Antimatter in the lab

Lecture 1

Jack Devlin

CERN

18/7/22 10:25

Overview

Lecture 1: Introduction

1. What is antimatter?
2. Why study antimatter?
3. How do we make antimatter at CERN?

Lecture 2: Experiments at the Antimatter Factory

What is antimatter?

How to combine quantum mechanics and special relativity for the electron?

A relativistic particle in state $|\boldsymbol{p}\rangle$ with momentum $\boldsymbol{p}$ has energy $E_p = \sqrt{p^2 + m^2}$,
what equation of motion, consistent with the Schrodinger equation, governs its motion?

$$i\hbar \frac{\partial}{\partial t} |\psi\rangle = H |\psi\rangle$$

$$i\hbar \frac{\partial}{\partial t} |\psi\rangle = \left(m + \frac{p^2}{2m} - \frac{p^4}{8m^3} + \ldots\right)|\psi\rangle$$ ✗

Leads to non-covariant, nonlocal physics

$$H = \sqrt{p^2 + m^2} = m + \frac{p^2}{2m} - \frac{p^4}{8m^3} + \ldots$$

Take an extra time derivative

$$-\frac{\partial^2}{\partial t^2} |\psi\rangle = H^2 |\psi\rangle$$

$$(\underbrace{p^2}_{-\nabla^2} + \frac{\partial^2}{\partial t^2} + m^2)|\psi\rangle = 0$$

Relativistic Klein-Gordon Equation, fine for spin-0 charged particles, but what about the electron?

Imagine factorizing the term in brackets to make two linear equations

$$(iX + m)\,(iX - m)|\psi\rangle = 0$$

Where $X^2 = \frac{\partial^2}{\partial t^2} - \nabla^2 = \partial^\mu \partial_\mu = \gamma^\mu \partial_\mu\, \gamma^\nu \partial_\nu$
so long as $\gamma^\mu \gamma^\nu = \eta^{\mu\nu}$

$$(iX + m)\,|\psi\rangle = 0 \qquad (iX - m)\,|\psi\rangle = 0$$

?   ✓

With $X = \gamma^\mu \partial_\mu$ and γ^μ 4x4 matrices
Dirac equation

Two equally valid solutions for positive or negative mass (or energy) particles, with opposite charge

Modern Quantum Mechanics, Ch. 8, J.J. Sakaurai, J. Napolitano

The free particle solutions

$$(i\gamma^{\mu}\partial_{\mu} - m)\,\Psi(\boldsymbol{x},t) = 0$$

$$\partial_0 = \partial_0, \partial_1 = \partial_x,\ \partial_2 = \partial_y,\ \partial_3 = \partial_z\ ,\Psi(\boldsymbol{x},t) = \langle x|\psi\rangle$$

$\gamma^{\mu}\gamma^{\nu} = \eta^{\mu\nu}$ 4x4 matrices will do, e.g.

$$\gamma^0 = \begin{pmatrix} \mathbb{I}_2 & 0 \\ 0 & -\mathbb{I}_2 \end{pmatrix}, \qquad \gamma^i = \begin{pmatrix} 0 & \sigma_i \\ -\sigma_i & 0 \end{pmatrix} \quad i \neq 0$$

σ_i 2x2 Pauli matrices

Spin has popped out, brilliant!

But what to do about these negative energy solutions?

Plane wave free particle solutions

$$\Psi(\boldsymbol{x},t) = Ne^{-i(Et\ \ \boldsymbol{p}.\boldsymbol{x})} = Ne^{-ip^{\mu}x_{\mu}}$$

$$\begin{pmatrix} m & 0 & p & 0 \\ 0 & m & 0 & -p \\ p & 0 & -m & 0 \\ 0 & -p & 0 & -m \end{pmatrix} \Psi = \mathrm{E}\ \Psi$$

$$E = +E_p = +\sqrt{p^2 + m^2}$$

$$\Psi_1 = A \begin{pmatrix} 1 \\ 0 \\ \frac{p}{m+E_p} \\ 0 \end{pmatrix} e^{-ip^{\mu}x_{\mu}}$$

$$\Psi_2 = A \begin{pmatrix} 0 \\ 1 \\ 0 \\ \frac{-p}{E_p+m} \end{pmatrix} e^{-ip^{\mu}x_{\mu}}$$

$$E = -E_p = -\sqrt{p^2 + m^2}$$

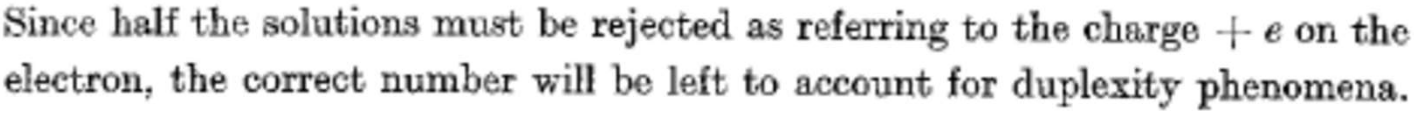
$$\Psi_3 = A \begin{pmatrix} \frac{-p}{E_p+m} \\ 0 \\ 1 \\ 0 \end{pmatrix} e^{-ip^{\mu}x_{\mu}}$$

$$\Psi_4 = A \begin{pmatrix} 0 \\ \frac{p}{E_p+m} \\ 0 \\ 1 \end{pmatrix} e^{-ip^{\mu}x_{\mu}}$$

Modern Quantum Mechanics, Ch. 8, J.J. Sakaurai, J. Napolitano

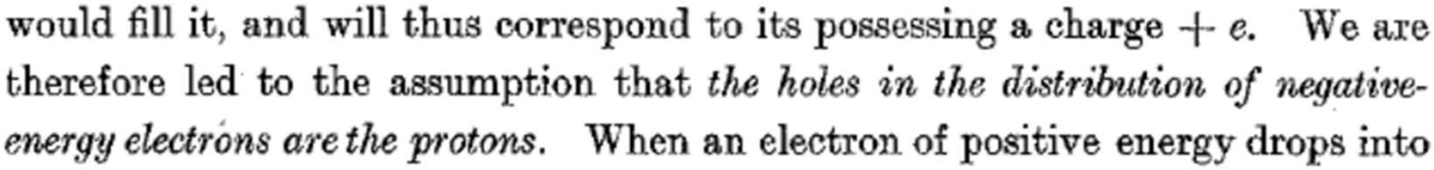
What to do?

P.A.M. Dirac, The Quantum Theory of the Electron (1928)



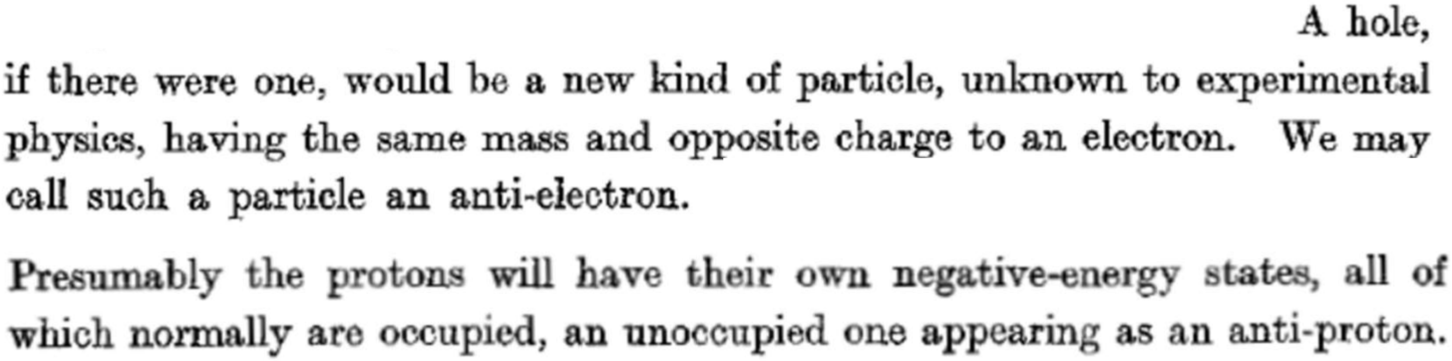
Since half the solutions must be rejected as referring to the charge $+e$ on the electron, the correct number will be left to account for duplexity phenomena.

P.A.M. Dirac, A theory of Electrons and Protons (1930)



would fill it, and will thus correspond to its possessing a charge $+e$. We are therefore led to the assumption that *the holes in the distribution of negative-energy electrons are the protons*. When an electron of positive energy drops into

P.A.M. Dirac, Quantised Singularities in the Electromagnetic field (1931)

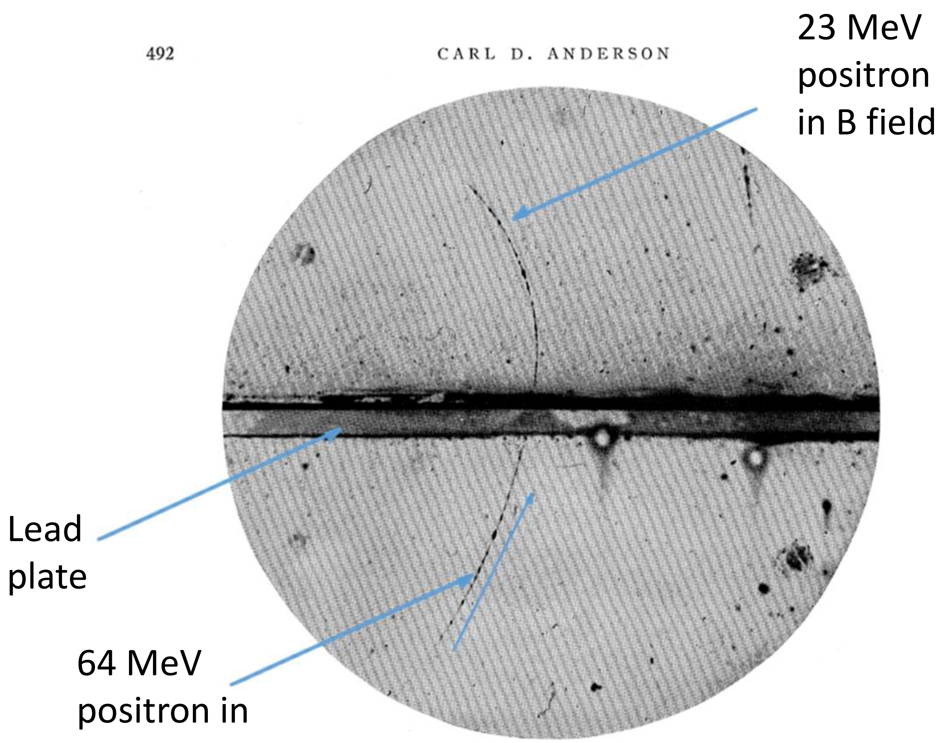


A hole, if there were one, would be a new kind of particle, unknown to experimental physics, having the same mass and opposite charge to an electron. We may call such a particle an anti-electron.

Presumably the protons will have their own negative-energy states, all of which normally are occupied, an unoccupied one appearing as an anti-proton.

Discovery of antimatter

492 CARL D. ANDERSON


23 MeV positron in B field

Lead plate

64 MeV positron in B field

Fig. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

$$E = \frac{1}{2} m \omega_c^2 \rho^2 = \frac{1}{2} m \left(B \frac{q}{m}\right)^2 \rho^2$$

First discovered by Carl Anderson (1932)

Mass of particle <20x electron mass, positive charge

Almost simultaneously observed but not identified until later by Blackett and Occhialini, Joliot and Irene Curie

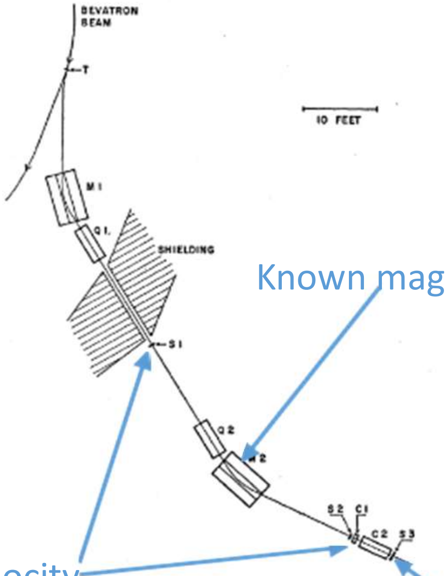
Despite what you might think, none of these people was looking for Dirac's anti-electron!

C. D. Anderson Phys. Rev. **43**, 491 (1933)
M. Leone, American Journal of Physics **80**, 534 (2012)

Discovery of the antiproton 1955

Measurement of mass of negatively charges particles –
By measurement of veleocity and momentum

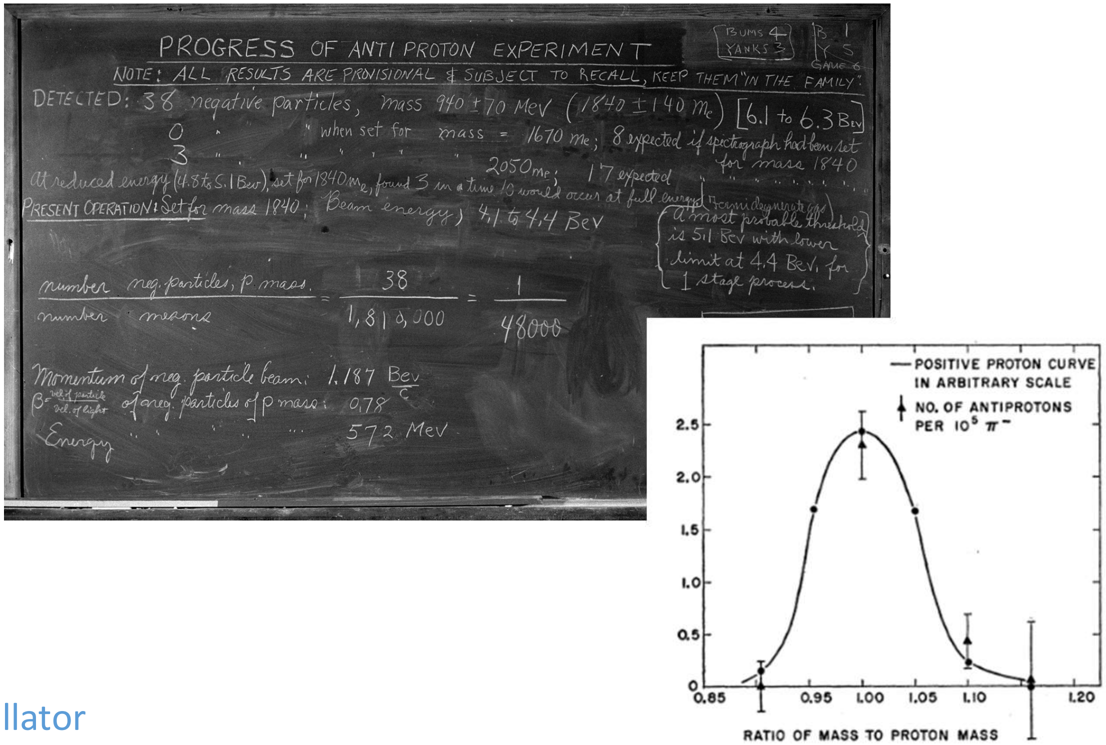
At Bevatron – Proton accelerator at Berkley (California)



Known magnetic field

Velocity measured

Scintillator



PROGRESS OF ANTI PROTON EXPERIMENT

BUMS 4
YANKS 3

B 1
Y 5
GAME 6

NOTE: ALL RESULTS ARE PROVISIONAL & SUBJECT TO RECALL, KEEP THEM "IN THE FAMILY".

DETECTED: 38 negative particles, mass 940 ± 70 MeV ($1840 \pm 140\ m_e$) [6.1 to 6.3 Bev]
0 " " when set for mass = 1670 me; 8 expected if spectrograph had been set for mass 1840
3 " " " " " " 2050 me; 17 expected " " " " " " " "

At reduced energy (4.8 to 5.1 Bev), set for 1840 m_e, found 3 in a time 10 would occur at full energy

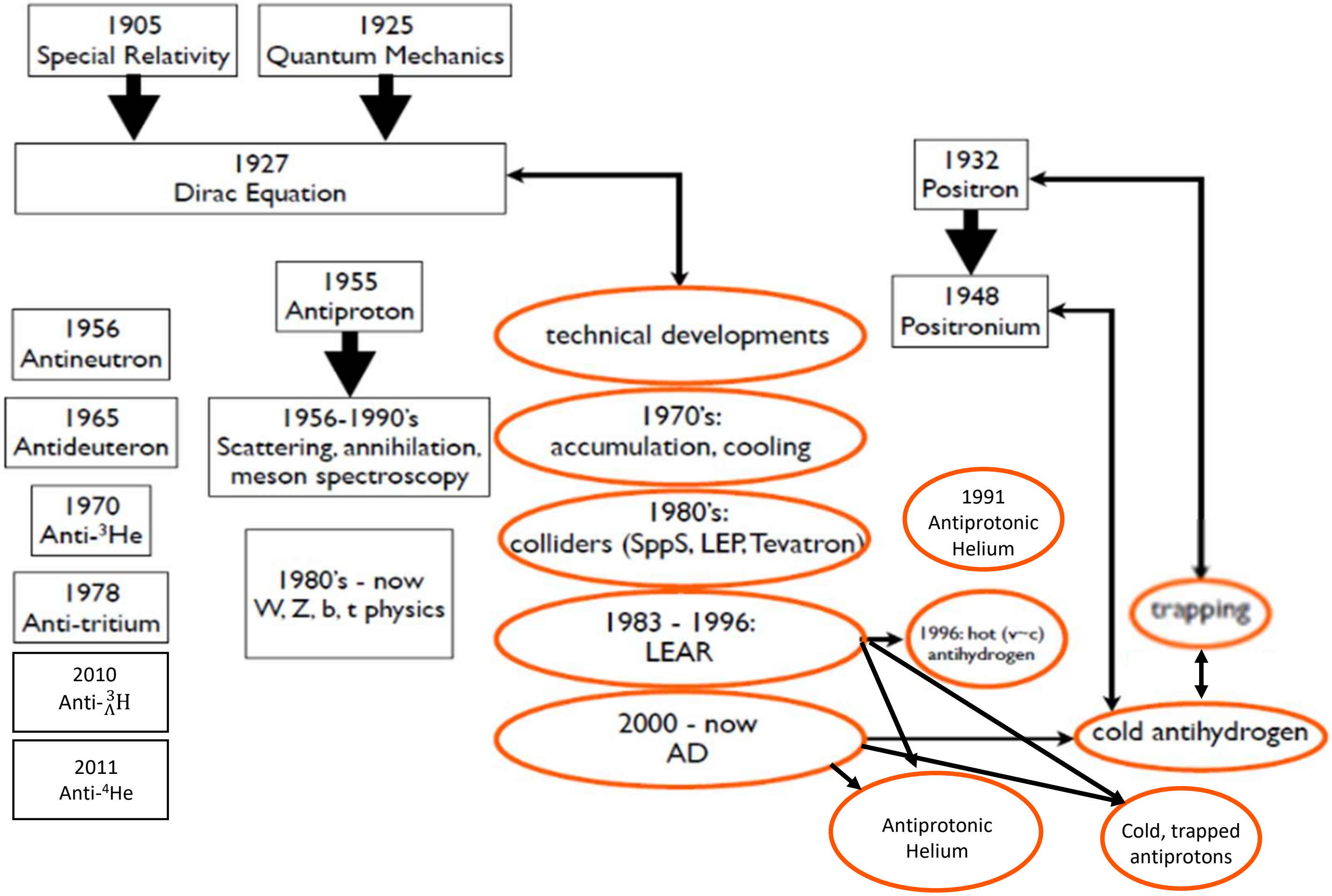
PRESENT OPERATION: Set for mass 1840; Beam energy) 4.1 to 4.4 Bev

(Fermi degenerate gas) a most probable threshold is 5.1 Bev with lower limit at 4.4 Bev, for 1 stage process.

$$\frac{\text{number neg. particles, p mass.}}{\text{number mesons}} = \frac{38}{1{,}810{,}000} = \frac{1}{48000}$$

Momentum of neg. particle beam: 1.187 $\frac{\text{Bev}}{c}$
$\beta = \frac{\text{vel. of particle}}{\text{vel. of light}}$ of neg. particles of p mass: 0.78
Energy " " " " " 572 MeV

Ever more complicated antimatter



1905
Special Relativity

1925
Quantum Mechanics

1927
Dirac Equation

1932
Positron

1948
Positronium

1955
Antiproton

1956
Antineutron

1965
Antideuteron

1970
Anti-^{3}He

1978
Anti-tritium

2010
Anti-$^{3}_{\Lambda}$H

2011
Anti-^{4}He

1956-1990's
Scattering, annihilation, meson spectroscopy

1980's - now
W, Z, b, t physics

technical developments

1970's:
accumulation, cooling

1980's:
colliders (SppS, LEP, Tevatron)

1983 - 1996:
LEAR

2000 - now
AD

1991
Antiprotonic Helium

1996: hot (v~c) antihydrogen

trapping

cold antihydrogen

Antiprotonic Helium

Cold, trapped antiprotons

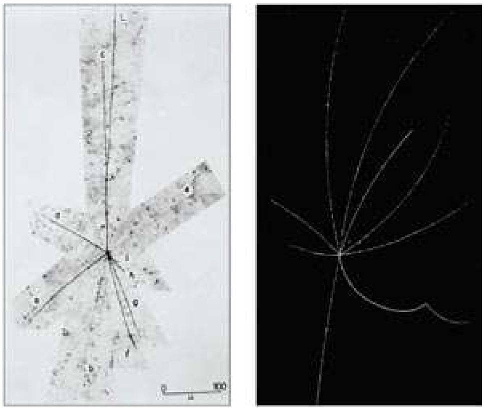
Basic properties

-Whenever they’ve been measured:

- The lifetime and mass of particles and antiparticles have been equal
- Their charge and magnetic moment have been equal in magnitude and opposite in sign

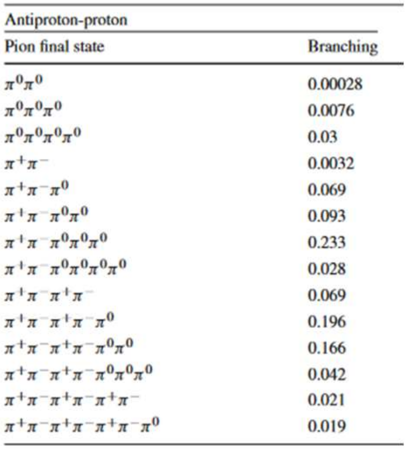
-When antimatter and matter meet, they annihilate:

$$e^- + e^+ \rightarrow \gamma + \gamma \text{ at 511 keV}$$



https://cerncourier.com/a/fifty-years-of-antiprotons/

$$p + \bar{p} \rightarrow$$



Antiproton-proton	
Pion final state	Branching
$\pi^0\pi^0$	0.00028
$\pi^0\pi^0\pi^0$	0.0076
$\pi^0\pi^0\pi^0\pi^0$	0.03
$\pi^+\pi^-$	0.0032
$\pi^+\pi^-\pi^0$	0.069
$\pi^+\pi^-\pi^0\pi^0$	0.093
$\pi^+\pi^-\pi^0\pi^0\pi^0$	0.233
$\pi^+\pi^-\pi^0\pi^0\pi^0\pi^0$	0.028
$\pi^+\pi^-\pi^+\pi^-$	0.069
$\pi^+\pi^-\pi^+\pi^-\pi^0$	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

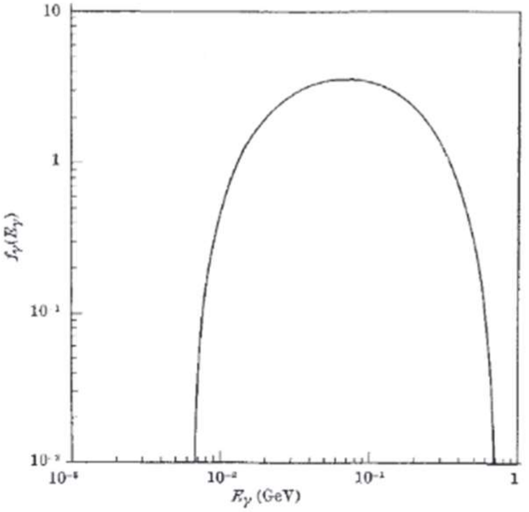


Fig. 1. The normalized local differential gamma ray spectrum from proton-antiproton annihilation.

+2.2% other channels

T. Aumann et al., Eur. Phys. J. A (2022) 58:88

Why study antimatter?

Is this interesting?

A skeptical voice:

Why bother?

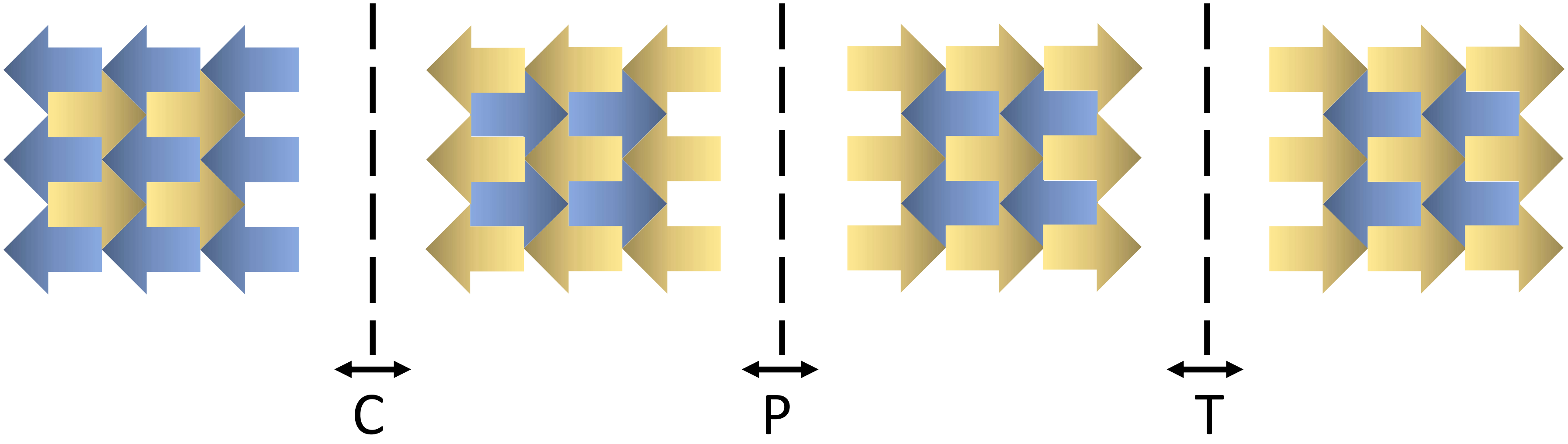
A skeptical voice with extensive physics training

- Any “reasonable”[1], Lorentz-covariant quantum field theory will be CPT symmetric

[1] Reasonable:
- A Lorentz and translation covariant Hilbert space
- A vacuum state
- Field operators with spin & mass that can be associated with point particles
- Energy positivity
- Microscopic causality (locality)

CPT symmetry

CPT symmetry: the combined symmetry of:
C, Charge-conjugation: all particles swapped for antiparticles
P, Parity: spatial coordinates $\boldsymbol{r} \longrightarrow -\boldsymbol{r}$
T, Time reversal: reverse time coordinates coordinates $\boldsymbol{t} \longrightarrow -\boldsymbol{t}$

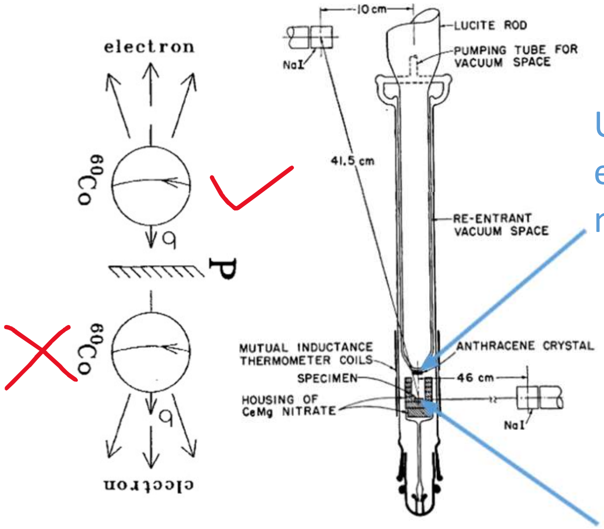


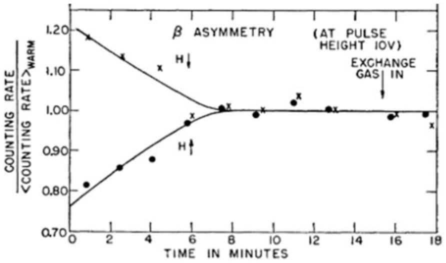
CPT implies matter and antimatter particles have the same properties (up to a sign)

Assume makes …

C, P and T and CP have been measurably broken

C. S. Wu’s P-violation experiment





Upwards β-emission measured

Polarised cobalt-60

More β-emission upwards when Co-60 polarised downwards

Why is CPT special?

Fitch-Cronin experiment CP violation

$K_L^0 \longrightarrow$ 3 pions , CP -1, (common)
$K_L^0 \longrightarrow$ 2 pions , CP $+1$, (rare)

Conclusion: K_L^0 not a pure CP state

But if CP is conserved,
Rate($\bar{K}^0 \rightarrow K^0$)= Rate($K^0 \rightarrow \bar{K}^0$)
K_L^0 should be a pure CP state
CP broken (indirect CP violation)

CPLEAR, NA48 (CERN), BarBar, KTeV…

Direct CP and T violation

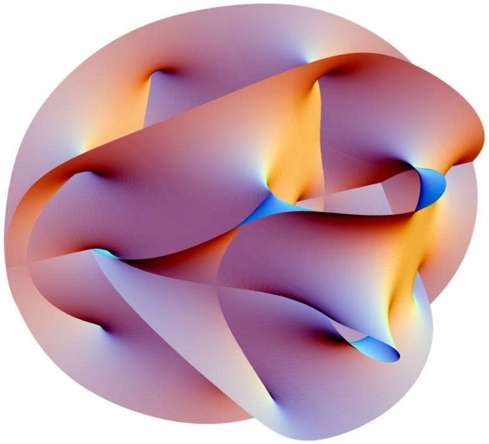
Why specifically might CPT be broken?

Any “reasonable”[1], Lorentz-covariant quantum field theory will obey the CPT theorem

Some Beyond the Standard Model theories would, at our energy scales, break Lorentz covariance…

E.g. Lorentz symmetry could be spontaneously broken in string theories which are nevertheless Lorentz symmetric a fundamental level-

– Would be one way to turn very high dimension string theories into effective theories with 4 spacetime dimensions



V. A. Kostelecký, S. Samuel, Spontaneous breaking of Lorentz symmetry in string theory Phys. Rev. D 39 (1989)
D. Colladay, V. A. Kostelecký, Phys. Rev. D58 (1997)
S.M. Carroll, G.B. Field, R. Jackiw, Phys. Rev. D 41, 1231 (1990)

The Standard Model Extension

The Standard Model

$$\mathcal{L}_{\text{lepton}} = \tfrac{1}{2}i\overline{L}_A\gamma^\mu \overleftrightarrow{D}_\mu L_A + \tfrac{1}{2}i\overline{R}_A\gamma^\mu \overleftrightarrow{D}_\mu R_A \quad , \tag{4}$$

$$\begin{aligned}\mathcal{L}_{\text{quark}} &= \tfrac{1}{2}i\overline{Q}_A\gamma^\mu \overleftrightarrow{D}_\mu Q_A + \tfrac{1}{2}i\overline{U}_A\gamma^\mu \overleftrightarrow{D}_\mu U_A \\ &\quad +\tfrac{1}{2}i\overline{D}_A\gamma^\mu \overleftrightarrow{D}_\mu D_A \quad ,\end{aligned} \tag{5}$$

$$\begin{aligned}\mathcal{L}_{\text{Yukawa}} &= -\left[(G_L)_{AB}\overline{L}_A\phi R_B + (G_U)_{AB}\overline{Q}_A\phi^c U_B \right. \\ &\quad \left. +(G_D)_{AB}\overline{Q}_A\phi D_B\right] + \text{h.c.} \quad ,\end{aligned} \tag{6}$$

$$\mathcal{L}_{\text{Higgs}} = (D_\mu\phi)^\dagger D^\mu\phi + \mu^2\phi^\dagger\phi - \frac{\lambda}{3!}(\phi^\dagger\phi)^2 \quad , \tag{7}$$

$$\mathcal{L}_{\text{gauge}} = -\tfrac{1}{2}\text{Tr}(G_{\mu\nu}G^{\mu\nu}) - \tfrac{1}{2}\text{Tr}(W_{\mu\nu}W^{\mu\nu}) - \tfrac{1}{4}B_{\mu\nu}B^{\mu\nu} \ . \tag{8}$$

Minimal Standard Model Extension (SME)

$$\begin{aligned}\mathcal{L}_{\text{lepton}}^{\text{CPT-even}} &= \tfrac{1}{2}i(c_L)_{\mu\nu AB}\overline{L}_A\gamma^\mu \overleftrightarrow{D}^\nu L_B \\ &\quad +\tfrac{1}{2}i(c_R)_{\mu\nu AB}\overline{R}_A\gamma^\mu \overleftrightarrow{D}^\nu R_B \quad ,\end{aligned} \tag{9}$$

$$\mathcal{L}_{\text{lepton}}^{\text{CPT-odd}} = -(a_L)_{\mu AB}\overline{L}_A\gamma^\mu L_B - (a_R)_{\mu AB}\overline{R}_A\gamma^\mu R_B \quad , \tag{10}$$

$$\begin{aligned}\mathcal{L}_{\text{quark}}^{\text{CPT-even}} &= \tfrac{1}{2}i(c_Q)_{\mu\nu AB}\overline{Q}_A\gamma^\mu \overleftrightarrow{D}^\nu Q_B \\ &\quad +\tfrac{1}{2}i(c_U)_{\mu\nu AB}\overline{U}_A\gamma^\mu \overleftrightarrow{D}^\nu U_B \\ &\quad +\tfrac{1}{2}i(c_D)_{\mu\nu AB}\overline{D}_A\gamma^\mu \overleftrightarrow{D}^\nu D_B \quad ,\end{aligned} \tag{11}$$

$$\begin{aligned}\mathcal{L}_{\text{quark}}^{\text{CPT-odd}} &= -(a_Q)_{\mu AB}\overline{Q}_A\gamma^\mu Q_B - (a_U)_{\mu AB}\overline{U}_A\gamma^\mu U_B \\ &\quad -(a_D)_{\mu AB}\overline{D}_A\gamma^\mu D_B \quad .\end{aligned} \tag{12}$$

$$\begin{aligned}\mathcal{L}_{\text{Yukawa}}^{\text{CPT-even}} &= -\tfrac{1}{2}\left[(H_L)_{\mu\nu AB}\overline{L}_A\phi\sigma^{\mu\nu}R_B \right. \\ &\quad +(H_U)_{\mu\nu AB}\overline{Q}_A\phi^c\sigma^{\mu\nu}U_B \\ &\quad \left. +(H_D)_{\mu\nu AB}\overline{Q}_A\phi\sigma^{\mu\nu}D_B\right] + \text{h.c.}\end{aligned} \tag{13}$$

$$\begin{aligned}\mathcal{L}_{\text{Higgs}}^{\text{CPT-even}} &= \tfrac{1}{2}(k_{\phi\phi})^{\mu\nu}(D_\mu\phi)^\dagger D_\nu\phi + \text{h.c.} \\ &\quad -\tfrac{1}{2}(k_{\phi B})^{\mu\nu}\phi^\dagger\phi B_{\mu\nu} \\ &\quad -\tfrac{1}{2}(k_{\phi W})^{\mu\nu}\phi^\dagger W_{\mu\nu}\phi \quad ,\end{aligned} \tag{14}$$

$$\mathcal{L}_{\text{Higgs}}^{\text{CPT-odd}} = i(k_\phi)^\mu\phi^\dagger D_\mu\phi + \text{h.c.} \quad . \tag{15}$$

$$\begin{aligned}\mathcal{L}_{\text{gauge}}^{\text{CPT-even}} &= -\tfrac{1}{2}(k_G)_{\kappa\lambda\mu\nu}\text{Tr}(G^{\kappa\lambda}G^{\mu\nu}) \\ &\quad -\tfrac{1}{2}(k_W)_{\kappa\lambda\mu\nu}\text{Tr}(W^{\kappa\lambda}W^{\mu\nu}) \\ &\quad -\tfrac{1}{4}(k_B)_{\kappa\lambda\mu\nu}B^{\kappa\lambda}B^{\mu\nu} \quad .\end{aligned} \tag{16}$$

$$\begin{aligned}\mathcal{L}_{\text{gauge}}^{\text{CPT-odd}} &= (k_3)_\kappa\epsilon^{\kappa\lambda\mu\nu}\text{Tr}(G_\lambda G_{\mu\nu} + \tfrac{2}{3}ig_3G_\lambda G_\mu G_\nu) \\ &\quad +(k_2)_\kappa\epsilon^{\kappa\lambda\mu\nu}\text{Tr}(W_\lambda W_{\mu\nu} + \tfrac{2}{3}igW_\lambda W_\mu W_\nu) \\ &\quad +(k_1)_\kappa\epsilon^{\kappa\lambda\mu\nu}B_\lambda B_{\mu\nu} + (k_0)_\kappa B^\kappa \quad .\end{aligned} \tag{17}$$

A concrete example

In the minimal SME, Dirac equation becomes

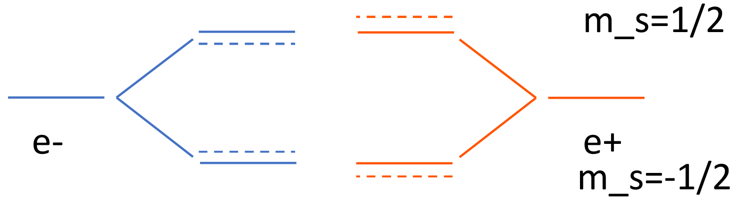
$\gamma_5 = i\,\gamma_0\gamma_1\gamma_2\gamma_3$

$$(\boxed{i\gamma^\mu\partial_\mu - m} - \boxed{a^e_\mu\gamma^\mu - b^e_\mu\gamma_5\gamma^\mu} - \boxed{\tfrac{1}{2}H^e_{\mu\upsilon}\sigma^{\mu\upsilon} + i\,c^e_{\mu\upsilon}\,\gamma^\mu\,\partial^\upsilon + i\,d^e_{\mu\upsilon}\,\gamma_5\gamma^\mu\,\partial^\upsilon})\,\Psi(\boldsymbol{x},t) = 0$$

Normal CPT breaking Lorentz-symmetry breaking

$a^e_\mu, b^e_\mu, H^e_{\mu\upsilon}, c^e_{\mu\upsilon}, d^e_{\mu\upsilon}$ new terms which need to be measured. Suppose just $b = b^e_3$ was non-zero. Then the eigenvalue equation for the Dirac equation looks like:

$$\begin{pmatrix} m-b & 0 & p & 0 \\ 0 & m+b & 0 & -p \\ p & 0 & -m+b & 0 \\ 0 & -p & 0 & -m-b \end{pmatrix}\Psi = E\,\Psi$$



In a magnetic field

This is a universal background magnetic field which couples oppositely to electrons and positrons, equivalent term for protons/antiprotons

D. Colladay, V. A. Kostelecký, Phys. Rev. D58 (1997)

So far, observation of CPT breaking possible "accident" of more fundamental theory.

Any reason to think it might be desirable to have CPT symmetry breaking?

Antimatter is rare

Higher or Lower – antimatter encounters

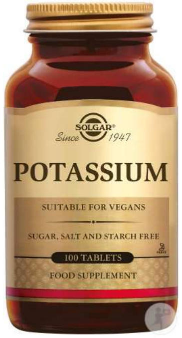
10^{24} gas molecules hitting 1 cm^3 of your skin every second – higher or lower than…

CERN/ENLIGHT/ENVISION/Nymus3d

1 scan,
PET
scanner

8 mSv for adults using 400 MBq ^{18}F-Fluorodeoxyglucose, 3.8×10^{12} positrons absorbed

higher or lower than…



β^+ decay from potassium-40 in our bodies, over a lifetime

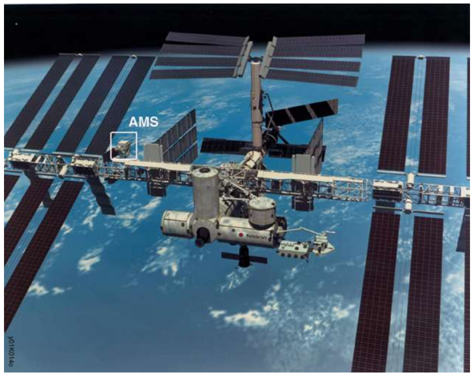
1×10^8 positrons absorbed

higher or lower than…

A 6 month stay on the ISS (ignoring shielding)

1×10^8 positrons

and ~3×10^7 antiprotons



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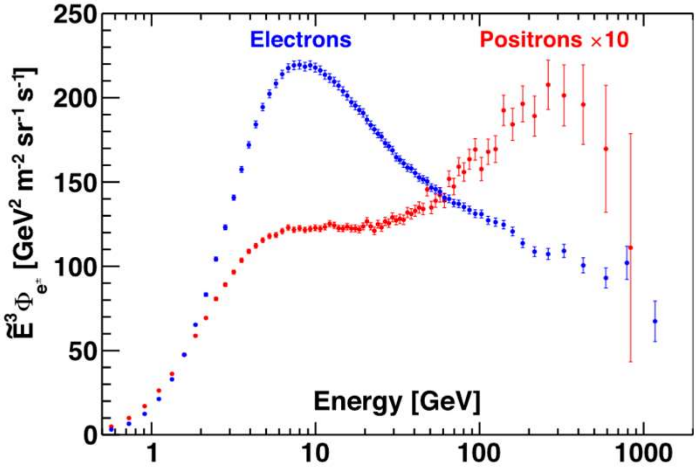
Antibaryons are rare in space

Antimatter fluxes in Low Earth Orbit

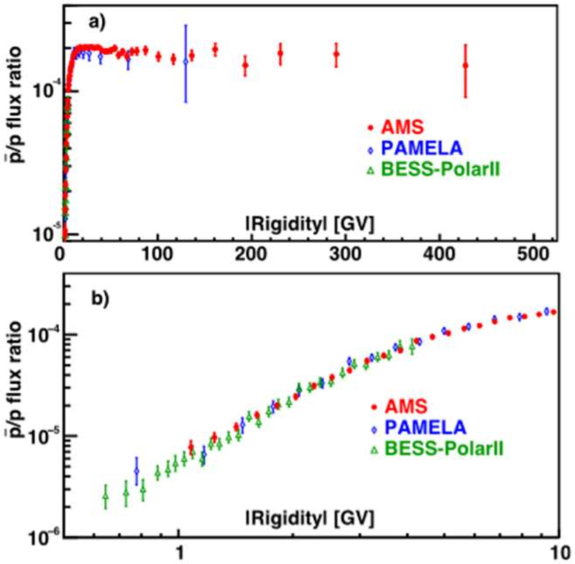
AMS-2 experiment (on ISS, CERN involvement)

https://ams02.space/

Electrons/positrons



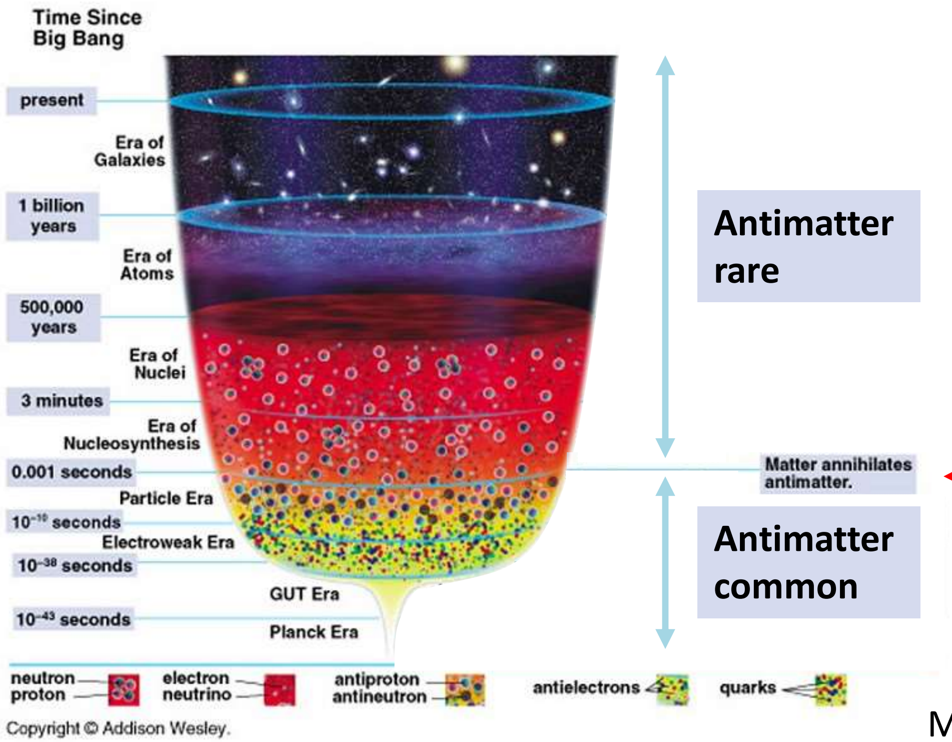
Protons/antiprotons



Mostly from high energy astrophysical processes, not from early universe

M. Aguilar et al., Physics Reports **894** (2021)

Our understanding of the early universe



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Antimatter rare

Antimatter common

SHOULD NOT EXIST (according to known physics)

Problem: one billion times more matter left over than expected

Figure adapted from "The Essential Cosmic Perspective", by Bennett, Voit, and Donahue

Measured baryon to photon ratio $\eta = \frac{N_B - N_{\bar{B}}}{\gamma} \sim 6 \times 10^{-1}$

Seems to be no Big Bang antimatter remnant

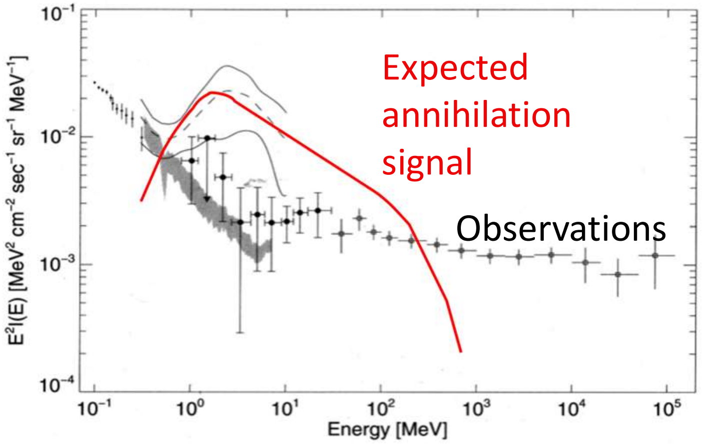
Why?

1) Just the way it is, initial state of the universe asymmetric

2) Equal amounts of matter and antimatter created, but they separated into distinct regions – no annihilation signal

3) Some more dense antimatter objects hiding somewhere (antistars, exotic dense antimatter objects like Axion Quark Nuggets) – let's see, can look for signatures (e.g. AMS-2)

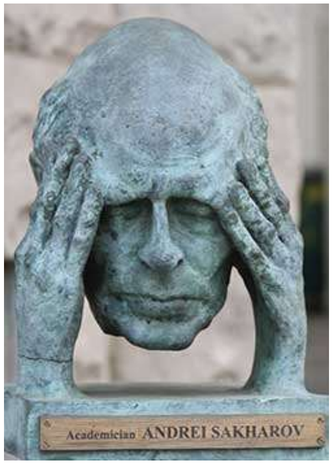
4) Dynamical process – initially matter-antimatter symmetric, then some process occurred to favour matter



F. W. Stecker, Proc. Of Gamma Ray Observatory Science Workshop, 4-73 (1989)
V. Schönfelder, The Universe in Gamma Rays (2001)
A. Zhitnitsky Modern Physics Letters A, **36** 18 (2021)

WMAP (2003), Planck (2018)
M. Aguilar, Physics Reports **894** (2021)

Dynamical Baryon asymmetry



Sakharov conditions

- Baryon number non-conserving process
- Breaking of C and CP
- Departure from equilibrium

Need new sources of CP violation

Many, many constructive beyond-the-SM theories with predictions for EDMs, particles and so on

Photo: dbking/flickr.com

A.D. Sakharov, JETP Lett. 5 (1967) 24.

CPT violation

- Baryon number non-conserving process
- Breaking of CPT symmetry

O.Bertolami, Don Colladay, V.Alan Kostelecký, R.Potting PLB 395, 3, 13 (1997)

A.D. Dolgov and Ya.B. Zeldovich, Rev. Mod. Phys. 53 (1981)

Why study antimatter?

A way to test the most basic assumptions of our physical theory (CPT, Lorentz invariance)

A possible explanation for why we’re all here

Producing antimatter at CERN

A rich history at CERN…

1972 Simon van der Meer (CERN) proposes stochastic cooling

1974 Stochastic cooling demonstrated at Intersecting Storage Ring ICR

1976 Suggestion (Rubbia et al.) to build an antiproton/proton collider at CERN or Fermilab

1978 Antiprotons produced by colliding protons and stored in ICE ring for 85 hours CERN, electron and stochastic cooling demonstrated

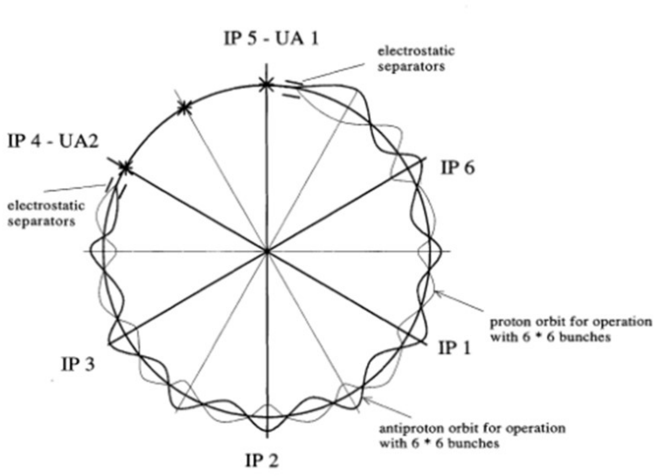
1981 First proton-antiproton collisions in ISR and later Sp$\bar{p}$S

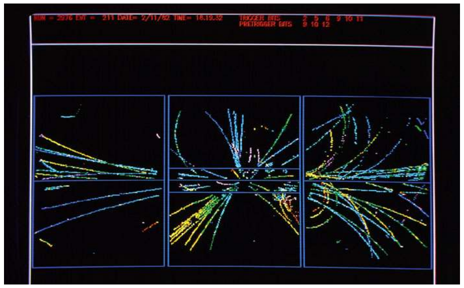
1982 Low Energy Antiproton Ring completed

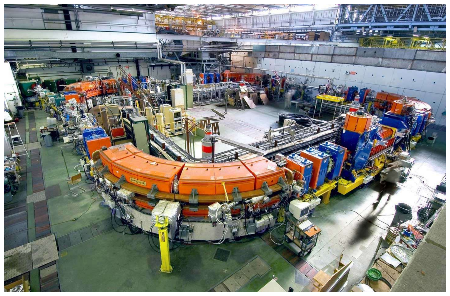
1983 W and Z bosons discovered with $p\bar{p}$ collisions in Sp$\bar{p}$S

1990’s Proton-to-antiproton Charge-to-Mass ratio compared to 90 parts per trillion (Gabrielse et al.) with LEAR $\bar{p}$’s

1995 First hot antihydrogen produced at LEAR



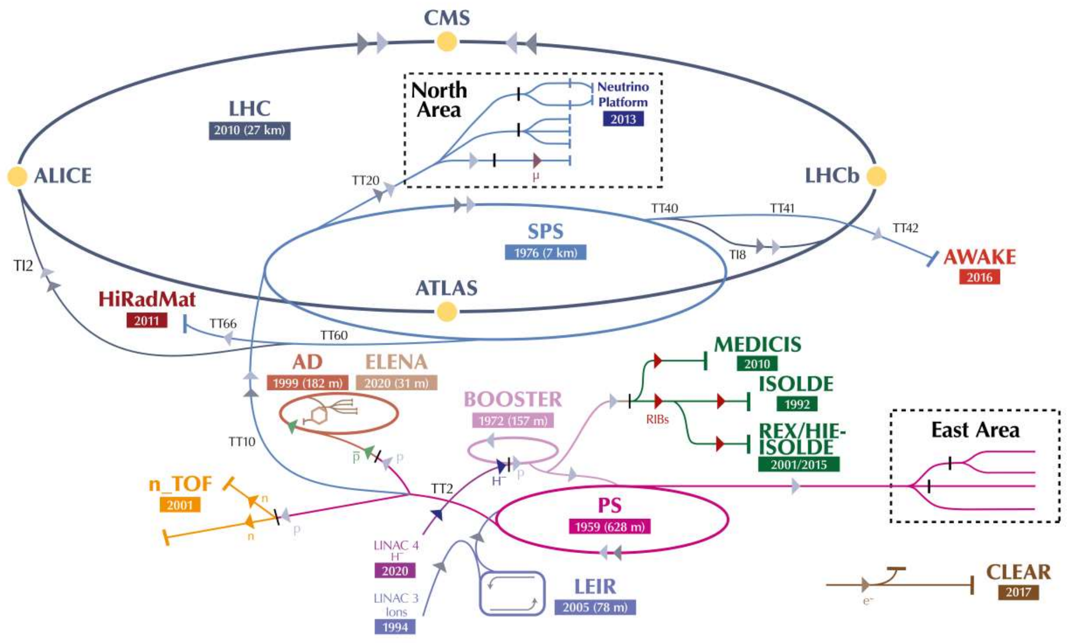




R. Schmidt, Particle Accelerators, **50**, (1995)

CERN today

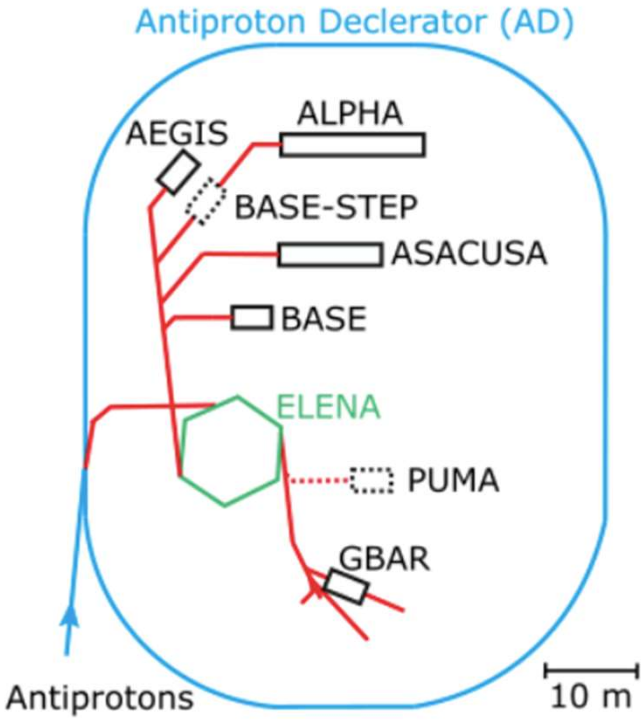
The CERN accelerator complex
Complexe des accélérateurs du CERN



▶ H^- (hydrogen anions) ▶ p (protons) ▶ ions ▶ RIBs (Radioactive Ion Beams) ▶ n (neutrons) ▶ p̄ (antiprotons) ▶ e^- (electrons) ▶ μ (muons)

LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive EXperiment/High Intensity and Energy ISOLDE // MEDICIS // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // Neutrino Platform

The Antimatter Factory



New facility after shutdown of LEAR in 1996

First beam 2000

Two decelerators,

Current experiments running/under construction

GBAR, ASACUSA-1, ASACUSA-2, BASE, BASE-STEP, PUMA, ALPHA, ALPHA-g, AEGIS

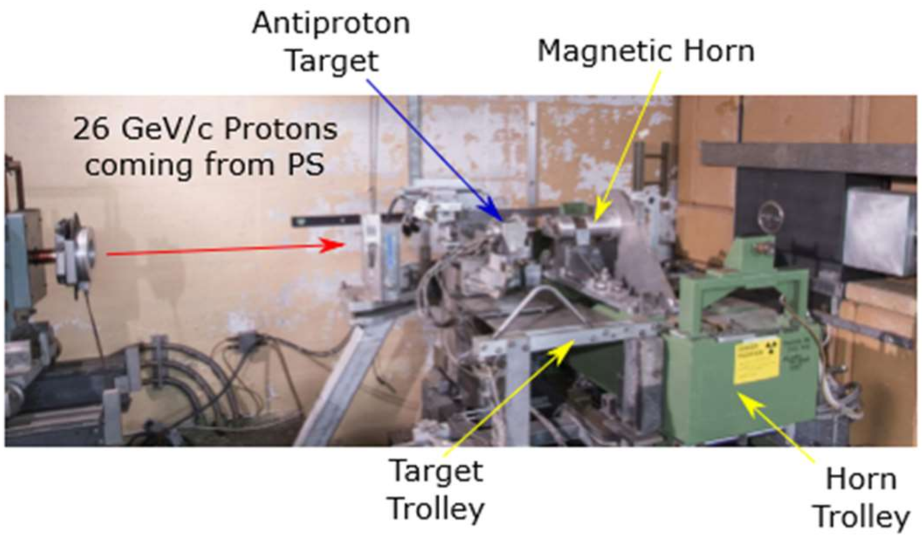
ELENA

(Maximilien Brice/CERN)

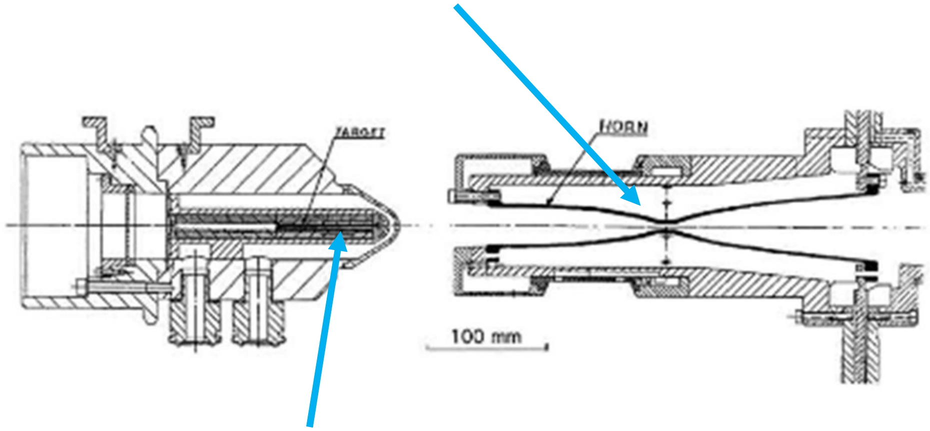
The Antiproton Decelerator

(CERN)

The Target



400 kA current applied to magnetic horn focusses beam



Heavy metal (e.g. Iridium)

$$p + \text{nucleus} \rightarrow \text{Excited nucleus} + p + \bar{p} + \text{other particles}$$

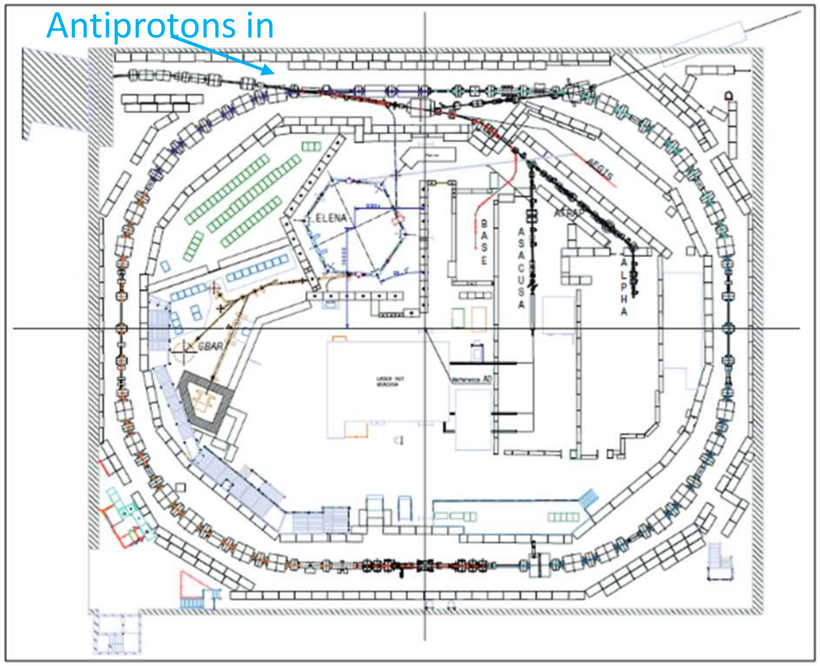
Threshold 5.6 GeV/c, carried out at 26 GeV/c

After horn 5*10^7 $\bar{p}$’s at 3.6 GeV/c , $\frac{\Delta p}{p} = 6\%$, 30 m long pulse

Extreme temperatures: 2000 degrees rise in 0.5 microseconds

C. Torregrosa Martin, PhD Thesis (CERN-THESIS-2017-357)
C. Torregrosa Martin et al., Proceedings of IPAC2017

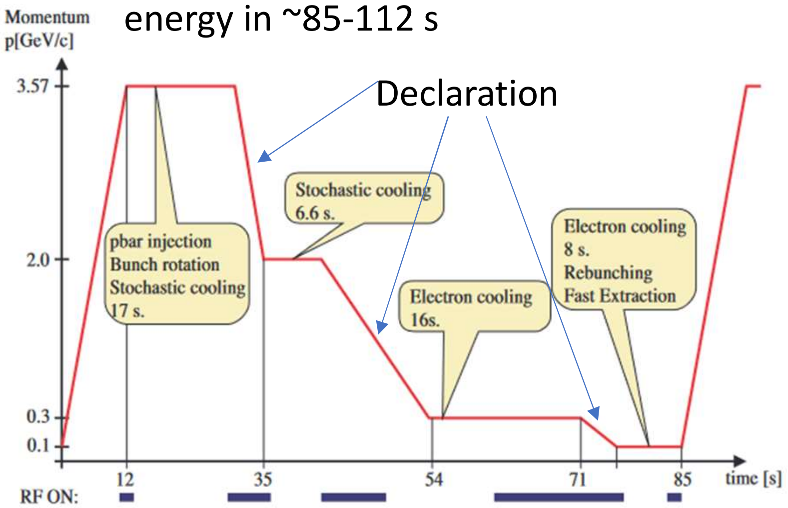
The Antiproton Declarator



Antiprotons in

In 2014 (more experiments now)

Slows from 3.6 GeV/c to 100 MeV/c (53 MeV energy in ~85-112 s



Declaration

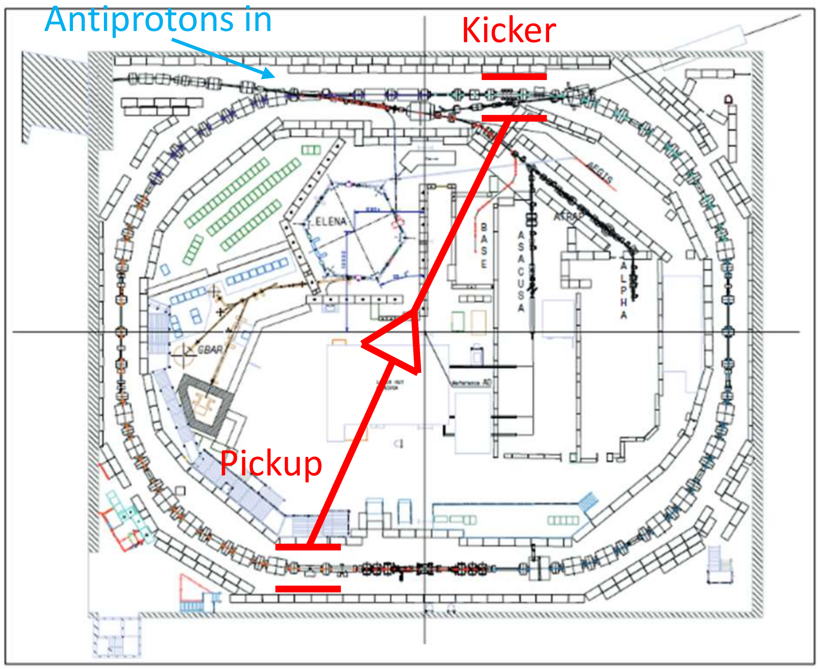
Cools momentum spread from $\frac{\Delta p}{p} = 6\%$ to $\frac{\Delta p}{p} = 0.01\%$

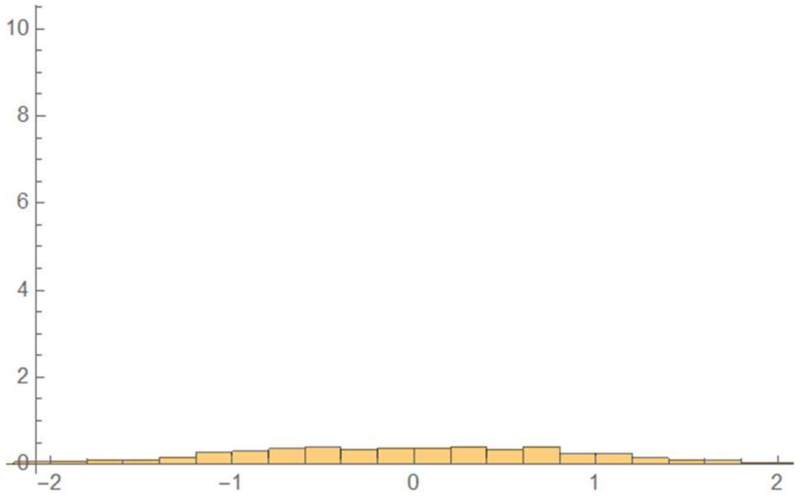
Extra Low ENergy Antiproton (ELENA) ring
and its Transfer Lines, CERN design report (2014)
P. Belochitskii, T. Eriksson, and S. Maury, Nucl. Instrum. Meth. Phys. Res. A **214** (2004)

Stochastic cooling

$$\langle (x-\langle x\rangle)^2\rangle < \langle x^2\rangle$$

So, if you can measure and correct the mean of a distribution (and it randomizes between measurements), you can reduce its spread

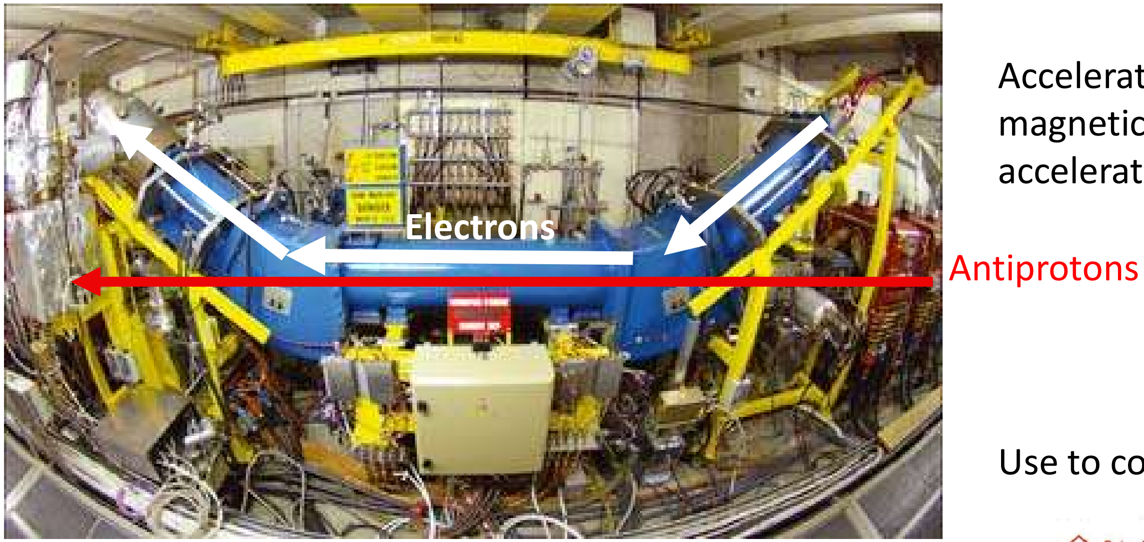




2 stages of stochastic cooling reduces momentum spread (4σ) from 1%->0.1%->0.015%

P. Belochitskii, T. Eriksson, and S. Maury, Nucl. Instrum. Meth. Phys. Res. A **214** (2004)

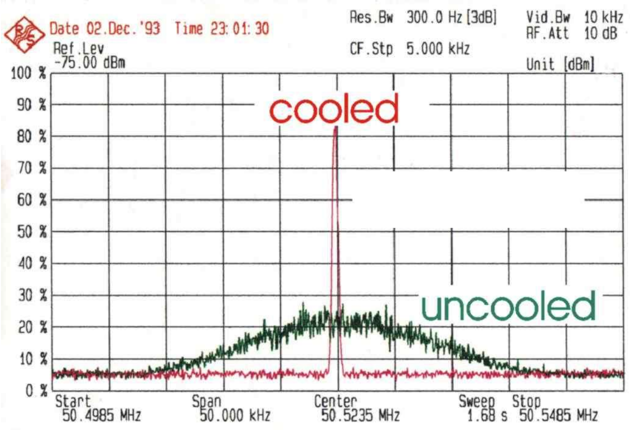
Electron cooling



Accelerated charge radiates- Electrons in a magnetic field orbit in circles, continually accelerated, loose energy with time constant

$$\tau = \frac{3\pi\epsilon_0 m^3 c^3}{e^4}\frac{1}{B^2}$$

Use to cool sympathetically cool antiprotons

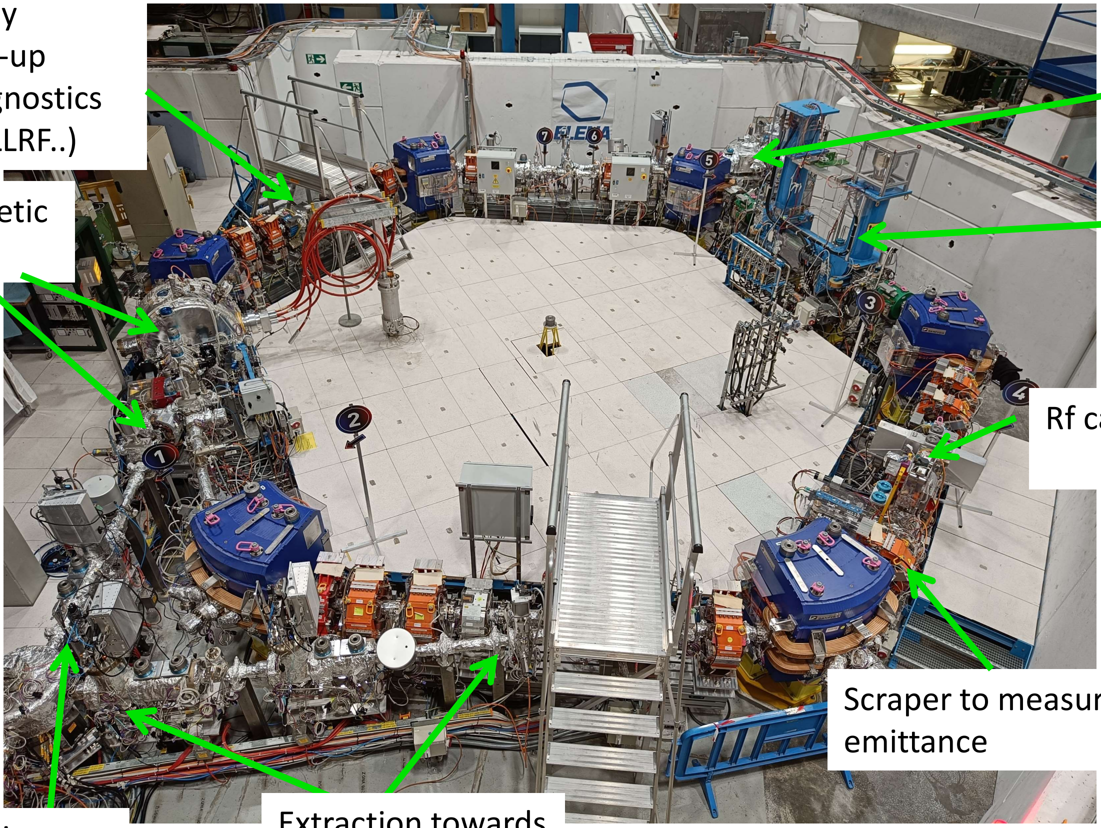


The AD electron cooler- built to last!
Parts recycled from ICE, first antiproton cooling experiment at CERN, 48 years ago

Momentum spread in 2 stages reduced (4σ) from 0.015%->0.01%

P. Belochitskii, T. Eriksson, and S. Maury, Nucl. Instrum. Meth. Phys. Res. A **214** (2004)

ELENA: The Extremely Low Energy Antiproton facility



High sensitivity magnetic Pick-up (Schottky diagnostics for intensity, LLRF..)

Injection with magnetic septum and kicker

Extraction towards GBAR

Electron cooler

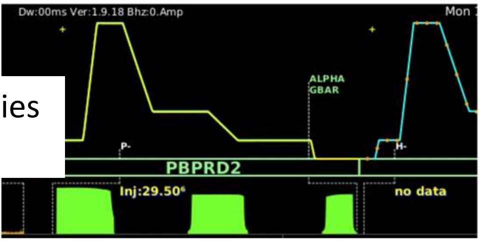
Rf cavities

Scraper to measure emittance

100 keV final energy

Line From AD

Extraction towards other experiments



Extra Low ENergy Antiproton (ELENA) ring and its Transfer Lines, CERN design report (2014)

What’s the cost of a gram of antimatter?

In 2018

Electricity used cost 67 million Swiss Franc, and uses 1.25 TWh per year when running

10% spent on Proton Synchrotron, AD takes ~2.4 s/112 s= 2% of cycles

Costs ~130,000 CHF in electricity per year to produce antiprotons

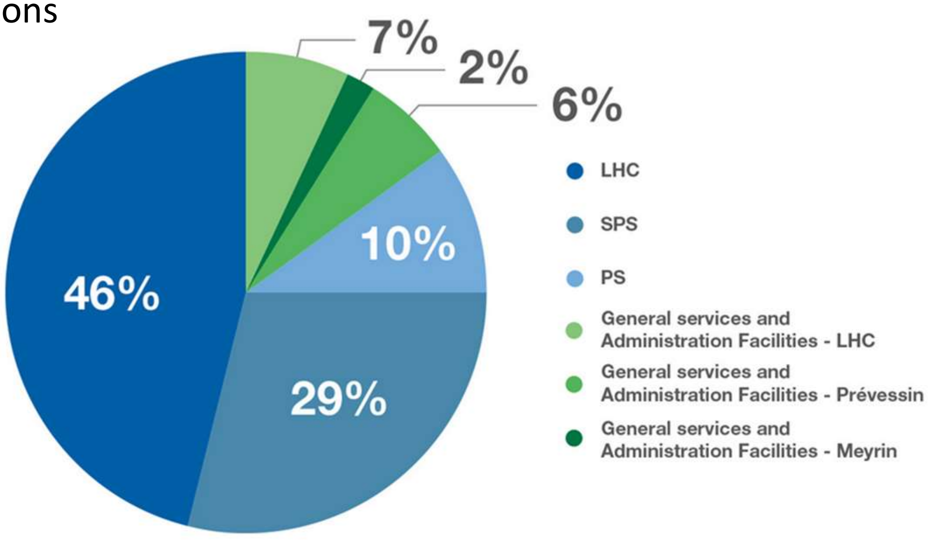
~10 trillion antiprotons produced per year ~12 picograms

Cost per gram ~**8000 trillion Swiss Franc (100x world GDP/y)**

- Not including people to operate the machine!

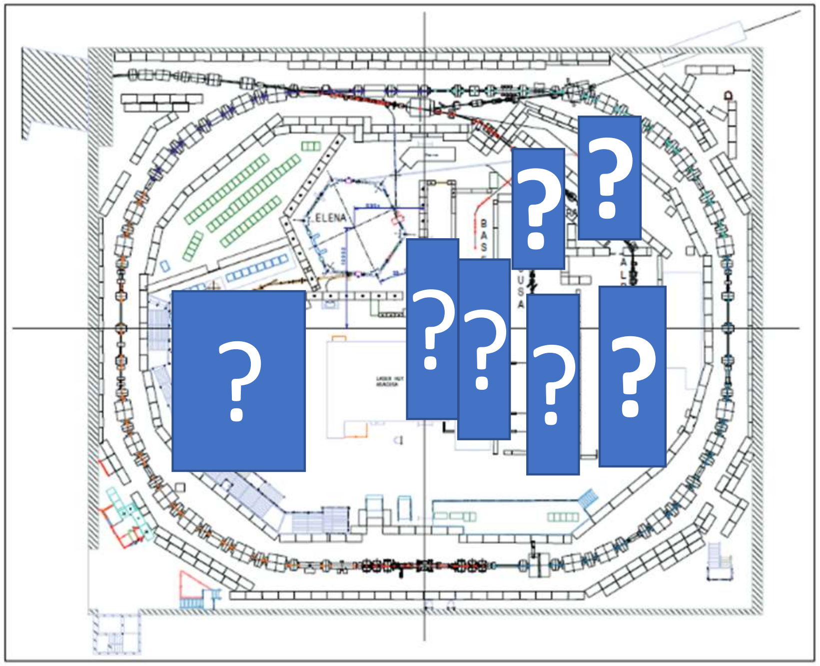
Not a cheap way to make lots of antimatter

Or looking at it another way – cost per particle
12 nano Swiss Francs or 40 cents per shot



CERN Financial Budget 2018
https://hse.cern/environment-report-2017-2018/energy

Until next time…



Thanks to Stefan Ulmer, Christian Smorra & Andi Mooser for providing slides and materials for these lectures

And thank you for listening