Advancements in Computing and Simulation Techniques for the HIBEAM-NNBAR Experiment

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NNBAR

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UNIVERSITY OF TECHNOLOGY

What is this talk about?

- A future baryon number violation experiment in Sweden using neutrons

Motivation in one minute

- Baryon number violation (BNV) essential condition for baryogenesis
- Baryon number an accidental SM symmetry and is broken in extensions
- BNV in SUSY, dark matter (hidden sector), extra dimensions
- Neutron oscillations to antineutrons or sterile neutrons unique probe of BNV processes in which only BN is violated
- An opportunity to test a global symmetry with three orders of magnitude better precision than previously done is rare

NNBAR

Free NNBAR search in 1 minute

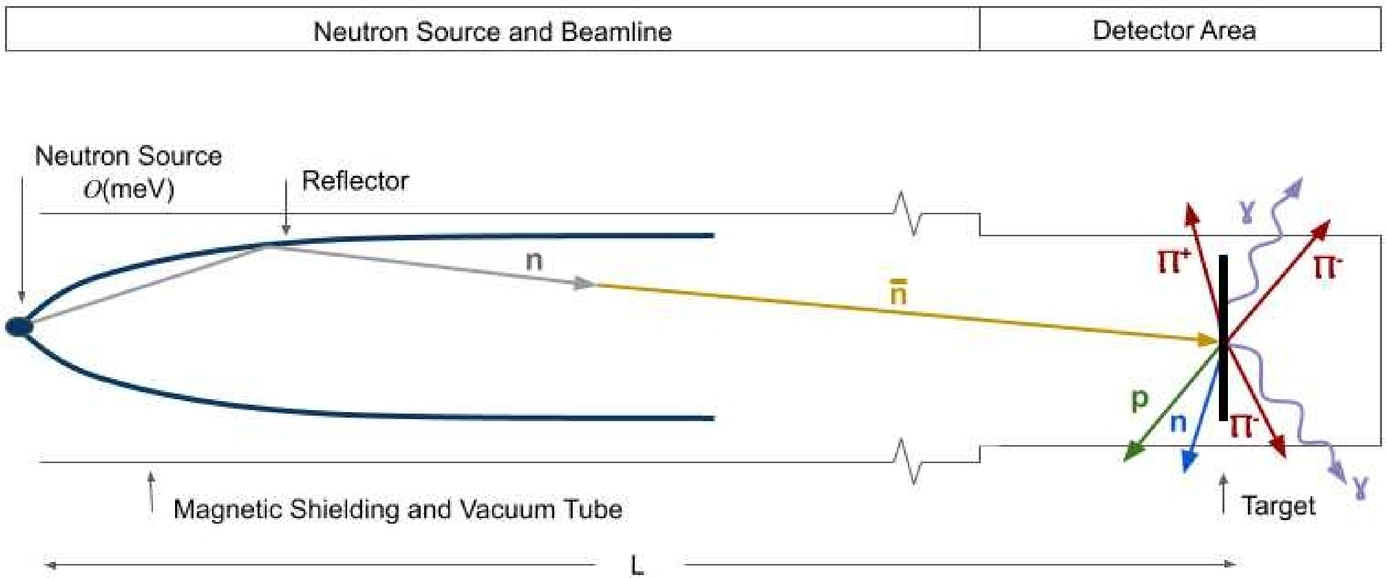
- Goal: observe neutron → antineutron ($n \rightarrow \bar{n}$)
- Sensitivity 3 orders of magnitude greater than previous experiment
- Strategy: let as many cold neutrons "fly" for as long as possible
- Probability of free neutron transformation into an antineutron:

$$P(\bar{n},t)=(t/\tau)^2$$

FOM= Nt^2

- t → neutron flight time; τ → "oscillation time" (BSM predicted, model dependent)

$\tau > 8.7\ 10^7$s (ILL)

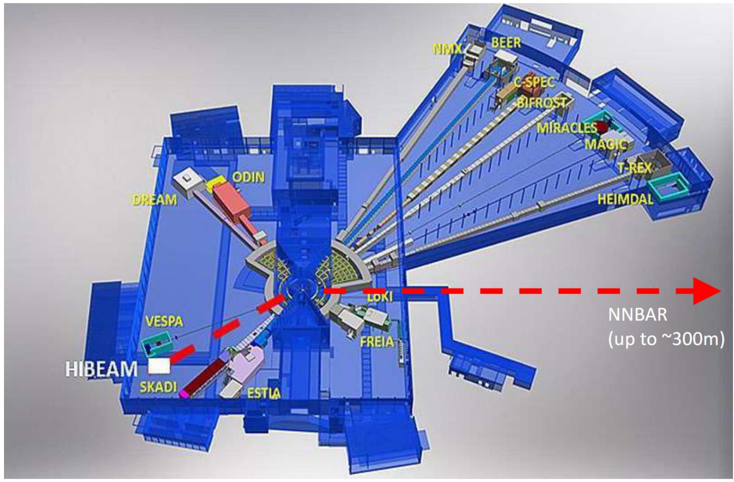


European Spallation Source (ESS)

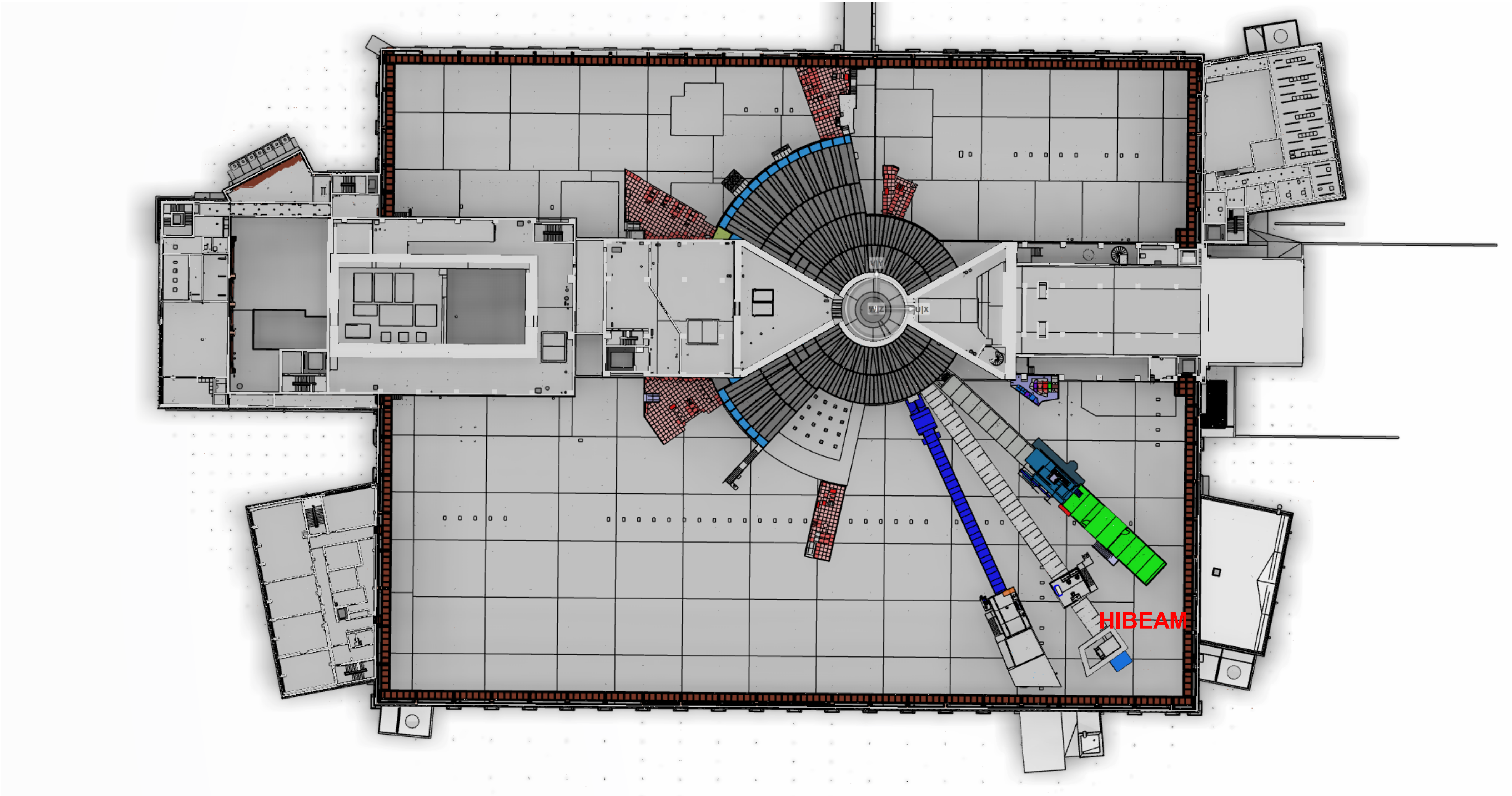
- Will be most powerful spallation neutron source
- Place: Lund, Sweden
- Under construction: Beam on target in 2025, start of user program in 2027.

HIBEAM and NNBAR

- Staged experiment
- 1. HIBEAM (High Intensity Baryon Extraction and Measurement)
  - late 2020's
  - world leading searches $n \rightarrow n'$
  - search for $n \rightarrow \bar{n}$
  - also search for $n \rightarrow \bar{n}$ via sterile neutrons. *First such search*.
  - search for axions-like particles
  - R&D for full experiment.
- 2. NNBAR
  - extremely high precision searches $n \rightarrow \bar{n}$
  - improve sensitivity to oscillation probability by ~ 10^3
  - After 2030



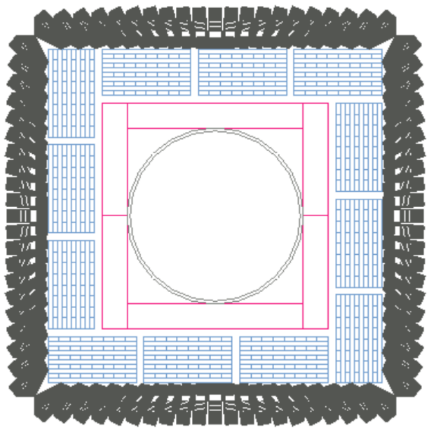
HIBEAM



NNBAR

Detector

HIBEAM (top) and NNBAR (bottom) detectors



Aluminum tube

0.55 m inner radius
2 cm thick
6 m long (z direction)

Time Projection Chamber

Two different dimensions
- 0.16 m x 0.73 m
- 1.14 m x 0.16 m

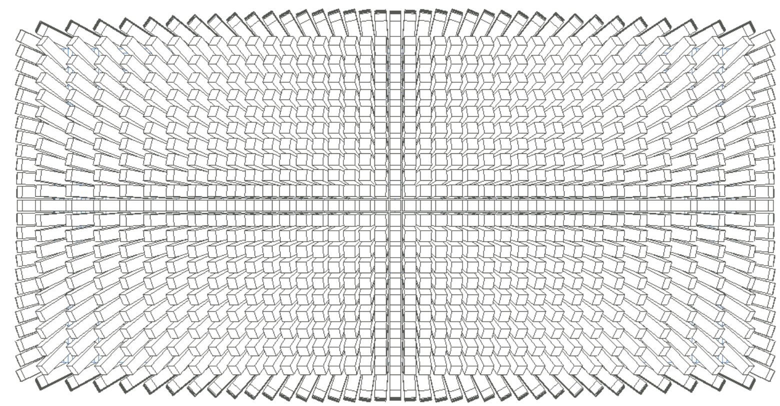
2m long (z direction)
80% Ar + 20% CO2

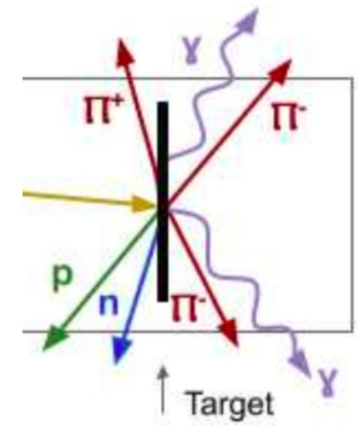
Scintillator Modules

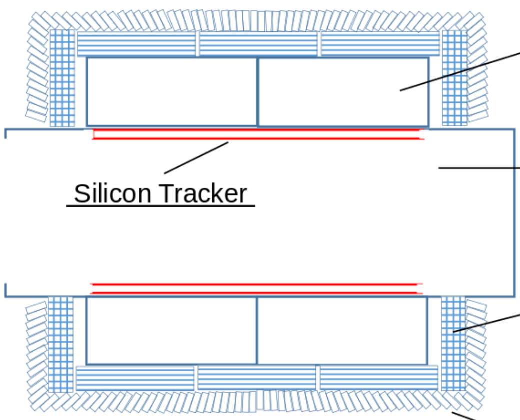
10 layers of plastic scintillator
3 cm thick for each layer

Lead Glass Blocks

Base: 8 cm x 8 cm
Height: 25 cm
Pointing towards the **center of**







Time Projection Chamber

Two different dimensions
- 0.85 m x 1.87 m
- 2.04 m x 0.85 m

2m long (z direction)
80% Ar + 20% CO2

Aluminum tube

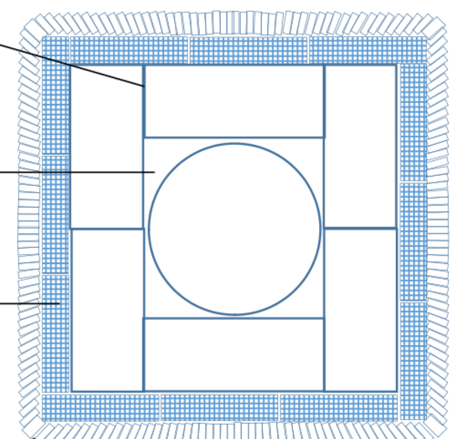
1 m inner radius
2 cm thick
6 m long (z direction)

Scintillator Modules

10 layers of plastic scintillator
3 cm thick for each layer

Lead Glass Blocks

Base: 8 cm x 8 cm
Height: 25 cm
Pointing towards the **center of the detector**



Requirements for the detector:

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

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

by 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]

Event displays in Geant4

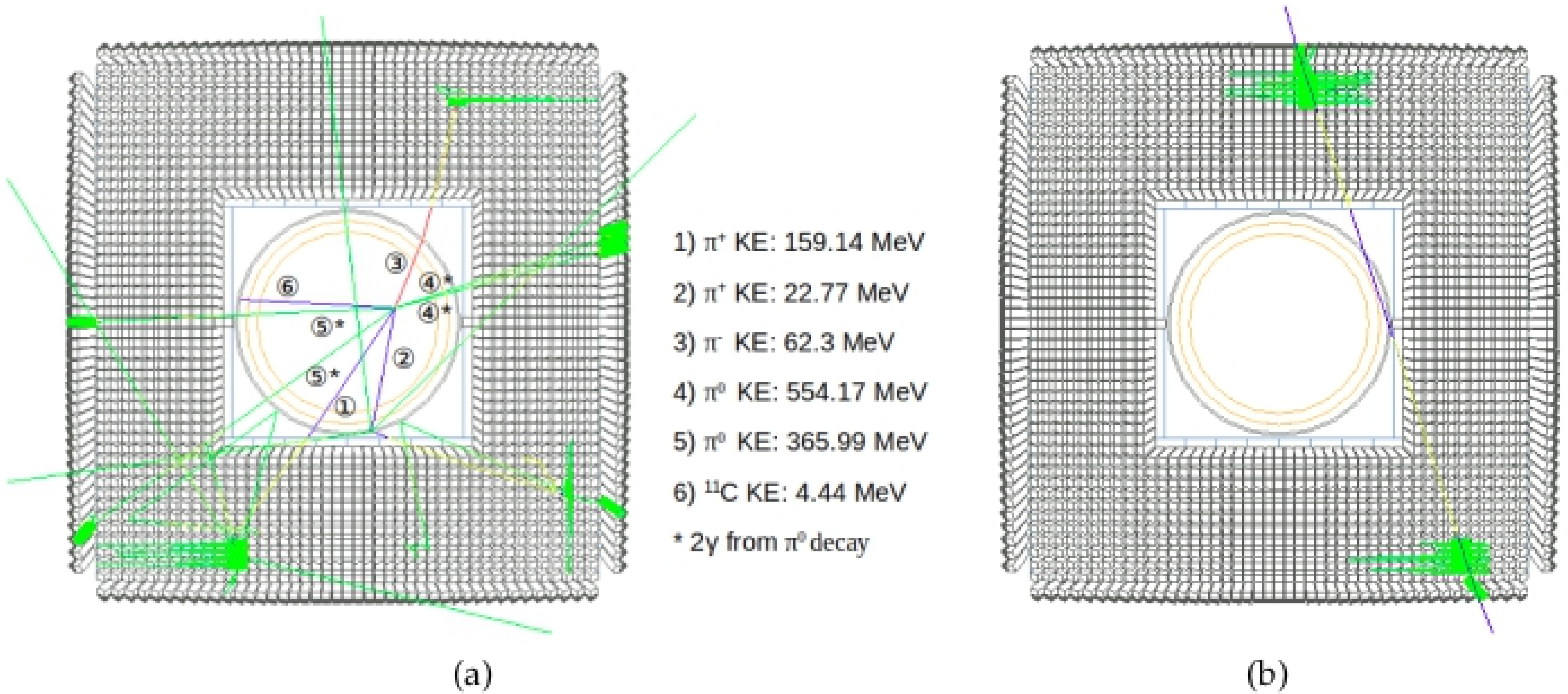


Figure 4. Event displays with the NNBAR detector showing (a) a signal event with five pions (b) a cosmic muon.

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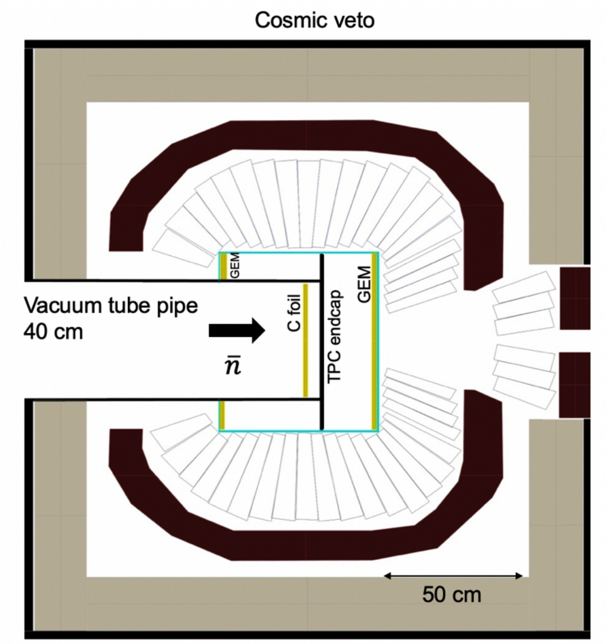
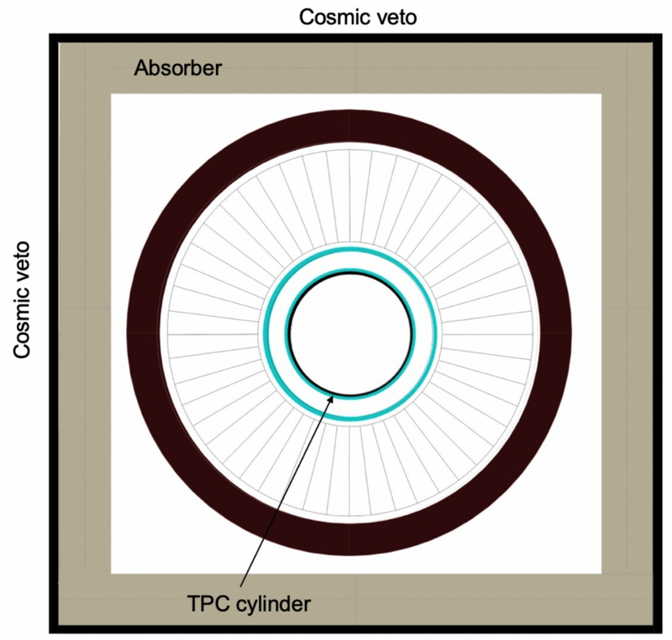
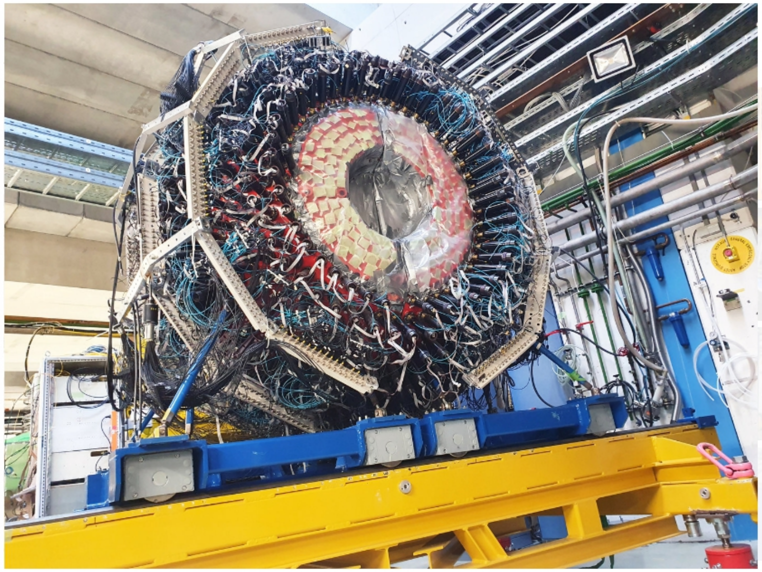
WASA detector (HIBEAM)

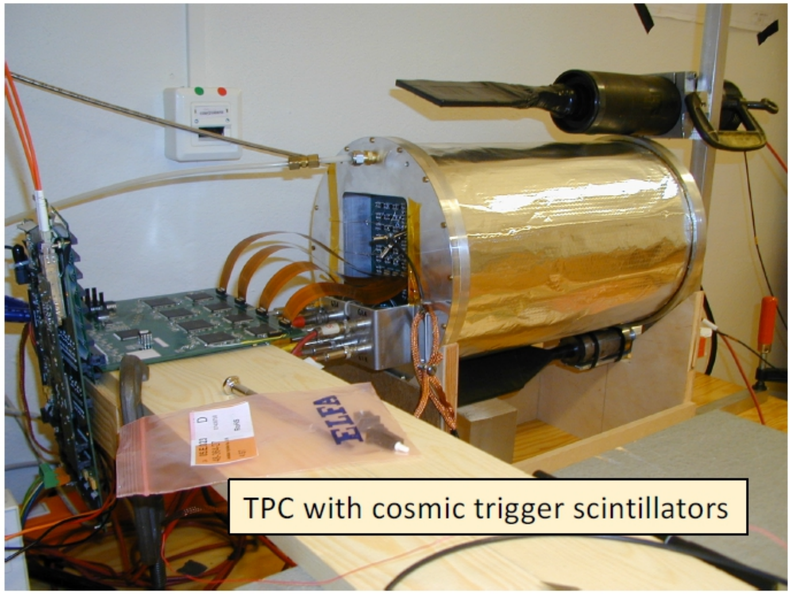




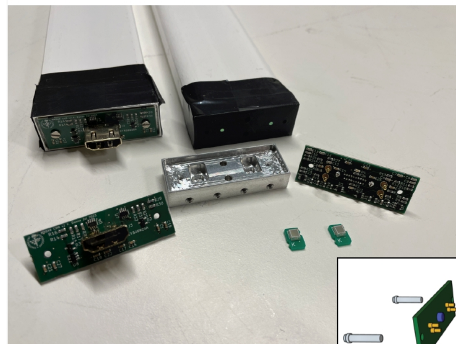


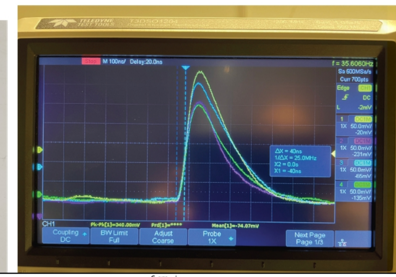
HIBEAM Prototypes

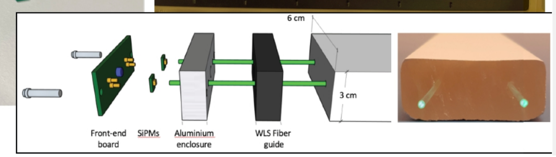
S. Silverstein (Stockholm University)
M. Wolke (Uppsala University)
A. Oskarsson (Lund University)
B. Rataj (Lund University)
E. Kemp (UNICAMP)
A. Kozela (IFJ PAN)
K. Pysz (IFJ PAN)
M. Holl (ESS)
T. Quirino (UERJ)
J. Amaral (UERJ)

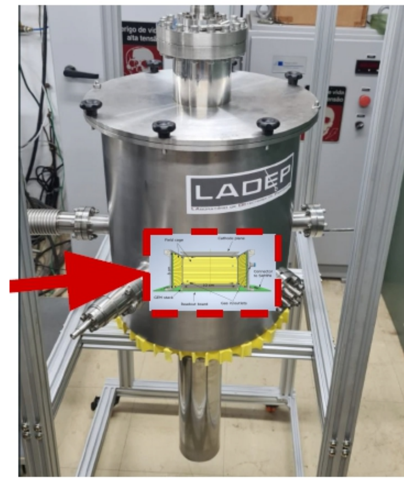

TPC with cosmic trigger scintillators

HRD prototype

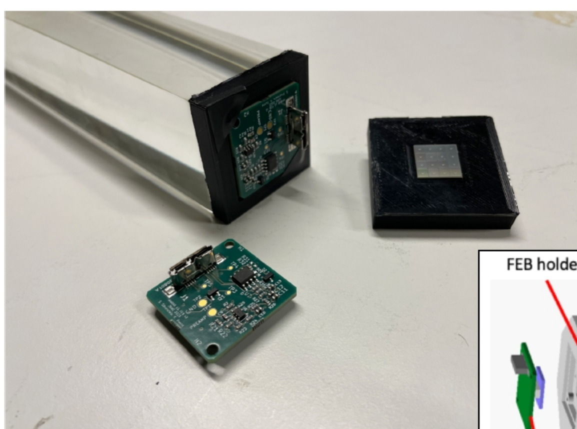




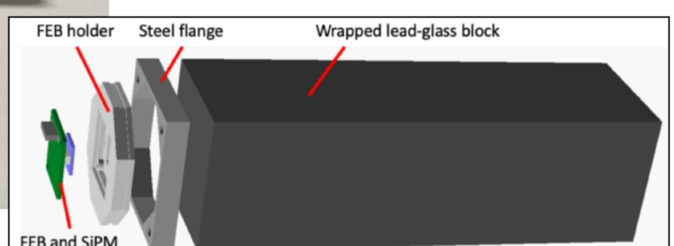




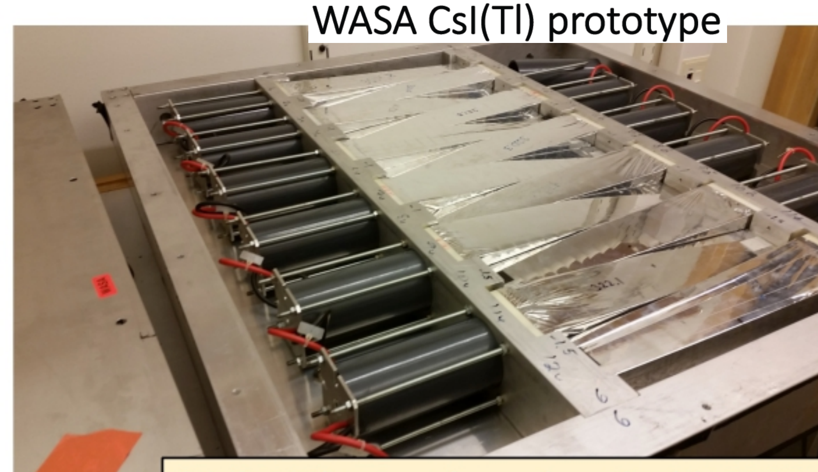
LEC prototype



- The LEC front-end board is based on the HRD design.
- We will produce a revised version once the HRD front-end is validated



WASA CsI(Tl) prototype


24 CsI(Tl) crystals equipped with PMTs

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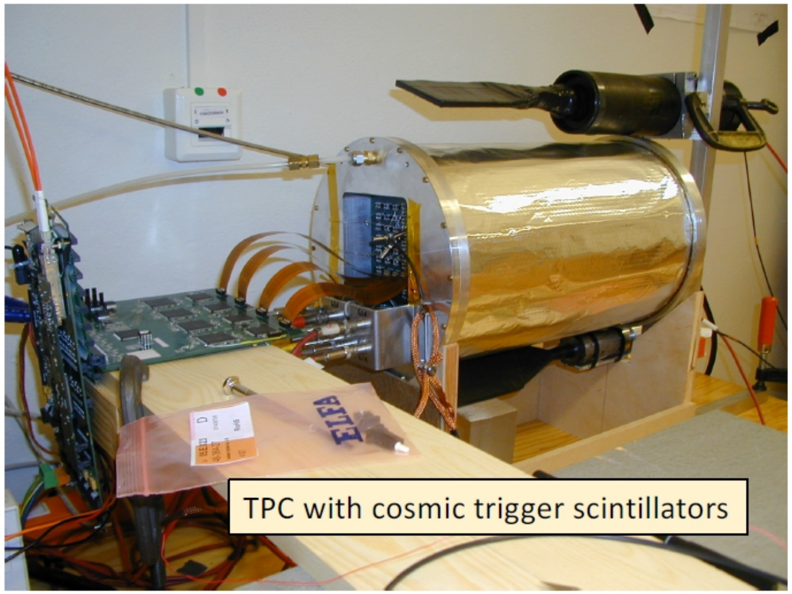
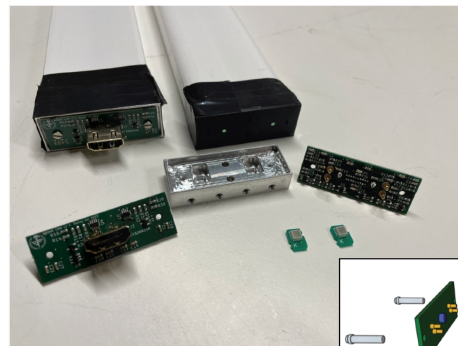
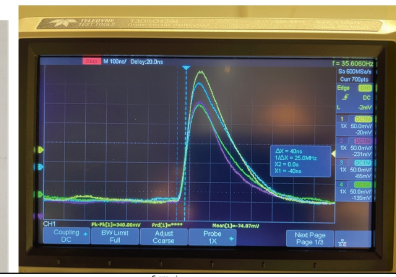
Cosmic veto system being developed in Krakow!

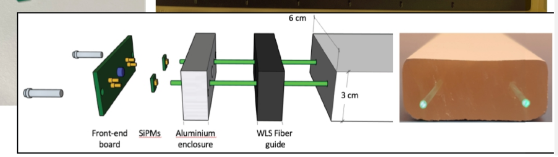


TPC with cosmic trigger scintillators

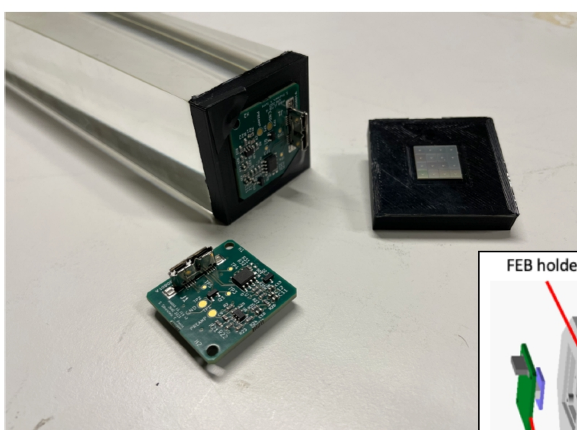
HRD prototype







LEC prototype



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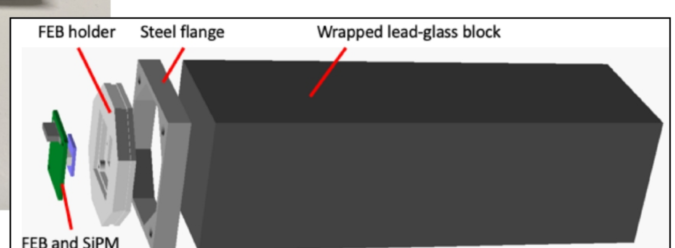
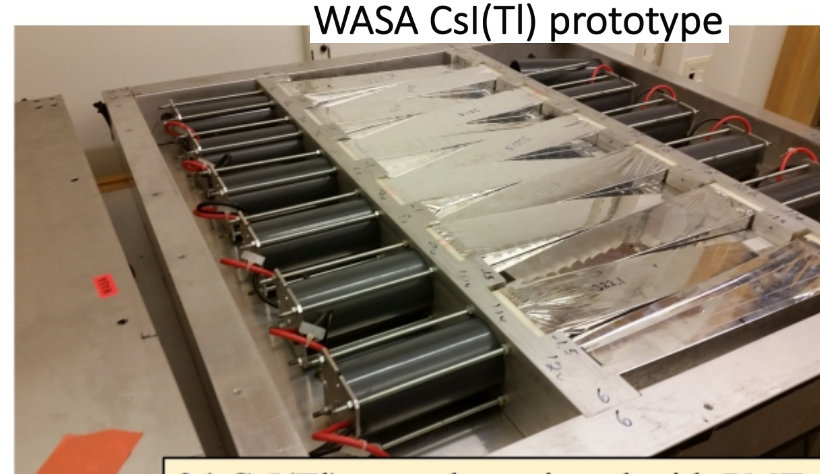


WASA CsI(Tl) prototype



24 CsI(Tl) crystals equipped with PMTs

Readout

Table 1: Estimated channel numbers and readout parameters for the HIBEAM subdetectors

Subdetector	#channels	Dynamic range	Data size	Readout
TPC	2600 ASICs	10 bits	~1.5 kb/track	Free running (possible trigger)
HRD	1400 staves 5600 SiPMs	10-12 bits	~128-192 b/hit/ch	Self-triggered
LEC	15000 counters 15000 SiPM arrays	11-13 bits	~128-192 b/hit/ch	Self-triggered
Cosmic veto	1000 staves 2000 SiPMs	~10 bits	~100 b/hit/chan	Self-triggered

- HRD, LEC and veto have “fast” channels (~ns level) timing information critical for s/b.
- TPC track information arrives later and must be matched to hits recorded in the calorimeters.
- Initial event candidate identification based on calorimeter and veto data.
- Separate TPC readout in parallel with the other subdetectors

- PANDA self-triggered DAQ readout system is suitable for HIBEAM.
- The PANDA DAQ is a good paradigm for HIBEAM
- Also exploits existing investment within the collaborating institutes

Expected rates

Table 4: Simulated cosmic ray background flux at the detector using CRY. The data is sorted by ranges of kinetic energy (KE) and shown for various particle types.

Cosmic Ray Background Particle Flux ($m^{-2}s^{-1}$)					
KE(GeV)	Muon	Electron	Proton	Neutron	Gamma
0-0.5	20.9	48.7	2.49	52.2	292
0.5-1	23.7	1.26	0.570	1.72	1.44
1-5	94.2	0.68	0.448	0.855	0.552
5-10	32.1	0.25	0.0202	0.0196	0.0139
10-50	25.3	0.0	0.0121	0.0105	0.00204
$>$50	2.26	0.0	0.00810	0.000631	0.000150

Table 5: The expected number of incoming cosmic particles in 3 years of running time using CRY. The data are split into different ranges of kinetic energy (KE) and shown for various particle types.

Expected number of cosmic ray background particles					
KE(GeV)	Muon	Electron	Proton	Neutron	Gamma
0-0.5	1.98×10^9	4.60×10^9	2.36×10^8	4.94×10^9	2.76×10^{10}
0.5-1	2.24×10^9	1.19×10^8	5.39×10^7	1.62×10^8	1.36×10^8
1-5	8.91×10^9	6.41×10^7	4.24×10^7	8.09×10^7	5.22×10^7
5-10	3.03×10^9	2.40×10^6	1.91×10^6	1.85×10^6	1.31×10^6
10-50	2.39×10^9	0.0	1.14×10^6	10.1×10^5	1.93×10^5
$>$50	2.14×10^8	0.0	7.67×10^4	5.97×10^4	1.42×10^4

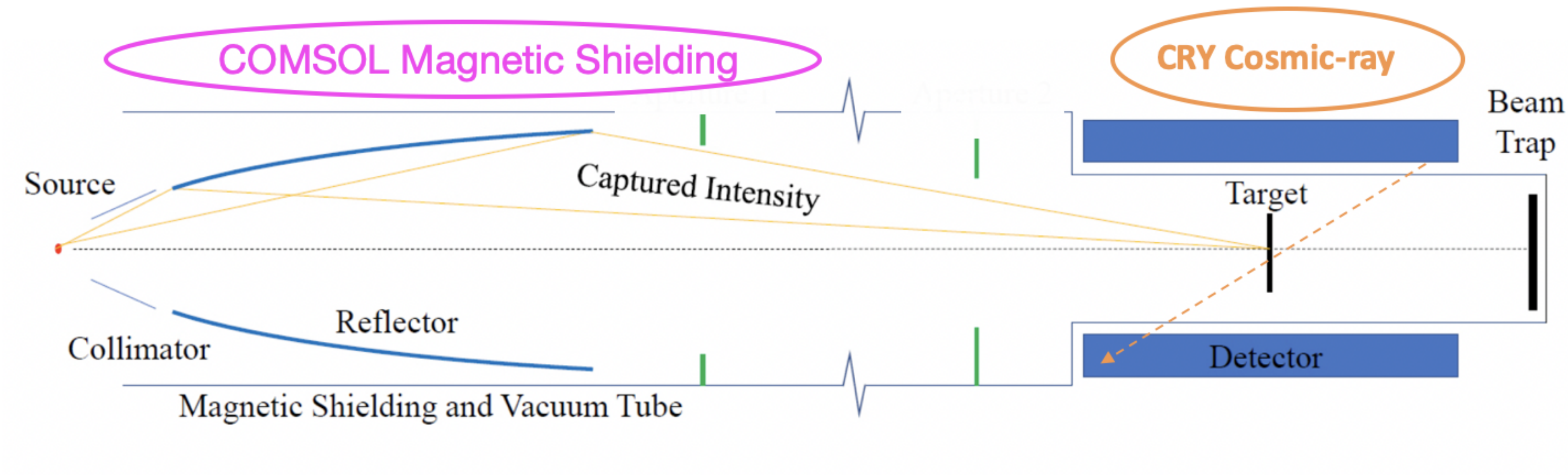
Computing

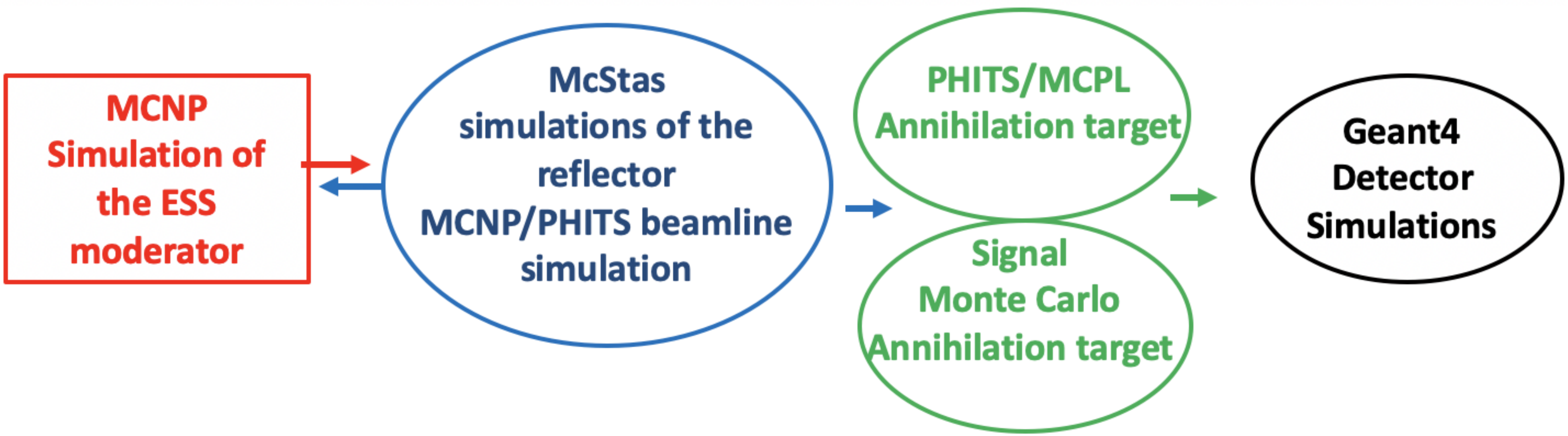
Computing in HIBEAM-NNBAR

- As a “in development” stage experiment, computing and simulations are core activities.
- Simulations play a role in defining technologies and experimental design since ultimate decision is an interplay between cost and performance.
- **Future:** Fast simulation development to use prototype-informed resolutions and efficiencies due to the impracticality of generating enough Monte Carlo events for three years of data.

Simulation Framework

HIBEAM-NNBAR Simulation Framework





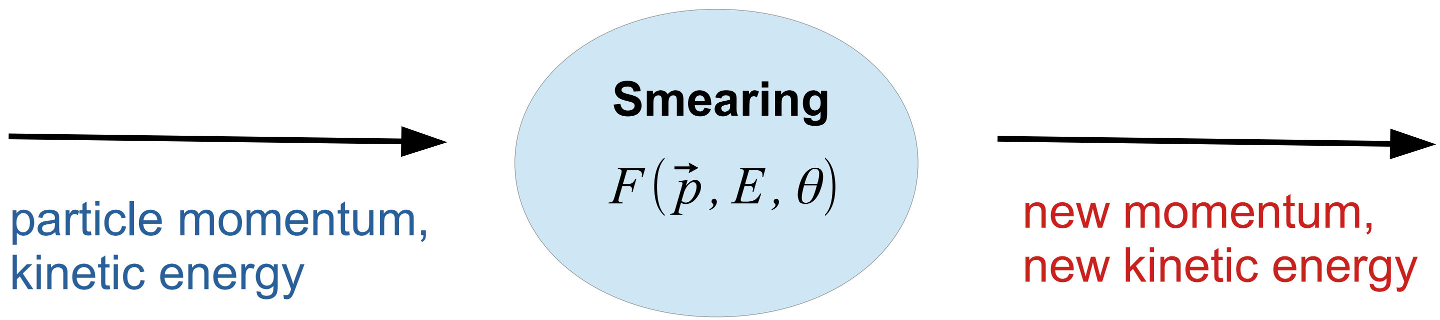
Fast Simulation in Geant4

Fast Simulation

A. Nepomuceno (UFF)

Goal: to develop a Geant4 application to perform fast simulation of a given NNBAR detector model.

Idea: Parametrization of the overall response of each sensitive detector



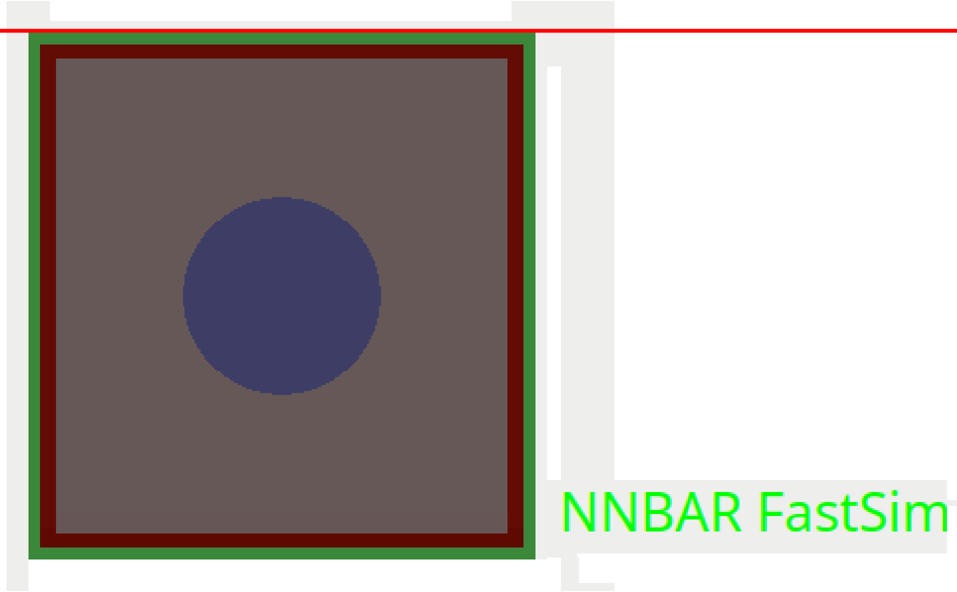
The parametrization must accounts for physical effects, the detector performance and the reconstruction procedure.

Fast Simulation – Two Approaches

Two Approaches have been developed:

- "Generic" Detector : the energy is smeared with a Gaussian distribution whose standard deviation are the resolutions of known HEP detectors, but using the NNBAR geometry.
- NNBAR Detector: the energy is smeared according to a model derived from the full simulation. Single particles events of specific energies are simulates in details and response model is derived.

Both approaches use the same simplified geometry (only lead glass and scintillators for the time been).



Fast Simulation – Generic Detector

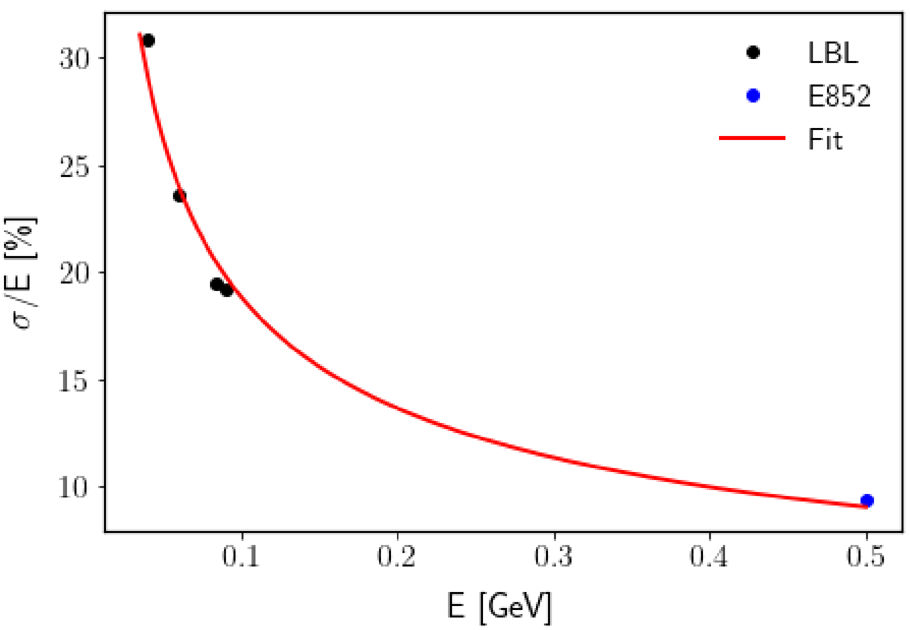
A. Nepomuceno (UFF)

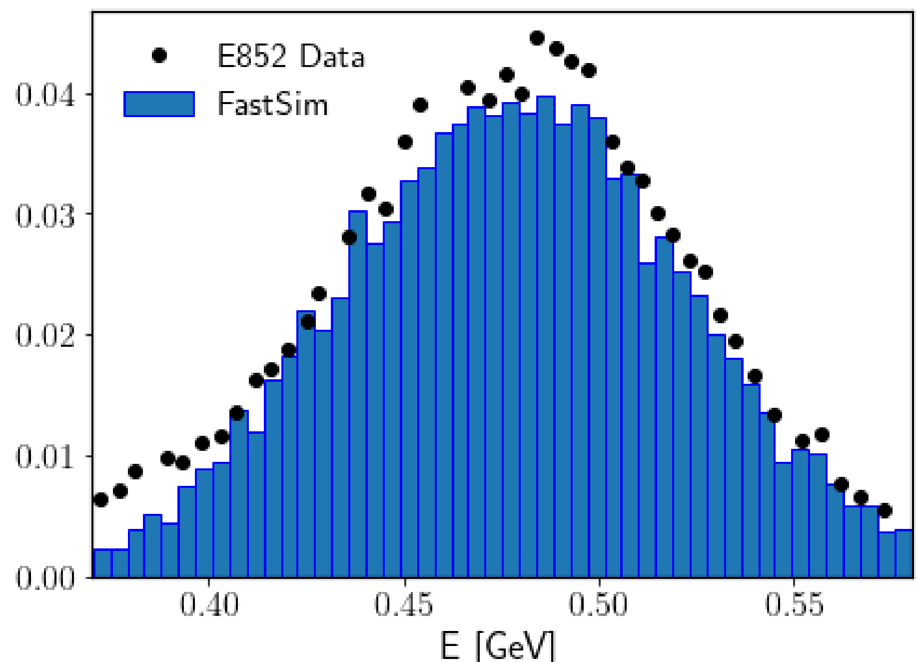
Model resolution for the Lead Glass Calorimeter

Model based on test beam data from

1. M P Budiansky *et al* NIMA 199 (1982) 453-460)
2. BB Bradson *et al* NIMA A 332 (1993) 419-443
3. The PHENIX Collaboration, NIMA A 499 (2003) 521-536

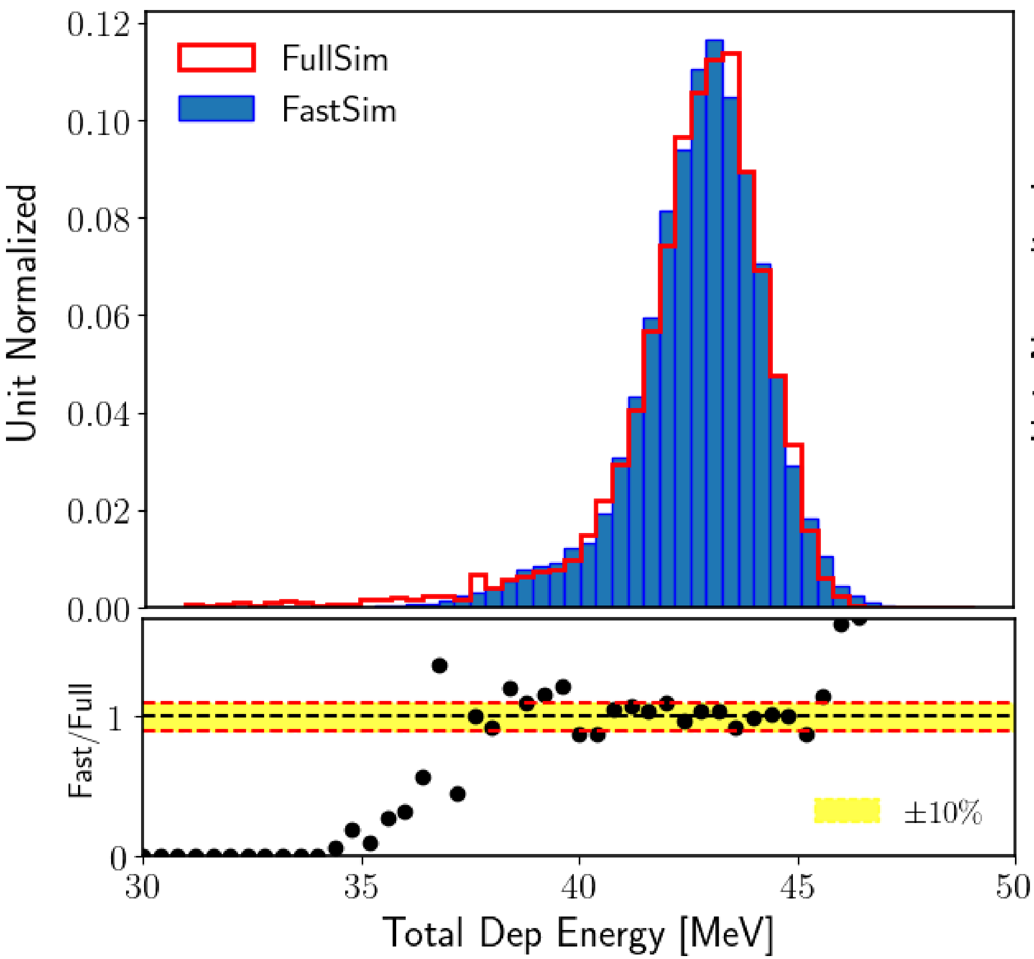
$$\frac{\sigma}{E} = \frac{5.6\,\%}{\sqrt{E[GeV]}} + 1.1\,\%$$

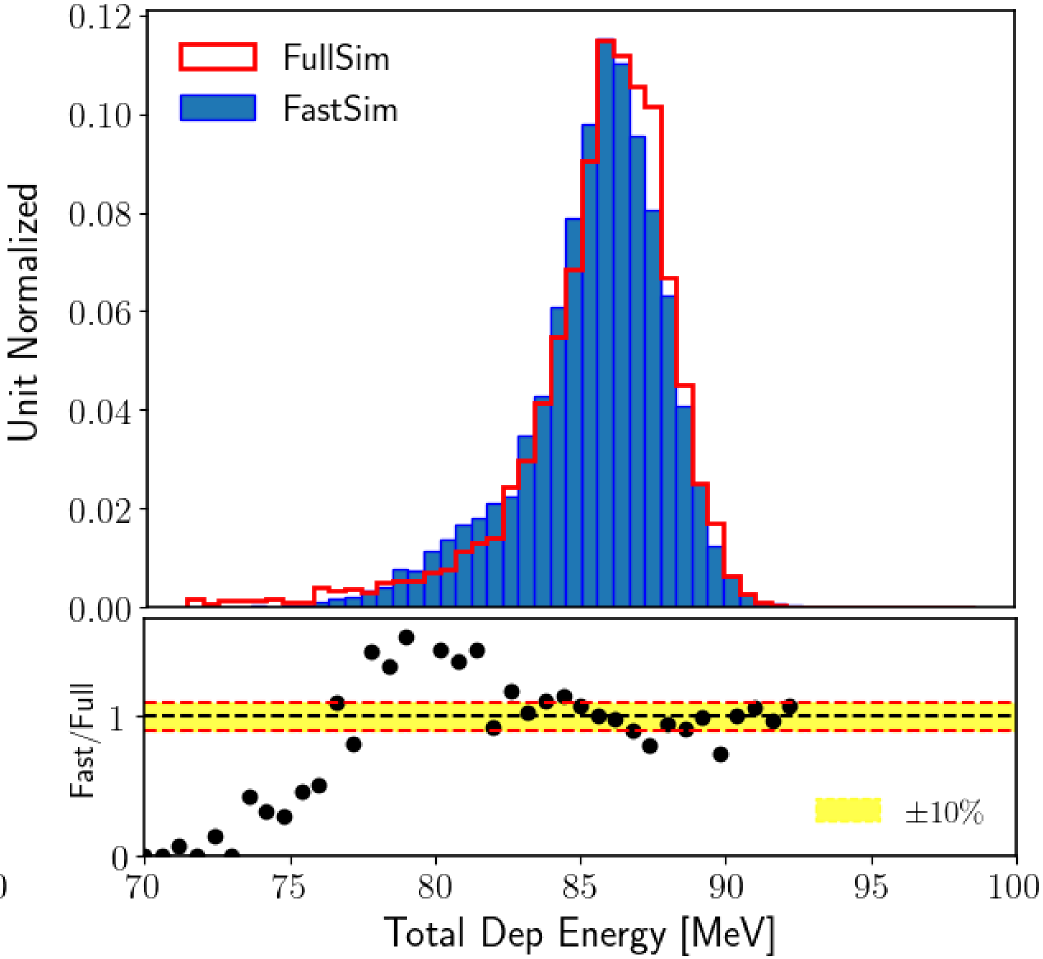




Fast Simulation – NNBAR Lead Glass

The Gaussian used for smearing in each event is randomly selected based on a probability derived from the full simulation.





Machine Learning

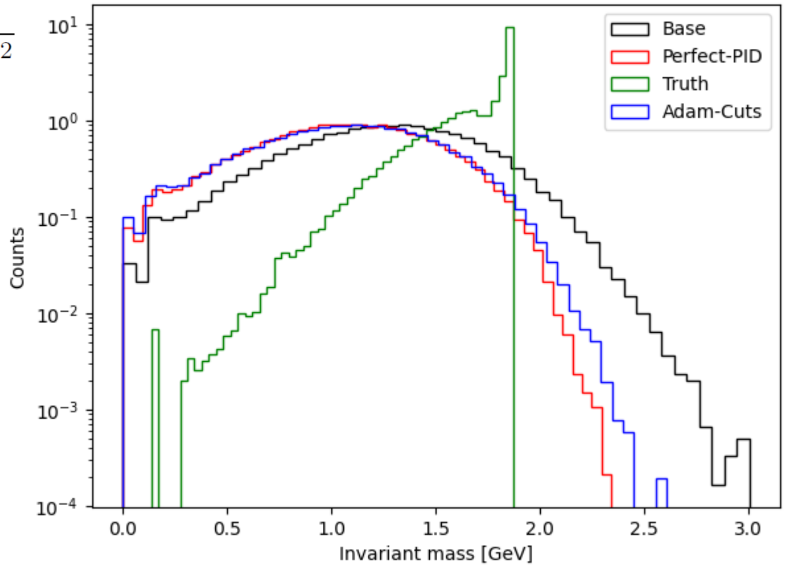
Particle identification

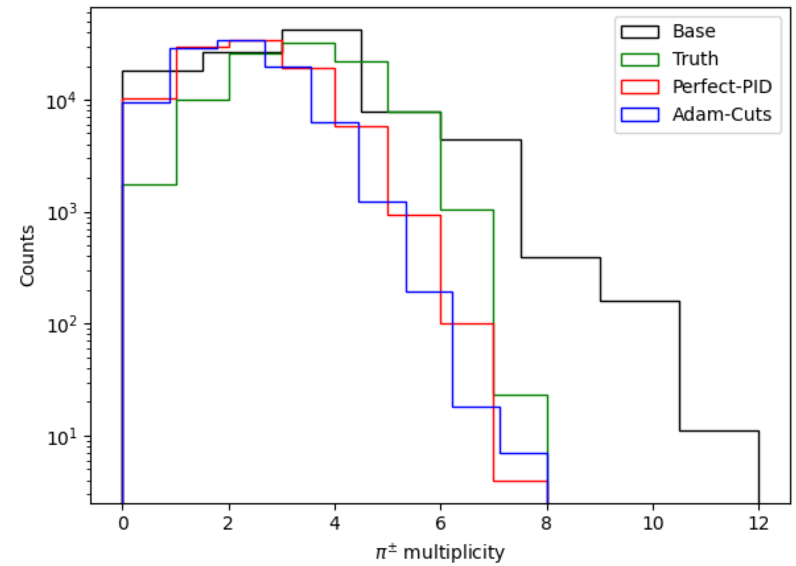
L. Åstrand (Lund University)

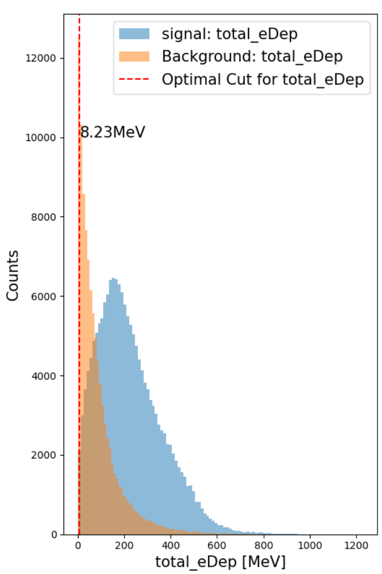
$$W = \sqrt{\left(\sum_i E_i\right)^2 - \left|\sum_i \vec{p}_i\right|^2}$$

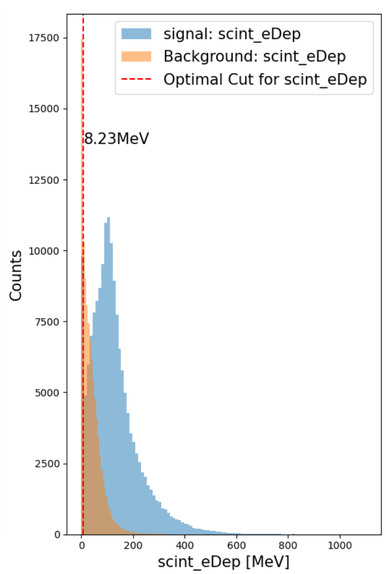
$$E_n = \sqrt{m_n^2 + p_n^2}$$

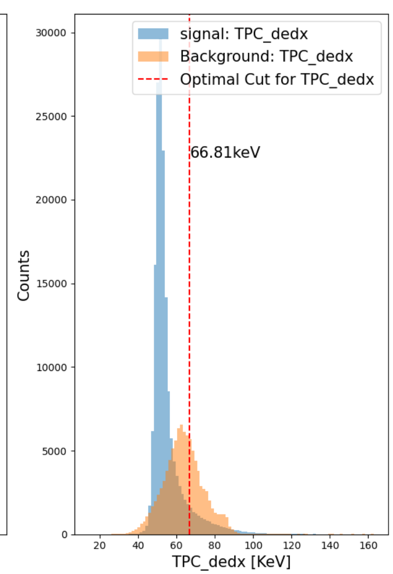
$$p_n = \sqrt{\mathrm{KE}_n^2 + 2 \cdot \mathrm{KE}_n \cdot m_n}$$







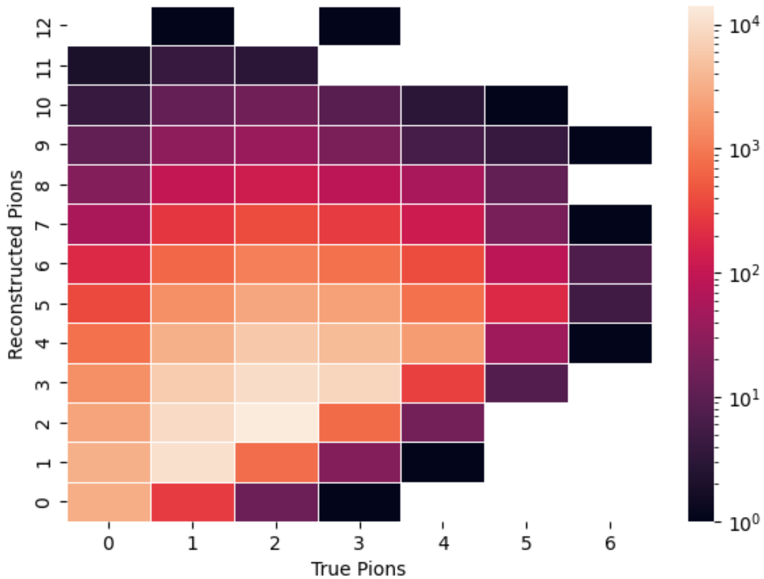


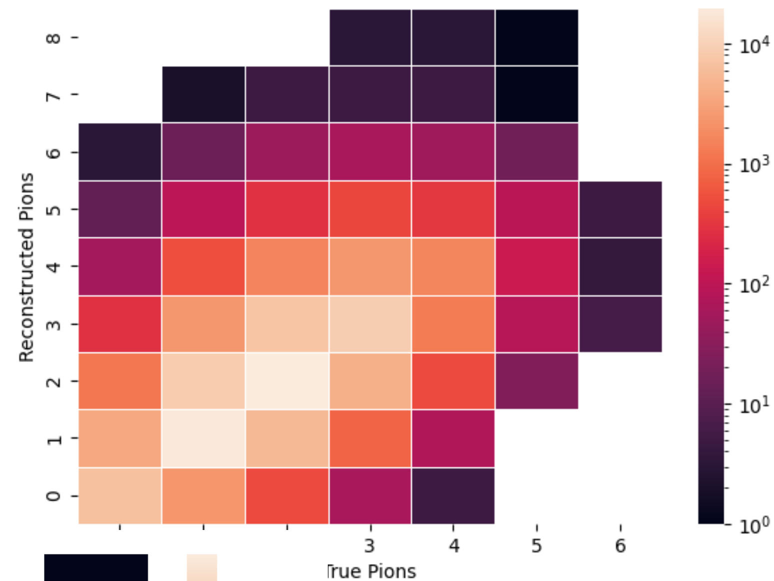


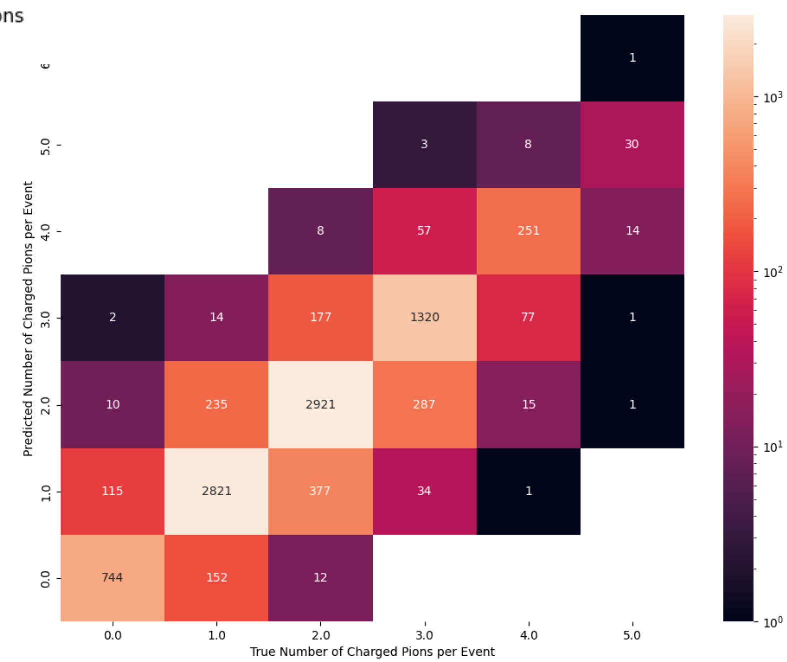
Cut	$\pi^{\pm}$	$e^{\pm}_{\mathrm{miss}}$
Tot_eDep > 8.23 MeV	99%	91%
scint_eDep > 8.23 MeV	97%	79%
TPC_dedx < 66.81 keV	86%	44%

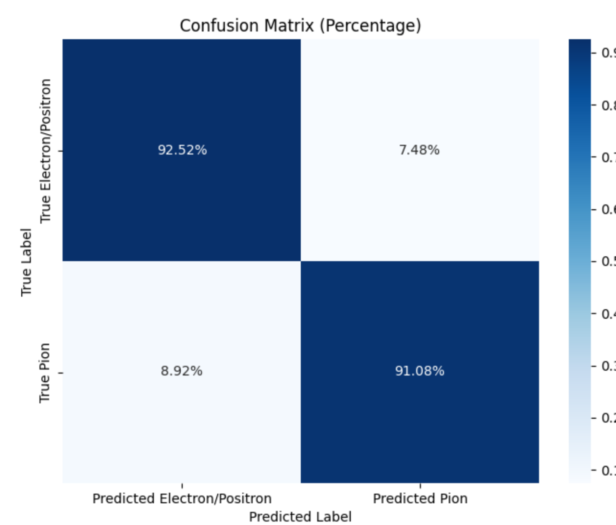
L. Åstrand (Lund University)

Particle identification









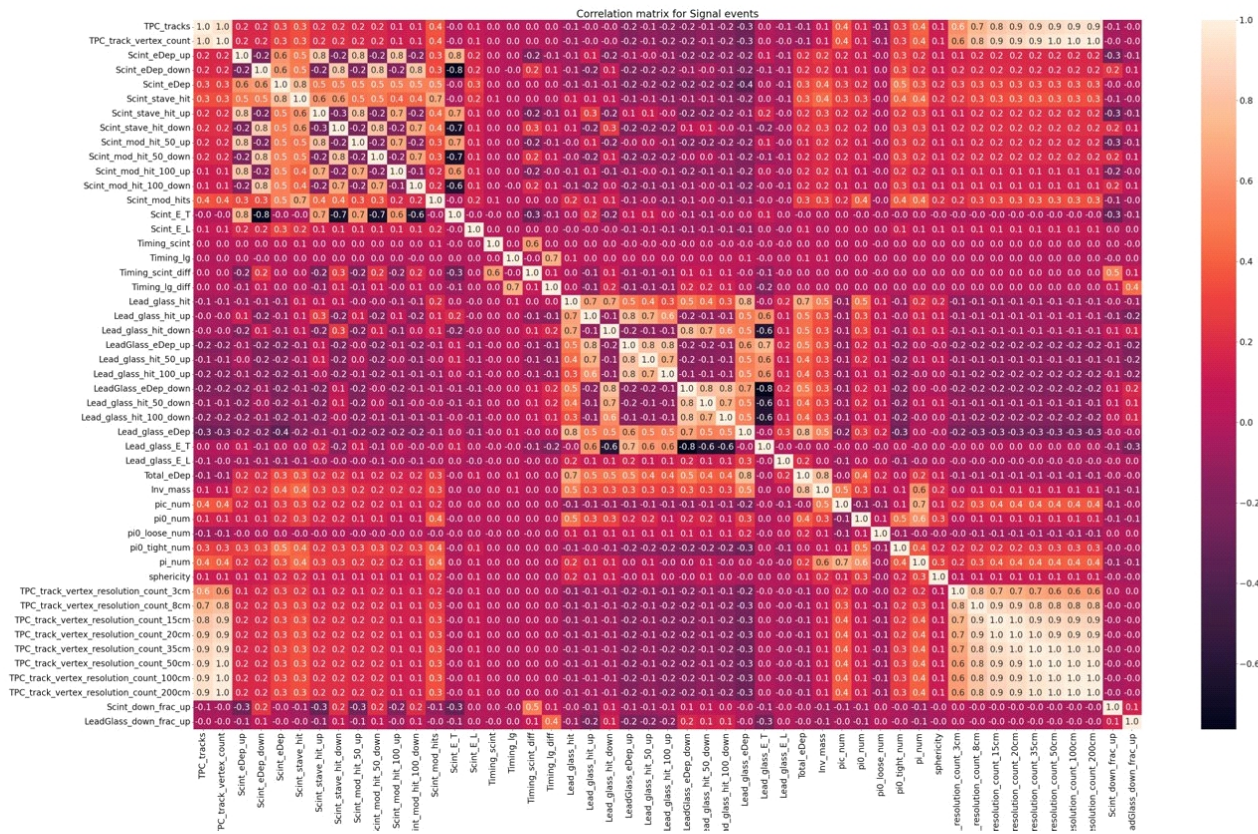
Event selection with ML

- HIBEAM-NNBAR focus on rare even searches
- Requires zero background
- Strategy different from usual “optimize S/B”
- Attention to overtraining
- Final result important but equally: what can be learned?

W. Lejon (Stockholm University)

Correlations

- 49 detector variables (6 groups)
- Decrease used variables: 49 → 18
- Example of variables: number of pions, invariant mass, sphericity, transversal energy of the lead glass modules, time difference between the first activation in the top and bottom scintillator staves/lead-glass modules, etc.



ML event selection in HIBEAM

Train and Seach for hyperparameters

Find the threshold } 50%

Performance on unseen data } 50%

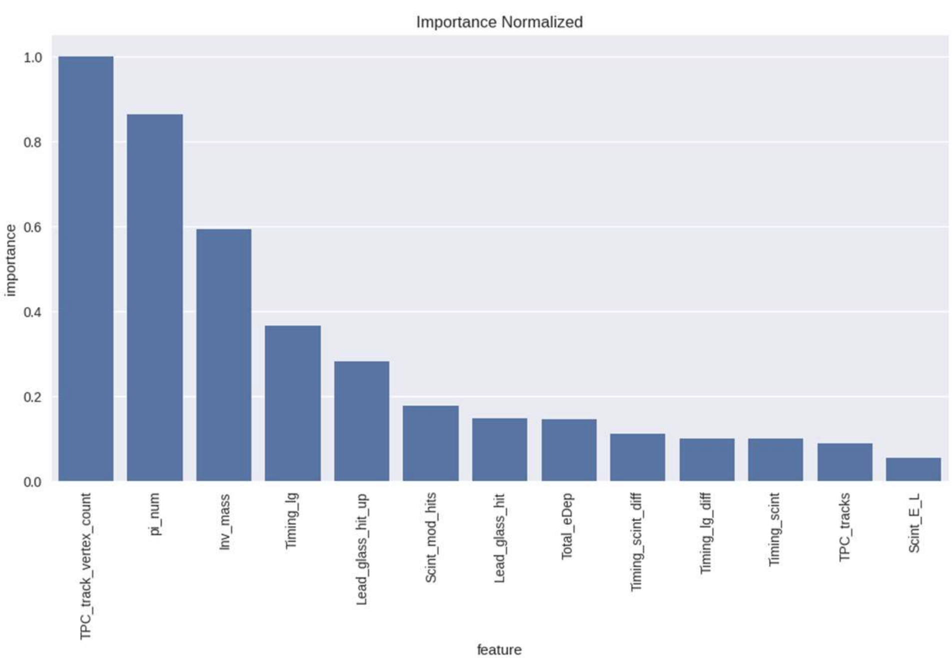
J. Amaral (UERJ)

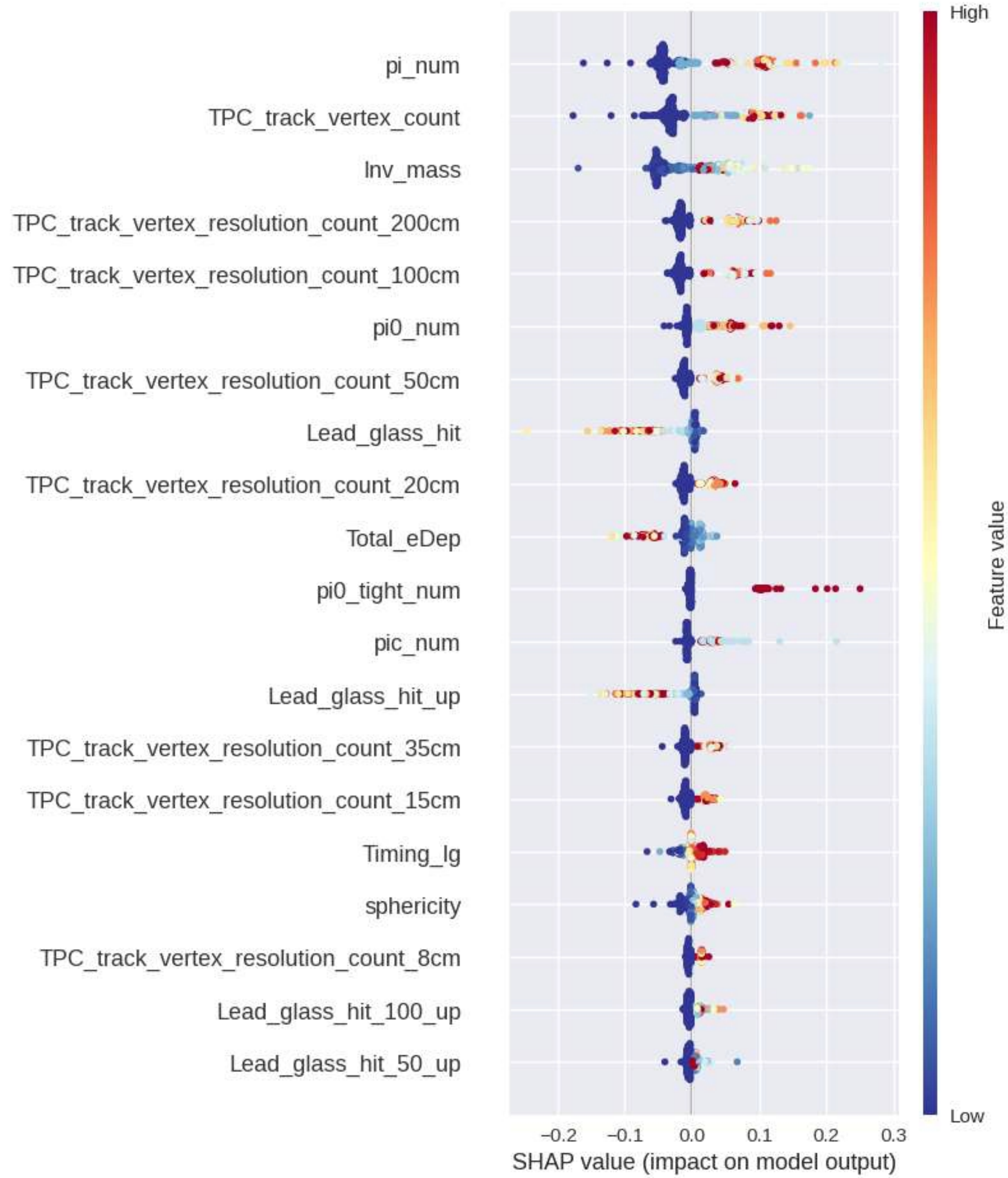
Model	Metric	Variables	Rejection before	Efficiency before	Threshold	Rejection after	Efficiency after
Random Forest (WL)	Accuracy	51	99.91	99.45	0.973	100	92.92
Random Forest (optuna)	Custom	51	99.88	99.44	0.933	100	95.81
XGB (optuna)	Custom	51	99.86	99.71	0.999	100	98.71
LGBM (optuna)	Custom	51	99.88	99.70	0.999	100	98,69
LGB(optuna) +correlation selection (0.85)	Custom	26	99.73	99.76	0.997	100	98%
LGB(optuna) +PCA	Custom	17	99.74	98.55	0.999	100%	74%

What can we learn?

J. Amaral (UERJ)

- SHAP (SHapley Additive exPlanations) explains individual model predictions by calculating each attribute's contribution.
- It is based on Shapley Values, which fairly distribute contributions among team members in cooperative games.
- SHAP ensures a fair assessment of each attribute's impact on the model's prediction.





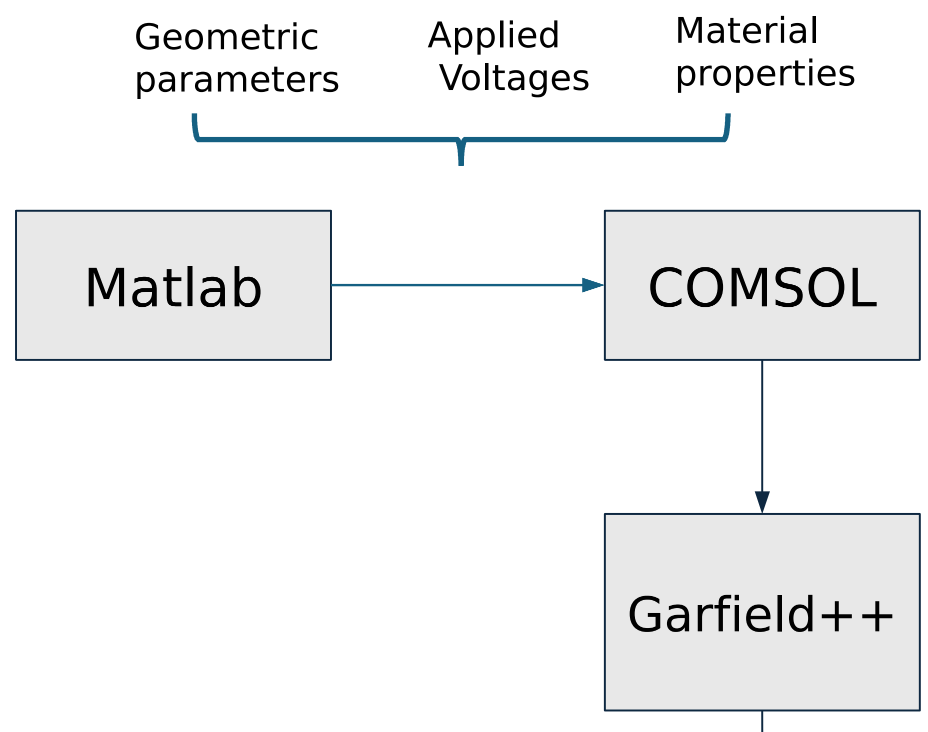
Summary and outlook

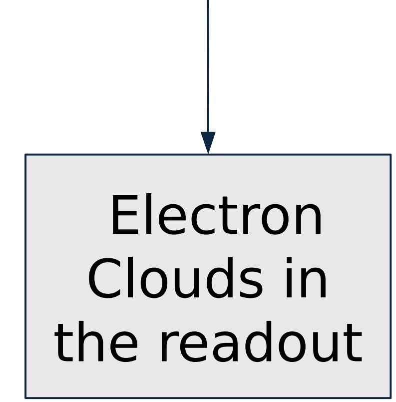
- BNV is expected in Nature.
- HIBEAM/NNBAR active experimental program for the ESS.
- Addresses BNV (ΔB = 1 and ΔB = 2)!
- HIBEAM – world leading sterile neutron searches + pilot free $n \longrightarrow \bar{n}$ search.
- NNBAR – world leading neutron-antineutron oscillation searches.
- HIBEAM-NNBAR computing program diverse, with simulation and computing guiding efforts on many fronts, from data analysis to hardware simulations.

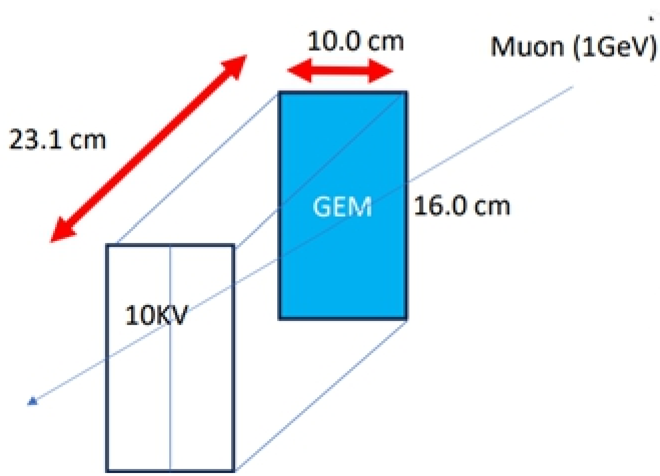
TPC prototype simulation

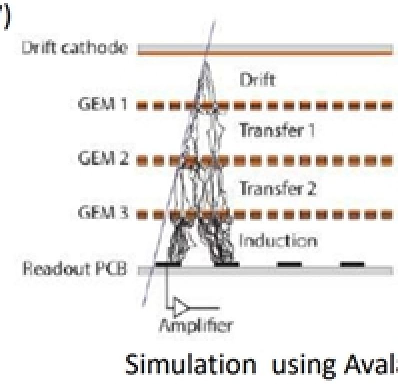
J. Amaral (UERJ)

- Simulating TPC prototype in Garfield++ to study electron cloud arrival at readout pads.
- Zig-zag pad geometry optimization aims to improve resolution.
- Simulation combines Matlab (interface), COMSOL (mesh, electric field), and Garfield++ (electron cloud behavior).
- Electron cloud dispersion is 0.12 mm; Optuna optimizes pad geometry.
- Optimized zig-zag pads reduce mean absolute error from 0.95 mm to 0.45 mm.







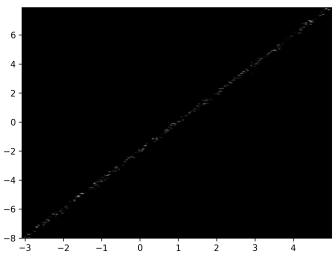


TPC prototype simulation

J. Amaral (UERJ)

COMSOL/Garfield ++

Electron clouds in the readout

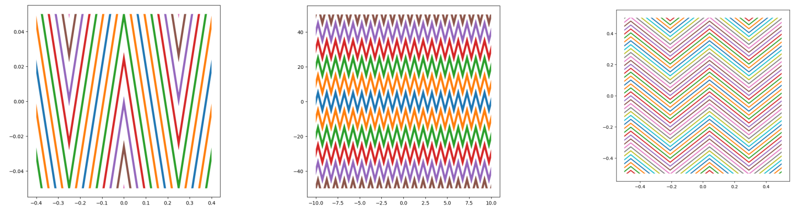


Optimizer

Function to optimize:
Mean Absolute error and the percentagem of electrons that reach the readout pads.

Different zig-zag configurations

Try different geometric parameters for the zig-zag readout



For each electron cloud i do

Calculate the position
X(i)

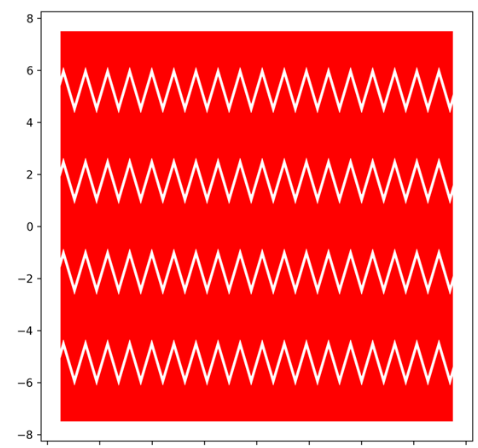
Calculate the Error
Error (i)= X(i)- X_{true}(i)

End for

Calculate mean Absolute error

Penalties: The algorithm penalizes the number of tracks in excess.

Result from the optimization (zoom)
27 tracks MAE: 0.45 mm



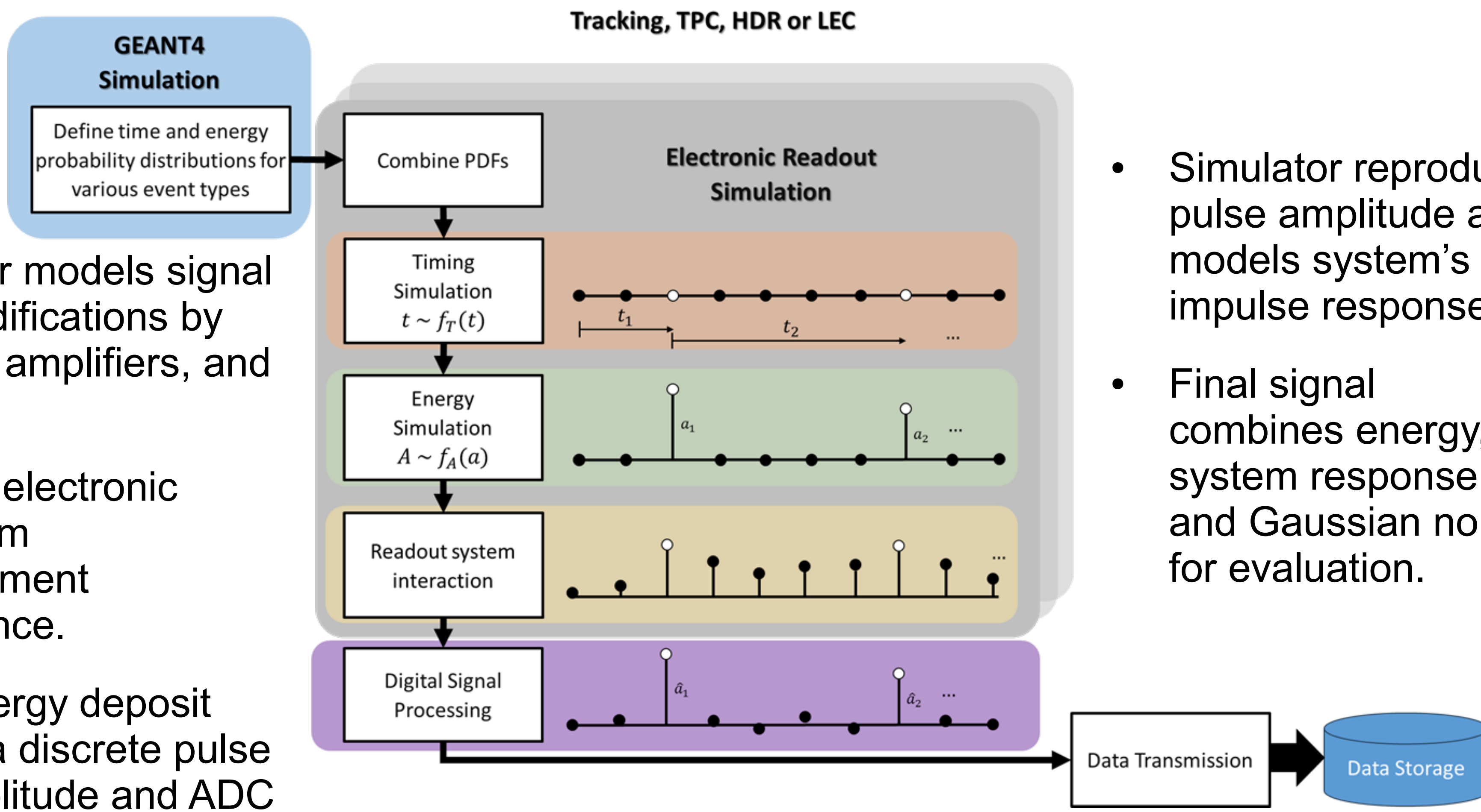
Prototype simulations

Dziękuję!

Backup

Readout simulations

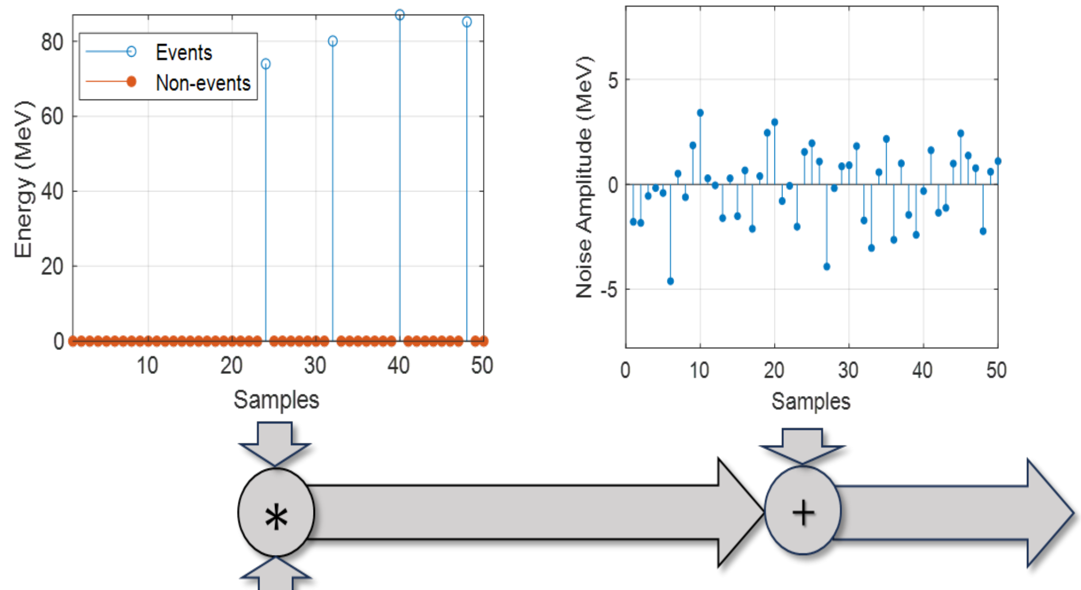
T. Quirino (UERJ)

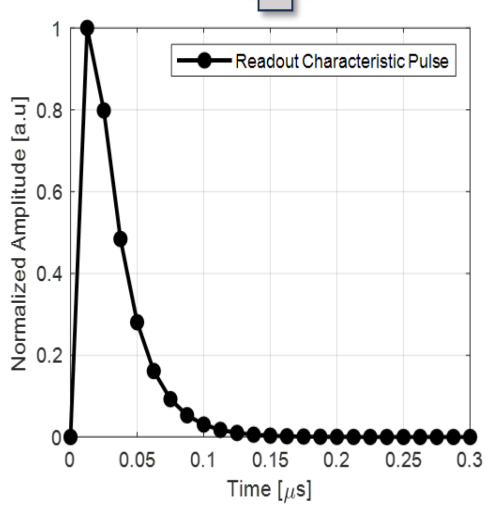


- Simulator models signal post-modifications by sensors, amplifiers, and circuits.
- Includes electronic noise from measurement interference.
- Each energy deposit creates a discrete pulse with amplitude and ADC duration.
- Event intervals are based on GEANT simulations and a probability distribution.

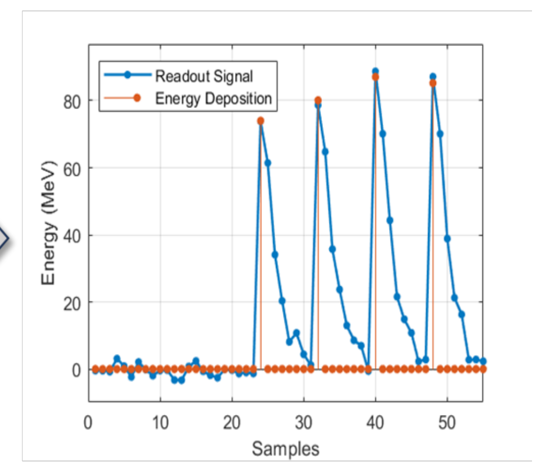
- Simulator reproduces pulse amplitude and models system's impulse response.
- Final signal combines energy, system response, and Gaussian noise for evaluation.

Hadronic Range Detector (HRD) Signal Simulation





T. Quirino (UERJ)



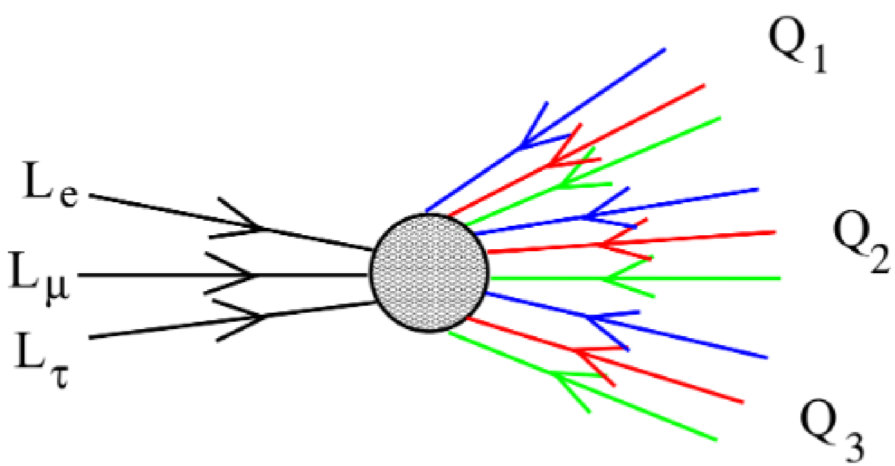
* is a convolutional operator, that combines the readout models system's impulse response and energy deposit signal.

Why Baryon Number Violation?

Baryon number in the SM

- Even within the SM, B is subject only to approximate conservation law.
- In fact only B-L is exactly conserved.
- BNV exists in the SM baryon due to nonperturbative effects (t'Hooft [Phys. Rev. Lett. 37 (1976) 8]).
- Baryon number can be violated by triangle anomaly, where left handed quarks annihilate with leptons.

$$\partial_\mu J^\mu_{B_L+L_L} = \frac{3g}{32\pi}\epsilon_{\mu\nu\rho\sigma} W_a^{\mu\nu} W_a^{\rho\sigma}$$



$$\Delta B = \Delta L = \pm 3$$

- **1. Tiny effects imply that the minimal Standard Model already has B violation.**
- **2. However: SM B violation too small to produce observed baryon asymmetry!**

Precision tests of the equivalence principle

- Electromagnetic gauge invariance leads to electric charge conservation → true local symmetry with associated gauge boson (photon).
- Baryon number is only global symmetry → no associated mediator.
- Precision tests of equivalence principle offer **no evidence for a long range force coupled to baryon number.**

Test of the Equivalence Principle Using a Rotating Torsion Balance

S. Schlamminger, K.-Y. Choi, T. A. Wagner, J. H. Gundlach, and E. G. Adelberger
Phys. Rev. Lett. **100**, 041101 – Published 28 January 2008

- **Meaning:**

  Suppose there is a small Coulomb-like force coupling to B=number of protons+neutrons in a nucleus.

  Different chemical elements would fall at a different rate because the B per kilogram is a bit different due to the binding energies.

- Key (missing!) requirement for hypothetical local gauge symmetry forbidding BNV.

NNBAR

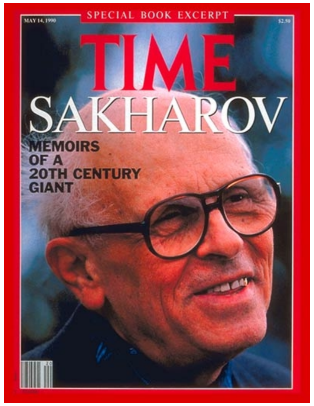
Sakharov conditions for baryogenesis

- Baryogenesis: hypothetical physical process that took place in the early Universe responsible for baryon asymmetry.
- Necessary ingredients needed to create a baryon asymmetry:
- **1. Baryon number violation (BNV)**
- **2. Loss of thermal equilibrium**
- **3. C, CP violation**
- These principles have come to be attributed to Sakharov (JETP Lett. 5 1967).

Violation of *CP* invariance, *C* asymmetry, and baryon asymmetry of the universe

A. D. Sakharov

(Submitted 23 September 1966)
Pis'ma Zh. Eksp. Teor. Fiz. **5**, 32–35 (1967) [JETP Lett. **5**, 24–27 (1967).
Also S7, pp. 85–88]



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- Necessary ingredients needed to create a baryon asymmetry:
- **1. Baryon number violation (BNV)**
- **2. Loss of thermal equilibrium**
- **3. C, CP violation**
- These principles have come to be attributed to Sakharov (JETP Lett. 5 1967).
- **Need for BNV is obvious**.

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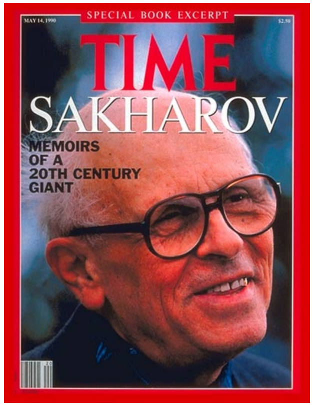
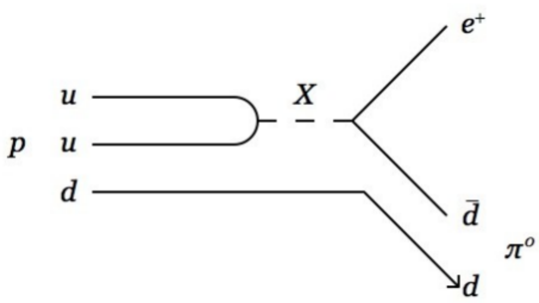


Testing selection rules

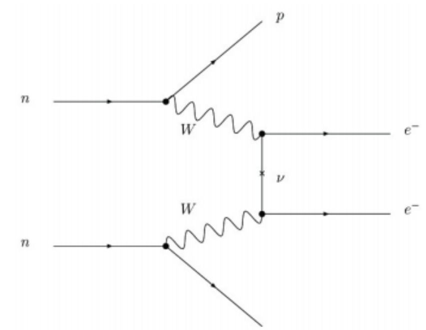
- Neutron oscillations provide **clean channel to probe BNV-only process.**
- From a purely experimental point: test different selection rules for BNV and LNV.

Proton decay
$p \rightarrow e^{+} + \pi^{0}$



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

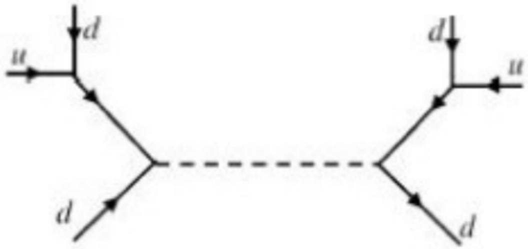
Neutrinoless double beta decay
$0\nu 2\beta$



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

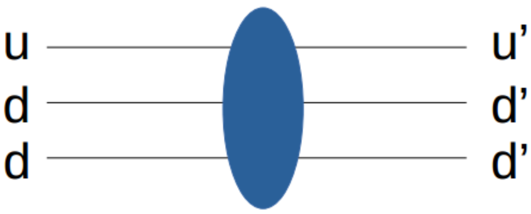
Neutron Oscillation

Neutron antineutron oscillation
$n \rightarrow \bar{n}$



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

Neutron sterile neutron oscillation
$n \rightarrow n'$



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

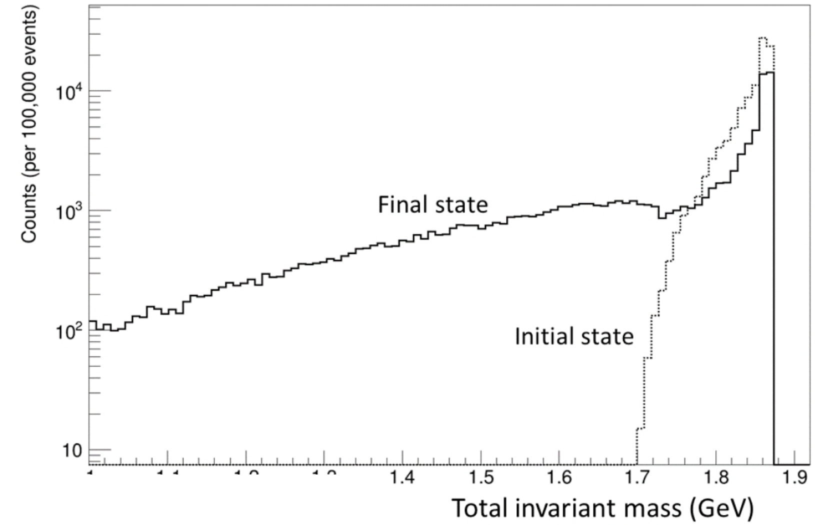
List of backgrounds

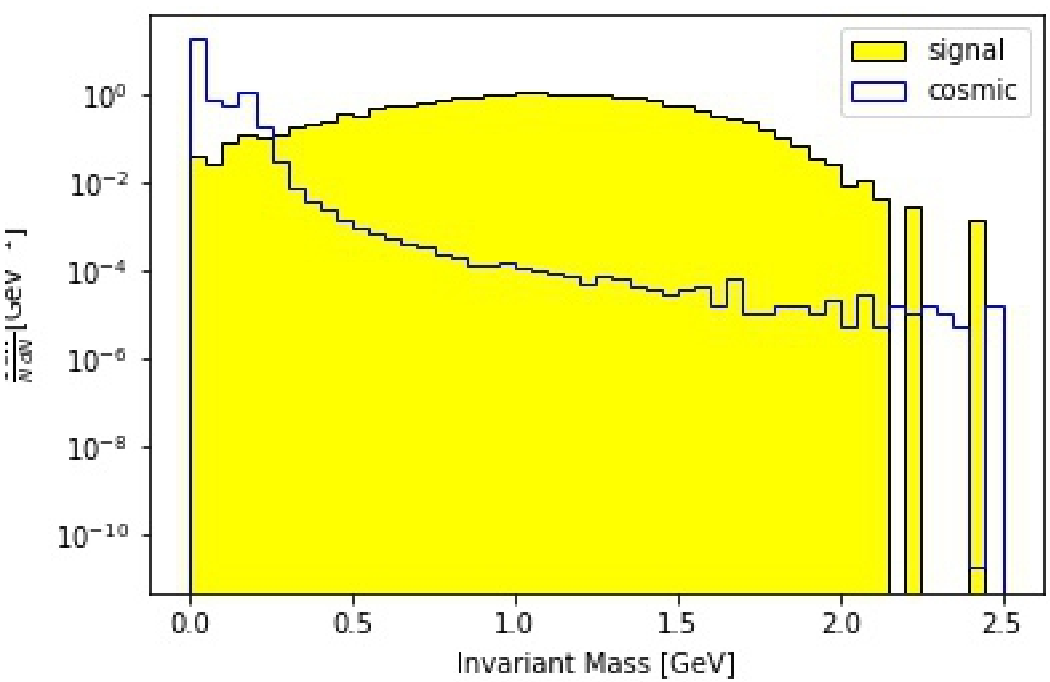
- Cosmic rays
- Neutron capture in the annihilation target $\rightarrow$ gammas
- Neutron capture at the neutron guide $\rightarrow$ gammas
- Accelerator skyshine
- Neutron cross-talk from neighboring beamlines
- Free neutron background (if neutrons decay inside tracker)
- *High energy spallation backgrounds*

Invariant mass

$$W = \sqrt{\left(\sum_i E_i\right)^2 - \left|\sum_i \vec{p}_i\right|^2}$$

$$E_n = \sqrt{m_n^2 + p_n^2} \qquad p_n = \sqrt{\mathrm{KE}_n^2 + 2 \cdot \mathrm{KE}_n \cdot m_n}$$





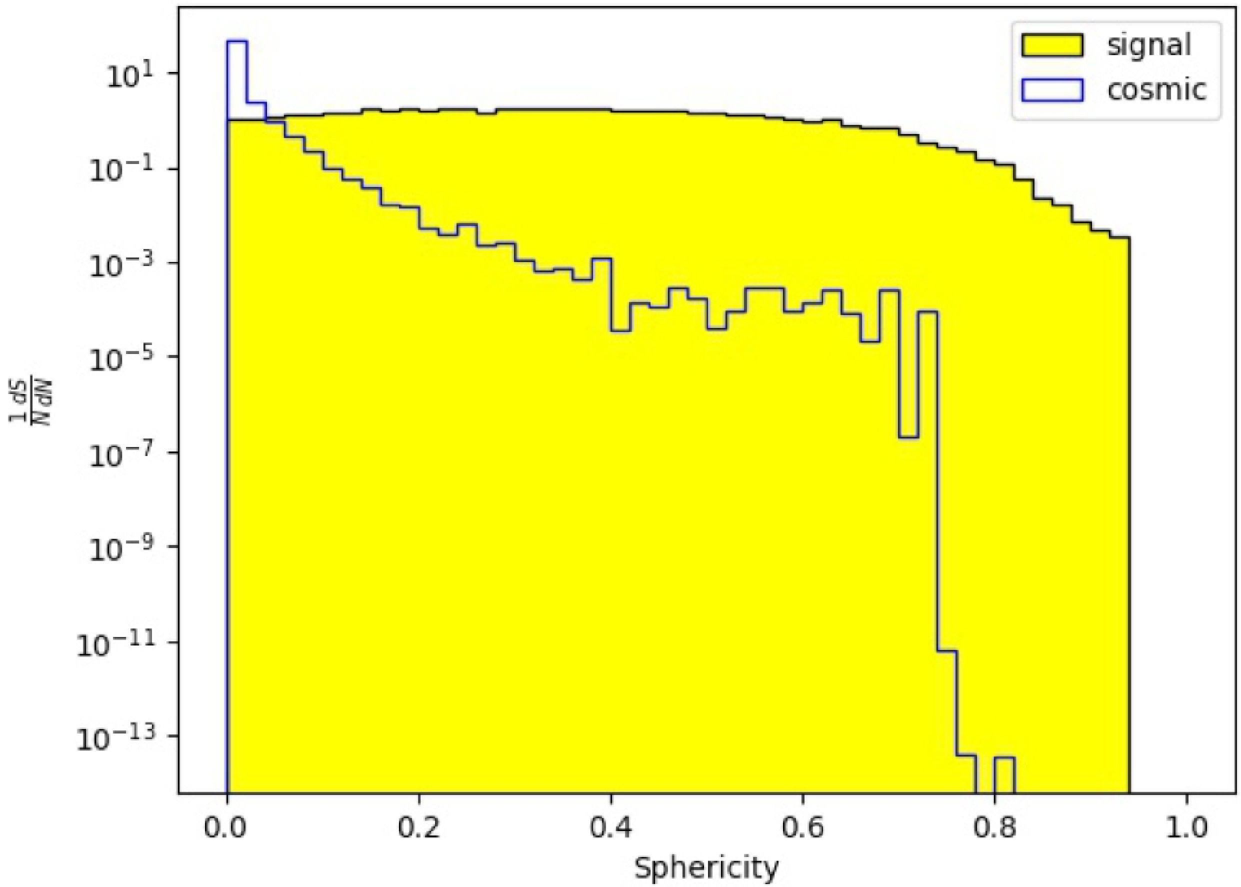
Sphericity

$$M_{xyz} = \sum_i \begin{pmatrix} p_{xi}^2 & p_{xi}p_{yi} & p_{xi}p_{zi} \\ p_{yi}p_{xi} & p_{yi}^2 & p_{yi}p_{zi} \\ p_{zi}p_{xi} & p_{zi}p_{yi} & p_{zi}^2 \end{pmatrix}$$

Eigenvalues $\lambda_1, \lambda_2, \lambda_3$

$\lambda_1 > \lambda_2 > \lambda_3$

$$S = \frac{3}{2}(\lambda_2 + \lambda_3)$$



Event selection

Table 6: Survival portion of annihilation signal events, cosmic ray background, and muon after each consecutive cut with globally optimized thresholds.

Selection	Signal	Non-muon background	Muon background
Scintillator energy loss $\in [20, 2000]$ MeV	0.95	0.15	1.8×10^{-6}
TPC track cut	0.92	7.1×10^{-3}	1.2×10^{-6}
Number of pion ≥ 1	0.86	6.1×10^{-8}	1.1×10^{-8}
Invariant mass $W \geq 0.5$ GeV	0.83	1.4×10^{-8}	9.5×10^{-9}
Sphericity ≥ 0.2	0.73	8.1×10^{-11}	6.1×10^{-9}
$E_{\text{scint}, y>0, \text{filtered}} \leq 320$ MeV & $E_{\text{scint}, y<0, \text{filtered}} \leq 930$ MeV	0.73	-	-

We reach our goal within the limits of our statistics...

Control of fields in which the neutrons propagate

Eg Free $n \longrightarrow \bar{n}$ state

$$\Psi = \binom{n}{\bar{n}} \qquad H = \begin{pmatrix} E_n & \varepsilon \\ \varepsilon & E_{\bar{n}} \end{pmatrix}$$

ε =mixing mass term

Probability to find an antineutron at time t is given by

$$P_{n\bar{n}}(t) = \frac{\varepsilon_{n\bar{n}}^2}{(\Delta E/2)^2 + \varepsilon_{n\bar{n}}^2} \sin^2\left[t\sqrt{(\Delta E/2)^2 + \varepsilon_{n\bar{n}}^2}\right] e^{-t/\tau_n},$$

$\Delta E = E_n - E_{\bar{n}}$ Require degeneracy between $n, \bar{n}$

$\Rightarrow$ Zero magnetic field (<10^{-5} G)

Similarly for $n \longrightarrow n'$

Magnetic field in dark sector

$\Rightarrow$ Scan for -1G <B<+1G in ~mG steps

$n \rightarrow \bar{n}$ probability via sterile neutron

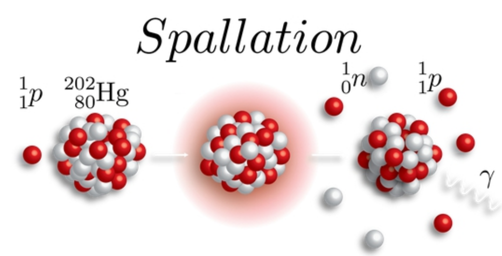
$$P_{n\bar{n}}(t) = \frac{1}{4}\alpha^2_{n\bar{n}'}\alpha^2_{n\bar{n}'}t^4 \sin^2\beta = \frac{\sin^2\beta}{4}\left(\frac{t}{0.1\ \mathrm{s}}\right)^4\left(\frac{10^2\ \mathrm{s}^2}{\tau_{nn'}\tau_{n\bar{n}'}}\right)^2 \times 10^{-8}$$

- Magnetic scans for HIBEAM is analogous to magnetic shielding for NNBAR → reach quasi-free condition
- For NNBAR, $\Delta E \ll t$ (achieved via B < 10 nT)
- For HIBEAM, that's $|\mathbf{B} - \mathbf{B}'| \sim 0$
- B field necessary to compensate B' field to allow $n \rightarrow n' \rightarrow \bar{n}$
- Note: **FOM ~ Nt^4**

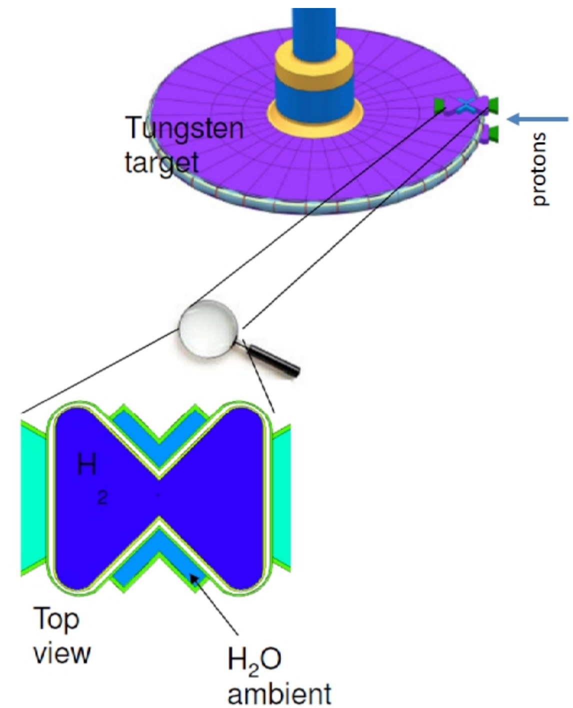
Search for neutron oscillations

- Neutrons are bound in nuclei → several MeV for liberation

→ fission
→ spallation (can be kept under full control)



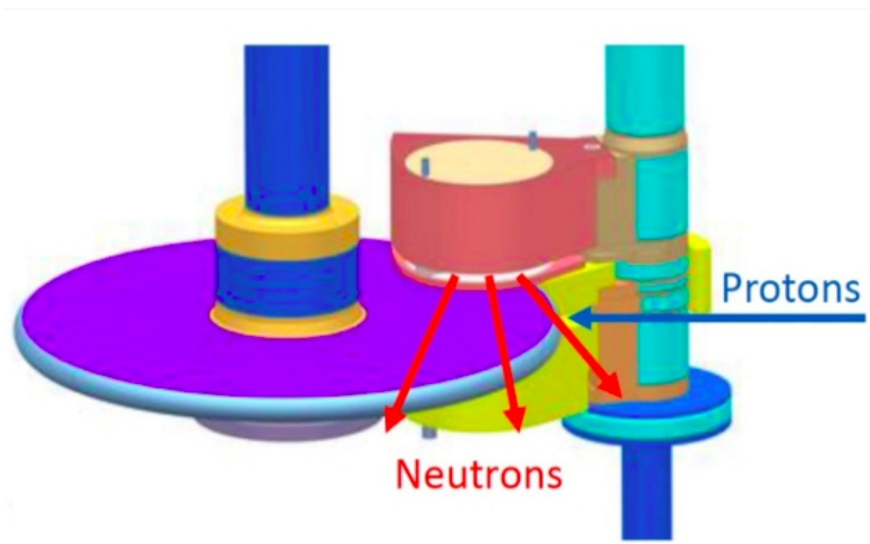
Extract of figure from Mads Ry Vogel Jørgensen, Aarhus University

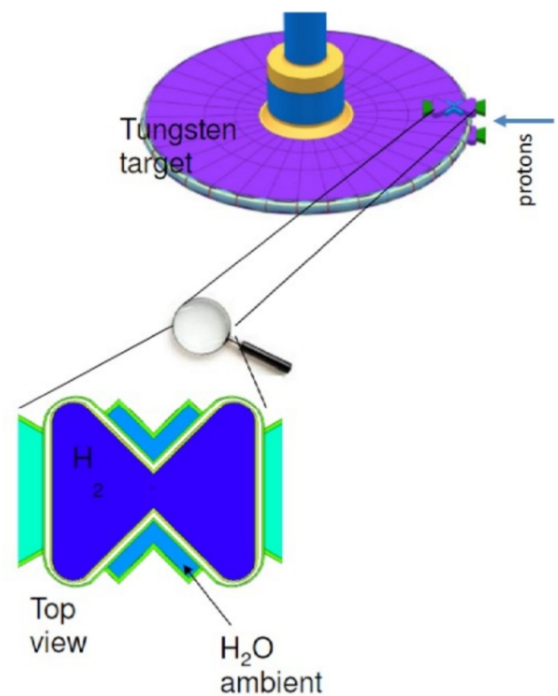


- **To increase *probability of*** $n \rightarrow \bar{n}$:
- t large → slow (a.ka. "cold" → few meV) need lots of collisions → moderators
- We also want as many neutrons as possible.

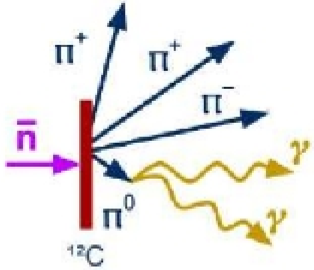
ESS – a neutron factory

- High intensity spallation source
- 2 GeV protons (3ms long pulse hit rotating tungsten target)
- Cold neutrons after interaction with moderators (~ $10^{12\text{-}13}$ n/s)





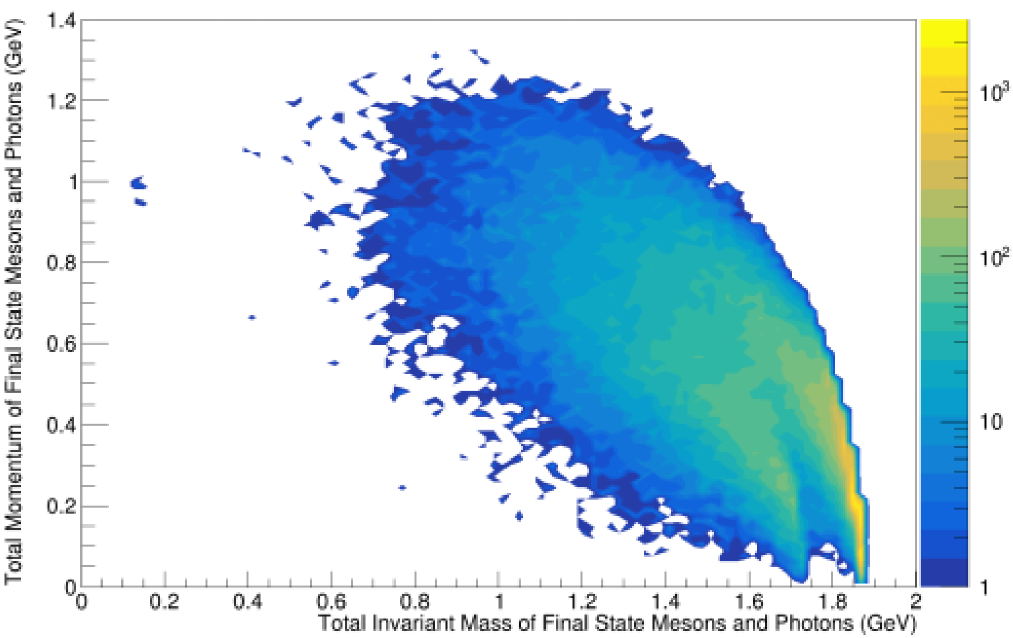
Antineutron annihilation signal

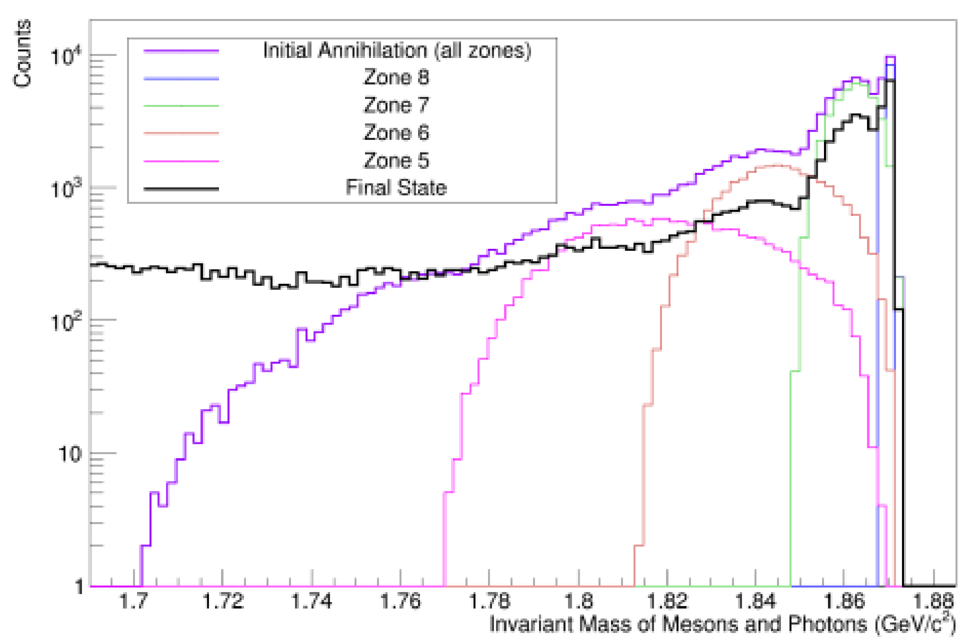


Model of $\bar{n}$ annihilation in experimental searches for $\bar{n}$ transformations

E. S. Golubeva, J. L. Barrow, and C. G. Ladd
Phys. Rev. D **99**, 035002 – Published 5 February 2019

- Energy release of ~ 2*mn ~ 1.88 GeV
- Distributed over several pions (5 in average), e.g.: $n + \bar{n} \rightarrow \pi^+ + \pi^- + 3\pi^0$
- However: in a real experiment antineutron would annihilate inside a nucleus – this is NOT the same as annihilation in free space.
- Neutron is strongly interacting particle - ^{12}C nucleus acts as strong medium

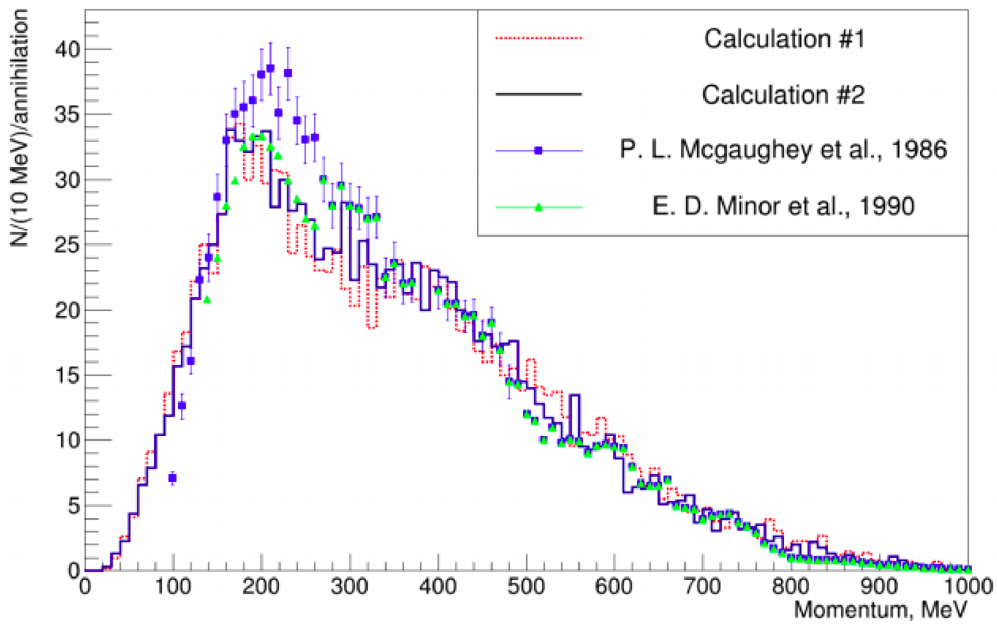




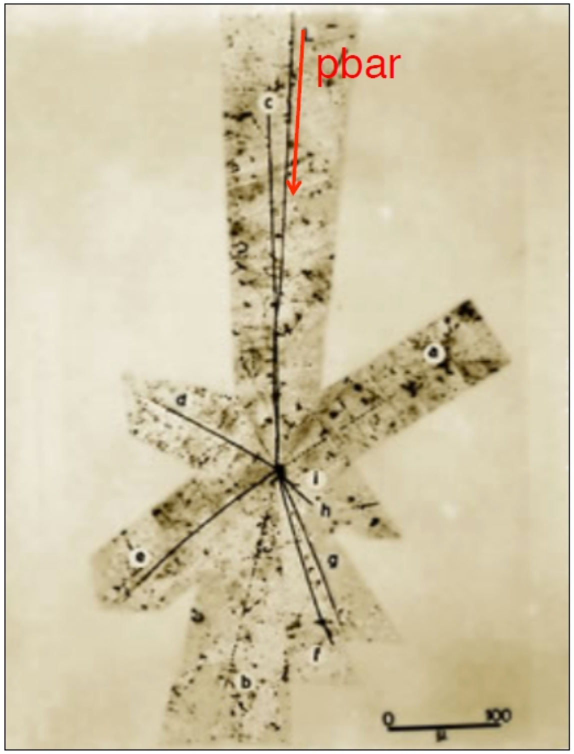
Antineutron annihilation

- Final states extrapolated from antiproton-nucleon:

$\bar{p}C \rightarrow \pi^+$ Spectrum Matches Experiment Well



Based on 10,000 events
See here and here



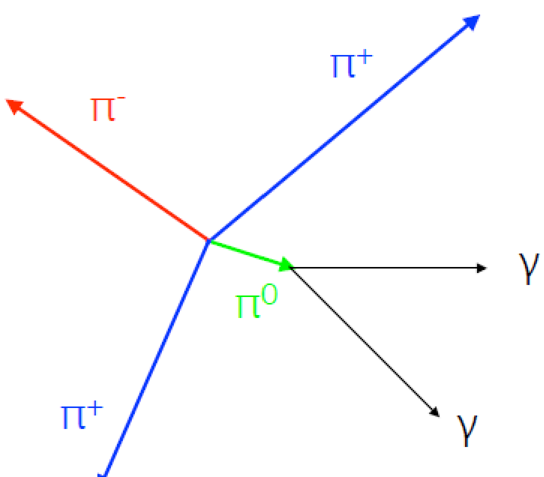


Figure by J. Hewes

Antiproton Star Observed in Emulsion*

O. Chamberlain, W. W. Chupp, G. Goldhaber, E. Segrè, and C. Wiegand, *Radiation Laboratory, Department of Physics, University of California, Berkeley, California*

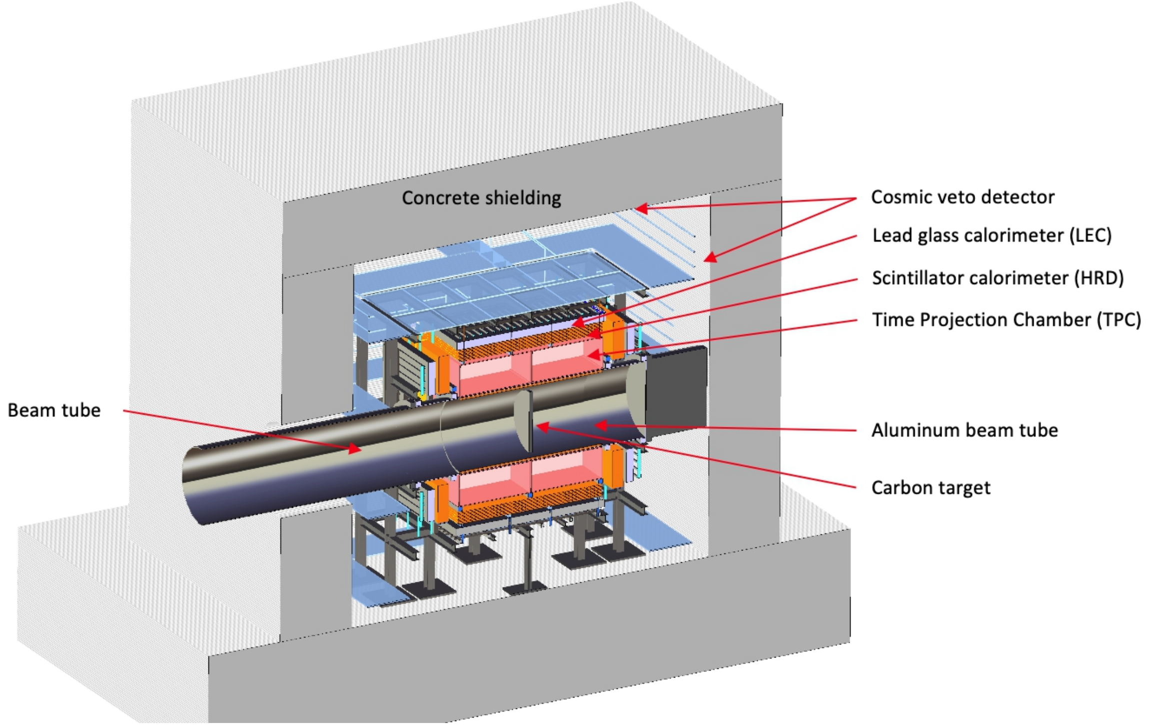
AND

E. Amaldi, G. Baroni, C. Castagnoli, C. Franzinetti, and A. Manfredini, *Istituto di Fisica della Università, Roma Istituto Nazionale di Fisica Nucleare, Sezione di Roma, Italy*

(Received December 16, 1955)

Technology and Material choices

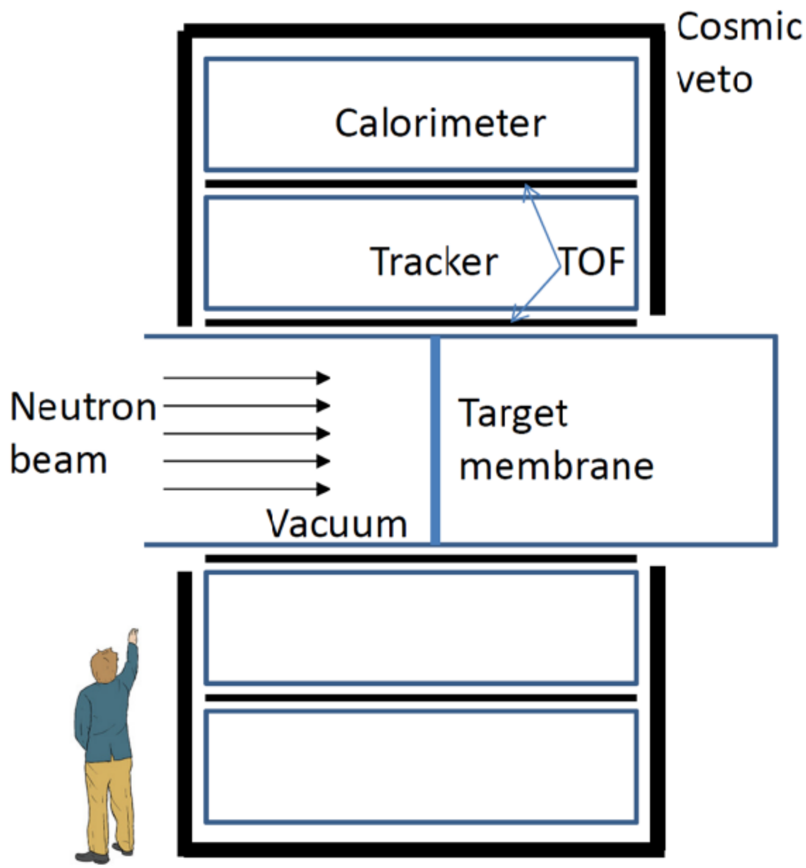
- Target: 100 µm carbon foil
- Tracking: TPC (+ silicon strips inside vacuum tube: multiple scattering)
- H cal: hadronic range detector (HRD)
- EM cal: lead glass calorimeter (LEC)
- Timing: all sub-detectors
- active cosmic veto: scintillating staves + passive shielding: concrete



Annihilation target

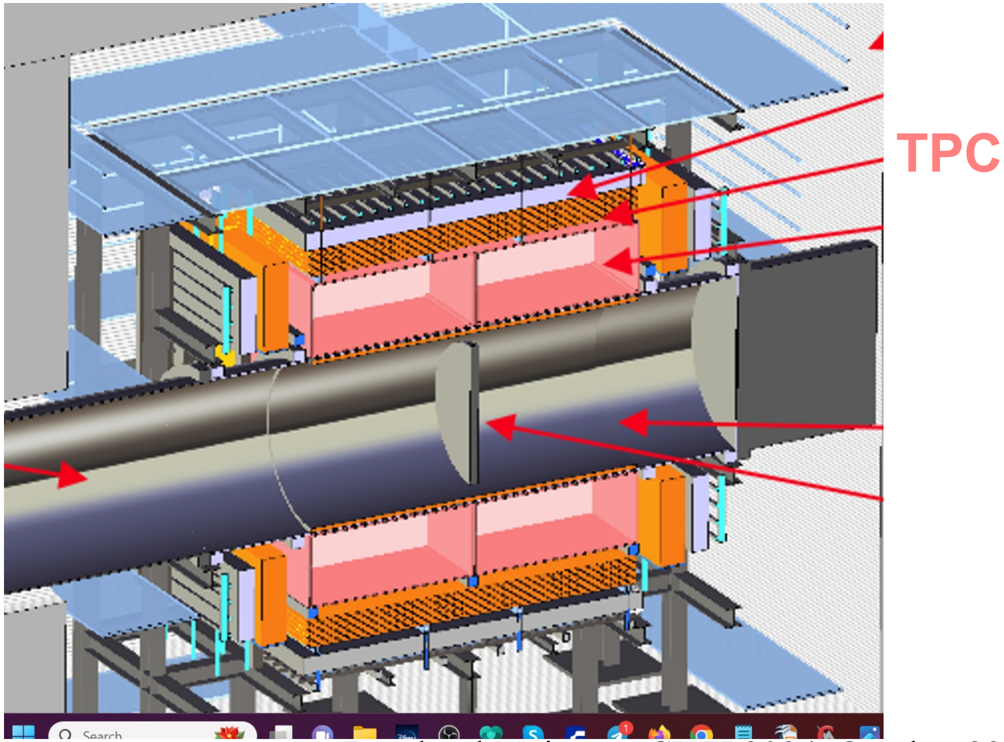
- Target: 100 μm carbon foil
- Low cross section for absorption

$$\sigma_{annihilation} \sim 4\text{Kb}$$
$$\sigma_{nC,capture} \sim 4\text{mb}$$



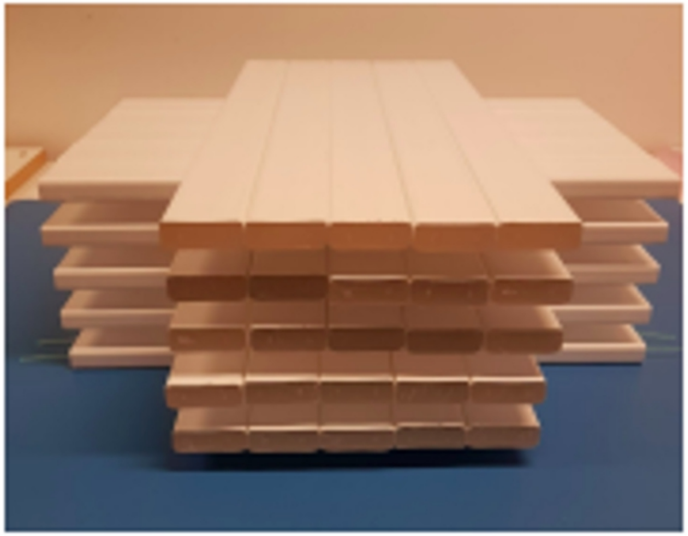
Time Projection Chamber (TPC)

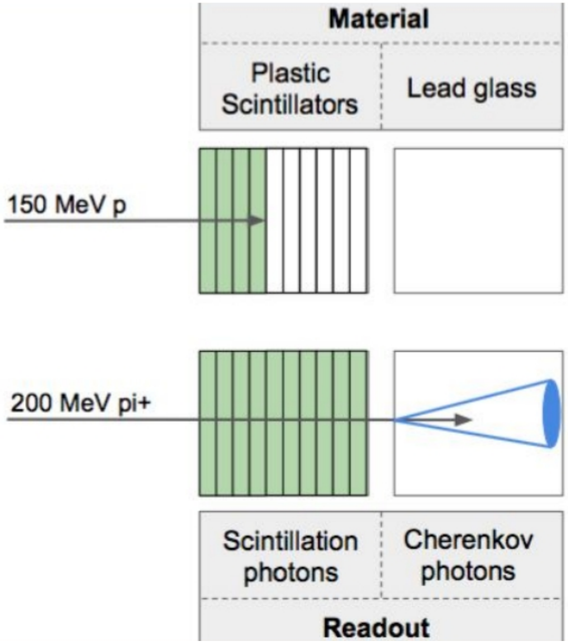
- 3D charged particle tracking: event vertex identification + track matching.
- PID through dE/dX measurements.
- From ALICE TPC: straight track efficiency of 99%, 5% dE/dX resolution.
- 8 rectangular chambers (70 cm deep, 200 cm long, 280 cm wide)
- Gas composition: 80:20 Ar/CO_2 mixture.



Hadronic Range Detector

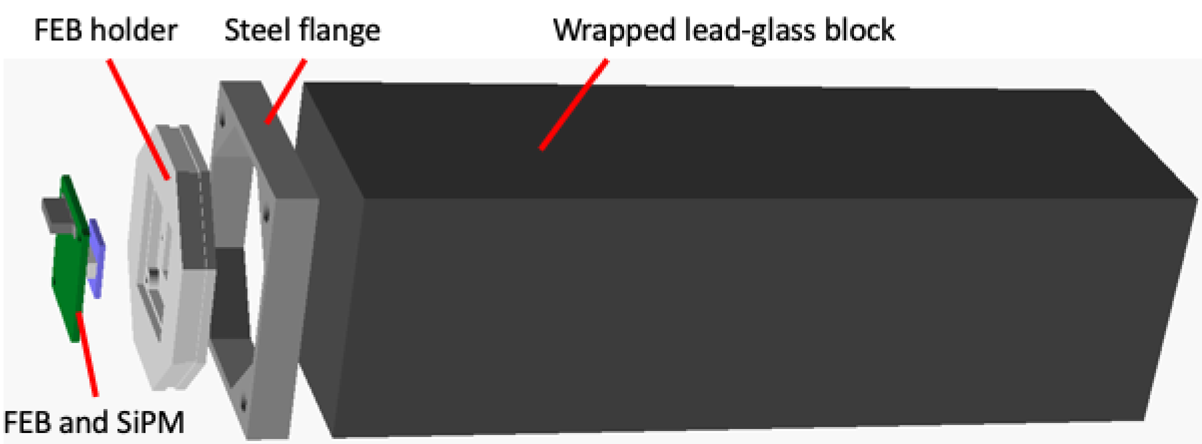
- Multi-layer calorimeter with plastic scintillator staves
  → active material and absorber
- Identify and measure minimum-ionizing energy deposits from low-energy charged pions traversing the scintillator
- Staves in each layer run perpendicular to those in neighboring layers
- Distinguish between proton and pion tracks by dE/dX.
- Total thickness of 30 cm; 10 layers of scintillating staves (width 6 cm, thickness 3 cm)



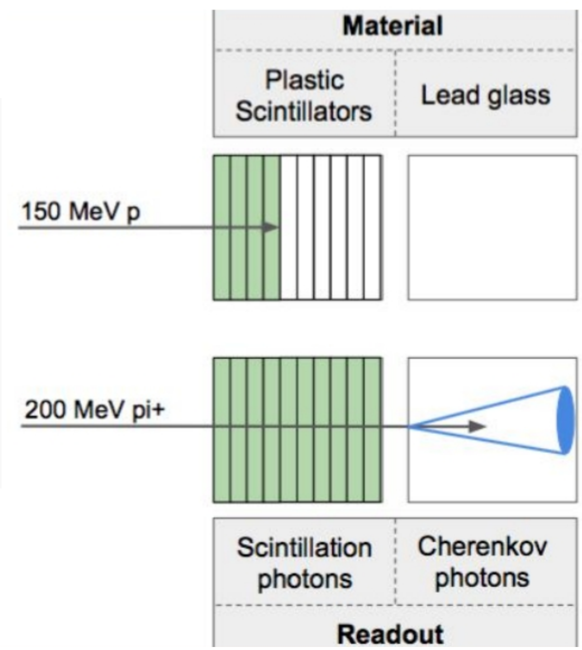


Lead Glass Calorimeter (LEC)

- > 32000 instrumented glass blocks.
- High granularity to cope with flux of gammas from neutron capture.
- measure gammas from neutral pion decays
- + higher-energy charged pions not stopped in HRD.

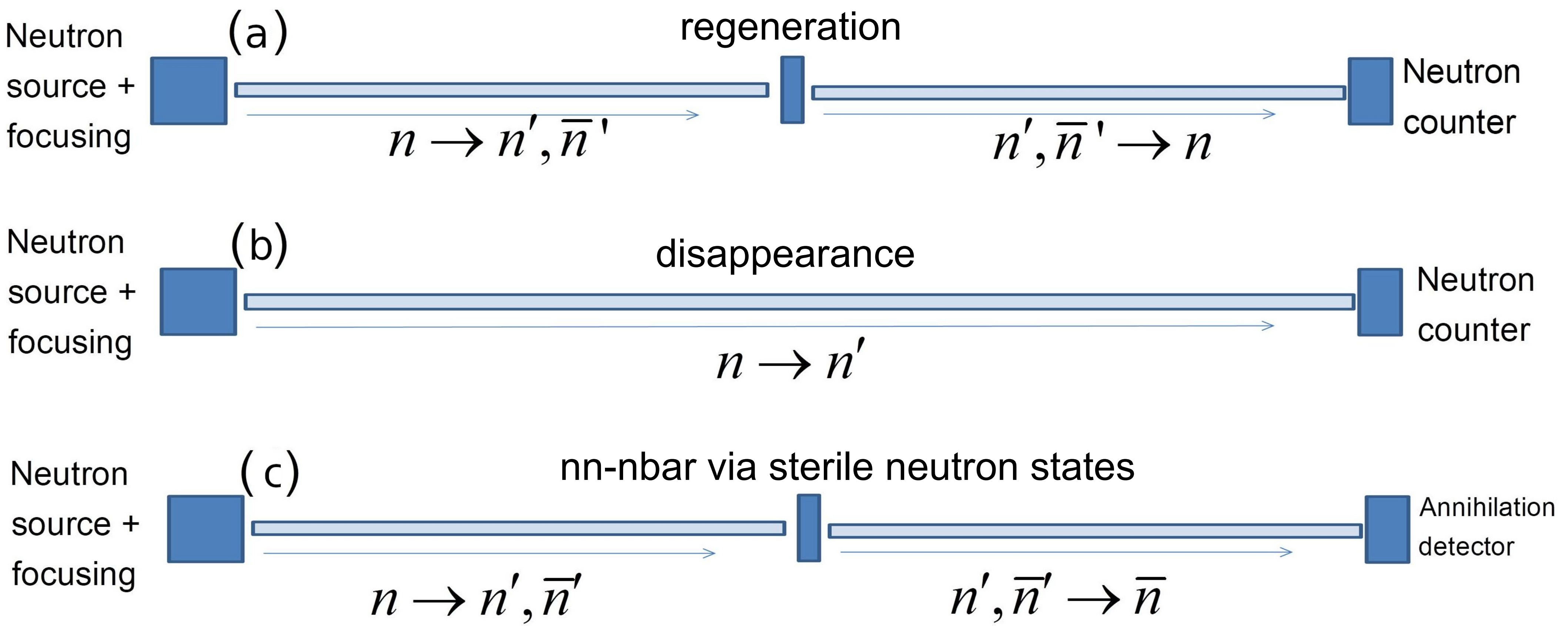


6 x 6 cm area and 20 cm depth (15 radiation lengths)



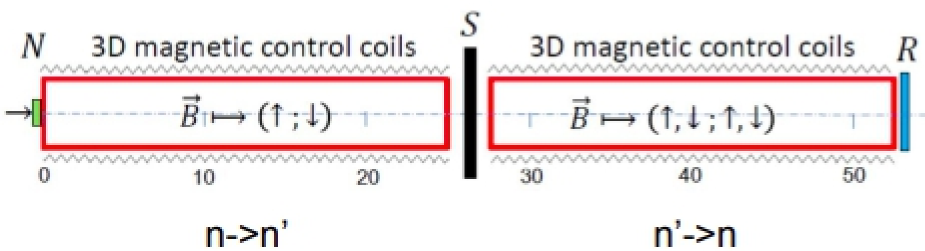
HIBEAM searches

$n \rightarrow n'$ possible with a non-zero B-field that must be scanned/optimized to match the B-field in the dark sector

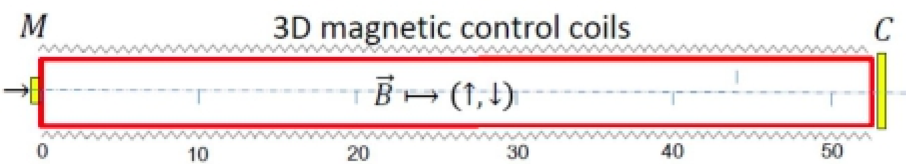


HIBEAM discovery sensitivity

Regeneration



Disappearance



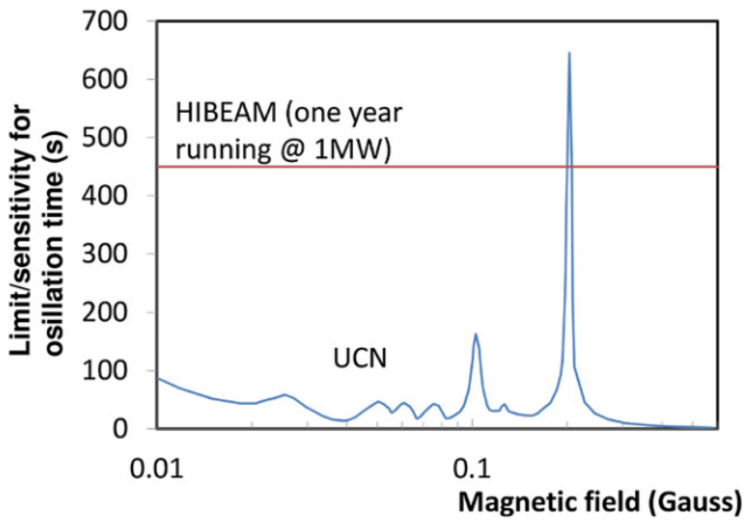


Figure 22. Excluded neutron oscillation times in blue for $n \to n'$ disappearance from UCN experiments [40, 42, 44–47] as a function of the magnetic field $\mathbf{B}'$. The projected sensitivity for HIBEAM (disappearance mode) is also shown in magenta for 1 year's running at the ESS assuming a power of 1 MW.

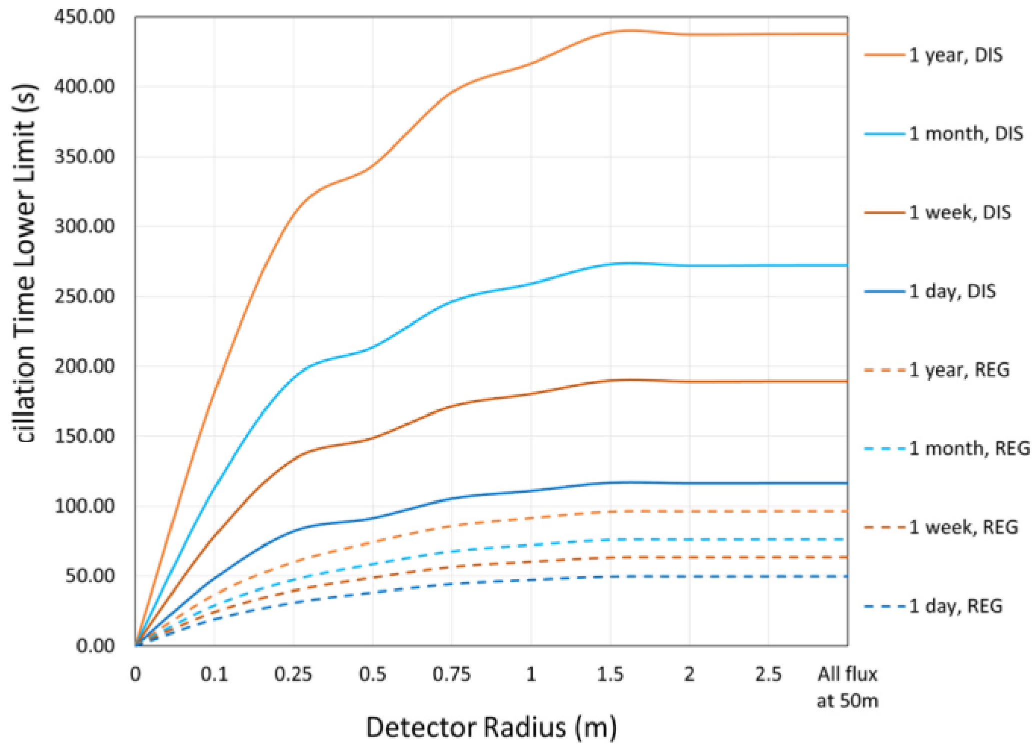
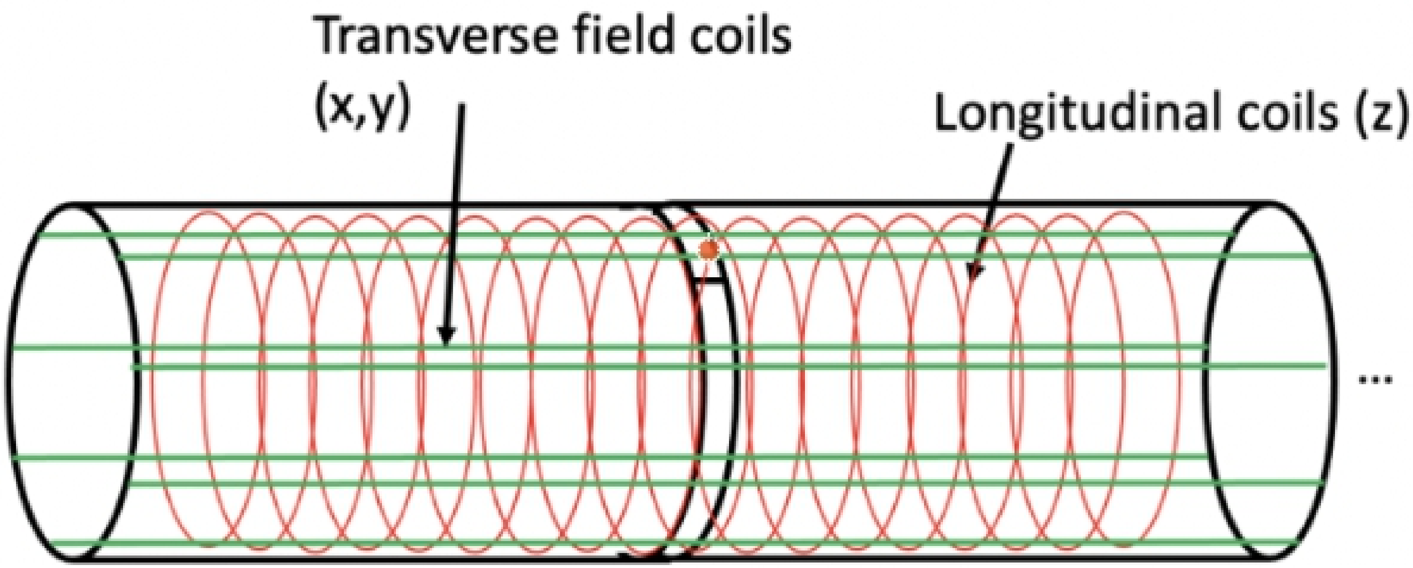


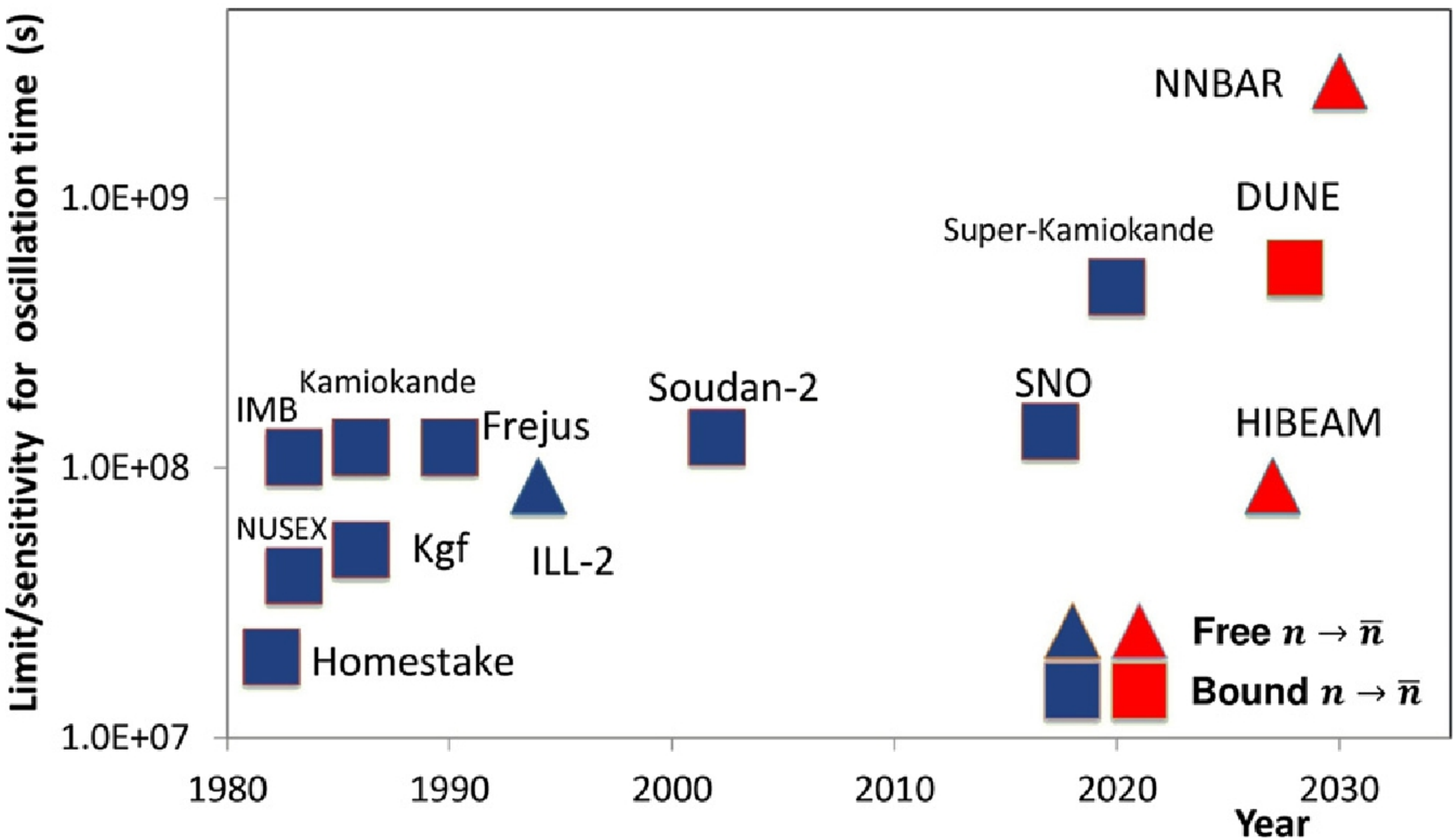
Figure 21. Sensitivity at 95% CL for the discovery of $\tau^{\rm dis}_{n\to n'}$ (disappearance, 'dis') and $\tau^{\rm reg}_{n\to n'}$ (regeneration, 'reg') for various detector radii for the nominal 1 MW HIBEAM/ANNI flux at 50 m. A background rate of 1 n s^{-1} is assumed for the regeneration search. Plots have been smoothed.

Magnetic control beam line

- Full 3D control of the magnetic field will be needed
- Level of ~2 mG.
- Achieved with 3D current coils
- Non-uniformity reduced with mu-metal shielding



Comparison with past and future experiments



Searches for Ultralight Axion Dark Matter in HIBEAM

- HIBEAM can search for ultralight axion dark matter (DM)
- Traditional searches focus on axion DM's coupling to photons, but HIBEAM targets its coupling to neutron spins.
- An axion DM field causes spin-polarized neutrons to precess in response to the DM momentum, an effect measurable using Ramsey's method of separated oscillating fields.
- The precession alters the Larmor precession frequency, providing a detectable signal.
- The HIBEAM search probes ultralight axions with sub-eV masses and improves sensitivity by 2-3 orders of magnitude compared to other lab-based magnetometry searches.
- The axion-neutron coupling is parameterized by fa/CN, where fa is the axion decay constant and CN is a model-dependent constant.
- One year of run time at HIBEAM can yield significant constraints, with astrophysical bounds from supernovae providing additional context.