Experimental Investigation of Pontecorvo Reactions in ^{3}He Using a Simplified Apparatus

Luca Venturelli
Università di Brescia & INFN-Pavia

On behalf of the ASACUSA Collaboration

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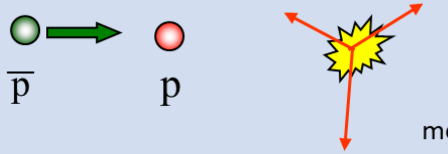
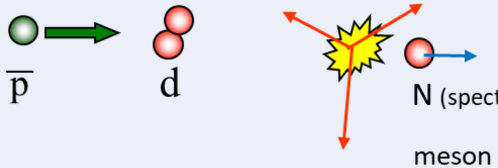
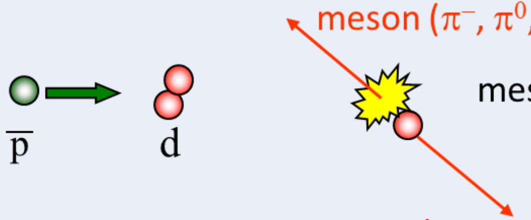
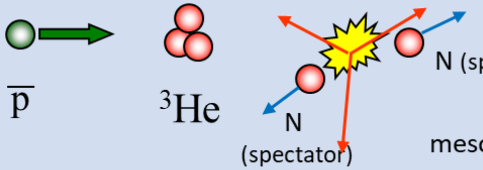
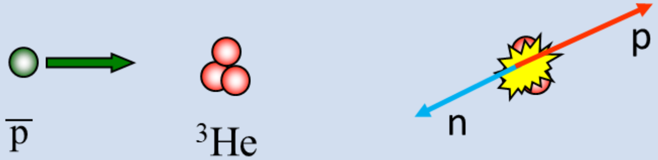
Pontecorvo reactions

Their existence was suggested by Pontecorvo in 1956 (only a few months after the antiproton discovery at Bevatron)

Pontecorvo reactions are (rare): antinucleon annihilations forbidden on a free nucleon but allowed on nucleons bound in nuclei

For antiproton annihilations at rest:

TARGET	USUAL ANNIHILATIONS B.R. ≈ 100%	PONTECORVO REACTIONS
H_2		
D_2		 exp. B.R. ≈ $10^{-6} - 10^{-5}$
^{3}He		 exp. B.R. ≈ ?

Interest on Pontecorvo reactions

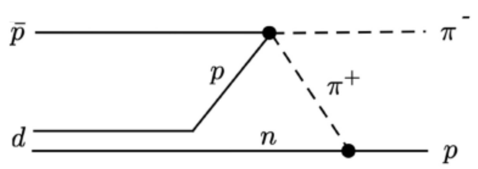
- Pontecorvo reactions are **sensitive to the small internucleon separations** in nuclei, can provide info on **dynamics between nucleons** in nuclei

2 main theoretical approaches

e.g.

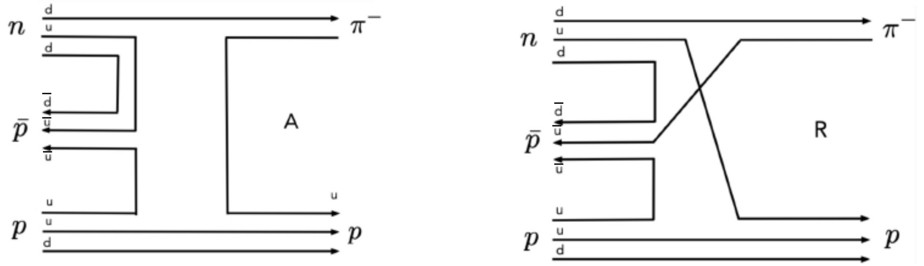
$\bar{p}\, d \rightarrow \pi^- \, p$

Rescattering model



2-step model: antiproton annihilates on proton and the (virtual) π+ is absorbed by neutron

Fireball model



compound system ('fireball') formed by the 3 antiquarks and 6 quarks decaying statistically

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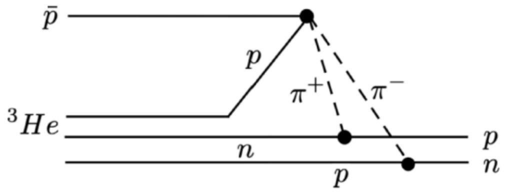
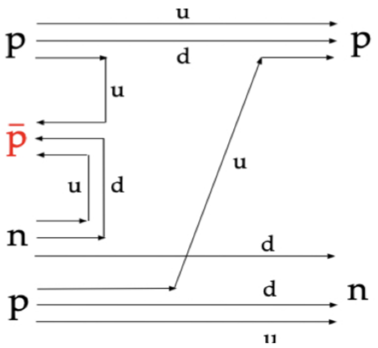
$\bar{p}\, {}^3He \rightarrow n\, p$



B.R. 10^{-8} - 10^{-7}



B.R. 10^{-6}

Example of rearrangement

Different predictions between the 2 models

Existing data

- First measurements (6 events) in bubble chambers in the 1960s
- Preliminary measurements at LEAR by Asterix
- Pontecorvo reactions were **systematically measured at rest in deuterium** at LEAR(CERN) by Crystal Barrel and OBELIX in 1990s

B.R. ≈ $10^{-6} - 10^{-5}$

Pontecorvo reactions measured at LEAR in liquid deuterium and in gas

Reaction	Branching ratio		Experiment
$\bar{p}d \to \pi^- p$	1.46 ± 0.08	$\times 10^{-5}$	OBELIX (in gas)
$\bar{p}d \to \pi^0 n$	7.02 ± 0.72	$\times 10^{-6}$	Crystal Barrel
$\bar{p}d \to \eta n$	3.19 ± 0.48	$\times 10^{-6}$	Crystal Barrel
$\bar{p}d \to \omega n$	22.8 ± 4.1	$\times 10^{-6}$	Crystal Barrel
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$\bar{p}d \to \phi n$	$3.56 \pm 0.20^{+0.2}_{-0.1}$	$\times 10^{-6}$	OBELIX (in gas)
$\bar{p}d \to \rho^- p$	2.9 ± 0.6	$\times 10^{-5}$	OBELIX (in gas)
$\bar{p}d \to \pi^- \Delta^+ (\to \pi^0 p)$	1.01 ± 0.08	$\times 10^{-5}$	OBELIX (in gas)
$\bar{p}d \to \pi^0 \Delta^0 (\to \pi^- p)$	1.12 ± 0.20	$\times 10^{-5}$	OBELIX (in gas)
$\bar{p}d \to \pi^0 \Delta^0 (\to \pi^0 n)$	2.21 ± 0.24	$\times 10^{-5}$	Crystal Barrel
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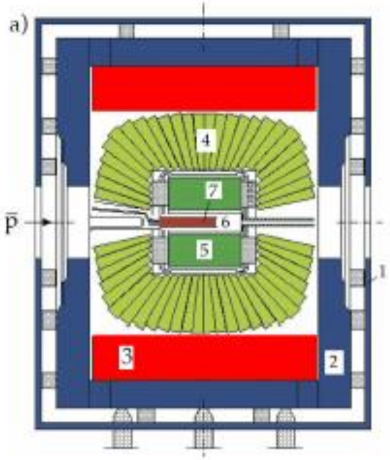
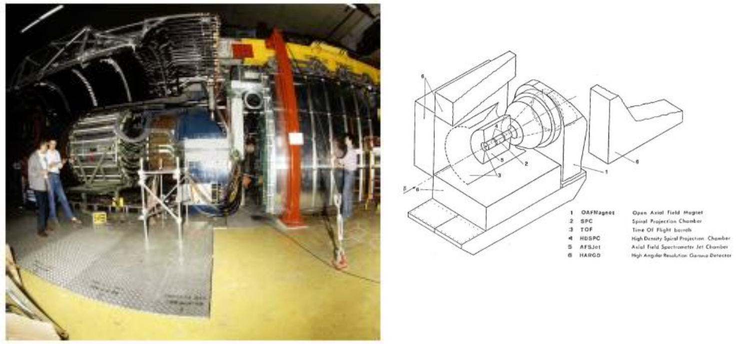


Crystal Barrel

OBELIX



- also data from KEK (Chiba et al., PRD 1997)

$B(\overline{pd} \to \pi^0 n) = (1.03 \pm 0.41) \times 10^{-5}$, $B(\overline{pd} \to \pi^0 \Delta^0) = (4.67 \pm 1.66) \times 10^{-5}$,
$B(\overline{pd} \to \eta n) < 8.94 \times 10^{-6}$ (95% C.L.), and $B(\overline{pd} \to \eta \Delta^0) < 6.49 \times 10^{-5}$ (95% C.L.).

More in-depth on existing data

The data **from Crystal Barrel and OBELIX are in agreement**
(when they can be compared)

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good agreement, assuming charge independence (refers to $\bar{p}d \to \pi^- p$ and $\bar{p}d \to \pi^0 n$)

good agreement, assuming isospin invariance (refers to the three $\pi\Delta$ reactions)

More in-depth on existing data

Theoretical models are **not always in agreement**

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the 2 theoretical models agree well with the ratio of these B.R.s

the rescattering model agrees well with the ratio of these B.R.s

these B.R.s are in **good agreement with the fireball model** and in **disagreement with the rescattering model**

More in-depth on existing data

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good agreement, assuming isospin invariance

these B.R.s are in **good agreement with the fireball model** and in **disagreement with the rescattering model**

More experimental data could help …

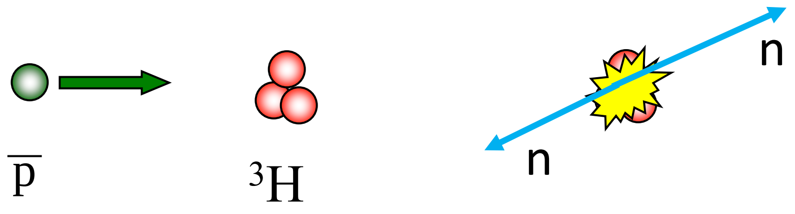
(Non-)existing data

- Pontecorvo annihilations **on three nucleons have never been measured**

$\bar{p}\ {}^3He \rightarrow n\ p$ or $\bar{p}\ {}^3H \rightarrow n\ n$

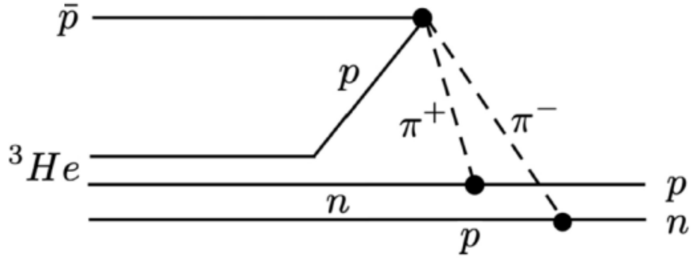
E(n) ~1 GeV

E(p) ~1 GeV



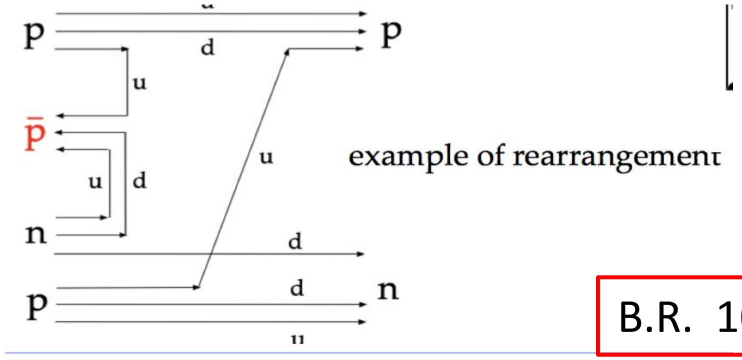
Interest: different models predict **different rates** (by 1-2 orders of magnitude)

Rescattering model



B.R. 10^{-8} - 10^{-7}

Fireball model



B.R. 10^{-6}

$\bar{p}\ {}^{3}He \to n\ p$ measurement in ASACUSA

ASACUSA is studying the possibility of measuring $\bar{p}\ {}^{3}He \to n\ p$

Difficulties:

- Need of a DC antiproton beam
- Pontecorvo reactions are rare processes (B.R.=10^{-5}-10^{-8})
- Background

Measurement at rest in ^{3}**He** can be performed by the **ASACUSA** collaboration

2 options:

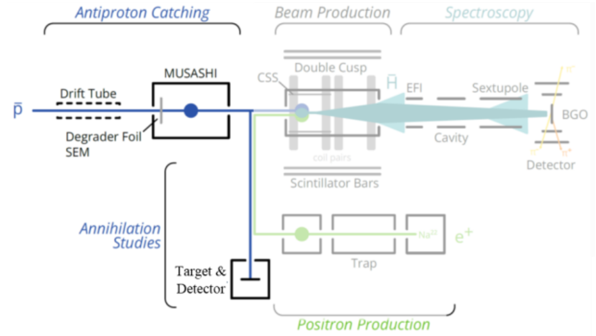
1) using the **DC** slow antiprotons from the new **secondary line in ASACUSA**

or

2) using the antiprotons from **ELENA modified** to deliver a **DC** beam

ASACUSA at CERN-AD

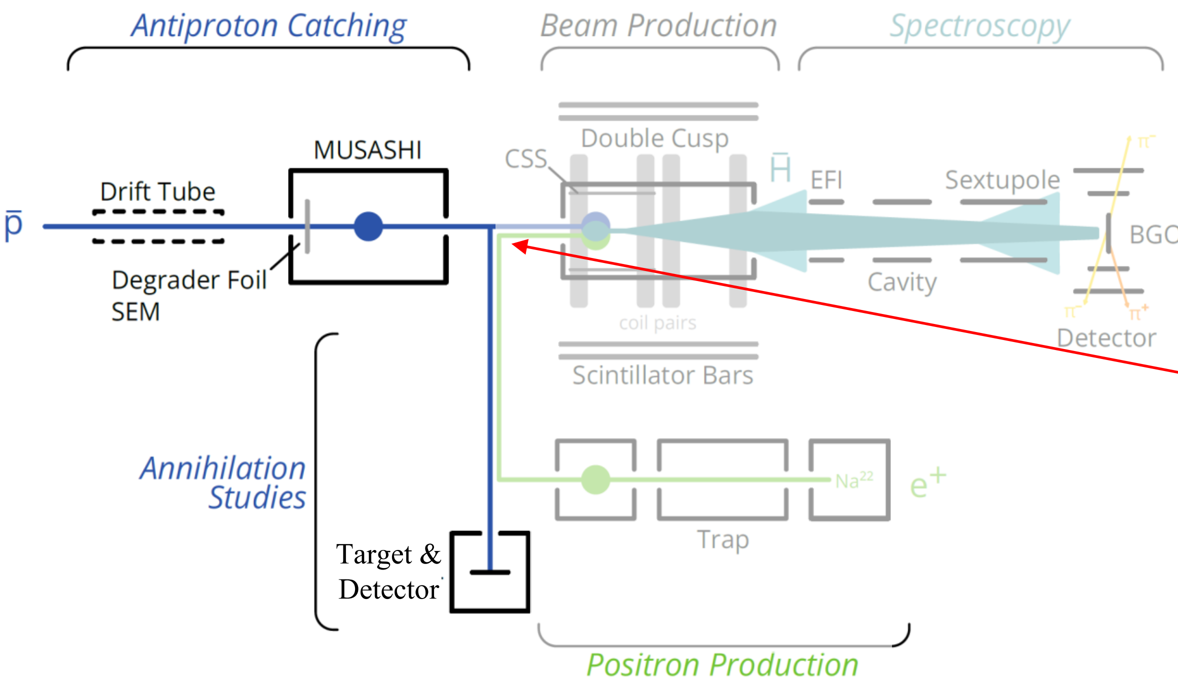
- antiprotonic helium atoms with laser spectroscopy to test CPT
- antihydrogen ground-state hyperfine structure to test CPT
- atomic and nuclear collision cross sections of antiprotons at low energies

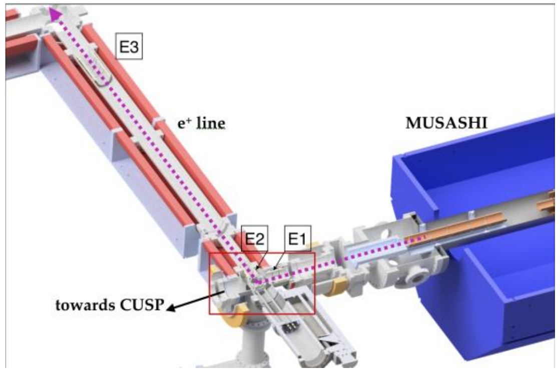


1) using the DC slow antiprotons from the new secondary line in ASACUSA

see Angela Gligorova's talk

ASACUSA-CUSP set-up





The antiproton trap, MUSASHI, can deliver a DC-like beam of antiproton

In MUSASHI: 2 x 10^6 antiprotons captured, cooled and trapped for each ELENA shot (7 x 10^6 antiprotons)

DC extraction: (expected in the target) **10^5 antiprotons**/100 s cycle **@250 eV** → **1000 $\bar{p}$/s**

1 μm window of the cryogenic ^{3}He target requires **re-acceleration** to at least 100 keV

… antiprotons decelerated and then re-accelerated 🤔

2) using the antiprotons from ELENA modified to deliver a DC beam

see Davide Gamba's talk

AD-ELENA

The only low-energy $\bar{p}$ source

AD: 5.3 MeV **pulsed** beam: 3x10^7 $\bar{p}$ every ~ 100 s

ELENA: 5.3 MeV → 100 keV
4 experiments run in parallel (24h/day)

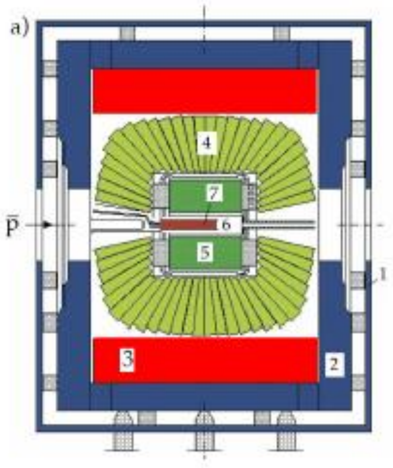
ELENA could be modified to have a **slow extracted** (DC) antiproton beam at 100 keV

(expected in the target) **4-6 10^4 $\bar{p}$/s** x 10-100 better than with MUSASHI

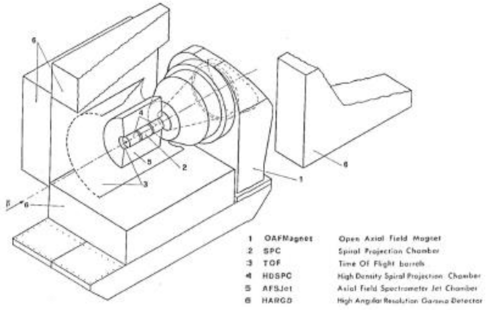
… and no need to re-accelerate

Typical apparatus for Pontecorvo reactions is a magnetic spectrometer

Crystal Barrel



OBELIX



Made of:

- Magnet
- Tracking detector (drift chambers, …)
- T.o.F. system
- e.m. calorimeter

Features:

- reconstruct the trajectories of (all) the particles
- Determine their energy-momentum → **PID**
- Determine missing mass

is it possible to use a simpler apparatus?

Goal: Design a "simple" apparatus to measure the B.R. of $\bar{p}\ ^3He \rightarrow n\ p$

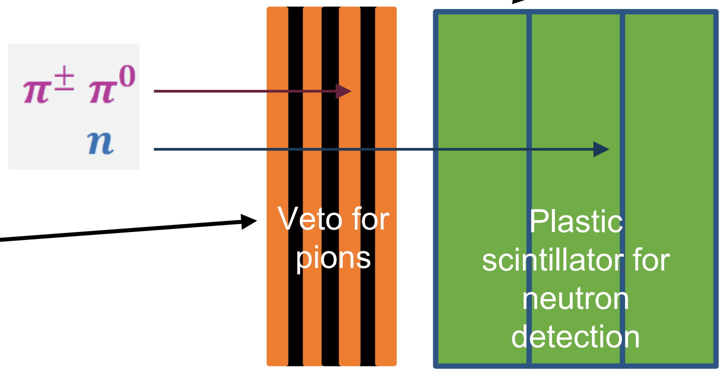
The idea is to use:

- an **efficient detector for 1 GeV neutron**

  → Thick plastic scintillators

- a highly **efficient veto system** mainly for other neutral particles (especially γ's from π^0's)

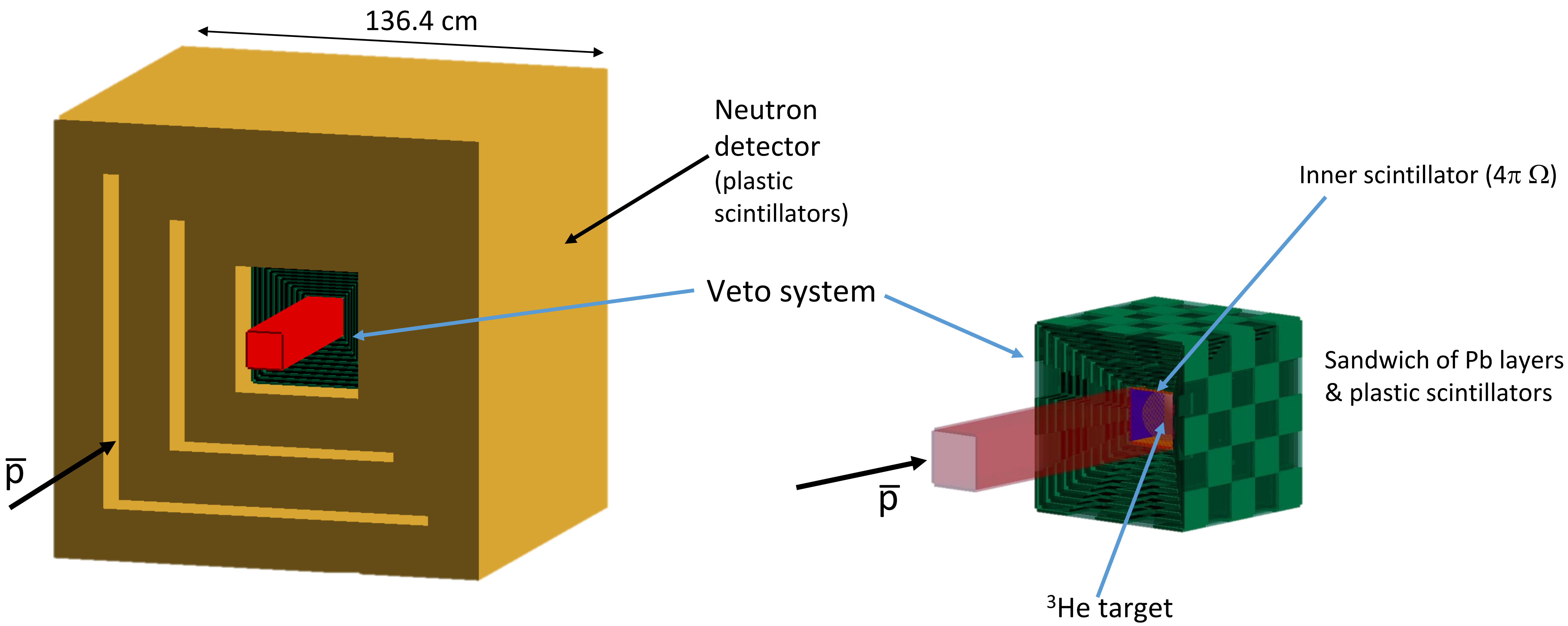
  → Sandwich of Pb layers & plastic scintillators



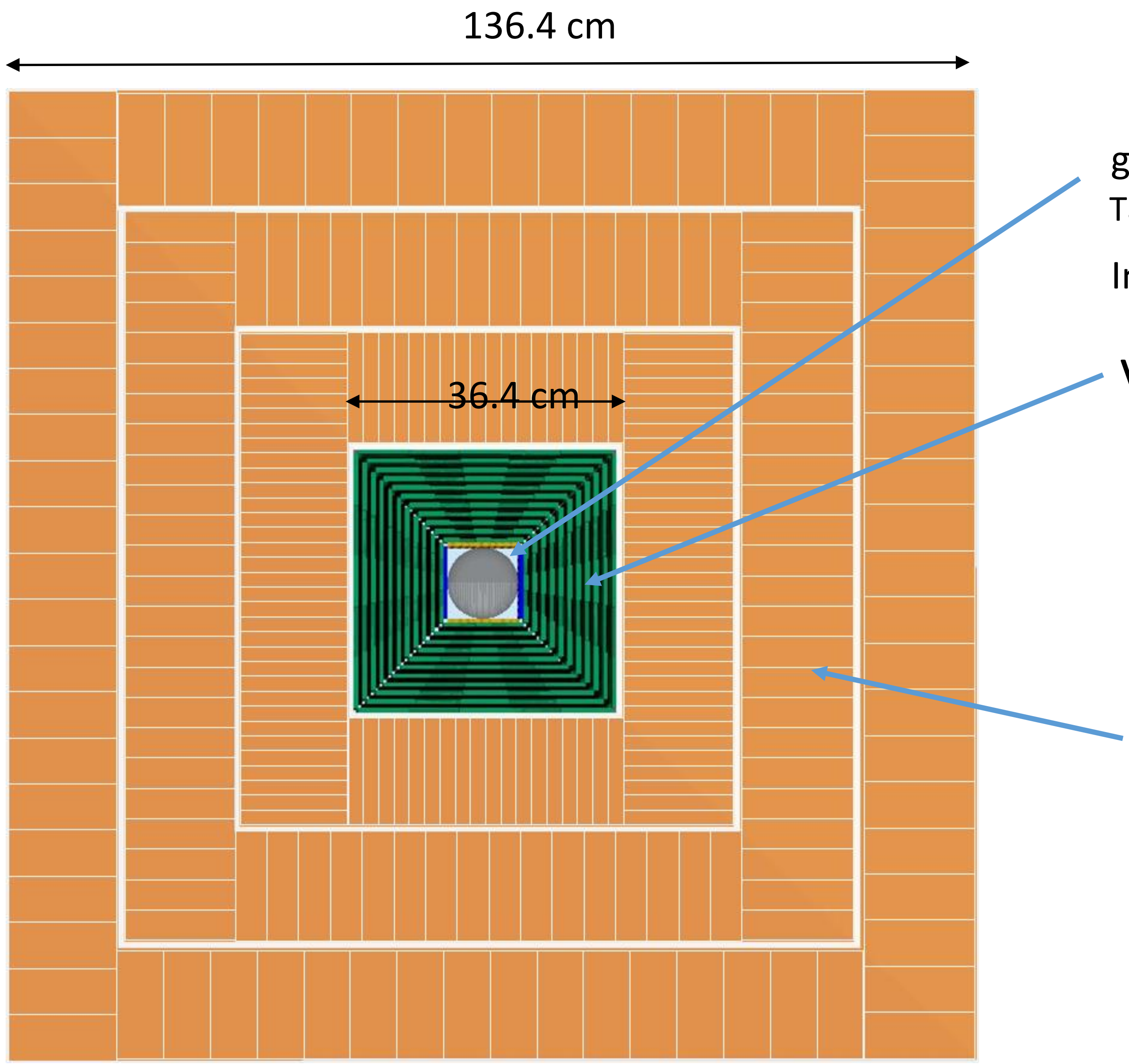
The design is driven by Monte Carlo simulations with GEANT4

DETECTOR

Cube-like geometry with only 4 faces (2/3 4π solid angle)



Geometry



Neutron detector and veto system are segmented

gaseous ^{3}He target (radius = 5 cm)
Target Al vessel thickness = 0.32 mm

Inner cube length =10 cm

Veto system: sandwich of scintillators & Pb layres

# of scintillator layers = 12
scintillator layer thickness = 6 mm

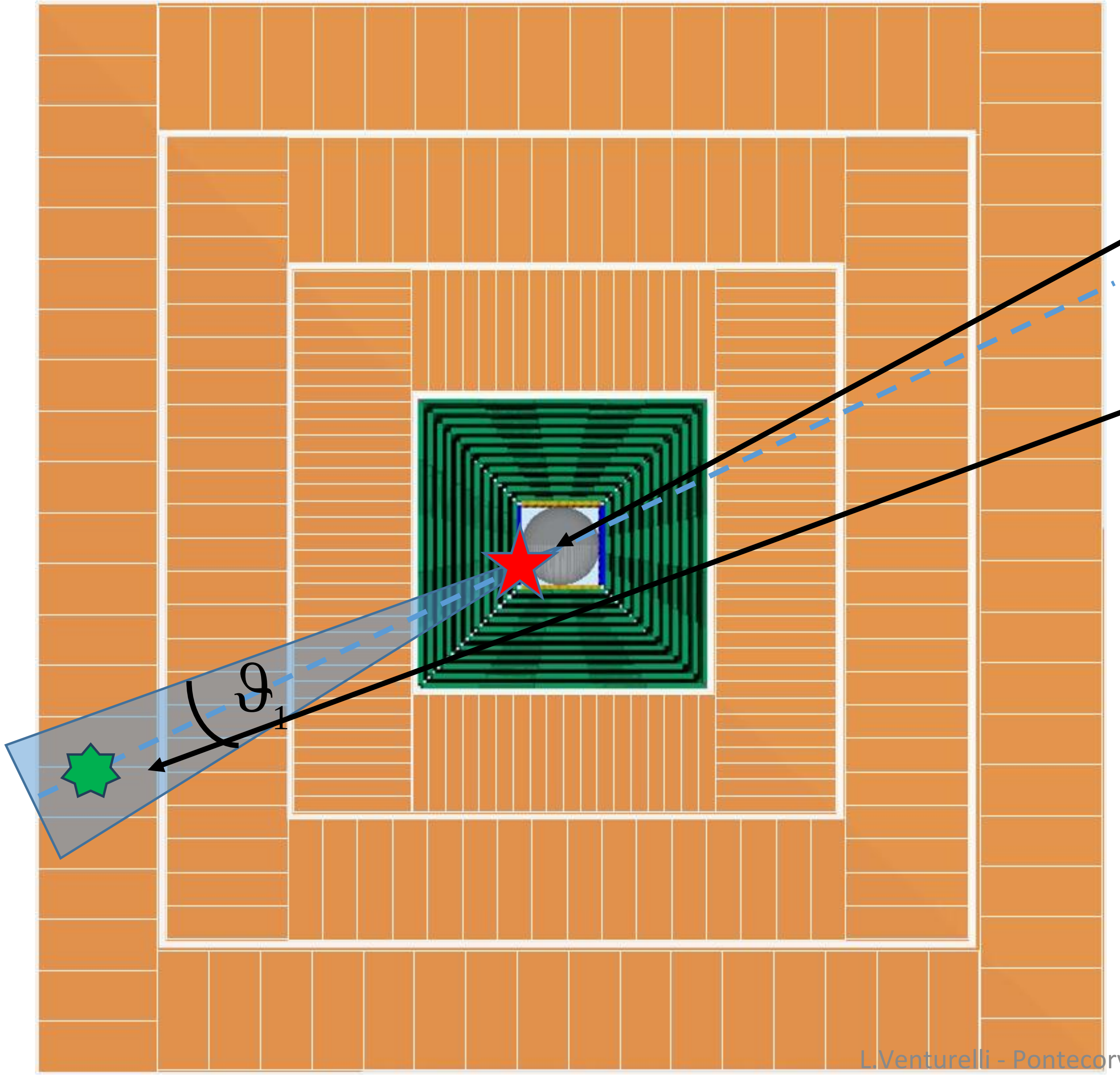
# of Pb layers = 10
Pb layer thickness = 6 mm

Neutron scintillator detector

# of layers =3
layer thickness = 15 cm

# of electronic readout channels = 9762

Topology-based event selection



Applied selection to acquire $\bar{p}\,{}^3He \rightarrow n + p$ **and to reject BKG**

- Only 1 hit on the first scintillator layer of veto

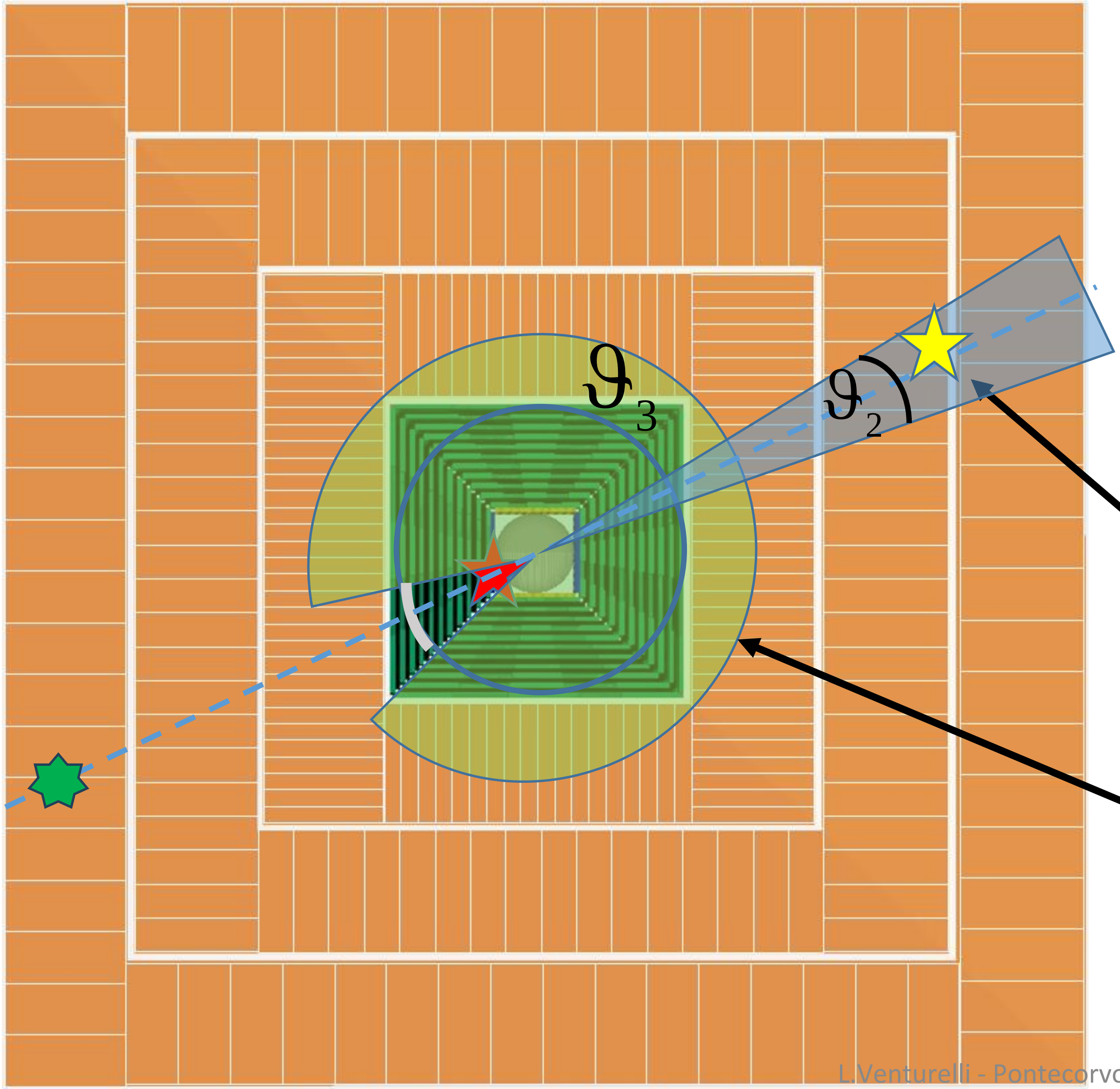
("proton" signal)

AND

- A signal in the neutron detector behind the red hit $\vartheta_1 < 10°$ *("fast proton" signal)* to reject the spectator proton

AND

Topology-based event selection



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- A signal in the neutron detector behind the red hit $\vartheta_1 < 10°$ *("fast proton" signal)* to reject the spectator proton

AND

- A signal in the neutron detector in the opposite direction $\vartheta_2 < 10°$ *("neutron" signal)*

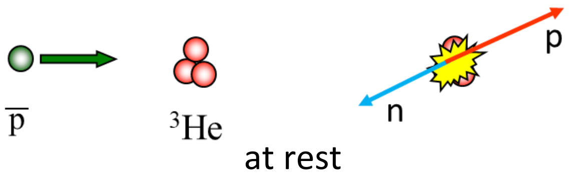
AND

- No signal in the veto system far from the "proton" $\vartheta_3 < 300°$ *(no other particle)*

Monte Carlo results

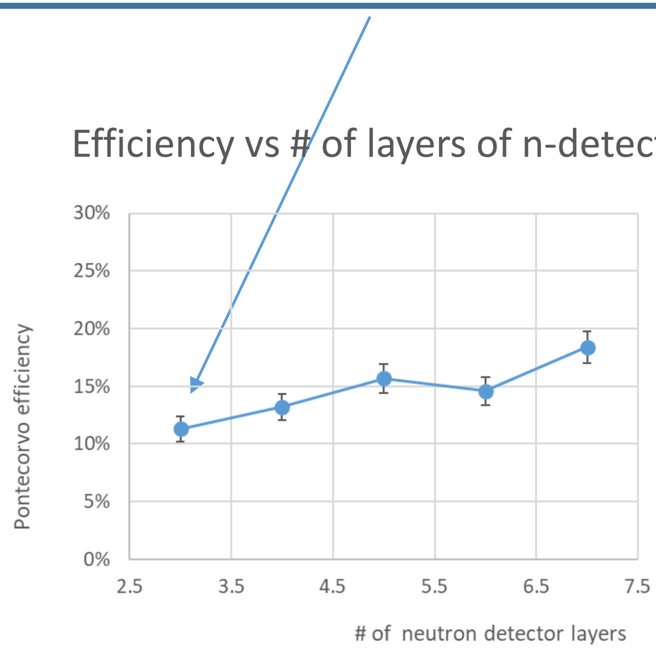
SIGNAL

$$\bar{p}\ {}^{3}He \rightarrow n + p$$



Detection efficiency for Pontecorvo reaction is 11%

Efficiency vs # of layers of n-detector

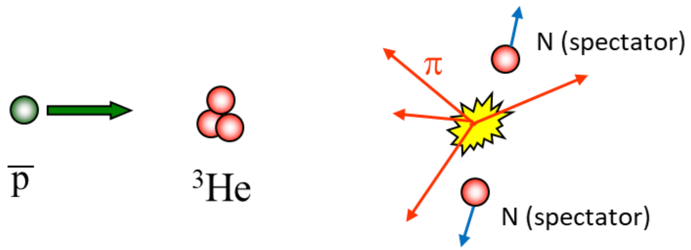


BACKGROUND

Selected Geant4 Physics list: FTFP_BERT_HP + STD + HP

It uses quark gluon string model for high energy interactions

For annihilations at rest B.R. values expected to be not very realistic



# of generated $\bar{p}\ {}^{3}He$ annihilations = 1.8×10^{8}

# of fake Pontecorvo events = 2

no BKG events for other reactions (not in GEANT4):

- Another Pontecorvo reaction: $\bar{p}\ {}^{3}He \rightarrow d\ \pi^{0}$
- Semi-Pontecorvo reactions (antiproton annihilates on a correlated (pn) pair in ${}^{3}He$):

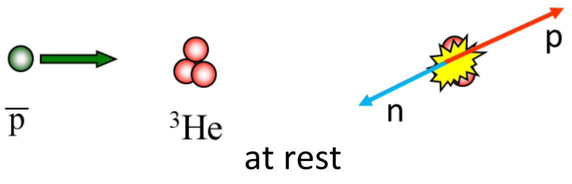
e.g. $\bar{p}\ {}^{3}He \rightarrow \pi^{-}\ p\ p$ $\quad \bar{p} << d >> \rightarrow \pi^{-}\ p$

<<d>> quasi-deuteron

Monte Carlo results

SIGNAL

$$\bar{p}\ {}^{3}He \rightarrow n + p$$



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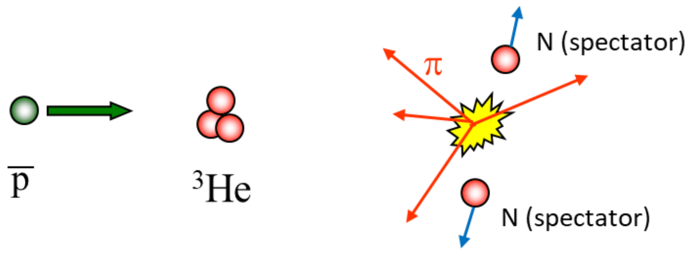

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Validation of the GEANT4 simulations

Experimental data are needed to validate the GEANT4 simulations of high-energy neutrons

Detection efficiency of a plastic scintillator for 1 GeV neutron can be measured at the n_TOF facility at CERN

<<d>> quasi-deuteron

Rate estimate in ASACUSA

To measure in ASACUSA: antiproton acceleration (100 keV?)

^{3}He	
Antiprotons (**from MUSASHI**)	10^5/spill=10^5/115s
B.R. ($\bar{p} + {}^3He \rightarrow n + p$)	10^{-6}
Detection efficiency	11%
S/N	10
# of ELENA spills for 1 Pontecorvo event	90 spills = 3 h

similar results in ^{3}H

(but safety issues)

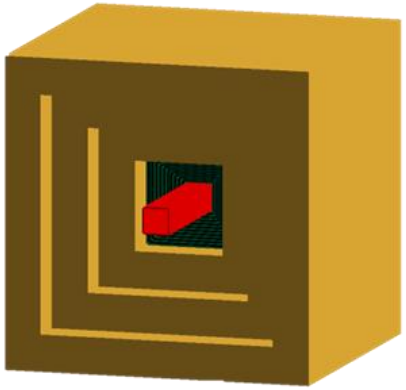
x 10-100 better with a DC beam from ELENA

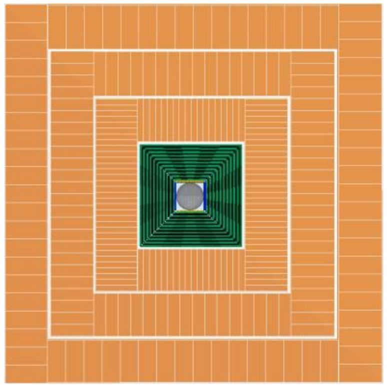
N.B. also acquire data of antiproton annihilations in hydrogen → useful to study the BKG

Other options

Consider the following options:

- Reduce the material





Present configuration:
Cube-like geometry with 4 faces (2/3 4π solid angle)
Inner cube length =10 cm   Outer cube length= 136 cm

Stuff: 165 kg of Pb
20 kg of veto scintillators
1500 kg of neutron detector scintillators

- Reduce the segmentation/number of electronic readout channels

  number of electronic readout channels = 9800

- veto system: use crystals instead of lead and scintillator

  (In principle more expensive but it could be possible to recycle a dismissed calorimeter from completed experiments)

Conclusions

On paper, an apparatus with **only scintillator detectors** seems to work

The apparatus has to be optimized

Pros: the apparatus is relatively cheap, not difficult to build and to maintain

but …

no PID
not multipurpose: no other measurements can be performed

Consider a totally different scenario: → use a **magnetic spectrometer**

Pros:

- PID implemented
- multipurpose apparatus → different measurements are possible:
  - In the same data sample other reactions can be studied (included the search of the sexaquark ***S***)
  - Using a H_2 target, the e.m. proton form factor in the time-like region (B.R. 10^{-7}) could be measured

see the talks by Glennys Farrar and Michael Doser

Cons:

- expensive
- many expert groups should be involved

Thank you very much for your attention

Short reviews:

C. Amsler, arXiv 1908.08455 (2019)
A. Donnachie, Physics Reports (2004)

Credits: