Searches for baryon number violation via neutron conversions at the European Spallation Source

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NNBAR

CONFERENCE ON SCIENCE AT THE
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Outline of the presentation

1) Introduction

2) HIBEAM and NNBAR experiment at the ESS

3) NNBAR detector simulation studies

1. Introduction

1.1 Baryon and Lepton number violation

1) Baryon Number and Lepton Number are accidental symmetries in SM at **perturbative level**

- ✯ At **non-perturbative level**, these can be violated

2) Many **SM extensions** predicts the BN and LN violation

- ✯ SUSY
- ✯ GUTs (M ~ 10^15 GeV)
- ✯ Extra dimensions models

3) BNV is a key ingredient for **Baryogenesis**

For experimental physicists:

Explore different selection rules of BN and LN:

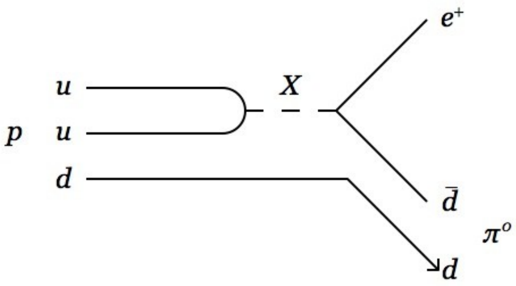
$$\Delta B \neq 0, \Delta L = 0, \Delta(B-L) \neq 0$$
$$\Delta B = 0, \Delta L \neq 0, \Delta(B-L) \neq 0$$
$$\Delta B \neq 0, \Delta L \neq 0, \Delta(B-L) \neq 0$$

Examples on the next slide !

1.2 Channels to observe Baryon and Lepton number violation

Proton decay

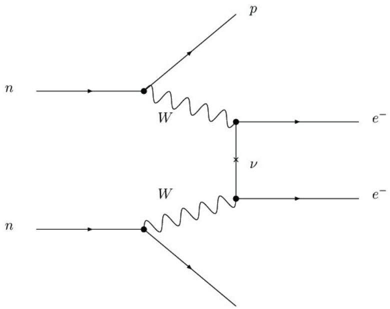
$p \rightarrow e^+ + \pi^0$



$$\Delta B \neq 0, \Delta L \neq 0$$

Neutrinoless double beta decay

$0\nu 2\beta$

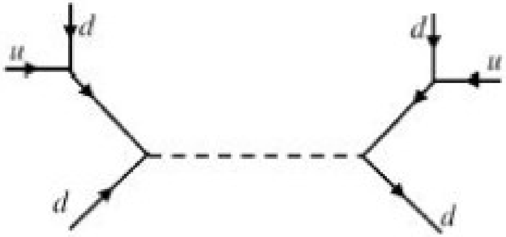


$$\Delta B = 0, \Delta L \neq 0$$

Neutron Oscillation

Neutron antineutron oscillation

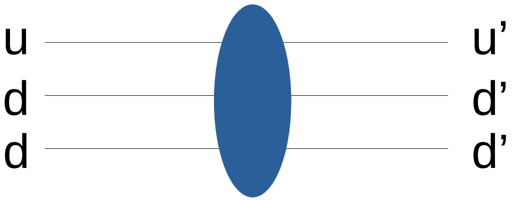
$n \rightarrow \bar{n}$



$$\Delta B = 2, \Delta L = 0$$

Neutron sterile neutron oscillation

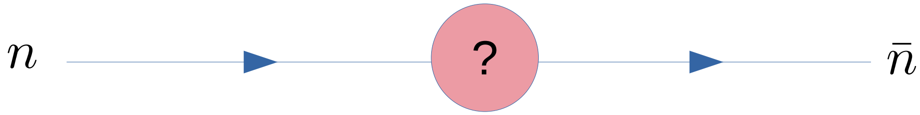
$n \rightarrow n'$



$$\Delta B = 1, \Delta L = 0$$

1.3 Probing Free Neutron Oscillations

Strategy for probing : let as many **cold** neutrons fly as long time as possible



Mixed n and nbar QM state

$$i\hbar\frac{\partial}{\partial t}\begin{pmatrix} n \\ \bar{n} \end{pmatrix} = \begin{pmatrix} E_n & \delta m \\ \delta m & E_{\bar{n}} \end{pmatrix}\begin{pmatrix} n \\ \bar{n} \end{pmatrix}$$

Transition probability to anti-neutron at t:

$$p(t) = \left(\frac{\delta m}{\Delta E}\right)^2 sin^2(\Delta E \times t)$$

At quasi free condition $\Delta E t << 1$ (achieved in vacuum with very low magnetic field)

$$p(t) \approx (\delta m \times t)^2$$

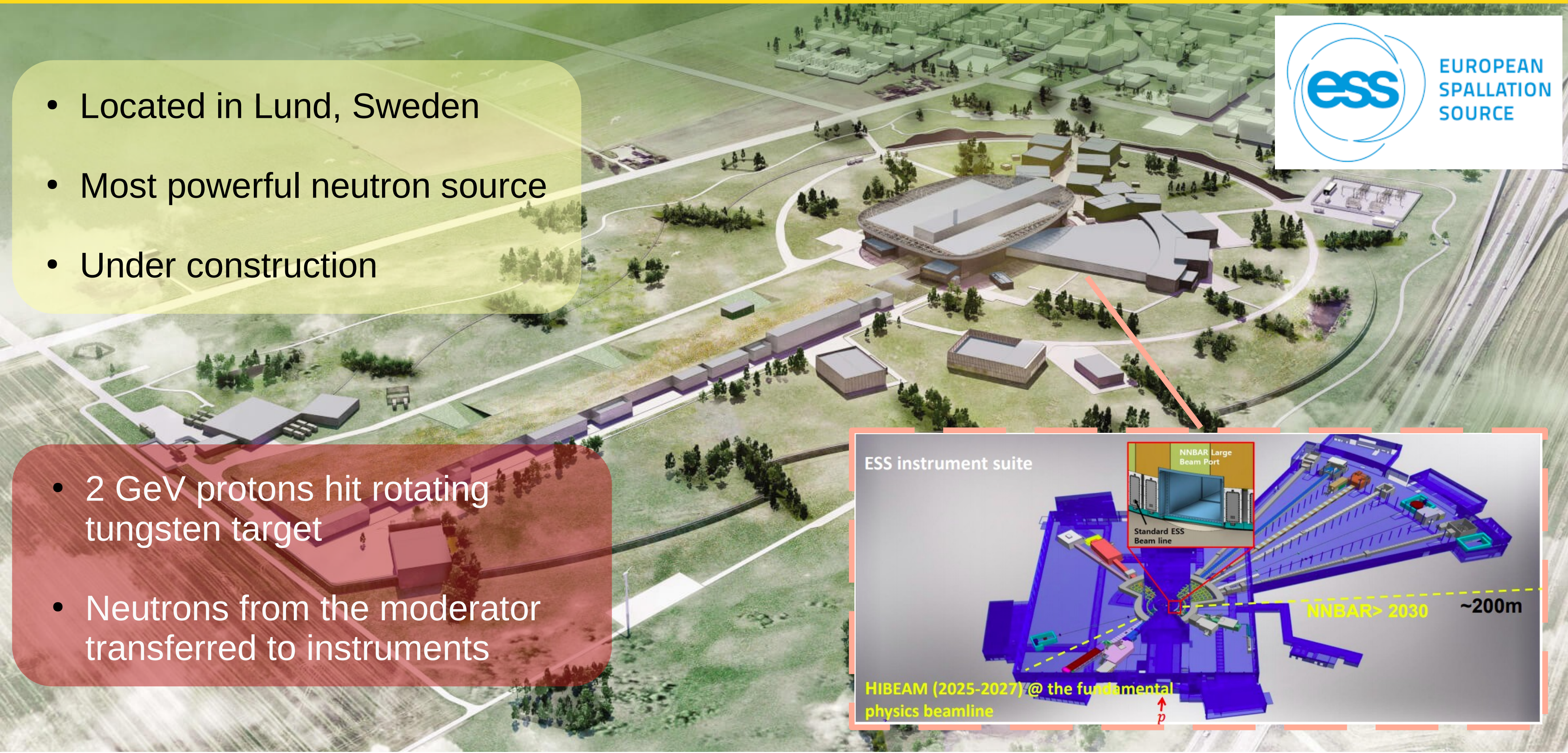
2. HIBEAM/NNBAR at the European Spallation Source

2.1 European Spallation Source (ESS)

EUROPEAN
SPALLATION
SOURCE

- Located in Lund, Sweden
- Most powerful neutron source
- Under construction

- 2 GeV protons hit rotating tungsten target
- Neutrons from the moderator transferred to instruments



2.2 HIBEAM/NNBAR experiment at the ESS

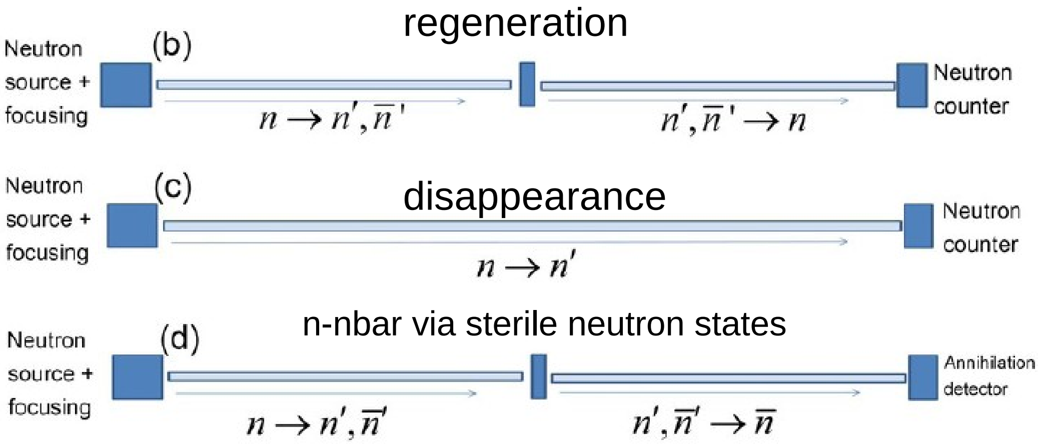
- **Proposed Two Stage Experiment at the ESS – HIBEAM/NNBAR**

- *Phase 1* – HIBEAM: Search for $n \rightarrow n'$
  - Use cold neutrons from a dedicated fundamental physics beamline

- *Phase 2* – NNBAR: Search for $n \rightarrow \overline{n}$
- Use cold neutrons from the **Large Beam Port**
- 1000 times increase in sensitivity compared to the free neutron search done at ILL in 1990's

2.3 Probing sterile neutrons (HIBEAM)

- n -> n' is possible with a non-zero B-field that must be scanned/optimised to match the B-field in the dark sector
- Search for regeneration, disappearance and n-nbar via sterile neutron states



HIBEAM has better sensitivity in various magnetic field regions compared to previous search

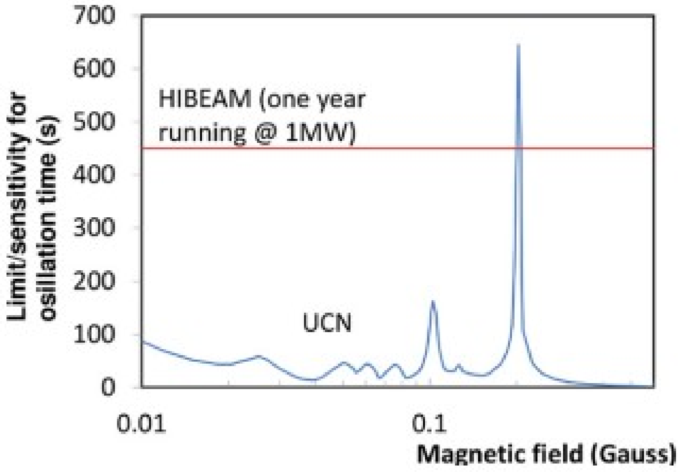
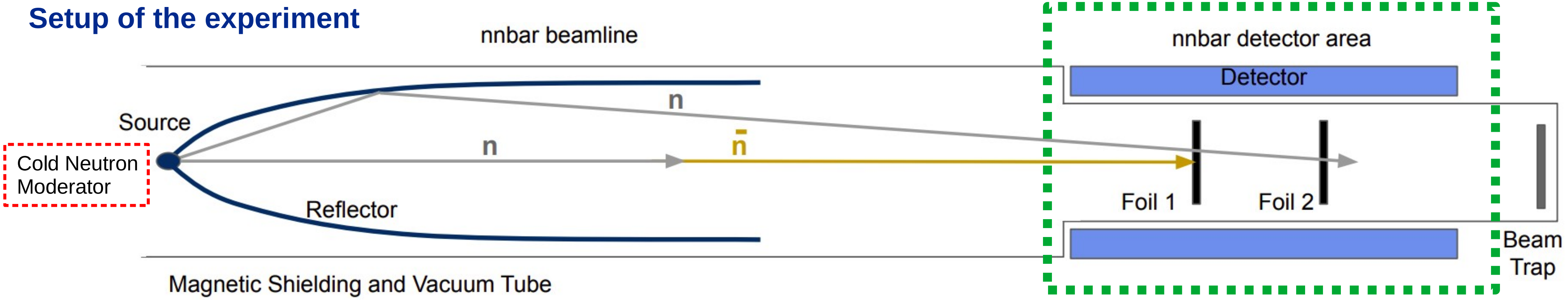


Figure 22. Excluded neutron oscillation times in blue for $n \rightarrow n'$ disappearance from UCN experiments [40, 42, 44–47] as a function of the magnetic field $\mathbf{B}'$. The projected sensitivity for HIBEAM (disappearance mode) is also shown in magenta for 1 year's running at the ESS assuming a power of 1 MW.

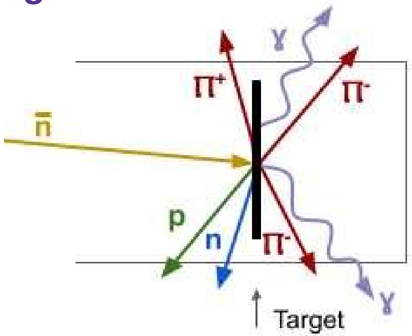
2.4 NNBAR experiment

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 promptly to **2 photons**
  - **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**

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

2.5 The Annihilation Detector

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

y direction

Time Projection Chamber

80% Ar + 20% CO2
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

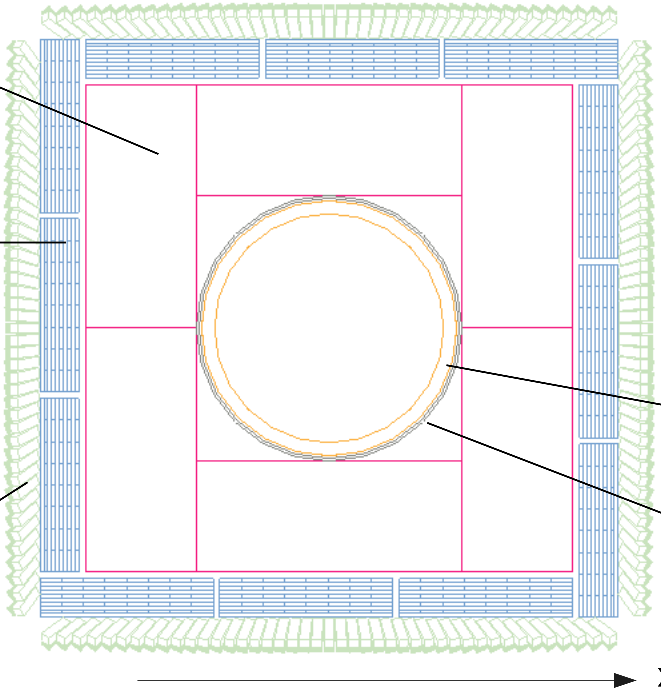
10 layers of plastic scintillator
3 cm thick for each layer

Each layer is divided into 8 staves

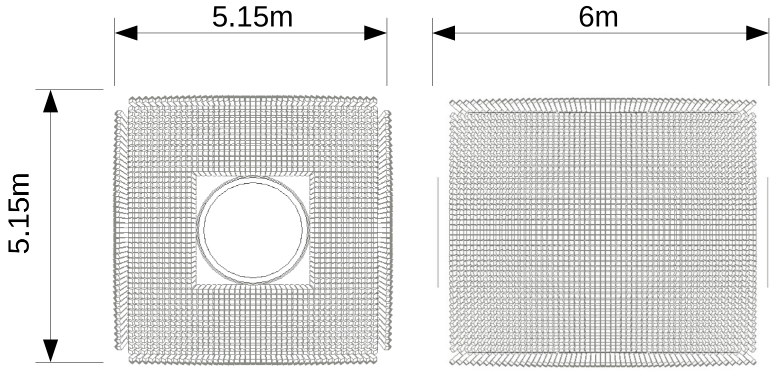
Consecutive layers are perpendicular

Lead Glass Blocks

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



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

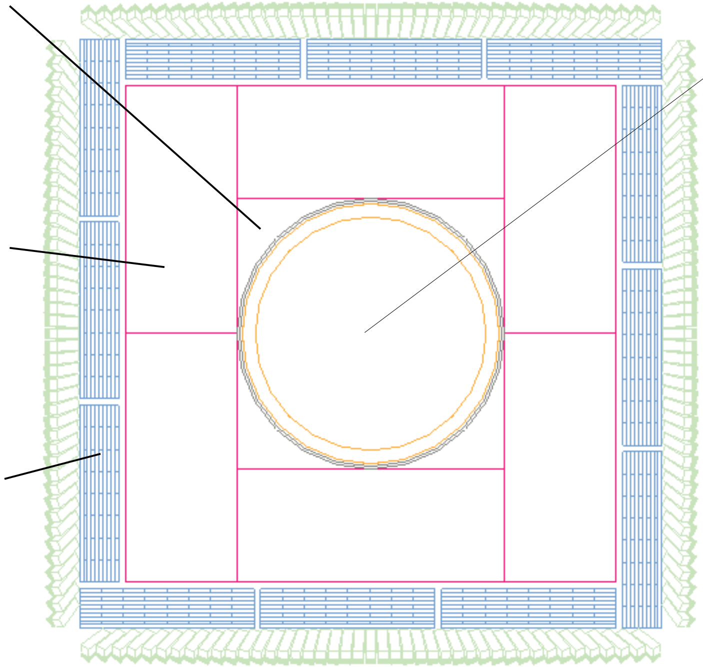
1 m inner radius
2 cm thick
6 m long (z direction)

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

3. NNBAR detector simulation studies

3.1 List of detector simulation studies and event variables

- We have been studying different components of the full detector systematically



Outside the detector

Cosmics

Shielding

Target Disk

Spallation background

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

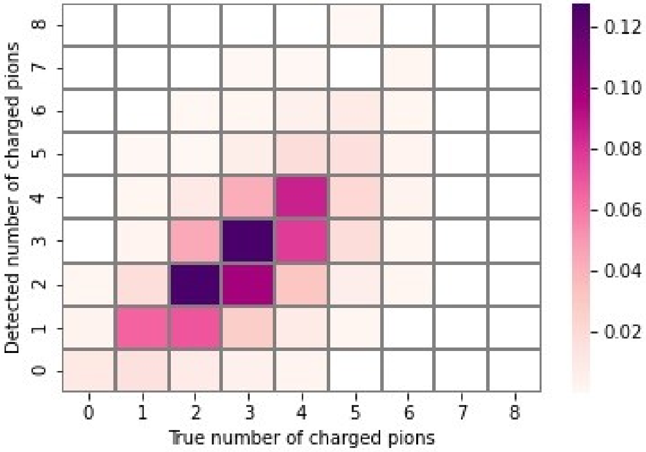
Signal timing

3.2 Pion multiplicity

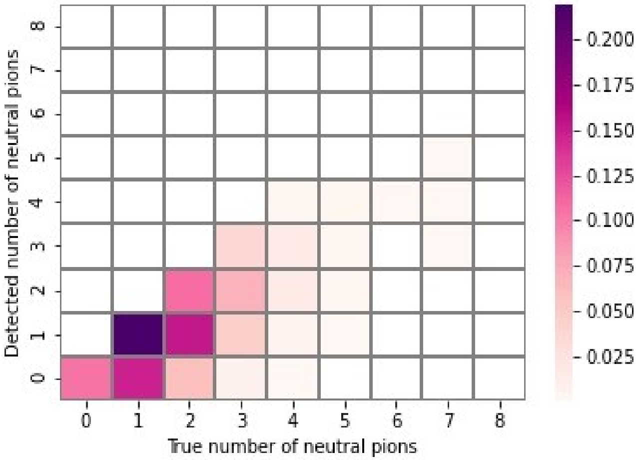
- An annihilation event on average gives 4 – 5 pions:
- Check the **total number of detected pions** in each annihilation event

After simulating 10000 annihilation events in GEANT4, the particle energies are reconstructed and particle species are identified

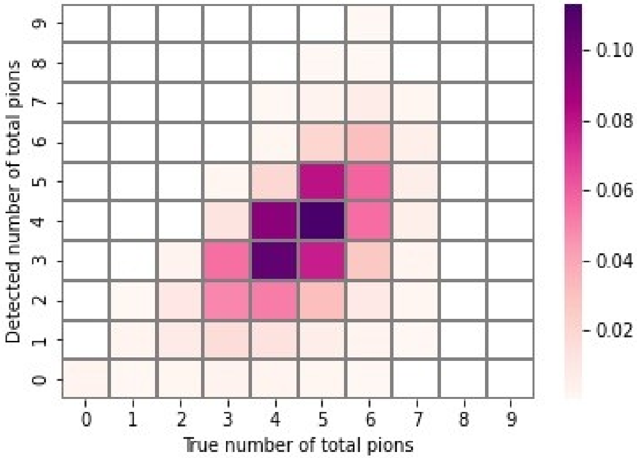
Charged pions



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

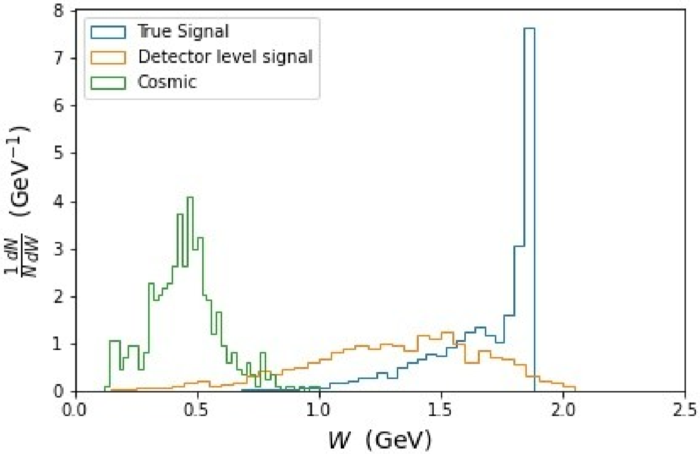
$$W = \sqrt{(E_1 + E_2 + ... + E_n)^2 - |\mathbf{p}_1 + \mathbf{p}_2 + ...\mathbf{p}_n|^2}$$

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

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

- Invariant mass of (**truth**) **signal** and **cosmic muon** events

Spallation background is also being studied



- **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?

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

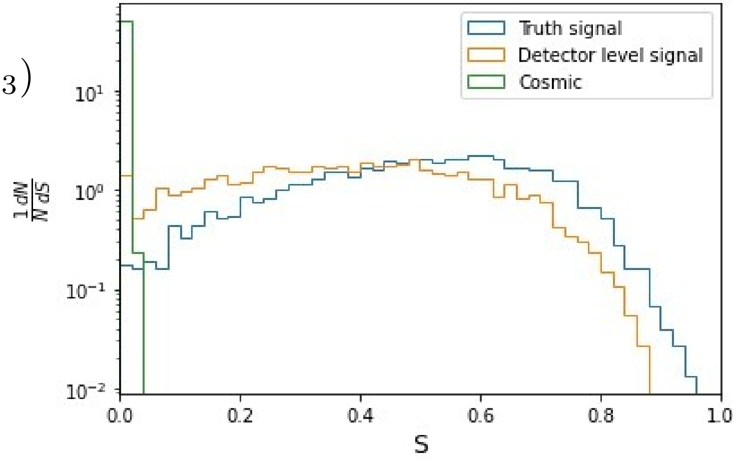
Eigenvalues

$$\lambda_1, \lambda_2, \lambda_3$$

$$\lambda_1 > \lambda_2 > \lambda_3$$

Sphericity:

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



4. List of recent publications

- Status of the design of an annihilation detector to observe neutron-antineutron conversions at the European Spallation Source
- The HIBEAM/NNBAR Calorimeter Prototype, TIPP, arXiv:2107.02147
- A Computing and Detector Simulation Framework for the HIBEAM/NNBAR arXiv:2106.15898
- Experimental Program at the ESS, CHEP2021, arXiv:2106.15898
- New high-sensitivity searches for neutrons converting into antineutrons and/or sterile neutrons at the European Spallation Source, J. Phys. G: Nucl. Part. Phys. 48 070501, arXiv:2006.04907

A. Addazi, K. Anderson, S. Ansell, K. Babu, J. Barrow, D.V. Baxter, P.M. Bentley, Z. Berezhiani, R. Bevilacqua, C. Bohm, G. Brooijmans, J. Broussard, R. Biondi, B. Dev, C. Crawford, A. Dolgov, K. Dunne, P. Fierlinger, M.R. Fitzsimmons, A. Fomin, M. Frost, S. Gardner, A. Galindo-Uribarri, E. Golubeva, S. Girmohanta, G.L. Greene, T. Greenshaw, V. Gudkov, R. Hall-Wilton, L. Heilbronn, J. Herrero-Garcia, G. Ichikawa T.M. Ito, E. Iverson, T. Johansson, L. Joensson, Y-J. Jwa, Y. Kamyshkov, K. Kanaki, E. Kearns, M. Kitaguchi, T. Kittelmann, E. Klinkby, L.W. Koerner, B. Kopeliovich, A. Kozela, V. Kudryatsev, A. Kupsc, Y. Lee, M. Lindroos, J. Makkinje, J.I. Marquez, R. Mohapatra, B. Meirose, T.M. Miller, D. Milstead, T. Morishima, G. Muhrer, H.P. Mumm, K. Nagamoto, V.V. Nesvizhevsky, T. Nilsson, A. Oskarsson, E. Paryev, R.W. Pattie Jr, S. Penttil, Y. N. Pokotilovski, I. Potashnikova, C. Redding, J-M Richard, D. Ries, E. Rinaldi, A. Ruggles, B. Rybolt, V. Santoro, U. Sarkar, A. Saunders, G. Senjanovic, A.P. Serebrov, H.M. Shimizu, R. Shrock, S. Silverstein, D. Silvermyr, W.M. Snow, A. Takibayev, L. Townsend, I. Tkachev, L. Varriano, A. Vainshtein, J. de VRies, R. Woracek, Y. Yamagata, A.R. Young, L. Zanini, Z. Zhang, O. Zimmer

5. Summary

- Observation of BNV via neutron oscillation
- HIBEAM/NNBAR at ESS
- Annihilation detector design and prototype development work ongoing

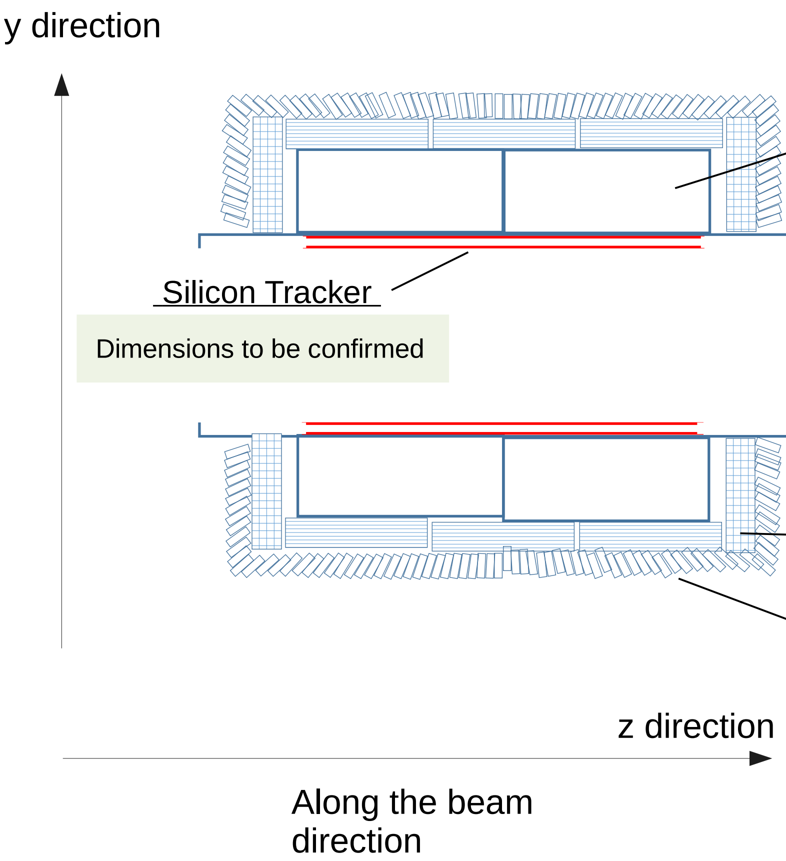
The End

Thank you for listening!

Backup slides

Cylindrical Geometry

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



Silicon Tracker

Dimensions to be confirmed

Time Projection Chamber

85 cm thick (radial length)
2 m long (z direction)
80% Ar + 20% CO2

Aluminum tube

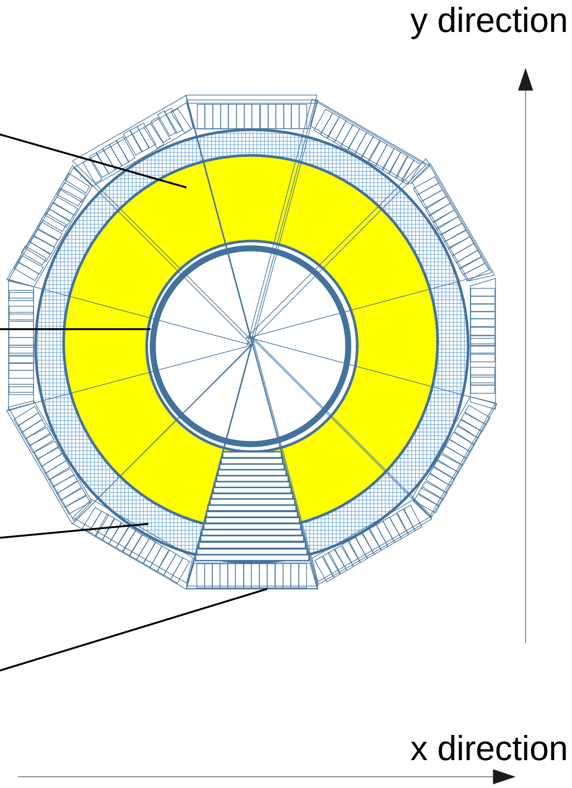
1 m inner radius
2 cm thick
6 m long (z direction)

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**



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:

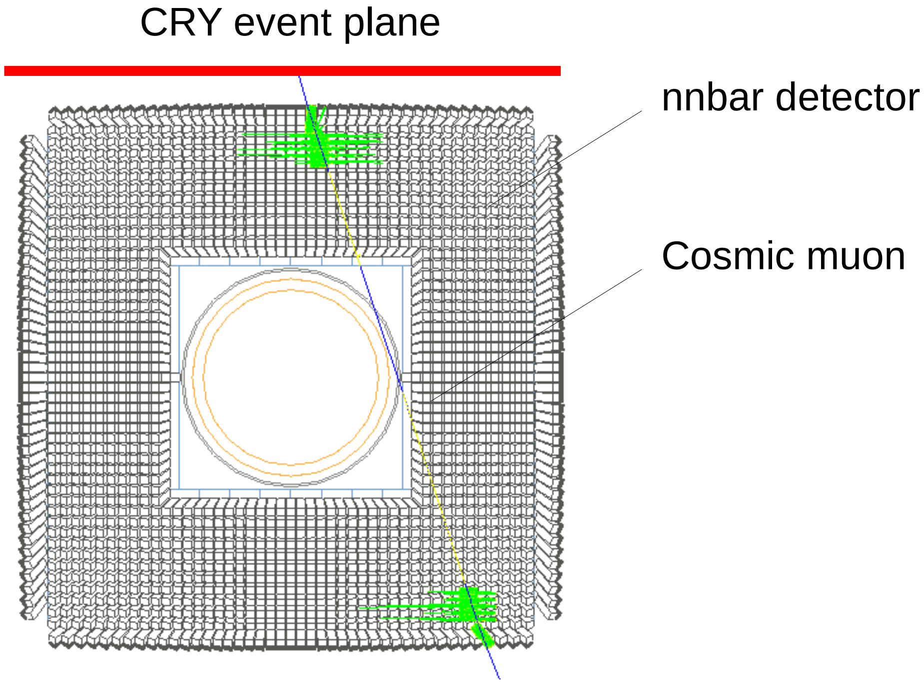
- Easy to build and prototype it (scalable)
- Easier to repair the TPC: modules can be easily replaced
- No dead areas

Cons:

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

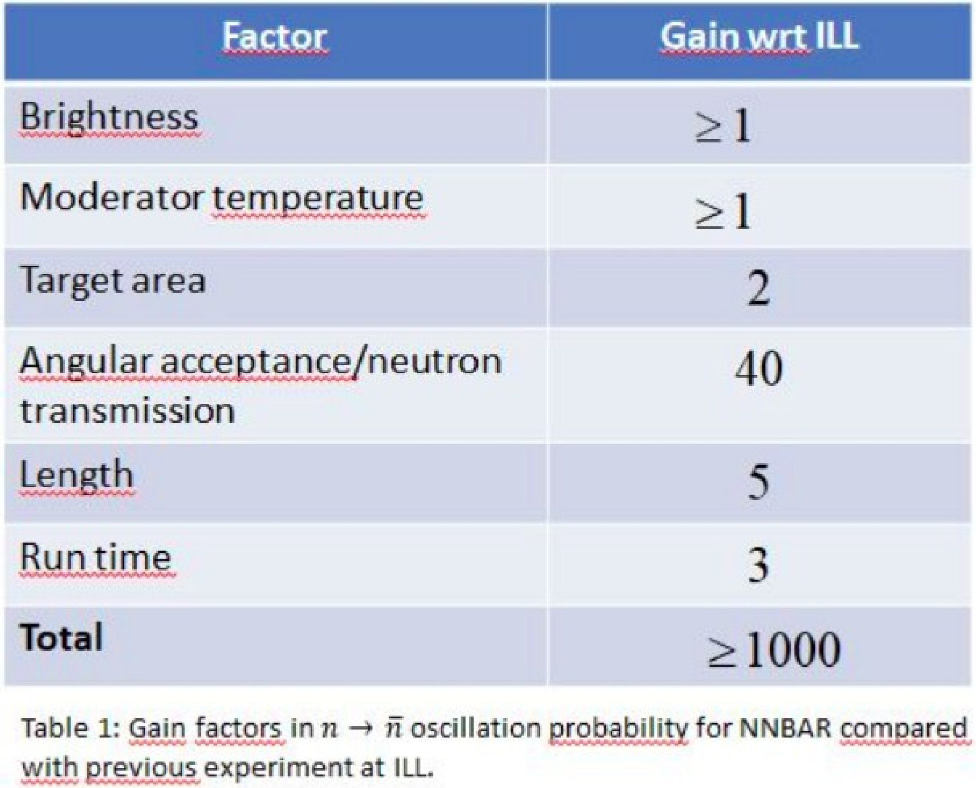
Cosmic ray background

- 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

Figure of Merit

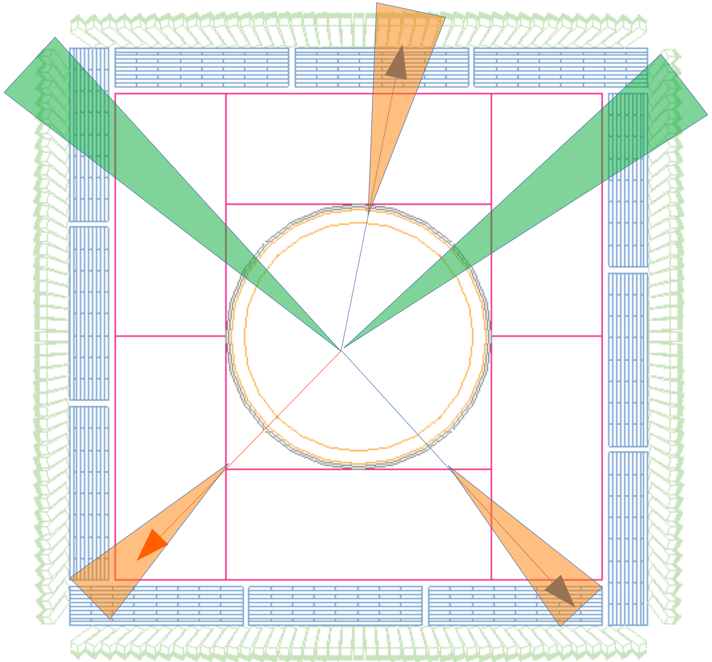


Factor	Gain wrt ILL
Brightness	≥ 1
Moderator temperature	≥ 1
Target area	2
Angular acceptance/neutron transmission	40
Length	5
Run time	3
Total	≥ 1000

Table 1: Gain factors in $n \to \bar{n}$ oscillation probability for NNBAR compared with previous experiment at ILL.

Energy and momentum reconstruction

Cones for energy collection



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**

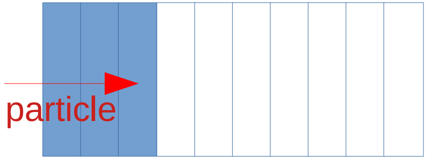
Object definition – Charged signal particles

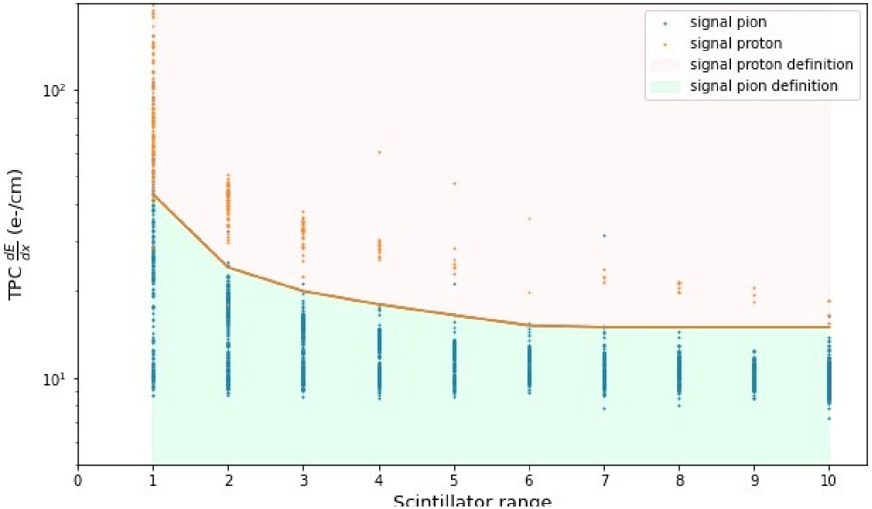
- What is an **object**?

  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**

Scintillator range = 3





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

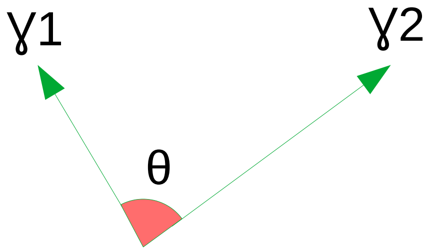
Object definition – Neutral pions

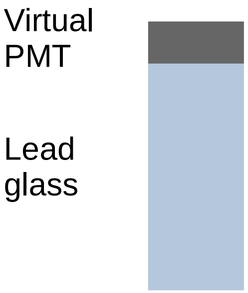
- **Neutral pion identification**

- Assume neutral hits are caused by gammas
- Check the mass m0 of any two gammas

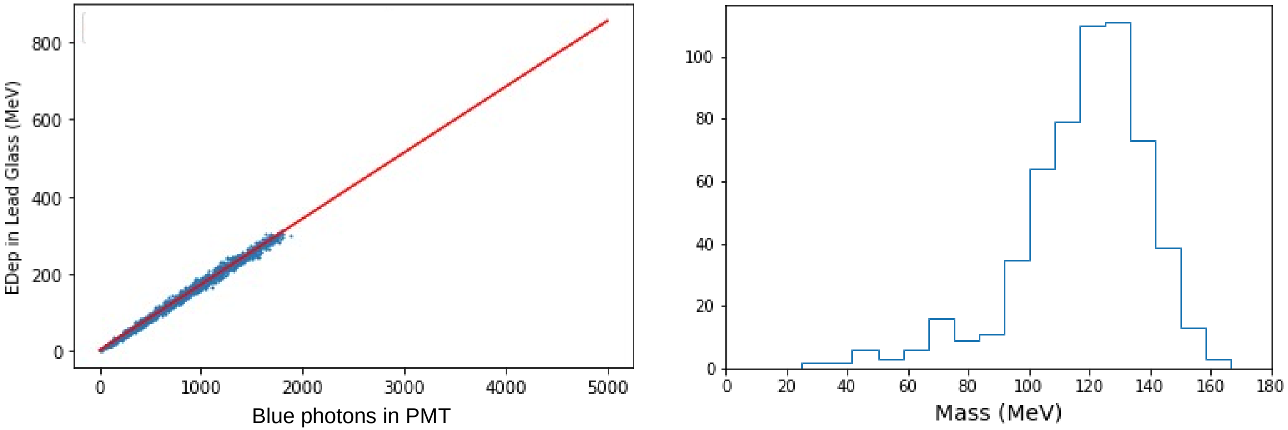
$$m_0 = \sqrt{2E_1E_2(1-cos\theta)}$$

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





Results from shooting neutral pions at 200 MeV KE



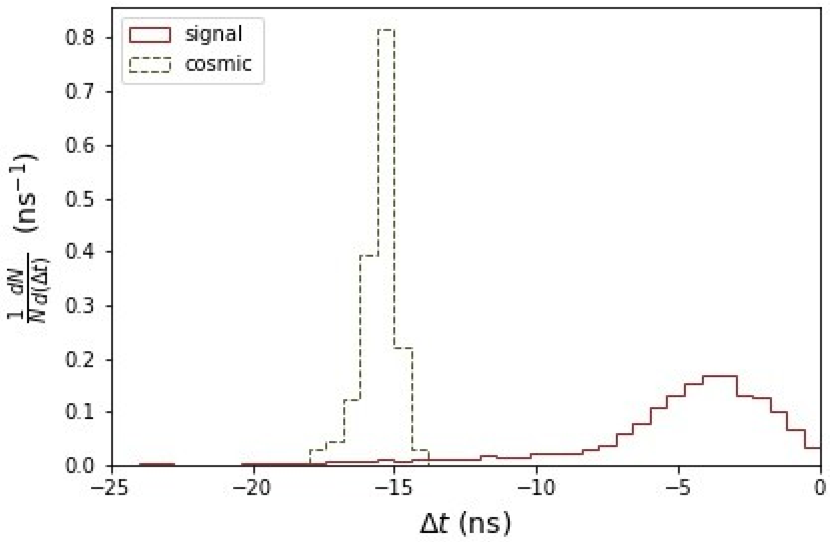
Signal timing

- 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



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