The HIBEAM & NNBAR Experiments

Searching for neutron oscillations and beyond

Dr. Alexander Burgman
Stockholm University

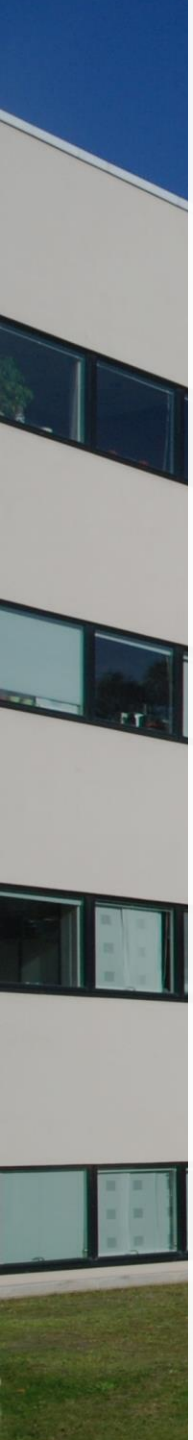
Partikeldagarna 2024

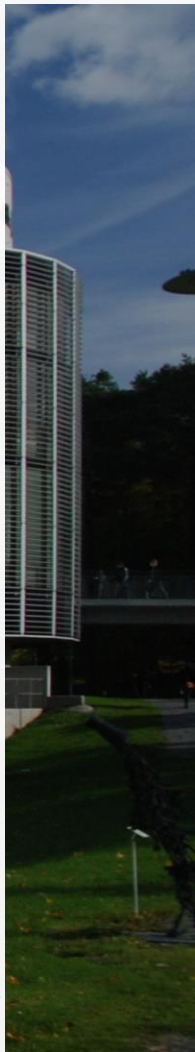
2024-10-22

Outstanding questions

Standard Model (SM) of particle physics does not describe nature completely:

- Matter/antimatter asymmetry
- Dark matter
- Dark energy
- Grand unification (strong+electroweak)
- Gravity





Matter/antimatter asymmetry

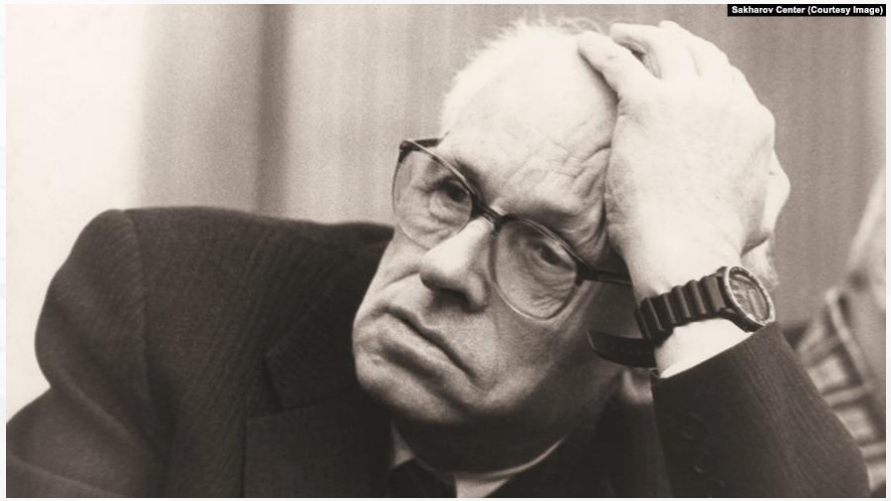
Standard Model (SM) of particle physics does not describe nature completely:

- Matter/antimatter asymmetry
- Dark matter
- Dark energy
- Grand unification (strong+electroweak)
- Gravity

Sakharov conditions:

for matter-/antimatter asymmetry

- Baryon number *B* violation
- *C*- and *CP*-symmetry violation
- Interactions out of thermal equilibrium



Baryon and lepton number violation

Standard Model (SM) of particle physics does not describe nature completely:

- Matter/antimatter asymmetry
- Dark matter
- Dark energy
- Grand unification (strong+electroweak)
- Gravity

Sakharov conditions:
for matter-/antimatter asymmetry

- Baryon number *B* violation
- *C*- and *CP*-symmetry violation
- Interactions out of thermal equilibrium

Baryon/lepton number violations

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

Different processes:

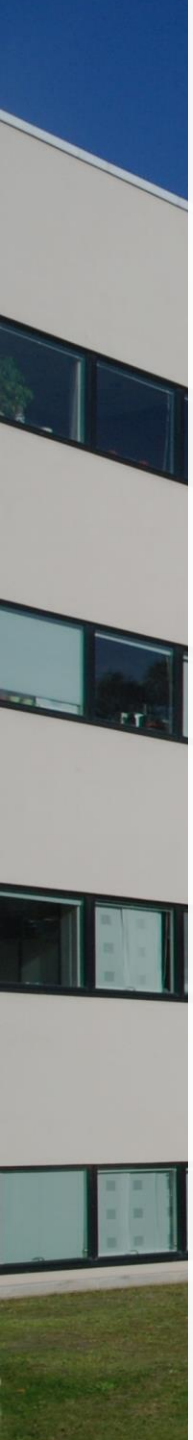
Sphaleron processes

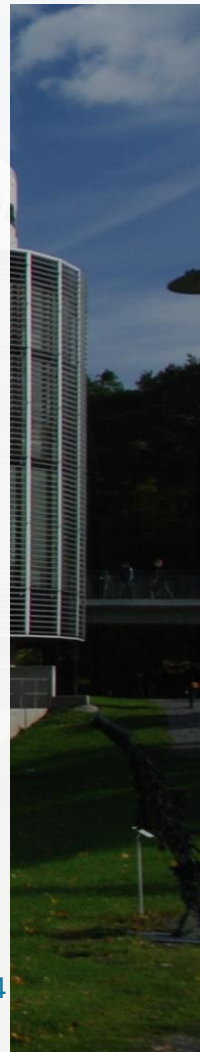
Unification models

Supersymmetry

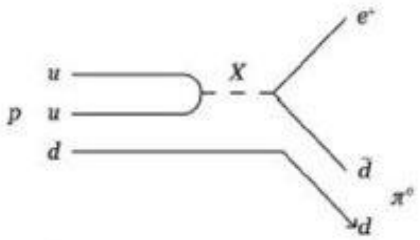
Hidden sector

[...]



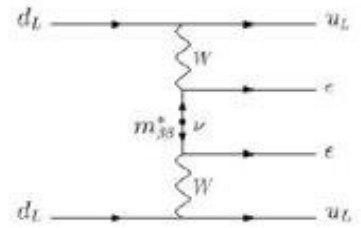


Baryon and lepton number violation



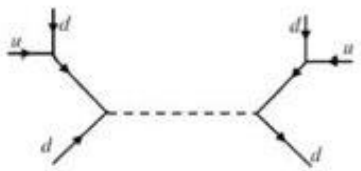
$$p \to e^+ + \pi^0$$
$$\Delta B \neq 0, \Delta L \neq 0$$

$\Delta B{\neq}0 \quad \Delta L{\neq}0 \quad \Delta[B{-}L]{=}0$



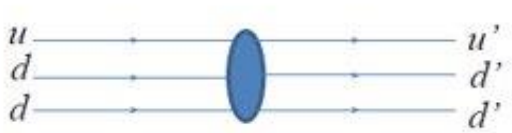
$$0\nu 2\beta$$
$$\Delta B = 0, \Delta L \neq 0$$

$\Delta B{=}0 \quad \Delta L{\neq}0 \quad \Delta[B{-}L]{\neq}0$



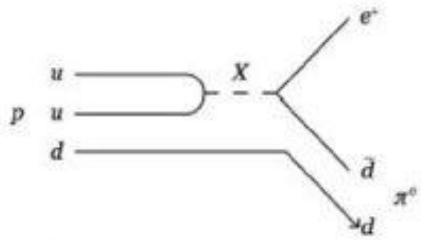
$$n \to \bar{n}$$
$$\Delta B = 2, \Delta L = 0$$

$\Delta B{\neq}0 \quad \Delta L{=}0 \quad \Delta[B{-}L]{\neq}0$

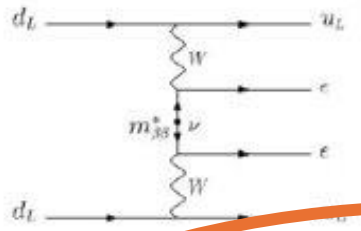


$$n \to n' \text{ (mirror)}$$
$$\Delta B = 1, \Delta L = 0$$

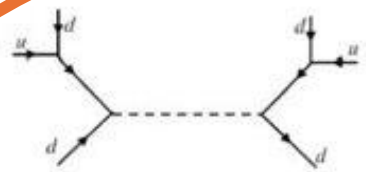
Baryon and lepton number violation



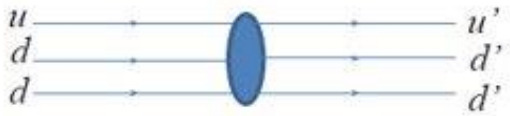
$$p \to e^+ + \pi^0$$
$$\Delta B \neq 0, \Delta L \neq 0$$



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



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



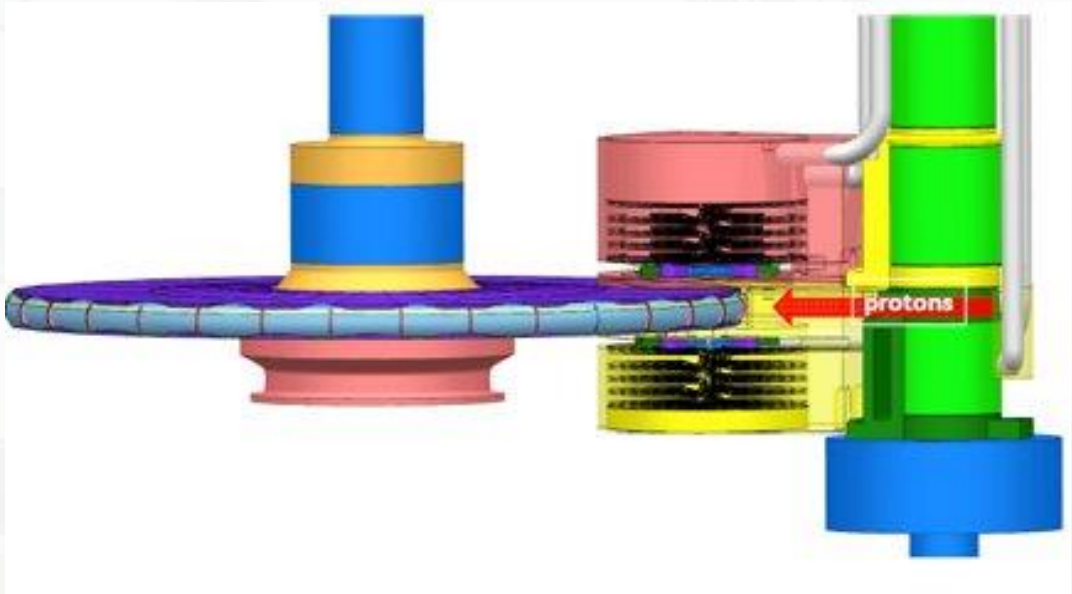
$$n \to n' \text{ (mirror)}$$
$$\Delta B = 1, \Delta L = 0$$

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

few searches: last free neutron/antineutron in 1990s

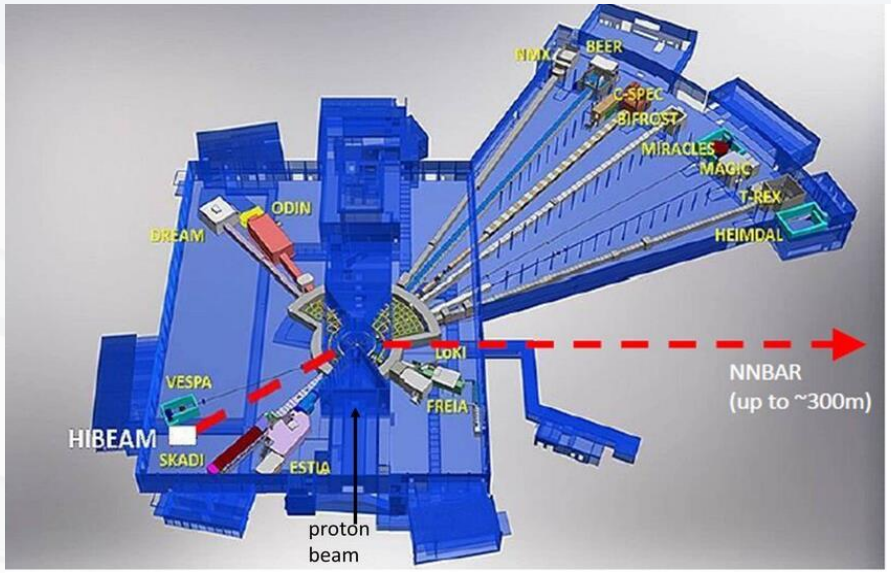
The European Spallation Source (ESS)

- Multi-disciplinary research centre
  - The world's highest intensity source of spallation neutrons
- 17 European nations participating
- Lund, Sweden
  Hosts: Sweden, Denmark
- Start operations in 2027/2028.

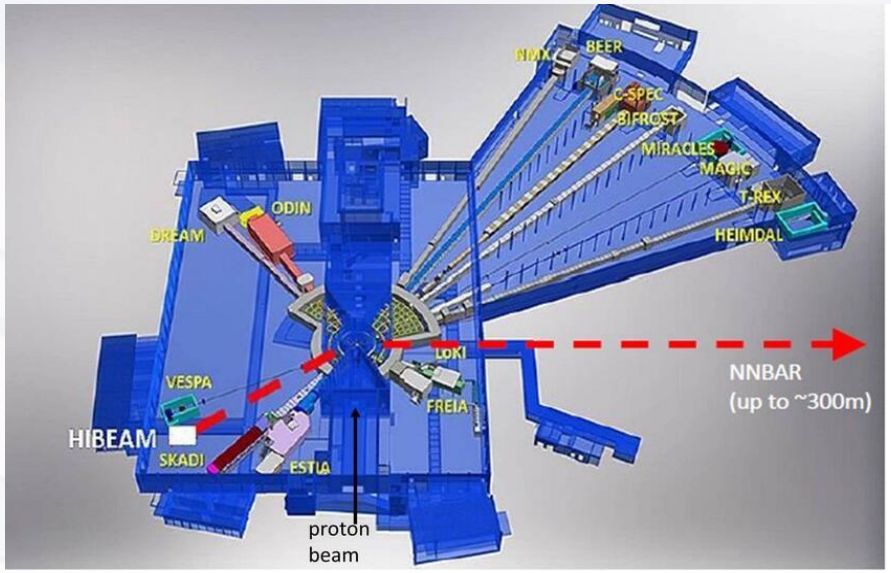


- Spallation neutrons:
  - Nominally 2 GeV protons
    3 ms pulse, 14 Hz, (2;5) MW
  - Rotating tungsten target
- Neutrons cold after interaction with moderators
- 15 beamlines/instruments

Beamlines and the proposed HIBEAM/NNBAR program



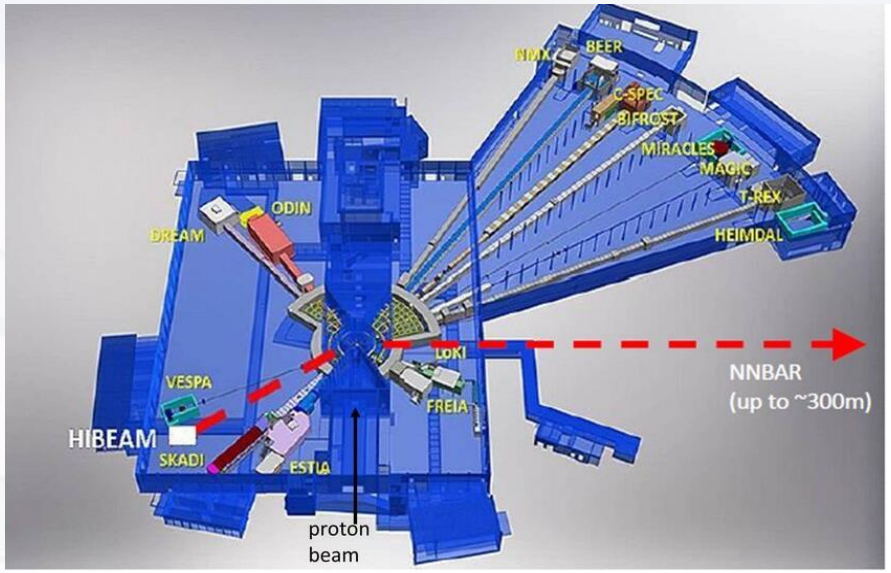
Beamlines and the proposed HIBEAM/NNBAR program



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

TDRs and small scale experiment at ESS

Beamlines and the proposed HIBEAM/NNBAR program



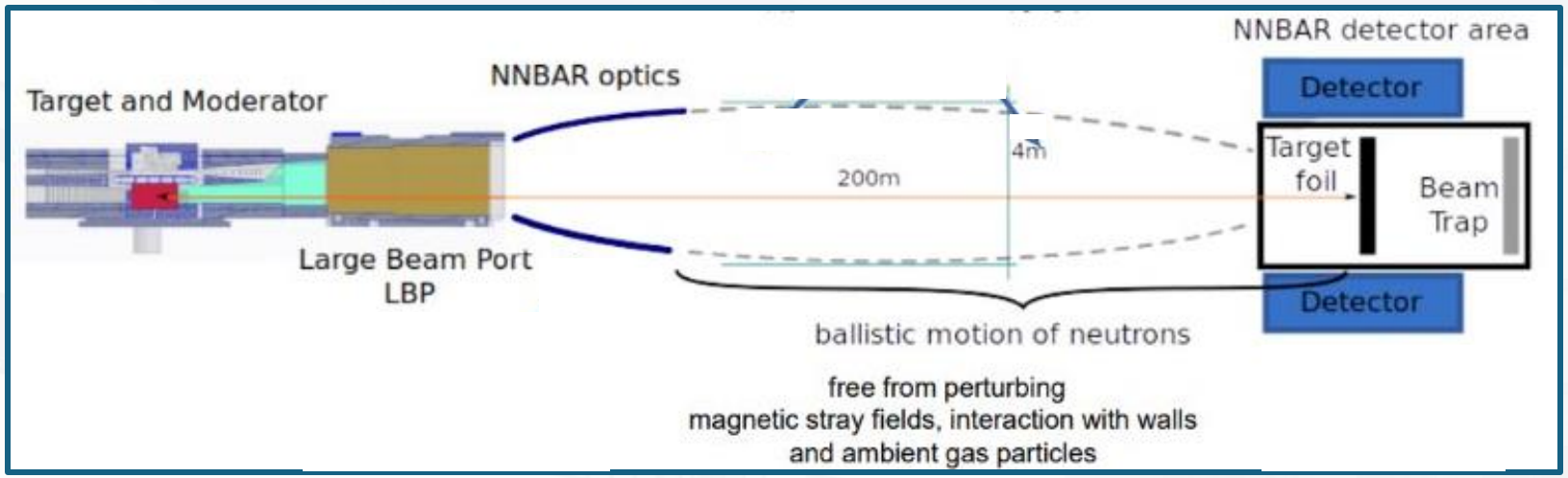
R&D
Annihilation detector prototype
Conceptual design reports for HIBEAM/NNBAR

TDRs and small scale experiment at ESS

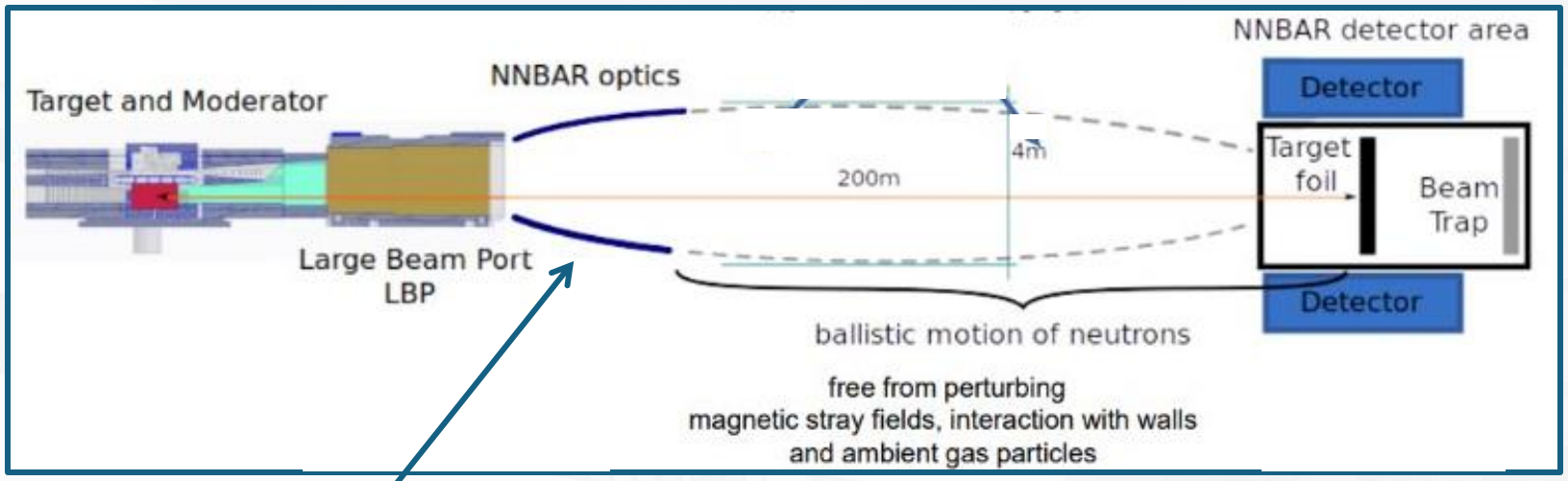
HIBEAM
High precision induced:
$n \to n'$, $n \to \bar{n}$ (x10 improvement)
First search for free $n \to \bar{n}$ at a spallation source

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

The NNBAR experiment

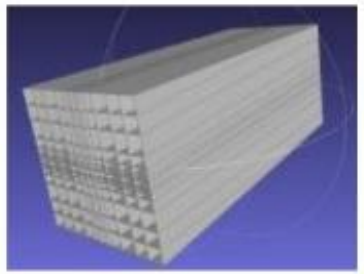


The NNBAR experiment



Reflector Optics

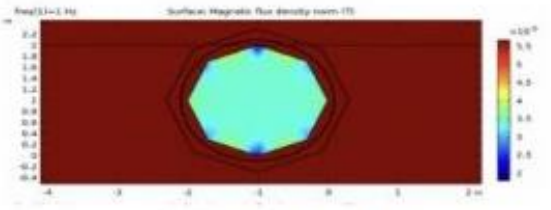
collect large solid angle of emitted neutrons and re-focus to detector area



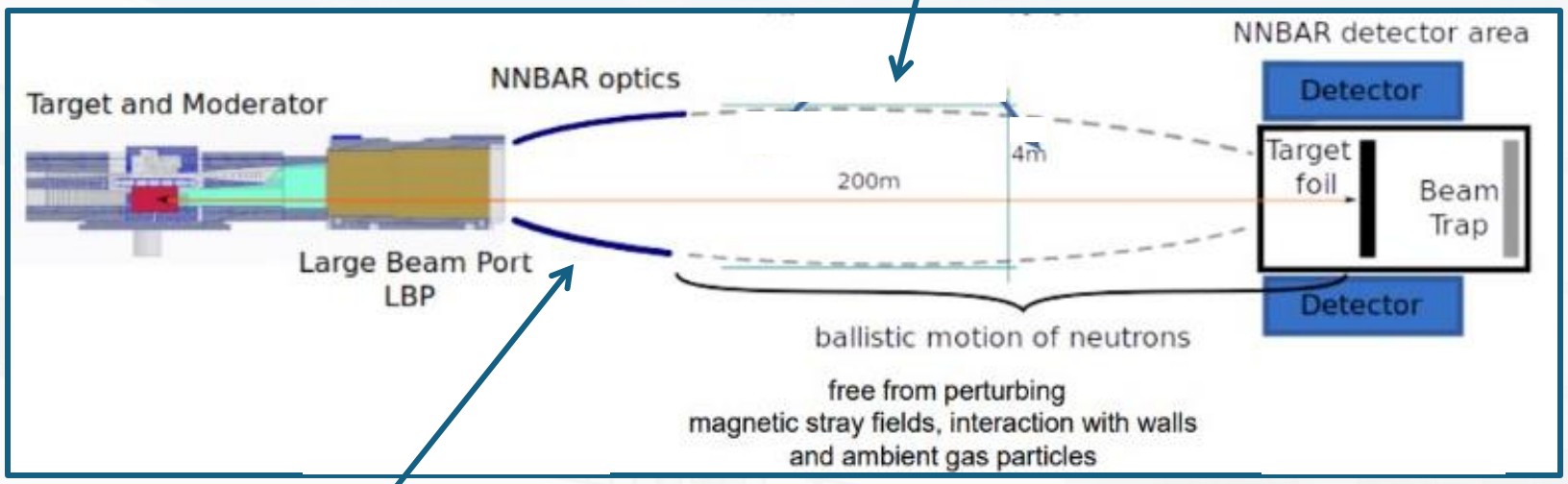
Eg double planar reflector

The NNBAR experiment

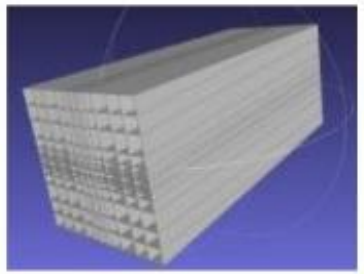
Outer and inner octagon-shaped passive shield of 1-2 mm thick sheets of mumetal.



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



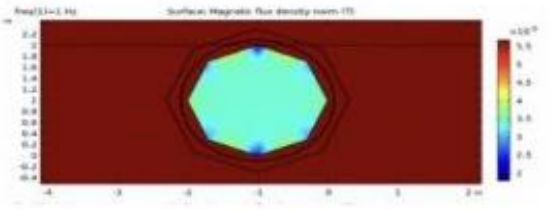
Reflector Optics
collect large solid angle of emitted neutrons and re-focus to detector area



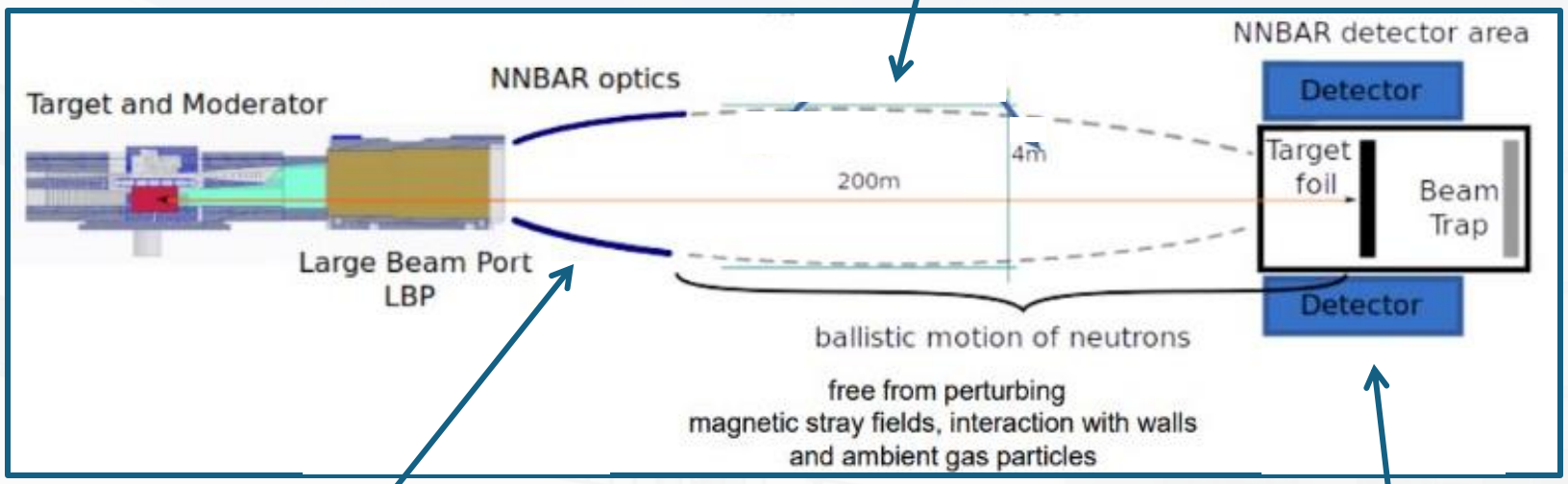
Eg double planar reflector

The NNBAR experiment

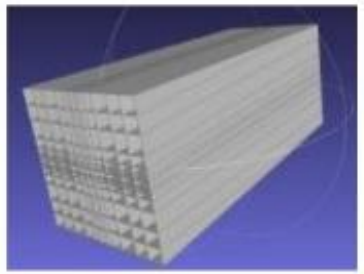
Outer and inner octagon-shaped passive shield of 1-2 mm thick sheets of mumetal.



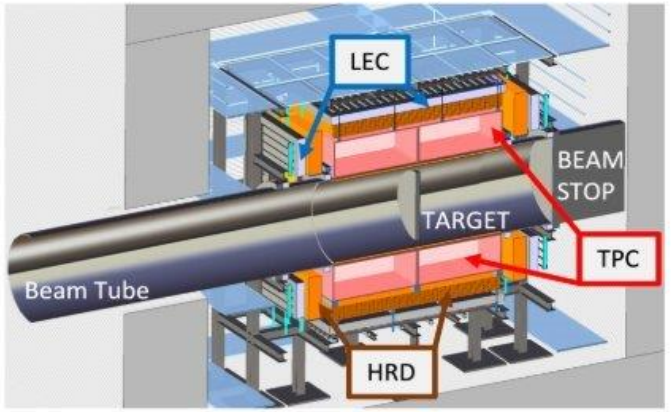
Residual B field <10 nT
Residual vacuum < 10 -5 P



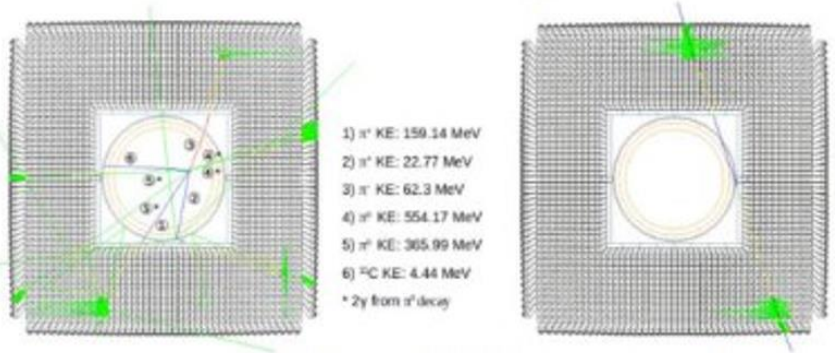
Reflector Optics
collect large solid angle of emitted neutrons and re-focus to detector area



Eg double planar reflector



Anti-neutron annihilation detector

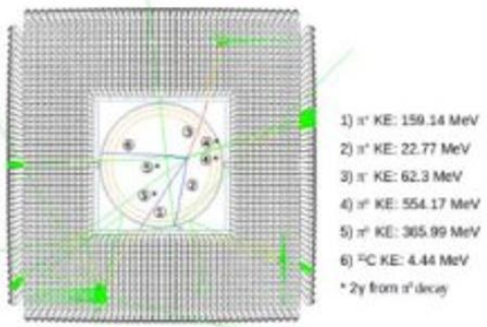


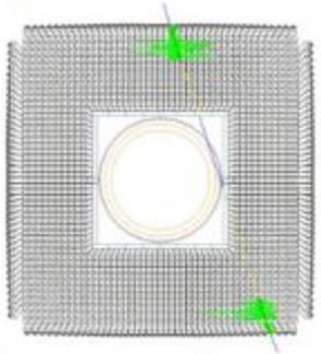
$$\bar{n}N \longrightarrow 5\pi$$

$$\sqrt{s} \sim 1.8 \text{ GeV}$$

TPC + scintillators and lead-glass

Anti-neutron annihilation detector





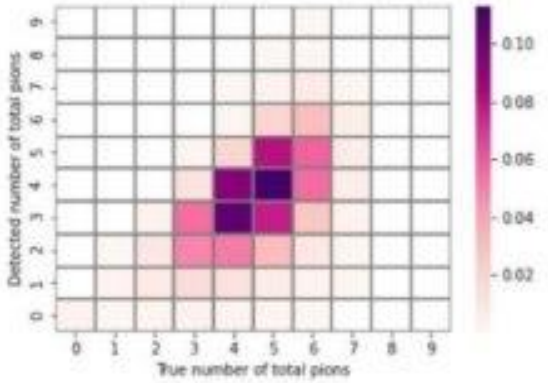
$$\bar{n}N \longrightarrow 5\pi$$

$$\sqrt{s} \sim 1.8\ \text{GeV}$$

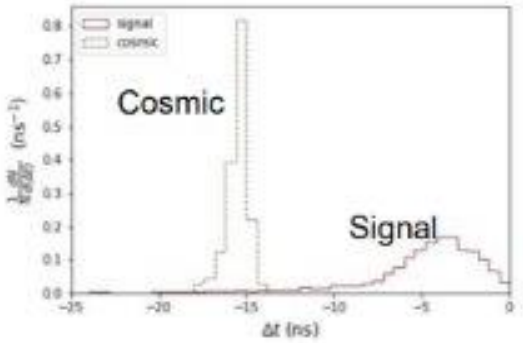

A Computing and Detector Simulation Framework for the HIBEAM/NNBAR Experimental Program at the ESS

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

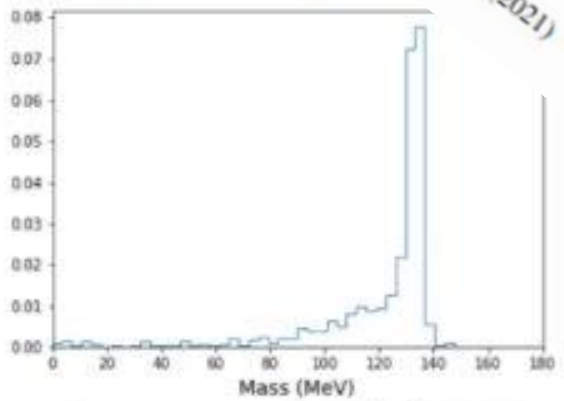
Pion multiplicity

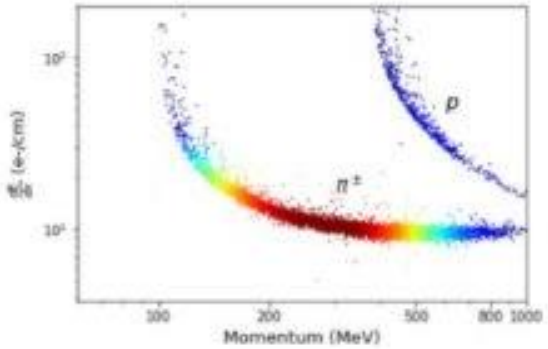


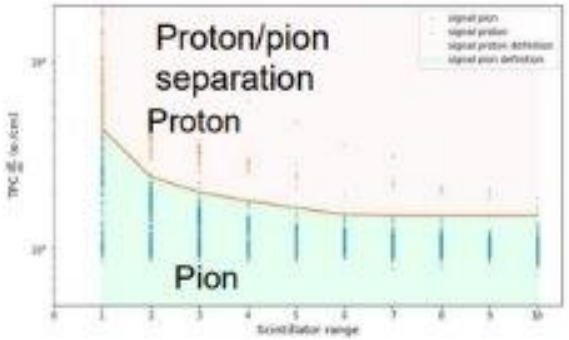
Event timing

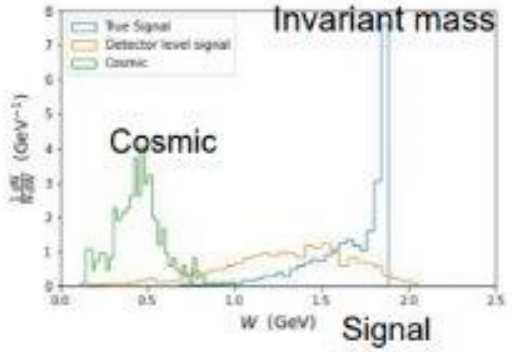


π⁰ mass reconstr.







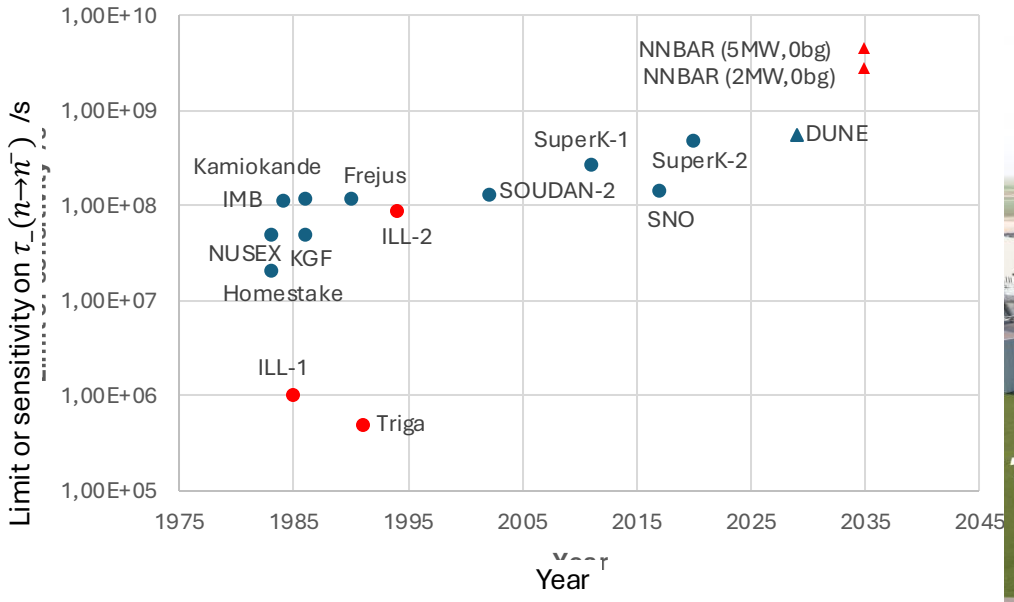


Capability of NNBAR

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

- Zero background experiment
- 1000-fold increase in discovery potential over previous experiments

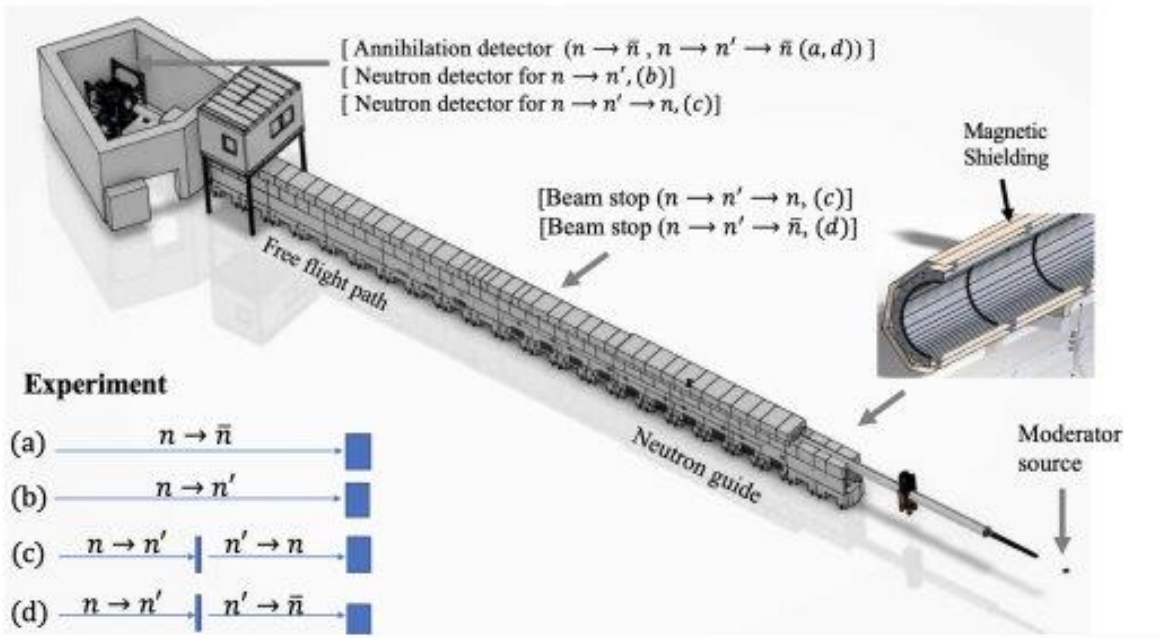
Selection	Signal	Non-muon background	Muon background
Scintillator energy loss $\in [20, 2000]$ MeV	0.89	0.008	0.3
TPC track cut	0.87	2.3×10^{-3}	9.0×10^{-3}
Pion count $\geqslant 1$	0.82	7.8×10^{-9}	5.9×10^{-4}
Invariant mass $W \geqslant 0.5$ GeV	0.8	7.8×10^{-9}	1.5×10^{-4}
Sphericity $\geqslant 0.2$	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	-	-

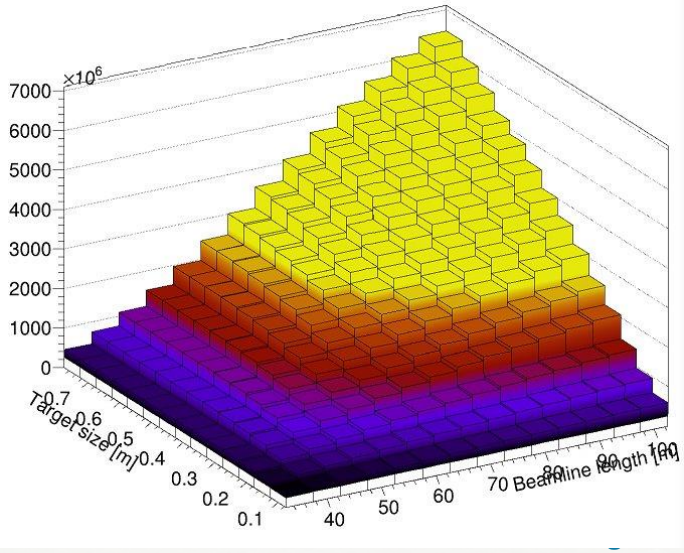


HIBEAM neutron conversion searches

- Bespoke annihilation detector or
- WASA (CsI) crystal calorimeter

Sensitive to all neutron mixings



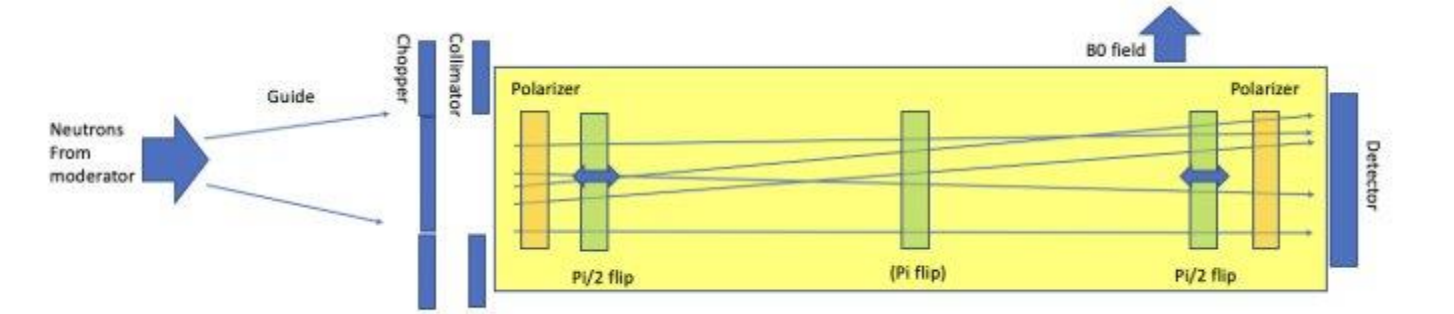


×10 improvement

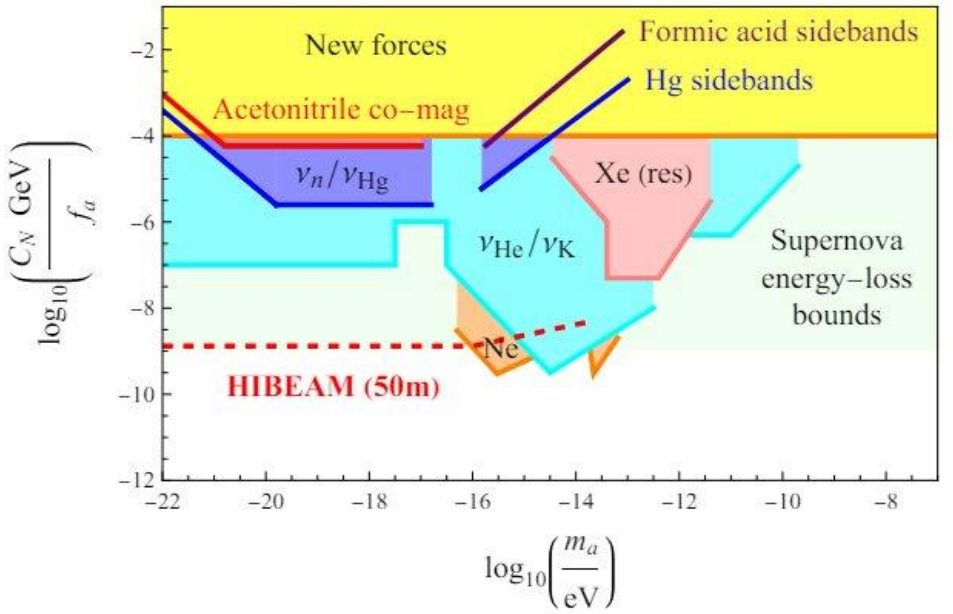
- Neutron to antineutron
- Neutron to sterile neutron

HIBEAM searching for axions

HIBEAM sensitive to axions as a dark matter candidate arXiv:2404.15521



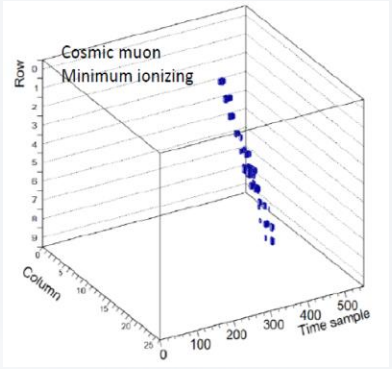
- Ambient axions act as a pseudomagnetic field
- Changes the Larmor frequency (magnetic moment precession)
- Detected through Ramsey interferometry

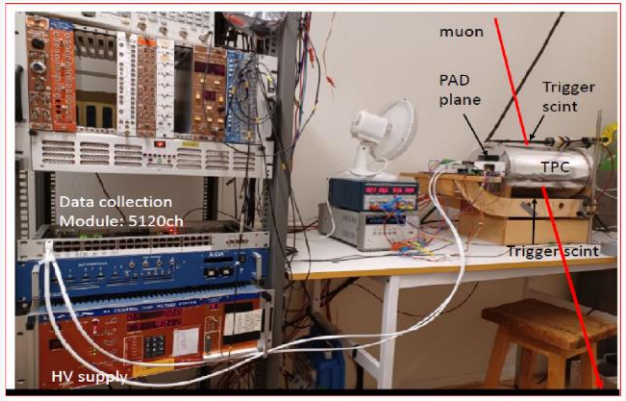


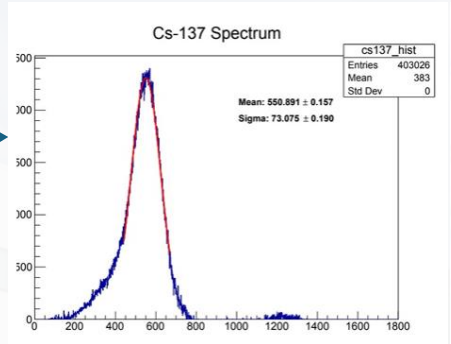
Towards HIBEAM

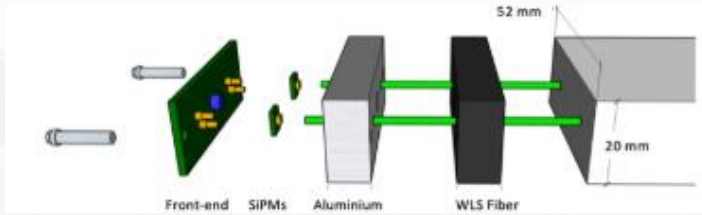
SRC RFI
Stockholm U, Lund U, Chalmers TU, ESS

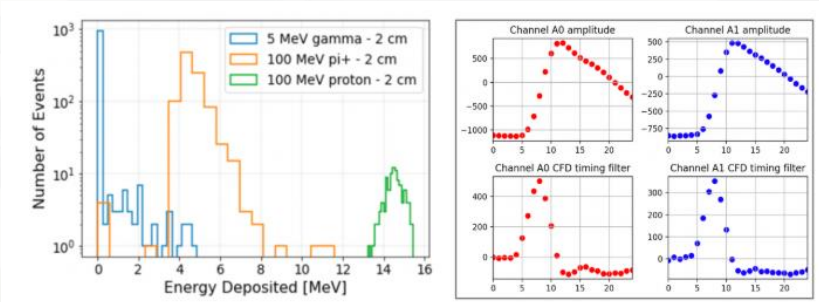
- Prototype development
  - Time projection chamber
  - WASA crystal calorimeter
  - Scintillator/lead-glass calorimeter
- Annihilation detector
- Neutron detector
- Beamline design









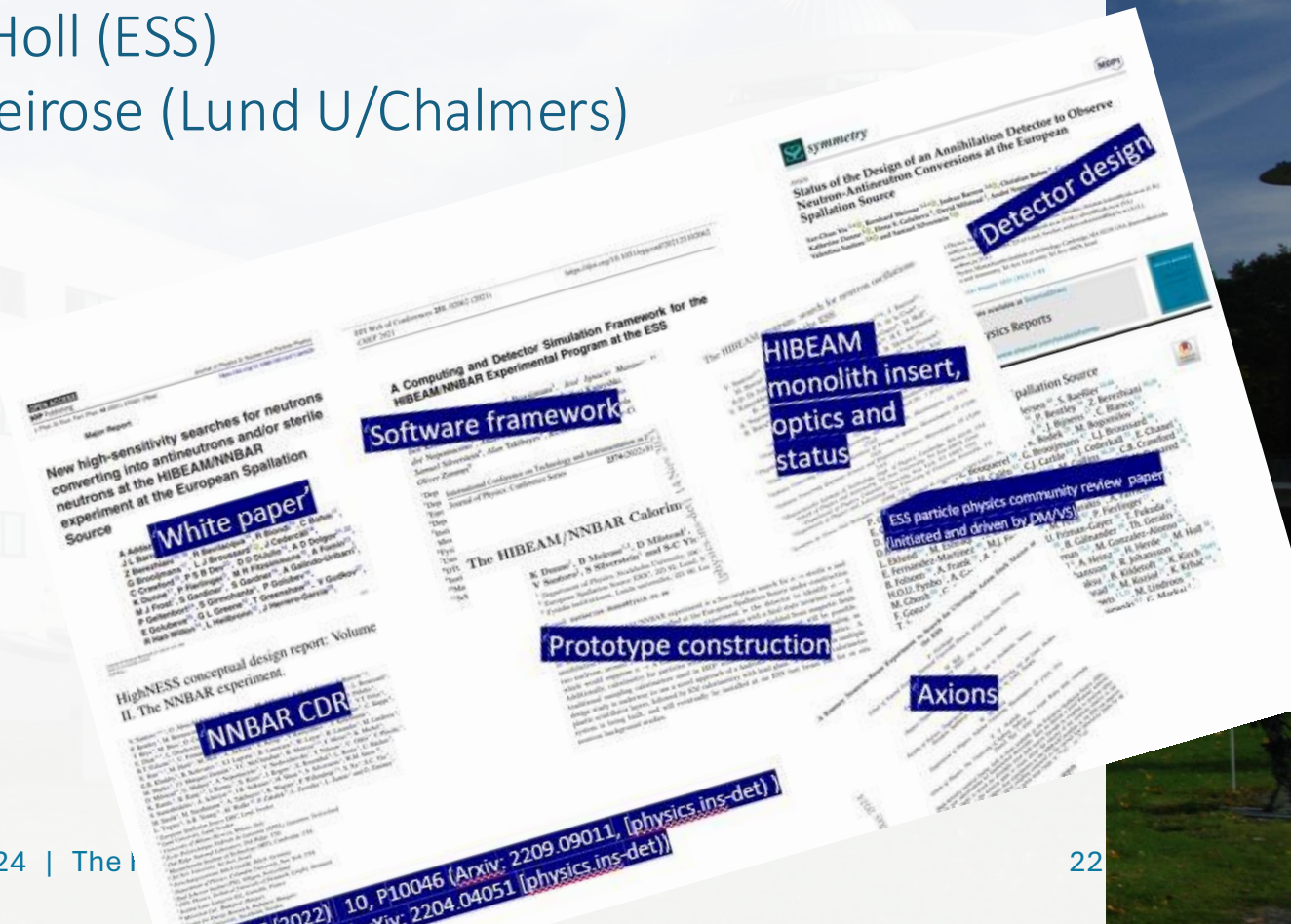


The HIBEAM/NNBAR collaboration

Co-spokespersons: G. Brooijmans (Columbia U),
D. Milstead (Stockholm U)
Lead scientist: Y. Kamyshkov (Tennesee U)
Technical coordinator: V. Santoro (ESS, Lund U)
Prototype coordinator: M. Holl (ESS)
Detector simulation coordinator: B. Meirose (Lund U/Chalmers)

Many active institutes:

- SE: SU, CTU, UU, LU
- SE/DK: ESS
- DE: TUM
- US: Tennessee, Columbia, ORNL
- PL: Krakow
- BR: Rio, Campinas



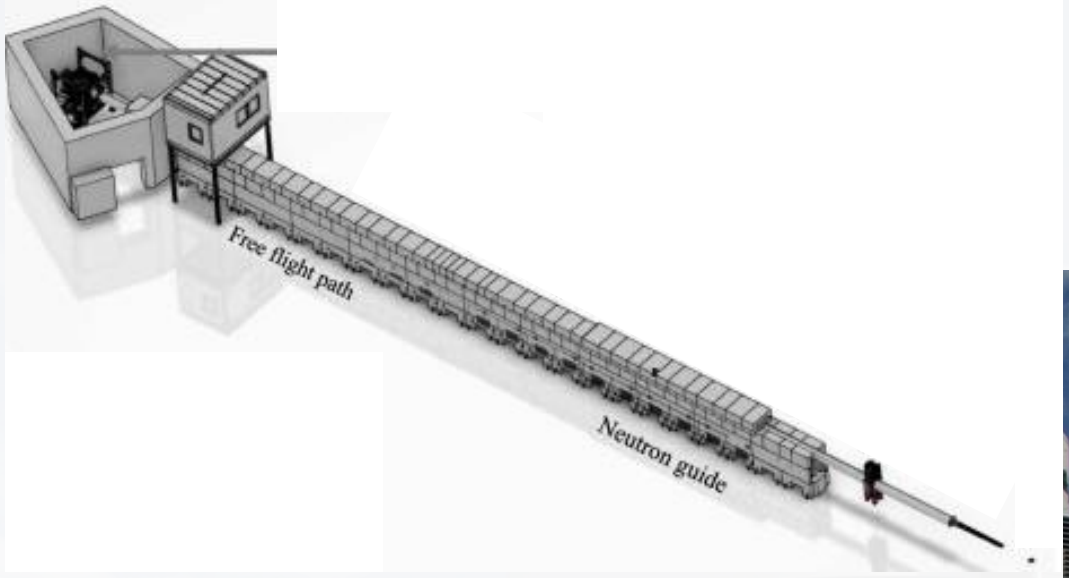
Summary

Neutron oscillations

- Key portal for new physics, rarely explored
- Baryon number violation
  - Baryogenesis

New discovery window at the ESS

- HIBEAM/NNBAR: a proposed multistage program to increase sensitivity by ~1000
  - Prototype development
  - Wide range of applications (neutron/antineutron, neutron/mirror neutron, axions, rare decays etc.)



Thank you

Backup

Backup