The PUMA (antiProton Unstable Matter Annihilation) Experiment at CERN

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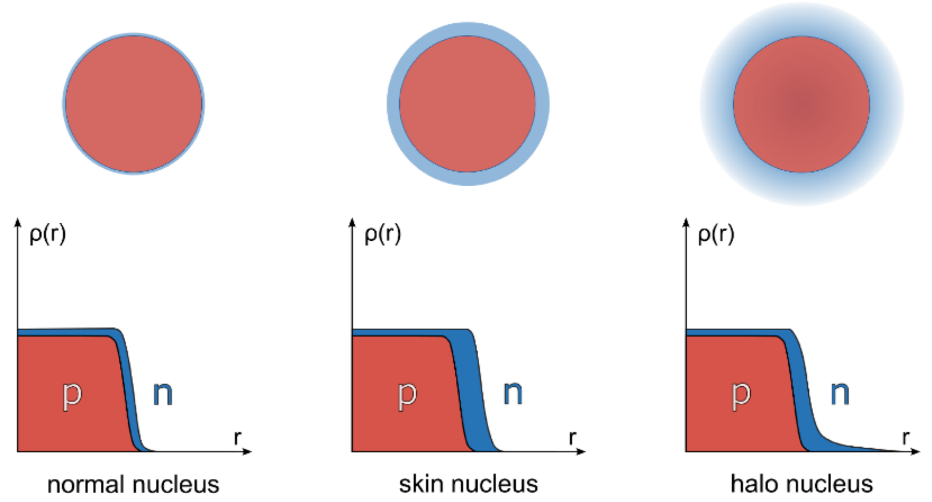
Technische Universität Darmstadt, Institut für Kernphysik

TECHNISCHE UNIVERSITÄT DARMSTADT

EMIS 2022

03 - 07 October 2022

Scientific Motivation: Halos and Skins



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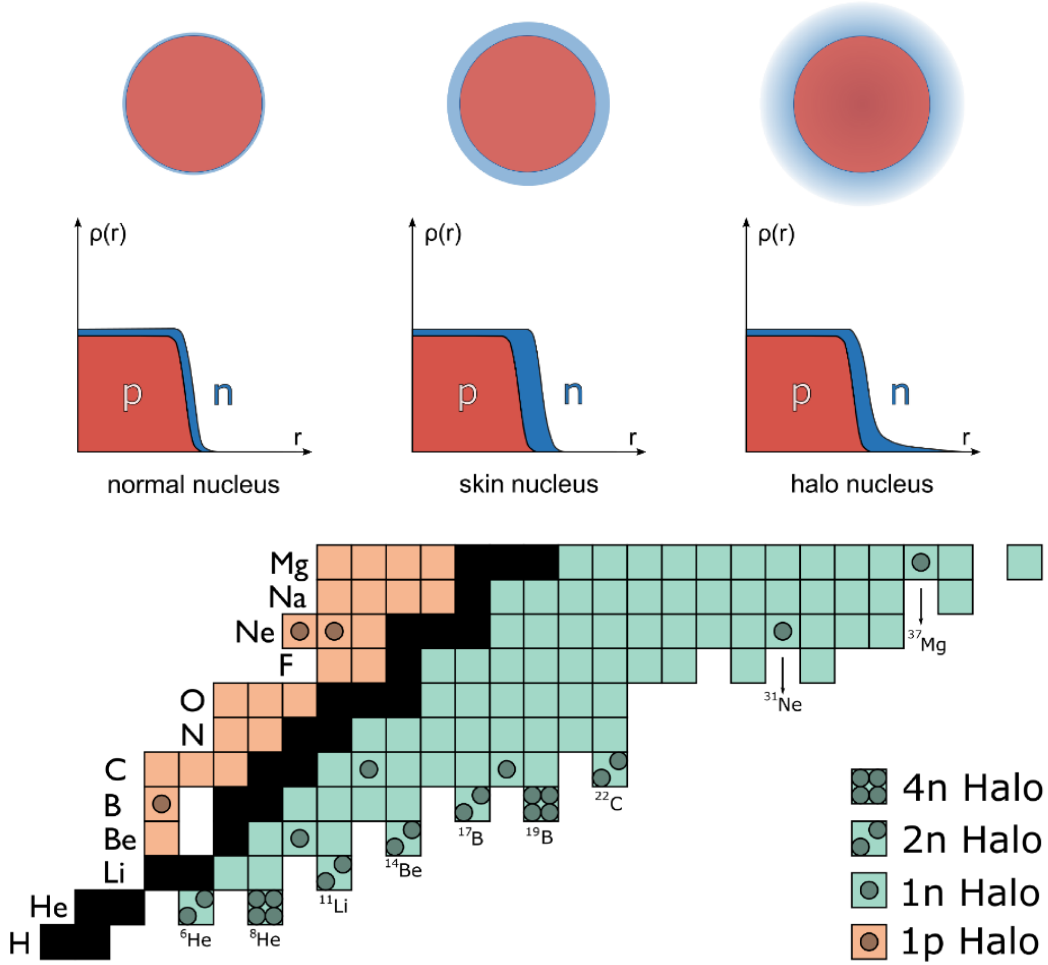
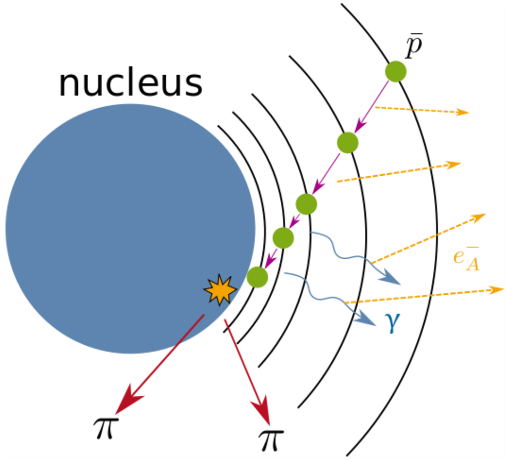


Antiprotonic Atoms



- p̄ captured in excited antiprotonic orbital
- Decay via emission of Auger e⁻ and X-rays

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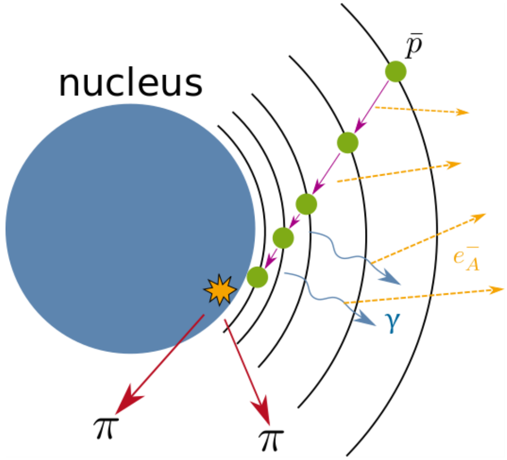

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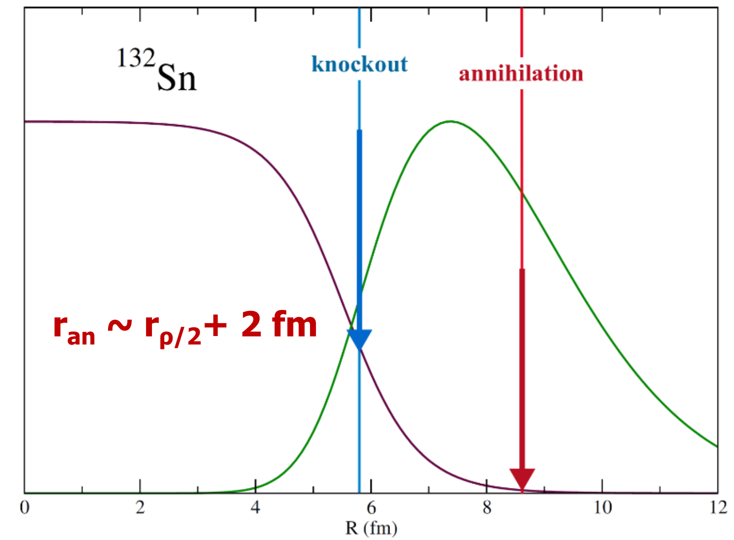
- Annihilation in the tail of nuclear density → emission of pions



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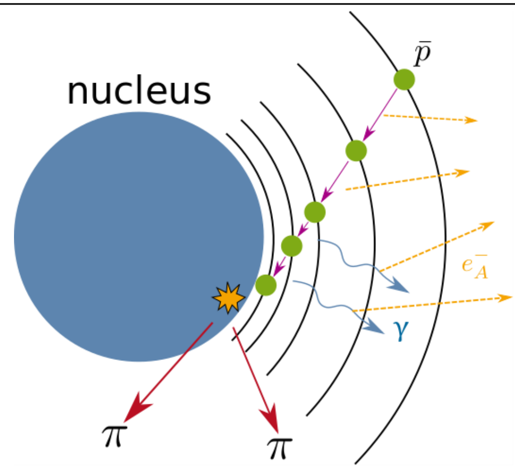

antiproton-proton		antiproton-neutron	
Pion final state	Branching	Pion final state	Branching
$\pi^0\pi^0$	0.00028	$\pi^-\pi^0$	0.0075
$\pi^0\pi^0\pi^0$	0.0076	$\pi^- k\pi^0 (k > 1)$	0.169
$\pi^0\pi^0\pi^0\pi^0$	0.03	$\pi^-\pi^-\pi^+$	0.0023
$\pi^+\pi^-$	0.0032	$\pi^-\pi^-\pi^+\pi^0$	0.17
$\pi^+\pi^-\pi^0$	0.069	$\pi^-\pi^-\pi^+ k\pi^0 (k > 1)$	0.397
$\pi^+\pi^-\pi^0\pi^0$	0.093	$\pi^-\pi^-\pi^-\pi^+\pi^+$	0.042
$\pi^+\pi^-\pi^0\pi^0\pi^0$	0.233	$\pi^-\pi^-\pi^-\pi^+\pi^+\pi^0$	0.12
$\pi^+\pi^-\pi^0\pi^0\pi^0\pi^0$	0.028	$\pi^-\pi^-\pi^-\pi^+\pi^+ k\pi^0 (k > 1)$	0.066
$\pi^+\pi^-\pi^+\pi^-$	0.069	$\pi^-\pi^-\pi^-\pi^-\pi^+\pi^+\pi^+ k\pi^0 (k \geq 0)$	0.0035
$\pi^+\pi^-\pi^+\pi^-\pi^0$	0.196		
$\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$	0.166		
$\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0\pi^0$	0.042		
$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$	0.021		
$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-\pi^0$	0.019		

- $\bar{p}$ captured in excited antiprotonic orbital
- Decay via emission of Auger e^- and X-rays
- Annihilation in the tail of nuclear density
  → emission of pions

$$\sum_{\pi} q_\pi = \begin{cases} 0 \text{ for } \bar{p}p \\ -1 \text{ for } \bar{p}n \end{cases}$$

Overview of the PUMA Experiment

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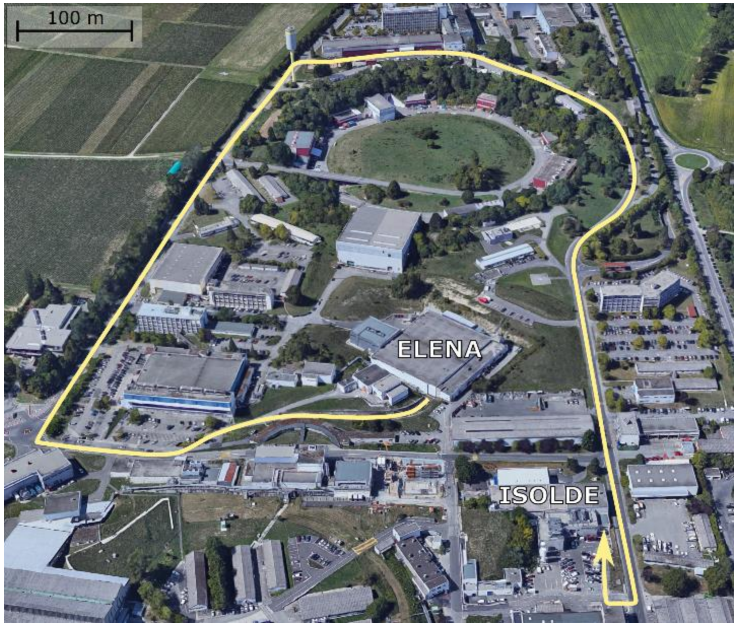
- Transport antiprotons from the Antimatter Factoy (ELENA) to ISOLDE at CERN



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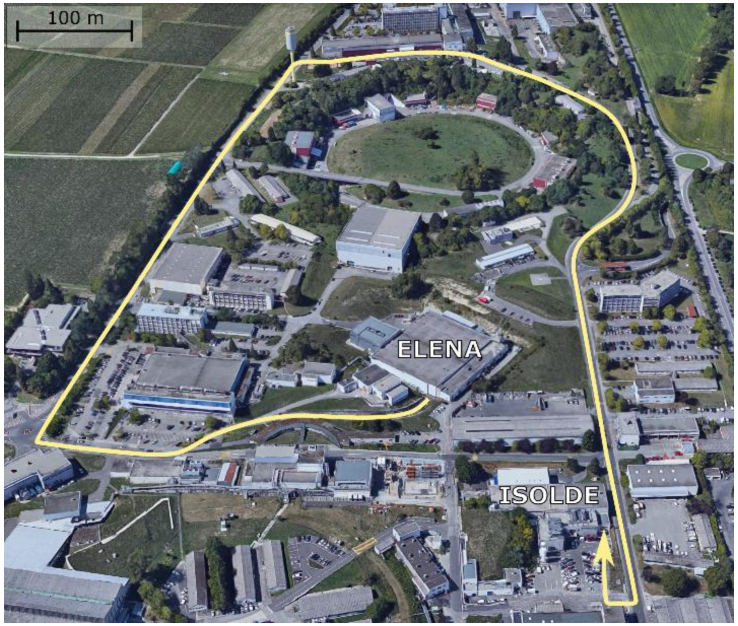
- Store 10^9 antiprotons with storage time > 30 days

  → initial benchmark with 10^7 antiprotons



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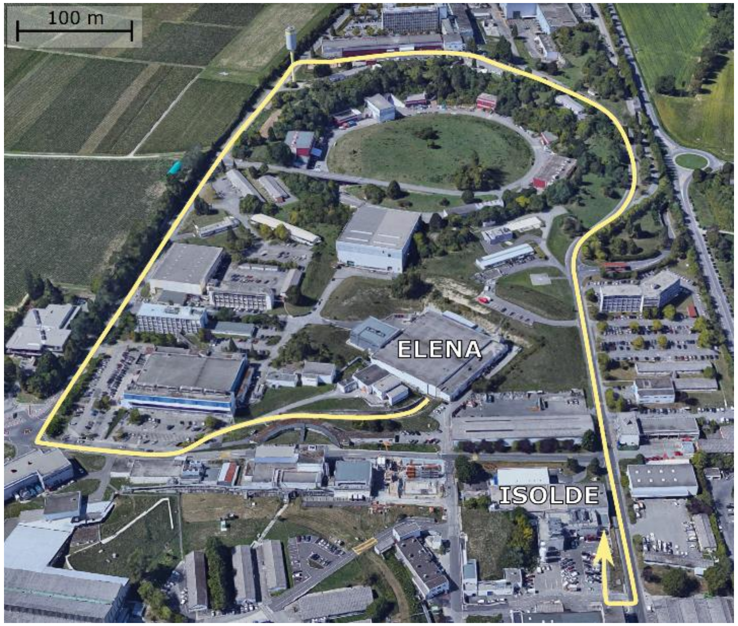

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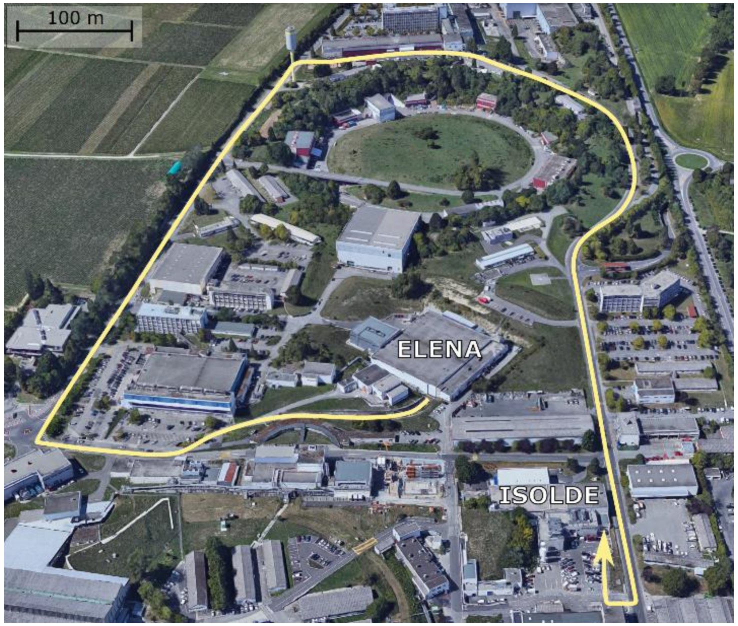
- Measure and identify charged pions resulting from annihilation

  → neutron-to-proton annihilation ratio



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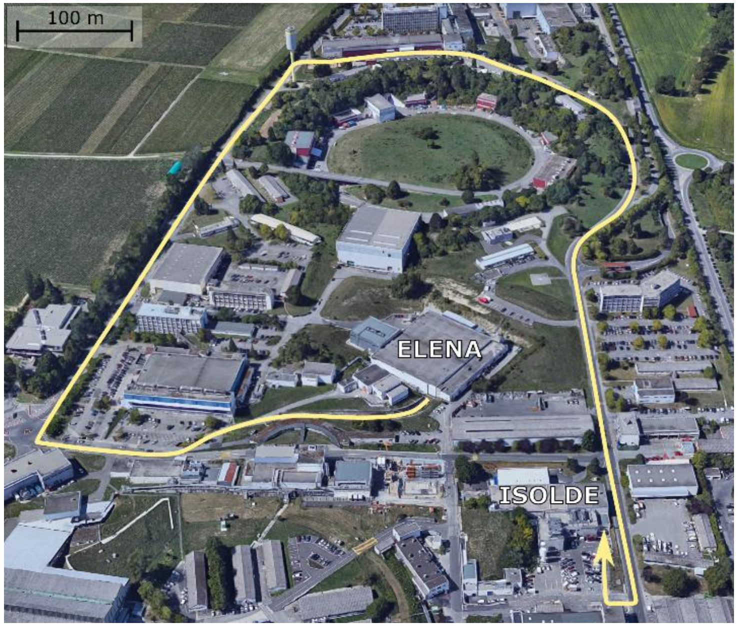
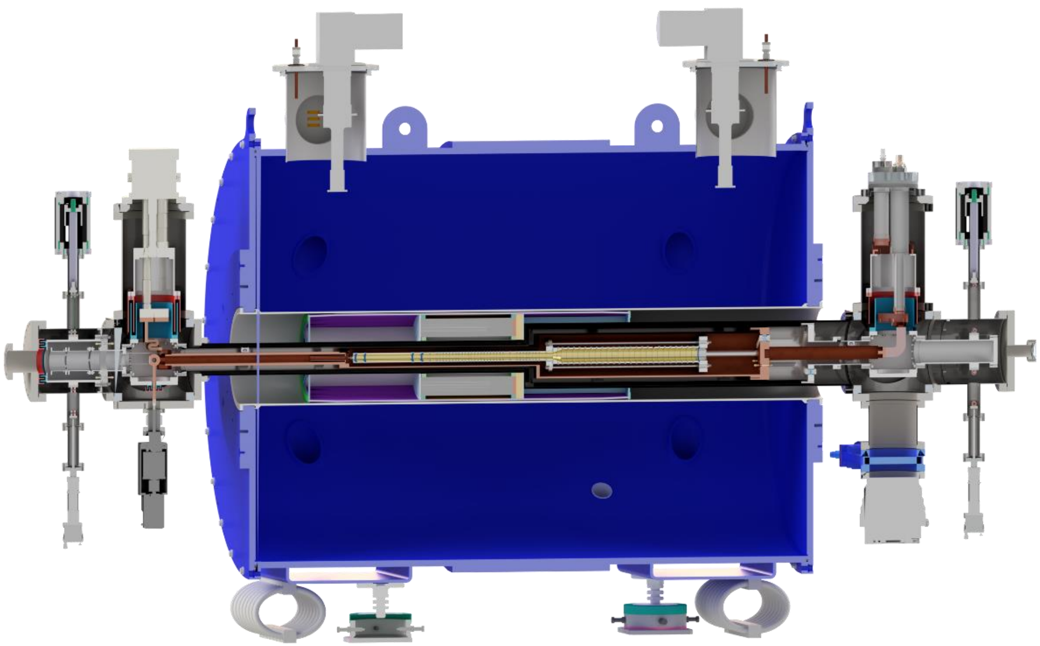
  → neutron-to-proton annihilation ratio
- Accepted in 2021 as new experiment at CERN



Experimental Setup

- Antiproton storage time and measurements limited by residual gas pressure
  → cyrogenic double-trap assembly, 20 particles per cm^3 (~10^{-17} mbar)



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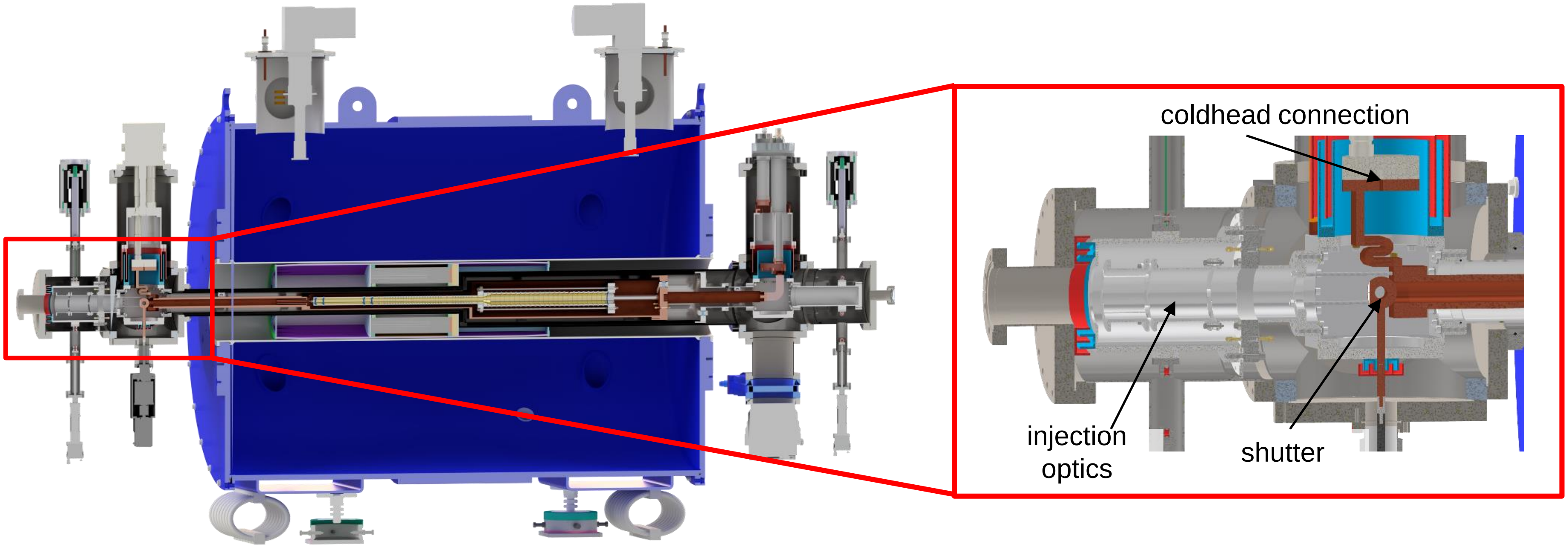

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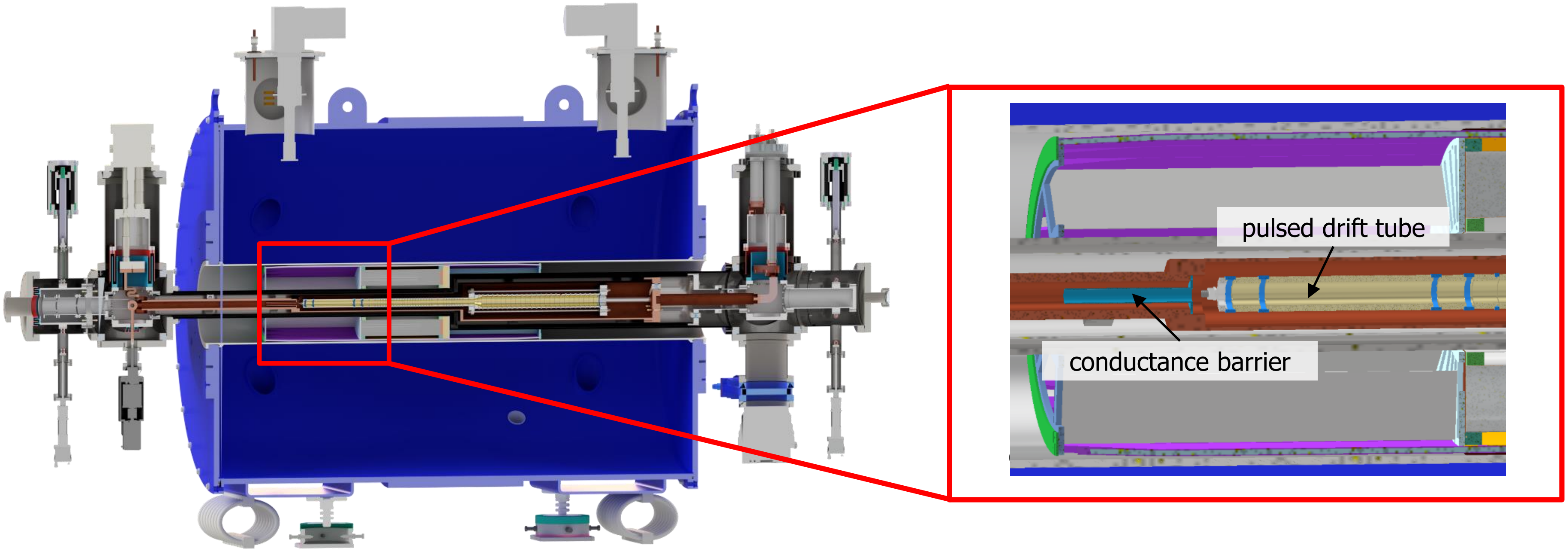

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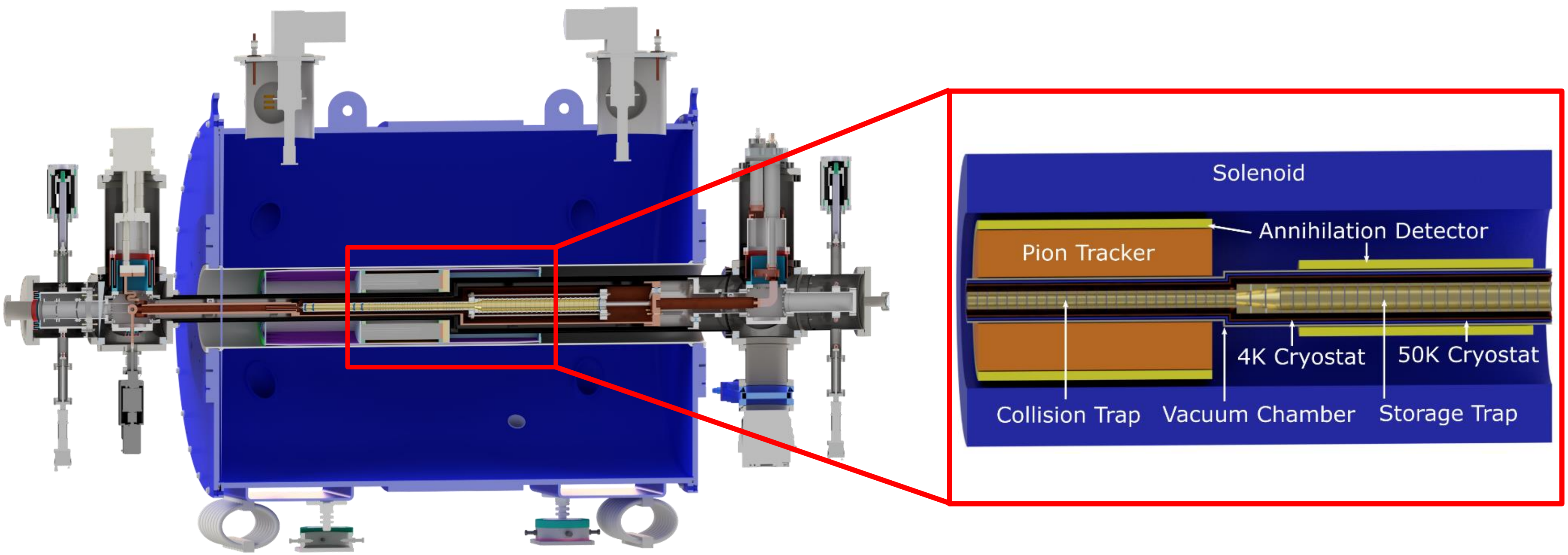

The PUMA Experimental Setup

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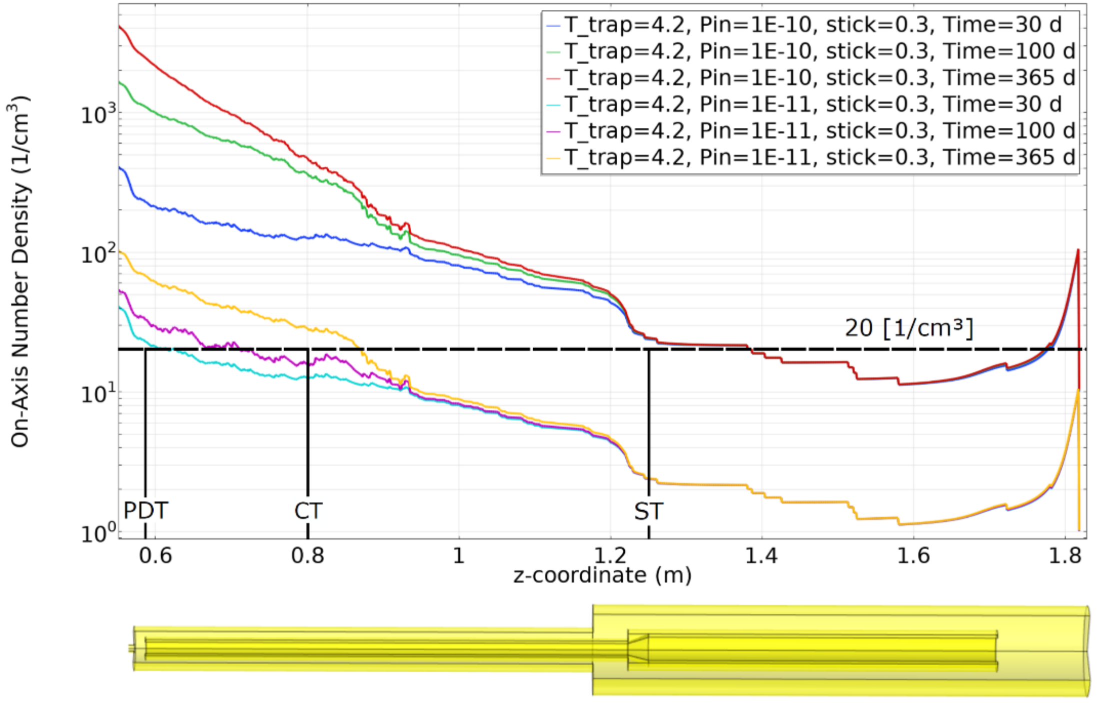
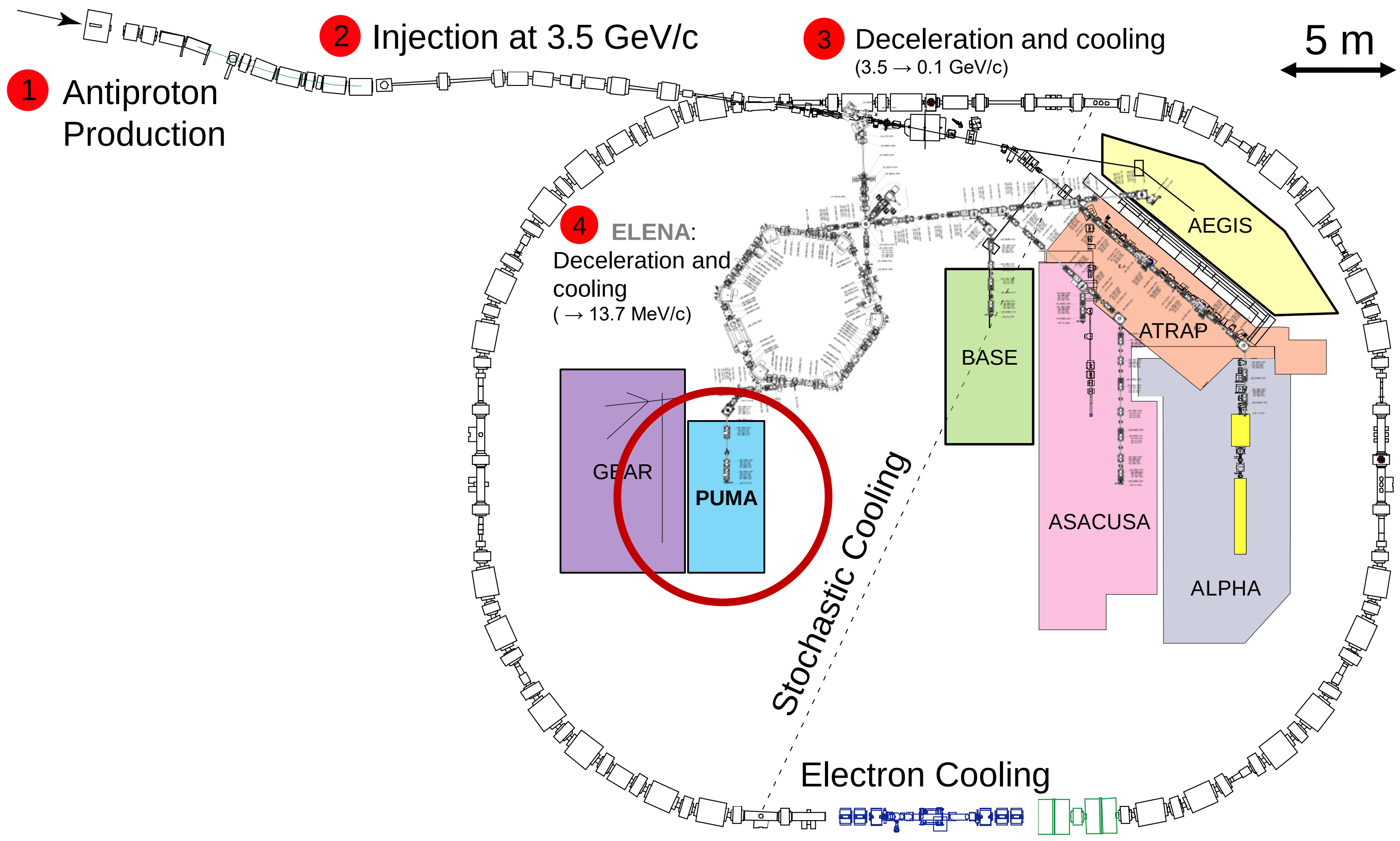
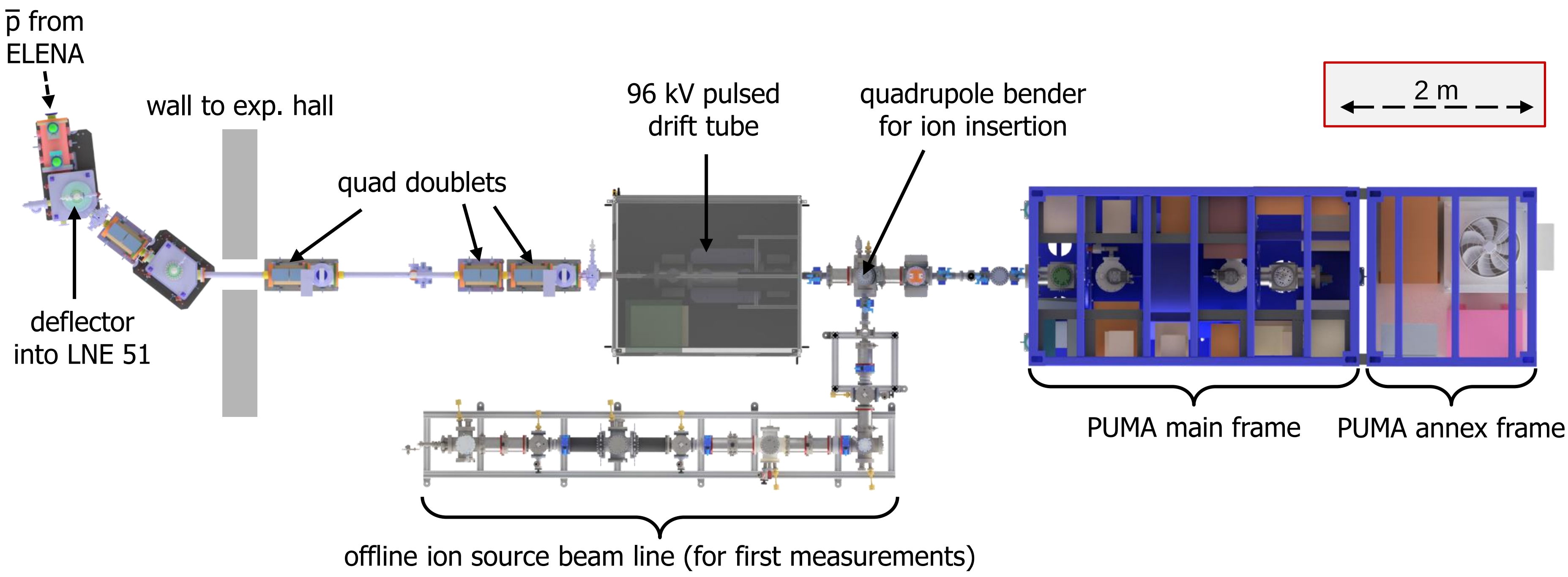


The Antimatter Factory



Experimental Setup at ELENA



Current Status at ELENA

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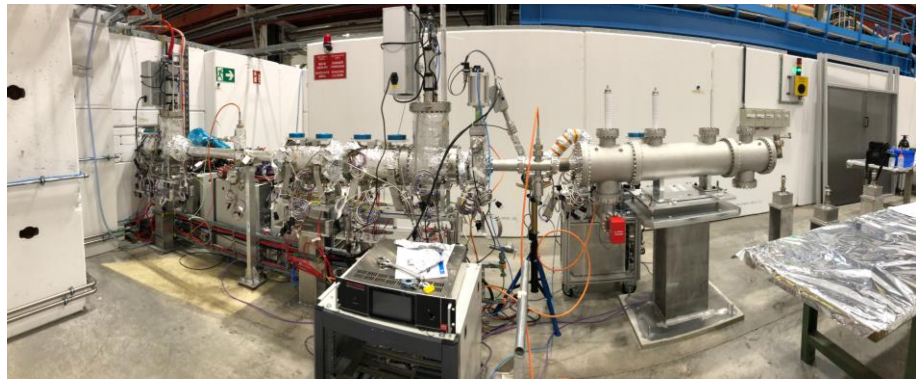
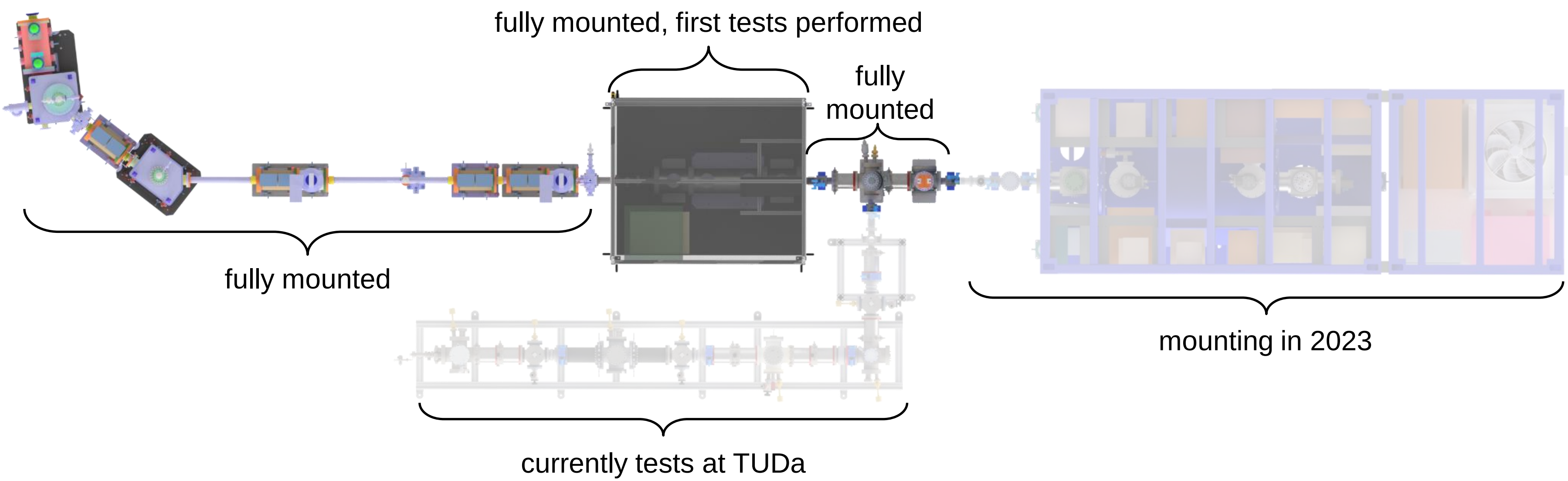
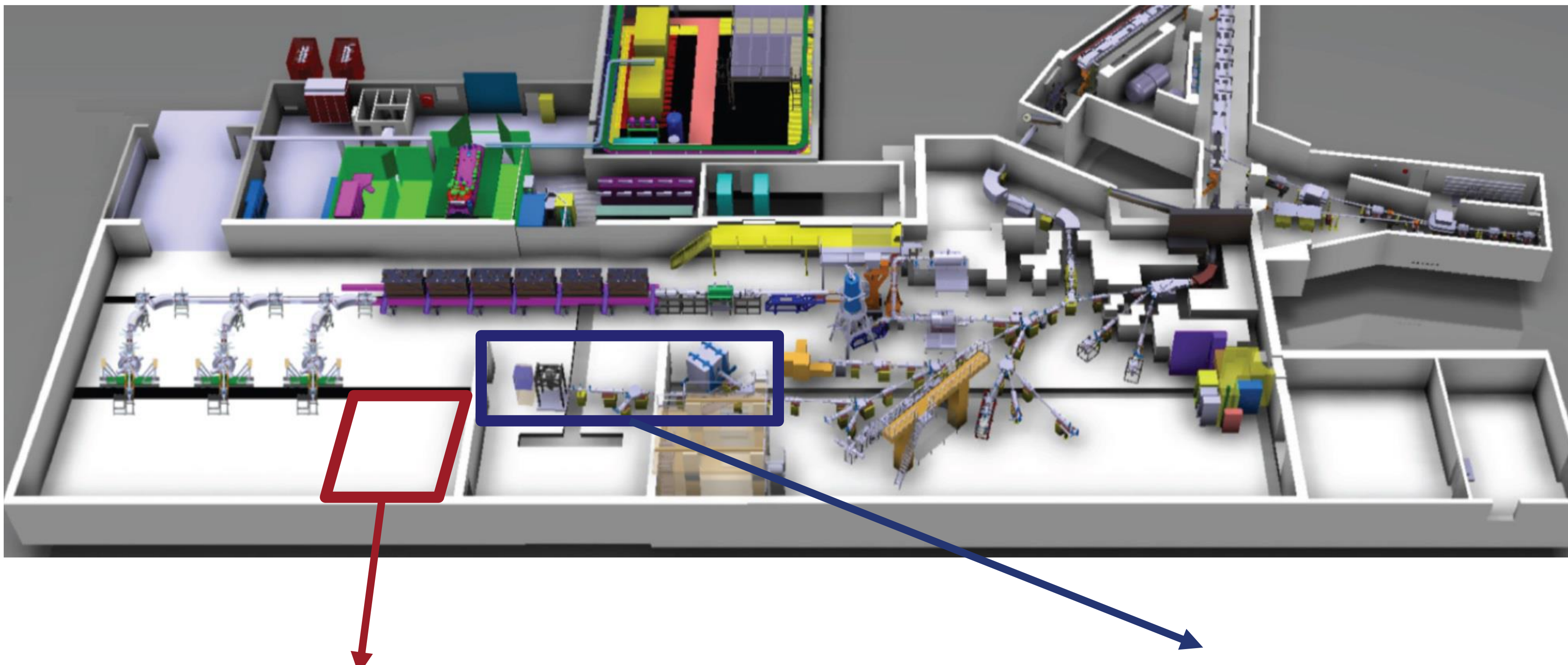




PUMA at ISOLDE

beamline at ISOLDE under design



PUMA experimental zone
XHV (10^{-11} mbar)

low-energy beamline
isotopic selection and bunching
UHV (10^{-8} mbar)

First Physics Cases

- **at ELENA:** investigation of neutron skin evolution of stable isotopic chains
  - gas ionization source: $^{36\text{-}40}Ar$, $^{128\text{-}132,134,136}Xe$
  - laser ablation source: $^{40\text{-}48}Ca$, $^{110\text{-}126}Sn$, ^{208}Pb

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- **at ISOLDE:** investigation of thick skins and halos in unstable nuclei

Nucleus	Half-life $T_{1/2}$	Statistics (1 day of beam)	Expected ρ_n/ρ_p
^{6}He	807 ms	10^{8}	> 100 → neutron halo
^{8}He	119 ms	$4 \cdot 10^{7}$	> 70(10) → thick skin
^{17}Ne	109 ms	10^{5}	< 0.01 → proton halo

Summary

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- PUMA provides new observable in neutron-to-proton ratio in nuclear density tail
- Fully transportable cryogenic Penning trap and detection setup
- Approved as official CERN experiment in 2021

- Experiments with antiprotons and **stable** ions at **ELENA**
- Experiments with antiprotons and **short-lived** ions at **ISOLDE**

The PUMA Collaboration

T. Aumann, N. Azaryan, W. Bartmann, A. Bouvard, O. Boine-Frankenheim, A. Broche, F. Butin, D. Calvet, J. Carbonell, P. Chiggiato, H. De Gersem, R. De Oliveira, T. Dobers, F. Ehm, J. Ferreira Somoza, J. Fischer, M. Fraser, E. Friedrich, M. Gomez-Ramos, J.-L. Grenard, G. Hupin, K. Johnston, C. Klink, M. Kowalska, Y. Kubota, P. Indelicato, R. Lazauskas, S. Malbrunot-Ettenauer, N. Marsic, W. Müller, S. Naimi, N. Nakatsuka, R. Necca, D. Neidherr, A. Obertelli, Y. Ono, S. Pasinelli, N. Paul, E. C. Pollacco, L. Riik, D. Rossi, H. Scheit, M. Schlaich, R. Seki, A. Schmidt, L. Schweikhard, S. Sels, E. Siesling, T. Uesaka, M. Wada, F. Wienholtz, S. Wycech, C. Xanthopoulou, S. Zacarias

Scientific Motivation: Neutron Skins

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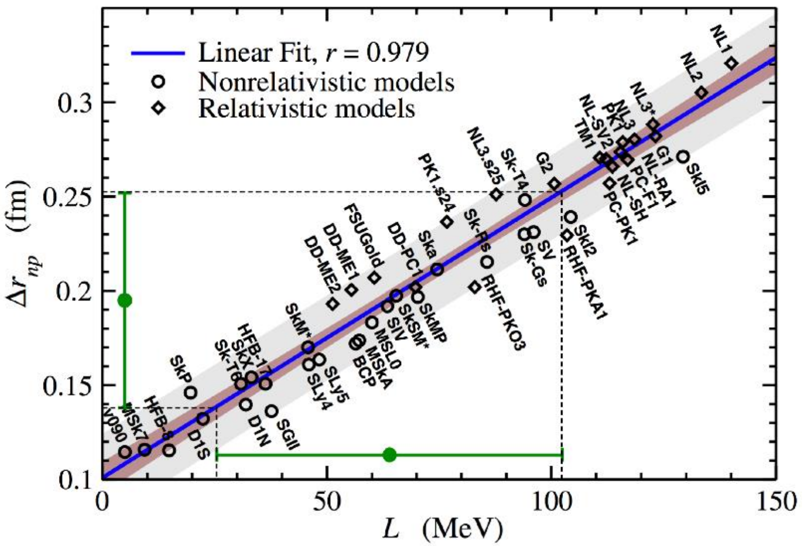
- Neutron skin thickness: $\Delta r_{np} = \langle r_n^2 \rangle^{1/2} - \langle r_p^2 \rangle^{1/2}$

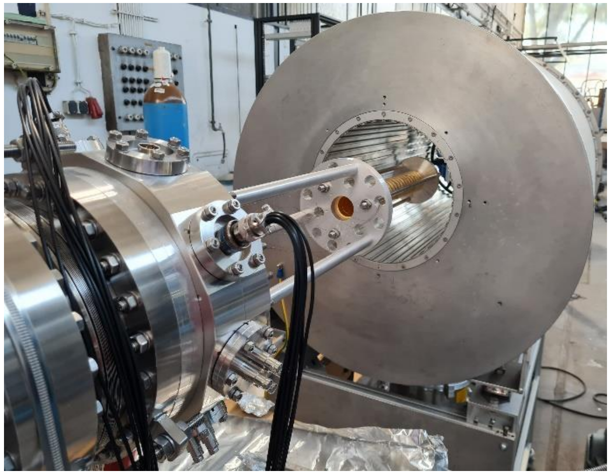
- Neutron skin thickness correlated to slope parameter L of nuclear EoS

$$\frac{E}{A}(\rho_n, \rho_p) = \frac{E_0}{A}(\rho) + S(\rho) \cdot \left(\frac{\rho_n - \rho_p}{\rho}\right) \quad \text{with} \quad L \propto \left.\frac{\partial S(\rho)}{\partial \rho}\right|_{\rho_0}$$



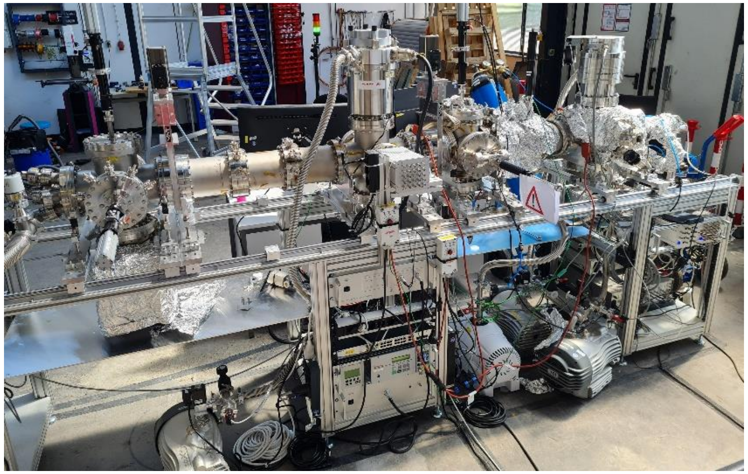
X. Roca-Maza *et al.*, PRL 106 (2011)

Current Status at TUDa



test setup with 3 T solenoid and RT trap

PUMA magnet and transport frame



offline ion source beam line test stand

(see poster of Moritz Schlaich)

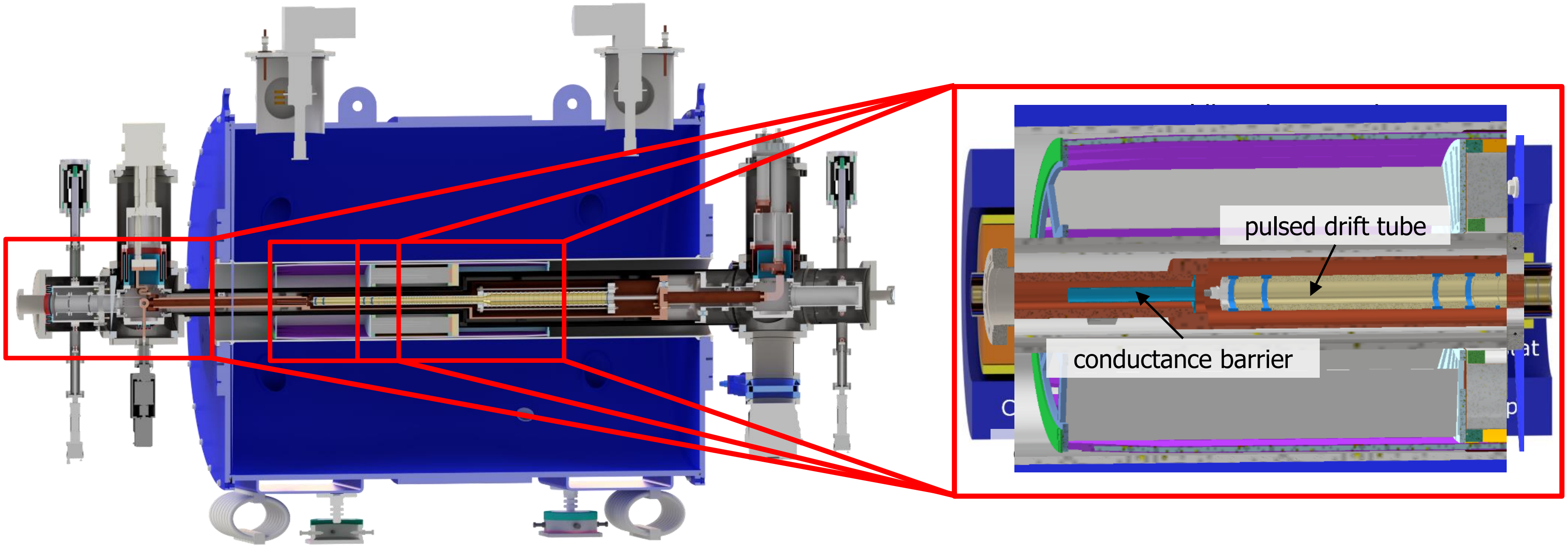
The PUMA Experimental Setup

- Antiproton lifetime and measurements limited by residual gas pressure

  → cyrogenic double-trap assembly

τ [days] ~ $6 \cdot 10^{-16} \cdot T$ [K] / P [mbar]

- Time-projection chamber and plastic scintillator barrel as detection setup

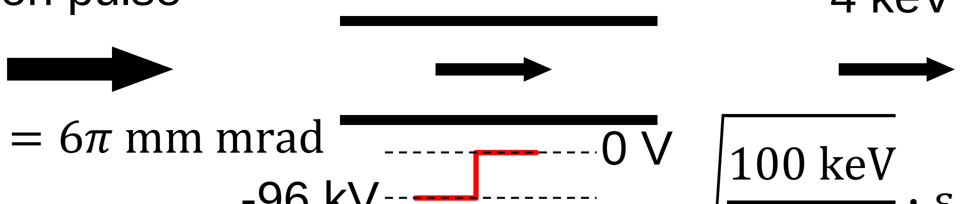


Pulsed Drift Tube (PDT)

- ELENA gives us antiprotons with a kinetic energy of 100keV
- we need ~4keV to trap -> solution: pulsed drift tube
- put an electrode with -96kV to decelerate the antiprotons
- so the antiprotons are not re-accelerated we switch to 0V while particles are inside the electrode “without the particles noticing“

100 keV antiproton pulse

4 keV antiproton pulse



$$\varepsilon_{\text{transversal, in}} = 6\pi \text{ mm mrad}$$

$$\sqrt{\frac{100 \text{ keV}}{4 \text{ keV}}} \cdot \varepsilon_{\text{transv, in}} = 30\pi \text{ mm mrad}$$

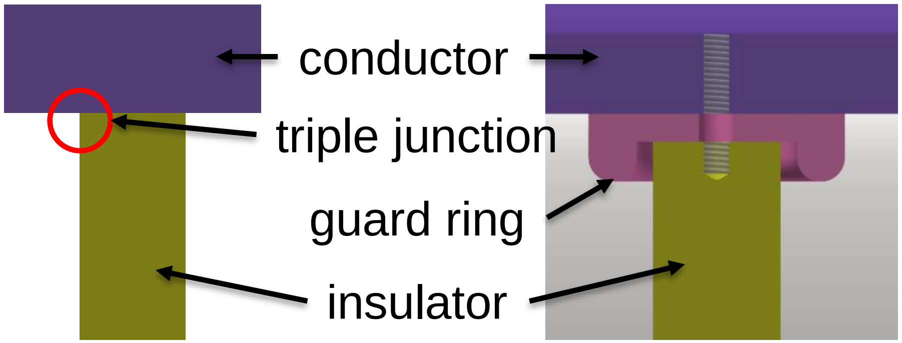
100 kV is a lot

challenges

- good vacuum, < 10^{-10} mbar
- personal safety
- electrical safety
- fast switching times, ~ 100 ns
- RC circuit, $\tau = RC$

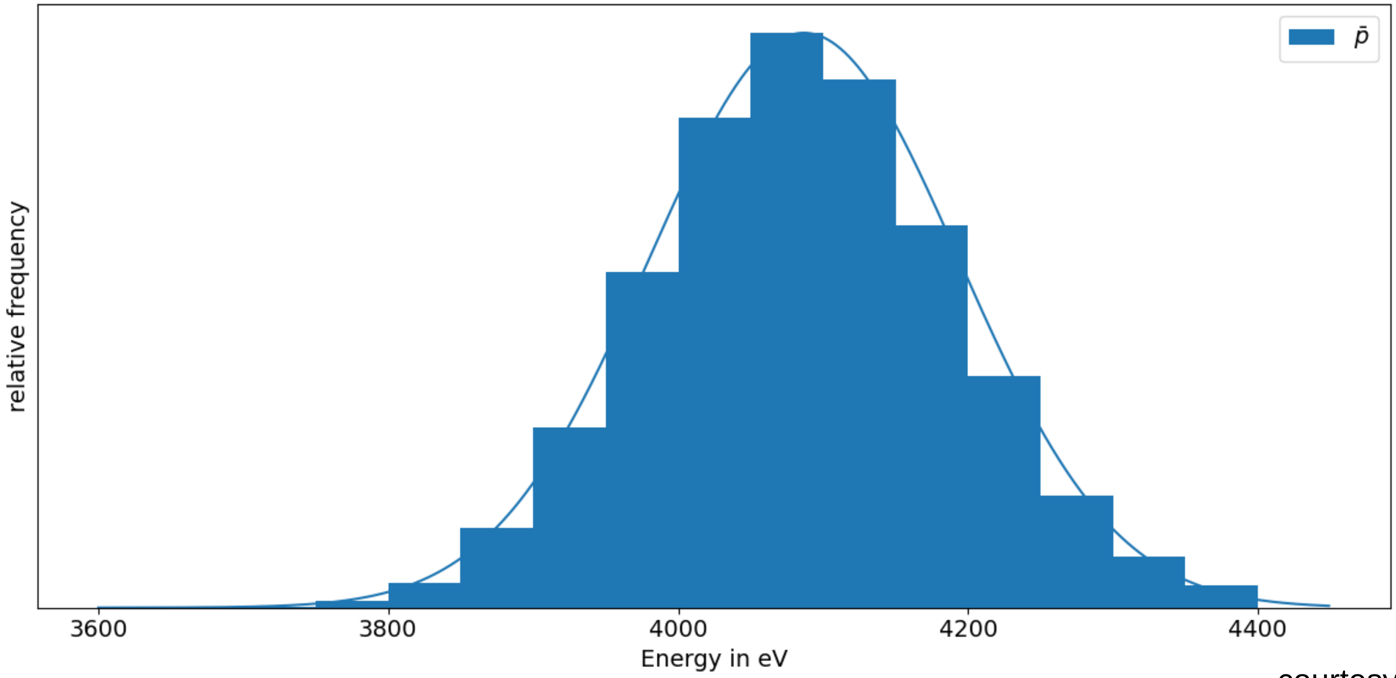
ansatz

- NEG, aluminium, Macor
- safety cage, interlock
- no edges, triple junctions
- MOSFET switch
- low resistance, high current



Deceleration

SIMION simulation, bunch $100\ \mathrm{keV} \pm 100\ \mathrm{eV}$
voltage drops exponentially with $\tau = RC \sim 50\ \mathrm{ns}$ from -96kV
energy spread (std) increases from 100eV to 107eV
simulated trapping efficiency (geometrical and energy constraints) > 65%



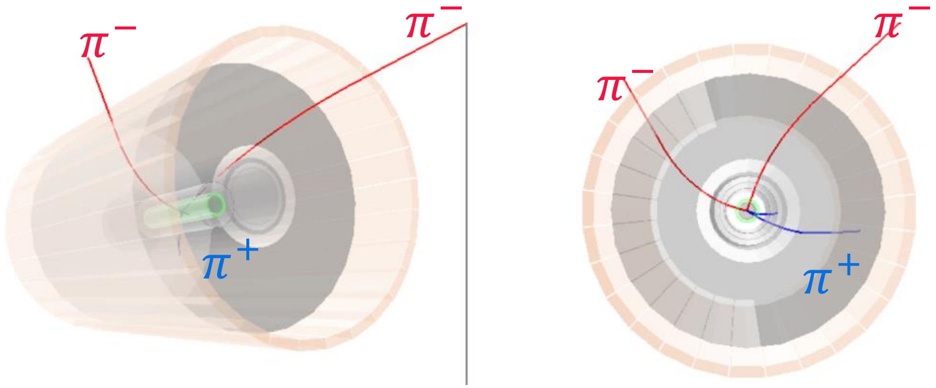
courtesy of A. Schmidt

Pion detection with PUMA

Time Projection Chamber (TPC) & plastic scintillator barrel within a 4T magnet will be used.

Requirements:

- Reliability (long term without maintenance).
- >60% detection efficiency.
- Resolution 400 μm.
- E field = 200 V/cm (ie: Cathode @ -6kV).
- Field uniformity.
- Minimization of sparks and microsparks.



Typical event simulation with Geant 4

Time Projection Chamber (TPC) in a nutshell

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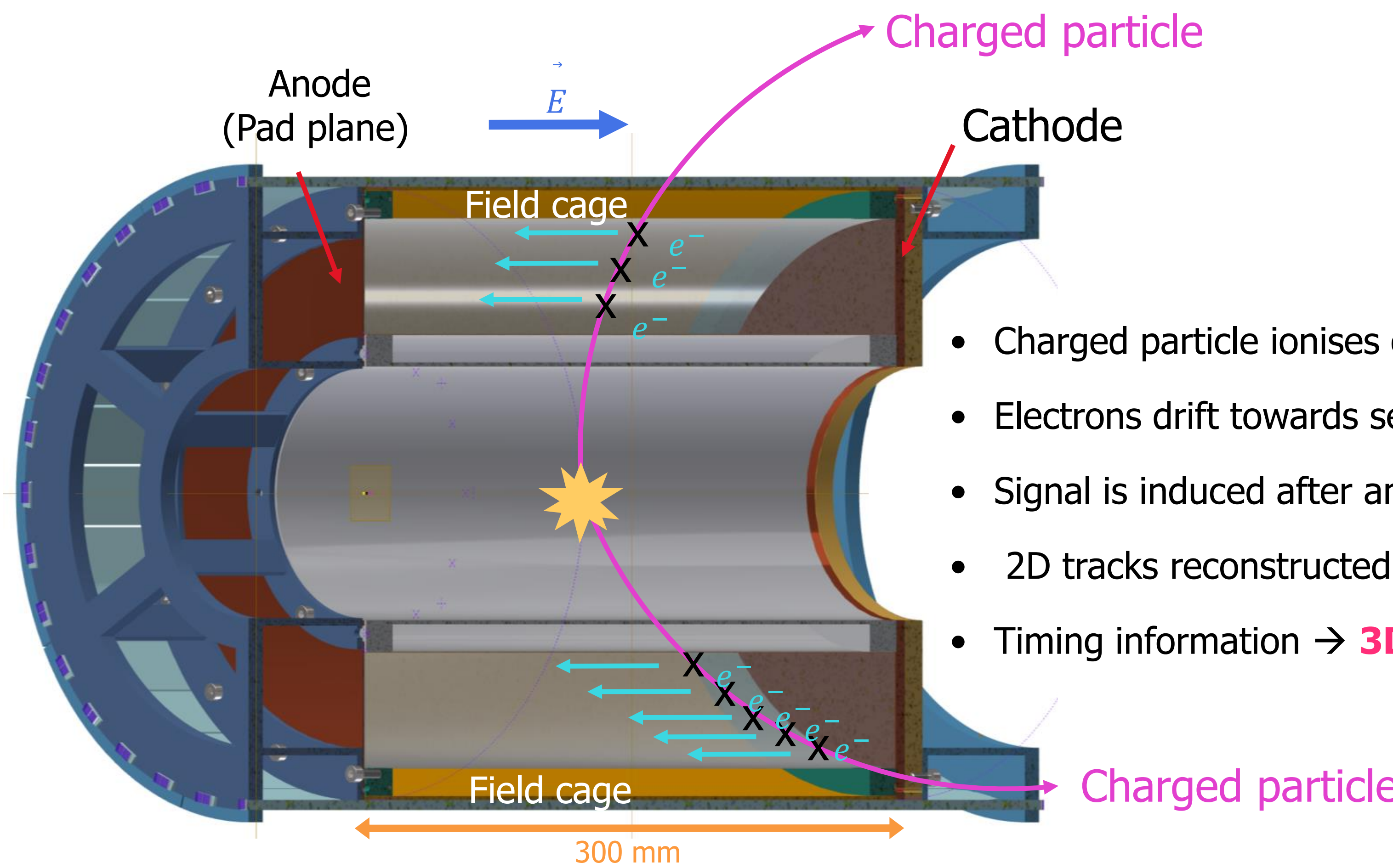

- Charged particle ionises gas.
- Electrons drift towards segmented anode.
- Signal is induced after amplification.
- 2D tracks reconstructed.
- Timing information → **3D reconstruction**.

TPC Simulations

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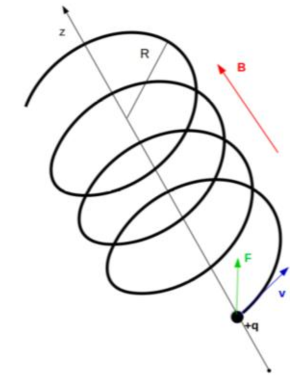
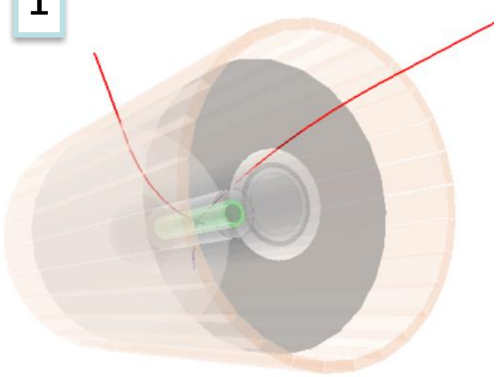
Performed with GEANT 4 and analysed with ROOT.*



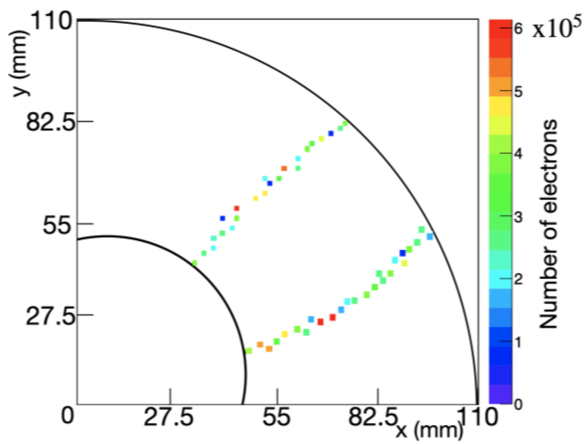
Main Steps:

1. Generation of realistic events in the trap.
2. Drift of ionized electrons in the gas towards the signal collection pads.
3. Determination of the charge (π^+ / π^-) based on the curvature of the track.

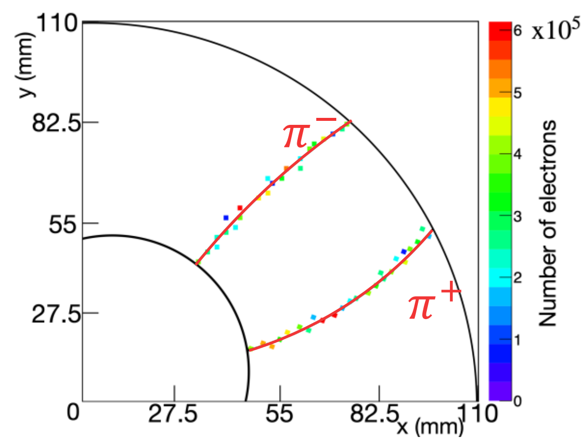
1



2

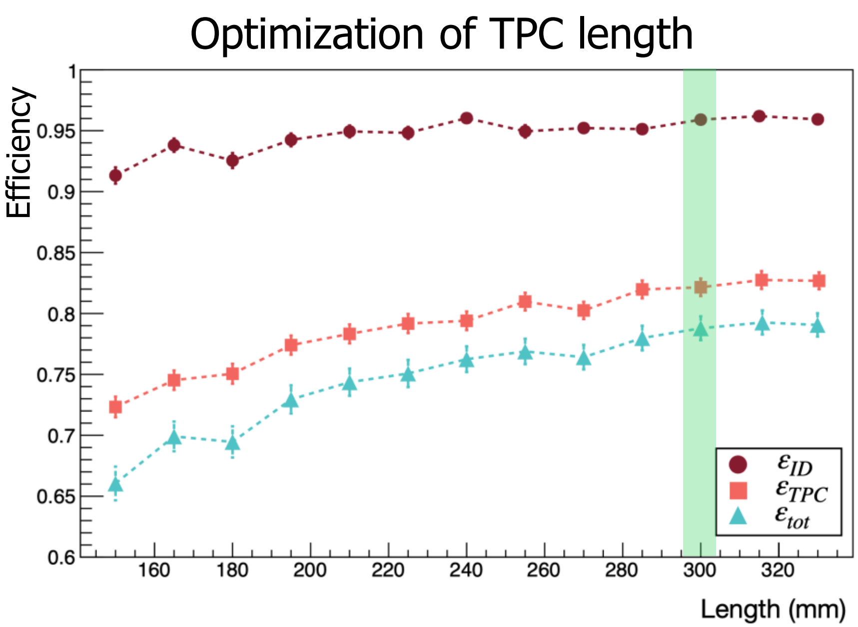


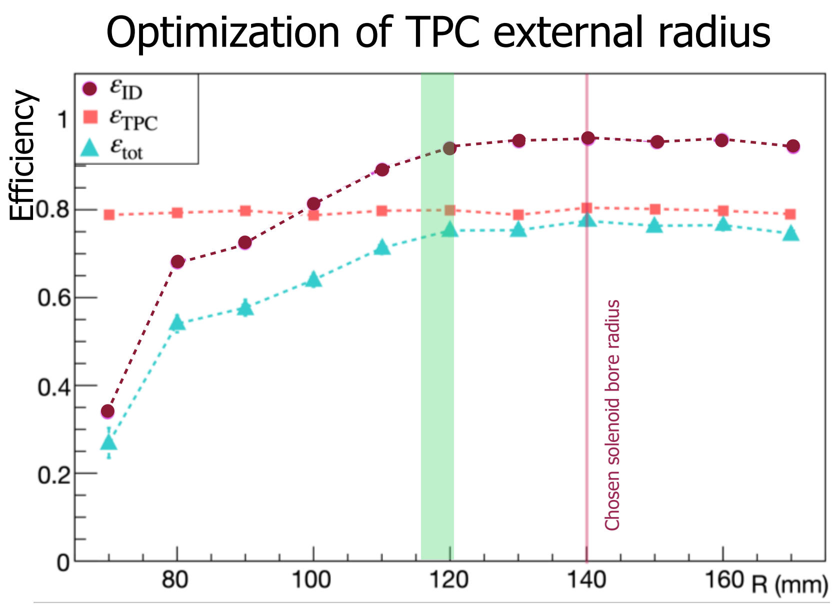
3



*Based on MINOS TPC simulation

TPC Simulations: Results





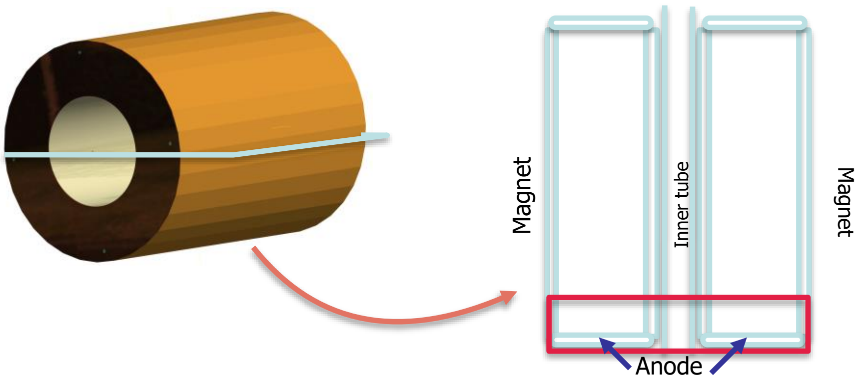
- Simulations carried out show 75% efficiency (pion detection + ID).

TPC Field cage

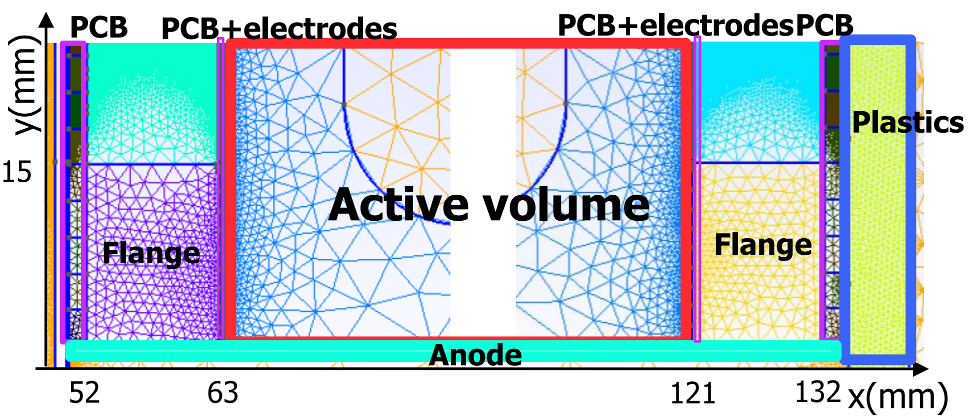
- To be built by CERN (EP-DT).

Field simulations:

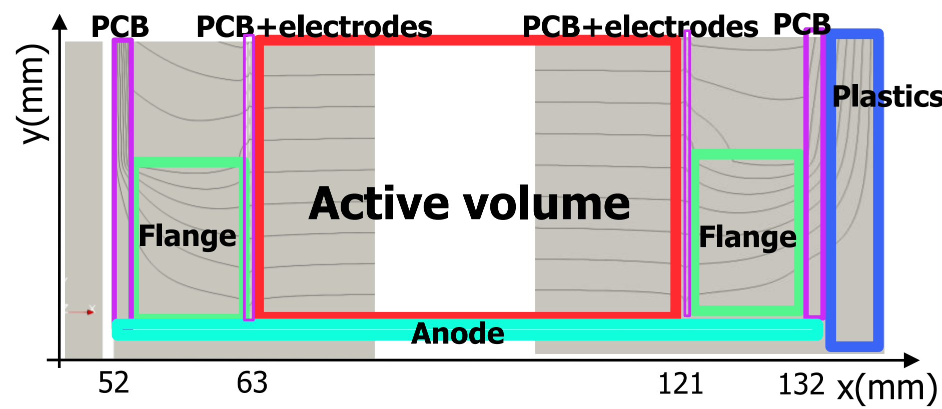
- Geometry and meshing produced with **Gmsh**.
- Poisson’s equation solved with **ElmerFem**.
- Electron drift simulated with **Garfield++**.



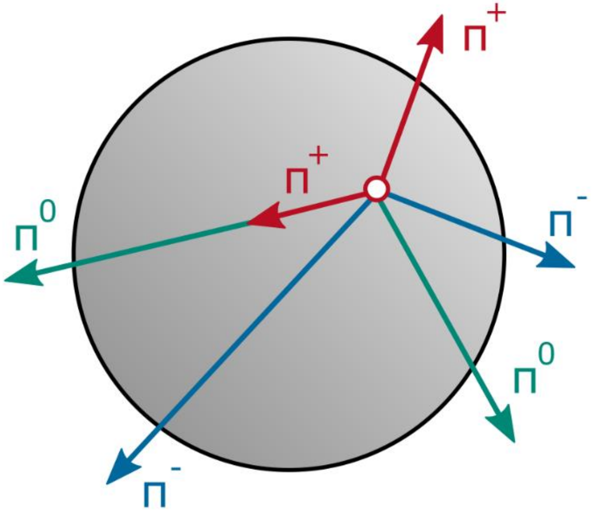
2D Mesh



2D Potential contours



Final State Interactions (FSIs)



Initial state:

$(\pi^+, \pi^-, \pi^0) = (2,2,1)$

$\Sigma = 0$, $M = 4$

Final state:

$(\pi^+, \pi^-, \pi^0) = (1,2,2)$

$\Sigma = -1$, $M = 3$

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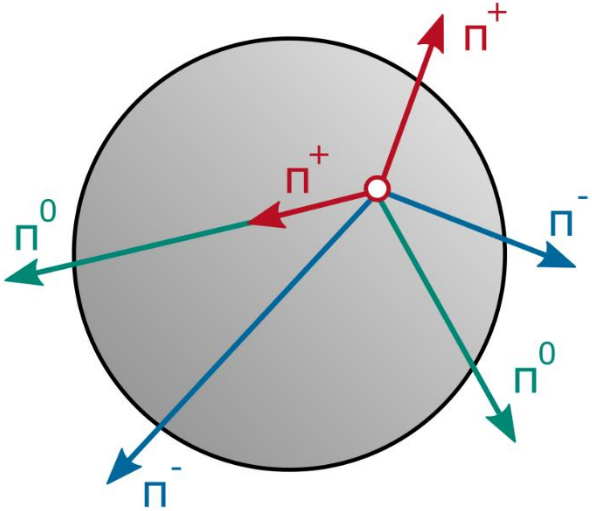

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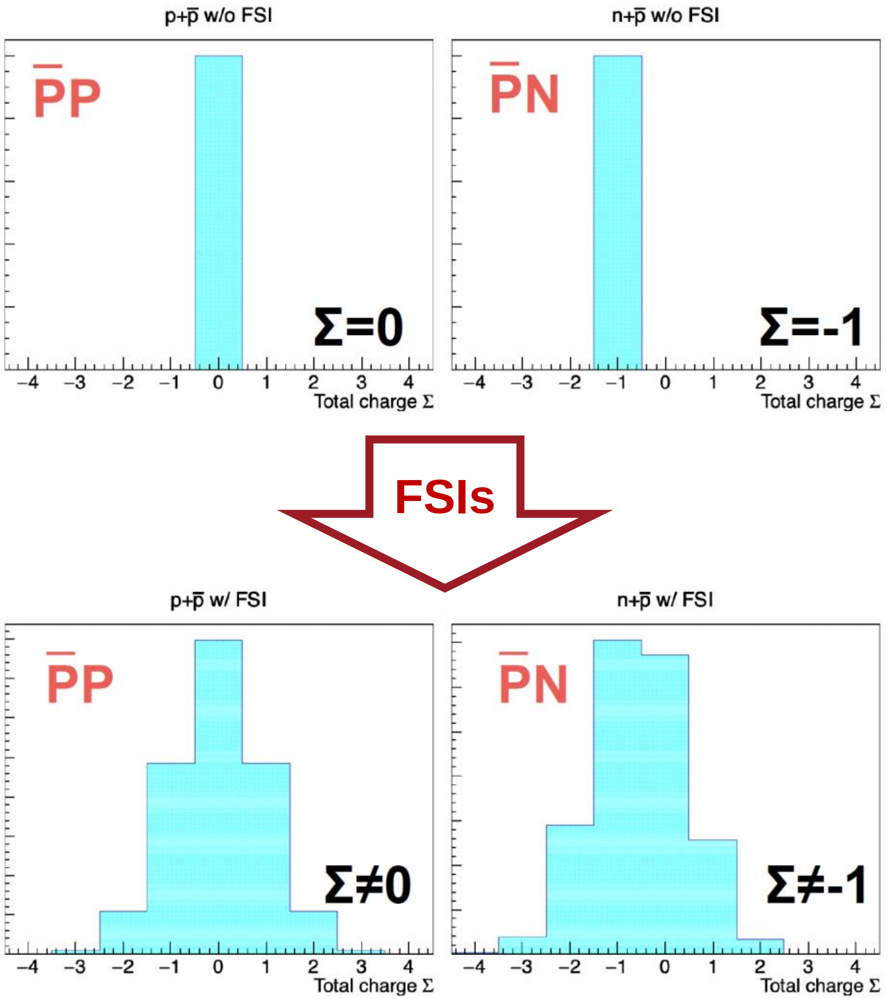
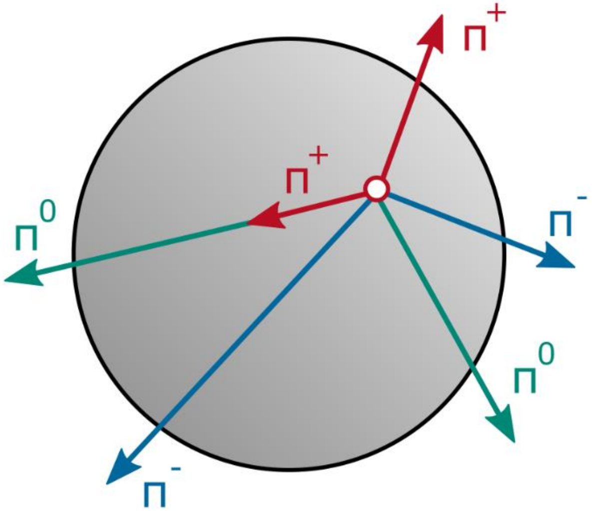


Final State Interactions (FSIs)



4-parameter model of FSIs:

- $\boldsymbol{\lambda_+}$ **,** $\boldsymbol{\lambda_-}$: charge exchange reaction
- $\boldsymbol{\omega_+}$ **,** $\boldsymbol{\omega_-}$: absorption in residue

→ Statistical analysis of charged pion multiplicities

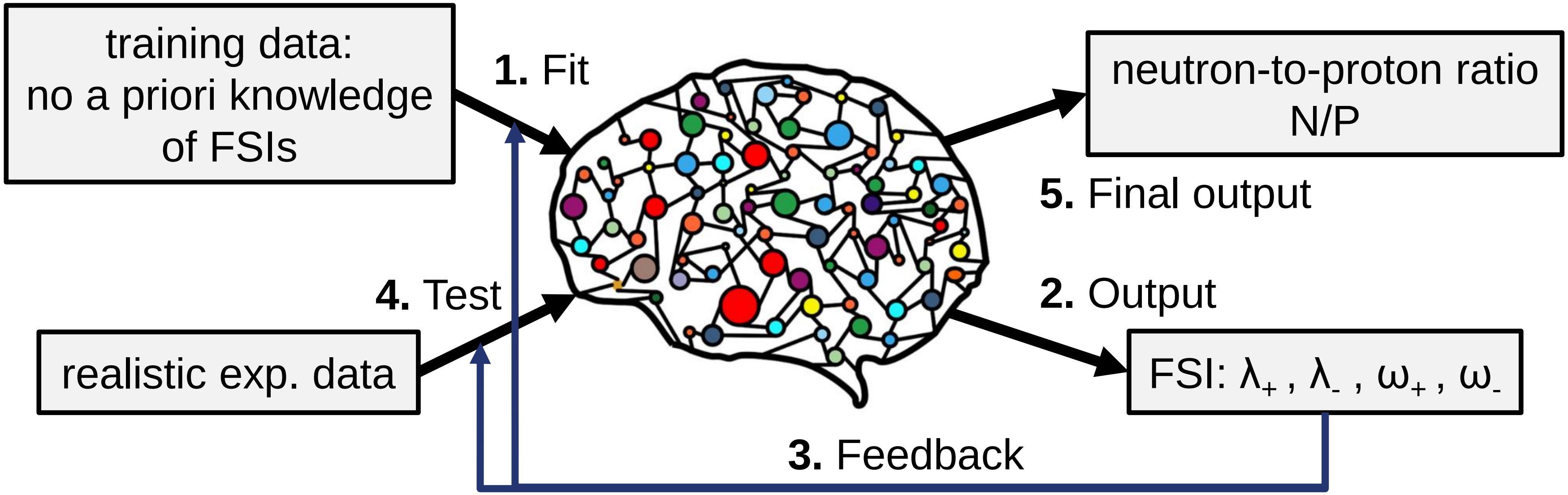
Neural Network Approach

- Use M-Σ matrix as input data for statistical analysis via neural network

$M\backslash\Sigma$	-5	-4	-3	-2	-1	0	$+1$	$+2$	$+3$	$+4$
0	0	0	0	0	0	1384	0	0	0	0
1	0	0	0	0	2696	0	4079	0	0	0
2	0	0	0	1403	0	18331	0	2188	0	0
3	0	0	284	0	12946	0	13783	0	280	0
4	0	27	0	2993	0	23029	0	2035	0	18
5	2	0	313	0	6414	0	4189	0	111	0
6	0	21	0	634	0	2116	0	232	0	3
7	0	0	20	0	312	0	142	0	5	0
8	0	0	0	3	0	4	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0

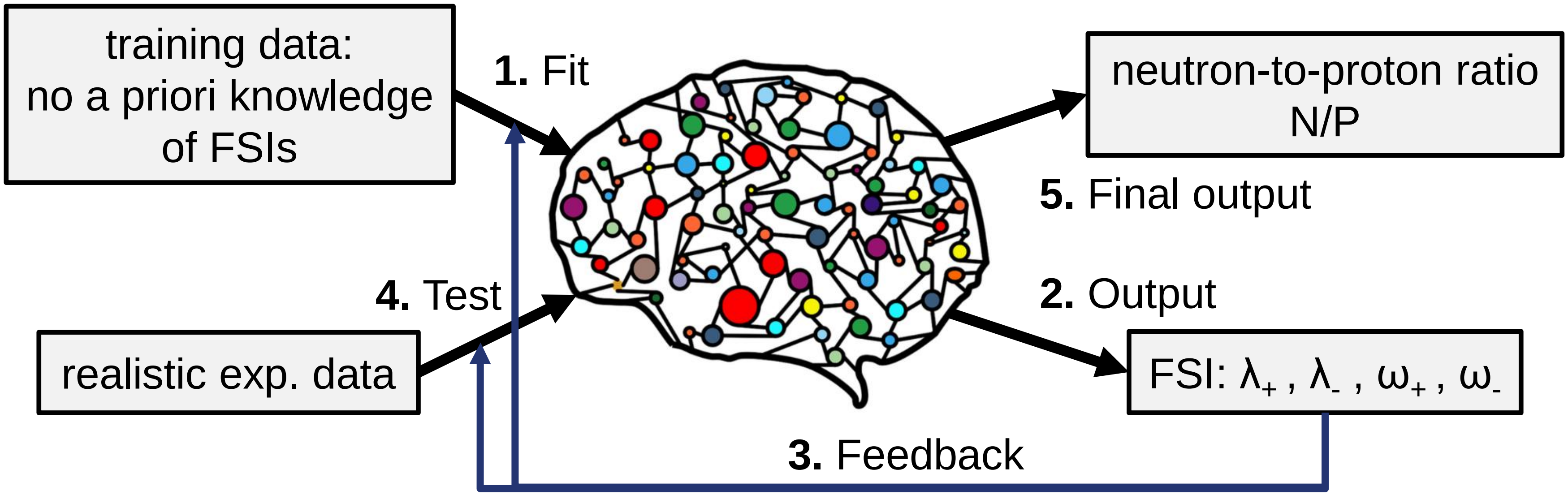
Neural Network Approach

- Use M-Σ matrix as input data for statistical analysis via neural network



Neural Network Approach

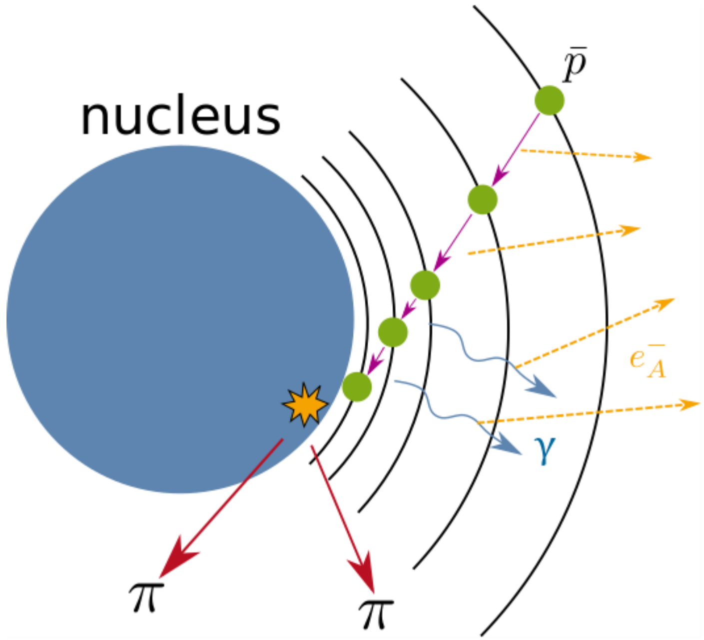
- Use M-Σ matrix as input data for statistical analysis via neural network



- Benchmark tests on realistic intranuclear cascade model simulations

  → precision of ~ 93 % and accuracy of ~ 92 % reached!

Antiprotonic Atoms



$$\sum_{\pi} q_{\pi} \approx \begin{cases} 0 \text{ for } \bar{p}p \\ -1 \text{ for } \bar{p}n \end{cases}$$