Matter and Anti-Matter

What is the Matter with Them?

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QuarkNet Seminar

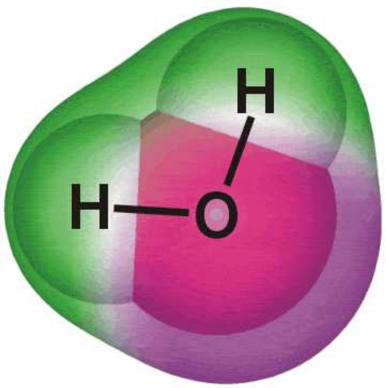
OUTLINE

- What is matter: molecules, atoms, nucleus, etc
- What is anti-matter: positron vs. electron
- Prediction and observation of anti-matter
- Anti-matter in our every-day life
- Creation of anti-matter in a laboratory
- Why does matter dominate in our Universe
- Time-reversal symmetry violation as a condition
- Summary

Part I: Matter and anti-matter around us

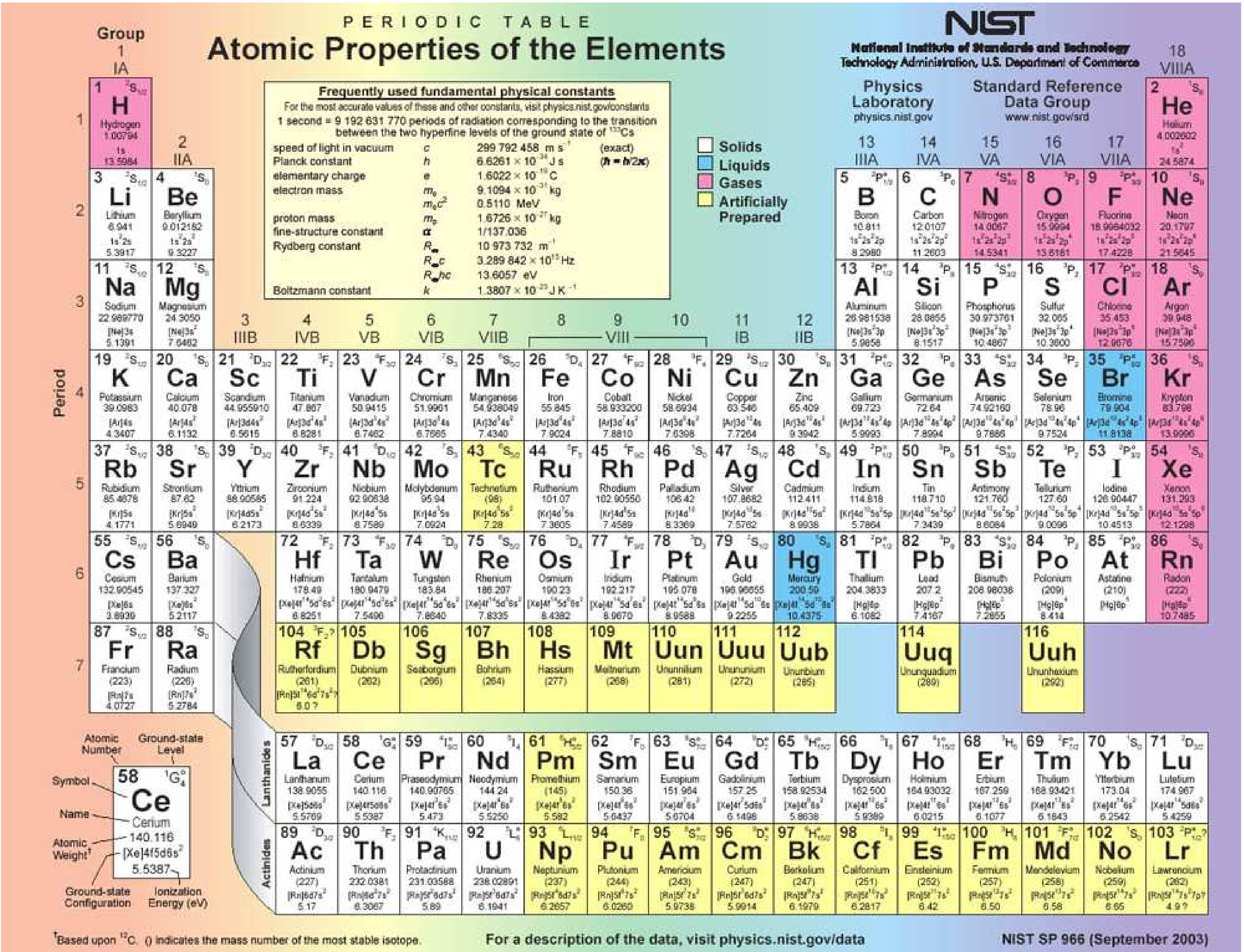
What We Know about Matter: Molecules

- Everything around us is made from molecules (including us)
- Example of water molecule: H_2O (e.g Cavendish, 1781)
  - molecules (solids) made of atoms
  - "chemistry" can break molecules



- Atoms cannot be broken through "chemistry"
- Periodic table of atomic elements (Mendeleev, 1868)
  - about 100 elements
  - need Quantum Mechanics (1920) to understand the structure

What We Know about Matter: Atoms

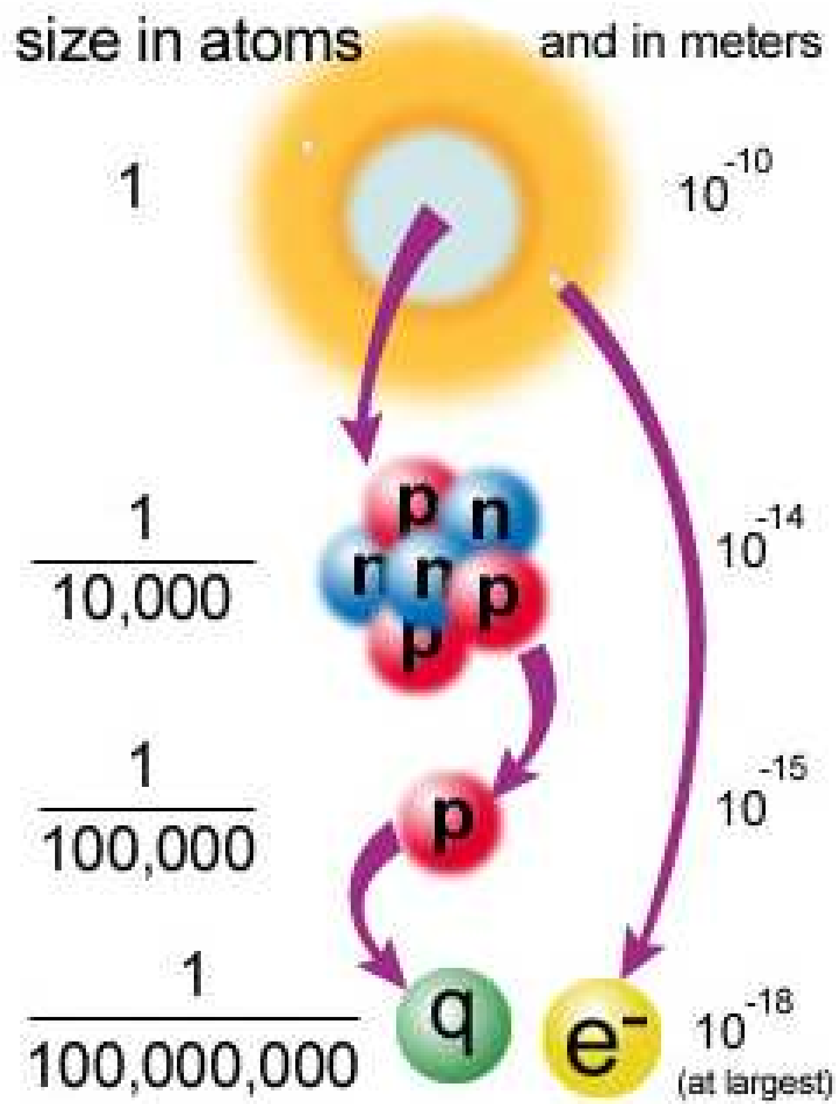


What We Know about Matter: Nucleus

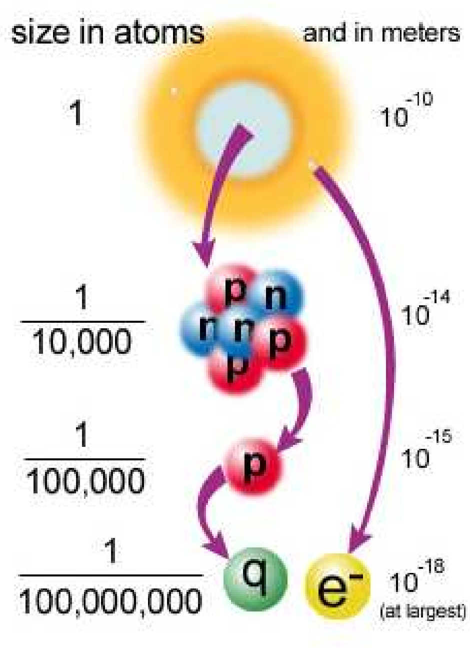
Atom: nucleus and electrons

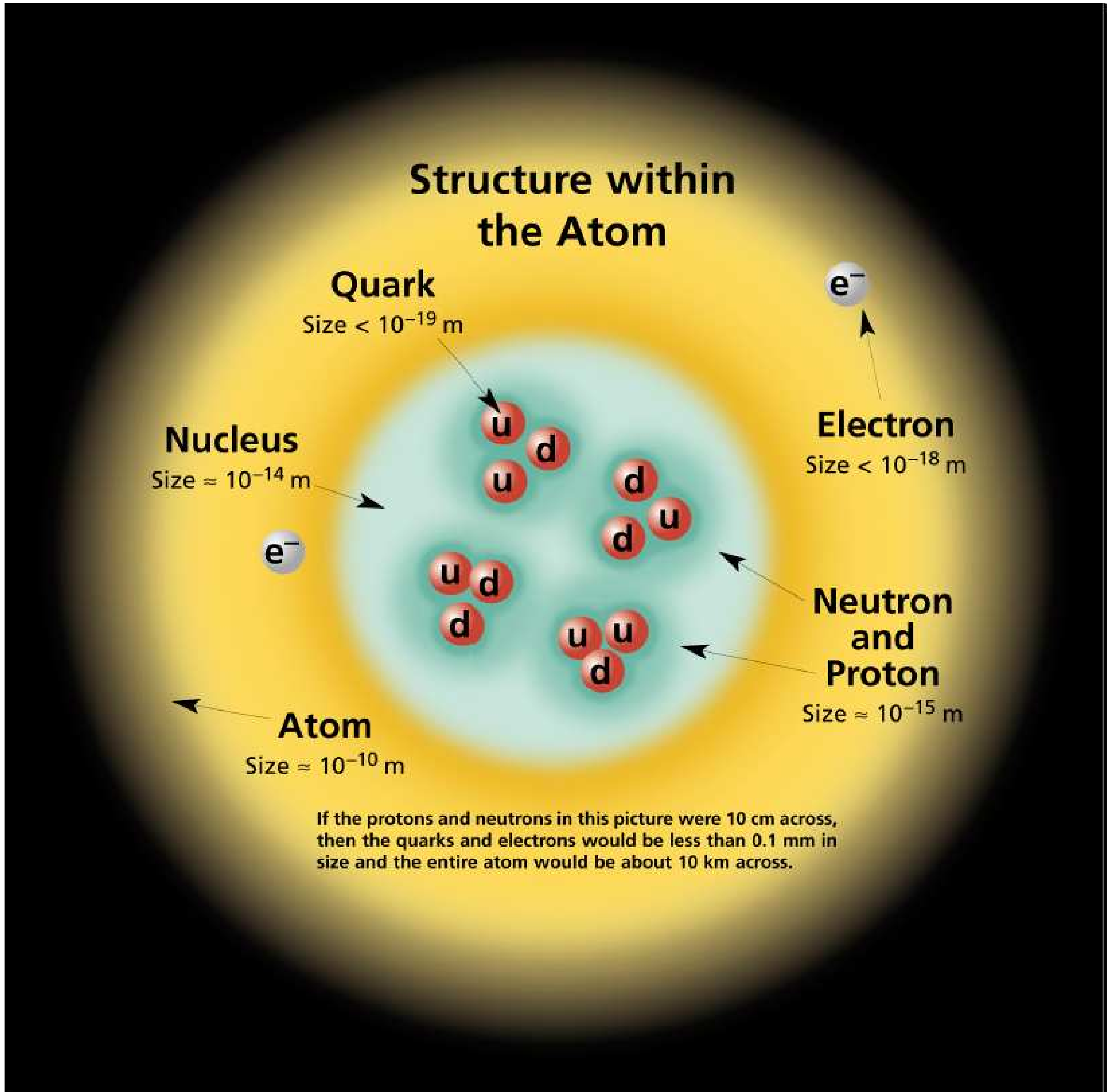
Nucleus: protons and neutrons

Protons and neutrons: quarks



What We Know about Matter: Quarks/Electrons





Matter and Anti-Matter

- For each Quark or Lepton (like electron): Anti-particle

$$\begin{array}{cccccccccc} & \multicolumn{4}{c}{\text{matter}} & & \multicolumn{4}{c}{\text{anti-matter}} \\ & \multicolumn{2}{c}{\text{quarks}} & \multicolumn{2}{c}{\text{leptons}} & & \multicolumn{2}{c}{\text{anti-quarks}} & \multicolumn{2}{c}{\text{anti-leptons}} \\ & \begin{pmatrix} d \\ s \\ b \end{pmatrix} & \begin{pmatrix} u \\ c \\ t \end{pmatrix} & \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix} & \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} & & \begin{pmatrix} \bar{d} \\ \bar{s} \\ \bar{b} \end{pmatrix} & \begin{pmatrix} \bar{u} \\ \bar{c} \\ \bar{t} \end{pmatrix} & \begin{pmatrix} \bar{e} \\ \bar{\mu} \\ \bar{\tau} \end{pmatrix} & \begin{pmatrix} \bar{\nu}_e \\ \bar{\nu}_\mu \\ \bar{\nu}_\tau \end{pmatrix} \\ & \text{-e/3} & \text{2e/3} & \text{-e} & 0 & \text{charge} & \text{e/3} & \text{-2e/3} & \text{e} & 0 \end{array}$$

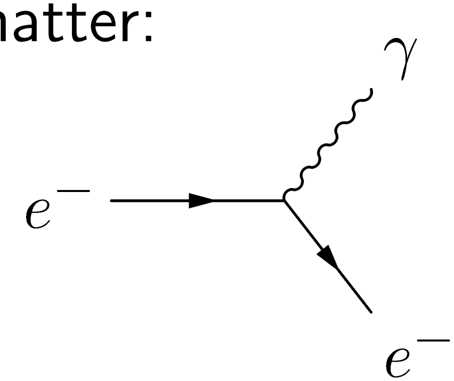
- "Forces" are the same for matter and anti-matter:

  Electromagnetic (γ)

  Gravity (graviton ?)

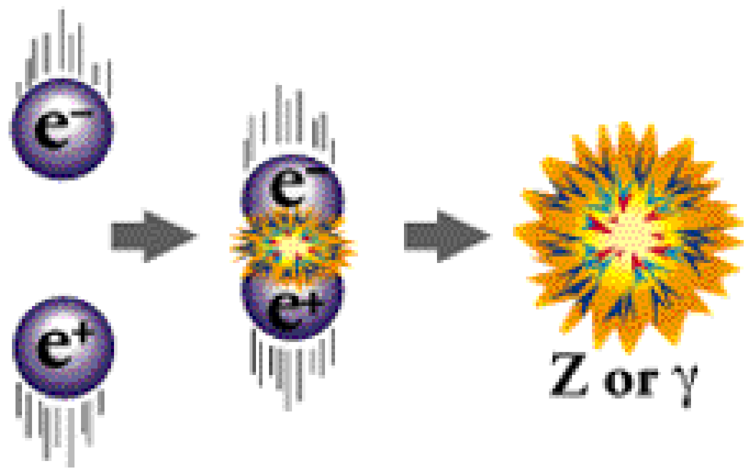
  Weak (Z^0, $W^\pm$)

  Strong (gluons)



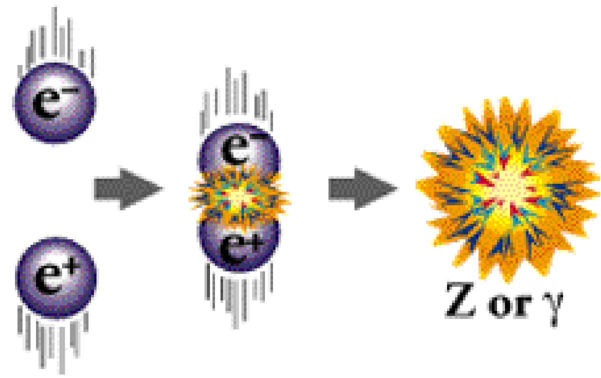
The Simplest Anti-Matter: Positron

- Electron e^- - simplest matter (all around us)
  - Positron (or Anti-Electron) - simplest anti-matter
  - anti-matter has opposite charge: e^+
- What happens if matter and anti-matter meet:
  - they annihilate into energy (e.g. photon, $\Delta E \Delta t \sim \hbar$)



- We do not encounter anti-matter around us (fortunately!)

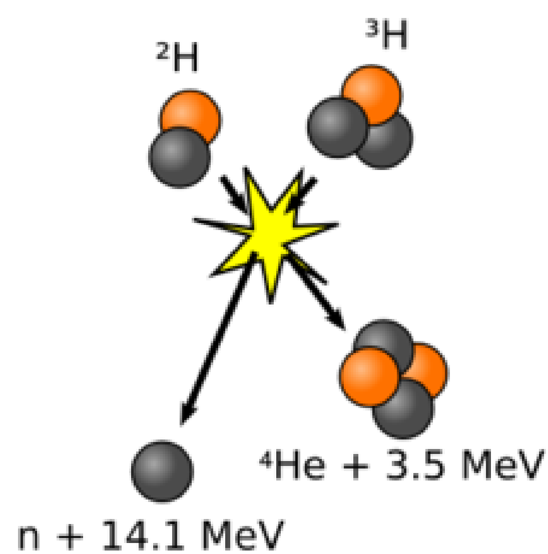
Matter-Anti-Matter Annihilation



- Famous Einstein's mass-energy:

$$E = mc^2$$

- Matter-Anti-Matter is the most efficient "bomb"
- More efficient than atomic/H bomb
  - nucleus binding energy
    fraction of proton/neutron mass
- Matter-Anti-Matter "bomb" is not practical
  - nearly impossible to store anti-matter



Prediction of Anti-Matter: Positron

- Dirac equation (1928)

$$\hat{H} = \alpha_0 mc^2 + \sum \alpha_i p_i c$$

Quantum Mechanical operator $\hat{H}$ for e^- wave-function $\psi(x)$

$$\hat{H}\psi(x) = E\psi(x)$$

- Solution (compare Einstein's mass-momentum-energy):

$$E = \pm\sqrt{(mc^2)^2 + \sum (p_i c)^2}$$

Negative solution $E = -\sqrt{\dots}$ is a "hole" or e^+

- Dirac was not confident enough to call it e^+

suggested it was a proton p^+ (wrong)

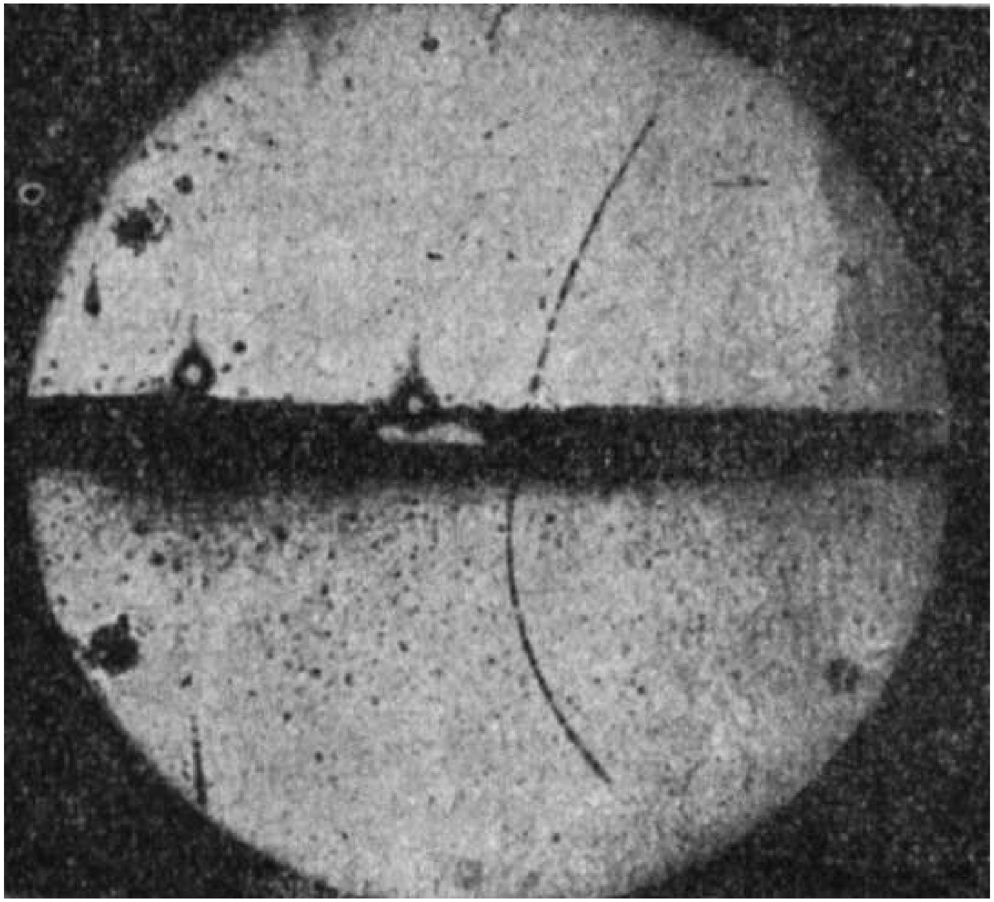
Observation of Anti-Matter: Positron

- Observation by C.D. Anderson in Cosmic Rays:

  "The Positive Electron" Physical Review 43, 491 (1933)

  cloud chamber
  in magnetic field

  (Nobel Prize in 1936)



Anti-Matter in a Classroom

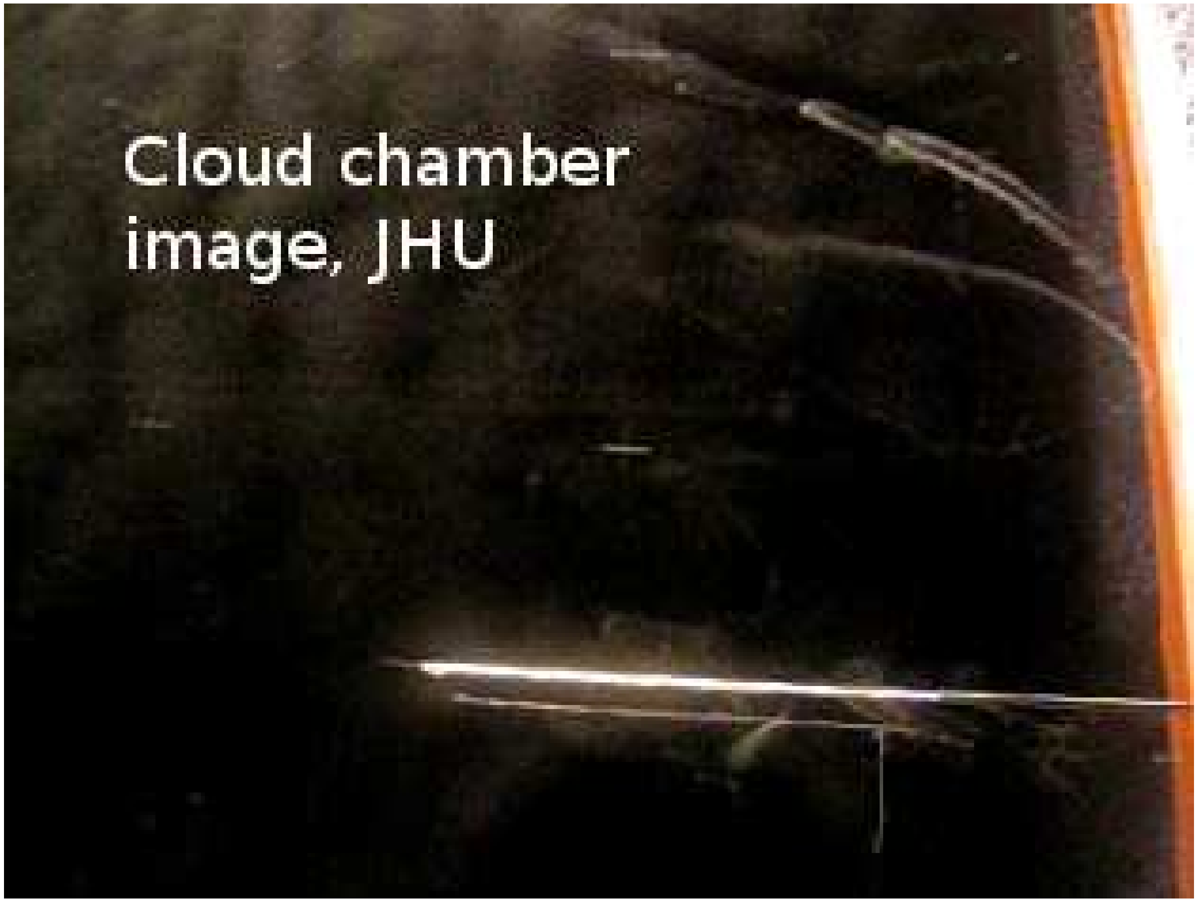
- Cloud chamber
- Two sources:

  (1) Radioactive isotopes,

$^{228}_{90}$Th$\rightarrow$ ... $\rightarrow$ $^{212}_{84}$Po$+6\alpha 3\beta$

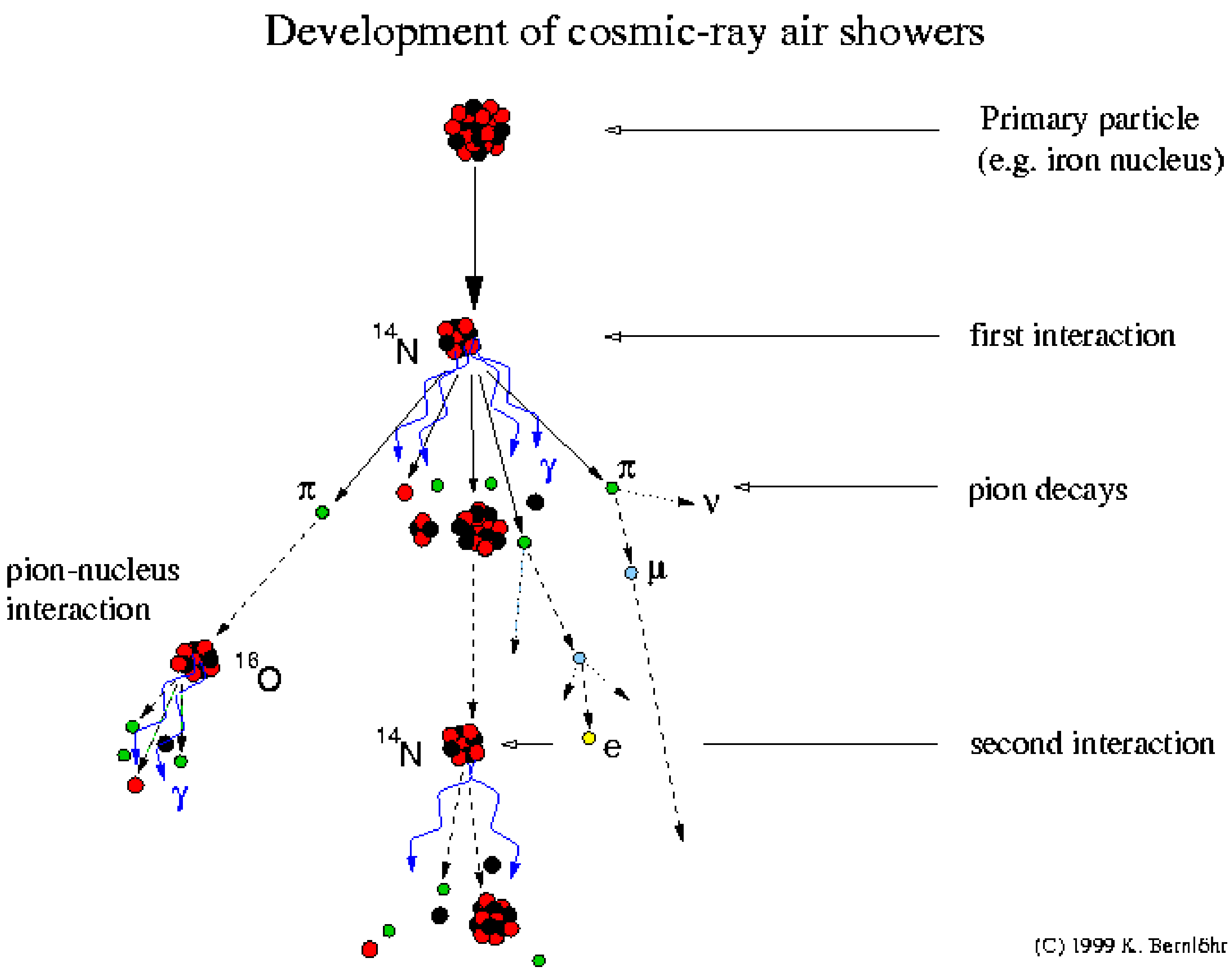
  (2) Cosmic rays

example: $^{22}_{11}\text{Na} \rightarrow {}^{22}_{10}\text{Ne} + \nu_e + e^+$
deep: (bound) $p \rightarrow n + \nu_e + e^+$
deeper: (bound) $u \rightarrow d + \nu_e + e^+$
deepest: $u \rightarrow d + W^+; W^+ \rightarrow \nu_e + e^+$



Cosmic Rays: Source of Anti-Matter

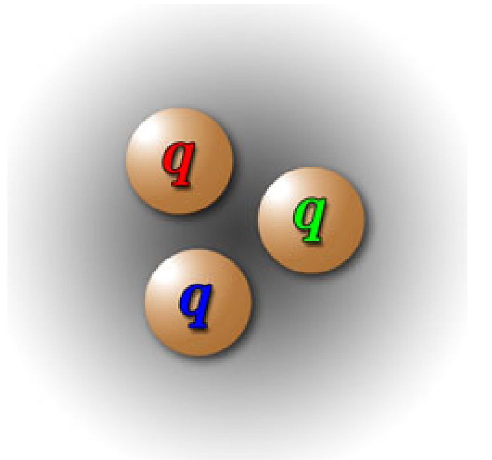
- Observed muon $\mu^{\pm}$ like electron/positron, just heavy



Anti-Matter from Cosmic Rays

- Incoming cosmic particles are matter (e.g. protons)
- Large energy transformed into

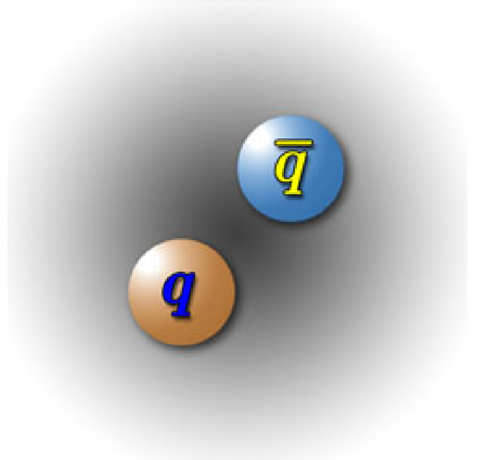
  new matter-anti-matter (e.g. mesons $q\bar{q}$)



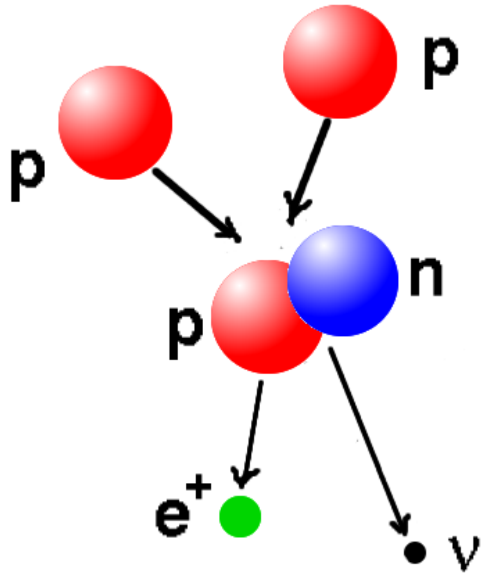
$$E = mc^2$$

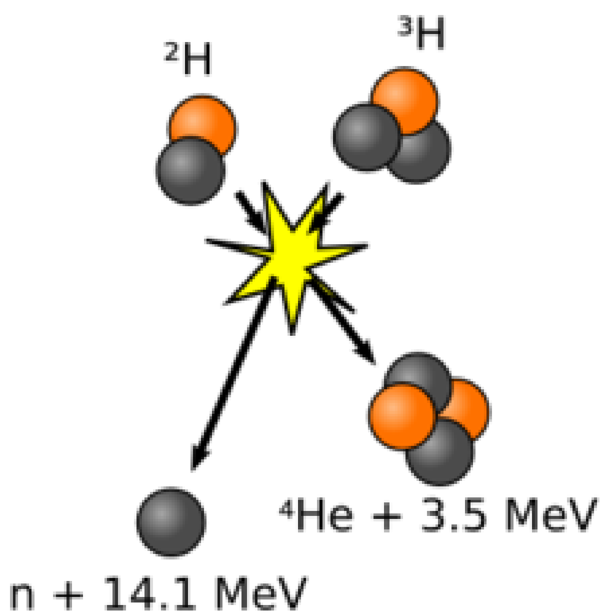
- Eventually anti-matter interacts or decays

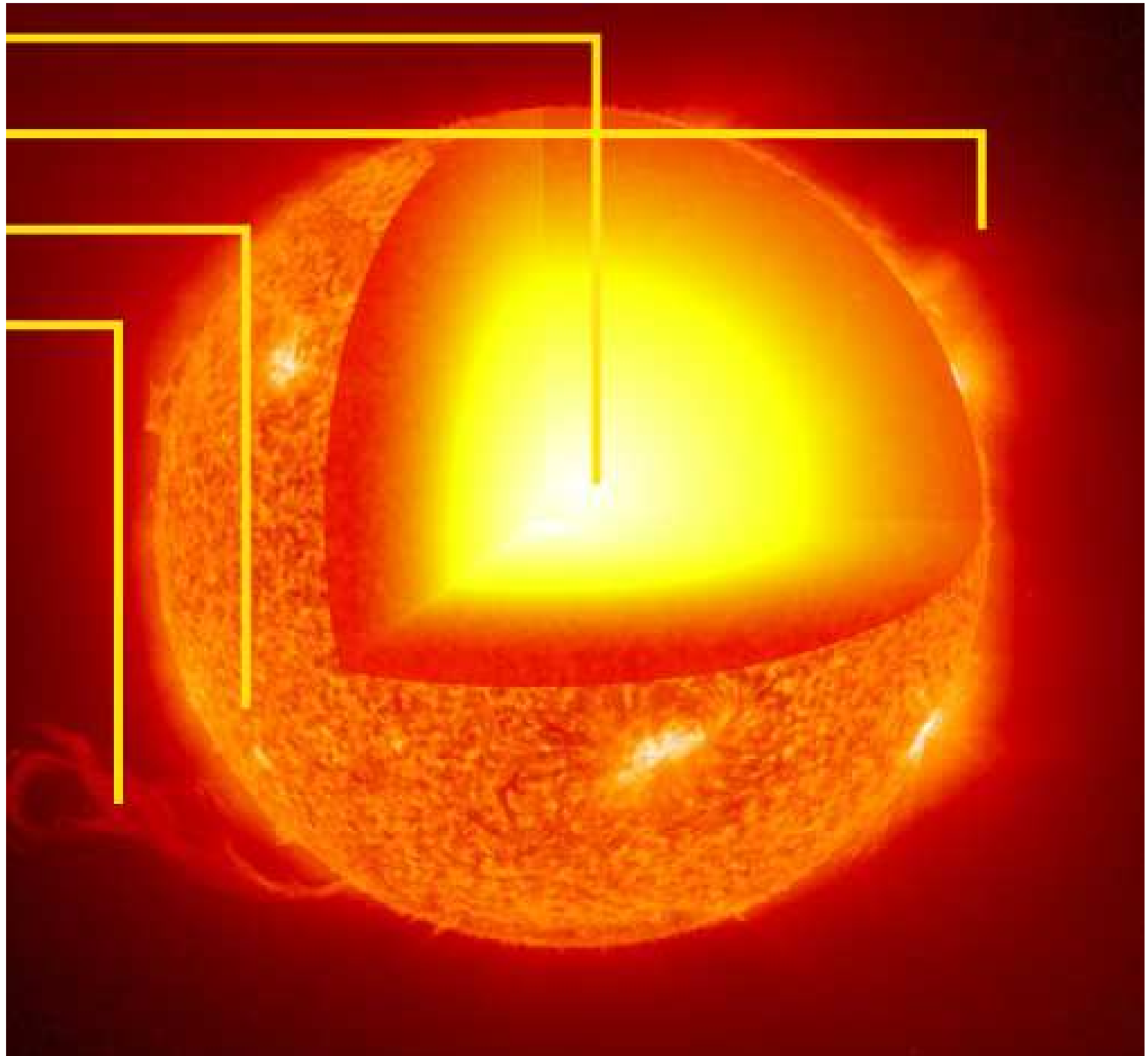
  annihilates



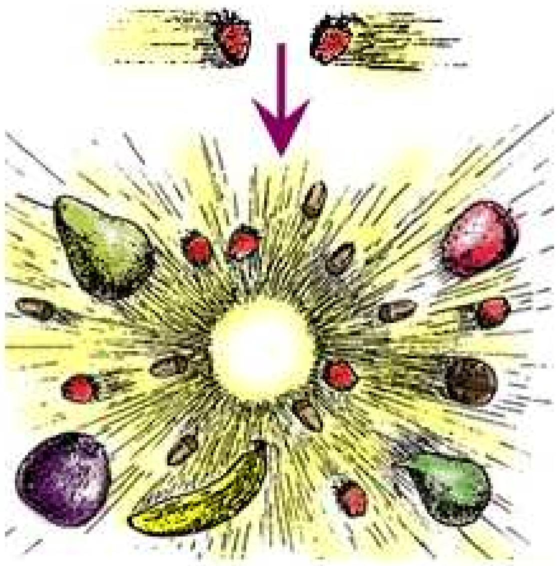
Anti-Matter as Part of Energy from the Sun







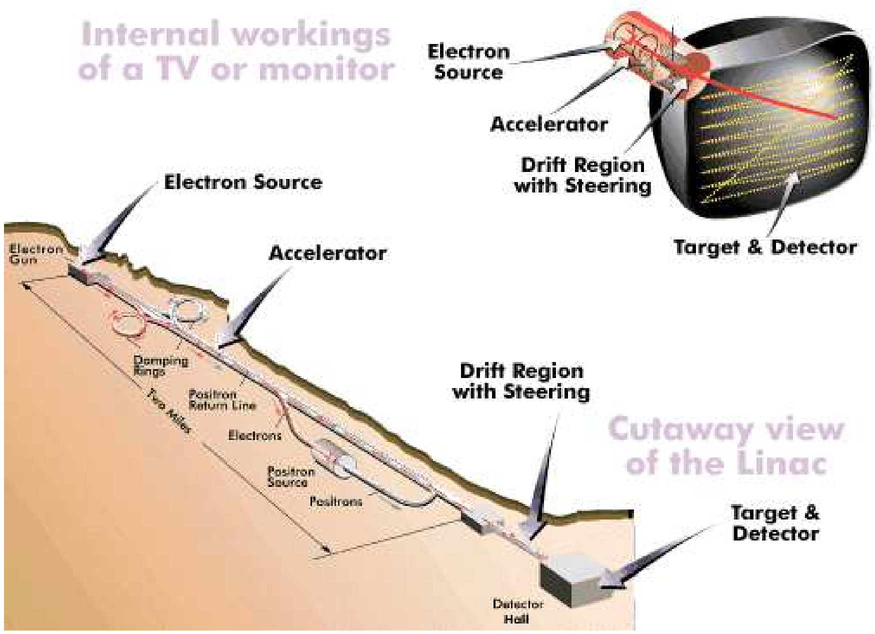
Anti-Matter in Accelerators

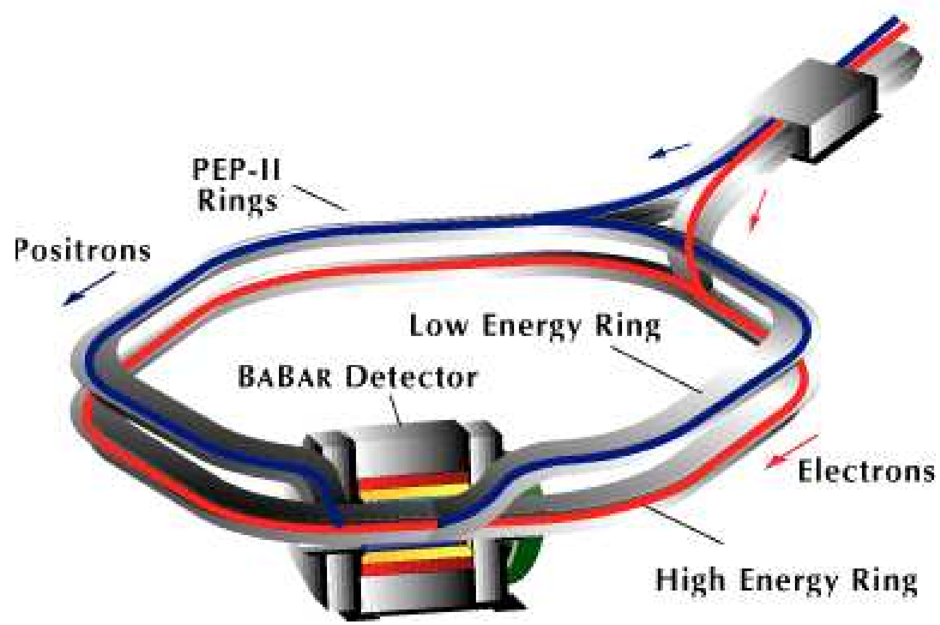


Smash at high energy

$$E = mc^2$$

Stanford Linear Accelerator Center





Observation of Anti-Matter: Anti-proton

- Collide proton (p) with a target (proton/neutrons p/n)

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

Observation of Antiprotons

Phys. Rev. 100, 947 (1955)

(Nobel Prize 1959)

Observation of Antiprotons*

Owen Chamberlain, Emilio Segrè, Clyde Wiegand, and Thomas Ypsilantis

Radiation Laboratory, Department of Physics, University of California, Berkeley, California

(Received October 24, 1955)

ONE of the striking features of Dirac's theory of the electron was the appearance of solutions to his equations which required the existence of an anti-particle, later identified as the positron.

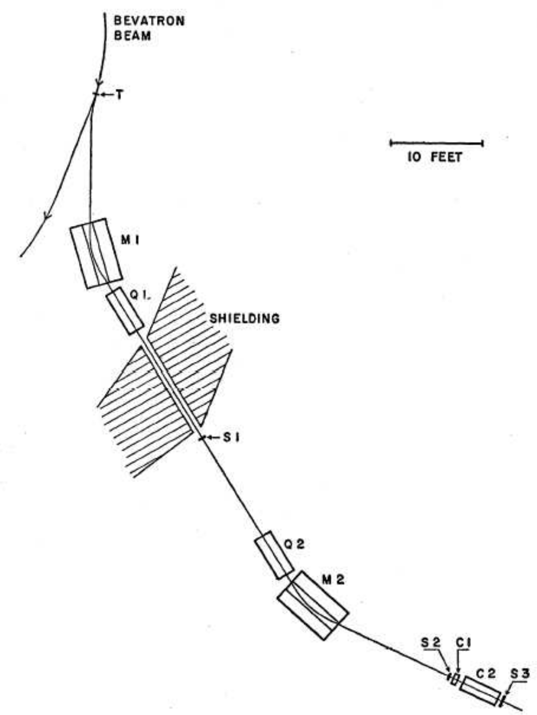
The extension of the Dirac theory to the proton requires the existence of an antiproton, a particle which bears to the proton the same relationship as the positron to the electron. However, until experimental proof of the existence of the antiproton was obtained, it might be questioned whether a proton is a Dirac particle in the same sense as is the electron. For instance, the anomalous magnetic moment of the proton indicates that the simple Dirac equation does not give a complete description of the proton.

The experimental demonstration of the existence of antiprotons was thus one of the objects considered in the planning of the Bevatron. The minimum laboratory kinetic energy for the formation of an antiproton in a nucleon-nucleon collision is 5.6 Bev. If the target nucleon is in a nucleus and has some momentum, the threshold is lowered. Assuming a Fermi energy of 25 Mev, one may calculate that the threshold for formation of a proton-antiproton pair is approximately 4.3

Table I. Characteristics of components of the apparatus.

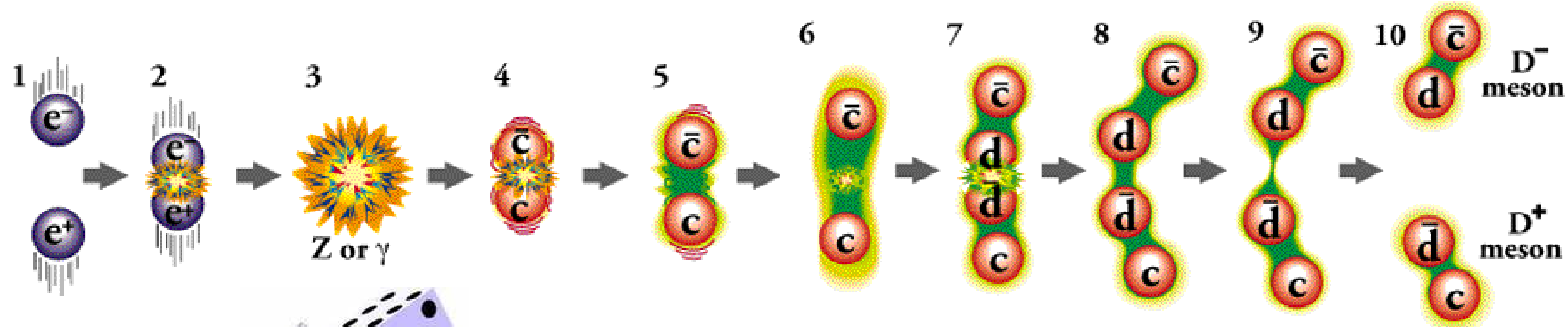
$S1$, $S2$	Plastic scintillator counters 2.25 in. diameter by 0.62 in. thick.
$C1$	Čerenkov counter of fluorochemical 0-75, ($C_8F_{16}O$); $\mu_D=1.276$; $\rho=1.76$ g cm^{-3}. Diameter 3 in.; thickness 2 in.
$C2$	Čerenkov counter of fused quartz: $\mu_D=1.458$; $\rho=2.2$ g cm^{-3}. Diameter 2.38 in.; length 2.5 in.
$Q1$, $Q2$	Quadrupole focusing magnets: Focal length 119 in.; aperture 4 in.
$M1$, $M2$	Deflecting magnets 60 in. long. Aperture 12 in. by 4 in. $B\cong 13\,700$ gauss.

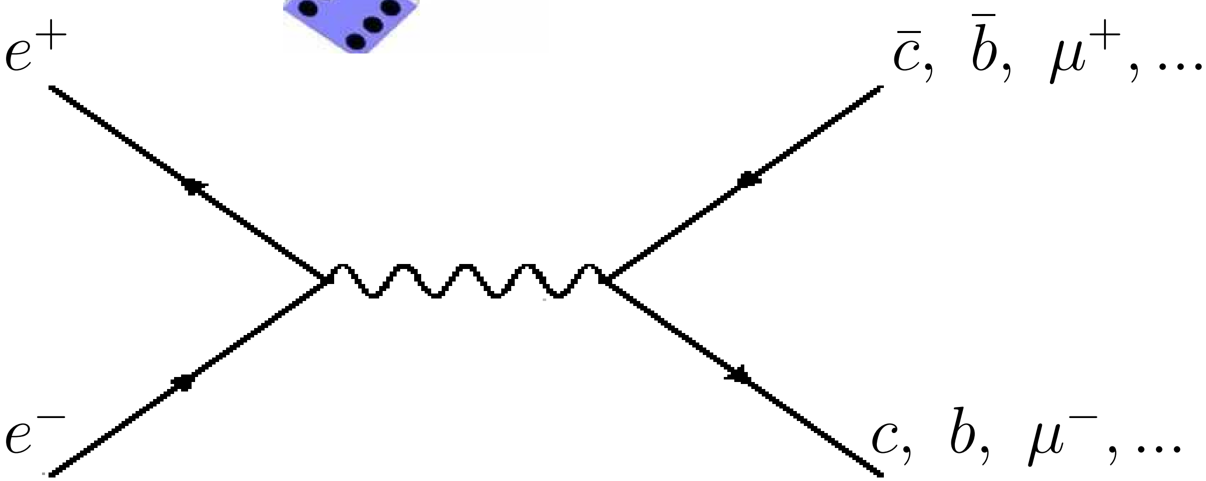
Figure 1 shows a schematic diagram of the apparatus. The Bevatron proton beam impinges on a copper target and negative particles scattered in the forward direction with momentum 1.19 Bev/c describe an orbit as shown in the figure. These particles are deflected 21° by the field of the Bevatron, and an additional 32° by magnet $M1$. With the aid of the quadrupole focusing magnet $Q1$ (consisting of 3 consecutive quadrupole magnets) these particles are brought to a focus at counter $S1$, the first scintillation counter. After passing through counter $S1$, the particles are again focused (by $Q2$), and deflected (by $M2$) through an additional angle of 34°, so that they are again brought to a focus at counter $S2$.



Anti-Matter in Accelerators

- Modern accelerators: e^+e^- and $\bar{p}p$
  - most efficient utilization of energy $E = mc^2$
  - kind of matter-anti-matter “bomb”



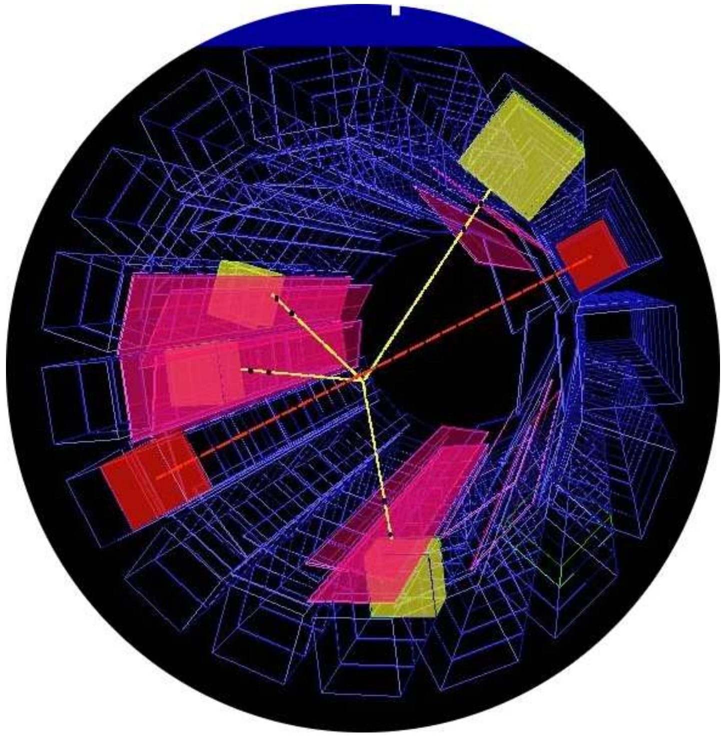


Building up Anti-Matter

- Put together anti-proton and positron ($\bar{p}^- e^+$)
  - anti-Hydrogen atom (anti-atom)
- 1995 PS210 experiment (CERN, Europe)
  - high-energy ("hot") anti-H
- 2002 the ATHENA project (CERN, Europe)
  - "cold" anti-H
  - neutral anti-atoms impossible to store

    annihilate with walls
- No attempts to create anti-molecules

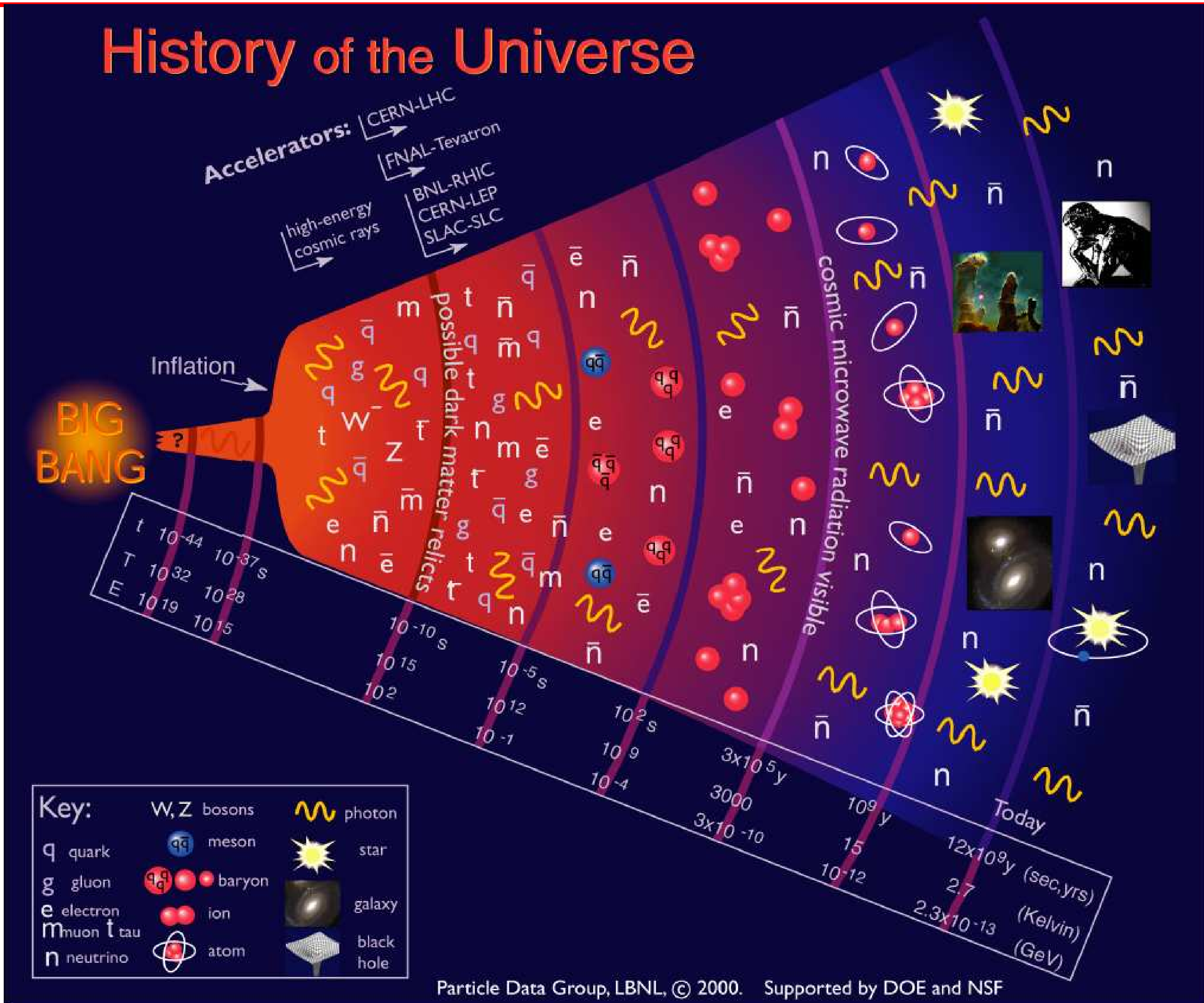
  or anti-nucleus

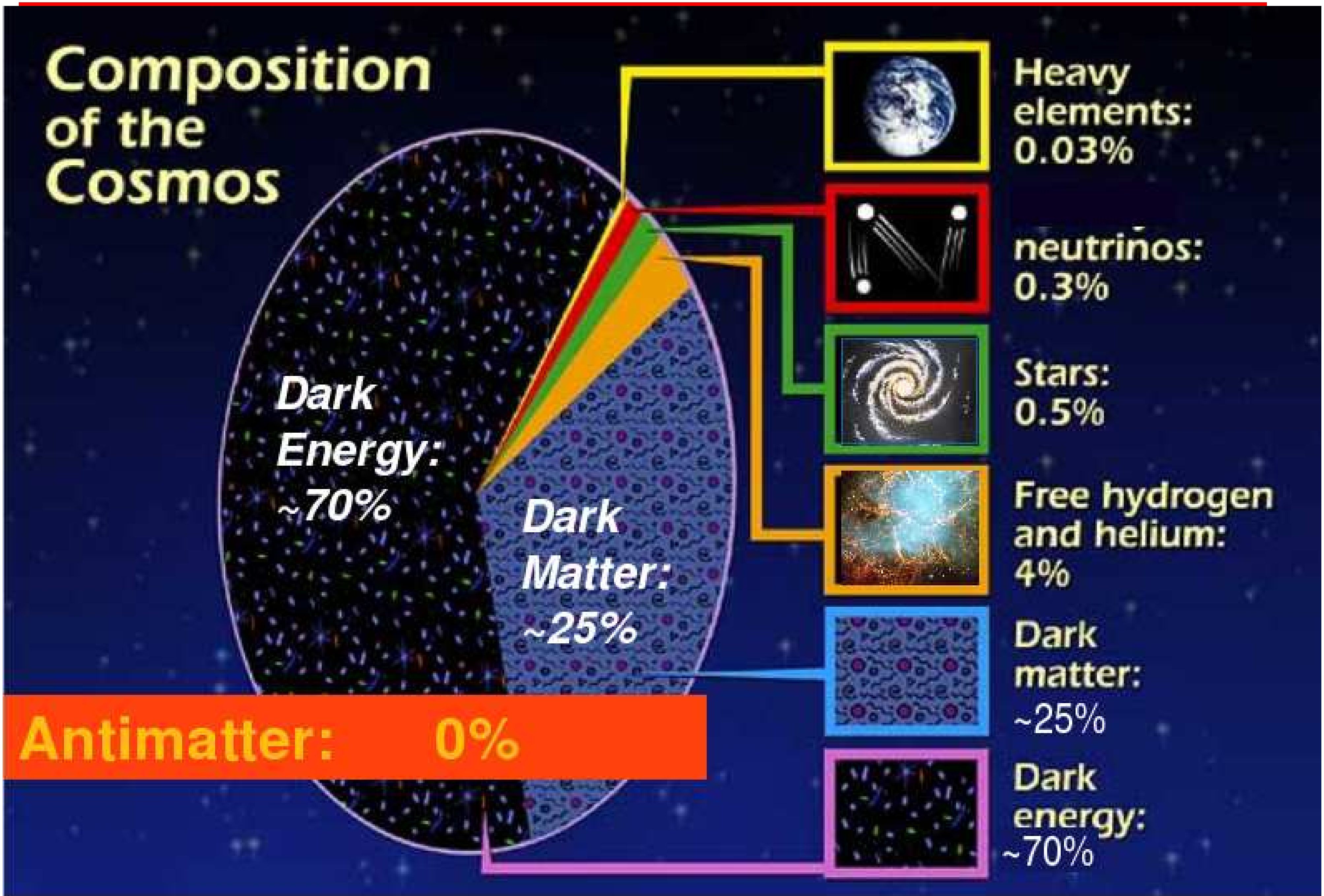


Part II: Why we are made of matter

Anti-Matter Universe?

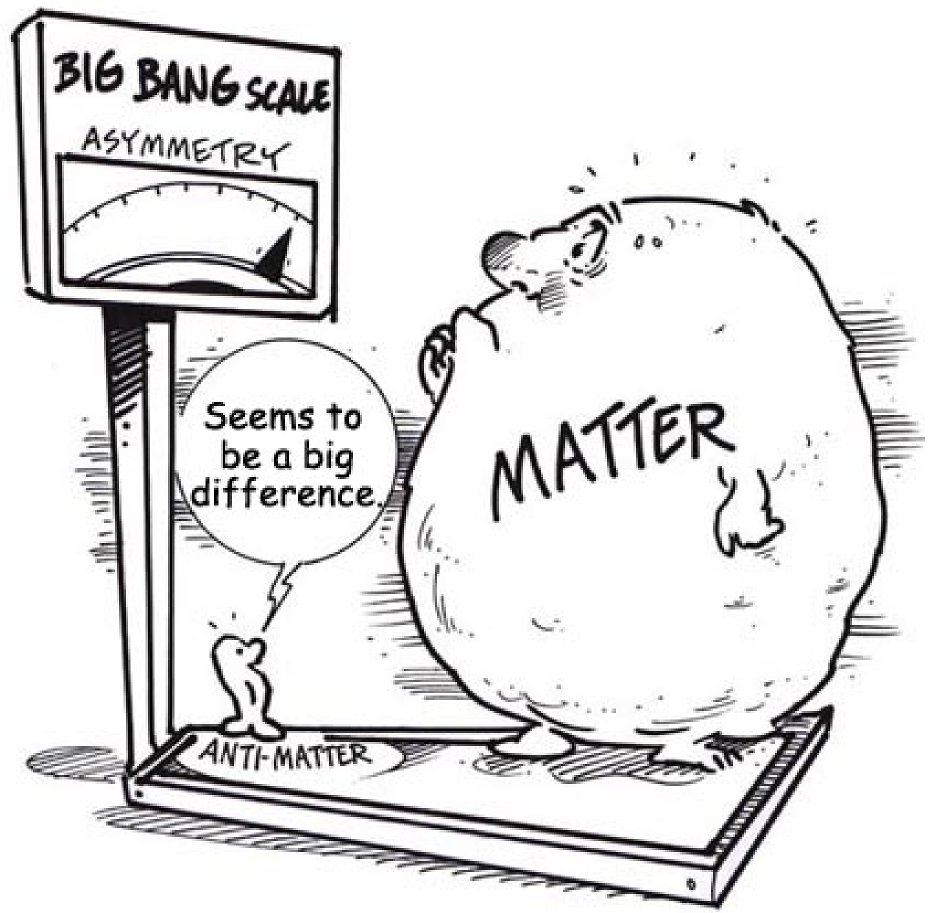
- A science fiction story:
  - parallel Universe made of anti-matter, possibly with anti-humans
  - annihilate if try to meet, but can send radio-waves (γ)
  - how do we tell we are matter and they are anti-matter ?
  - impossible? Only Particle Physics gives an answer (tell you later)...
- Reality:
  - no evidence for Anti-Matter Universe
  - would see "explosions" $e^+e^- \to \gamma\gamma$, $p\bar{p}$... on the boundaries
  - visible universe is predominantly matter over anti-matter


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10-12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF


Composition of the Cosmos
Dark Energy: ~70%
Dark Matter: ~25%
Heavy elements: 0.03%
neutrinos: 0.3%
Stars: 0.5%
Free hydrogen and helium: 4%
Dark matter: ~25%
Dark energy: ~70%
Antimatter: 0%

Why Matter Dominates Over Anti-Matter

- Start with symmetric Big Bang
  - end up with matter asymmetry



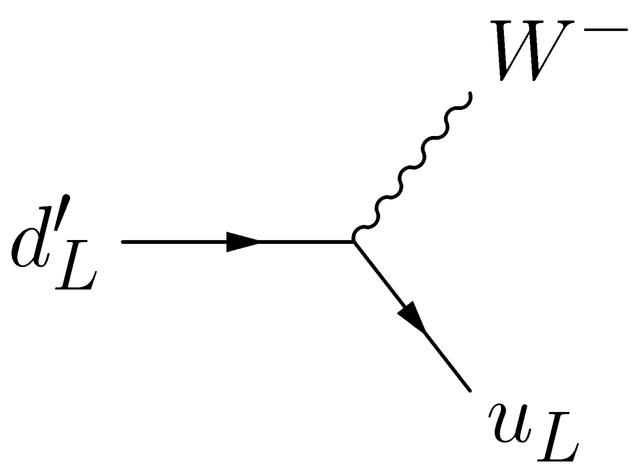
- Why does MATTER dominate (Sakharov, 1966):
  - CP-asymmetry
  - baryon non-conservation
  - non-equilibrium

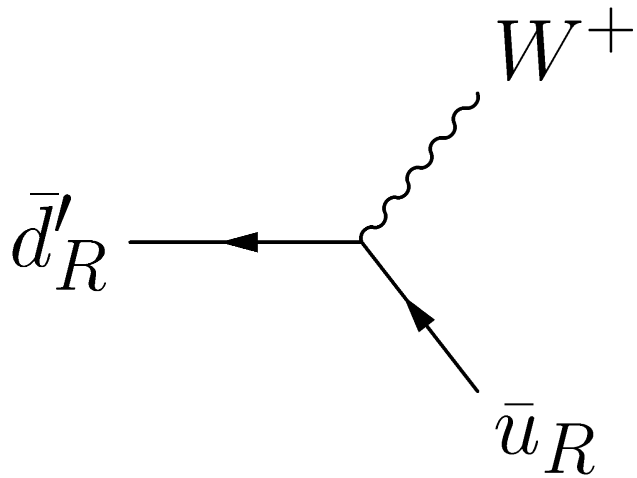
Fundamental Symmetries

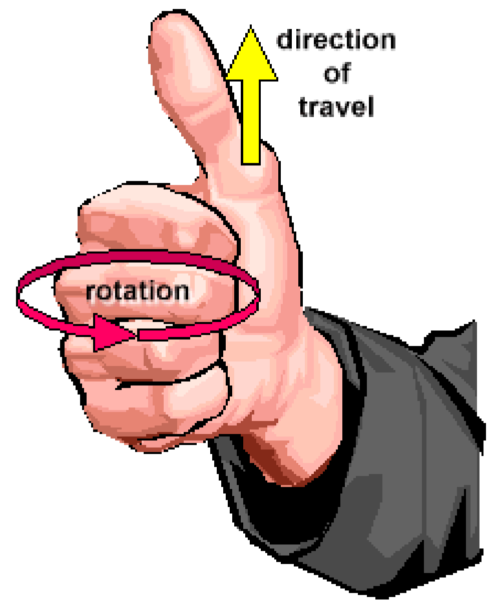
- Symmetries $\Rightarrow$ conservation laws

Charge + Parity (mirror) transformation

Matter $\Longleftrightarrow$ Antimatter







- CP asymmetry $\Longleftrightarrow$ matter and antimatter difference

Time Reversal

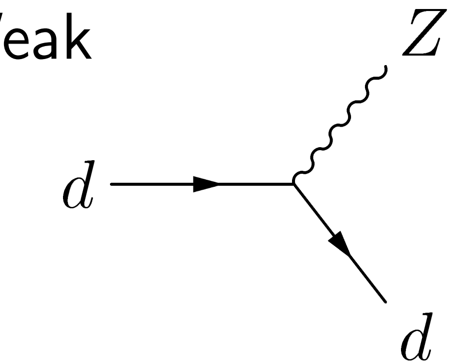
- Fundamental CPT Theorem
  - all physics laws are invariant under CPT transformation:

    Charge $+$ Parity $+$ Time reversal

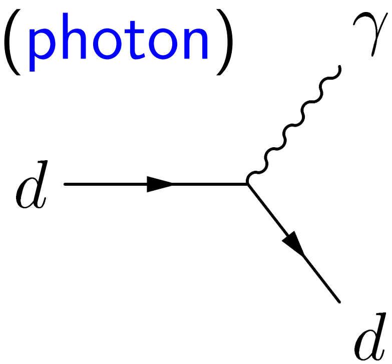
- Time reversal symmetry ("backwards movie")
  - symmetric in most interactions (EM, gravity, strong)
  - second law of thermodynamics (entropy increase)
    is simply probability
    not microscopic process dynamics
  - BUT: T (and CP) violated in weak interactions (with $W^{\pm}$)

What is Special about Weak Interactions

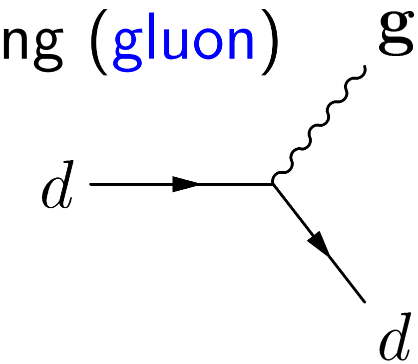
- Weak

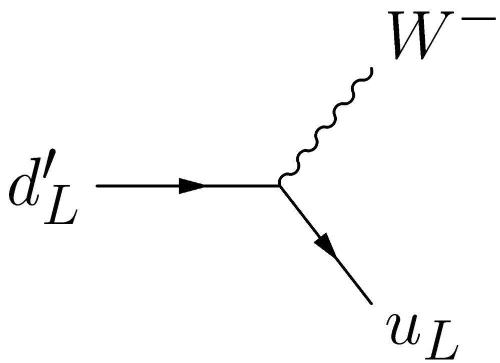


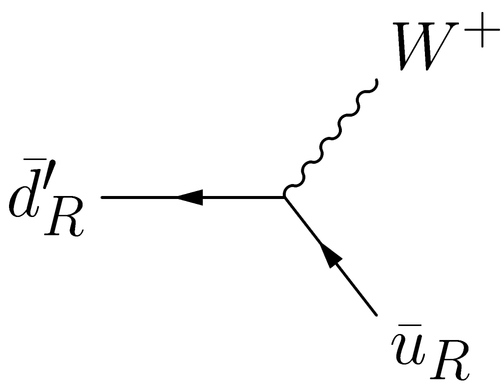
- EM (photon)



- Strong (gluon)







- Weak interactions are special:

  (1) change of quark "flavor" (e.g. $b \to u$)

  $$|d'\rangle = V_{ud} \cdot |d\rangle + V_{us} \cdot |s\rangle + V_{ub} \cdot |b\rangle$$

  (2) couple "left-handed" fermions

  helicity λ = spin·direction $= -\frac{1}{2}$

- Violate Charge and Parity symmetry

  might violate CP (?)

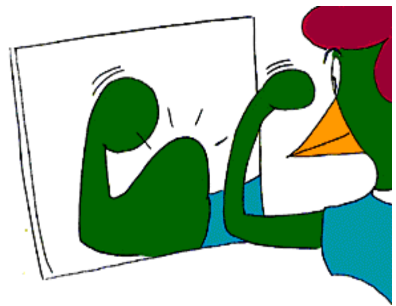
Example of $\boldsymbol{CP}$ Symmetry Violation

B^0 (anti-matter) $= \bar{b}d$

$B^0 \to K^+ + \pi^-$

$(\bar{b}d) \to (\bar{s}u) + (\bar{u}d)$

10% more often



$\bar{B}^0$ (matter) $= b\bar{d}$

$\bar{B}^0 \to K^- + \pi^+$

$(b\bar{d}) \to (s\bar{u}) + (u\bar{d})$

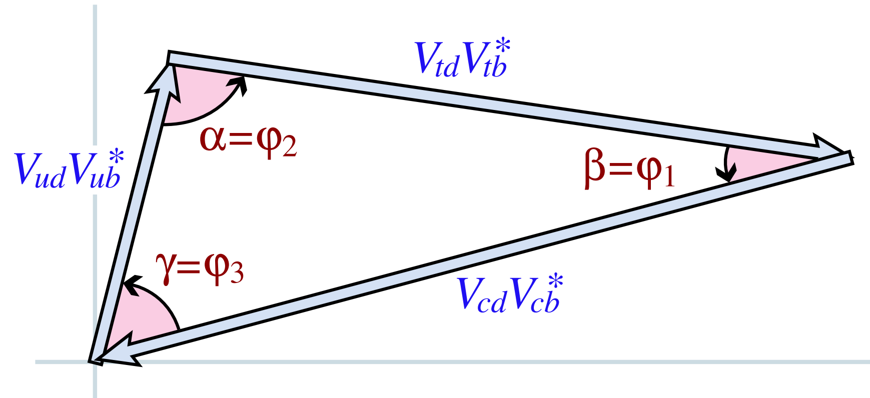
- Observed 10% difference in 2004 (BABAR and BELLE)
- First CP violation $\sim 0.2\%$ in K^0_L decays in 1964
- Cosmological question: how to tell matter vs anti-matter
  - communicate results to another Universe
    choice of "$+$" and "$-$" is arbitrary
  - we are made of d and u quarks
    which are more frequent in $B \to K^\pm \pi^\mp$ decays

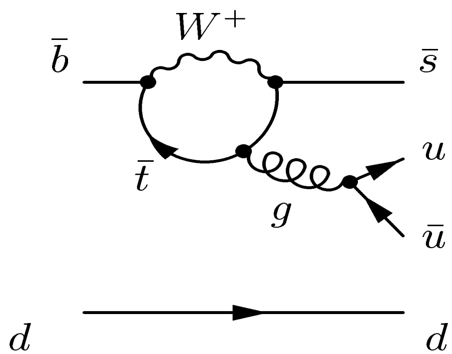
Example of CP Violation: How It Works

$B^0 \to K^+ + \pi^-$

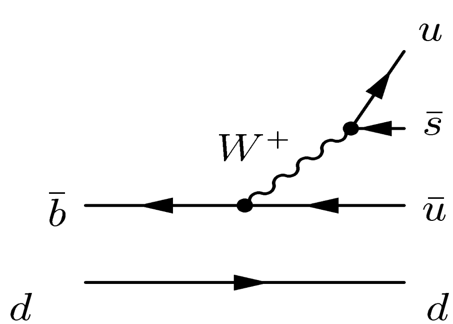
$(\bar{b}d) \to (\bar{s}u) + (\bar{u}d)$

Feynman diagrams of decay





Penguin

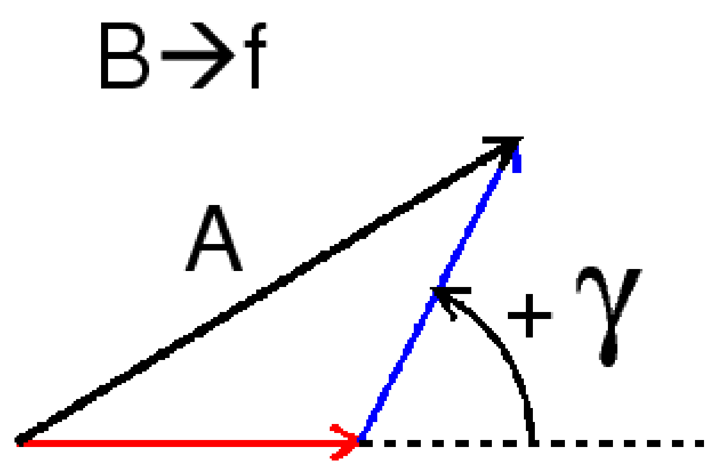


Tree

Probability from complex numbers

"amplitudes" (A) are vectors

Probability $\propto |A|^2 = |A_P + A_T|^2$

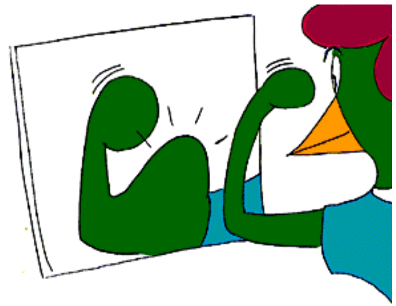


Example of $\boldsymbol{CP}$ Violation: How It Works

$B^0 \to K^+ + \pi^-$

$(\bar{b}d) \to (\bar{s}u) + (\bar{u}d)$

larger probability



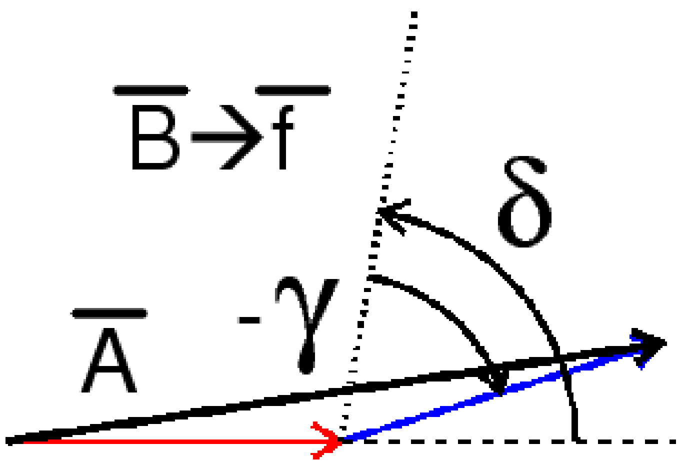
$\bar{B}^0 \to K^- + \pi^+$

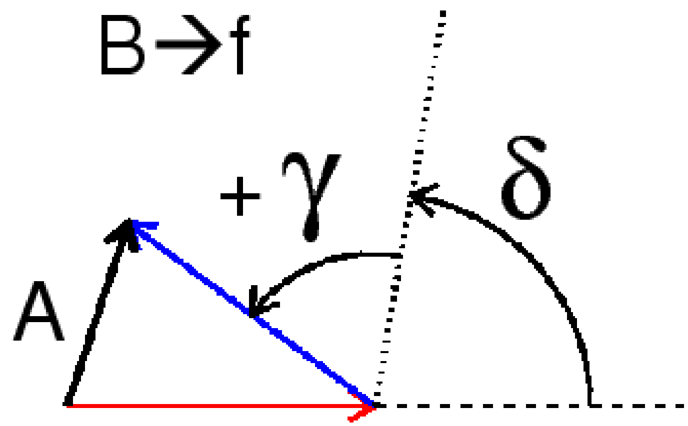
$(b\bar{d}) \to (s\bar{u}) + (u\bar{d})$

smaller probability

- Need overall "phase" difference (δ) between Penguin and Tree
- Angle (γ) changes sign under CP, "interference" of two amplitudes:

$$|\bar{A}|^2 = |\bar{A}_P + \bar{A}_T|^2 \qquad > \qquad |A|^2 = |A_P + A_T|^2$$



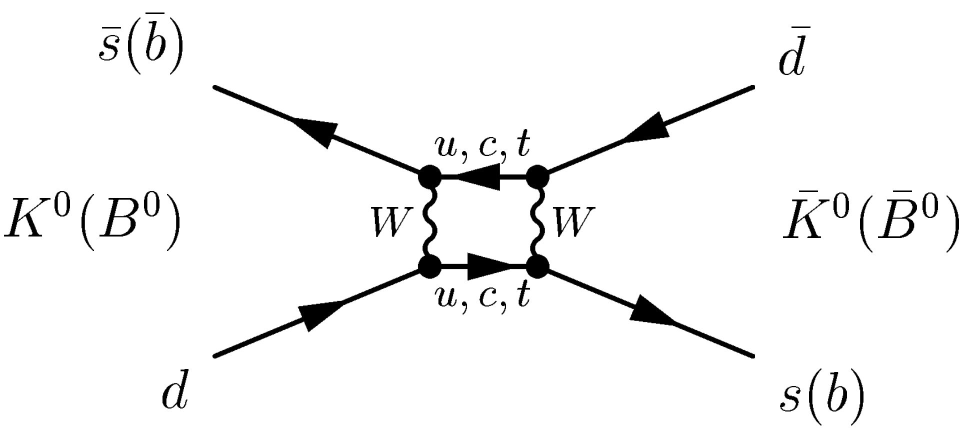


Observation of CP Violation

- Evidence for the 2π Decay of the K_2^0 Meson (1964) (Nobel prize 1980)

$$K_2^0 \to \pi^+ + \pi^- \ (?)$$

$$(CP = -1) \to (CP = +1)$$



VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

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(Received 10 July 1964)

This Letter reports the results of experimental studies designed to search for the 2π decay of the K_2^0 meson. Several previous experiments have served[1,2] to set an upper limit of 1/300 for the fraction of K_2^0's which decay into two charged pions. The present experiment, using spark chamber techniques, proposed to extend this limit.

In this measurement, K_2^0 mesons were produced at the Brookhaven AGS in an internal Be target bombarded by 30-BeV protons. A neutral beam was defined at 30 degrees relative to the circulating protons by a $1\frac{1}{2}$-in. × $1\frac{1}{2}$-in. × 48-in. collimator at an average distance of 14.5 ft. from the internal target. This collimator was followed by a sweeping magnet of 512 kG-in. at ~20 ft. and a 6-in. × 6-in. × 48-in. collimator at 55 ft. A $1\frac{1}{2}$-in. thickness of Pb was placed in front of the first collimator to attenuate the gamma rays in the beam.

The experimental layout is shown in relation to the beam in Fig. 1. The detector for the decay products consisted of two spectrometers each composed of two spark chambers for track delineation separated by a magnetic field of 178 kG-in. The axis of each spectrometer was in the horizontal plane and each subtended an average solid angle of 0.7×10^{-2} steradians. The spark chambers were triggered on a coincidence between water Cherenkov and scintillation counters positioned immediately behind the spectrometers. When coherent K_1^0 regeneration in solid materials was being studied, an anticoincidence counter was placed immediately behind the regenerator. To minimize interactions K_2^0 decays were observed from a volume of He gas at nearly STP.

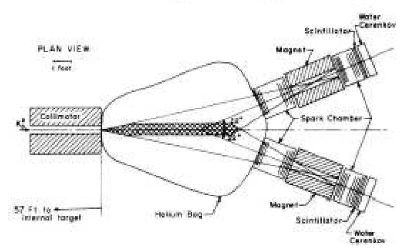


FIG. 1. Plan view of the detector arrangement.

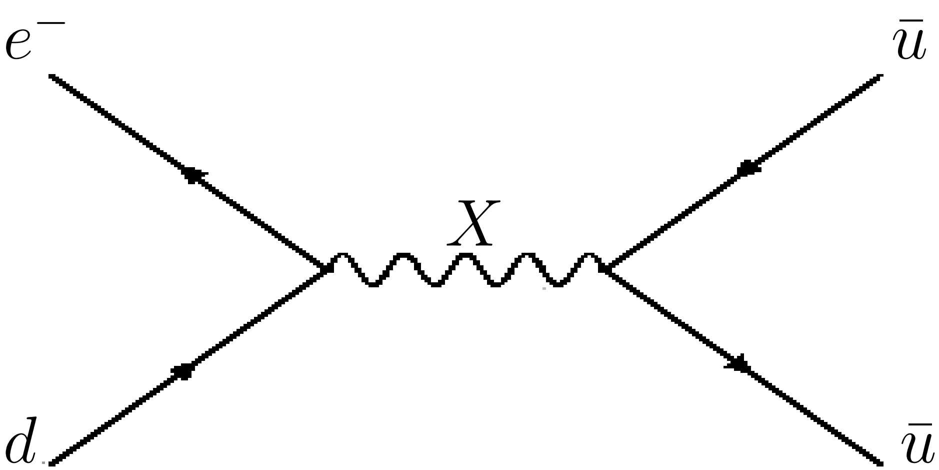
The analysis program computed the vector momentum of each charged particle observed in the decay and the invariant mass, m^*, assuming each charged particle had the mass of the charged pion. In this detector the K_{e3} decay leads to a distribution in m^* ranging from 280 MeV to ~536 MeV; the $K_{\mu 3}$, from 280 to ~516; and the $K_{\pi 3}$, from 280 to 363 MeV. We emphasize that m^* equal to the K^0 mass is not a preferred result when the three-body decays are analyzed in this way. In addition, the vector sum of the two momenta and the angle, θ, between it and the direction of the K_2^0 beam were determined. This angle should be zero for two-body decay and is, in general, different from zero for three-body decays.

An important calibration of the apparatus and data reduction system was afforded by observing the decays of K_1^0 mesons produced by coherent regeneration in 43 gm/cm² of tungsten. Since the K_1^0 mesons produced by coherent regeneration have the same momentum and direction as the K_2^0 beam, the K_1^0 decay simulates the direct decay of the K_2^0 into two pions. The regenerator was successively placed at intervals of 11 in. along the region of the beam sensed by the detector to approximate the spatial distribution of the K_2^0's. The K_1^0 vector momenta peaked about the forward direction with a standard deviation of 3.4 ± 0.3 milliradians. The mass distribution of these events was fitted to a Gaussian with an average mass 498.1 ± 0.4 MeV and standard deviation of 3.6 ± 0.2 MeV. The mean momentum of the K_1^0 decays was found to be 1100 MeV/c. At this momentum the beam region sensed by the detector was 300 K_1^0 decay lengths from the target.

For the K_2^0 decays in He gas, the experimental distribution in m^* is shown in Fig. 2(a). It is compared in the figure with the results of a Monte Carlo calculation which takes into account the nature of the interaction and the form factors involved in the decay, coupled with the detection efficiency of the apparatus. The computed curve shown in Fig. 2(a) is for a vector interaction, form-factor ratio $f^-/f^+ = 0.5$, and relative abundance 0.47, 0.37, and 0.16 for the K_{e3}, $K_{\mu 3}$, and $K_{\pi 3}$, respectively.[3] The scalar interaction has been computed as well as the vector interaction

Summary: Do We Understand Matter Dominance?

- CP symmetry violation can separate matter and anti-matter
  - the known source in Standard Model is still not enough !
- Baryon non-conservation needed
  - not allowed in Standard Model
- We still do not know all the answers
  - expect answers Beyond the Standard Model



example Baryon number violation

mass(X)$> 10^{14} \times$mass(p)

would allow proton decay

$p \longrightarrow \pi^0 + e^+$ (not seen yet)

Part III: Back-up slides

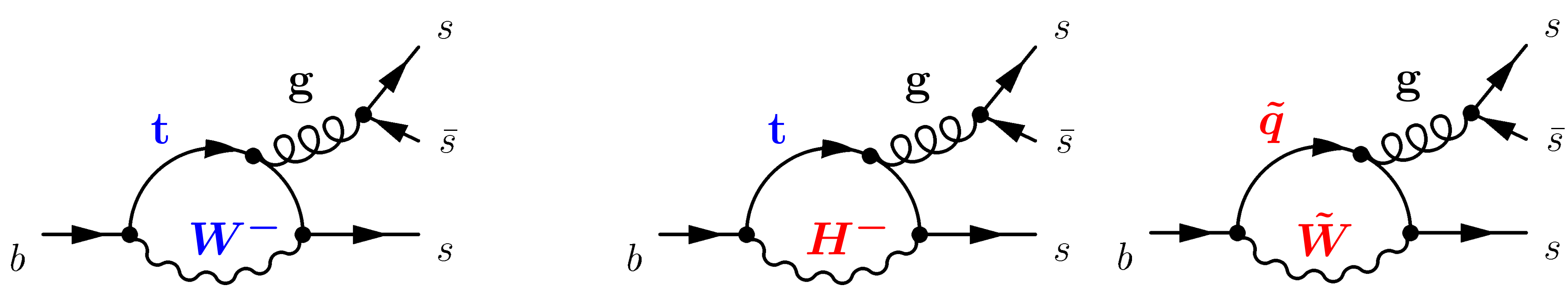
Access to New Particles

- Brute force: new particles at highest energy (e.g. CMS, CDF)

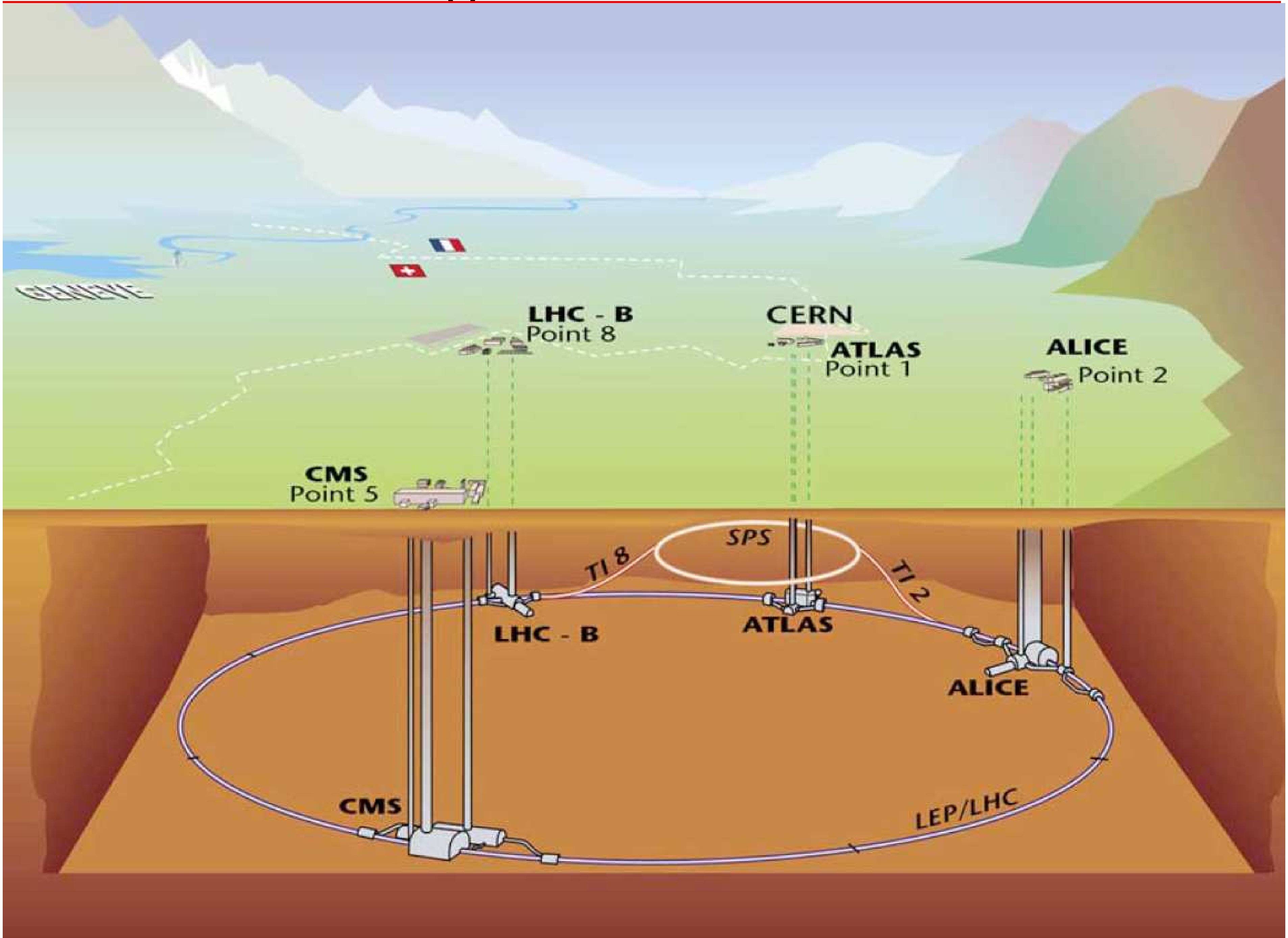
  (exceed current $E = mc^2 \sim 100$ GeV)

- Virtual production: $\Delta E \Delta t \sim \hbar$ (e.g. BaBar and CDF)

  Standard Model new particles in loops



Producing New Matter: Near Future

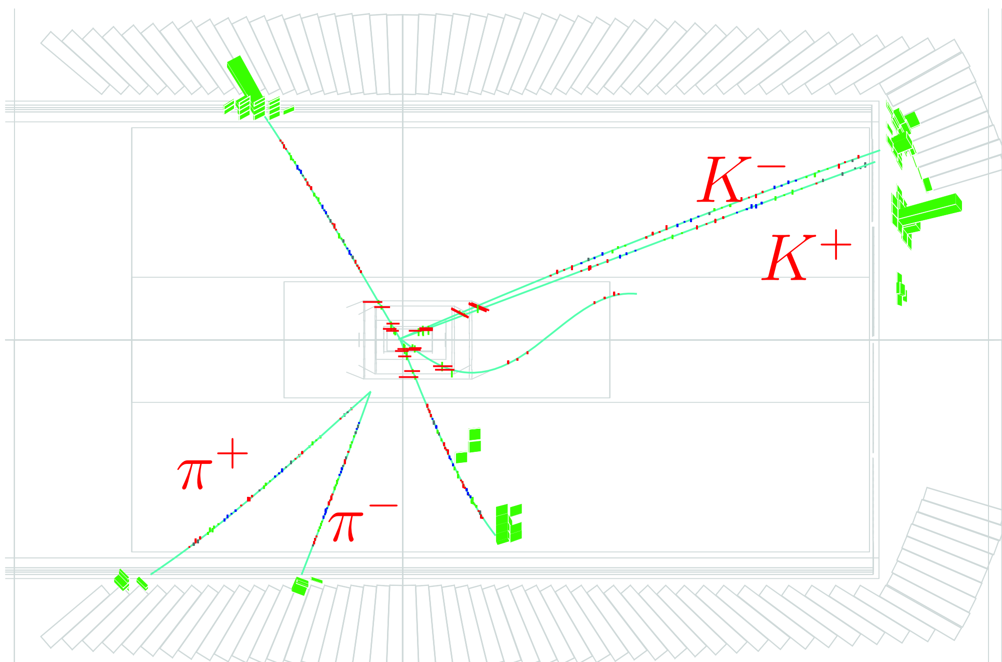


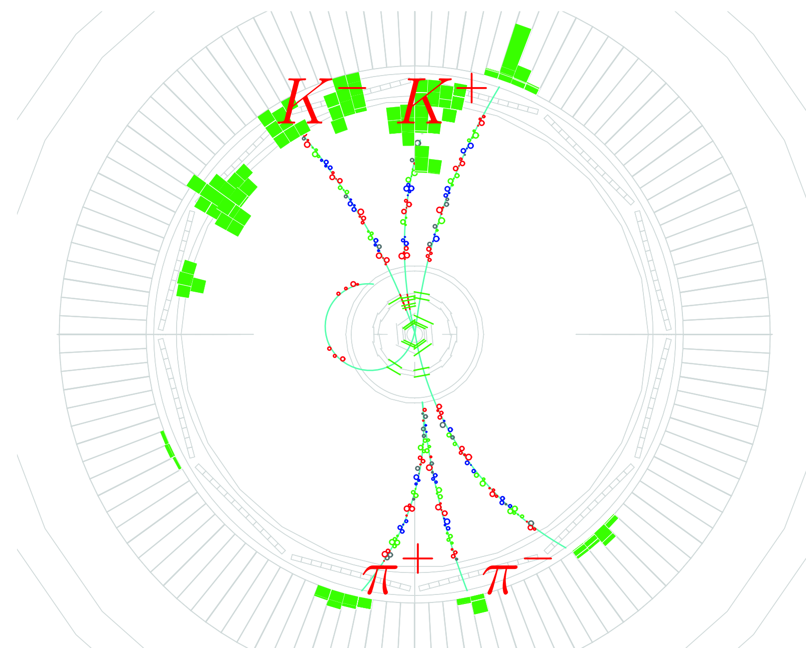
Detecting Particles

- Example: B meson decay products on BABAR at SLAC

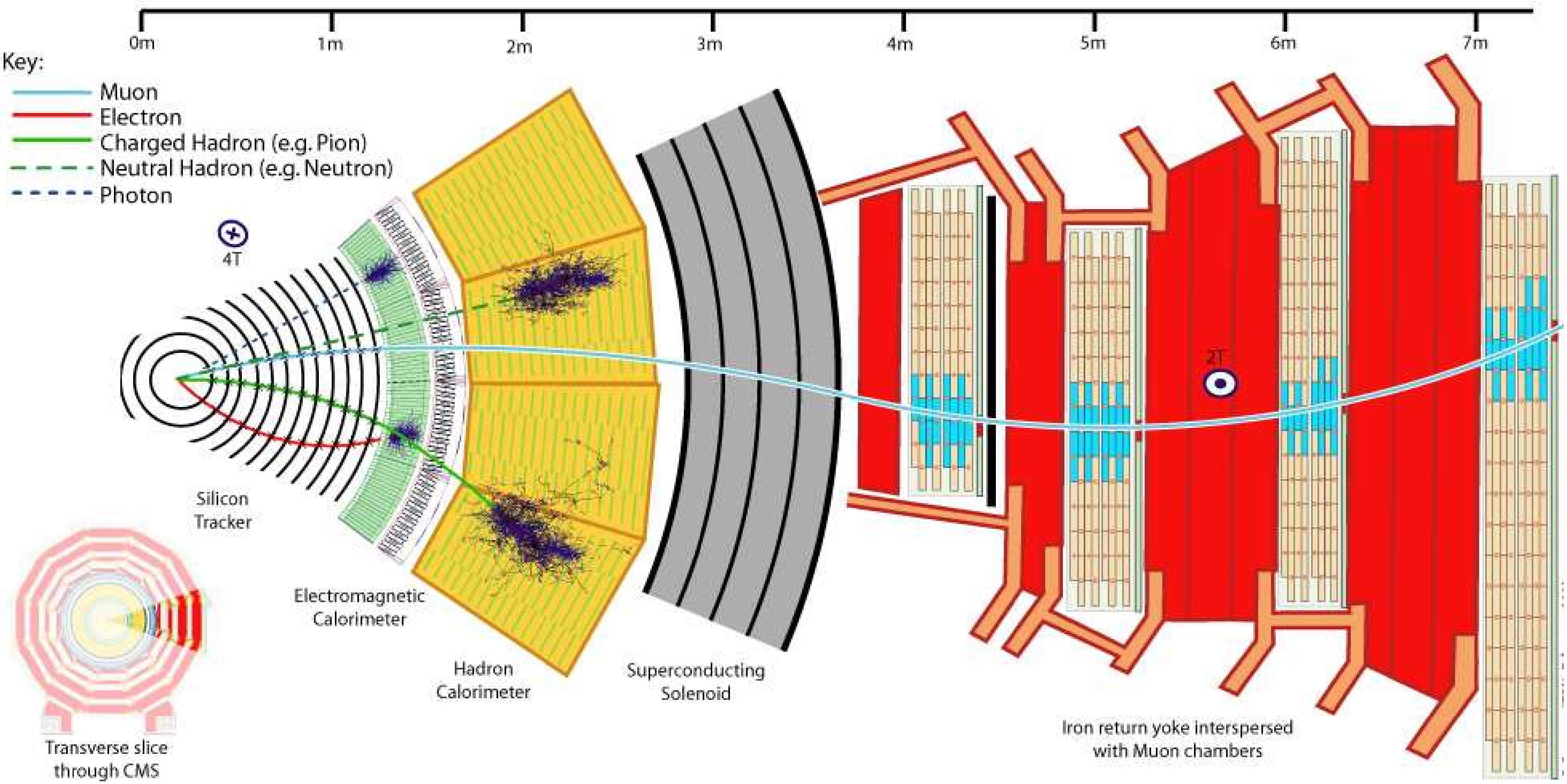
  e.g. $B^0 \to \phi K^0 \to (K^+K^-)(\pi^+\pi^-)$

- Different detector subsystems

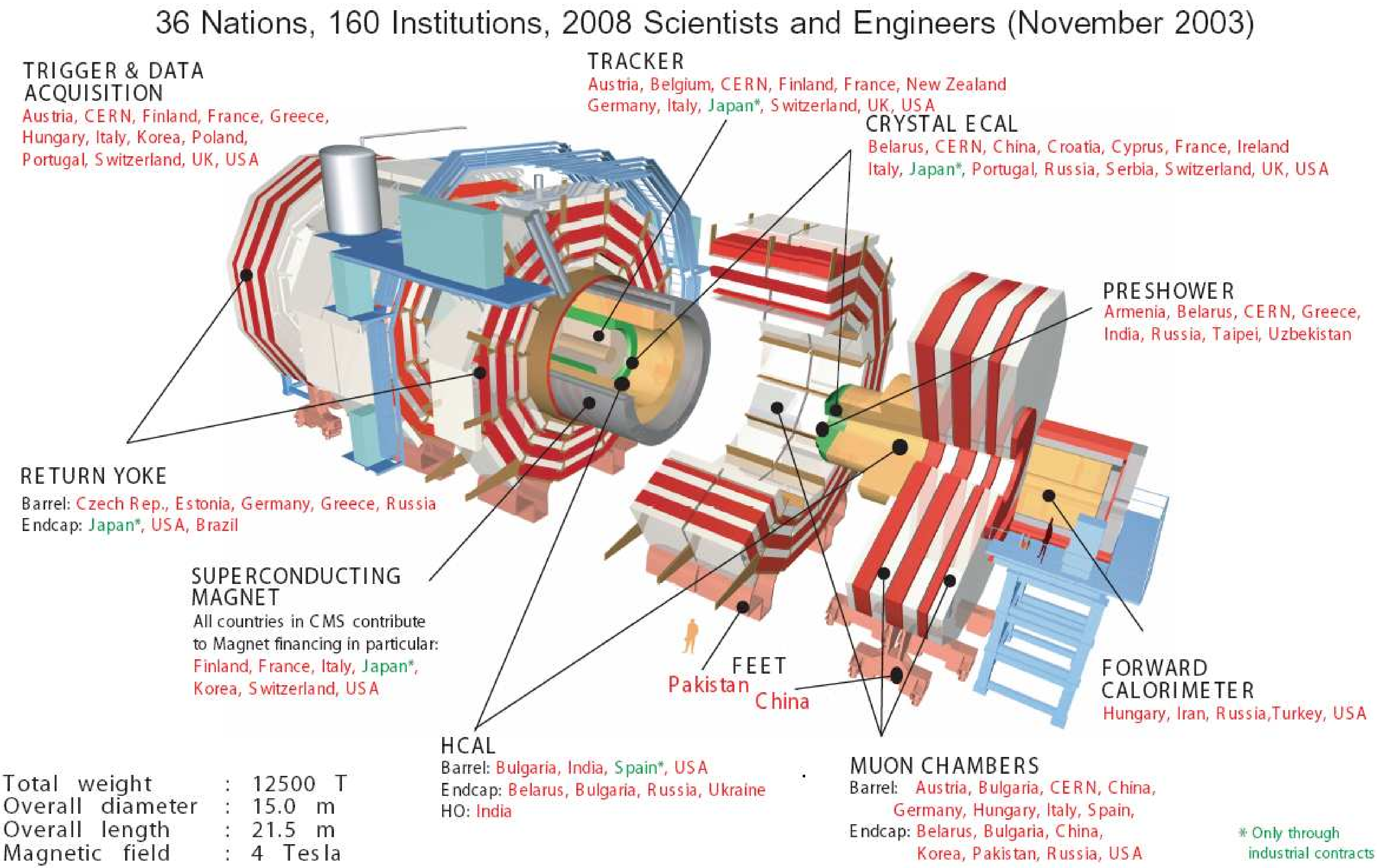




Detecting Particles at CMS

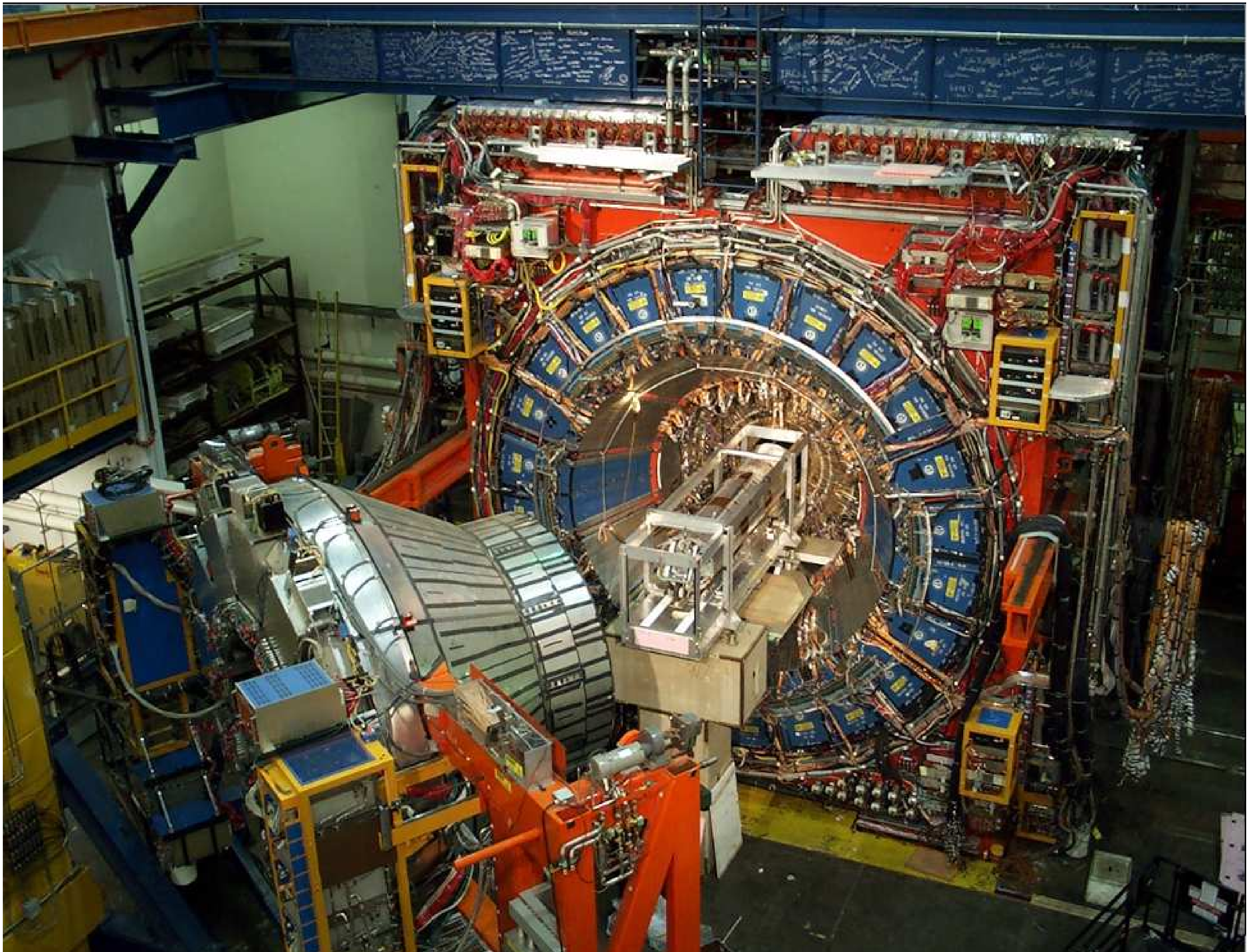


CMS Experiment

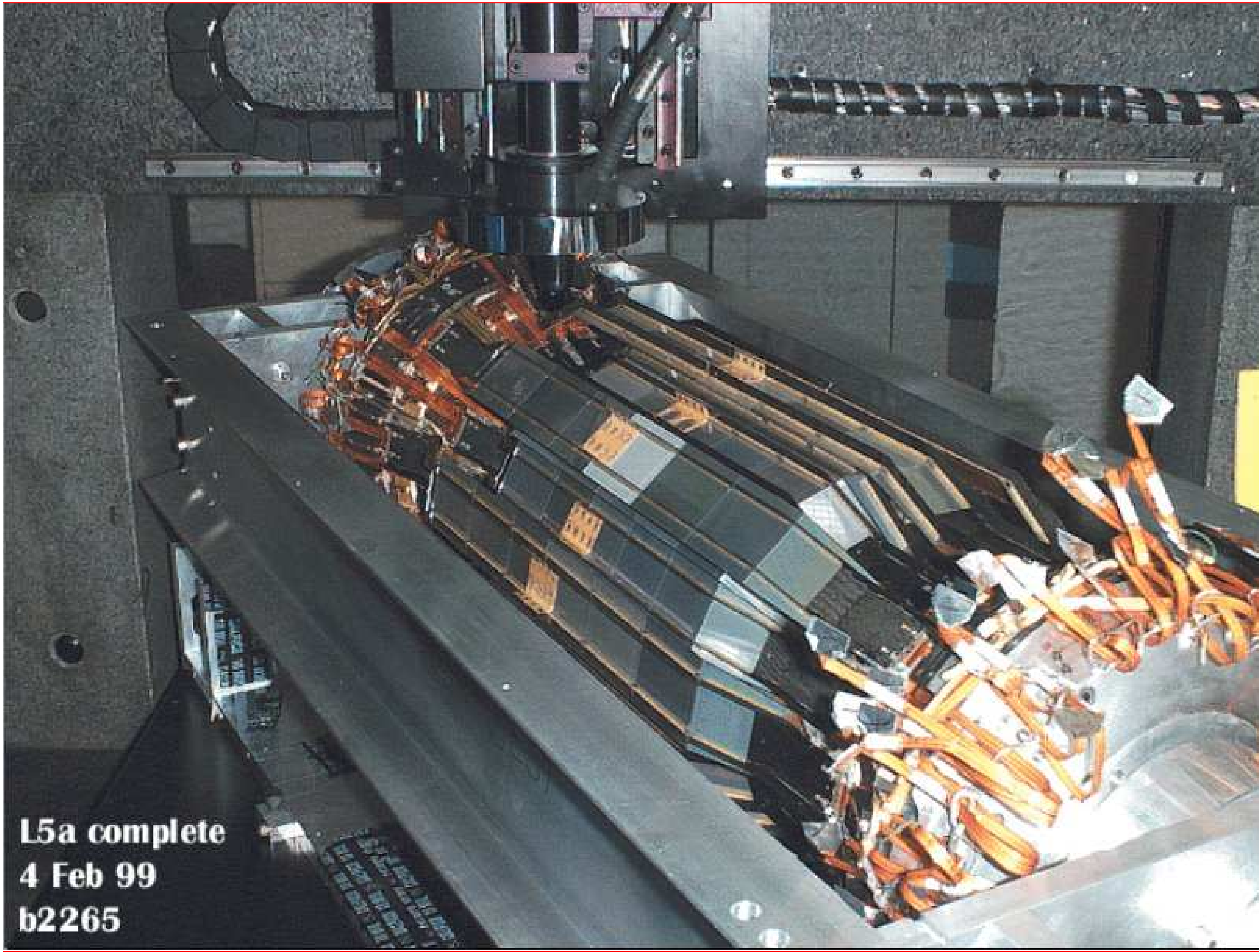


Total weight	:	12500 T
Overall diameter	:	15.0 m
Overall length	:	21.5 m
Magnetic field	:	4 Tesla

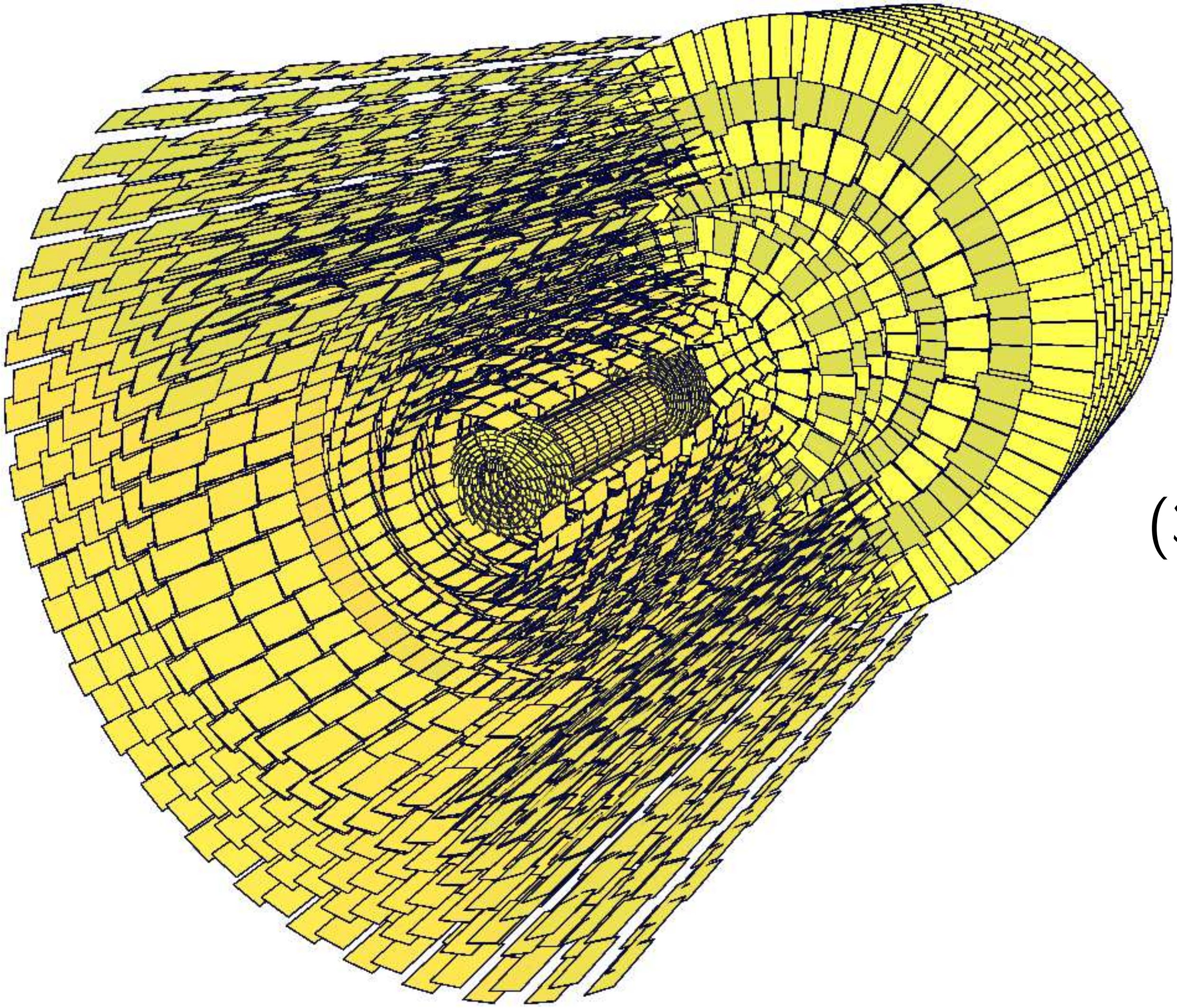
How It Looks: CDF Experiment



BABAR Silicon Vertex Detector Assembly



Modern Tracking Detectors

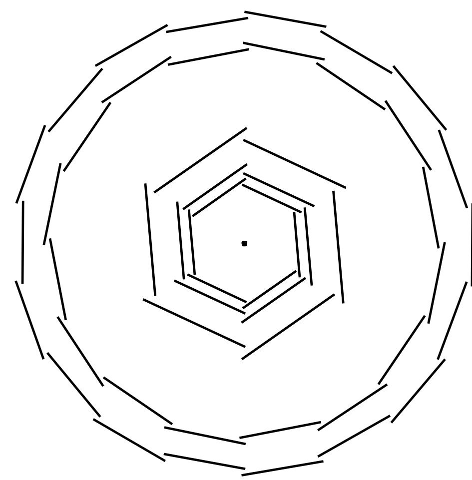


← CMS tracker

(>20,000 sensors)

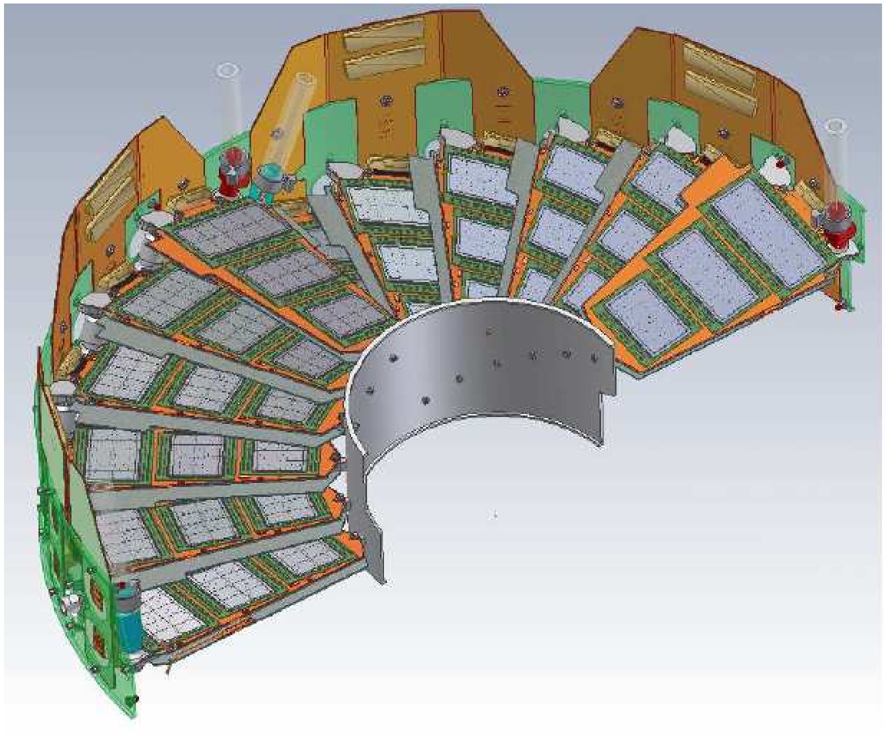
↓ BABAR silicon

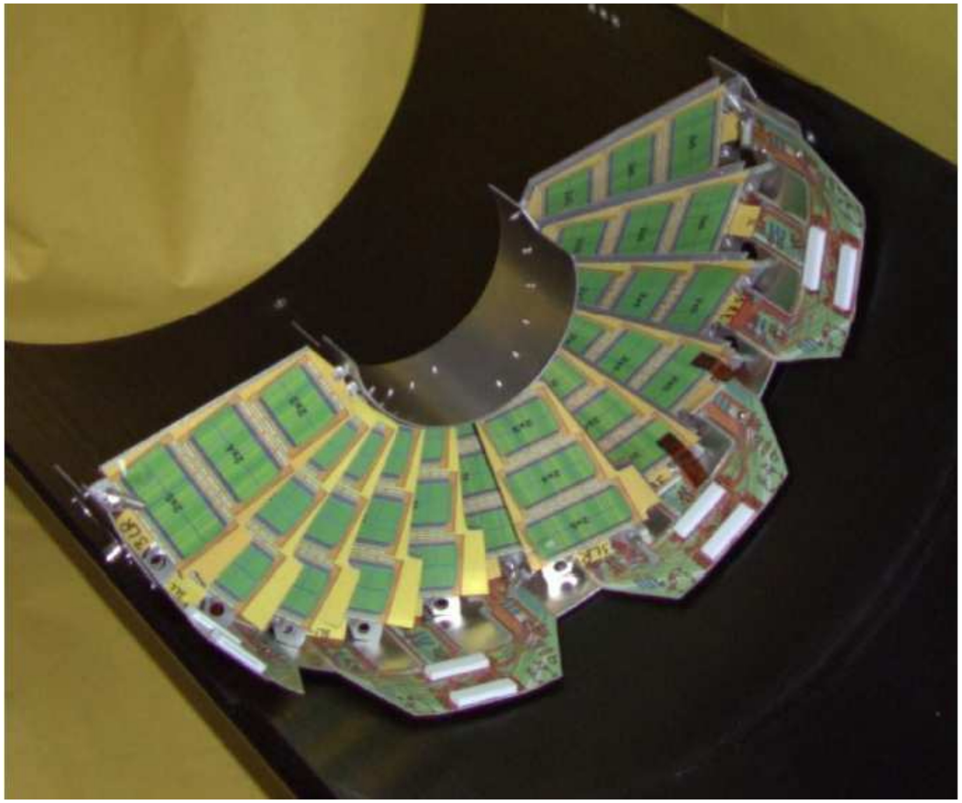
(340 sensors, R∼15cm)



Example: CMS Forward Pixel Detector

- CMS Forward Pixel (optical survey at Fermilab):
  - 3 or 4 sensors on a panel
  - 2 panels back-to-back in a blade = 7 sensors
  - 12 blades in a half-disk
  - half-disks in a cylinder,   cylinder in CMS



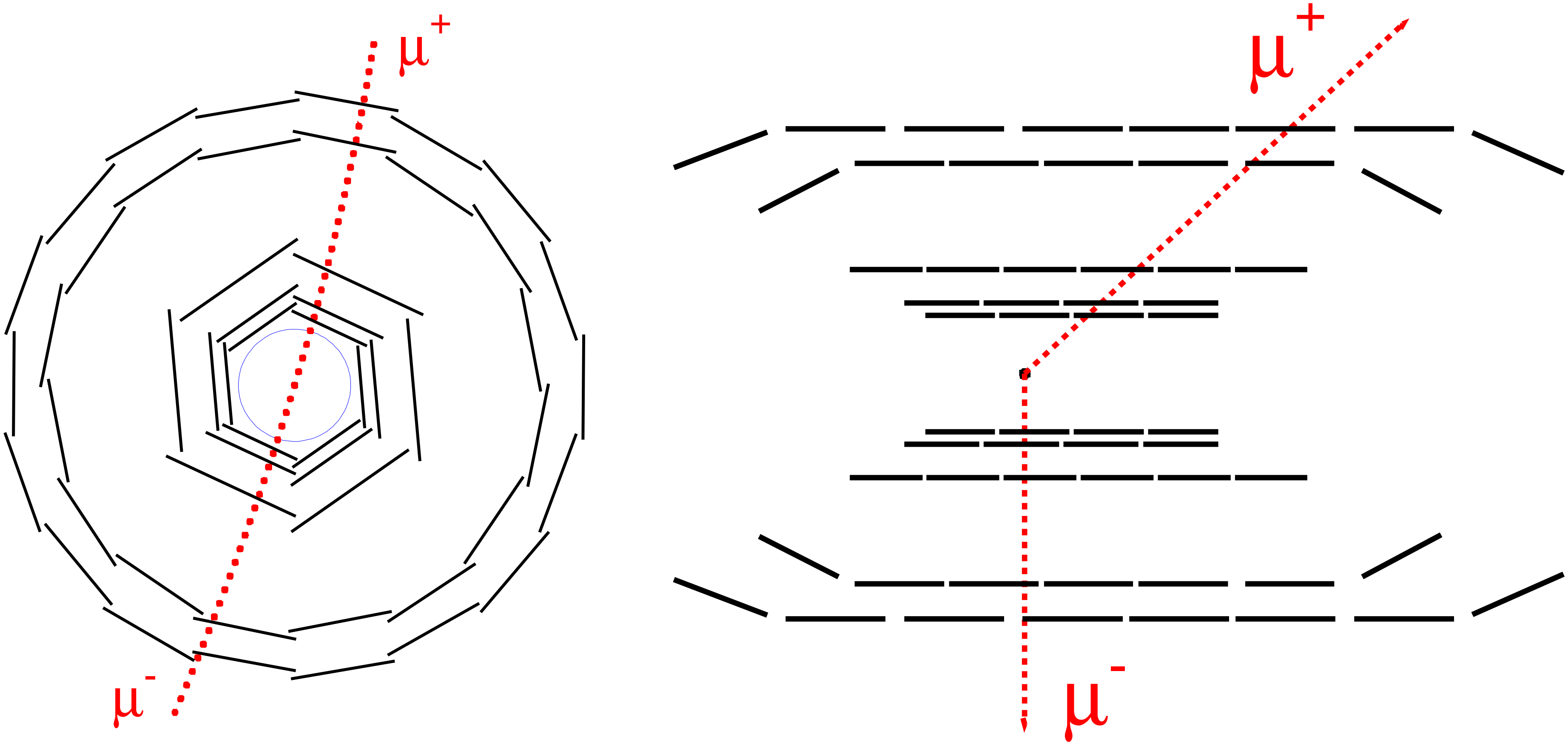


Need Good Vertex Resolution

- Silicon "alignment" with particle tracks

  crucial for precise particle detection: BaBar and CMS

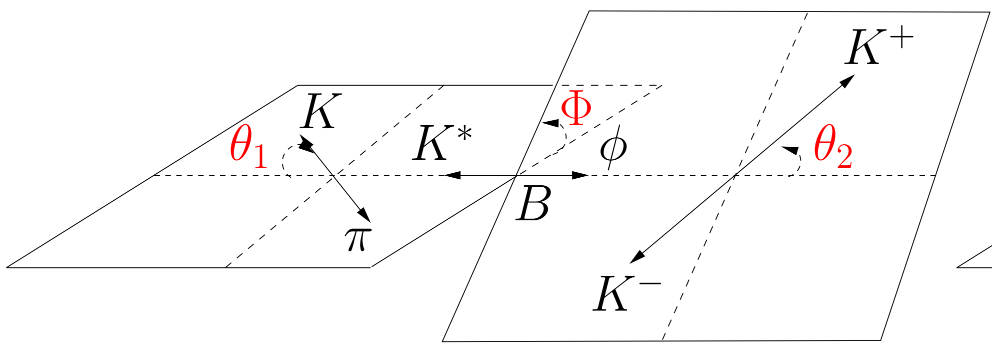
- Other technical aspects of detector operation

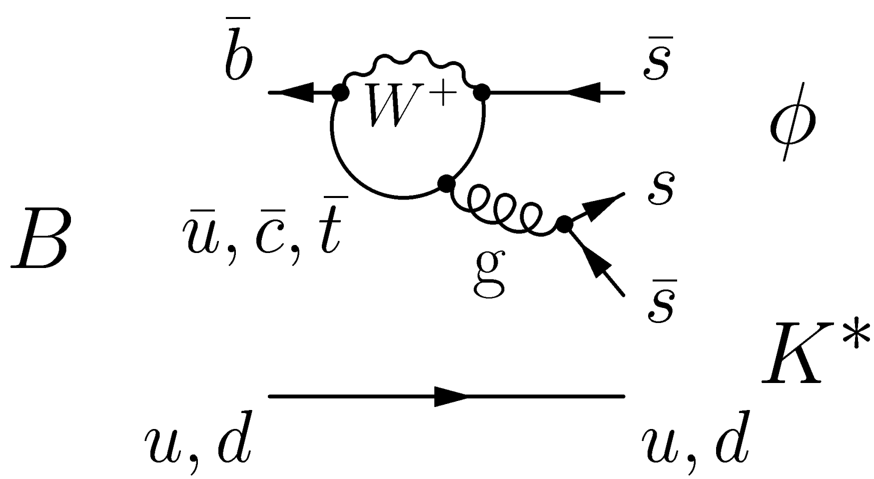


What We Study

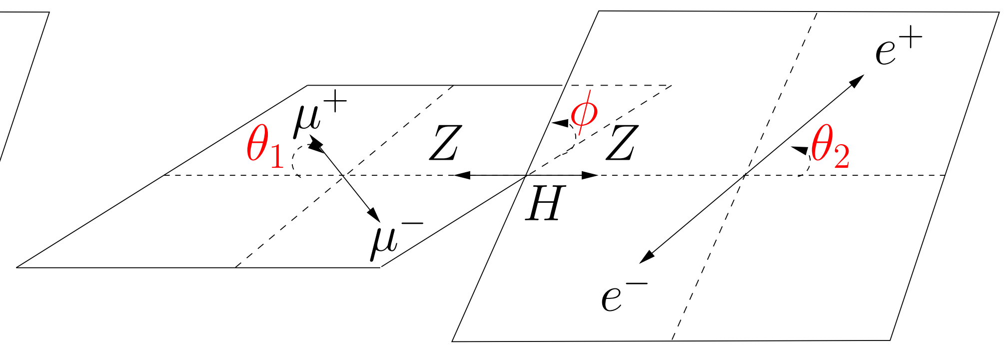
- Analysis of decay products:

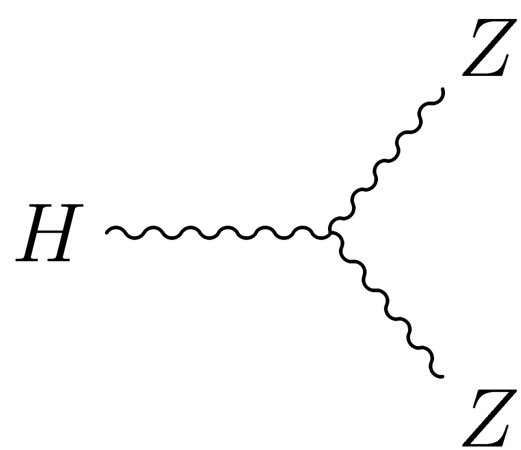
at BABAR





at CMS





More information (and some graphics in this talk) on particle physics:

http://particleadventure.org/particleadventure/

http://pdg.lbl.gov/

http://www2.slac.stanford.edu/vvc/

http://public.web.cern.ch/Public/Welcome.html

http://www.fnal.gov/

http://en.wikipedia.org/wiki/