Anti-matter

Peter H. Garbincius – at Fermilab since 1976

home of world's *former* highest energy particle accelerator

first presented May 21, 2006

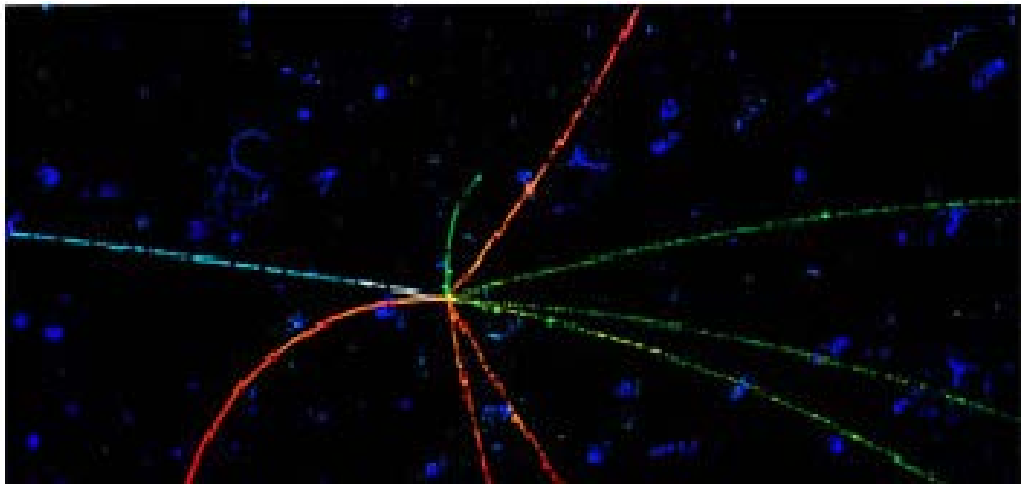
- **what's the (anti-)matter?**
- **history of anti-matter**
- **anti-matter = a useful tool**
- **continuing questions**
- ~~**Starship Enterprise**~~

8july2015 version

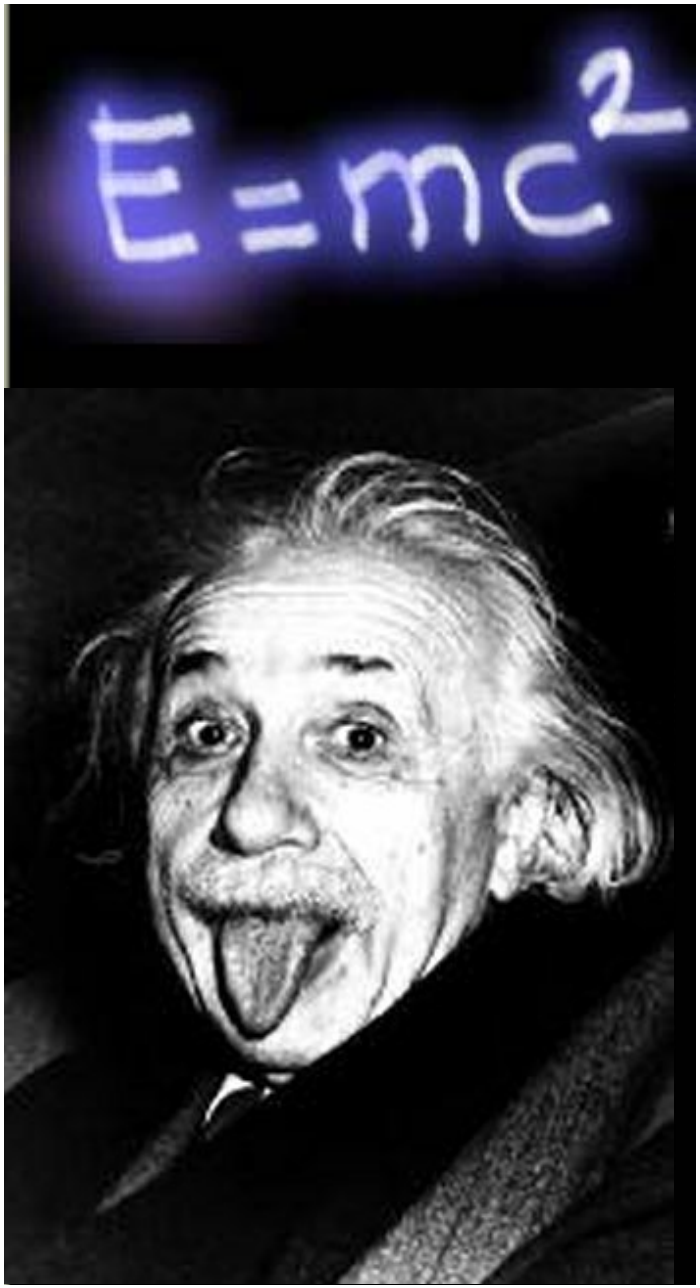
anti-matter

- a "***symmetric***" or mirror world of particles
- somewhat ***opposite*** to our world of matter
- when they meet, anti-matter and matter ***annihilate*** into other particles or pure energy!
- conservation laws (baryon #, lepton #, etc.) => produce matter and anti-matter ***in pairs***

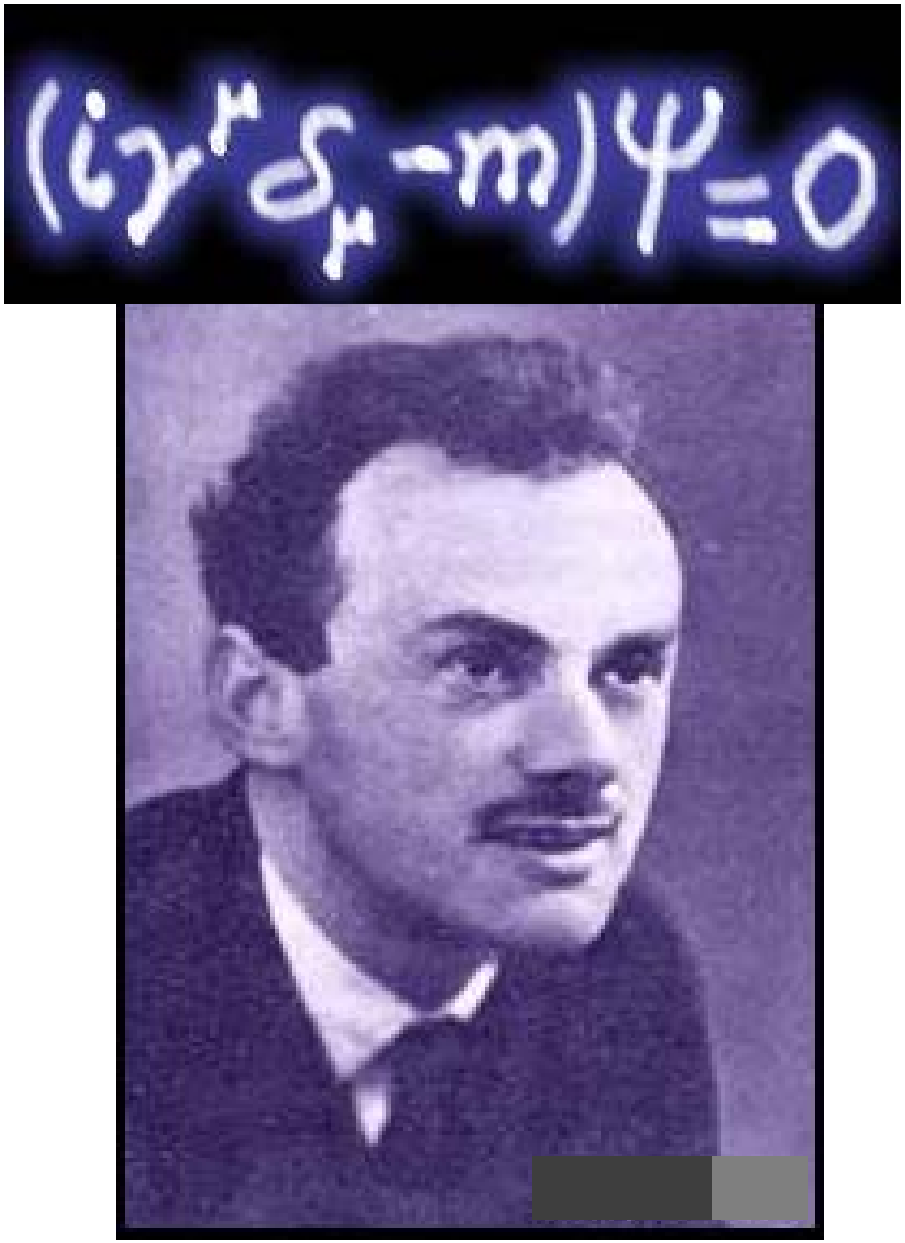
$\bar{p}$



$$\bar{p} + p \rightarrow 4\,\pi^{+} + 4\,\pi^{-}$$



1905



1928

First observation (1933) of anti-matter positrons (positive electrons) e^+

Carl David Anderson
1936 Nobel Prize

Phys. Rev. 43, 491 (1933)

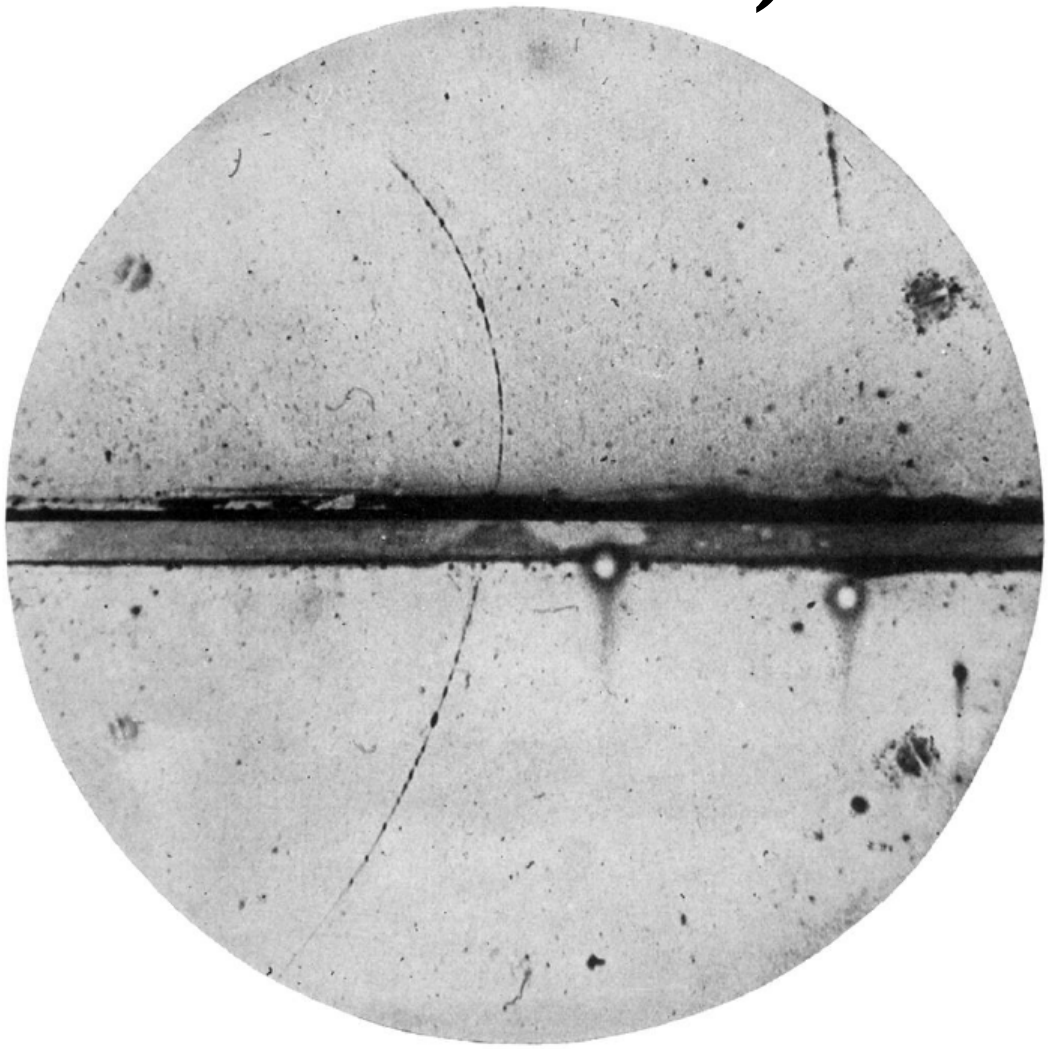


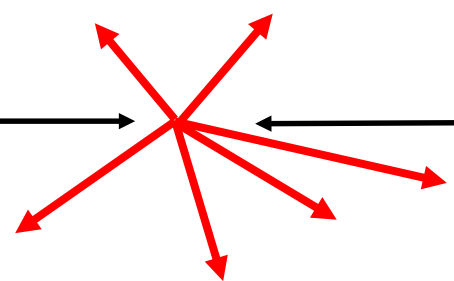
FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

Energy

$$E = Mc^2$$

protons		*anti-protons*
+1	electric charge	-1
938 MeV/c^2	mass	938 MeV/c^2
+1	baryon number	-1

annihilation



Discovery of the antiproton - 1955

$p + \mathrm{Cu} \rightarrow$

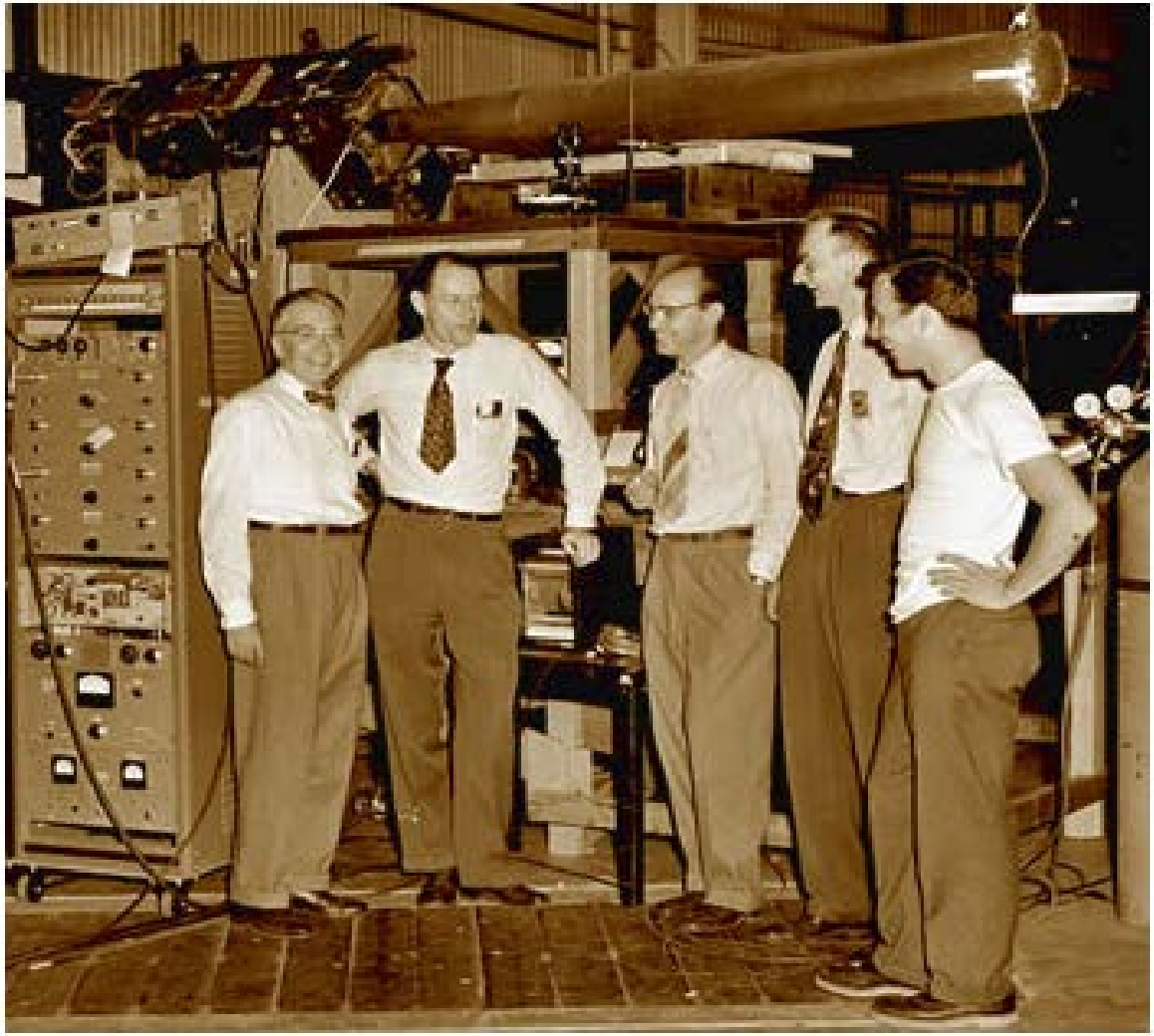
$p + \mathrm{Cu} + p + \bar{p}$

Have to produce p & $\bar{p}$ in pairs!

Bevatron @ Berkeley

***key*: at a given momentum**

$\bar{p}$ *slower* than π^-

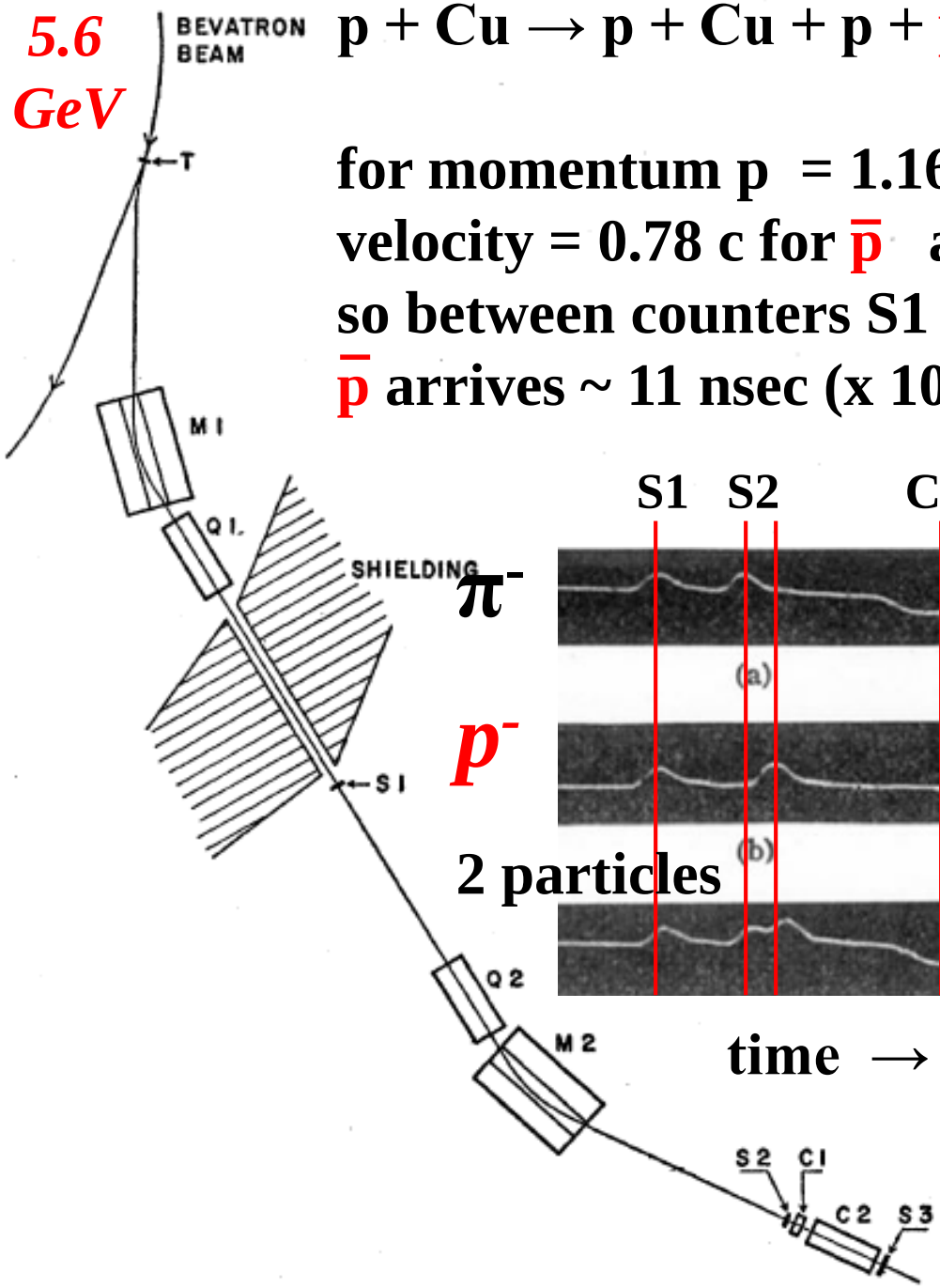


From left, Emilio Segrè, Clyde Wiegand, Edward Lofgren, Owen Chamberlain, and Thomas Ypsilantis, members of the team that discovered the antiproton

5.6 GeV

$p + Cu \rightarrow p + Cu + p + \bar{p}$ (1.16 GeV) & many more π^-

for momentum p = 1.16 GeV = mass * γ * velocity
velocity = 0.78 c for $\bar{p}$ and 0.99 c for π^-
so between counters S1 and S2 (separated by 40 feet)
$\bar{p}$ arrives ~ 11 nsec (x 10^{-9}) second later than π^-



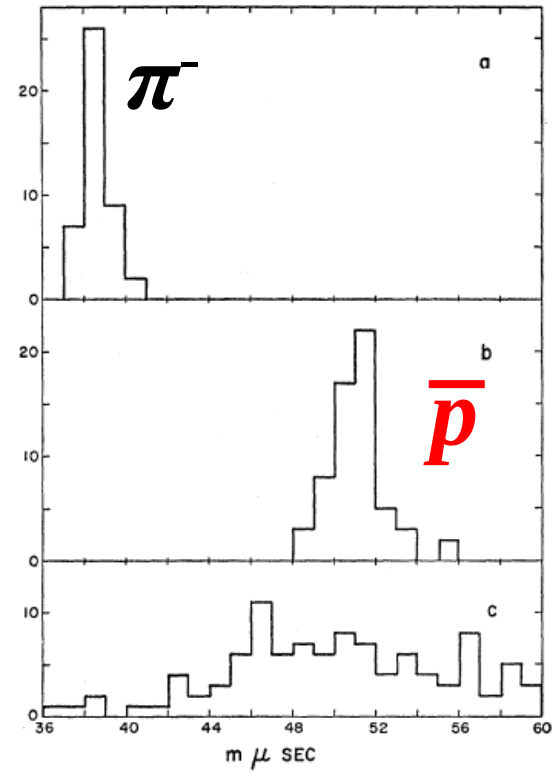


FIG. 3. (a) Histogram of meson flight times used for calibration. (b) Histogram of antiproton flight times. (c) Apparent flight times of a representative group of accidental coincidences. Times of flight are in units of 10^{-9} sec. The ordinates show the number of events in each 10^{-10}-sec intervals.

What is the universe made of, and how does it work?

What is this made of, Daddy?

What's inside of that?

What's that made of?

What inside of that?

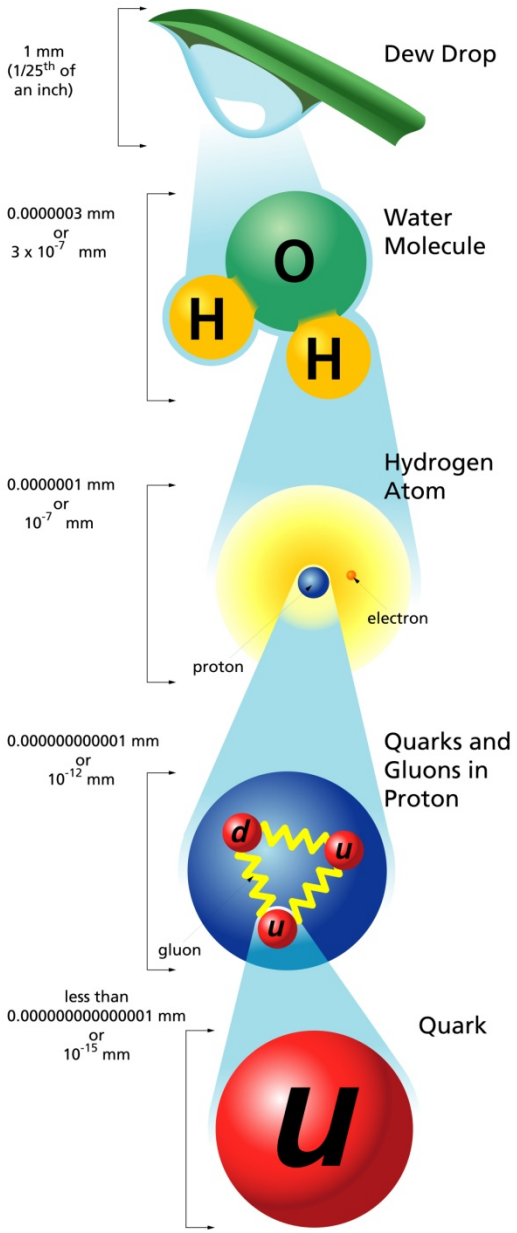
. . . .

Questions of

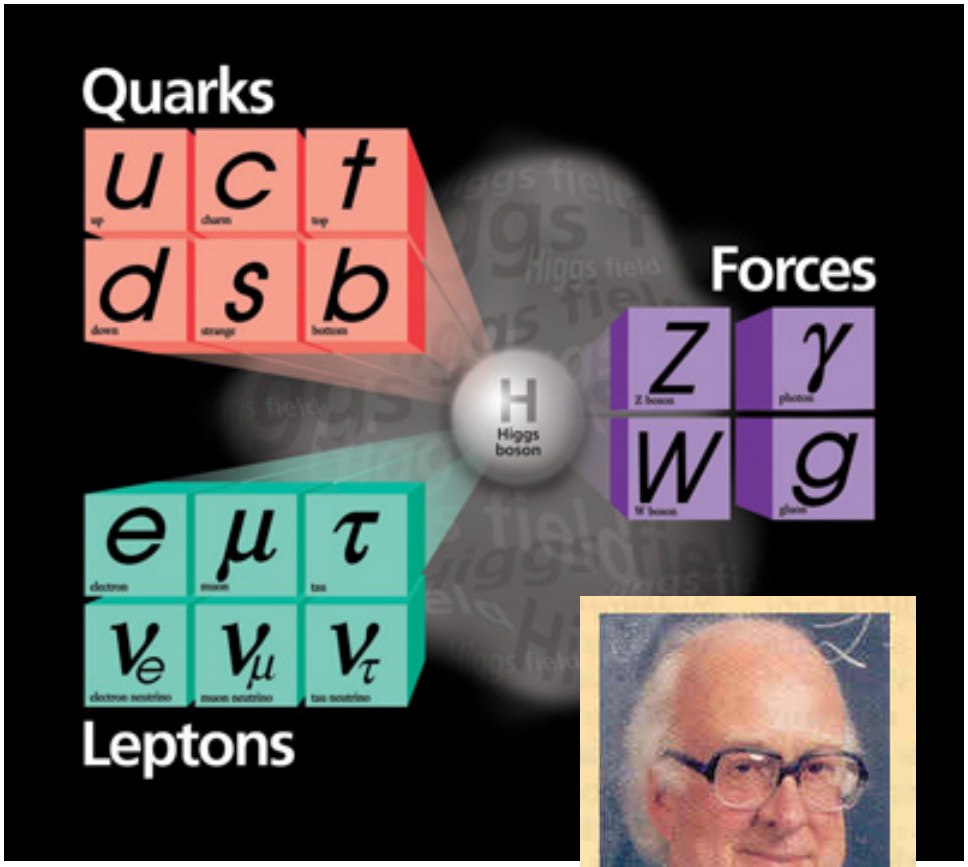
little children →

ancient Greeks (atoms) →

today's physicists



Our "*Periodic Table*"



Quarks, Leptons, & Forces

b, t, ν_τ discovered at FNAL

Electromagnetism
Strong Nuclear Force
Weak Nuclear Force
(radioactive decay)
Gravity is too weak for us

fundamental particles
no size – without parts
can't break them apart
(at least with today's accelerators)

"In the beginning…"

~14 billion years ago, at the Big-Bang

energy **→ equal amounts of matter & anti-matter**

the early universe was completely *symmetric!*

somehow that symmetry was lost…*how?*

We look at the universe and we see only matter,

well, maybe a little bit of anti-matter produced

in well-understood interactions….for example,

in cosmic ray interactions,

γ-rays hitting interstellar hydrogen gas, etc.

So what's the matter with the anti-matter?

If you want anti-matter, you have to *produce* it!

The general scheme for doing Elementary Particle Physics

Accelerators give protons lots of energy to make beams of antiprotons, neutrinos, *etc*.

Collide these beams with protons/neutrons to make interesting "new particles" $E=mc^2$

Study their interactions, properties, & decays with large detectors

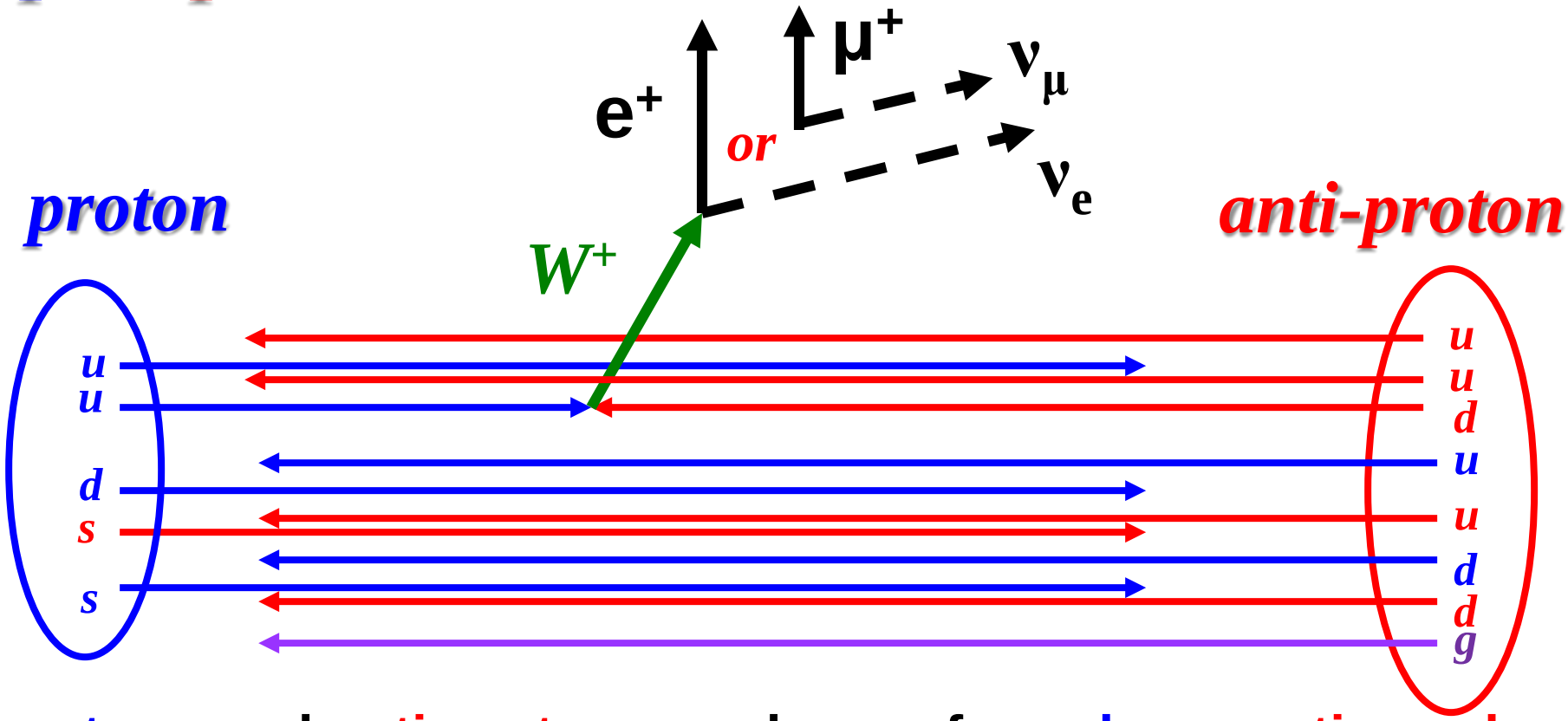
Why do we want *anti-protons* at Fermilab?

- **Interesting in their own right, we study their properties and interactions, are they the same as protons (but opposite Q, B, etc.)? quarks in proton = *anti-quarks* in *anti-proton***
- **As a source of high energy *anti-quarks* some interactions just happen via q-$\bar{q}$**
- **Only need *one accelerator ring* (engineering) accelerate & collide protons & anti-protons in the same ring…**

  ***but* need special pbar source,**

  but that's a big but…

$$p + \bar{p} \rightarrow W^+ + X \quad or \quad u + \bar{d} \rightarrow W^+$$



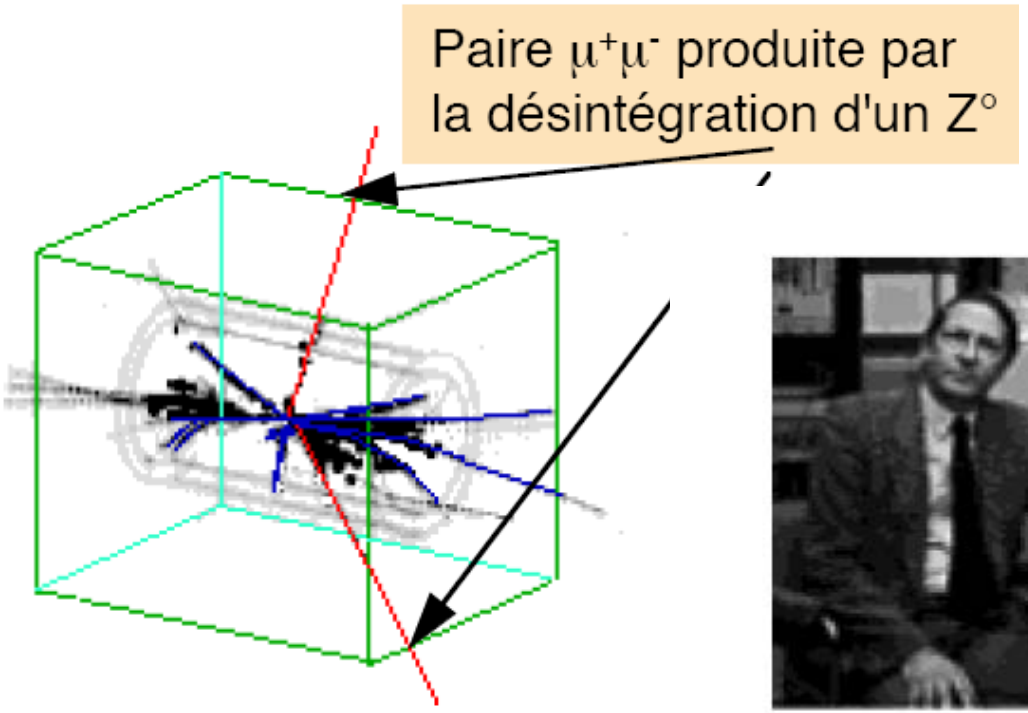
protons and anti-protons are bags of quarks or anti-quarks (& quark - anti-quark pairs) & *gluons (STONG force carrier)*

we study the interactions of these smaller constituents *inside* the original beam particles

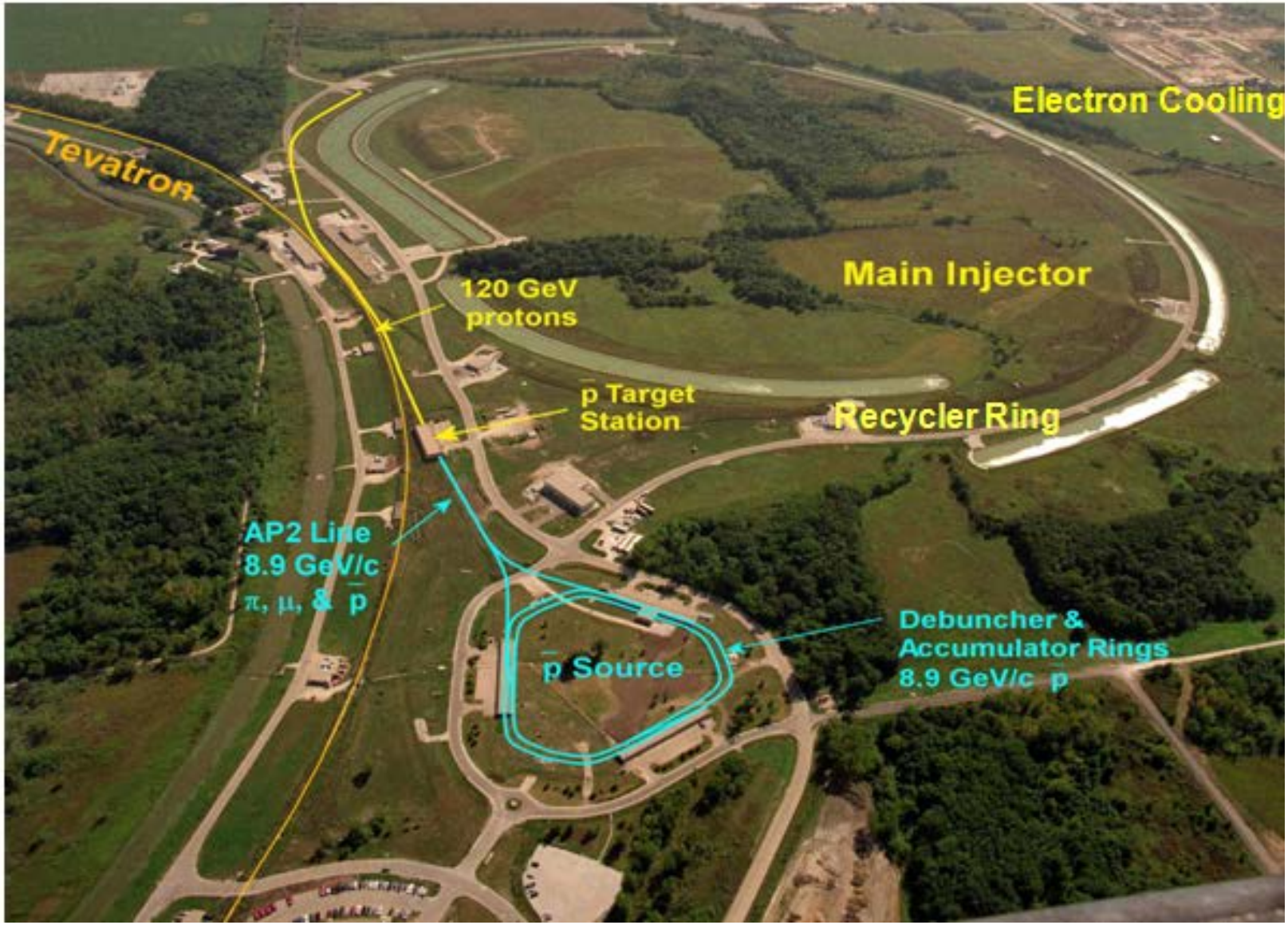
$p + \bar{p} \rightarrow W^{\pm}$ and Z^0 at CERN 1983

Simon Van der Meer: stochastic cooling of antiprotons

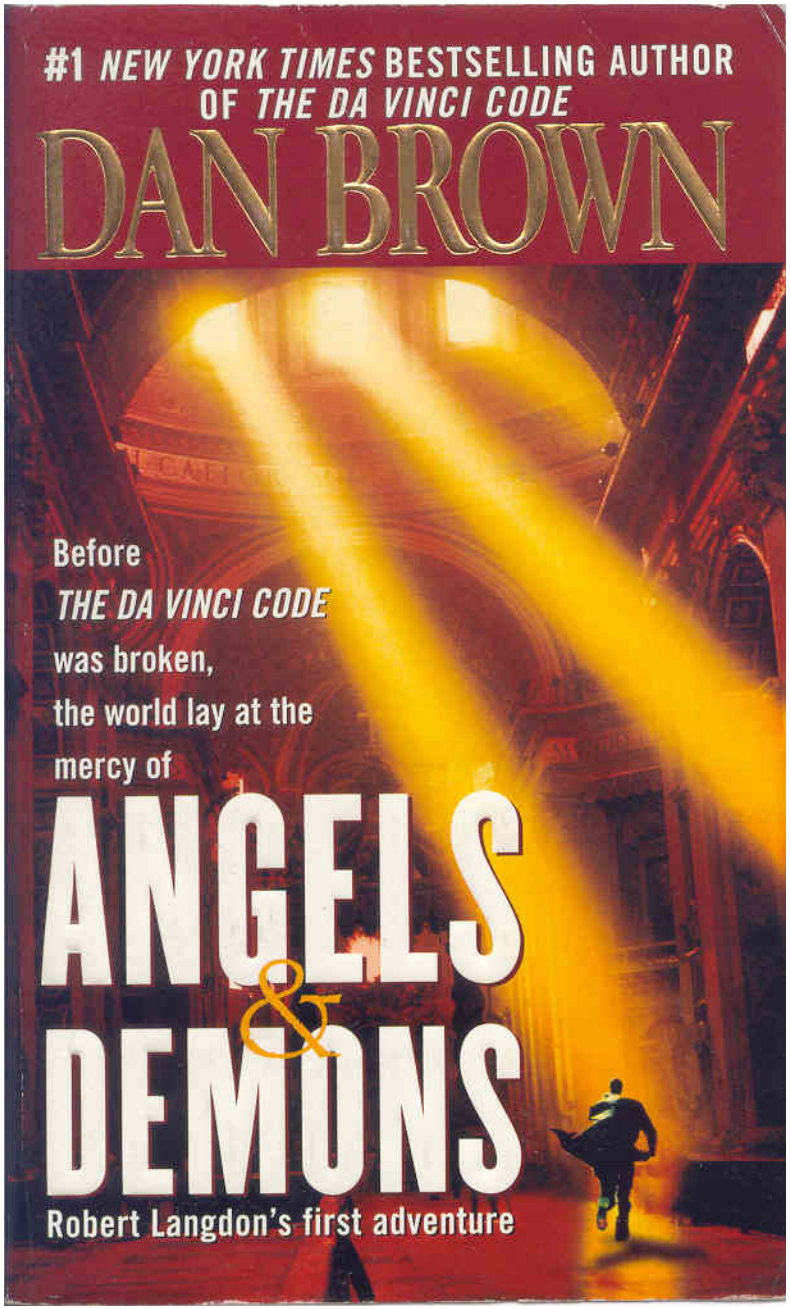
Carlo Rubbia: led experiment that discovered $W^{\pm}$ & Z^0



Simon Van der Meer et Carlo Rubbia



store only ~1 anti-proton per 10^6 p



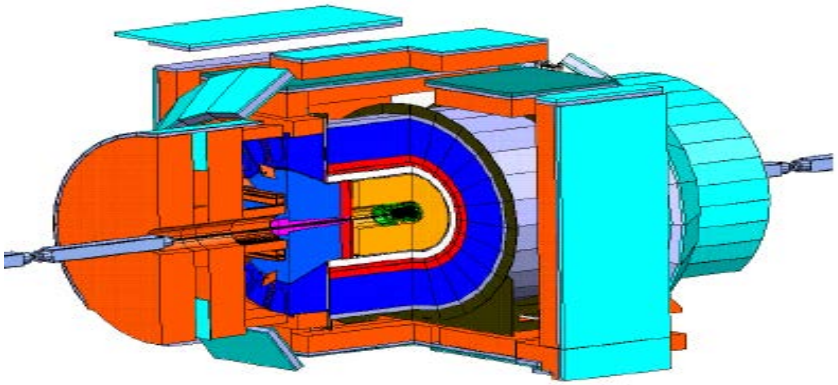
No, I'm not doing a book or movie review!

Only problem with story is the *economics* of producing anti-matter, it's just too expensive!

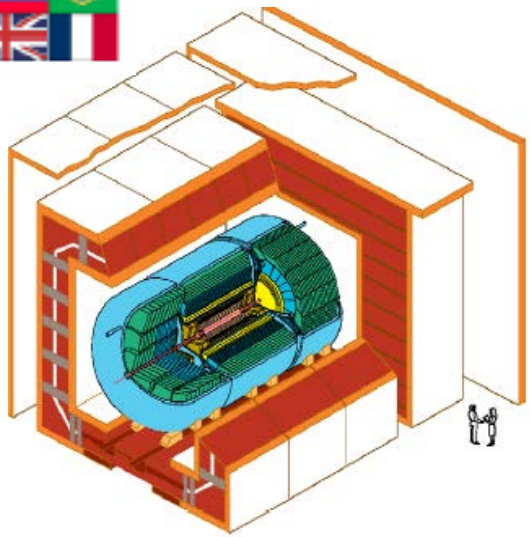
In 20 years at Fermilab, we've produced lots of antiprotons & science, but only ~ 15 nano-grams, or 15 billionths of gram

= 2.5 gram

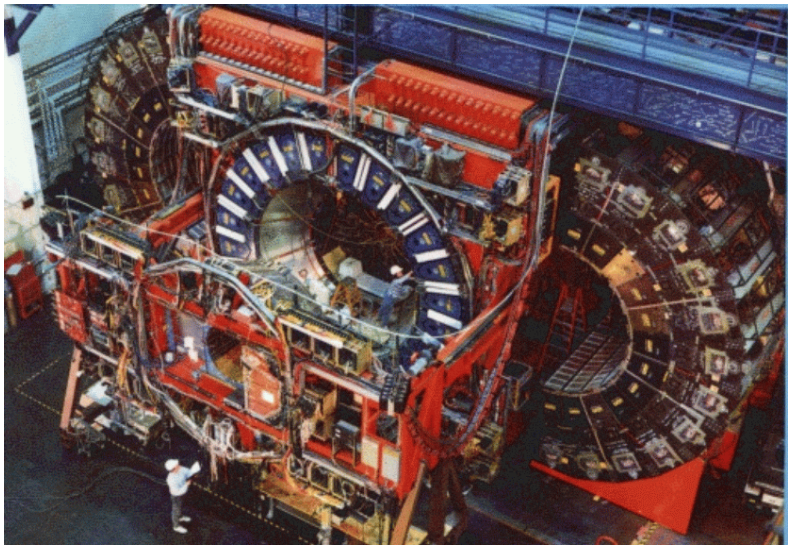
CDF and D-Zero Experiments

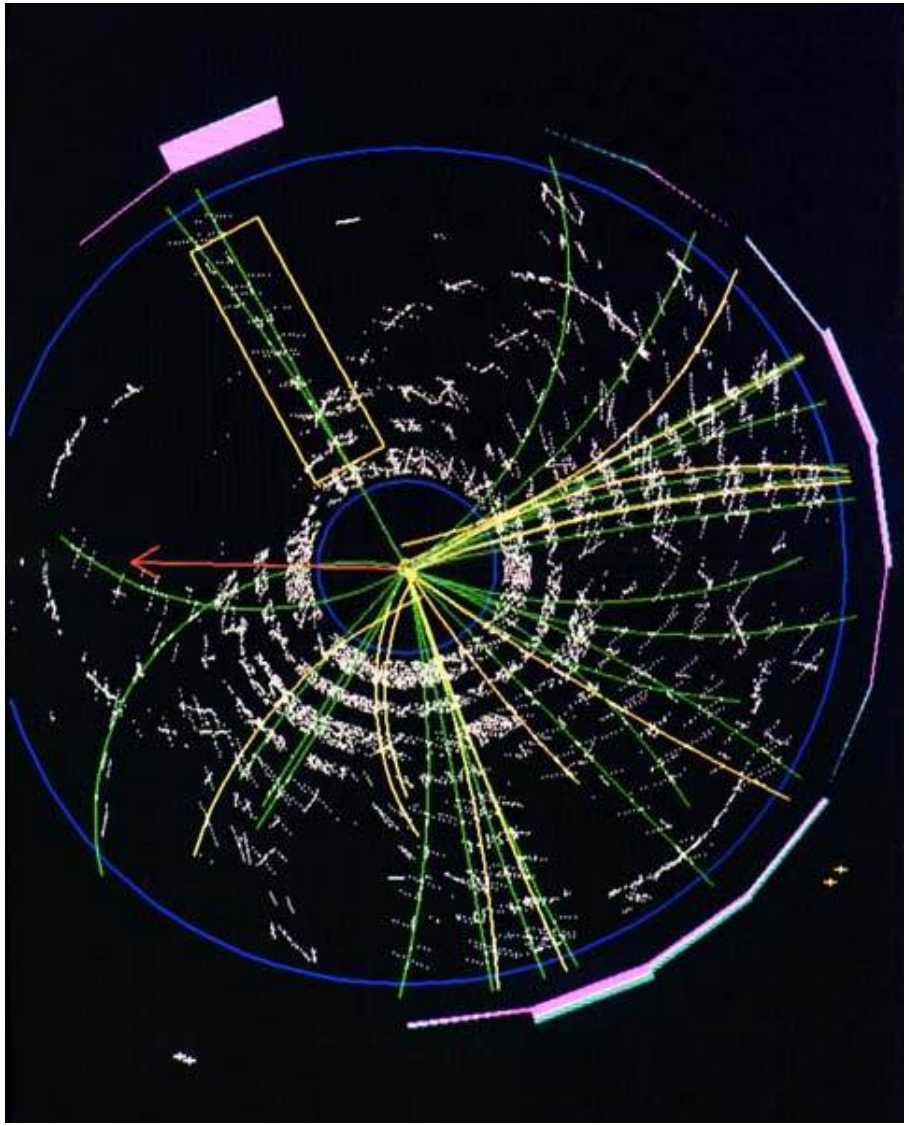


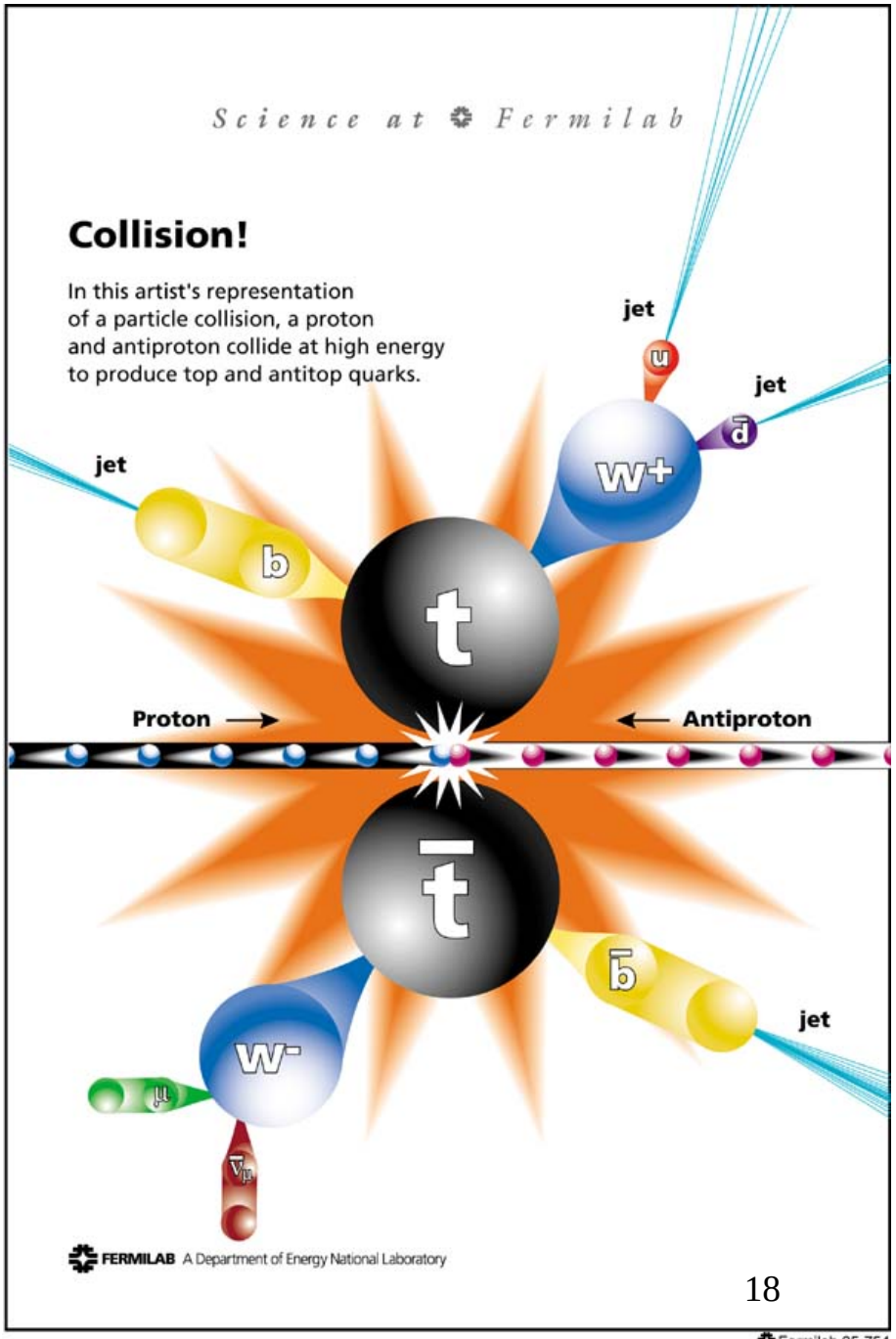
CDF Detector



DØ Detector






Science at Fermilab
Collision!
In this artist's representation of a particle collision, a proton and antiproton collide at high energy to produce top and antitop quarks.
jet
jet
jet
jet
u
d̄
W+
b
t
Proton
Antiproton
t̄
b̄
W−
μ
ν̄μ
FERMILAB A Department of Energy National Laboratory
Fermilab 95-754

Fermilab discontinued *anti-proton* physics on September 30, 2011

Why? **CERN LHC proton-proton collider coming on at 7 times the Fermilab energy**

Energy Frontier → *Intensity Frontier*

***higher beam power* (at lower energy) for neutrino and muon physics**

Upgrade and Reuse:

Cockcroft-Walton => RFQ

Booster => more RF cavities => more protons

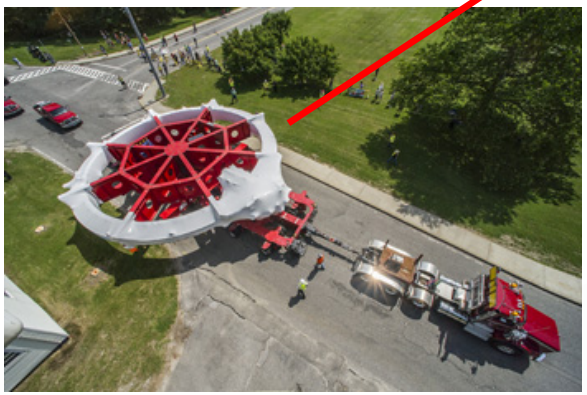
Recycler => injector ring for Main Injector

pbar Source => Muon Delivery Ring

preparations for *Muon g-2* & *Mu2e*

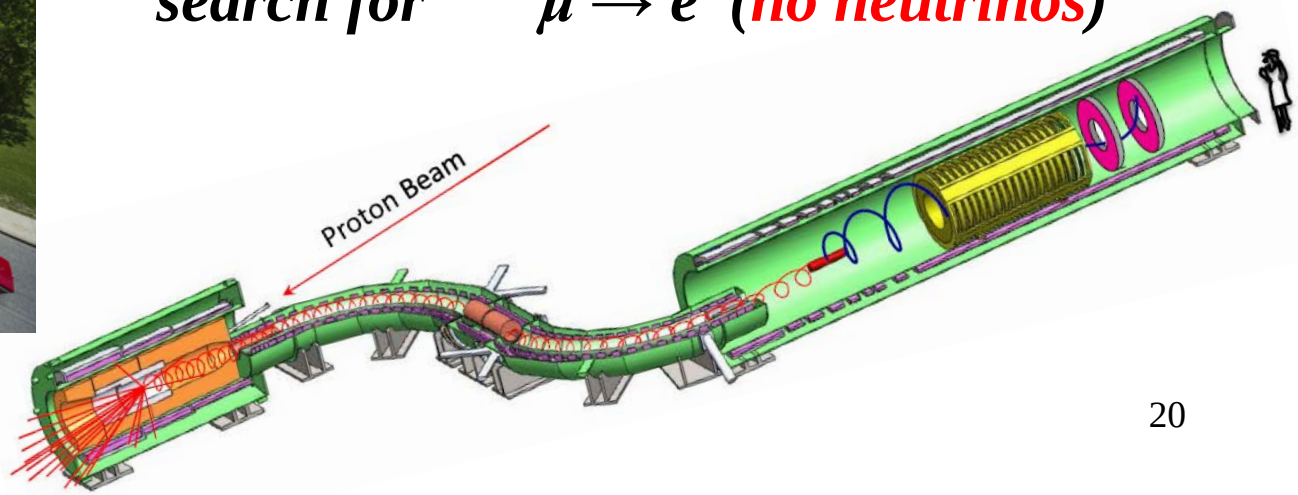
July 4, 2015

power testing



usually $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$

search for $\mu^- \rightarrow e^-$ (***no neutrinos***)



Some New and Continuing Puzzles!

What happened to the anti-matter produced in big bang?

CP violation: particle - anti-particle oscillations

$$K^0 \Leftrightarrow \text{anti-}K^0 \quad \text{and} \quad B^0 \Leftrightarrow \text{anti-}B^0$$

$$\tau(\text{particle}) \neq \tau(\text{anti-particle})$$

$$\text{Rate(particle => anti-particle)} \neq \text{Rate(antiparticle => particle)}$$

neutrinos always have left-handed spin

anti-neutrinos always have right-handed spin

Are neutrinos their own antiparticles? Double β decay

Does Antimatter Fall Up?

Using anti-matter in our daily lives!

Positron ***E*mission *T*omography** (***PET*** scan)

isotope F^{18} => fluorodeoxyglucose

1.87 hr $\hookrightarrow O^{18} + e^{+} + \nu_e$

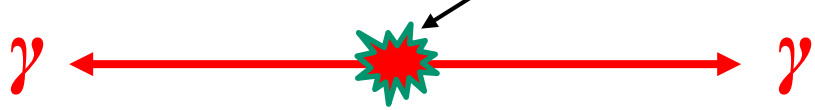
then $e^{+} + e^{-} \longrightarrow \gamma + \gamma$

momentum conservation:

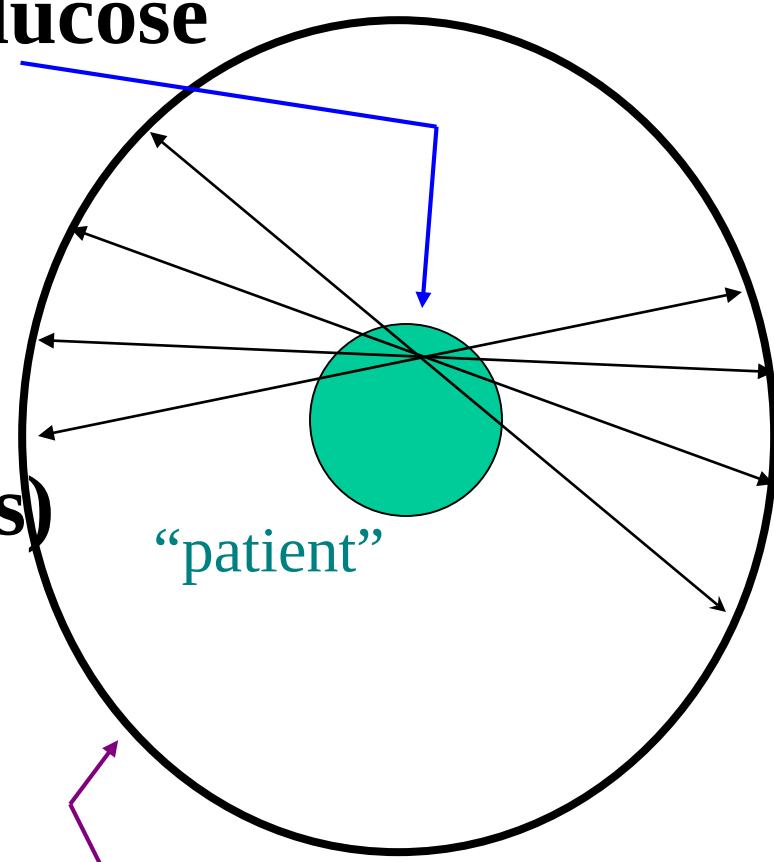
(remember from physics class)

the 2 γ-rays are back-to-back

co-linear ***annihilation***

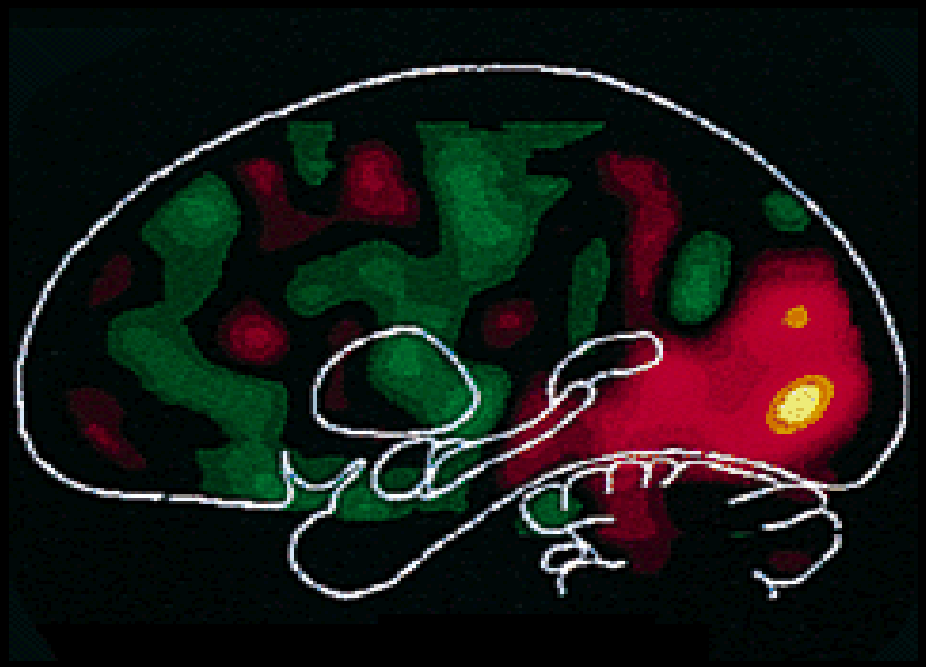


$$2\,E_\gamma = 2\,m_e c^2 = 2*(0.511\text{MeV})$$

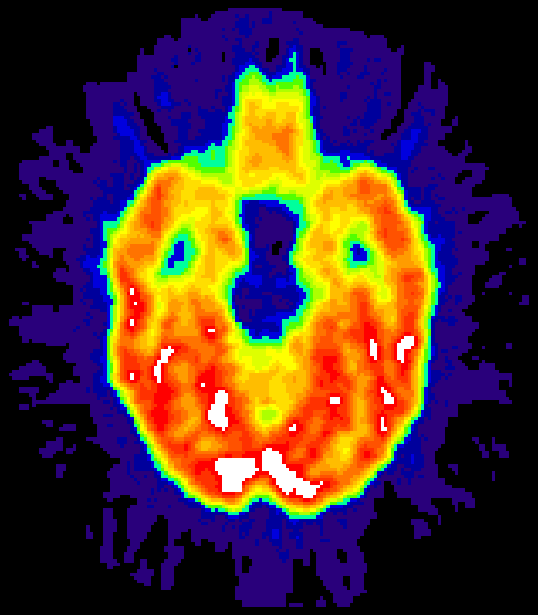


ring of γ-ray detectors
images radioactive sugar

examples of PET scans



PET scan of a brain "in action": the person is ***seeing*** *words*



Pet scan of the brain of a physicist

thinking about…..physics

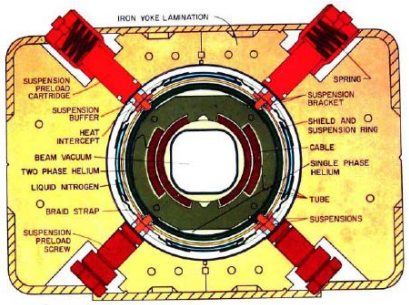
things to remember about antimatter

- Every ***particle*** has a corresponding ***anti-particle***
- e^+ & ***anti-proton*** were theoretically predicted ***before*** their observation
- Tools for discovery: $\bar{p}$-$p \rightarrow W^{\pm}, Z^0$, ***top quark***
  $e^+e^- \rightarrow \psi(c\bar{c})$, ***gluons***
- Precision studies: $e^+e^- \rightarrow Z^0, \Upsilon(b\bar{b}), B \Leftrightarrow \bar{B}$
- Lots of Nobel prizes
- Conservation Laws: electric charge (always), Baryon # (not absolutely), Lepton # (maybe not)
- Positron Emission Tomography (PET) is a useful medical diagnostic

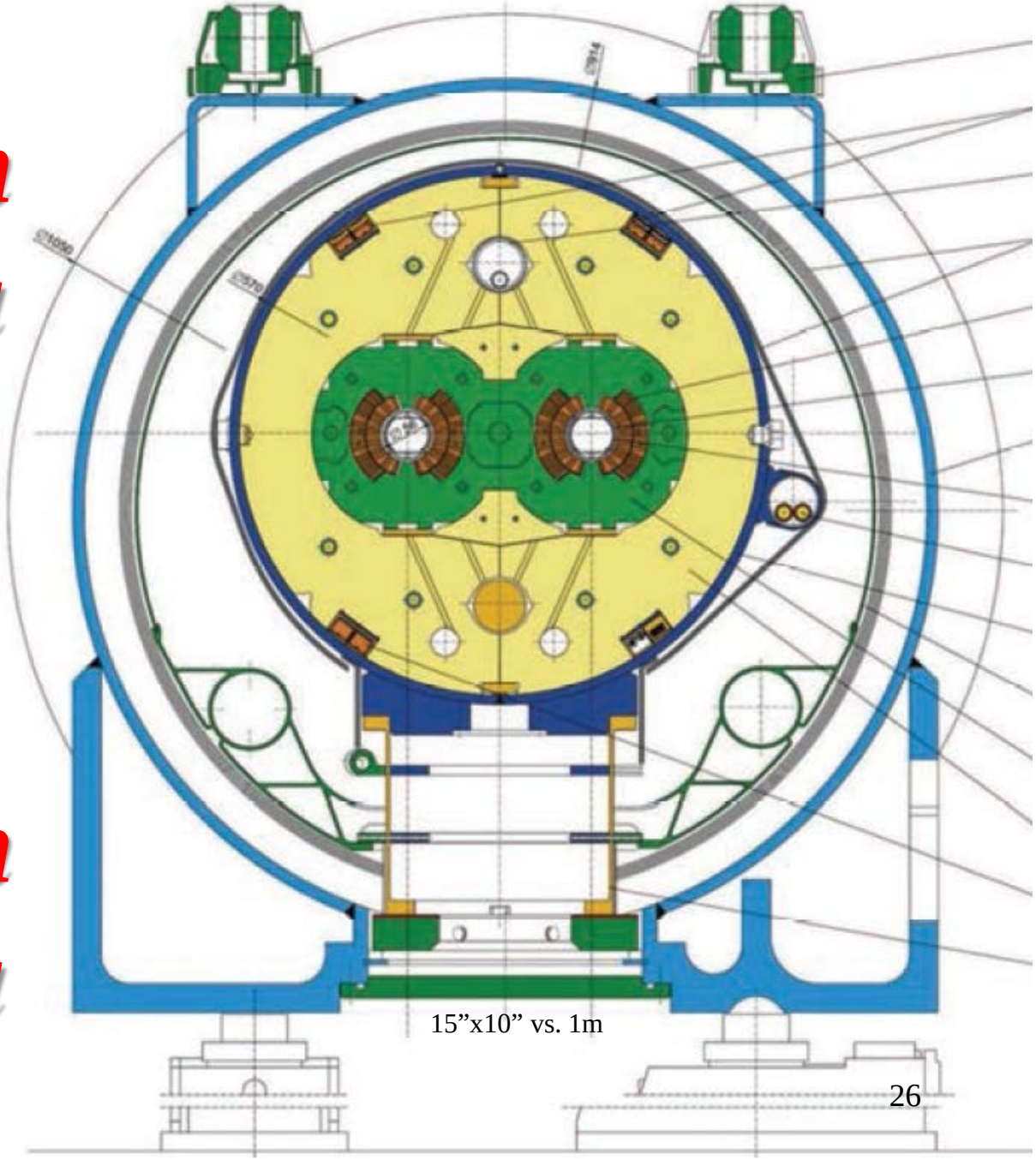
so, antimatter is
not only fun for physicists,
but also
has useful medical applications

End of Presentation

Tevatron
1 TeV/beam
@ 4.4 Tesla



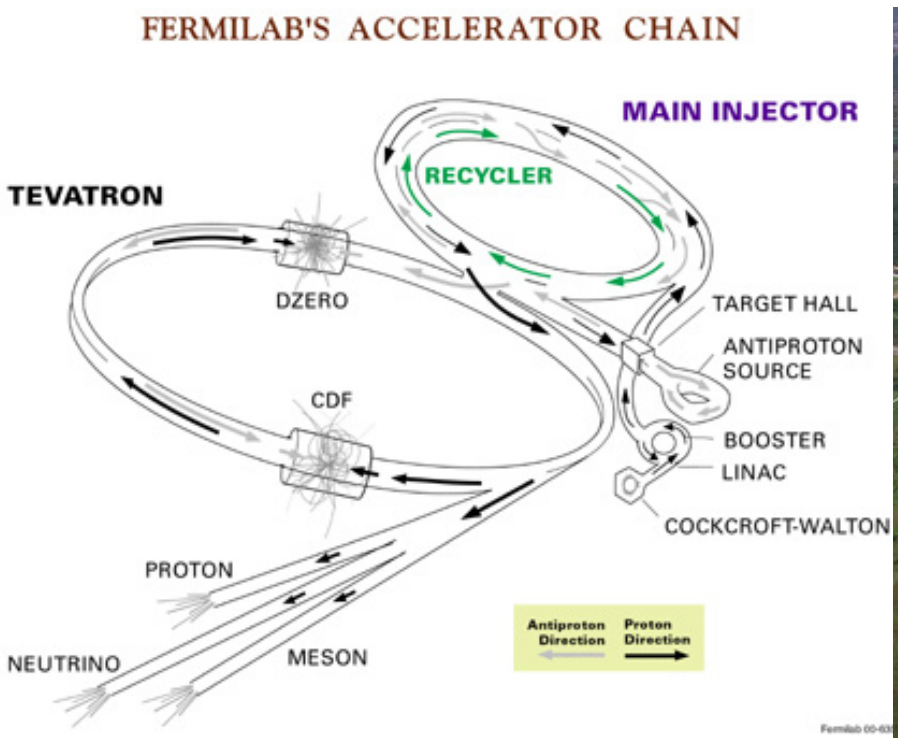
LHC
7 TeV/beam
@ 8.3 Tesla

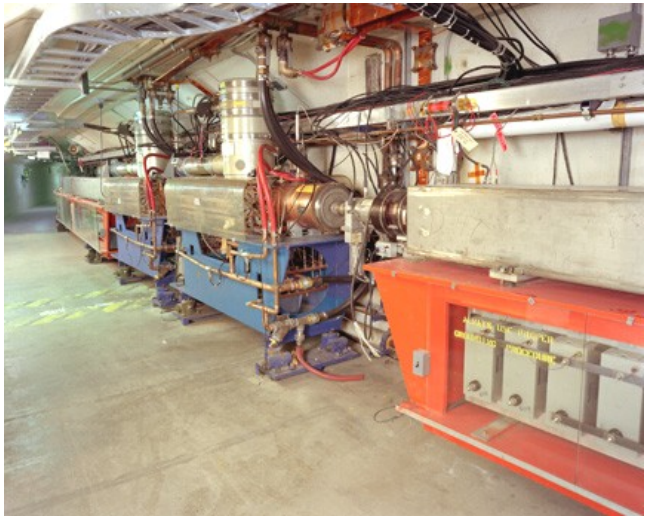


15”x10” vs. 1m

Fermilab Accelerator Complex

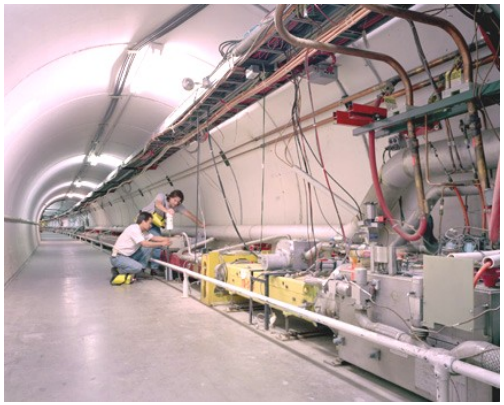
http://www-bd.fnal.gov/public/





Cockcroft-Walton 750 KeV **LINAC 400 MeV** **Booster 8 GeV**

velocity = 0 → ***0.04 c*** → ***0.71 c*** → ***0.994 c***

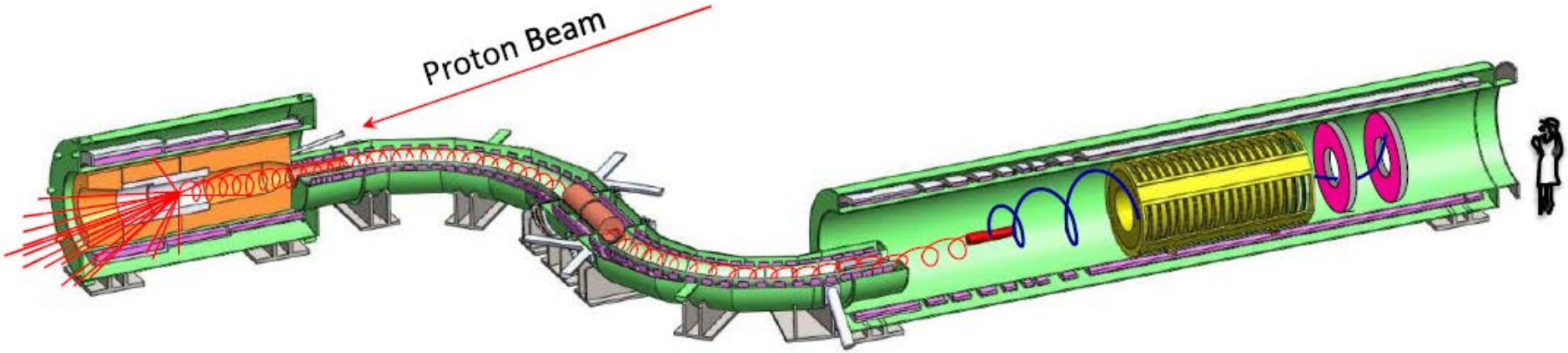


(Recycler 8 GeV)

Main Injector 150 GeV **Antiproton "Bottle"** **Tevatron 1000 GeV = 1 TeV**

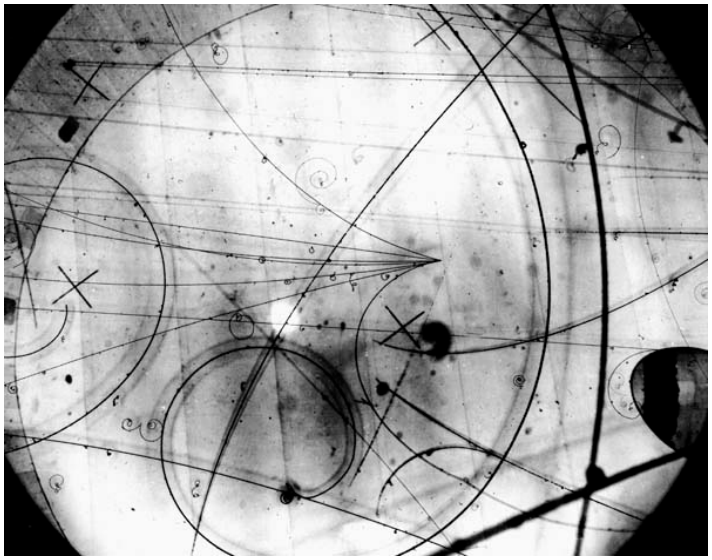
0.994 c → ***0.99998 c*** ***@ 8 GeV*** ***0.99998 c*** → ***0.9999995 c***

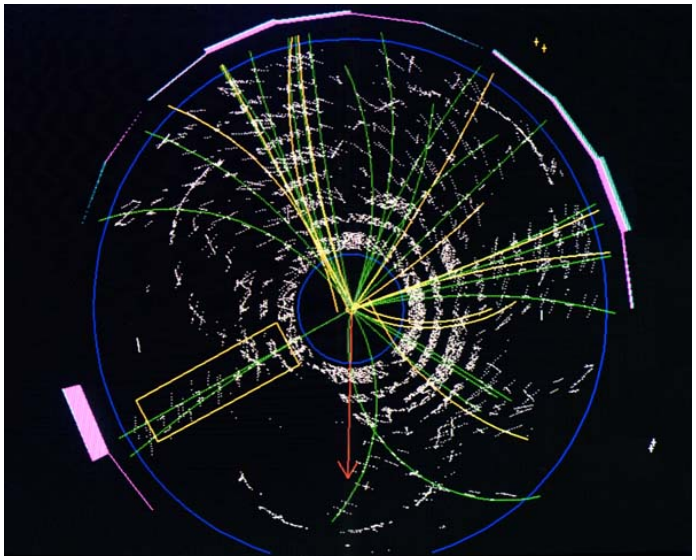
Mu2e Experiment



How do you “see” such tiny particles?

Q: How do you see the wind? **A: Indirectly**





tracks in optical bubble chamber & electronic detectors

tracks bending in magnetic-field (bend ~ 1/momentum)

calorimetry (# shower particles is proportional to energy)

decays: reconstruct mass of unseen parent particles

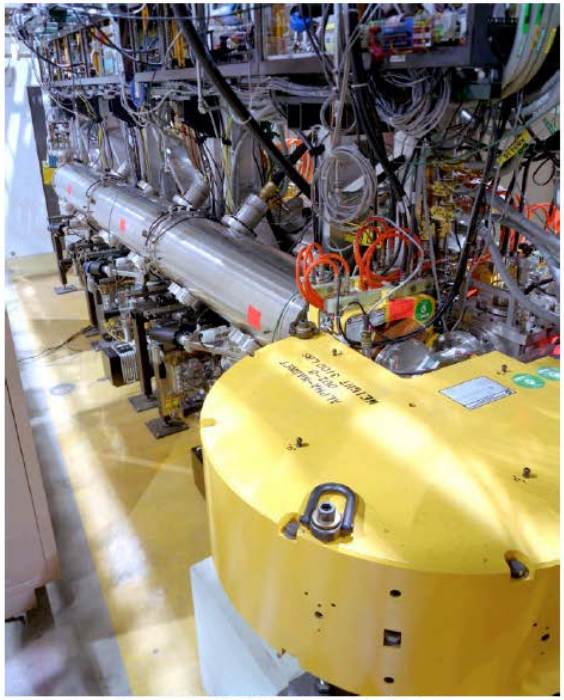
FAIR

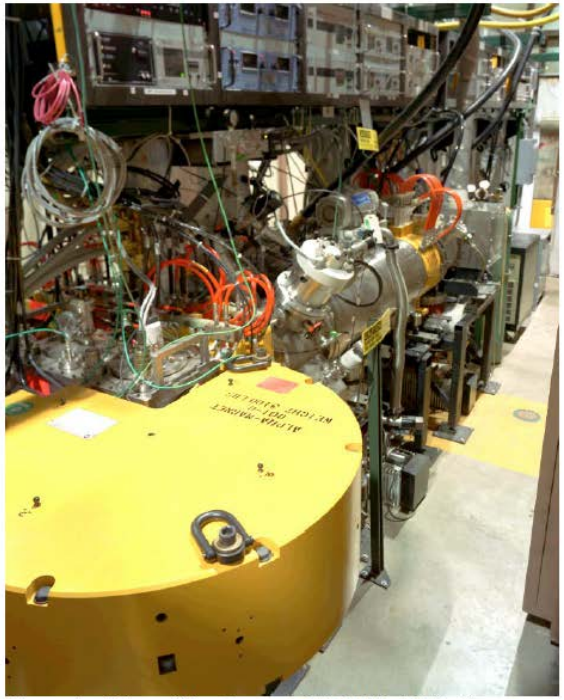
Facility for (low energy) ***A***ntiproton(s) and (heavy) ***I***on ***R***esearch

- Being built @ Darmstadt, Germany (~Frankfort)
- Heavy ions up to 1 GeV/nucleon (<< RHIC)
- Protons up to 29 GeV (AGS = 33, PS = 26)
- ***antiproton*** beams 1-15 GeV
- HESR will store ***antiprotons*** up to 14.5 GeV
  - compare to Fermilab pbar source at 8 GeV
  - ***PANDA*** exp – anti***P***roton ***AN***nihilation at ***DA***rmstadt
- Construction started in 2011
- First beam expected in 2018

- http://www.symmetrymagazine.org/article/april-2015/ten-things-you-might-not-know-about-antimatter

In 1997, Fermilab built an RFQ accelerator for ***PET*** isotope production for the Biomedical Research Foundation of NW Louisiana (Shreveport)





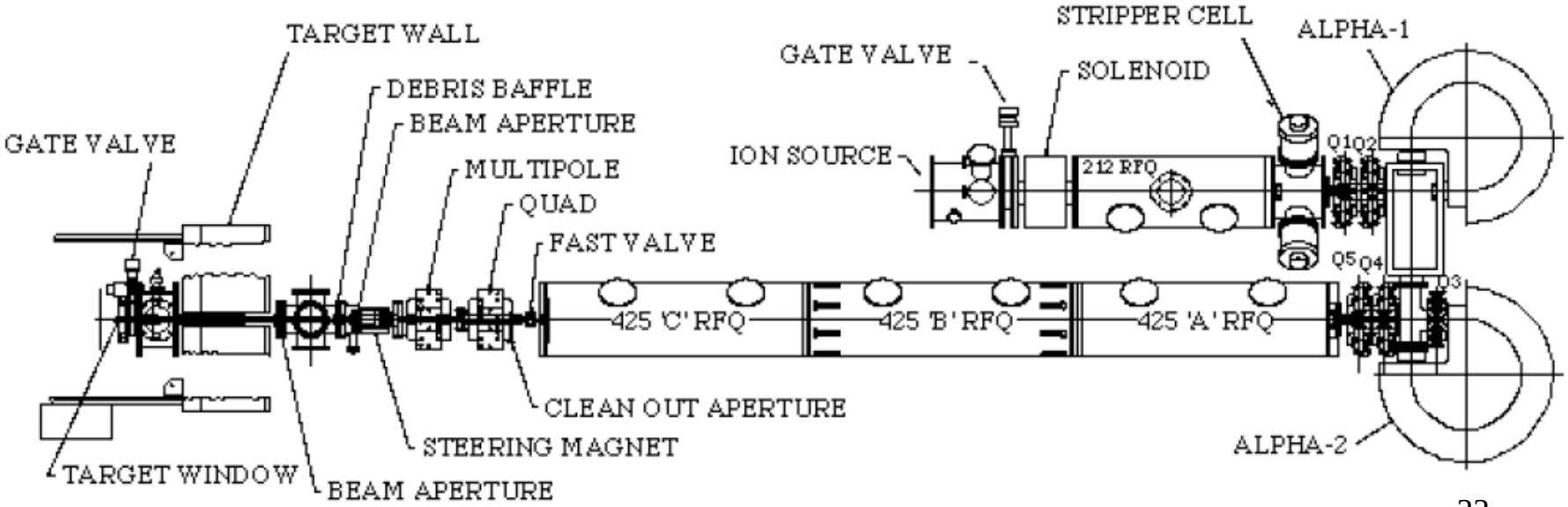


Figure 1. Layout of 10.5 MeV $3He^{++}$ PET accelerator.

FERMILAB-Conf-97/129-E

a 13 week accelerator shutdown started July 4 to:

install a new beamline to send 8-GeV protons from the Recycler to the Muon Campus;

remove old Main Ring components to allow more efficient beam delivery to the Muon Campus;

add radio-frequency accelerating cavities to the Booster;

upgrade the Recycler vacuum for future high-intensity running;

replace NuMI Horn 1;

install a laser notching system in the Linac;

and perform needed maintenance.

The accelerator complex will come back online by Oct. 5.

Neutrino Interactions

- ν's interact very weakly (the weak force!)
- total νp cross section (interaction probability)

  $\sigma(\nu p) = 6.7 \times 10^{-39}$ cm^2 at 1 GeV

  $\sigma(pp) = 2.2 \times 10^{-26}$ cm^2 (strong force)

  $\sigma(\gamma p) = 2 \times 10^{-28}$ cm^2 (E.M. force - photons)
- EM force/Gravitation $\approx 10^{36}$ between 2 protons
- only 650 out of 1 billion ν's interact before reaching Soudan (735 km earth)
- only 40 out of 1 trillion ν's interact in detector