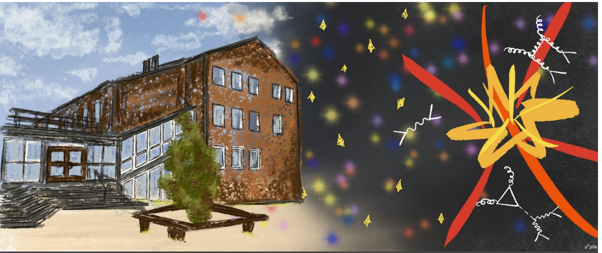
Vertex reconstruction with the HIBEAM TPC

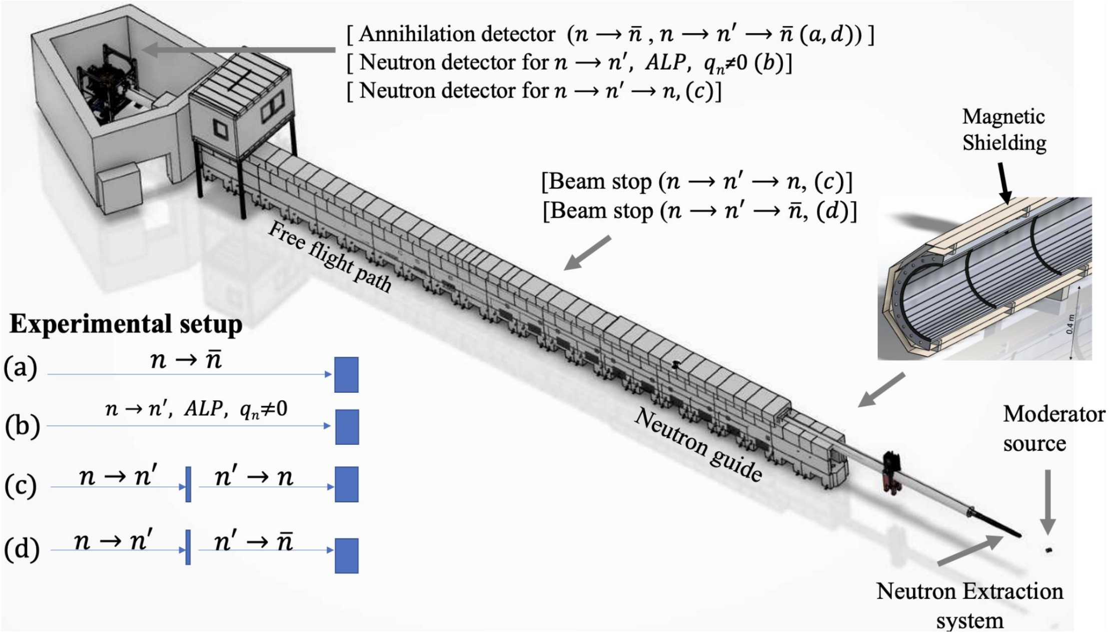
Alexander Burgman (Stockholm U.)
for the FINESSE/NNBAR Collaboration



Partikeldagarna 2026

HIBEAM → FINESSE

- HIBEAM → FINESSE high-flux configuration (Linus' talk this morning)
  - $n \to \bar{n}$ sens. × 10
  - $n \to n'$ $\tau \sim 230$ s
  - axions sens. × 10^2–10^3
  - q_n sens. × 700
  - nEDM underway
  - etc.



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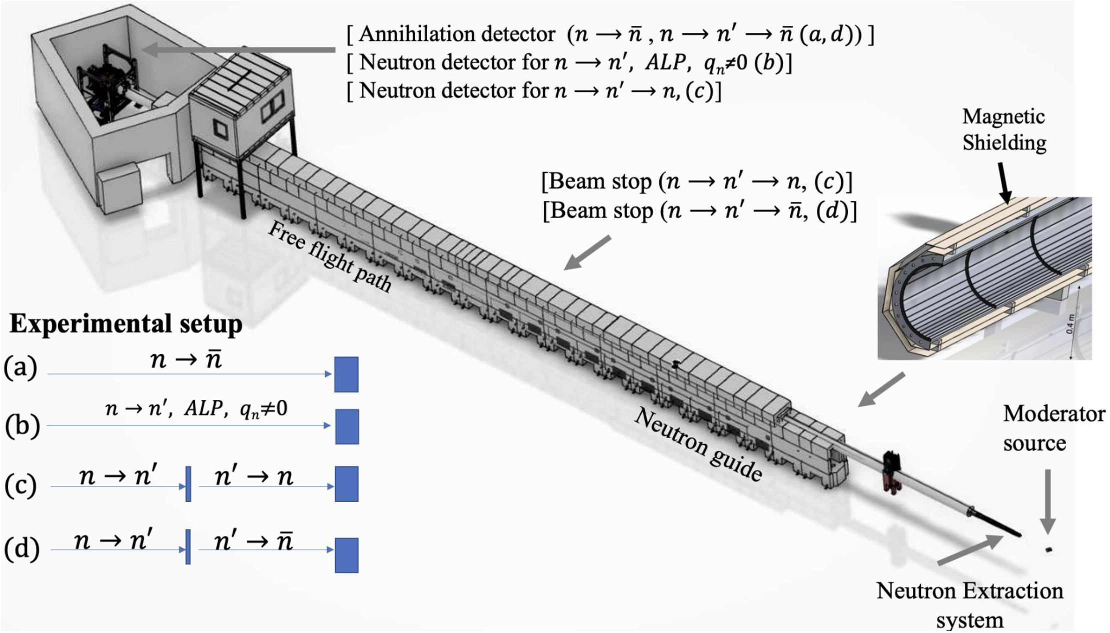
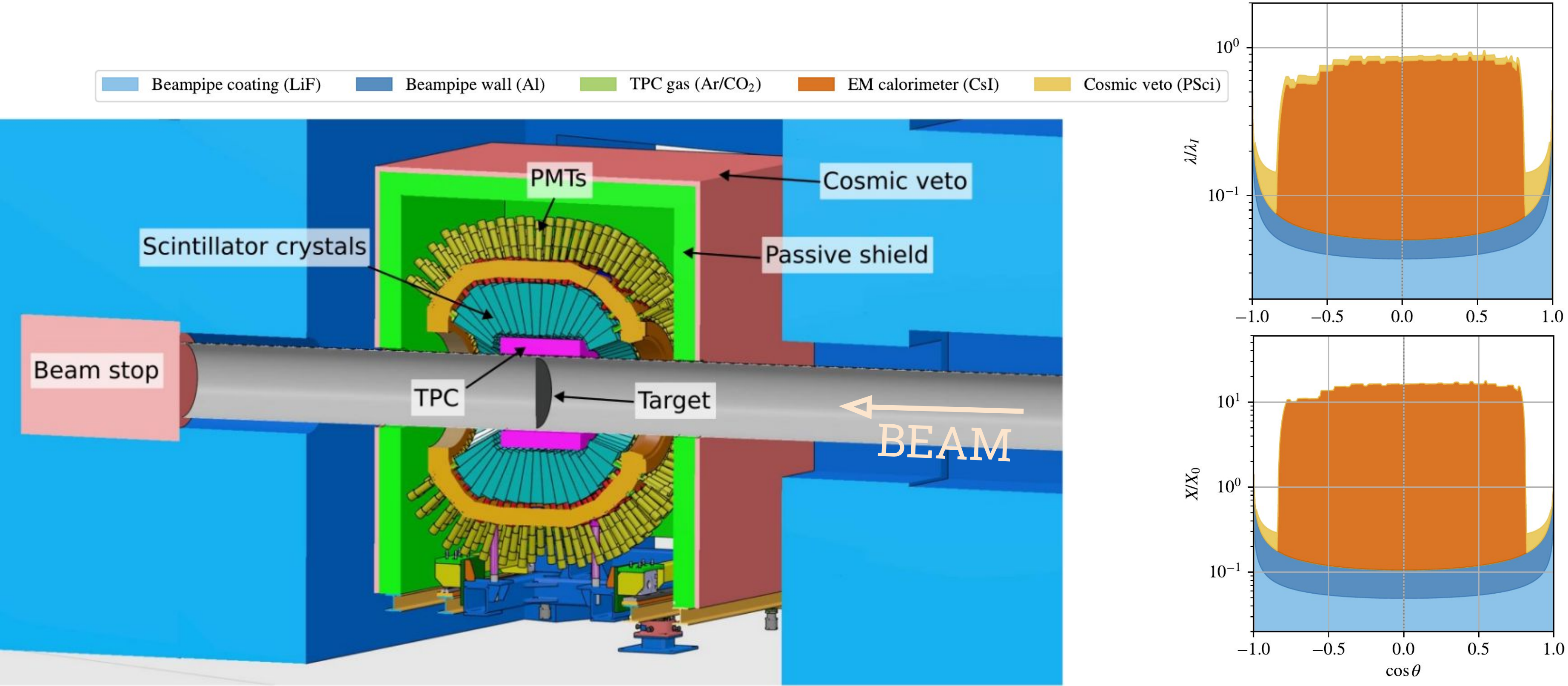
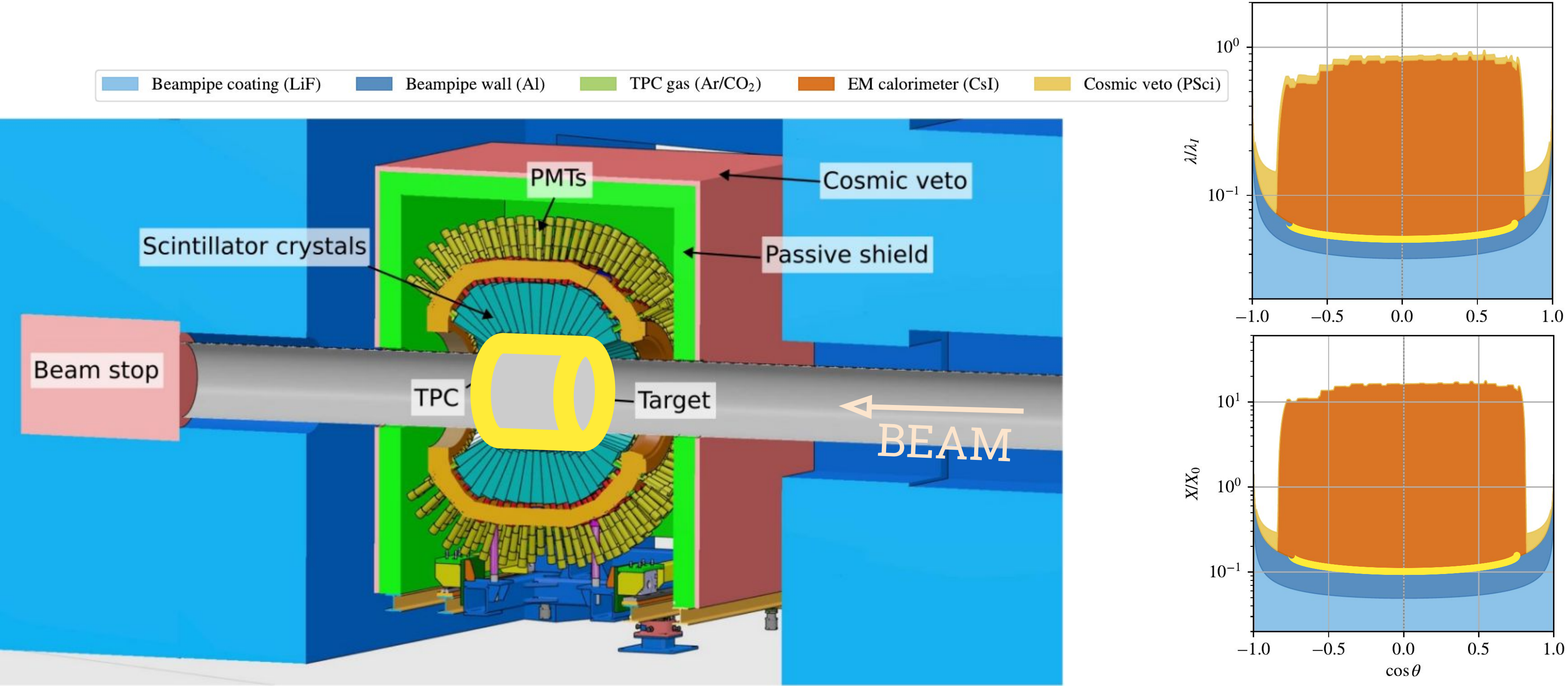


Annihilation detector



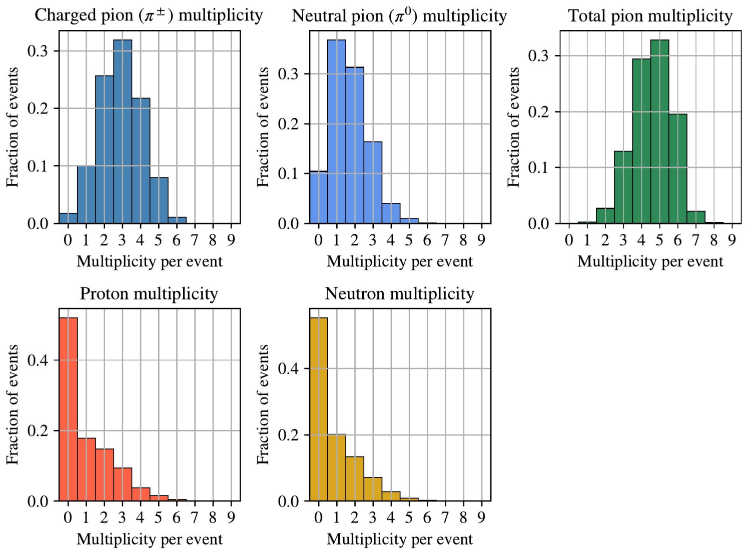
Annihilation detector

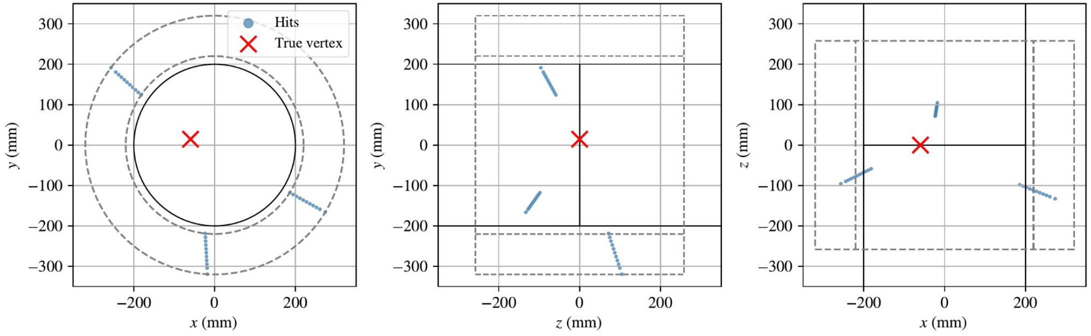


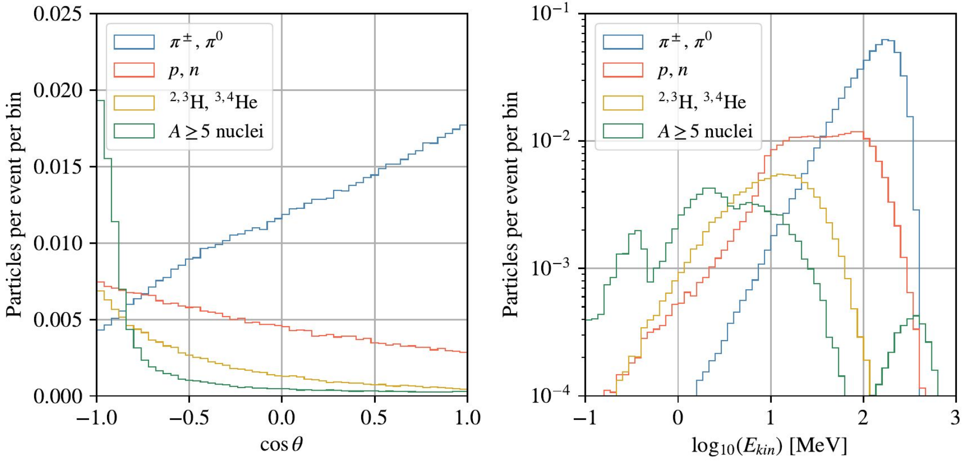
Annihilation signature

$\bar{n} + A \rightarrow (3\text{–}4)\pi + (0\text{–}1)p/n + A'$

Vertex in *xy* plane, 40 cm foil







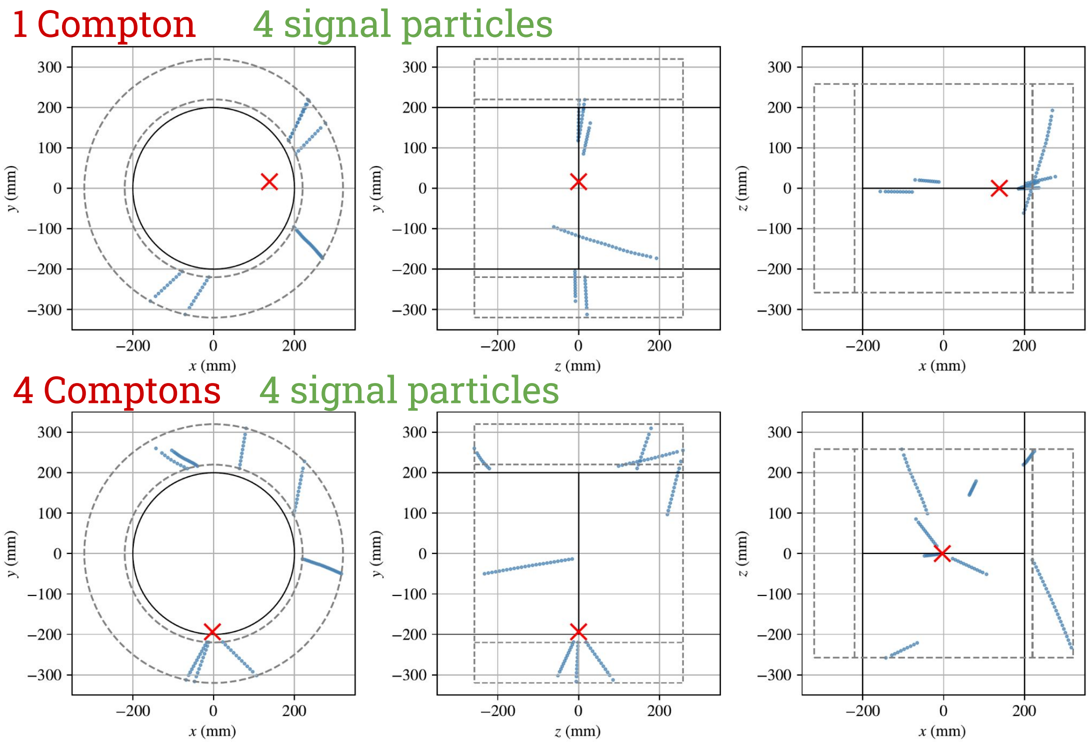
Background: Compton electrons

Compton electrons

- from beampipe walls
- < 0.05 Comptons/event

Benchmarking by adding:

- 1, 2, 4, 8 Compton/event



4 methods for vertex reconstruction

Kalman	*standard / off-the-shelf*	*classical*
TrackLess	*custom-made*	*classical*
GraphNeT	*standard / off-the-shelf*	*ML-based*
IterGNN	*custom-made*	*ML-based*

4 methods: Kalman

Kalman

TrackLess

GraphNeT

IterGNN

- Clustering hits by proximity
  $\Rightarrow$ track candidates
- Each track fitted by Kalman filter and smoothed
  - projected to foil plane (incl. multiple-scattering)
- Least-squares vertex fit $\Leftarrow$ tracks pointing to foil plane.

standard / off-the-shelf   *classical*

4 methods: TrackLess

Kalman

TrackLess

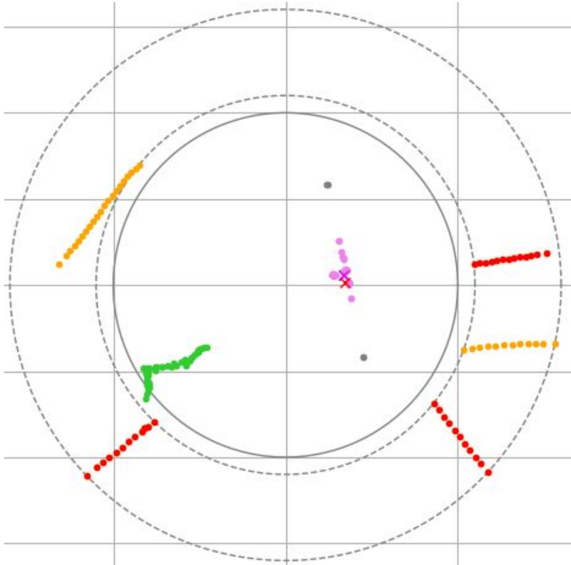
GraphNeT

IterGNN

- Evaluating all combinatorial pairs of hits
  - if < 5 cm and project back to the foil ⇒ vertex candidate
- Candidates clustered by proximity
- Primary cluster (most candidates)

  ⇒ reconstructed vertex

- Rejecting single-track events
  - ≥1 hit-pair in primary cluster with opening angle >12°



custom-made *classical*

4 methods: GraphNeT

Kalman filter

TrackLess

GraphNeT

IterGNN

Open-source graph neural network based framework built for IceCube, based on PyTorch. Modular and general enough to be applicable in other experiments

- 90/10 training/validation
- Nearest-neighbour hit clustering as input to GNN
- Two training heads:
  - built-in *PositionReconstruction* for vertex reconstruction
  - regression for track counting (based on the number of signal particles)

standard / off-the-shelf *ML-based*

4 methods: IterGNN

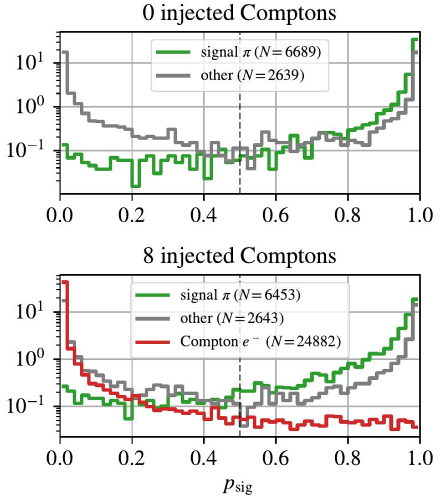
Kalman filter

TrackLess

GraphNeT

IterGNN

- Cluster hits by proximity
- Principal direction of clusters ⇒ seed-vertex
- *TrackGNN* scores tracks on signal-likeness
  - track parameters, compatibility with seed vertex, etc.
- *VertexGNN* correction to seed-vertex
  - track parameters, TrackGNN score, seed vertex, etc.
- 90/10 training/validation



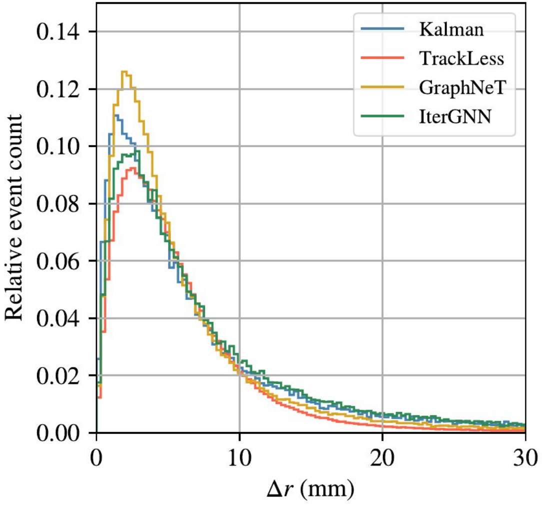
custom-made *ML-based*

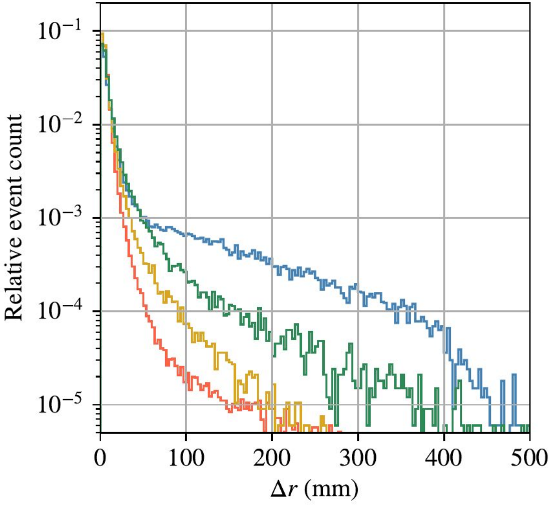
Results: no Comptons

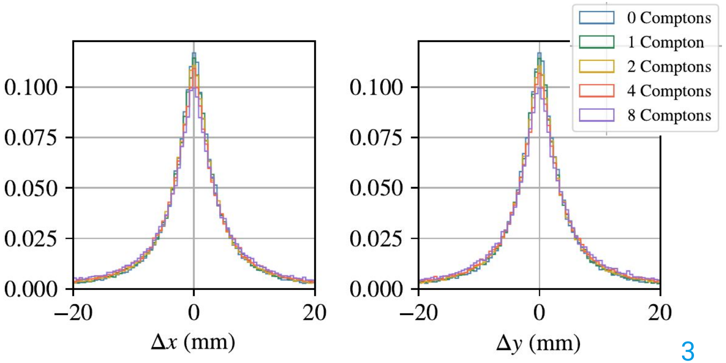
- Similar performance for median event
- Tail differs

Containment	Compton multiplicity	Kalman Δr (mm)	TrackLess Δr (mm)	GraphNeT Δr (mm)	IterGNN Δr (mm)
50 %	0	6.1	4.6	4.3	5.6
90 %	0	107	12	15	28

	ε (%)	ε (%)	ε (%)	ε (%)
0	79	68	80	79





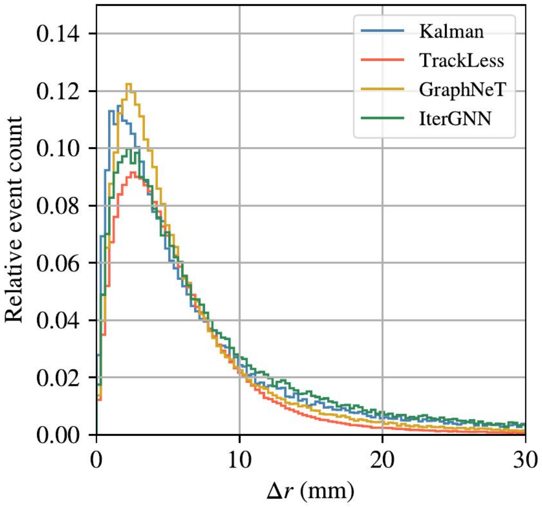


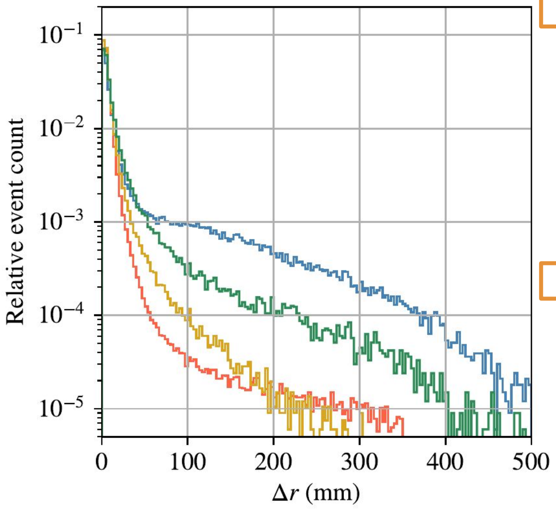
Results: 1 Compton

- TrackLess and GraphNeT stable
- Tails growing
- Background leakage

Containment	Compton multiplicity	Kalman Δr (mm)	TrackLess Δr (mm)	GraphNeT Δr (mm)	IterGNN Δr (mm)
50 %	0	6.1	4.6	4.3	5.6
	1	6.9	4.7	4.5	6.1
	2	7.8	4.7	5.1	6.5
	4	12	4.9	5.5	7.3
	8	54	5.4	7.0	8.7
90 %	0	107	12	15	28
	1	145	12	16	35
	2	170	13	18	44
	4	206	15	22	68
	8	244	30	32	116

	ε (%)	ε (%)	ε (%)	ε (%)
0	79	68	80	79
1	82	67	80	83
2	85	67	79	85
4	89	68	80	89
8	94	70	80	94



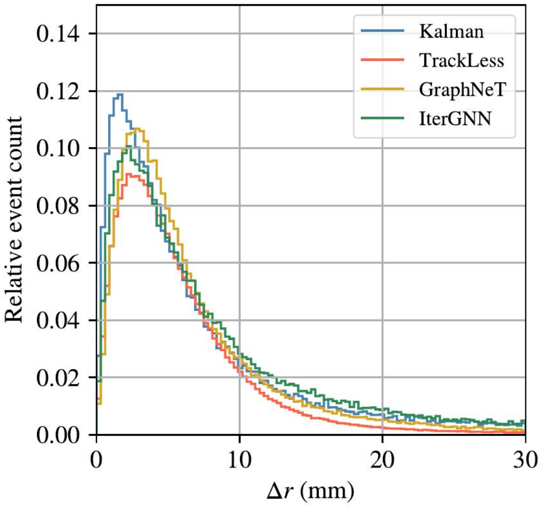


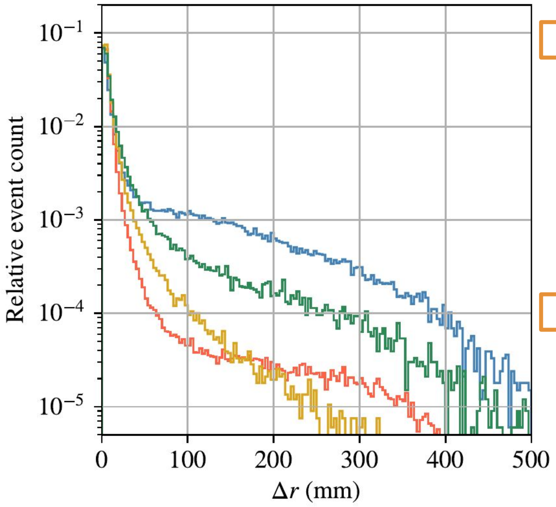
Results: 2 Comptons

- TrackLess and GraphNeT stable
- Tails growing
- Background leakage

Containment	Compton multiplicity	Kalman Δr (mm)	TrackLess Δr (mm)	GraphNeT Δr (mm)	IterGNN Δr (mm)
50 %	0	6.1	4.6	4.3	5.6
	1	6.9	4.7	4.5	6.1
	2	7.8	4.7	5.1	6.5
	4	12	4.9	5.5	7.3
	8	54	5.4	7.0	8.7
90 %	0	107	12	15	28
	1	145	12	16	35
	2	170	13	18	44
	4	206	15	22	68
	8	244	30	32	116

	ε (%)	ε (%)	ε (%)	ε (%)
0	79	68	80	79
1	82	67	80	83
2	85	67	79	85
4	89	68	80	89
8	94	70	80	94



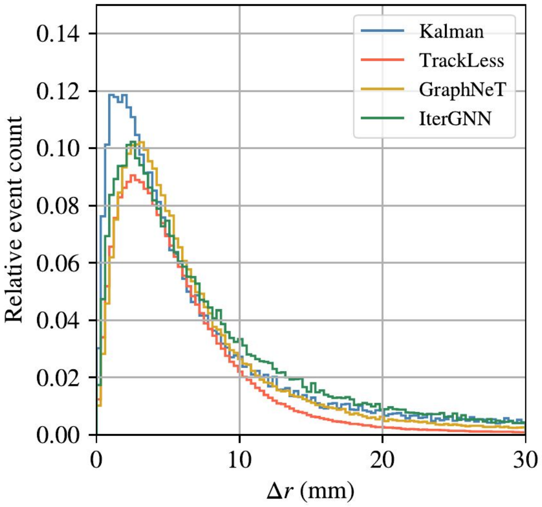


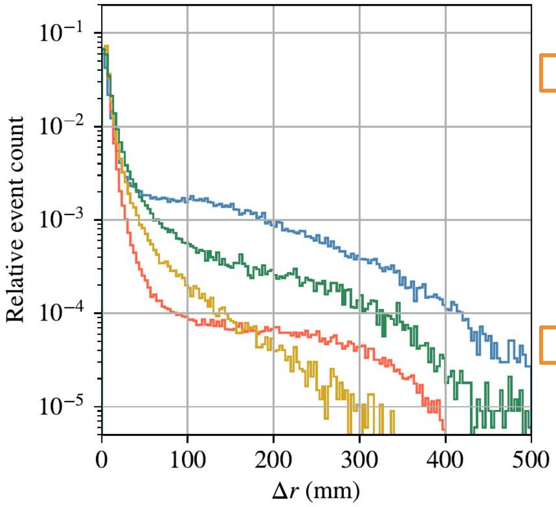
Results: 4 Comptons

- TrackLess and GraphNeT stable
- Tails growing
- Background leakage

Containment	Compton multiplicity	Kalman Δr (mm)	TrackLess Δr (mm)	GraphNeT Δr (mm)	IterGNN Δr (mm)
50 %	0	6.1	4.6	4.3	5.6
	1	6.9	4.7	4.5	6.1
	2	7.8	4.7	5.1	6.5
	4	12	4.9	5.5	7.3
	8	54	5.4	7.0	8.7
90 %	0	107	12	15	28
	1	145	12	16	35
	2	170	13	18	44
	4	206	15	22	68
	8	244	30	32	116

	ε (%)	ε (%)	ε (%)	ε (%)
0	79	68	80	79
1	82	67	80	83
2	85	67	79	85
4	89	68	80	89
8	94	70	80	94



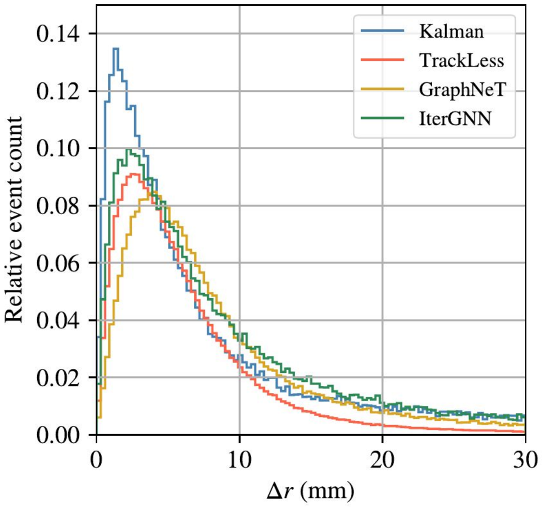


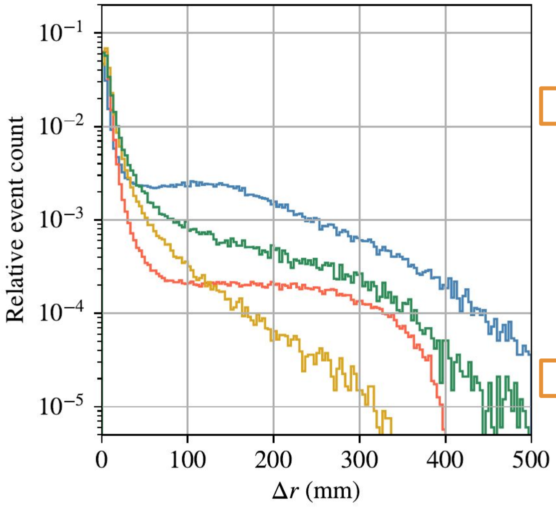
Results: 8 Comptons

- TrackLess and GraphNeT stable
- Tails growing
- Background leakage

Containment	Compton multiplicity	Kalman Δr (mm)	TrackLess Δr (mm)	GraphNeT Δr (mm)	IterGNN Δr (mm)
50 %	0	6.1	4.6	4.3	5.6
	1	6.9	4.7	4.5	6.1
	2	7.8	4.7	5.1	6.5
	4	12	4.9	5.5	7.3
	8	54	5.4	7.0	8.7
90 %	0	107	12	15	28
	1	145	12	16	35
	2	170	13	18	44
	4	206	15	22	68
	8	244	30	32	116

	ε (%)	ε (%)	ε (%)	ε (%)
0	79	68	80	79
1	82	67	80	83
2	85	67	79	85
4	89	68	80	89
8	94	70	80	94





Including the single-track events

Containment	Compton multiplicity	Kalman Δr (mm)	TrackLess Δr (mm)	GraphNeT Δr (mm)	IterGNN Δr (mm)
50 %	0	6.1	4.6	4.3	5.6
	1	6.9	4.7	4.5	6.1
	2	7.8	4.7	5.1	6.5
	4	12	4.9	5.5	7.3
	8	54	5.4	7.0	8.7
90 %	0	107	12	15	28
	1	145	12	16	35
	2	170	13	18	44
	4	206	15	22	68
	8	244	30	32	116

Containment	Compton multiplicity	Kalman Δr (mm)	TrackLess Δr (mm)	GraphNeT Δr (mm)	IterGNN Δr (mm)
50 %	0	6.4	5.2	4.6	5.7
	1	9.5	5.5	5.1	6.3
	2	11	5.7	5.8	6.7
	4	18	6.2	6.4	7.6
	8	62	7.2	7.9	9.0
90 %	0	110	25	20	30
	1	189	41	28	48
	2	199	83	35	64
	4	217	163	49	94
	8	244	217	57	132

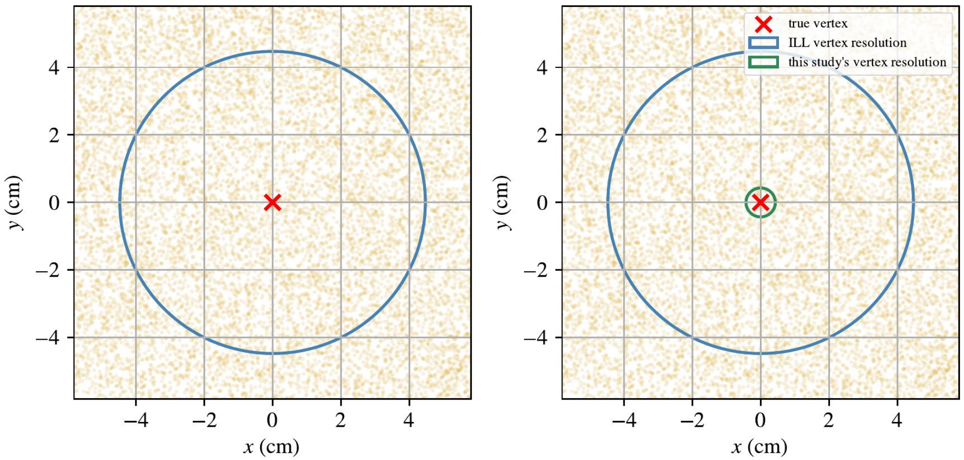
	ε (%)	ε (%)	ε (%)	ε (%)
0	79	68	80	79
1	82	67	80	83
2	85	67	79	85
4	89	68	80	89
8	94	70	80	94

	ε (%)	ε (%)	ε (%)	ε (%)
0				
1				
2	~ 100			
4				
8				

Earlier results

Currently world leading results on $n \to \bar{n}$ conversion (ILL, 1994):

- $\tau_{n \to \bar{n}} > 8.6 \times 10^7$ s
- corresponding Δr = 4.5 cm



This study

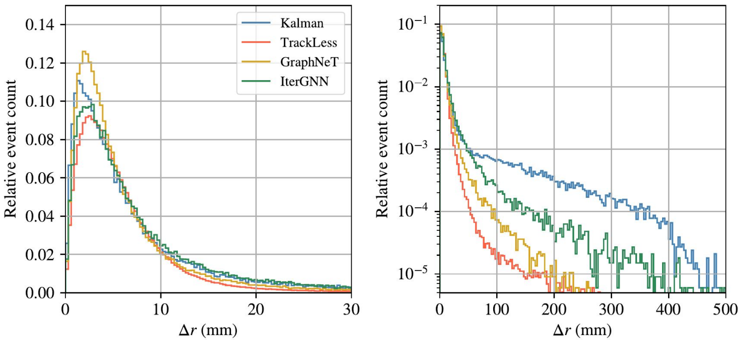
- Best Δr = 4.3 mm

⇒ × 110 less Compton contamination

Summary

Four different vertex reconstruction methods benchmarked for the HIBEAM TPC:

- *custom-made* *standard / off-the-shelf*
- *classical* *ML-based*



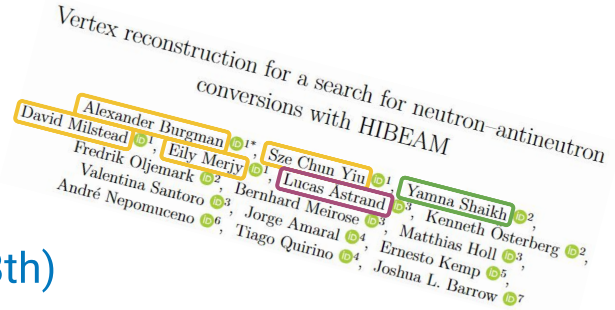
Similar performances on median event with low BG

- simple geometry, few straight tracks

Main contributors: **SU**, **LU**, **HIP**

← *open PHD student position*

please apply! (deadline Sep 28th)


Vertex reconstruction for a search for neutron–antineutron conversions with HIBEAM

David Milstead[1], Alexander Burgman[1*], Eily Merjy[1], Sze Chun Yiu[1], Fredrik Oljemark[2], Lucas Astrand[3], Yamna Shaikh[2], Valentina Santoro[3], Bernhard Meirose[3], Kenneth Österberg[2], André Nepomuceno[6], Jorge Amaral[4], Matthias Holl[3], Tiago Quirino[4], Ernesto Kemp[5], Joshua L. Barrow[7]

Thank you

Backups

Outstanding questions

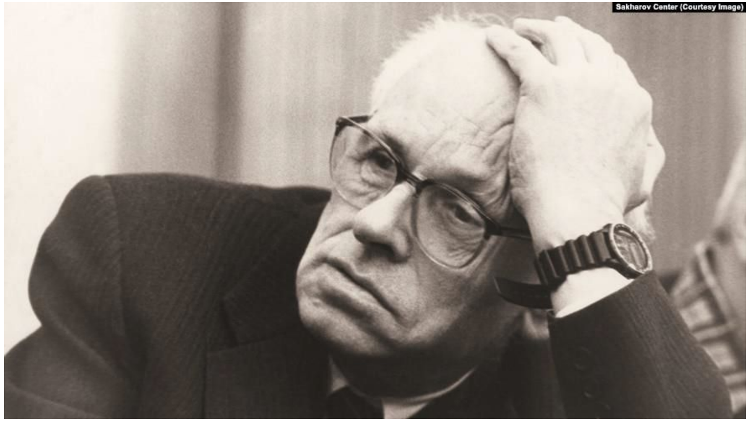
Standard Model (SM) of particle physics does not describe nature completely:

- 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 $\Leftarrow$ Sakharov conditions
  - Baryon number *B* violation
  - *C*- and *CP*-symmetry violation
  - Interactions out of thermal equilibrium



Baryon number violation

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

- Matter/antimatter asymmetry ⇐ Sakharov conditions
  - Baryon number *B* violation (and lepton *L*)

Sphaleron processes,

Unification models

Supersymmetry

Hidden sector

[...]

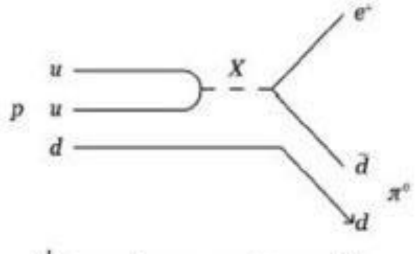
Baryon number violation

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

- Matter/antimatter asymmetry ⇐ Sakharov conditions
  - Baryon number *B* violation (and lepton *L*)

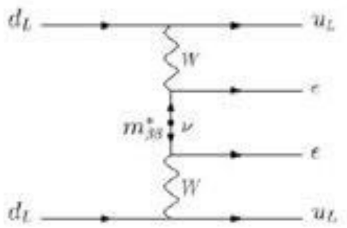
$p \to e^{+} + \pi^{0}$

$\Delta B \neq 0, \Delta L \neq 0$



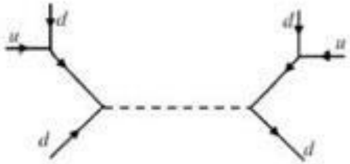
$0\nu 2\beta$

$\Delta B = 0, \Delta L \neq 0$



$n \to \bar{n}$

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



$n \to n'$ (mirror)

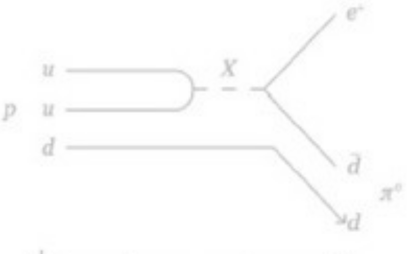
$\Delta B = 1, \Delta L = 0$

Baryon number violation

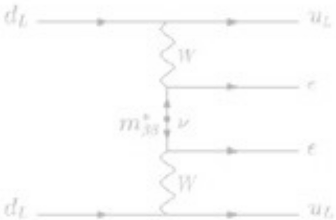
Standard Model (SM) of particle physics does not describe nature completely:

- Matter/antimatter asymmetry $\Leftarrow$ Sakharov conditions
    - Baryon number *B* violation (and lepton *L*)

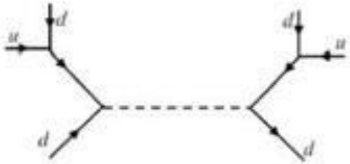
$p \to e^+ + \pi^0$
$\Delta B \neq 0, \Delta L \neq 0$



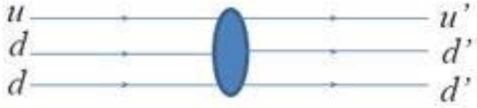
$0\nu 2\beta$
$\Delta B = 0, \Delta L \neq 0$



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



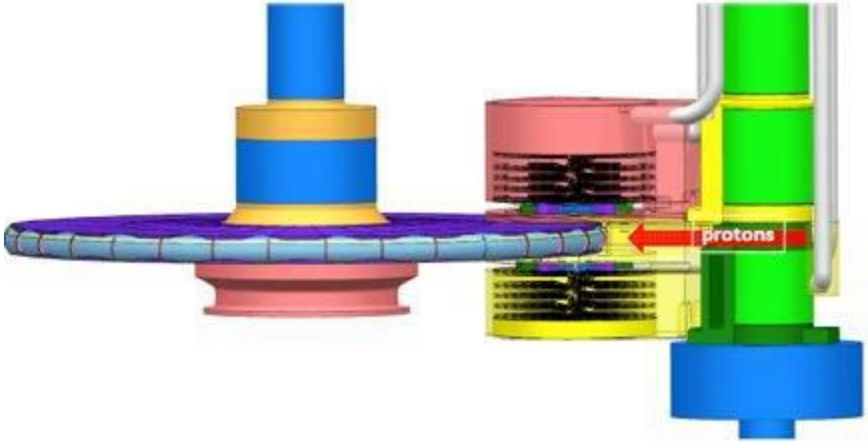
$n \to n'$ (mirror)
$\Delta B = 1, \Delta L = 0$



The European Spallation Source (ESS)

World's highest intensity neutron source

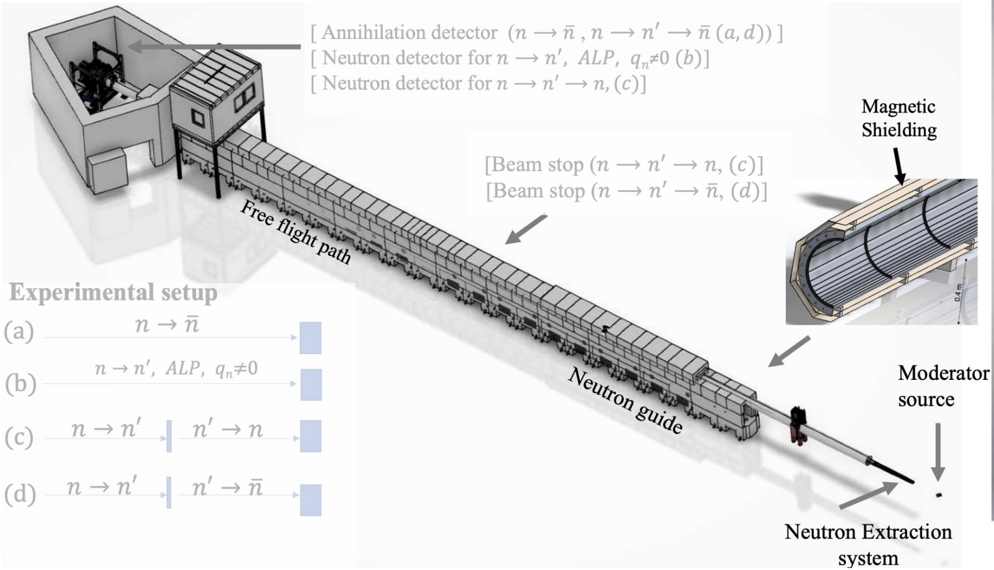
- Lund, Sweden
- Operations from 2027/2028
- Neutron imaging material, lifescience

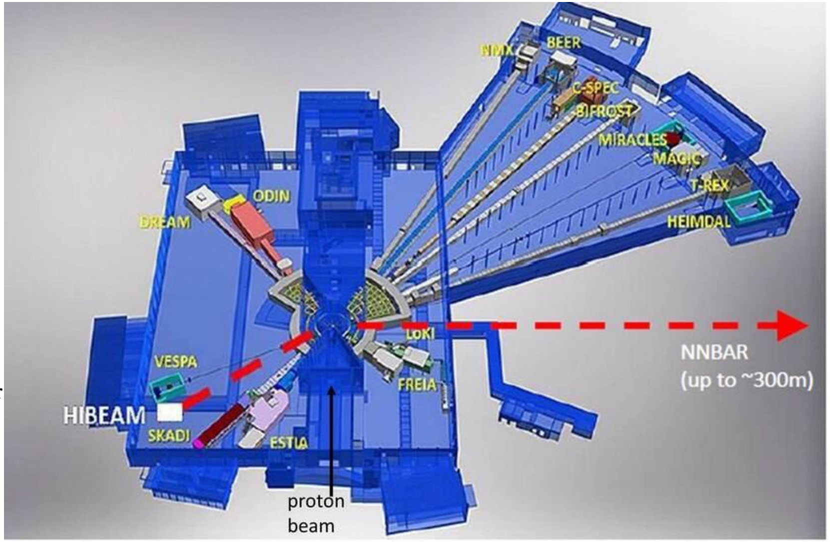


- Nominally 2 GeV protons,
  3 ms pulse, 14 Hz, (2;5) MW
- Rotating tungsten target
- Neutrons cold after moderators
- 15 beamlines/instruments (+ 22?)

The HIBEAM Beamline

arXiv:2311.08326





Magnetically shielded 50 m beamline

WASA (CsI) crystal calorimeter + TPC

$n \to \bar{n}$

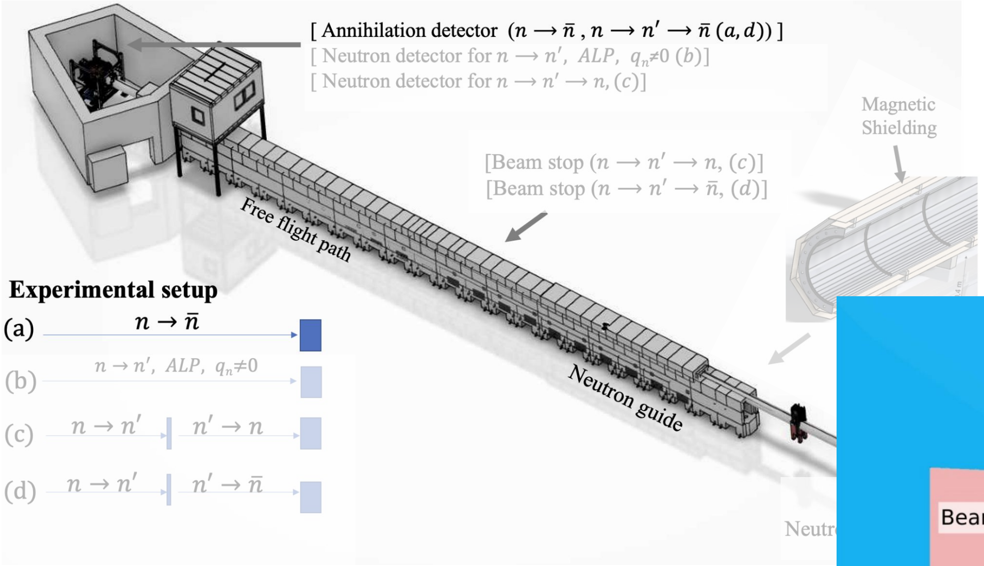
$n \to n'$

q_n

axions

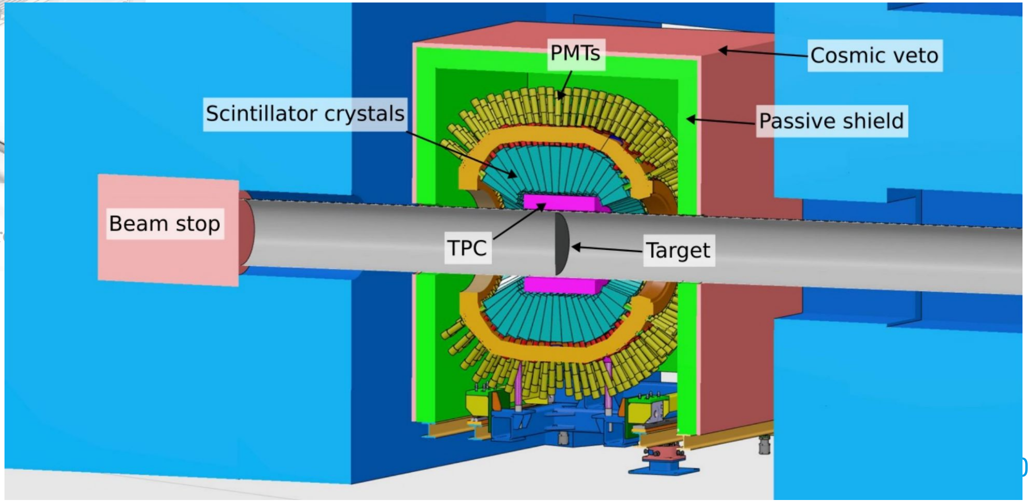
nEDM

Antineutrons $n \to \bar{n}$



Neutron beam oscillating to antineutrons, incident on annihilation detector

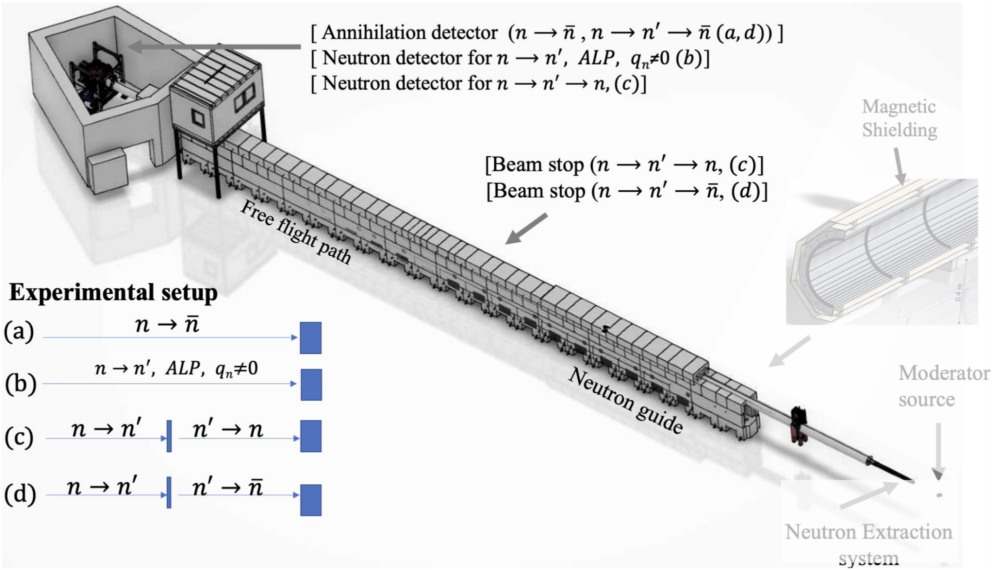
Most recent search 1994 (ILL)
$\longrightarrow$ neutron lifetime $\tau_{n \to \bar{n}} > 8.6 \times 10^7$ s



10^{12} n/s, runtime 3–4 yr

Sensitivity improvement $\times$ 10

Sterile neutrons $n \rightarrow n'$



Magnetic field scan ± 2 G (200 µT)
to find degeneracy with sterile sector

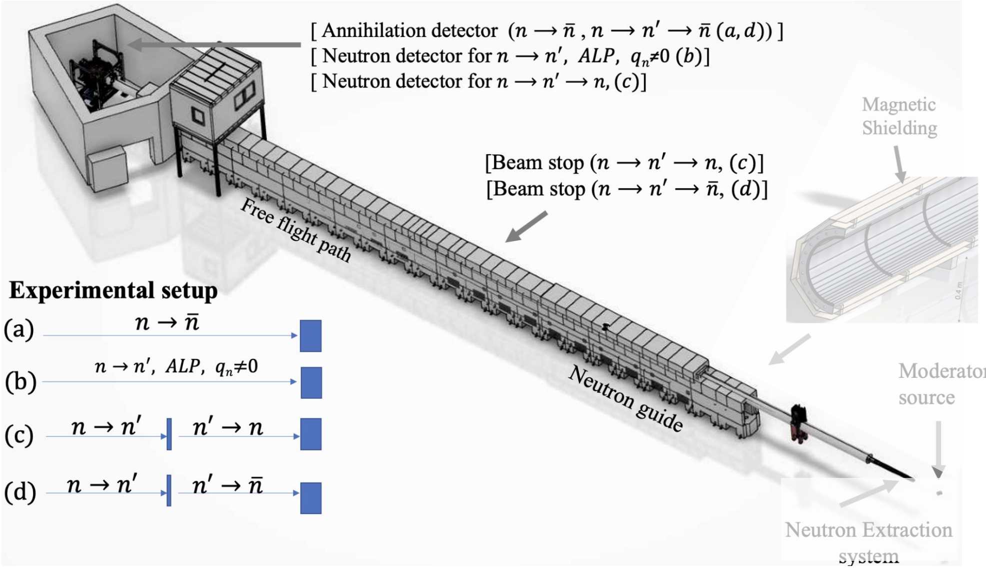
Possible beam stop to allow regeneration search

disappearance $n \rightarrow n'$

regeneration $n \rightarrow n' \rightarrow n$

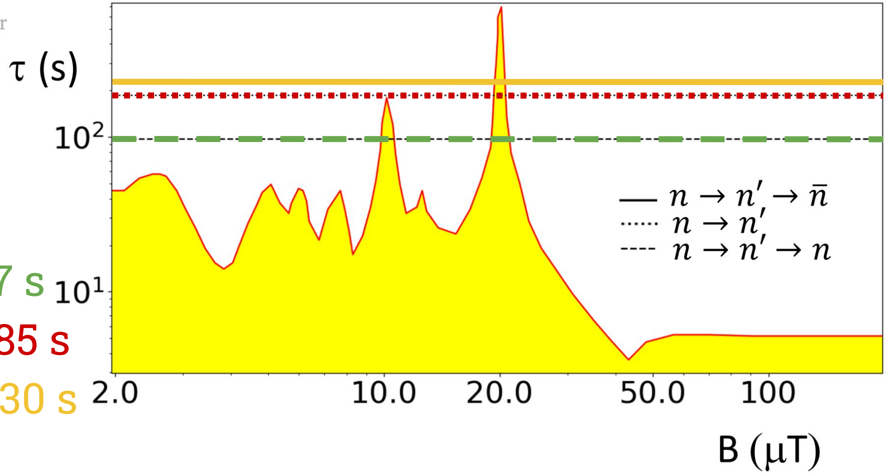
anti-regen. $n \rightarrow n' \rightarrow \bar{n}$

Sterile neutrons $n \to n'$



Magnetic field scan ± 2 G (200 μT)
to find degeneracy with sterile sector

Possible beam stop to allow
regeneration search



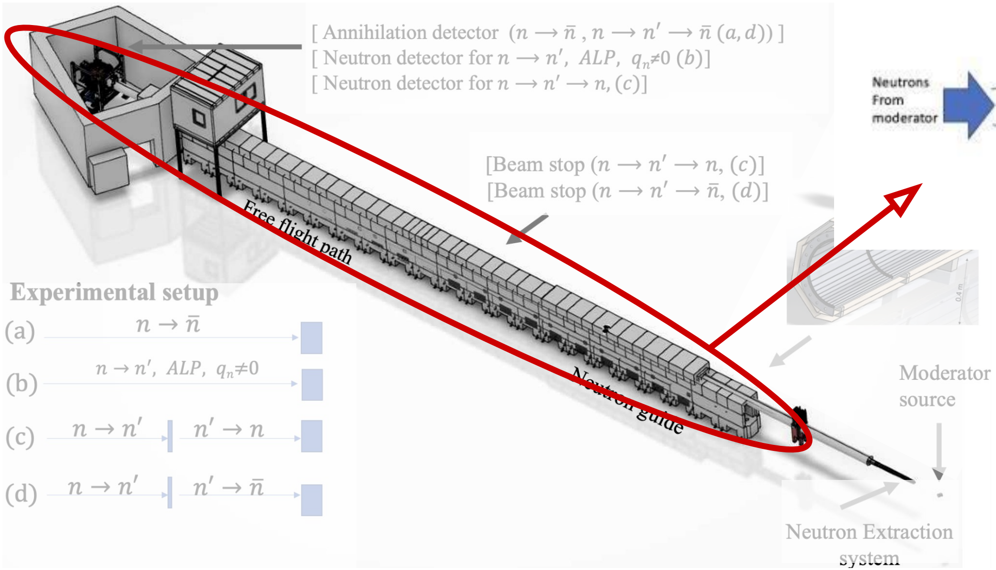
disappearance $n \to n'$ $\tau_{n \to n'} \sim 97$ s

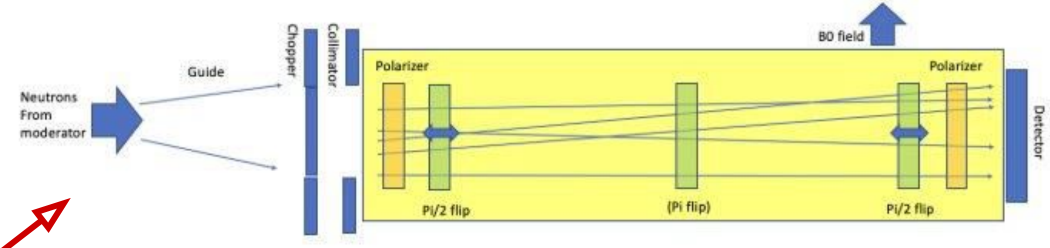
regeneration $n \to n' \to n$ $\tau_{n \to n'} \sim 185$ s

anti-regen. $n \to n' \to \bar{n}$ $\sqrt{(\tau_{n \to n'} \tau_{\bar{n} \to n'})} \sim 230$ s

Axions

arXiv:2404.1552





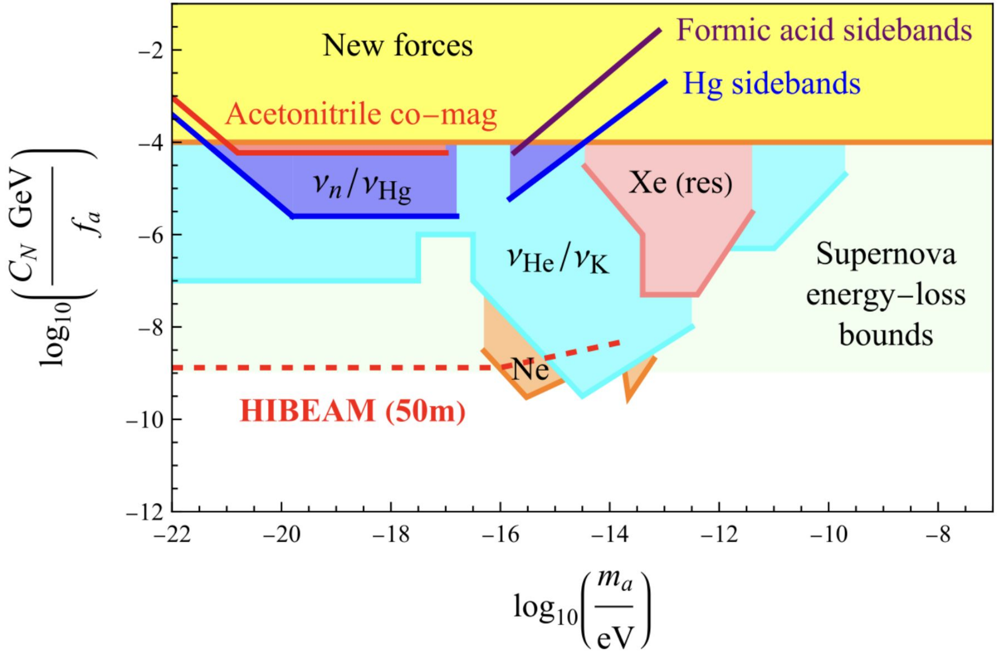
Ambient axions as pseudomagnetic field

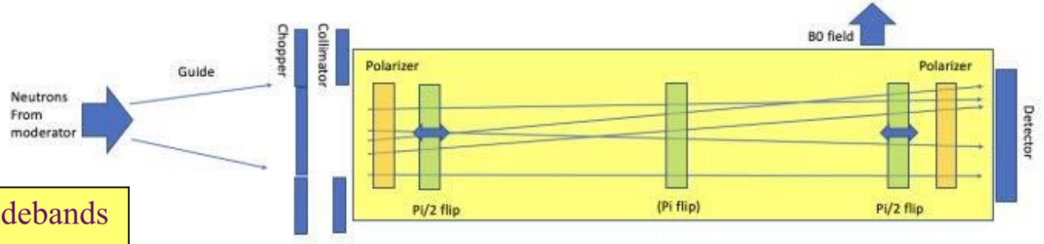
Changes the Larmor frequency (magnetic moment precession)

Detected through Ramsey interferometry

Axions

arXiv:2404.1552





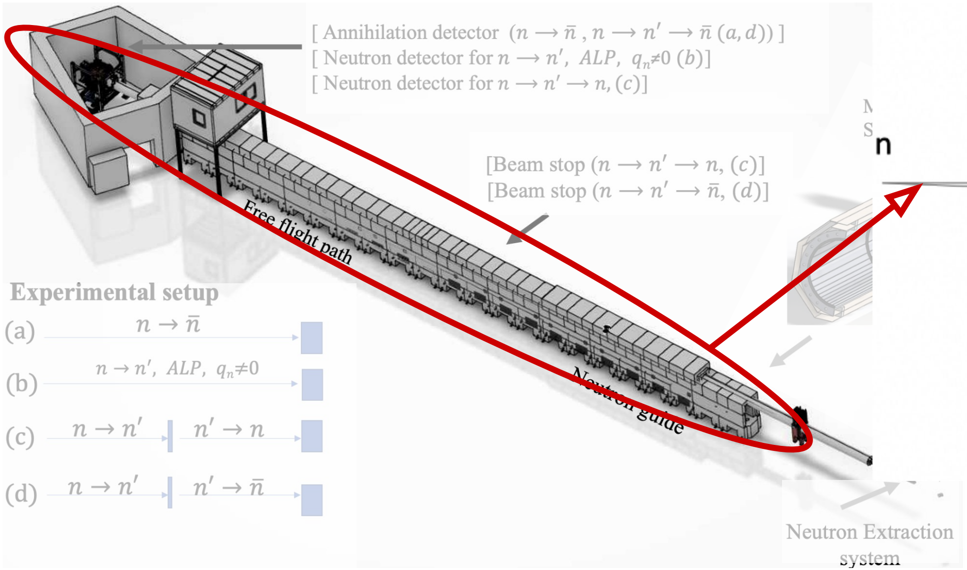
Ambient axions as pseudomagnetic field

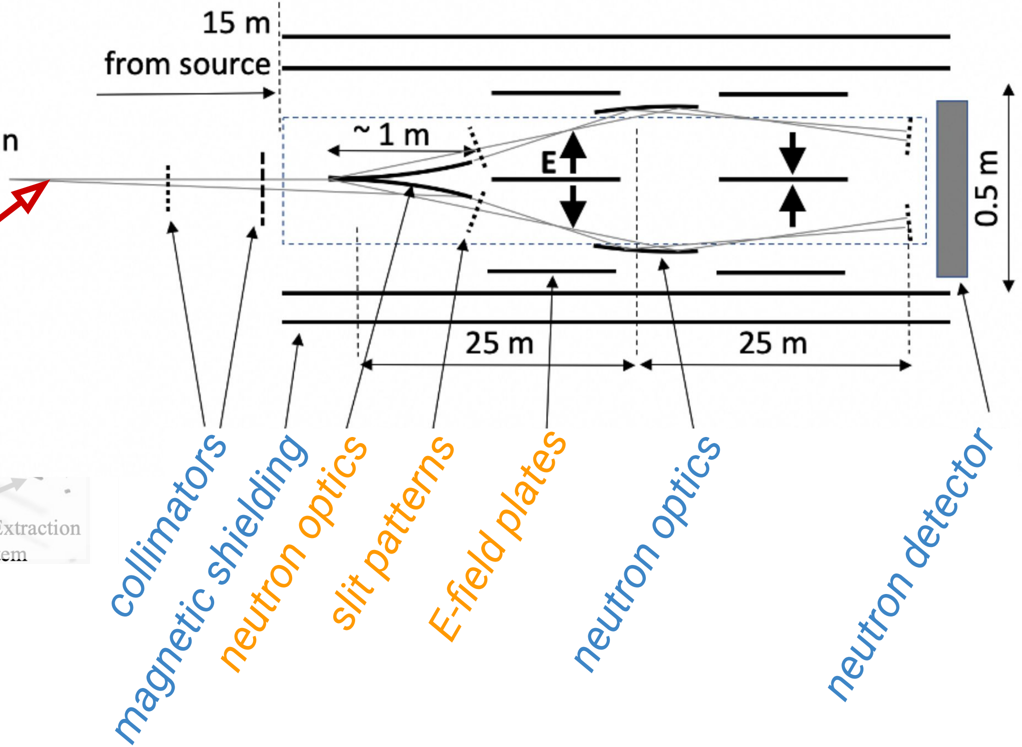
Changes the Larmor frequency (magnetic moment precession)

Detected through Ramsey interferometry

Sensitivity improvement × 10^2–10^3 for 10^{-22} eV < m_a < 10^{-16} eV

Neutron electric charge q_n



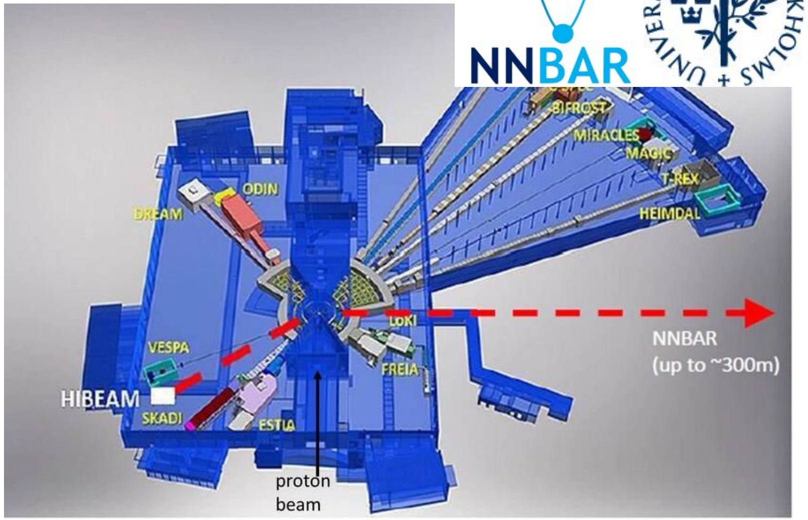


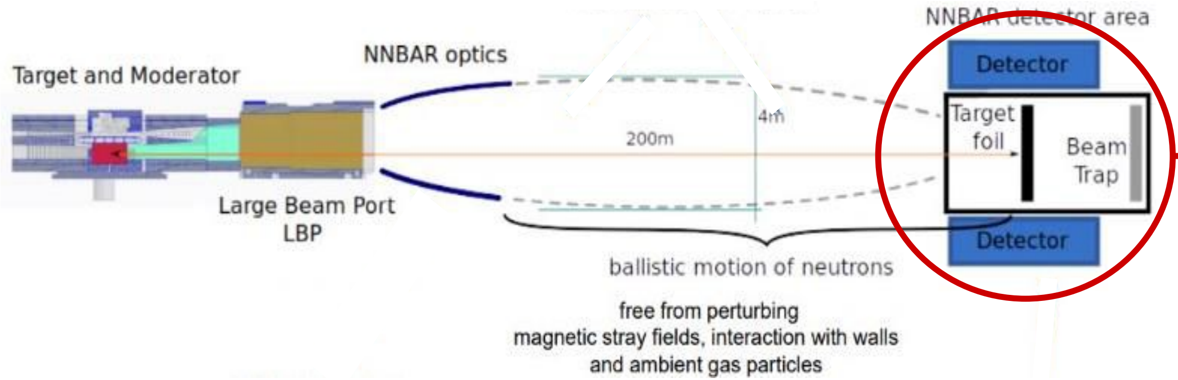
beam deflection ~ 0.1 nm per 10 m
(with $q_n \sim 10^{-21}\ e$)

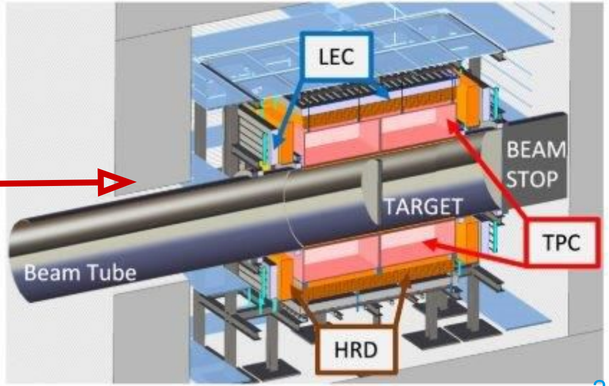
Sensitivity improvement × 700

NNBAR

×4 larger beamport, 4 m diameter, 200 m beampipe
improved neutron optics,
magnetic beampipe shielding
TPC, plastic scintillator, lead-glass calorimeter







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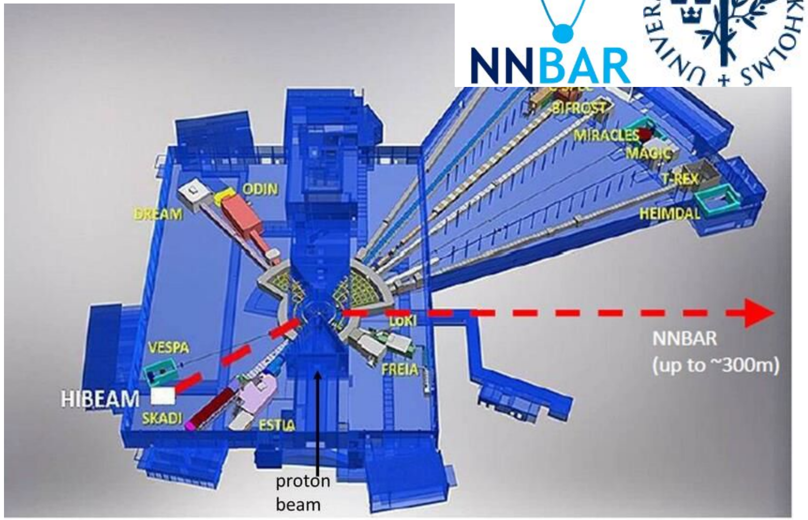
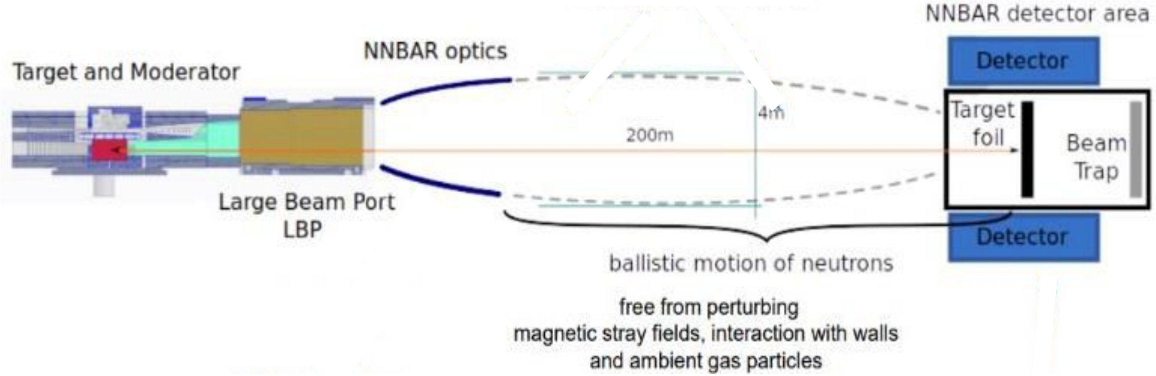




$(n \rightarrow \bar{n})$ $\tau_{n \rightarrow \bar{n}}$
sensitivity improvement $\times 10^3$
over ILL results

Conclusions

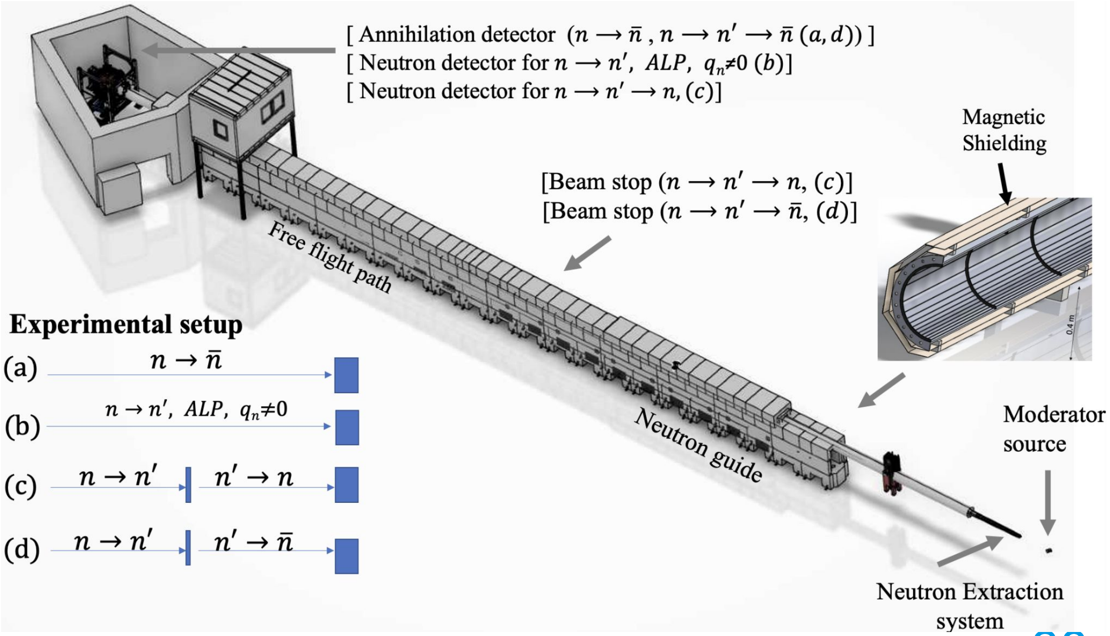
Enormous neutron flux at ESS
$\Rightarrow$ fundamental physics

HIBEAM

- $n \to \bar{n}$ sens. × 10
- $n \to n'$ $\tau \sim 230$ s
- axions sens. × 10^2–10^3
- q_n sens. × 700

NNBAR

- $n \to \bar{n}$ sens. × 10^3



Abstract

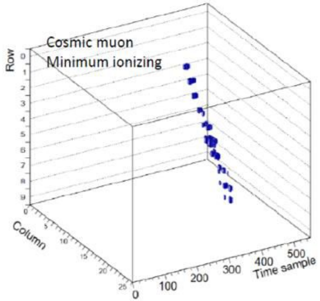
The HIBEAM/NNBAR programme at the European Spallation Source will search for neutrons converting to antineutrons. An important observable is the reconstructed vertex arising from charged particles produced by an antineutron annihilating on a thin target foil and which pass through a time projection chamber.

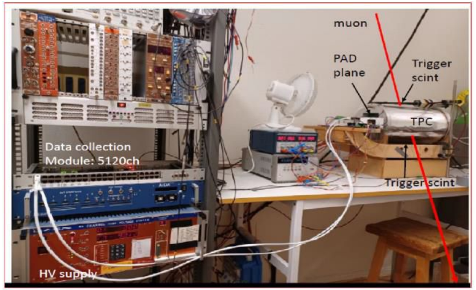
We present a comparison of four methods for vertex coordinate reconstruction: two machine learning (ML)-based methods and two non-ML methods, where one of each is tailored for this study.

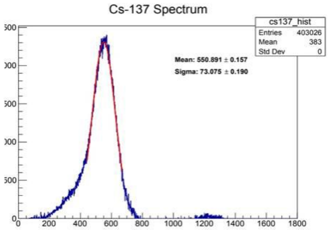
HIBEAM prototype

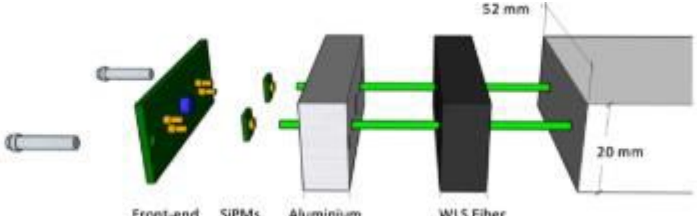
Swedish Research Council infrastructure grant to Stockholm U, Lund U, Chalmers TU, ESS

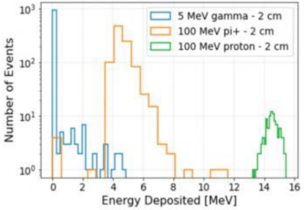
- Prototype development
  - Time projection chamber
  - WASA crystal calorimeter
  - Scintillator/lead-glass calorimeter
- Annihilation detector
- Neutron detector
- Beamline design

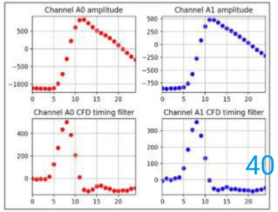










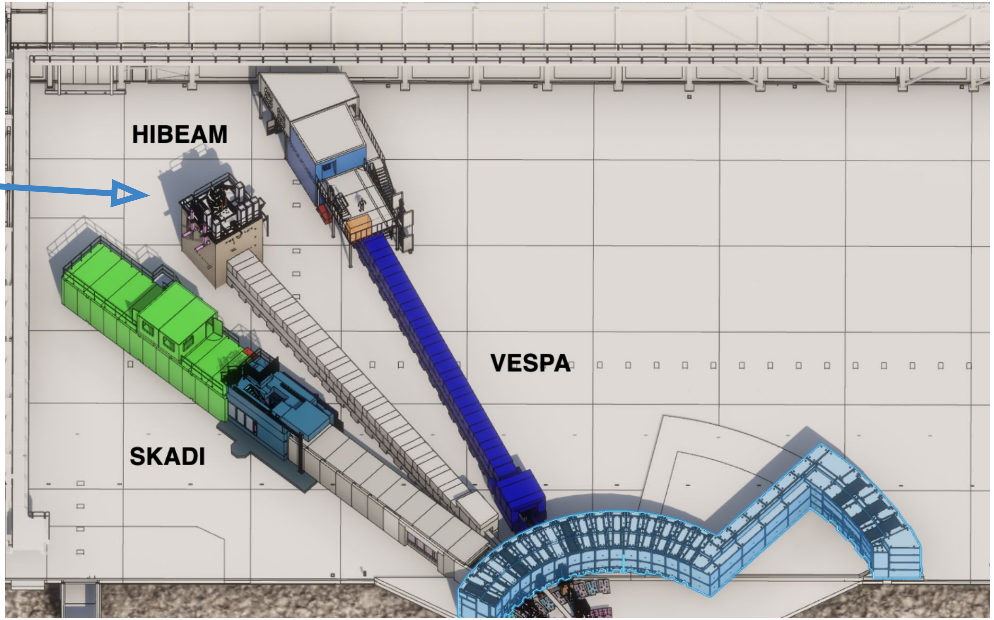


Electric dipole moment *nEDM*

Priority for neutron community

nEDM@SNS cancelled

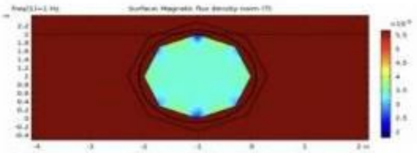
$\longrightarrow$ possible at the ESS?



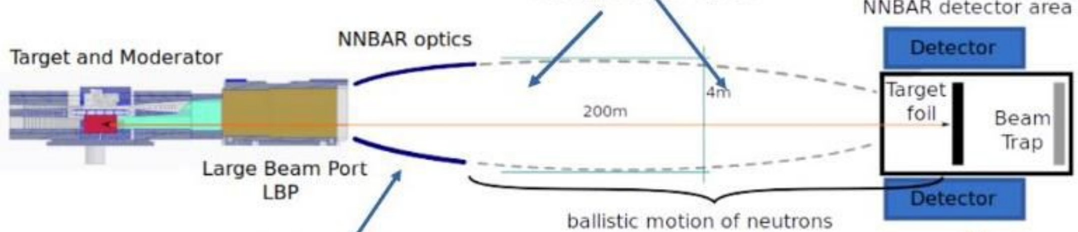
Investigations ongoing to reach the 10^{-29} $e\,\mathrm{cm}$ sensitivity!

NNBAR

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

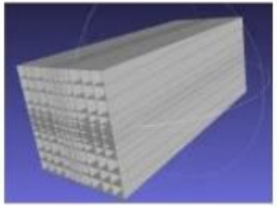


Residual B field <10 nT
Residual vacuum < 10 -5 P

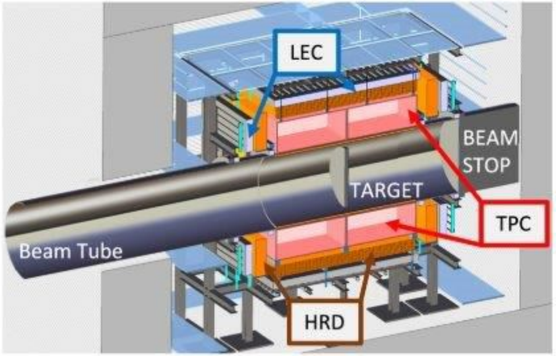


free from perturbing
magnetic stray fields, interaction with walls
and ambient gas particles

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



Eg double planar reflector



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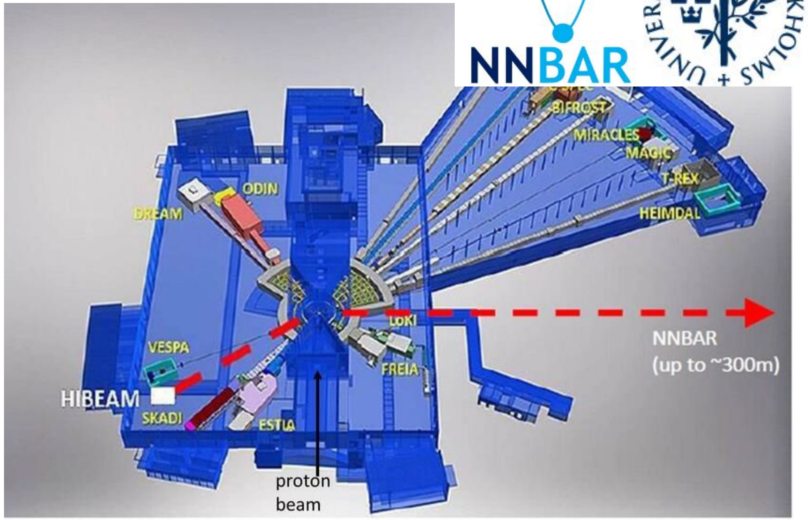

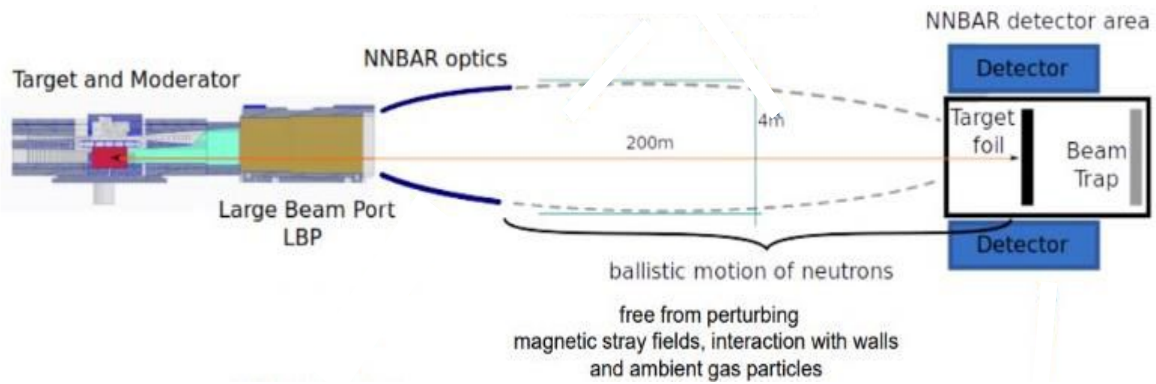

Neutron exotic decays

$n \rightarrow X + e/\nu \rightarrow$ [SM]

NNBAR sensitive,
discovery potential in 3 yr

Studies underway!
arXiv:2506.08701

Conclusions

Enormous neutron flux at ESS
$\Rightarrow$ fundamental physics

HIBEAM

- $n \to \bar{n}$ sens. × 10
- $n \to n'$ $\tau \sim 230$ s
- axions sens. × 10^2–10^3
- q_n sens. × 700
- nEDM underway!

NNBAR

- $n \to \bar{n}$ sens. × 10^3
- *exotic decays*

underway!