Modern Physics

Thornton and Rex,
Chapter 14

Elementary Particles

Most of Modern Physics today is concerned with the extremes of matter:

- Very low temperatures, very large numbers of particles, complex systems
  □ Condensed Matter Physics

- Very high temperatures, very large distances
  □ Astrophysics, Cosmology

- Very small distances, very high energies
  □ Elementary Particle Physics
  (High Energy Physics)

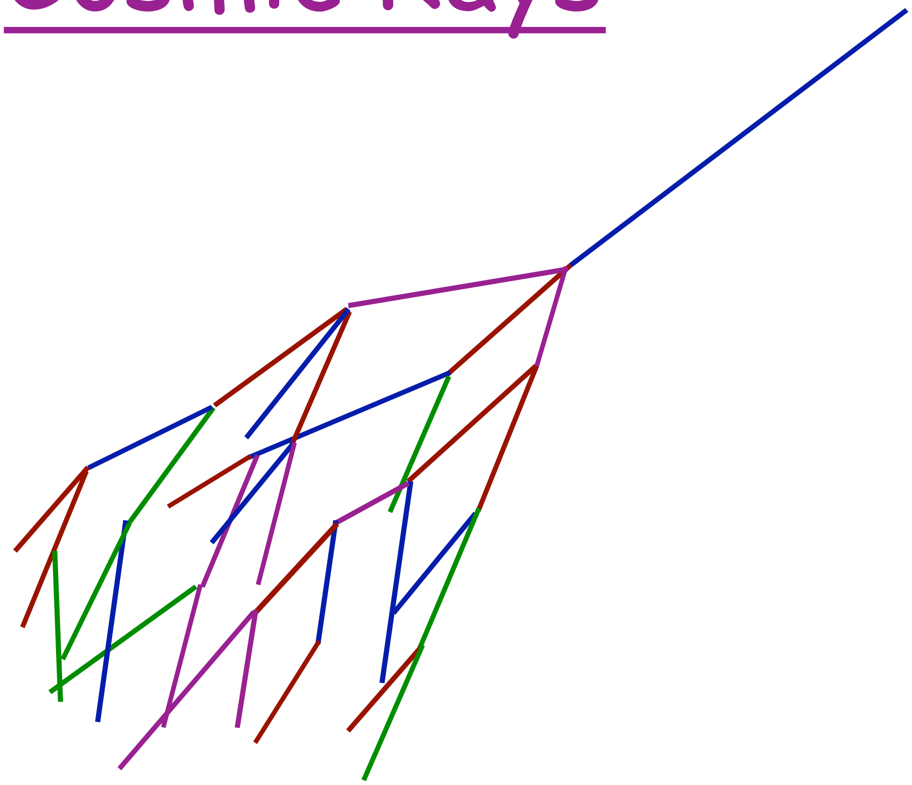
The fundamental particles (so far)

- Electron: charge -1, doesn't feel strong force
- Proton: charge +1, feels strong force
- Neutron: charge 0, feels strong force

- Positron: (the anti-electron)
  - Same mass and opposite charge as the electron.
  - Predicted in 1928 by Dirac based on relativistic generalization of the Schrodinger equation.
  - Discovered in Cosmic Rays in 1932.

(All particles have antiparticles. The anti-proton was discovered in 1956)

Cosmic Rays



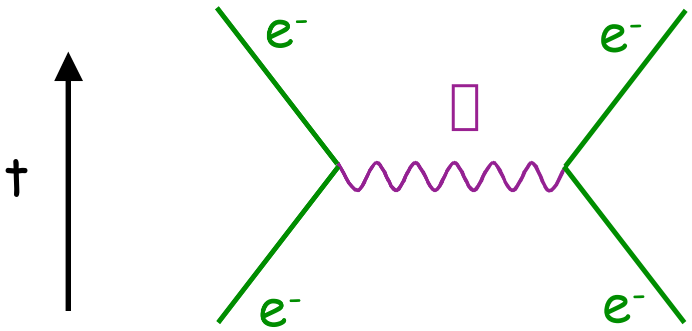
- Cosmic rays are very energetic particles, mostly protons, that come from interstellar space.
- They collide with particles in the earth's atmosphere, producing showers of very high energy particles.
- Their energies can be as high as 10^{21} eV, about a billion times the highest energy human-built accelerator.

The fundamental particles (so far) (continued)

- Neutrino:
  - charge 0, doesn’t feel strong force.
  - Predicted by Pauli in 1930, in order to conserve momentum in nuclear □ decay.
  - Discovered in 1956.

- Photon: charge 0, associated with the electromagnetic force

  The photon carries or mediates the EM force by being exchanged “virtually” between charged particles. This is represented in Feynman diagrams:



The prediction of the Pion

1935- Hideki Yukawa :

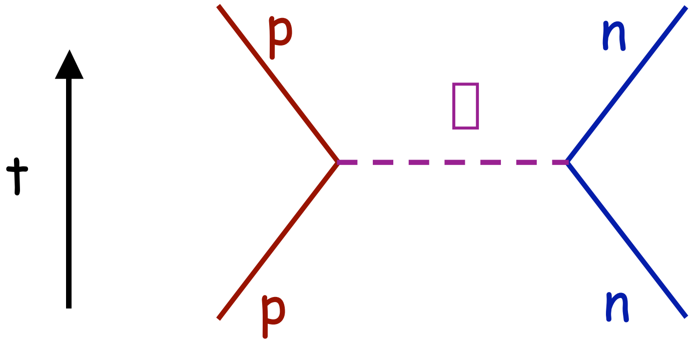
Based on analogy with the photon as mediator of the EM force, Yukawa argued that there also should be a particle that mediates the strong force.

The Mass of Yukawa's particle (the Pi meson or pion) can be estimated by the uncertainty principle:
Range of nuclear force is $\Delta x \sim 2$ fm.
A virtual pion travels this distance
in roughly time $\Delta t \sim \Delta x/c$.

The uncertainty in Energy necessary for the pion to exist for this amount of time is:

$$\Delta E \sim m_{\pi}c^2 \sim \hbar/\Delta t = hc/(2\ \mathrm{fm})$$
$$\sim 100\ \mathrm{MeV}$$

(note: $m_p > m_\pi > m_e$)



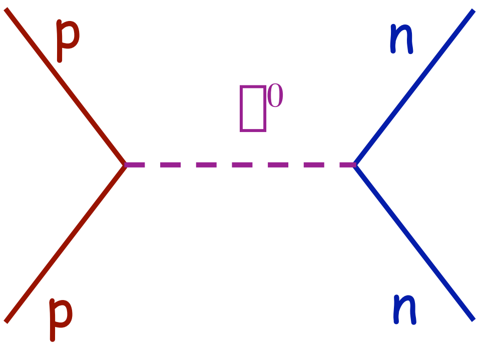
Only 2 years after Yukawa's prediction, a new particle was discovered in cosmic rays with just the right mass. <u>But it was not Yukawa's particle!!!</u> (more on this later.)

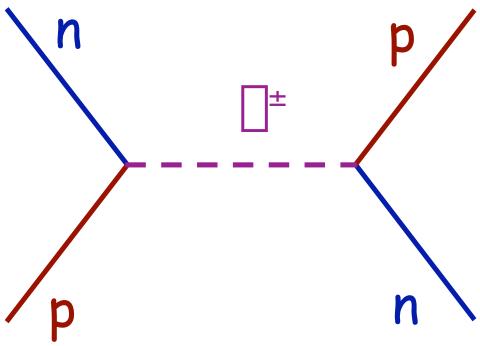
1947 - Yukawa's pion finally discovered in in cosmic rays.

It comes in three varieties:

- Charged pions $\square^{\pm}$, with charge ±1 and mass 140 MeV/c^2. They are anti-particles of each other. They live with a mean lifetime of 2.6×10^{-8} seconds before decaying to lighter particles.

- The neutral pion $\square^{0}$, with charge 0 and mass 135 MeV/c^2. It is its own anti-particle. It lives about 8.4×10^{-17} seconds before decaying into two photons.





More Particles

1938 - Muon discovered.

- Its mass was 106 MeV/c^2.
  (just right for Yukawa's particle)

- But subsequent experiments showed that it did not interact strongly, passing easily through dense matter.
  (not right for Yukawa's particle)

In many ways the muon (charge ±1) behaves like a heavy electron.

"Who ordered that?"
- I.I. Rabi

Many other new particles found in cosmic rays:

K-meson (Kaon) and the □-Baryon (heavier than the proton). These had some "Strange" properties, such as unexpectedly long life-times.

In 1950's more discoveries:
□-Baryons and □-mesons, and many more!

The particle zoo is getting crowded!
Some organization is needed.

Forces

Gravity: Important in everyday lives and in astronomical phenomena, but negligible for elementary particles.

Electromagnetic: Electricity and Magnetism unified into a single fundamental interaction by Maxwell. The force carrier is the photon, which can extend over long range.

Strong: Holds protons and neutrons inside nuclei. Very strong, but short range. Pion can be considered to carry the force, but a more fundamental description will come later.

Weak: A very short range force, which is responsible for □-decay of nuclei, and the decay of many other elementary particles.

Classification of Particles

There are three broad categores:

Leptons: Particles such as electrons, muons, and neutrinos, which do not feel the strong force. Leptons always have spin 1/2 $\hbar$.

Hadrons: Particles which do participate in strong interactions. (any spin)

Gauge particles (Gauge Bosons): The particles responsible for carrying the forces. The only one we have met so far is the photon.

Leptons

There are believed to be six leptons (along with their associated anti-leptons). They come in three generations (pairings of a charged lepton and a neutrino).

Generation	Particle	Charge	Mass
1	e	-1	0.5 MeV/c^2
	ν_e	0	~ 0
2	μ	-1	106 MeV/c^2
	ν_μ	0	~ 0
3	τ	-1	1784 MeV/c^2
	ν_τ	0	~ 0

- The τ (Tau) lepton was discovered by Martin Perl and collaborators at the Stanford Linear Accelerator (SLAC) in 1976.

- Heavier charged leptons decay to the lighter ones. For example:

$$\tau^{-} \rightarrow e^{-} + \nu_{\tau} + \bar{\nu}_{e}$$

(The τ can also have hadrons in its decay.)

- In the last couple years it has been verified that neutrinos do have a mass (although very small). This was seen indirectly through oscillations from one type of neutrino to another. These oscillations can only occur if the neutrinos have nonzero mass.

Hadrons

Hadrons feel the strong force. They can be further subdivided into Baryons and Mesons.

Mesons are hadrons with integral spin (mostly 0 or 1, but sometimes 2 or higher). Most have masses between that of the electron and proton. The pion (□), Kaon (K), and eta meson (□) are examples.

Baryons are hadrons with 1/2 integral spin (mostly 1/2, but sometimes 3/2 or higher). The lightest baryons are the nucleons (proton and neutron).

Force Particles

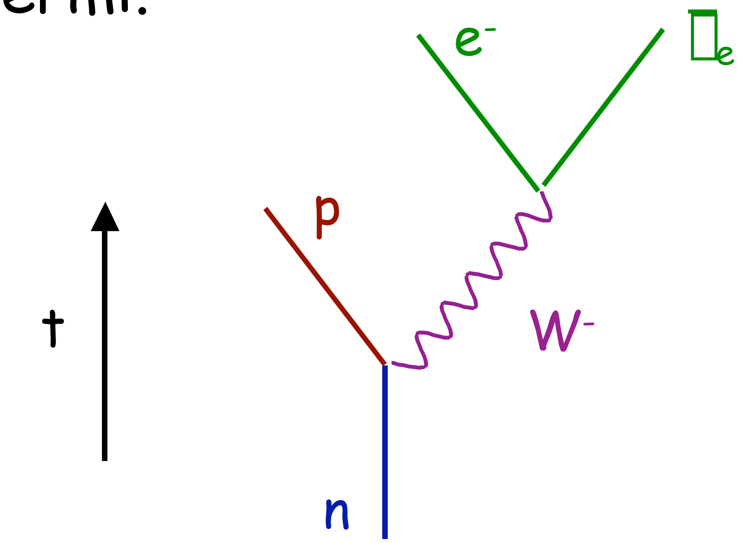
Each of the four basic forces is mediated by the exchange of a force particle.

Force	Particle
Electromagnetic	photon (□)
Strong nuclear	pion (□) *
Weak nuclear	Intermediate Boson ($W^{\pm}$, Z)
Gravity	Graviton

---

*The modern, more fundamental formulation of the strong force has the gluon (g) as the carrier, as we shall see.

1934 - W particles were first proposed by Fermi.



1982 - W± and Z particles discovered at CERN.

Gravitons not yet observed directly.

Conservation Laws

Certain quantities are always conserved. In addition to energy, momentum, and electric charge, they are:

Baryon number: The generalization of conservation of nucleons (each with baryon number 1). Anti-Baryons have baryon number -1. Mesons, leptons and gauge particles have baryon number 0.

$$e^- + p \;\square\; e^- + p + n + \bar{n}$$

$$\text{Baryon \#}\quad 0 + 1 = 0 + 1 + 1 + (-1)$$

Lepton number: The number of leptons <u>of each generation</u> is conserved. For example, e^- (electron) and $\square_e$ have electron number 1, e^+ (positron) and $\square_e$ have electron number -1.

Example, Muon Decay

$$\mu^{-} \rightarrow e^{-} + \nu_{\mu} + \bar{\nu}_{e}$$

muon # $1 = 0 + 1 + 0$

electron # $0 = 1 + 0 + (-1)$

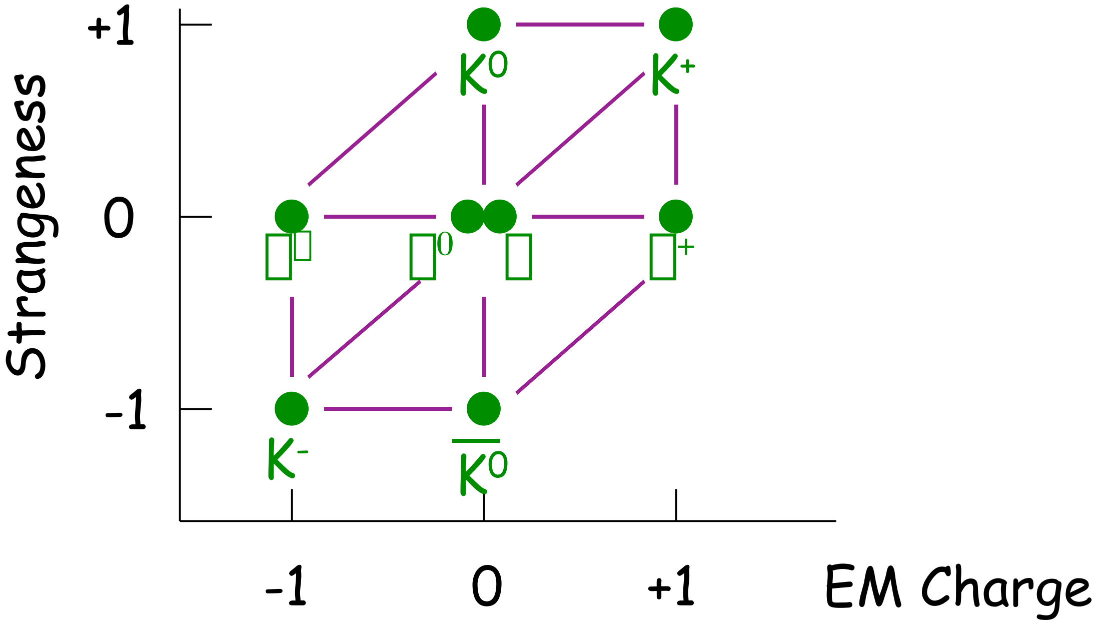
Strangeness: The K-mesons and □-baryons had "strange" properties. They were almost always produced in pairs, and their lifetimes were exceptionally long.

These properties could be explained by a new quantum number, Strangeness.

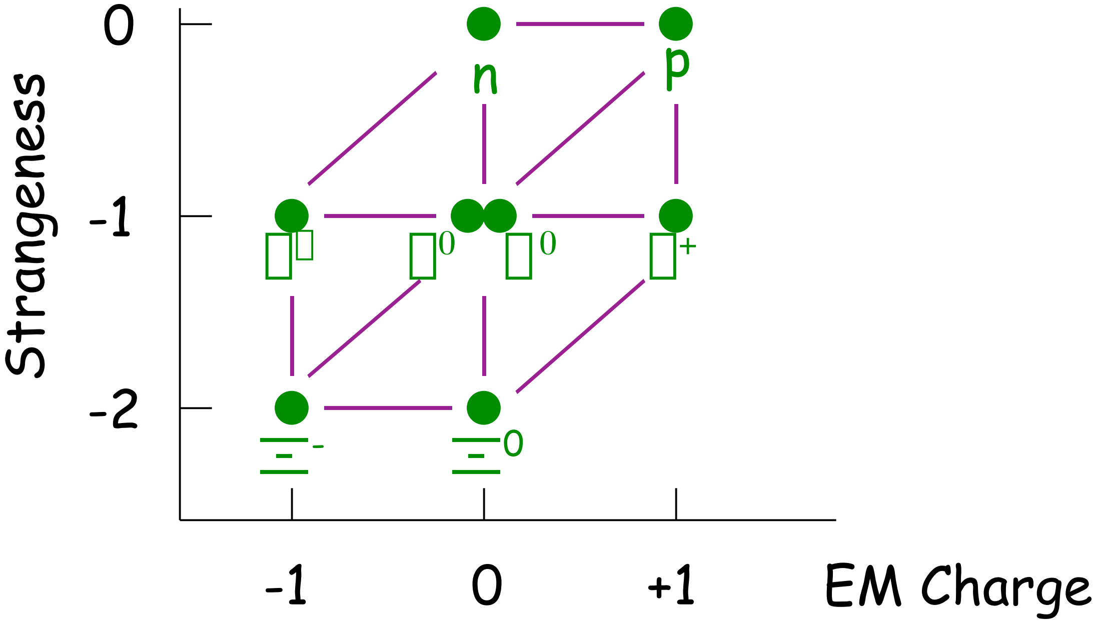
Strangeness is conserved by the EM and strong force, but not by the weak force. These particles are produced strongly, in strange - antistrange pairs. But they decay weakly with long lifetimes.

By plotting the strangeness vs. EM charge, many regularities were observed.

Mesons



Baryons



Quarks

Early 1960's - Murray Gell-Mann (and others) introduced the idea that the hadrons were built out of more fundamental objects, which he called "quarks".

Quarks have

- spin 1/2 and
- charges +2/3 and -1/3.

The protons and neutrons are made from "up" (+2/3) and "down" (-1/3) quarks.

A third "strange" quark (-1/3) accounts for "strangeness".

(Of course, there are also antiquarks, with opposite charges.)

Much later, three new (and heavier) quarks were discovered:

"Charm" (+2/3) was discovered in 1974 (by Ting and Richter).

"Bottom" (-1/3) was discovered in 1977 (by Lederman).

"Top" (+2/3) was discovered in 1995 (by D0 and CDF collaborations at Fermilab).

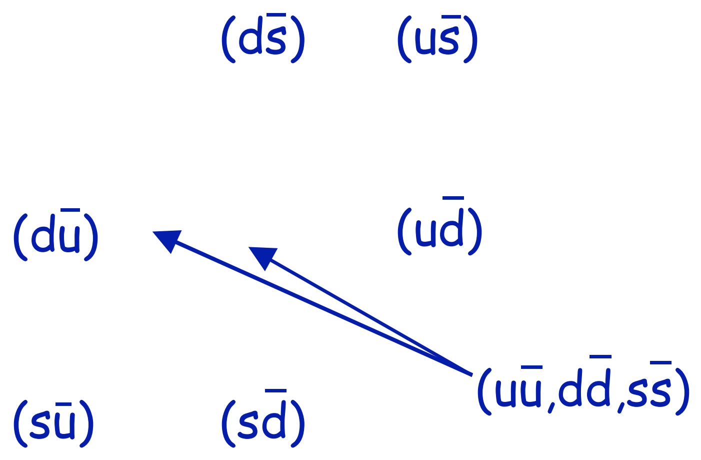
Just like the leptons, the quarks pair up into 3 generations.

Quarks

Generation	Particle	Charge	Mass
1	up (u)	+2/3	~3 MeV/c^2
	down (d)	-1/3	~7 MeV/c^2
2	charm (c)	+2/3	~1.3 GeV/c^2
	strange (s)	-1/3	~100 MeV/c^2
3	top (t)	+2/3	~174 GeV/c^2
	bottom (b)	-1/3	~4.3 GeV/c^2

The EM and strong forces cannot change the "flavor" of the quark, The weak force can change the sign of the quark, and can even change the generation (but with a suppression factor).

Quark Structure of Hadrons



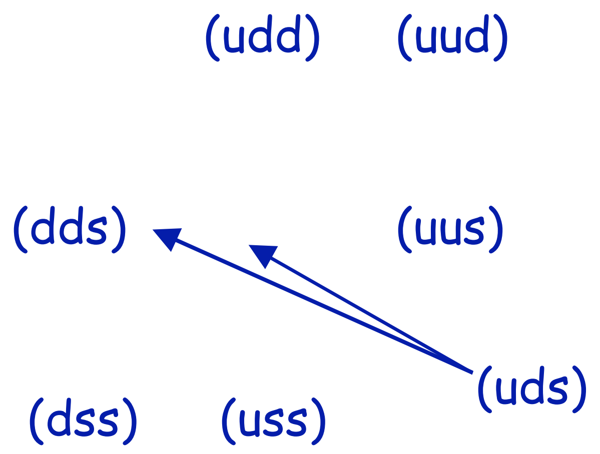
$(d\bar{s})$ $(u\bar{s})$

$(d\bar{u})$ $(u\bar{d})$

$(u\bar{u}, d\bar{d}, s\bar{s})$

$(s\bar{u})$ $(s\bar{d})$

Meson = quark + anti-quark



(udd) (uud)

(dds) (uus)

(uds)

(dss) (uss)

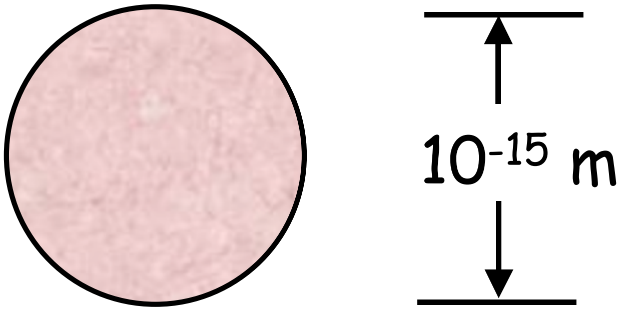
Baryon = 3 quarks

Evidence for Quarks

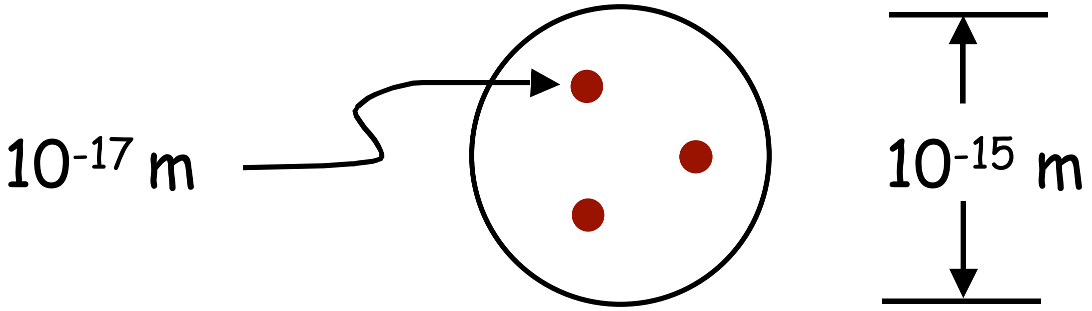
- Quarks were originally suggested as a mathematical invention to describe the properties of the hadrons.

- But later, evidence from scattering experiments showed that the quarks have a physical meaning as constituents of the hadrons.

1950's - Hofstadter at SLAC scattered electrons off protons, and found the proton to be a smooth, featureless sphere of about 10^{-15} meters.



1969 - a group (led by Friedman, Kendall, and Taylor) at SLAC did the same, but now with much higher energies of 20 GeV.   They found that at these high energies the electron appeared to scatter off point-like objects within the protons ===> The quarks!



Problems with the Quark Model

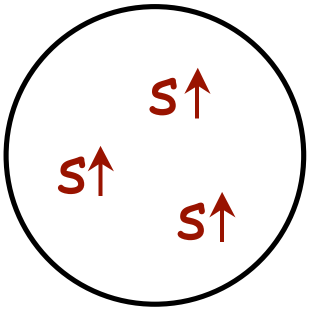
1. Quarks have not been directly observed.
2. The quark hypothesis seems to conflict with the Pauli exclusion principle.

Let's look at problem 2 first.

COLOR

There exists a baryon, $\square^-$, whose spin is 3/2, whose charge is -1, and whose strangeness is -3. The quark model then says that the state is

$\square^{\square}$

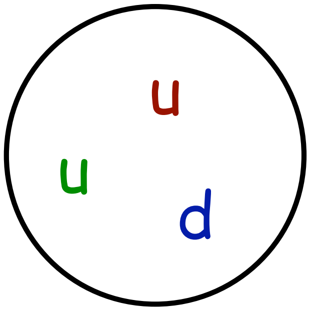


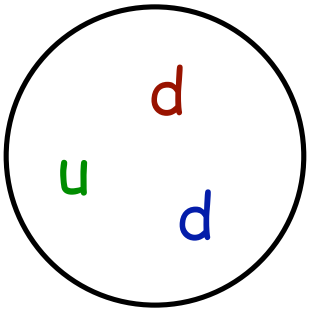
This is forbidden by the Pauli exclusion principle!

The resolution is a new quantum number called color (having nothing to do with the colors that we see). Each quark must be red, green, or blue and each anti-quark must be anti-red, anti-green, or anti-blue.

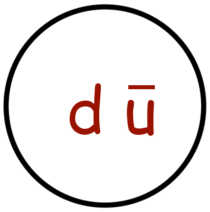
Furthermore, all hadrons must be formed out of color-less combinations of quark and/or anti-quarks.

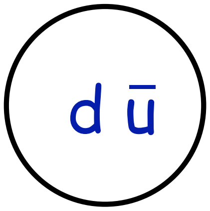
Thus, baryons are made out of 1 red quark, 1 green quark, and 1 blue quark:

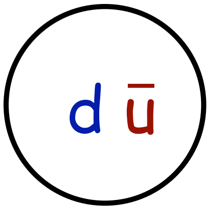
p


n


Mesons are made out of colored quark - anticolored antiquark combination:

□□


or


but not


Problem 2 solved.

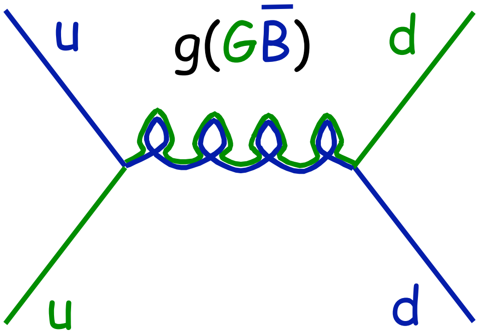
Quantum Chromodynamics

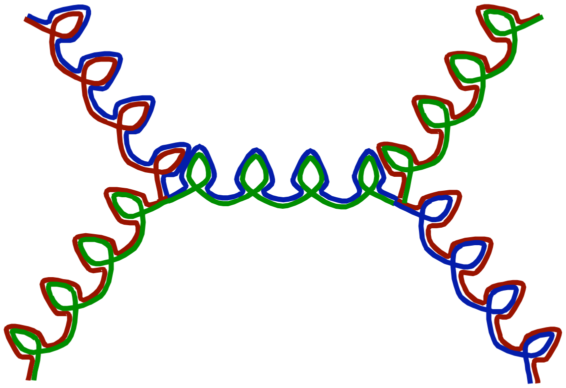
The addition of the color quantum number suggested to theorists a new explanation of the strong force!

Quantum Chromodynamics (QCD) is a generalization of Quantum Electrodynamics (QED). The colors play the role of the charge. The force carriers (analogous to the photon) are called gluons, and they carry color-anticolor charges. There are 8 gluons:

$$(R\overline{G}, G\overline{B}, B\overline{R}, G\overline{R}, R\overline{B}, B\overline{G}, \underbrace{R\overline{R}, B\overline{B}, G\overline{G}}_{\text{Only 2 combinations are gluons}})$$

Force between quarks and also between gluons:





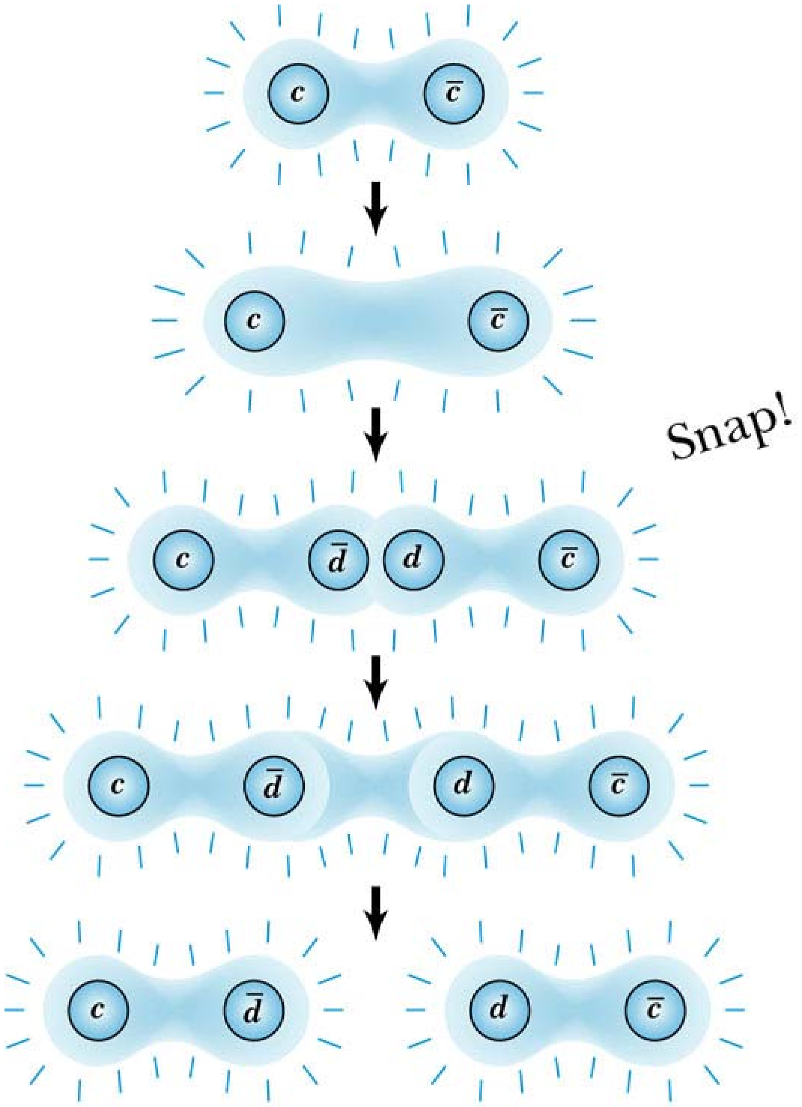
Due to the gluon self-coupling, the force of attraction between quarks increases as the separation between the quarks increases.

It would take an infinite amount of energy to separate two quarks. This concept is called confinement.

Quarks and gluons must combine into colorless objects. It is impossible to see a free colored quark.

Energetically favorable to create quark antiquark pair on which gluon flux can terminate

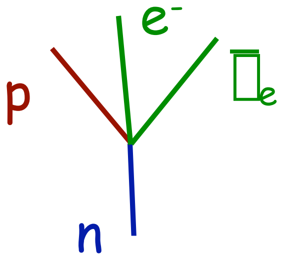
Energy is lowered by shortening the flux tube lengths



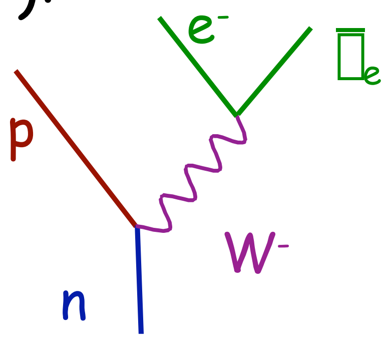
The Weak Force

- Responsible for β-decay.

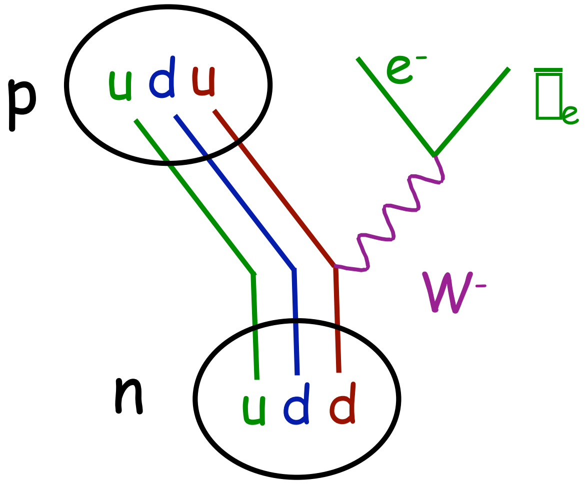
$n \rightarrow p + e^{-} + \bar{\nu}_e$



- In 1934, Fermi suggested that this occured through the exchange of a charged gauge particle (W):



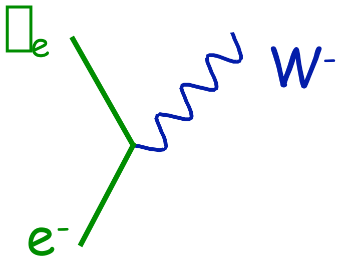
or in terms of quarks:

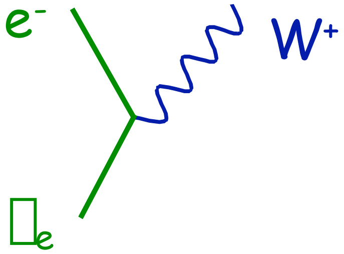


The weakness of the force is due to the fact that the W is very heavy (80 GeV).

Electroweak Unification

- Early 1960's Sheldon Glashow showed that the EM force could be "unified" with the weak force.





$$\begin{pmatrix} e^- \\ □_e \end{pmatrix} \quad □ \quad \begin{pmatrix} & W^- \\ W^+ & \end{pmatrix} \begin{pmatrix} e^- \\ □_e \end{pmatrix}$$

□, Z^0

□, Z^0

The $W^\pm$ and Z^0 were predicted to be very heavy ($M_{W^\pm} = 80$ GeV, $M_Z = 91$ GeV) and were discovered at CERN in 1982.

A problem:

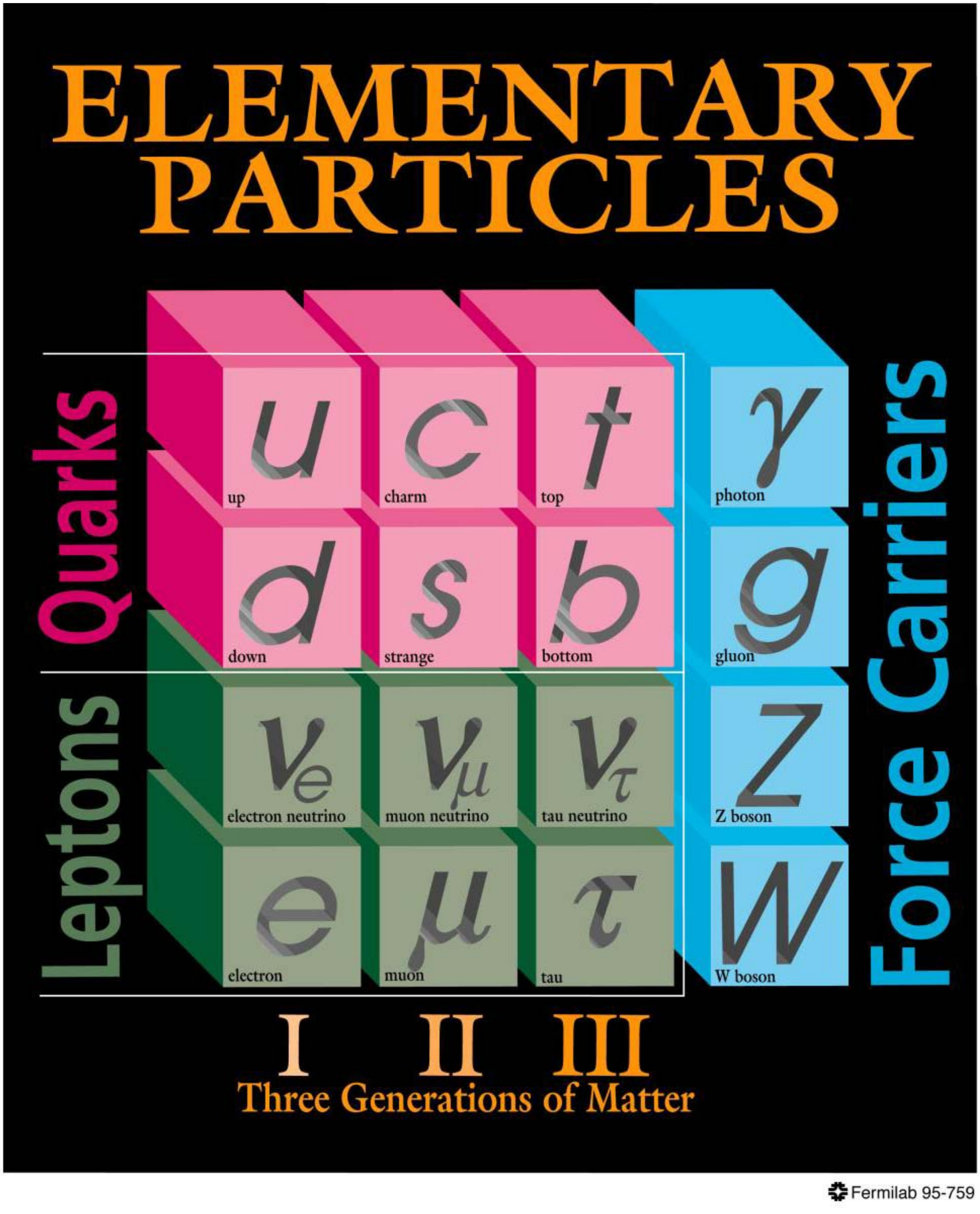
- The photon (□) is massless
- The W and Z are massive

□ The symmetry between them must be broken.

A mechanism for this was proposed by Steven Weinberg and Abdus Salam.

Glashow, Weinberg, and Salam won the Nobel Prize in 1979.

The simplest model for symmetry breaking predicts a single neutral particle, called the Higgs Boson. It is presently being searched for at Fermilab.



ELEMENTARY PARTICLES

	I	II	III	Force Carriers
Quarks	u up	c charm	t top	γ photon
Quarks	d down	s strange	b bottom	g gluon
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z Z boson
Leptons	e electron	μ muon	τ tau	W W boson

Three Generations of Matter

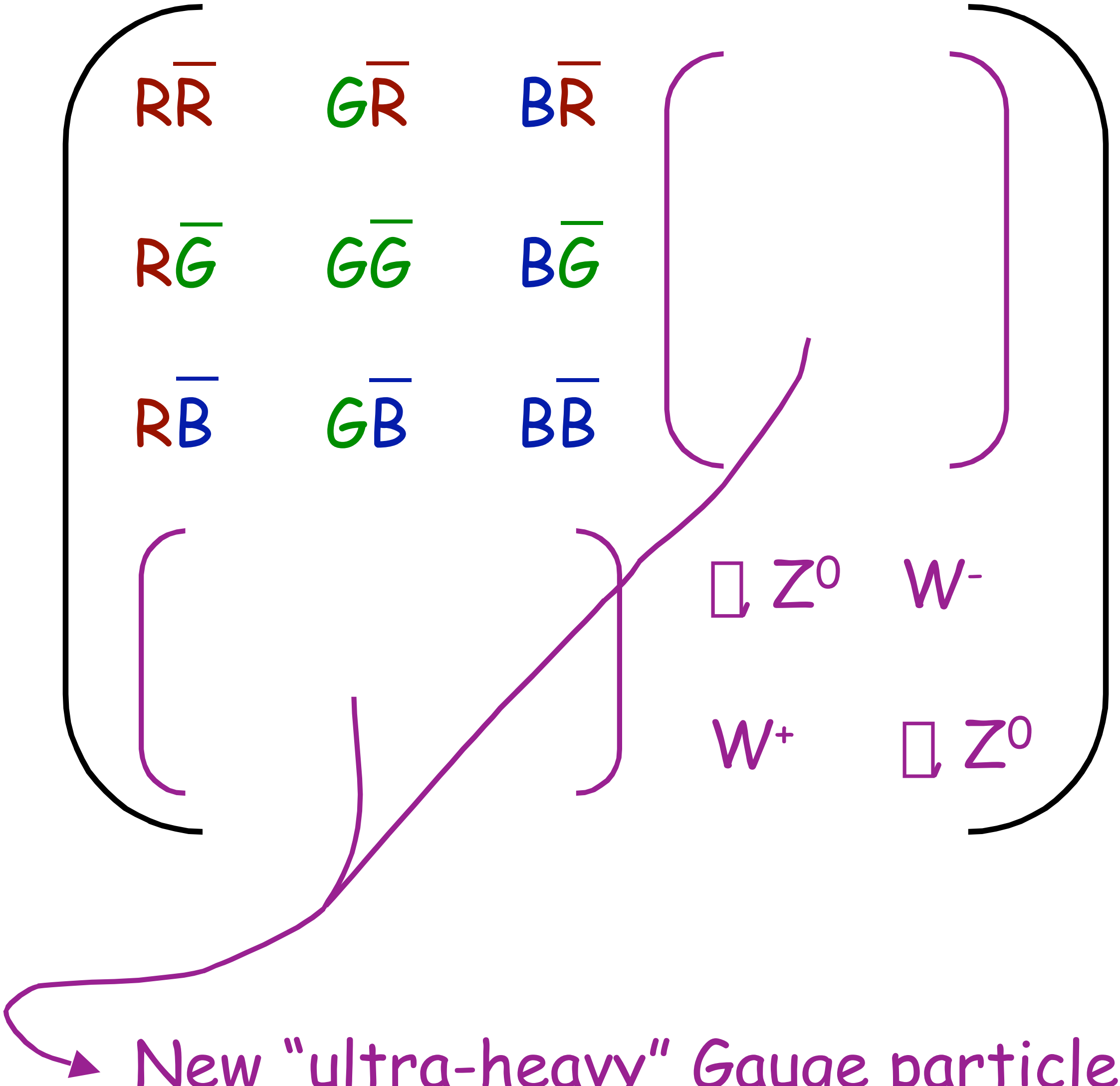
Fermilab 95-759

Grand Unified Theories

Grand Unified Theories (GUTS) are an attempt to extend ElectroWeak unification to include QCD (strong force), and eventually gravity.

GUTS usually predict new very massive particles, which can lead to Baryon-number-violating processes, such as Proton decay. This decay should be very rare and, as yet, has not been observed.

“SU(5) Unification”



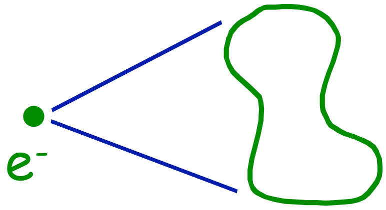
New “ultra-heavy” Gauge particles, which can lead to proton decay.

The unification of the other forces with gravity is very difficult.

(Gravity and quantum mechanics are difficult to reconcile. Einstein spent the last 35 years of his life devoted to this goal, without success).

Current ideas include:

String Theory: All types of particles are just different excitations of one type of (very tiny) string.



Supersymmetry: All particles come in (integer spin)-(1/2 integer) spin partners.

Extra-dimensions: More than 4 space-time dimensions.

Unanswered Questions

1. Why 3 generations?
2. Why the masses of the particles?
3. How is electroweak symmetry broken? Is there a single Higgs particle or something else?
4. Do the forces unify and how?
5. Are Strings, Supersymmetry, extra-dimensions real?
6. Why is the universe essentially all matter, but no anti-matter?
7. Are there other connections to the early universe, shortly after the big bang?

Collider Physics at Fermilab

Accelerators
Detectors
MSU’s involvement
W and top quark production

Particle Accelerators

First, radioactive sources, then cosmic rays - both difficult, rare, and uncontrolled as "beams"

- Rather, rely on electromagnetism to accelerate charged particles and to bend them where they are to go...

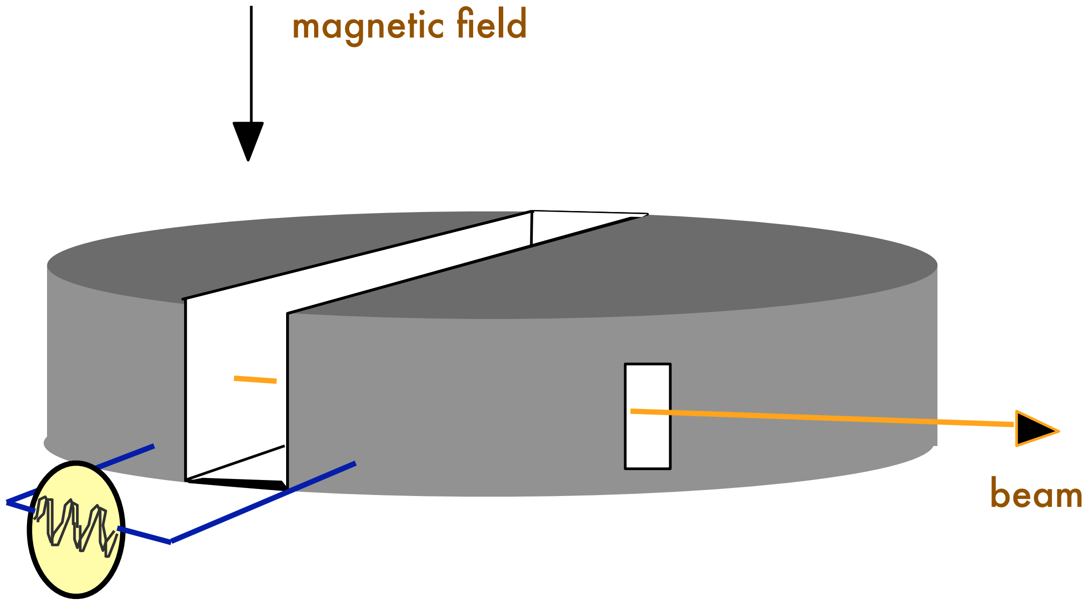
  electric fields accelerate

  magnetic fields bend

  a television set is a little particle accelerator

- Artificial beams were first produced in the late 1940's in the form of cyclotrons

now, these accelerators are used for nuclear physics research



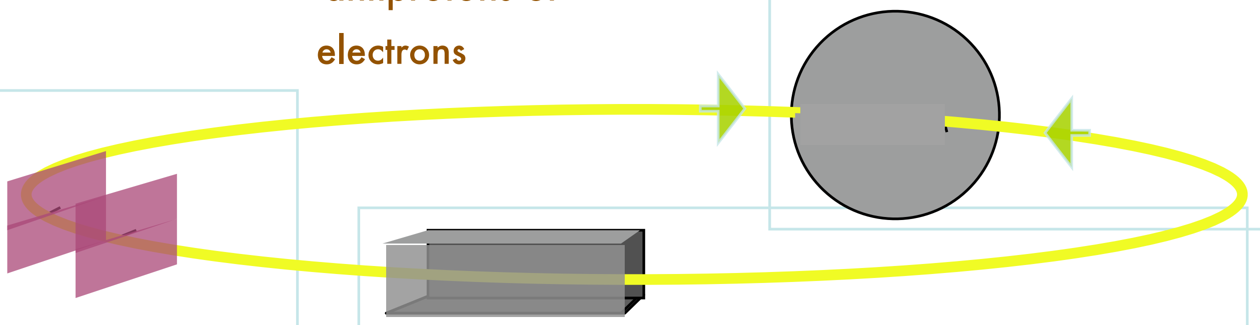
The best example in the world is the National Superconducting Cyclotron Laboratory here on campus

cont.

- Higher energies and particle fluxes required a different approach, the synchrotron

  much higher energies are possible

a cartoon of a colliding beam synchrotron accelerator



a detector sits inside the tunnel where the beams are forced to collide head-on

antiprotons or electrons

protons or positrons

electric field cavity accelerates particles in the beampipe

magnets all around the ring keep the beam going in a circle

what is Fermilab?

it's many things to me…

it's a dedicated scientific community

made up of:

- 1200 physicists, engineers, and staff
- >1000 faculty, post docs, and students
- from > 80 US & ~20 foreign institutions

it's an amazing scientific instrument

consisting of:

- A time machine
- A particle accelerator for antirotating beams of protons and antiprotons
- hand-made vehicles to explore the current and the very early universe
- A source of high energy/intensity beams of kaons and neutrinos

it's a beautiful single-purpose DOE national lab

located at:

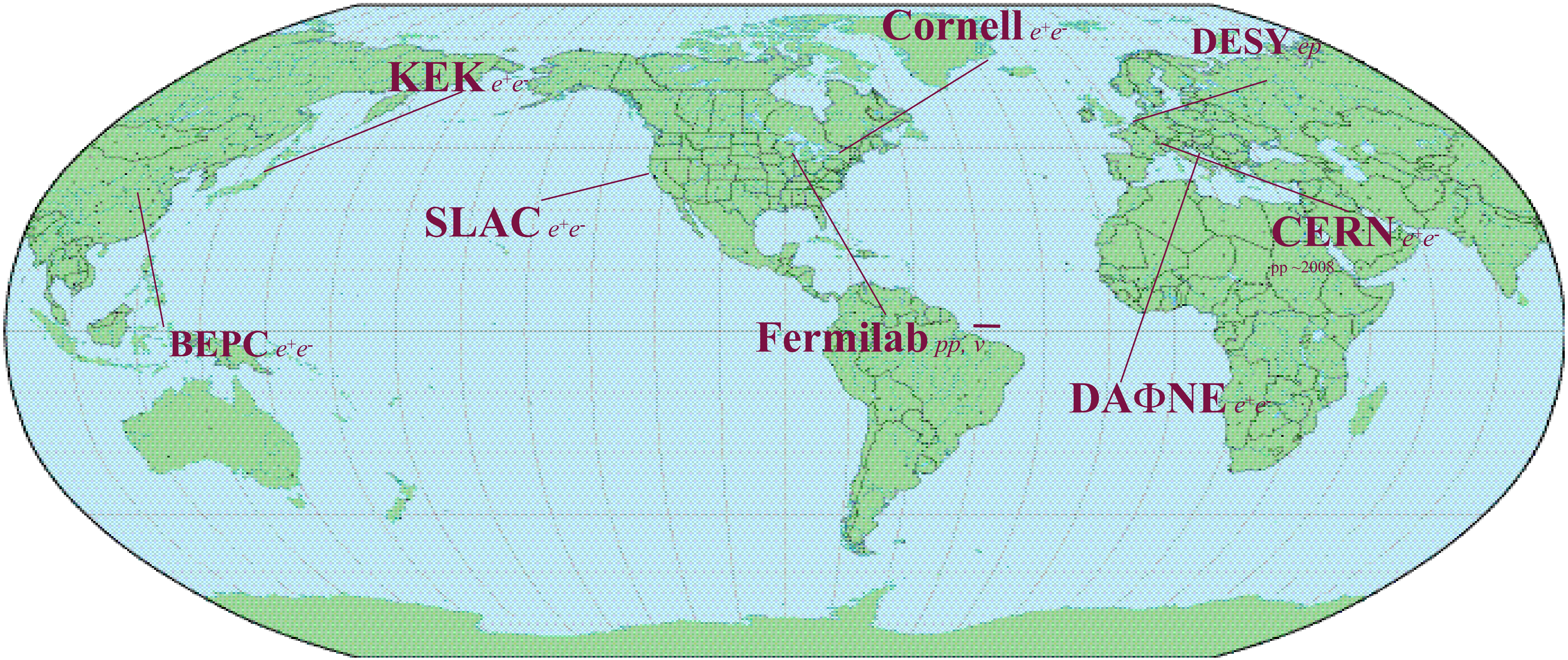
- real space: 60 mi west of Chicago

a truly inspiring place to work

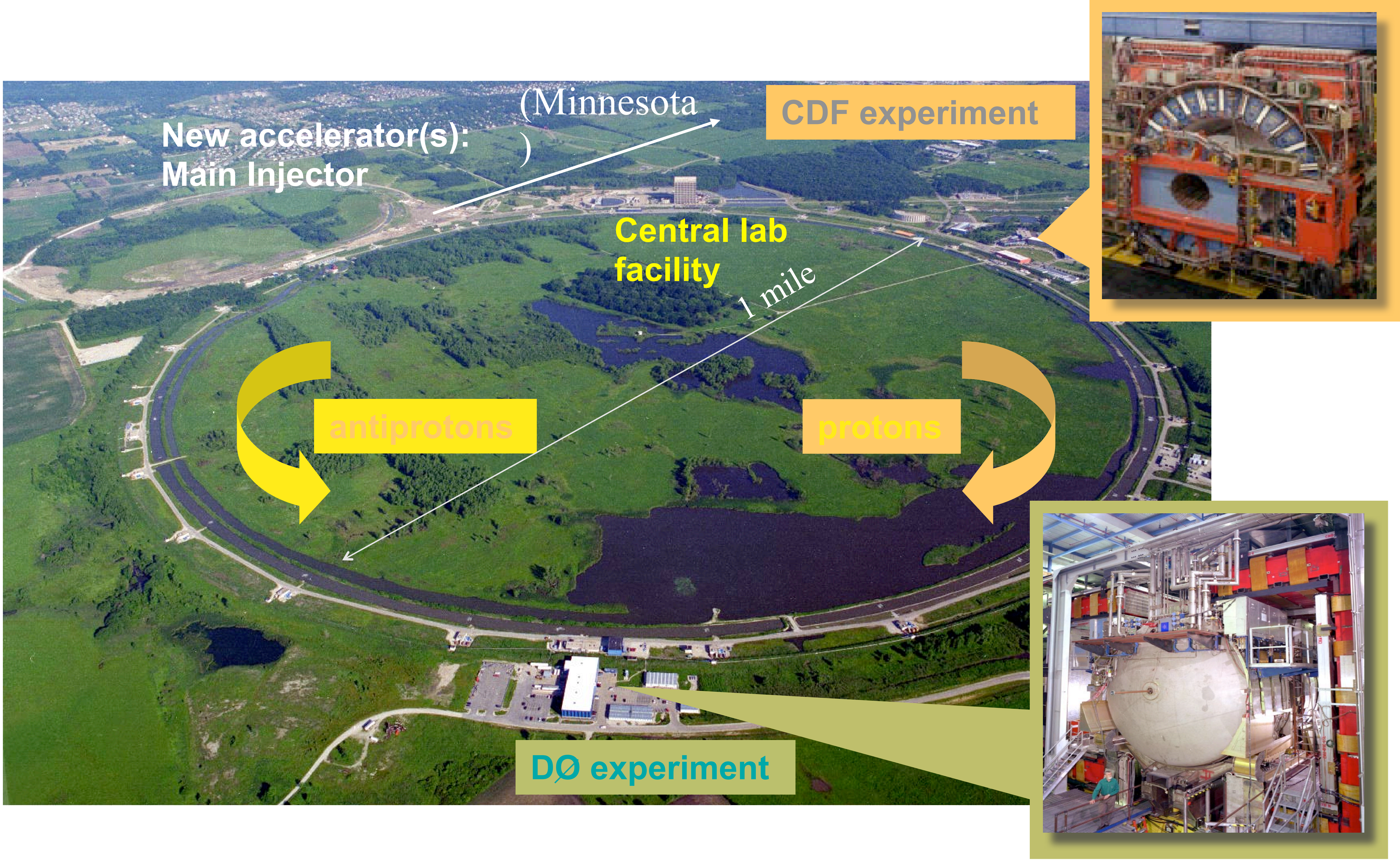
Wilson Hall

designed by the first director, Robert Wilson

HEP labs around the world, today.



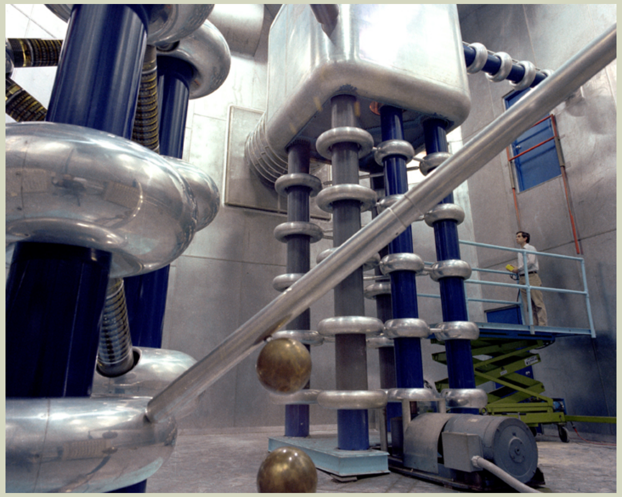
Fermi National Accelerator Laboratory

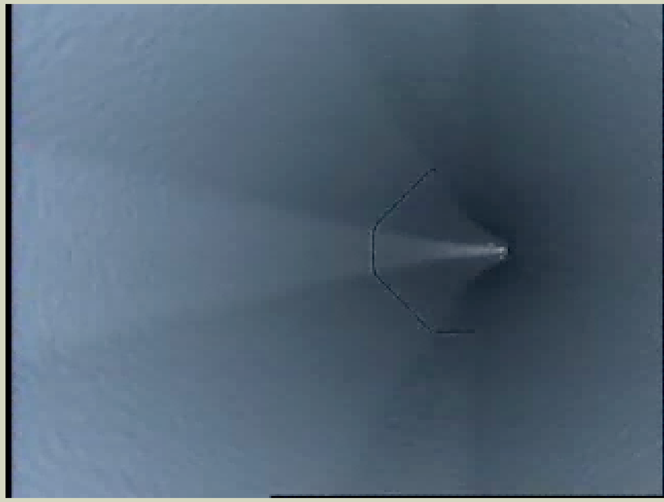


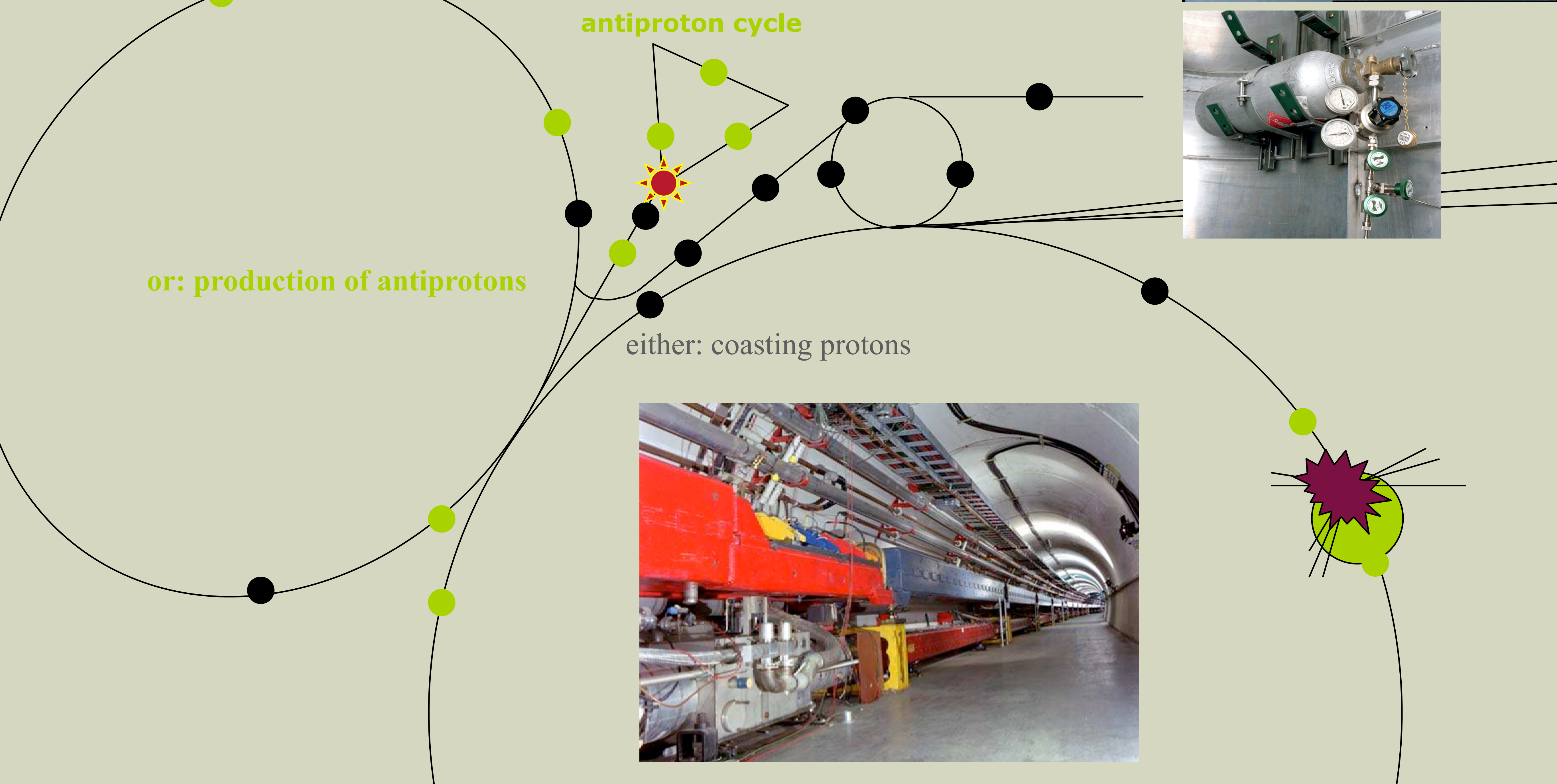
fermilab’s back yard

back

Accelerator Complex - the time machine







proton cycle

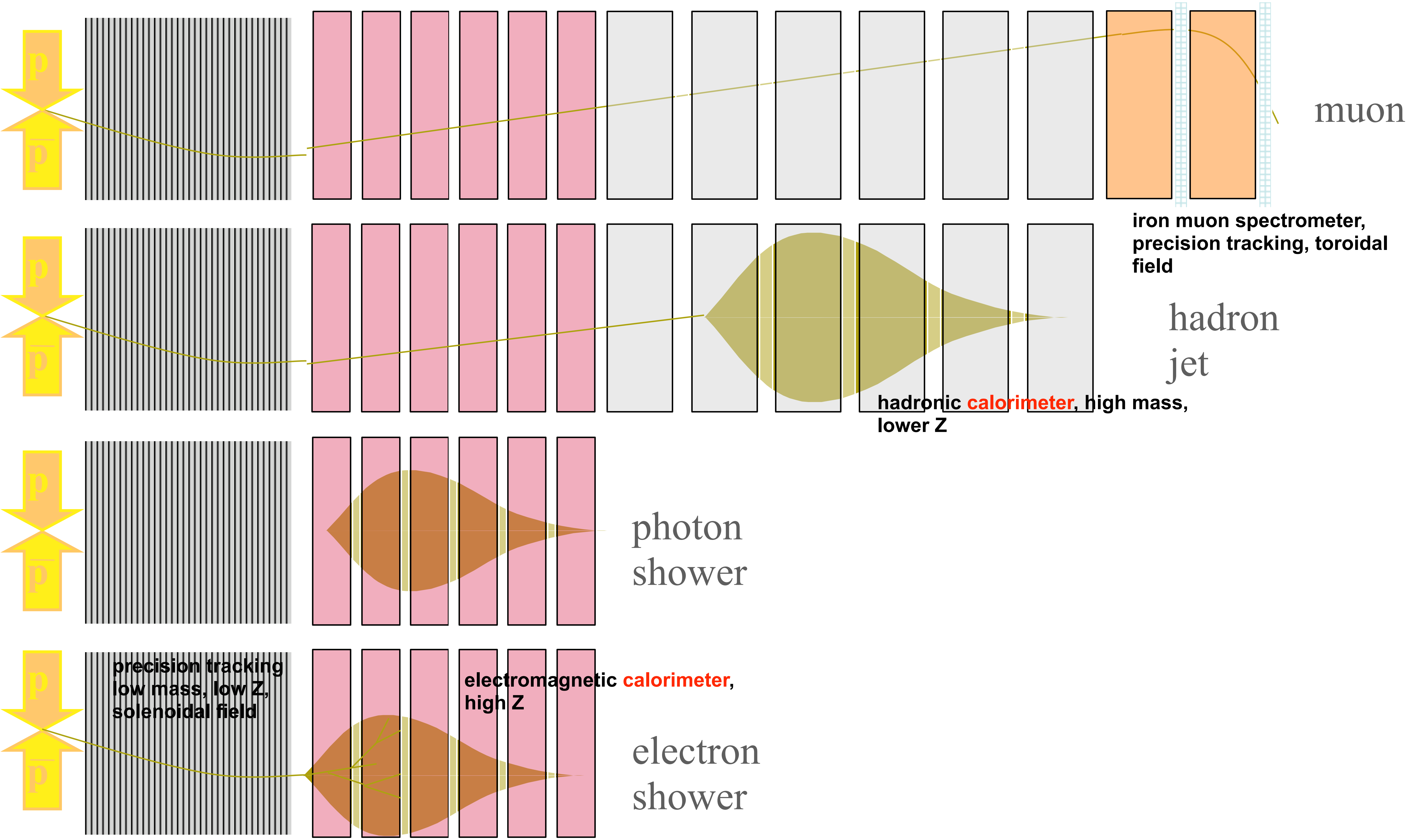
antiproton cycle

or: production of antiprotons

either: coasting protons

how do we detect particles?

– by the electromagnetic and strong interaction fingerprints that they leave behind in a sandwich of detector types:



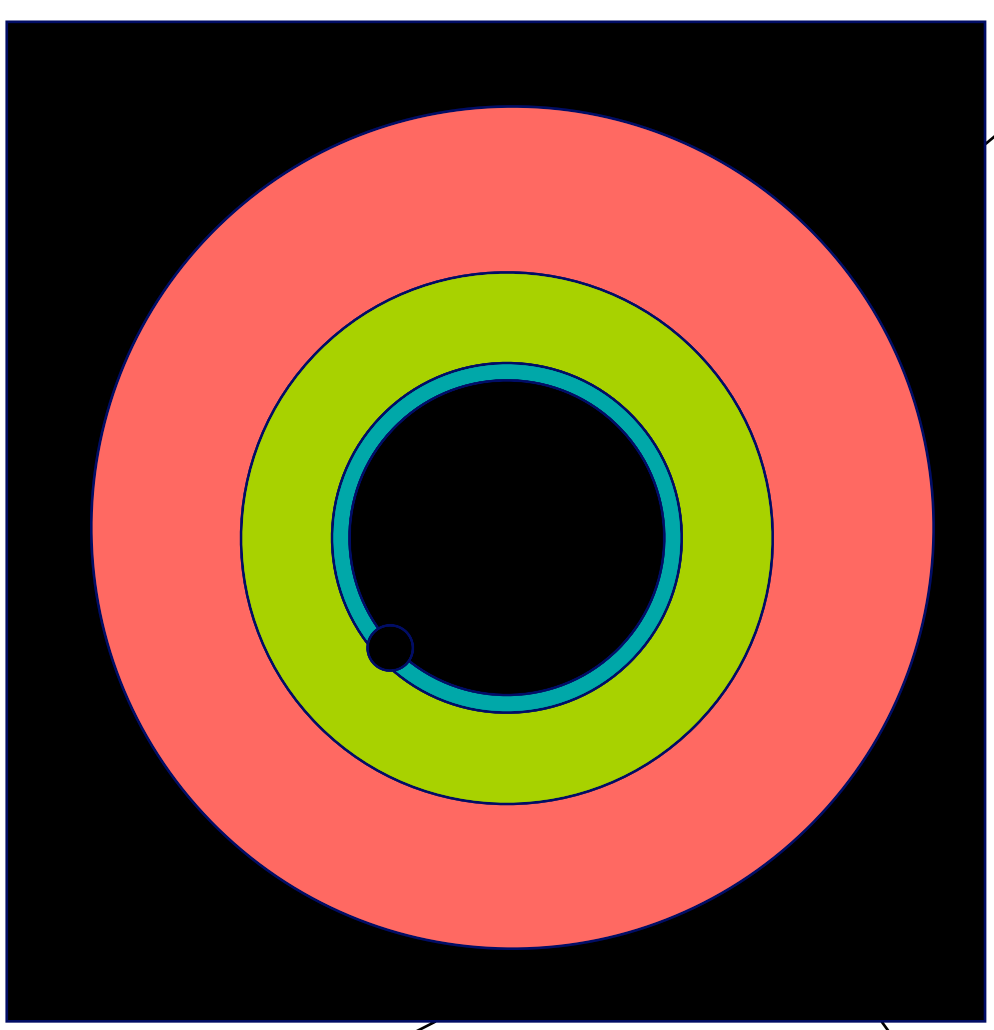
iron muon spectrometer, precision tracking, toroidal field

hadronic calorimeter, high mass, lower Z

precision tracking low mass, low Z, solenoidal field

electromagnetic calorimeter, high Z

Generic colliding beam detector-the vehicles



Muon tracking

Toroidal field

Iron shield

Charged particle tracking

Solenoidal field

Silicon strips & disks

Hadronic calorimetry

Protons, neutrons, pions, etc.

Electromagnetic calorimetry

electrons and photons

The DØ Collaboration, est. 1984:

75 institutions, from 18 countries, 650 Ph.D.'s

The DØ Collaboration

AZ U. of Arizona
CA U. of California, Berkeley
U. of California, Riverside
Cal. State U., Fresno
Lawrence Berkeley Nat. Lab.
FL Florida State U.
IL Fermilab
U. of Illinois, Chicago
Northern Illinois U.
Northwestern U.
IN Indiana U.
U. of Notre Dame
IA Iowa State U.
KS U. of Kansas
Kansas State U.
LA Louisiana Tech U.
MD U. of Maryland
MA Boston U.
Northeastern U.
MI U. of Michigan
Michigan State U.
NE U. of Nebraska
NJ Princeton U.
NY Columbia U.
U. of Rochester
SUNY, Stony Brook
Brookhaven Nat. Lab.
OK Langston U.
U. of Oklahoma
RI Brown U.
TX U. of Texas at Arlington
Texas A&M U.
Rice U.
VA U. of Virginia
WA U. of Washington

U. de Buenos Aires

LAFEX, CBPF, Rio de Janeiro
State U. do Rio de Janeiro
State U. Paulista, São Paulo

U. of Alberta
Simon Fraser U.

IHEP, Beijing

U. de los Andes, Bogotá

Charles U., Prague
Czech Tech. U., Prague
Academy of Sciences, Prague

LPC, Clermont-Ferrand
ISN, IN2P3, Grenoble
CPPM, IN2P3, Marseille
LAL, IN2P3, Orsay
LPNHE, IN2P3, Paris
DAPNIA/SPP, CEA, Saclay
IReS, Strasbourg
IPN, IN2P3, Villeurbanne

U. San Francisco de Quito

U. of Aachen
Bonn U.
U. of Freiburg
U. of Mainz
Ludwig-Maximilians U., Munich
U. of Wuppertal

Panjab U. Chandigarh
Delhi U., Delhi
Tata Institute, Mumbai

University College, Dublin

KDL, Korea U., Seoul

CINVESTAV, Mexico City

FOM-NIKHEF, Amsterdam
U. of Amsterdam / NIKHEF
U. of Nijmegen / NIKHEF

JINR, Dubna
ITEP, Moscow
Moscow State U.
IHEP, Protvino
PNPI, St. Petersburg

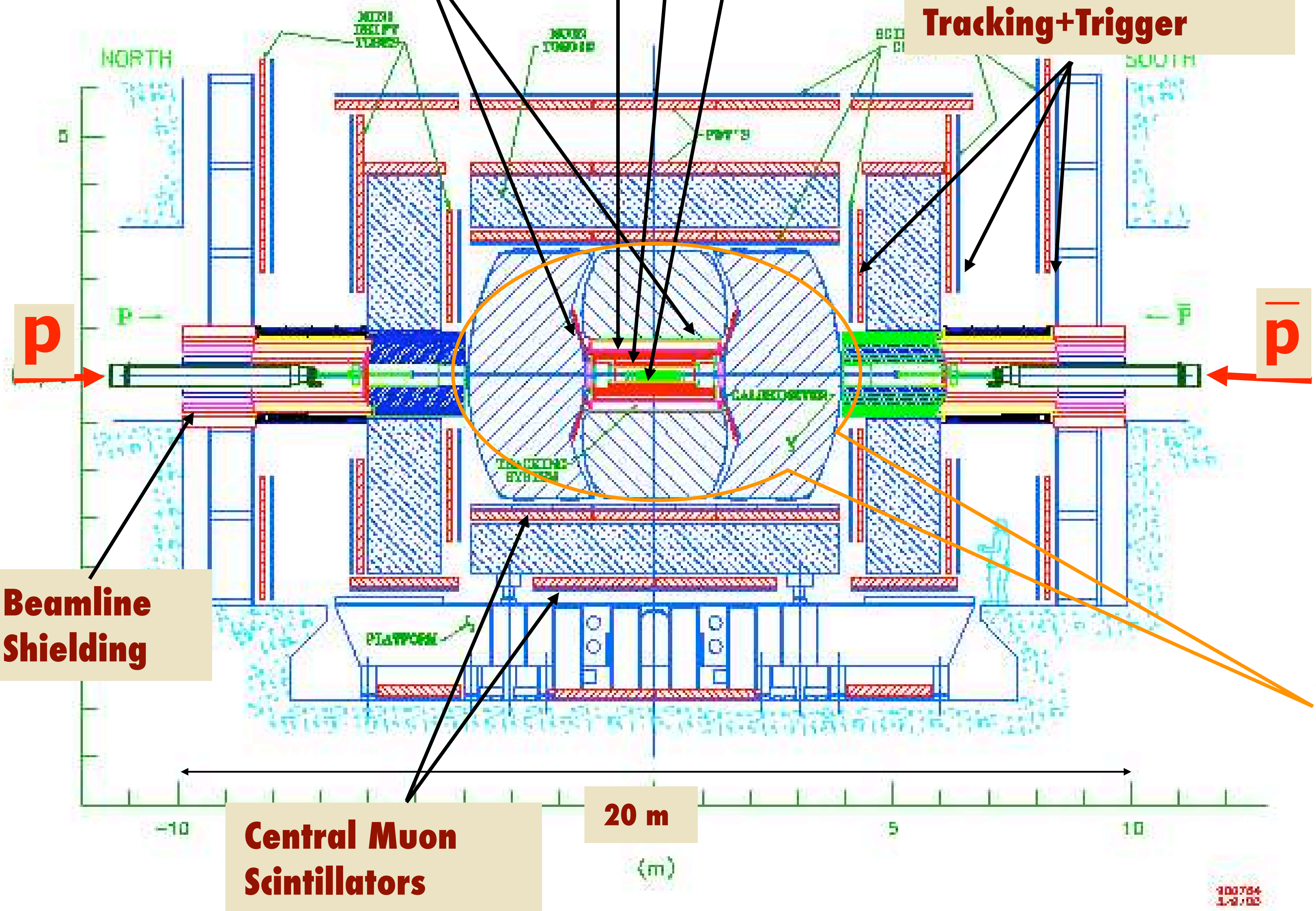
Lund U.
RIT, Stockholm
Stockholm U.
Uppsala U.

Lancaster U.
Imperial College, London
U. of Manchester

HCIP, Hochiminh City

Ann Heinson, UC Riverside

The DØ Detector



2T Solenoid

Fiber Tracker

Silicon m-strip Tracker

Preshowers

Forward Muon Tracking+Trigger

p

$\bar{p}$

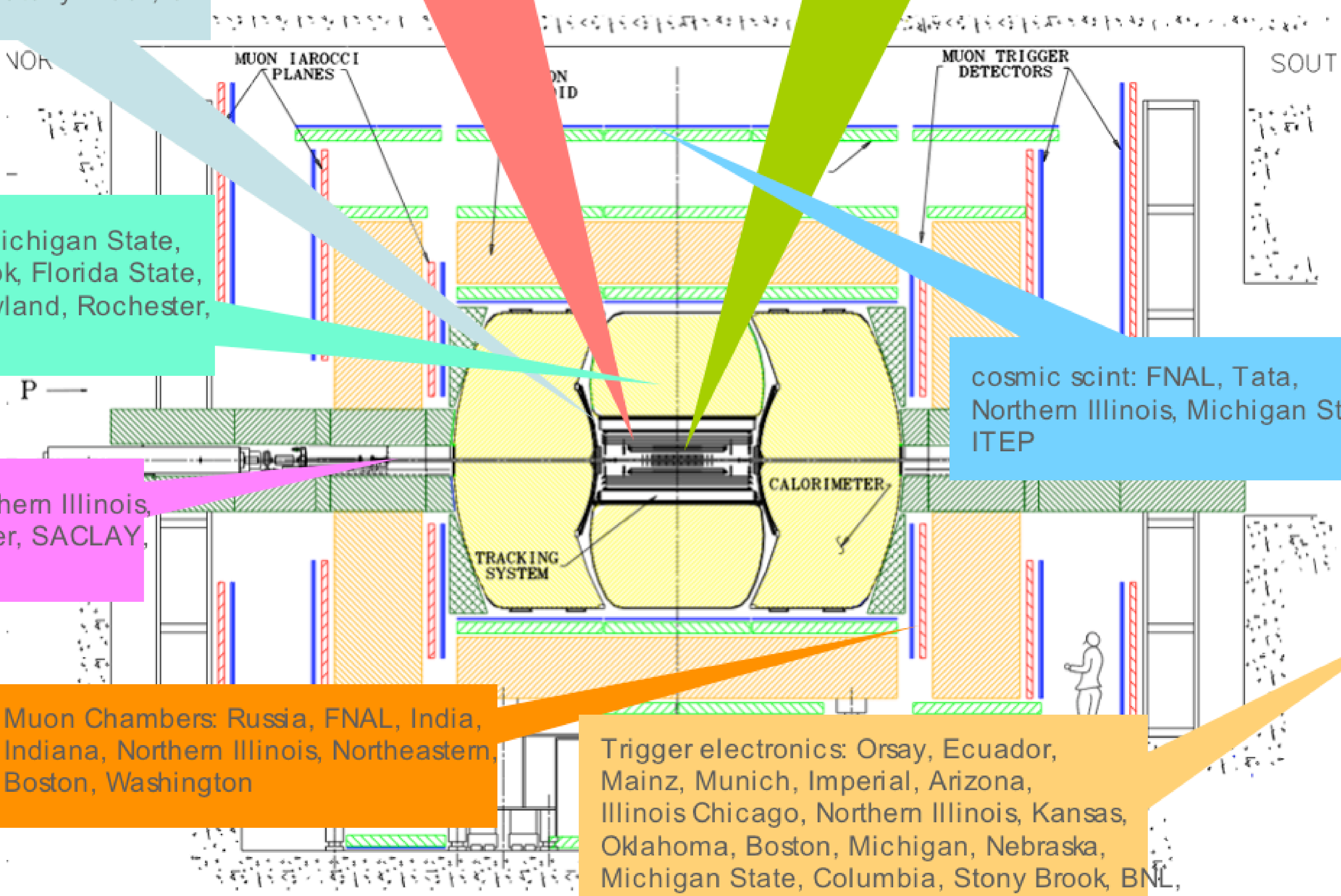
Beamline Shielding

Central Muon Scintillators

20 m

3 liquid Argon
"thermos bottles"
with plates of
depleted Uranium
instrumentated
electrically on
their surfaces

an arbitrary HEP detector:



Fiber Tracker: FNAL, Ecuador, Northern Illinois, Notre Dame, Michigan, Nebraska, Rochester, Stony Brook, BNL, Rice

Si Tracker: FNAL, NIKHEV, Marseille, Mexico, Fresno, Riverside, UIC, Kansas, Kansas State, Oklahoma, Washington

preshower: BNL, Stony Brook, UM

Calorimeter: FNAL, Michigan State, LBL, BNL, Stony Brook, Florida State, Northern Illinois, Maryland, Rochester, Louisiana Tech

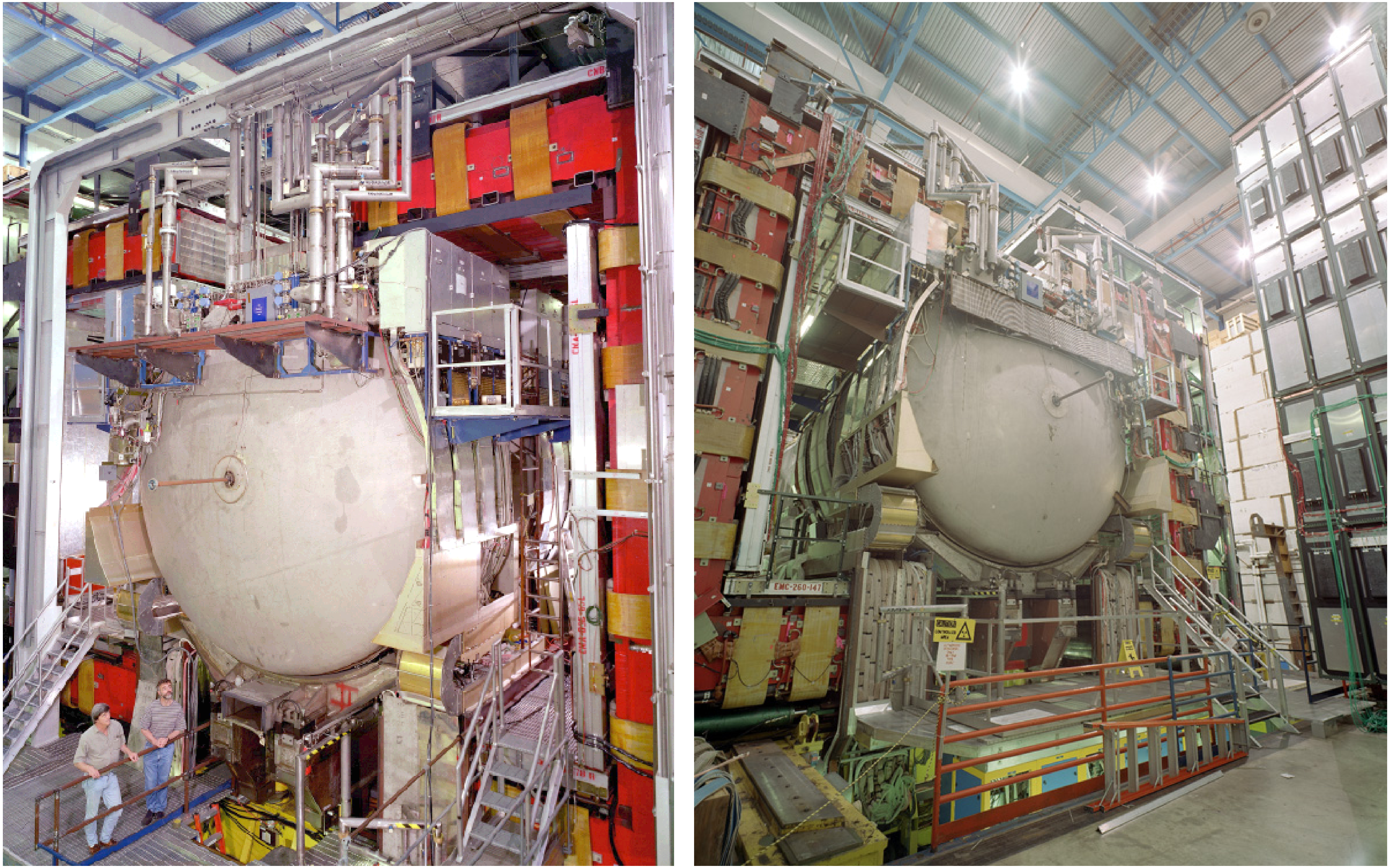
cosmic scint: FNAL, Tata, Northern Illinois, Michigan State, ITEP

FPD: Brazil, Arlington, Northern Illinois, Czechoslovakia, Manchester, SACLAY, Los Andes

Muon Chambers: Russia, FNAL, India, Indiana, Northern Illinois, Northeastern, Boston, Washington

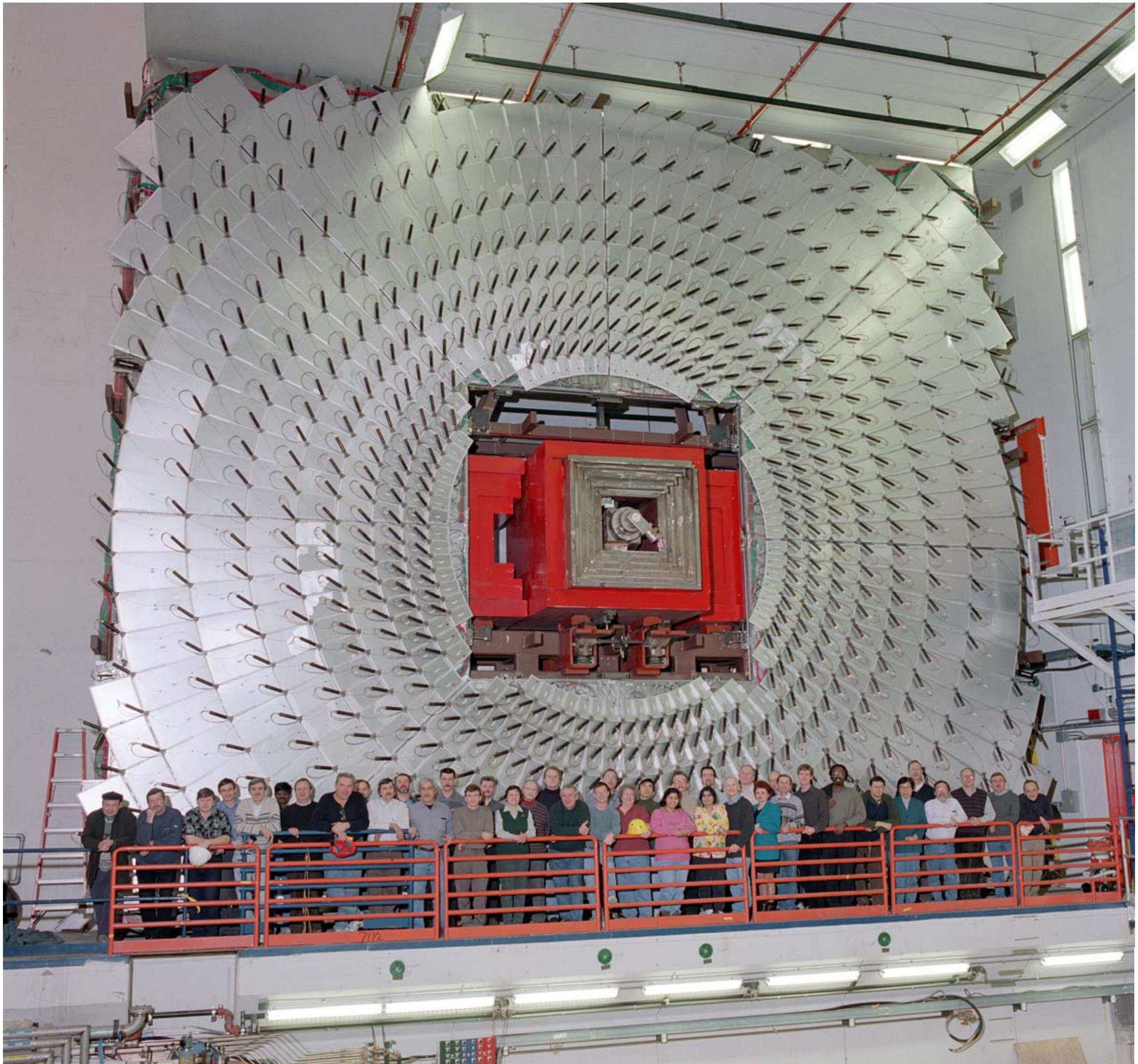
Trigger electronics: Orsay, Ecuador, Mainz, Munich, Imperial, Arizona, Illinois Chicago, Northern Illinois, Kansas, Oklahoma, Boston, Michigan, Nebraska, Michigan State, Columbia, Stony Brook, BNL, Brown, Virginia, Wisconsin, Michigan State

…inside



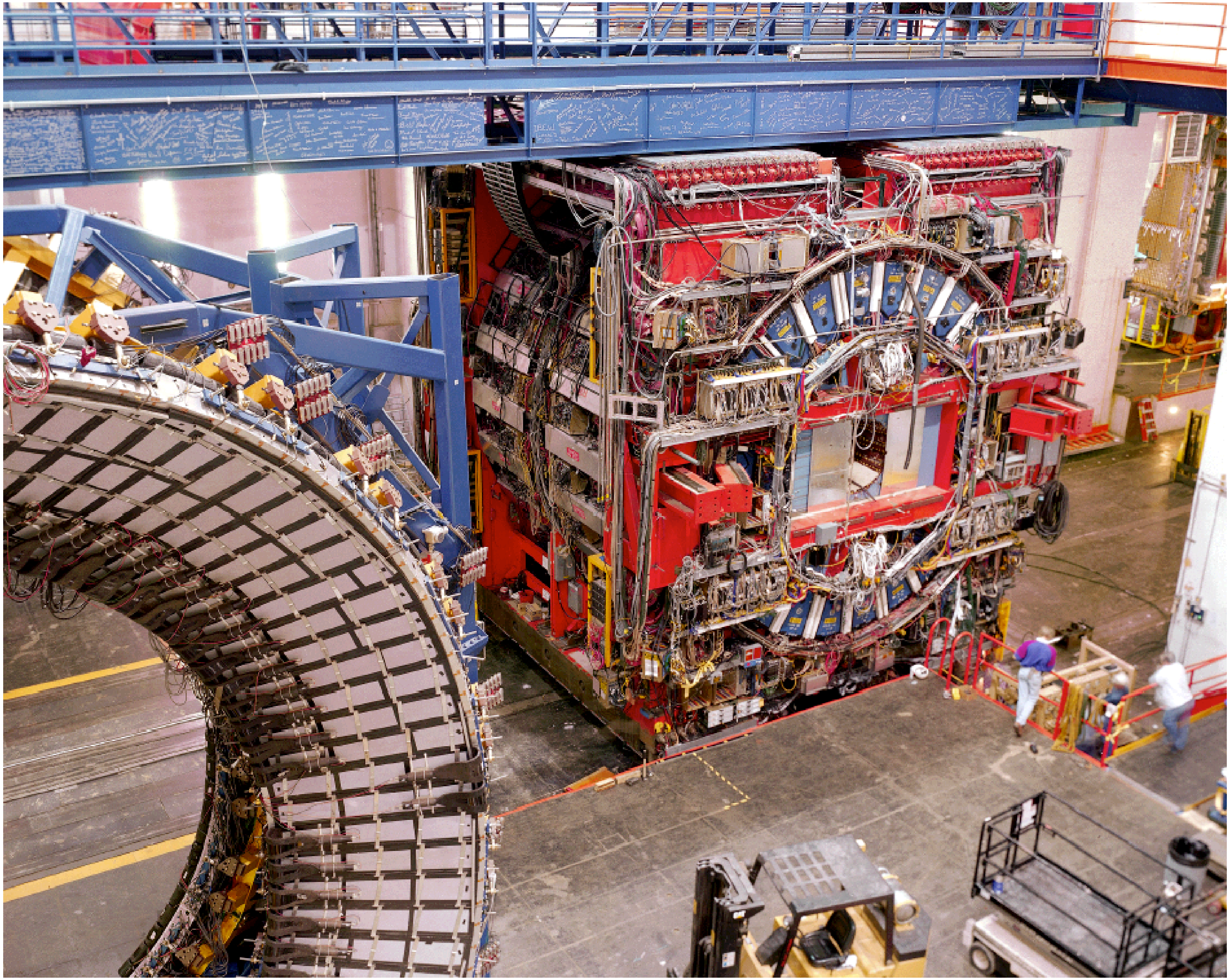
the D0 detector


NE0
SE0




DETECTOR REMOVAL
03/12/96 M15 C15 07:56:49

the other detector…CDF



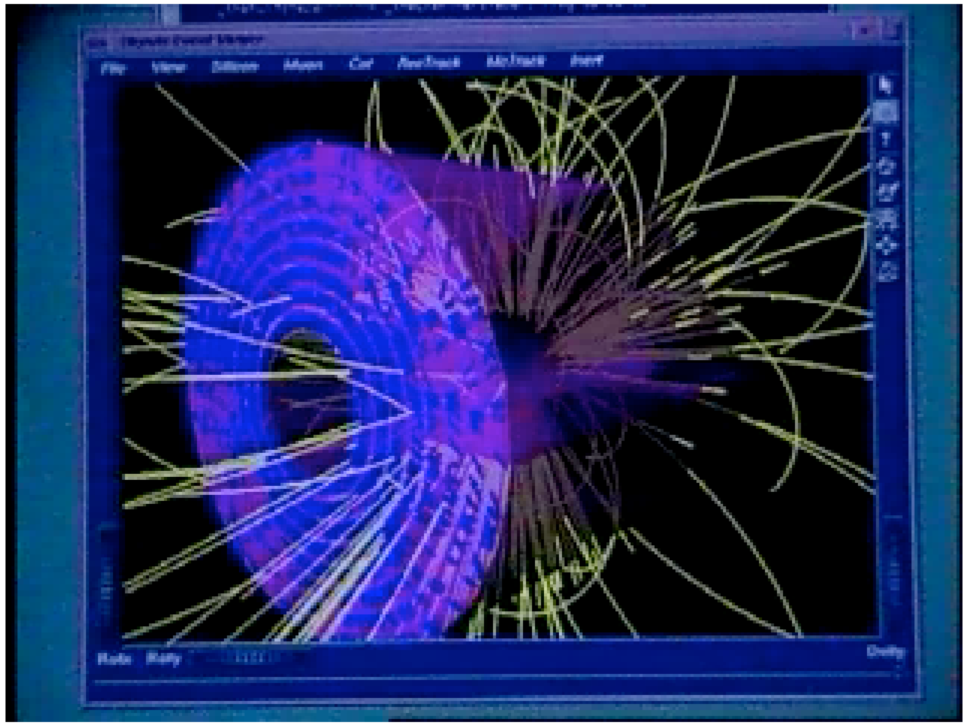
accelerator delivers, detector reads, computers analyze:

Every 396 ns…396 x 10^{-9} s

- the proton & anti proton beams are brought close together inside the detectors

  there, the actual interaction rate is 7.5MHz, 7.5x10^6 interactions per second

  each event record is ~250kB, so this would be a rate of 1.9TB/s - impossible



The experiment is outfitted with near-real time electronics, designed and produced here in our group

- which analyzes what's happening in each collision

  reading the information from ~500,000 electronic channels

- picks out those events which appear to match (much debated) physics priorities

  and processes 6kHz of these potentially interesting data to a series of dedicated, home-built processors (again, designed and built at MSU)

- Eventually, the information is reduced, combined, filtered to an output stream of 50Hz, at 250kB per event

These data are then processed on a dedicated computer farm of ~500 linux Pentium processors of the ~2GHz class

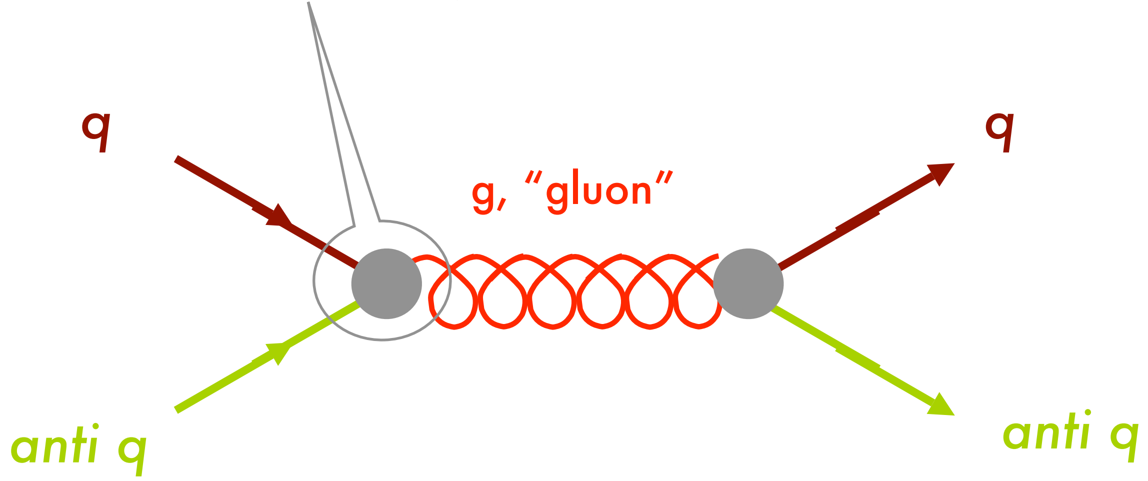
The overall data load of the experiment will be in the 5-8 PB (petabyte 10^{15} B… information

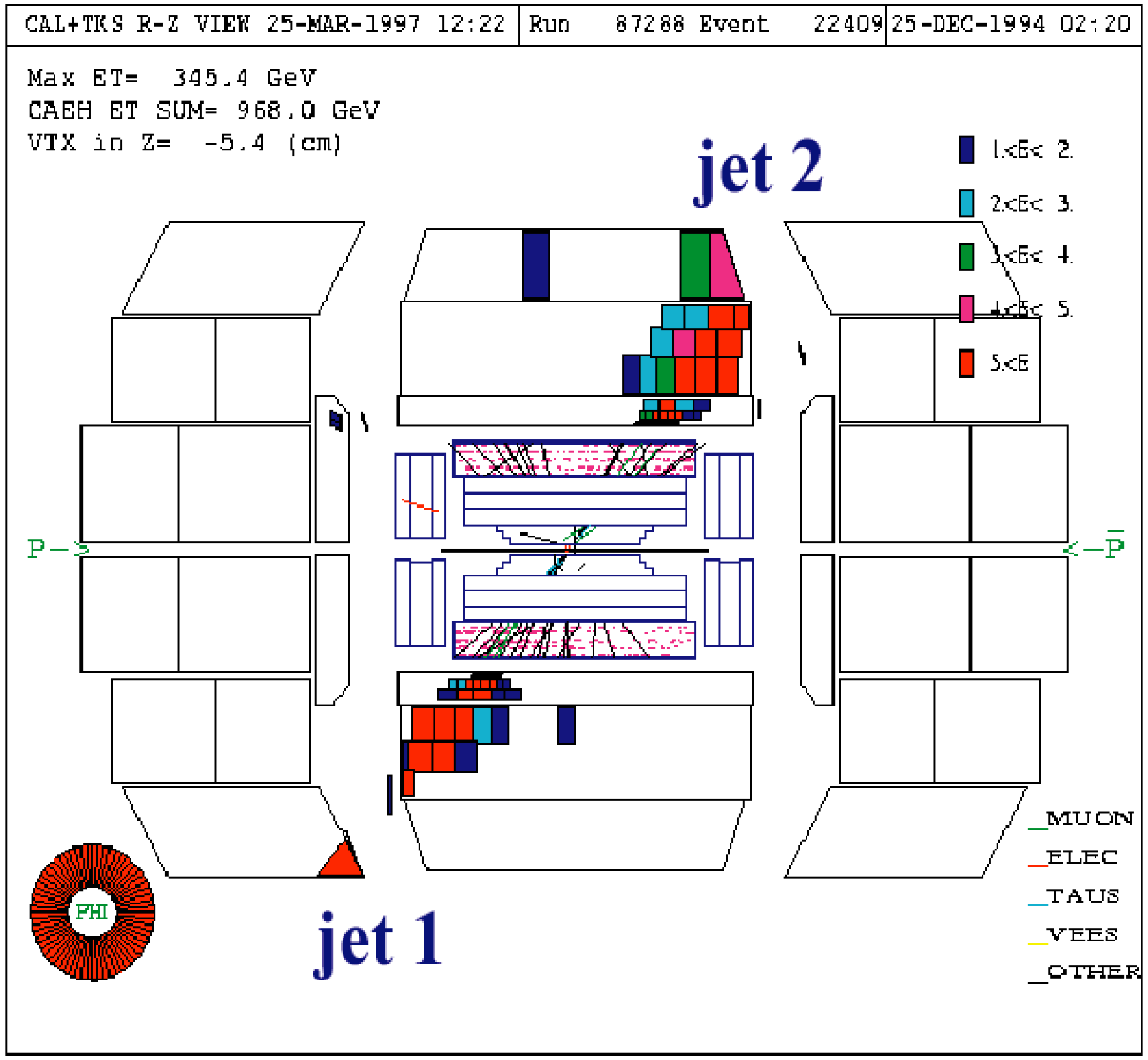
- in CD's: the height of ~100 Sears Towers
- processed and analyzed at institutions on 4 continents in a ~2000 processor computational grid

most violent elementary particle collision produced on earth

Rutherford Scattering of one quark in the proton off of another quark from the antiproton

with the exchange of a "gluon" a photon-like particle that transmits only the STRONG force.


"coupling" designating the strength of the interaction - STRONG


CAL+TKS R-Z VIEW 25-MAR-1997 12:22 Run 87288 Event 22409 25-DEC-1994 02:20

Max ET= 345.4 GeV
CAEH ET SUM= 968.0 GeV
VTX in Z= -5.4 (cm)

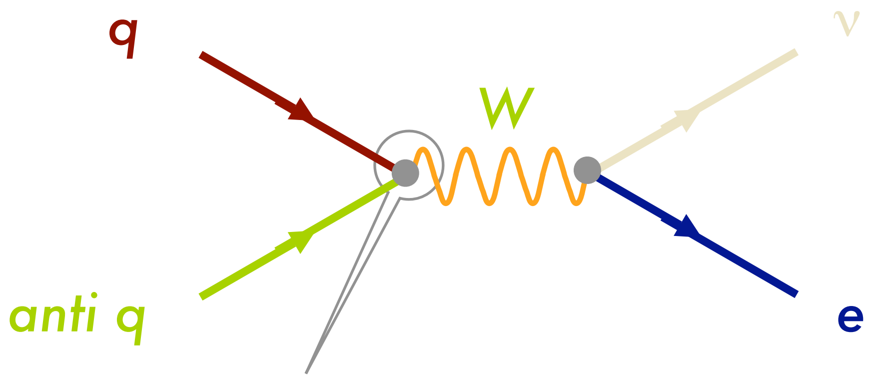
It required that
the quarks annihilated within 10^{-19} m of
one another or
1/10,000 the size of a proton

The energetics of this event is consistent with
interactions in the
early universe ~10^{-20} s after the big bang

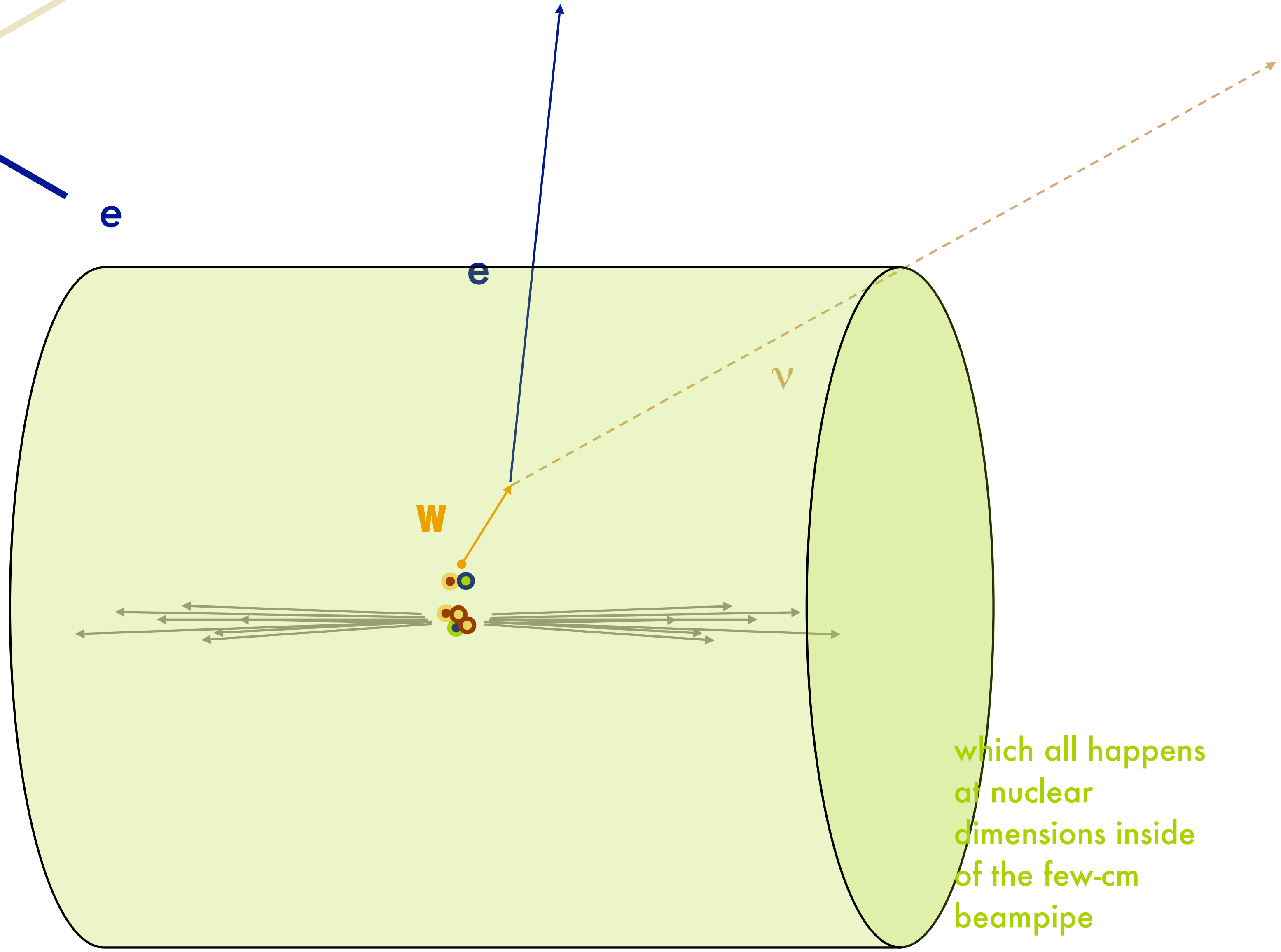
2 events: W boson production & detection

p + antip → W + uninteresting stuff

with W → e + ν



“coupling” designating
the strength of the interaction - WEAK

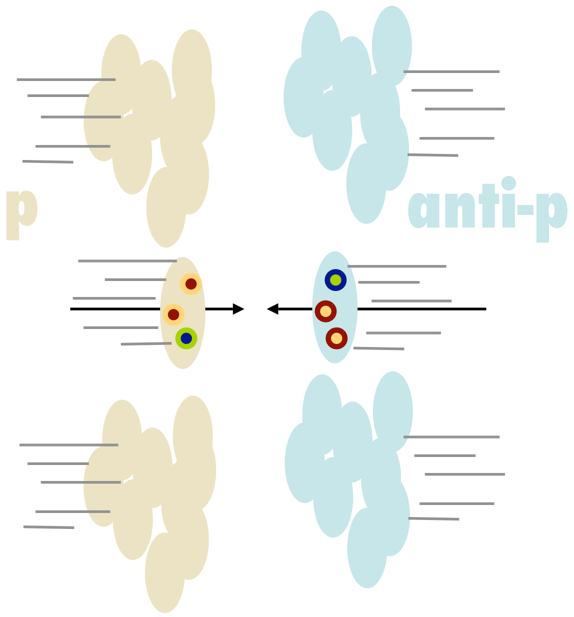


which all happens
at nuclear
dimensions inside
of the few-cm
beampipe

most go by without interacting

occasionally, a quark from the p and a quark from the anti-p are at particularly large momentum and annihilate, head-on with one another...

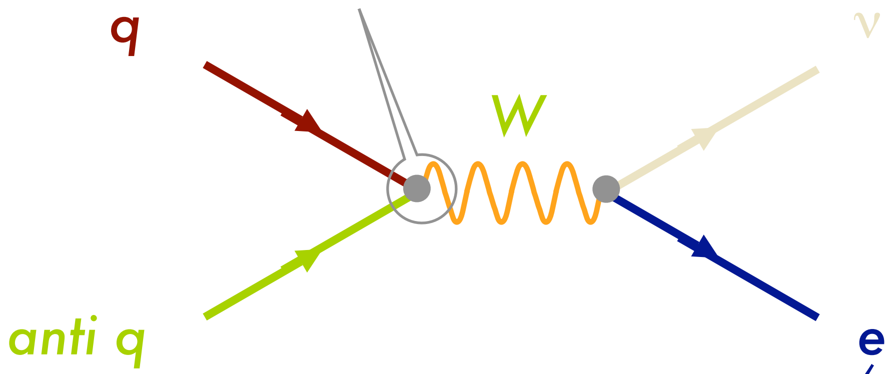
The other quarks interact, but with much lower initial momenta



every few hundred
nanoseconds - 10^{12} or so
protons and antiprotons
encounter one another

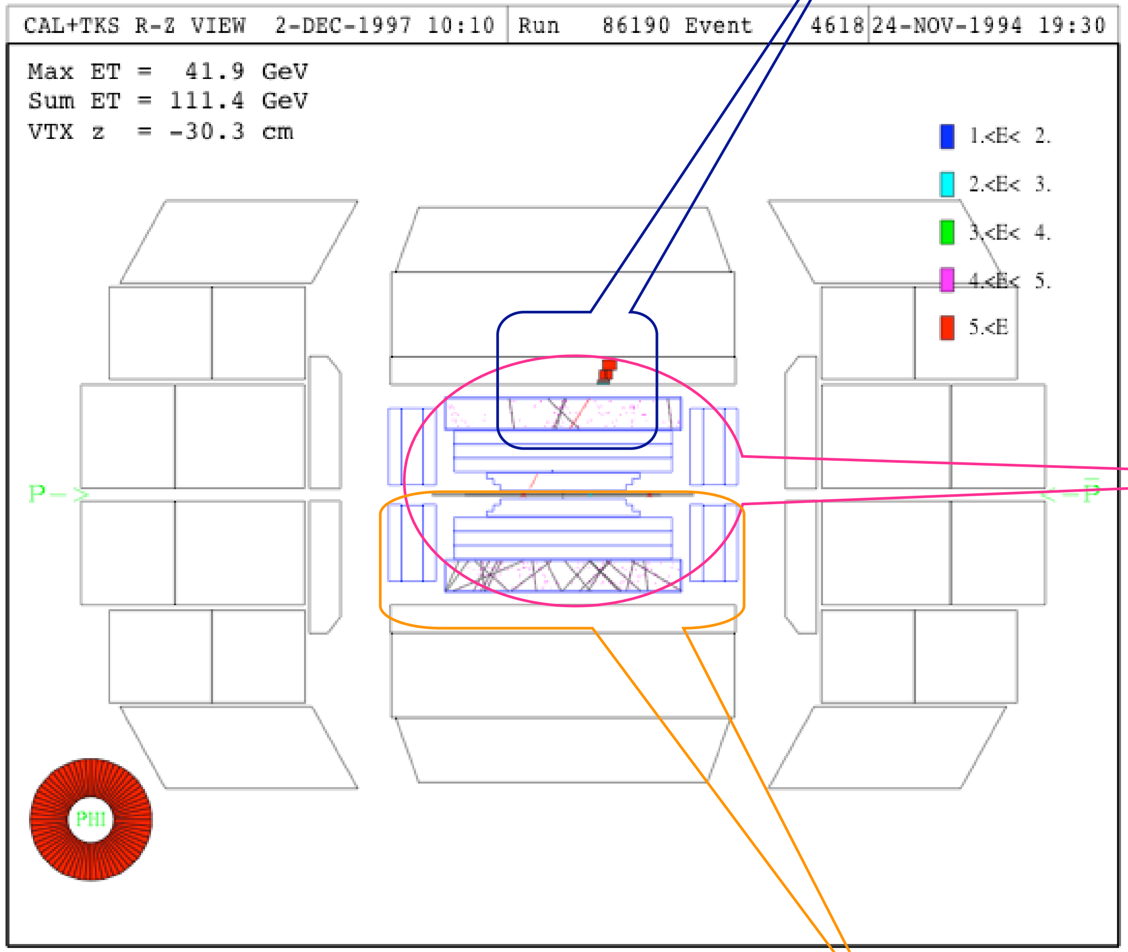
what the detector “sees”

“coupling” designating
the strength of the interaction - WEAK



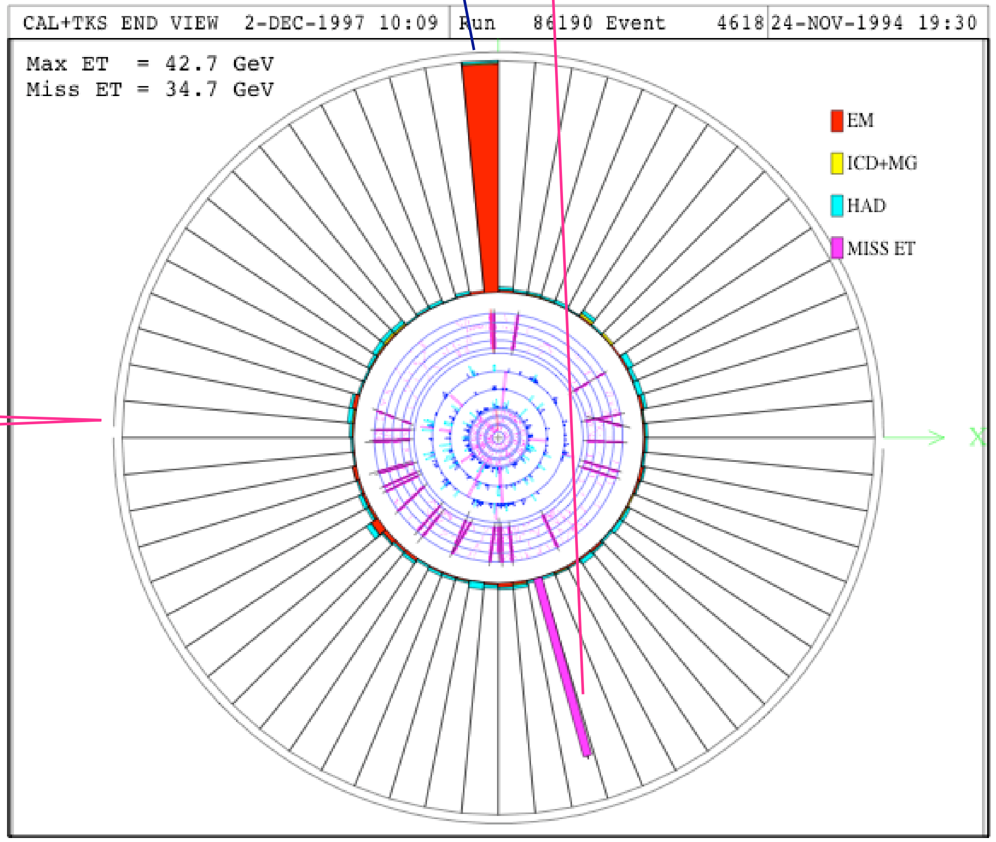
the computer’s calculation of the balancing momentum - presumed to be the neutrino’s momentum

the length of this bar is proportional to the amount of energy deposited...it’s a measured quantity



```
CAL+TKS R-Z VIEW  2-DEC-1997 10:10 | Run    86190 Event    4618|24-NOV-1994 19:30
Max ET =   41.9 GeV
Sum ET = 111.4 GeV
VTX z  = -30.3 cm
```

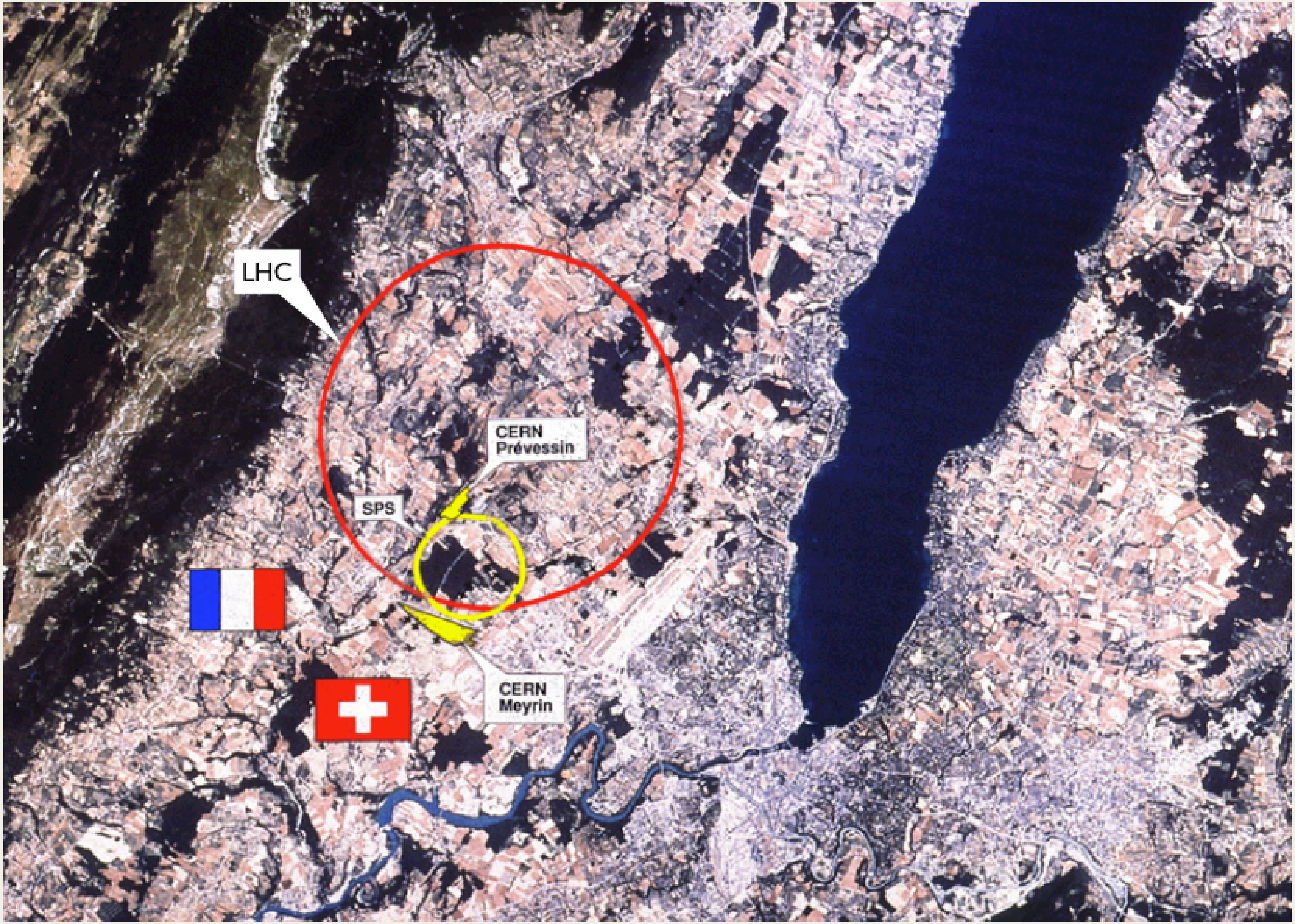
side view



```
CAL+TKS END VIEW  2-DEC-1997 10:09 | Run    86190 Event    4618|24-NOV-1994 19:30
Max ET  = 42.7 GeV
Miss ET = 34.7 GeV
```

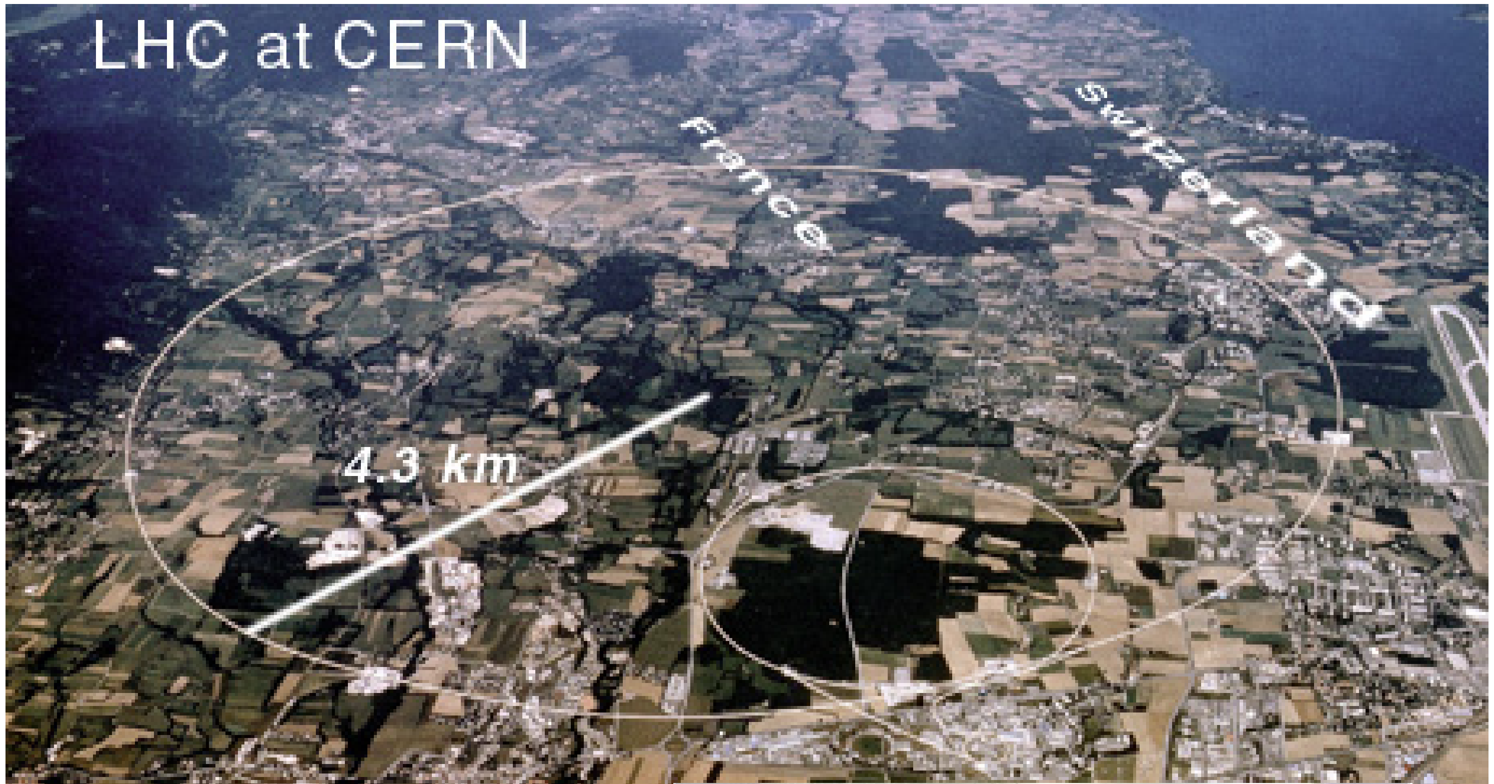
end view

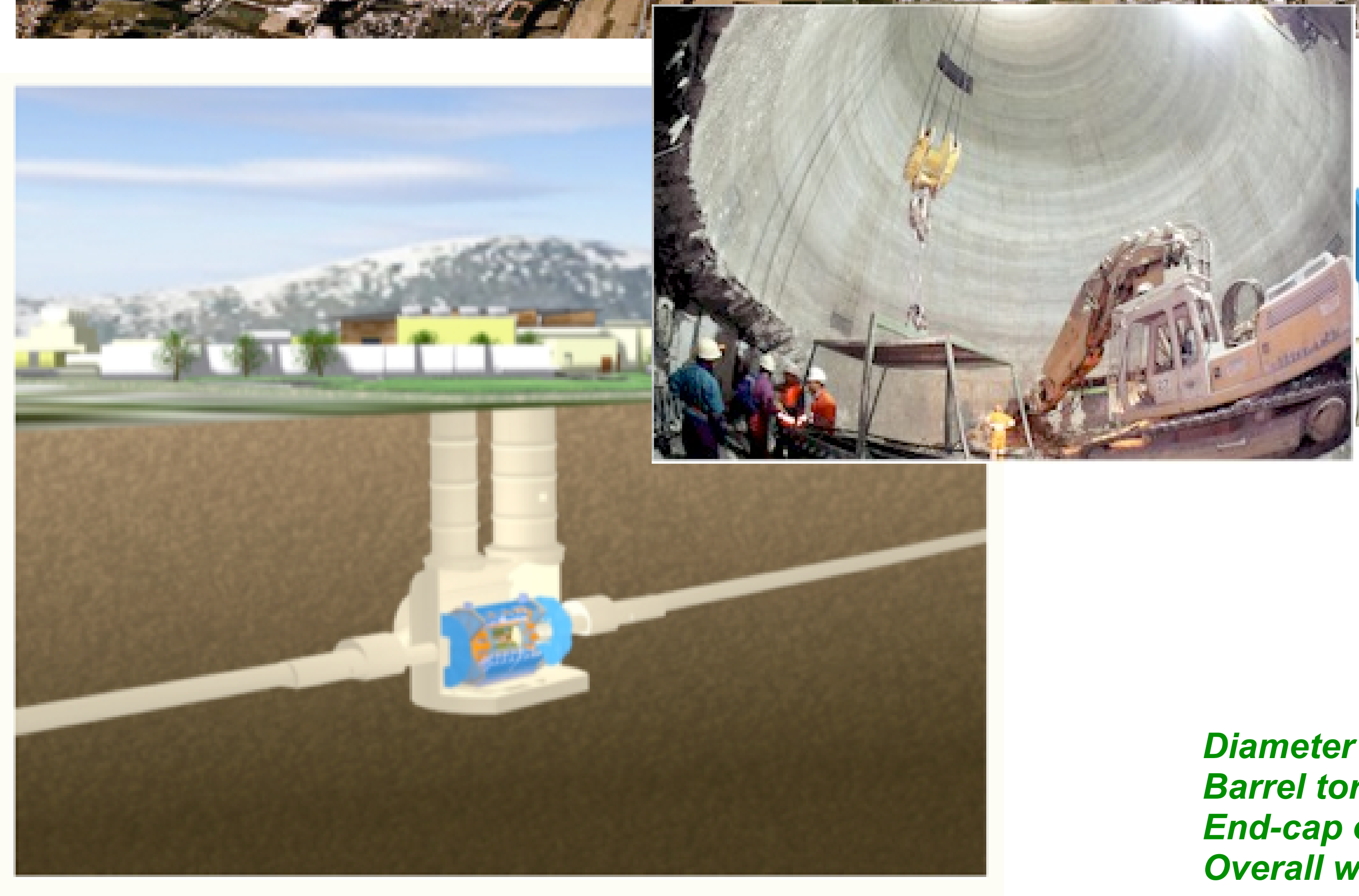
nothing counterbalancing momentum on the other side...suggest the missing neutrino

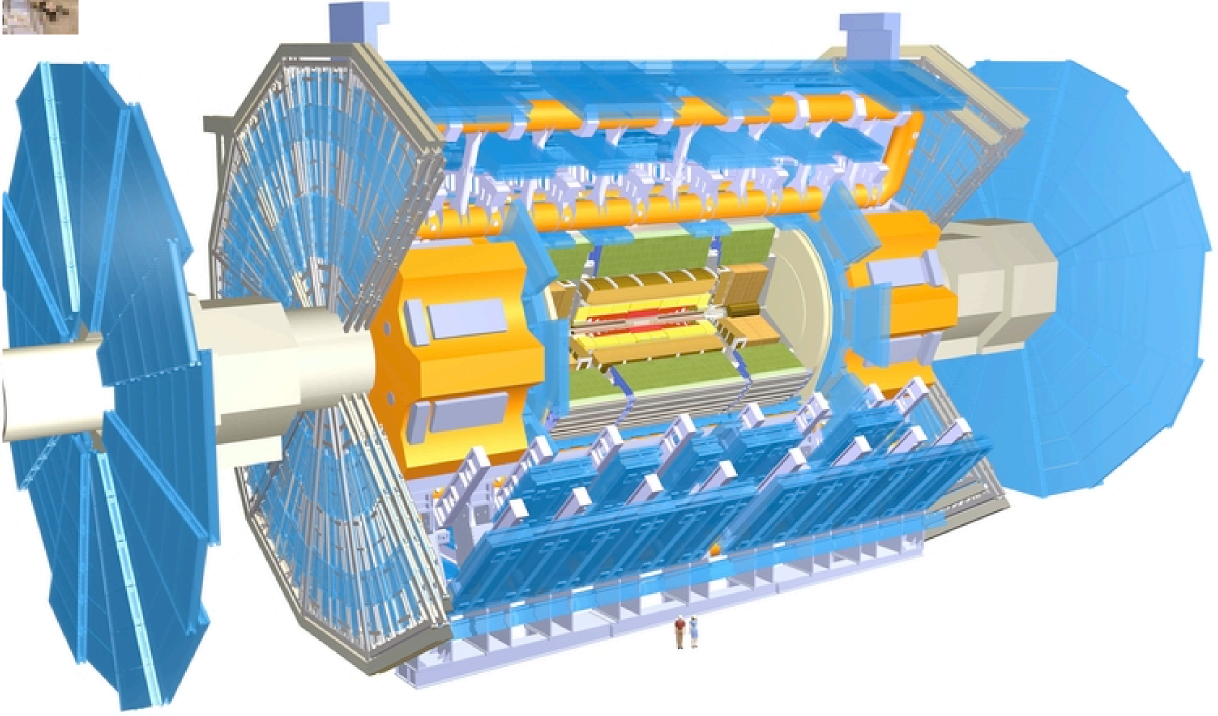

LHC
CERN
Prévessin
SPS
CERN
Meyrin

The next generation is in Europe...~2008

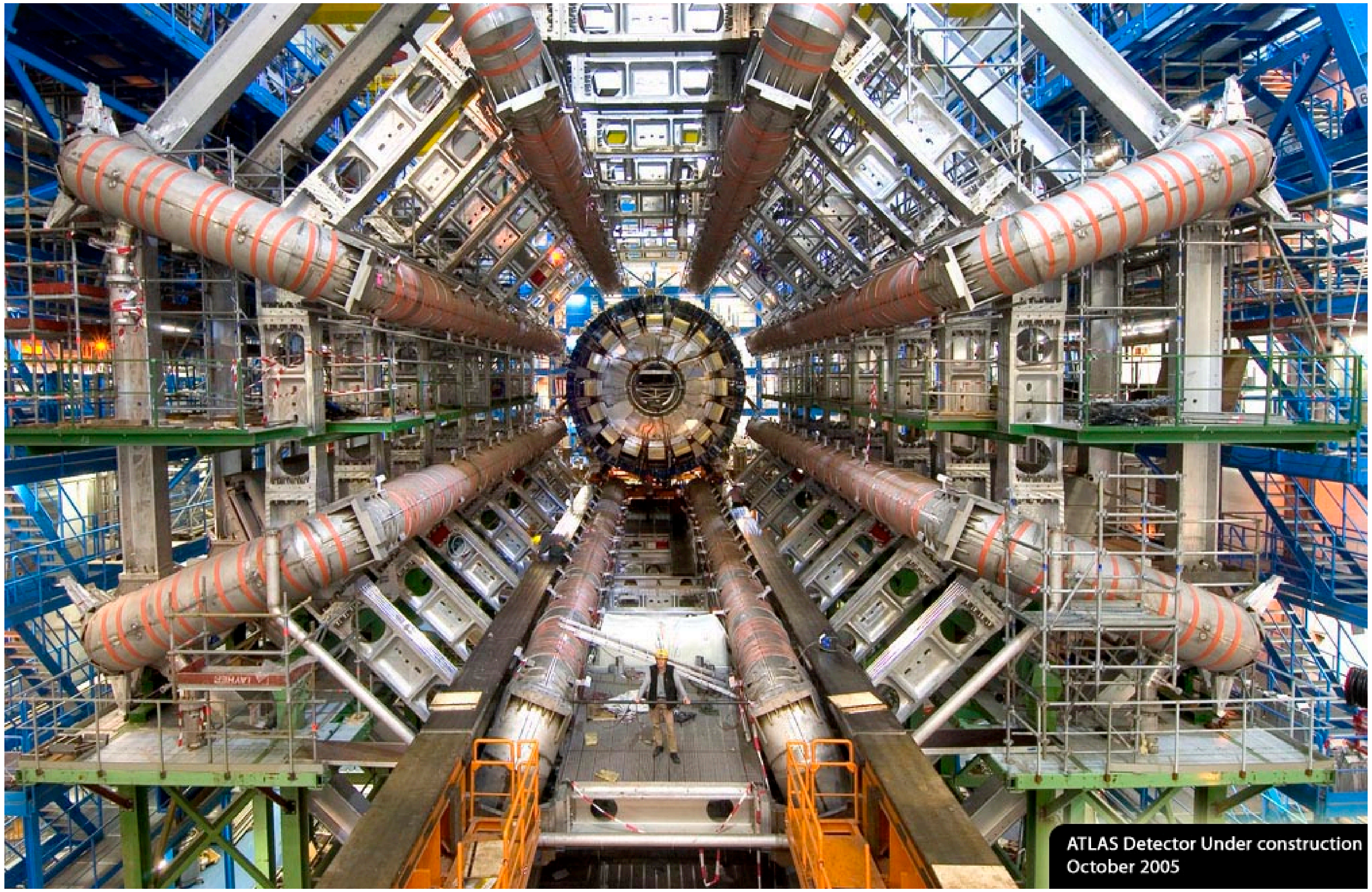
The “Atlas Experiment”





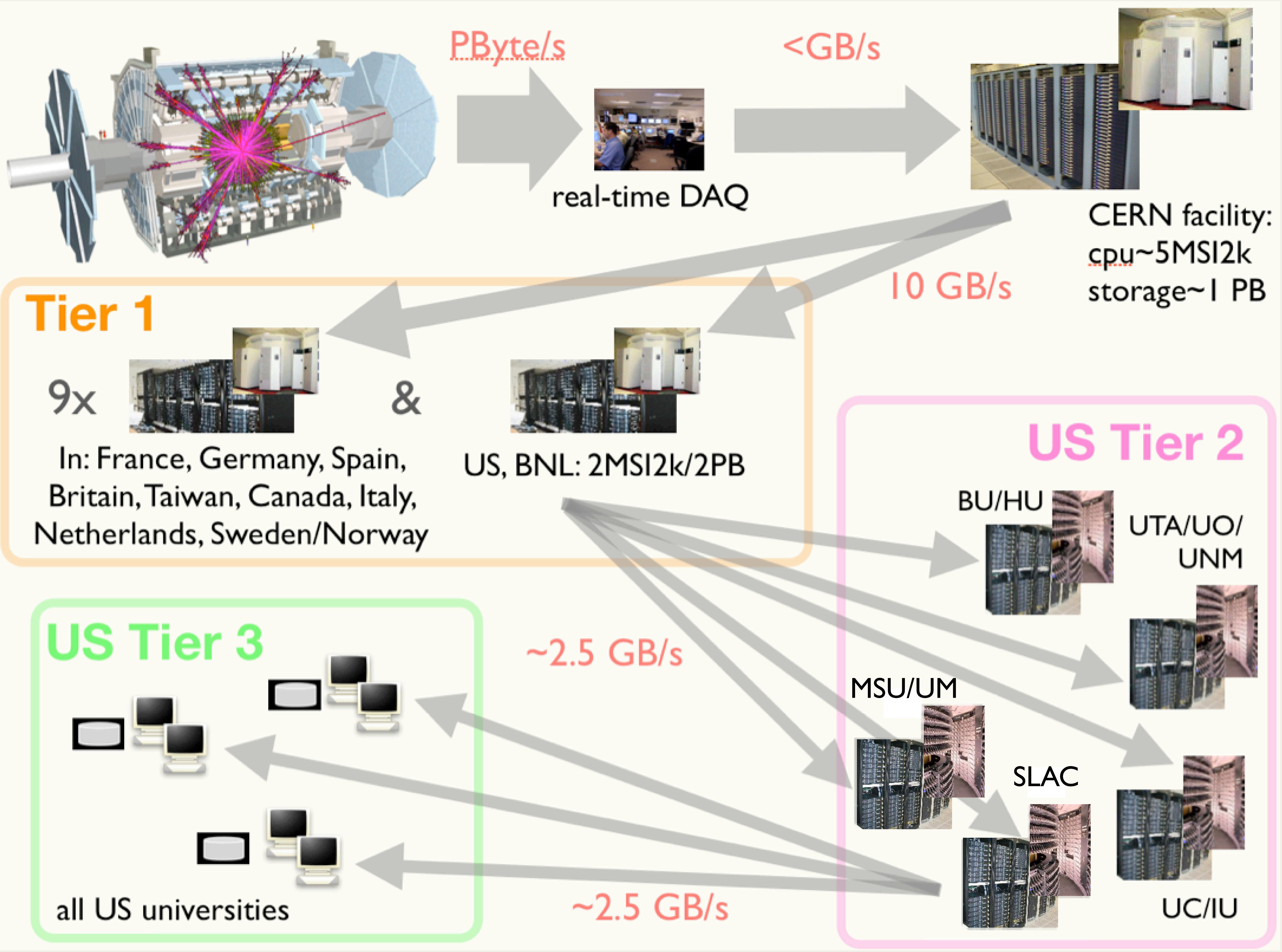


Diameter	*25 m*
Barrel toroid length	*26 m*
End-cap end-wall chamber span	*46 m*
Overall weight	*7000 Tons*



ATLAS Detector Under construction
October 2005


2006 2 21



PByte/s

real-time DAQ

<GB/s

CERN facility:
cpu~5MSI2k
storage~1 PB

10 GB/s

Tier 1

9x

In: France, Germany, Spain, Britain, Taiwan, Canada, Italy, Netherlands, Sweden/Norway

&

US, BNL: 2MSI2k/2PB

US Tier 2

BU/HU

UTA/UO/
UNM

MSU/UM

SLAC

UC/IU

US Tier 3

all US universities

~2.5 GB/s

~2.5 GB/s

This’ll keep us busy here at MSU for 20 years.

- better known as “retirement”