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Work Package 8 – Fundamental Physics

- Richard Wagner, ILL
- 21.06.2022

HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

Work package 8

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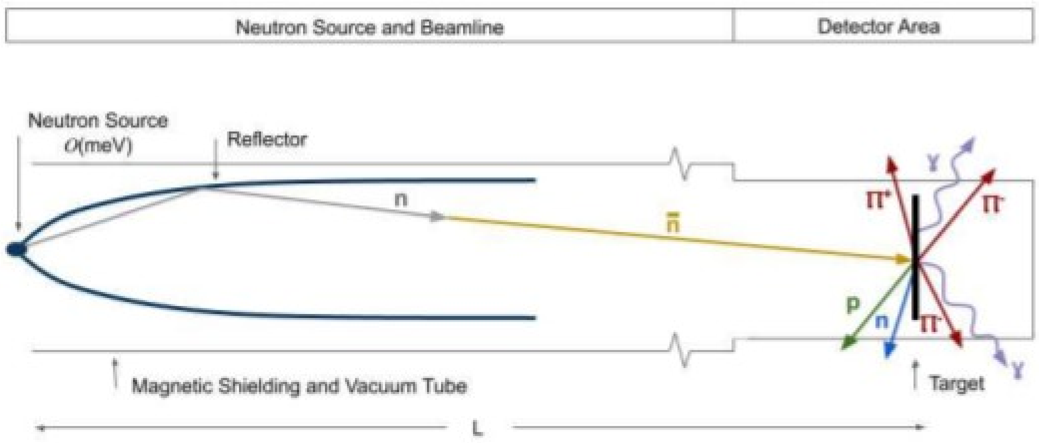
- SU/ILL with the NNBAR collaboration
- Fundamental aims
  - Explore conceptual designs of a NNBAR experiment: search for baryon number violation (BNV) caused by neutron (n) to antineutron (n̄) transformations.
  - Focusing and delivery of neutron beam in a field-free region to an annihilation detector.



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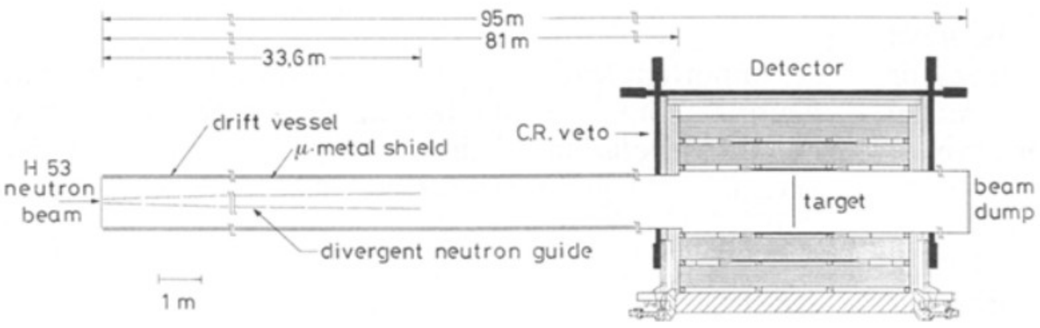
Motivation for NNBAR Experiment

- Baryon Number Violation (BNV) may be the key to the observed matter and antimatter asymmetry of baryogenesis
- BNV is a Sakharov condition and needed for theories of baryogenesis
- The process $n \rightarrow \bar{n}$ with $|\Delta B| = 2$ is one of the cleanest channels to observe BNV

- NNBAR experiment is use case for fundamental physics at the second moderator beam lines at the ESS to
- Fully utilize the high cold neutron intensities of the new LD_2 moderator
- Aim for a 1000 times improved sensitivity at the ESS compared over previous attempts

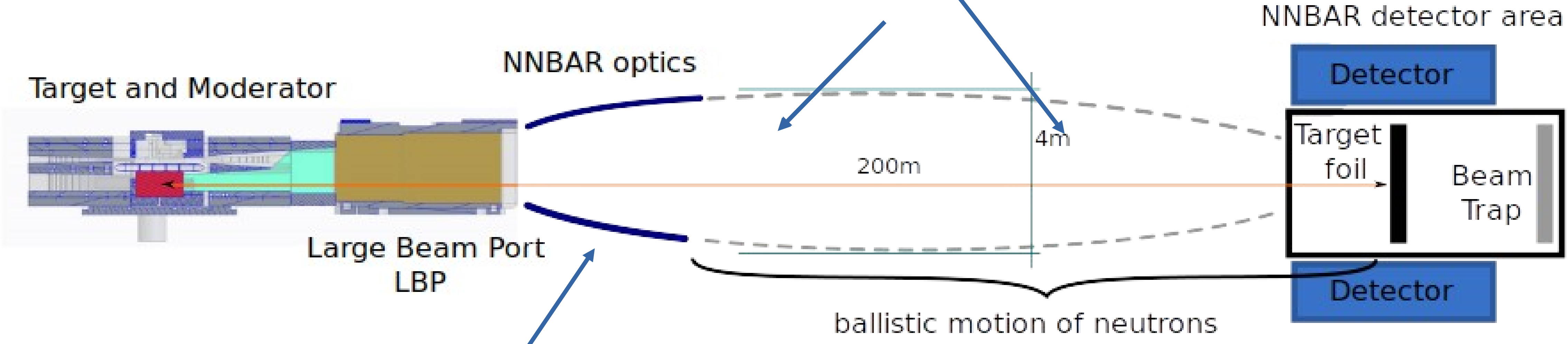
- Reference Experiment:
  1991 at the ILL
- Holding the current Limit
  for free neutron-anti neutron oscillation time:
  $\tau > 0.86 \times 10^8$ s.
- Unit for figure of merit (FOM): FOM = 1



From Baldo-Ceolin (1994)
DOI:10.1007/BF01580321

Schematics of ESS Experiment (not in scale)

Residual B field <10 nT
Residual vacuum < 10 -5 P



free from perturbing
magnetic stray fields, interaction with walls
and ambient gas particles

Reflector Optics
collect large solid angle of emitted neutrons and re-focus to detector area

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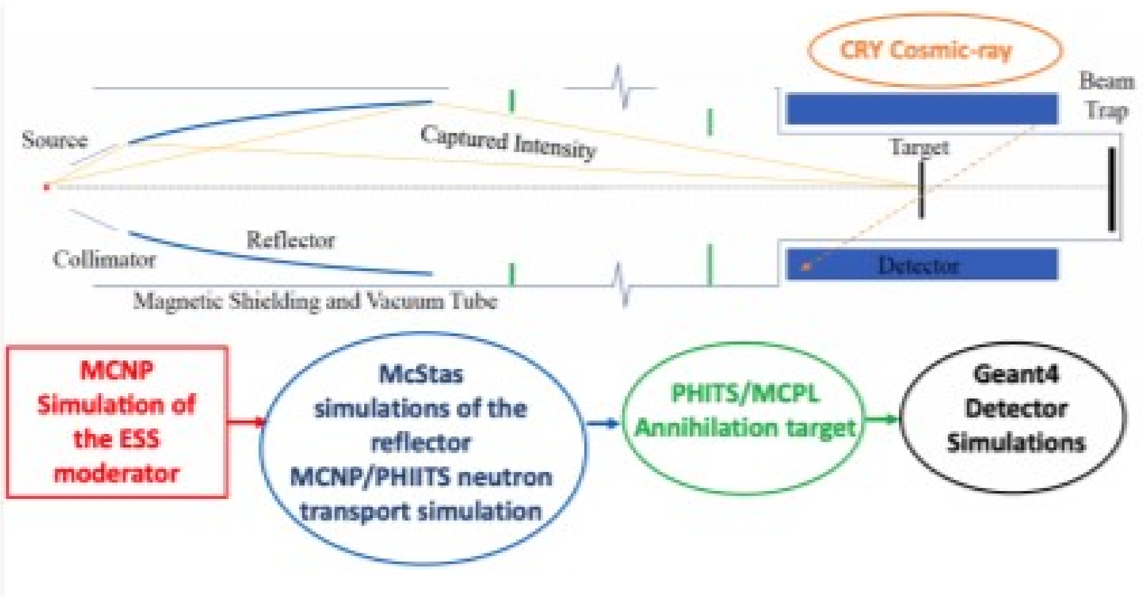
Monte Carlo Simulation Framework

Software environment set-up to interface predictions of neutron flux and backgrounds with detector simulation with Geant-4.
Needed for detector and experiment optimization,

A Computing and Detector Simulation Framework for the HIBEAM/NNBAR Experimental Program at the ESS

Joshua Barrow[10,11], *Gustaaf* Brooijmans[2], *José Ignacio Marquez* Damian[3], *Douglas* DiJulio[3], *Katherine* Dunne[4], *Elena* Golubeva[5], *Yuri* Kamyshkov[1], *Thomas* Kittelmann[3], *Esben* Klinkby[8], *Zsófi* Kókai[3], *Jan* Makkinje[2], *Bernhard* Meirose[4,6,*], *David* Milstead[4], *André* Nepomuceno[7], *Anders* Oskarsson[6], *Kemal* Ramic[3], *Nicola* Rizzi[8], *Valentina* Santoro[3], *Samuel* Silverstein[4], *Alan* Takibayev[3], *Richard* Wagner[9], *Sze-Chun* Yiu[4], *Luca* Zanini[3], and *Oliver* Zimmer[9]

EPJ Web of Conferences **251**, 02062 (2021)
CHEP 2021



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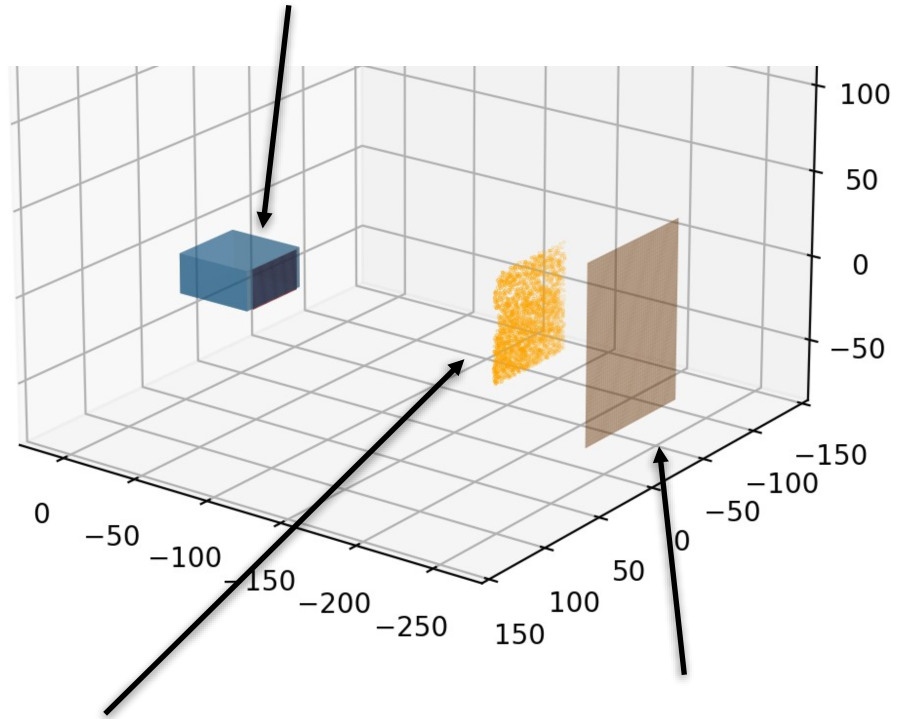
MCPL Source

MCPL – Monte Carlo Particle List
From MCNP Simulations WP4

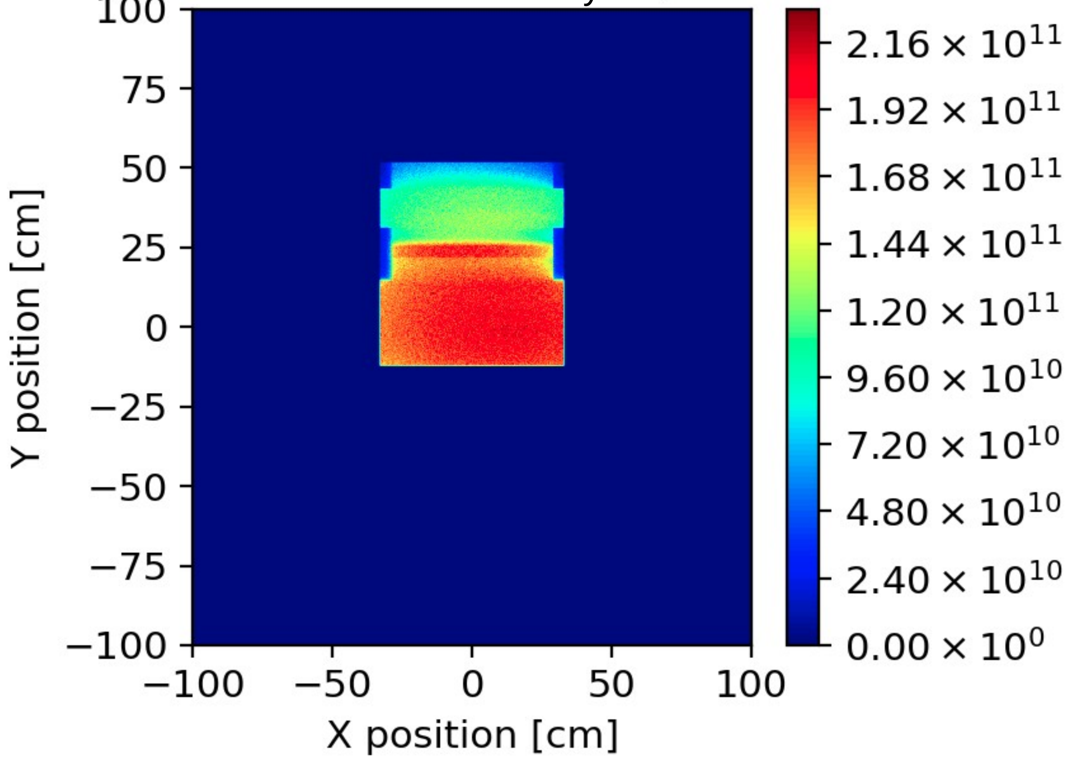
Moderator with exit window



Start of Particles
in mcpl File

Entry Large Beam Port

Intensity at 2m



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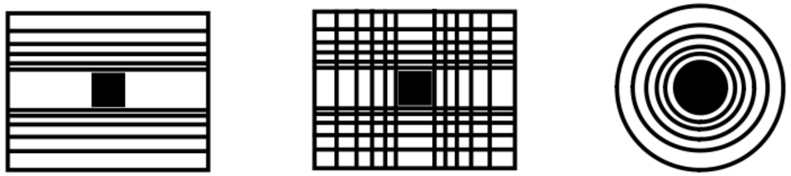
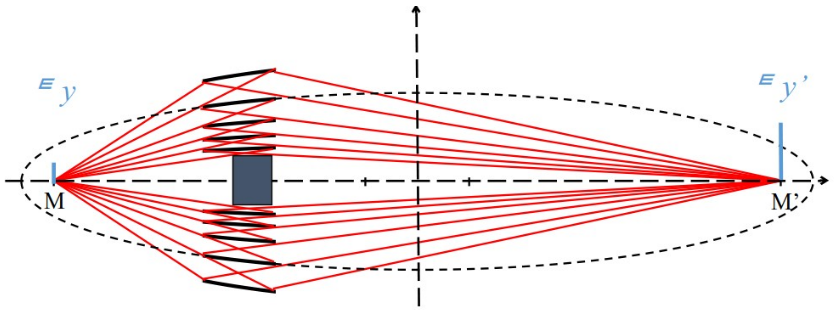
Optics I

- Design of a nested system of neutron mirrors
- Elliptical mirrors (foci located in moderator and detector) in planar or cylindrical arrangement
- McStas Simulations of performance of a given optical system
- Optical components for simulation are automatically generated
  Python Library → **Deliverable 8.1**





arXiv:1611.07353
Journal of Neutron Research 20 (2018) 91-98

Task 8.3: Development of McStas components for Single nested-mirror banks and Wolter optics

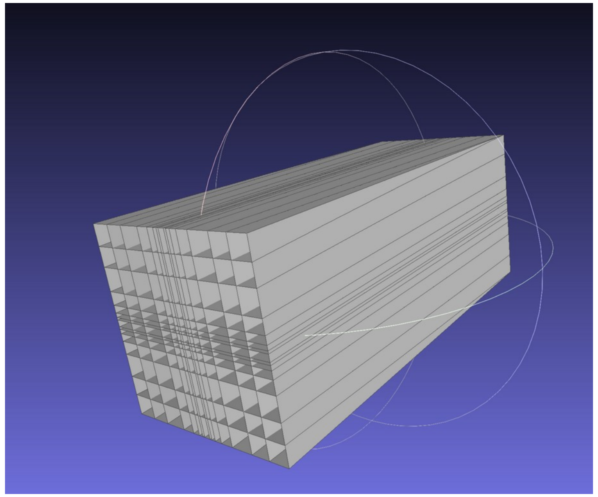
Different optics are compared using the quantity: $FOM = \sum_i \overbrace{N_i}^{\text{neutrons}} * \overbrace{t_i^2}^{\text{(uninterrupted) flight time}}$

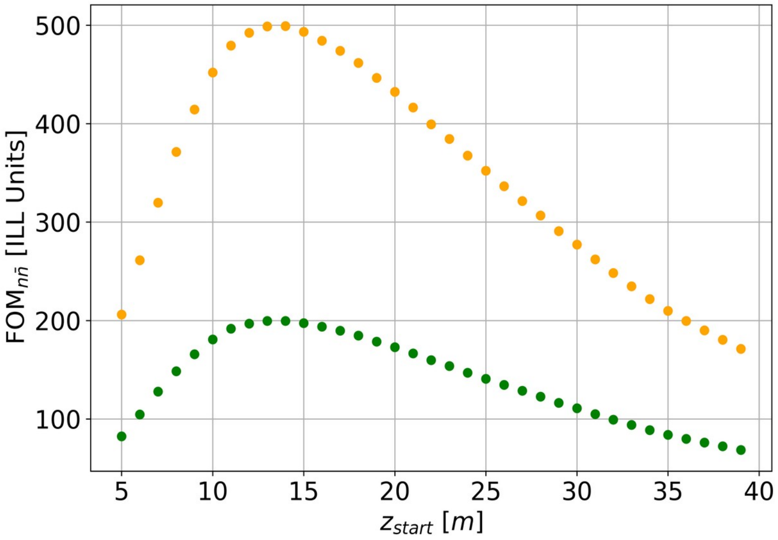
Unit is 1991 experiment

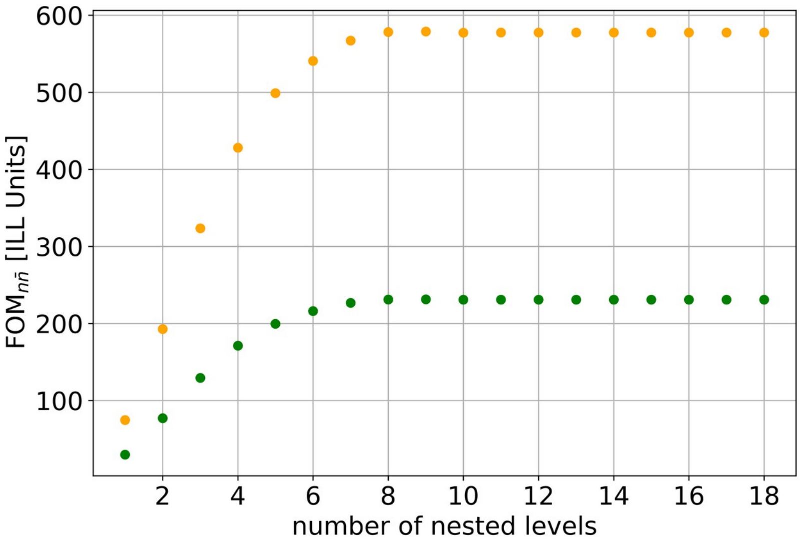
Optics II

Find the optimum optic by varying parameters (e.g. starting point, # of nested levels, ...)

Example: Simulations for a 10m Nested Reflector







5 MW
2 MW

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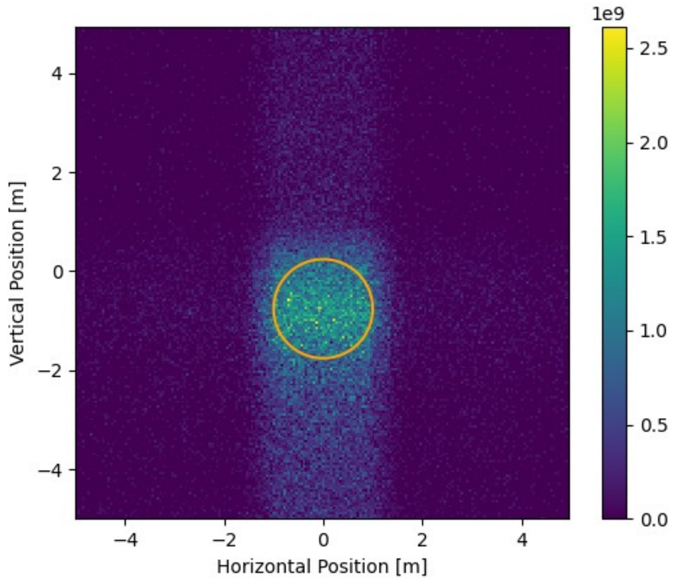
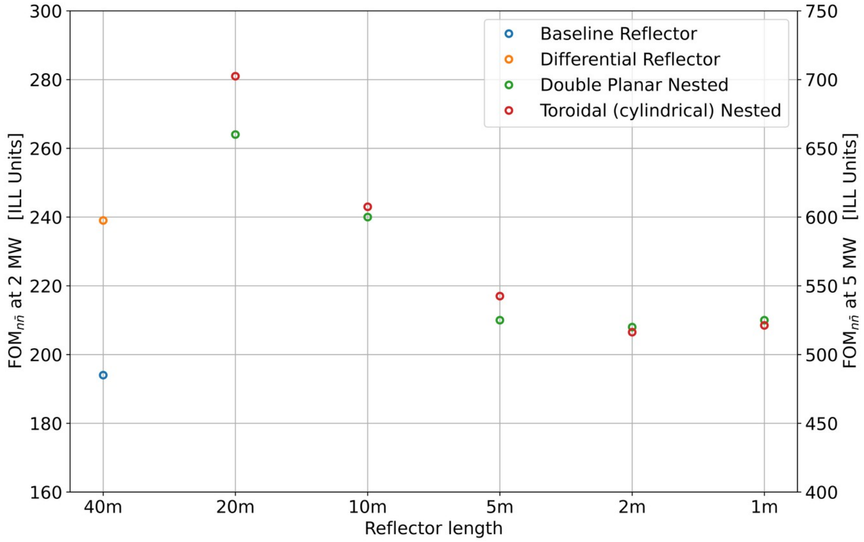
Optics III

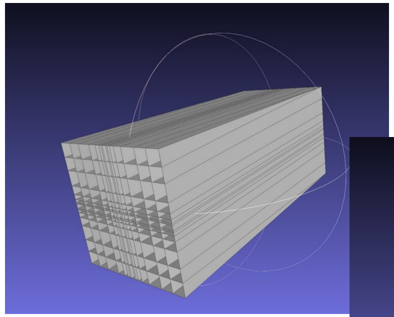
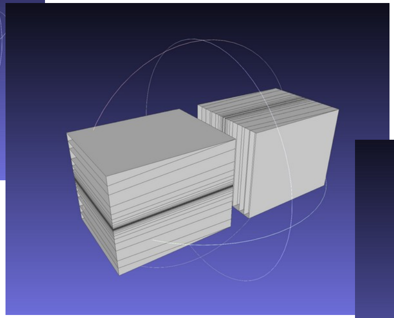
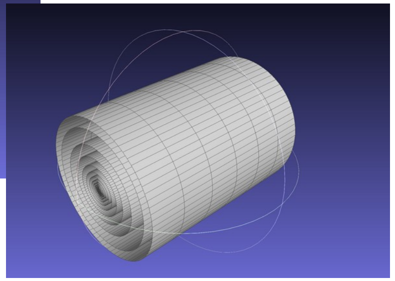
Example: Simulations for a 10m Nested Reflector



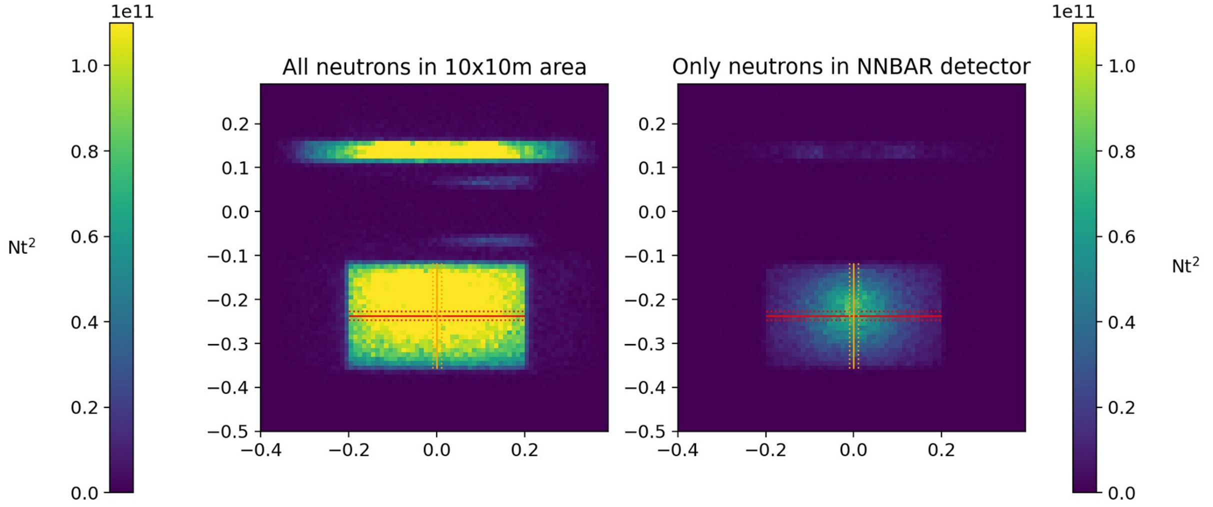
FOM: 240 (nested levels=7, 2 MW)

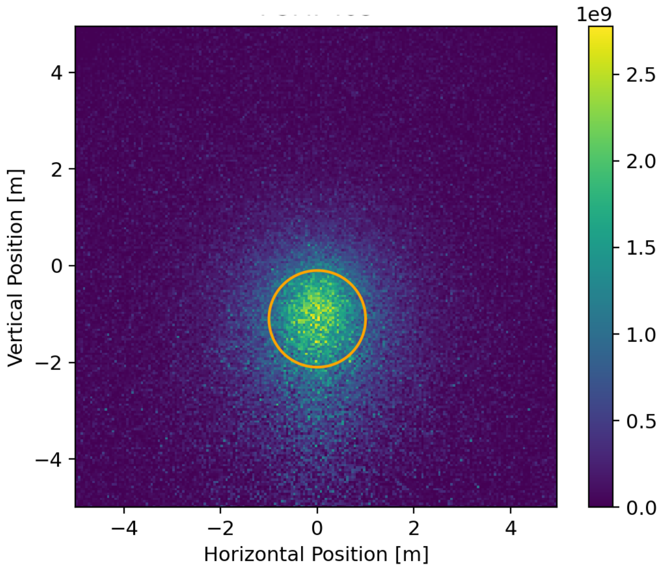
Collected results for different reflector systems

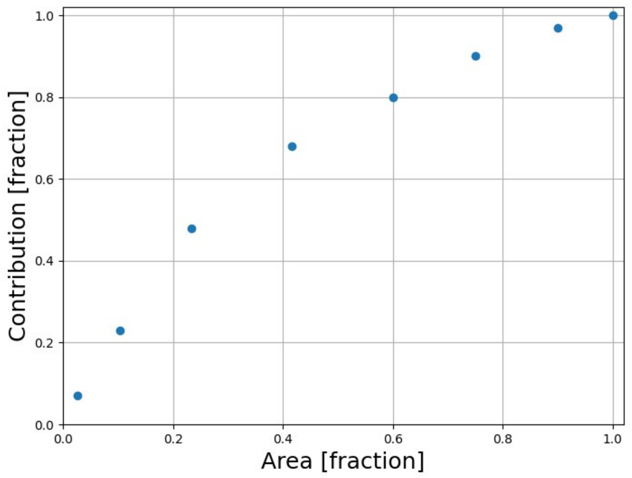


Where do neutrons originate that land in the detector?

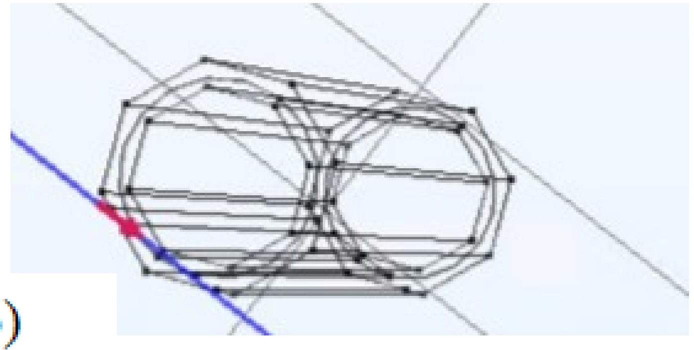




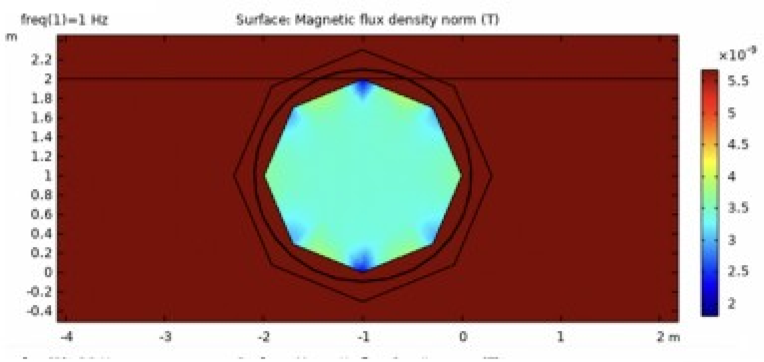


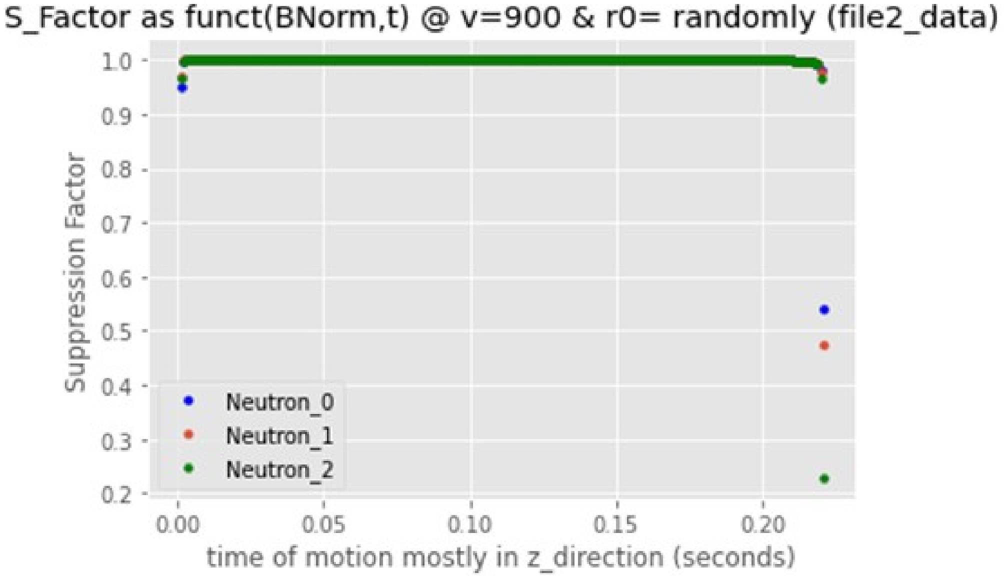
Magnetic shielding

Task 8.1 Design of the NNBAR magnetic shield **SU** (M1-6)



- Shield geometry
  - Outer + inner octagon shield from mu-metal
  - Round steel vacuum chamber: between shields
  - COMSOL simulations
- <10 nT
- Monte Carlo study of inefficiency due to finite magnetic field with field map





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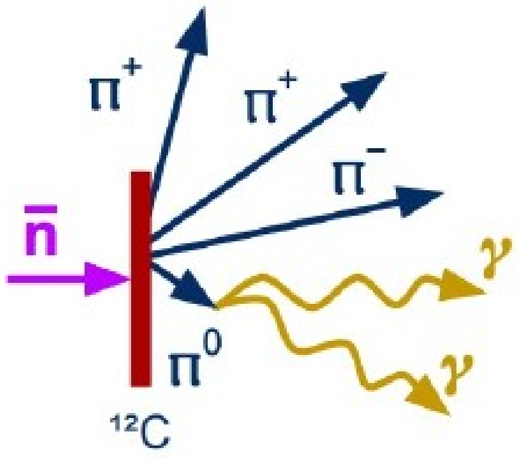
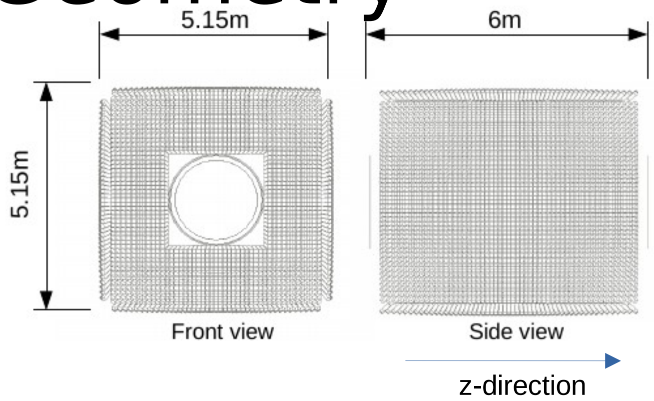
Detector Design

- Detect a multi-pion final state
- Created due to the annihilation of the anti-neutron in the carbon target foil
- An annihilation generates (on average) 4-5 pions, including a π^0 which decays immediately to 2 γ- rays
- The invariant mass of the final state matches 2 neutron masses: ~1.88 GeV
  - ➔ characteristic signature for a discovery



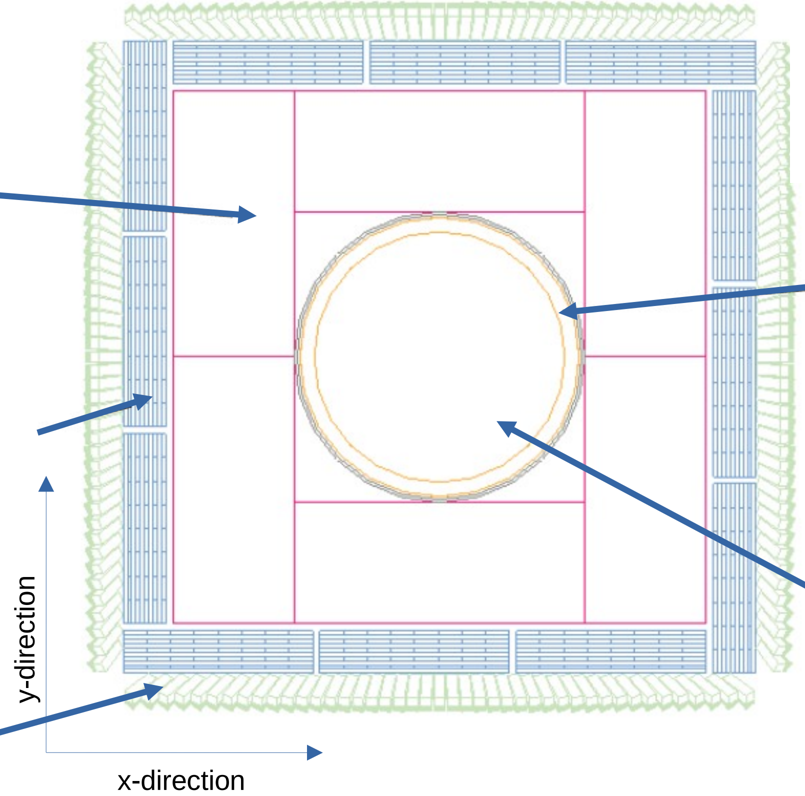
- Requirements for the Detector
  - Reconstruction of multi-pion final state
  - Invariant mass reconstruction
  - Particle identification
  - Timing sensitivity to reject cosmics and other out-of-time backgrounds

NNBAR Annihilation Detector – Box Geometry



Time Projection Chamber

Filling gas: 80% Ar, 20%CO_2
2 different dimensions (x-y):
0.85 m x 1.87 m
2.04 m x 0.85 m
Both:
2 m length in z-direction



Silicon Trackers

2	layers
6m	length
0.3 cm	thickness

Scintillator Modules (Calorimeter)

10	layers
3 cm	thickness per layer
8	staves per layer

consecutive layers are perpendicular

Vacuum tube

1 m	inner radius
2 cm	wall thickness
6 m	tube length

Lead Glass Blocks

8 x 8 cm	base area
25 cm	height

Oriented towards center of detector

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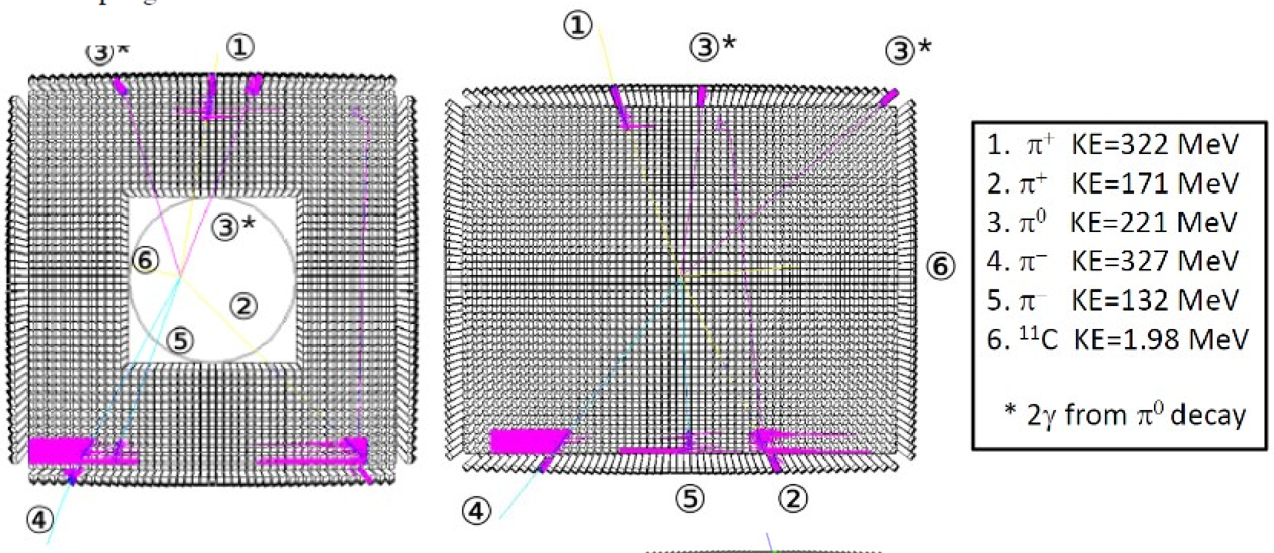
GEANT4 Simulations

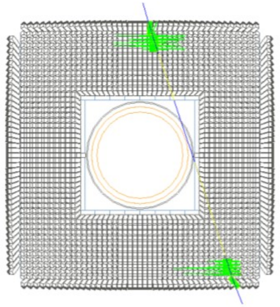
Task 8.2 Development of a Geant-based model of different detector geometries and technologies. This includes, e.g., silicon-based tracking vs a Time Projection Chamber and a crystal calorimeter vs a sampling calorimeter **SU** (M1-12)

- Exhaustive simulations for the development of the detector
(design, material geometry, optimization, cosmic background)
- Top Left:
example for the annihilation process of an antineutron with ^{12}C in the target foil

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



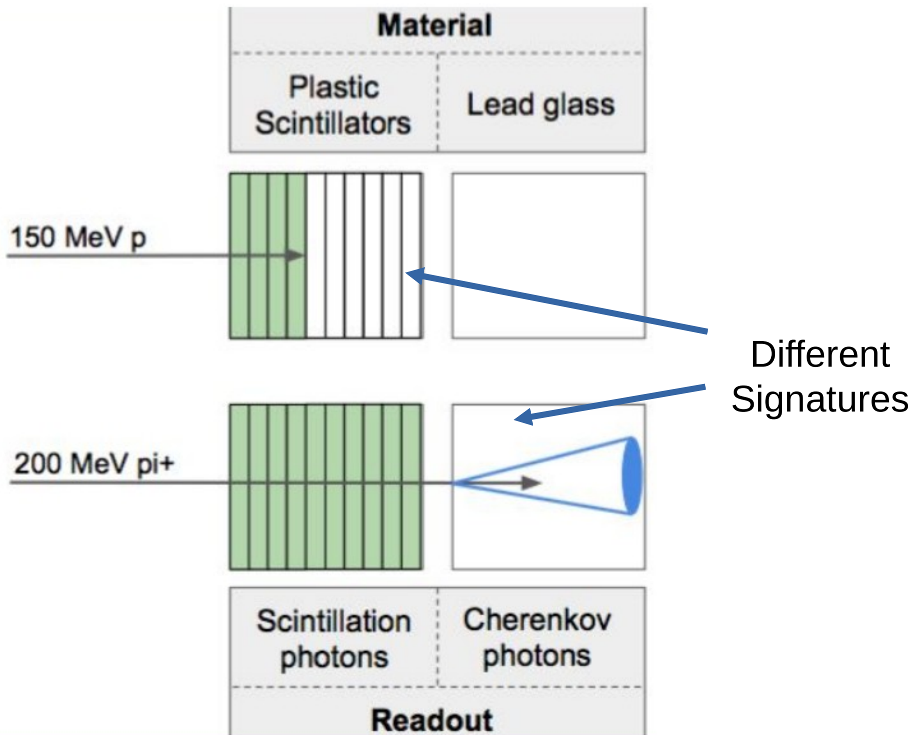
Cosmic muon background

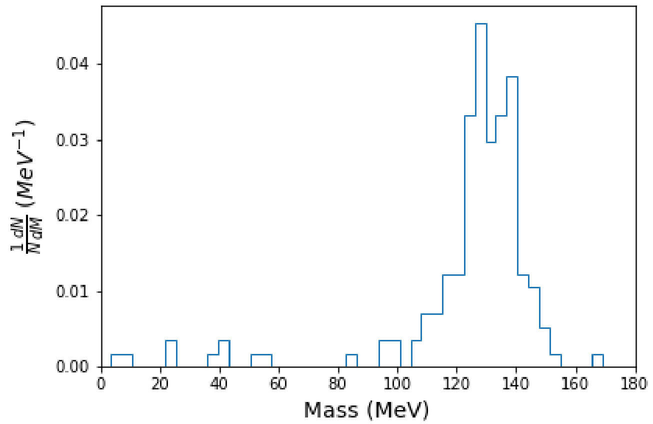


From
Computing and Detector Simulation Framework for the HIBEAM/NNBAR Experimental Program at the ESS
J. Barrow et al, EPJ Web Conf., vol. 251, p. 02062, 2021

Tracker and Calorimeter

- The time projection chambers (TPC) plays an important role in particle identification
- Discriminate pions from protons/muons
- Identification by measurement of the the continuous energy loss dE/dx .
- Components are concealed by an active cosmic muon shield made of scintillators and a passive enclosing overburden

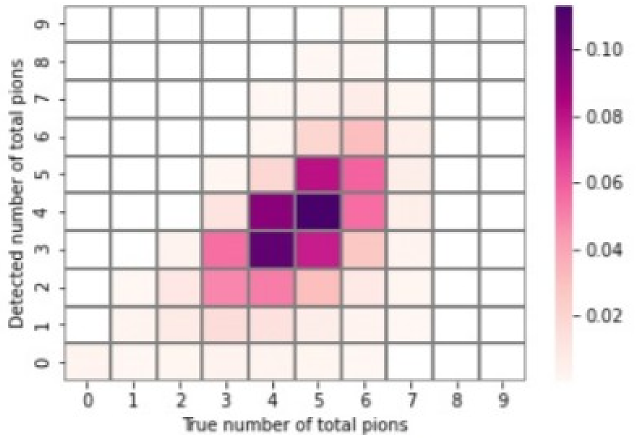


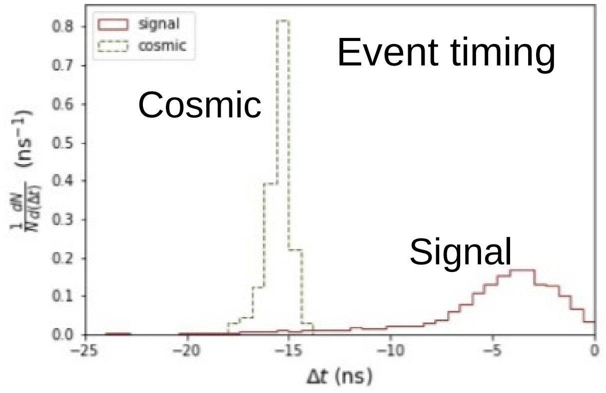


Example: Simulated π^0 mass reconstruction in the calorimeter

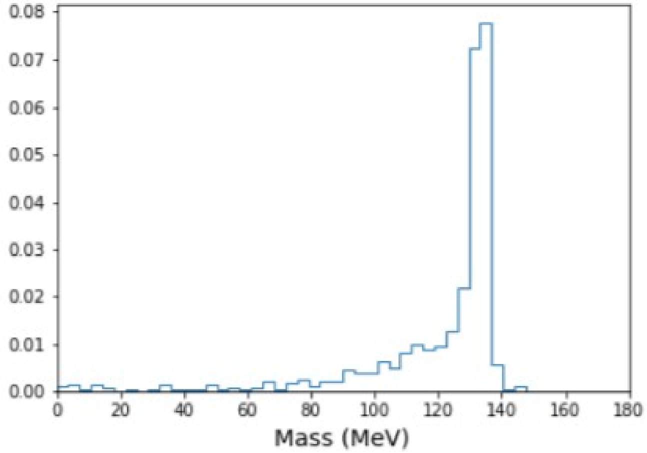
Detector simulation

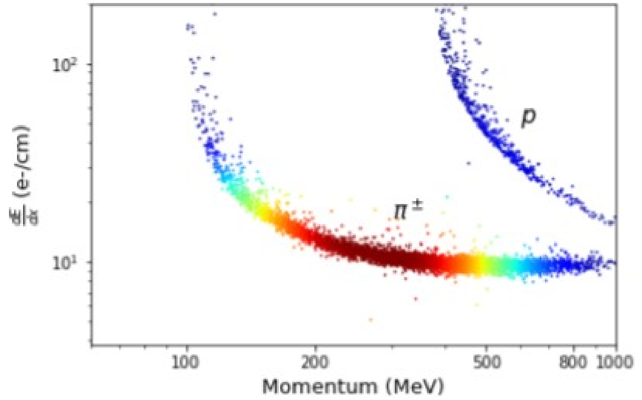
Pion multiplicity

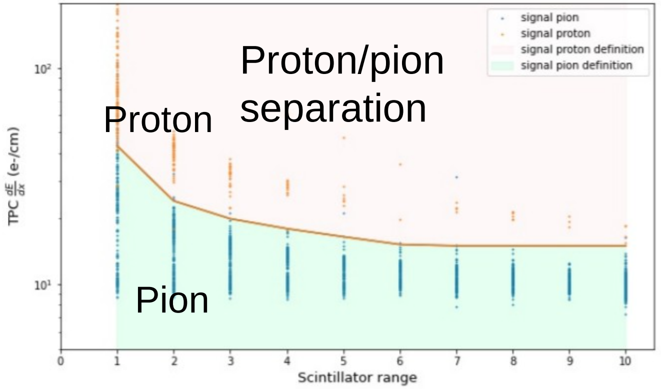


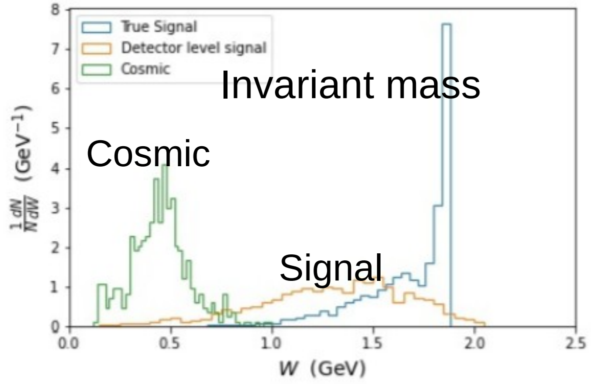


π^0 mass reconstruction



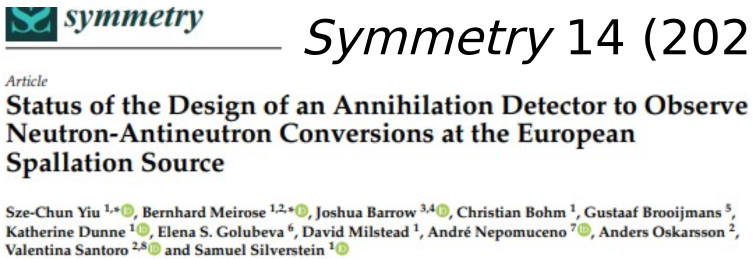






Geant 4 model designed and reproducing well expected distributions

Symmetry 14 (2022) 1, 76


symmetry

Article

Status of the Design of an Annihilation Detector to Observe Neutron-Antineutron Conversions at the European Spallation Source

Sze-Chun Yiu [1,*], Bernhard Meirose [1,2,*], Joshua Barrow [3,4], Christian Bohm [1], Gustaaf Brooijmans [5], Katherine Dunne [1], Elena S. Golubeva [6], David Milstead [1], André Nepomuceno [7], Anders Oskarsson [2], Valentina Santoro [2,8] and Samuel Silverstein [1]

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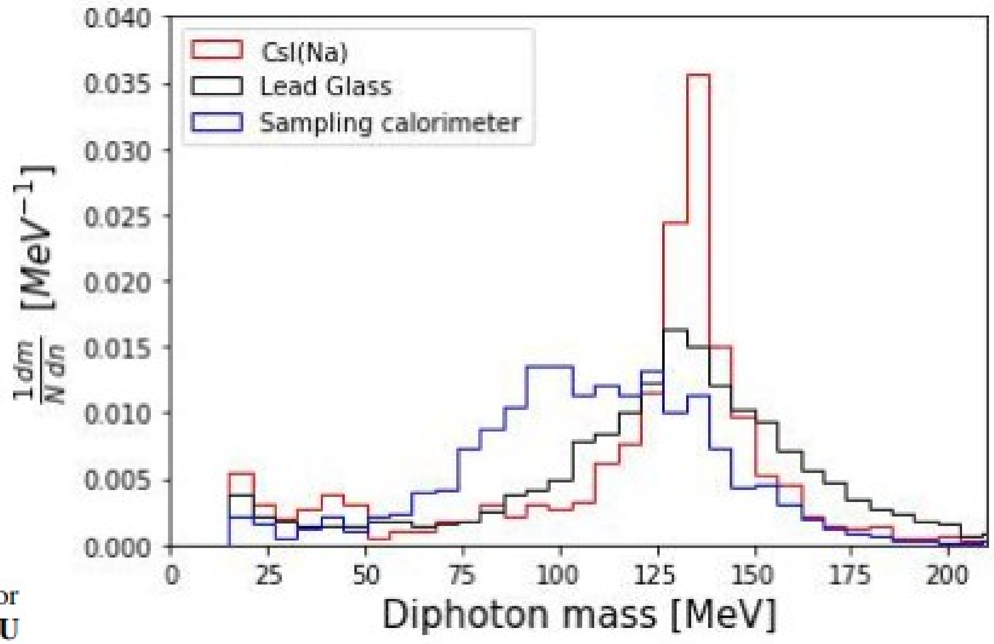
Variation of detector design

- Options for variation from baseline design
  - Turn on/off silicon tracking
  - Change detector size and granularity
  - Change calorimeter technology (eg sampling vs homogeneous) and active medium (lead-glass and other materials)
- Now set-up for optimization



Task 8.5 Development of a full model of the NNBAR experiment incorporating the Geant-based detector model with simulations of antineutron annihilation and flux estimations based on McStas simulations **SU** (M15-18)

D8.2 Paper submitted for publication on the development of a full model of the NNBAR experiment (M18)

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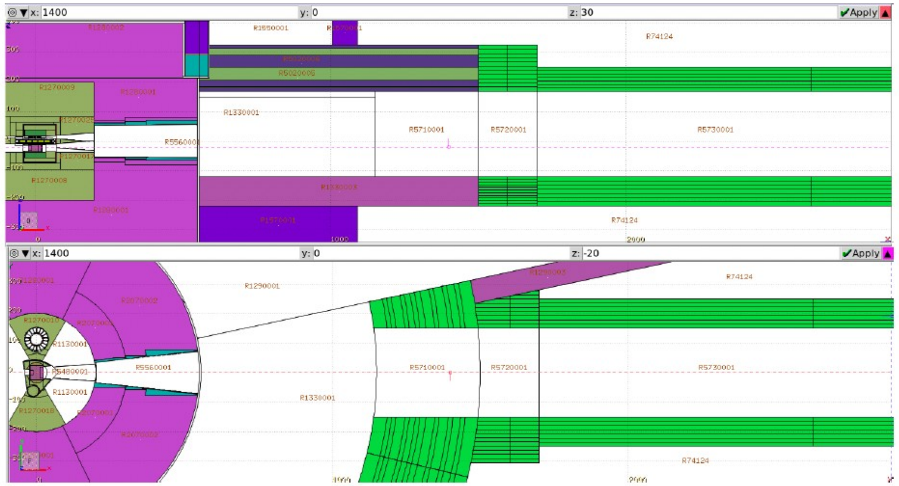
Ongoing and planned activities

- Shielding designs using Comblayer
- Full quantification of background yield and signal rejection
- Detector components timing model being developed for pile-up
- High energy spallation backgrounds
- Cosmics, Gamma bg from activation, delayed beta decays, skyshine ….

- Conclude the Optics Simulations
- Update with new iterations of the moderator
- Evaluate the option of two nested mono-planar components
- Implement and simulate a nested reflector in Wolter-Optics geometry



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Thank you for your attention!

Credits: Sze Chun Yiu, Kathie Dunne, Jonathan Collin, Gautier Daviau, Bernhard Meirose, Valentina Santoro, David Milstead, Peter Fierlinger, Nicola Rizzi, Luca Zanini, Oliver Zimmer

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