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

Spåtind 2023
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Outline of the presentation

1) Introduction

2) HIBEAM and NNBAR experiment at the ESS

More discussion
=> Bernhard's talk tmr

3) NNBAR detector simulation studies and status

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:

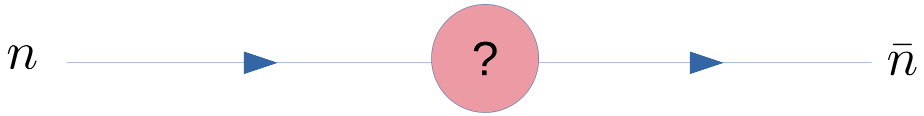
$$\Delta B \neq 0, \Delta L = 0, \Delta(B-L) \neq 0$$ **nnbar**

$$\Delta B = 0, \Delta L \neq 0, \Delta(B-L) \neq 0$$ **0v2B**

$$\Delta B \neq 0, \Delta L \neq 0, \Delta(B-L) \neq 0$$ **Proton decay**

1.2 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 $\Delta Et << 1$ (achieved in vacuum with very low magnetic field)

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

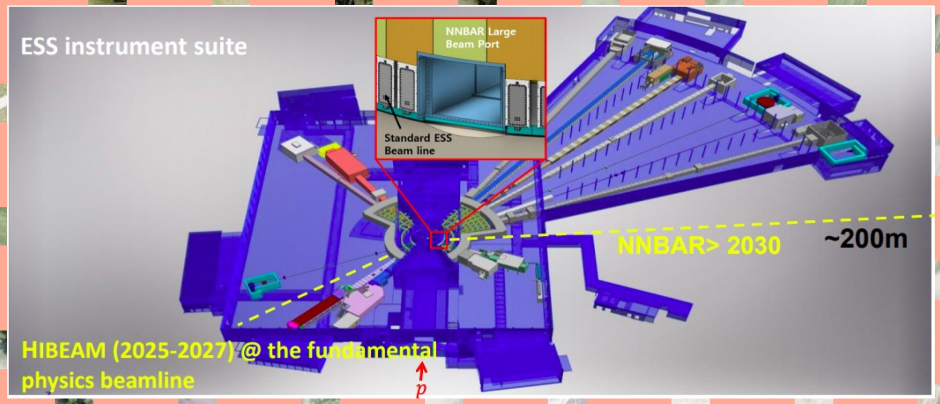
2. HIBEAM/NNBAR at the European Spallation Source

2.1 European Spallation Source (ESS)

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

EUROPEAN SPALLATION SOURCE

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



2.2 HIBEAM/NNBAR experiment at the ESS

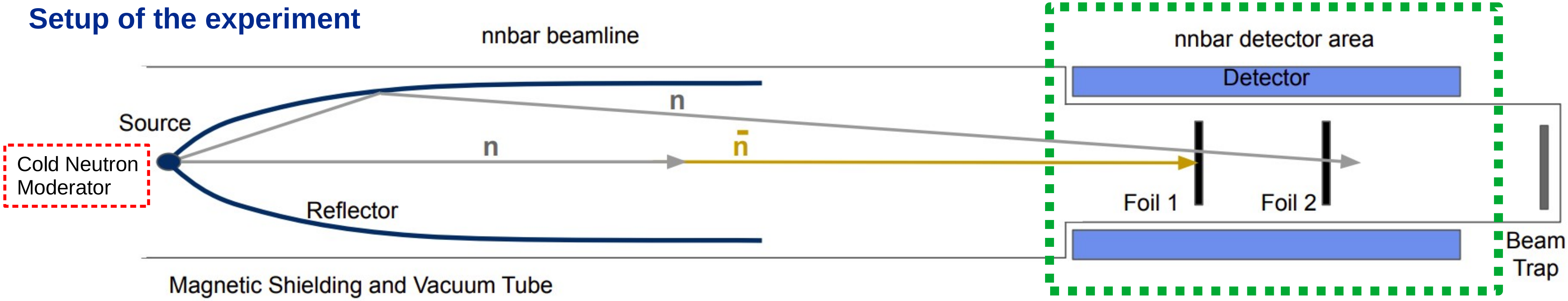
- **Proposed Two Stage Experiment at the ESS – HIBEAM/NNBAR**

- *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

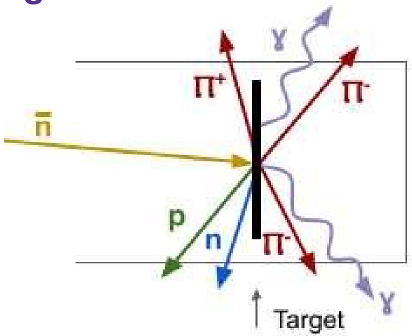
2.3 NNBAR experiment

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)



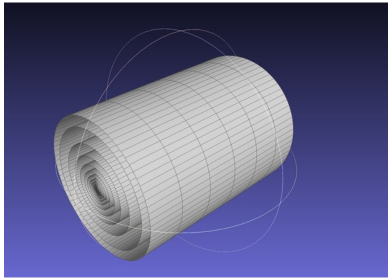
Annihilation product simulation

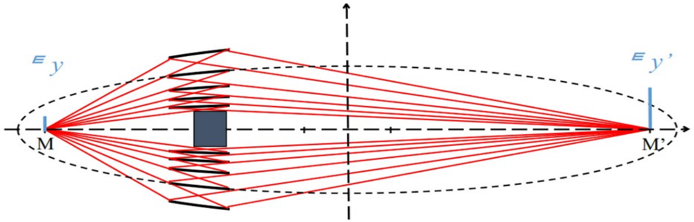
- Simulation of the products was done*
- List of annihilation products → Used by the detector simulation studies through **GEANT4**

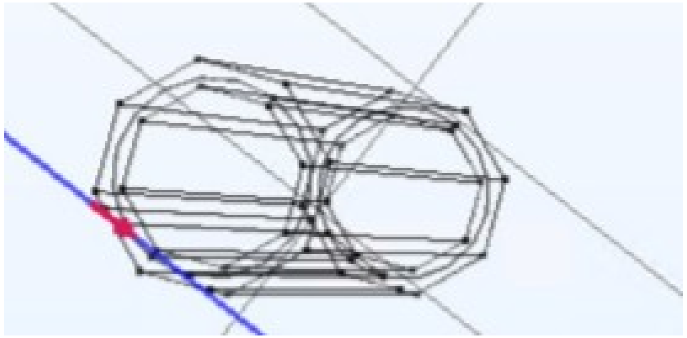
* J. Barrow, E. Golubeva, C. Ladd, *"A model of antineutron annihilation in experimental searches for neutron-antineutron transformations"*

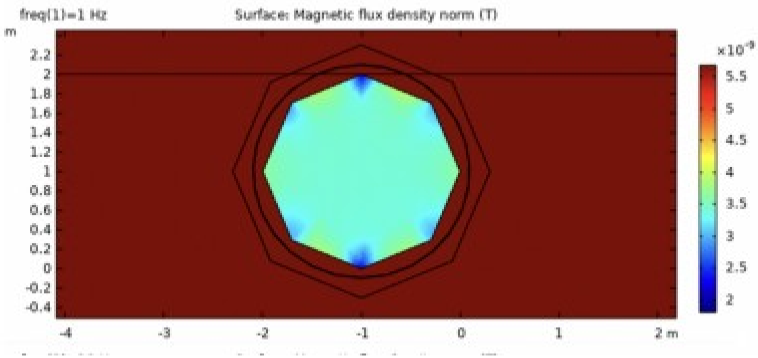
2.4 NNBAR optics and magnetic shielding

Nested Reflector
McStas simulation
Sensitivity per year
~"300 ILL units"









More discussions in Bernhard's talk

Outer + inner octagon shield from mu-metal

Round steel vacuum chamber: between shields

COMSOL simulations < 10 nT

2.5 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

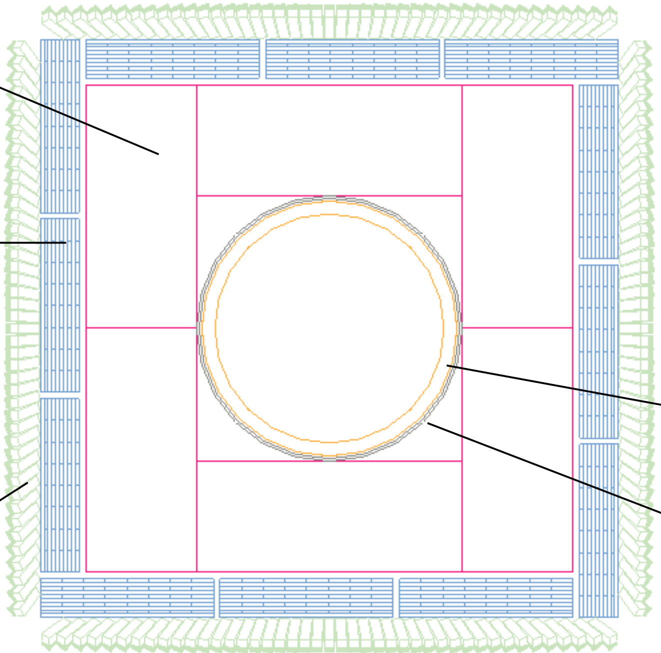
10 layers of plastic scintillator
3 cm thick for each layer

Each layer is divided into 8 staves

Consecutive layers are perpendicular

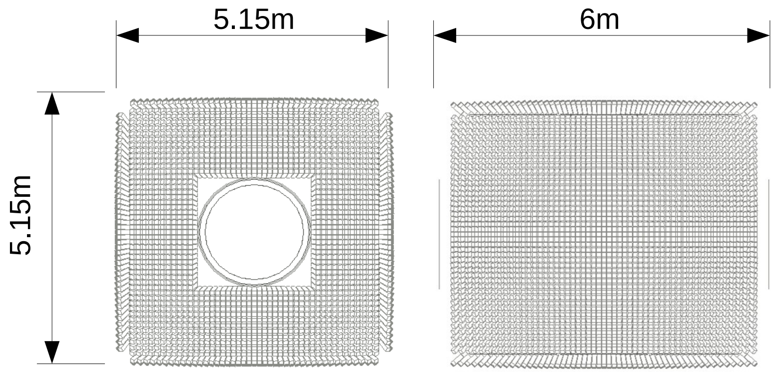
Lead Glass Blocks

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)

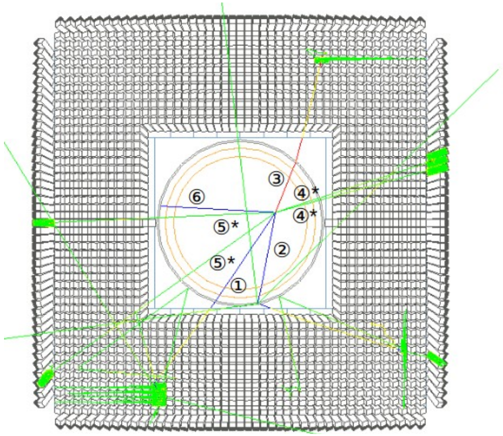
* GEANT4 version: geant4.10.06.p02
** Dimensions here are preliminary. These numbers are only used in the simulations as a reference.

3. NNBAR detector studies

3.1 GEANT4 based detector studies

Particle interactions of different kinds of interaction with the detector is studied through GEANT4

- **Annihilation events**
  - A typical event display of an neutron-antineutron annihilation simulated in GEANT4 [shown on right side] ►



- **Backgrounds**

  1. Cosmic ray background

  It was the dominant of background in the previous free neutron search

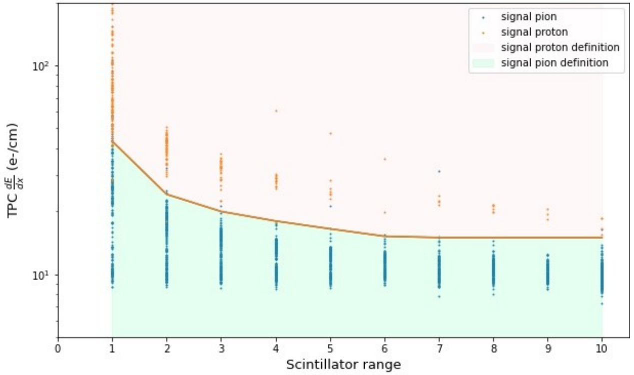
  2. Neutron beam background

  Neutrons from the beam may interact with the detector or the detector structure

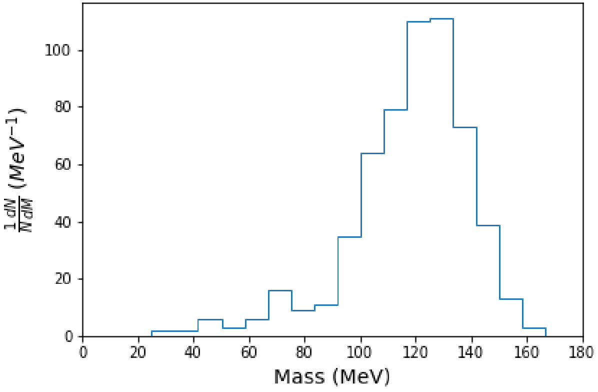
  May create signatures similar to the annihilation events

3.2 GEANT4 based detector studies

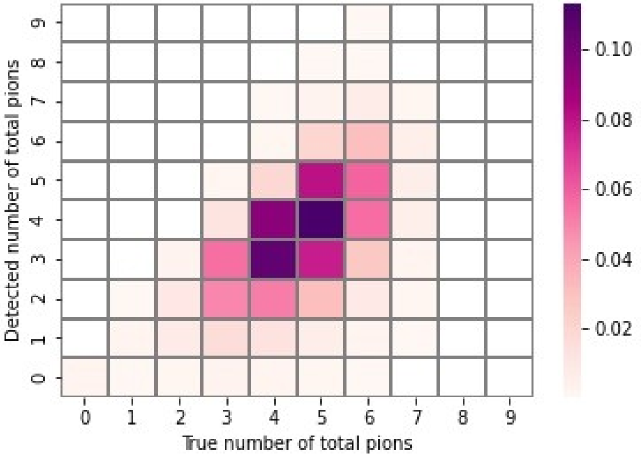
Object definition



Diphoton mass reconstruction



Signal event pion multiplicity



Detector signature can be characterized by the following event variables

Invariant Mass W:

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

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

Sphericity S:

The sphericity 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 $\lambda_1, \lambda_2, \lambda_3$

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

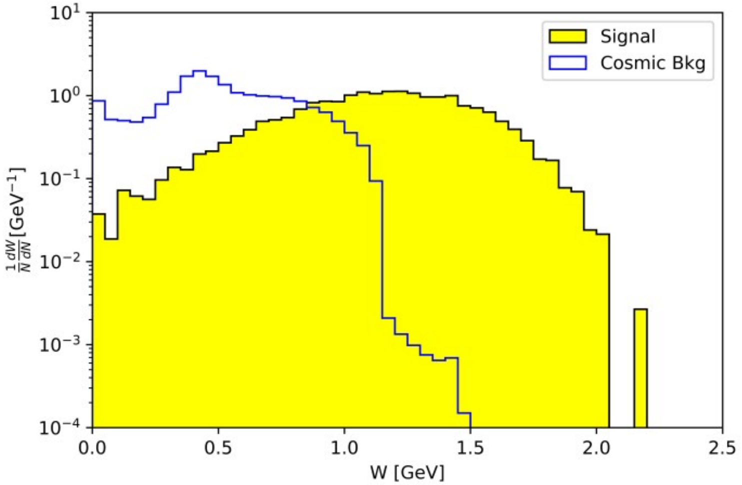
$$S = \frac{3}{2}(\lambda_2 + \lambda_3)$$

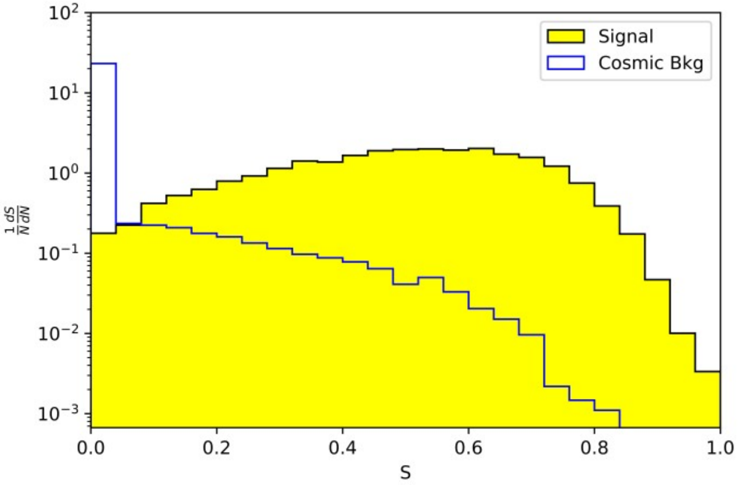
3.2 Event variables

For the **annihilation signal** and **cosmic background**, we have shown a good separation under these event variables

We achieved a good efficiency in signal acceptance and cosmic background rejection by selection based on event variables

Aiming at gaining more statistics on the cosmic ray background





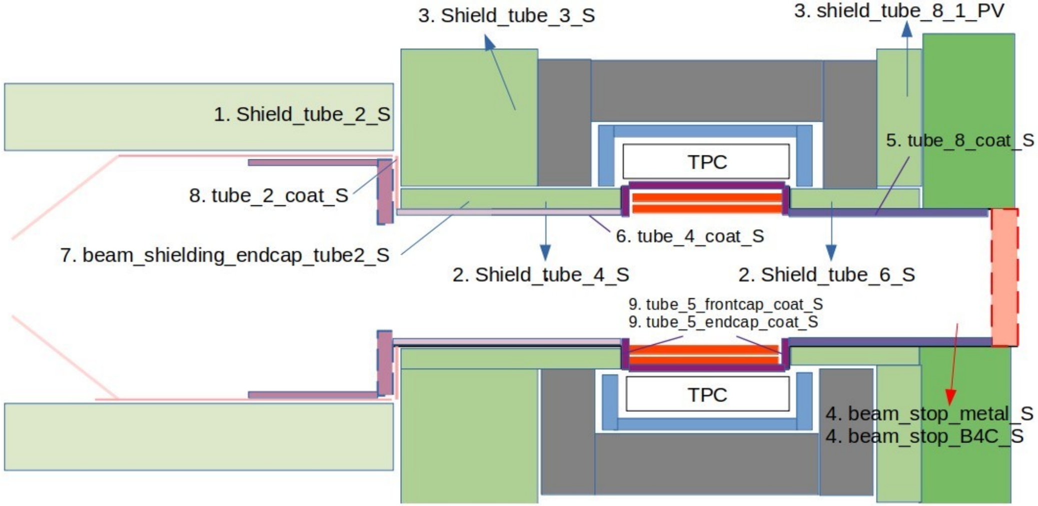
Backman, F., Barrow, J., Beßler, Y., Bianchi, A., Bohm, C., Brooijmans, G., ... & Zimmer, O. (2022). The development of the NNBAR experiment. Journal of Instrumentation, 17(10), P10046.

Yiu, S-C, et al. "Status of the Design of an Annihilation Detector to Observe Neutron-Antineutron Conversions at the European Spallation Source."Â SymmetryÂ 14.1 (2022): 76.

3.3 Neutron beam background studies

Work on understanding neutron beam background is ongoing

- Worked on the **neutron beam shielding**
- Tested different configurations
  - Neutron absorber material
  - Shielding material
  - Length of beam pipe
- Studying particles going into each detector subsystem

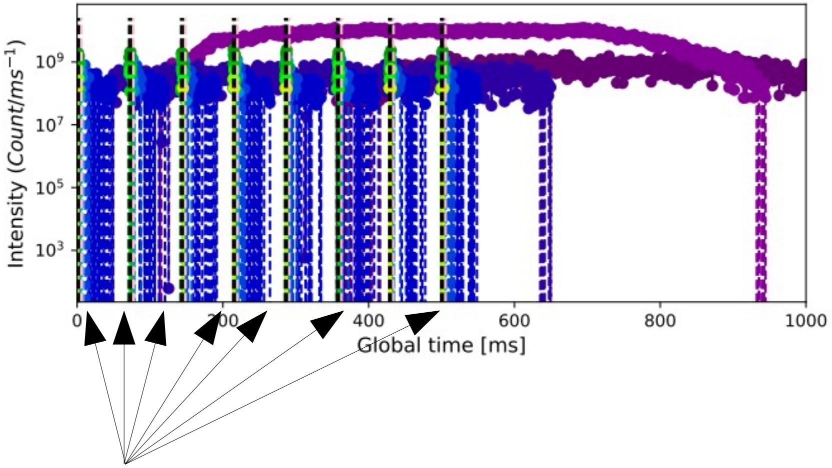


A few questions that we need to answer:

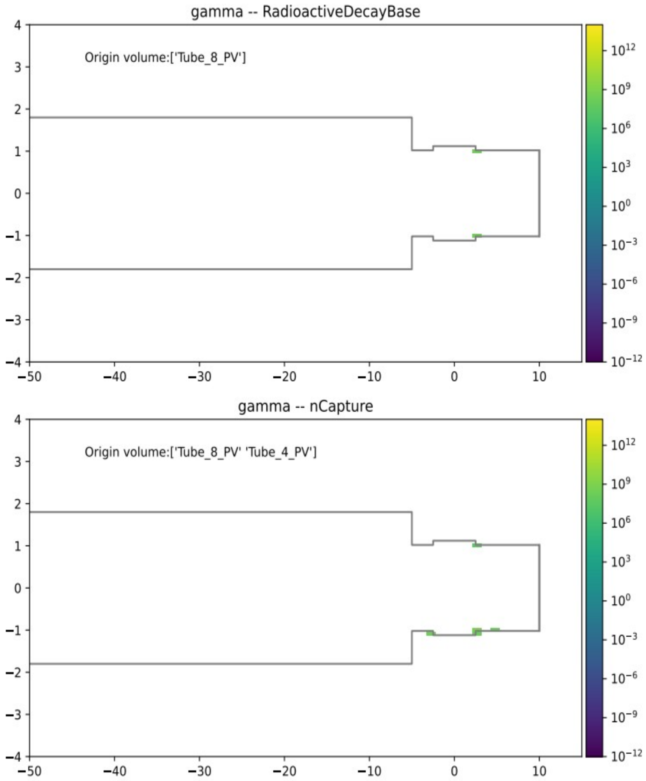
1) What interactions between neutrons and material are possible? ◄
2) What are the possible secondary particles? ◄
3) Rate of particles going into the detector area ◄
4) How much energy will they deposit? ◄

3.3 Status of the neutron beam background studies

Neutron intensity at the carbon target



ESS neutron pulses



Examples of **gammas** going into the calorimeter

◄A map of where these gammas are produced and the interaction type

4. Summary

- Observation of BNV via neutron oscillation
- HIBEAM/NNBAR experiment at ESS
- Annihilation detector study is ongoing

List of recent publications:

- Abele, H., et al. "Particle Physics at the European Spallation Source."Â arXiv preprint arXiv:2211.10396Â (2022).
- Backman, Fredrik, et al. "The development of the NNBAR experiment." Journal of Instrumentation 17.10 (2022): P10046.
- The Development of a Model for the NNBAR experiment
- 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

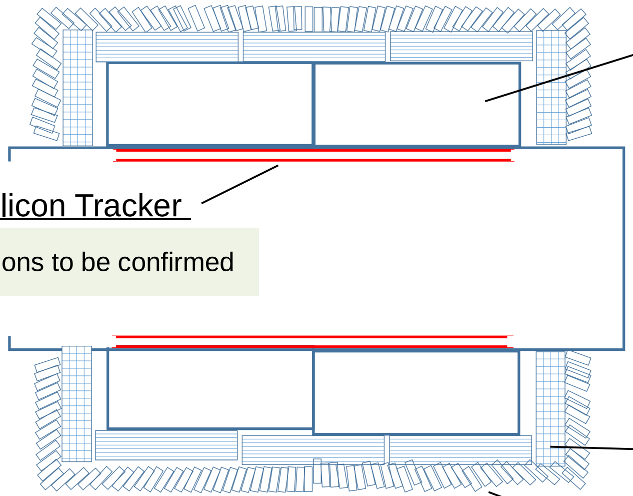
Thank you very much!

Backup slides

Cylindrical Geometry

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

y direction



z direction

Along the beam direction

Silicon Tracker

Dimensions to be confirmed

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)

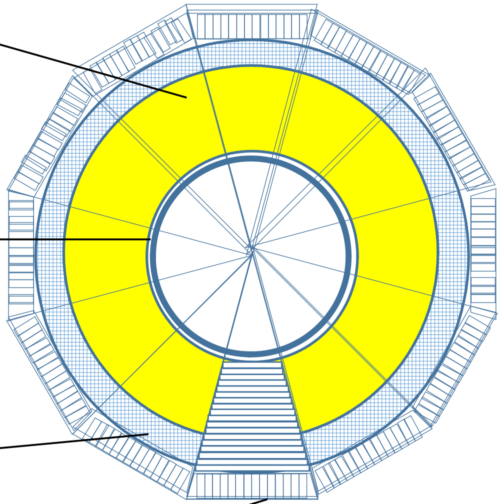
Scintillator Modules

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

3.1 List of detector simulation studies and event variables

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

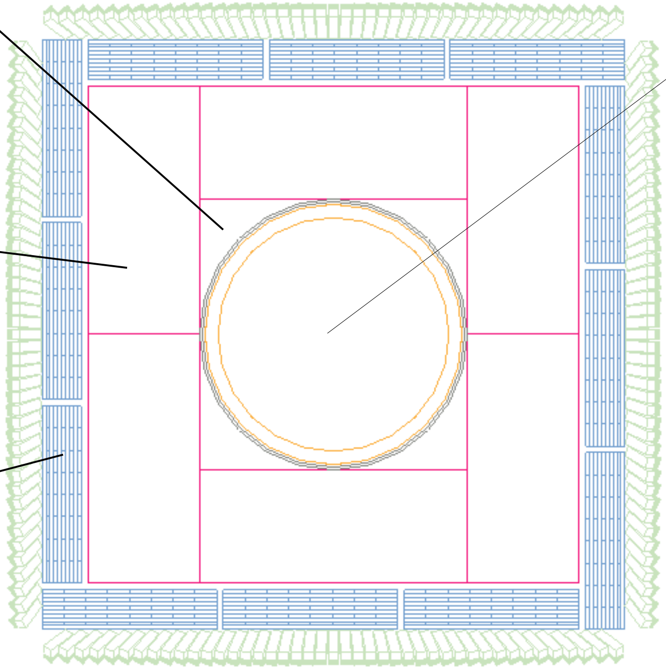
Outside the detector
- Cosmics
- Shielding

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

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:

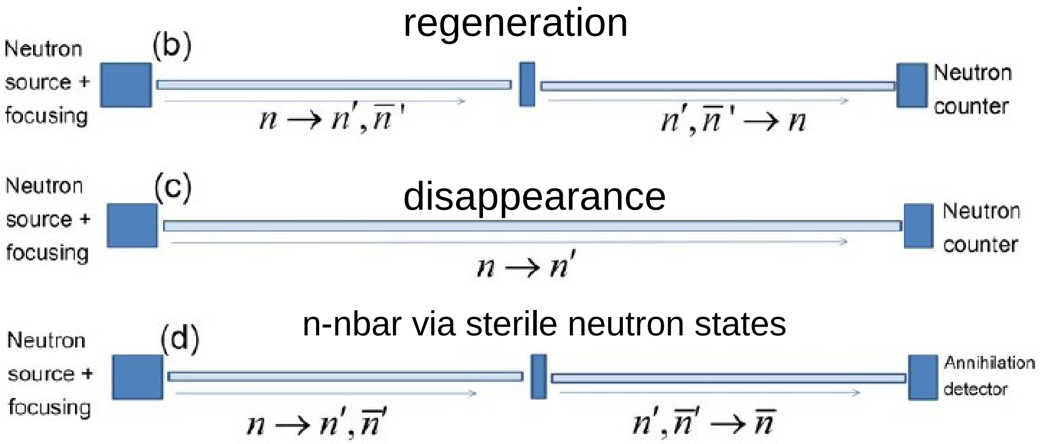
- Easy to build and prototype it (scalable)
- Easier to repair the TPC: modules can be easily replaced
- No dead areas

Cons:

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

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

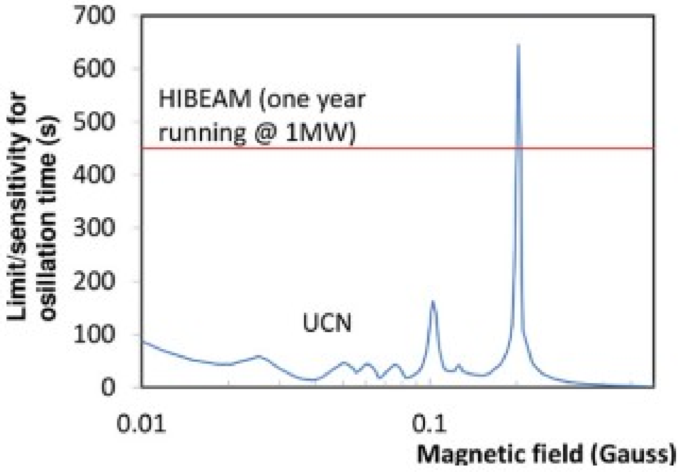


Figure 22. Excluded neutron oscillation times in blue for $n \to n'$ disappearance from UCN experiments [40, 42, 44–47] as a function of the magnetic field $\mathbf{B}'$. The projected sensitivity for HIBEAM (disappearance mode) is also shown in magenta for 1 year's running at the ESS assuming a power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

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

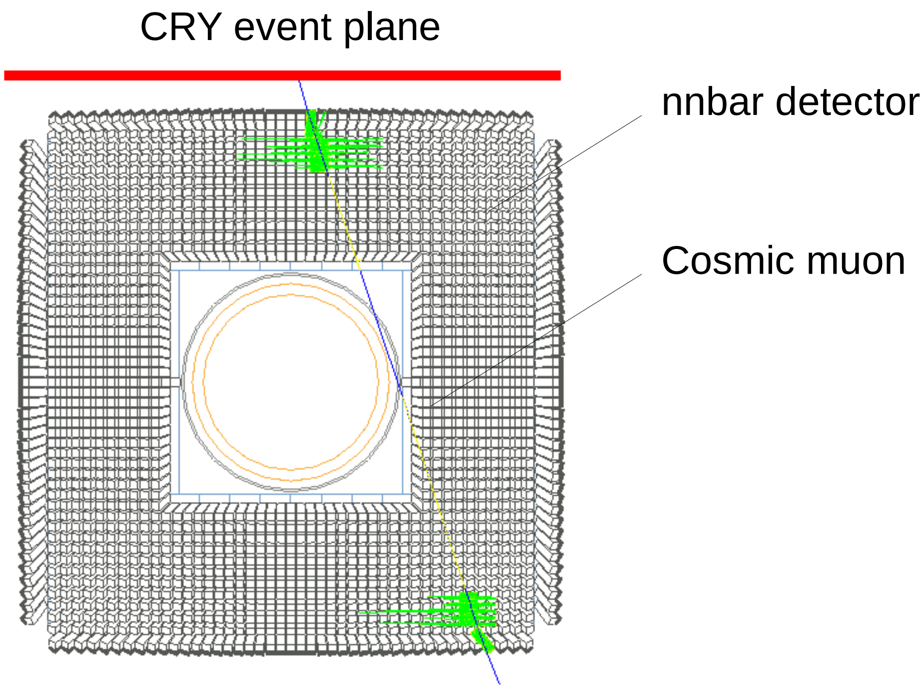


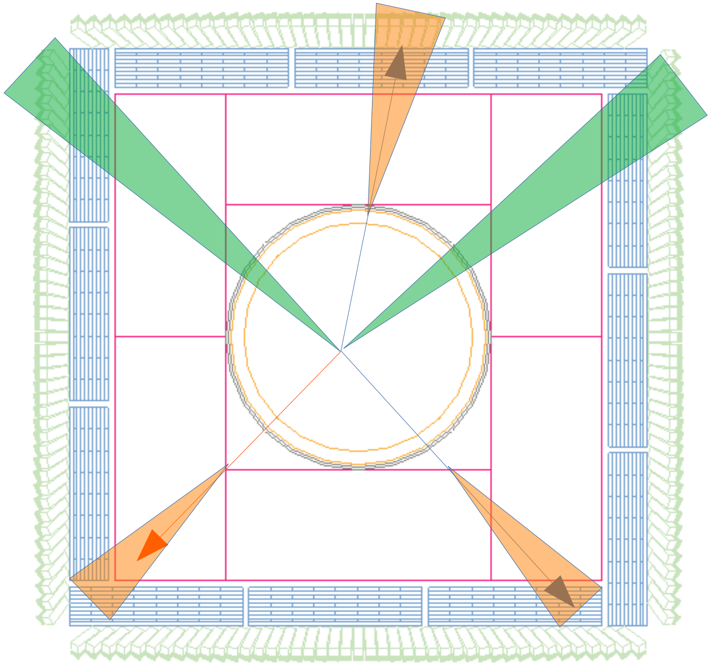
Figure of Merit

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 $n \rightarrow \bar{n}$ oscillation probability for NNBAR compared with previous experiment at ILL.

Energy and momentum reconstruction

Cones for energy collection



Energy and momentum direction reconstruction

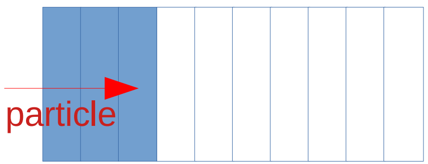
- We developed an algorithm to reconstruct the energy and momentum of **charged** and **neutral** particles
- Reconstruction of **charged particles** relies on the TPC track information and silicon tracker information
- Energy is collected if a signal is inside any cone
- Hits that cannot be associated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

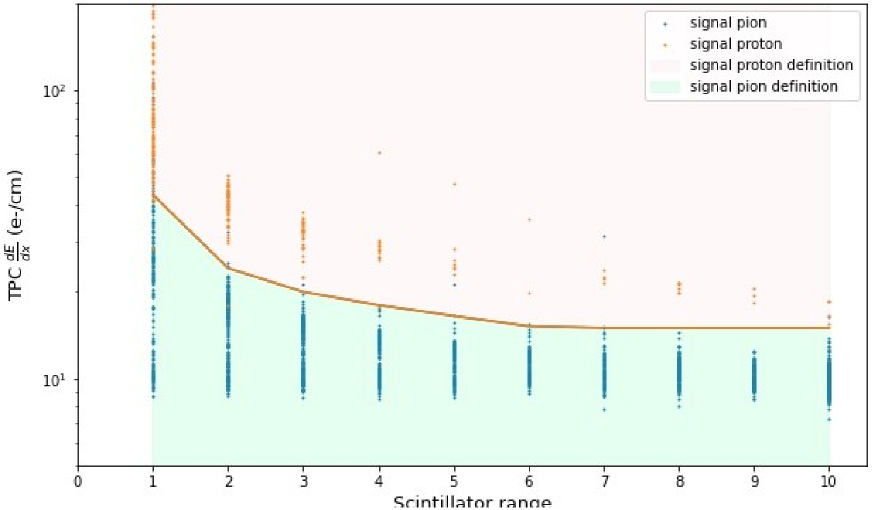
Object definition – Charged signal particles

- 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**





Definition of pion:

TPC dEdx < t_N

Definition of proton:

TPC dEdx >= t_N

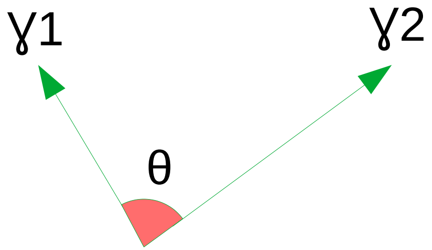
t_N is the cut value
N = number of scintillator layers it penetrates
The cut value depends on how many layers it penetrates

Object definition – Neutral pions

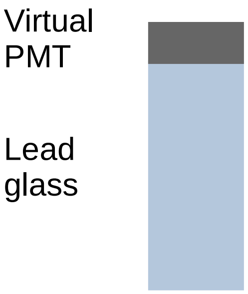
- **Neutral pion identification**
  - Assume neutral hits are caused by gammas
  - Check the mass m0 of any two gammas

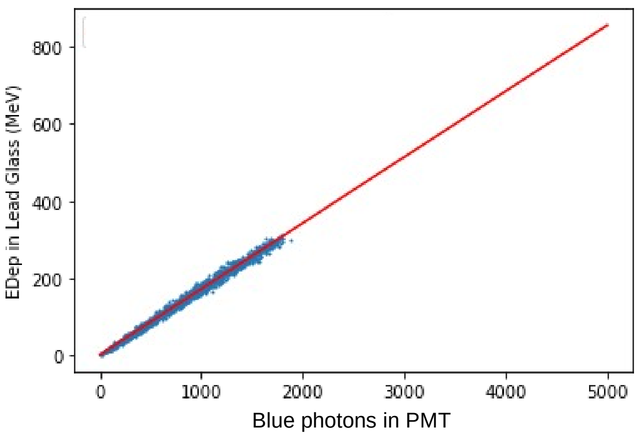
$$m_0 = \sqrt{2E_1E_2(1 - cos\theta)}$$

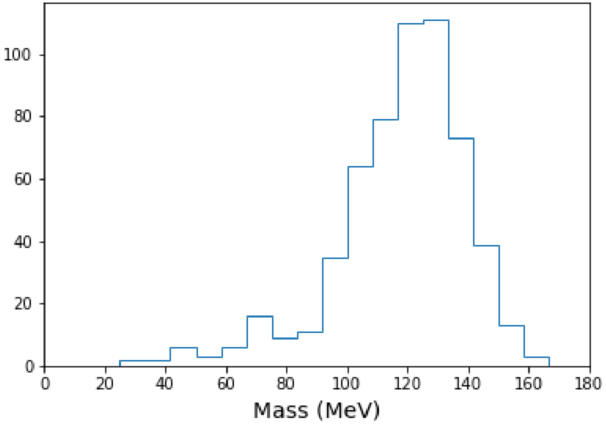
  - If m1 < m0 < m2, identify the two gammas to be π^0 decay products



Results from shooting neutral pions at 200 MeV KE







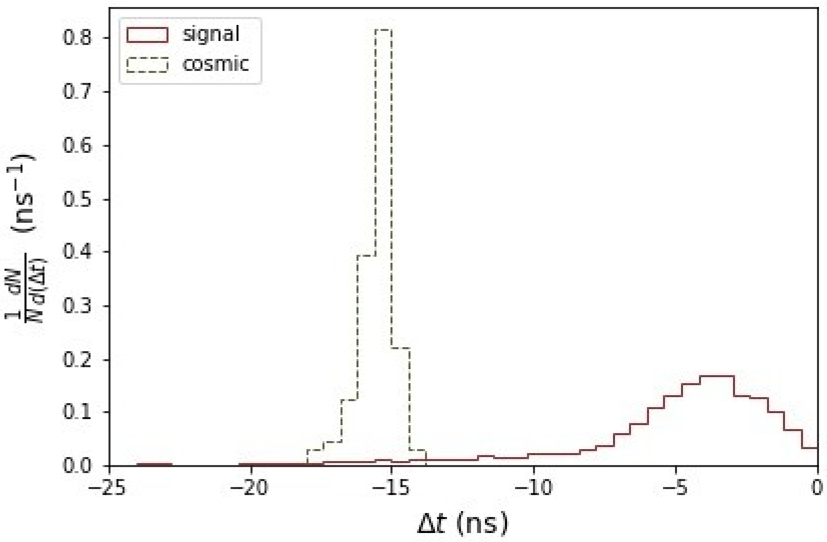
Signal timing

- 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



Particle Intensity into the TPC

Energy range (MeV)	Particle	Particles/s		
		Config. 1 No coating	Config. 2 B_4C	Config. 3 ^{6}LiF
$10^{-2} - 10^{-1}$	Photon	1×10^{11}	6×10^{10}	6×10^{8}
$10^{-1} - 10^{-0}$		4.6×10^{11}	2×10^{11}	6×10^{8}
$10^{0} - 5 \times 10^{0}$		5×10^{11}	1×10^{9}	8×10^{8}
$5 \times 10^{0} - 10^{1}$		2×10^{11}	5×10^{8}	2×10^{8}
$2 \times 10^{-11} - 10^{-10}$	Neutron	5×10^{8}		
$10^{-10} - 10^{-9}$		3×10^{10}		
$10^{-9} - 10^{-8}$		4×10^{11}		
$10^{-8} - 10^{-7}$		4×10^{11}		
$10^{-1} - 10^{0}$				2×10^{7}
$10^{0} - 5 \times 10^{0}$				1×10^{8}
$5 \times 10^{0} - 10^{1}$				2×10^{7}
$1 \times 10^{1} - 5 \times 10^{1}$				3×10^{7}
$10^{-2} - 10^{-1}$	Electron	2×10^{9}	5×10^{8}	
$10^{-1} - 10^{0}$		1×10^{10}		
$10^{0} - 5 \times 10^{0}$		3×10^{10}	5×10^{8}	1×10^{7}
$5 \times 10^{0} - 10^{1}$		3×10^{9}		3×10^{7}
$10^{-2} - 10^{-1}$	Positron	2×10^{9}	5×10^{8}	
$10^{-1} - 10^{0}$				
$10^{0} - 5 \times 10^{0}$		3×10^{9}		

Table 2: Particle intensities into the TPC for Configurations 1,2 and 3.