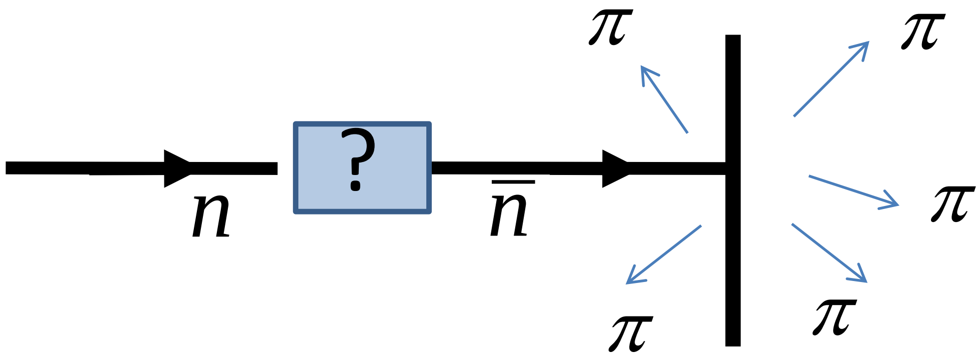
The HIBEAM/NNBAR program

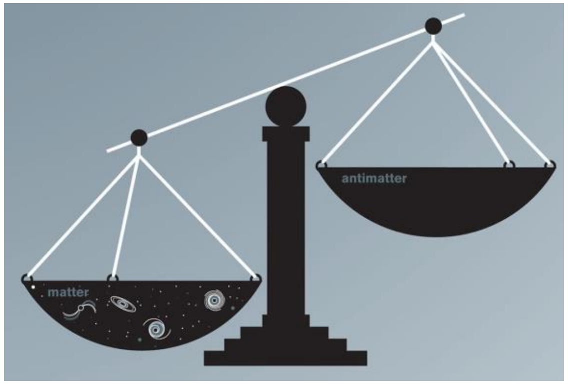


D. Milstead

Stockholm University

Conservation of baryon and lepton numbers

Of all the empirically observed conservation laws – baryon and lepton number are the most fragile.



BNV needed for baryogenesis
(Sakharov condition)

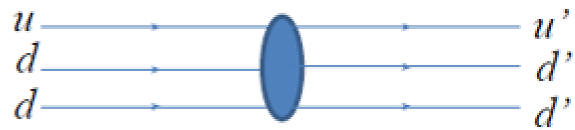
The Standard Model accommodates baryon and lepton numbers as "accidental symmetries" and breaks them in ultra-rare sphaleron processes.

BNV, LNV occurs routinely in theories that extend the Standard Model , eg SUSY.

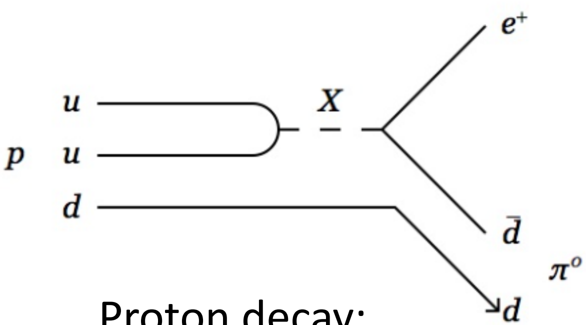
We don't expect BN or LN to be conserved and any observation of their violation would be of fundamental significance

Key observables and the need for the ESS

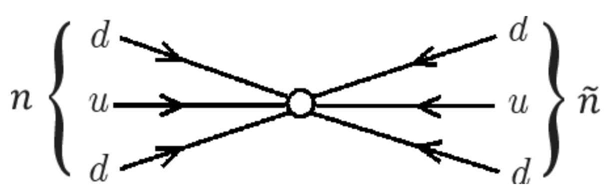
Relatively unexplored



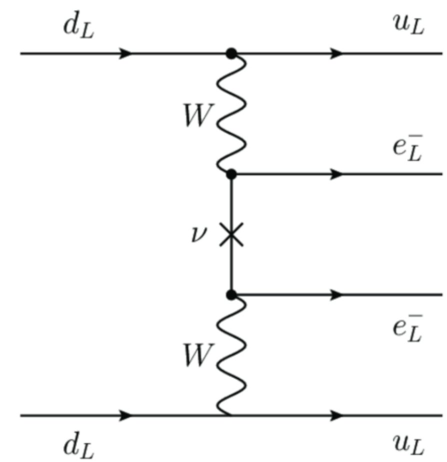
Neutron-sterile neutron:
$n \longrightarrow n', \Delta B = 1, \Delta L = 0$



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

All three processes = SM sphaleron
If two processes are seen, the other must exist.
Combinations of processes routinely occur in unification theories

Neutron-antineutron oscillations

- R-parity violating supersymmetry, minimal flavour violation SUSY
- Unification models: $M \sim 10^{15}$ GeV
- Left-right symmetric models ($n\bar{n}$ and $0\nu 2\beta$)
- Extra dimensions models
- Post-sphaleron baryogenesis
- etc, etc: [arXiv:1410.1100]

High precision $n \to \bar{n}$ search

$\Rightarrow$ Scan over wide range of phase space for generic BNV

+

$\Rightarrow$ model constaints.

Sterile neutrons

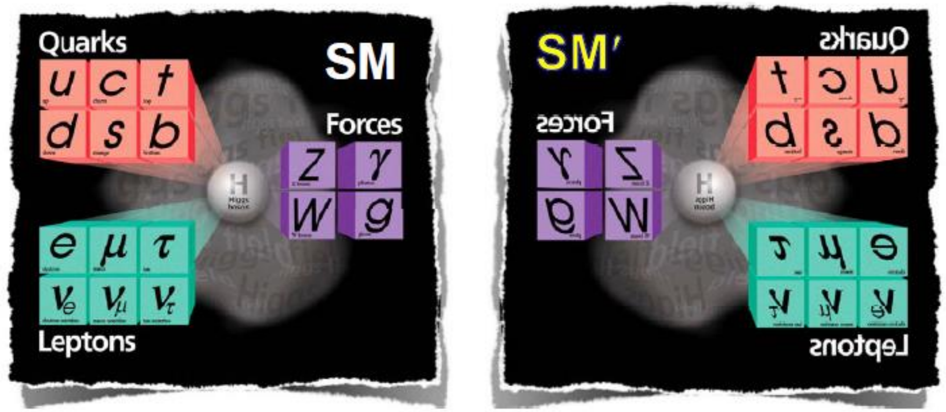
Eg “Hidden” sector of particles.
Generic search for dark/sterile sector via neutrons

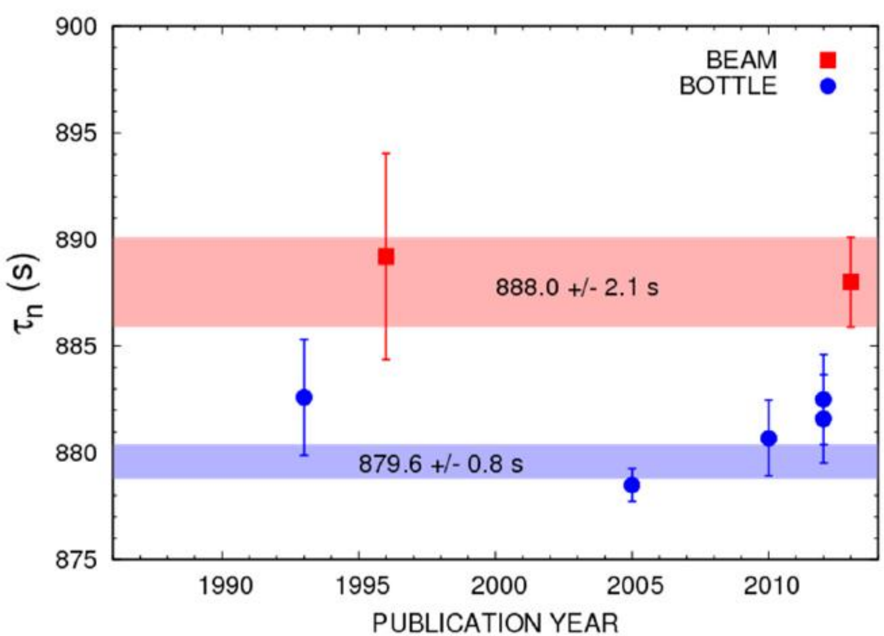
Searches made with copiously produced and long-lived electrically neutral particles: γ, ν, n ...

$n \rightarrow n' \; (\Delta B = 1)$

Sterile neutron transformations are feeble interactions occurring in theories of dark sectors (dark matter) and co-genesis

Can explain the beam/bottle discrepancy in neutron lifetime measurements.





Neutron mixing

$$\hat{\mathscr{H}} = \begin{pmatrix} E_n & \varepsilon_{n\bar{n}} \\ \varepsilon_{n\bar{n}} & E_{\bar{n}}, \end{pmatrix}.$$

Free $n \to \bar{n}$

$$P_{n\bar{n}}(t) = \varepsilon_{n\bar{n}}^2 t^2 = \frac{t^2}{\tau_{n\bar{n}}^2} = \left(\frac{t}{0.1\ \mathrm{s}}\right)^2 \left(\frac{10^8\ \mathrm{s}}{\tau_{n\bar{n}}}\right)^2 \times 10^{-18},$$

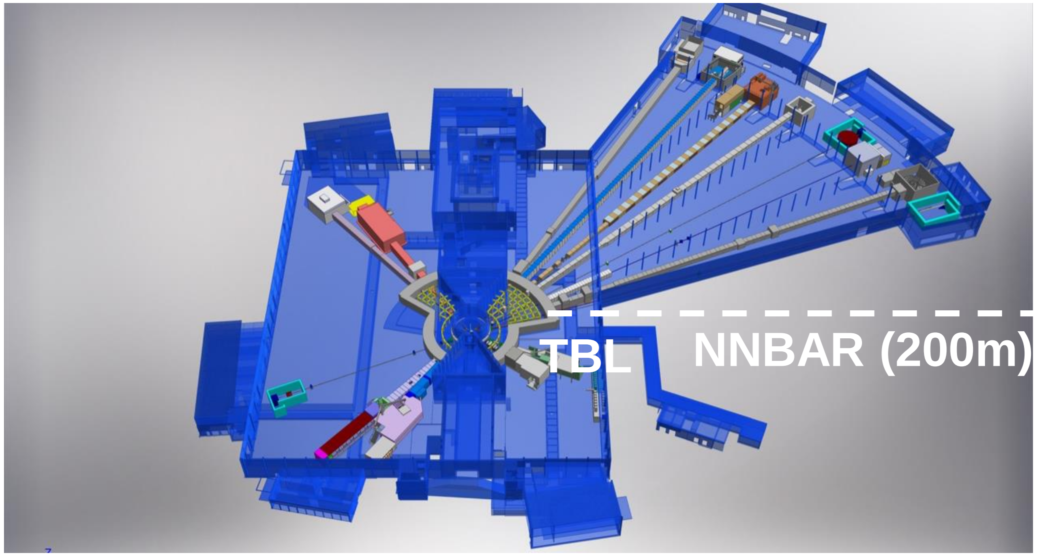
$$\hat{\mathscr{H}} = \begin{pmatrix} m_n + \vec{\mu}_n \vec{B} & \varepsilon_{n\bar{n}} & \alpha_{nn'} & \alpha_{n\bar{n}'} \\ \varepsilon_{n\bar{n}} & m_n - \vec{\mu}_n \vec{B} & \alpha_{n\bar{n}'} & \alpha_{nn'} \\ \alpha_{nn'} & \alpha_{n\bar{n}'} & m_{n'} + \vec{\mu}_{n'} \vec{B}' & \varepsilon_{n\bar{n}}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

Induced with B-field:
$n \to \bar{n}$, $n \to n'$

$$P_{n\bar{n}}(t) = \frac{1}{4}\alpha_{n\bar{n}'}^2 \alpha_{n\bar{n}'}^2 t^4 \sin^2\beta = \frac{\sin^2\beta}{4}\left(\frac{t}{0.1\ \mathrm{s}}\right)^4 \left(\frac{10^2\ \mathrm{s}^2}{\tau_{nn'}\tau_{n\bar{n}'}}\right)^2 \times 10^{-8}$$

Figure of merit ~ (number of neutrons)x(flight time)^2 (first order)
~ (number of neutrons)x(flight time)^4 (second order)

Beamlines and program



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

TDRs and small scale experiment at ESS test beamline

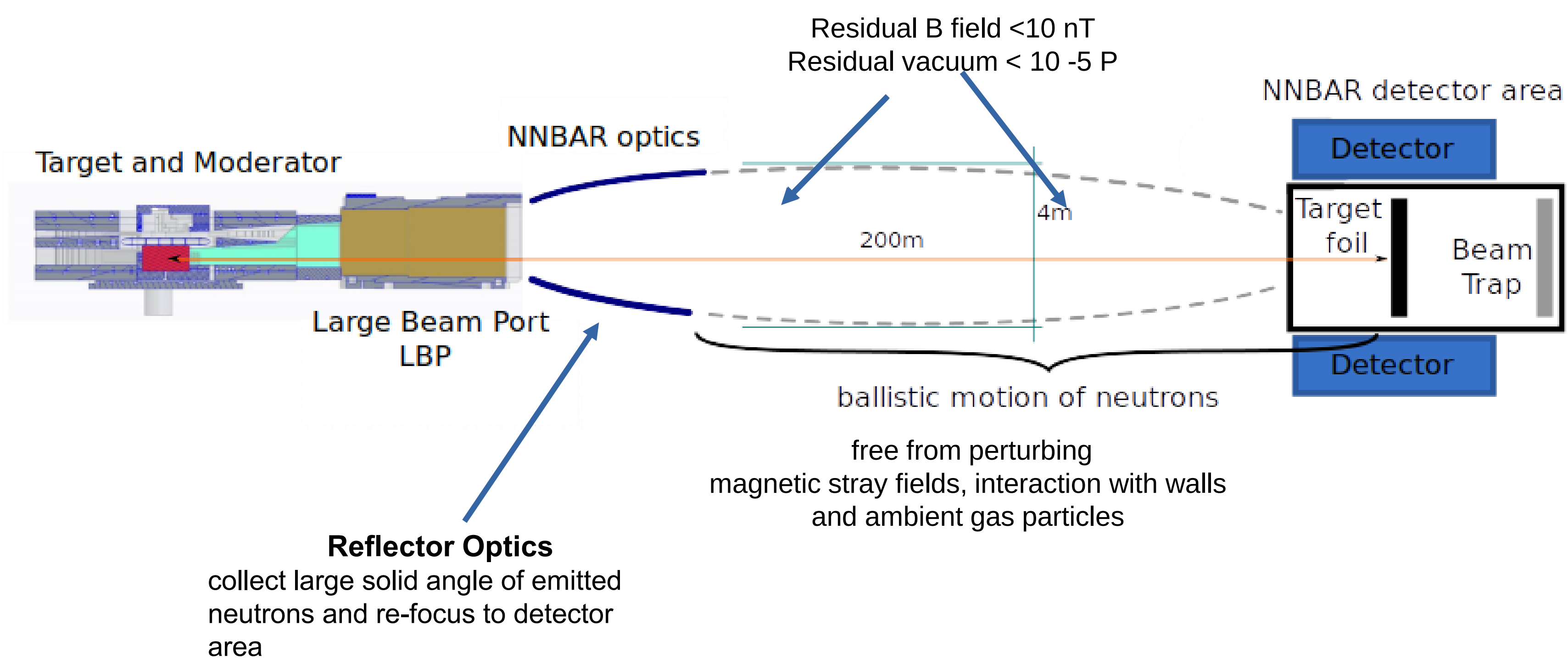
HIBEAM
High precision induced:
$n \to n'$, $n \to \bar{n}$ (x10 improvement)
First search for free $n \to \bar{n}$ at a spallation source
Eg at upgraded test beamline

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

NNBAR

NNBAR Experiment

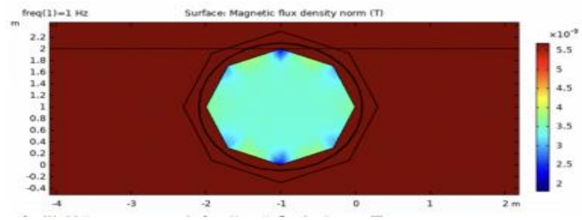
Maximise the discovery potential with a high flux from the LBP (10^{13} n/s) of slow neutrons arriving after 200m of free flight.
Sensitivity@2MW ~ 10^3 x last search (ILL)



CDR work as part of HighNESS program

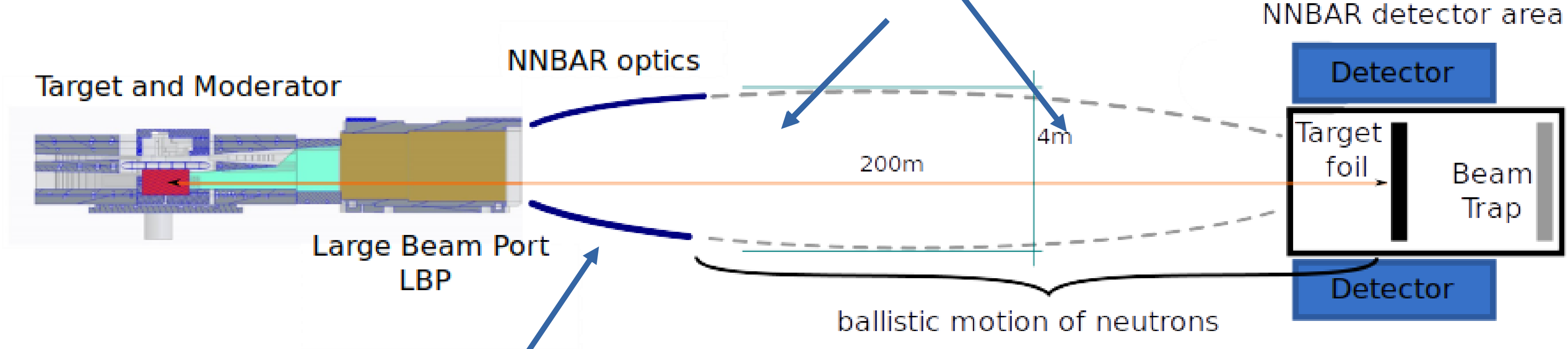
NNBAR Experiment

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



COMSOL

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

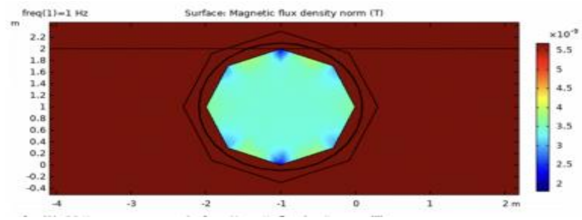


free from perturbing
magnetic stray fields, interaction with walls
and ambient gas particles

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

NNBAR Experiment

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



COMSOL

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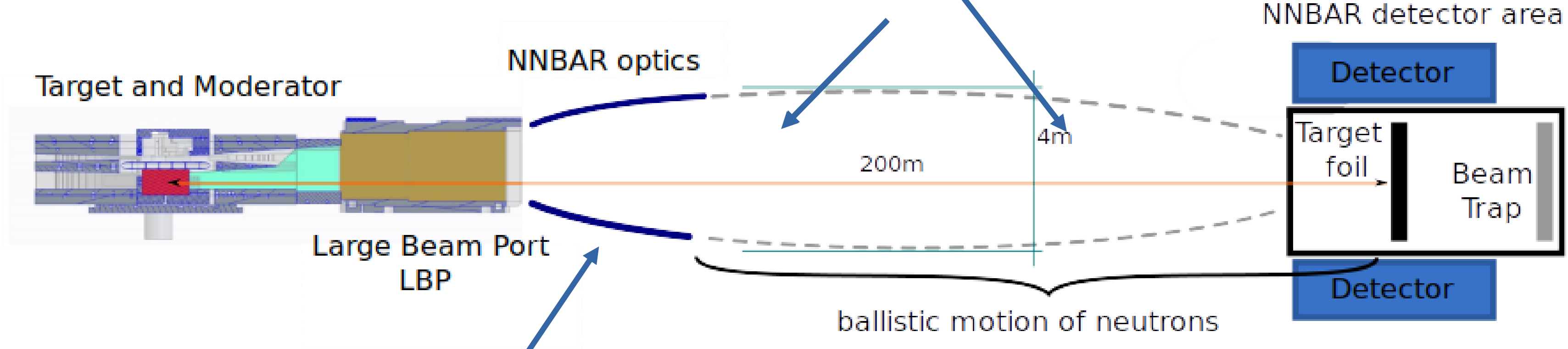

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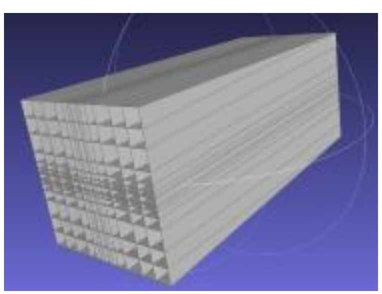
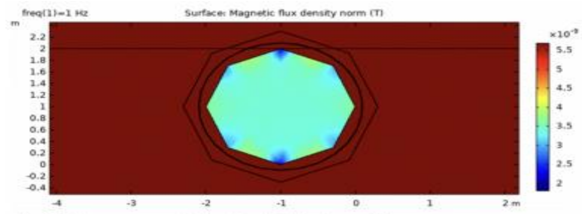


Eg double planar reflector

NNBAR Experiment

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



COMSOL

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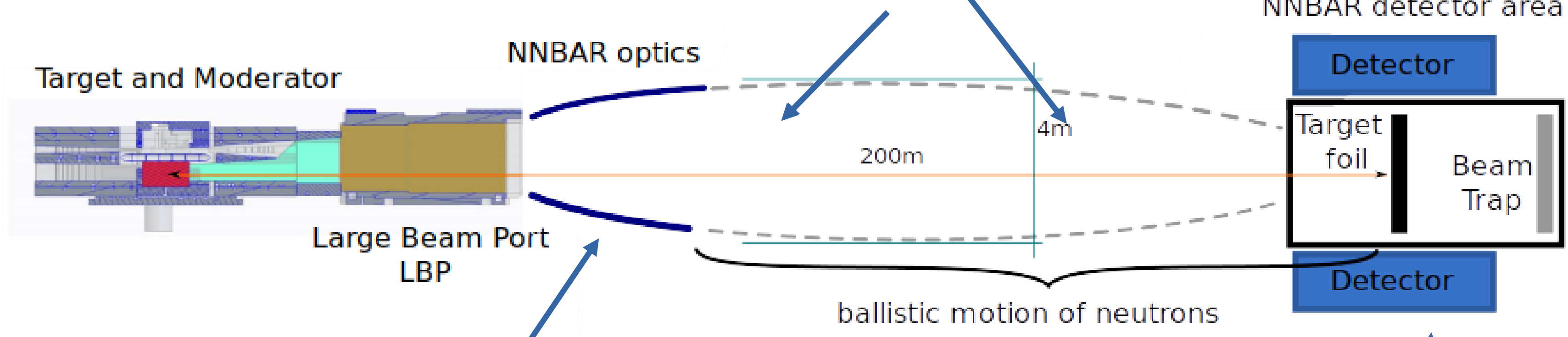

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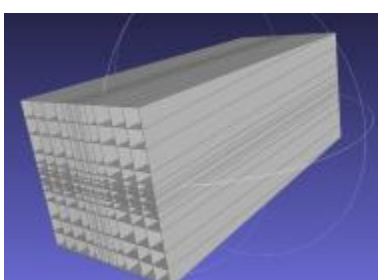
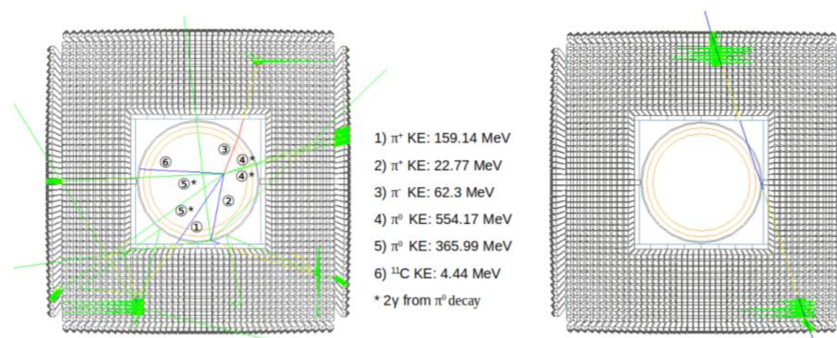
collect large solid angle of emitted neutrons and re-focus to detector area

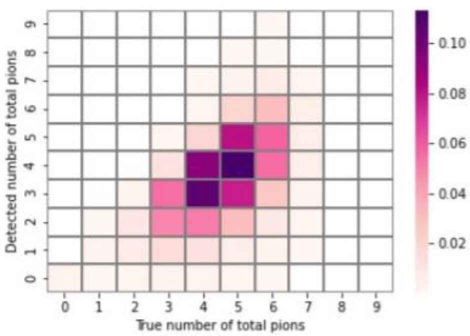


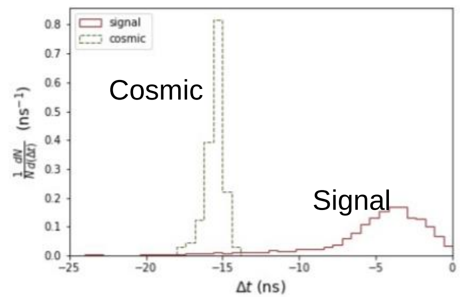
Eg double planar reflector

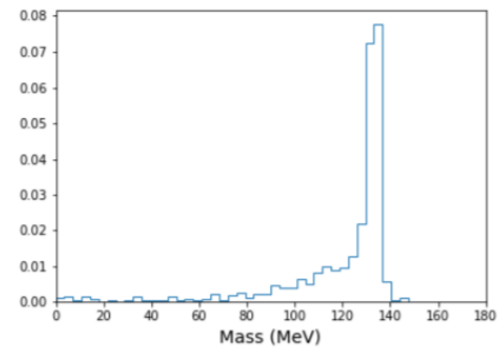


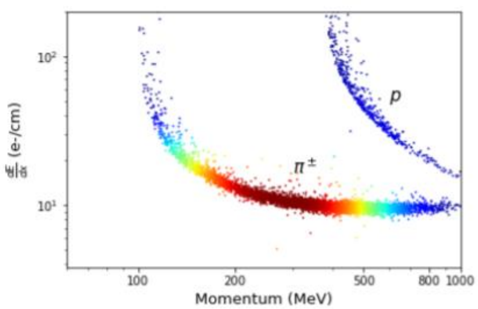
TPC + scintillators and lead-glass

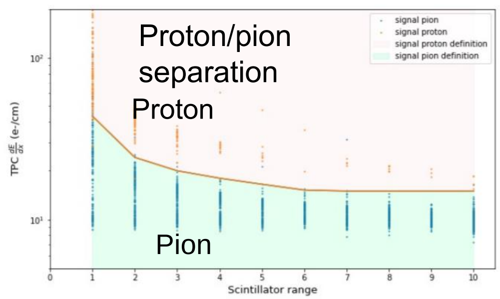
Geant-4 detector simulation

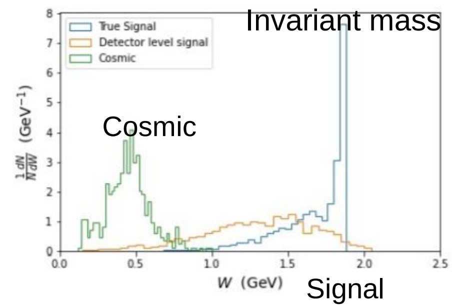












A Computing and Detector Simulation Framework for the HIBEAM/NNBAR Experimental Program at the ESS

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 [illegible]

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

symmetry

Article

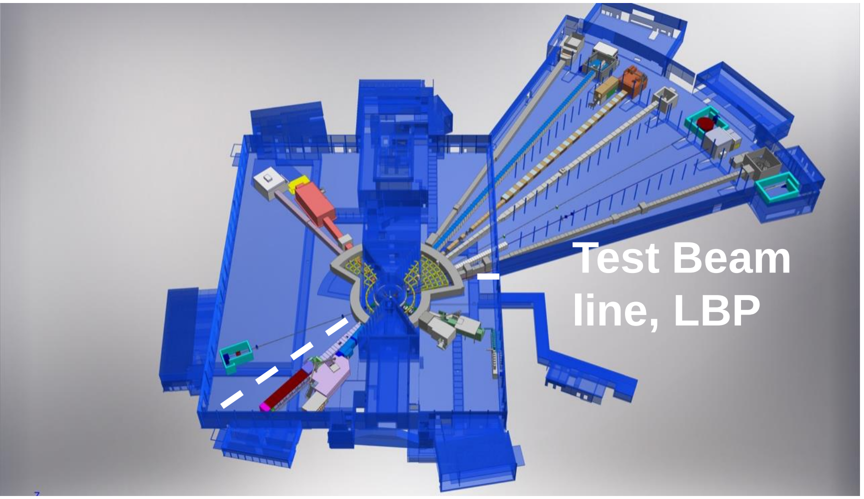
Status of the Design of an Annihilation Detector to Observe Neutron-Antineutron Conversions at the European Spallation Source

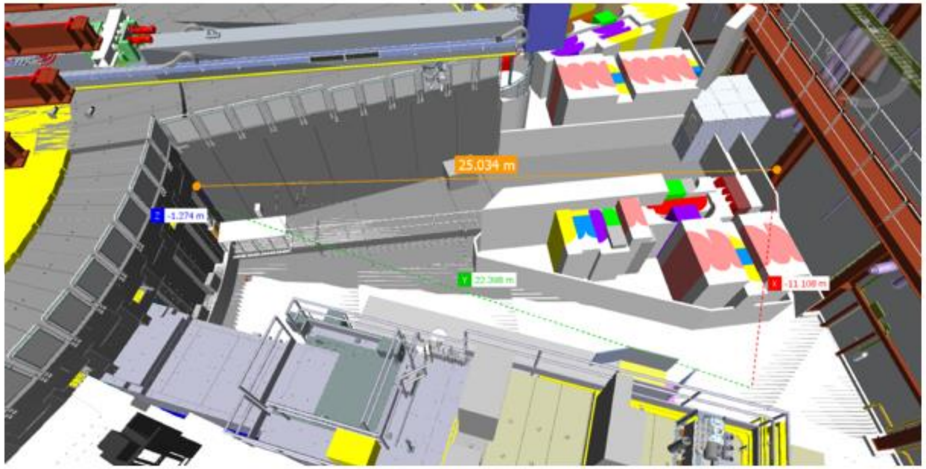
Sze-Chun Yiu [1,*], Bernhard Meirose [1,2,*], Joshua Barrow [3,4], Christian Bohm [1], Gustaaf Brooijmans [5], Katherine Dunne [1], Elena S. Golubeva [6], David Milstead [1], André Nepomuceno [7], Anders Oskarsson [2], Valentina Santoro [2,8] and Samuel Silverstein [1]

Symmetry 14 (2022) 1, 76

HIBEAM

HIBEAM



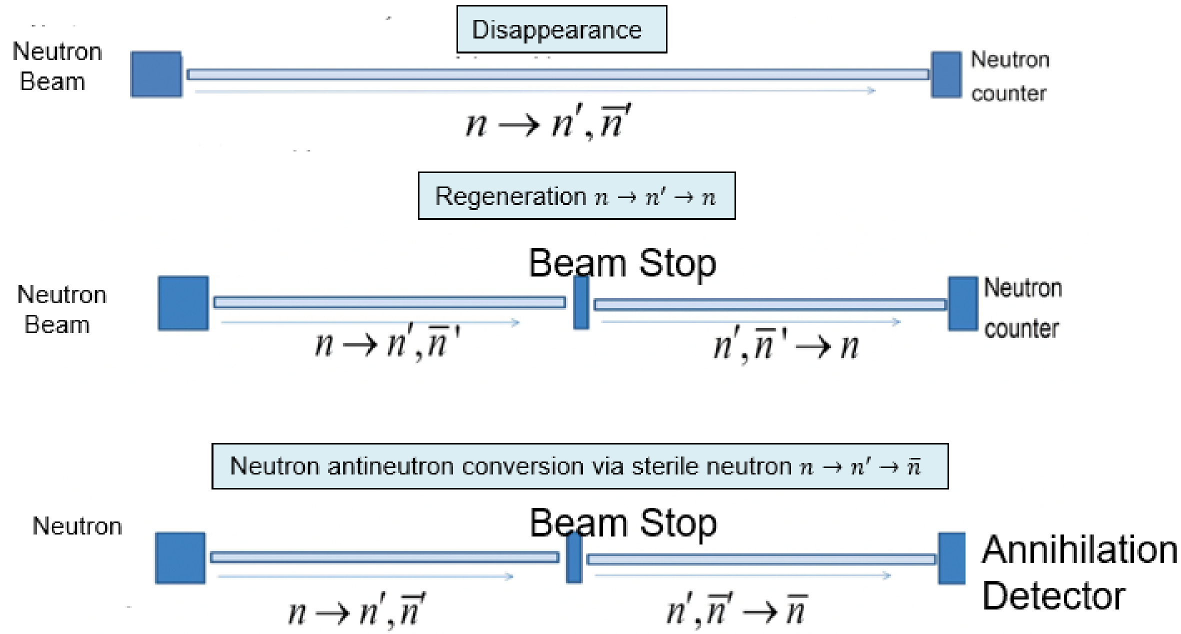


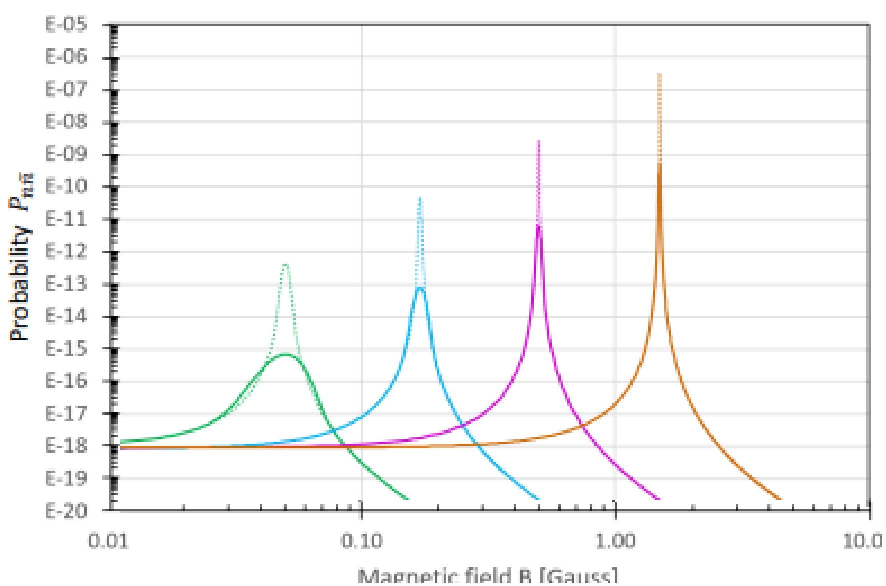
Require a dedicated fundamental physics beamline
Can be a standard beamline
Can be achieved cheaply (~2.5MEuro) with an upgrade of the Test Beamline.
25m of flight path.
Will be used for R&D – prototype and magnetics tests and first search for sterile neutron regeneration.
Grants from Swedish Foundation for Strategic Science

Search for sterile neutron oscillations at HIBEAM

Complementary suite of searches to constrain mixing Hamiltonian

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





Explore disappearance, regeneration and induced $n \to n'$

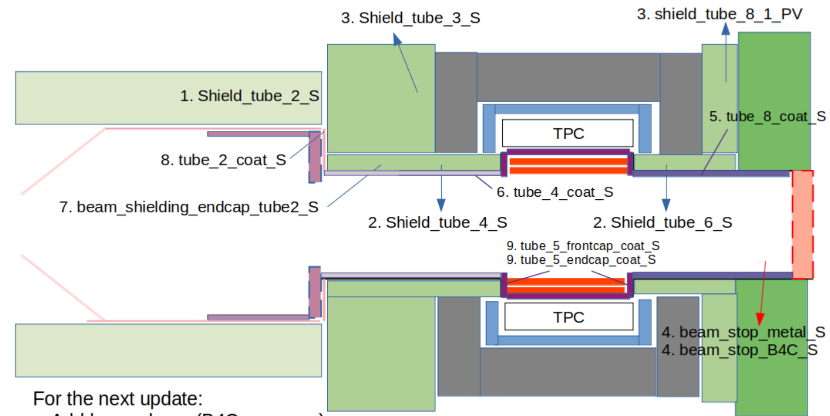
Use custom annihilation detector and WASA CsI (Na) crystal calorimeter for the annihilation detector

Extend sensitivity in oscillation time by x10

Pilot experiment for free $n \longrightarrow \bar{n}$

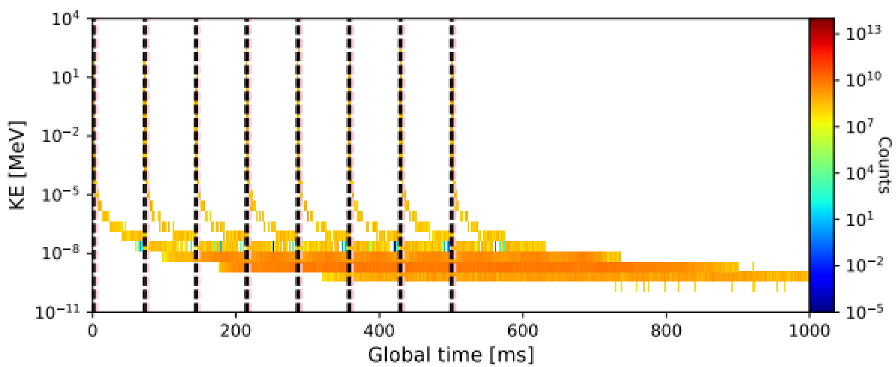
NNBAR to have pile-up background from, eg 10^9 photons/s

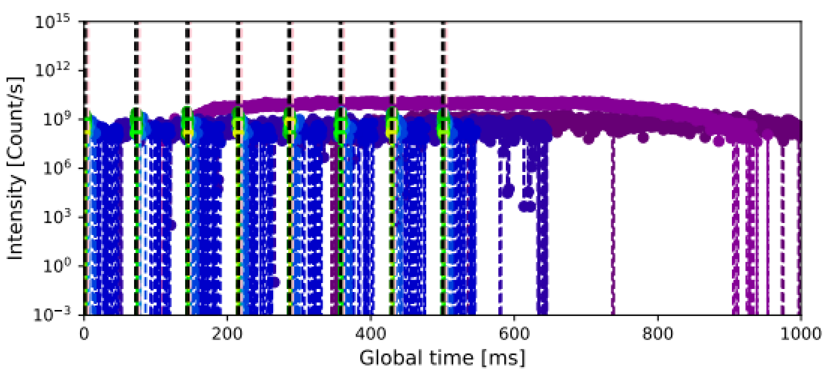
Measurements of spallation backgrounds and benchmark of simulations

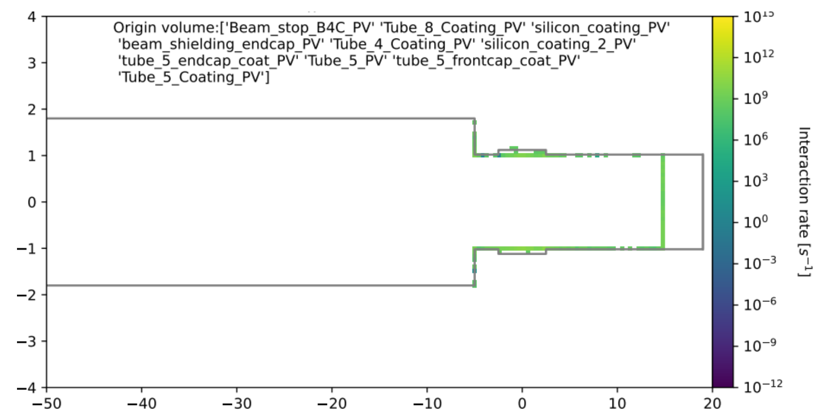


For the next update:
- Add beam dump (B4C + copper)
- Add more shielding indicated by the green region

z



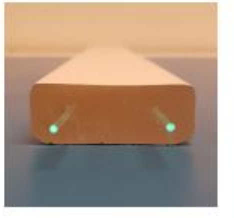


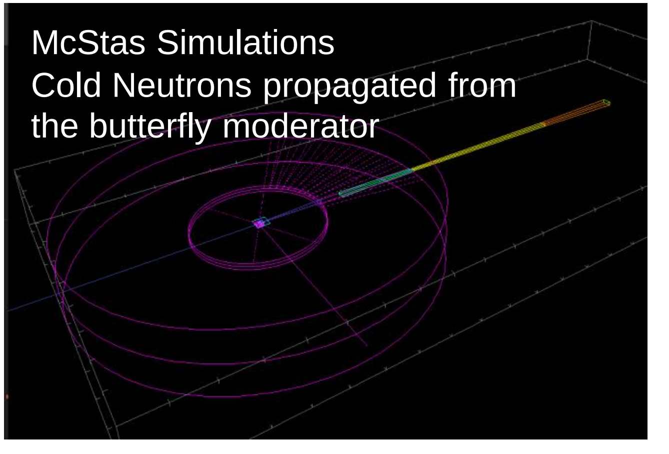


Getting to HIBEAM

Getting to HIBEAM

- VR RFI
- ESS, LU, CTU, UU, SU
- Detector prototype development and testing
    - Time Projection Chamber
    - Hybrid Scintillator - Lead Glass Calorimeter
    - Integrated DAQ design
- Annihilation detector design simulations
- Neutron detector choice
- Beamline design





HIBEAM/NNBAR

- Developed from an Expression of Interest for a $n \rightarrow \bar{n}$ at the ESS (2015). Signatories from 26 institutes , 8 countries.
- Developed into multi-stage HIBEAM/NNBAR
  - Major effort SV,FR,DK,DE,US
  - Co-spokespersons G. Brooijmans (Columbia), D. Milstead (Stockholm)
  - Lead scientist (Y. Kamyshkov, Tennessee)
  - Technical Coordinator (V. Santoro, ESS)
- HIBEAM is supported by the Swedish Research Council (1.4MEuro, project and RFI), Swedish Foundation for Strategic Research (1.5MEuro)
- NNBAR is supported as part of a 3MEuro H2020 for an upgraded ESS with a new lower moderator

New high-sensitivity searches for neutrons converting into antineutrons and/or sterile neutrons at the European Spallation Source

A. Addazi[h,at], K. Anderson[aq], S. Ansell[bm], K. S. Babu[az], J. Barrow[w], D. V. Baxter[d,e,f], P. M. Bentley[ac], Z. Berezhiani[b,l], R. Bevilacqua[ac], R. Biondi[b], C. Bohm[ba], G. Brooijmans[an], L. J. Broussard[aq], B. Dev[ay], C. Crawford[z], A. D. Dolgov[ai,ao], K. Dunne[ba], P Fierlinger[o], M. R. Fitzsimmons[w], A. Fomin[n], M. Frost[aq], S. Gardiner[c], S. Gardner[z], A. Galindo-Uribarri[aq], P. Geltenbort[p], S. Girmohanta[bb], E. Golubeva[ah], G. L. Greene[w], T. Greenshaw[aa], V. Gudkov[k], R. Hall-Wilton[ac], L. Heilbronn[x], J. Herrero-Garcia[be], G. Ichikawa[bf], T. M. Ito[ab], E. Iverson[aq], T. Johansson[bg], L. Jönsson[ad], Y-J. Jwa[an], Y. Kamyshkov[w], K. Kanaki[ac], E. Kearns[g], B. Kerbikov[al,aj,ak], M. Kitaguchi[ap], T. Kittelmann[ac], E. Klinkby[ae], A. Kobakhidze[bl], L. W. Koerner[s], B. Kopeliovich[bi], A. Kozela[y], V. Kudryavtsev[ax], A. Kupsc[bg], Y. Lee[ac], M. Lindroos[ac], J. Makkinje[an], J. I. Marquez[ac], B. Meirose[ba,ad], T. M. Miller[ac], D. Milstead[ba,*], R. N. Mohapatra[j], T. Morishima[ap], G. Muhrer[ac], H. P. Mumm[m], K. Nagamoto[ap], F. Nesti[l], V. V. Nesvizhevsky[p], T. Nilsson[r], A. Oskarsson[ad], E. Paryev[ah], R. W. Pattie, Jr.[t], S. Penttilä[aq], Y. N. Pokotilovski[am], I. Potashnikova[bi], C. Redding[x], J-M. Richard[bj], D. Ries[af], E. Rinaldi[au,bc], N. Rossi[b], A. Ruggles[x], B. Rybolt[u], V. Santoro[ac], U. Sarkar[v], A. Saunders[ab], G. Senjanovic[bd,bn], A. P. Serebrov[n], H. M. Shimizu[ap], R. Shrock[bb], S. Silverstein[ba], D. Silvermyr[ad], W. M. Snow[d,e,f], A. Takibayev[ac], I. Tkachev[ah], L. Townsend[x], A. Tureanu[q], L. Varriano[i], A. Vainshtein[ag,aw], J. de Vries[a,bh], R. Woracek[ac], Y. Yamagata[bk], A. R. Young[as], L. Zanini[ac], Z. Zhang[ar], O. Zimmer[p]

[a]Amherst Center for Fundamental Interactions, Department of Physics, University of Massachusetts, Amherst, MA, USA
[b]INFN, Laboratori Nazionali del Gran Sasso, 67010 Assergi AQ, Italy
[c]Fermi National Accelerator Laboratory, Batavia, IL 60510-5011, USA
[d]Department of Physics, Indiana University, 727 E. Third St., Bloomington, IN, USA, 47405
[e]Indiana University Center for Exploration of Energy & Matter, Bloomington, IN 47408, USA
[f]Indiana University Quantum Science and Engineering Center, Bloomington, IN 47408, USA
[g]Department of Physics, Boston University, Boston, MA 02215, USA
[h]Center for Theoretical Physics, College of Physics Science and Technology, Sichuan University, 610065 Chengdu, China

- Pre-CDR white paper:*J.Phys.G* 48 (2021) 7, 070501

See also:

- *JINST* 17 (2022) 10, P10046 (Arxiv: 2209.09011, [physics.ins-det))
- Proc AccApp 21 (arXiv: 2204.04051 [physics.ins-det))
- Symmetry 14 (2022) 1,76
- Proc vCHEP2021, *EPJ Web Conf.* 251 (2021) 02062, Arxiv: 2106.15898 [physics.ins-det])

Summary

- HIBEAM/NNBAR
  - Rare opportunities to improve sensitivity by three orders of magnitude on a global symmetry and address dark matter and baryogenesis
  - Fits well with a 2MW ESS
  - R&D underway for CDRs
  - Program of work leading up to ESS operations
  - Fits well in the particle physics landscape and strategy

Update to the Strategy for European Particle Physics

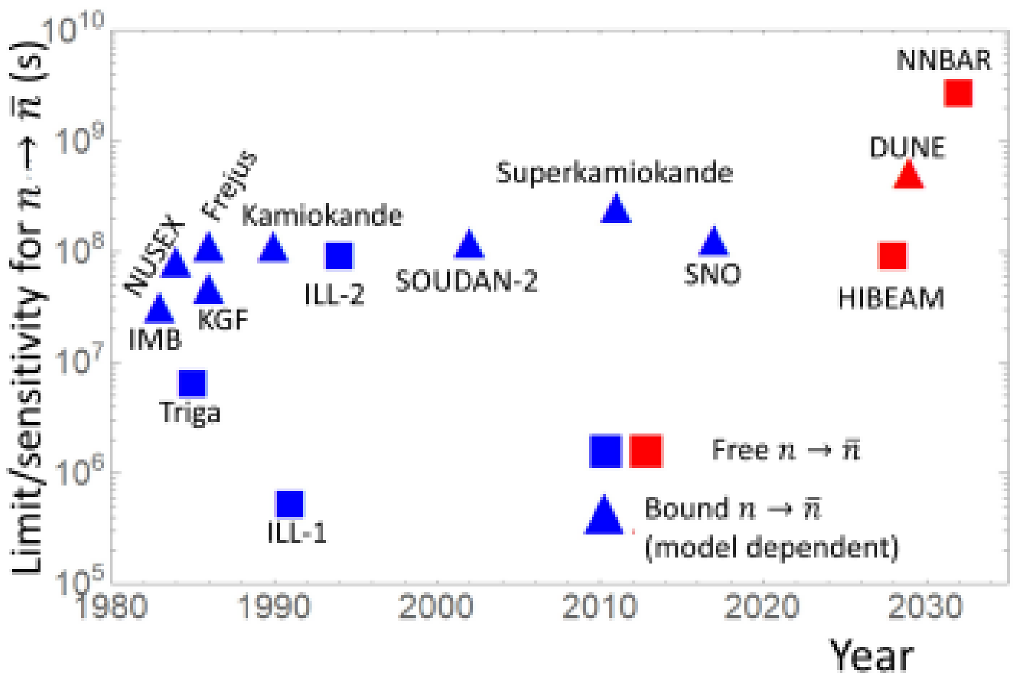
"Essential activities"

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.***

Bonus slides

Ongoing and planned activities

- Annihilation detector prototypes
- Further developments of optics, magnetics, and moderator designs
- Background campaign
  - Shielding designs using Comblayer
  - High energy spallation backgrounds, Cosmics, Gamma bg from activation, delayed beta decays, skyshine ….
  - Zero bg experiment at the ILL (1990’s)
  - Aim to reproduce this.



An experimentalist’s view

Hypothesis: baryon number is weakly violated. How do we look for it ?

Need processes in which only BNV takes place.

Single nucleon decay searches, eg, $p \rightarrow \pi^0 + e^+$?

$\Rightarrow \ |\Delta B| = 1$, $|\Delta L| = 1$!

Decays without leptons, eg, $p \rightarrow \pi + \pi,$ impossible due to angular momentum conservation.

$|\Delta B| \neq 0$, $\Delta L = 0$ observables restricted by Nature.

$n \rightarrow \bar{n}, n'$ and dinucleon decay searches sensitive to BNV-only.

Free $n \rightarrow \bar{n}, n'$ searches $\Rightarrow$ cleanest experimental and theoretical approach.

Baryon and lepton number violation

- *BN,LN* "accidental" SM symmetries at perturbative level
  - *BNV, LNV* in SM non-perturbatively (eg instantons)
  - *B-L* is conserved, not *B*, *L* separately.
- *BNV* needed for baryogenesis (Sakharov condition)
- *BNV,LNV* generic features of SM extensions (eg SUSY,extra dimensions)
- Need to explore the possible selection rules:

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

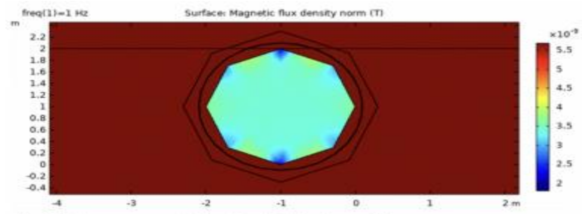
$$\Delta B = 0 \ , \ \Delta L \neq 0, \ \Delta\left[B - L\right] \neq 0$$

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

.....

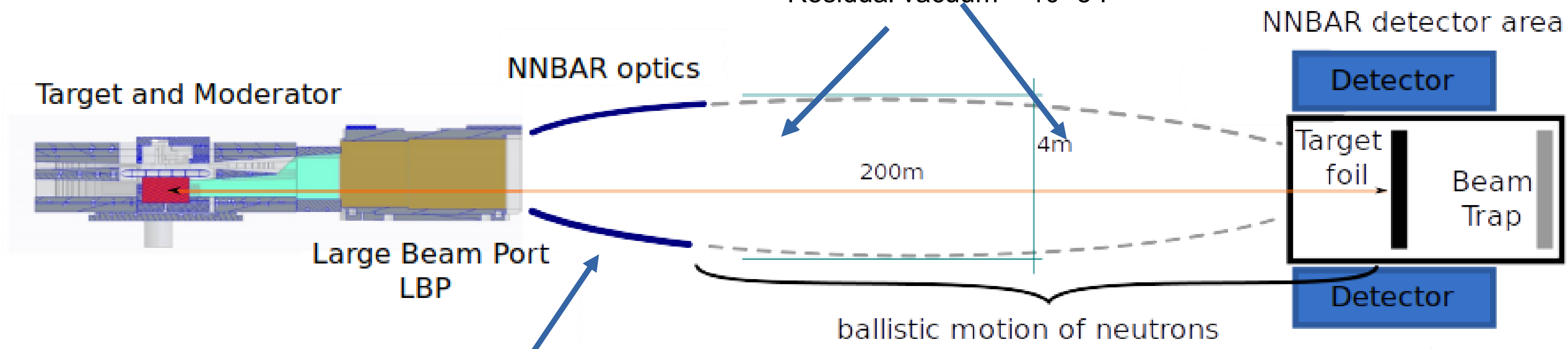
NNBAR Experiment

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



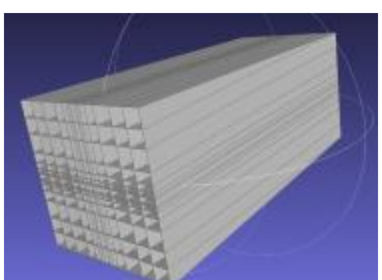
COMSOL

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

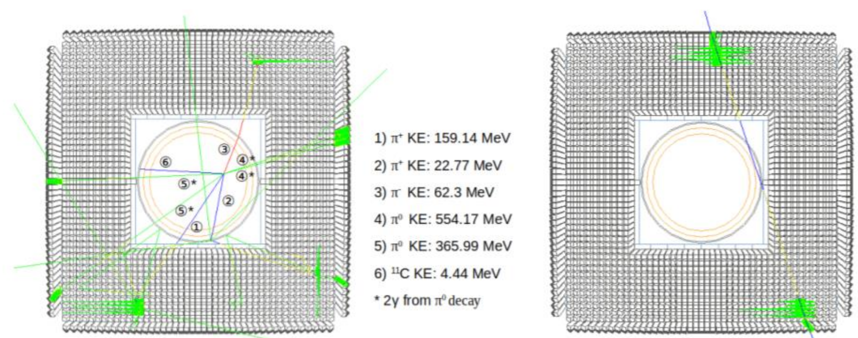


free from perturbing
magnetic stray fields, interaction with walls
and ambient gas particles

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



Eg double planar reflector

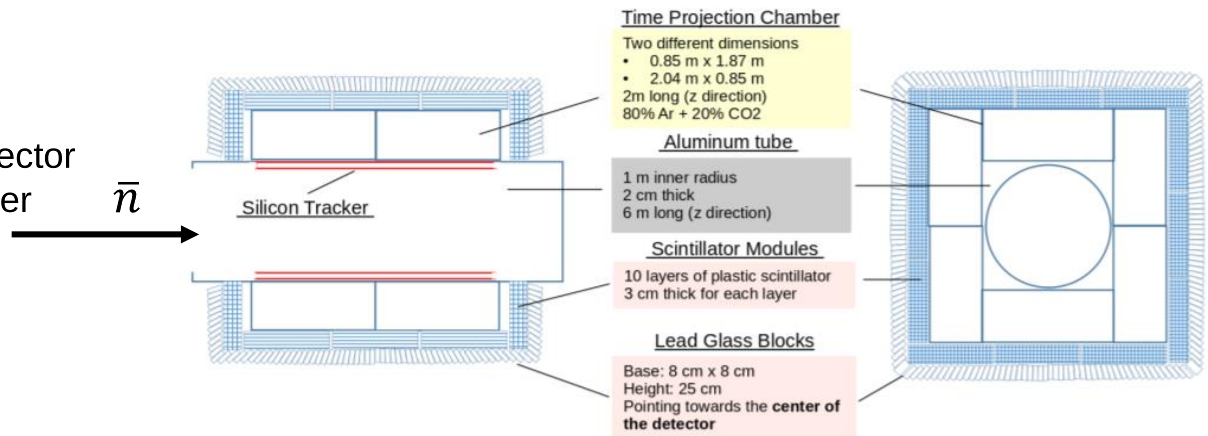


TPC + scintillators and lead-glass

Annihilation detector

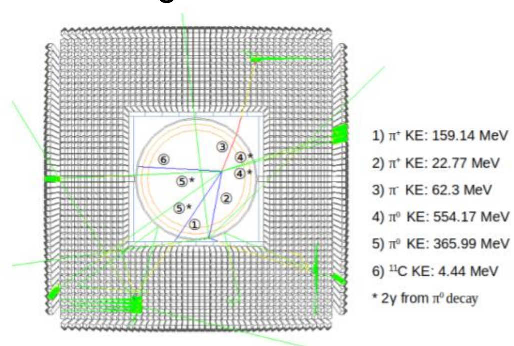
Signal: 1-2 GeV c.o.m. energy , 4-7 pions

- Baseline detector
  - Silicon tracker
  - TPC
  - Scintillator range detector
  - Lead-glass calorimeter

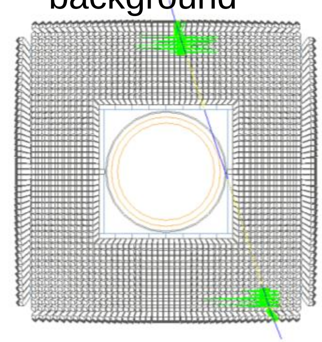


- Requirements
  - Reconstruction of multi-pion final state
  - Invariant mass reconstruction
  - Particle identification
  - Timing sensitivity to reject cosmics and other out-of-time backgrounds

Signal



Cosmic muon background



Prototype under construction: arXiv:2107.02147 [physics.ins-det].

For HIBEAM stage can also borrow existing detector, eg WASA detector