낮은 에너지 반양성자의 소멸 반응의 검출

Jongwon Hwang

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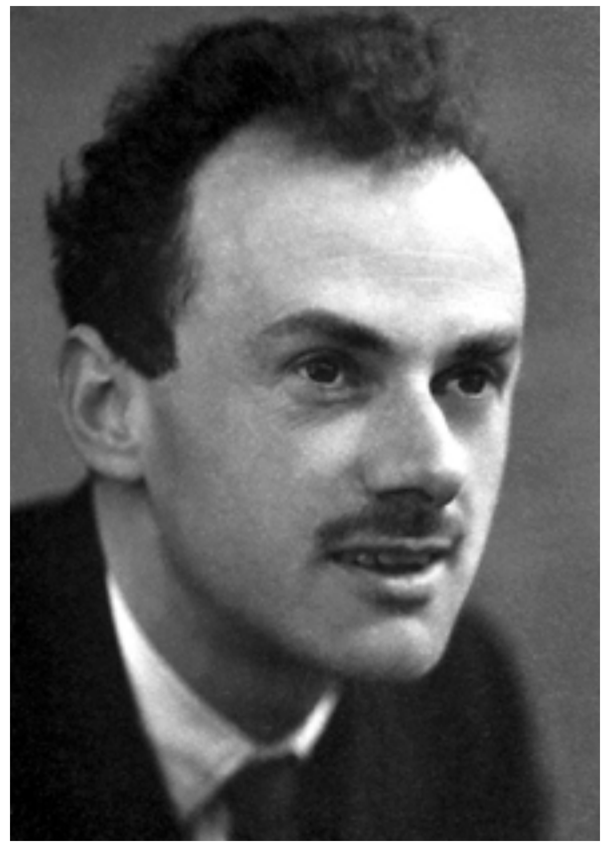
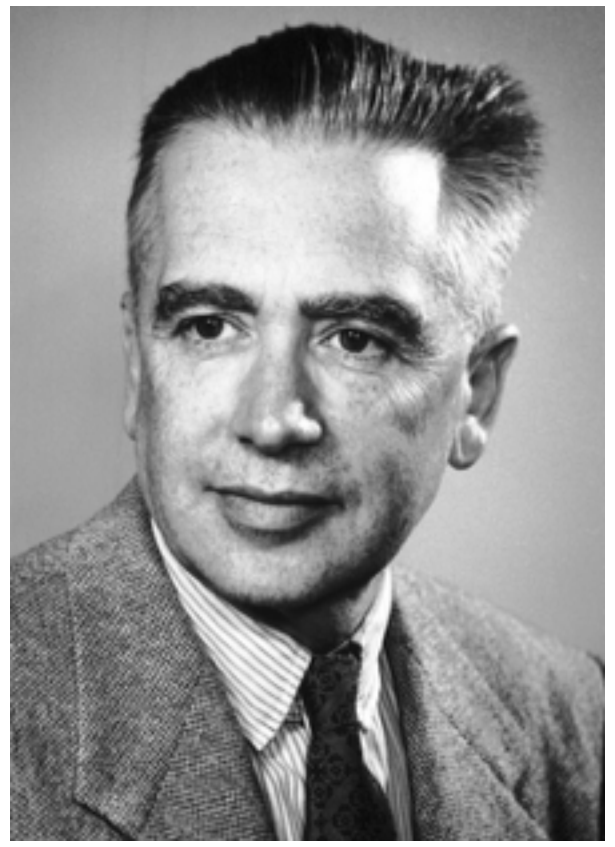
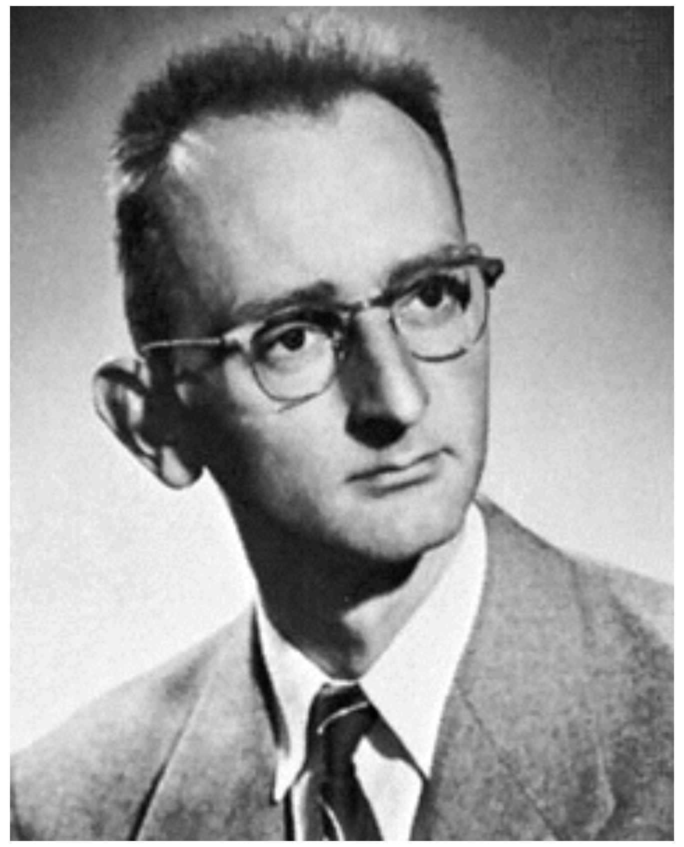
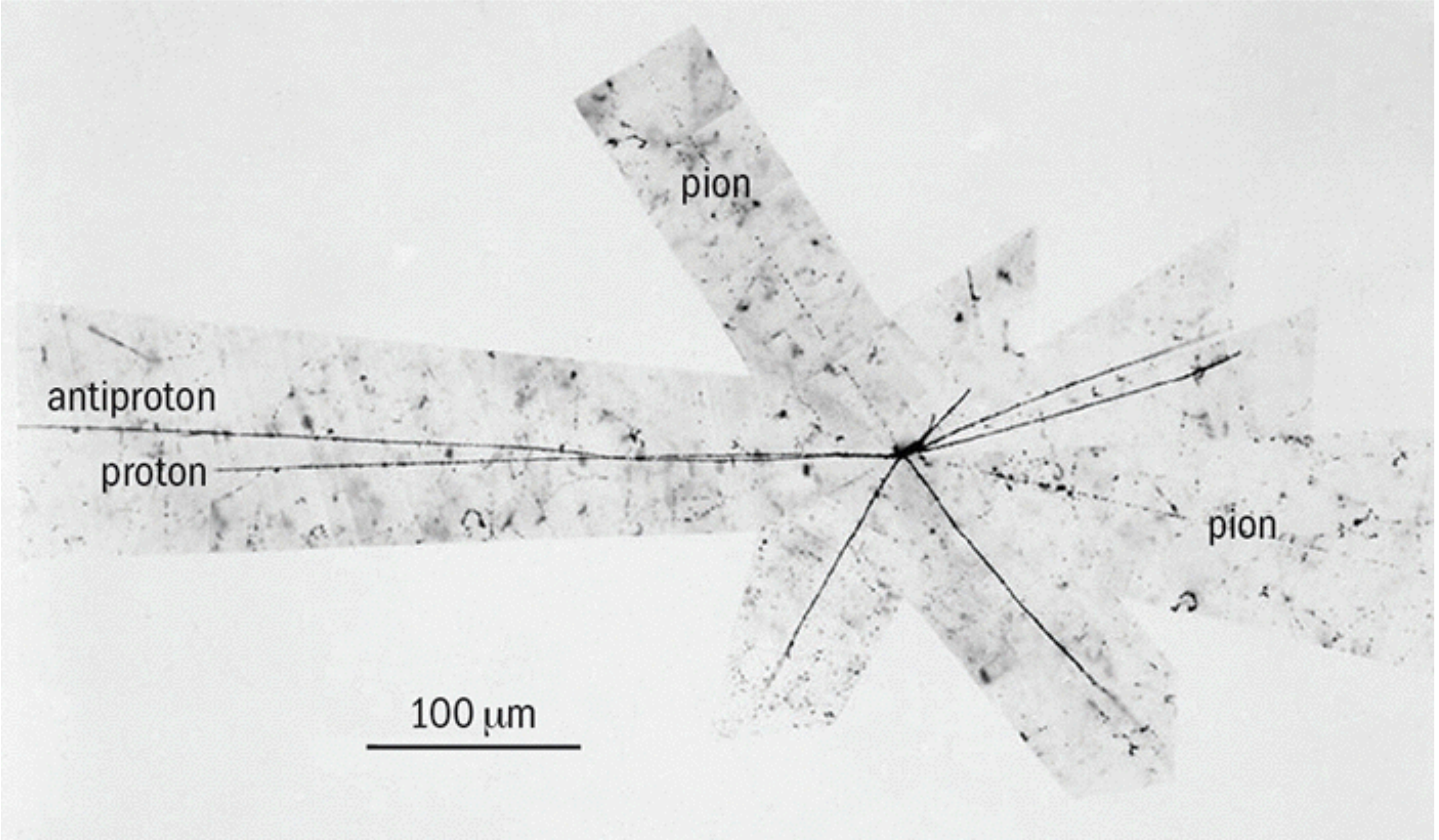
Outline

- Antiproton
- Source
- Annihilation
- Experiment
  - Crystal Barrel
  - ASACUSA (Atomic Spectroscopy And Collisions Using Slow Antiprotons)

Antiproton: History

- **Prediction**: Paul Dirac (1933, Nobel Prize lecture)
  - Winning Nobel Prize (prediction of positron)
  - Prediction of antiparticle of nucleons(p, n)
- **Discovery**: Emilio Segrè, Owen Chamberlain (1955, Bevatron @ LBNL, Berkeley)
  - Bubble Chamber experiment
  - Nobel Prize winner (1959)

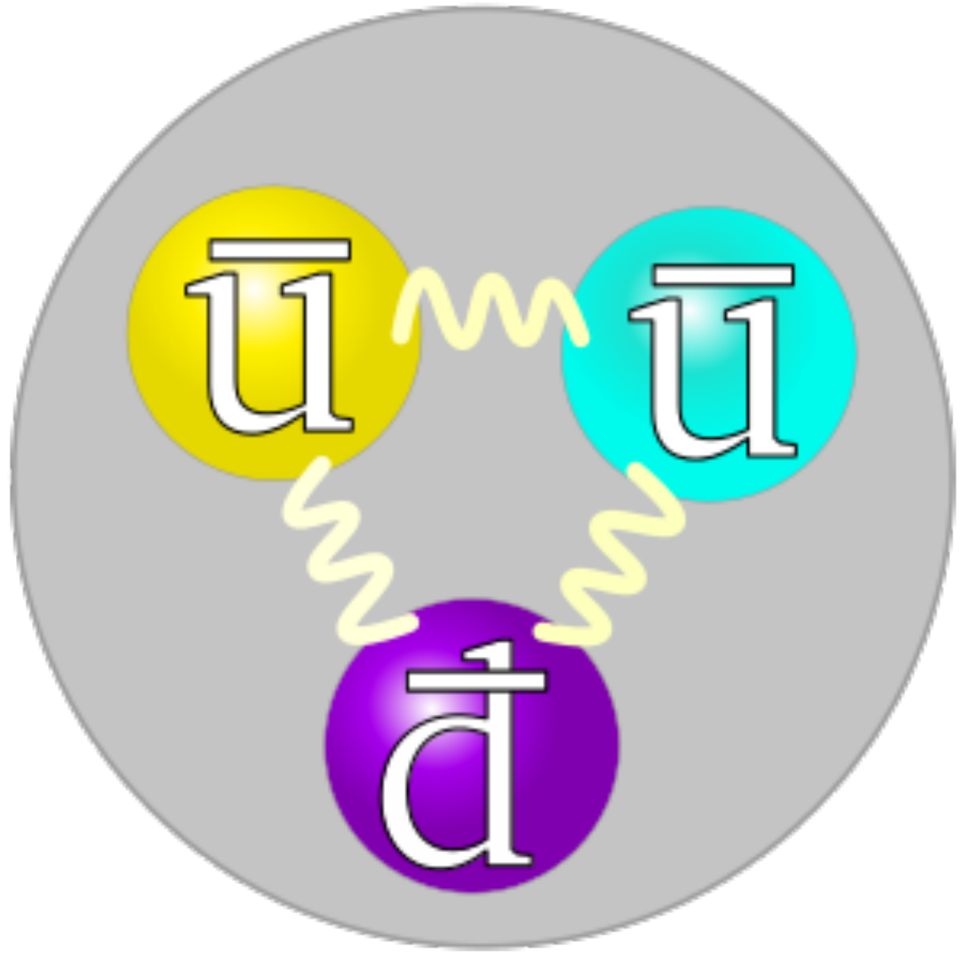


One of the first annihilations of an antiproton observed at the Bevatron with a photographic emulsion.

Antiproton: Characteristics

- antiparticle of proton: $|\bar{p}>= C|p>$
- mass: $m_{\bar{p}} = m_p = 938.2720813 \text{ MeV}$
  (in 10^{-12} accuracy from q/m measurement)
- charge: $q_{\bar{p}} = -q_p = -e$
- spin: $s_{\bar{p}} = s_p = 1/2$
- isospin: $I_{3,\bar{p}} = -I_{3,p} = -1/2$

$$\bar{p} = \bar{u}\bar{u}\bar{d}$$



Source: Cosmic-ray

- Antiproton can be detected in cosmic rays.
- produced in collisions of cosmic ray protons (secondary production)

$$p + A \to p + \bar{p} + p + A$$

- experiments (measuring flux, energy)
  - balloon-borne experiment (BESS, CAPRICE, HEAT)
  - space(satellite)-based detectors (AMS, PAMELA)
  - information about universe (dark matter)

Source: Accelerator

- Tevatron (Fermilab, inactive)
  - a hundred GeV of proton impinging a target → choosing, cooling, and accumulating → about 10^{10} per hour
  - proton-antiproton collision (larger momentum transfer than proton-proton)
  - APEX collaboration: lifetime measurement by the search for antiproton decay

- Proton-Synchrotron-based (CERN)
  - a few tens GeV of proton impinging a target → choosing, cooling, and accumulating → about 10^{12} per day (p ~ 3.5 GeV/c)
  - used in collision experiment (re-injected into PS), or …
  - LEAR (Low Energy Antiproton Ring, 1983-1996): p = 60 ~ 1940 MeV/c, intensity ~ 10^6 per second
  - AD (Antiproton Decelerator, now): p ~ 100 MeV/c, intensity ~ 10^6 per second

Antiproton: Annihilation

- Pair annihilation: $p + \bar{p} \rightarrow \ \ ?$
- "⋯ the so-called "annihilation" does not imply actual annihilation of all incoming quarks and antiquarks, but simply results from their rearrangement into quark-antiquark pairs."
  (E. Klempt, et al., Physics Reports 413 (2005) 197-317)
- A few simple variables to describe the nature:
  mean number of pions, their distribution, η-produced events

$$p + \bar{p} \rightarrow ? \rightarrow \pi + \pi + ...$$

other mesonic states

Antiproton: Annihilation

Table 3
Momenta for $\bar{p}p$ annihilation at rest into two mesons

Channel		Momentum (MeV/c)	Channel		Momentum (MeV/c)
$\bar{p}p \rightarrow$	$\pi^0\pi^0$	928.5	$\bar{p}p \rightarrow$	$\rho\rho$	536.3
	$\pi^+\pi^-$	927.8		$\omega\rho$	527.5
	$\pi^0\eta$	852.3		$\omega\omega$	518.5
	K^+K^-	797.9		$\eta\phi$	499.7
	$K^0\overline{K}^0$	795.4		$\pi f_2(1270)$	491.2
	$\pi\rho$	773.2		$\pi a_2(1320)$	459.9
	$\pi^0\omega$	768.4		$\eta'\rho$	364.4
	$\eta\eta$	761.0		$\eta'\omega$	350.5
	$\eta\rho$	663.5		$K^*\overline{K}^*$	285.2
	$\pi^0\eta'$	658.7		$\rho\phi$	280.3
	$\eta\omega$	656.4		$\omega\phi$	260.8
	$\pi^0\phi$	652.4		$\eta f_2(1270)$	206.2
	$K\overline{K}^*$	616.2		$\eta a_2(1320)$	91.2
	$\eta\eta'$	546.1		$\omega f_2(1270)$	See text

"Due to its relatively large mass, the antiproton-proton system possesses a large variety of two-body annihilation modes."

Antiproton: Annihilation

- Pion multiplicity

$$n_{\pi} = 4.98 \pm 0.13$$

$$n_{\pi^{\pm}} = 3.05 \pm 0.04$$

$$n_{\pi^{0}} = 1.93 \pm 0.12$$

Table 7
Annihilation frequencies of $\bar{p}p$ annihilation at rest in liquid H_2 into pionic final states (in units of 10^{-3}), from [2,48,216]

Final state	BNL	CERN	Crystal Barrel
All neutral	32 ± 5	41^{+2}_{-6}	35 ± 3
$2\pi^0$			0.65 ± 0.03
$3\pi^0$			7.0 ± 0.4
$4\pi^0$			3.1 ± 0.2
$5\pi^0$			9.2 ± 0.4
$6\pi^0$ (1)			0.12 ± 0.01
$7\pi^0$ (1)			1.3 ± 0.1
$8\pi^0$ (2)			0.012 ± 0.001
$9\pi^0$ (2)			0.025 ± 0.003
Non-multipion			15 ± 5
$\pi^+\pi^-$	3.2 ± 0.3	3.33 ± 0.17	3.14 ± 0.12
$\pi^+\pi^-\pi^0$	78 ± 9	69.0 ± 3.5	67 ± 10
$\pi^+\pi^-2\pi^0$			122 ± 18
$\pi^+\pi^-3\pi^0$			133 ± 20
$\pi^+\pi^-4\pi^0$			36 ± 5
$\pi^+\pi^-5\pi^0$ (1)			13 ± 2
$\pi^+\pi^-$MM	345 ± 12	358 ± 8	65 ± 20*
$2\pi^+2\pi^-$	58 ± 3	69 ± 6	56 ± 9
$2\pi^+2\pi^-\pi^0$	187 ± 7	196 ± 6	210 ± 32
$2\pi^+2\pi^-2\pi^0$			177 ± 27
$2\pi^+2\pi^-3\pi^0$			6 ± 2
$2\pi^+2\pi^-$MM	213 ± 11	208 ± 7	30 ± 15*
$3\pi^+3\pi^-$	19 ± 2	21.0 ± 2.5	
$3\pi^+3\pi^-\pi^0$	16 ± 3	8.5 ± 1.5	40 ± 3[a]
$3\pi^+3\pi^-$MM	16 ± 3	3 ± 1	
Sum	954 ± 18	986 ± 6	970 ± 58

Antiproton: Annihilation

- Pion multiplicity

$$n_{\pi} = 4.98 \pm 0.13$$
$$n_{\pi^{\pm}} = 3.05 \pm 0.04$$
$$n_{\pi^{0}} = 1.93 \pm 0.12$$

Table 8
Pionic multiplicity distribution

	From Table 7	From [263]
2 pions	0.38 ± 0.03%	0.38 ± 0.03%
3 pions	7.4 ± 0.3%	7.8 ± 0.4%
4 pions	18.1 ± 1.8%	17.5 ± 3.0%
5 pions	35.2 ± 3.7%	45.8 ± 3.0%
6 pions	23.3 ± 2.8%	22.1 ± 1.5%
7 pions	3.3 ± 0.3%	6.1 ± 1.0%
8 pions		0.3 ± 0.1%

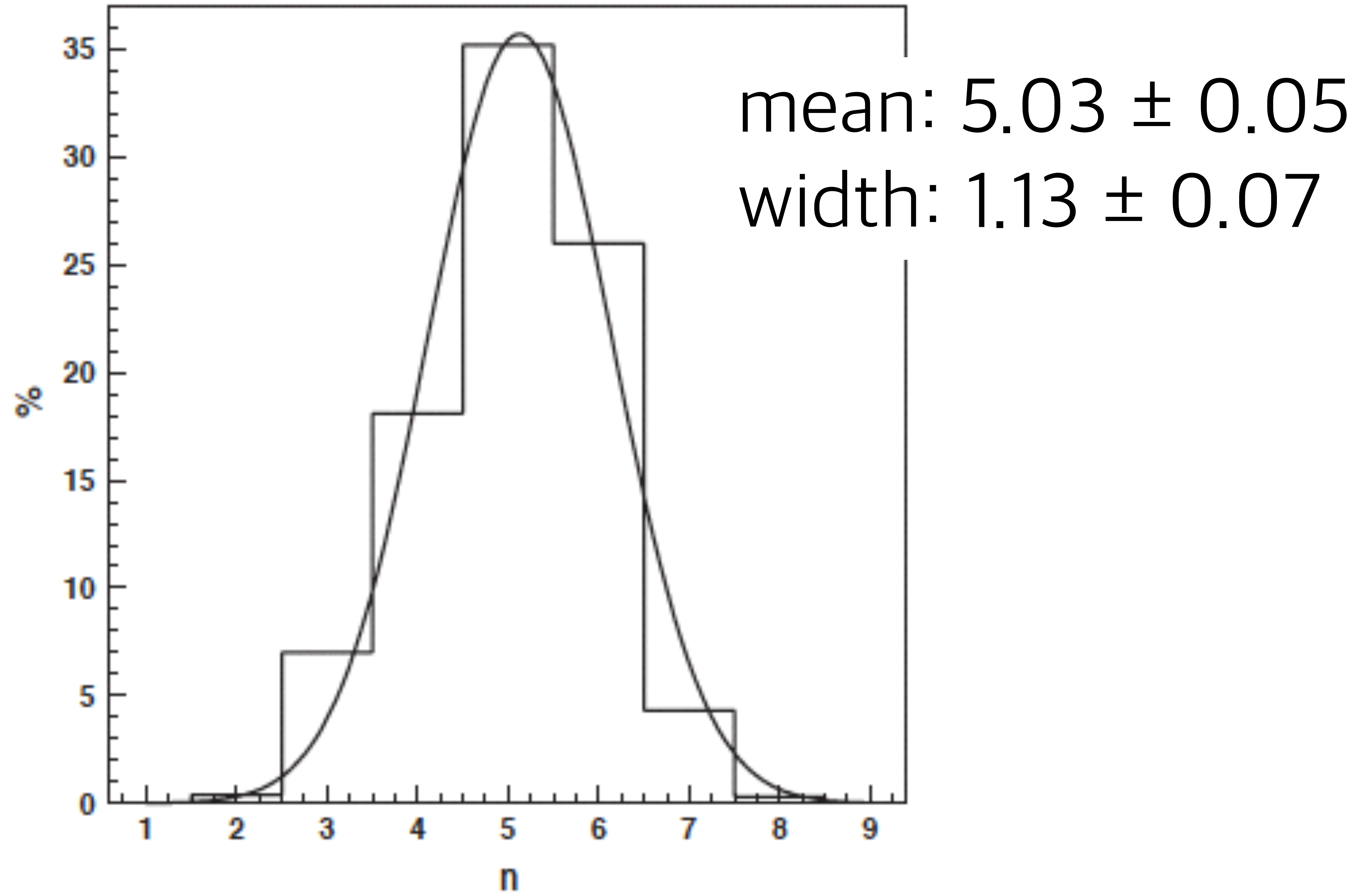


Fig. 11. The pion multiplicity distribution (in %) from Crystal Barrel data, Table 8.

Antiproton: Annihilation

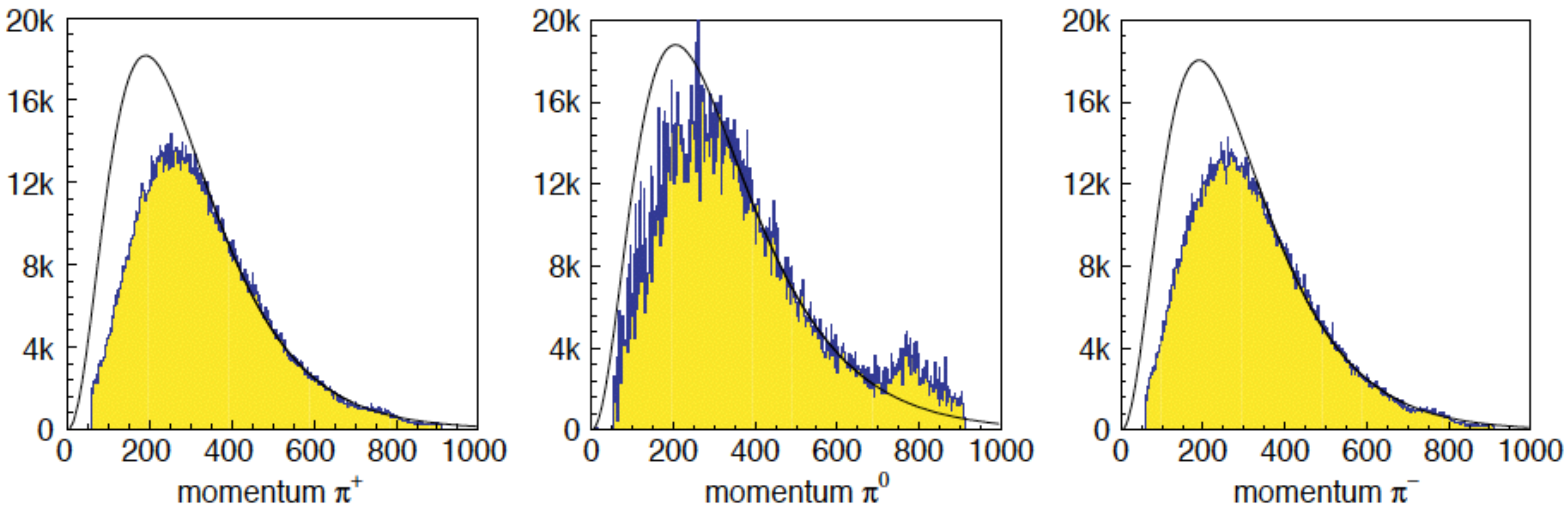


Fig. 12. The momentum distribution of charged and neutral pions.

- Crystal Barrel results
- Maxwell-Boltzmann distribution fitting (~ 120 MeV of temp.)
  Low momenta mismatch: now due to the eff. of detector but the nature of pions

Experiment: New states with quarks-antiquarks

- Baryonium (baryon-antibaryon states): main motivation of LEAR (CERN)
  - "none of the baryonium states were confirmed at LEAR."

- New mesons (meson spectroscopy): hydrogen bubble chamber exp.
  - ASTELIX, OBELIX, Crystal Barrel, JETSET (at LEAR)
  - discovery of new mesons (E meson (η(1440)), D meson (f_1(1285)), etc.)

- glueball (a state made only of gluons)
  - Crystal Barrel: specialized in the multi-neutral events ($\pi^0 \rightarrow \gamma\gamma$)
  - spin-0 mesons: f_0(980), f_0(1500) → a good candidate for a glueball
  - spin-2 mesons: f_2(1270), f_2(1565)

Experiment: To test CPT

- CPT(Charge, Parity, Time) theorem: NO CPT violation…?
  "CPT violation is possible at very small length scales, and could lead to slight differences between the properties of particles an antiparticles,"
  (C. Amsler, "In the steps of the antiproton", CERN Courier)

- Comparing Q/m of p, anti-p (TRAP, LEAR): same at the level of 9×10^{-11}

- Comparing mass of p, anti-p (ASACUSA, LEAR): same at the level of 10^{-9}

- Magnetic moment of anti-p (BASE, LEAR): at the level of 10^{-9}

- Atomic structure of H, anti-H

Experiment: To test WEP

- Weak equivalence principle: all objects accelerated in the same way in G-field → never tested with antimatter
- AEgIS collaboration (at AD)
- and GBAR

Crystal Barrel (LEAR)

- PS 197: the Crystal Barrel experiment
  - meson spectroscopy (glueballs (gg), hybrid mesons from pp and pd)
  - study of pp and pd annihilation dynamics
  - study of radiative and rare meson decays
  - efficient photon detection for a neutral pion measurement

Crystal Barrel (LEAR): Experimental Setup

- 200 MeV/c antiproton beam
- 4cm-LH_2 target or 21cm-GH_2 target
- 1.5T solenoid (beam direction)
- PWCs (multiwire proportinal chamber) or SVTX (microstrip vertex detector)
- cylindrical JDC (Jet Drift Chamber)
- 1380 CsI(Tl) calorimeter

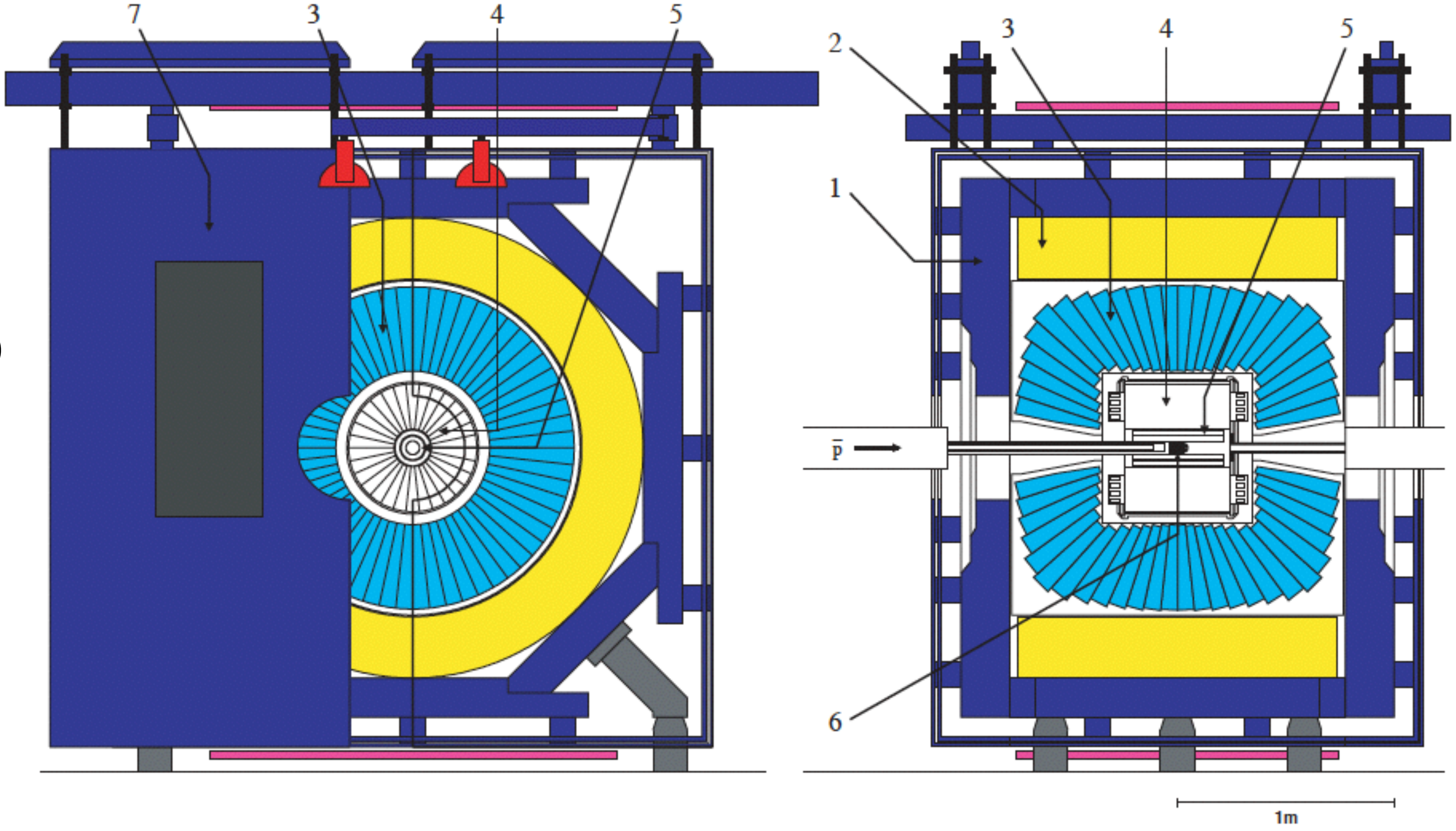


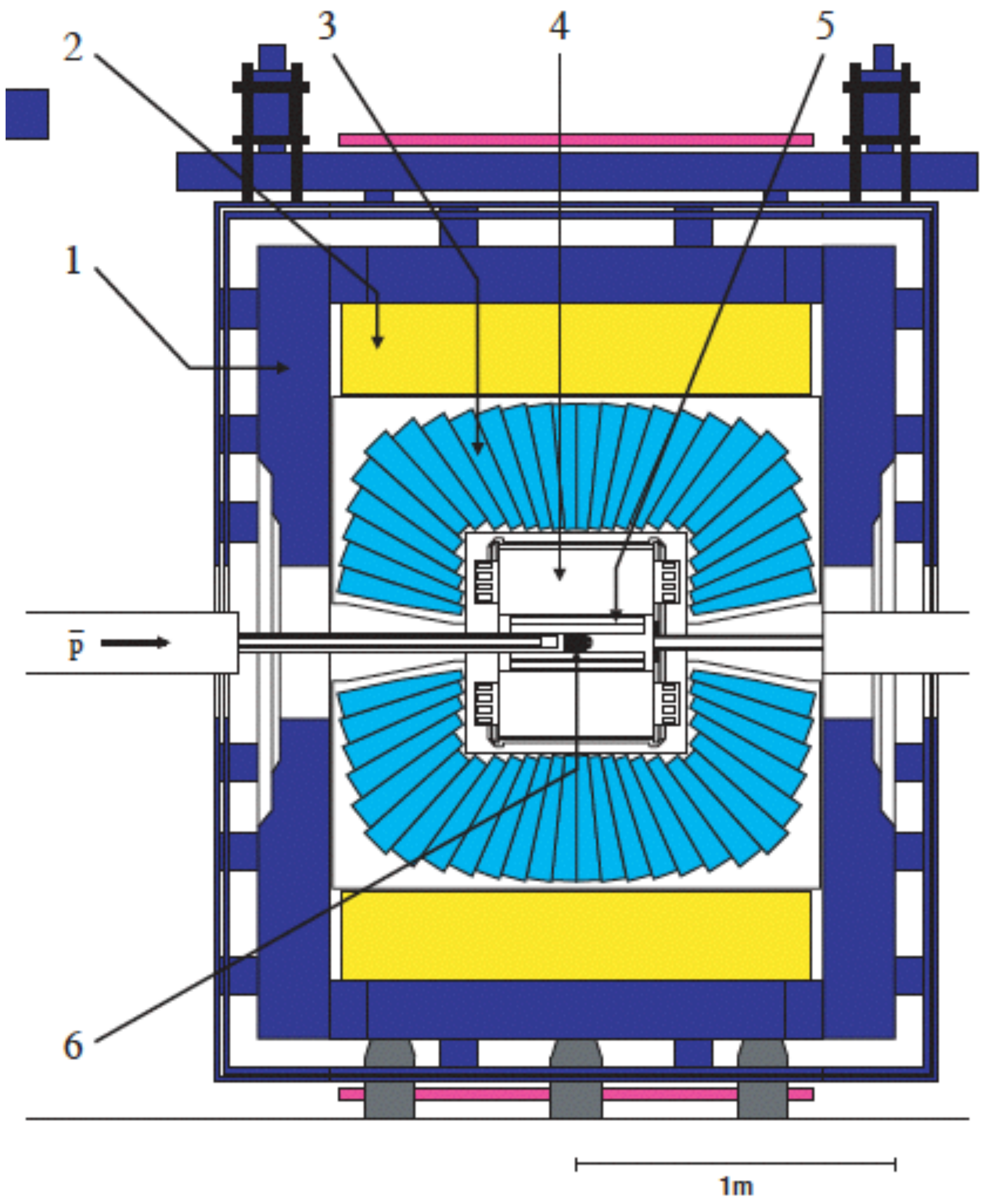
Fig. 4. Overall layout of the crystal barrel detector showing (1) magnet yoke, (2) magnet coils, (3) CsI barrel, (4) jet drift chamber, (5) proportional chamber, (6) liquid hydrogen target, (7) one half of endplate. Left—longitudinal cross section; Right—transverse view.

Crystal Barrel (LEAR): Detector

- 2 PWCs (beam direction wire):
  - (r, ϕ) coordinates information for the vertex reconstruction
  - the trigger for the final state charged multiplicity

- JDC (30 radial sector)
  - 23 wires for each sector
  - charged particle tracking

- CsI(Tl) crystals
  - almost 4π coverage
  - mass reso.: 10 MeV (π^0) / 17 MeV (η)



Crystal Barrel (LEAR): Feature

- multi-level trigger on charged and neutral multiplicities: concentrating on the specific rare channels

- invariant mass combinations of the neutral secondary particles

- beam intensity: 10^4 per second at 200 MeV/c for liquid or 105 MeV/c for 12-bar gas target

ASACUSA (AD)

- ASACUSA Collaboration
  - a wide physics program
  - antiproton annihilation cross sections on different nuclei
  - a Stren-Gerlach-type experiment with an antihydrogen beam
  - stopping antiprotons in helium

ASACUSA (AD): Experimental Setup

- Vessel (1300 mm-long, 600 mm-diameter)
- Solid target (four targets)
- Vertex detector (to reconstruct the annihilation vertices)
- Beam counter (pion counter, plastic)
- Vacuum level ~ 10^{-7} mb
- designed to reduce the contamination coming from the annihilation on the walls

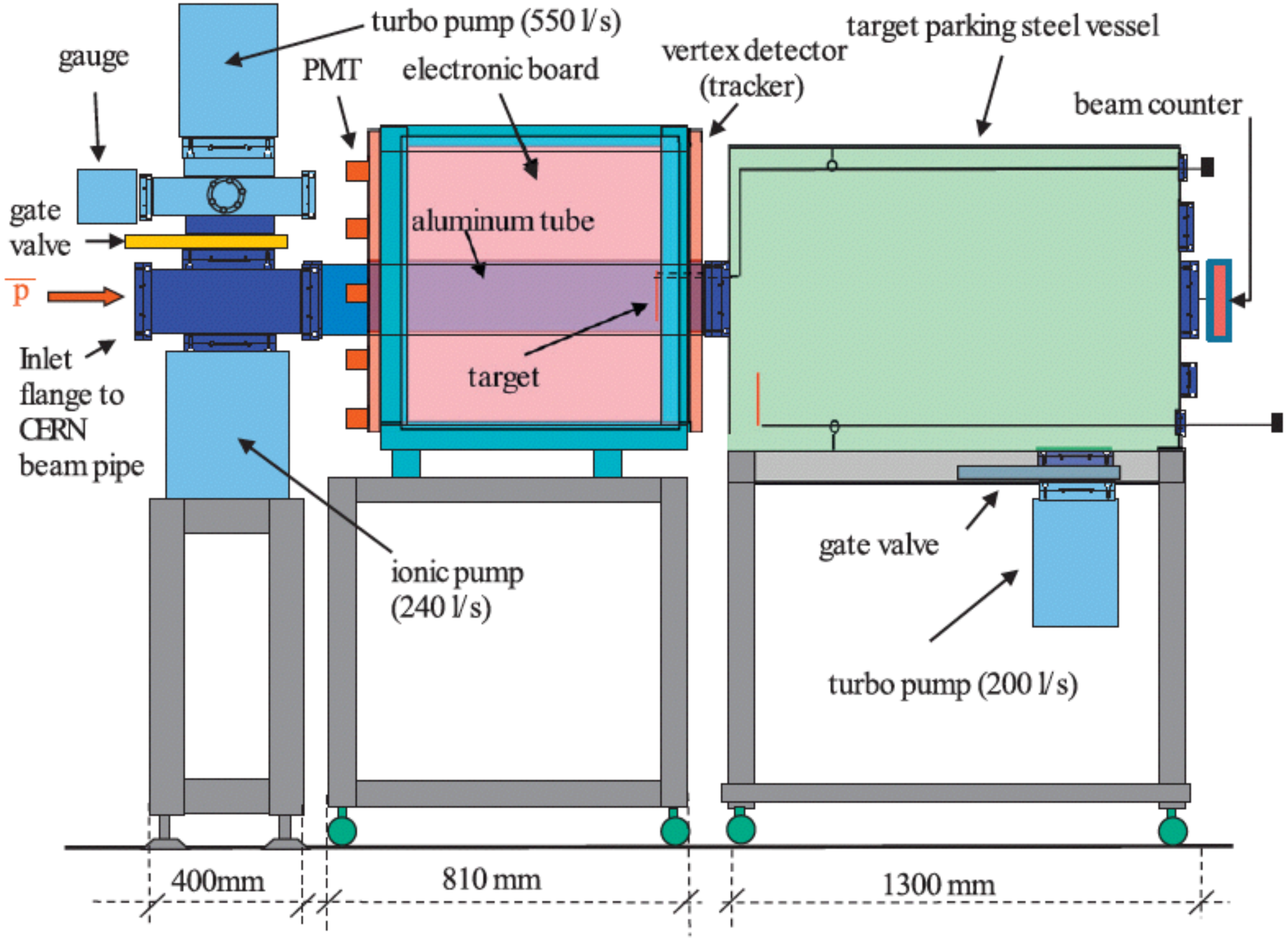


Fig. 1. Experimental setup.

ASACUSA (AD): Vertex detector

- scintillating fibers (d = 1 mm)
  4 fibers / ch 334 ~ 451 ch / layer
  3 layers / shell 2 cylindrical shells
- beam-direction layer
  ±20° rotated layers
- PMT at the one end
- point = 3 hits for each layer
  track = 2 point for each shell
- cosmic-ray test:
  single layer eff. ~ 95%
  spatial resolution of the hit:
  radial ~ 1.4 / 1.7 mm / beam ~ 2.8 mm

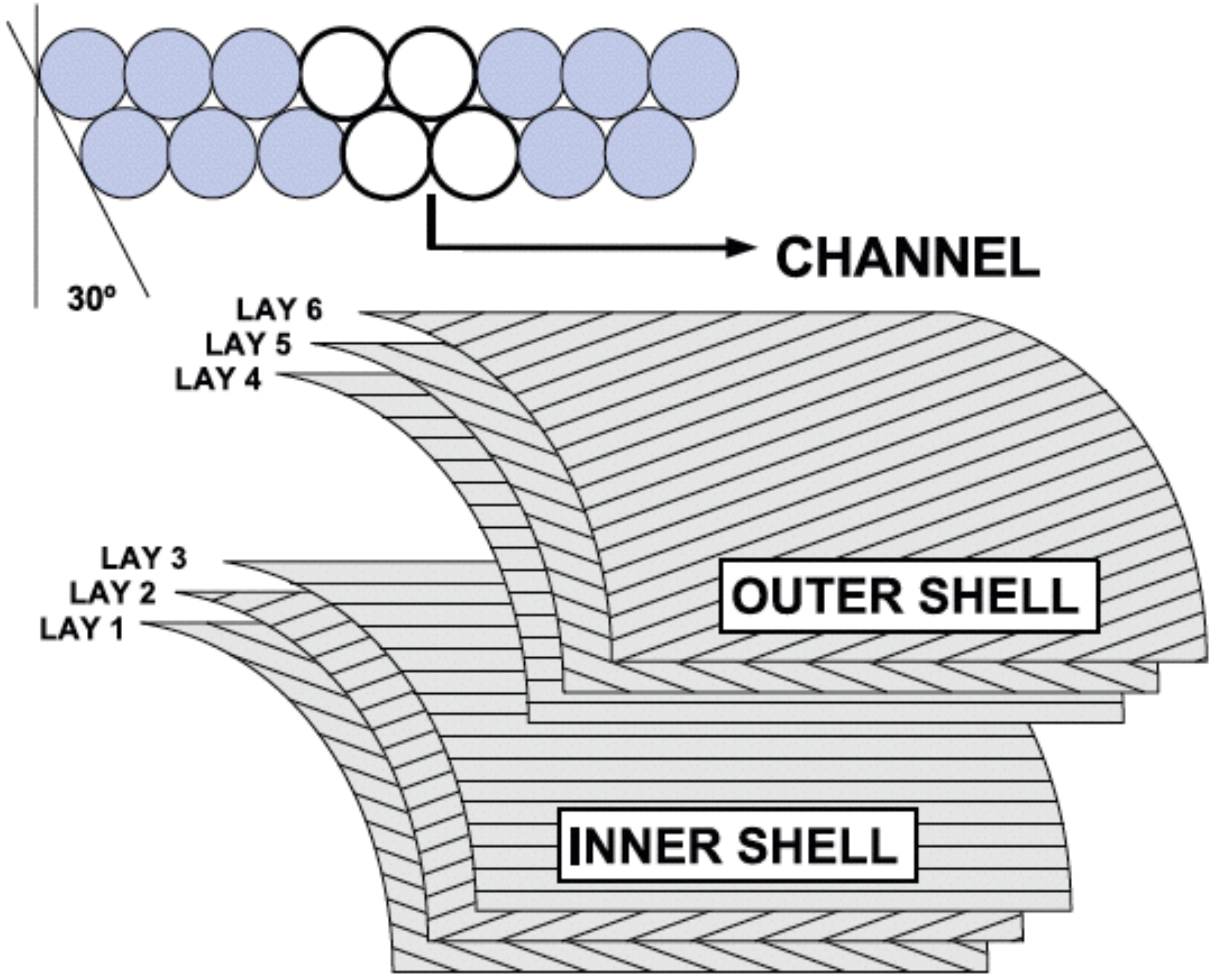


Fig. 2. Layout of the vertex detector; top drawing: zoom on a layer.

ASACUSA (AD): Vertex detector

- Hit Reconstruction:
  1. All the intersections
  2. All the possible triangles
  3. Smallest height
  4. Consider the hit at h/2

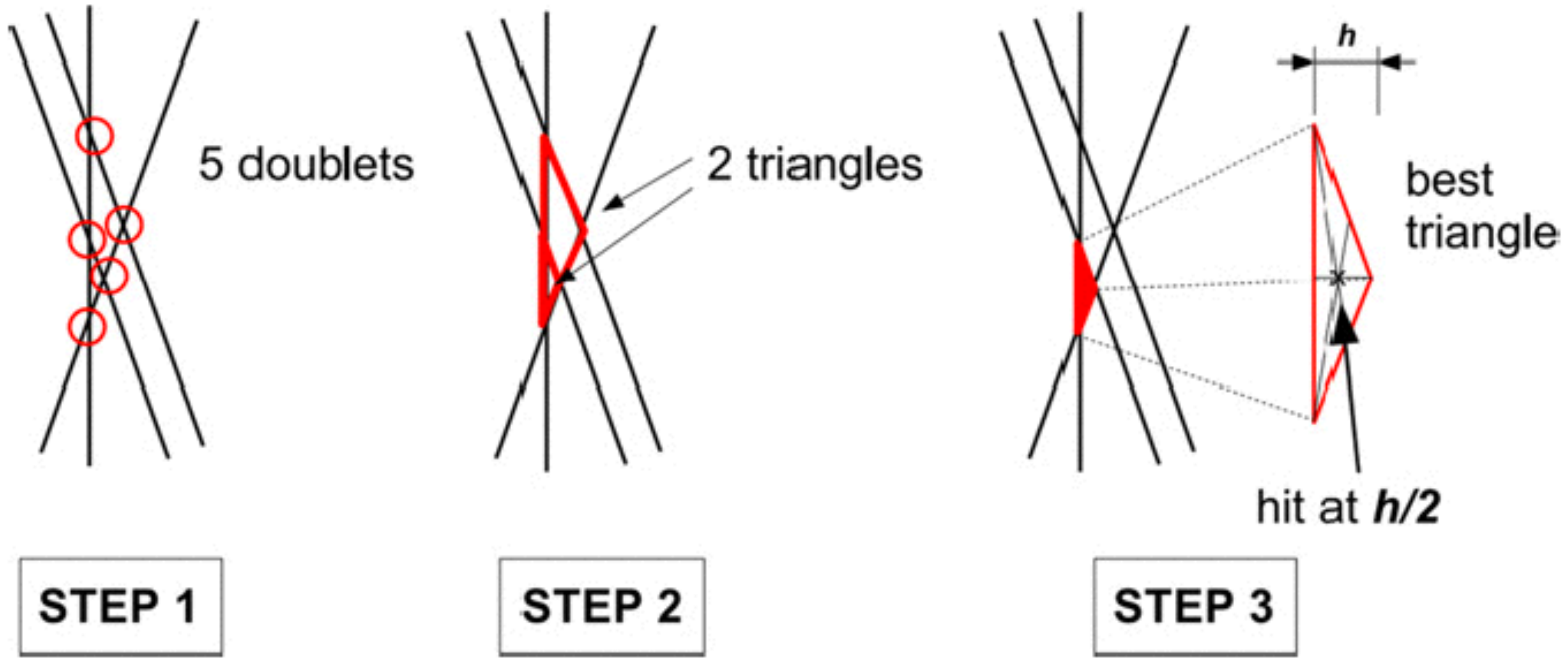
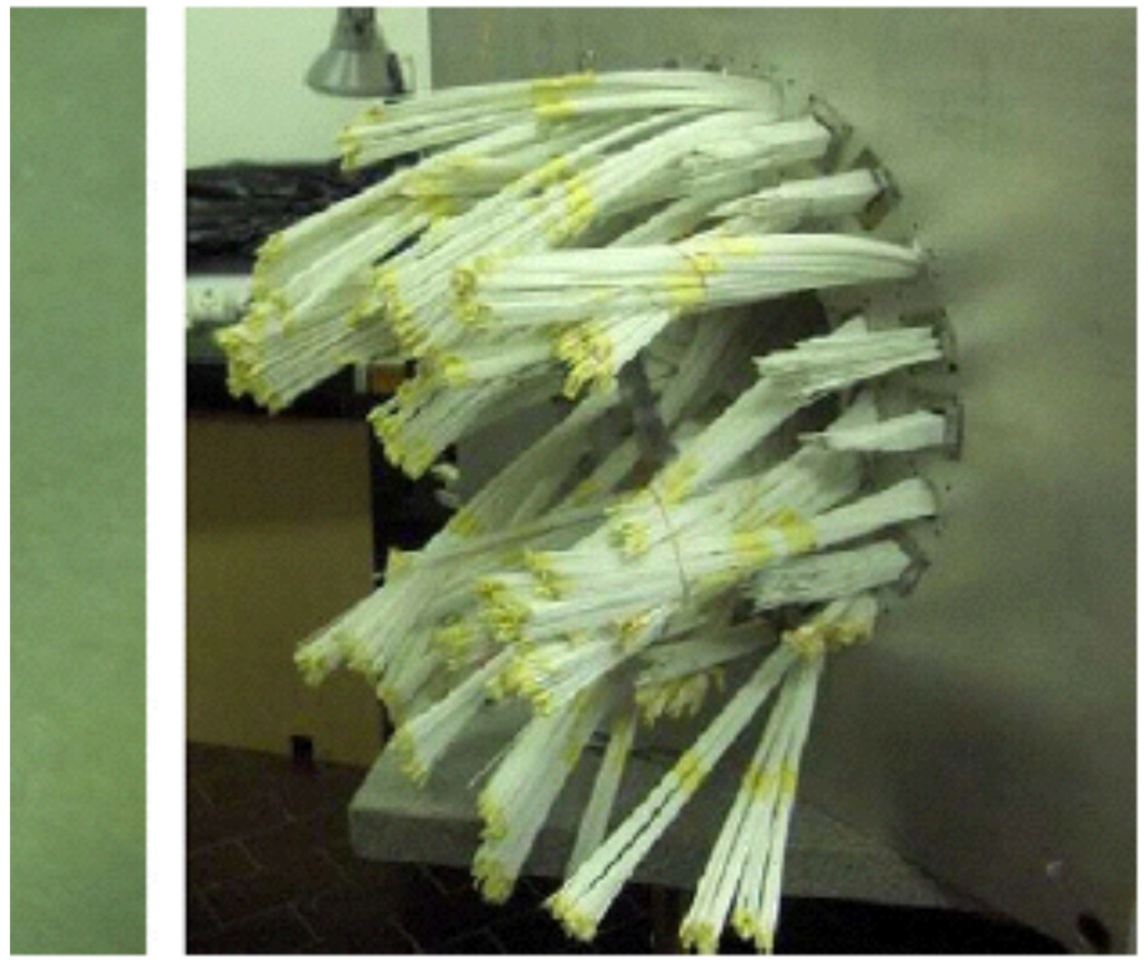


Fig. 11. Algorithm used to define the particle hit position on the fiber layers.



tal we have 18 cookies for the inner cylinder and 24 cookies for the outer one (right).

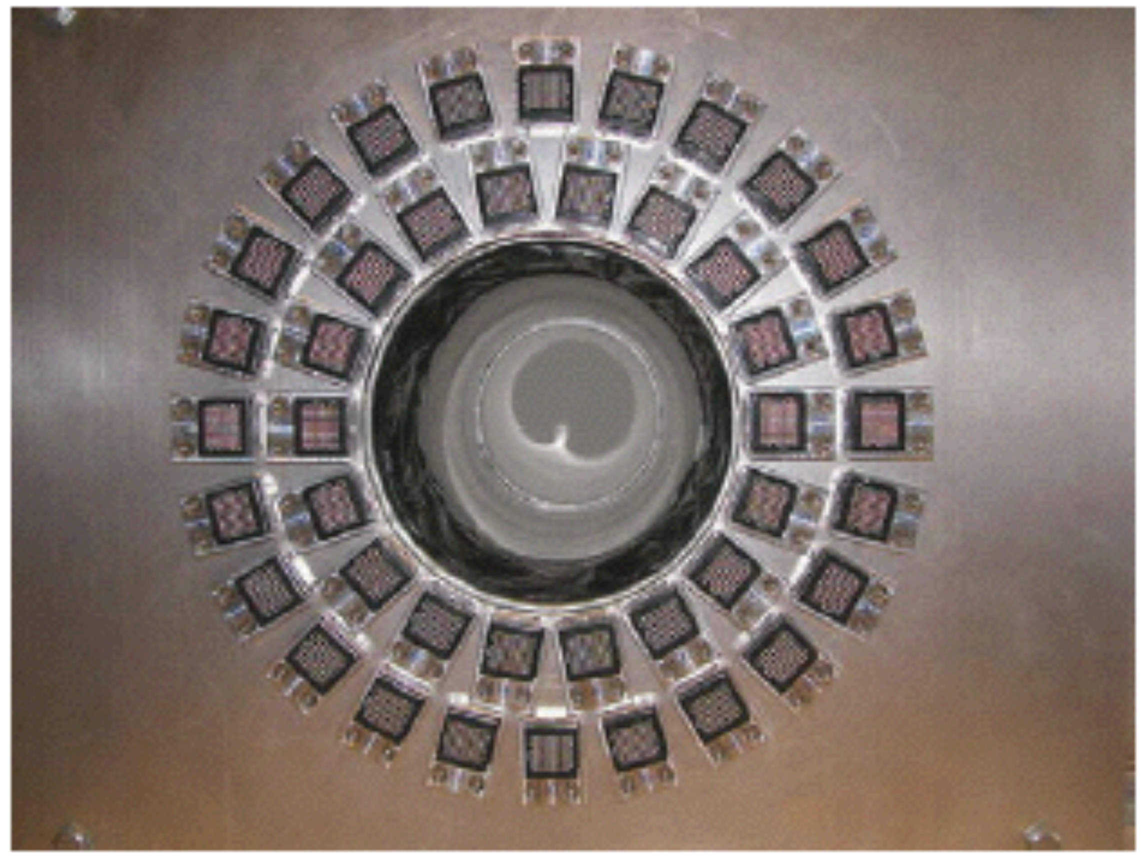


Fig. 6. The last plate with the PMTs inserted in their masks.

ASACUSA (AD): Target

- 0.9 um-Mylar foil support
- metal (Ni, Sn, Pt) layers deposited by sputtering
- Thickness chosen: expected annihilations in metals ≃ the one in Mylar at K = 5.3 MeV
- Beam diameter did not exceed few mm beyond the metal spot.

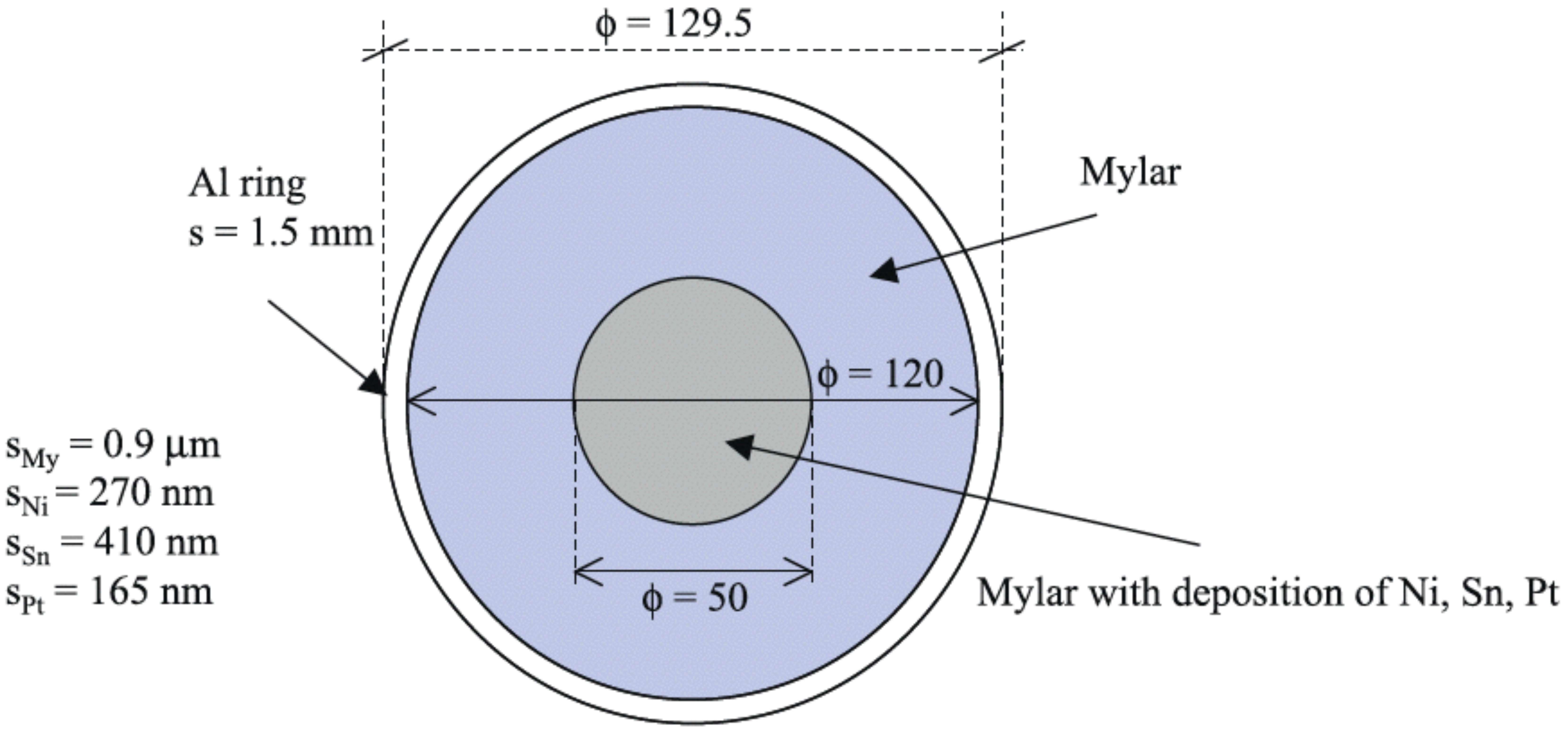


Fig. 13. The targets.

ASACUSA (AD): Software

- Online: DAQ (C, Tcl/Tk)
- Offline: MC sim. / vertex reconstruction code
- How to find a vertex: combinatorial algorithm
  1. all possible tracks
  2. all possible points of miming distance between each couple of tracks
  3. average of theses points
- 70% eff. (all the 6 hits of each track) spatial reso.: beam ~ 0.5 cm / transverse ~ 0.4 cm

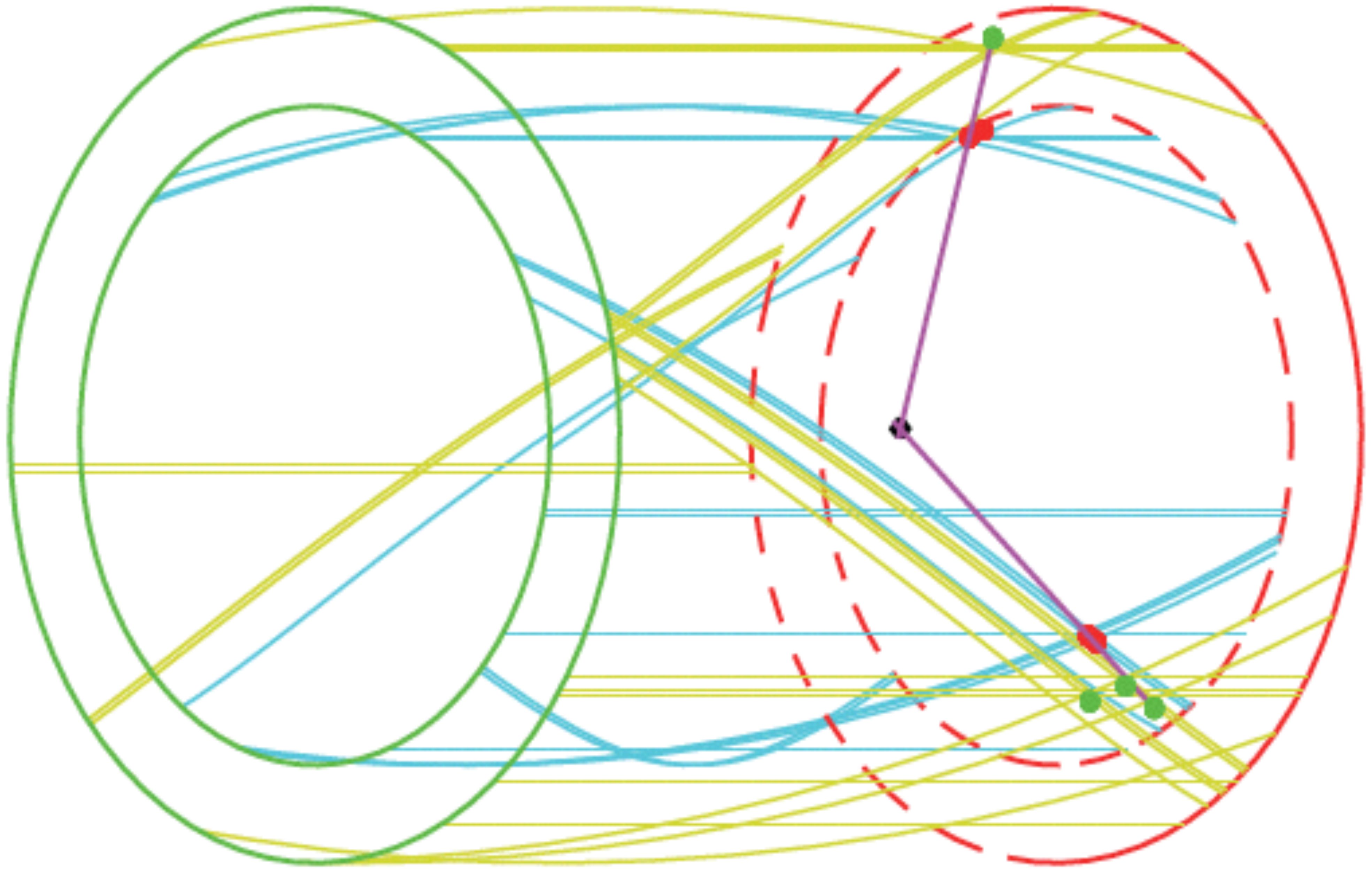


Fig. 16. Picture of a "typical" event. The edges of the two shells of scintillating fibers are shown in red and in green. The fired fibers in the selected time window are shown either in cyan (inner shell) or in yellow (outer shell). For each shell the triple intersections of the fired fibers (after a radial projection on the central cylindrical surface of the shell) define the hits, depicted here as red dots (inner layer) or green dots (outer layer). The hits give the reconstructed tracks (shown in purple) and these pinpoint the reconstructed vertex (purple dot). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

Summary

- Since the discovery of antiproton on 1955, antiprotons have become a prominent tool for studies in particle physics and also nuclear physics.
- Antiprotons have been detected or/and used in the several ways: originated from the universe or the atmosphere, created by high energy protons, utilized collision proton-antiproton, decay or annihilation experiment, etc.
- We have studied the fundamental symmetry of physics, the meson physics as well as the characteristics of an antiproton.

References

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