Search for neutron conversions and beyond with the HIBEAM/NNBAR experiment

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Baryon and lepton number violation

- BN, LN "accidental" SM symmetries at perturbative level
  - BNV, LNV in SM non-perturbatively (eg instantons)
- BNV, LNV generic features of SM extensions
- BNV Sakharov condition for baryogenesis
- Important to explore the possible selection rules:

$$\Delta B \neq 0\,, \Delta L = 0, \Delta[B-L] \neq 0$$

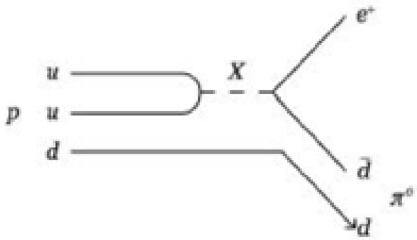
Few searches.
Last search for free $n \to \bar{n}$ 1990s

$$\Delta B = 0\,, \Delta L \neq 0, \Delta[B-L] \neq 0$$

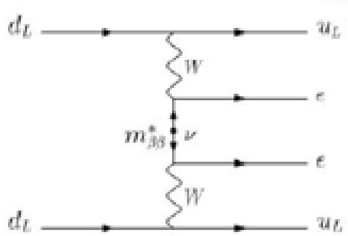
$$\Delta L \neq 0\,,\ \Delta B \neq 0, \Delta[B-L] = 0$$

.....

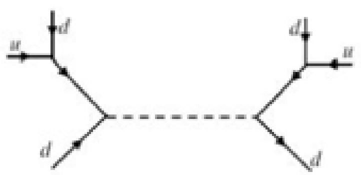
Neutron conversions in the $\not{B}, \not{L}$ landscape



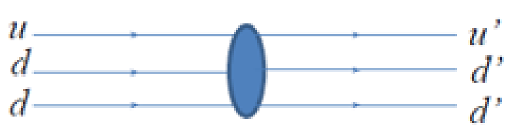
$p \rightarrow e^+ + \pi^0$
$\Delta B \neq 0, \Delta L \neq 0$



$0\nu 2\beta$
$\Delta B = 0, \Delta L \neq 0$



$n \rightarrow \bar{n}$
$\Delta B = 2, \Delta L = 0$



$n \rightarrow n'$ (mirror)
$\Delta B = 1, \Delta L = 0$

Electroweak sphaleron process:
QQQQQQ QQQL LL
~
$(p \rightarrow e + \pi) \times (n \rightarrow \bar{n}) \times (0\upsilon 2\beta)$

Unification models
Supersymmetry
Extra dimensions
Post-sphaleron baryogenesis
Hidden sector
……

Neutron oscillations are a key part of the landscape of new physics
Probe >> TeV scale (e.g. $n \rightarrow \bar{n}$ dimension 9, 6-quark operator – PeV scale)
Symbiosis with other processes

The European Spallation Source

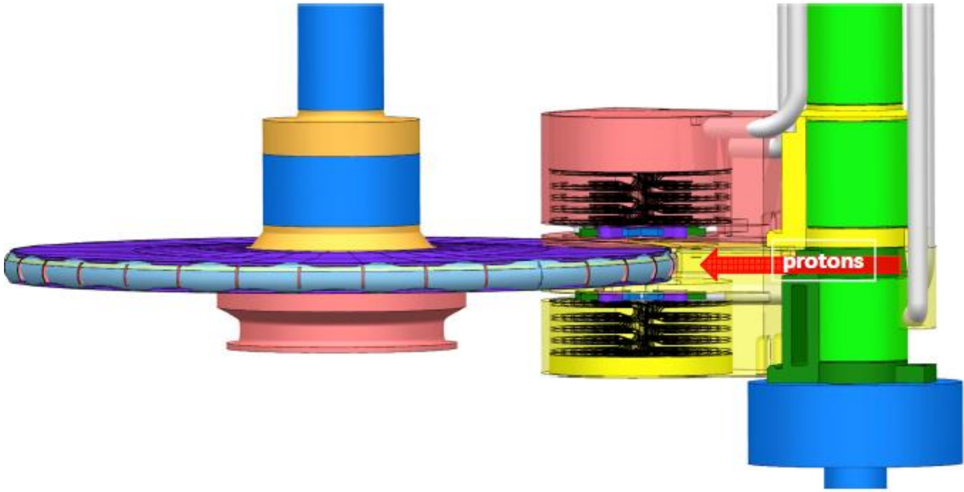
High intensity spallation neutron source

Multidisplinary research centre with 17 European nations participating.

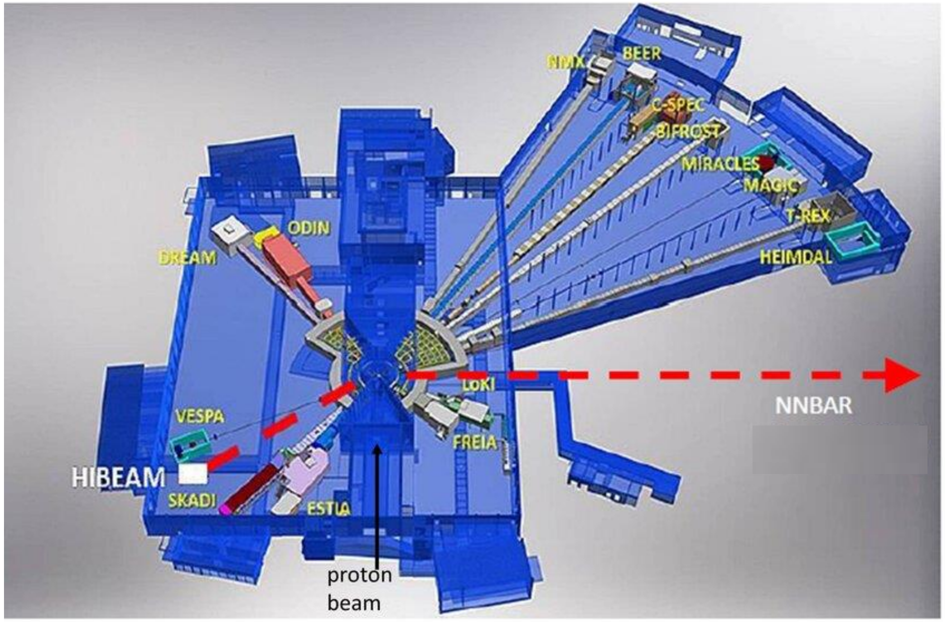
Lund, Sweden.
Start operations in 2027/2028.

Up to 2 GeV protons (3ms long pulse, 14 Hz) hit rotating tungsten target.

Cold neutrons after interaction with moderators.
15 beamlines/instruments



Beamlines and HIBEAM/NNBAR proposed program



Annihilation detector prototype
Conceptual design reports for HIBEAM/NNBAR

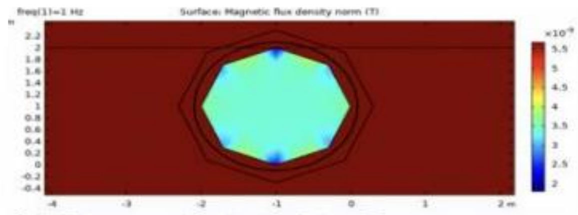
TDRs and small scale experiment

HIBEAM
High precision induced:
$n \rightarrow n'$, $n \rightarrow \bar{n}$ (x10 improvement)
First search for free $n \rightarrow \bar{n}$ at a spallation source

NNBAR
High sensitivity free $n \rightarrow \bar{n}$ (x1000 improvement)
At the Large Beam Port

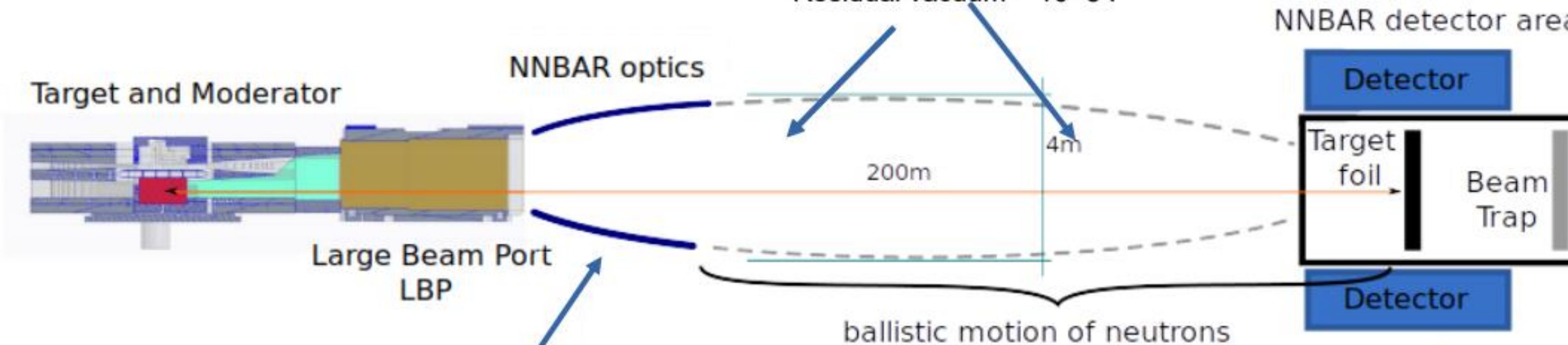
The NNBAR Experiment

octagon-shaped passive shield of 1-2 mm thick sheets of mumetal.



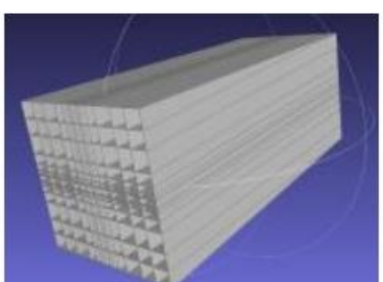
COMSOL

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

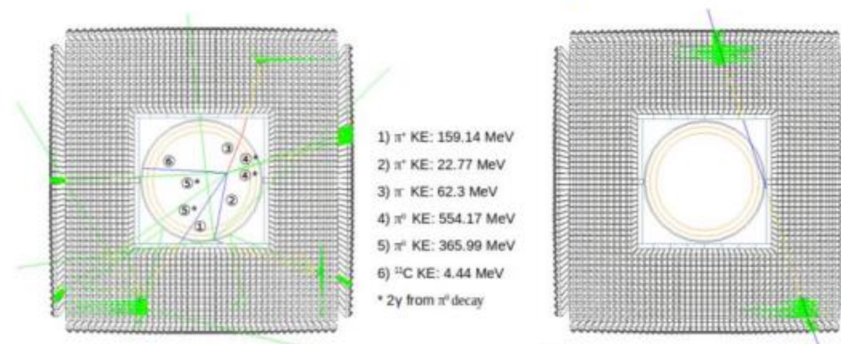


free from perturbing
magnetic stray fields, interaction with walls
and ambient gas particles

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



Eg double planar reflector

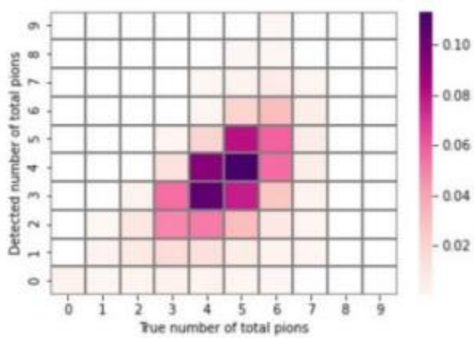


TPC + scintillators and lead-glass

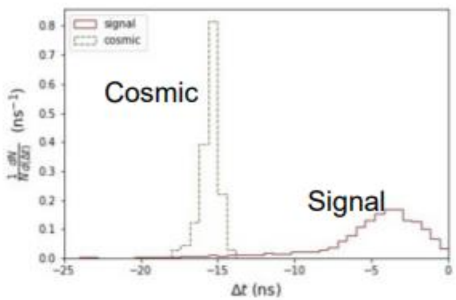
$\bar{n}$ annihilation detector

$\bar{n}N \longrightarrow 5\pi$ ($\sqrt{s}$~ 1.8 GeV

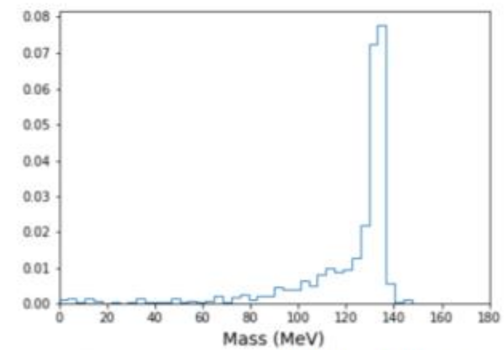
Pion multiplicity

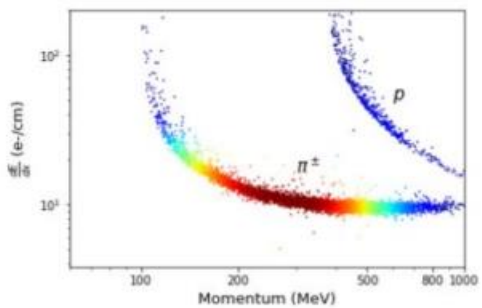


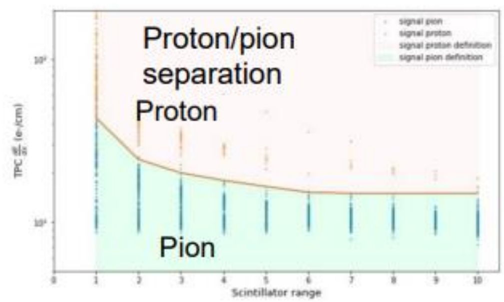
Event timing

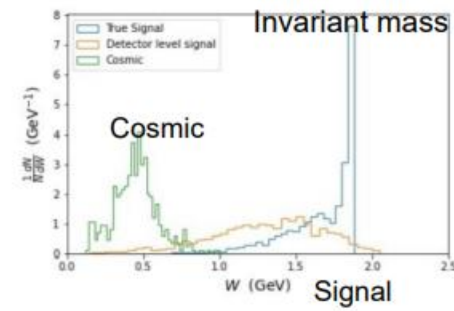


π^0 mass reconstruction





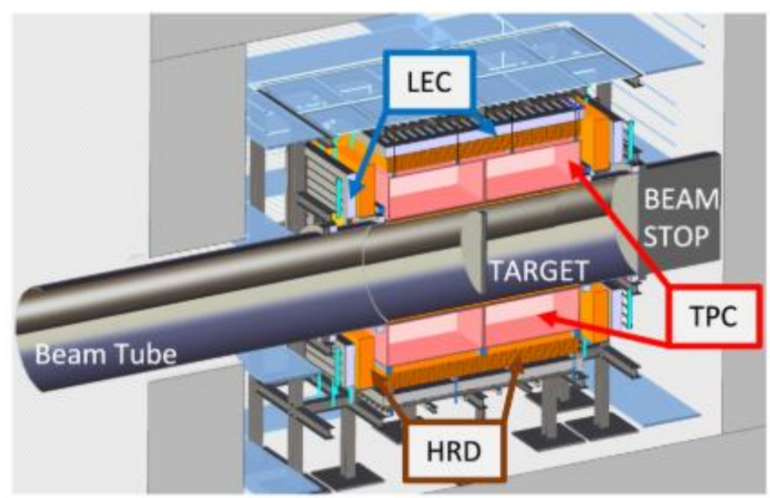




A Computing and Detector Simulation Framework for the HIBEAM/NNBAR Experimental Program at the ESS

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

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



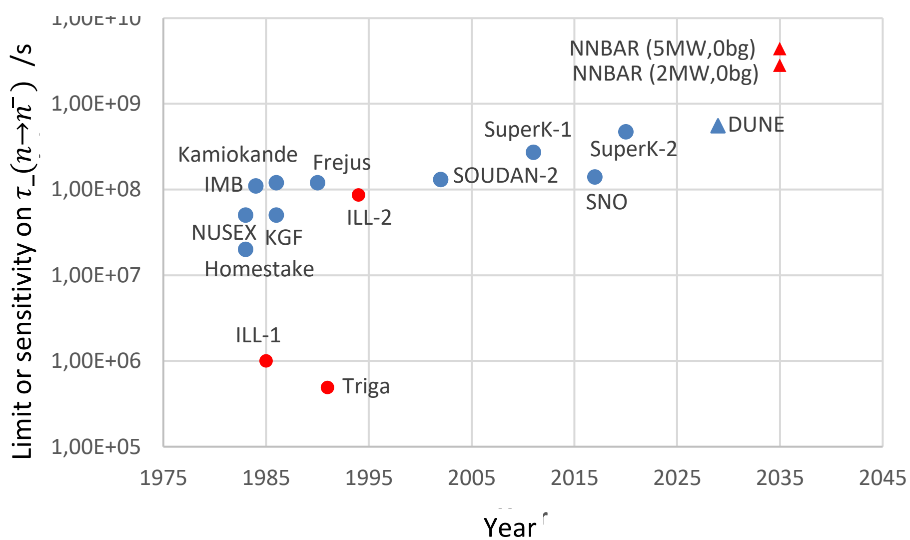
Capability of NNBAR

CDR (*J.Neutron Res.* 25 (2024) 3-4, 315-406)

Aim for zero bg experiment.

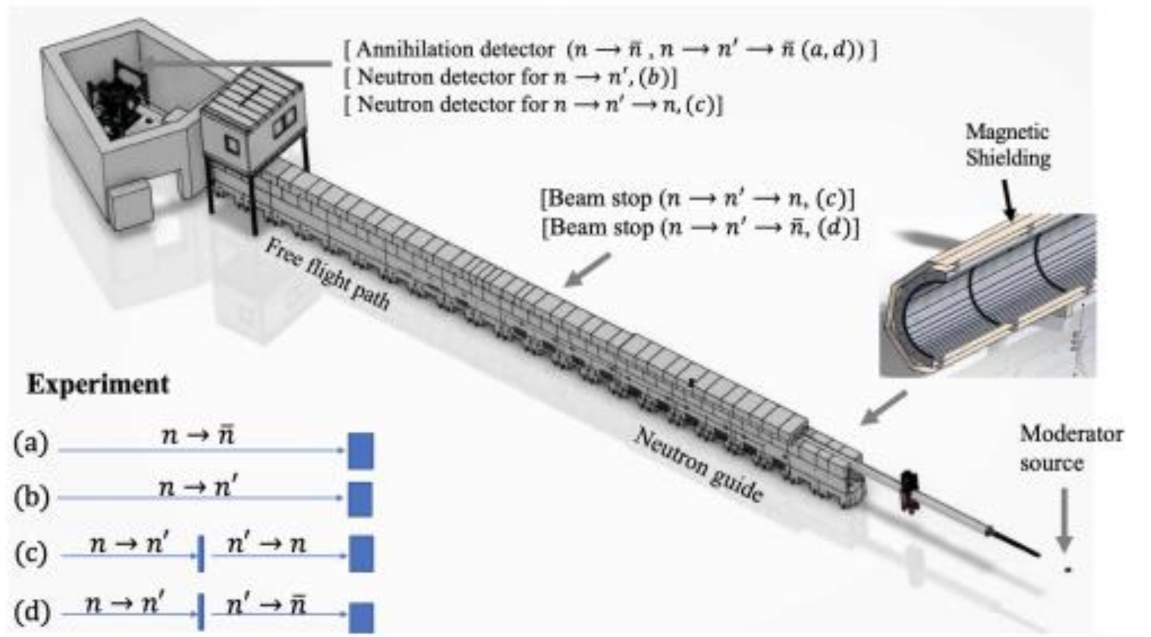
10^3 increase in discovery potential compared to previous experiment

Selection	Signal	Non-muon background	Muon background
Scintillator energy loss $\in [20, 2000]$ MeV	0.89	0.008	0.3
TPC track cut	0.87	2.3×10^{-3}	9.0×10^{-3}
Pion count $\geqslant 1$	0.82	7.8×10^{-9}	5.9×10^{-4}
Invariant mass $W \geqslant 0.5$ GeV	0.8	7.8×10^{-9}	1.5×10^{-4}
Sphericity $\geqslant 0.2$	0.71	1.8×10^{-11}	7.8×10^{-9}
$E_{\text{scint}, y>0, \text{filtered}} \leqslant 320$ MeV & $E_{\text{scint}, y<0, \text{filtered}} \leqslant 930$ MeV	0.68	-	-



HIBEAM neutron conversions searches

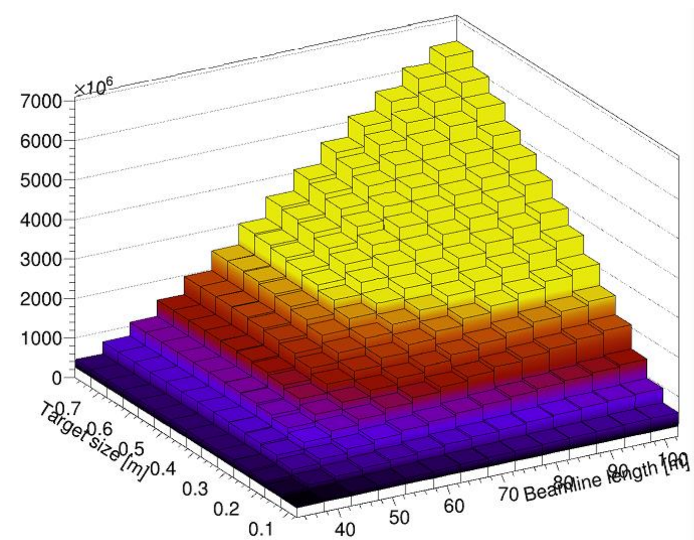
$$\hat{\mathcal{H}} = \begin{pmatrix} m_n + \vec{\mu}_n \vec{B} & \varepsilon_{n\bar{n}} & \alpha_{nn'} & \alpha_{n\bar{n}'} \\ \varepsilon_{n\bar{n}} & m_n - \vec{\mu}_n \vec{B} & \alpha_{n\bar{n}'} & \alpha_{nn'} \\ \alpha_{nn'} & \alpha_{n\bar{n}'} & m_{n'} + \vec{\mu}_{n'} \vec{B}' & \varepsilon_{n'\bar{n}'} \\ \alpha_{n\bar{n}'} & \alpha_{nn'} & \varepsilon_{n'\bar{n}'} & m_{n'} - \vec{\mu}_{n'} \vec{B}' \end{pmatrix}$$



Sensitive to the full mixing Hamiltonian for $n, \bar{n}, n', \overline{n'}$

Can use bespoke annihilation detector or WASA (CsI) crystal calorimeter.

Order of magnitude improvements in $n \longrightarrow \bar{n}, n'$



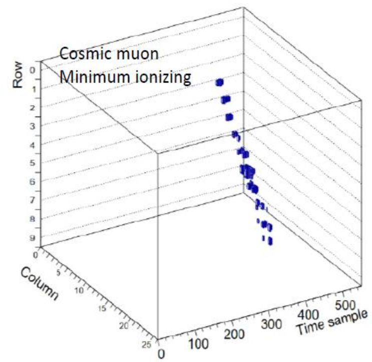
Getting to HIBEAM

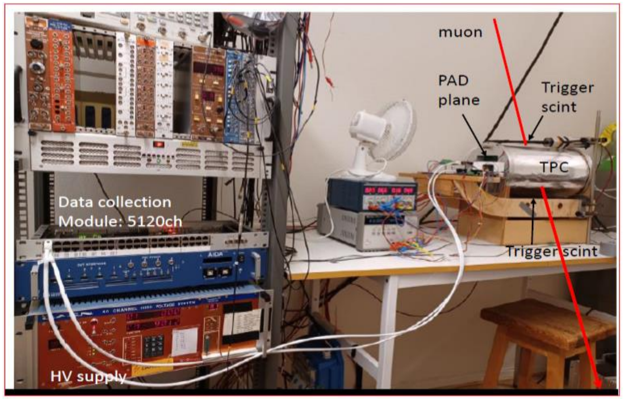
VR RFI

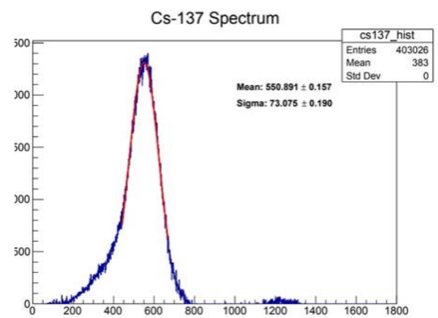
Stockholm, Lund, Chalmers, ESS

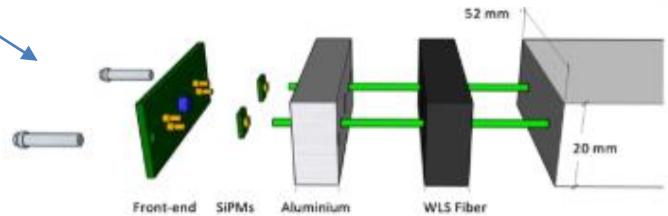
Prototype development
- TPC
- WASA crystal calorimeter
- Scintillator/lead-glass calorimeter

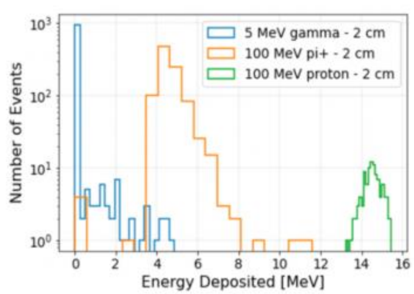
Annihilation detector
Neutron detector
Beamline design

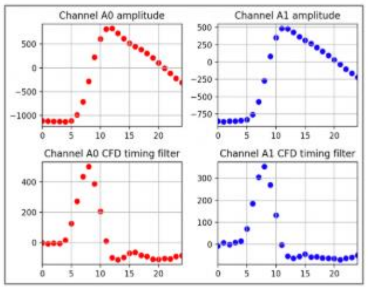












Axions@HIBEAM

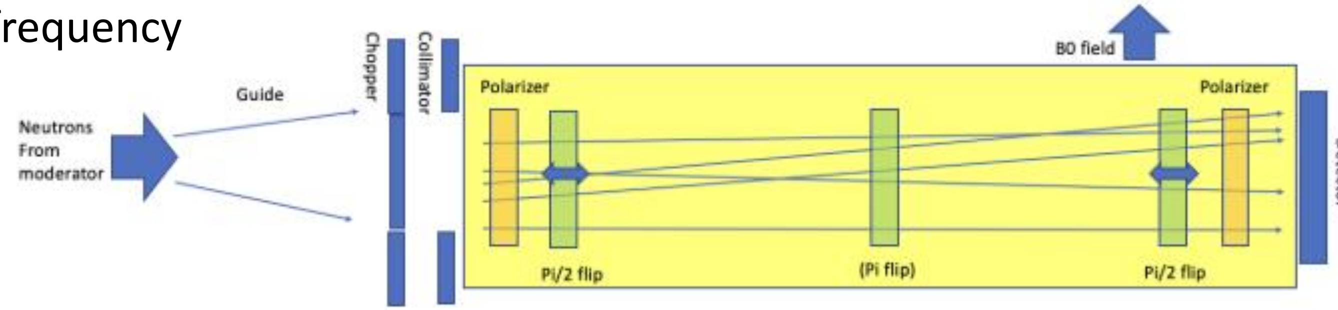
Dark matter candidate - axion.
Coupling of axions to a nucleon
Axions act as a pseudomagnetic field

$$H_{\rm int}(t) \approx \frac{C_N a_0}{2 f_a} \sin(m_a t)\, \boldsymbol{\sigma}_N \cdot \boldsymbol{p}_a$$

Change in Larmor frequency due to axions

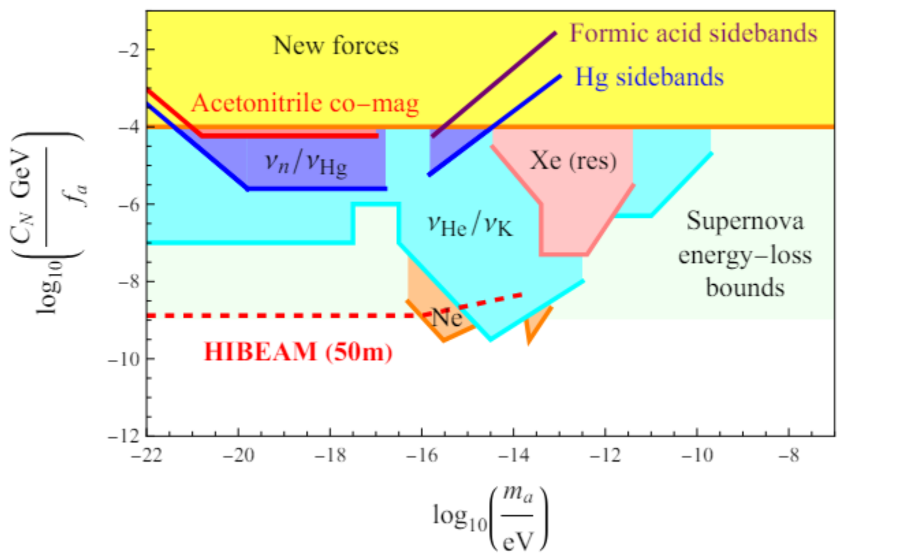
$$\hbar\omega_L = -\gamma \boldsymbol{\sigma}_N \boldsymbol{B} = H_{\rm int}(t).$$

Ramsey set up for Larmor frequency



Fringe shifts

Arxiv:2404.15521 (hep-ph)



HIBEAM/NNBAR

Co-spokespersons: G. Brooijmans (Columbia),
D. Milstead (SU)
Lead scientist: Y. Kamyshkov (Tennesee)
Technical Coordinator : V. Santoro (ESS, LU)
Prototype coordinator : M. Holl (ESS)
Computing and Detector Simulation: B. Meirose (LU,CTH)

Many active institutes: SU,CTU,UU,LU (SV), TMU (DE), Tennessee, Columbia, ORNL (US), Krakow (PL), Brazil (Rio), Poland (Krakow)….

HIBEAM is supported by the Swedish Research Council (1.4Mero) , the Swedish Foundation for Research Strategy (1.5MEuros), Olle Engkvist Foundation (0.4MEuro)
+ VR grant for collaborating with Italian institutes

NNBAR was supported as part of a 3MEuro H2020 grant for an upgraded ESS with a new lower moderator.

STINT award for collaboration with Brazilian institutes

Selection of HIBEAM/NNBAR publications

Summary

- Neutron oscillations are a key but rarely explored portal for new physics
  - baryogenesis, BNV physics, dark matter
- The ESS is opening a new discovery window
- HIBEAM/NNBAR is a proposed multi-stage program designed to increase sensitivty by ~1000
  - From prototype development to physics
- HIBEAM offers a wide range of applications (neutron oscillations, axions, rare decays etc.).
- Fits well within the 2020 Update to the European Particle Physics Strategy (“Essential activities)

A. The quest for dark matter and the exploration of flavour and fundamental symmetries are crucial components of the search for new physics. This search can be done in many ways, for example through precision measurements of flavour physics and electric or magnetic dipole moments, and searches for axions, dark sector candidates and feebly interacting particles. There are many options to address such physics topics including energy-frontier colliders, accelerator and non-accelerator experiments. A diverse programme that is complementary to the energy frontier is an essential part of the European particle physics Strategy. ***Experiments in such diverse areas that offer potential high-impact particle physics programmes at laboratories in Europe should be supported, as well as participation in such experiments in other regions of the world.***