Antimatter in the lab

Lecture 1

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24/7/23 11:25

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?

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

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

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

$$H = \sqrt{p^2 + m^2}$$

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

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

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

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

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

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

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

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

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

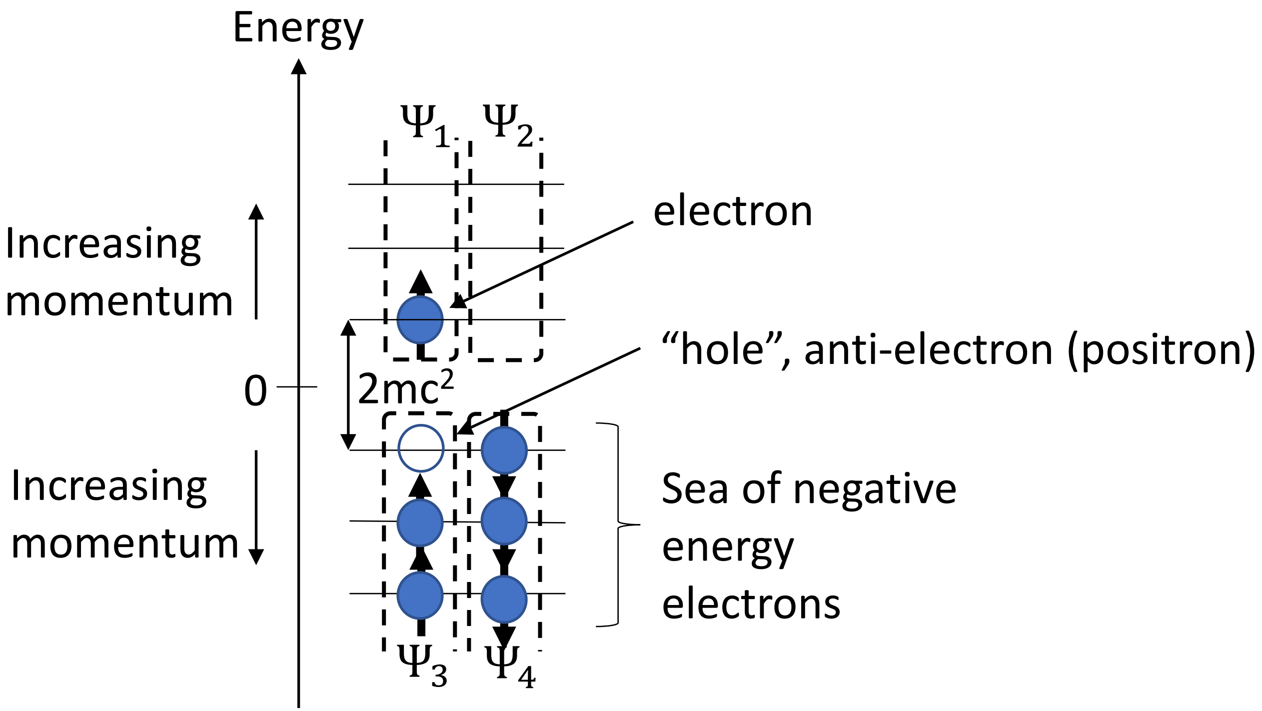
$$\Psi_3 = A \begin{pmatrix} \frac{-p}{E_p+m} \\ 0 \\ 1 \\ 0 \end{pmatrix} e^{-ip^\mu x_\mu}$$

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

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

Different pictures

The Dirac sea



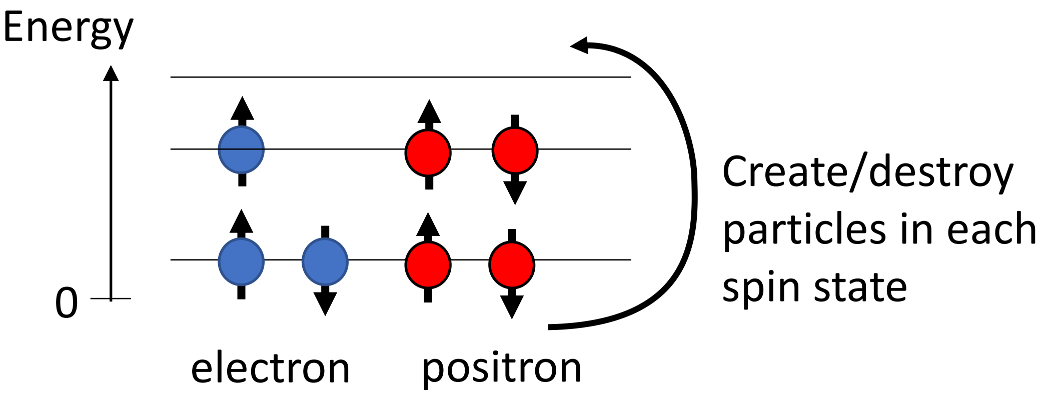
$$q_{hole} = (Q_{sea} - q_{electron}) - Q_{sea} = -q_{electron}$$

Many processes explainable (e.g. low energy electron-photon scattering)

But- single particle theory, how to deal with e.g. beta (plus) decay when a positron just appears

$p \dashrightarrow n + e^{+} + \nu_e$?

Allow each of the 4 components of $\Psi(\boldsymbol{x}, t)$ to represent a quantised field which can be excited. Some rewriting show that there are 4 excitations for spin up and spin down electron/positrons



Ch 3-9, Advanced Quantum Mechanics, J.J. Sakaurai

Discovery of antimatter

492 CARL D. ANDERSON

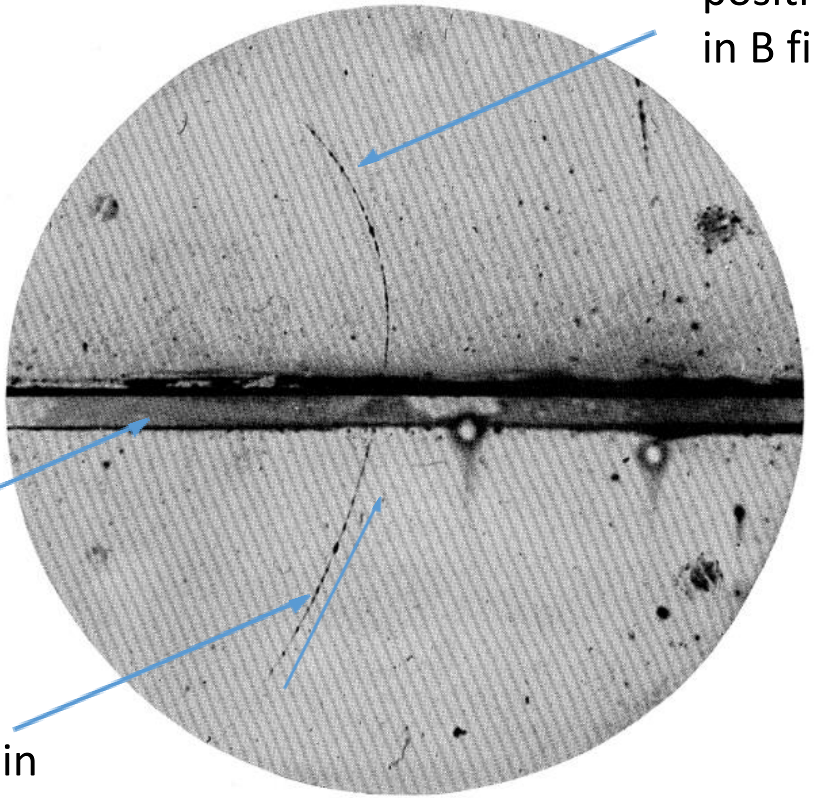


Fig. 1. A 63 million volt positron ($H\rho = 2.1\times10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5\times10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

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

First discovered by Carl Anderson (1932)

Mass of particle <20x proton mass, positive charge

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

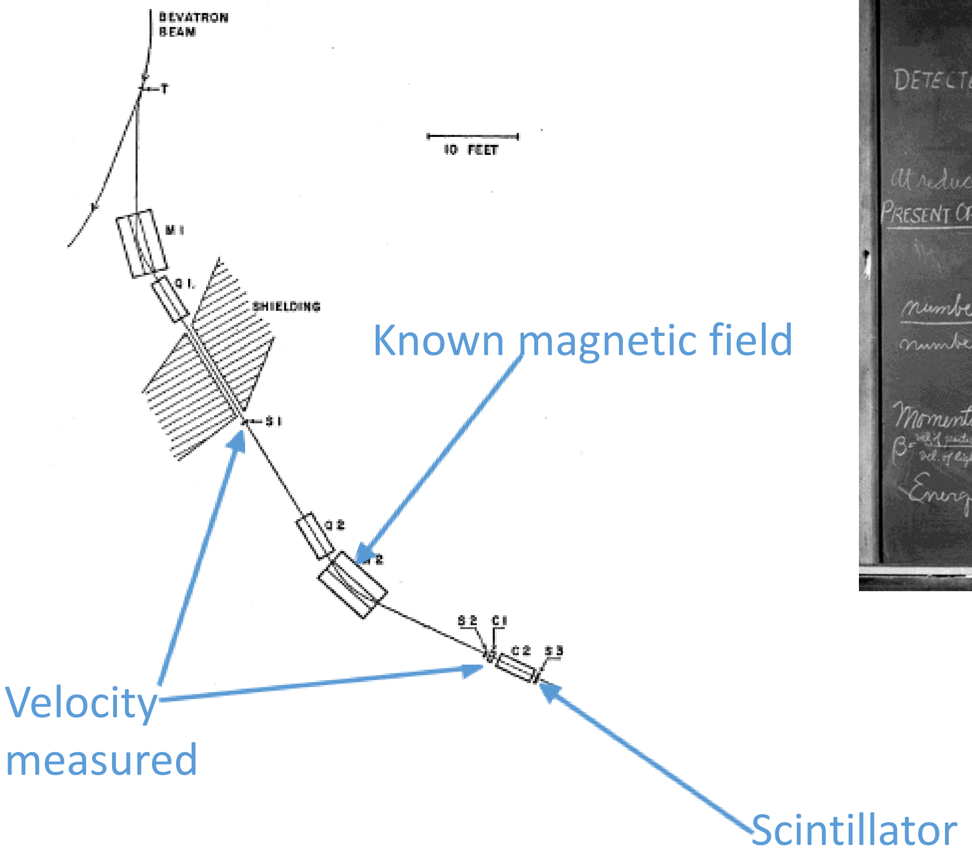
Despite what you might think, none of these people was looking for Dirac's anti-electron!

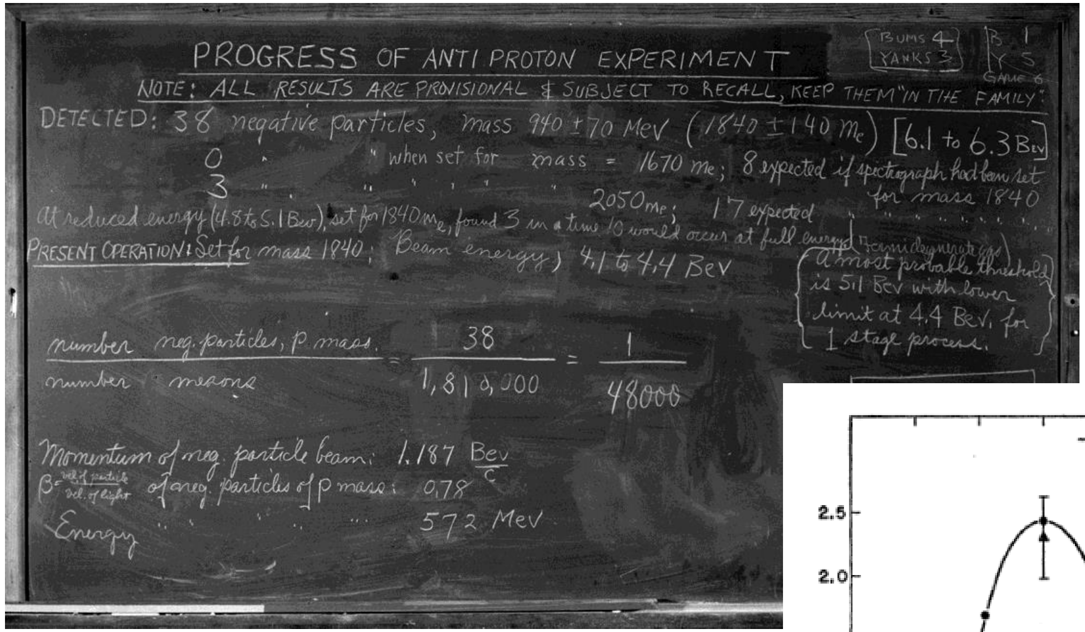
C. D. Anderson Phys. Rev. **43**, 491 (1933)
M. Leone, American Journal of Physics **80**, 534 (2012)

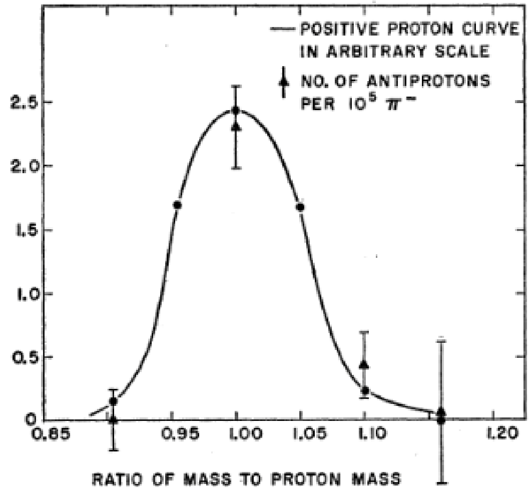
Discovery of the antiproton 1955

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

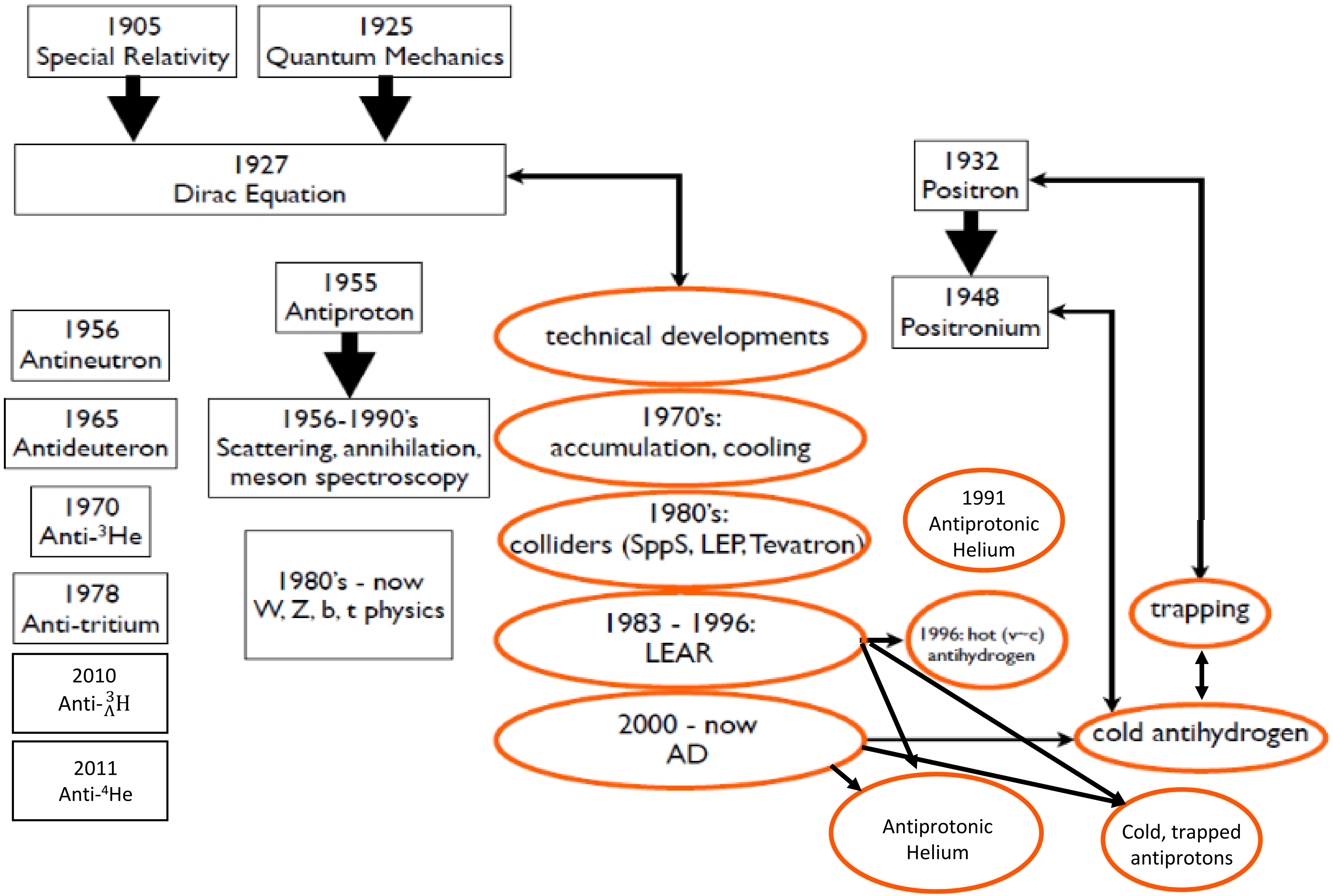
At Bevatron – Proton accelerator at Berkley (California)







Ever more complicated antimatter



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:

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

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

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

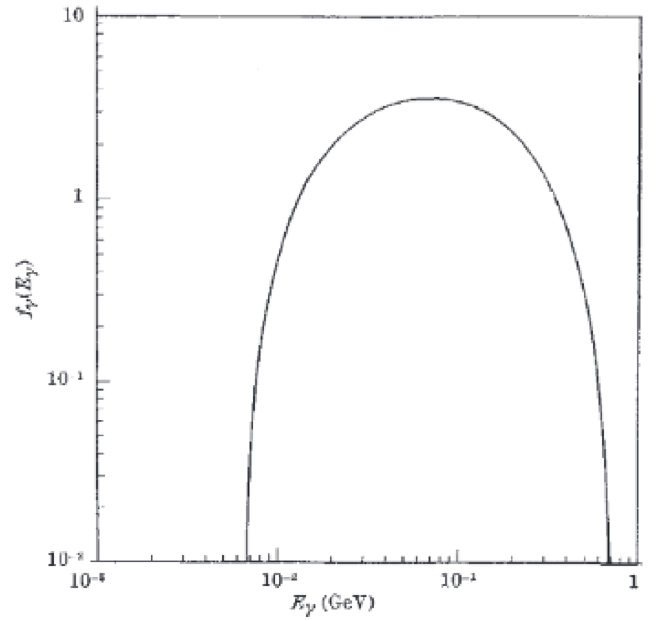


Fig. 1. The normalized local differential gamma ray spectrum from proton–antiproton annihilation.

+2.2% other channels

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

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

Why study antimatter?

Is this interesting?

A skeptical voice:

Is it possible for matter and antimatter properties to differ?

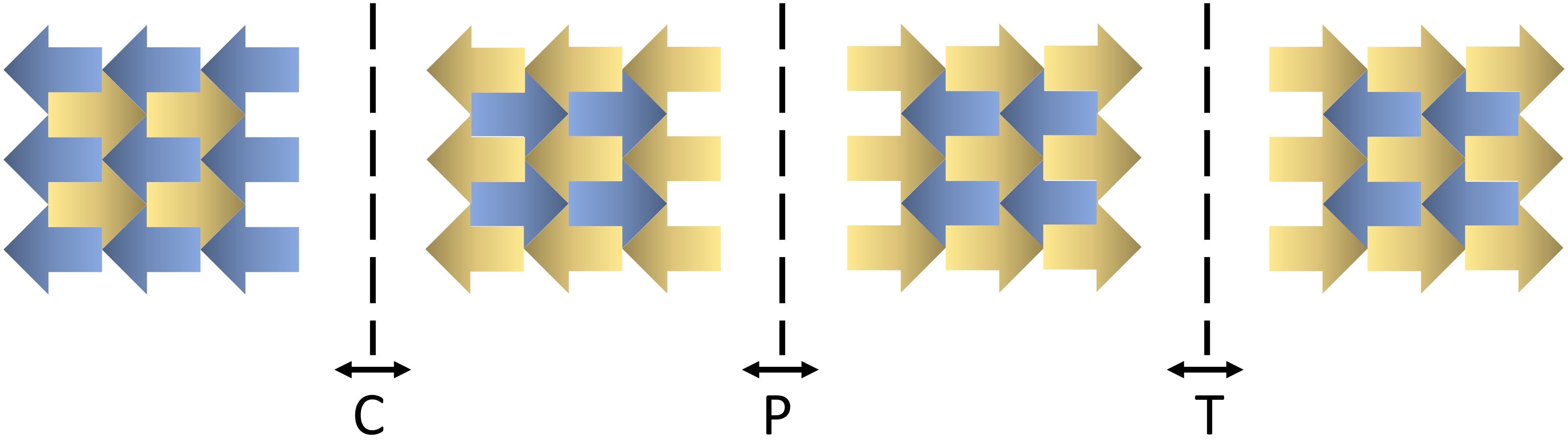
A skeptical voice with extensive physics training

Any “reasonable”, Lorentz-covariant quantum field theory will be CPT symmetric.

CPT symmetry means matter and antimatter properties are the same.

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 $t \longrightarrow -t$

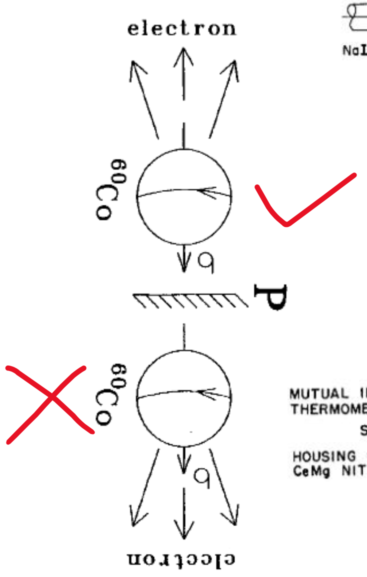


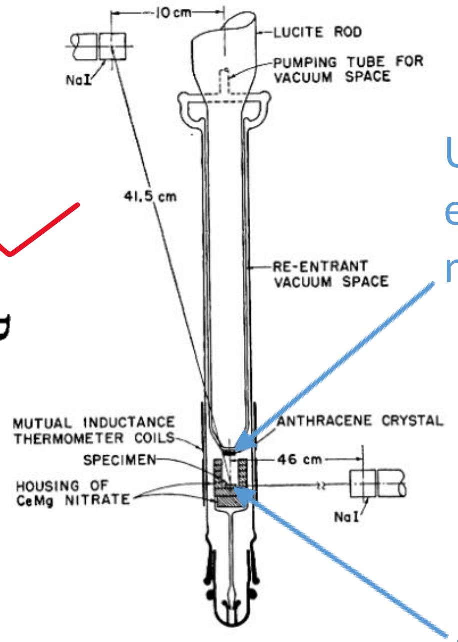
CPT implies matter and antimatter particles have the same properties (up to a sign)

Assume makes …

C, P and T and CP have been measurably broken

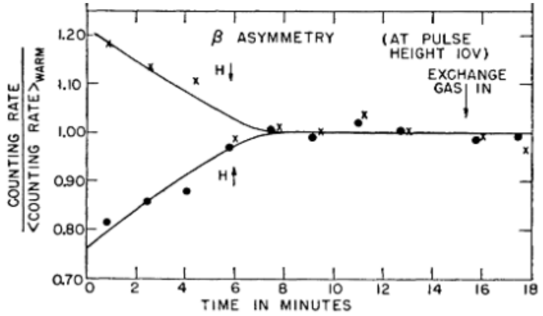
C. S. Wu's P-violation experiment





Upwards β-emission measured

More β-emission upwards when Co-60 polarised downwards



Polarised cobalt-60

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

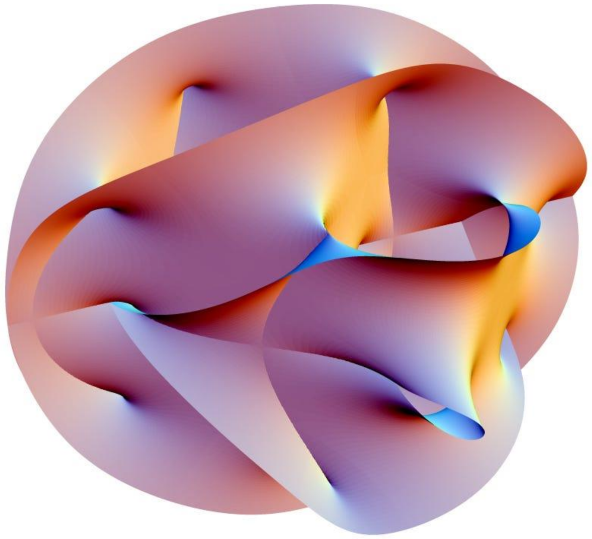
Why specifically might CPT be broken?

Any “reasonable”, 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

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

$$\mathcal{L}_{\text{quark}} = \tfrac{1}{2} i \overline{Q}_A \gamma^\mu \overleftrightarrow{D_\mu} Q_A + \tfrac{1}{2} i \overline{U}_A \gamma^\mu \overleftrightarrow{D_\mu} U_A + \tfrac{1}{2} i \overline{D}_A \gamma^\mu \overleftrightarrow{D_\mu} D_A \quad , \qquad (5)$$

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

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

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

Minimal Standard Model Extension (SME)

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

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

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

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

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

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

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

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

$$\mathcal{L}^{\text{CPT-odd}}_{\text{gauge}} = (k_3)_\kappa \epsilon^{\kappa\lambda\mu\nu} \text{Tr}(G_\lambda G_{\mu\nu} + \tfrac{2}{3} i g_3 G_\lambda G_\mu G_\nu) + (k_2)_\kappa \epsilon^{\kappa\lambda\mu\nu} \text{Tr}(W_\lambda W_{\mu\nu} + \tfrac{2}{3} i g W_\lambda W_\mu W_\nu) + (k_1)_\kappa \epsilon^{\kappa\lambda\mu\nu} B_\lambda B_{\mu\nu} + (k_0)_\kappa B^\kappa \quad . \qquad (17)$$

A concrete example

In the minimal SME, Dirac equation becomes

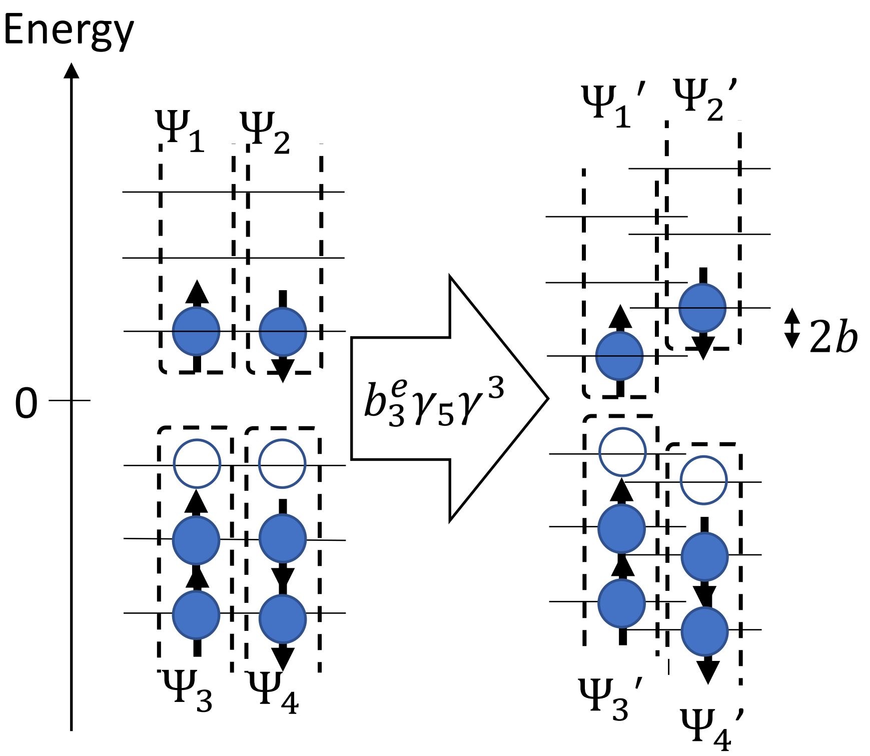
γ_5=i $\gamma_0\gamma_1\gamma_2\gamma_3$

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

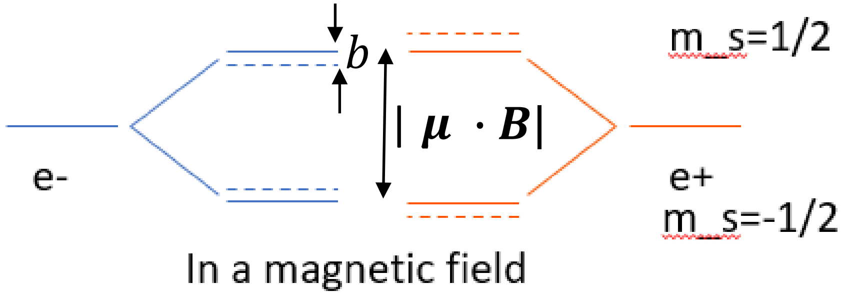
Normal — CPT breaking — Lorentz-symmetry breaking

$a^e_\mu, b^e_\mu, H^e_{\mu\upsilon}, c^e_{\mu\upsilon}, d^e_{\mu\upsilon}$ new terms which need to be measured. Suppose just $b = b^e_3$ was non-zero. Then, the free particle solutions become:

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



Magnet moment of the electron no longer equal to the positron!



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

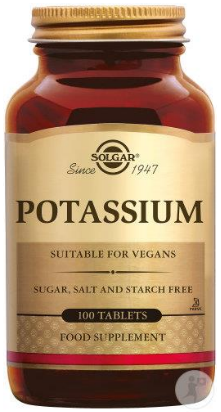
10^{24} gas molecules hitting 1 cm^2 of your skin every second – higher or lower than…

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

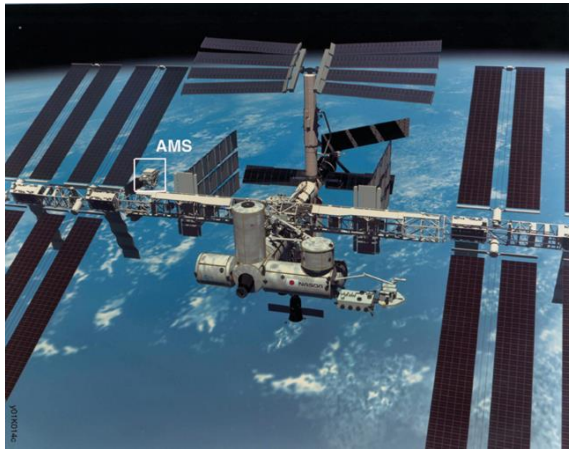
1×10^8 positrons absorbed

higher or lower than…

A 6 month stay on the ISS (ignoring shielding)

1×10^8 positrons

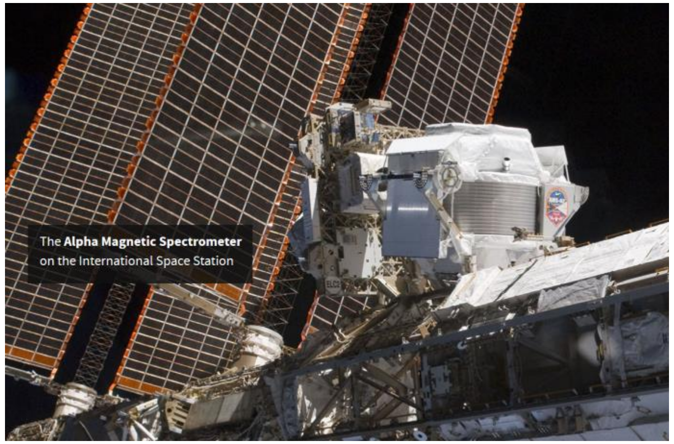
and ~3×10^7 antiprotons



Antibaryons are rare in space

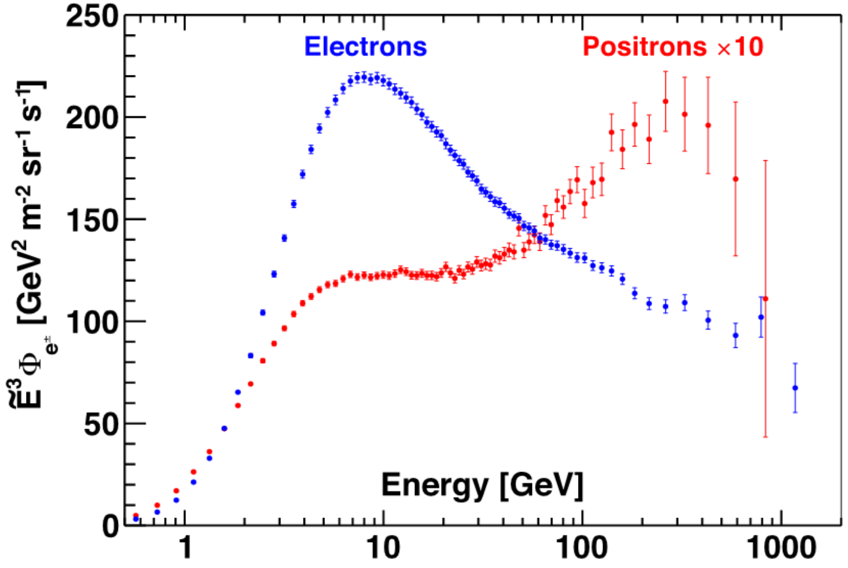
Antimatter fluxes in Low Earth Orbit

AMS-2 experiment (on ISS, CERN involvement)

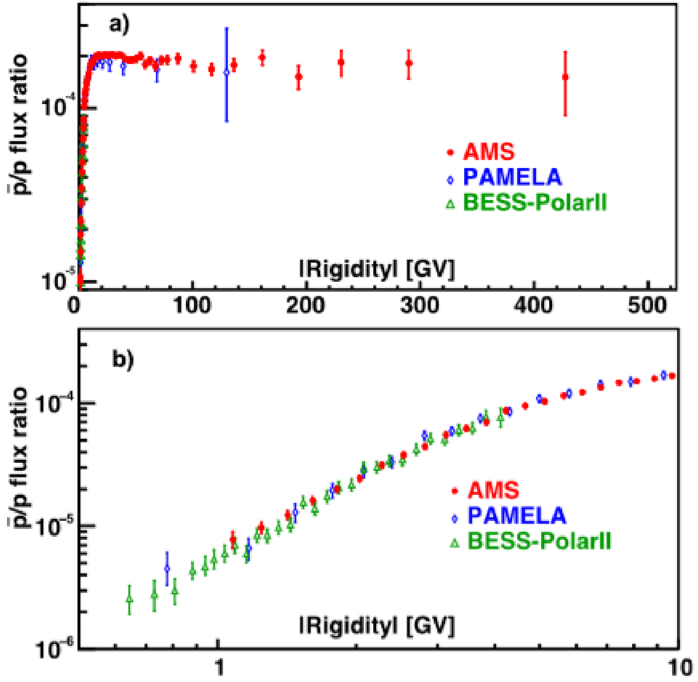


https://ams02.space/

Electrons/positrons



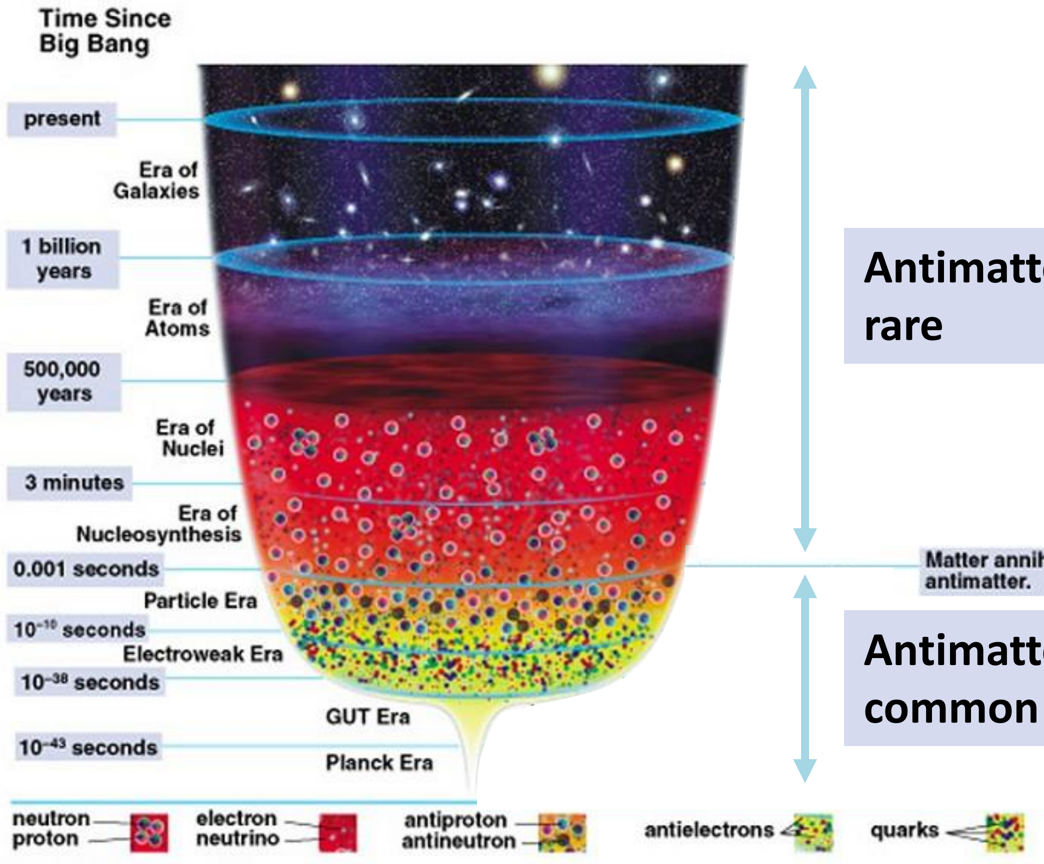
Protons/antiprotons



Mostly from high energy astrophysical processes, not from early universe

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

Our understanding of the early universe



Antimatter rare

Antimatter common

SHOULD NOT EXIST (according to known physics)

Problem: one billion times more matter left over than expected

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

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

Seems to be no Big Bang antimatter remnant

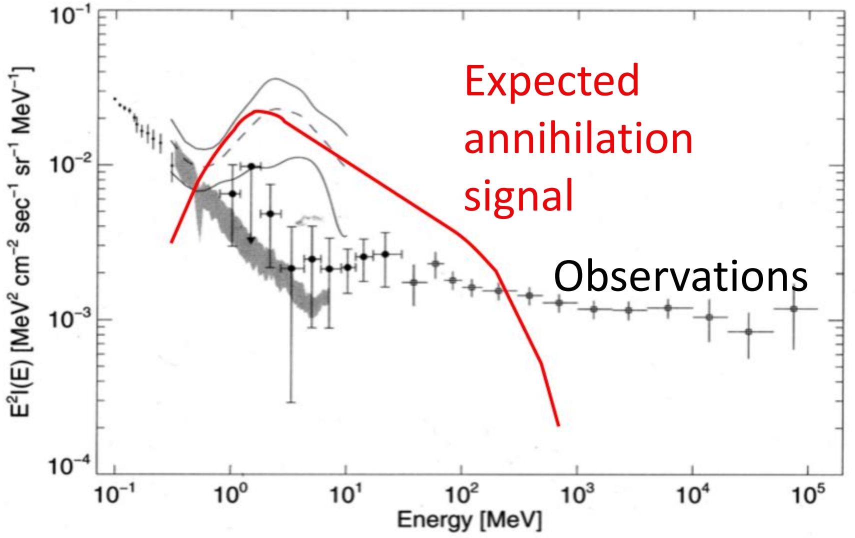
Why?

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) – let's see, can look for signatures (e.g. AMS-2)

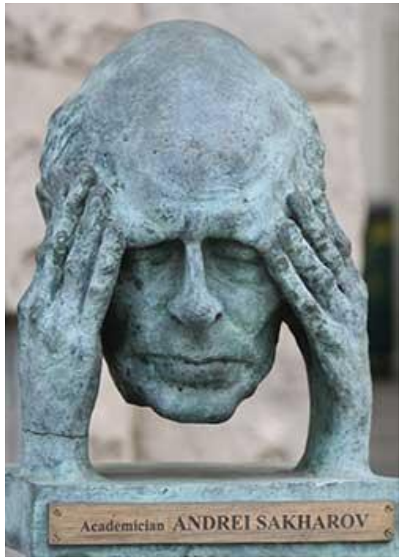
4) Dynamical process – initially matter-antimatter symmetric, then some process occurred to favour matter



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

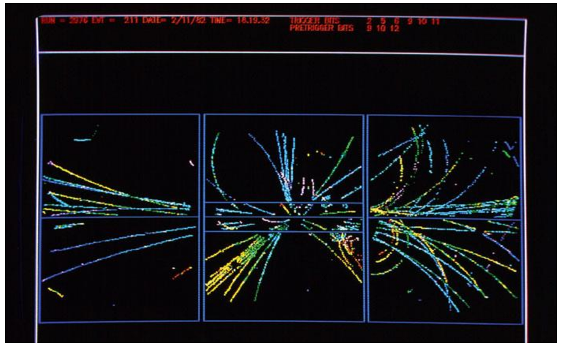
1981 First proton-antiproton collisions in ISR and later $Sp\bar{p}S$

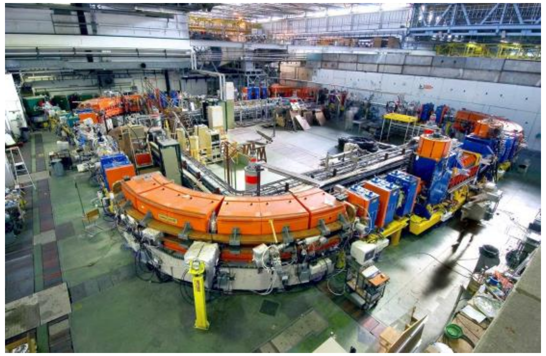
1982 Low Energy Antiproton Ring completed

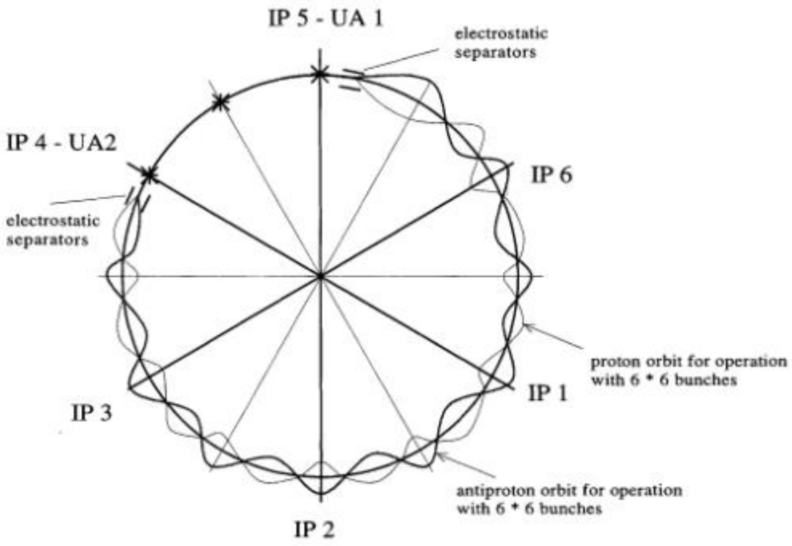
1983 W and Z bosons discovered with $p\bar{p}$ collisions in $Sp\bar{p}S$

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

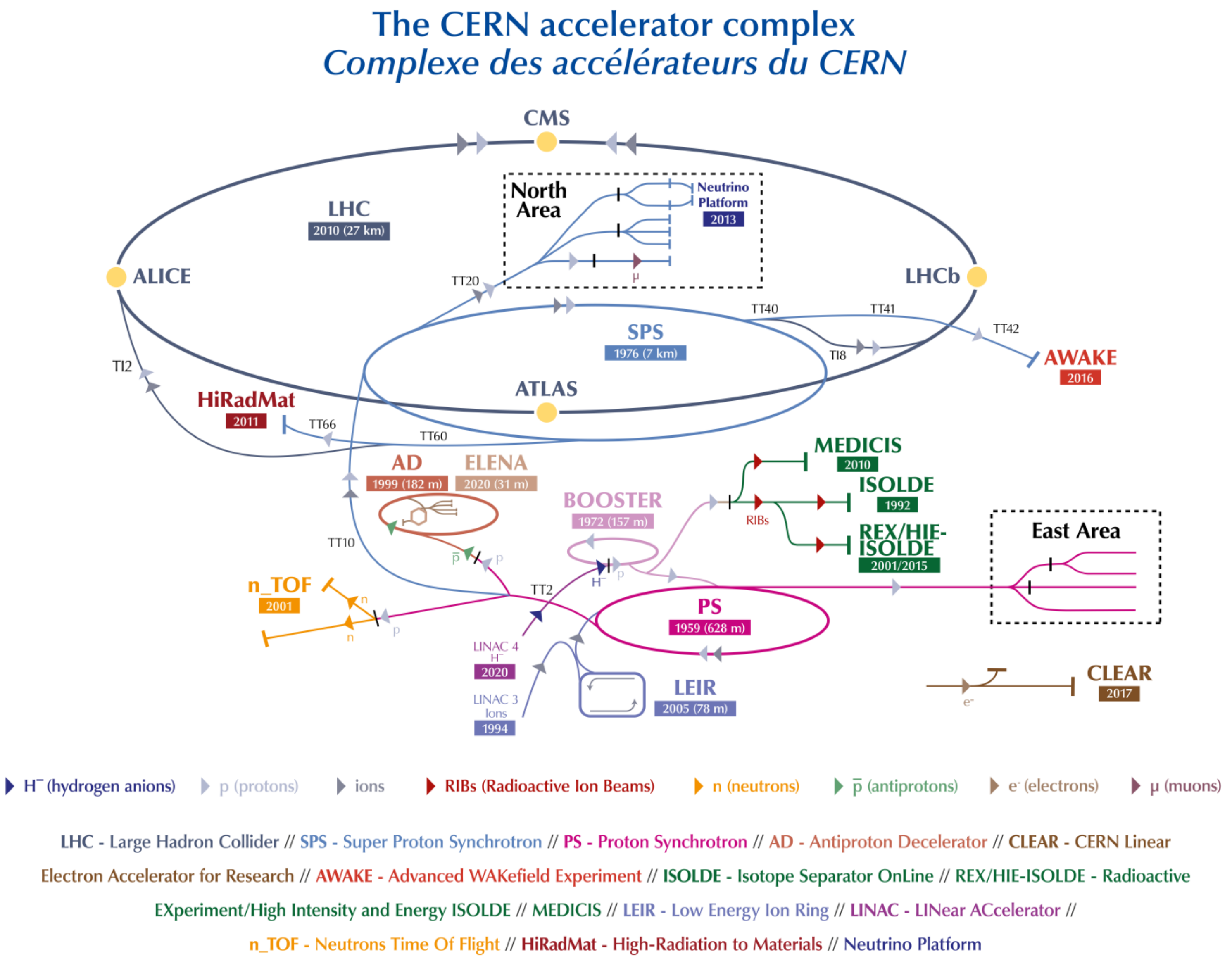




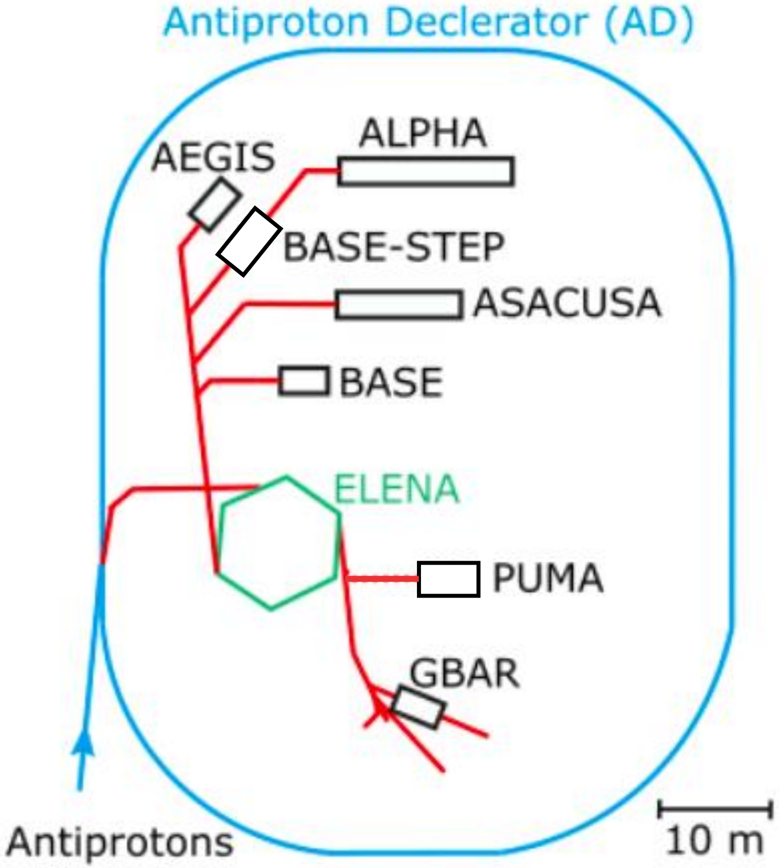


R. Schmidt, Particle Accelerators, **50**, (1995)

CERN today


The CERN accelerator complex
Complexe des accélérateurs du CERN
CMS
LHC
2010 (27 km)
North Area
Neutrino Platform
2013
ALICE
LHCb
TT20
TT40
TT41
TT42
SPS
1976 (7 km)
TI8
AWAKE
2016
TI2
ATLAS
HiRadMat
2011
TT66
TT60
AD
1999 (182 m)
ELENA
2020 (31 m)
MEDICIS
2010
ISOLDE
1992
BOOSTER
1972 (157 m)
RIBs
REX/HIE-ISOLDE
2001/2015
East Area
TT10
n_TOF
2001
TT2
PS
1959 (628 m)
LINAC 4
H⁻
2020
LINAC 3
Ions
1994
LEIR
2005 (78 m)
CLEAR
2017
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

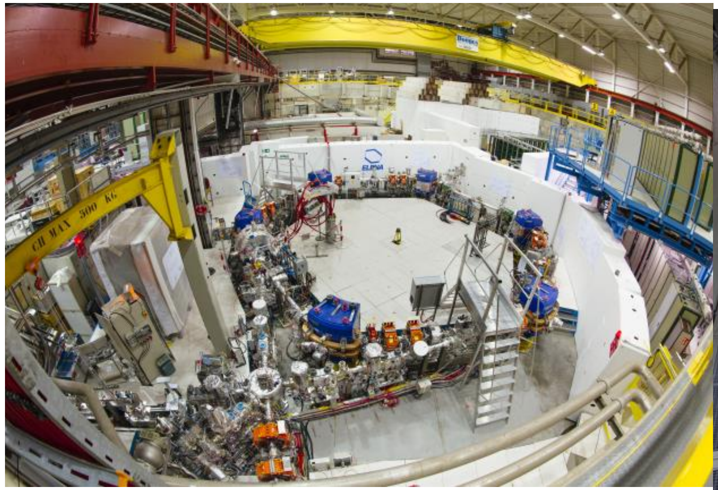
First beam 2000

Two decelerators,

Current experiments running/under construction

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

ELENA

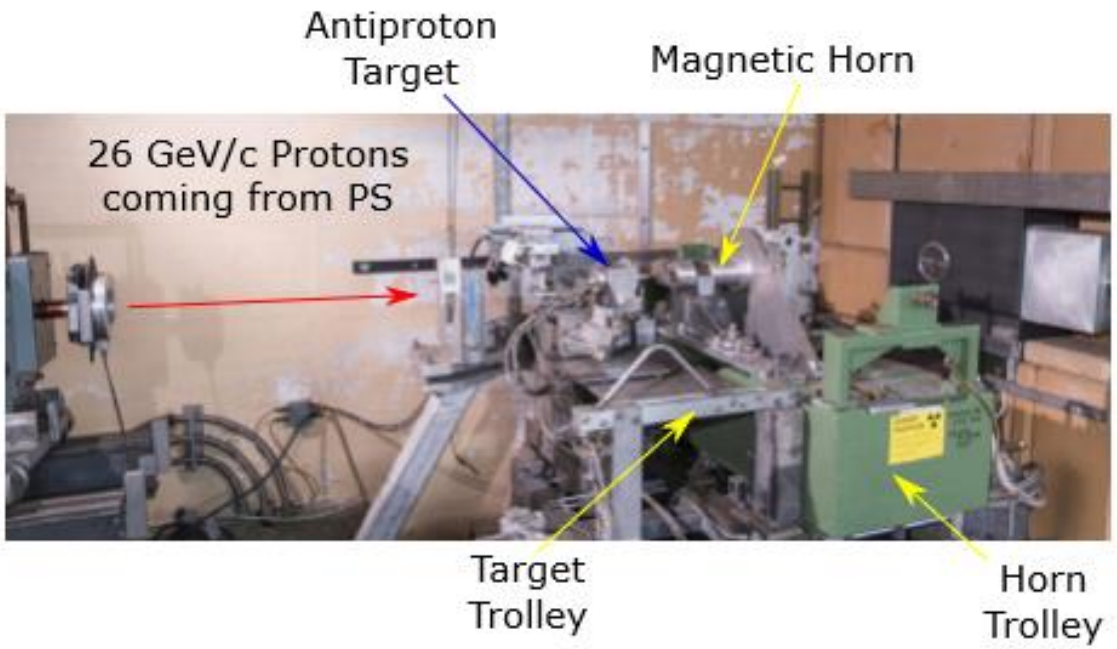


(Maximilien Brice/CERN)

The Antiproton Decelerator

(CERN)

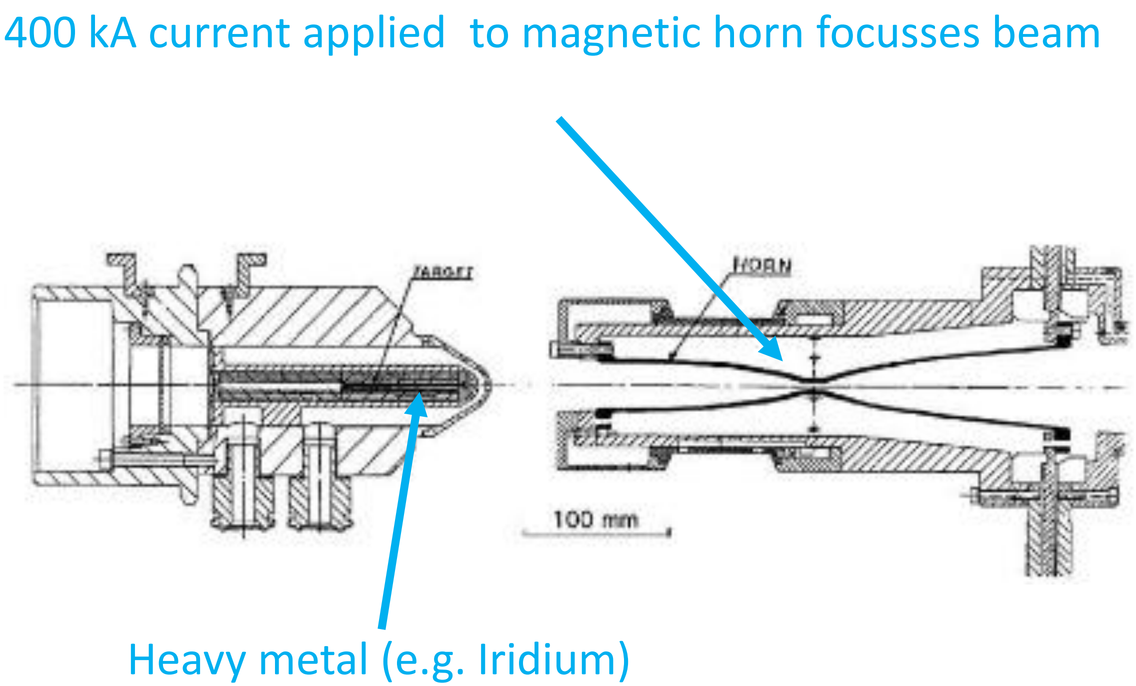
The Target



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

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

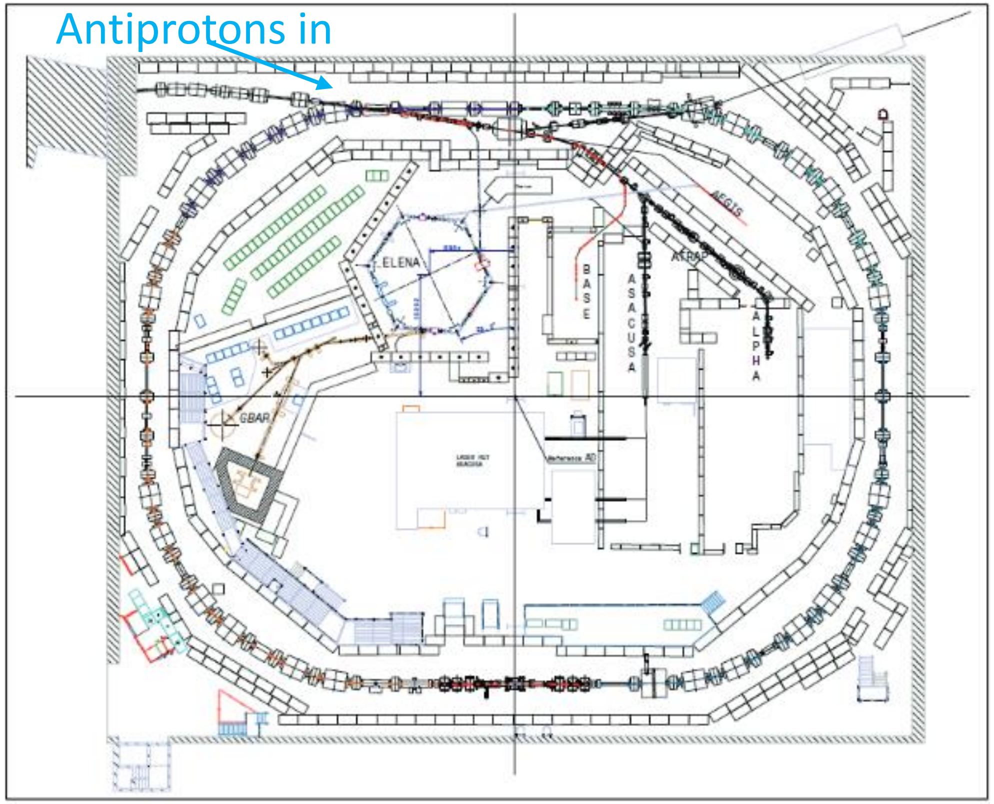
After horn 5*10^7 $\bar{p}$'s at 3.6 GeV/c , $\frac{\Delta p}{p} = 6\%$, 30 m long pulse



Extreme temperatures: 2000 degrees rise in 0.5 microseconds

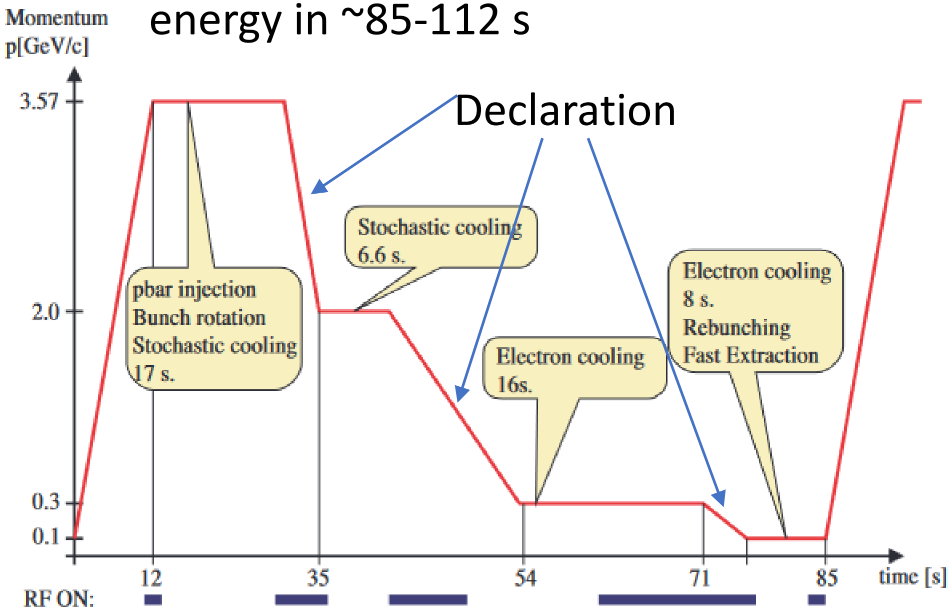
C. Torregrosa Martin, PhD Thesis (CERN-THESIS-2017-357)
C. Torregrosa Martin et al., Proceedings of IPAC2017

The Antiproton Decelerator



In 2014 (more experiments now)

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



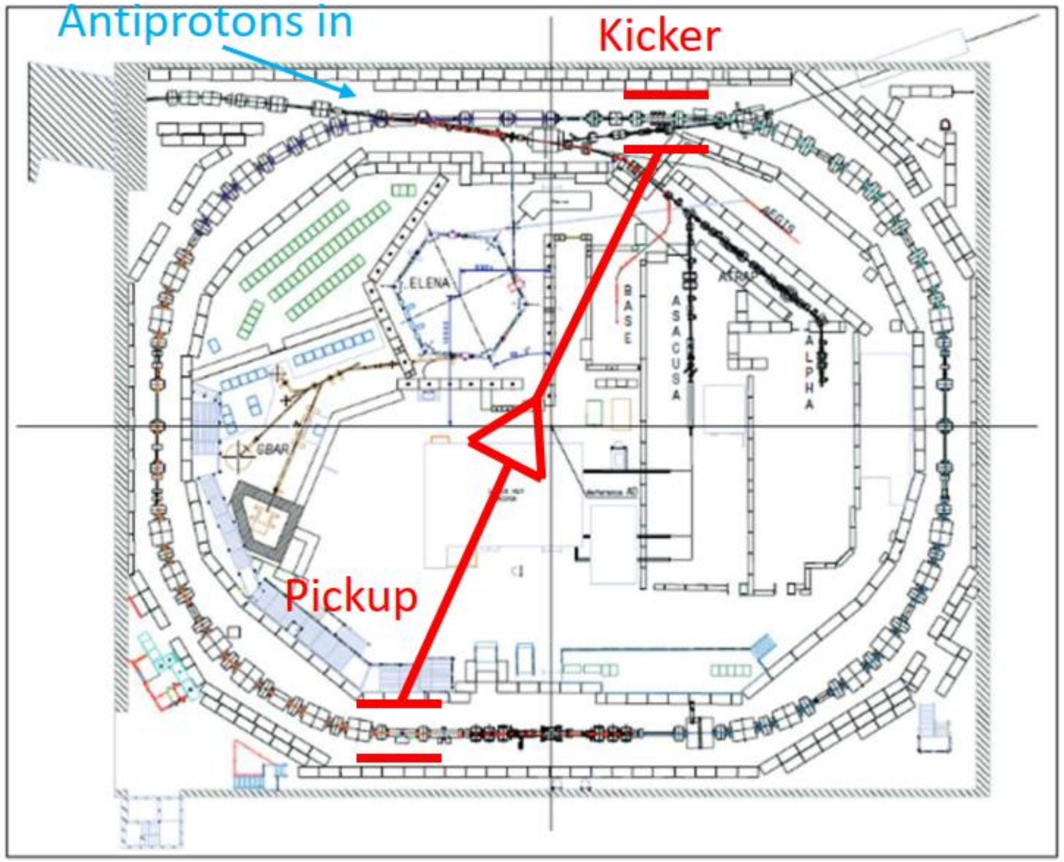
Cools momentum spread from $\frac{\Delta p}{p} = 6\%$ to $\frac{\Delta p}{p} = 0.01\%$

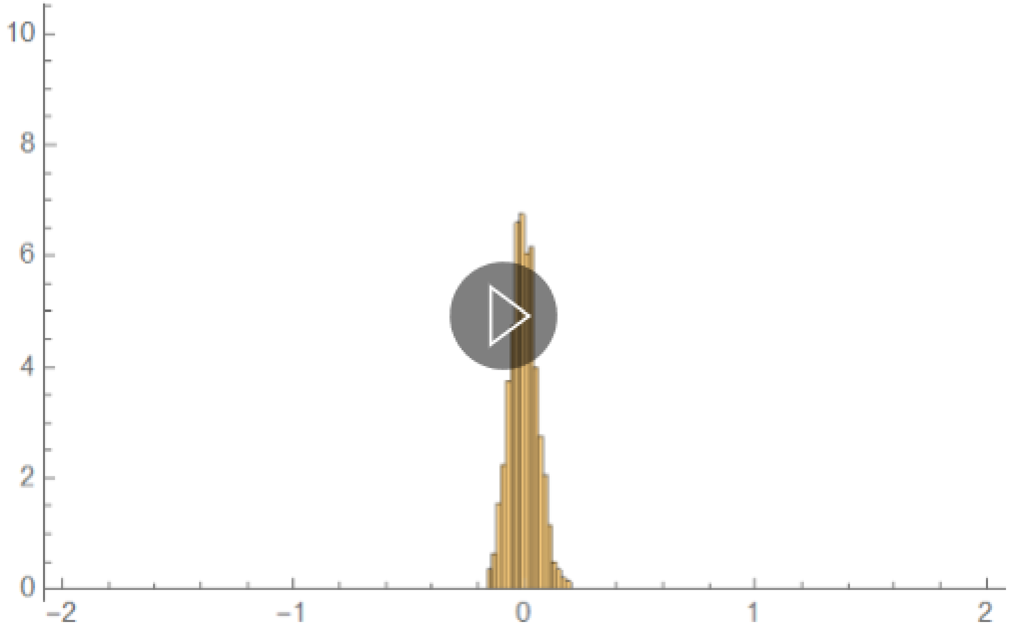
Extra Low ENergy Antiproton (ELENA) ring
and its Transfer Lines, CERN design report (2014)
P. Belochitskii, T. Eriksson, and S. Maury, Nucl. Instrum. Meth. Phys. Res. A **214** (2004)

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

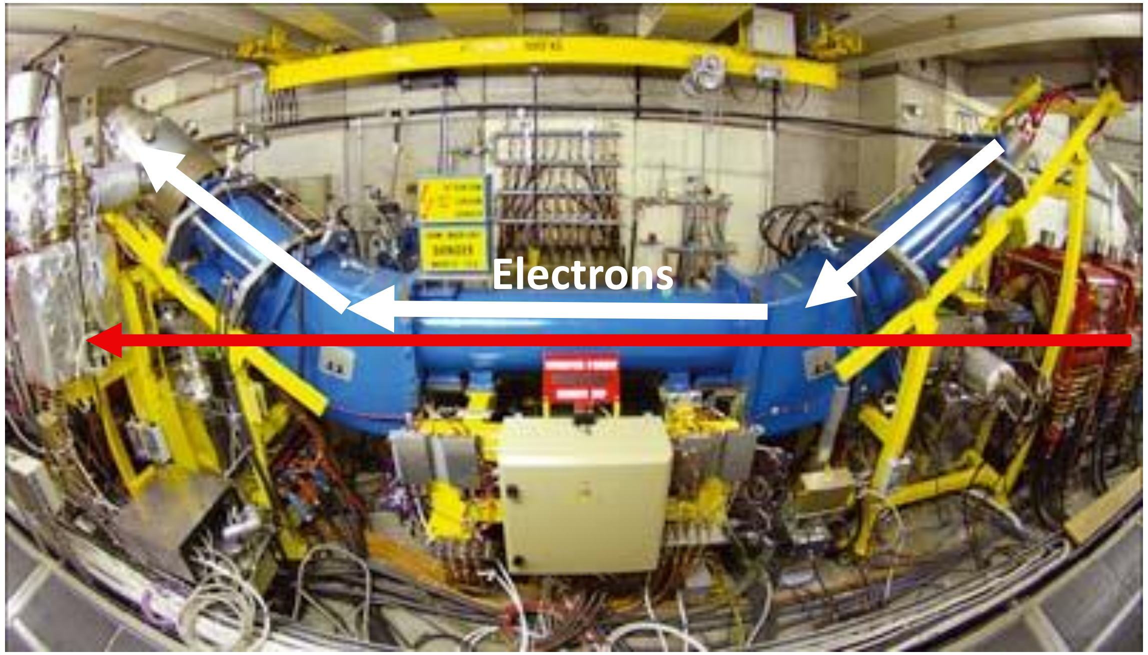




2 stages of stochastic cooling reduces momentum spread (4σ) from 1%->0.1%->0.015%

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

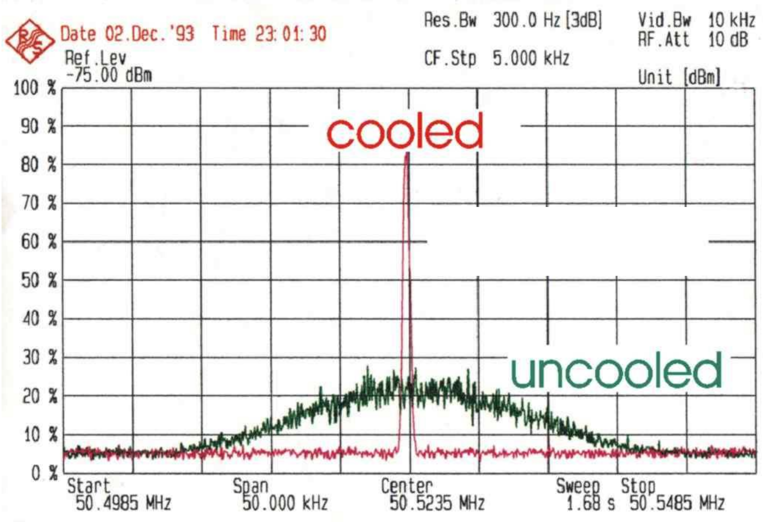
Electron cooling



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

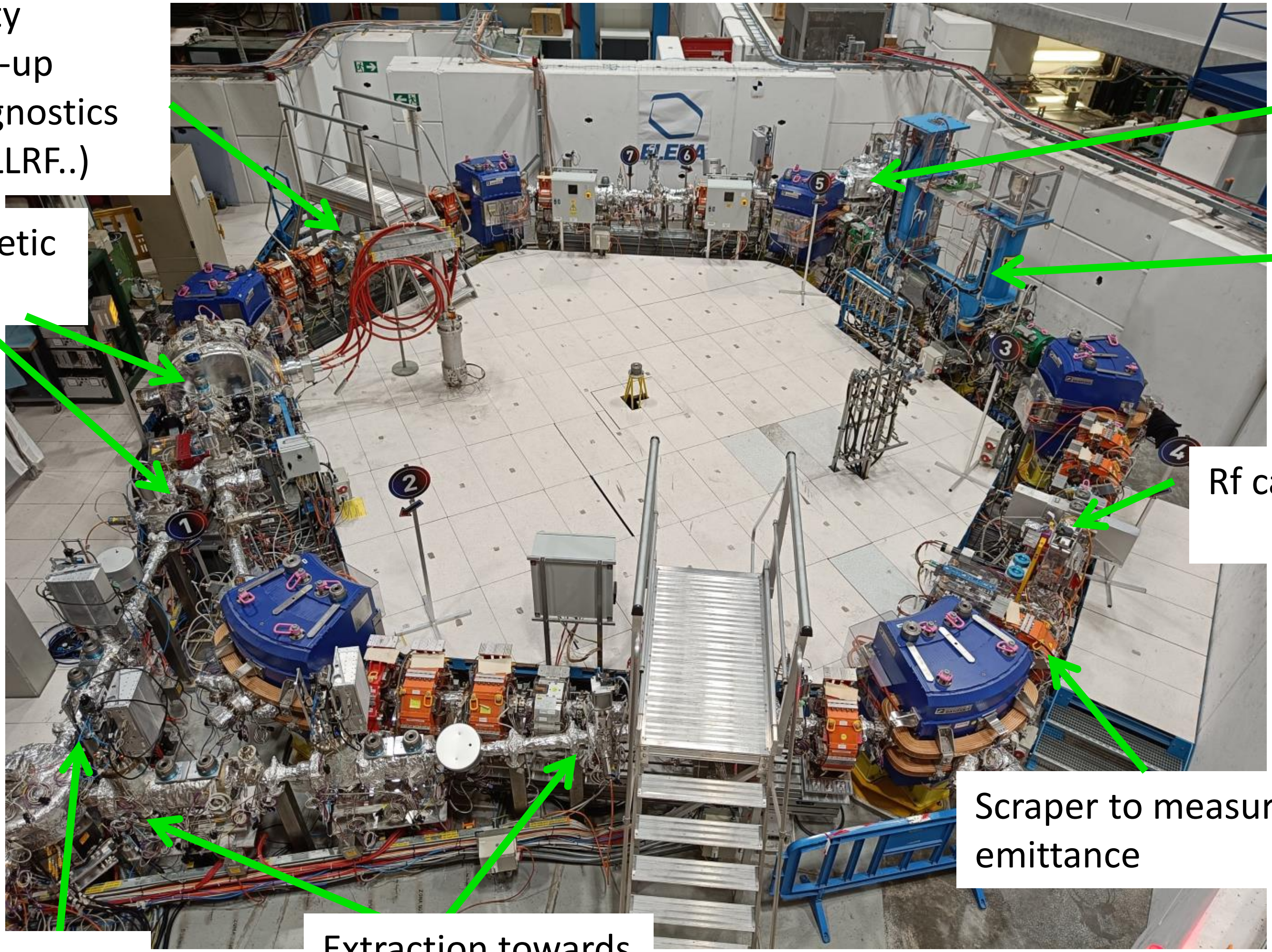
Momentum spread in 2 stages reduced (4σ) from 0.015%->0.01%

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

ELENA: The Extremely Low Energy Antiproton facility

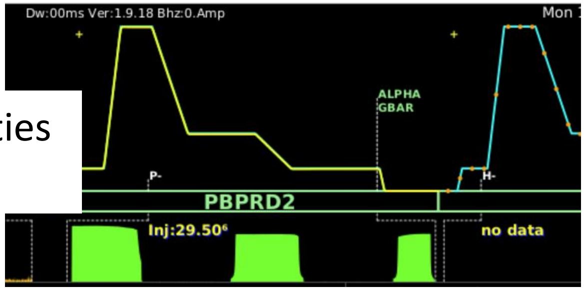
High sensitivity magnetic Pick-up (Schottky diagnostics for intensity, LLRF..)

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?

<u>In 2018</u>
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

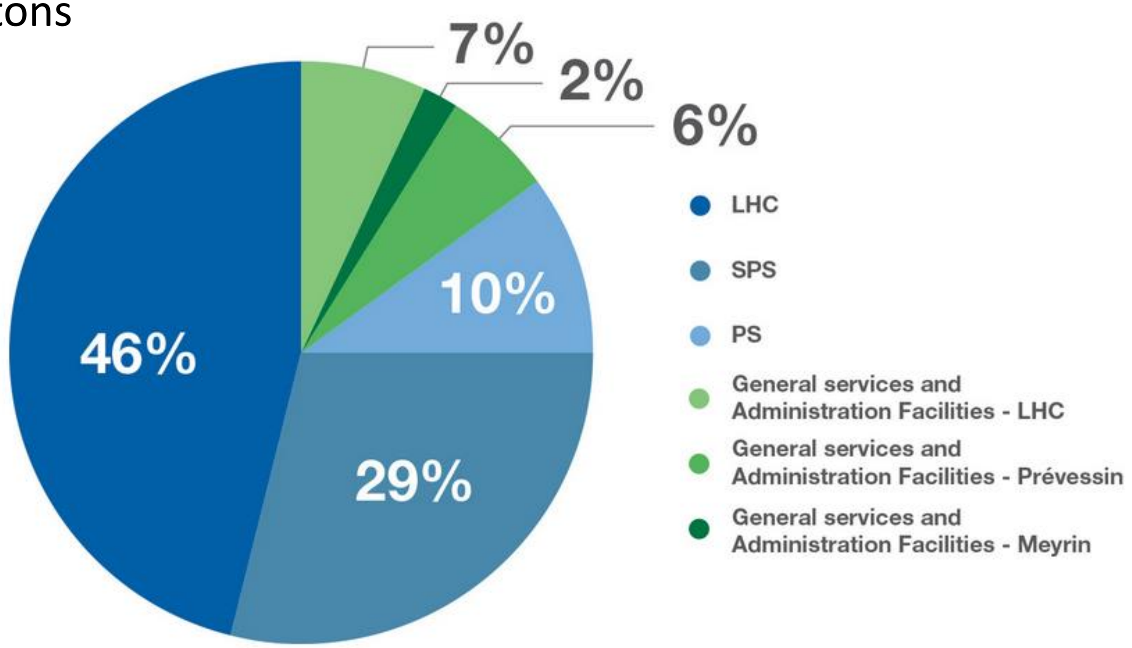
~10 trillion antiprotons produced per year ~12 picograms

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

- Not including people to operate the machine!

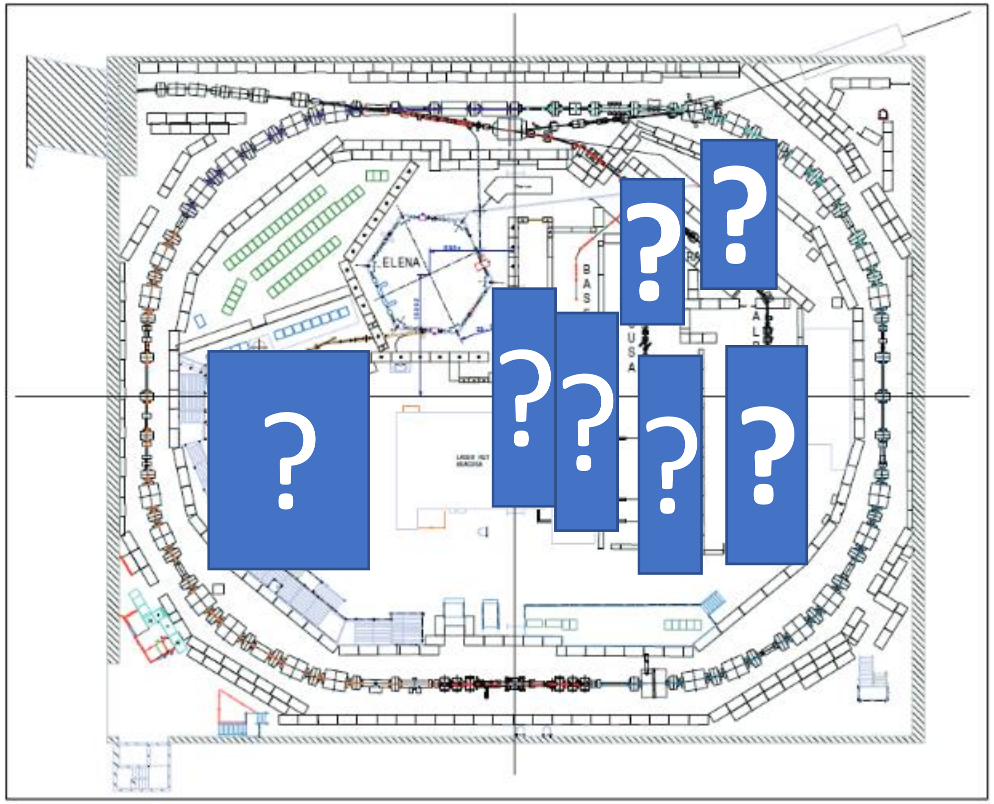
Not a cheap way to make lots of antimatter

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