Neutron – antineutron conversions

D. Milstead
Stockholm University

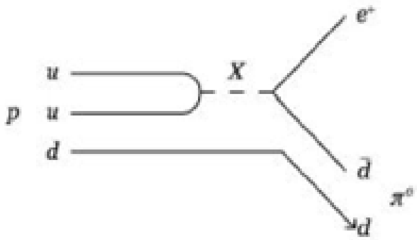
Baryon and lepton number violation

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

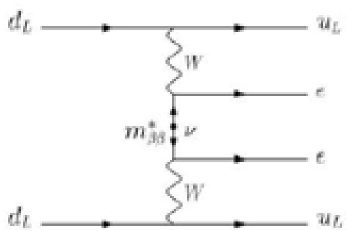
$$\Delta B \neq 0\,,\ \Delta L = 0, \Delta[B - L] \neq 0$$
$$\Delta B = 0\,,\ \Delta L \neq 0, \Delta[B - L] \neq 0$$
$$\Delta L \neq 0\,,\ \Delta B \neq 0, \Delta[B - L] = 0$$

.....

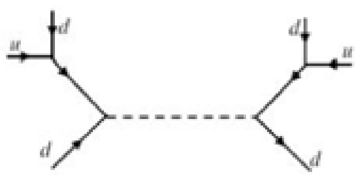
Candidate BNV,LNV processes



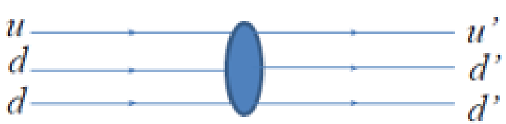
$$p \to e^+ + \pi^0$$
$$\Delta B \neq 0, \Delta L \neq 0$$



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



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



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

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

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

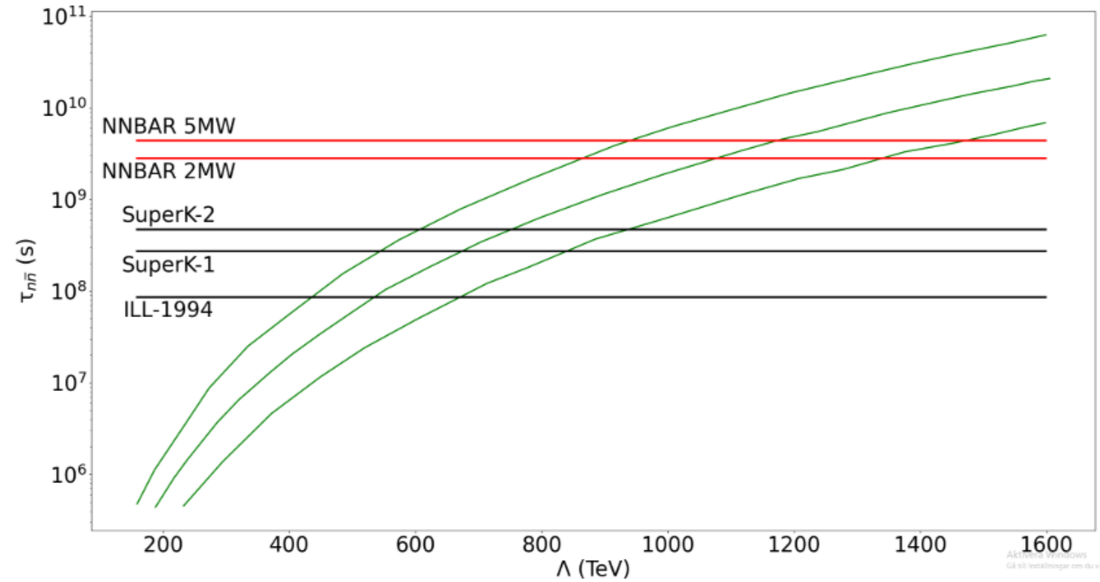
Neutron oscillations are a key part of the landscape of new physics
Symbiosis with other processes

Energy scale of new physics for $n \to \bar{n}$?

Simple EFT approach
Dimension 9 (6 quark) operator

$$\mathcal{O}_{\Delta\mathcal{B}=2} = \frac{1}{\mathcal{M}^5}(udd)^2 + \text{h.c.}$$

$$\varepsilon_{n\bar{n}} = \frac{C\Lambda_{\text{QCD}}^6}{\mathcal{M}^5}$$



JHEP 05 (2016) 14

A search for $n \to \bar{n}$ probes the PeV scale for new physics

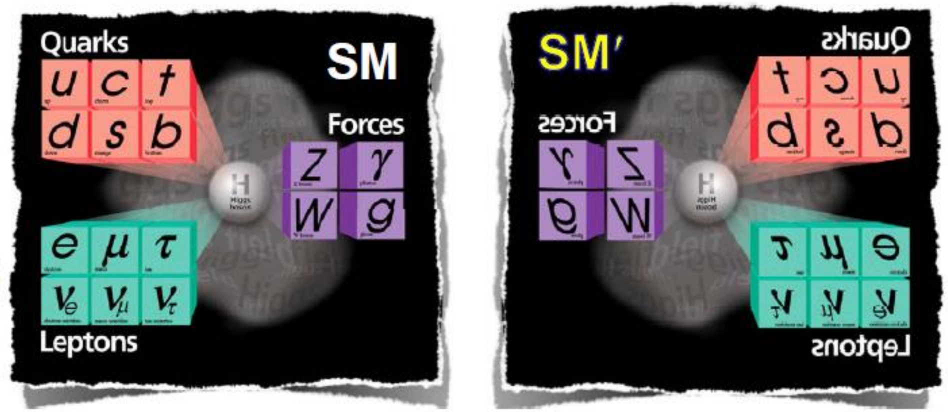
Sterile neutrons

"Hidden/mirror" sector

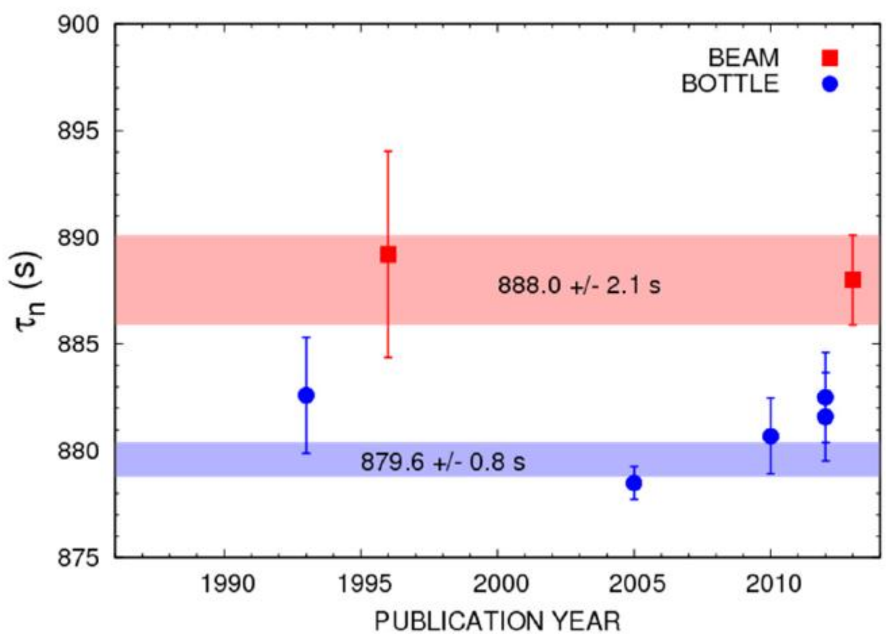
Restores parity symmetry.

Possible mixing for $Q = 0$ particles, eg, $n \to n'$

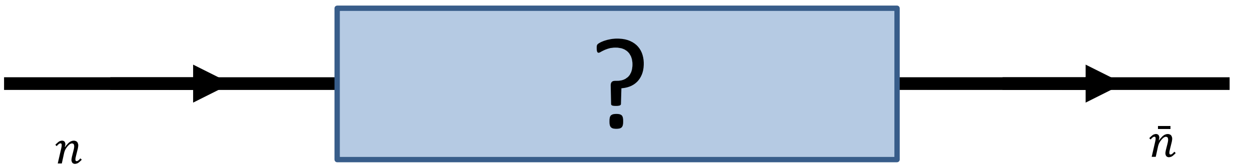
Mirror matter : dark matter candidates (m< 10 GeV)



Can explain 5σ neutron lifetime discrepancy seen in bottle and beam experiments.



$n \rightarrow \bar{n}$ mixing formalism



$$i\hbar \frac{\partial}{\partial t}\binom{n}{\bar{n}} = \begin{pmatrix} E_n & \delta m \\ \delta m & E_{\bar{n}} \end{pmatrix}\binom{n}{\bar{n}}$$

$\delta m = \langle \bar{n}|H_{eff}|n\rangle < 10^{-29}$ MeV = $n\bar{n}$ mixing physics

$$P_{n\rightarrow\bar{n}} = \left(\frac{\delta m}{\Delta E}\right)^2 \sin^2(\Delta E \times t) \quad ; \Delta E = E_n - E_{\bar{n}}$$

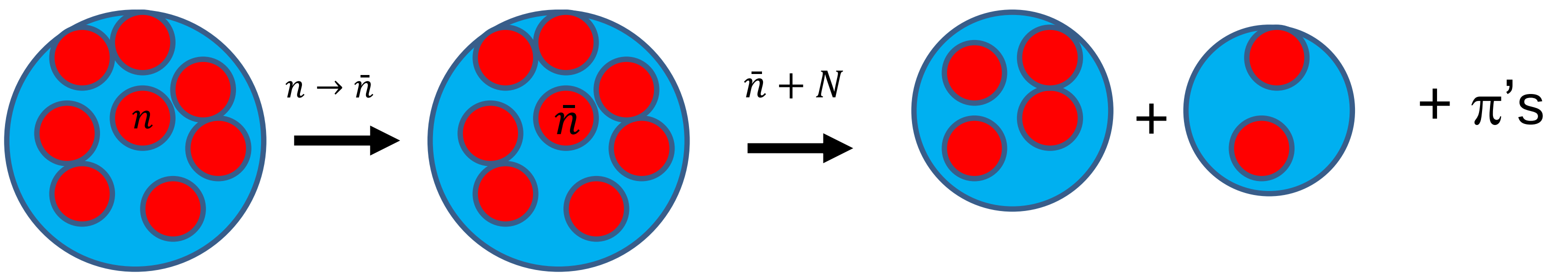
Two interesting cases:

- Free neutron oscillation: $\Delta E \times t \ll 1 \Rightarrow P \sim (\delta m \times t)^2$
- Bound neutron oscillation: $\Delta E \times t \gg 1$

Quasi-free limit : $\Delta E t \sim 1 \;\Rightarrow P \sim (\delta m \times t)^2$

Searching with bound neutrons

Nuclear disintegration after neutron oscillation



$$P_{n\to\bar{n}} = \left(\frac{\delta m}{\Delta E}\right)^2 \sin^2(\Delta E \times t) \ ,$$

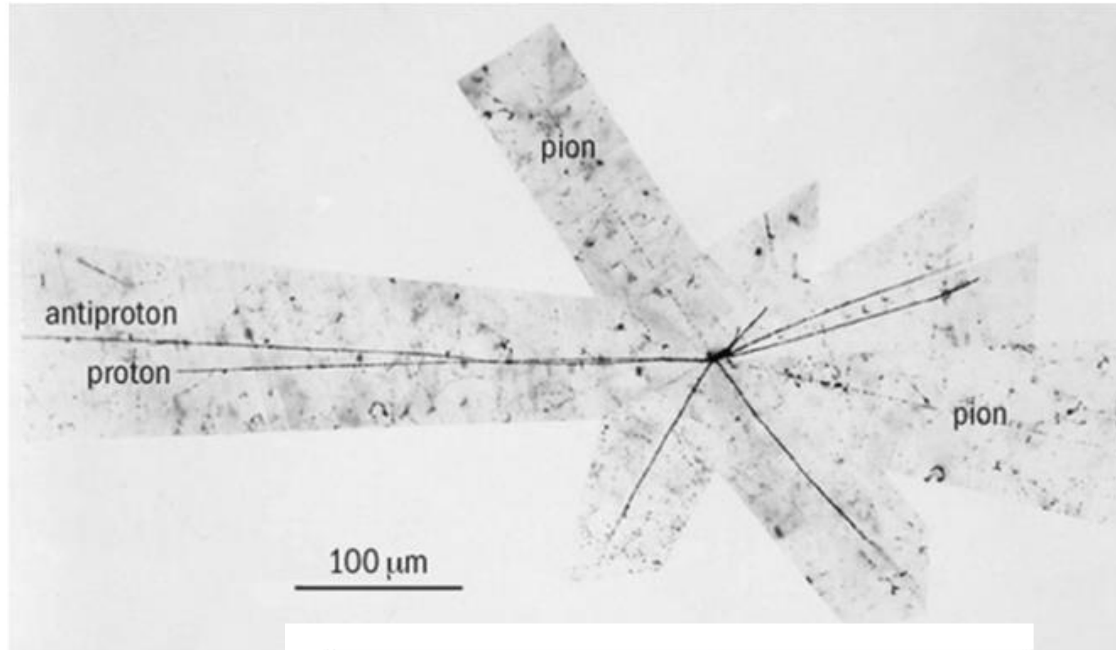
$$\Delta E \sim 10 - 100 \text{ MeV} .$$

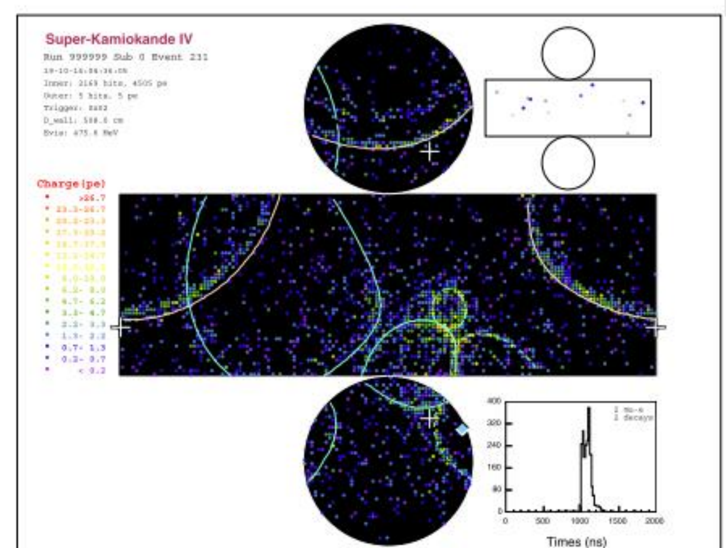
$$\Rightarrow \text{Suppression: } \left(\frac{\delta m}{\Delta E}\right)^2 < 10^{-60}$$

Best current limits (SuperKamiokande) $\Rightarrow$ $\tau_{free} > 4.7 \times 10^8$ s
Large model-dependent correction factors needed to compare free/bound
Both needed.

Signature

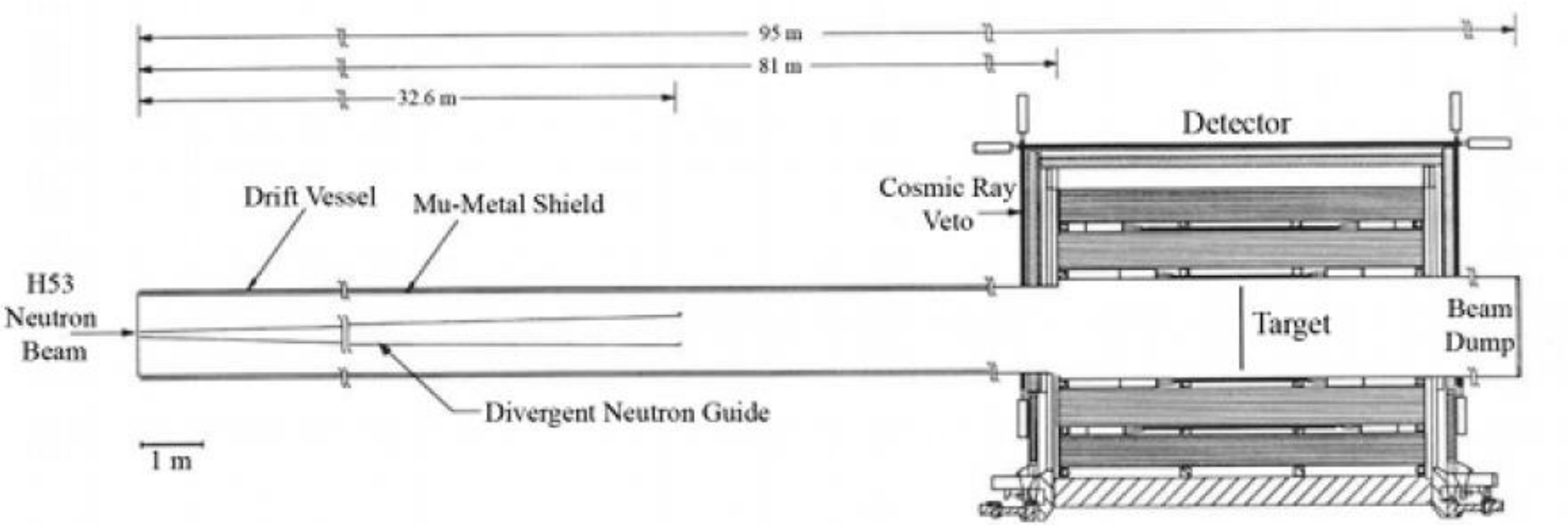
- Annihilation star
- Pionic final state with centre-of-mass energy~1.8 GeV





Super-Kamiokande

Free neutron search at ILL



Institute Laue−Langevin (Early 1990′s).
Cold neutron beam from 58MW reactor.
$\sim 130\mu$m thick carbon target
100m propagation in field-free region

Signal of at least two tracks with $E > 850$ MeV
0 candidate events, 0 background.
$\Rightarrow \tau_{n\to\bar{n}} > 0.86 \times 10^8$s.

The European Spallation Source

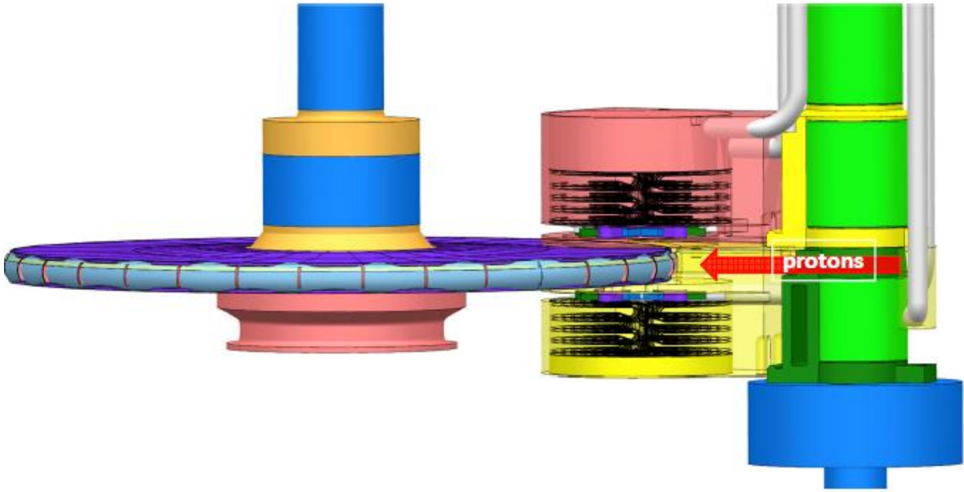
High intensity spallation neutron source

Multidisplinary research centre with 17 European nations participating.

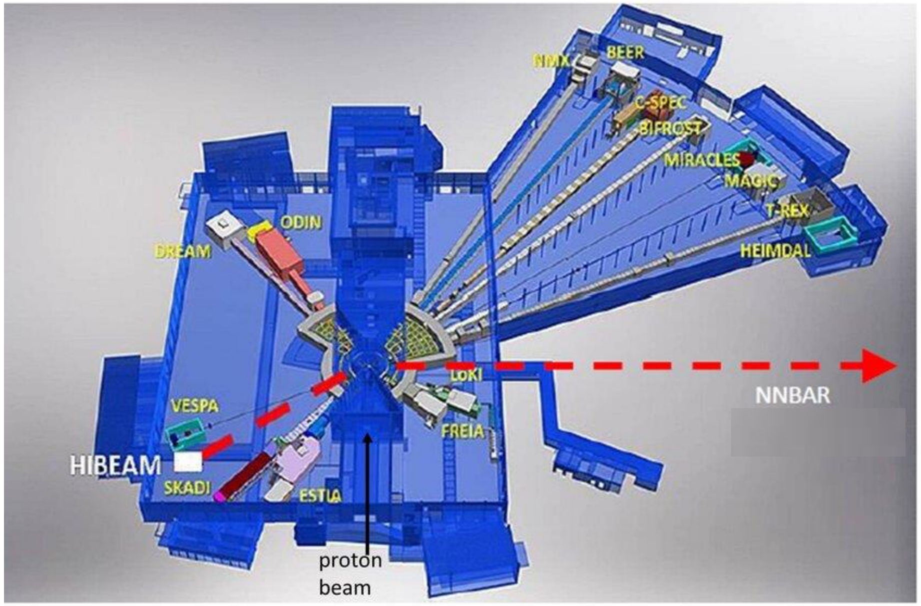
Lund, Sweden.
Start operations in 2027/2028.

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

Cold neutrons after interaction with moderators.
15 beamlines/instruments – none are Swedish-led



Beamlines and program



R&D
Annihilation detector prototype
Conceptual design reports for HIBEAM/NNBAR

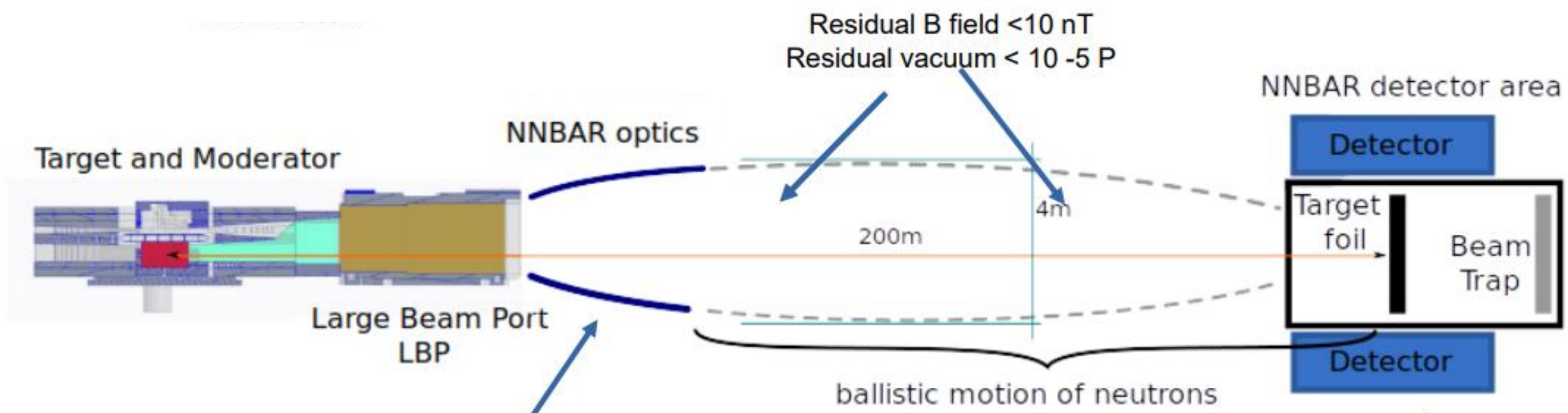
TDRs and small scale experiment at ESS test beamline

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

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

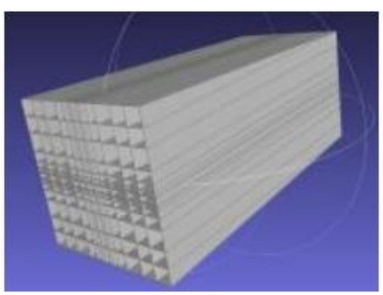
NNBAR

The NNBAR Experiment

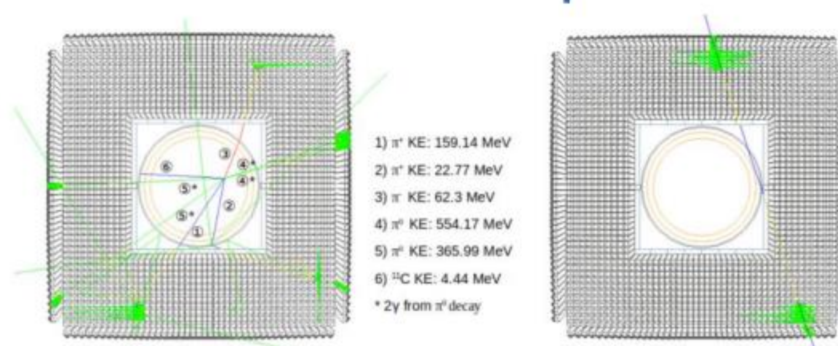


free from perturbing magnetic stray fields, interaction with walls and ambient gas particles

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

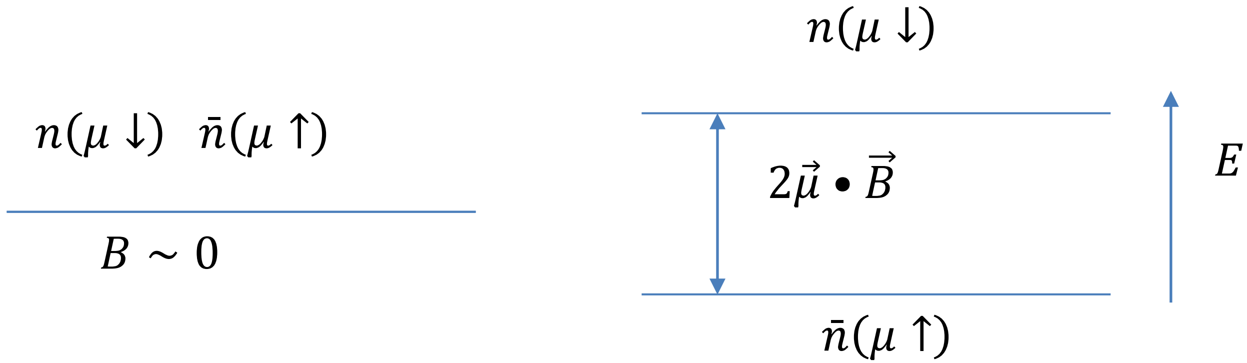


Eg double planar reflector



TPC + scintillators and lead-glass

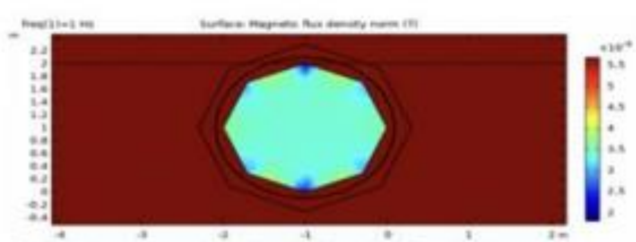
The need for magnetic shielding



Degeneracy of $n, \bar{n}$ broken in B−field due to dipole interactions: $\Delta E = 2\vec{\mu} \bullet \vec{B}$

Flight time $\leq$ 1s
For quasi−free condition $\Delta E \times t \ll 1$
$\Rightarrow B \leq$ 10nT and vacuum $\leq 10^{-5}$ Pa.

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

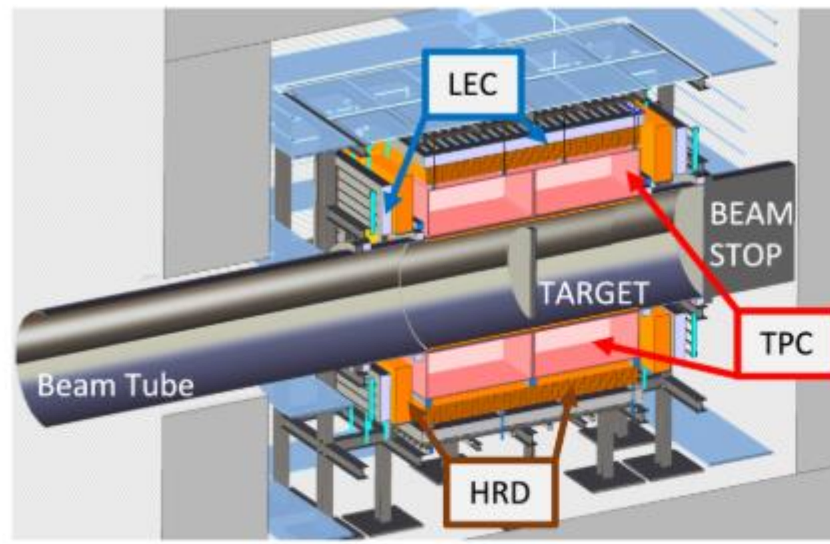


COMSOL

Residual B field <10 nT

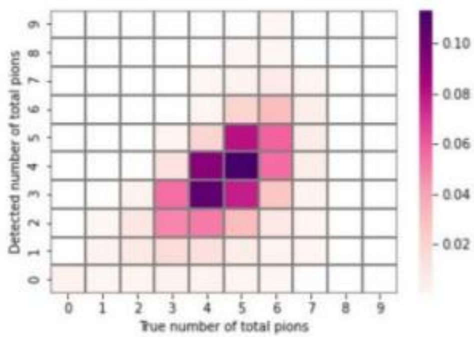
NNBAR detector

- ~2 GeV invariant mass pionic final state
- Lead-glass em calo
- Scintillator staves
- TPC
- Cosmic veto (scintillators)

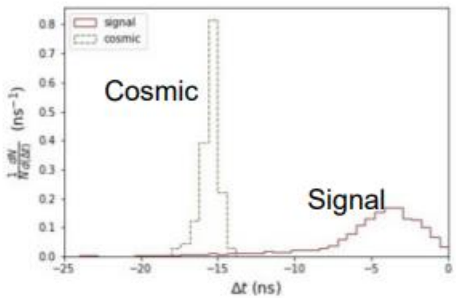


Geant-4 detector simulation

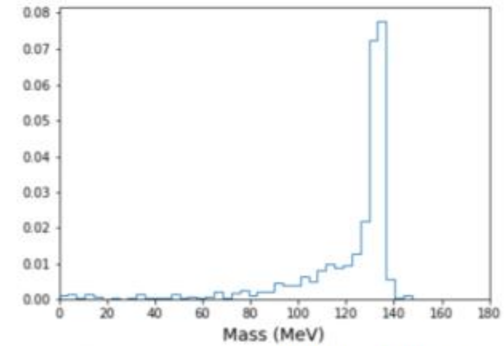
Pion multiplicity

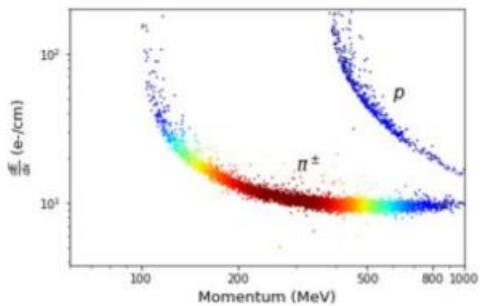


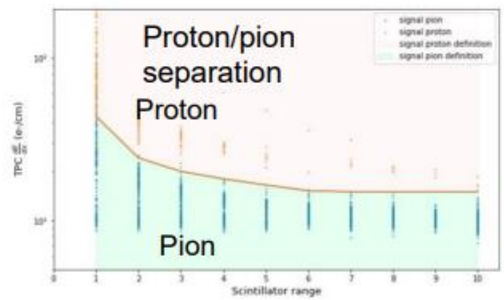
Event timing

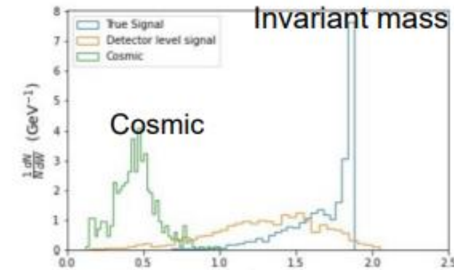


π^0 mass reconstruction









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

symmetry

Article

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

Symmetry 14 (2022) 1, 76

Backgrounds

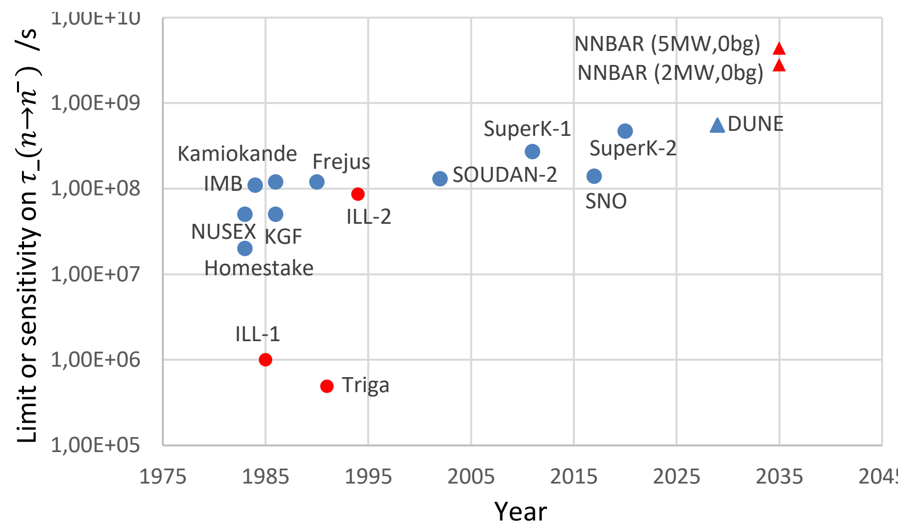
- Cosmic rays (neutral and charged - dominant at ILL)
- Thermal neutrons, beta-delayed neutrons
- Low energy photons - from the activation of the target + beamline. While these are low energy (1 MeV), pile-up happens.
- Spallation bg -high energy, can be removed with timing
- Nuclear fragments
- Geant4 and MCNP study for different beamline configurations and neutron poisons

Capability of the experiment

Background suppression selections.

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	-	-

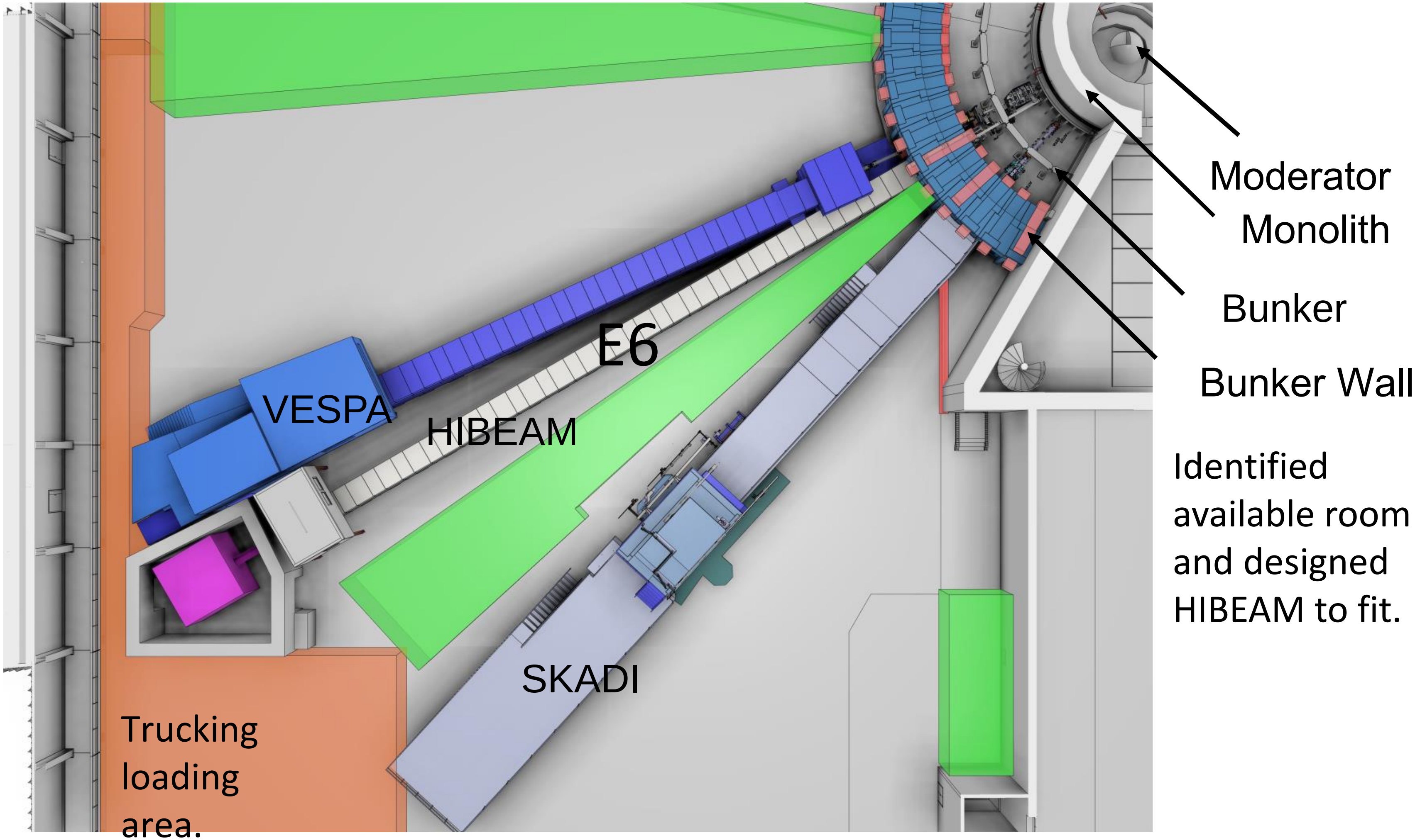
10^3 increase in discovery potential compared to previous experiment



Conceptual design report for NNBAR: *J.Neutron Res.* 25 (2024) 3-4, 315-406

HIBEAM

HIBEAM optimal beamline: E6

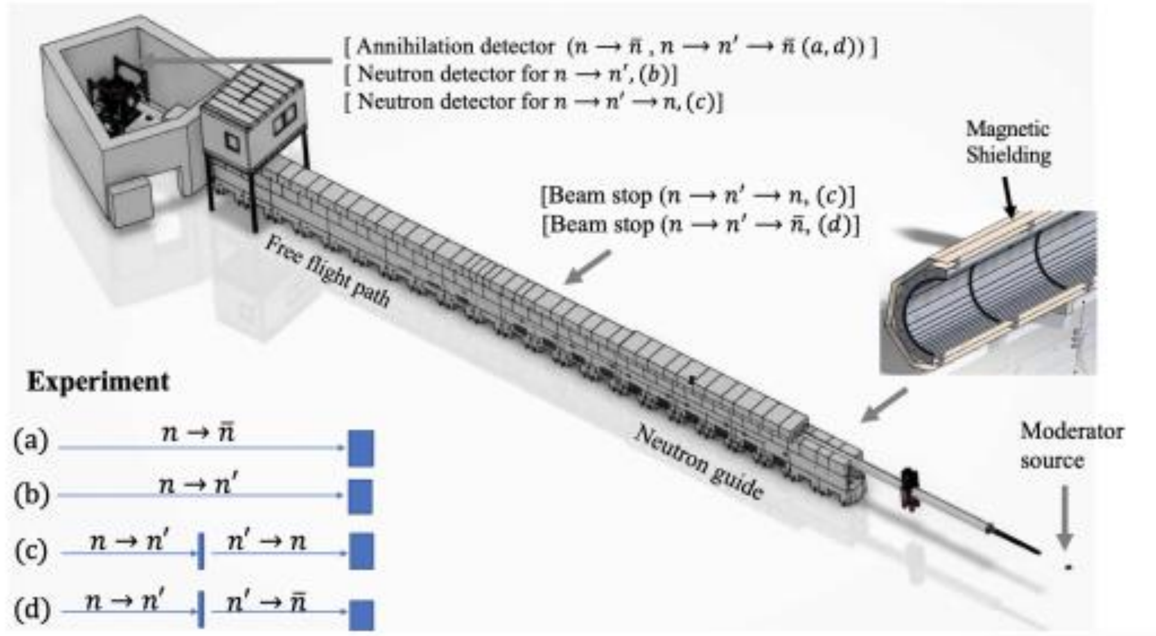


Identified available room and designed HIBEAM to fit.

Investment by ESS for beam extraction system of HIBEAM design (1.1MEuro). Without this, impossible for any new instrument to operate before 2030’s.

HIBEAM neutron conversions searches

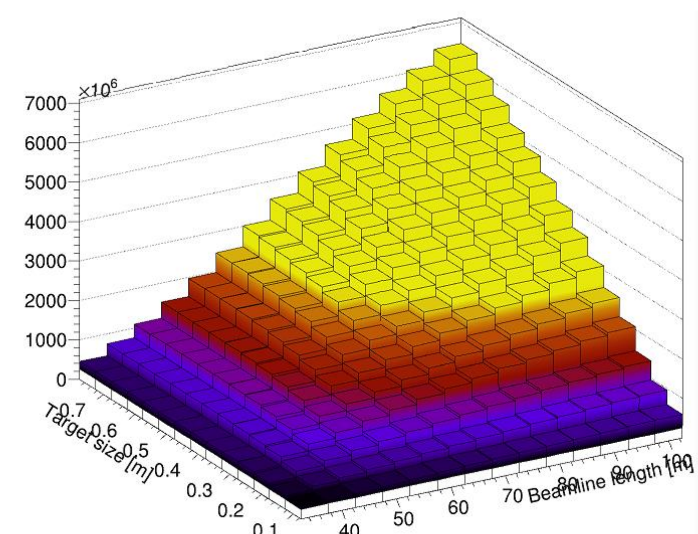
$$\hat{\mathcal{H}} = \begin{pmatrix} m_n + \vec{\mu}_n \vec{B} & \varepsilon_{n\bar{n}} & \alpha_{nn'} & \alpha_{n\bar{n}'} \\ \varepsilon_{n\bar{n}} & m_n - \vec{\mu}_n \vec{B} & \alpha_{n\bar{n}'} & \alpha_{nn'} \\ \alpha_{nn'} & \alpha_{n\bar{n}'} & m_{n'} + \vec{\mu}_{n'} \vec{B}' & \varepsilon_{n'\bar{n}'}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



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

Can use bespoke annihilation detector or WASA (CsI) crystal calorimeter co-owned by UU.

Can exceed ILL experiment by factor 10



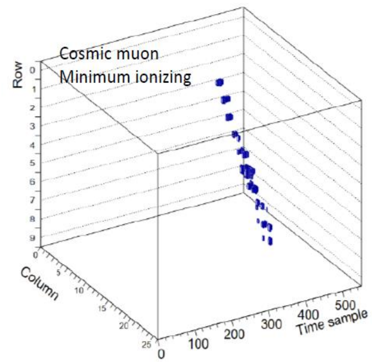
Getting to HIBEAM

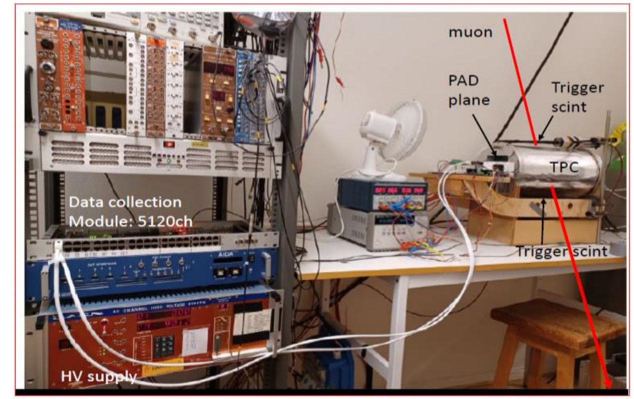
VR RFI

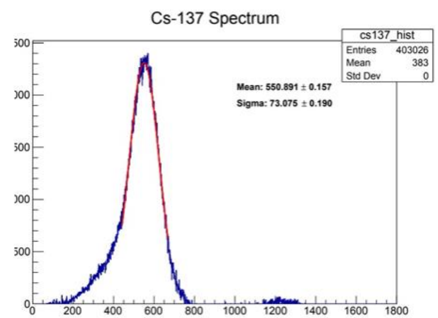
Stockholm, Lund, Chalmers, ESS

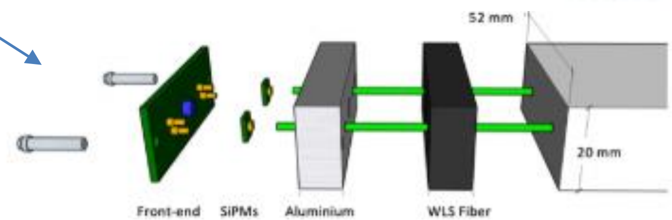
Prototype development
- TPC
- WASA crystal calorimeter
- Scintillator/lead-glass calorimeter

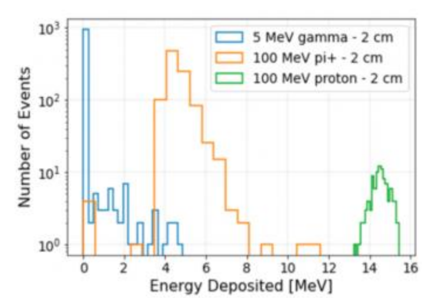
Annihilation detector
Neutron detector
Beamline design

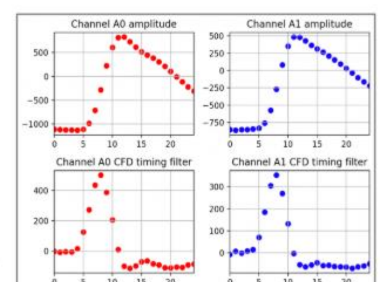












Axions@HIBEAM

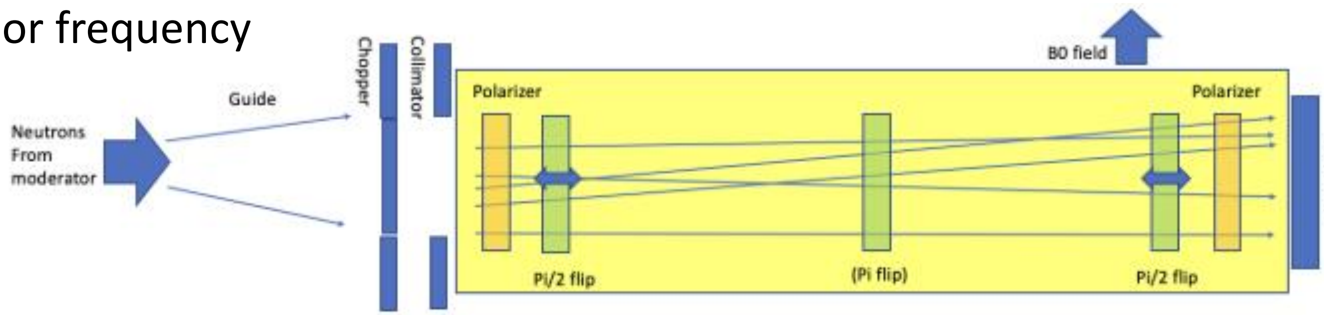
Dark matter candidate - axion.
Coupling of axions to a nucleon
Axions act as a pseudomagnetic field

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

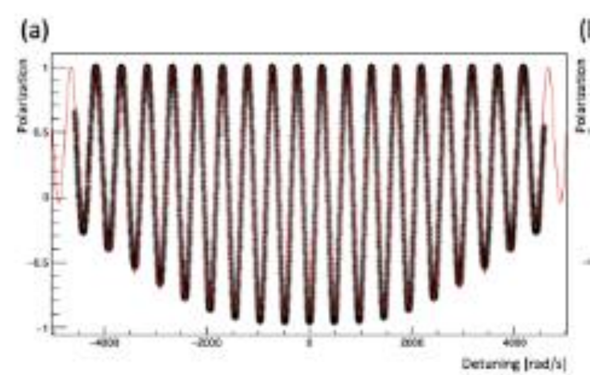
Change in Larmor frequency due to axions

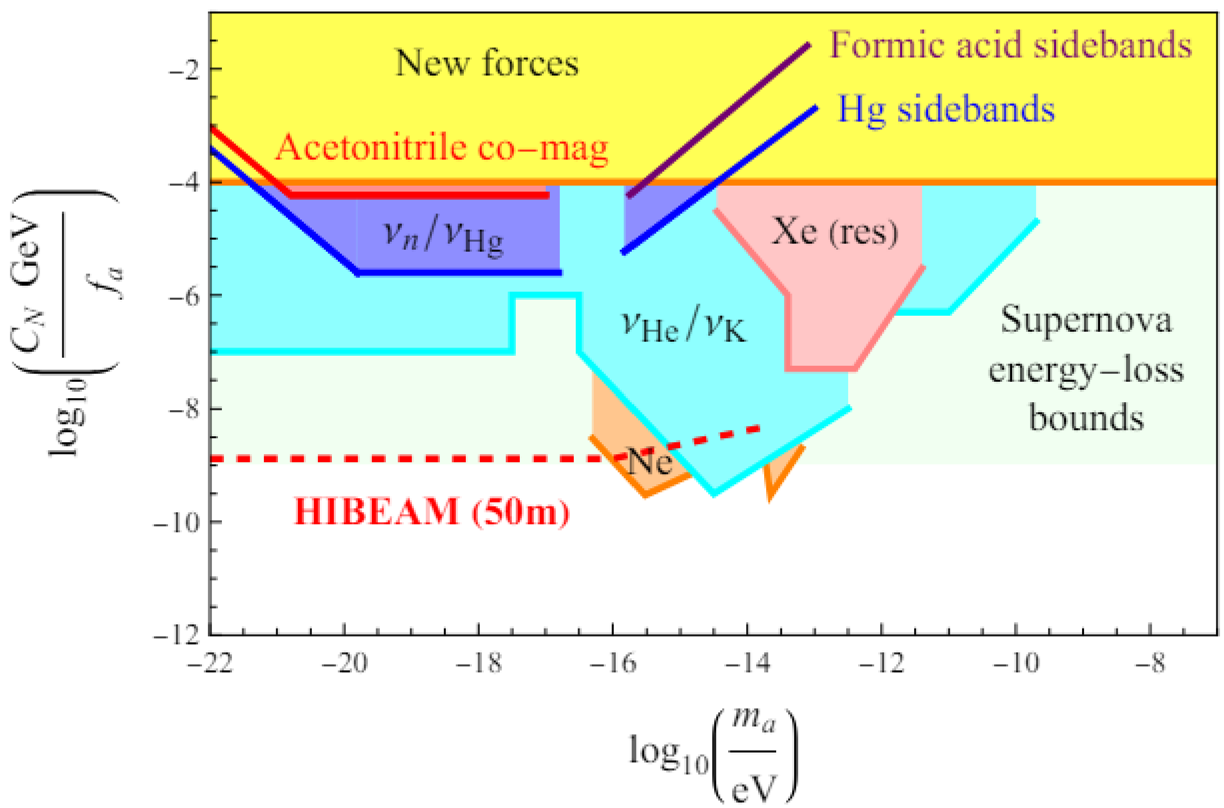
$$\hbar\omega_L = -\gamma \boldsymbol{\sigma}_N \boldsymbol{B} = H_{\text{int}}(t).$$

Ramsey set-up for Larmor frequency



Fringe shifts





Arxiv:2404.15521 (hep-ph) – accepted by PRL

Sensitivity from a small-scale pilot experiment at the ESS

Most of the kit already acquired (magnetics ..) or can be borrowed.

Only thing missing is data.
Many uses for HIBEAM beyond neutron-antineutron.

HIBEAM/NNBAR

Started as an Expression of Interest for a neutron-antineutron search at the ESS (2015)

Signatories from 26 institutes, 8 countries.

Developed into multi-stage HIBEAM/NNBAR project

Co-spokespersons: G. Brooijmans (Columbia), D. Milstead (SU)
Lead scientist: Y. Kamyshkov (Tennesee)
Technical Coordinator (V. Santoro)
Prototype coordinator (M. Holl)

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 (B. Meirose).

Applications: Synergy Grant (SU, LU, TMU, Indiana) for ~construction of HIBEAM and first nnbar, nn' searches.

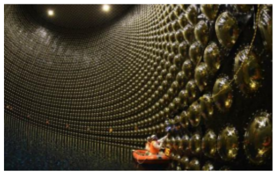
Selection of HIBEAM/NNBAR publications

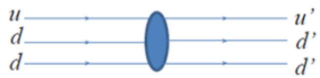
+ *JINST* 17 (2022) 10, P10046 (Arxiv: 2209.09011, [physics.ins-det))

+ Proc AccApp 21 (arXiv: 2204.04051 [physics.ins-det))

+ ….

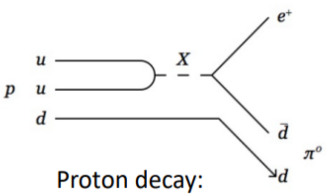
Fitting into the European landscape



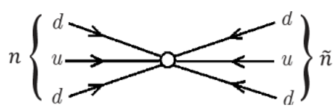


Neutron-sterile neutron:
$n \longrightarrow n', \Delta B = 1, \Delta L = 0$

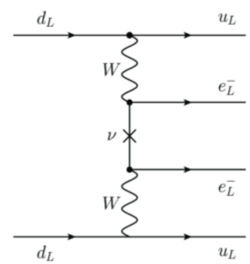
Relatively unexplored selection rules HIBEAM/NNBAR



Proton decay:
$p \longrightarrow \ell + meson$
$\Delta B = 1, \Delta L = 1$



Neutron-antineutron:
$n \longrightarrow \bar{n}$
$\Delta B = 2, \Delta L = 0$



Neutrinoless double beta decay, $0\nu 2\beta$
$\Delta B = 0, \Delta L = 2$

Plug the "observable gap" for B,L tests
+ sensitivity to many theories of physics beyond the SM (eg hidden sector (dark matter), SUSY, unification models, neutrino mass models etc.)

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.***

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 multi-stage program to increase sensitivty by ~1000
  - From prototype development to physics
- HIBEAM offers a wide range of applications (neutron oscillations, axions, rare decays etc.).