# The NNBAR experiment for the ESS

## - The full detector studies -

ESS science day
2nd June 2021

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NNBAR

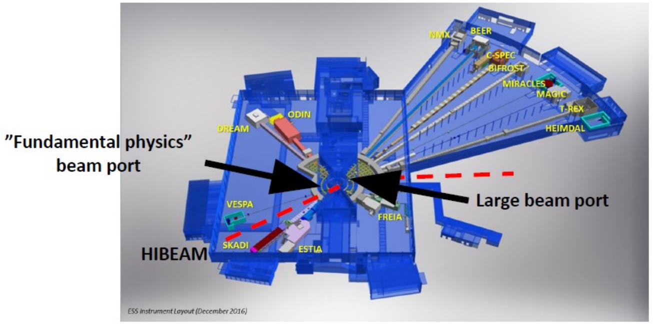
*Work done within HighNESS Project*

# Flow of the presentation

- Introduction to the NNBAR experiment and HighNESS project
- Possible design of the NNBAR detector
- Summary of the NNBAR detector studies
- Results from TPC simulation
- Current progress of object definition

- **Motivation of NNBAR experiment**
- Baryon Number Violation (BNV) may be the key to baryogenesis (Matter and antimatter asymmetry)
- BNV is a key ingredient of many BSM theories

- **Pure channels to observe BNV**
- The processes $n \to \overline{n}$ (|ΔB| = 2) and $n \to n'$ (|ΔB| = 1) are the cleanest channel to observe BNV

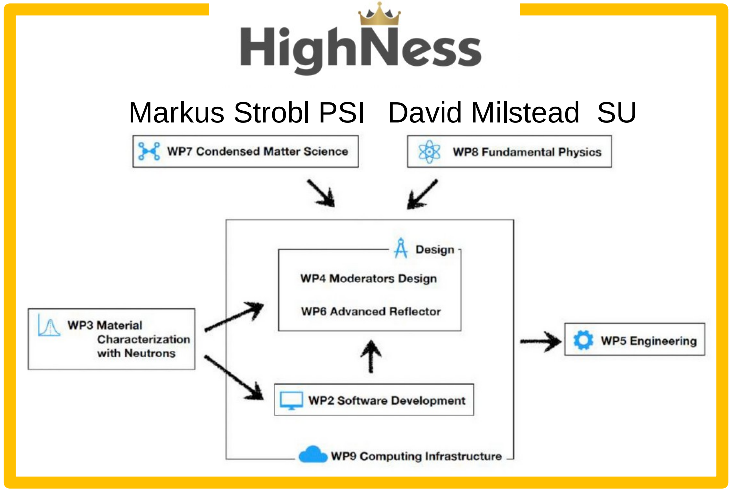



- **Proposed Two Stage Experiment at the ESS – HIBEAM/NNBAR**
- *Phase 1* – HIBEAM: Search for n → n′
  - Use cold neutrons from fundamental physics beam line
  - Low sensitivity but good for understanding the challenges
- *Phase 2* – NNBAR: Search for $n \to \overline{n}$
  - Use cold neutrons from the Large Beam Port
  - 1000 times increase in sensitivity compared to the free neutron search done at ILL in 1990's

# 1.2 The HighNESS project at ESS, started october 2020

- The HighNESS project (3 MEURO funded by the European Commission) has as purpose the development of the new source that will be installed at ESS >2030
- **Liquid deuterium** lower moderator that will serve a UCN moderator and a VCN source using advanced reflectors
- In the project will be also developed the associated instruments. The future instruments will complement the available instrument suite at ESS
- Design driven by needs of condensed matter (neutron spin echo, SANS, and imaging) and fundamental physics (NNBAR + UCN/VCN applications)
- **2 scientific Work Packages** dedicated to science that will set the requirements to the new source.

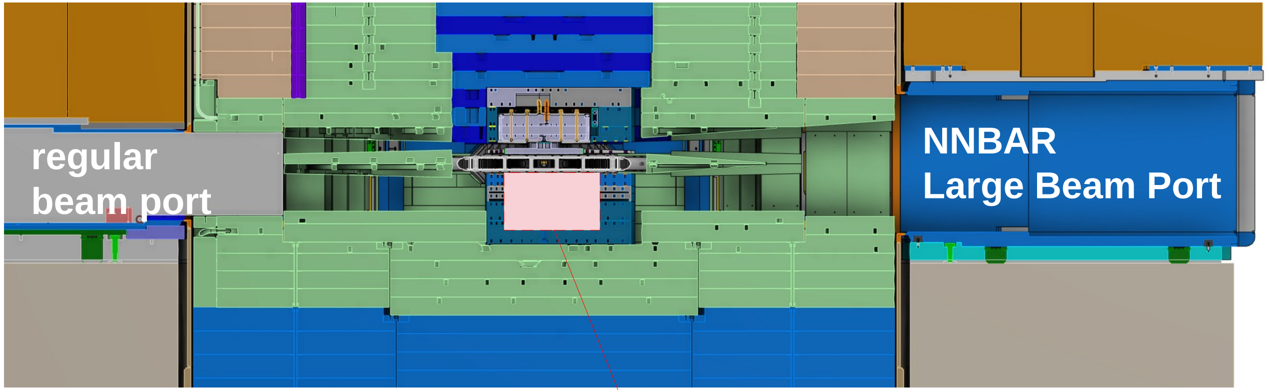
8 EU Institutes,
7 countries,
34 people presently involved



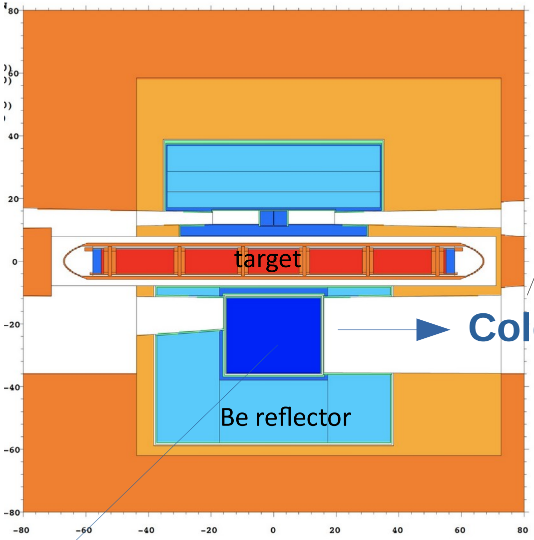

Conceptual Design Report of the new source expected by the end of 2023

# 1.3 NNBAR and HighNESS

- The design allows solid state applications to co-exist with NNBAR and avoid loss of necessary intensity
- Such moderator provides a stronger source of cold neutrons
  - Increases the sensitivity of NNBAR experiment (factor of ~ 1000)




Lower moderator location



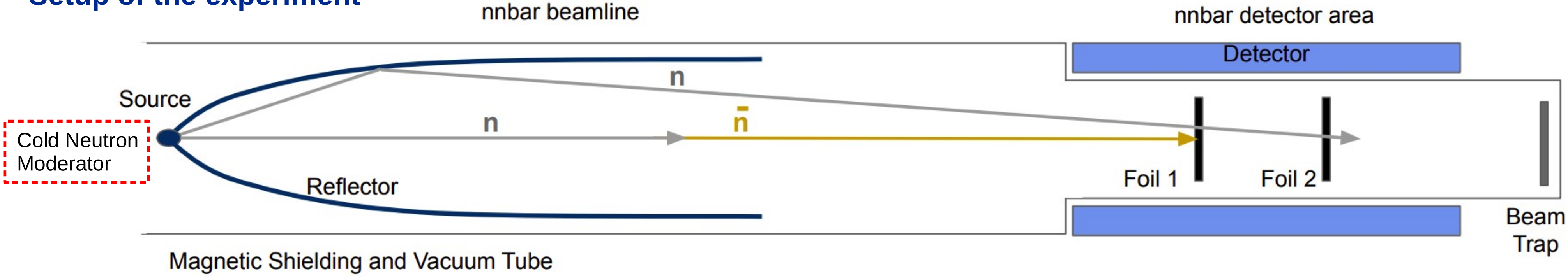

NNBAR opening

Cold neutrons

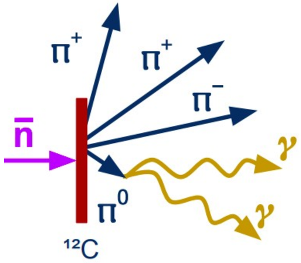
D2 moderator

# 1.4 The NNBAR experiment at ESS

## 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 $\pi^0$ 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



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

# 2.1 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

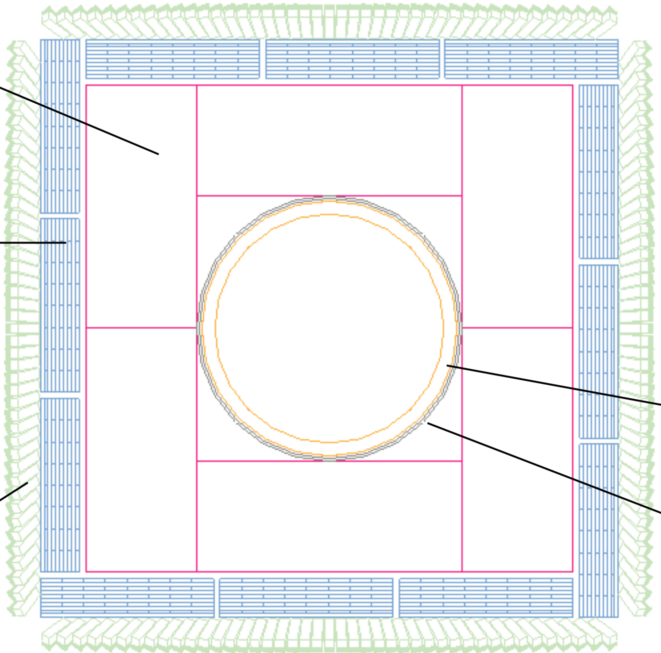
10 layers of plastic scintillator
3 cm thick for each layer

Each layer is divided into 8 staves

Consecutive layers are perpendicular

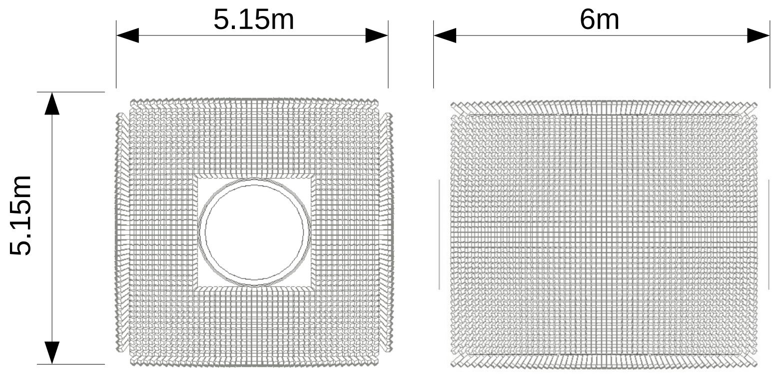
### Lead Glass Blocks

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 |

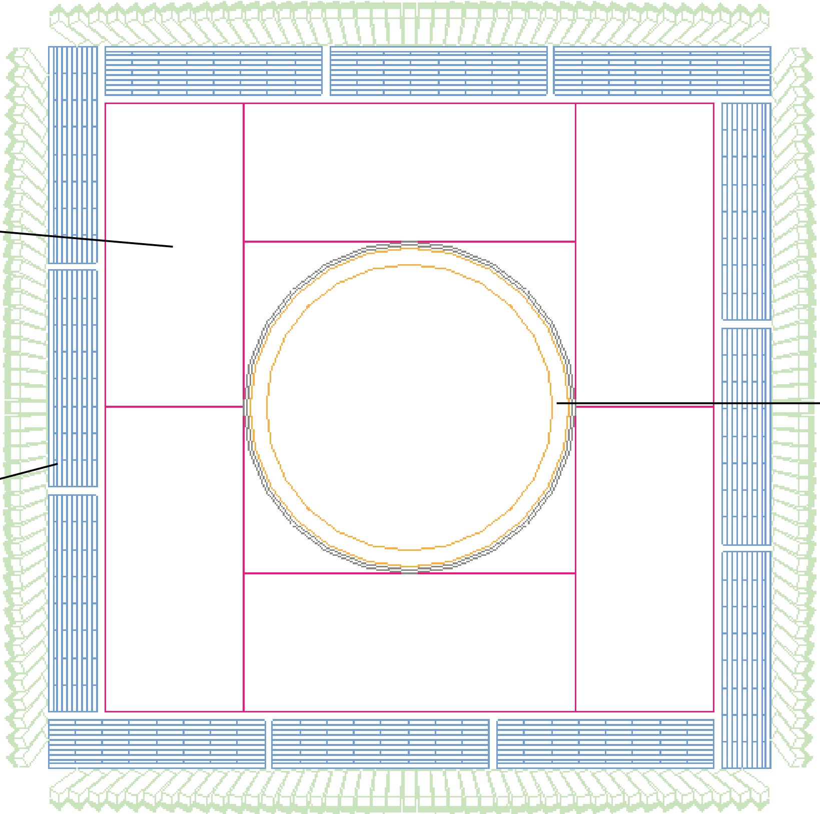
### Vacuum tube

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. Brief summary of studies we have done

- We studied different components of the full detector systematically



## TPC

- TPC track visualization
- ★ TPC dE/dx calculation

## Calorimeter

- Pi0 mass reconstruction
- Particle energy deposited vs initial KE
- Energy resolution

## Outside the detector

- Cosmics
- Shielding

## Inside the tube

- Beta decay electrons ★
- Nuclear fragments

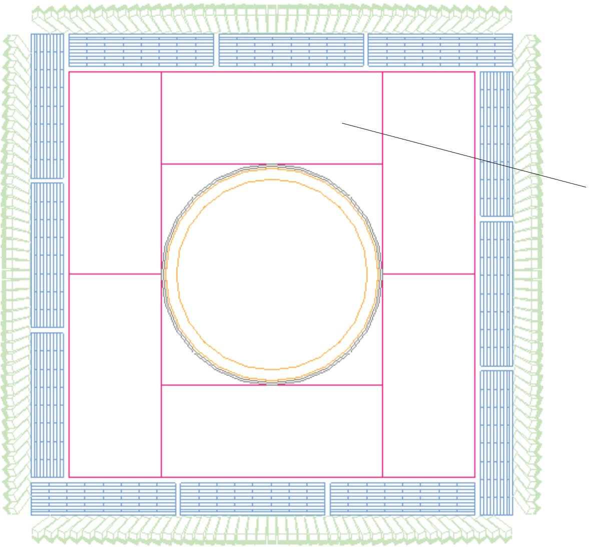
## Full detector

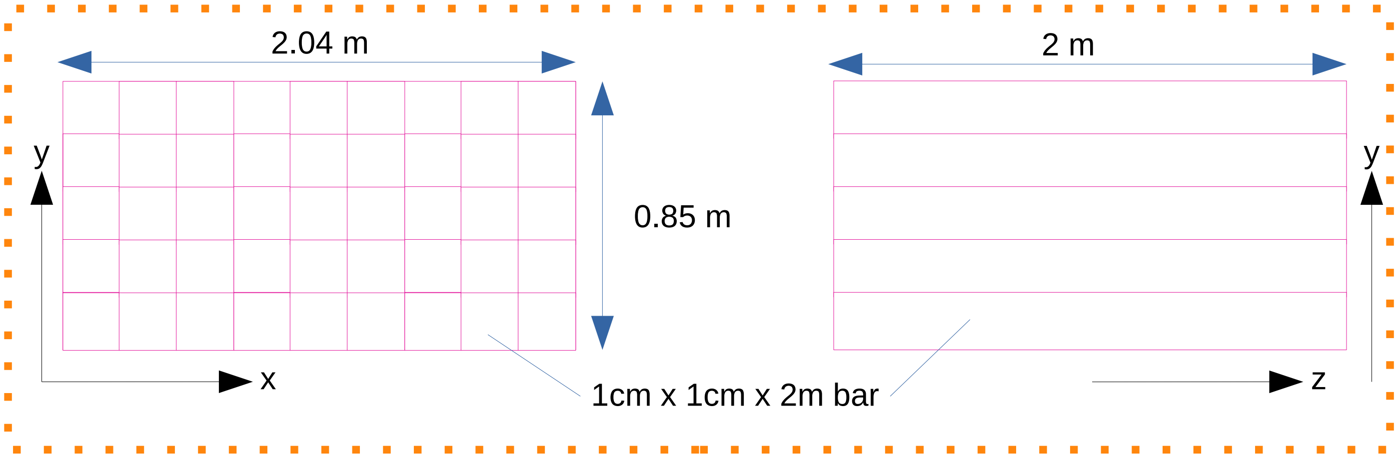
- Signal timing ★
- Event shape variables
- Object definition ★

★ Featured topics of today (red)
★ Brief discussion in appendix (green)

# 4.1 TPC simulation

- Details of the TPC Geometry and simulation
- The TPC volume is divided into **small bars** (1cm x 1cm x 2m each) to simulate the 1cm x 1cm readout pads






** The figures here are not drawn to scale.

# 4.2 TPC dEdx calculation

- The TPC dEdx plays an important role in particle identification

- We need to study the dEdx signal of charged particles in the TPC

- Calculation of TPC dEdx from our GEANT4 simulation:

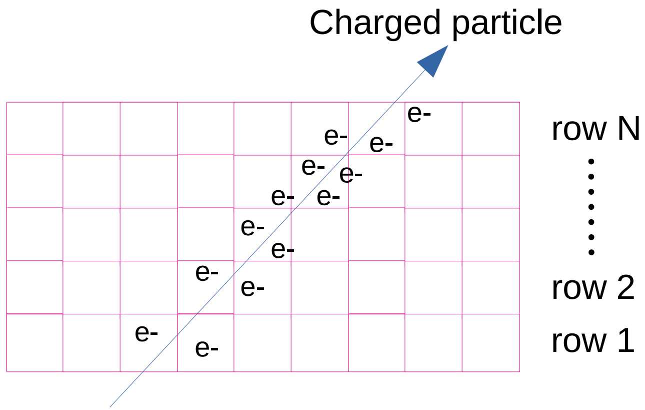
1) A charged particle passes through a TPC volume
2) Ionization electrons are produced along the path
3) The dE/dx of the particle at each row can be estimated by:

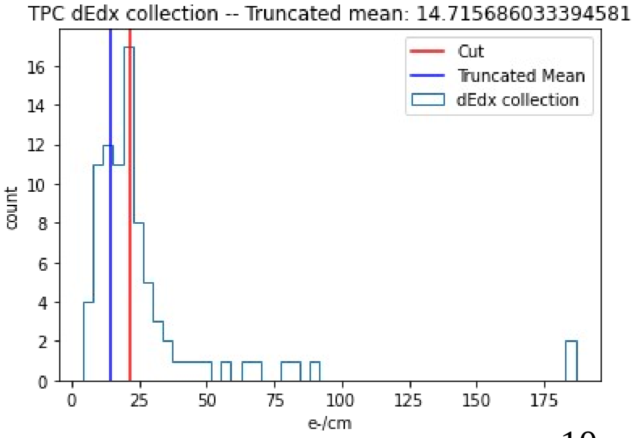
$$\frac{dE}{dx} = \frac{n}{L}$$

n is the number of electrons produced at the row
L is the total track length of the particle at the row
(Information can be obtained from GEANT4)

- Collecting the dE/dx value at each row gives a distribution

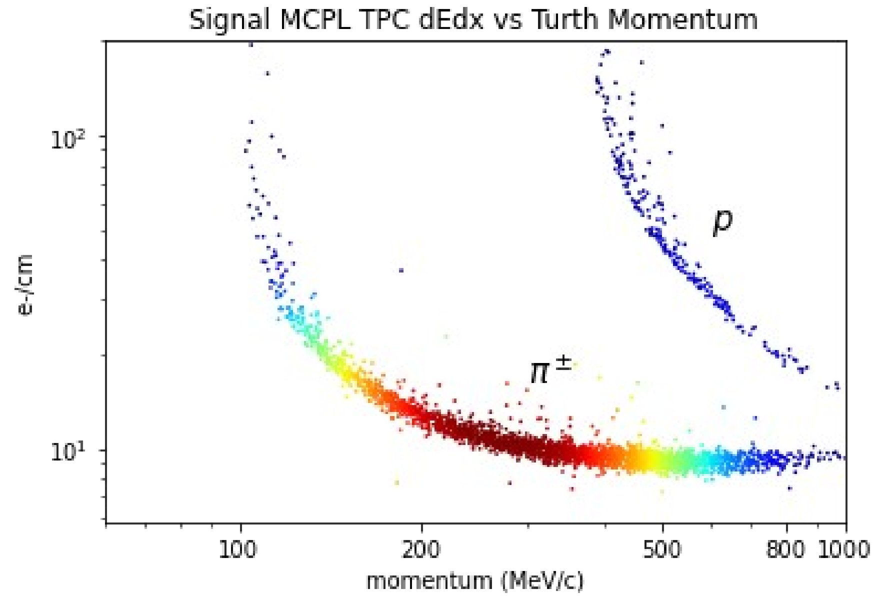
- The mean dE/dx value is just the truncated mean of that distribution i.e. the **upper 40%** population is cut away and take the **mean of the remaining population**



# 4.2 TPC dEdx calculation

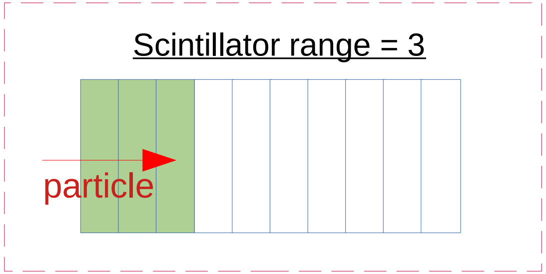
- For the particles from the signal MCPL, the dE/dx vs initial momentum plot can be made
- Note: In the real experiment we have no direct access to the momentum
- But this plot validates GEANT4 predictions and software set-up



# 5.1 Object definition – Charged Signal Particle

- **What is an object?**
  An object is a combination of info from the different detector components

- In the simulation, we got different numbers from different components
  - TPC dE/dx
  - Scintillator range (how many layers a particle passes through)
  - Photons in the calorimeter
  - Many more values ...



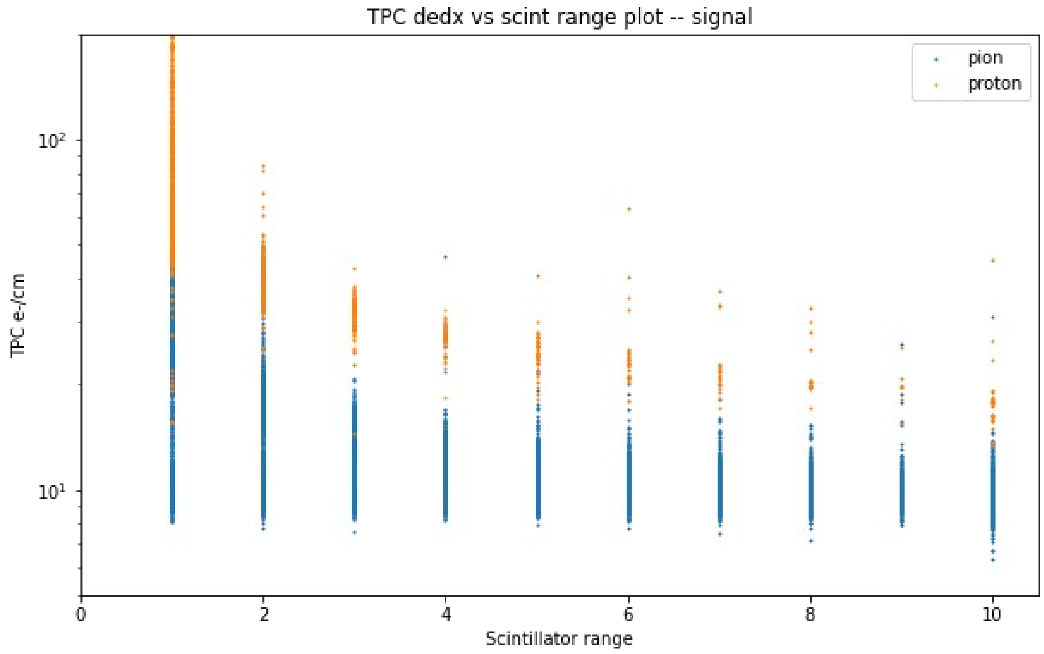

- To determine the type of particle by the above values, we need object definitions!
  - With object definitions, you are able to identify particles!
  - In practice, we **put cuts on these values**/distributions

- We are currently studying the **charged signal particle** (proton and $\pi^{\pm}$)

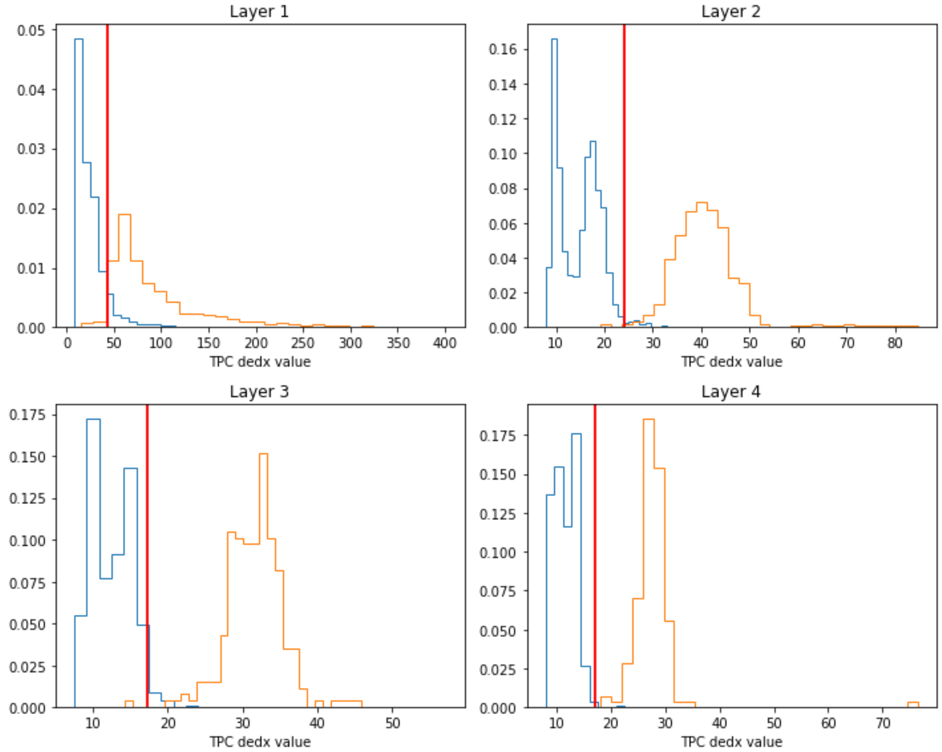
- We start with the key variables: **TPC dE/dx** and **scintillator range**
  - Combination mistake from these two values will be small

# 5.2 Object definition – Charged Signal Particle

From 100,000 annihilation products



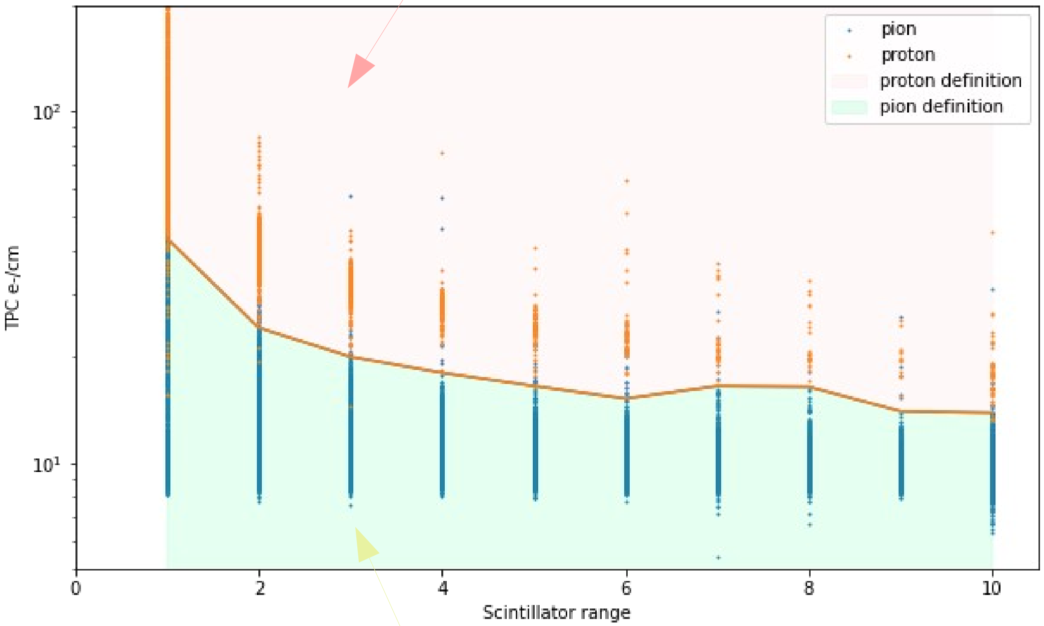

Find a cut in each range




Scintillator range : how many scintillator layers a particle passes through

# 5.2 Object definition – Charged Signal Particle

Data point in the pink region will be identified as signal proton




Data point in the green region will be identified as signal pion

## Definition of pion:

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

## 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

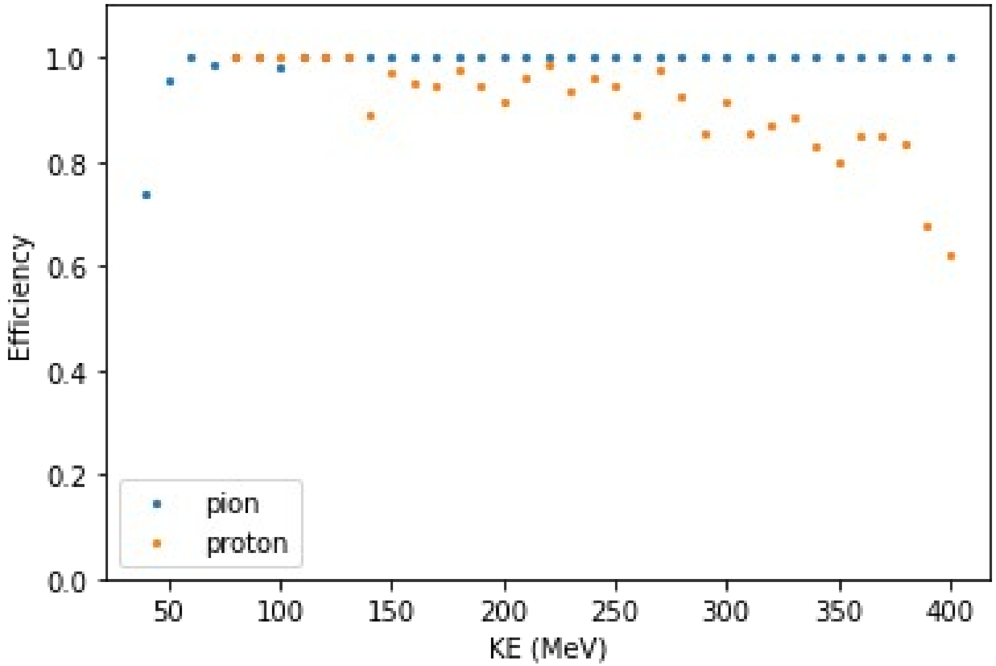
## Confusion matrix

Definition

Test particles from signal

| | pion | proton |
|---|---|---|
| pion | 0.99 | 0.01 |
| proton | 0.02 | 0.98 |

## Energy dependent identification efficiency



# 6. Summary and outlook

**Summary:**

- Introduced the NNBAR experiment
  - Motivation, signal products and experiment setup
- Introduced the HighNESS project
  - Goal, people involved and the connection to NNBAR
- Discussed a possible design of the NNBAR detector
- Discussed results from TPC simulation and object definition

The End

Thank you for listening!

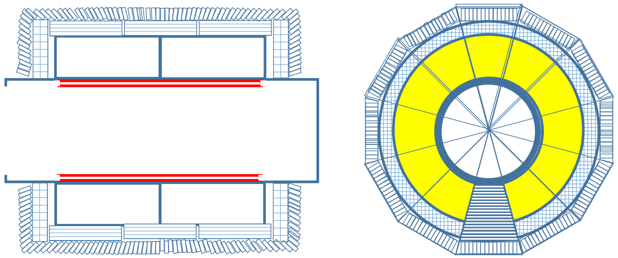
# APPENDIX 0 - Possible Designs of the Detector

## First ideas of how the detector may look like

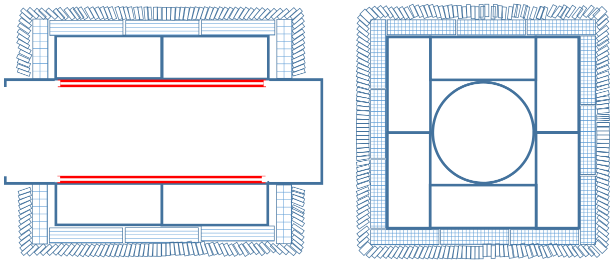
- We have no preference on the designs
- We will study both of them and access their performance
- These are just preliminary designs

Possible designs by Anders Oskarsson

Possible Design 1 – **Cylindrical Geometry**



Possible Design 2 – **Box Geometry**

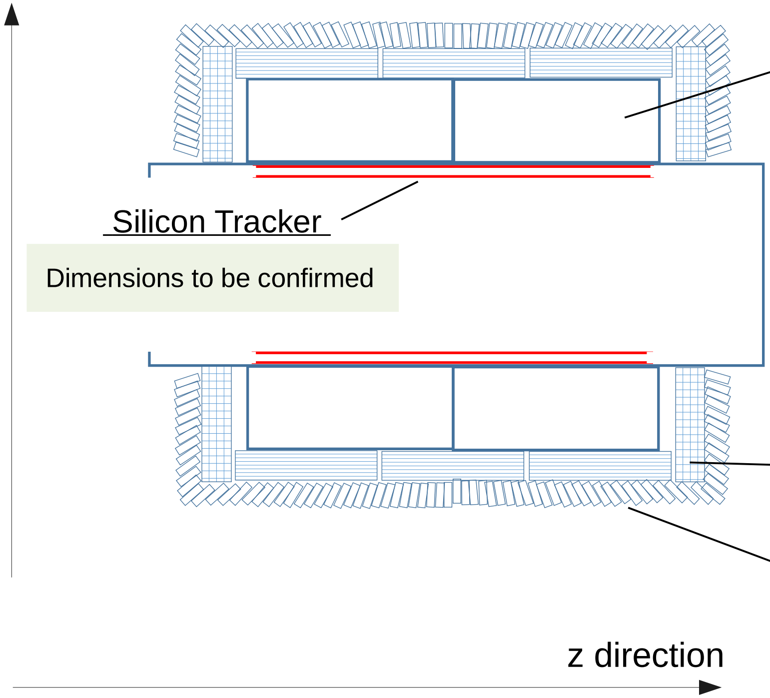


Detailed design can be found in APPENDIX I

# APPENDIX I - 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)

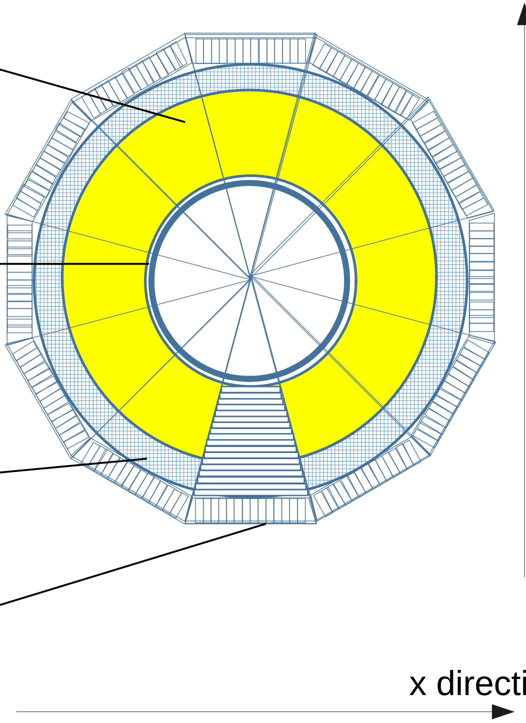
Scintillator Modules

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

# 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

# APPENDIX IV – Other detector simulation studies we did

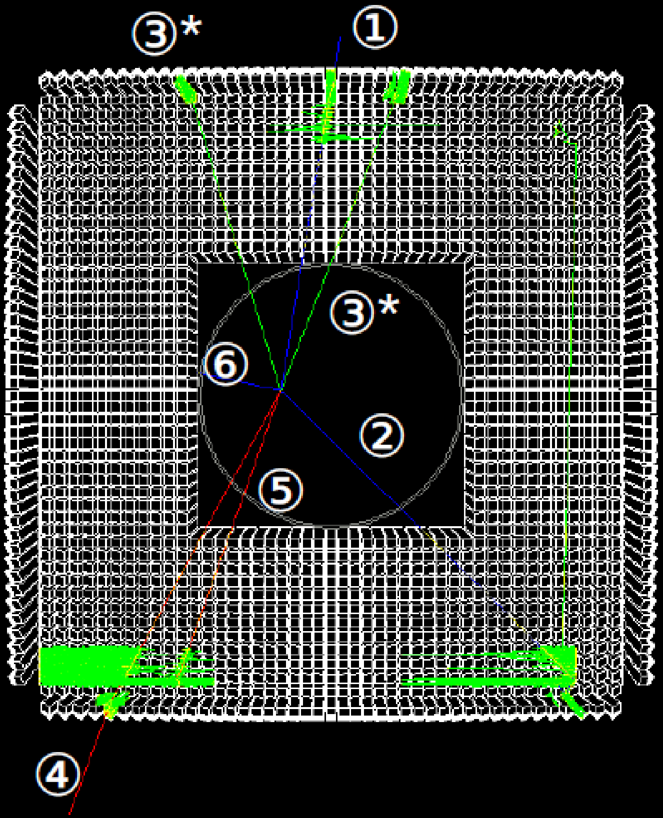
Some more simulation studies that we also did:

- **Timing studies of the signal particles**
  - Study the time of signal generation in the detector
  - Signals are generated at the ~O(10) ns
  - If pion → muon → e decay happens, we expect there will some late signals (due to muon lifetime ~O(μs))

- **Beta decay electrons in the full detector**
  - Study how much energy these electrons deposited in the full detector
  - No beta decay electrons pass through the Aluminum wall of 2 cm thickness

# APPENDIX V - TPC Track Visualization

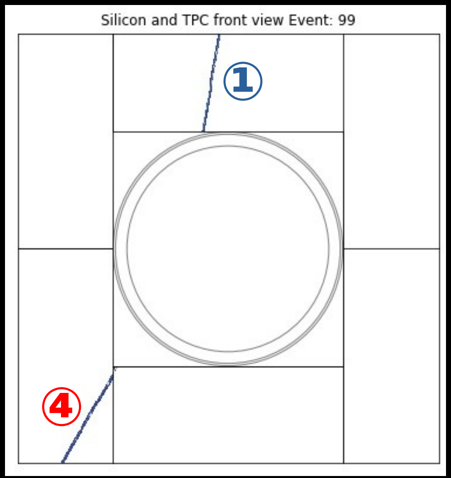
- An example of track visualization. A 5-pion annihilation event from the signal MCPL

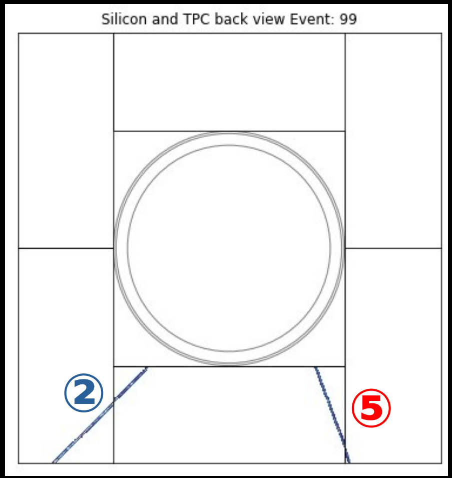



$$n\bar{n} \rightarrow 5\pi$$

1. $\pi^+$ KE: 321.52 MeV
2. $\pi^+$ KE: 170.69 MeV
3. $\pi^0$ KE: 221.14 MeV
4. $\pi^-$ KE: 327.19 MeV
5. $\pi^-$ KE: 131.87 MeV
6. $^{11}$C KE: 1.98 MeV

* 2$\gamma$ from $\pi^0$ decay




The particle tracks seem to be flipped, that is due to the viewing angle (from the front and back)