Experimental Particle Physics
PHYS6011

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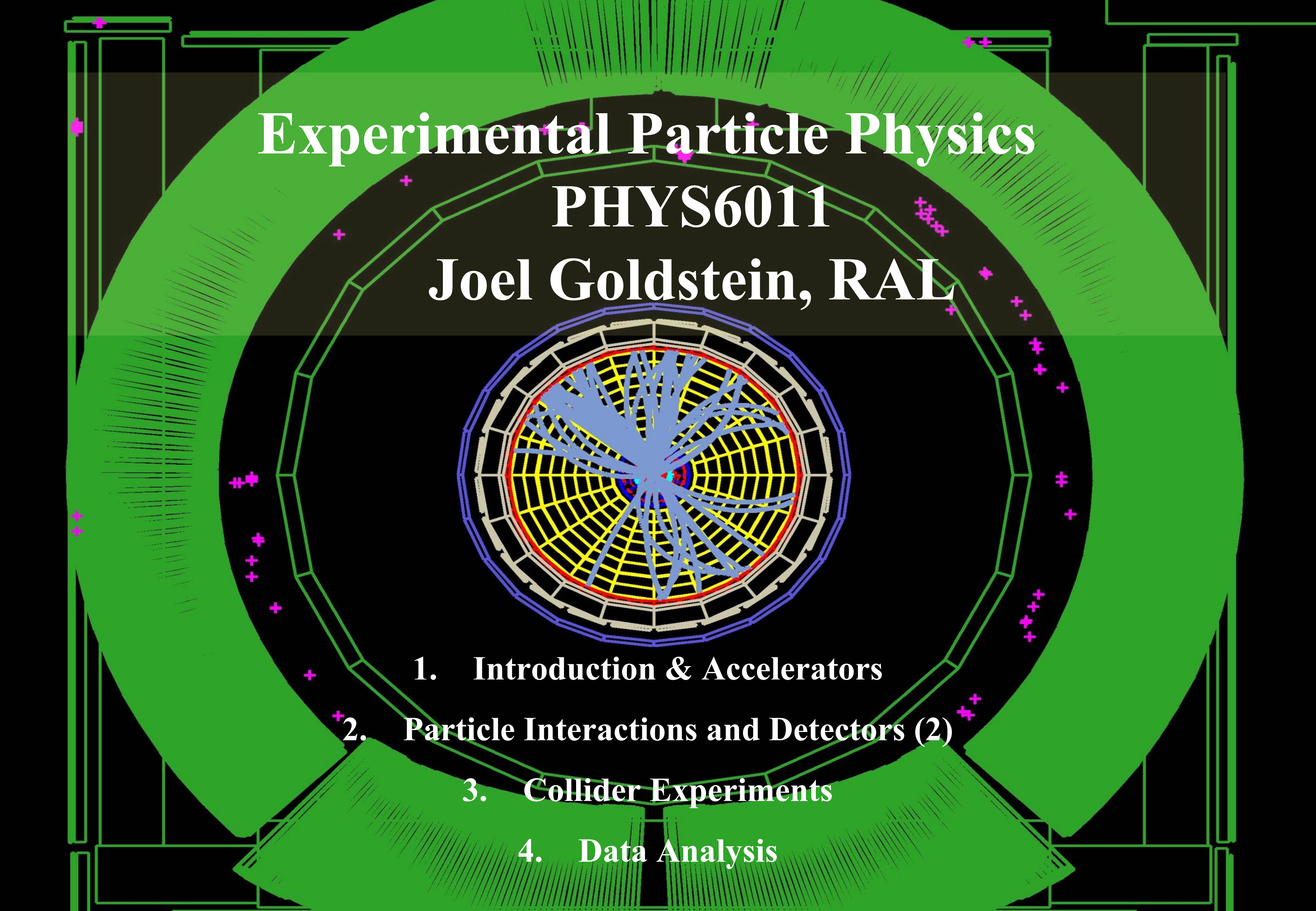


1. Introduction & Accelerators
2. Particle Interactions and Detectors (2)
3. Collider Experiments
4. Data Analysis

Administrative Points

- Three lectures now, two at end of term
- Notes for first part on web
  - A couple of typos in Table 1
  - *Let me know if you find more!*
  - Will update notes
- Accompanying problem set
  - Ready on Monday

$$\text{Mass of a proton} \approx 1\ \text{GeV}/c^2 \approx 1.7 \times 10^{-27}\ \text{kg}$$

$$\alpha = \frac{e^2}{4\pi\epsilon_0 \hbar c} \approx \frac{1}{137}$$

Introduction

- **Heisenberg, de Broglie, Boltzmann, Big Bang:**

High momentum ⇔ small distance ⇔ high temperature ⇔ early universe

- **Need sources of high energy particles and techniques to examine their interactions**

- **Natural units are natural for some calculations**

$$\hbar = c = 1$$

- **Not so natural for others:** ***try ordering*** 5×10^{9} ***GeV***$^{-1}$ ***thick aluminium!***
  - **Use whichever units are most convenient (cm, M$, mb….)**
  - **Know how to convert**
  - **Use common sense**

Useful Values

- In natural units
  - energy and momentum are measured in GeV
  - length and time are measured in GeV^{-1}
  - 1 = 197 MeV.fm

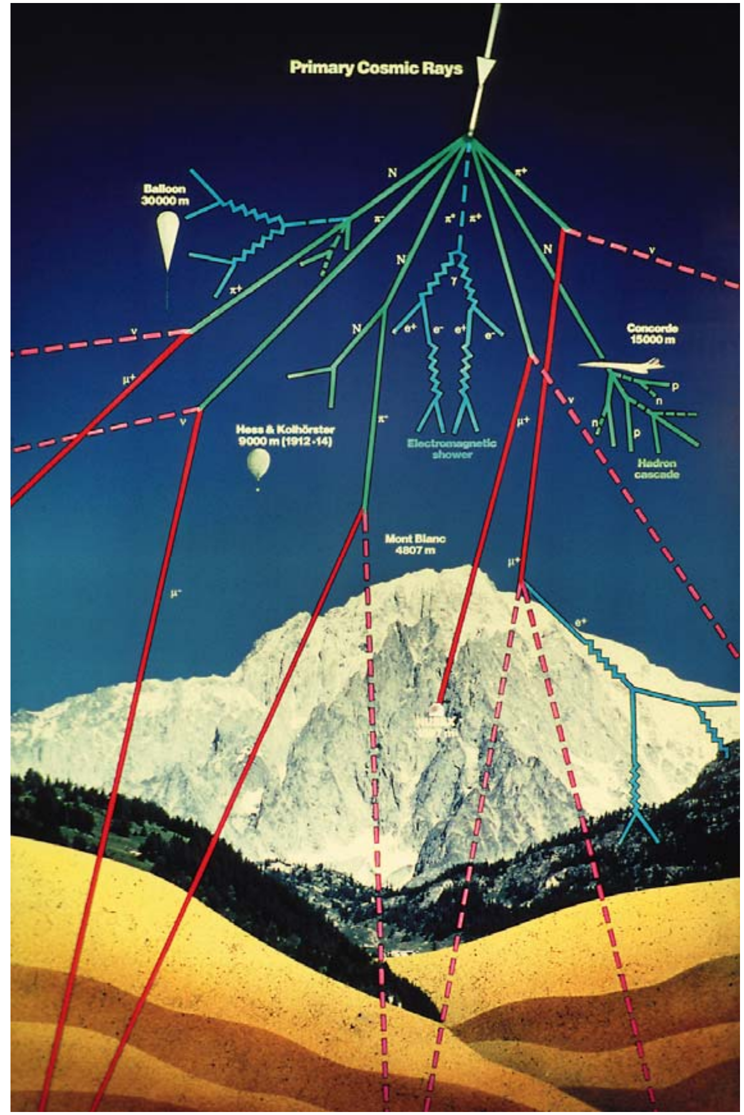
- Proton mass ≈ 1 GeV/c^2 ≈ 1 amu
- Fine structure constant $\alpha \approx 1/137$
- Speed of light ≈ 1 foot per nanosecond

Natural Radioactivity

- **First discovered in late 1800s**
- **Used as particle source in many significant experiments**
  - **Rutherford's 1906 experiment: elastic scattering $\alpha + N \rightarrow \alpha + N$**
  - **Rutherford's 1917 experiment: inelastic scattering $\alpha + N \rightarrow p + X$**
- **Common radioisotopes include**
  - **^{55}Fe: 6 keV γ**
  - **^{90}Sr: 500 keV β**
  - **^{241}Am: 5.5 MeV α**
- **Easy to control, predictable flux but low energy**
- **Still used for calibrations and tests**

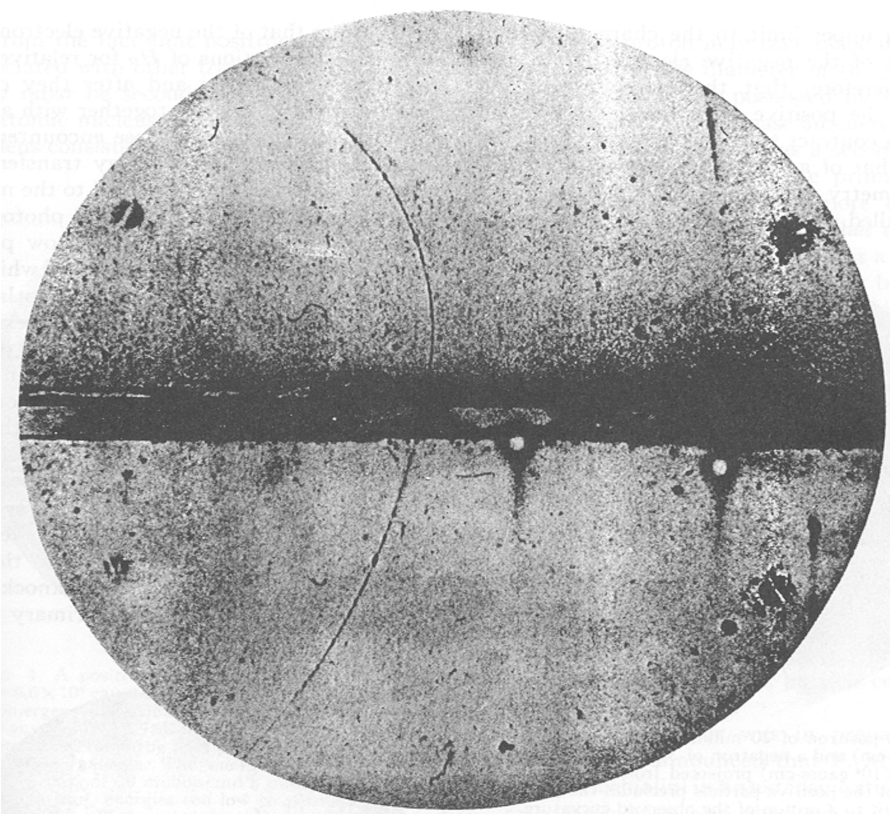
Cosmic Rays

- **Low energy cosmic rays from Sun**
  - Solar wind (mainly protons)
  - Neutrinos
- **High energy particles from sun, galaxy and perhaps beyond**
  - Neutrinos pass through atmosphere and earth
  - Low energy charged particles trapped in Van Allen Belt
  - High energy interact in atmosphere
  - Flux at ground level mainly muons: 100-200 s^{-1} m^{-2}
- **Highest energy ever seen ~10^{20}eV**



Cosmic Experiments

- **Primary source for particle physics experiments for decades**
- **Detectors taken to altitude for larger flux/higher energy**
- **Positron and many other particles first observed**



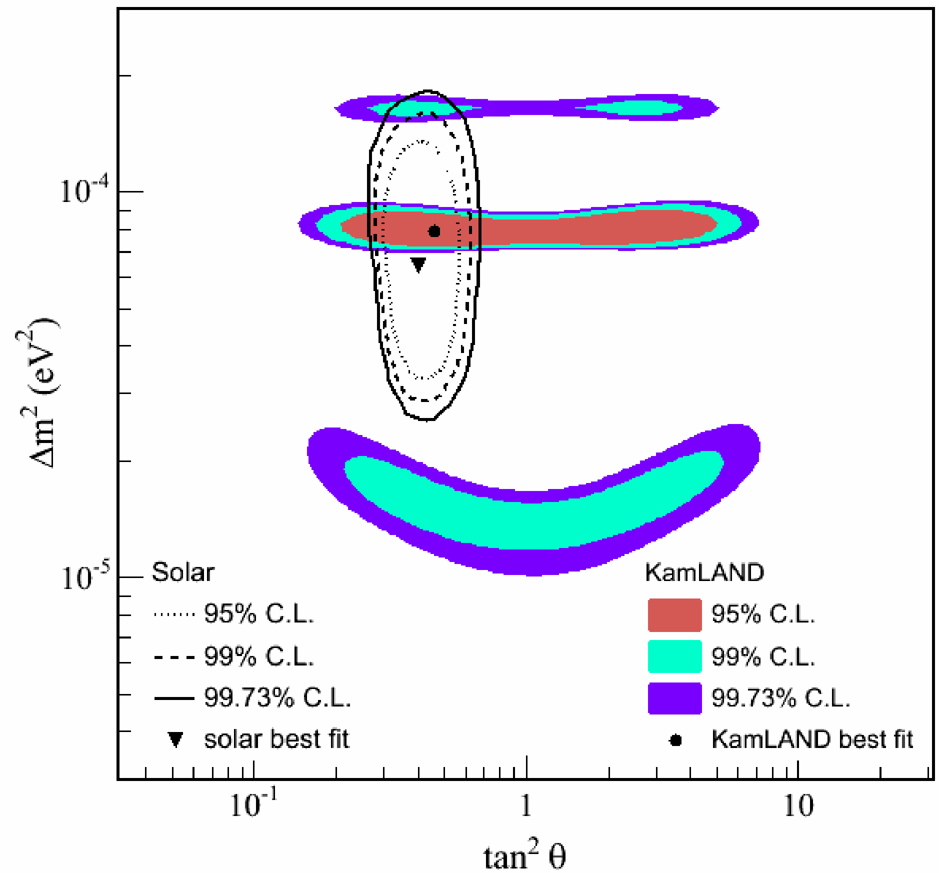
Modern experiments include:

- **Particle astrophysics**
  - **Space, atmosphere, surface, underground**
- **Neutrino**
  - **Solar, atmospheric**
- **“Dark Matter” searches**

Still useful for calibration and testing

Reactor Experiments

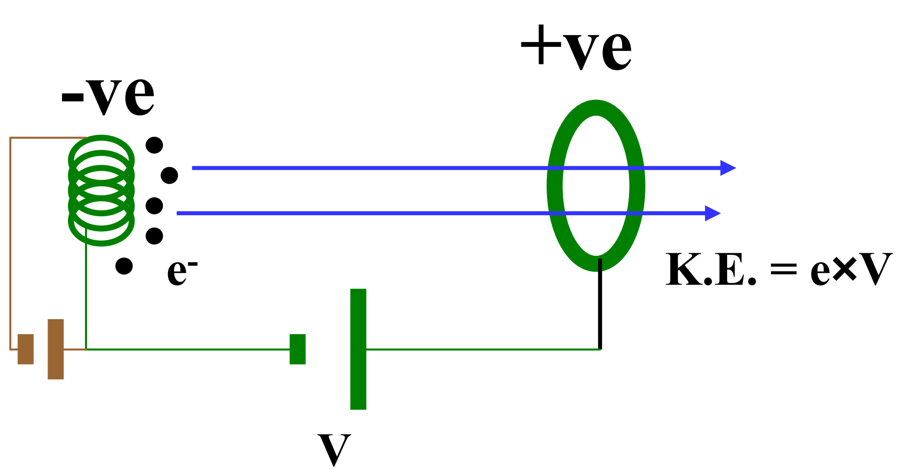
- **Huge fluxes of MeV neutrons and electron neutrinos**
- **First direct neutrino observation**
- **New results on neutrino oscillations**

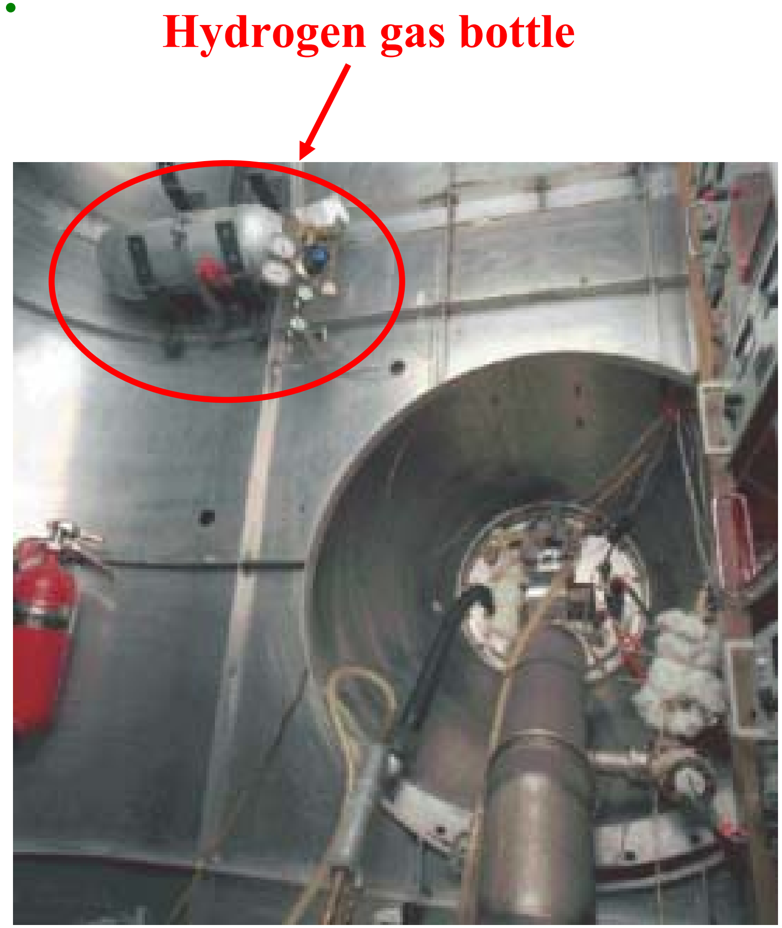


Particle Sources

Want intense monochromatic beams on demand:

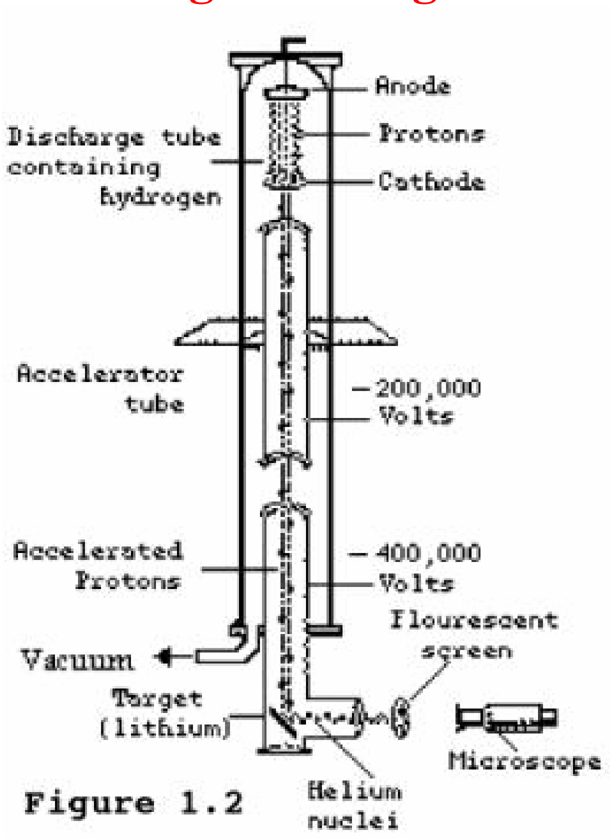
1. **Make some particles**
   - **Electrons: metal + few eV of thermal energy**
   - **Protons/nuclei: completely ionise gas**
2. **Accelerate them in the lab**





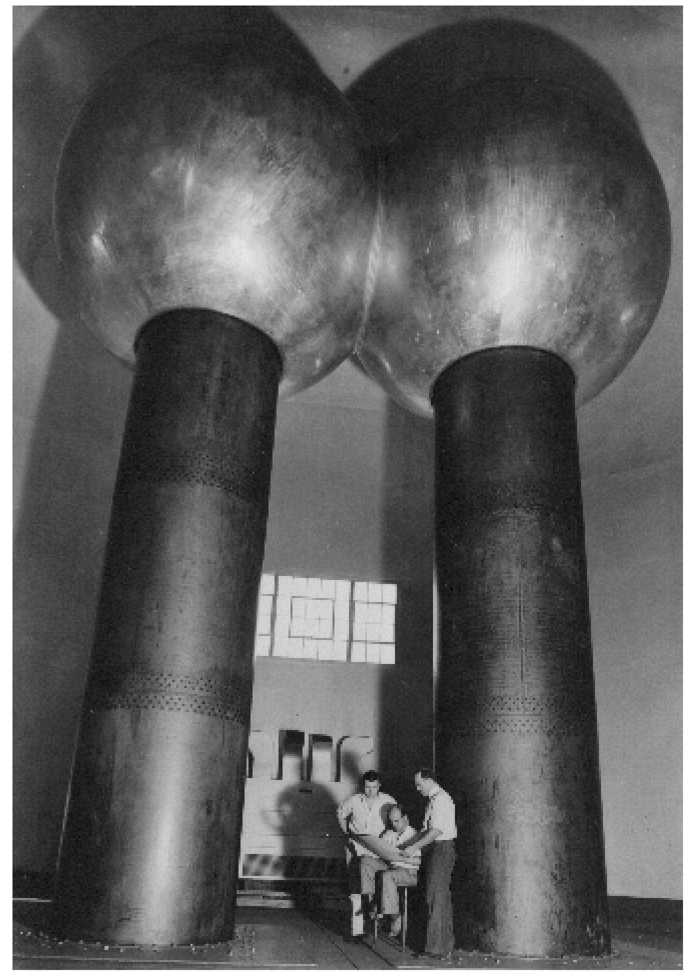
DC Accelerators

Cockroft and Walton's
Original Design



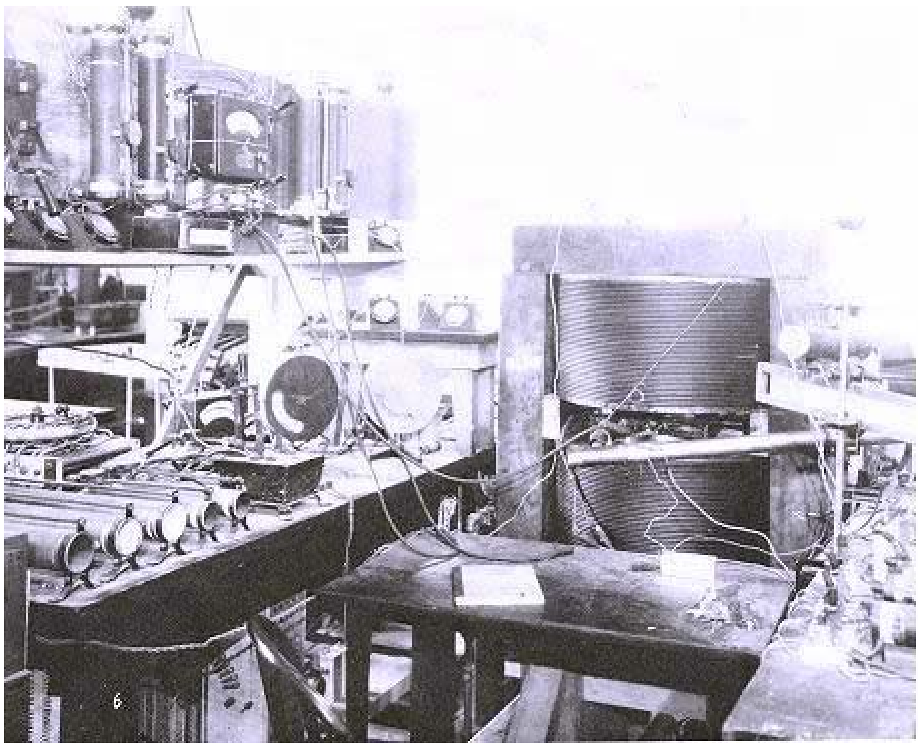
Fermilab's 750kV
Cockroft-Walton

Van de Graaff at MIT

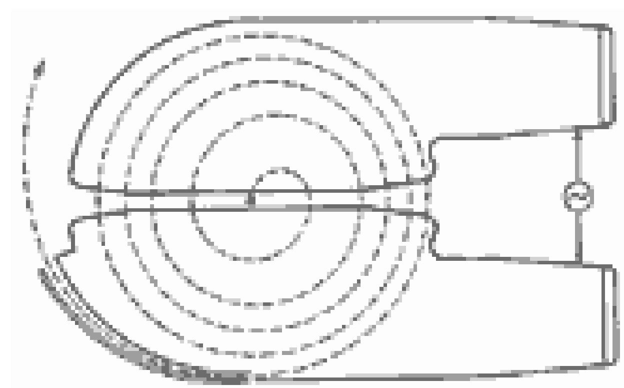


Cyclotrons

- DC accelerators quickly become impractical
  - Air breaks down at ~1MV/m



- Utilise motion in magnetic field: $p = kqBR$
- Apply AC to two halves
- Lawrence achieved MeV particles with 28cm diameter
- Magnet size scales with momentum…

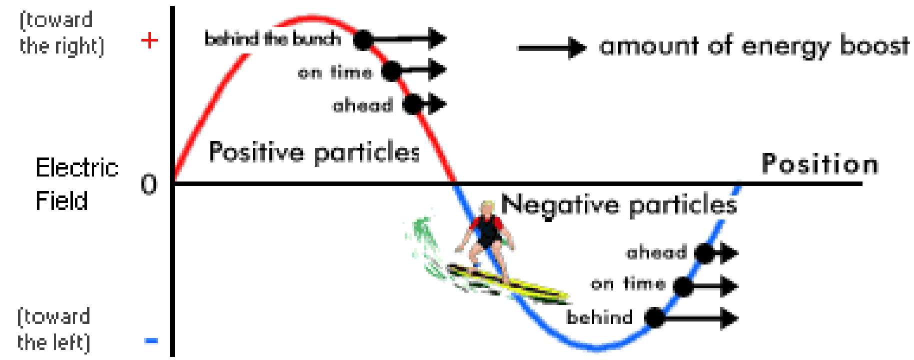


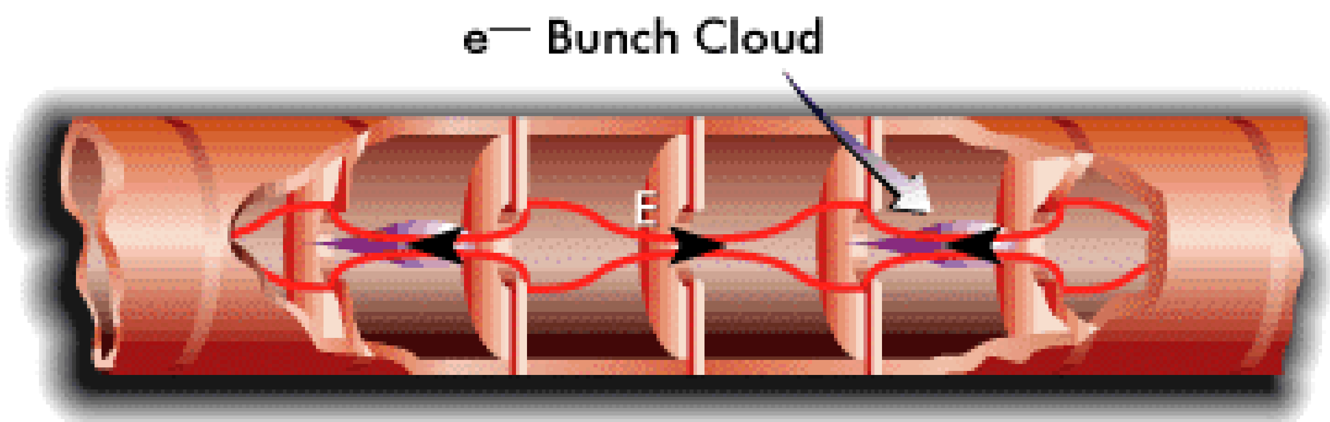
- Still used for medical purposes

Linear Accelerators

For energies greater than few MeV:

- use multiple stages
- RF easier to generate and handle
- Bunches travel through resonant cavities
- Spacing and/or frequency changes with velocity
- Can achieve 10MV/m and higher
- 3km long Stanford Linac reached 45 GeV



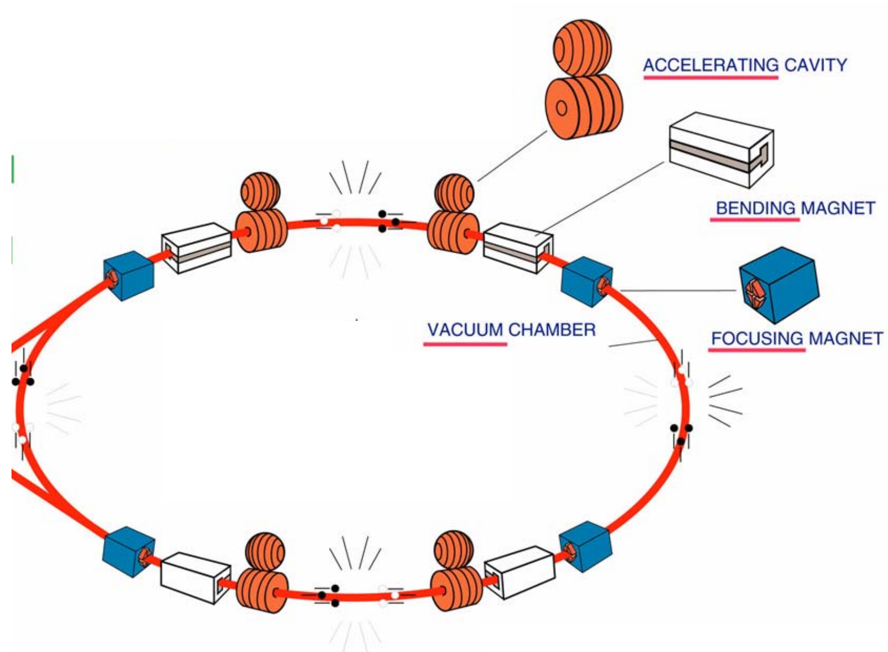


Superconducting Cavities

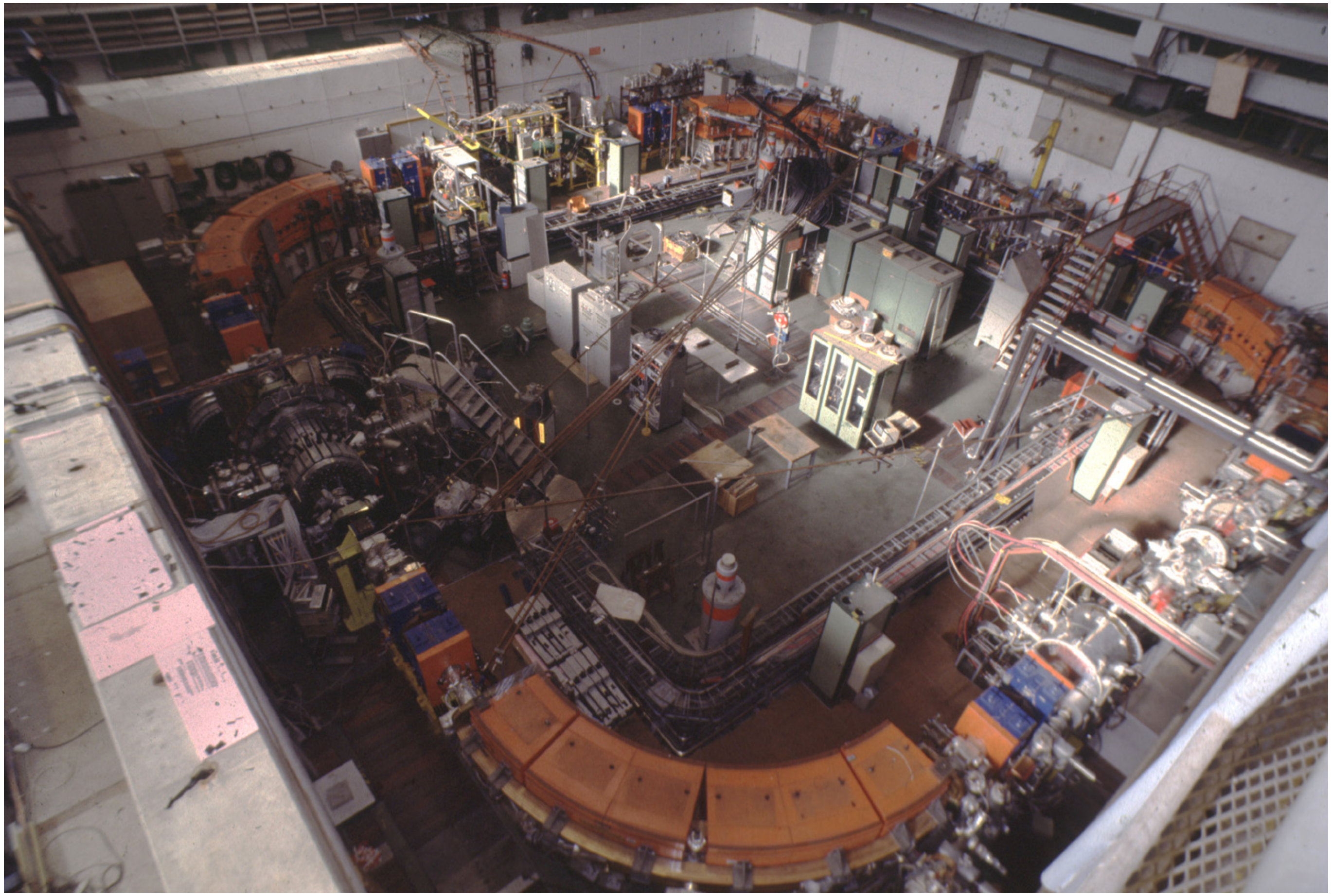
Synchrotrons

- $p = kqBR$

- Cyclotron has constant B, increasing R
- Increase B keeping R constant:
  - variable current electromagnets
  - particles can travel in small diameter vacuum pipe
  - single cavity can accelerate particles each turn
  - efficient use of space and equipment
- Discrete components in ring
  - cavities
  - dipoles (bending)
  - quadrupoles etc. (focusing)
  - diagnostics
  - control



A Real Synchrotron

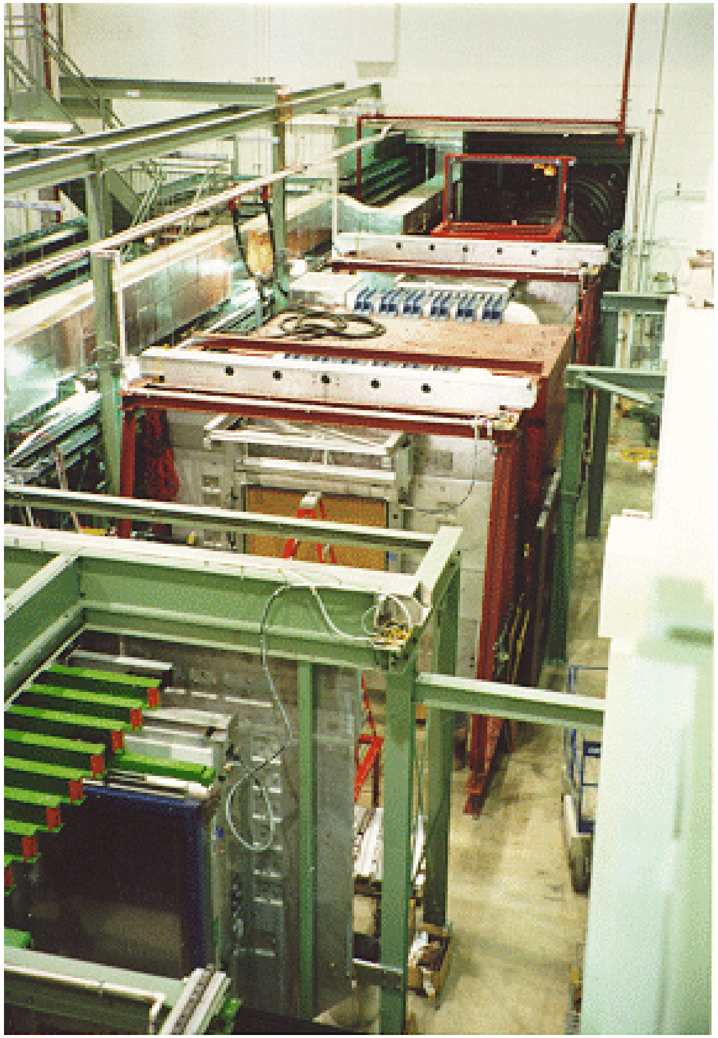


- *LEAR* – a particle decelerator and storage ring
- Why aren't all accelerators synchrotrons?

Synchrotron Radiation

- Accelerated charges radiate
- Average power loss per particle: $P = \frac{1}{6\pi\epsilon_0}\frac{e^2v^4}{c^3R^2}\gamma^4$
- Quantum process → spread in energy
- For a given energy ~ 1/mass^4
- Electron losses 10^{13} times proton
  - High energy electon machines have very large or infinite *R*
- Pulsed, intense X-ray source may be useful for some things....

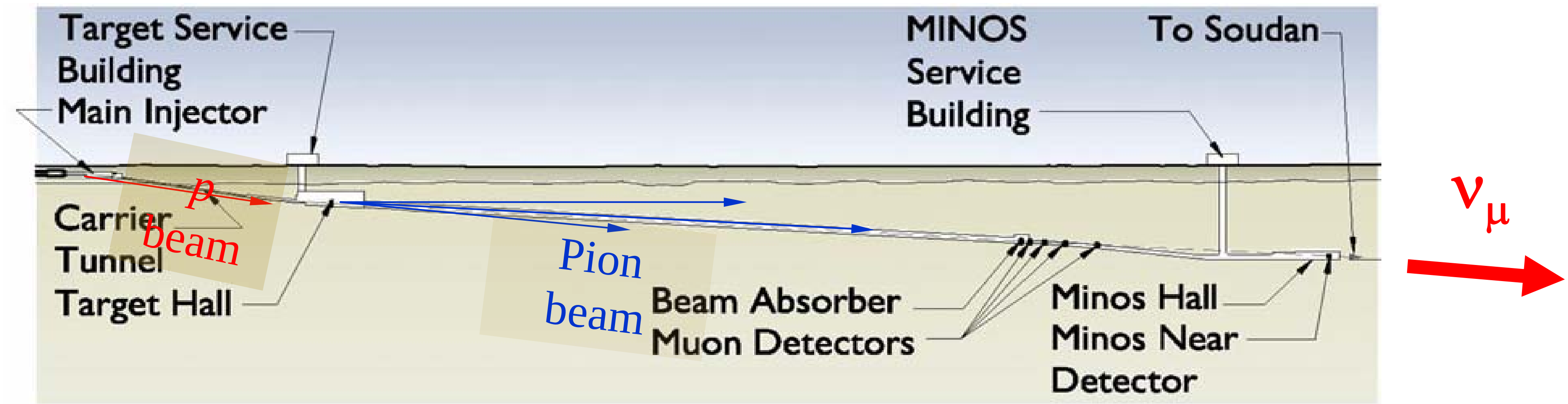
Fixed Target Experiments



Beam incident on stationary target

- Interaction products have large momentum in forward direction
- Large "wasted" energy ⇔ small $\sqrt{s}$
- Intense beams/large target ⇒ high rate
- Secondary beams can be made

Neutrino Beams



- Fermilab sends a muon-neutrino beam to Minnesota
- Looking for oscillations
- Detector at bottom of mine shaft

Antiparticle Production

1. Positrons and antiprotons produced in fixed target collisions
   – typical efficiency 10^5 protons per antiproton

2. Large phase space – must be "cooled"
   – synchrotron radiation damps electrons
   – antiproton cooling techniques won Nobel *(see LEAR photo)*

3. Decelerated and accumulated in storage rings

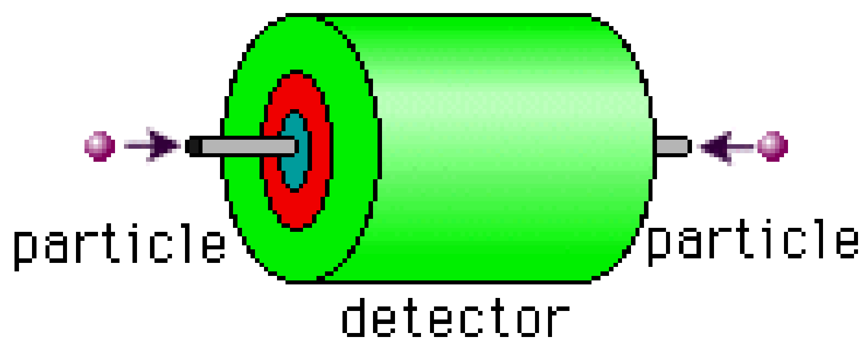
Colliders

- **Incoming momenta cancel**
- $\sqrt{s} = 2E_{beam}$
- **Same magnetic field deflects opposite charges in opposite directions ⇒ *Antiparticle accelerator for free!***
  - **particle/antiparticle quantum numbers also cancel**

- ***Technically challenging***

- **Luminosity** $\mathcal{L} = f n_1 n_2 / A$

- **Interaction rate =** $\mathcal{L}\sigma$



Different Colliders

- *p pbar*
  - energy frontier
  - difficult to interpret
  - limited by pbar production
  - *SPS, Tevatron*

- *e+ e-*
  - relatively easy analysis
  - high energies difficult
  - *LEP, PEP...*

- *p p*
  - high luminosity
  - energy frontier
  - *LHC*

- *e p*
  - proton structure
  - *HERA*

- *ion ion*
  - quark gluon plasma
  - *RHIC, LHC*

- $\mu^+ \mu^-$
  - some plans exist

- $\nu \nu$
  - !!!

Collider Parameters

	CESR (Cornell)	CESR-C (Cornell)	KEKB (KEK)	PEP-II (SLAC)	LEP (CERN)
Physics start date	1979	2002	1999	1999	1989
Physics end date	2002	—	—	—	2000
Maximum beam energy (GeV)	6	6	$e^- \times e^+$: 8×3.5	e^-: 7–12 (9.0 nominal) e^+: 2.5–4 (3.1 ") (nominal $E_{\rm cm}$ = 10.5 GeV)	101 in 1999 (105=max. foreseen
Luminosity (10^{30} cm^{-2}s^{-1})	1280 at 5.3 GeV/beam	35 at 1.9 GeV/beam	11305	6777	24 at Z^0 100 at > 90 GeV
Time between collisions (μs)	0.014 to 0.22	0.014 to 0.22	0.008	0.0042	22

Full details at pdg.lbl.gov

	HERA (DESY)	TEVATRON (Fermilab)	RHIC (Brookhaven)			LHC (CERN)	
Physics start date	1992	1987	2000			2007	2008
Physics end date	—	—	—			—	
Particles collided	ep	$p\bar{p}$	pp (pol.)	Au Au	d Au	pp	Pb Pb
Maximum beam energy (TeV)	e: 0.030 p: 0.92	0.980	0.1 40% pol	0.1 TeV/u	0.1 TeV/u	7.0	2.76 TeV/u
Luminosity (10^{30} cm^{-2}s^{-1})	75	50	6	0.0004	0.07	1.0×10^4	0.001
Time between collisions (μs)	0.096	0.396	0.213			0.025	0.100

Inside the Tunnels

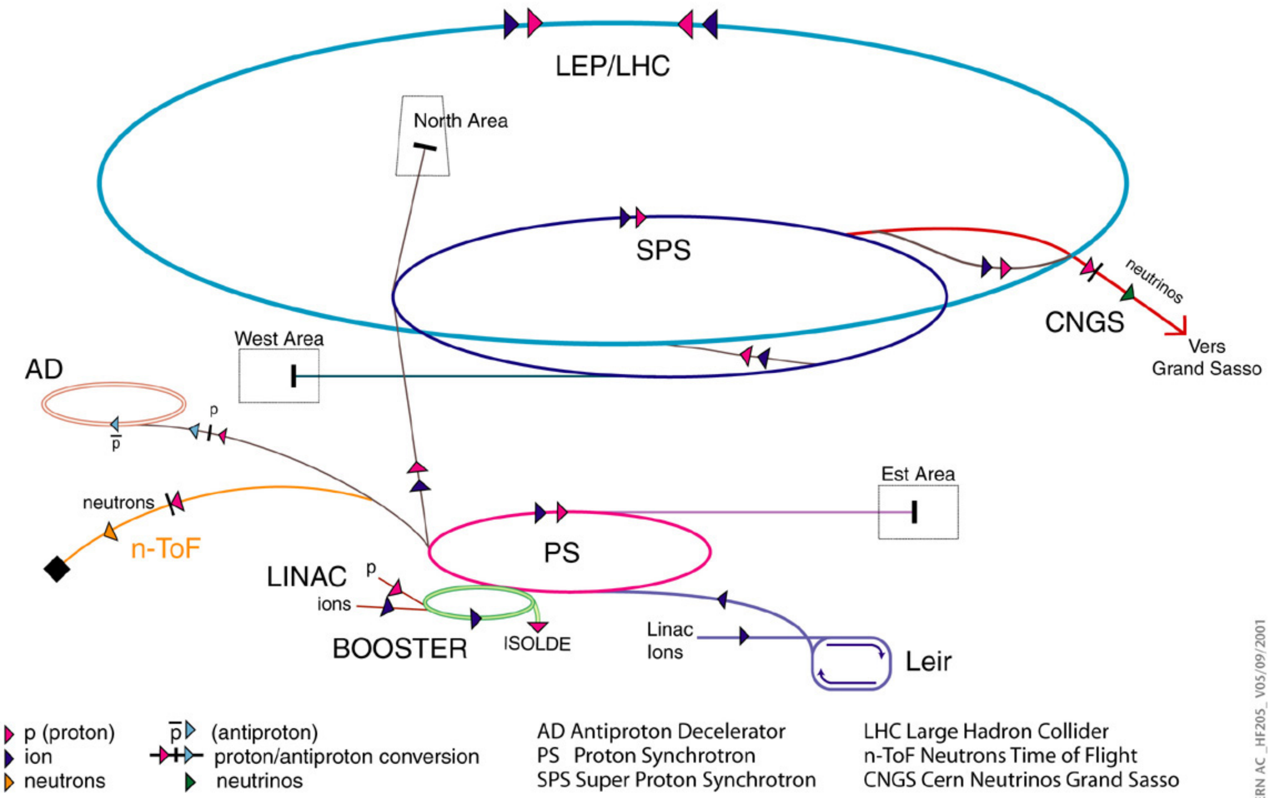
- **Underground for shielding and stability**

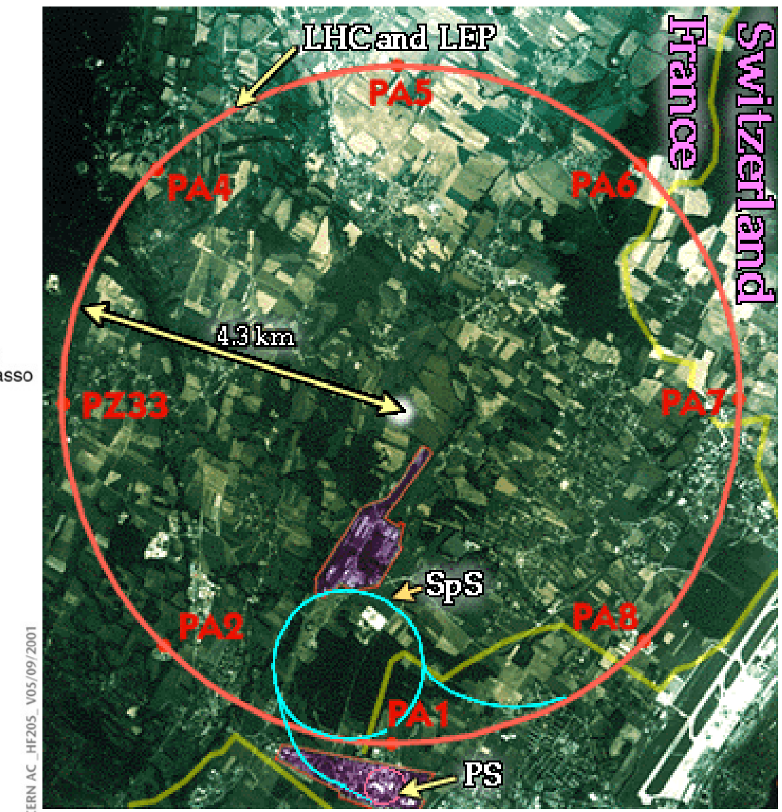
Focusing Magnet

Concrete Dipole

Complexes

- **Synchrotrons can't accelerate particles from rest**
- **Designed for specific energy range, normally about factor of 10**
  - **accelerators are linked into complexes**





Next Time...

Charged particle interactions and detectors