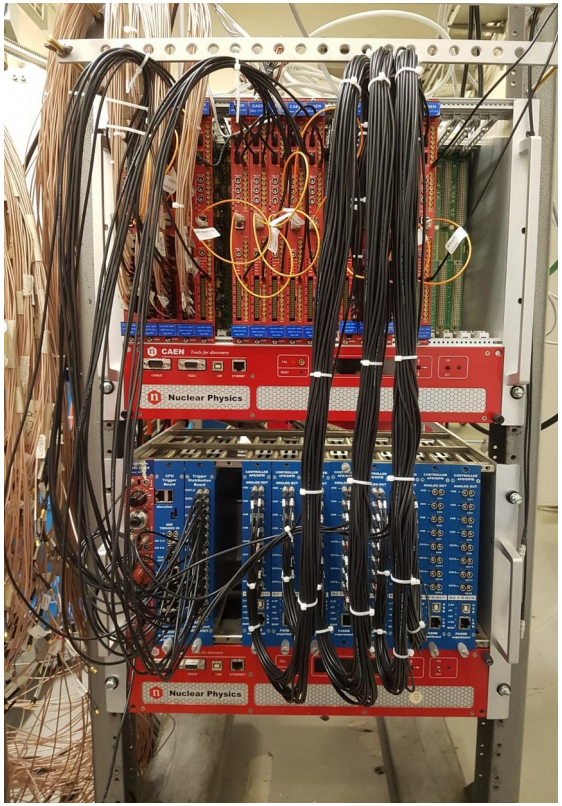




The Padme System: Triggers and DAQ

Positron Annihilation into Dark Matter Experiment

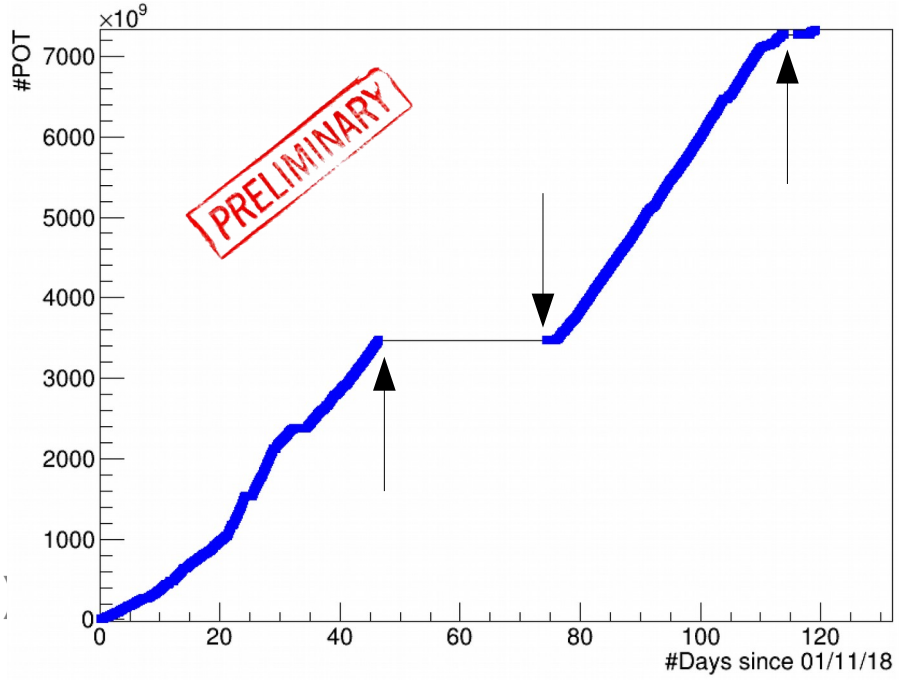
- VME digitizers CAEN V1742
  - Sampling speed of 1-5 Gs/s
  - 12-bit ADC signal range
  - 29 VME Boards
- Triggers
  - 2 Trigger boards
  - CPU trigger system
    - Physics, cosmics and random signals
    - 2x32 channels trigger distribution boards
  - 2 Trigger levels
    - L0: Data collection from single boards without suppression
    - L1: Event merging and selection based on full event information
- Data volume
  - ~900 kB/bunch
  - ~60 MB/s sustained data throughput



Data Collection: Run 1

Positron Annihilation into Dark Matter Experiment

- Run 1 complete
  - November 2018 ~ February 2019
  - 2 weeks maintenance break at the end of 2018
  - Primary positrons since mid-February 2019
- $7*10^{12}$ PoT (~270TB of data) collected, mostly from secondary positrons
- Clear beam background in data (much higher with secondary positrons)
- 20k e^+/bunch allows collection of $4*10^{13}$ events in 1.2 years

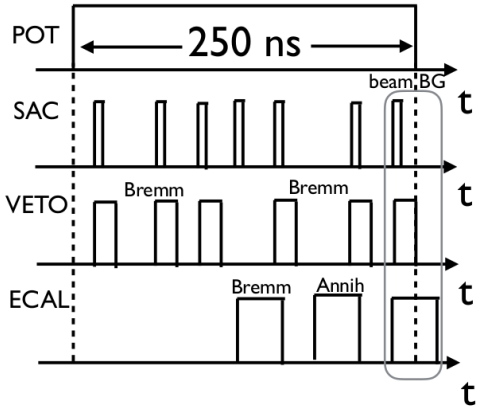


Data Analysis: Pile-ups and "catastrophic" e+

Positron Annihilation into Dark Matter Experiment

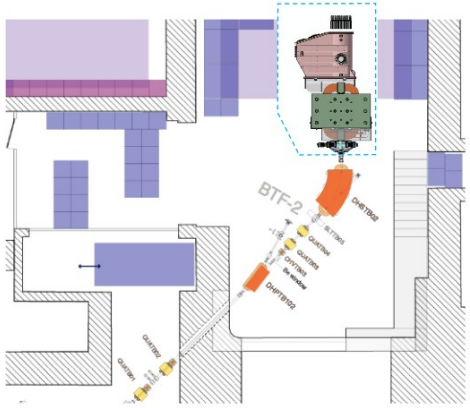
Temporal pile-ups

- Due to high event rate from large PoT/bunch
- Necessitates multi-hit reconstructions



"Catastrophic" e+

- e+ from beam non-gaussian energy tails may bend out of ideal orbits, producing particle showers from contact with beam pipe



Data Analysis: Strategy and Goals

Positron Annihilation into Dark Matter Experiment

- ECal and SAC absolute calibration with 1 positron per bunch
- Veto calibration for the momentum of bremsstrahlung (B) positrons from data with single positron per bunch and B-scan at fixed momentum
- Single channel time calibration
- Establishing the pile-up performance of each detector
- Beam background determination and development of mitigation measures
- High-performance multi-hits reconstruction for each detector based on digitized waveforms
  - Hit efficiency
  - Consecutive hit separation
  - Hit time resolution

PADME Experiment: Current Status

Positron Annihilation into Dark Matter Experiment

- The first experiment to search A' in the invisible channel using missing mass/pulsed beam
- Stable positron beams from LINAC @ BTF
- Detectors and DAQ have reached expected performance
- Collected $7*10^{12}$ PoT from secondary positrons
- Next:
  - Finalize detector absolute calibration
  - Measure physics signals (bremsstrahlung and annihilation) from data
  - Minimize beam background along the beam line
  - Collect $4*10^{13}$ PoT from primary positrons