Looking for Baryon Number Violation with HIBEAM/NNBAR Experiment

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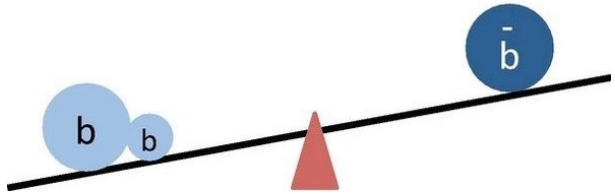
Baryon Asymmetry Problem

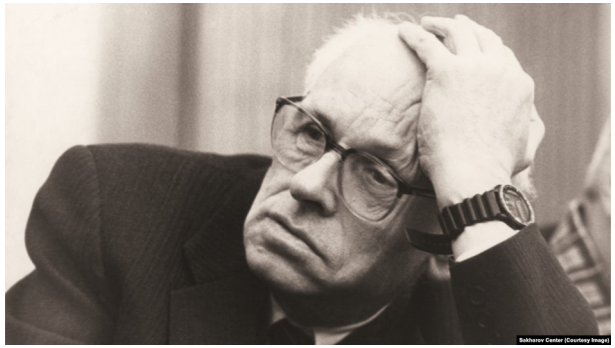
Baryon asymmetry of the Universe (BAU):

$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 10^{-10}$$



Sakharov conditions for baryogenesis:

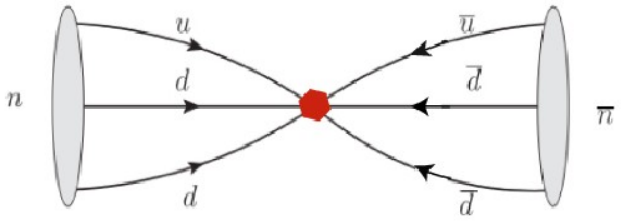
- baryon number violation (BNV);
- C and CP violation;
- interactions out of thermal equilibrium.



Baryon Number Violation

- BNV in SM is too small to produce the observed baryon asymmetry (BNV).
- Test BNV scenarios: **neutron oscillation**
- **Neutron oscillations provide clean channel to probe BNV-only process.**
- **Since neutron-antineutrons oscillation require BNV, it can be linked with baryogenesis.**

$$n \to \overline{n}, \quad \Delta B = 2$$



Transition matrix element

$$\Delta m = < \bar{n} | H_{eff} | n >$$

Neutron Oscillation Probability

Starting with a pure neutron state at $t = 0$, the probability of finding an antineutron at time t is

$$P_{n\overline{n}}(t) = \frac{\epsilon_{n\overline{n}}^2}{(\Delta E/2)^2 + \epsilon_{n\overline{n}}^2} sin^2 \left[t\sqrt{(\Delta E/2)^2 + \epsilon_{n\overline{n}}^2} \right] e^{-t/\tau_n}$$

- $\epsilon_{n\overline{n}}$ denotes the $n - \overline{n}$ mixing;
- $\Delta E = E_n - E_{\overline{n}}$;
- τ_n is the mean life of the free neutron.
- To prevent suppression: **vacuum on nearly zero magnetic field**.

In the quasi-free regime ($|\Delta E|t \ll 1$):

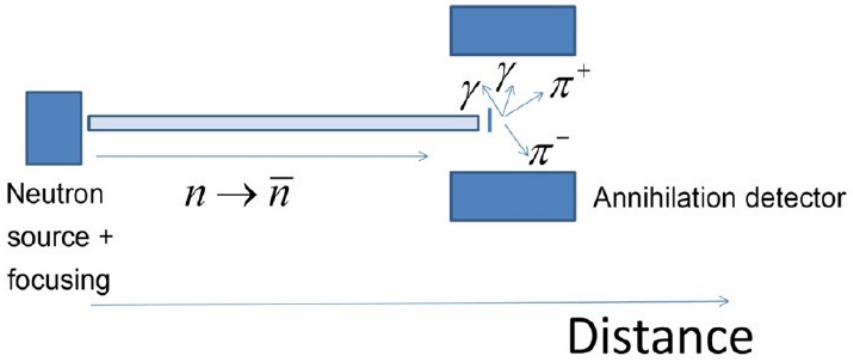
$$P_{n\overline{n}}(t) = \frac{t^2}{\tau_{n\overline{n}}^2}$$

Current limit on oscillation time (from ILL)

$\tau_{n\overline{n}} > 0.86 \times 10^8 s$ (Baldo-Ceolin M *et al*, '94)

Search for Neutron Conversion

Schematic view of a free neutron conversion experiment

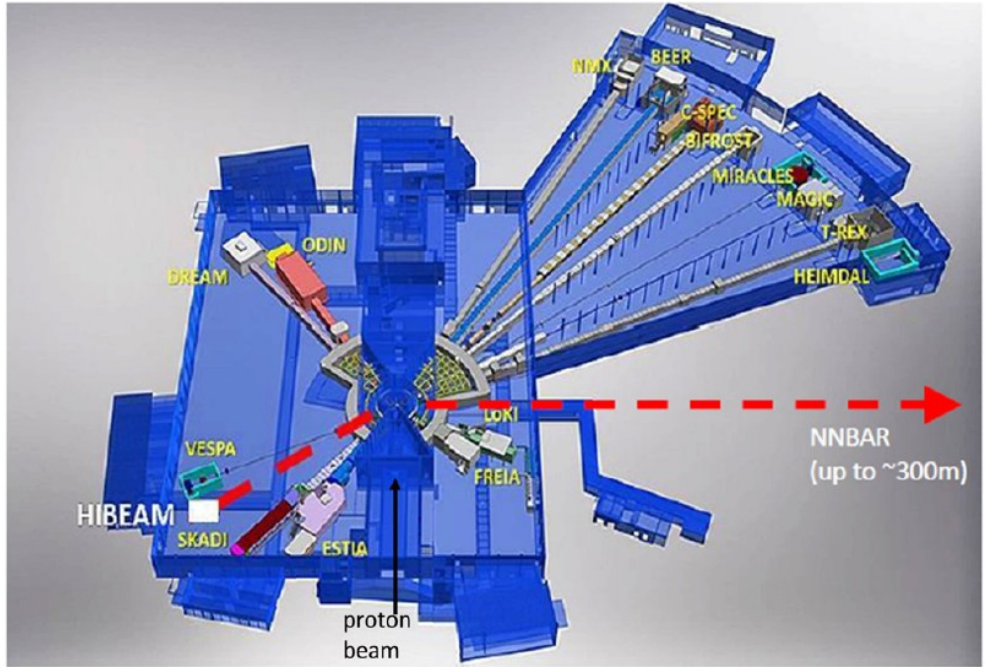


- Need a high intensity neutron source:
- Could neutrons (E < 5 meV) provided after interaction with moderators.
- Annihilation with a nucleon in the target (^{13}C) produce a multi-pion final state.

A high-precision search requires a large flux of slow neutrons.

The European Spallation Source (ESS)

- The ESS will be the world's most powerful facility for research using neutrons.
- The ESS uses a linear accelerator to accelerate protons to 2 GeV.
- The proton beam hits a rotating tungsten target to produce neutrons by spallation (neutrons with energies about 2 MeV).
- The high-energy spallation neutrons are slowed down in the neutron moderators.



For more information: https://europeanspallationsource.se/

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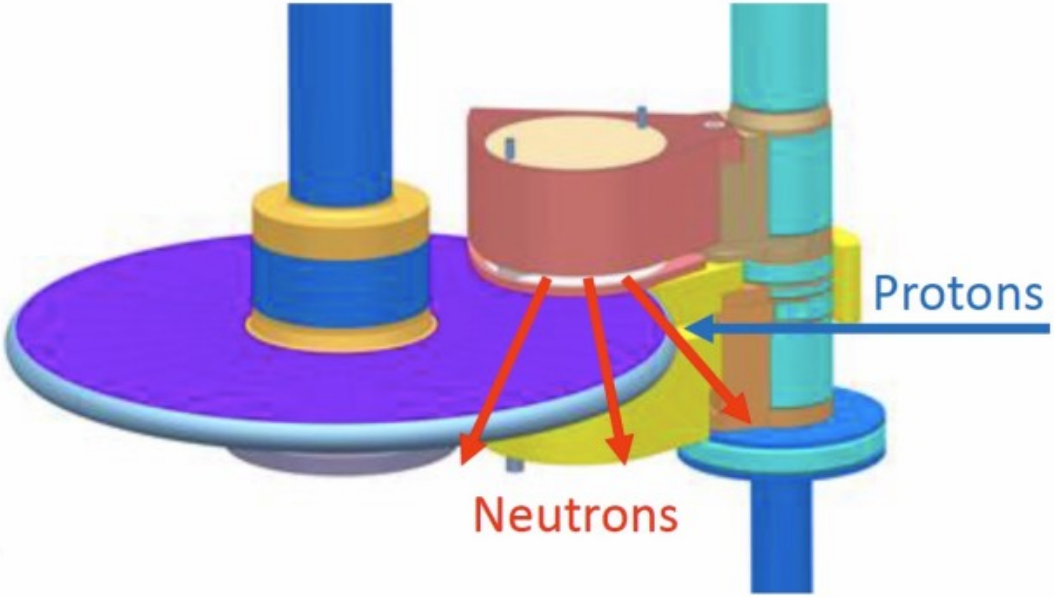
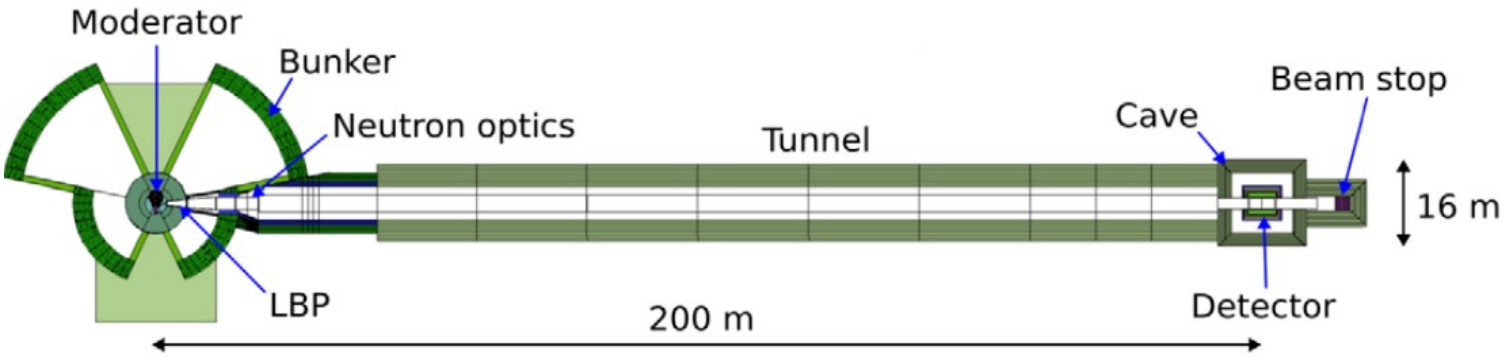


Starting operation in 2027

For more information: https://europeanspallationsource.se/

The NNBAR Experiment



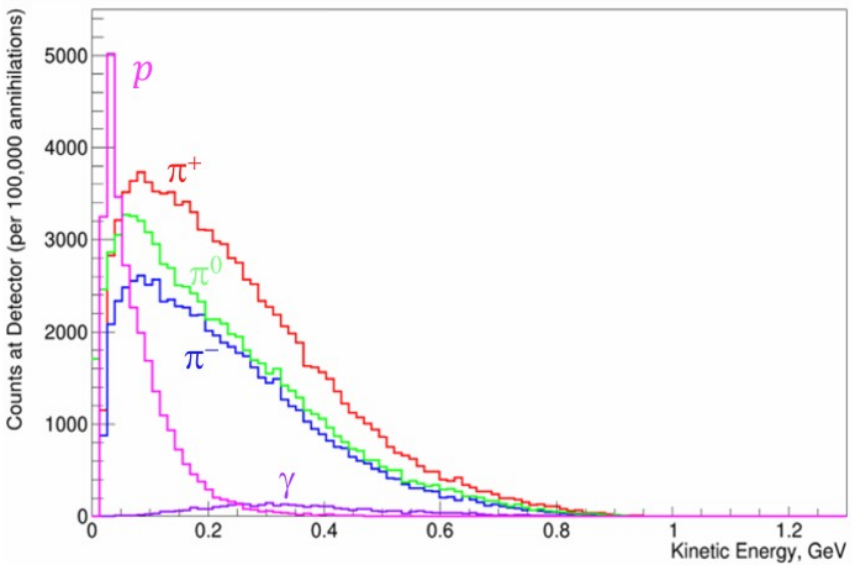
Expected sensitivity:
1000 x ILL

- Moderators ensure that a large flux of cold neutrons is available.
- A neutron mirror system focuses the beam toward a distant carbon target.
- The neutrons move out through the shielded bunker region into the NNBAR tunnel (~ 200 m)
- An annihilation target sits near the end of the beamline. This is foreseen to be made of carbon and with a thickness of 100 μm. The target is a circular disk of radius 1 m.
- **An annihilation detector sits in the shielded detector cave and surrounds the carbon target**.

Signal and Background

Signal

The annihilation will produce a final state with several pions (avg ~ 5), photons and nuclear fragments.

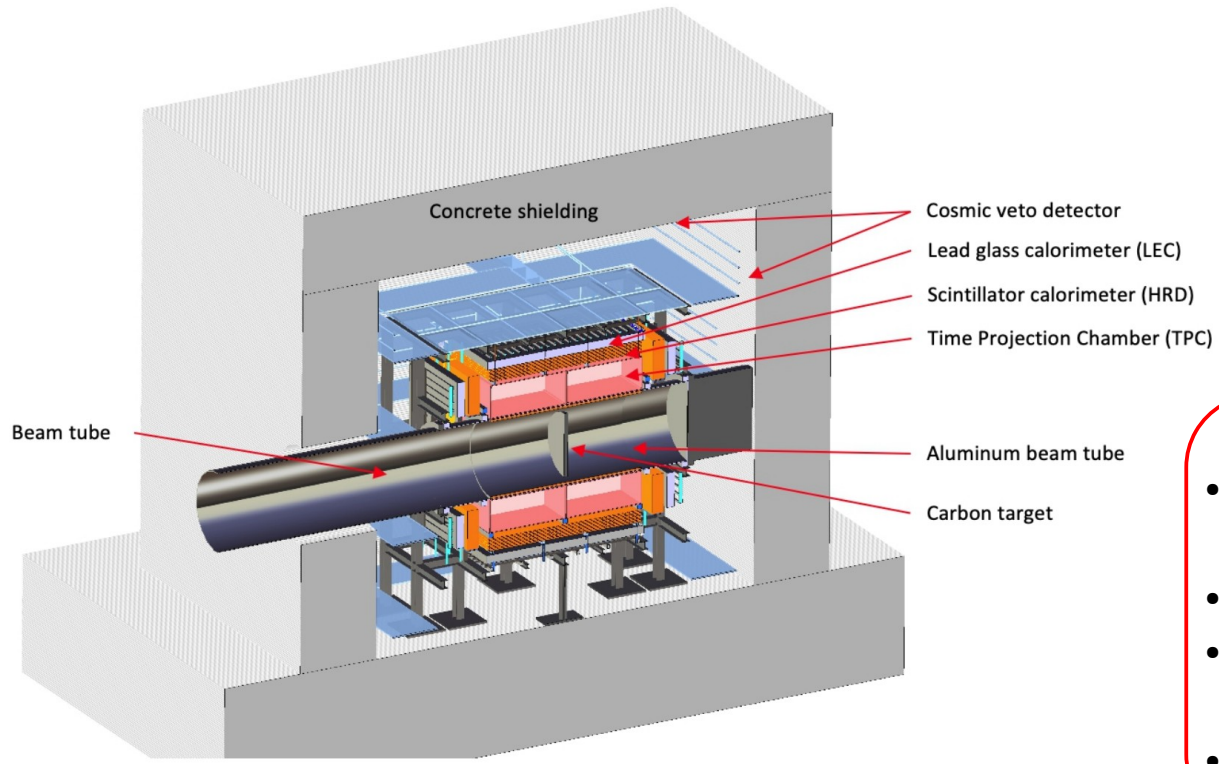


Background

- Cosmic Rays;
- cold neutron background;
- high energy particles from spallation source.

Reject **all** the background events is extremely important for the potential detection of an antineutron.

Annihilation Detector



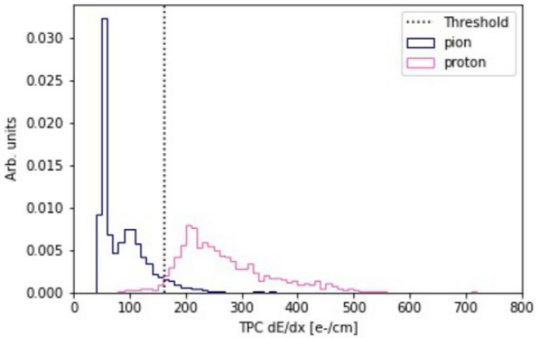
- **Box geometry**
- **Dimensions: 560 cm long (z direction)**
- **Width and height of 560 cm**

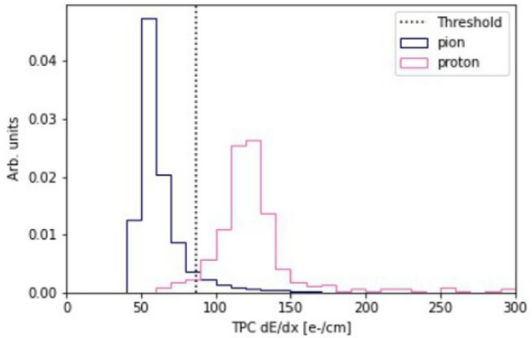
Detector Features

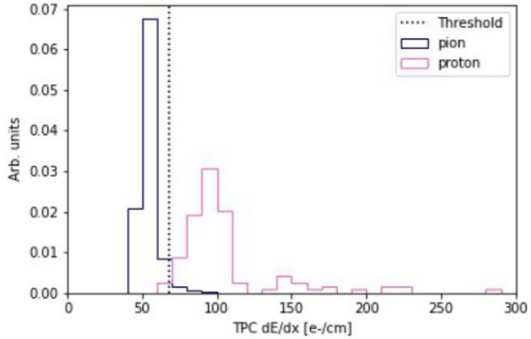
- Time projection chambers (TPCs) for tracking and dE/dx measurements;
- Scintillators for PID (10 slats);
- Electromagnetic calorimeter made of lead glass for photons from π^0 decays;
- Dedicated cosmic veto surrounding the detector.

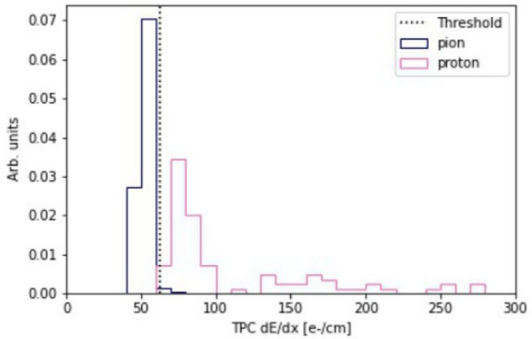
Particle Identification I

- Combine TPC and scintillator layers for particle identification.
- Good separation between protons and charged pions is observed (~ 99% efficiency)









$$\pi^{\pm} : TPC\ \frac{dE}{dx} < t_N$$

$$proton : TPC\ \frac{dE}{dx} > t_N$$

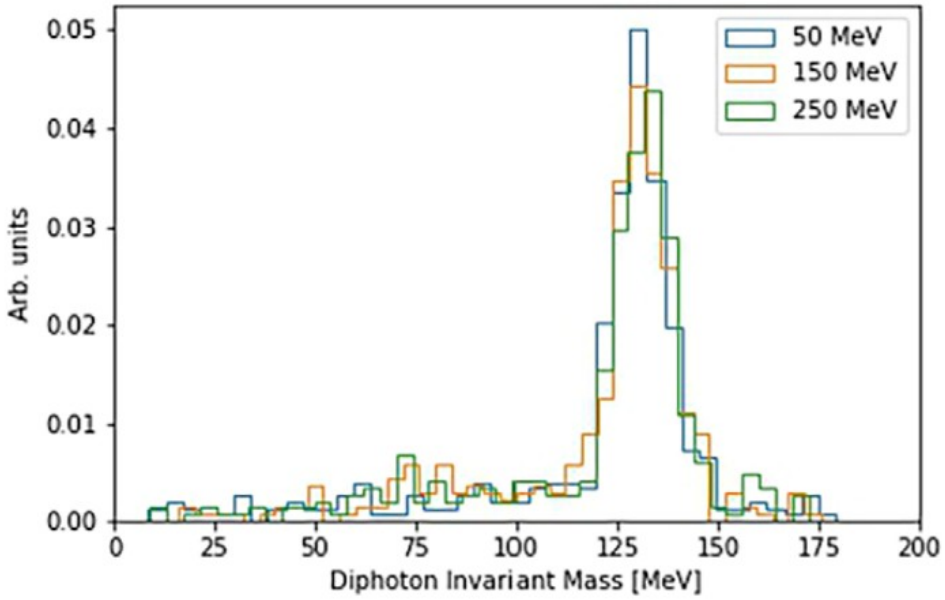
	Truth Particle Type	
Identified Particle Type	$\pi^{\pm}$	**Proton**
$\pi^{\pm}$	99%	1.3%
Proton	1%	98.7%

Particle Identification II

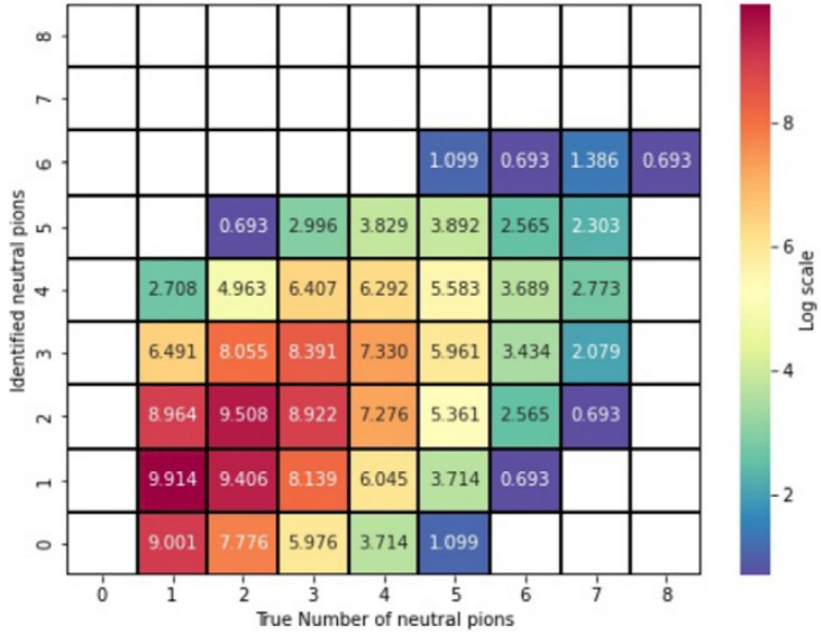
Neutral Pion Identification

Neutral pions can be reconstructed from the photon energies and angles between the photons measured in the calorimeter.

$$M^2 = 2E_1E_2(1 - cos\theta)$$

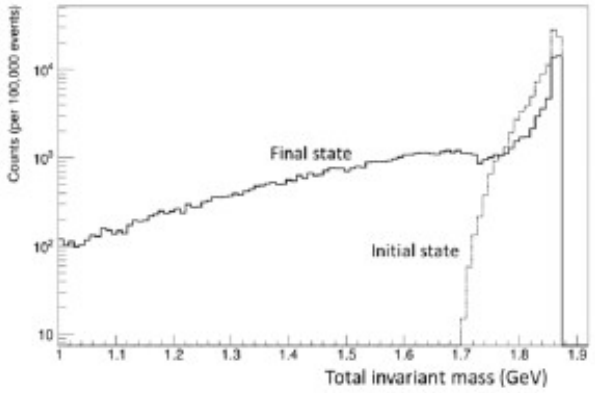


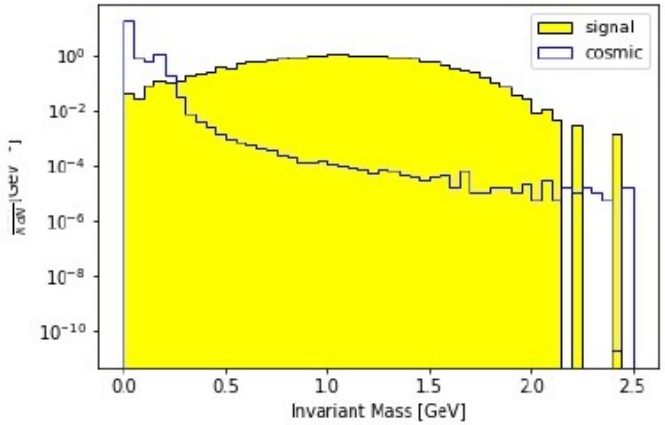
π^0 Multiplicity



Signal Identification

Expected final state invariant mass: ~ 1.88 GeV



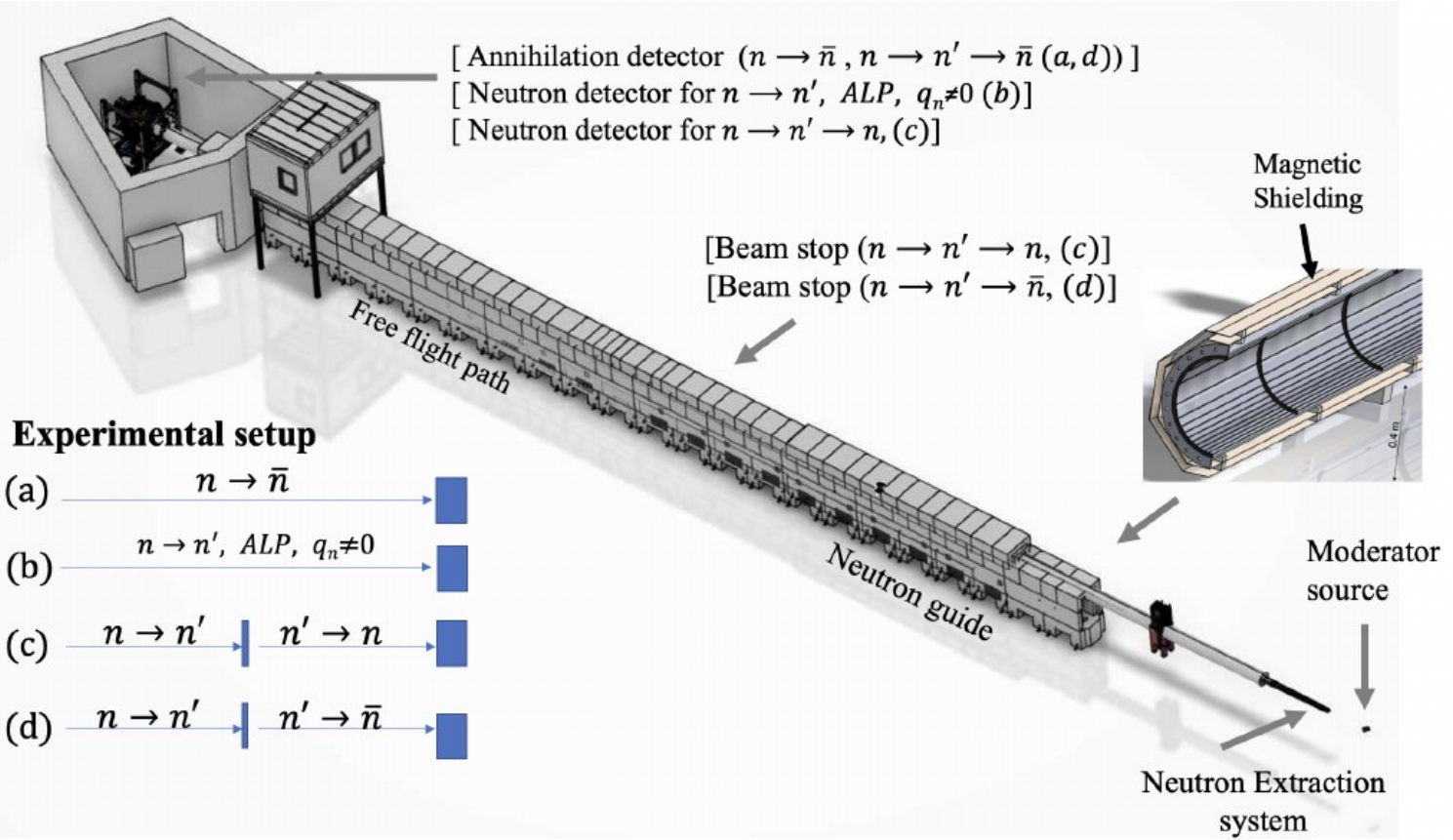


$$W = \sqrt{\left(\sum_i E_i\right)^2 - \left|\sum_i \vec{p}_i\right|^2}$$

Nuclear and detector effects complicate the scenario

Selection	Signal	Non-muon background	Muon background
Scintillator energy loss $\in [20, 2000]$ MeV	0.95	0.15	1.8×10^{-6}
TPC track cut	0.92	7.1×10^{-3}	1.2×10^{-6}
Number of pion ≥ 1	0.86	6.1×10^{-8}	1.1×10^{-8}
Invariant mass $W \geq 0.5$ GeV	0.83	1.4×10^{-8}	9.5×10^{-9}
Sphericity ≥ 0.2	0.73	8.1×10^{-11}	6.1×10^{-9}
$E_{\text{scint, } y>0, \text{ filtered}} \leq 320$ MeV & $E_{\text{scint, } y<0, \text{ filtered}} \leq 930$ MeV	0.73	-	-

The HIBEAM Experiment



HIBEAM/NNBAR Brazil Contributions

Fluminense Federal University (UFF)

- Andre Nepomuceno
- Vinicius Zaggato
- Marcel Oliveira

State University of Rio de Janeiro (UERJ)

- Jorge Amaral
- Tiago Quirino
- Antônio Vilela

State University of Campinas (Unicamp)

- Ernesto Kemp
- Edmilson Manganote

Centro Brasileiro de Pesquisas Físicas (CBPF)

- Antônio Vilela

Universidade Estadual de Feira de Santana

- Germano Gudes

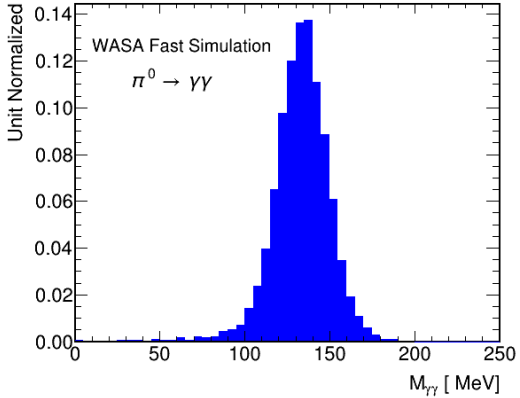
Students

- William Santos
- Gabriel Gomes dos Santos
- Guilherme Vieira Lickel
- Vitor Contato Palaveri
- Jean Barcelos
- Lucas Oliveira

HIBEAM/NNBAR Brazil Contributions

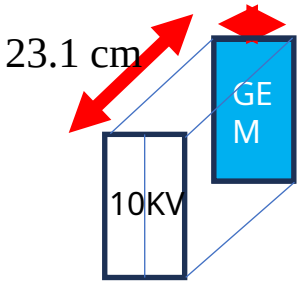
UFF

- Detector simulation
- Full and Fast Simulation



UERJ

- TPC simulation
- Electronics for calorimeters



TPC prototype

UNICAMP

- TPC prototype

Summary and Outlook

- BNV is a key ingredient to explain the baryon asymmetry of the universe.
- Observing a neutron oscillation would be a fantastic signal of physics BSM that could elucidate the mechanism responsible for the BAU.
- Simulations of the detector design for the NNBAR experiment show promising results in reconstructing the neutron-antineutrons annihilation event.
- With improve sensitivity of $O(10^3)$, NNBAR will be the world leading neutron-antineutron oscillation experiment.
- For more information: https://journals.sagepub.com/doi/10.3233/JNR-230950

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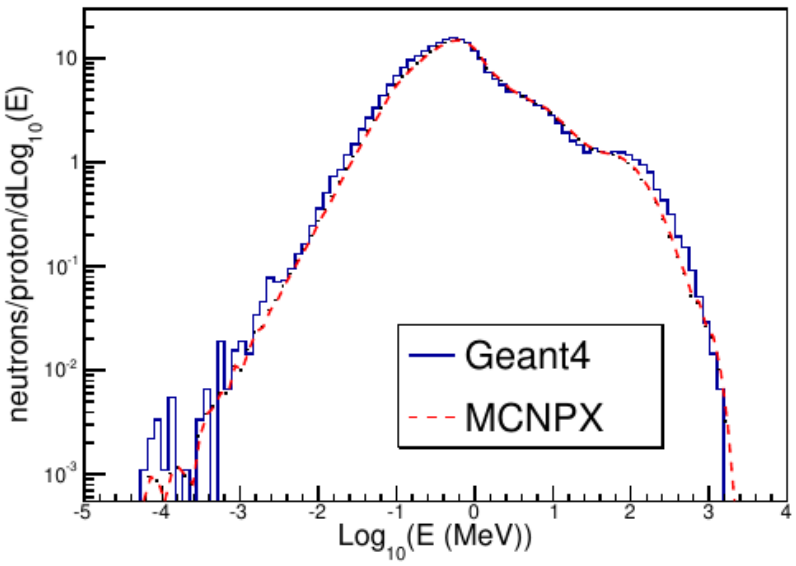
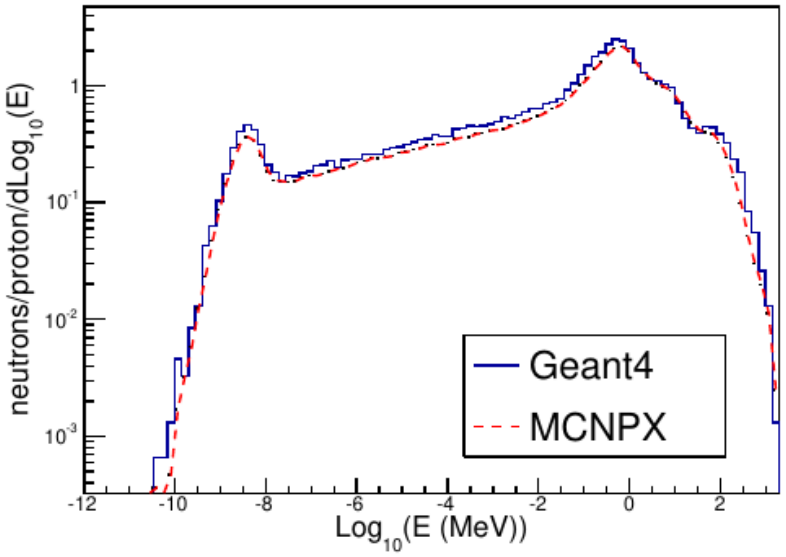
Backup Slides

Energy spectrum of the neutrons leaving the target





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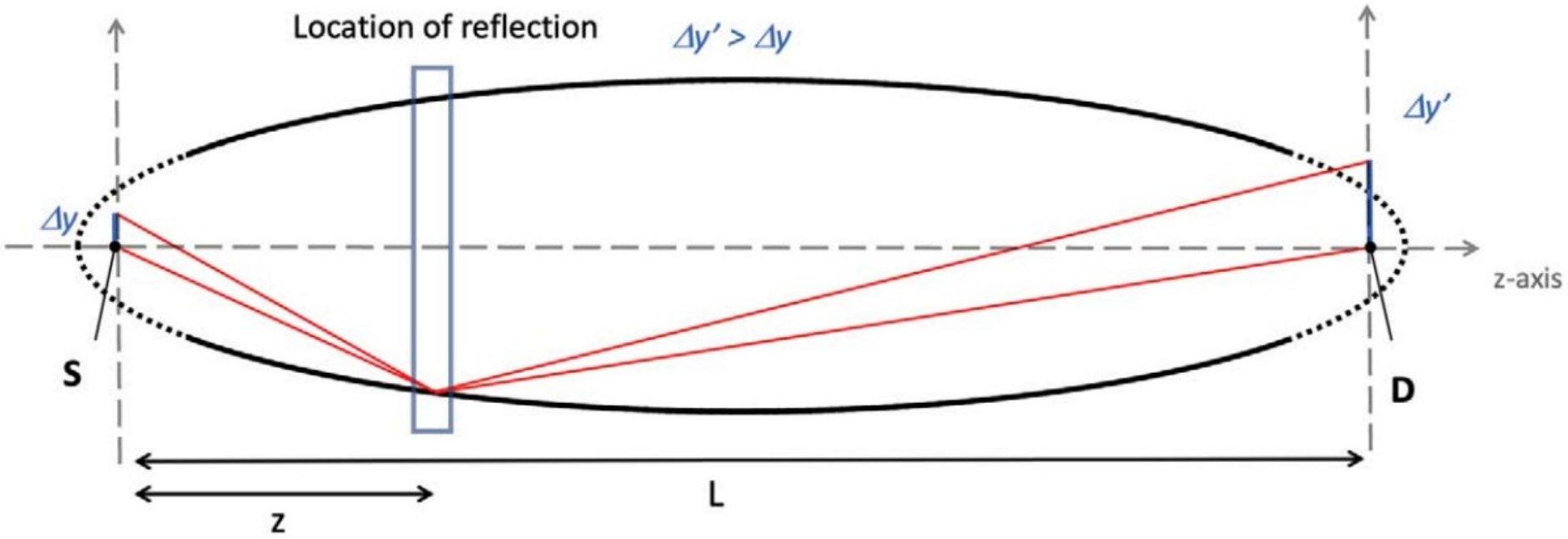
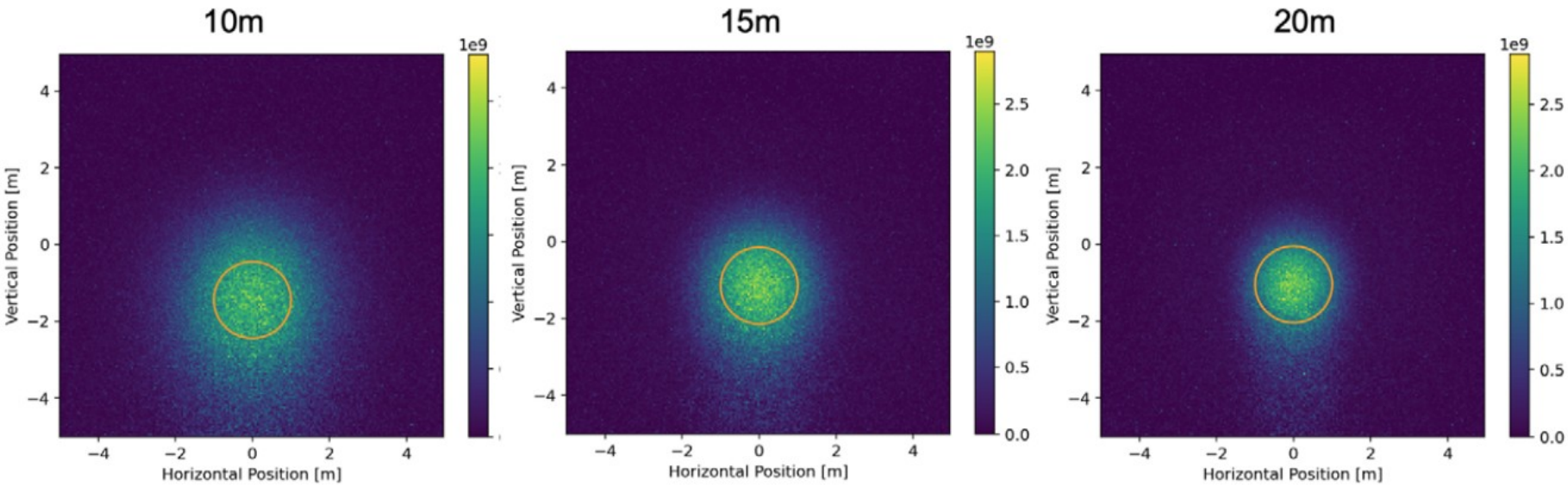
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