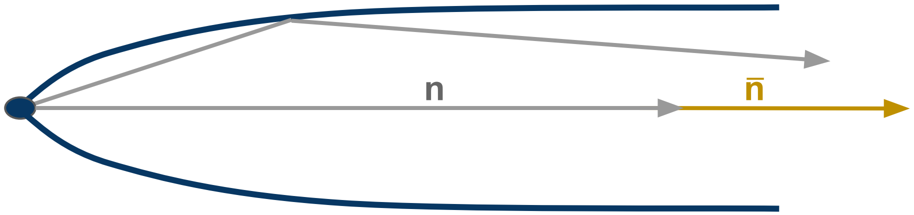

The HIBEAM/NNBAR Calorimeter Prototype

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on behalf of the NNBAR collaboration

Partikeldagarna 2021
Chalmers University, Gothenberg

Stockholm University

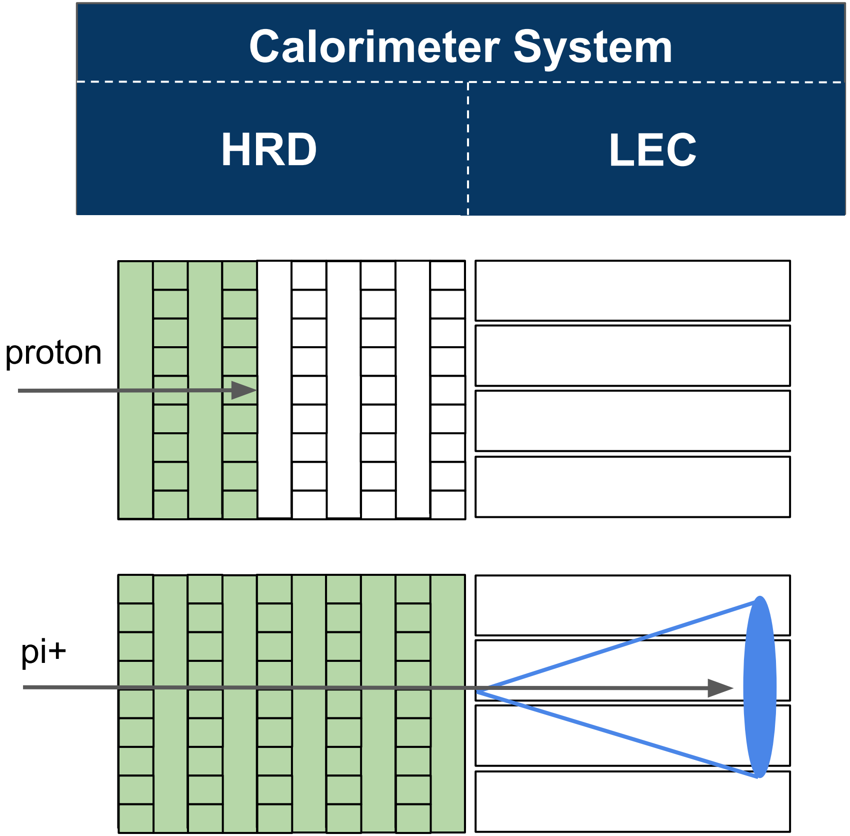
NNBAR

Introduction

- HIBEAM/NNBAR experimental program (see talk by B. Meirose) will be the leading-edge free neutron search for baryon number violation planned to be housed at the ESS [J.Phys.G 48 (2021)]
- Detector must identify neutron-antineutron annihilation event (see talk by S.-C. Yiu)
  - i.e. must reconstruct final state invariant mass of two nucleons (~1.9GeV)
  - This energy is carried mostly by pions (+/-/0) with kinetic energies below ~500 MeV
- These low energy pions are a challenge for calorimetry
  - Large fluctuations in energy depositions from showers created in traditional sampling calorimeters
- A novel, hybrid calorimeter design is proposed for the detector
  - A hadronic range measurement using scintillating plastic staves and wavelength shifting fibr
  - An energy measurement using lead glass blocks.
- ESS, LU, SU involved in design, simulation, and prototyping calorimeter system

The HIBEAM/NNBAR Calorimeter System

- **Hadronic Range Detector (HRD)**
  - Particles deposit energy, producing scintillation photons
  - Get particle energy using # of scintillator layers hit
  - Get particle position using perpendicular layers
- **Lead Glass EM Calorimeter (LEC)**
  - $\pi^{+/-}$, ɣ from π^0 decay enter LEC and produce Cherenkov light
  - Get particle energy by collecting Cherenkov photons
  - Particle position with shower sharing between blocks

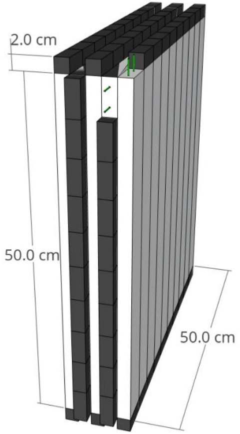


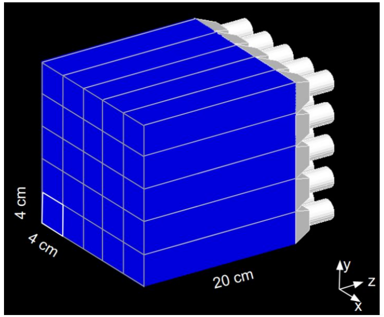
The Calorimeter Prototype at Stockholm

- Extensive Geant4 simulations already performed, prototype provides data to inform simulations of full detector. Details published in arXiv:2107.02147, arXiv:2106.15898
- Experience with system integration and TDAQ
- Tests with cosmic showers, dedicated test beams with electrons and protons, thermal neutron backgrounds at Lund neutron facility
- Ultimately deployed with a prototype TPC at a spallation source to validate *in situ* backgrounds (e.g. fast neutrons from spallation)

Calorimeter System

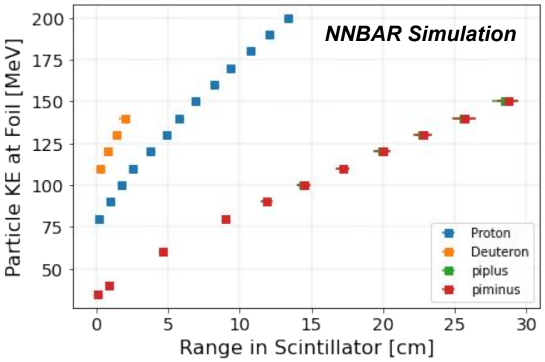
HRD	LEC
• Fifty 5x2x50 cm^3 scintillator staves • Read out with WLS + SiPM	• Twelve 4x4x20 cm^3 lead glass blocks • Read out with SiPM arrays

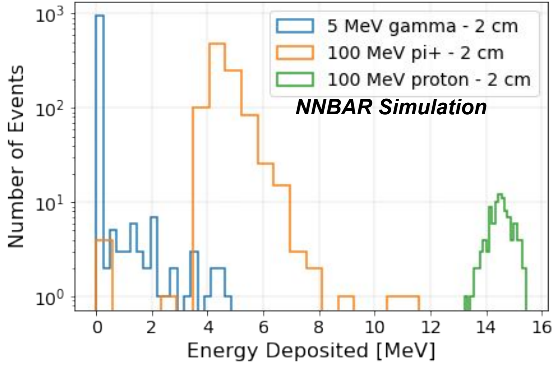


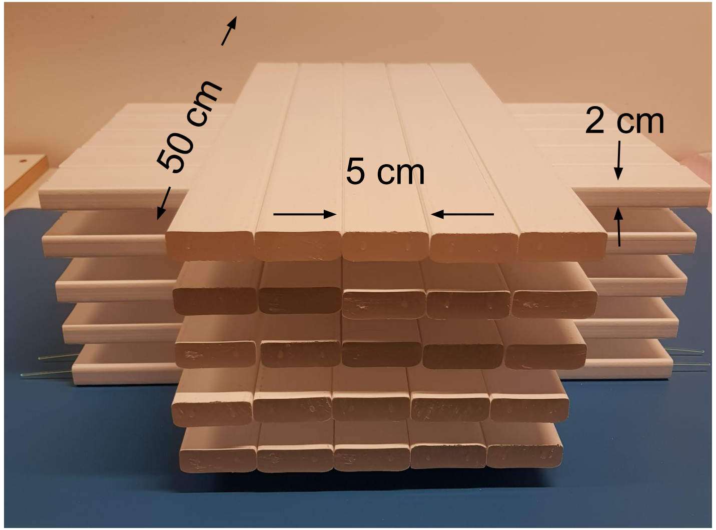


Hadronic Range Detector

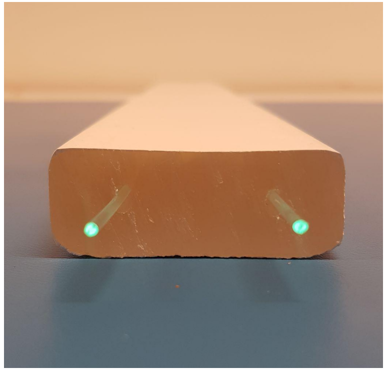
- **Energy Resolution**: studies with low energy protons on energy resolution using 2cm thick staves
- **Position/Timing Resolution:** both ends of stave read out for timing resolution <1 ns
- **Response to backgrounds**
  - low energy gammas using radioactive sources at SU
  - Cosmic showers at SU



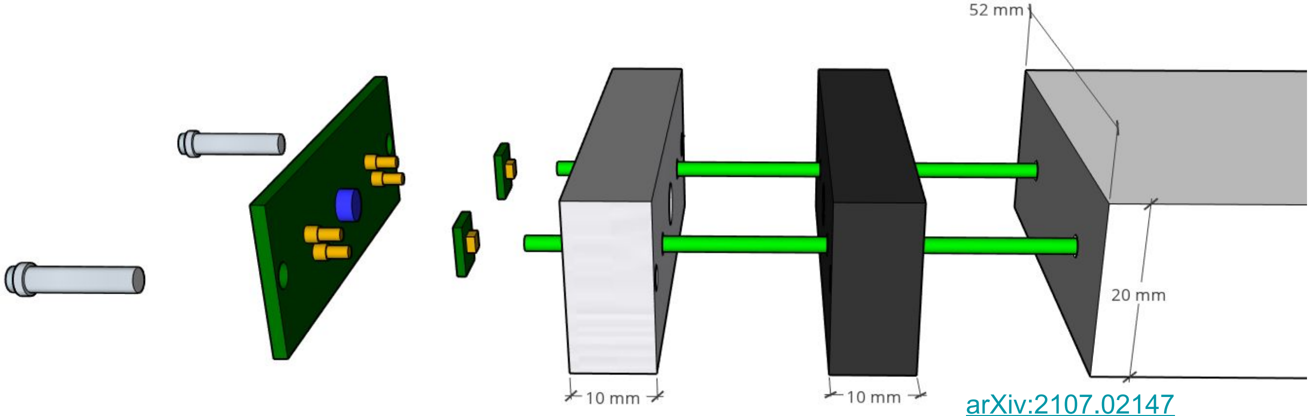




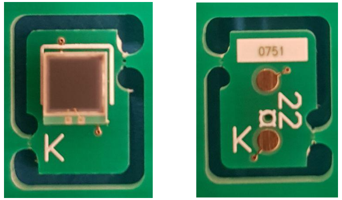
Hadronic Range Detector Mechanics



Extrusion from Fermilab

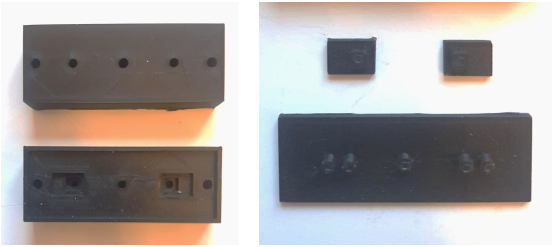


arXiv:2107.02147



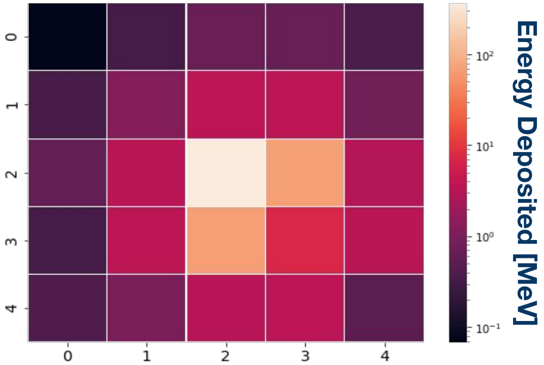
SiPM carrier Board

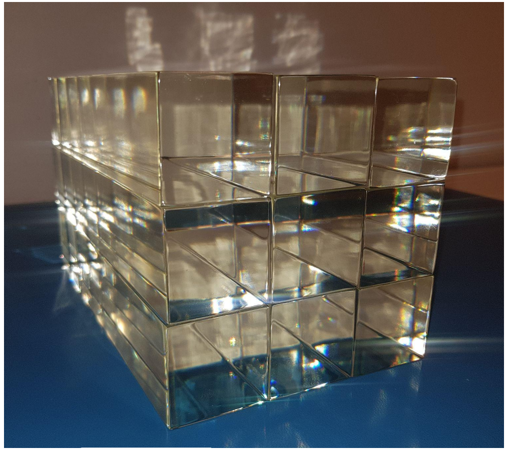
- Staves read out with wavelength shifting fibers + SiPM
- SiPM carrier boards designed from Hamamtsu designed for LDMX
- Electronics manifold inspired by that used in LDMX and Mu2e
- Designed for modular set-up for flexible number of layers

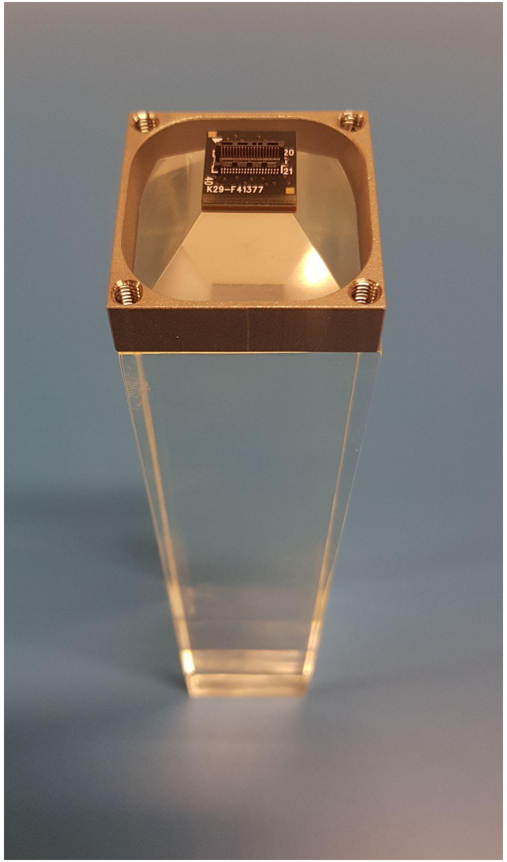


3D printed dummy pieces for help with dimensioning

Lead glass Electromagnetic Calorimeter

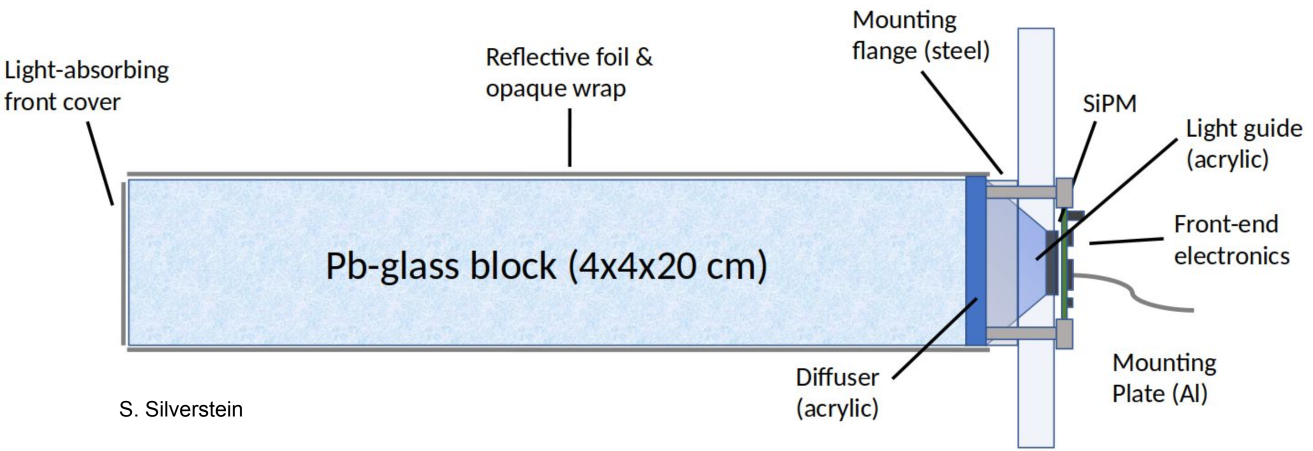


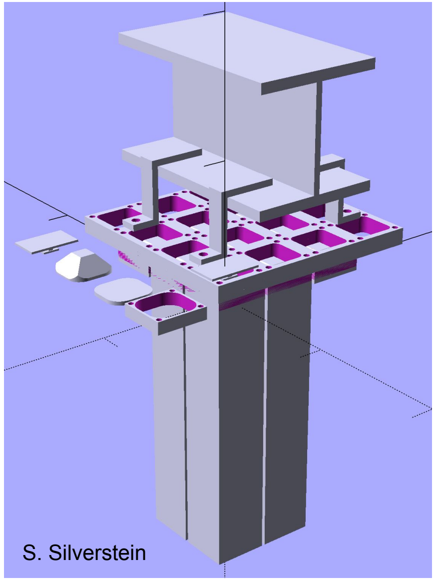


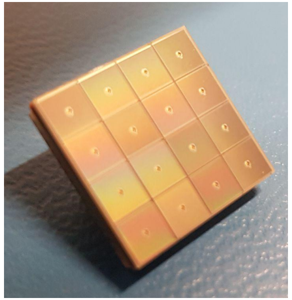


- **Energy Resolution:** studies on shower containment with chosen 20 cm depth, comparison with simulated sampling calorimeter
- **Position Resolution:** needed for identifying gammas from pi0 decay
- **Angular Resolution:** annihilation event can take place any point on foil, crucial to understand detector response to angle of incidence
- **Response to backgrounds**
  - Cosmics at SU

Lead Glass Electromagnetic Calorimeter Mechanics

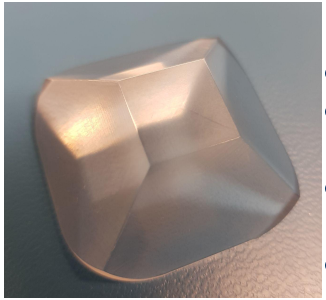






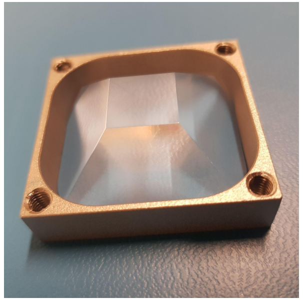
SiPM

- Hamamatsu S14161-1509
- 4x4 array
- 12mmx12mm



Light guide

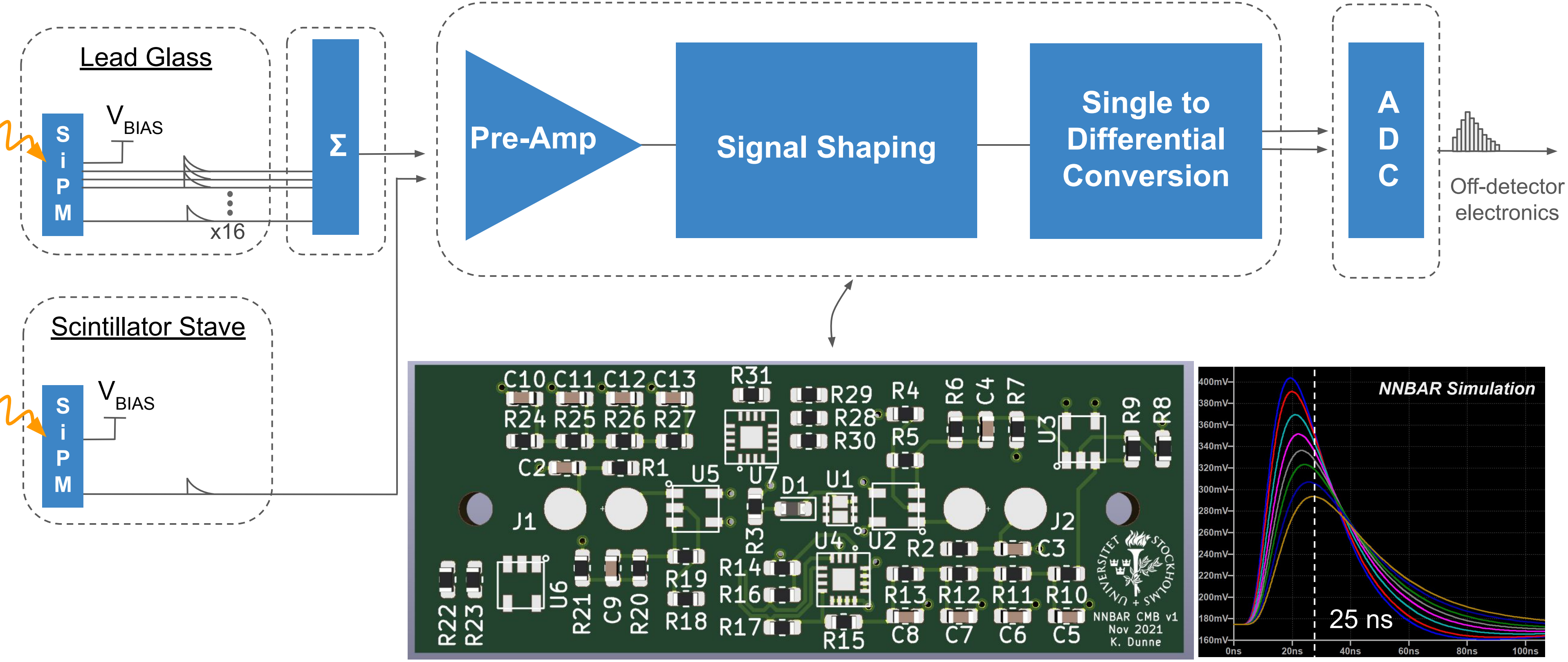
- Solid CNC-ed acrylic
- Polished sides (600nm smoothness)
- Will add 200nm Al mirror coating
- (> 97% reflectivity)



Mounting Flange

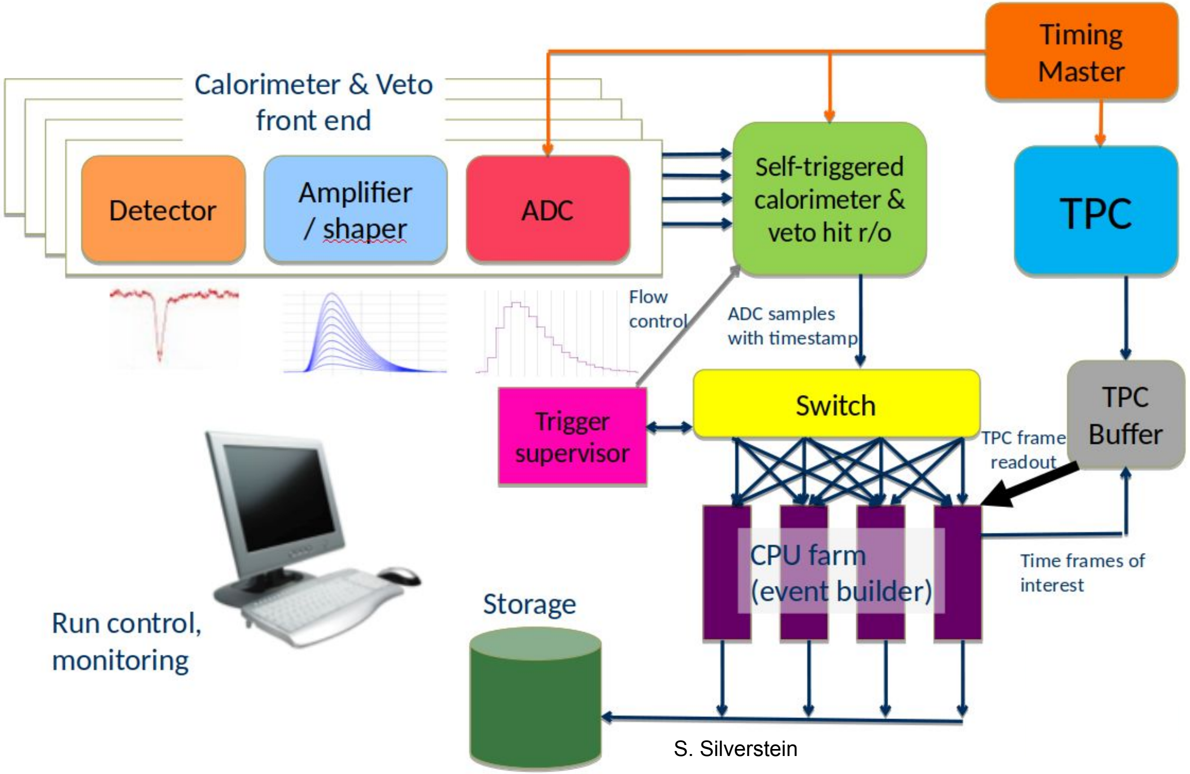
- 410 stainless steel
- Similar coefficient of expansion to the glass
- Threaded holes for mounting to the Al plate
- Will use UV hardened glue for fixing to the glass

Calorimeter Front End Electronics



Trigger and Data Acquisition

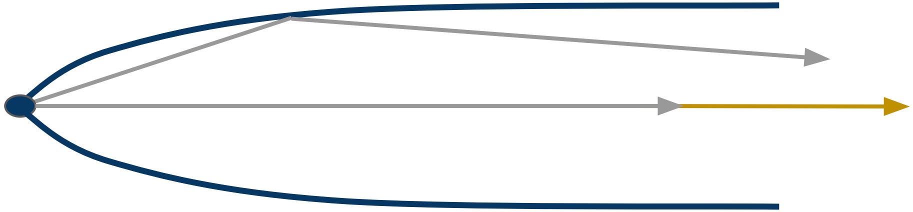
- Neutron beam essentially continuous
  - Event times unknown
- Calorimeter hit timing->TPC track data
- Self-triggered readout of calorimeter & veto channels



S. Silverstein

Summary and outlook

- **Prototype calorimeter** under construction at Stockholm University
- Geant4 simulations performed:
- Tests with **cosmics** and low energy **electrons** and **protons** planned
- Expected to be integrated along with **prototype TPC** in Lund
- Tests at spallation source (ESS - test beamline or alternative source, eg ORNL)

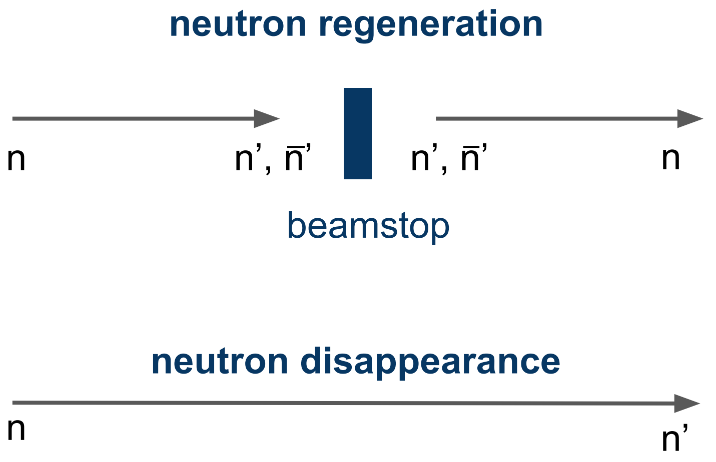


Back Up Slides

The HIBEAM/NNBAR Experimental Program

- Suite of experiments searching for baryon number violation
- Use high-flux beam of free neutrons at European Spallation Source (ESS) in Lund, SE

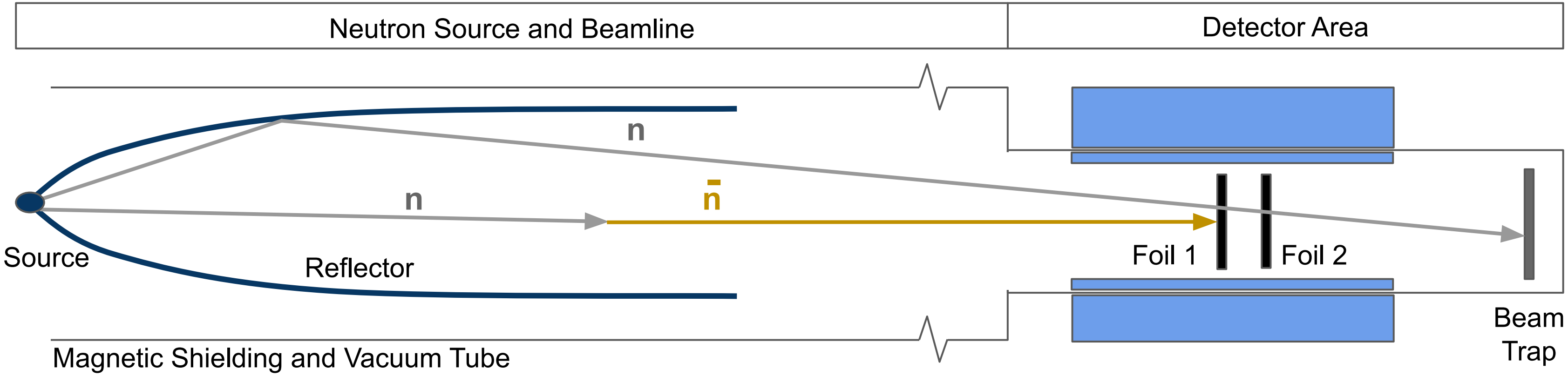
- **Stage 1: HIBEAM**
  - Suite of searches for BNV via two processes
    - neutron→sterile neutron
      - probe of hypothetical ‘dark sector’ of physics
    - neutron→antineutron
      - detector validation for next stage: NNBAR



The HIBEAM/NNBAR Experimental Program

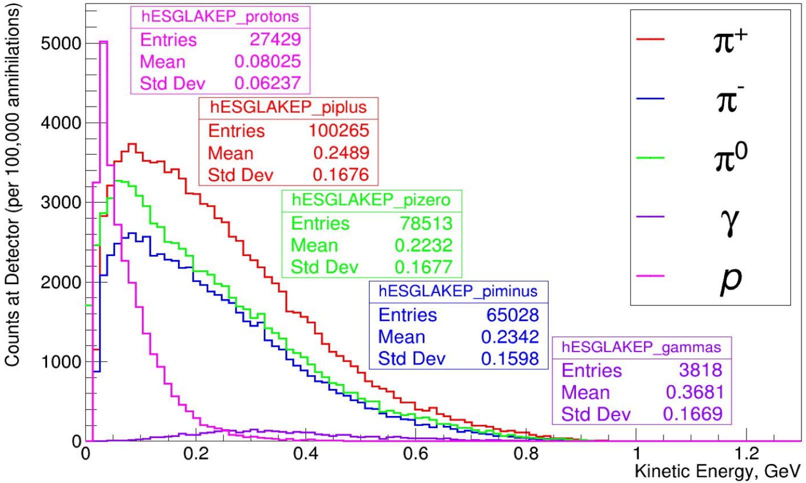
- Suite of experiments searching for baryon number violation
- Use high-flux beam of free neutrons at European Spallation Source (ESS) in Lund, SE

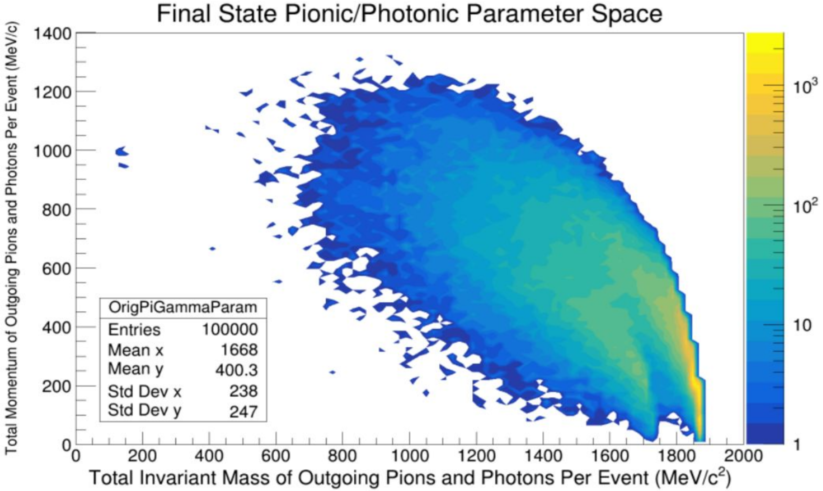
- **Stage 2: NNBAR**
  - Search for $n \rightarrow \bar{n}$ identified through annihilation of $\bar{n}$ in carbon target
  - $\geq 10^3$ increase in sensitivity over previous experiment at ILL M. Baldo-Ceolin et al. [Z. Phys. C 63]



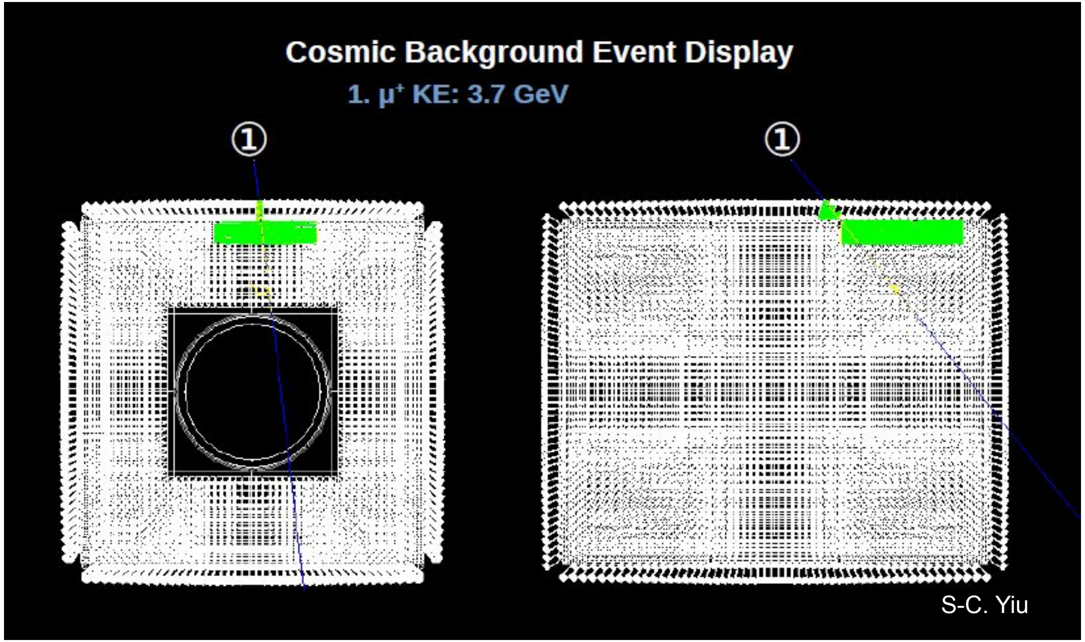
Signal

- Average of 4–5 pions, including $\pi^0 \rightarrow \gamma\gamma$, gammas, protons
- Final state invariant mass ~1.9 GeV
- Challenges:
  - **Energy Resolution:** Large energy fraction carried by nuclear products, energy carried by neutrons lost
  - **Rare event:** claim discovery with single event, no statistical corrections
  - **Backgrounds:** gammas from neutron capture in foil, neutrons from spallation source, cosmic showers (see [S-C. Yiu's talk])





J. Barrow, E. Golubeva, C. Ladd: [Phys. Rev. D 99, 035002], [Phys. Rev. D 99, 035002]


Cosmic Background Event Display
1. μ⁺ KE: 3.7 GeV
①
①
S-C. Yiu

Single Event Confirmation

Topology

- Common vertex + two charged pions
  - No vertex in 2nd foil
- 3D tracking with TPC
- 2D track inside vacuum

Particle Identification

- Identify charged particles as π or p
- Identify pairs of gammas as π^0
- TPC for dE/dx combined with E or range from calorimeter

Energy and Momentum

- Need PID
- Large energy fraction carried by nuclear fragments
- Energy by neutrons lost

Direction

- All particles must move outwards
- Veto charged Cosmics

Trigger and Data Acquisition in Calorimeter/TPC

Triggering

- Timing very useful
  - Coincidence windows for multi-pion events (ns resolution)
- Energy not as useful
  - Large uncertainties for low-energy particles

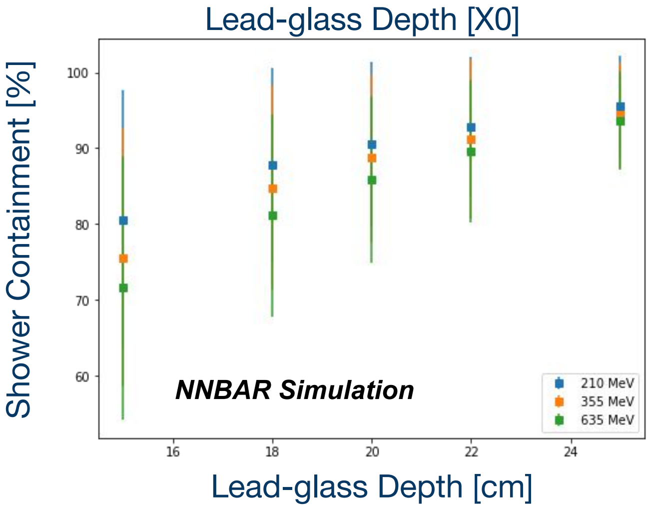
Background Rejection

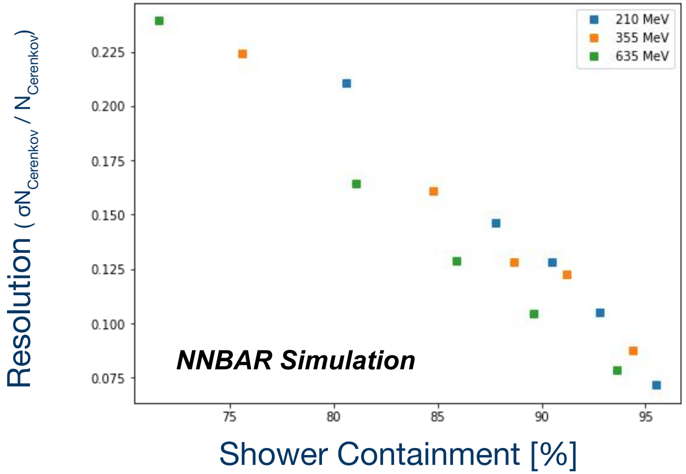
- Timing distinguish fake coincidences by cosmic hits
- Threshold to remove low energy photons, nuclear products

‘Triggerless’ DAQ

- Neutron beam essentially continuous
  - Event times unknown
- Calorimeter hit timing->TPC track data
- Self-triggered readout of calorimeter & veto channels

Simulations - Lead Glass Depth

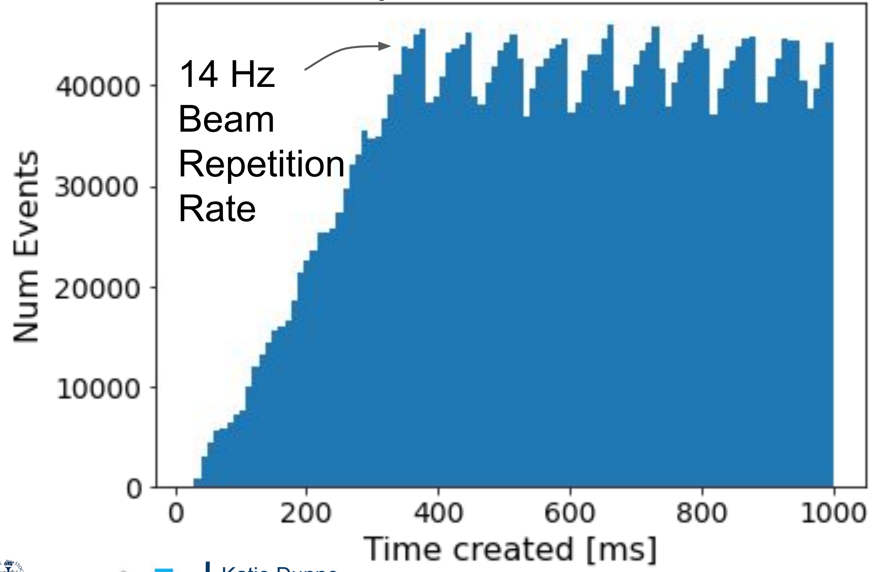




Low Energy Gamma Rate of Interaction in Scintillators

- MCPL file is simulation of 1 sec of ANNI beam interaction with carbon target
- **Interaction Rate** in scintillator materials is **1.4 kHz**

Simulation of Photon timing from neutron capture in Carbon Foil



Simulation of Photon KE from neutron capture in Carbon Foil