USPAS Course on Photocathode Physics

John Smedley, BNL and Matt Poelker, TJNAF

Lecture 1

Austin, TX January 16-20, 2011

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Lecture 1:
History of Particle Physics
Why "Polarized" Beam?
All in the context of accelerators

Austin, TX   January 16-20, 2011

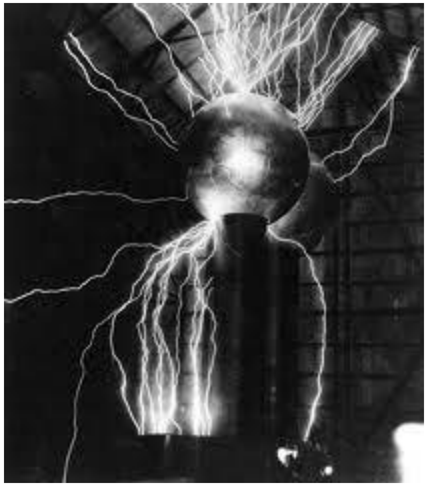
Who needs electrons?

Batteries, generators, circuits, free electrons and electron beams.....







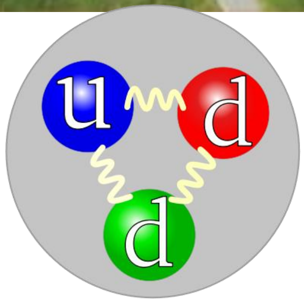


Jefferson Lab

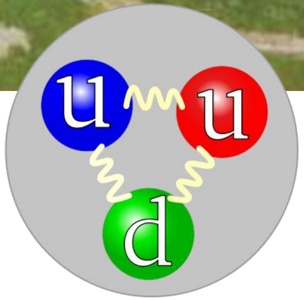
Thomas Jefferson National Accelerator Facility

Exploring the Nature of Matter

Electron

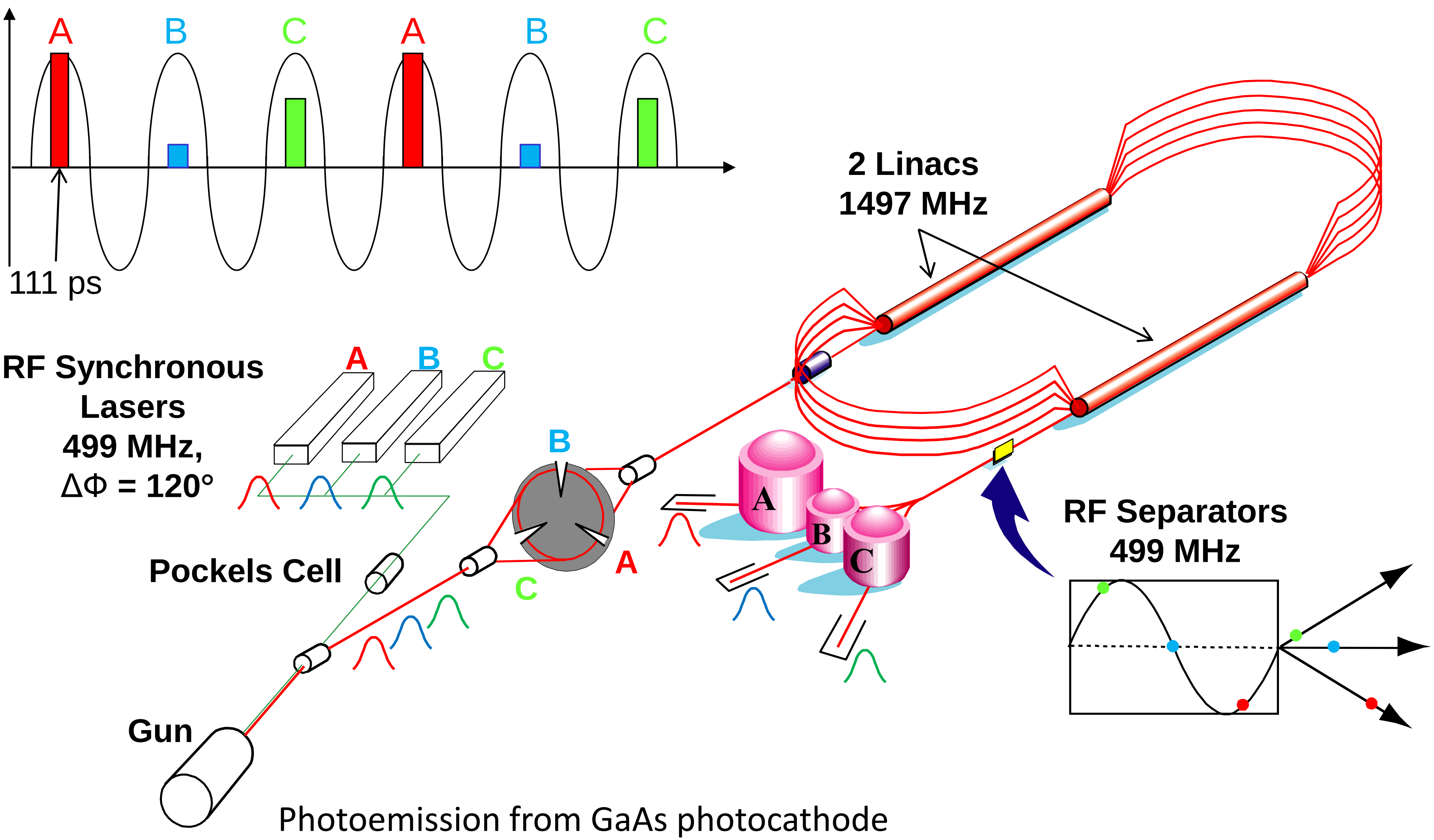


Neutron



Proton

Continuous Electron Beam Accelerator Facility… just a really big microscope



What Does “Polarized” Mean?

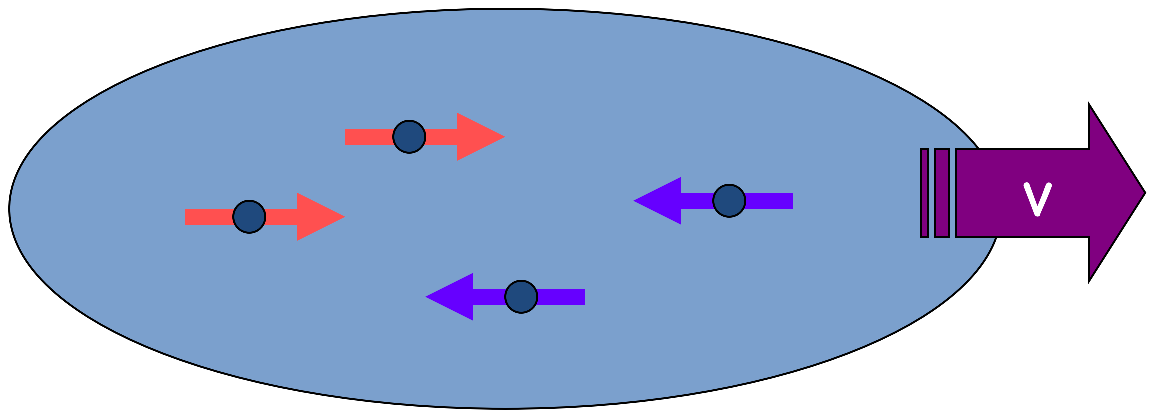
People with very different opinions

Light: a preference for the electric field vector to be oriented a certain way

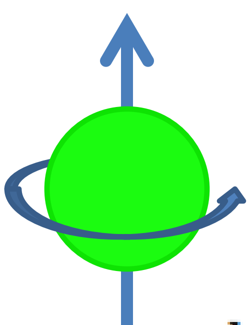
Electrons: a preference for electrons to spin in one direction

0% Polarization

☹

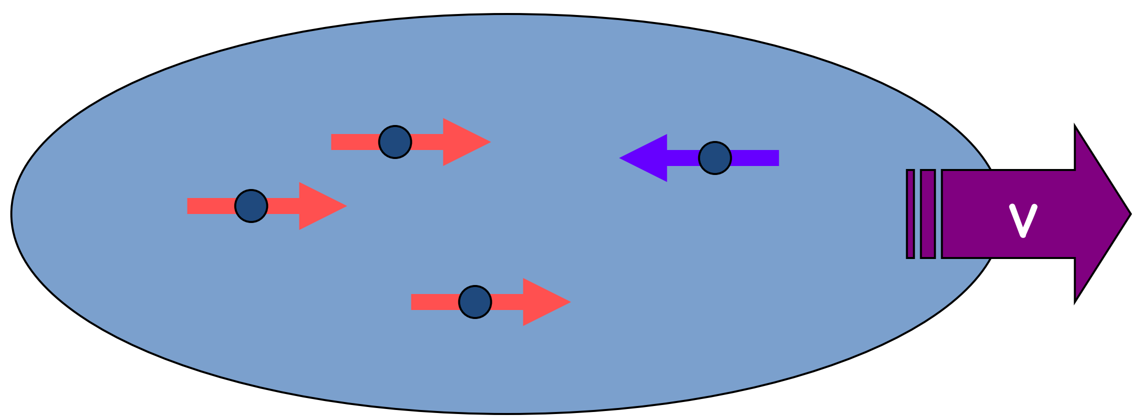


Electrons spin.....



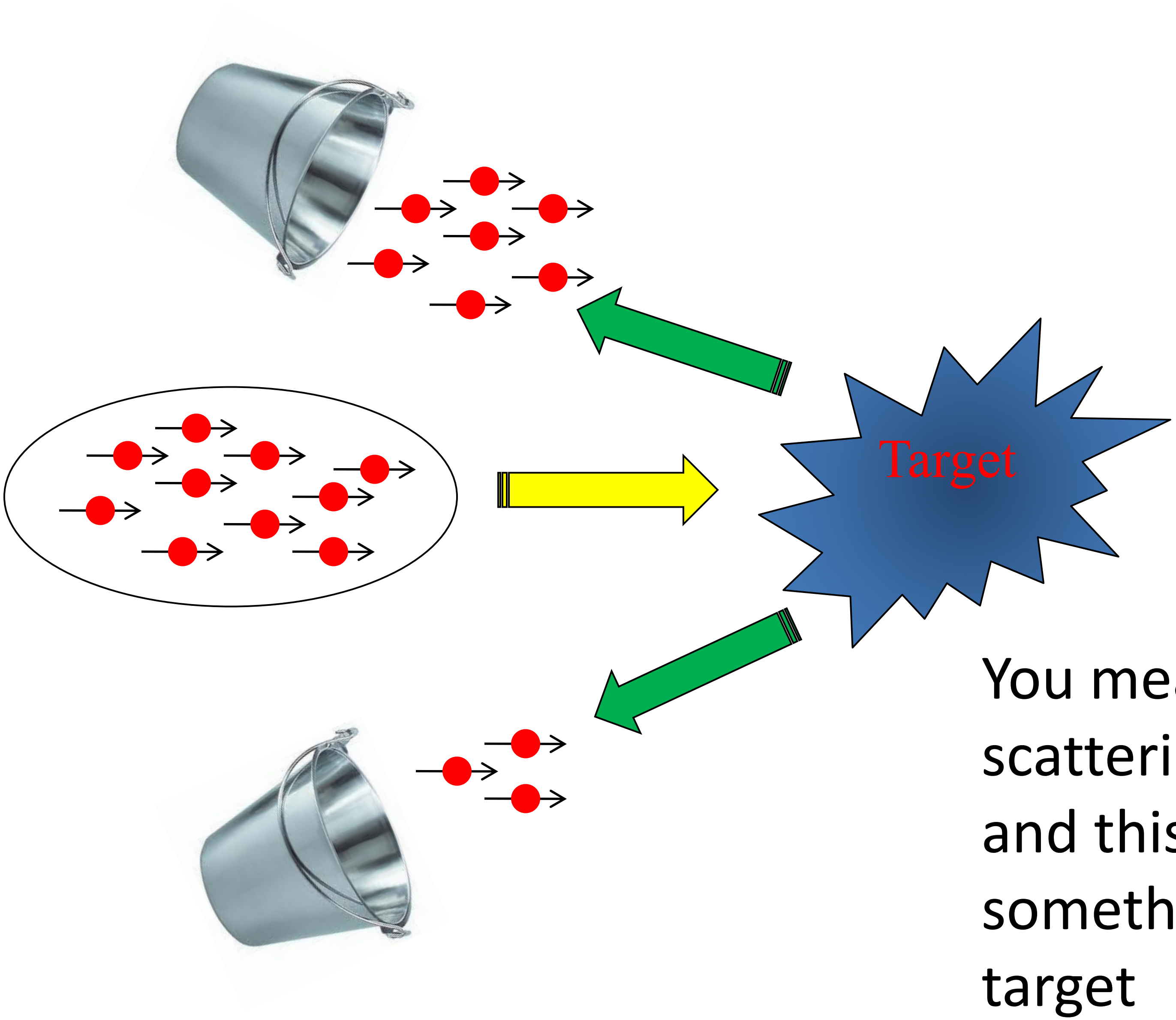
50% Polarization

☺



$$S = \pm \frac{h}{4\pi} = \pm \frac{\hbar}{2}$$

Probing with spin tells us something



You measure a scattering asymmetry, and this tells us something about the target

Kinds of Experiments at JLab

Energetic electrons hit a “fixed target”. Most of the electrons pass through target and hit the beam dump! Some of the electrons “hit” a nulceon…

- Electron Beam and Target Unpolarized
- Electron Beam Polarized, Target Unpolarized
- Electron Beam and Target Polarized

At CEBAF, all the experiments get electron beams from the same GaAs photocathode, so everyone gets spin polarized electrons, regardless if they want them or not

Brief History Lesson on Particle Physics

Many thanks to Prof. Steven Blusk of Syracuse University for providing an excellent tutorial on particle physics. Many of the following slides come from him….

Periodic Table of Elements

ОПЫТЪ СИСТЕМЫ ЭЛЕМЕНТОВЪ.

ОСНОВАННОЙ НА ИХЪ АТОМНОМЪ ВѢСѢ И ХИМИЧЕСКОМЪ СХОДСТВѢ.

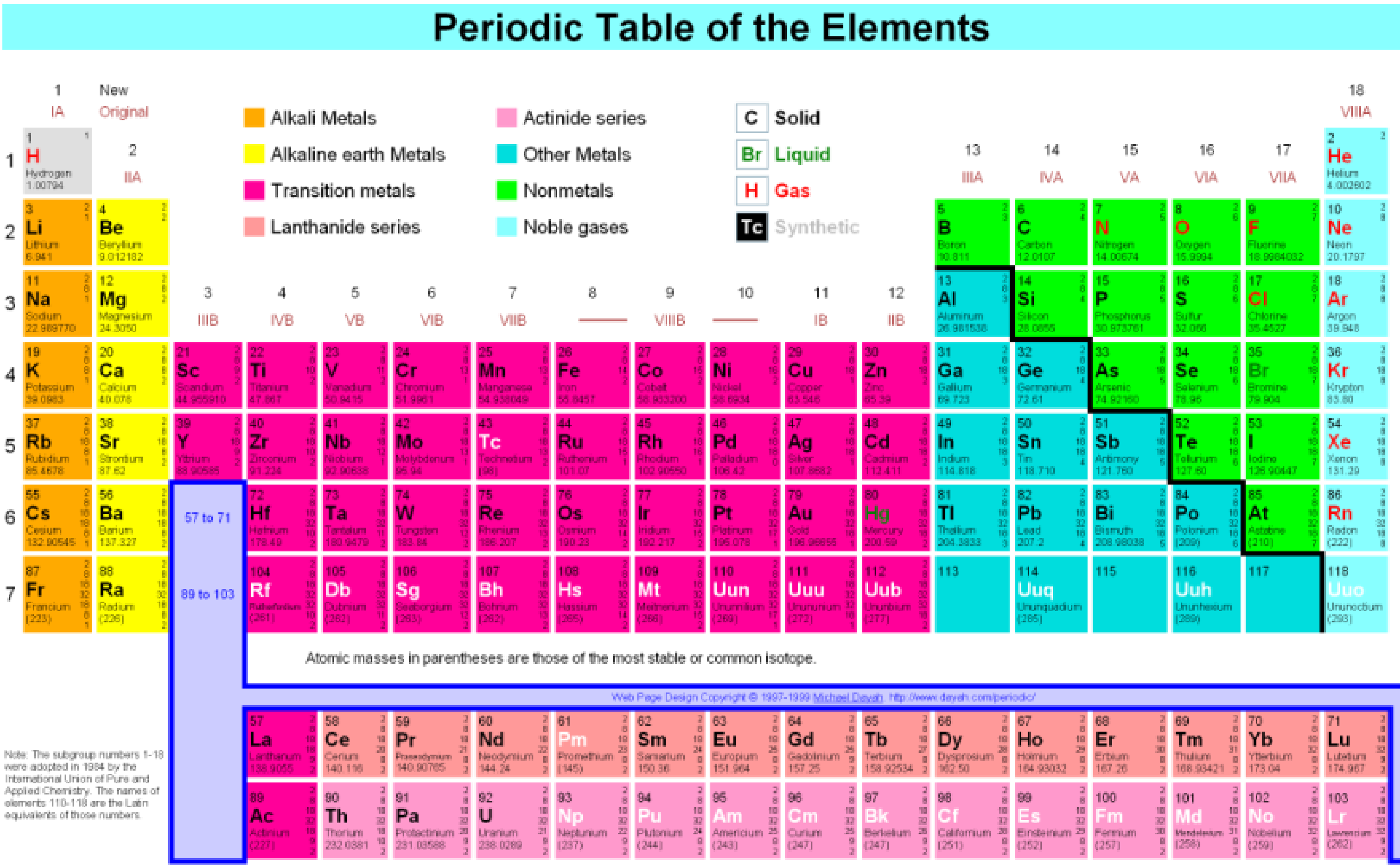
			Ti=50	Zr=90	?=180.
			V=51	Nb=94	Ta=182.
			Cr=52	Mo=96	W=186.
			Mn=55	Rh=104,4	Pt=197,1.
			Fe=56	Rn=104,4	Ir=198.
			Ni=Co=59	Pl=106,6	Os=199.
H=1			Cu=63,4	Ag=108	Hg=200.
	Be=9,4	Mg=24	Zn=65,2	Cd=112	
	B=11	Al=27,4	?=68	Ur=116	Au=197?
	C=12	Si=28	?=70	Sn=118	
	N=14	P=31	As=75	Sb=122	Bi=210?
	O=16	S=32	Se=79,4	Te=128?	
	F=19	Cl=35,5	Br=80	I=127	
Li=7	Na=23	K=39	Rb=85,4	Cs=133	Tl=204.
		Ca=40	Sr=87,6	Ba=137	Pb=207.
		?=45	Ce=92		
		?Er=56	La=94		
		?Yt=60	Di=95		
		?In=75,6	Th=118?		

Д. Менделѣевъ

- Dmitri Mendeleev, 1869 (and others…) grouped known elements by atomic weight and noticed certain periodic trends
- Successfully predicted new elements at the vacancies
- All this before the discovery of the proton, neutron, (and full appreciation of properties of electron)….

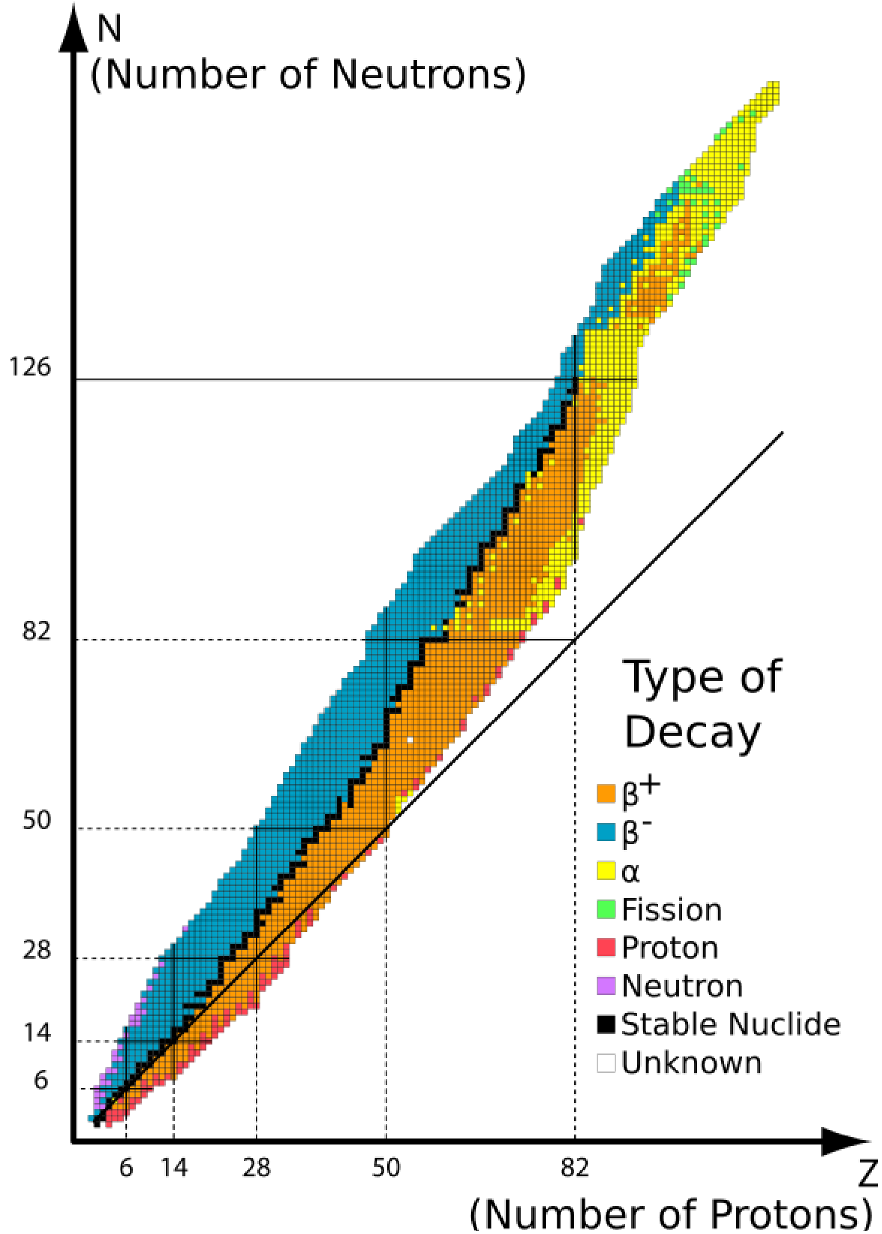
Modern Periodic Table

Elements identified by # of electrons, protons and neutrons

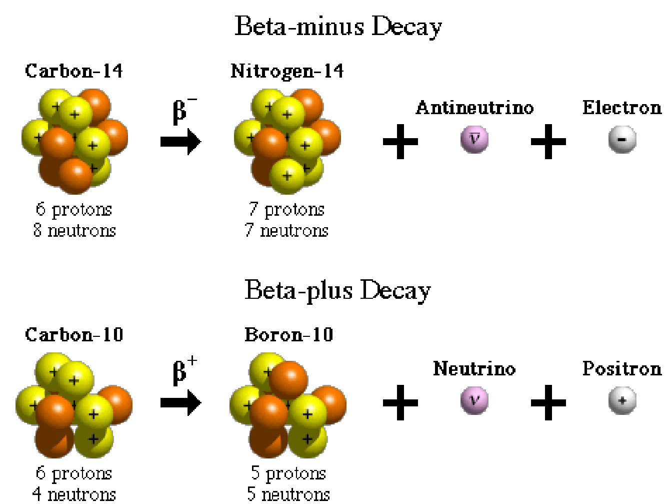


Slide courtesy Prof. Steven Blusk, Syracuse University

Chart of Nuclides



Why is there a trend toward more neutrons than protons?
Beta decay: change from one element to another but mass stays the same!

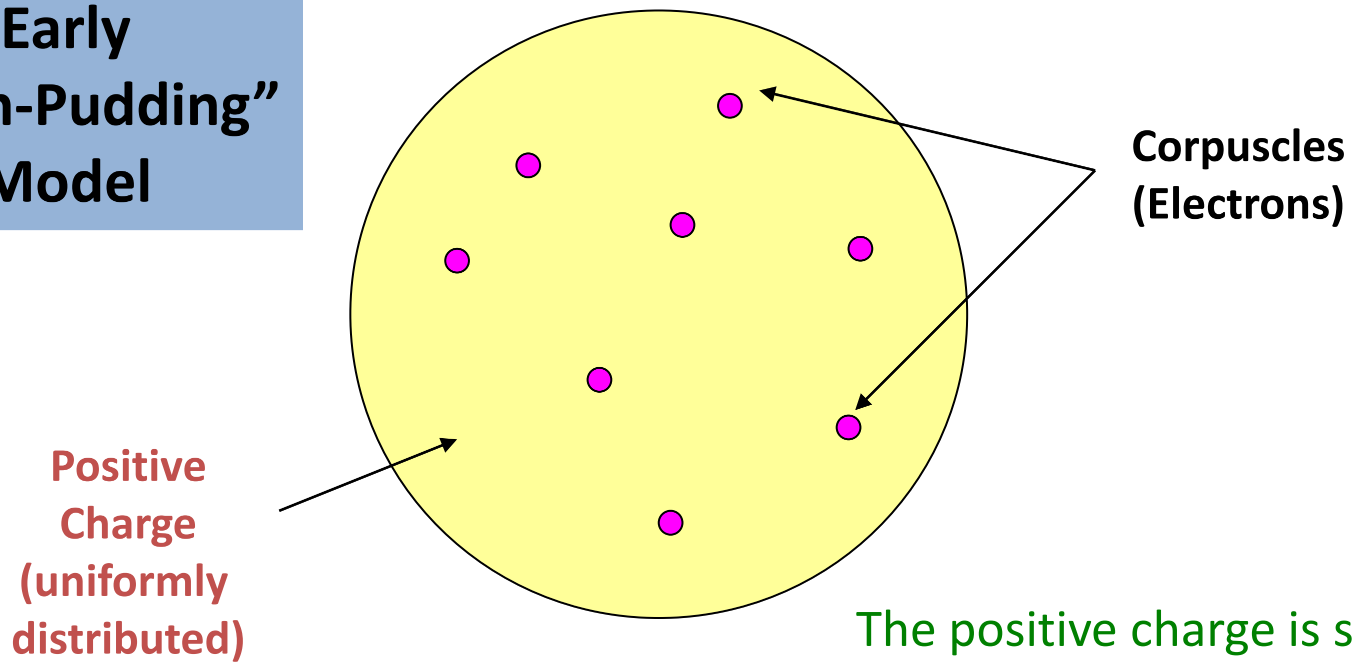


But what's inside "an element"

For each element, we associate an atom.

Prior to ~1905, nobody really knew:
" What does the inside of an atom look like ? "

Early "Plum-Pudding" Model



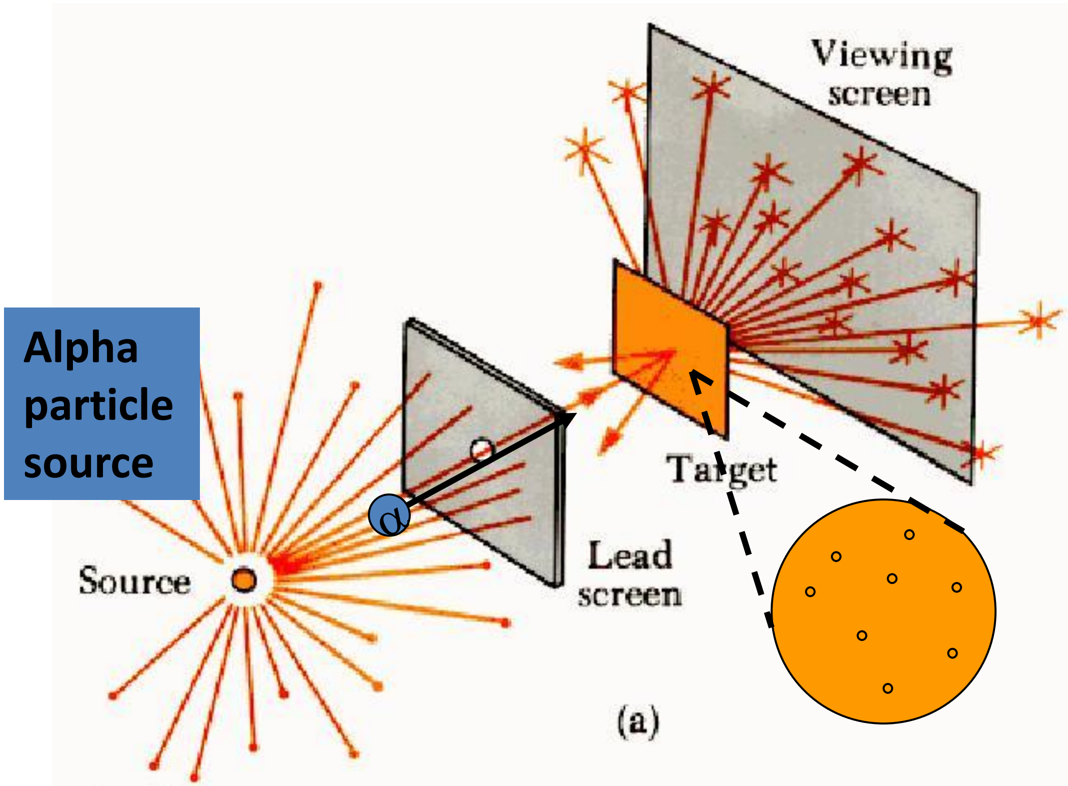
The positive charge is spread out like a "plum-pudding"

Electrons were discovered ~1900 by J. J. Thomson

Slide courtesy Prof. Steven Blusk, Syracuse University

Scattering Experiments

If the plum-pudding model was right, then matter is "soft". There's no "central, hard core"…



Ernest Rutherford
1871-1937

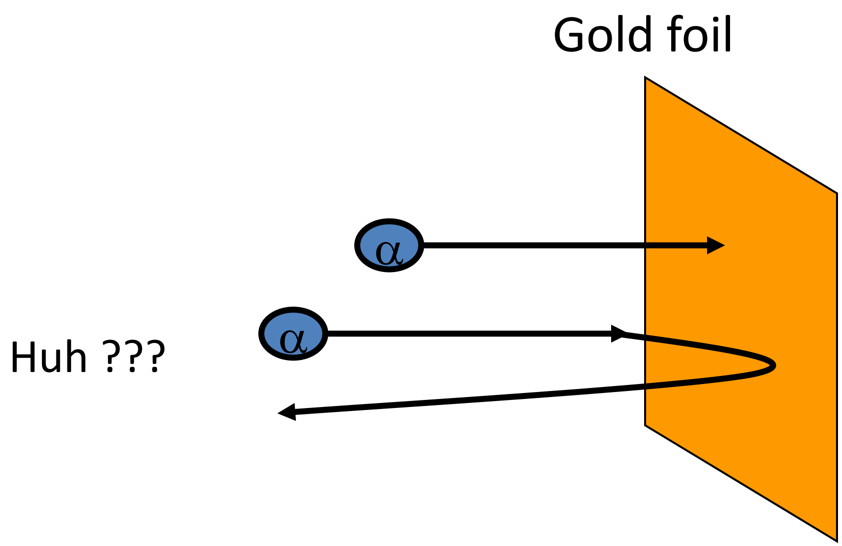
Nobel Prize in Chemistry 1908: Nuclear half-life and transmutation.
Then he goes on to discover the nucleus

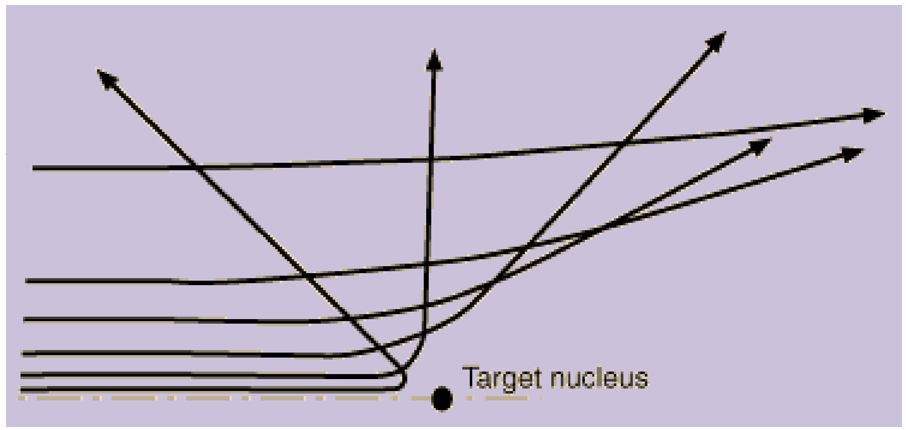
Calculations, based on the known laws of electricity and magnetism showed that the heavy alpha particles should be only slightly deflected by this "plum-pudding" atom…

Slide courtesy Prof. Steven Blusk, Syracuse University

Au Contraire

Contrary to expectations, Rutherford found that a significantly large fraction (~1/8000) of the alpha particles "bounced back" in the same direction in which they came…The theoretical expectation was that fewer than 1/10,000,000,000 should do this ???



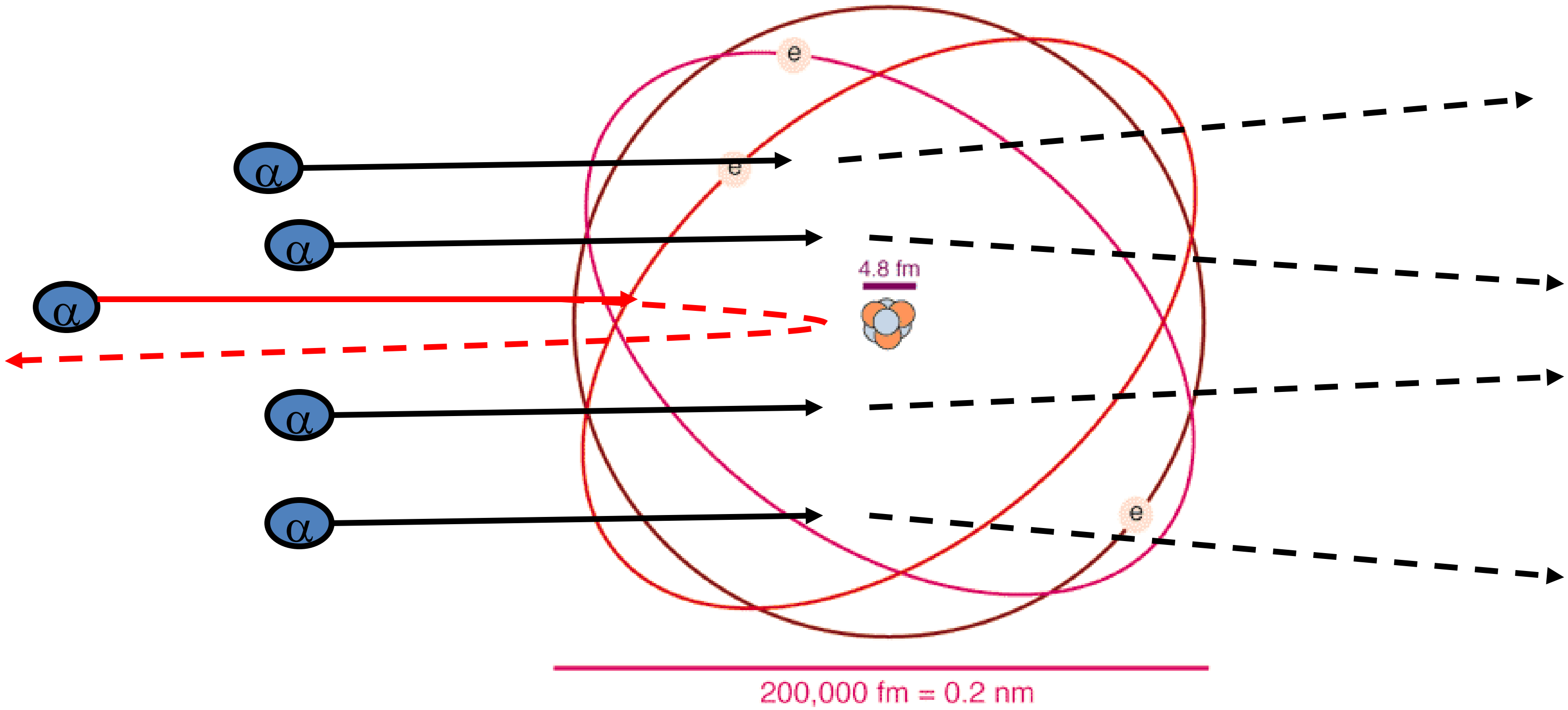


In Rutherford's words…
"It was quite the most incredible event that ever happened to me in my life. It was as if you fired a 15-inch naval shell at a piece of tissue paper and the shell came right back and hit you."

Slide courtesy Prof. Steven Blusk, Syracuse University

The (only) interpretation

The atom must have a **solid core** capable of imparting large electric forces onto an incoming (charged) particle.



Atoms are neutral, so nucleus must be composed of protons…

Slide courtesy Prof. Steven Blusk, Syracuse University

Neils Bohr and the Quantum Atom

Circa 1910-1925

- Pointed out serious problems with Rutherford's atom
  - Electrons should radiate as they orbit the nucleus, and in doing so, lose energy, until they spiral into the nucleus.
  - Atoms only emit quantized amounts of energy (i.e., as observed in Hydrogen spectra)
- He postulated
  - Electric force keeps electrons in orbit
  - Only certain orbits are stable, and they do not radiate energy

Radiation is emitted when an e^- jumps from an outer orbit to an inner orbit and the energy difference is given off as a radiation.

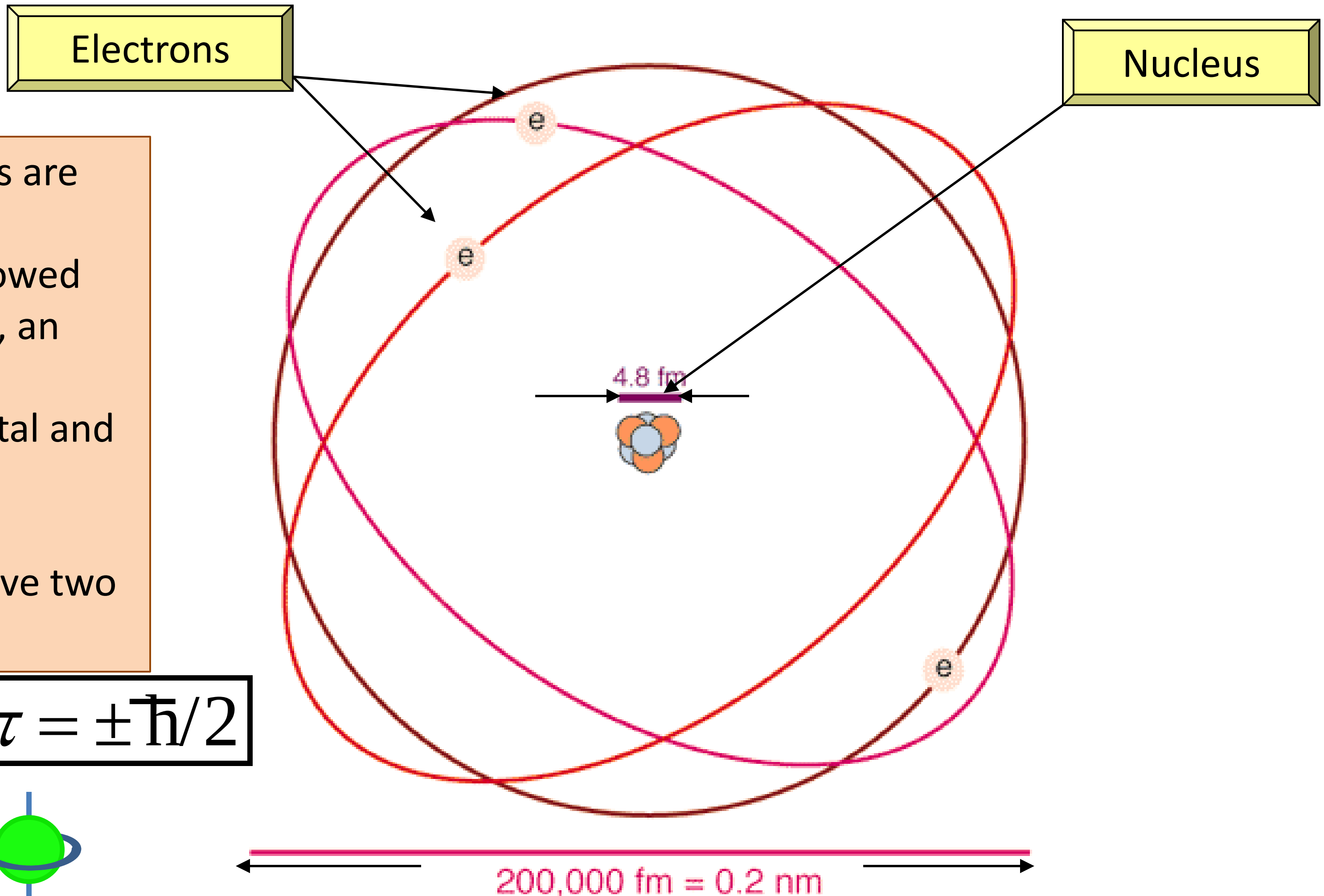
1885-1962

Awarded the Nobel Prize in 1922

Slide courtesy Prof. Steven Blusk, Syracuse University

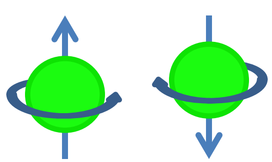
The Modern Atom

Atom: the smallest particle of an element that can exist either alone or in combination



- Energy levels are quantized
- For each allowed energy level, an electron has specific orbital and spin angular momentum
- electrons have two spin states

$$\boxed{S = \pm h/4\pi = \pm \hbar/2}$$



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James Chadwick and the Neutron

Circa 1925-1935

Picked up where Rutherford left off with more scattering experiments… (higher energy though!)

- Performed a series of scattering experiments with α-particles (recall a particles are He nucleus),

  ${}^{4}_{2}He + {}^{9}Be \longrightarrow {}^{12}C + {}^{1}_{0}n$

- Chadwick postulated that the emergent radiation was from a new, neutral particle, the neutron.

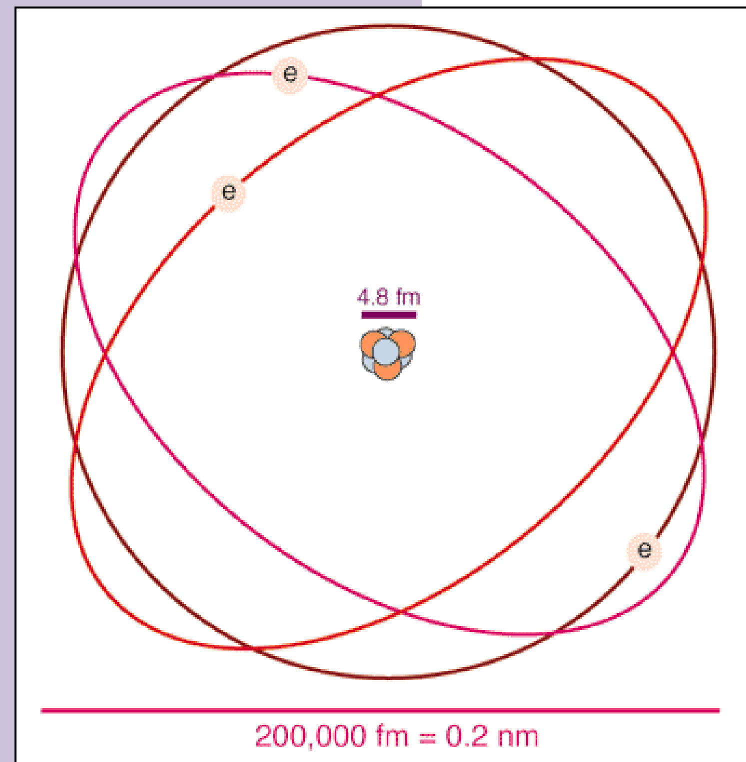
- Applying energy and momentum conservation he found that the mass of this new object was ~1.15 times that of the proton mass.

1891-1974

→ Awarded the Nobel Prize in 1935

Slide courtesy Prof. Steven Blusk, Syracuse University

- ❑ Electrons were discovered ~1900 by J. J. Thomson
- ❑ Protons being confined in a nucleus was put forth ~1905
- ❑ Neutrons discovered 1932 by James Chadwick
- ❑ Quantum theory of radiation had become "widely accepted", although even Einstein had his doubts
- ❑ Radiation is produced when atomic electrons fall from a state of high energy → low energy. Yields photons in the visible/ X-ray region.
- ❑ A nucleus can also be excited, and when it "de-excites" it also gives off radiation ➔ Typically gamma rays !

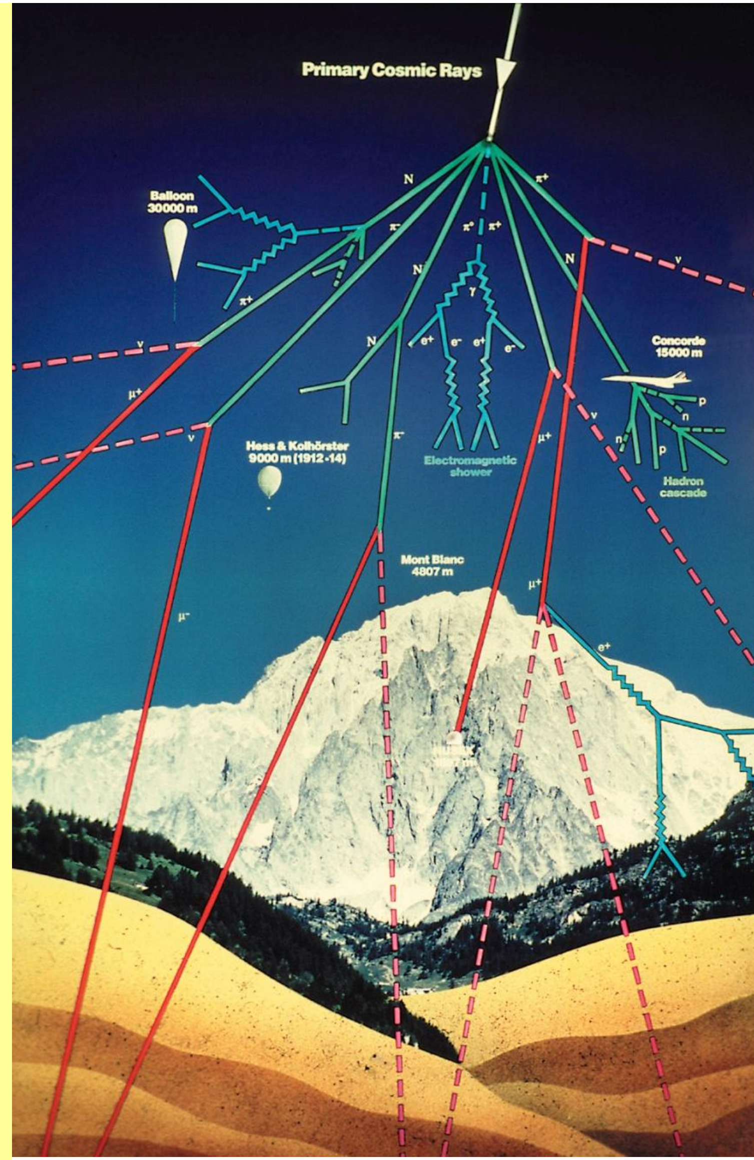


This completed the picture, or did it…

Slide courtesy Prof. Steven Blusk, Syracuse University

Cosmic Rays

- Cosmic Rays are energetic particles (e.g., electrons, protons, nuclei) that impinge on our atmosphere, from the sun or other faraway places in the Cosmos
- They come from all directions
- When these high energy particles strike atoms/molecules in our atmosphere, they produce a *spray* of particles
- Many “exotic” particles can be created, as long as they are not so massive as to violate energy conservation they can be created.
- Some of these particles are unstable and “decay” quickly into other stable particles
- Any of these exotic particles which live long enough to reach the surface of the earth can be detected !



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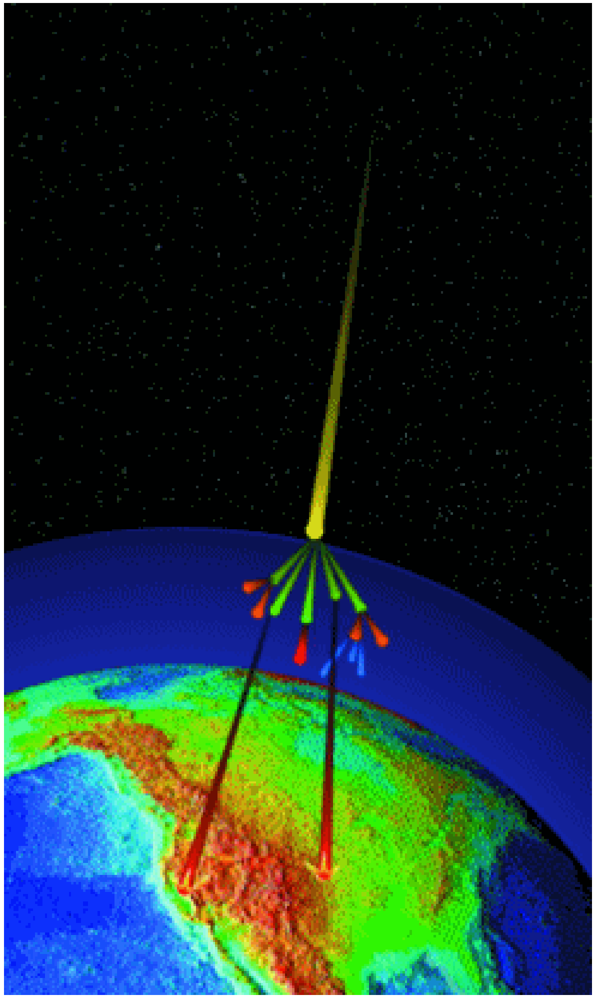
Discoveries in Cosmic Rays

- 1932 : Discovery of the antiparticle of the electron, the positron. Confirmed the existence and prediction that anti-matter does exist!!!

- 1937 : Discovery of the muon. It's very much like a "heavy electron".

- 1947 : Discovery of the pion.



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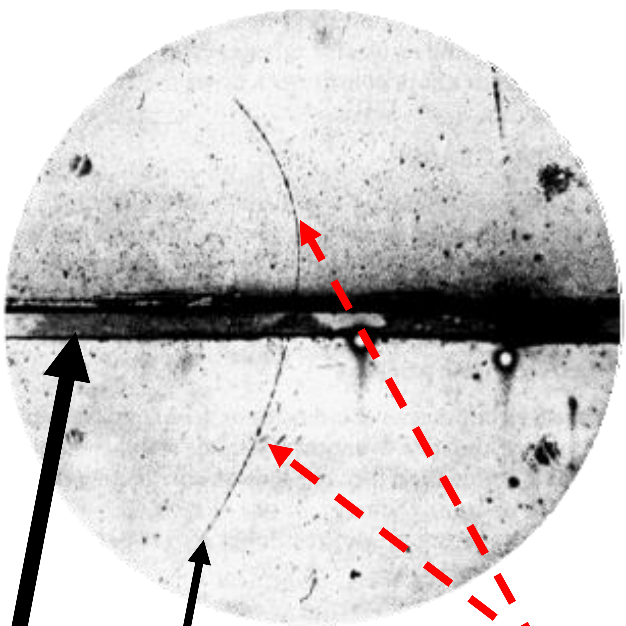
Positron Discovery in Cosmic Rays (1932)

Cloud Chamber Photograph



Lead plate

Positron

Larger curvature of particle above plate means it's moving slower (lost energy as it passed through)

A "Cloud Chamber" is capable of detecting charged particles as they pass through it.

The chamber is surrounded by a magnet.

The magnet bends positively charged particles in one direction, and negatively charged particles in the other direction.

By examining the curvature above and below the lead plate, we can deduce:

(a) the particle is traveling upward in this photograph.

(b) it's charge is positive

Using other information about how far it traveled, it can be deduced it's not a proton.

It's a particle who's mass is same as electron but has positive charge → POSITRON !

Slide courtesy Prof. Steven Blusk, Syracuse University

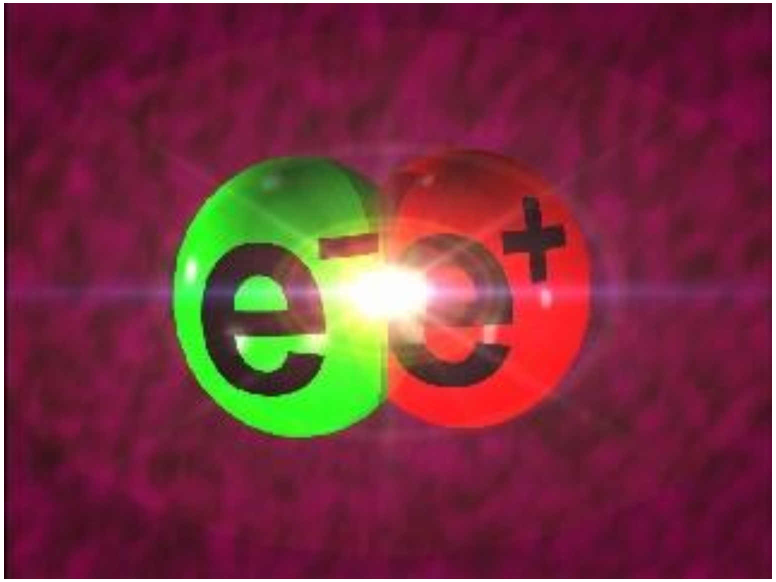
Significance of Positron Discovery

The positron discovery was the first evidence for ANTIMATTER.

That is, the positron has essentially all the same properties as an electron, except, it's charge is positive !

Carl Anderson award Nobel prize for the discovery of the positron

Carl Anderson
1905-1991



If an electron and a positron collide, they ANNIHILATE and form pure energy (EM Radiation).

This conversion of matter into energy is a common event in the life of physicists that study these little rascals…

Slide courtesy Prof. Steven Blusk, Syracuse University

The Plethora of Particles

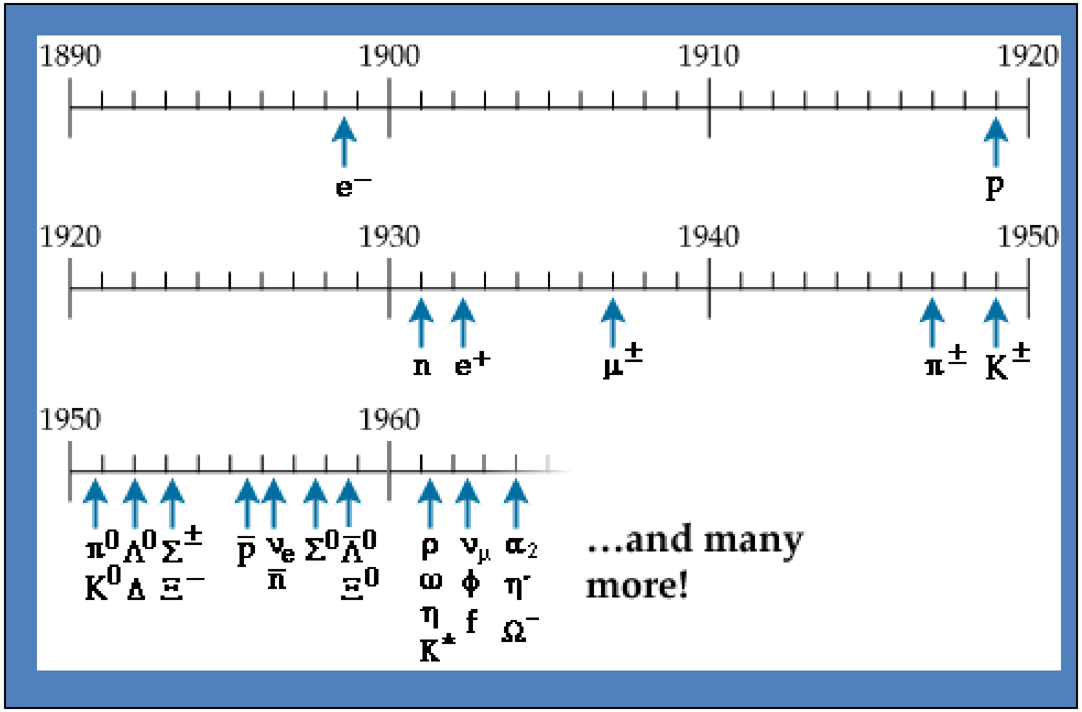
Because one has no control over cosmic rays (energy, types of particles, location, etc), scientists focused their efforts on accelerating particles in the lab and smashing them together. Generically people refer to them as "particle accelerators".

Circa 1950, these particle accelerators began to uncover many new particles.

Most of these particles are unstable and decay very quickly, and hence had not been seen in cosmic rays.

Notice the discovery of the proton's antiparticle, the antiproton, in 1955 !

Yes, more antimatter !



Slide courtesy Prof. Steven Blusk, Syracuse University

From Simplicity→ Complexity→ Simplicity

- ❑ Around 1930, life seemed pretty good for our understanding of "elementary (fundamental) particles".
- ❑ There was protons, neutrons & electrons. Together, they made up atoms → molecules → DNA → People !
- ❑ AAHHHHH, nature is simple, elegant, aaahhhh…

But the discoveries of dozens of more particles in accelerator experiments lead many to question whether the proton and neutron were really "fundamental".

1994 Nobel Prize
Winner in Physics

I. I. Rabi's famous quote <u>when the muon was discovered</u>.

Who ordered that" ?

Needless to say, the "zoo of new particles" that were being discovered at accelerators appeared to reveal that nature was not simple, but complicated? Until….

Slide courtesy Prof. Steven Blusk, Syracuse University

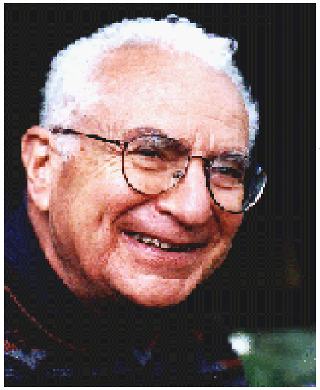
Quarks ?

- <u>First things first</u>: Where did the name "quarks" come from?

  Murray Gell-Mann had just been reading *Finnegan's Wake* by James Joyce which contains the phrase "*three quarks for Muster Mark*".
  He decided it would be funny to name his particles after this phrase.

  Murray Gell-Mann had a strange sense of humor!

In 1964, Murray Gell-Mann & George Zweig (independently) came up with the idea that one could account for the entire "Zoo of Particles", if there existed objects called quarks.



Murray Gell-Mann

George Zweig

The quarks come in 3 types ("flavors"): **<u>up(u), down(d),</u> and <u>strange(s)</u>** and they are fractionally charged with respect to the electron's charge

Flavor	Q/e
u	+2/3
d	-1/3
s	-1/3

Slide courtesy Prof. Steven Blusk, Syracuse University

How sure was Gell-Mann of quarks ?

When the quark model was proposed, it was just considered to be a convenient description of all these particles…

A mathematical convenience to account for all these new particles…

After all, fractionally charged particles…come on!

<u>An excerpt from Gell-Mann's 1964 paper:</u>

"A search for stable quarks of charge –1/3 or +2/3 and/or stable di-quarks of charge –2/3 or +1/3 or +4/3 at the highest energy accelerators would help to reassure us of the **<u>non-existence of real quarks".</u>**

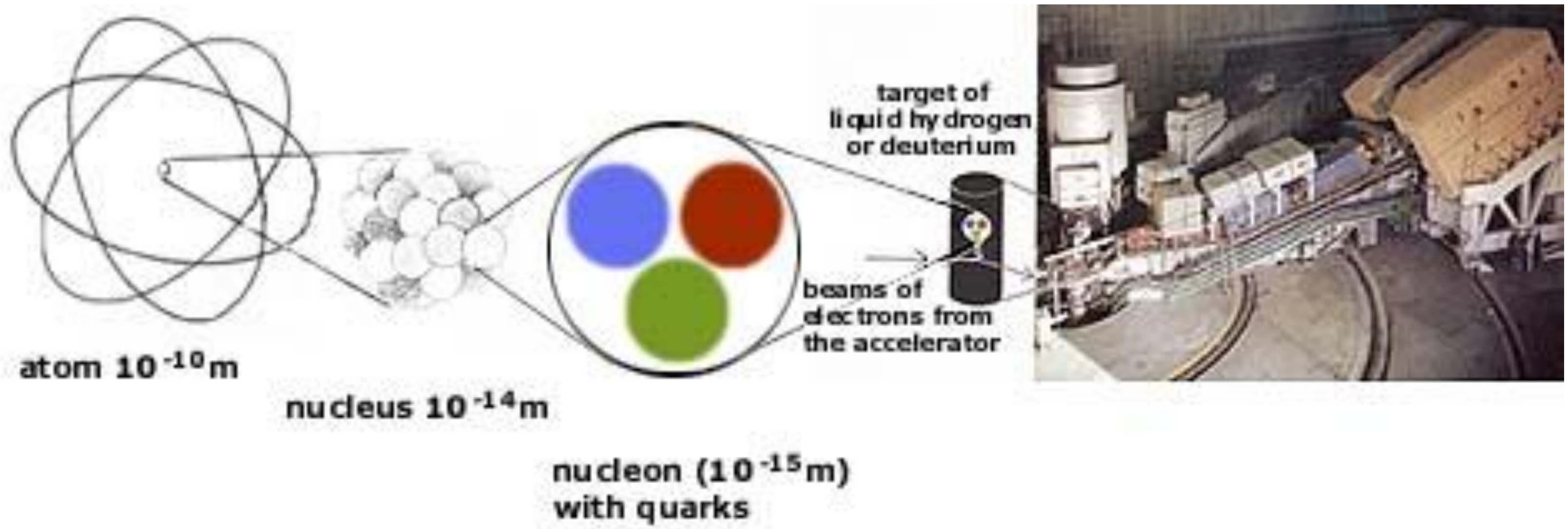
Well….

Slide courtesy Prof. Steven Blusk, Syracuse University

Are protons/neutrons fundamental ?

In 1969, a Stanford-MIT Collaboration was performing scattering experiments at SLAC

$e^- + p \Rightarrow e^- + X$ (X = anything)



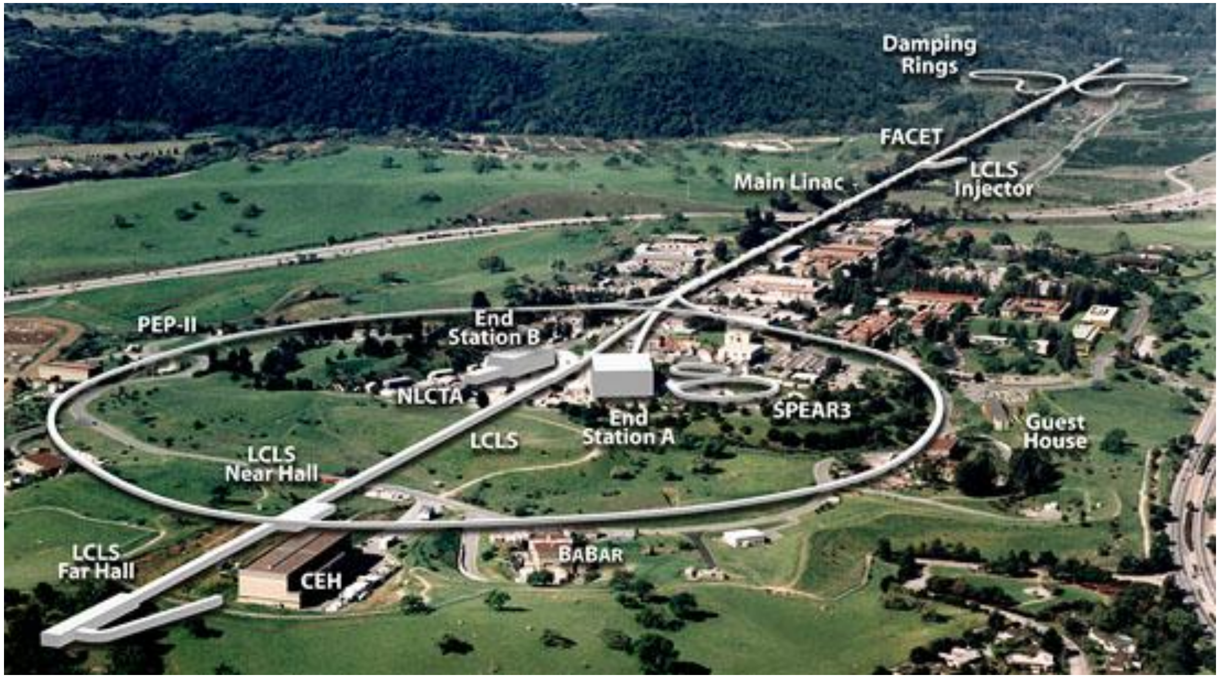
What they found was remarkable; the results were as surprising as what Rutherford had found more than a half-century earlier!

The number of high angle scatters was far in excess of what one would expect based on assuming a uniformly distributed charge distribution inside the proton.

It's as if the proton itself contained <u>smaller constituents</u>

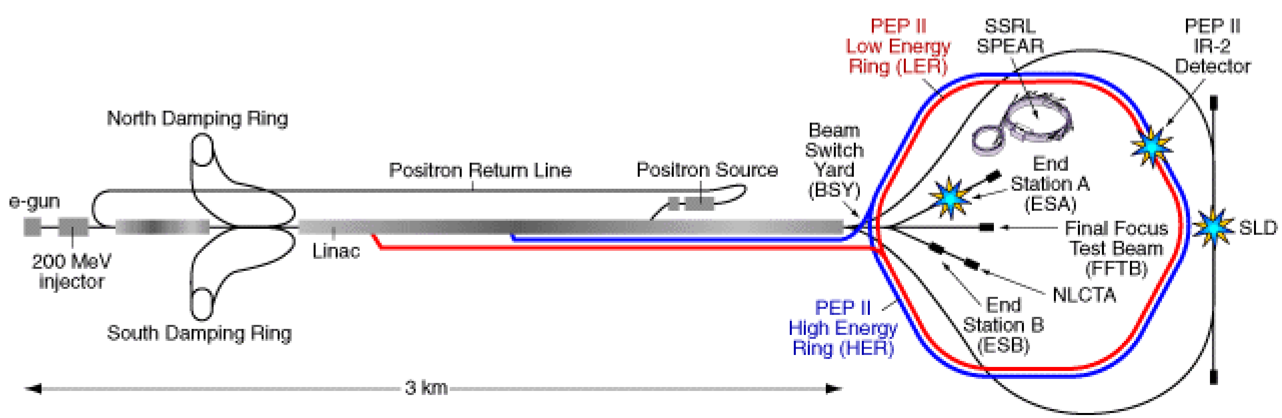
Slide courtesy Prof. Steven Blusk, Syracuse University

Particle Physics, big glamorous science



Stanford Linear Accelerator

Nobel Prizes in Physics
[1976](#) - Charm: The 4th Quark
[1990](#) - Quarks Revealed: Structure Inside Protons and Neutrons
[1995](#) - Tau: The Third Electron-Like Particle



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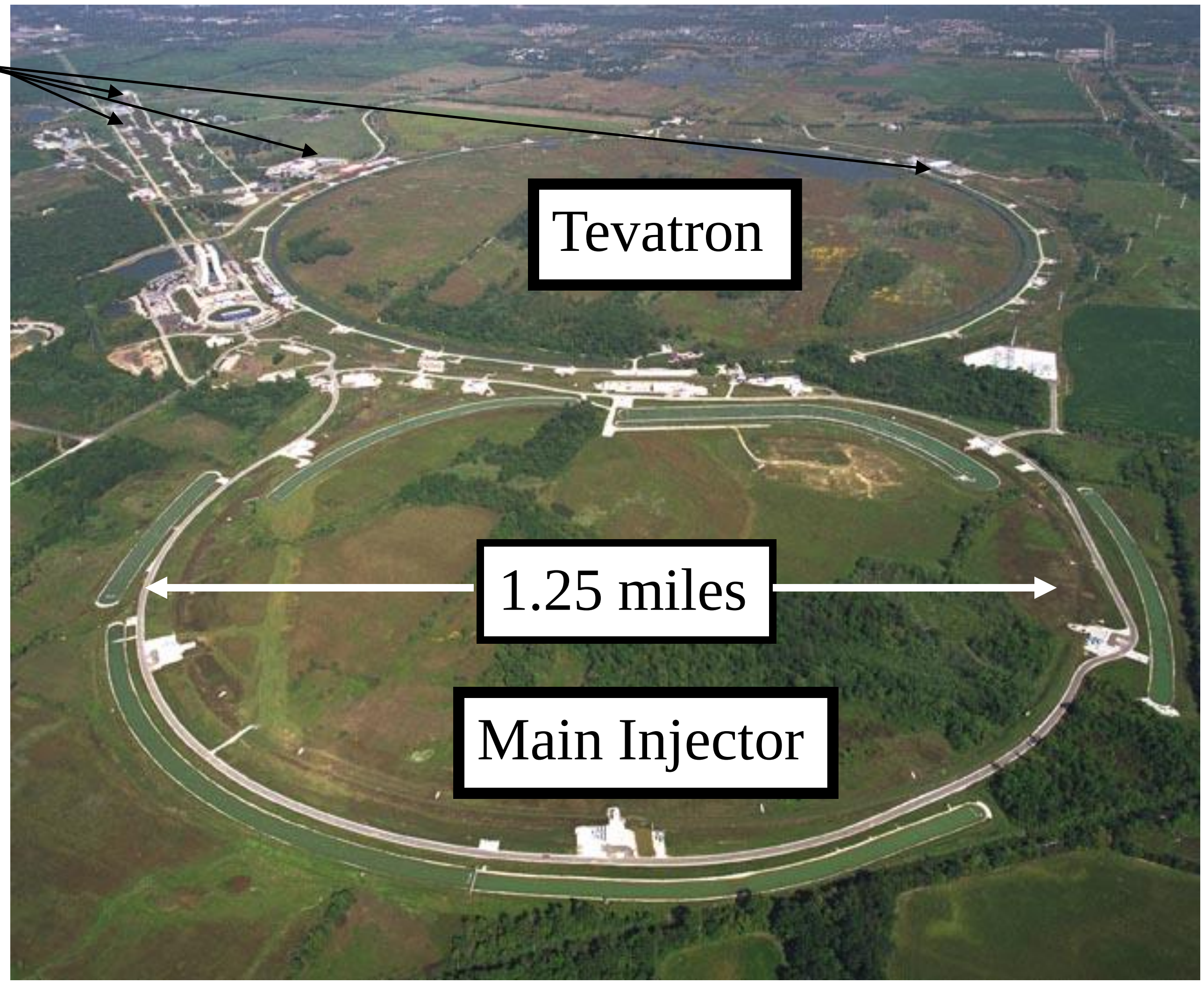
Fermilab: proton/antiproton collider

Experimental areas

Top Quark discovered at FNAL in 1995.



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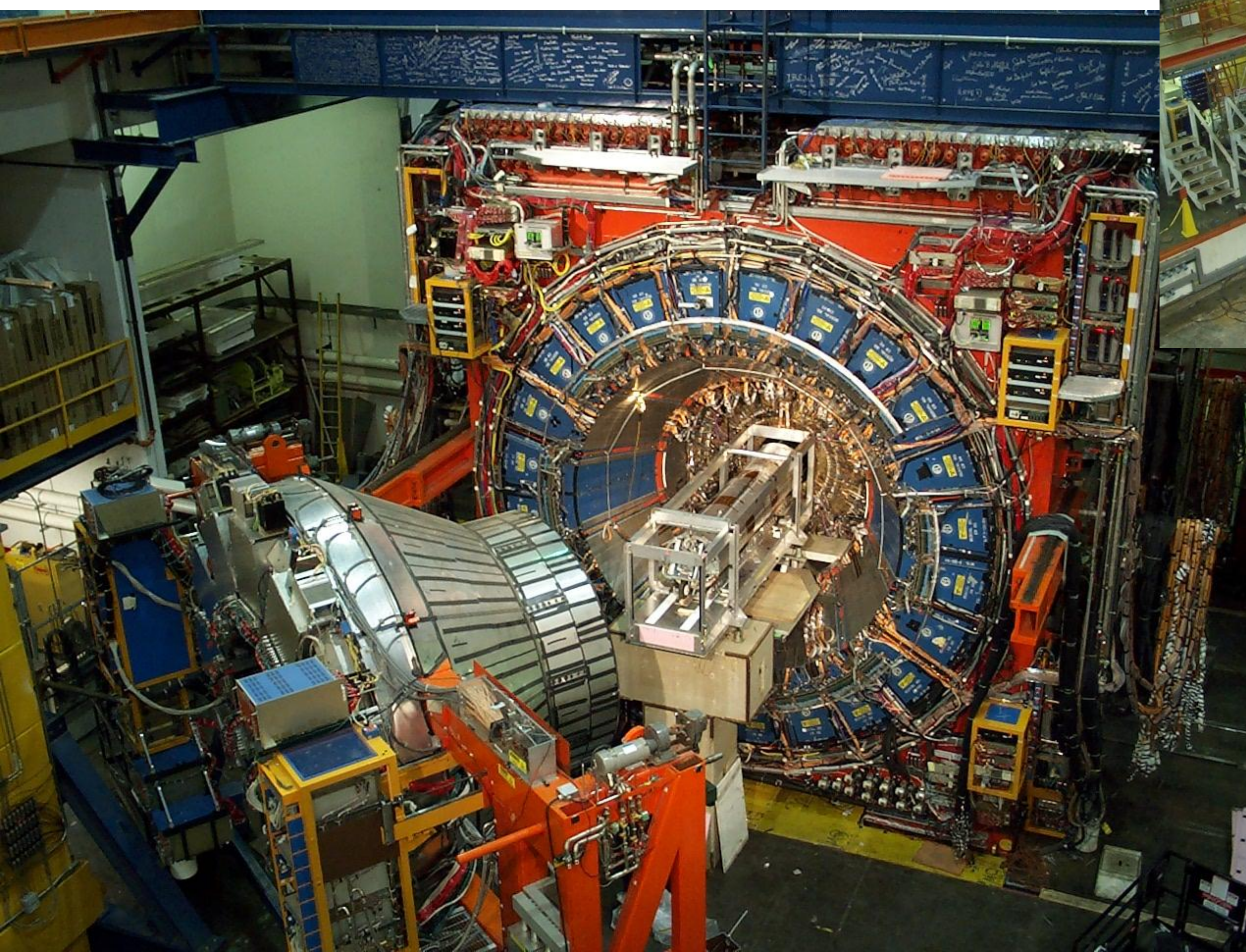
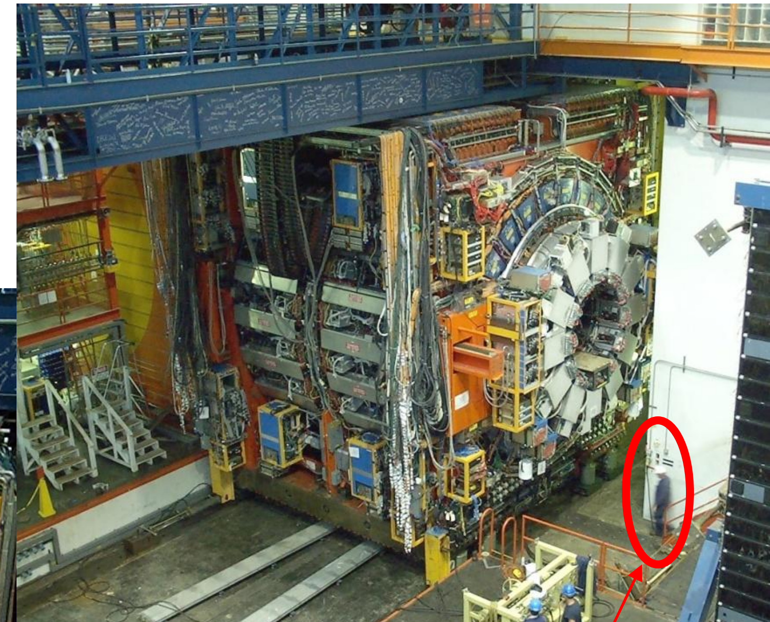
Mega-Science: "Typical" Particle Detector





~ 6 ft

The 6 Quarks, when & where…

Quark	Date	Where	Mass [GeV/c^2]	Comment
up, down	-	-	**~0.005, ~0.010**	Constituents of hadrons, most prominently, proton and neutrons.
strange	1947	-	**~0.2**	discovered in cosmic rays
charm	1974	SLAC/ BNL	**~1.5**	Discovered simultaneously in both pp and e^+e^- collisions.
bottom	1977	Fermi-lab	**~4.5**	Discovered in collisions of protons on nuclei
top	1995	Fermi-lab	**~175**	Discovered in $p\bar{p}$ collisions

Notice the units of mass !!!

Slide courtesy Prof. Steven Blusk, Syracuse University

Today's biggest questions

1. Are there undiscovered principles of nature:
   New symmetries, new physical laws, violations of Standard Model?
2. How can we solve the mystery of dark energy?
3. Are there extra dimensions of space?
4. Do all the forces become one?
5. Why are there so many kinds of particles?
6. What is dark matter?
   How can we make it in the laboratory?
7. What are neutrinos telling us?
8. How did the universe come to be?
9. What happened to the antimatter?

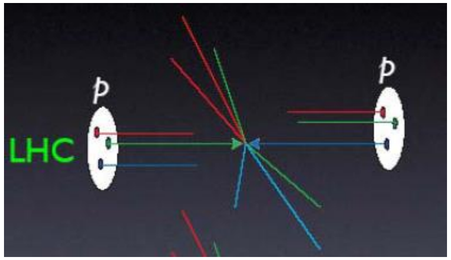
from the Quantum Universe

Addressing the Questions

- Neutrinos
  - Particle physics and astrophysics using a weakly interacting probe

- Particle Astrophysics/Cosmology
  - Dark Matter; Cosmic Microwave, etc

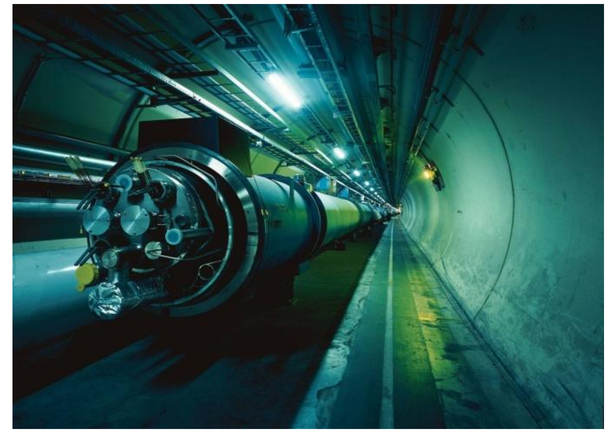
- High Energy pp Colliders
  - Opening up a new energy frontier (~ 1 TeV scale)

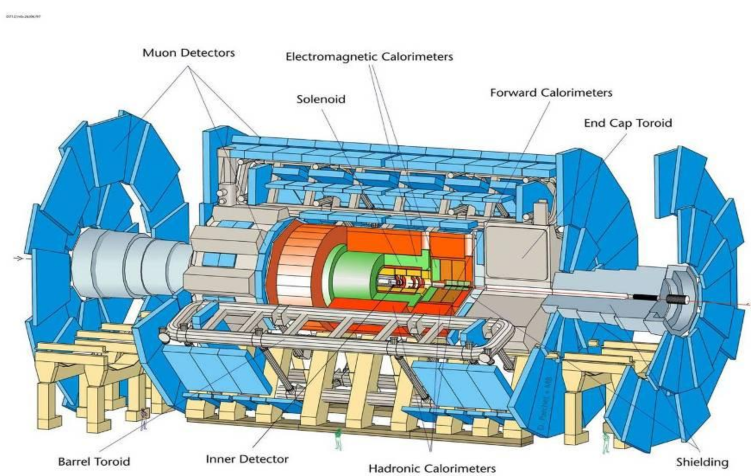


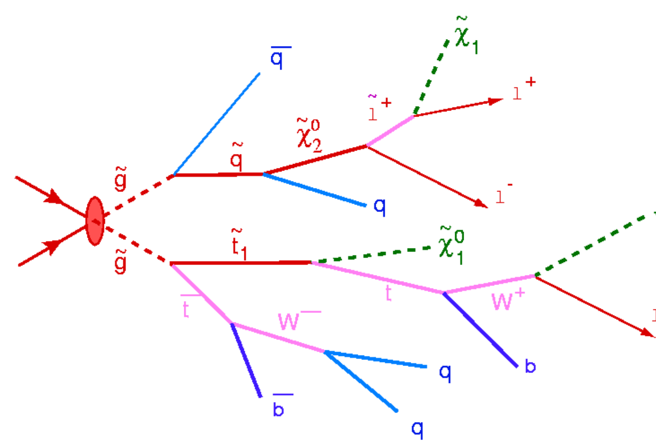
- High Energy e^+e^- Colliders
  - Precision Physics at the new energy frontier

Large Hadron Collider

Looking for Higgs boson, and new physics

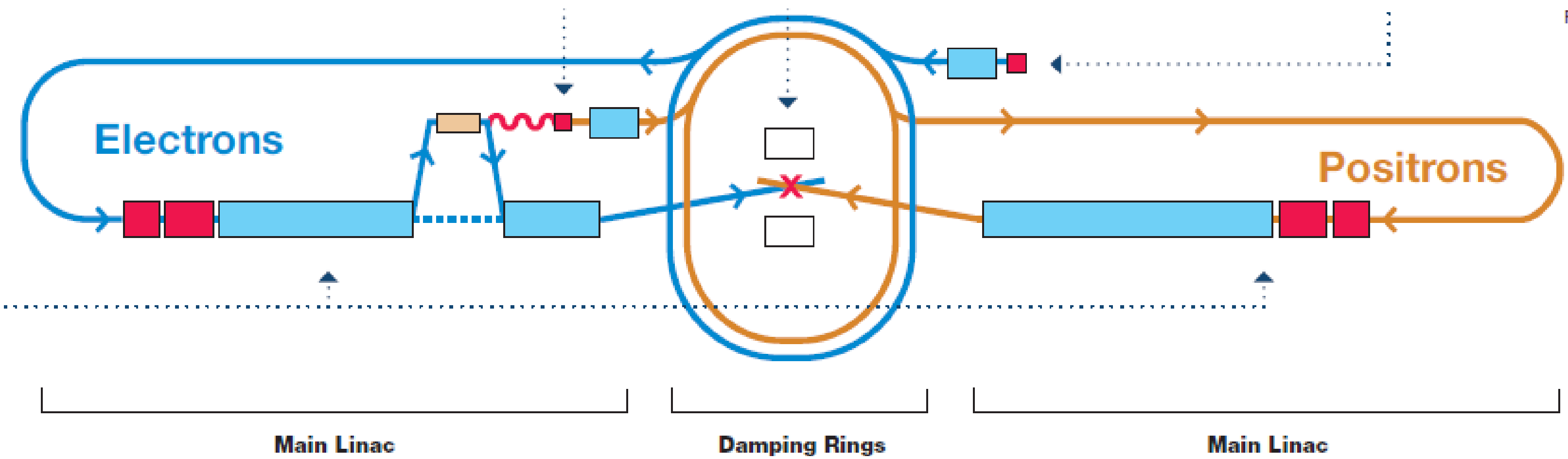


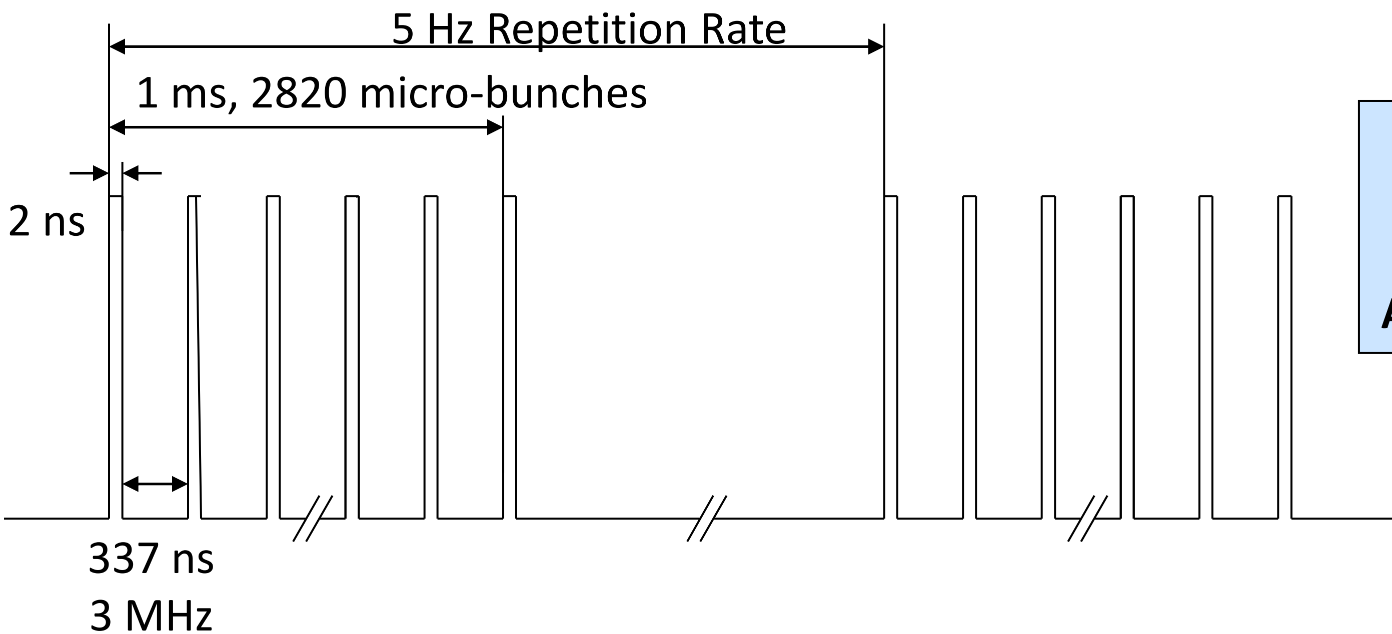




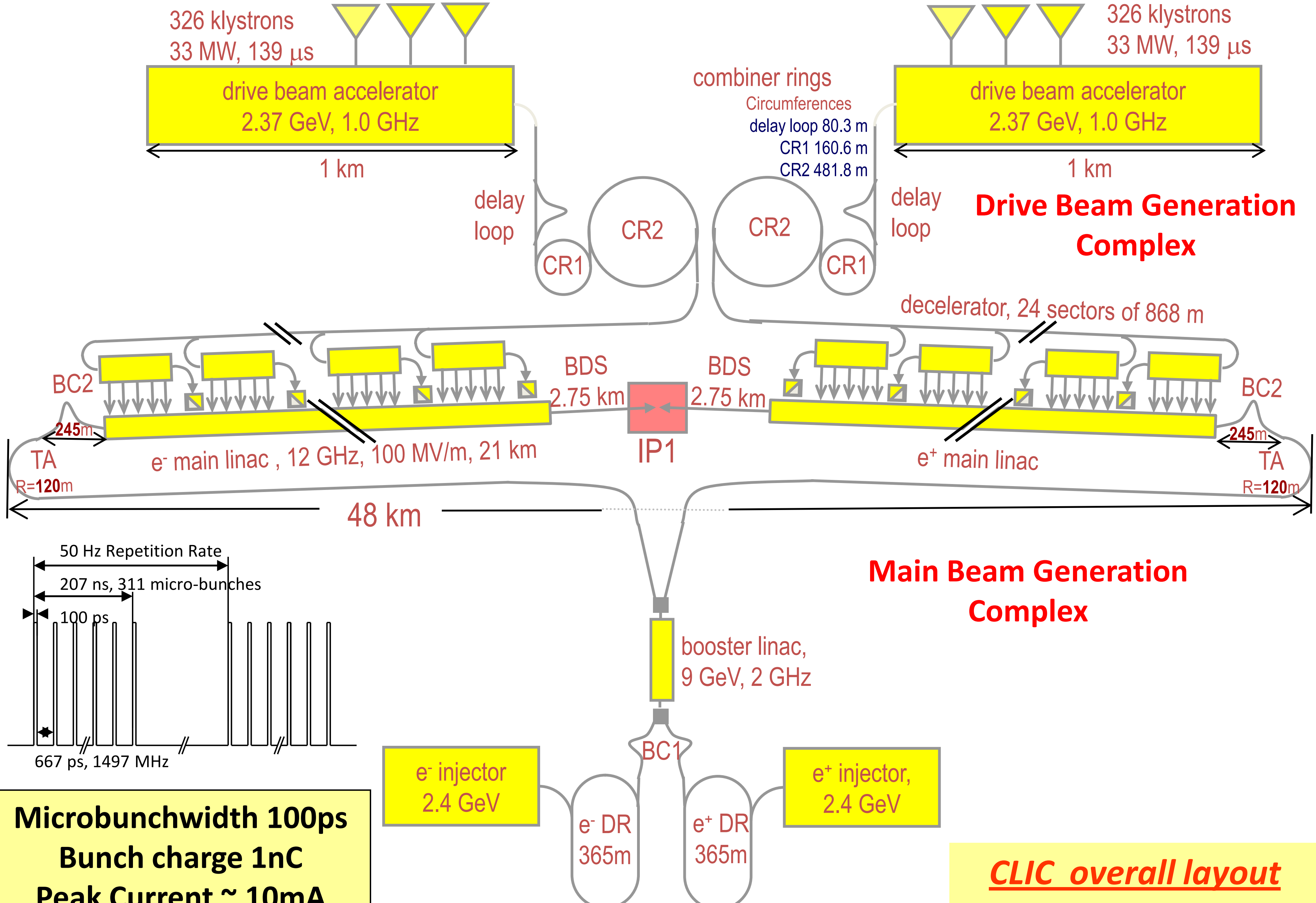
3 isolated leptons
+ 2 b-jets
+ 4 jets
+ E_t^{miss}

International Linear Collider: ILC





Bunch charge 5nC
Peak Current ~ 5mA
Current density 6A/cm²
Average Current ~ 100uA

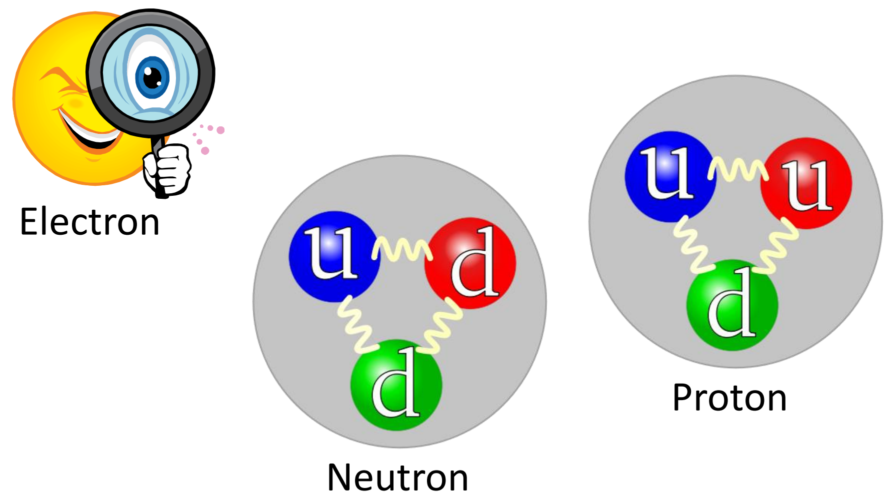


Microbunchwidth 100ps
Bunch charge 1nC
Peak Current ~ 10mA
Current density 12 A/cm²

CLIC overall layout
3 TeV

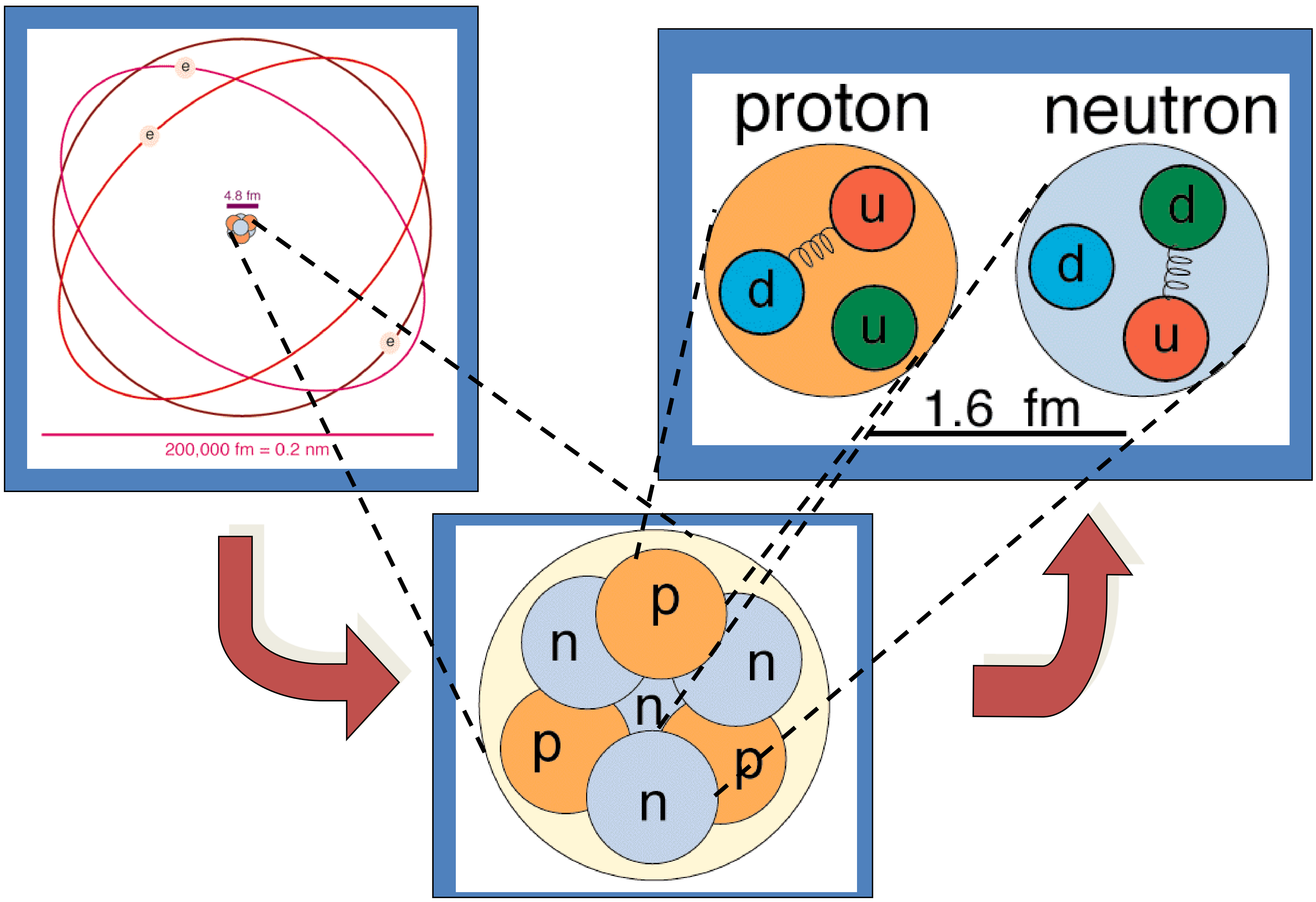
What good is lowly CEBAF?

We know hadrons are made of quarks and gluons but….



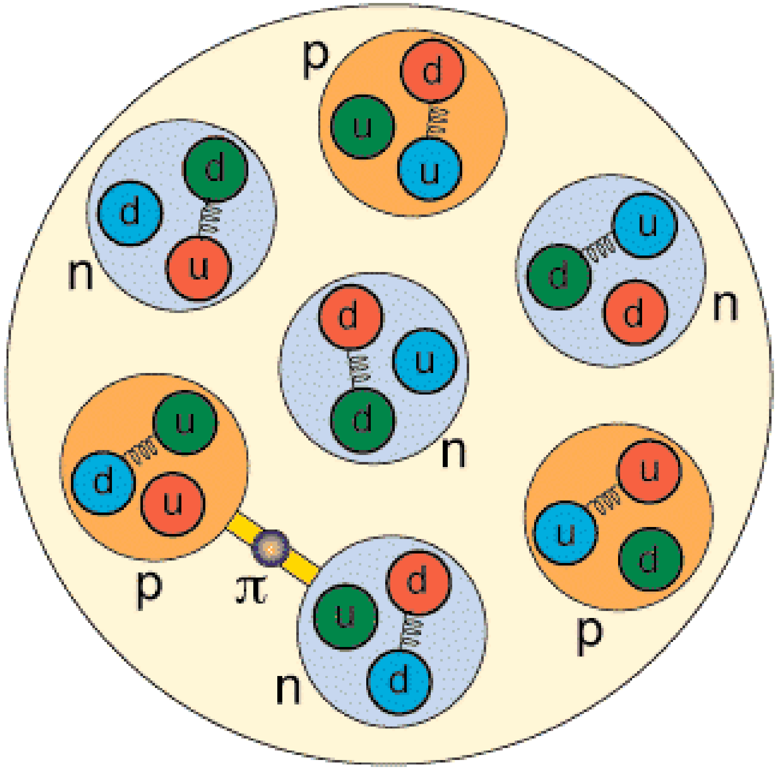
CEBAF: 5 mile long microscope!

Make electrons energetic enough to peek inside proton and neutron. Homework problem: pick e-beam energy to resolve what size particle?



Slide courtesy Prof. Steven Blusk, Syracuse University

Protons & Neutrons



To make a proton:

We bind **2 up quarks** of **Q = +2/3** and **1 down quark** of **Q = -1/3**. The total charge is

2/3 + 2/3 + (-1/3) = +1 !

To make a neutron:

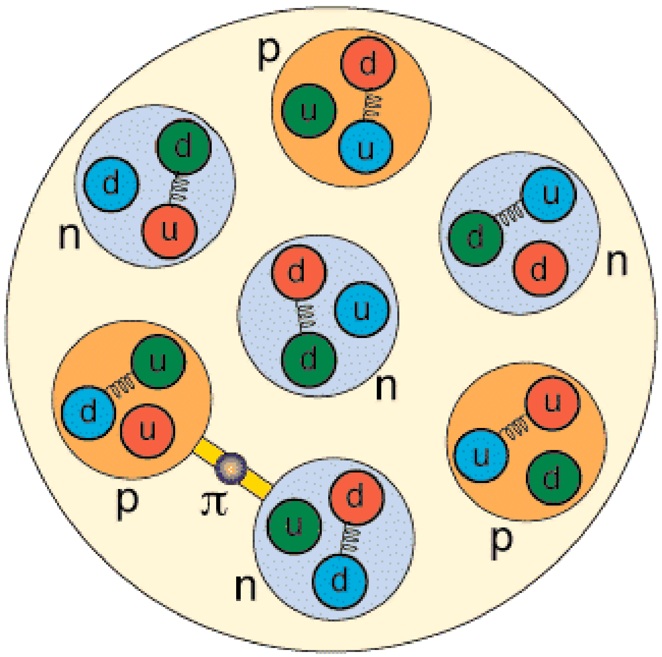
We bind **2 down quarks of Q= -1/3** with **1 up quark of Q = +2/3** to get:

(-1/3) + (-1/3) + (2/3) = 0 !

So, it all works out ! But, yes, we have **FRACTIONALLY CHARGED PARTICLES**!

Slide courtesy Prof. Steven Blusk, Syracuse University

Why does the nucleus stay together ?



So far, the only "fundamental" forces we know about are:
(a) Gravity
(b) EM force (Electricity + Magnetism)

Which one of these is responsible for binding protons to protons and protons to neutrons ???

- ❑ Since like sign charges repel, it can't be EM force?
- ❑ Gravity is way, way, way too weak…

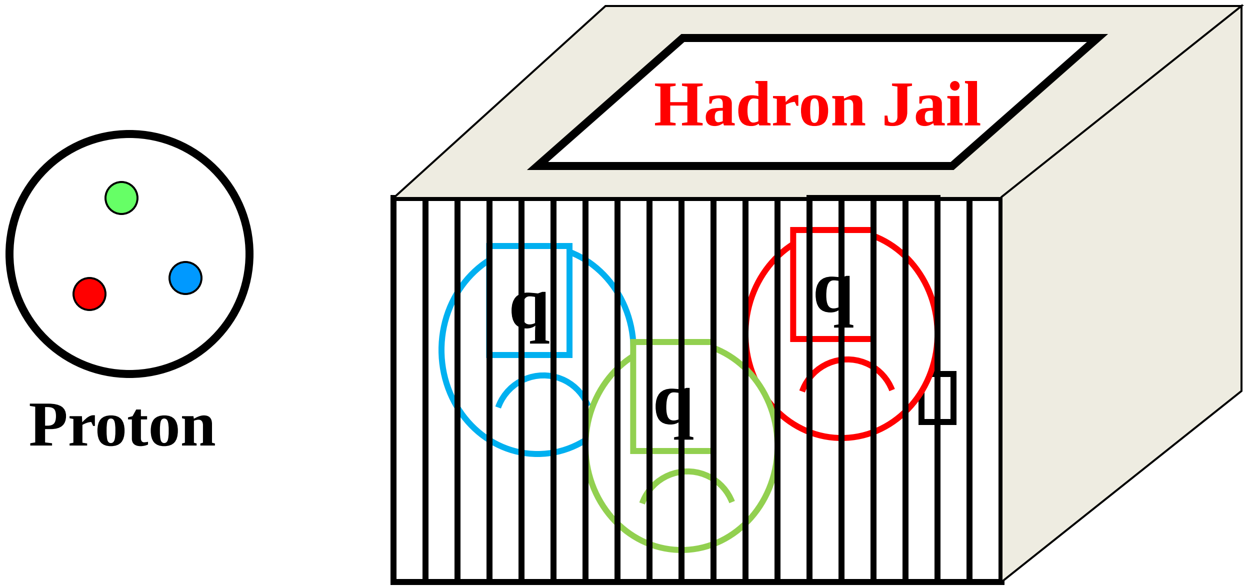
Then what is it???

Strong Force

This is the third **fundamental force** in nature and is by far the strongest of the four forces. (Weak force, also relevant, describes radioactive decay…)

Slide courtesy Prof. Steven Blusk, Syracuse University

Quark Confinement

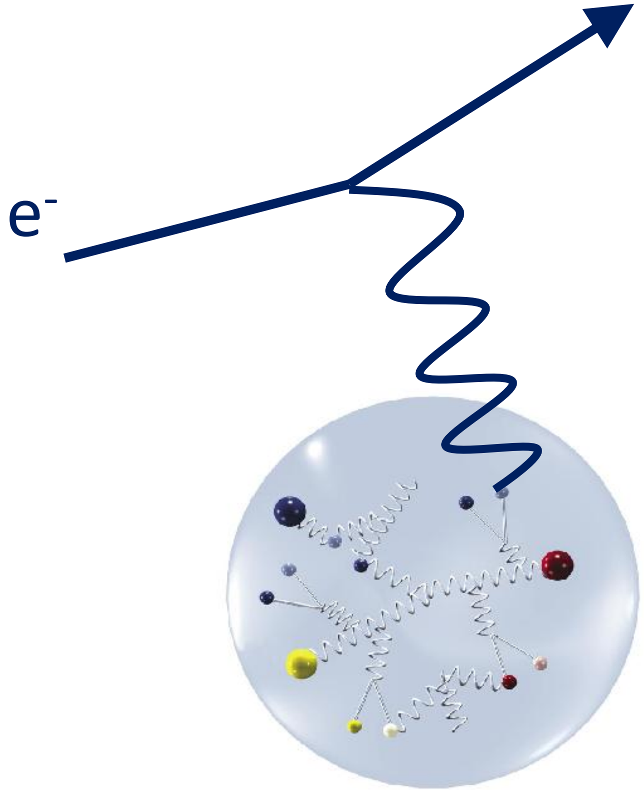


❑ **Quarks are "confined" inside objects known as "hadrons", i.e., protons and neutrons**
❑ **Understanding quark confinement is one of JLab's missions, among others….**

Slide courtesy Prof. Steven Blusk, Syracuse University

Nuclear Physics at Jefferson Lab

Atomic nuclei, protons and neutrons are described by Quantum Chromodynamics (QCD) - a theory of quarks and gluons



- Experiment: Electrons and photons provide simple, well-understood probes of the complex structure of nuclear matter
- Theory: QCD is simulated on a “lattice”
- Combination of theory and experiment is used to develop a fundamental understanding of nuclear particles

What Does Electron Beam Tell You?

- **Physics**
  - Measure a physical effect that is too small to be observed directly via a change in reaction probability (cross section)
  - Strategy: amplify the effect via interference with a large effect
- **Technique**
  - flip spin direction of electron beam and look for changes
  - Spin-flip frequency *>> time scale for change in experimental setup*
  - average over many reversal cycles (eliminates noise and changes)
  - experiments easy as long as beam parameters remain EXACTLY the same
- **Types of Experiments**

1. only electrons polarized
   - parity violation: effects are very small ($10^{-6} - 10^{-9}$)
2. electron **and target polarized**
   - typical example: *GE_n in Hall C (effects $10^{-1} - 10^{-3}$)*
   - hadron typically detected in direction of momentum transfer
3. electron polarized **and polarization of coincident final state particle measured**
   - typical example: *GE_p in Hall A*
4. electron polarized **and hadron detected away from momentum transfer**
   - typical example: pion electroproduction in Hall B's CLAS

From Bernhard Mecking, former Hall B Leader

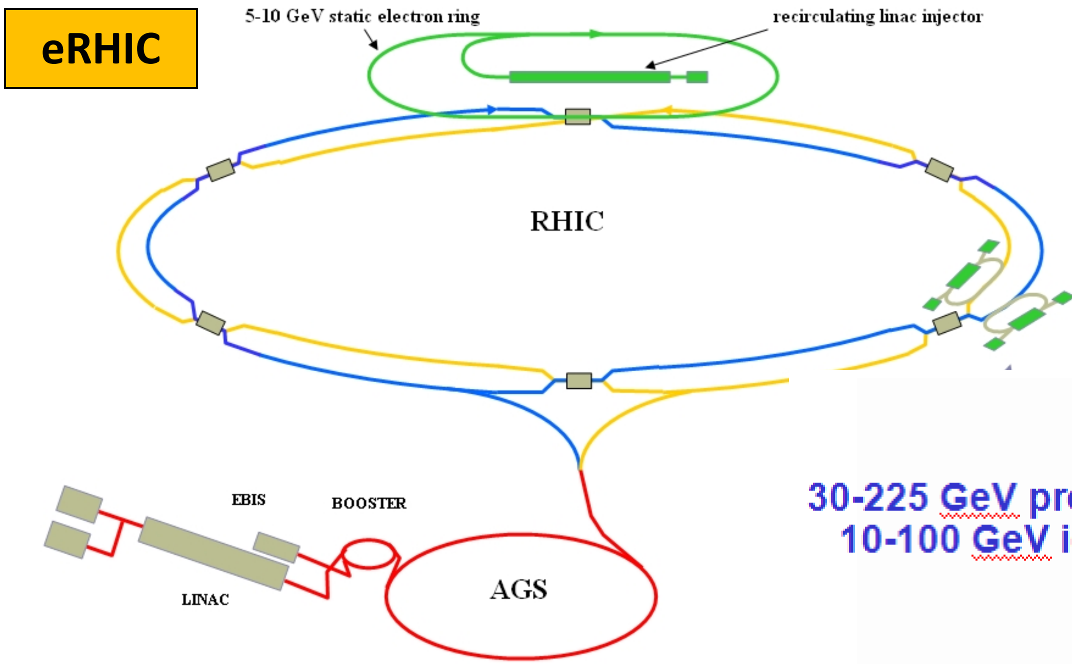
Polarized e-Beam Facilities

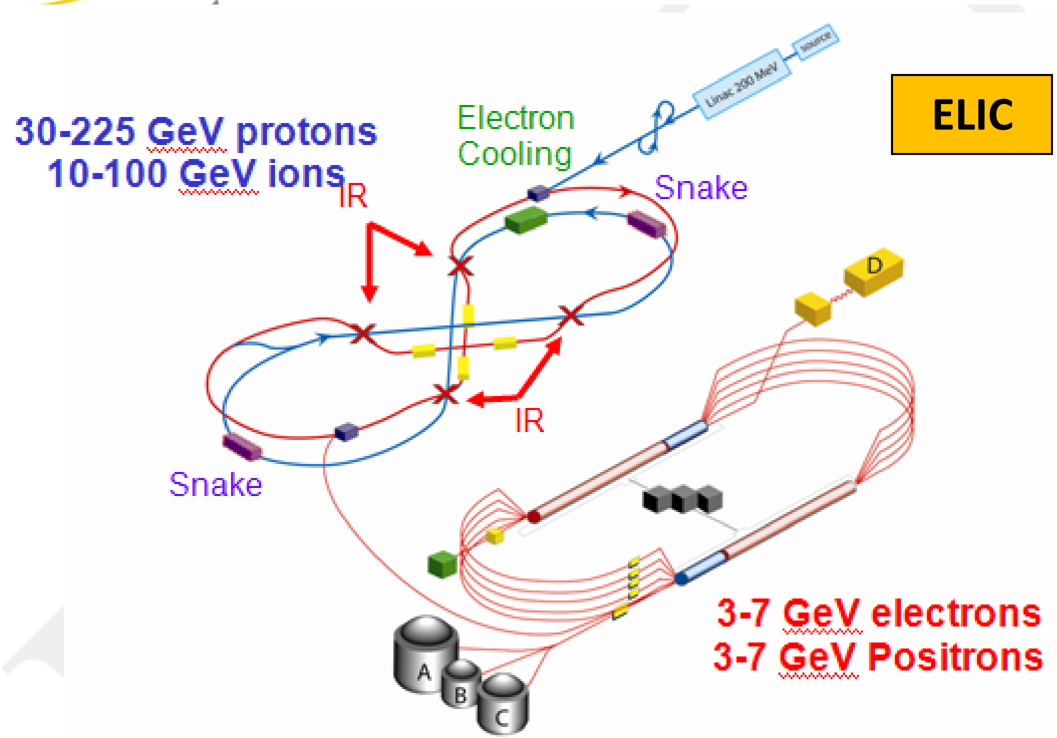
- CEBAF at JLab
- Mainz Microtron
- ELSA at Bonn University
- Darmstadt University
- MIT-Bates
- SLAC
- NIKHEV

Electron-Positron Colliders

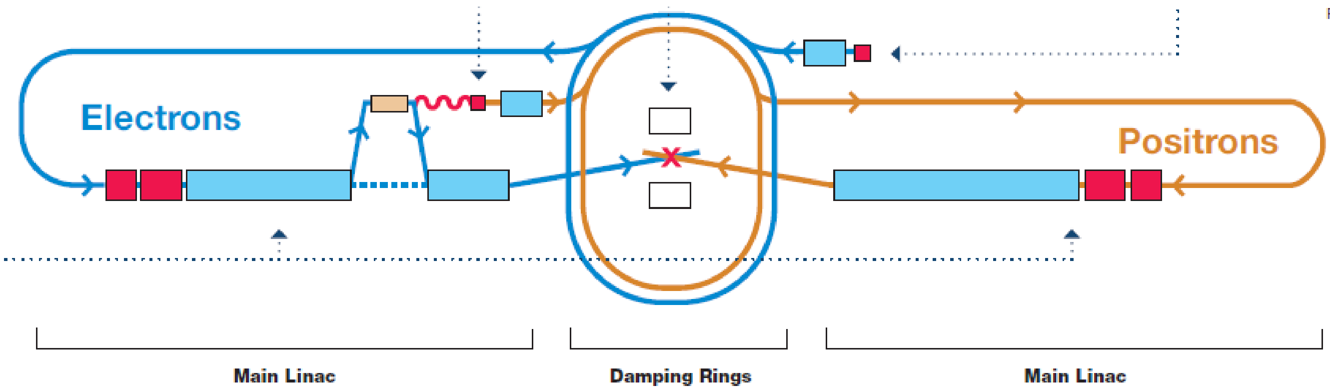
- ILC, CLIC (if LHC results suggest these are worthwhile)
- High Bunch Charge (~ nC).
  - Photocathode charge limit problems.
- Modest Average Current (< 100 uA).
  - Lifetime should be good with existing vacuum technology.
- Macropulse Operation with RF Microstructure.
  - Laser development necessary.

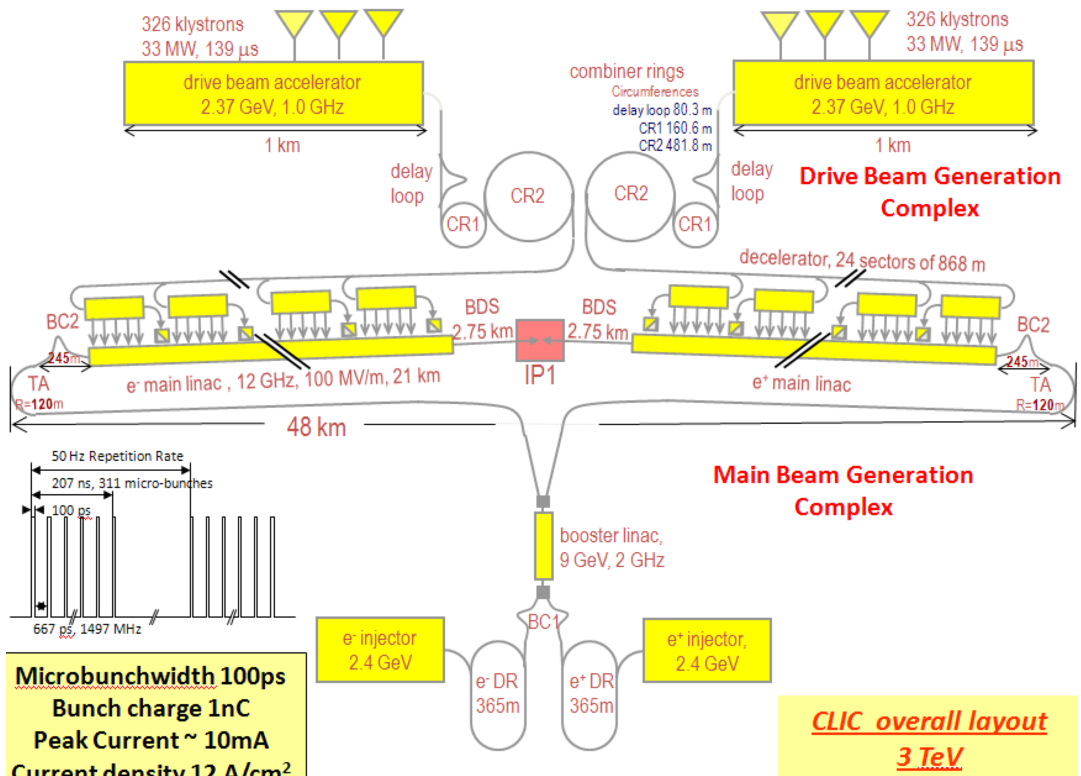
Electron Ion Colliders





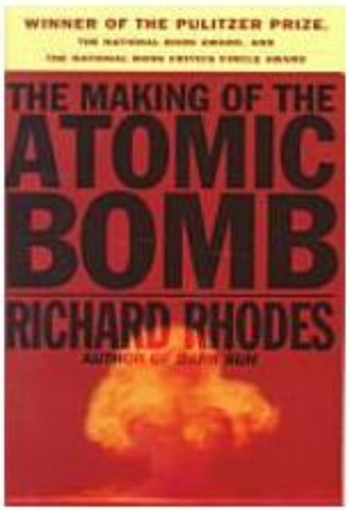
Electron Positron Colliders

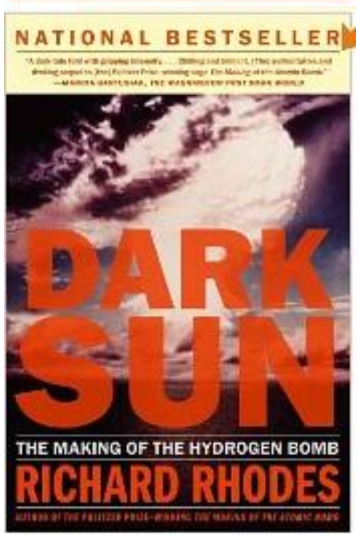




Microbunchwidth 100ps
Bunch charge 1nC
Peak Current ~ 10mA
Current density 12 A/cm²

Good Books to Read





- At school, you take classes and sometimes get the impression – maybe inadvertently - that we know the whole story. It's easy to lose sight of the fact that knowledge is/was obtained in bits and pieces by many people over a long period of time (depending on your perspective) and the process is still happening today….
- Richard Rhodes: birth of particle physics, history of atomic (fission) bomb and hydrogen (fusion) bomb
- Manhattan Project: started 1939, first atomic bomb 1945. Cost ~ 24B$ in today's money.
- Re: accelerators….Lawrence built cyclotrons for electromagnetic separation of U235 from U238