Progress on the design of an annihilation detector for the HIBEAM/NNBAR program at the European Spallation Source

Partikeldaganar 2021
22nd Nov 2021

Sze Chun Yiu

Stockholm University

NNBAR

Flow of the presentation

1) Introduction

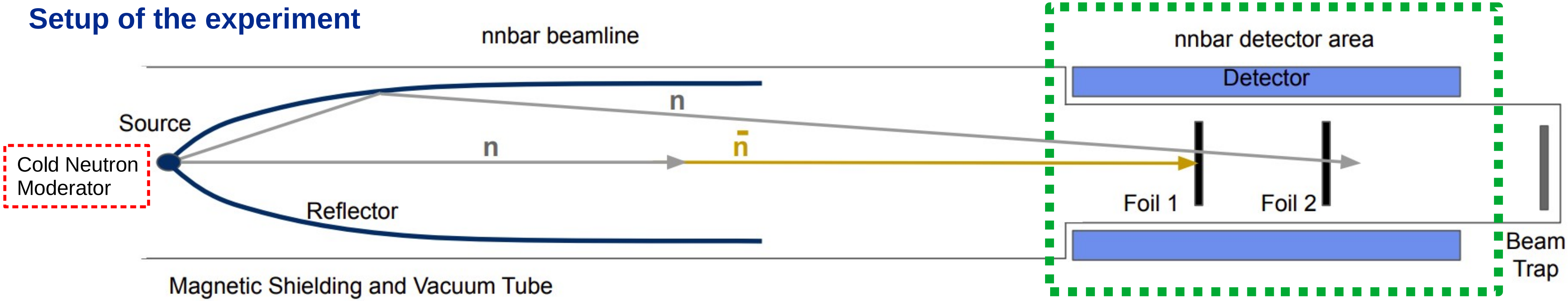
- NNBAR experiment
- Possible design of the NNBAR detector
- List of detector studies and event variables

2) Discussion

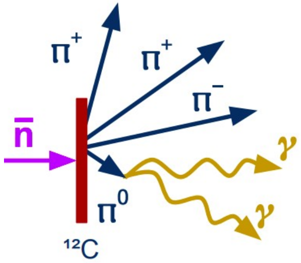
- Detector study based on the signal and cosmic events

1.1 Introduction to the NNBAR detector studies

Setup of the experiment



Goal of the experiment



- Claim a discovery of annihilation event between antineutron and neutron at the **Carbon foil target**
- Annihilation event at the C foil target would generate:
  - On average **4~5 pions**, including **π^0** which decays immediately to **2 gammas**
  - **Invariant mass** of the final state **~1.88 GeV** (2 neutron masses)

Annihilation product simulation

- Simulation of the products was done*
- List of annihilation products → Used by the detector simulation studies through **GEANT4**

* J. Barrow, E. Golubeva, C. Ladd, *"A model of antineutron annihilation in experimental searches for neutron-antineutron transformations"*

1.2 The Annihilation Detector

- Dimension of the detector components used in GEANT4* simulation**

y direction

Time Projection Chamber

80% Ar + 20% CO_2
Two different dimensions (x-y)
- 0.85 m x 1.87 m
- 2.04 m x 0.85 m

2m long (z direction)

Scintillator Modules

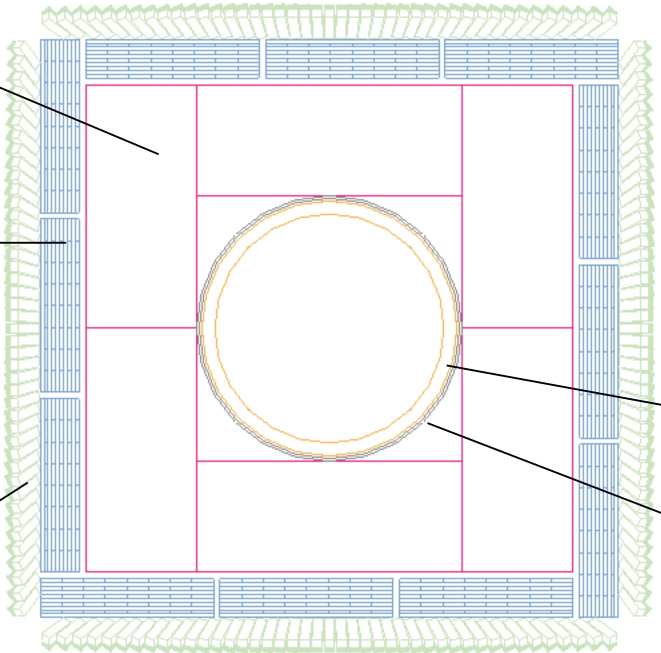
10 layers of plastic scintillator
3 cm thick for each layer

Each layer is divided into 8 staves

Consecutive layers are perpendicular

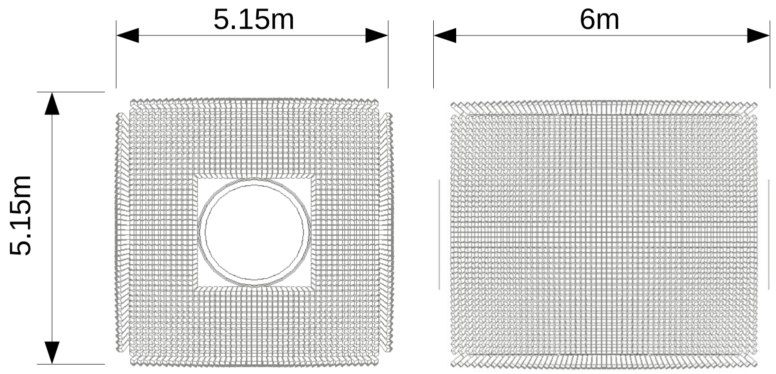
Lead Glass Blocks

Base: 8 cm x 8 cm
Height: 25 cm
Pointing towards the **center of the detector**



x direction

The full detector view



Front view | Side view

Silicon Trackers

Layer 1:	Layer 2:
Inner radius = 87.97 cm	Inner radius = 97.97 cm
Thickness = 0.03 cm	Thickness = 0.03 cm
Length = 6 m	Length = 6 m

Vacuum tube

1 m inner radius
2 cm thick
6 m long (z direction)

* GEANT4 version: geant4.10.06.p02
** Dimensions here are preliminary. These numbers are only used in the simulations as a reference.

1.3 List of detector studies and event variables

- We studied different components of the full detector systematically

Outside the detector

- Cosmics
- Shielding

Beampipe

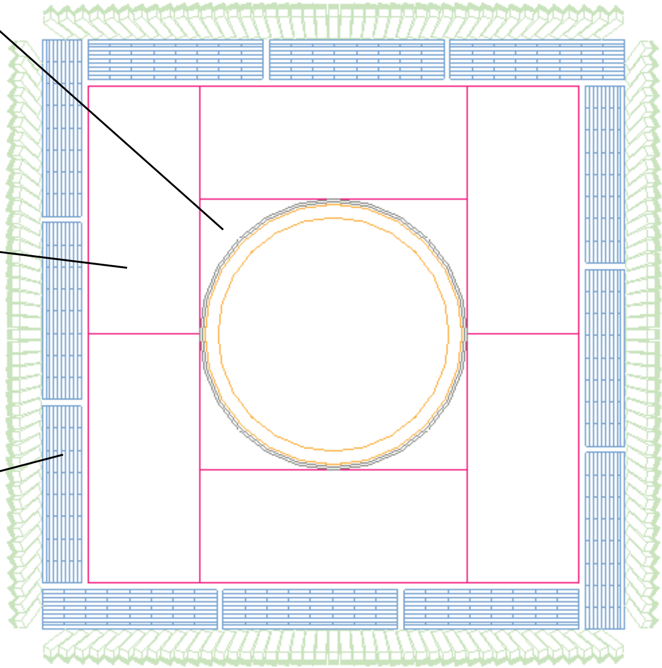
- Beta decay electrons
- Nuclear fragments

TPC

- TPC track visualization
- TPC dE/dx calculation

Calorimeter

- Pi0 mass reconstruction
- Energy reconstruction



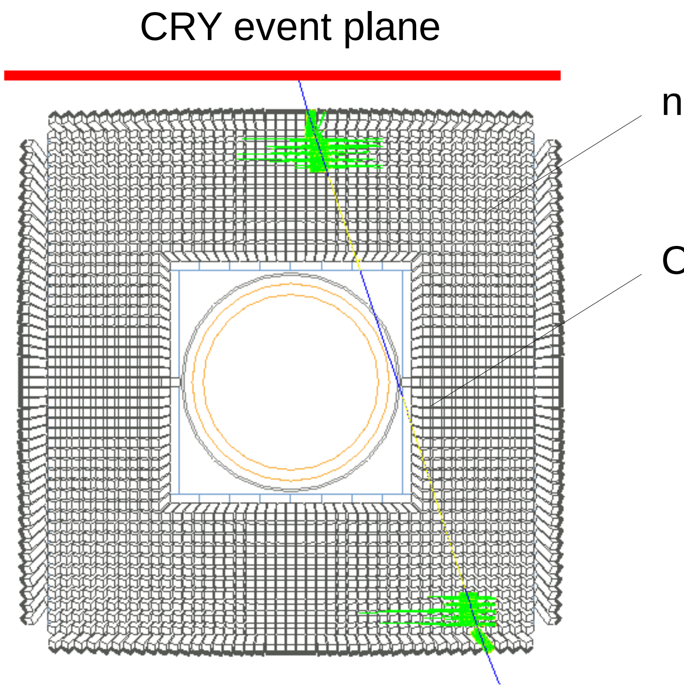
List of Event variables

- Object definition
- Pion multiplicity
- Invariant mass
- Event shape variables
- Signal timing

1.4 Cosmic ray background

- The cosmic background was the dominant background in the last free neutron search
- Understanding the signatures of the cosmic particles in the nnbar detector is crucial
- Cosmics particles are generated by an external library named **Cosmic-ray Shower Library (CRY)**
  Ref. for CRY: https://nuclear.llnl.gov/simulation/

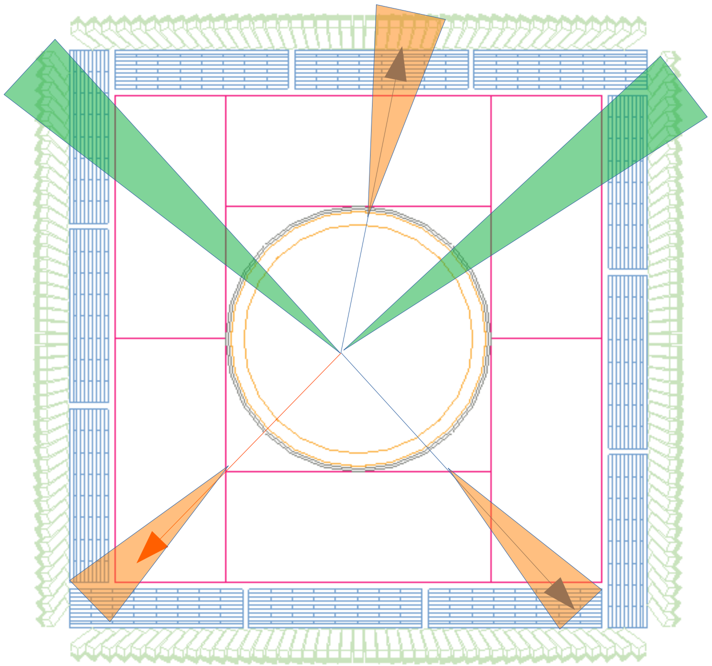
Study done in GEANT4 and a cosmic event display



Energy and momentum direction reconstruction

- We developed an algorithm to reconstruct the energy and momentum of **charged** and **neutral** particles
- Reconstruction of **charged particles** relies on the TPC track information and silicon tracker information
- Energy is collected if a signal is inside any cone
- Hits that cannot be associated with any charged track in the TPC are considered as a hit by **neutral particle**

Cones for energy collection



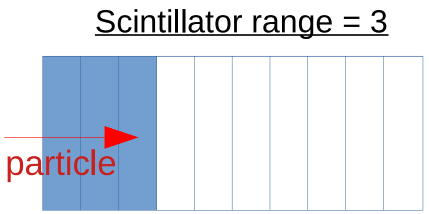
3.1 Object definition – Charged signal particles

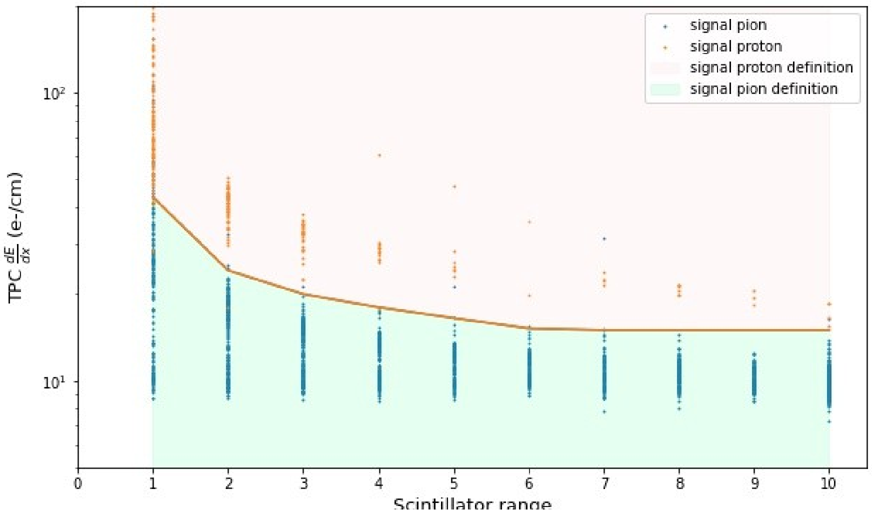
- What is an **object**?

  Collection of information from different detector components

- Object definition is used to **determine the type of particle** detected

- We developed an object definition to distinguish **charged signal pions** from **protons**





Definition of pion:

TPC dEdx < t_N

Definition of proton:

TPC dEdx >= t_N

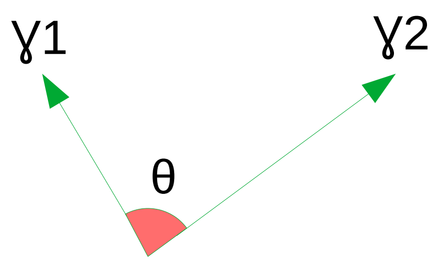
t_N is the cut value
N = number of scintillator layers it penetrates
The cut value depends on how many layers it penetrates

3.1 Object definition – Neutral pions

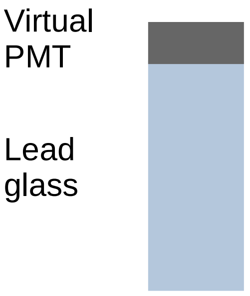
- **Neutral pion identification**
  - Assume neutral hits are caused by gammas
  - Check the mass m0 of any two gammas

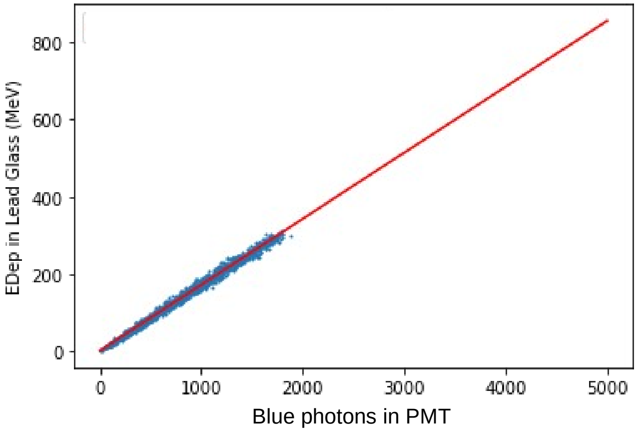
$$m_0 = \sqrt{2E_1E_2(1-cos\theta)}$$

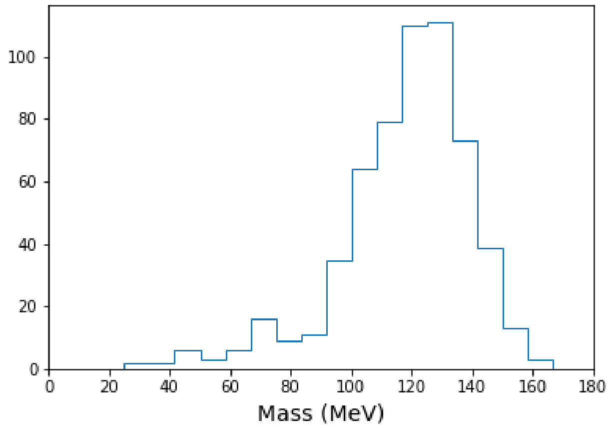
  - If m1 < m0 < m2, identify the two gammas to be π^0 decay products



Results from shooting neutral pions at 200 MeV KE

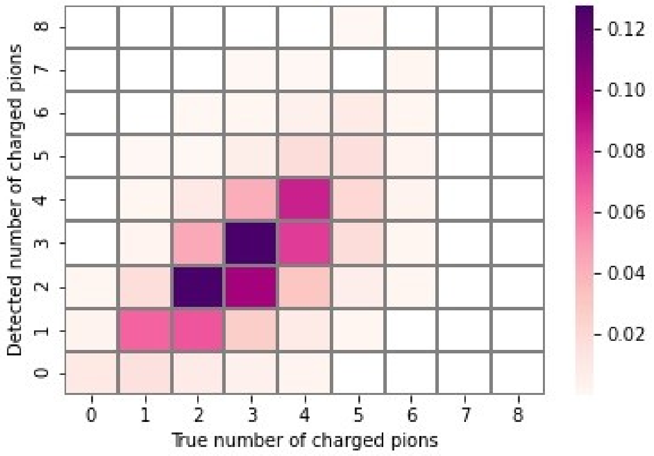




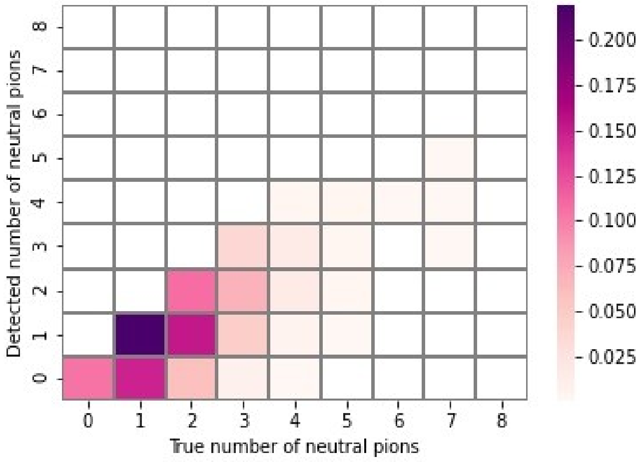


- An annihilation event on average gives 4 – 5 pions:
- Check the **total number of detected pions** in each annihilation event

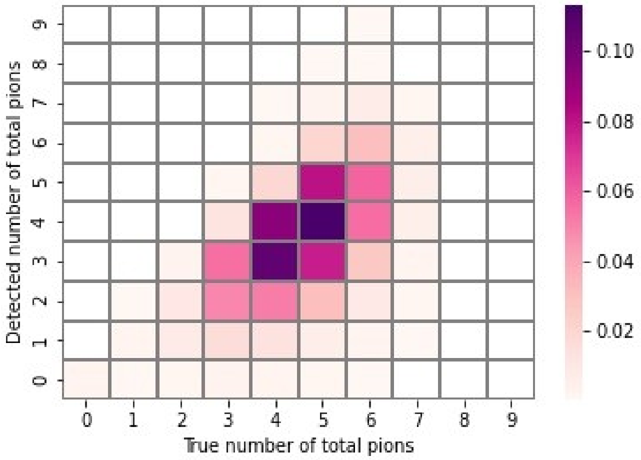
Charged pions



Neutral pions



All pions



3.3 Invariant mass and Event shape variable

- **Check of Energy Conservation:**

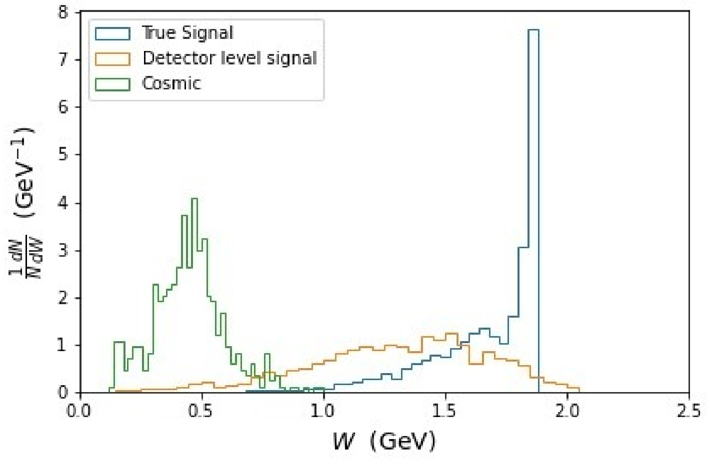
Calculate the invariant mass W of an event with the results from object definition and energy reconstruction

$$W = \sqrt{(E_1 + E_2 + ... + E_n)^2 - |\mathbf{p}_1 + \mathbf{p}_2 + ...\mathbf{p}_n|^2}$$

$$E_n = \sqrt{m_n^2 + p_n^2}$$

$$p_n \approx \sqrt{\mathrm{E}_{dep,n}^2 + 2 \cdot \mathrm{E}_{dep,n} \cdot m_n}$$

- Invariant mass of **signal** and **cosmic** **events**



- **Event Shape Variable:**

The event shape variables highlight the geometric properties of an event

We are interested in the sphericity of different types of event
Is the particle flow isotropic?

$$M_{xyz} = \sum_i \begin{pmatrix} p_{xi}^2 & p_{xi}p_{yi} & p_{xi}p_{zi} \\ p_{yi}p_{xi} & p_{yi}^2 & p_{yi}p_{zi} \\ p_{zi}p_{xi} & p_{zi}p_{yi} & p_{zi}^2 \end{pmatrix}$$

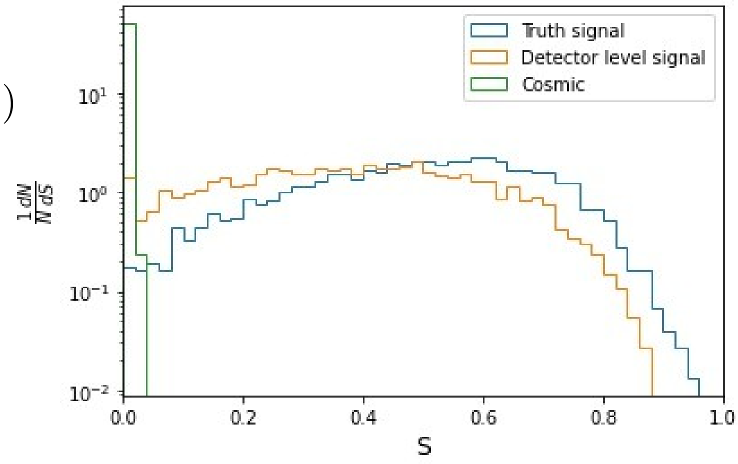
Eigenvalues

$\lambda_1, \lambda_2, \lambda_3$

$\lambda_1 > \lambda_2 > \lambda_3$

Sphericity:

$$S = \frac{3}{2}(\lambda_2 + \lambda_3)$$



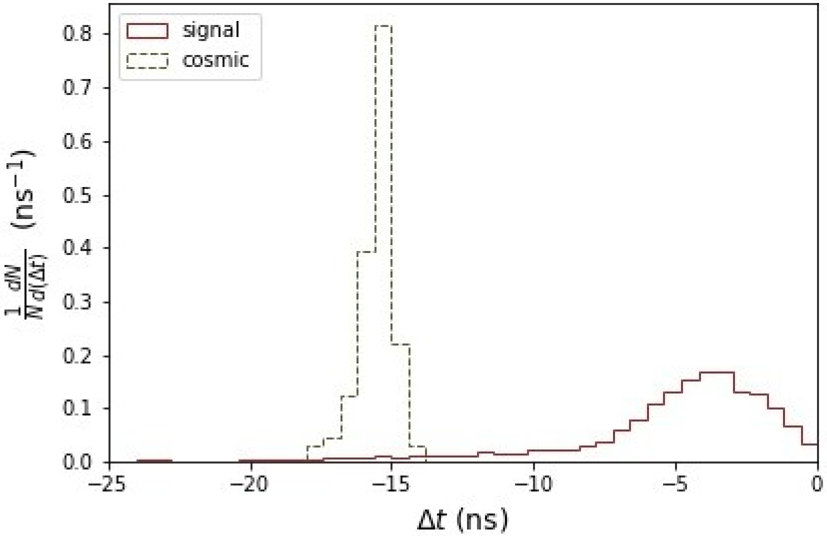
3.4 Signal timing

- Define a timing quantity:

$$\Delta t = t_0 - t_1$$

t1 = time when the last signal appears in the scintillator

t0 = time when the first signal appears in the scintillator



4 Summary and future works

Summary

- Introduced the NNBAR detector design concept
- Introduced different detector studies and event variables

Future works

- Cosmic shielding
- Look at different detector geometries
- Look for possible replacements to lead glass

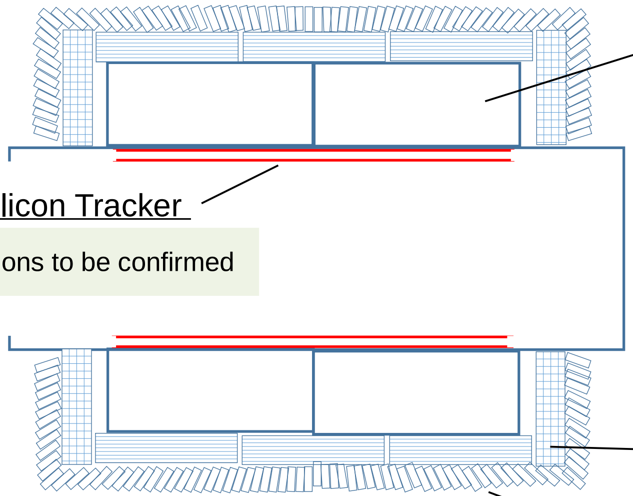
The End

Thank you for listening!

APPENDIX I - Cylindrical Geometry

** Dimensions here are preliminary. These numbers are only used in the simulations as a reference.

y direction



Silicon Tracker

Dimensions to be confirmed

z direction

Along the beam direction

Time Projection Chamber

85 cm thick (radial length)
2 m long (z direction)
80% Ar + 20% CO_2

Aluminum tube

1 m inner radius
2 cm thick
6 m long (z direction)

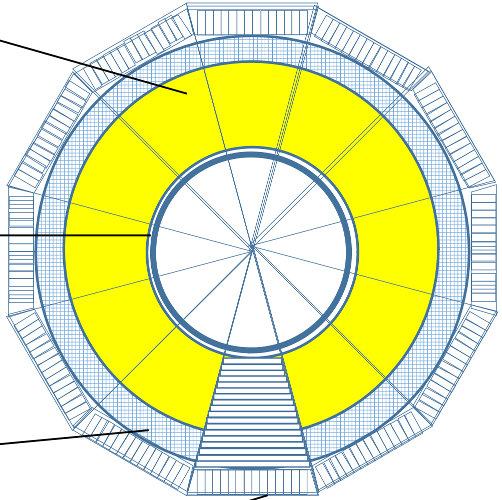
Scintillator Modules

10 layers of plastic scintillator
3 cm thick for each layer

Lead Glass Blocks

Base: 8 cm x 8 cm
Height: 25 cm
Pointing towards the **center of the detector**

y direction



x direction

APPENDIX II - Pros and Cons of Different Geometries

Cylindrical Geometry

Pros:

- Efficient way of using perpendicular area
- Less spending on lead glass
- Less tilting of lead glass blocks (Easier in terms of Engineering)

Cons:

- Cannot be easily prototyped (need to build the whole component)
- Not scalable
- Difficulties in repairing the TPC: need to open whole end surface/dismantled in clean room conditions
- Dead areas are larger than the box geometry

Box Geometry

Pros:

- Easy to build and prototype it (scalable)
- Easier to repair the TPC: modules can be easily replaced
- No dead areas

Cons:

- Not using perpendicular area as efficient
- More spending on lead glass
- Complicated tilting (Hard to engineer)

APPENDIX III – Possible Backgrounds of the experiment

- Major backgrounds of the experiment

- **Cosmic particle background**

  The cosmic background was the dominant background in the last free neutron search

  Understanding the signatures of the cosmic particles in the nnbar detector is crucial

- **Neutron Capture Gamma Background**

  Caused by slow neutron capture of the C-12 foil

$$^{12}C + n \rightarrow ^{13}C + \gamma$$

  High event rate, **10^6 gammas per second**

  It is exactly timely correlated with the beam and thus easier to deal with