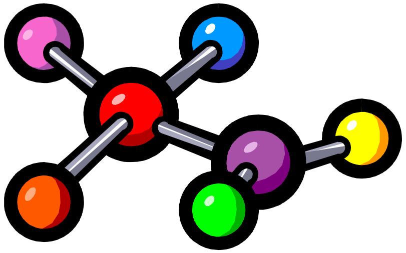
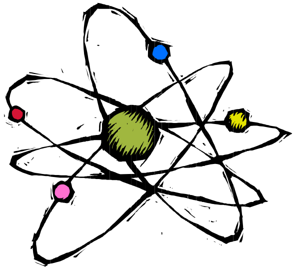
The Coming Era of New Physics at the Large Hadron Collider.

Amitabh Lath
Rutgers, The State University of New Jersey

So what's a collider do, exactly?

- Colliders (accelerators) have been essential tools to understand the structure of nature.
  - ...ie, what is stuff made of?

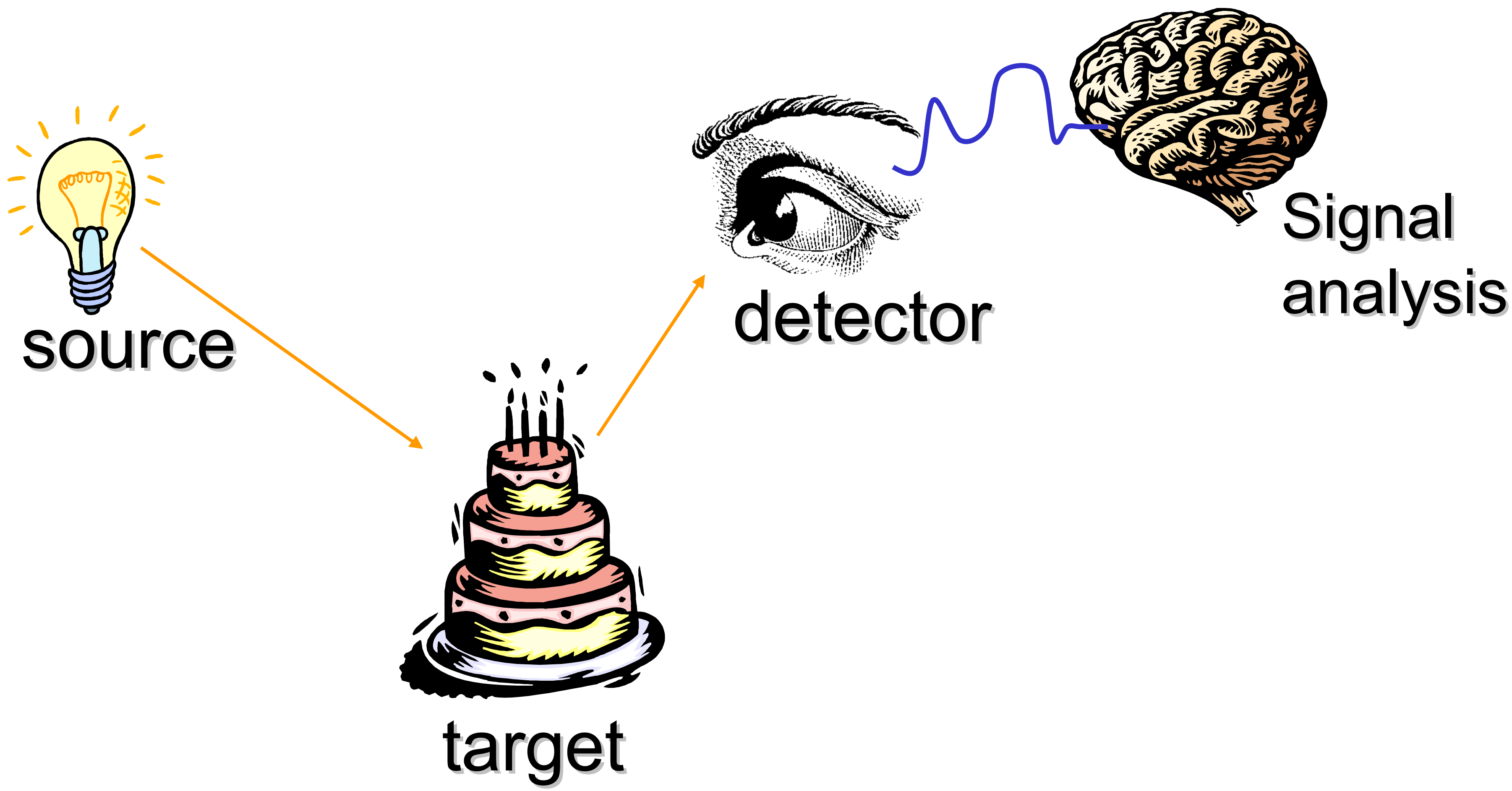




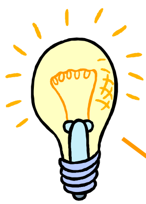
- In a remarkably short period of time, our understanding of the basic building blocks of nature has changed.
  - *Several times!*

- The technique used is called ***scattering***.

Scattering Basics

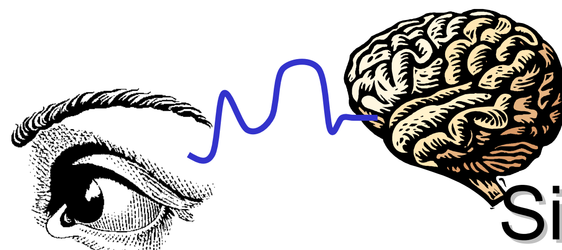


Scattering Basics



source

target

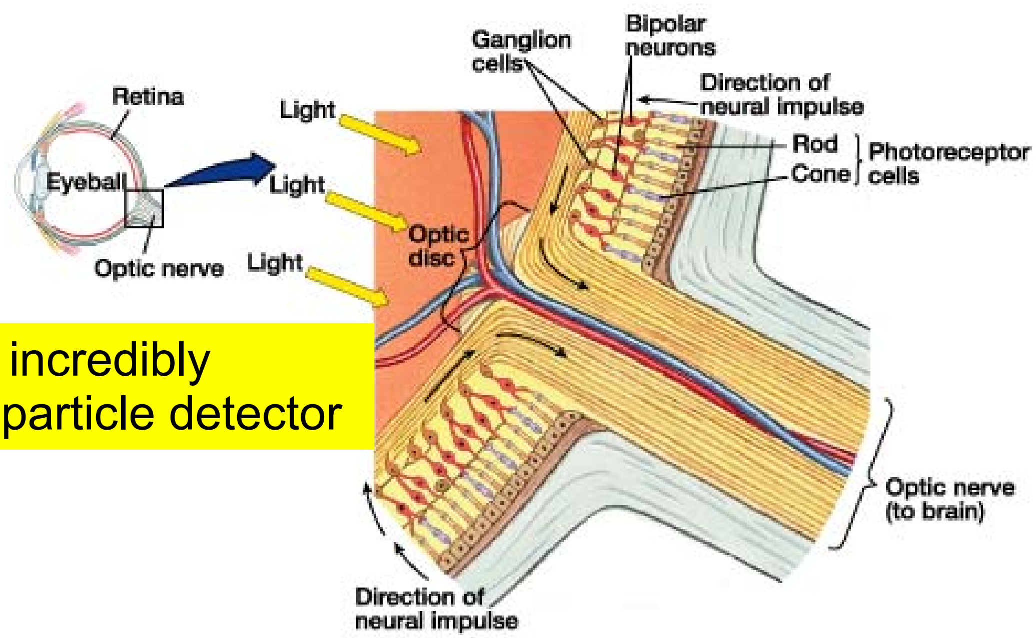


detect

or

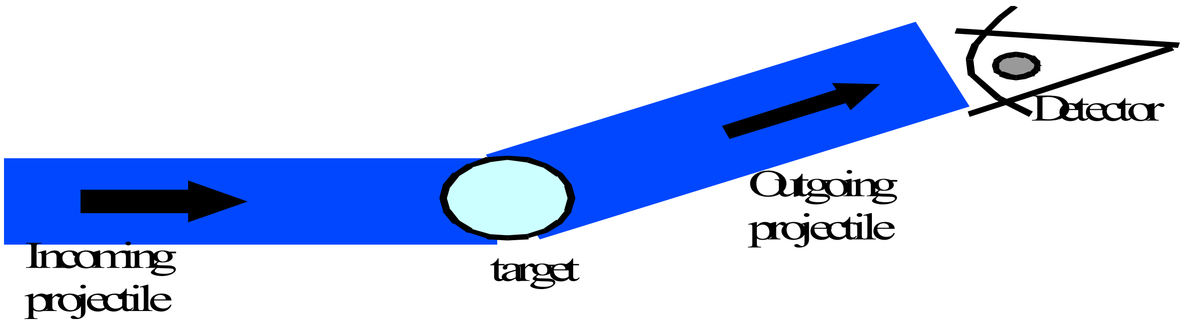
Signal
analysis

The eye is an incredibly
sophisticated particle detector



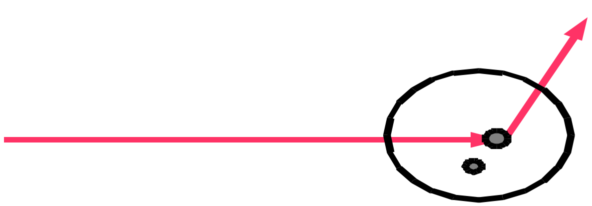
What you can see depends on *resolution*

Large wavelength,
Lower resolution

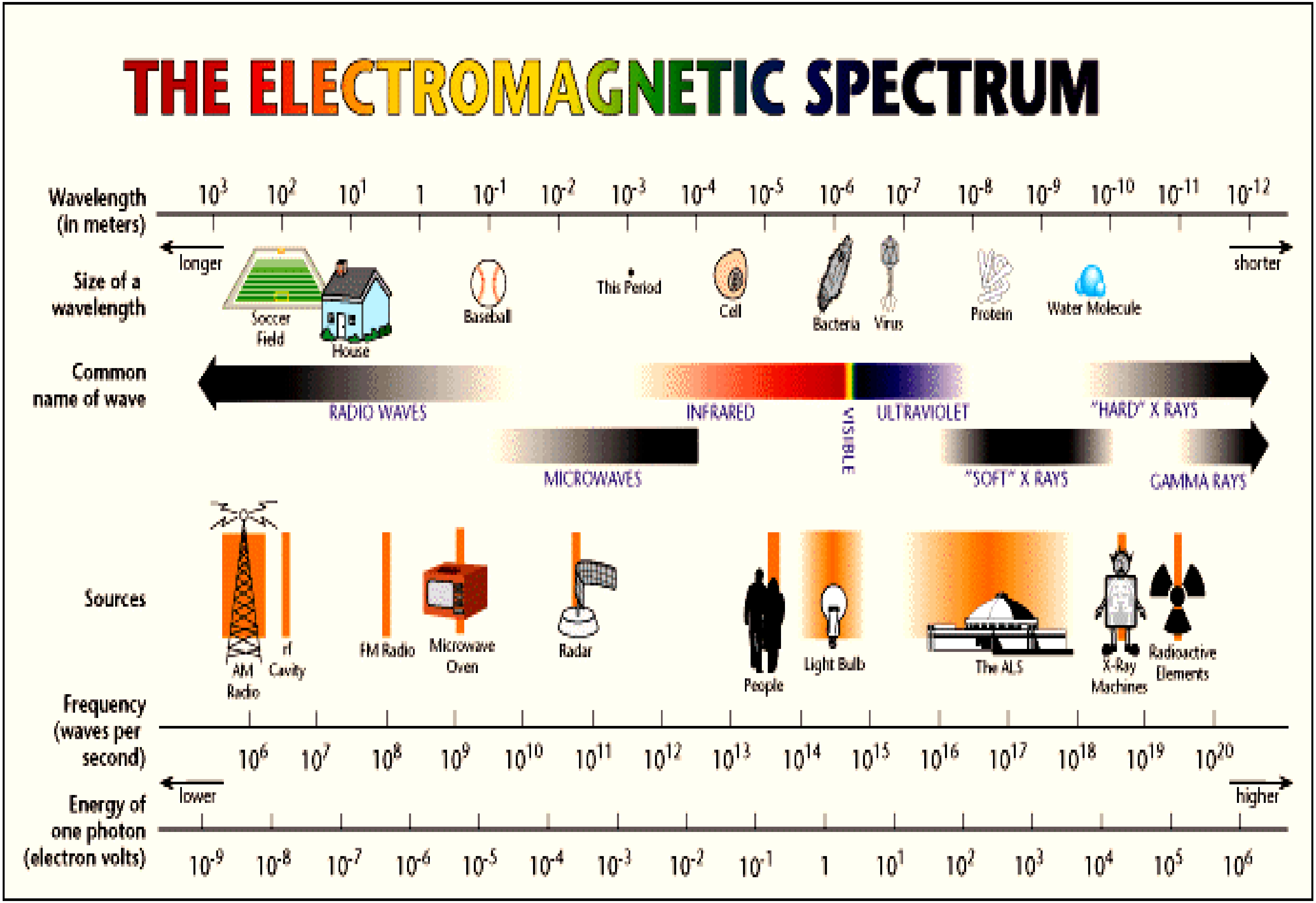


Large wavelength, low energy, target looks like a big blob.

Short wavelength,
Higher resolution

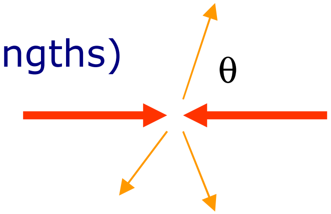


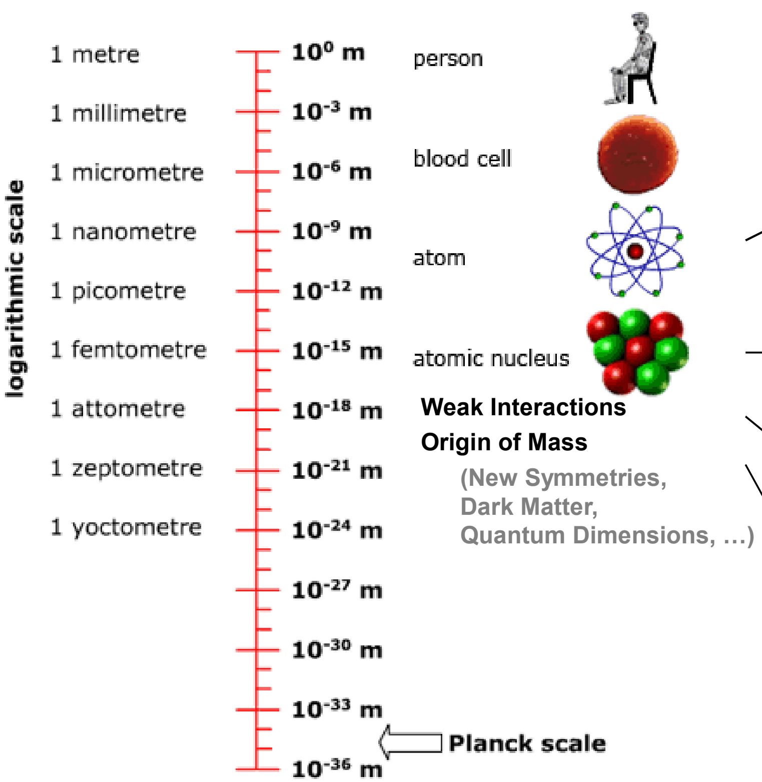
Small wavelength, high energy, constituents of targets become visible

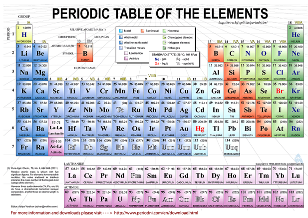

THE ELECTROMAGNETIC SPECTRUM
Wavelength (in meters)
10^3 10^2 10^1 1 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12}
longer
shorter
Size of a wavelength
Soccer Field
House
Baseball
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
Common name of wave
RADIO WAVES
INFRARED
VISIBLE
ULTRAVIOLET
"HARD" X RAYS
MICROWAVES
"SOFT" X RAYS
GAMMA RAYS
Sources
AM Radio
rf Cavity
FM Radio
Microwave Oven
Radar
People
Light Bulb
The ALS
X-Ray Machines
Radioactive Elements
Frequency (waves per second)
10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20}
lower
higher
Energy of one photon (electron volts)
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10^1 10^2 10^3 10^4 10^5 10^6

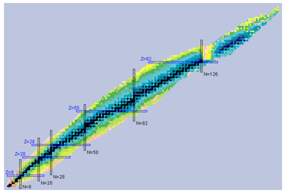
Scattering at higher energies (shorter wavelengths)

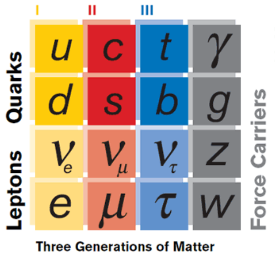
- Microscope to Short Distances
- New Substructure and Forces







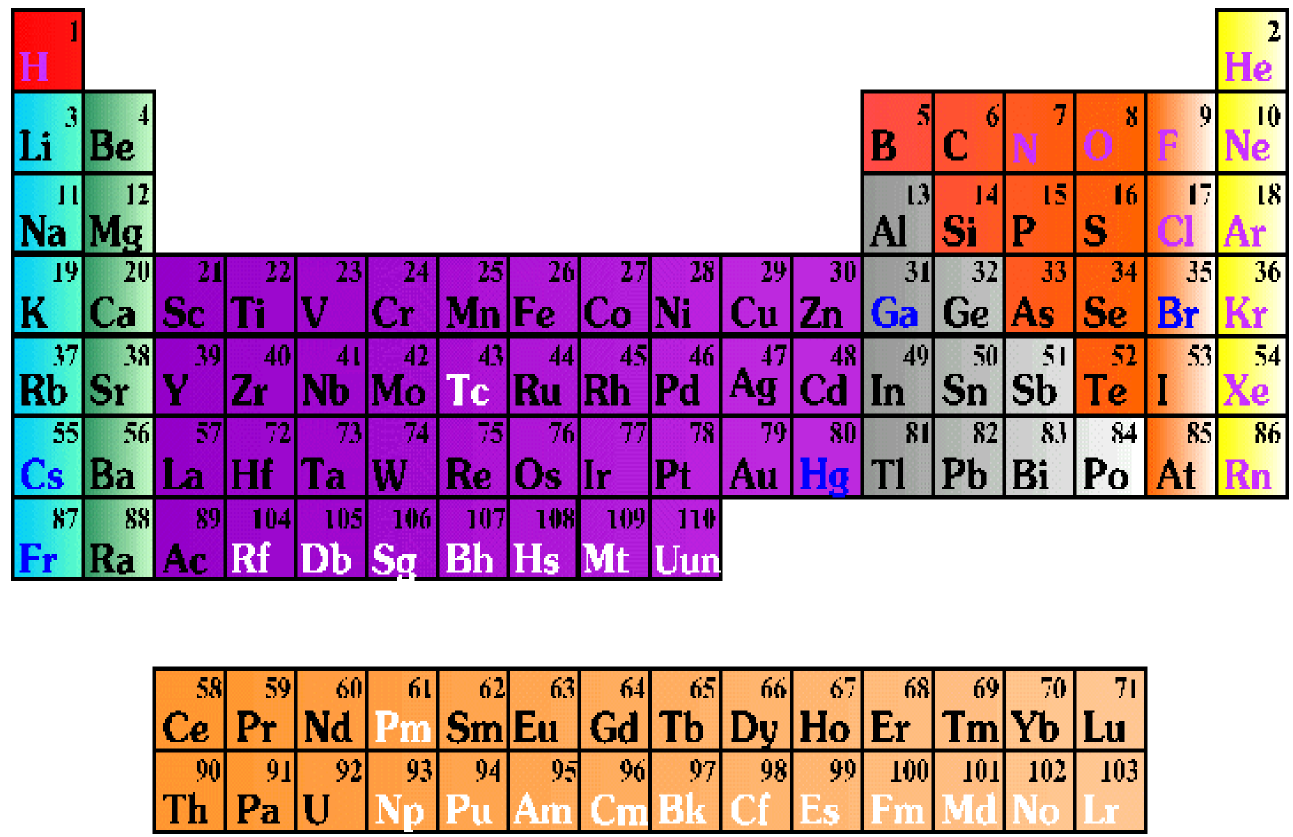




???

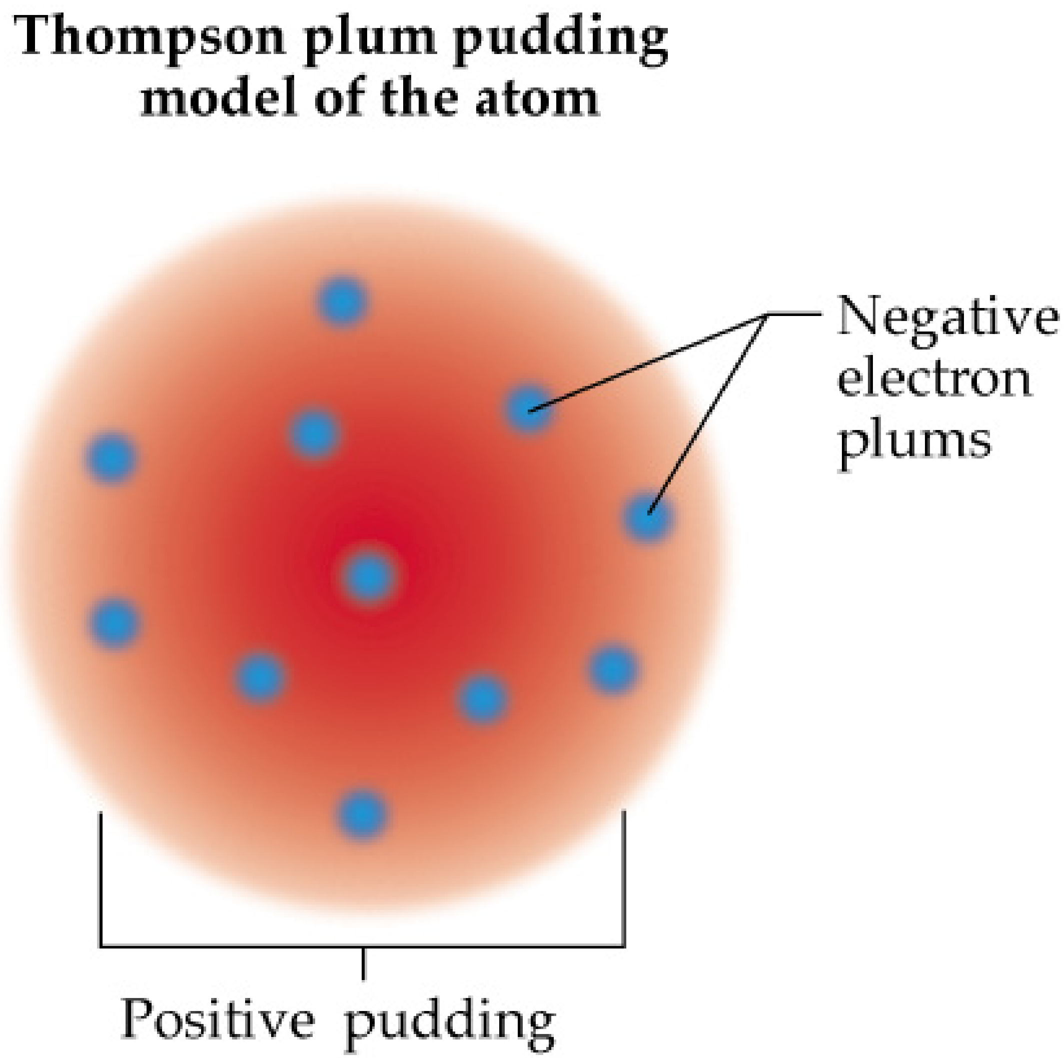
What are things made of ~1900

- **Dmitrii Mendeleev:** Periodic Table of Elements.
  - Everything is made up of mixtures of pure elements (*ATOMS*).



- **JJ Thompson:** electron.
  - ATOMS can eject these small, negatively charged bits that are also the carrier of electric current.

Picture of the Atom ~1900

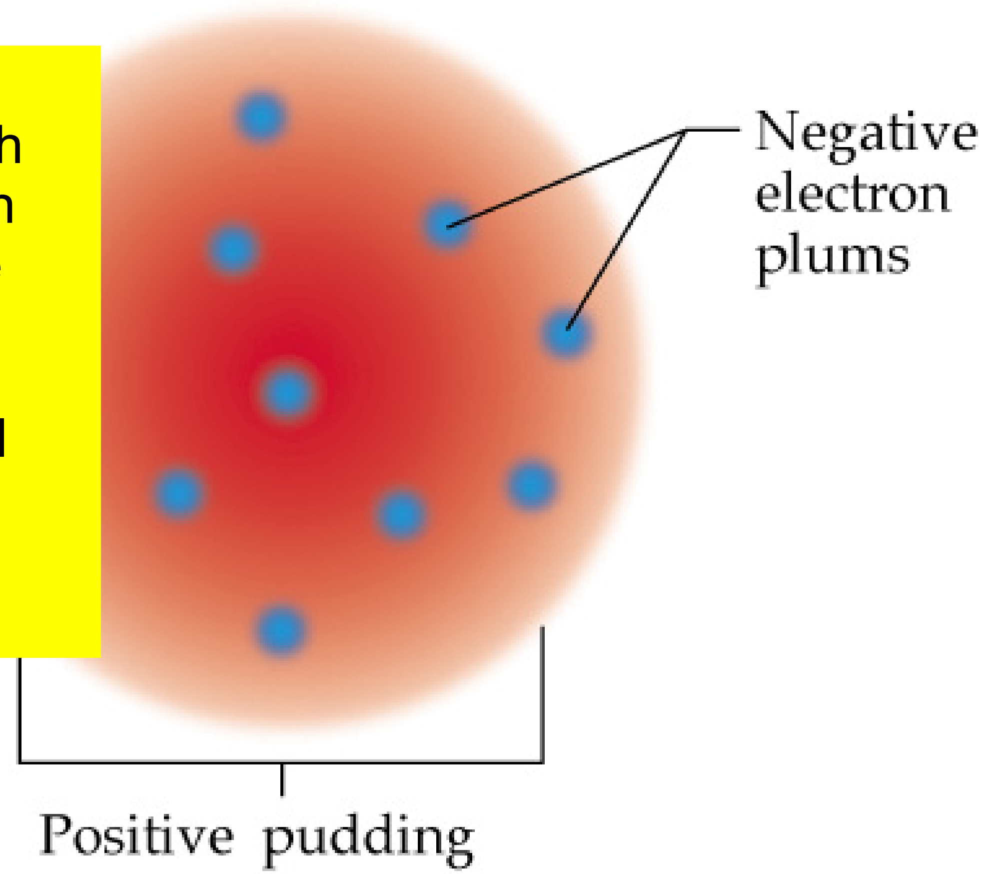


Picture of the Atom ~1900

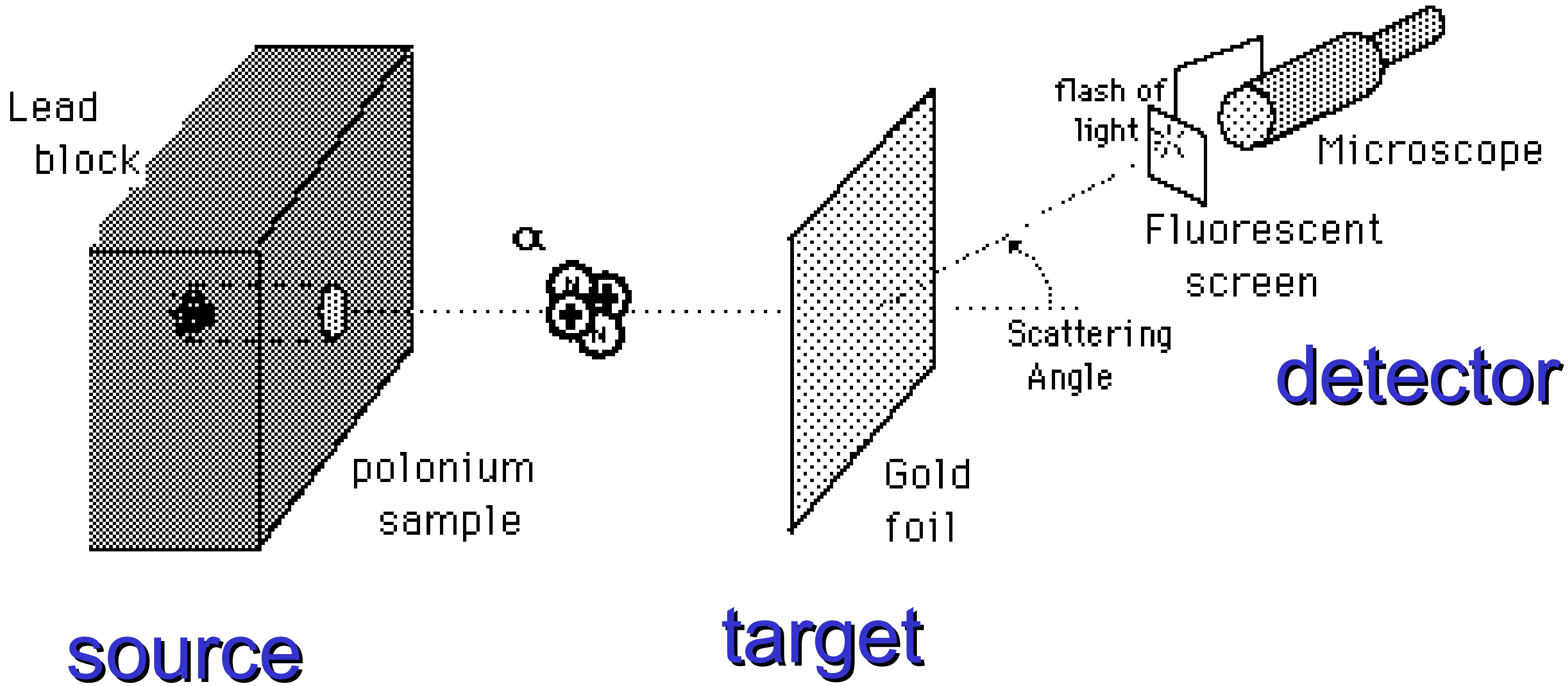
Thompson plum pudding model of the atom

Today, the plum pudding model is synonymous with the flat earth theory, but in its time it answered some important questions.

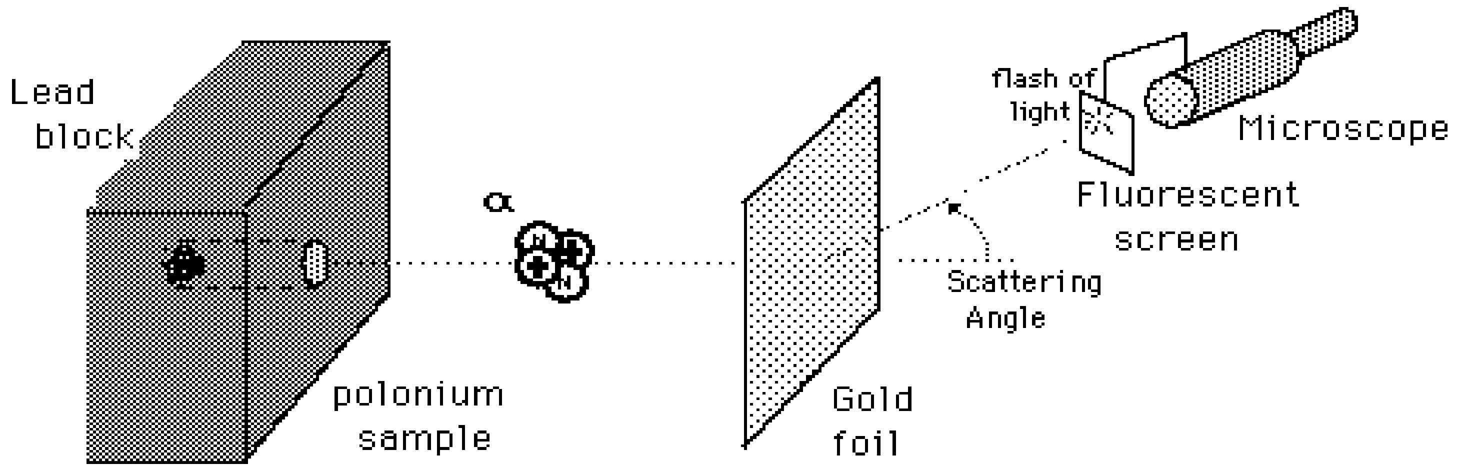
How can a heavy, overall neutral object emit light charged particles when heated (ionization?)



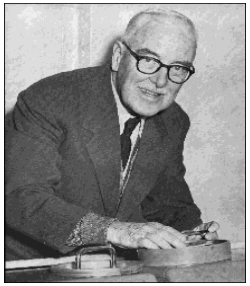
Rutherford Destroys the Plum Pudding Model



Rutherford Destroys the Plum Pudding Model

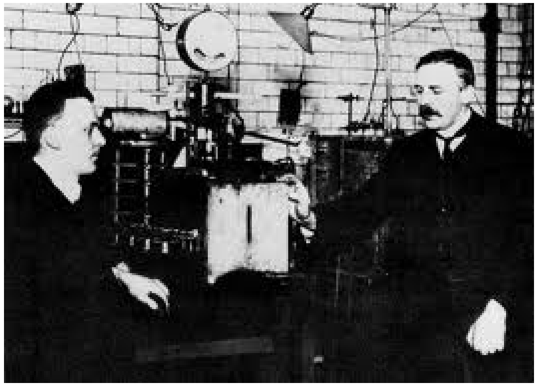


Geiger



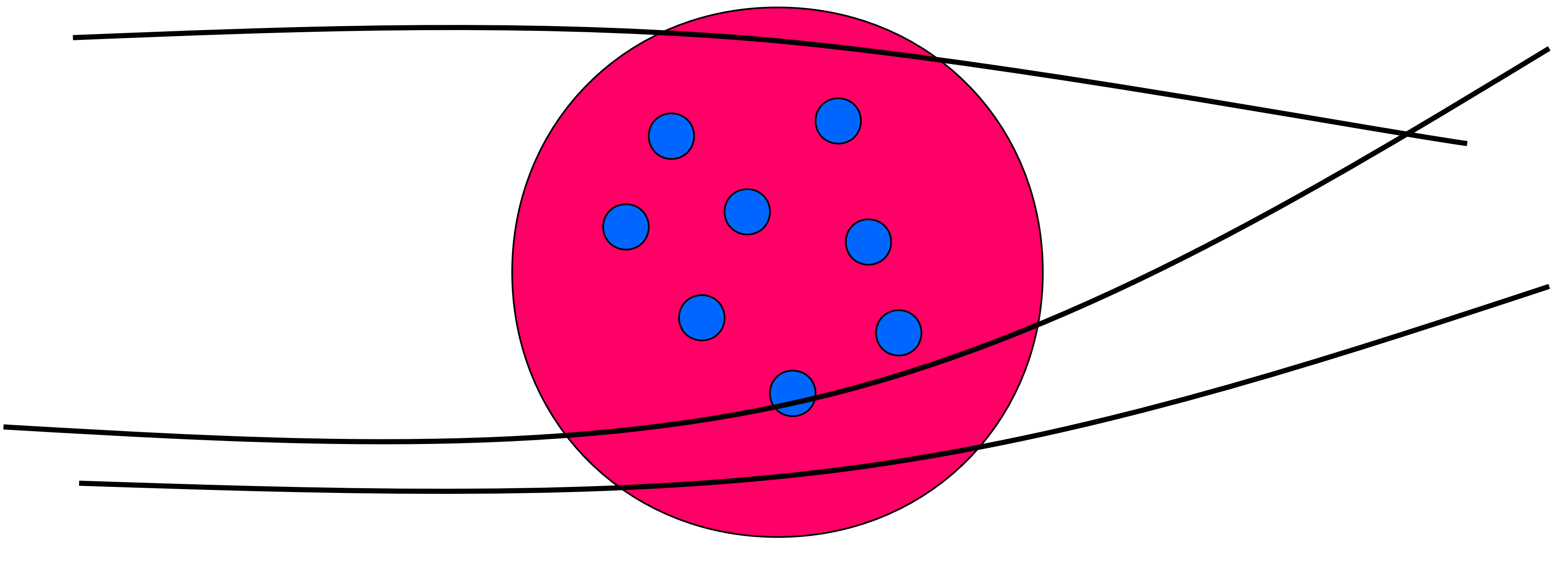
Marsden

Rutherford



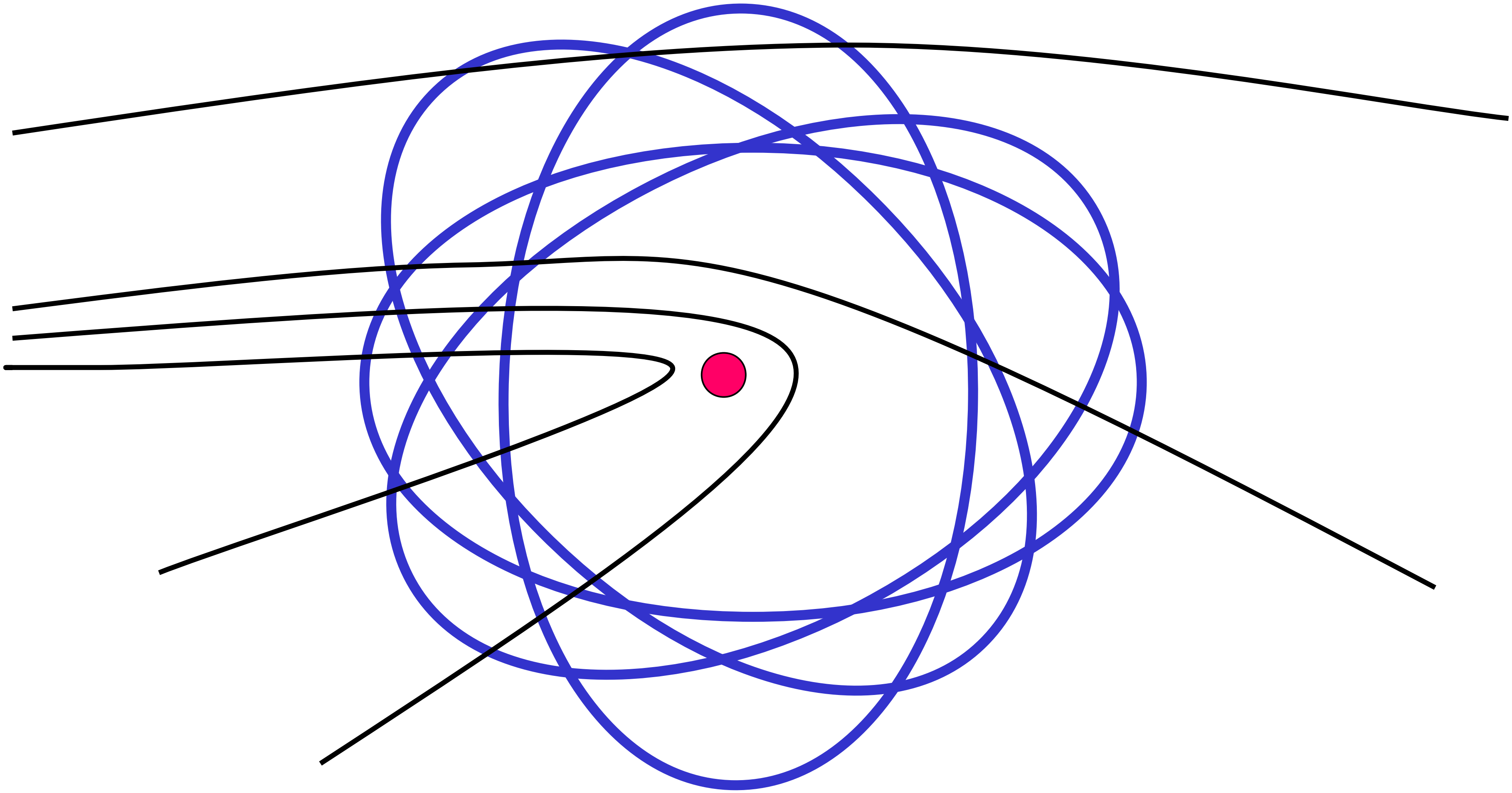
Brilliant example of **undergraduate** contribution to particle physics. Tradition continues to this day!

What Rutherford Expected



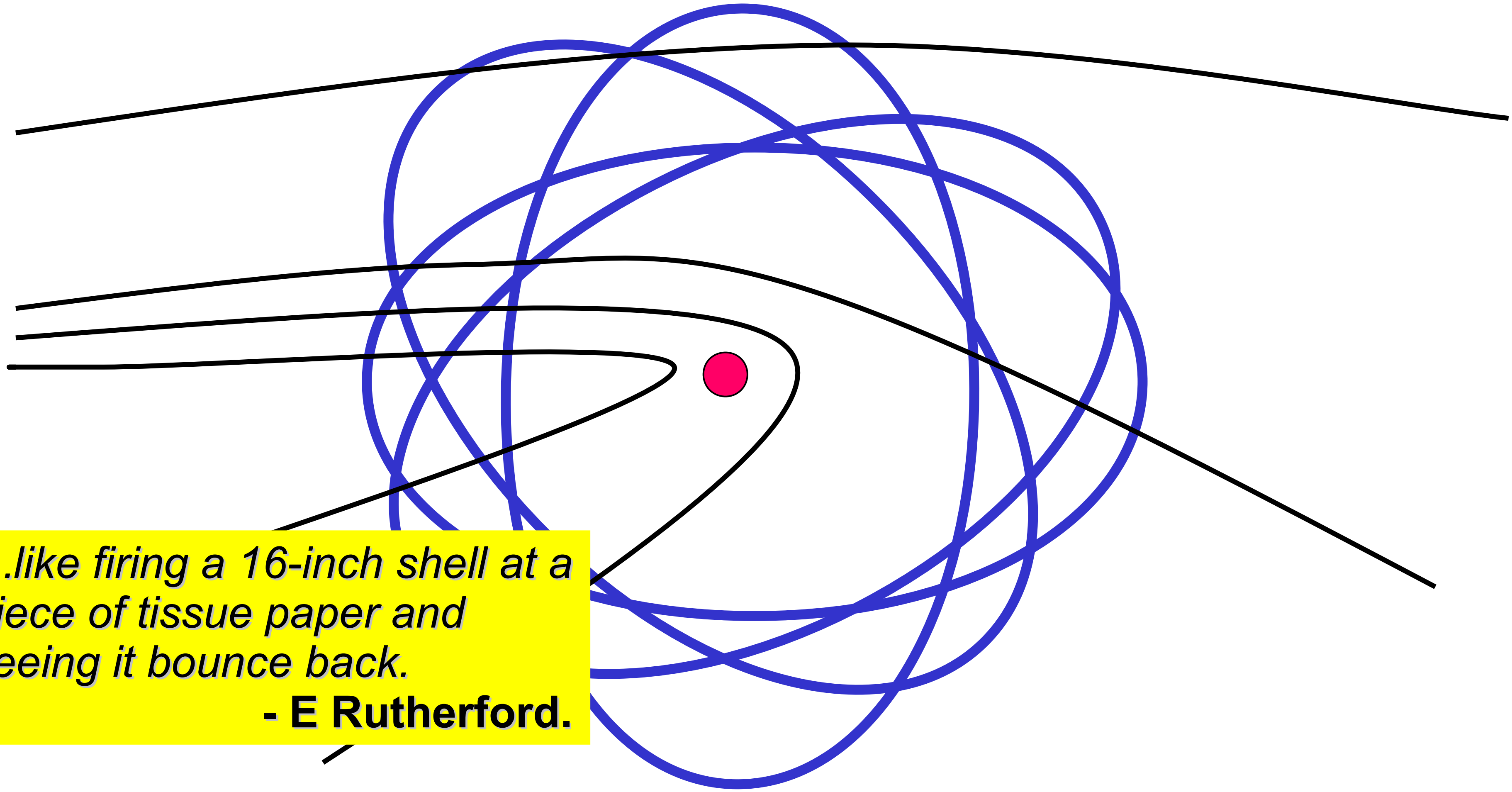
Projectiles (very fast He nuclei called *alpha particles*) will be *slightly* deflected by gold atoms

What Rutherford Saw



Occasionally (rarely) the projectile scattered at huge angles. Beginning of 20th century physics.

What Rutherford Saw



…like firing a 16-inch shell at a piece of tissue paper and seeing it bounce back.

- E Rutherford.

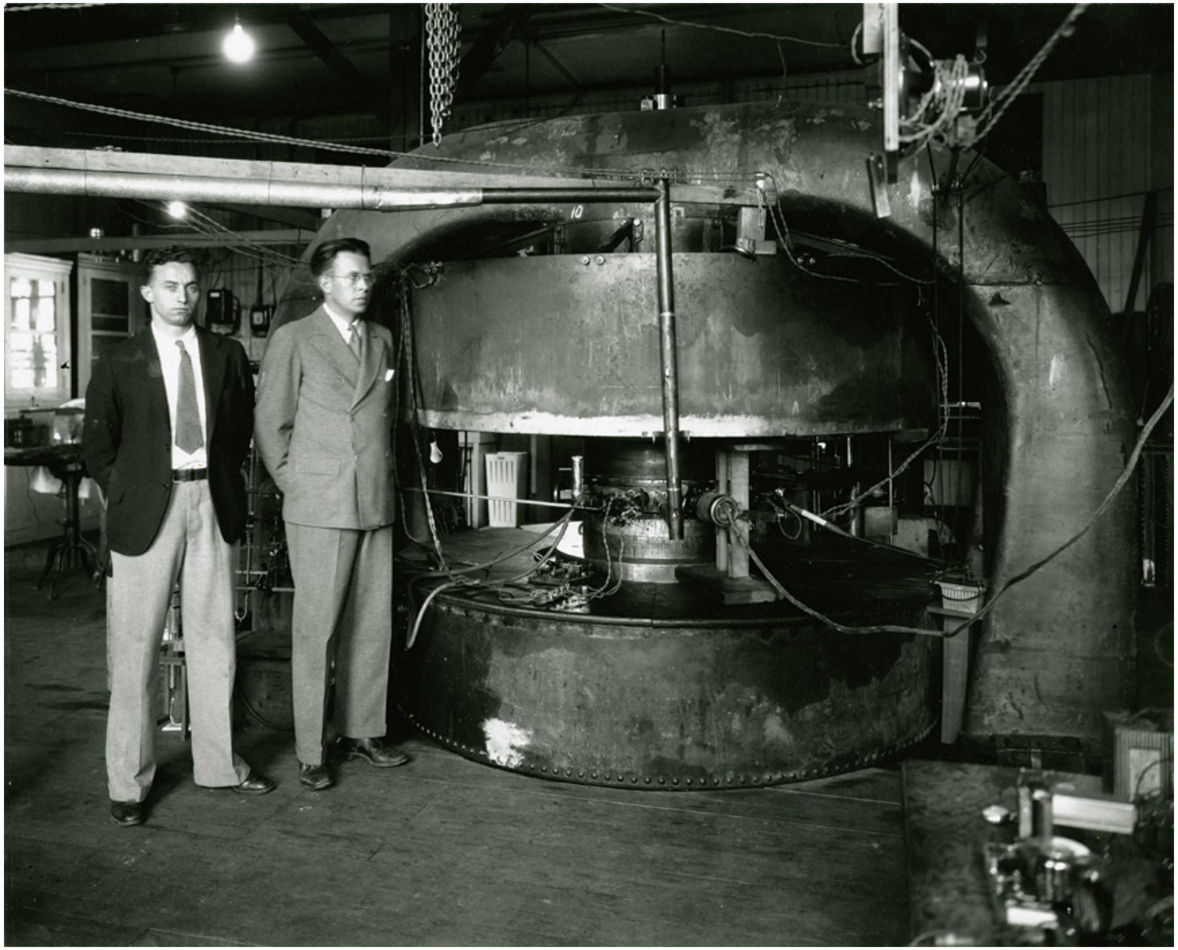
Occasionally (rarely) the projectile scattered at huge angles. Beginning of 20^{th} century physics.

Things started small...

The first cyclotron…

...and got bigger

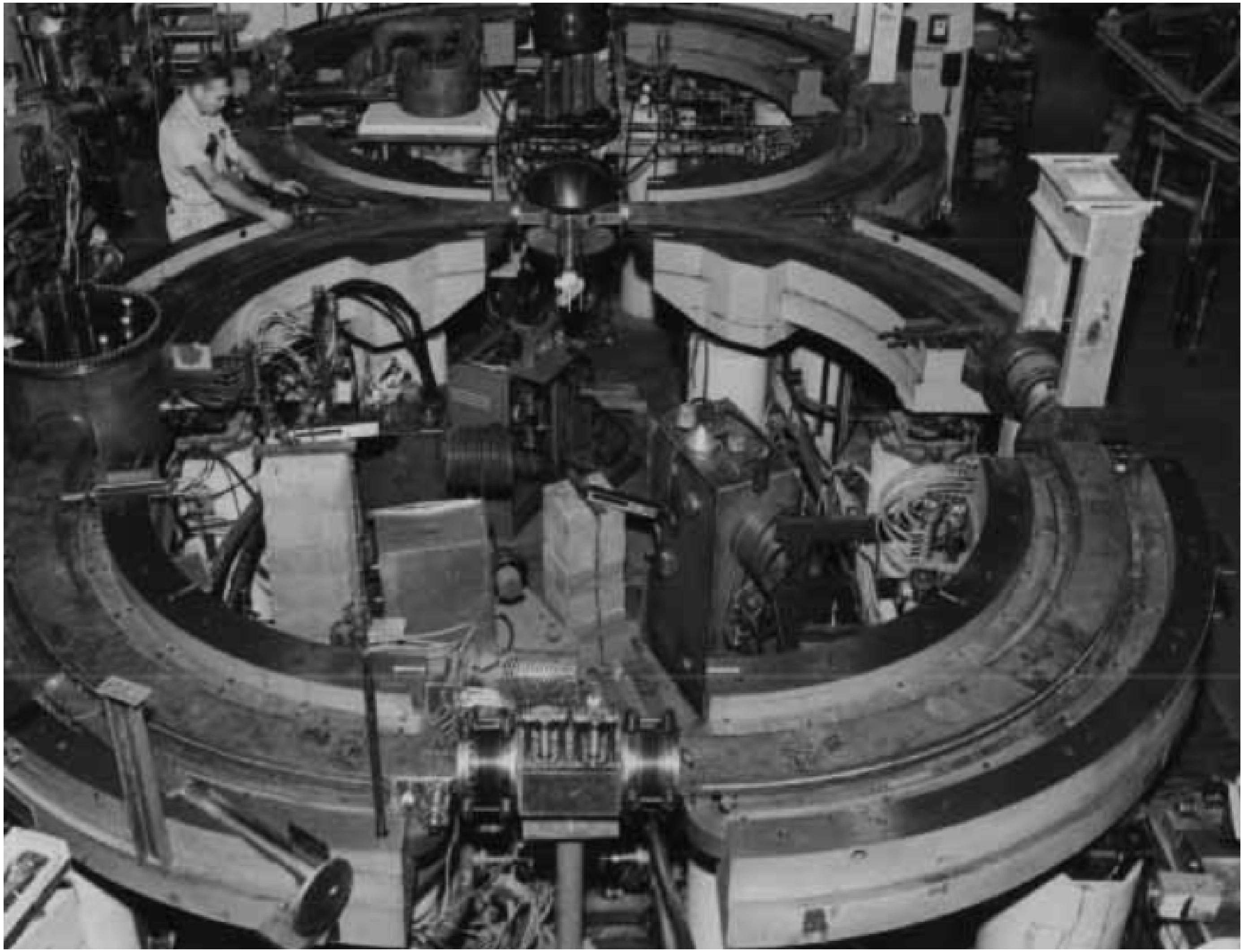
Lawrence next to the Berkeley cyclotron ...discovery of pions. *(~simultaneously with cosmic rays)*



...and even bigger

Princeton-
Stanford
accelerator
(Prin-Stan).

500 MeV, 2-ring
electron-electron
machine

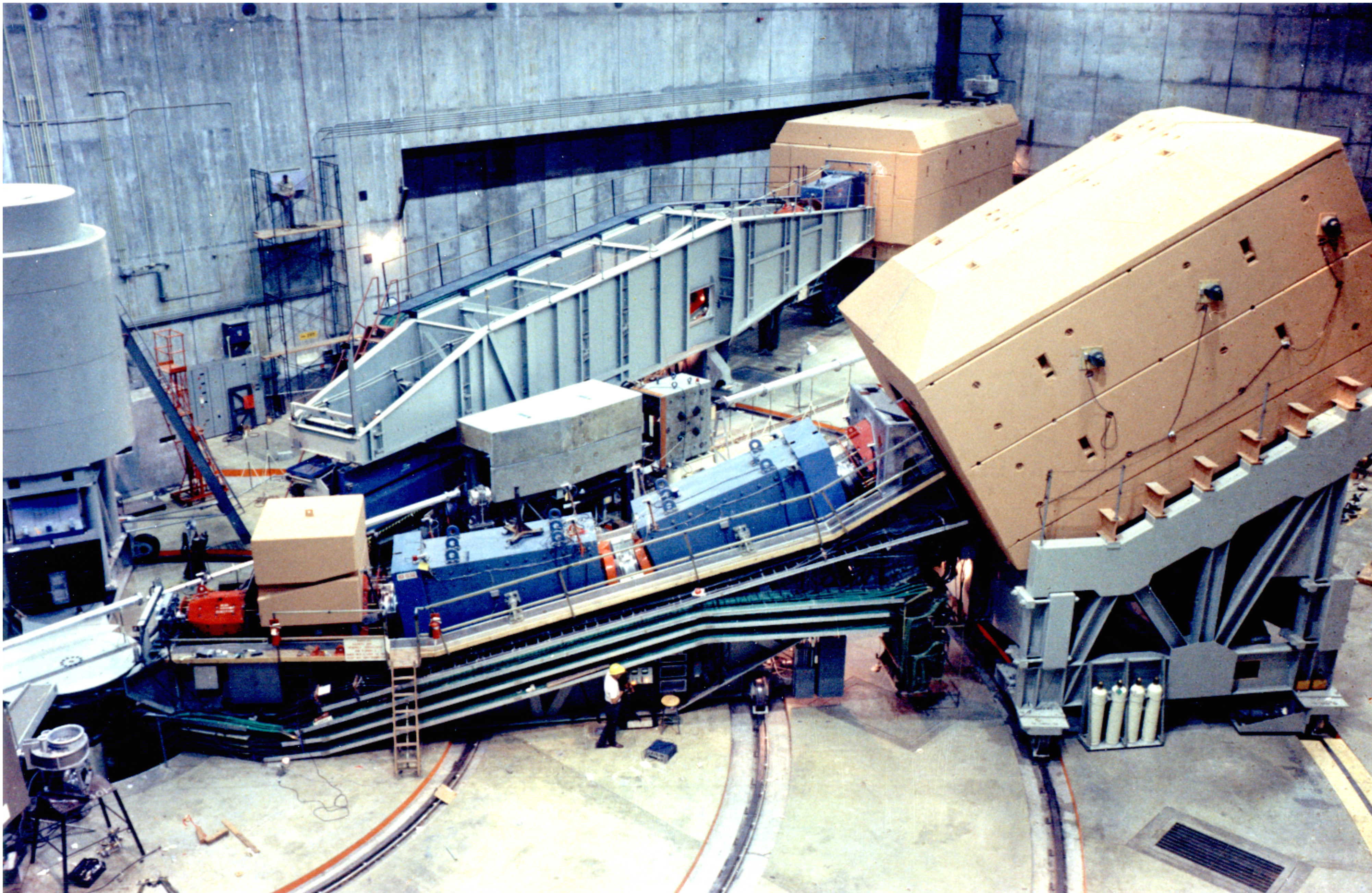


Not all were circular...

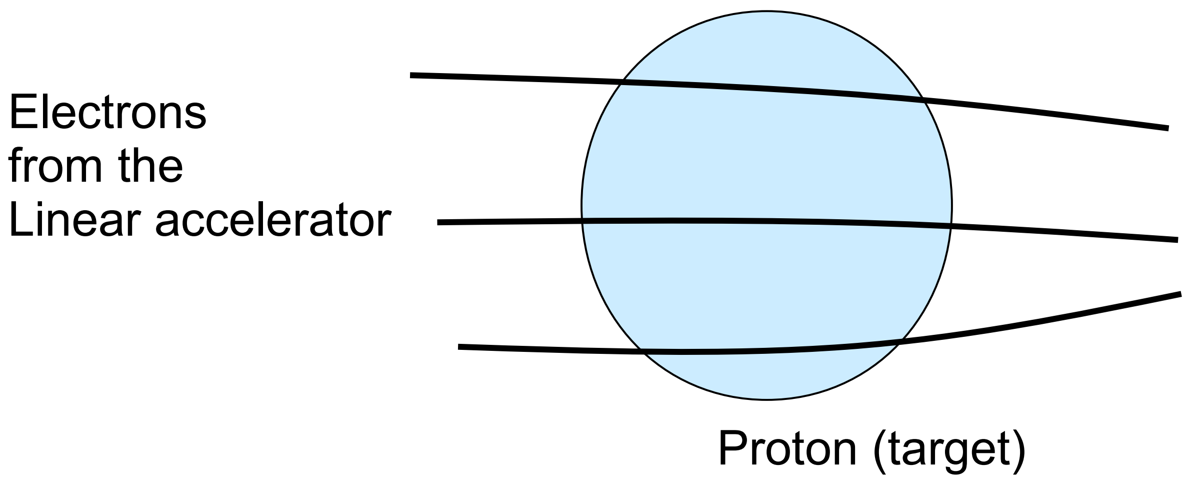
The Stanford Linear Accelerator.

Delivered 15 GeV electrons on target.

End Station A

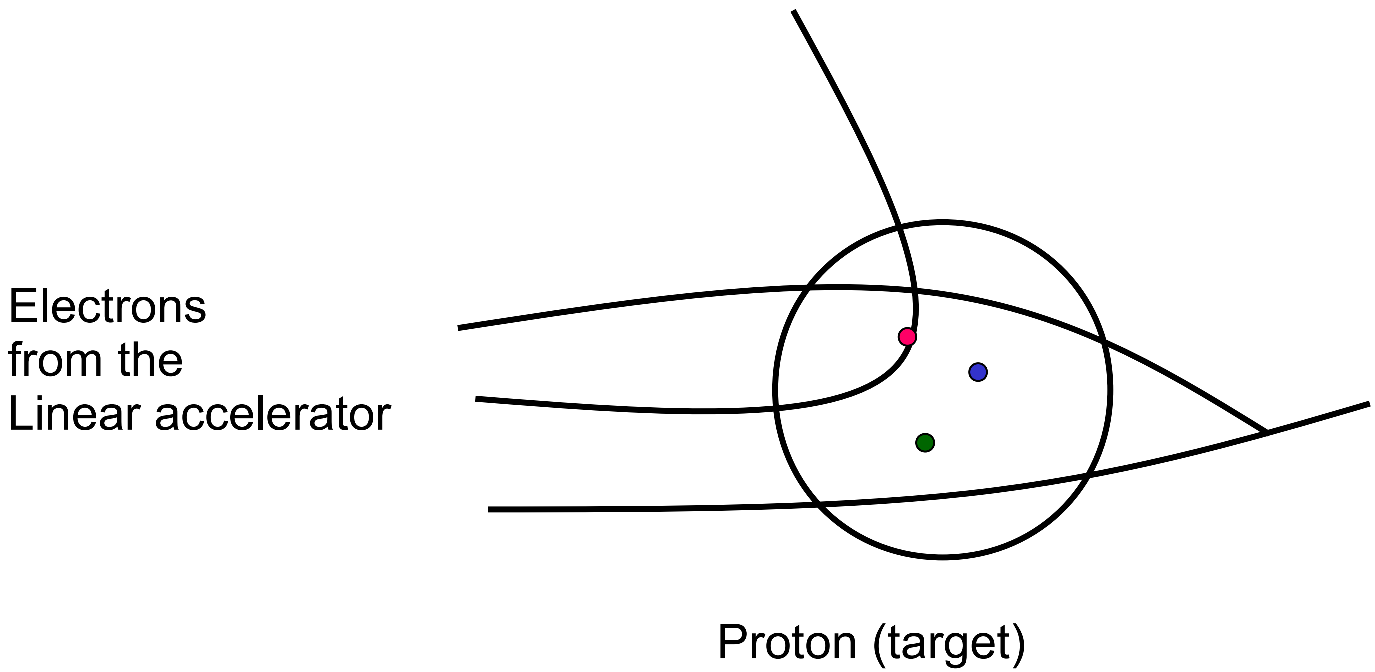


What Kendall, Friedman, and Taylor expected…



NO large angle scattering.

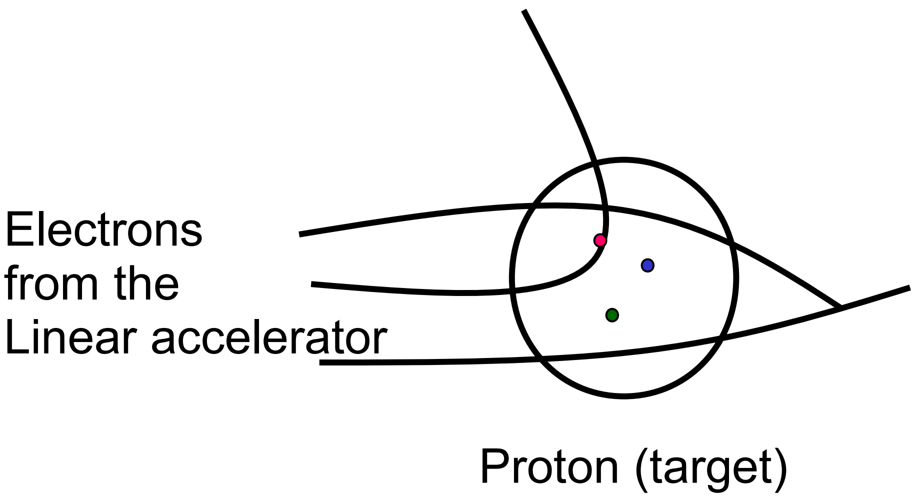
What Kendall, Friedman, and Taylor actually saw



Large angle scattering can happen.

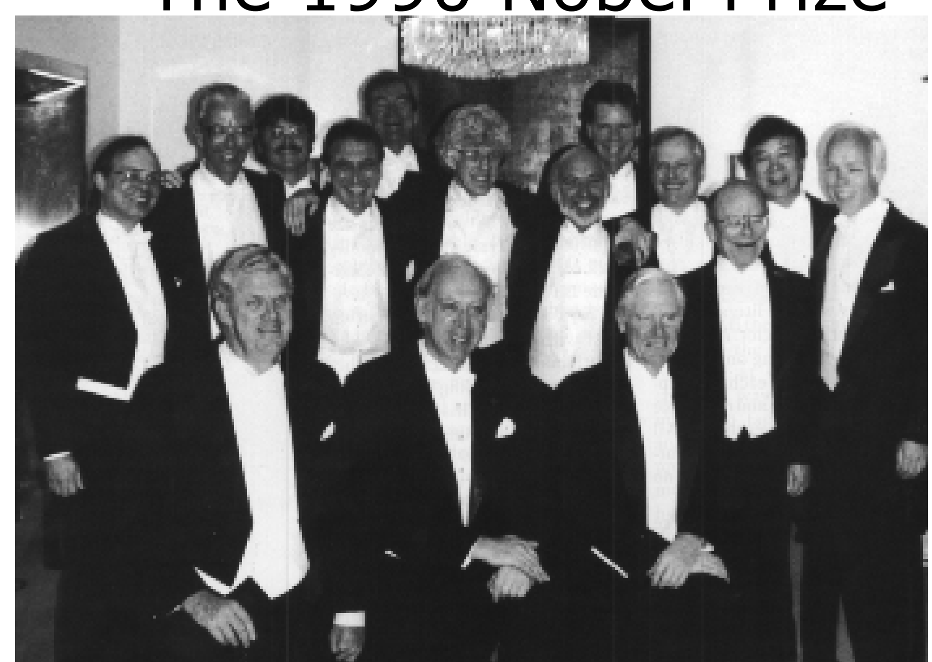
And did! Quarks!

What Kendall, Friedman, and Taylor actually saw



Quarks!

The 1990 Nobel Prize

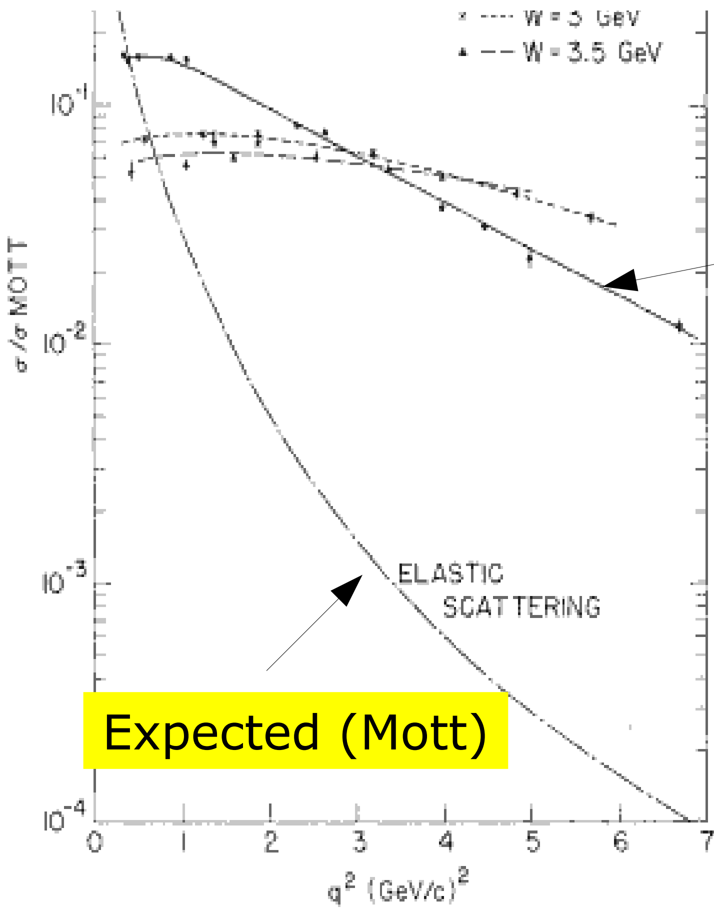


OBSERVED BEHAVIOR OF HIGHLY INELASTIC ELECTRON-PROTON SCATTERING

M. Breidenbach, J. I. Friedman, and H. W. Kendall
Department of Physics and Laboratory for Nuclear Science,*
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

E. D. Bloom, D. H. Coward, H. DeStaebler, J. Drees, L. W. Mo, and R. E. Taylor
Stanford Linear Accelerator Center,† Stanford, California 94305
(Received 22 August 1969)



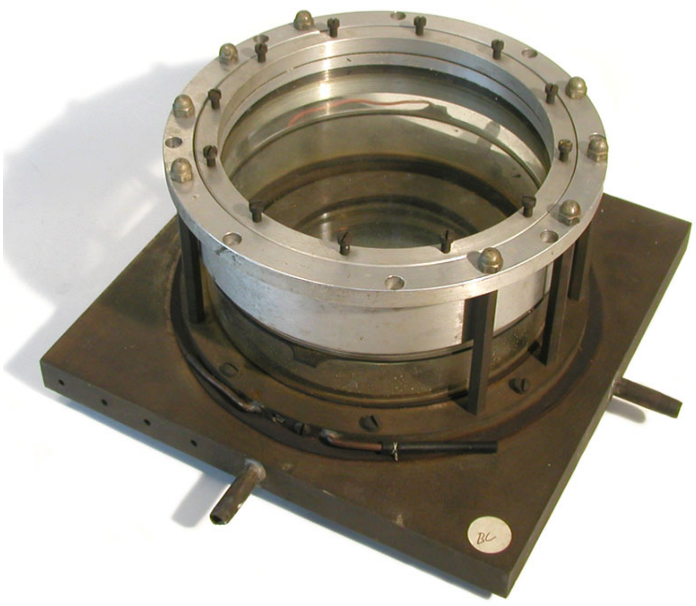
Seen
(Bjorken scaling, aka scattering off quarks)

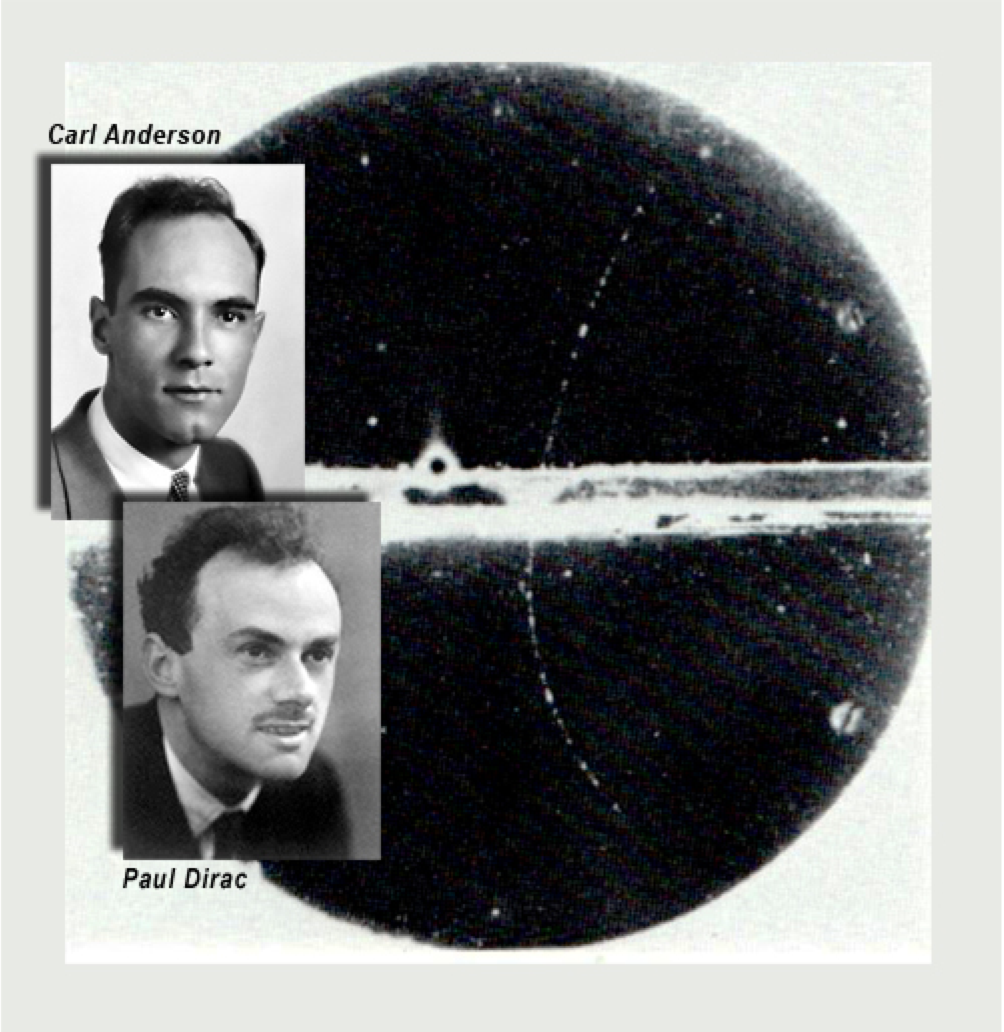
Expected (Mott)

FIG. 1. $(d^2\sigma/d\Omega dE')/\sigma_{\mathrm{Mott}}$, in GeV^{-1}, vs q^2 for W =2, 3, and 3.5 GeV. The lines drawn through the data are meant to guide the eye. Also shown is the cross section for elastic e-p scattering divided by σ_{Mott}, $(d\sigma/d\Omega)/\sigma_{\mathrm{Mott}}$, calculated for $\theta = 10°$, using the dipole form factor. The relatively slow variation with q^2 of the inelastic cross section compared with the elastic cross section is clearly shown.

PRL Vol 23, No 16, (1969)

Aside: Antimatter

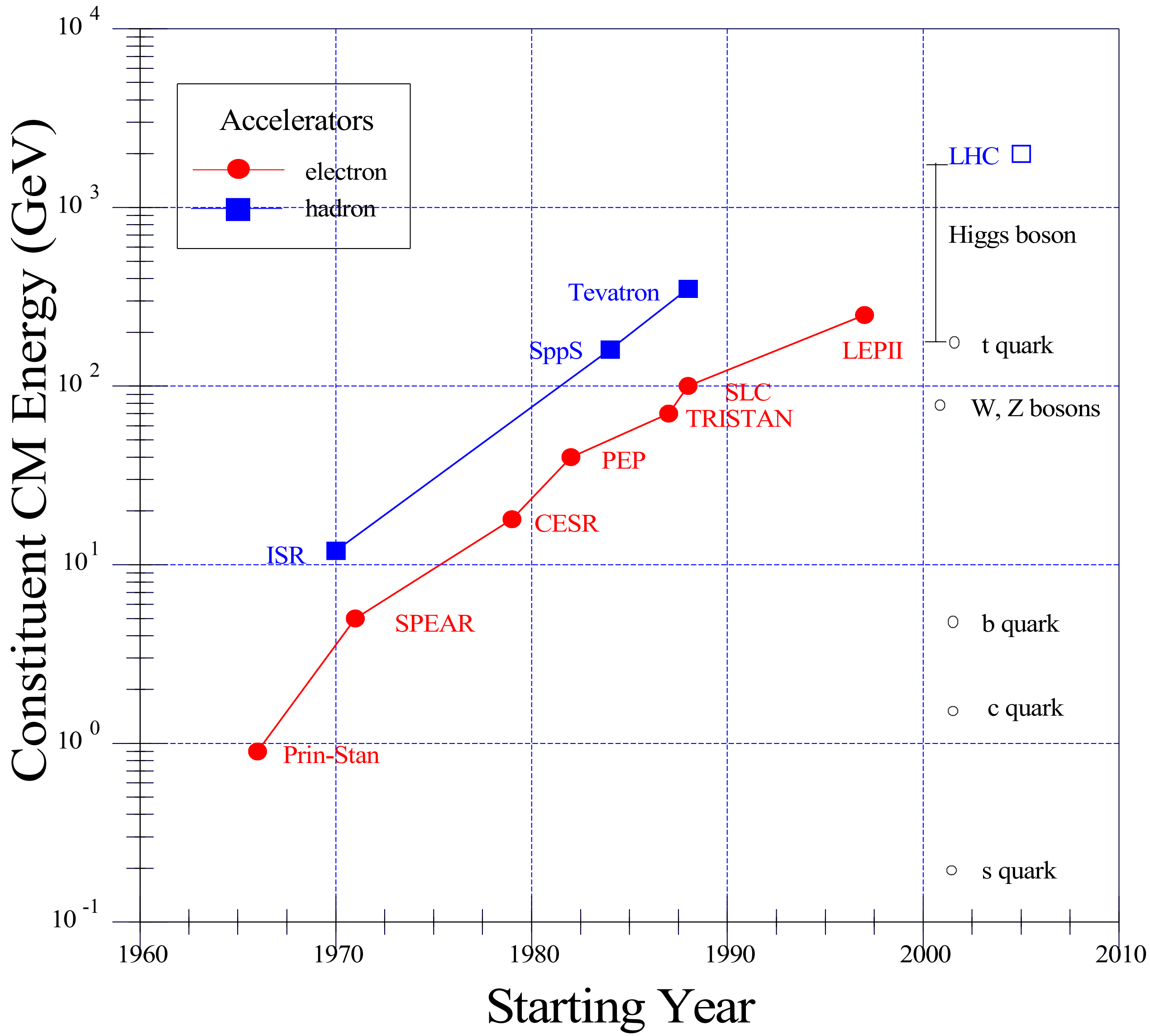




Dirac predicted antimatter as a consequence of combining relativity and quantum mechanics.

Anderson found it (an anti-electron, called positron) in cosmic ray data.

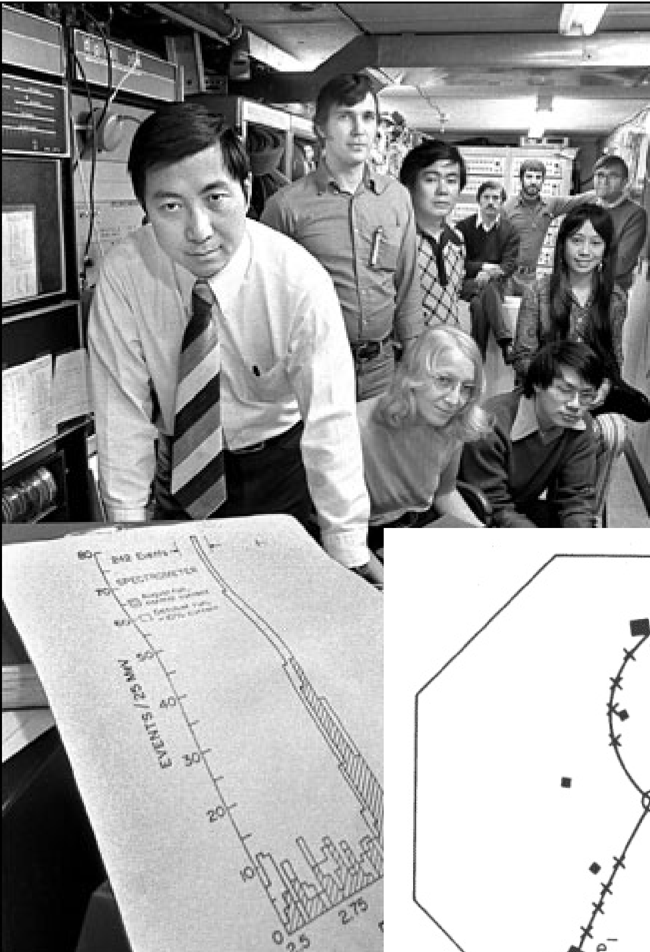
Even bigger Colliders
(now with matter-antimatter collisions!)

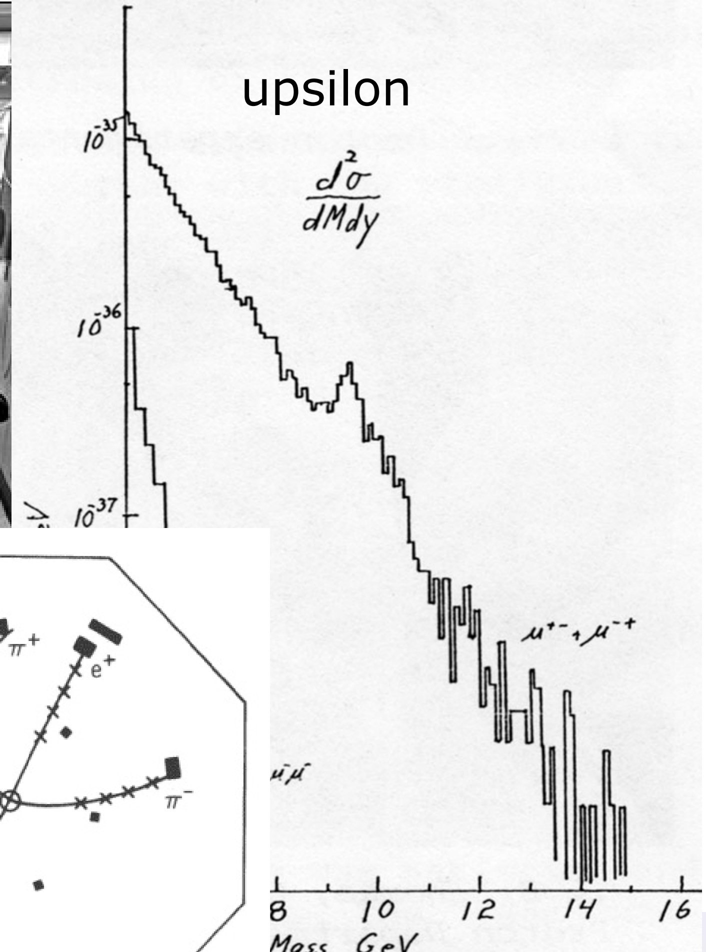


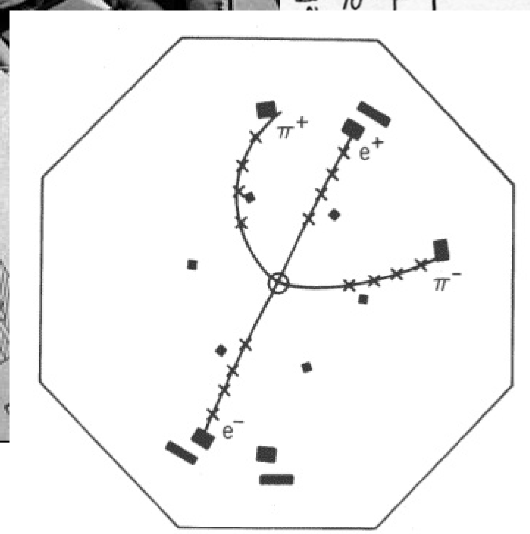
Most were just "let's build it and see what's there". Most discoveries in the field were indeed surprises!

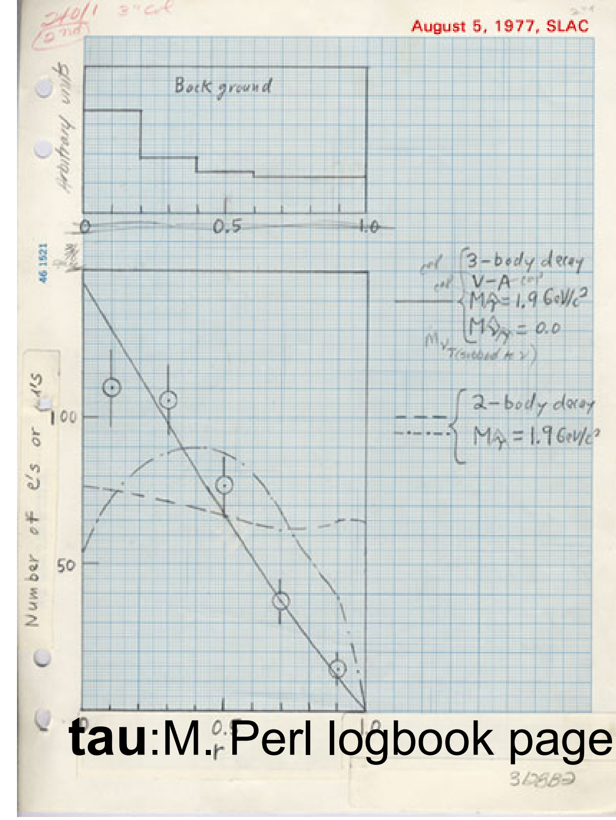
SppS was built to see W/Z for which there were precise predictions

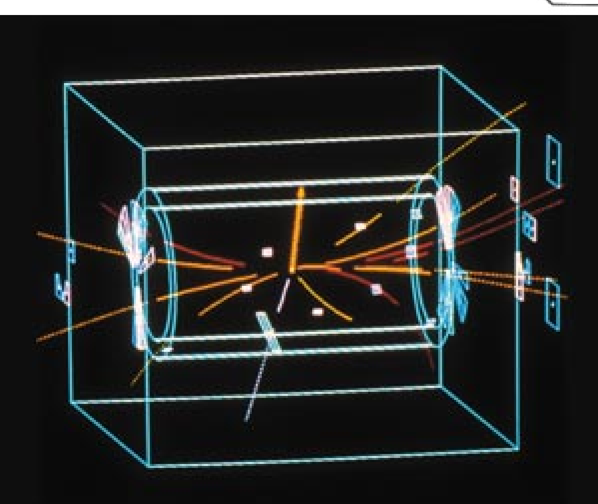
LHC is built to explore electroweak energy scale which it completely covers

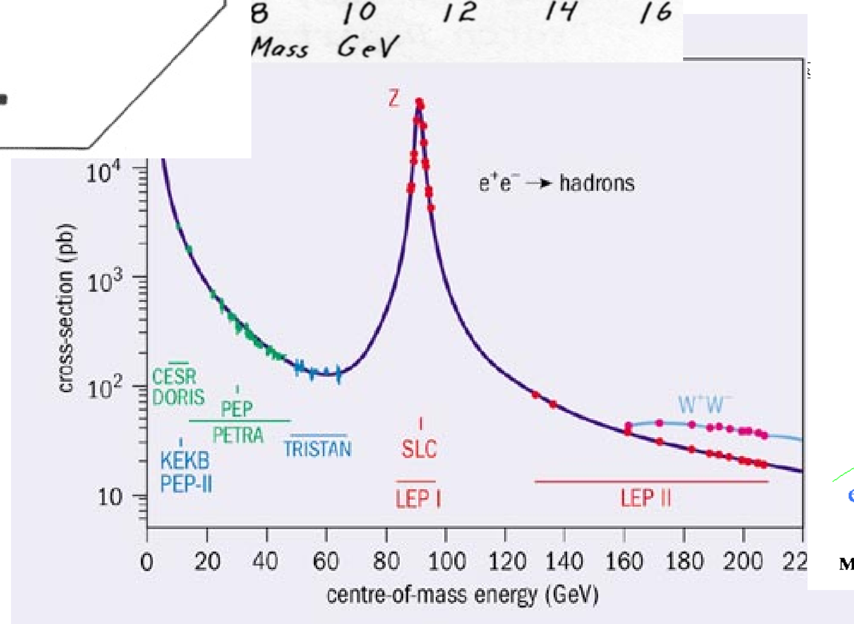

EVENTS / 25 MeV

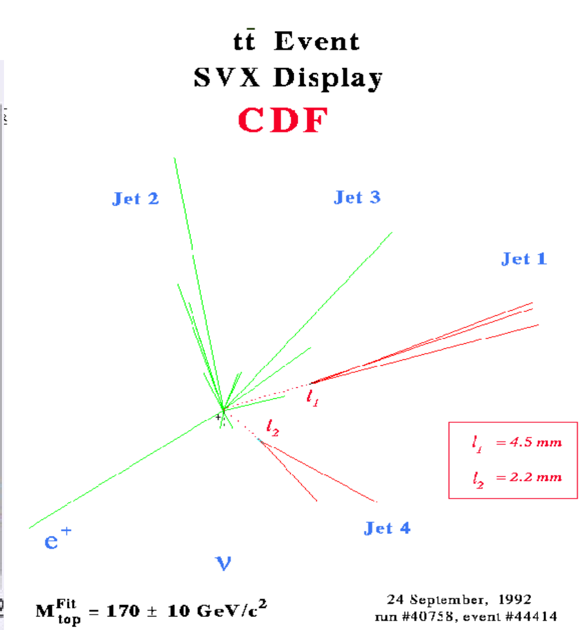

upsilon
$\frac{d^2\sigma}{dMdy}$
10^{-35}
10^{-36}
10^{-37}
$\mu^{+-}+\mu^{-+}$
8
10
12
14
16
Mass GeV


π^+
e^+
π^-
e^-


August 5, 1977, SLAC
Back ground
0
0.5
1.0
3-body decay
V-A
$M_A = 1.9\ GeV/c^2$
2-body decay
$M_A = 1.9\ GeV/c^2$
100
50
Number of e's or μ's
tau:M. Perl logbook page




Z
$e^+e^- \to$ hadrons
10^4
10^3
10^2
10
cross-section (pb)
CESR
DORIS
PEP
PETRA
TRISTAN
KEKB
PEP-II
SLC
LEP I
LEP II
W⁺W⁻
0
20
40
60
80
100
120
140
160
180
200
220
centre-of-mass energy (GeV)


$t\bar{t}$ Event
SVX Display
CDF
Jet 2
Jet 3
Jet 1
Jet 4
l_1
l_2
l_1 = 4.5 mm
l_2 = 2.2 mm
e^+
ν
M_{top}^{Fit} = 170 ± 10 GeV/c²
24 September, 1992
run #40758, event #44414

So what is everything made of?

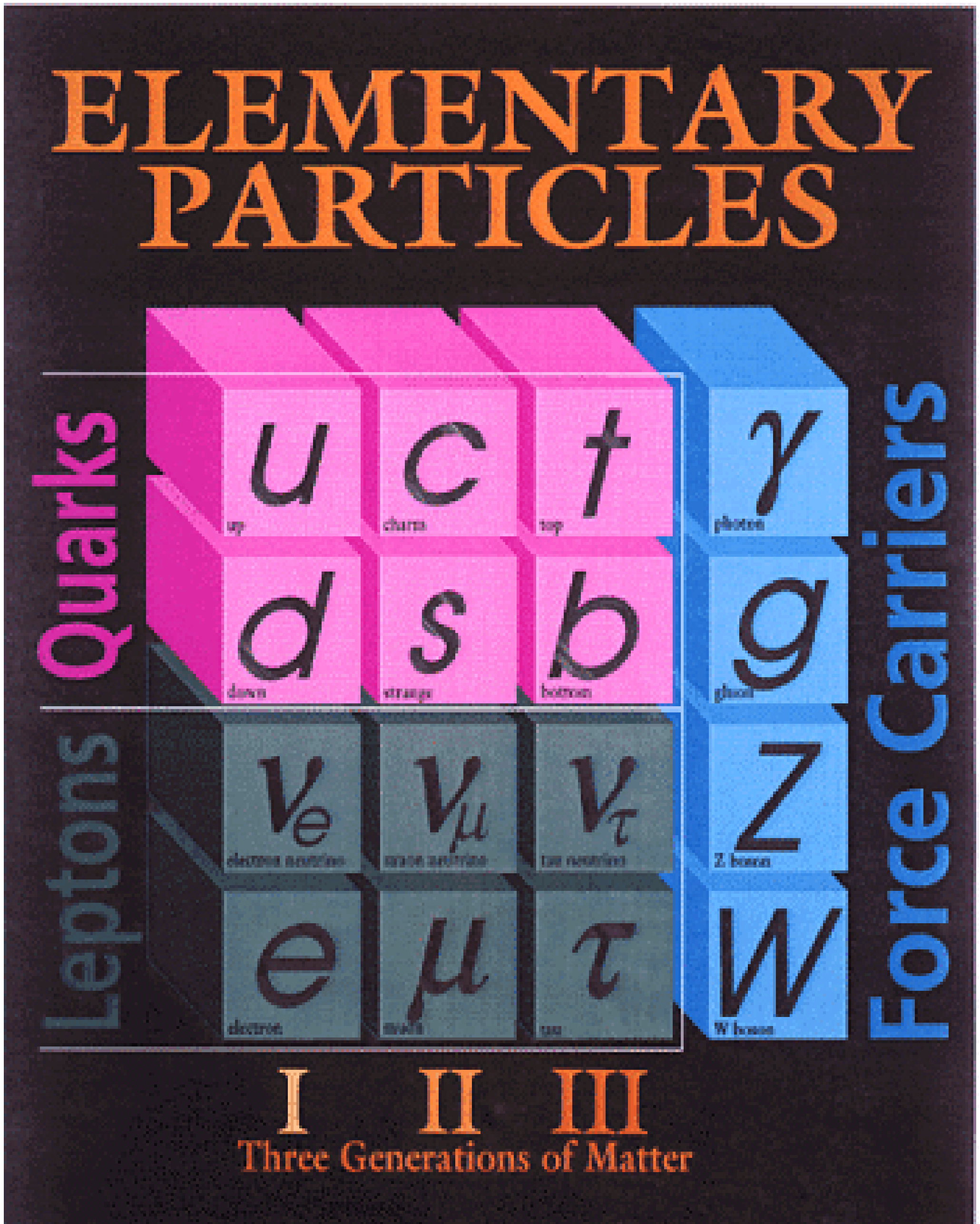
Status as of 2011

	Particles			Forces they feel: EM	Strong nuclear	Weak nuclear
Quarks	Up	Charm	Top	+2/3	yes!	yes
	Down	Strange	Bottom	-1/3	yes!	yes
Leptons	Electron	Muon	Tau	-1	no	yes
	e-neutrino	μ-neutrino	τ-neutrino	0	no	yes

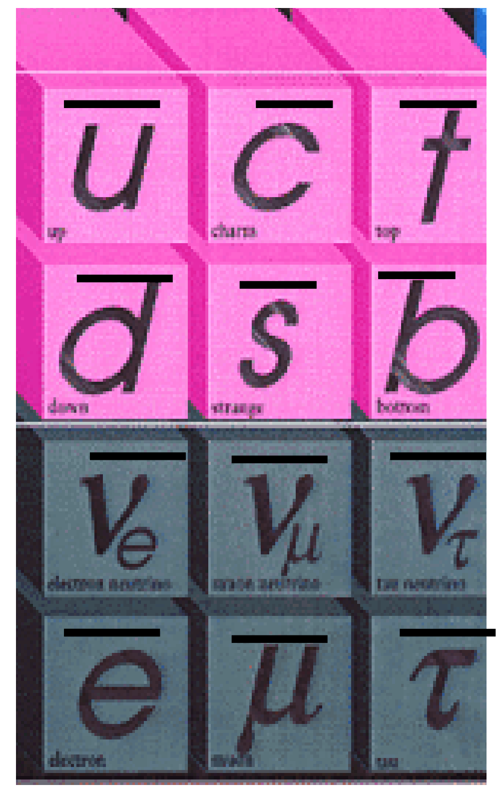
Everything in the universe is made of the 1st generation particles.

Quarks bind together with the strong force to make familiar particles such as protons and neutrons.

So why isn't this good enough?



+



antimatter

Go back 100 years...

$$\nabla \cdot \mathbf{E} = \rho / \varepsilon_0$$

$$\nabla \cdot \mathbf{B} = 0$$

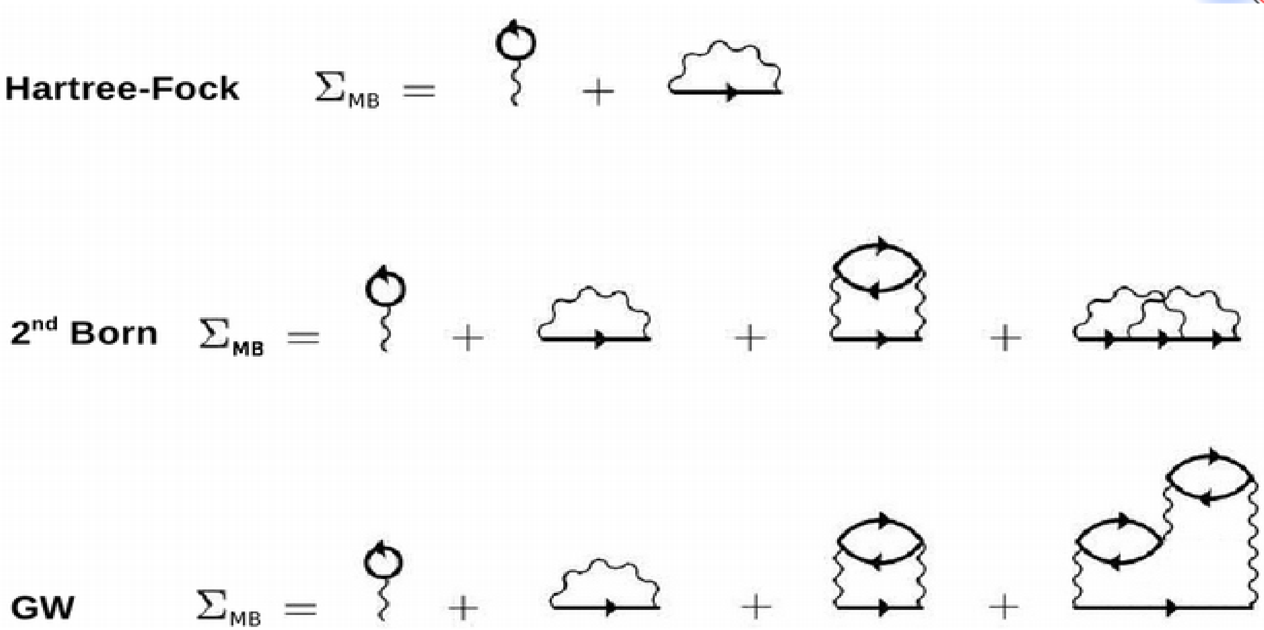
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

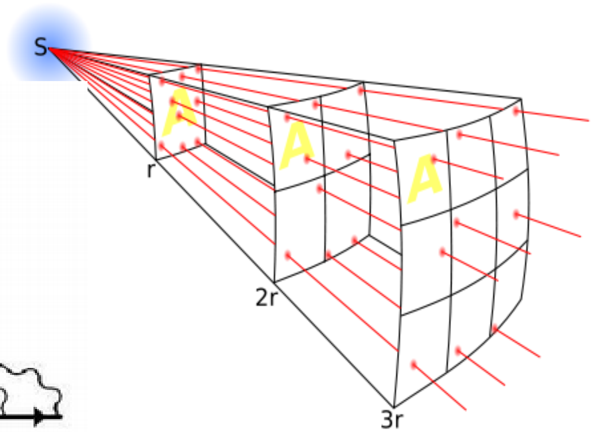
$$\nabla \times \mathbf{B} = \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \mu_0 \boldsymbol{j}_c$$

Isn't this good enough?

Even before QED, we knew that classical electrodynamics could not be the whole story . . .

The classical theory predicts its own demise with an infinite electron self-energy

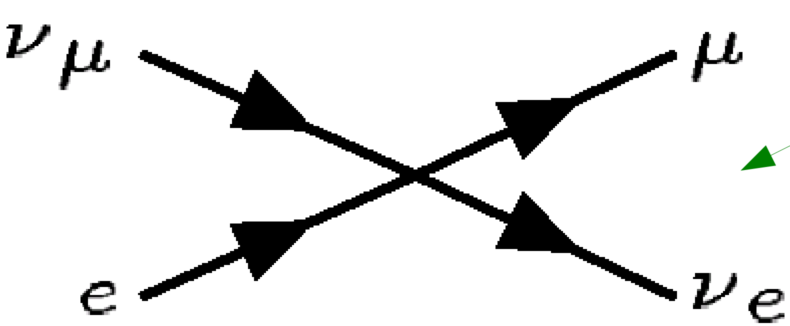




(This is a recurring and important theme)

Nonsensical predictions, and solutions

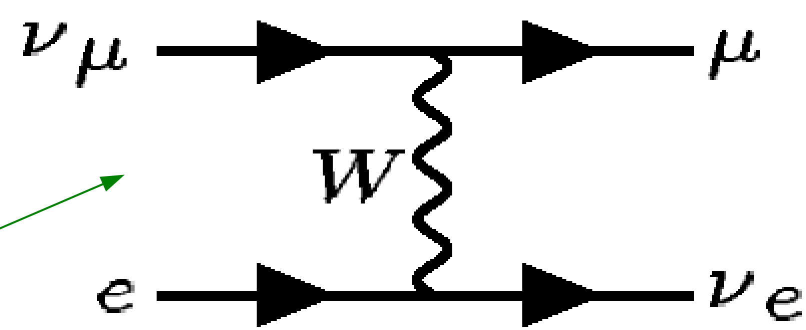
Fermi theory of the 1930's



This process violates unitarity at high energies

What do we do?

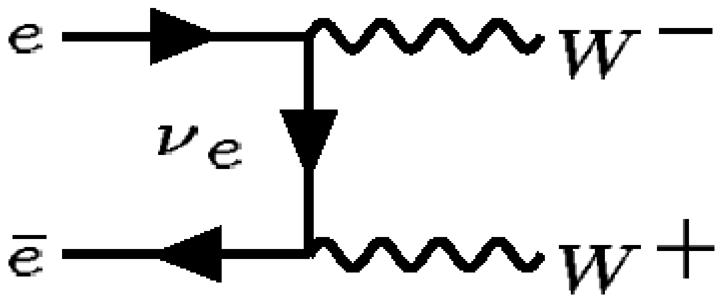
Modify the diagram to cancel the divergence



the W boson

(observed at CERN in 1983)

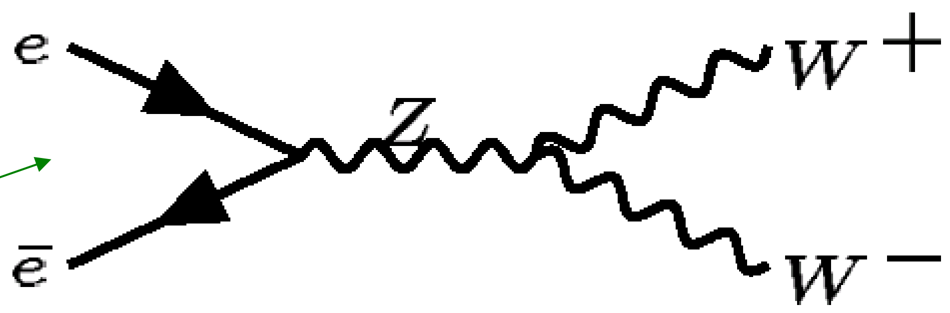
Nonsensical predictions, and solutions cont.



But now this process violates unitarity at high energies!

What do we do?

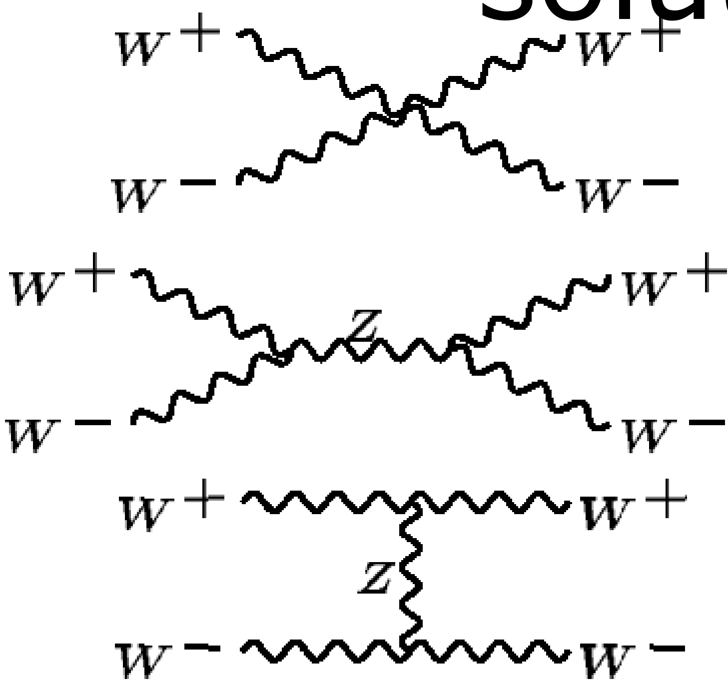
Introduce another diagram that cancels the divergence



the Z boson

(also observed at CERN in 1983)

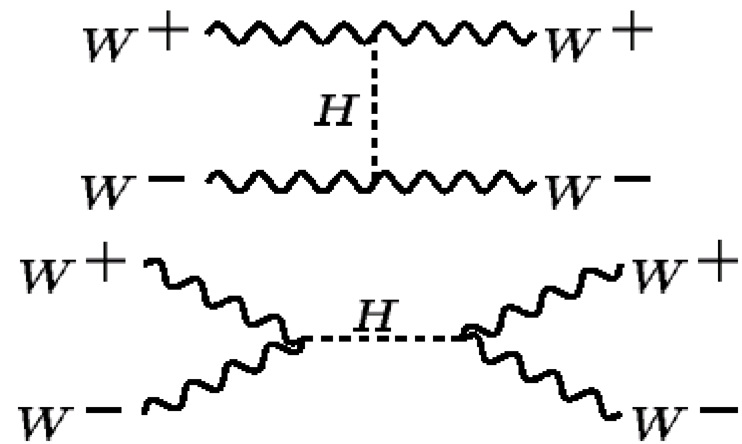
Nonsensical predictions, and solutions cont.



But now *these* processes violate unitarity at high energies!

What do we do?

Introduce *other* diagrams to cancel the divergence

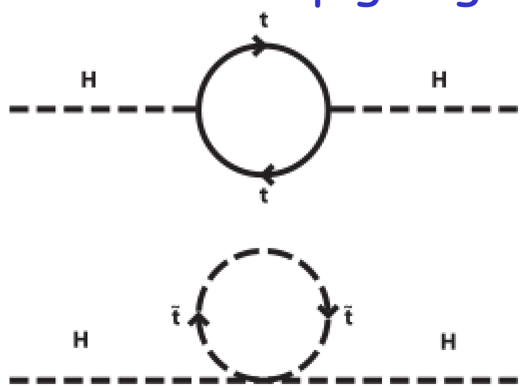


the Higgs boson

Nonsensical predictions, and solutions cont.

Thus far we have <u>no direct evidence</u> for the Higgs boson*

but let's keep going:



If the Higgs exists, these types of processes violate unitarity at high energies unless a parameter is "unnaturally" fine-tuned ("fine-tuning problem")

What do we do?

Introduce other diagrams to cancel the divergence without fine-tuning

- supersymmetry
- strong dynamics
- extra dimensions

Symmetries

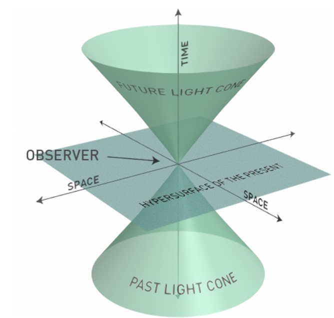
Symmetries are the Central Organizing Principle in Our Understanding of Fundamental Physics !!!

Spatial Translation Invariance (Momentum)

Time Translation Invariance (Energy)

Spatial Rotation Invariance (Angular Momentum)

Space-Time Rotation / Boost Invariance

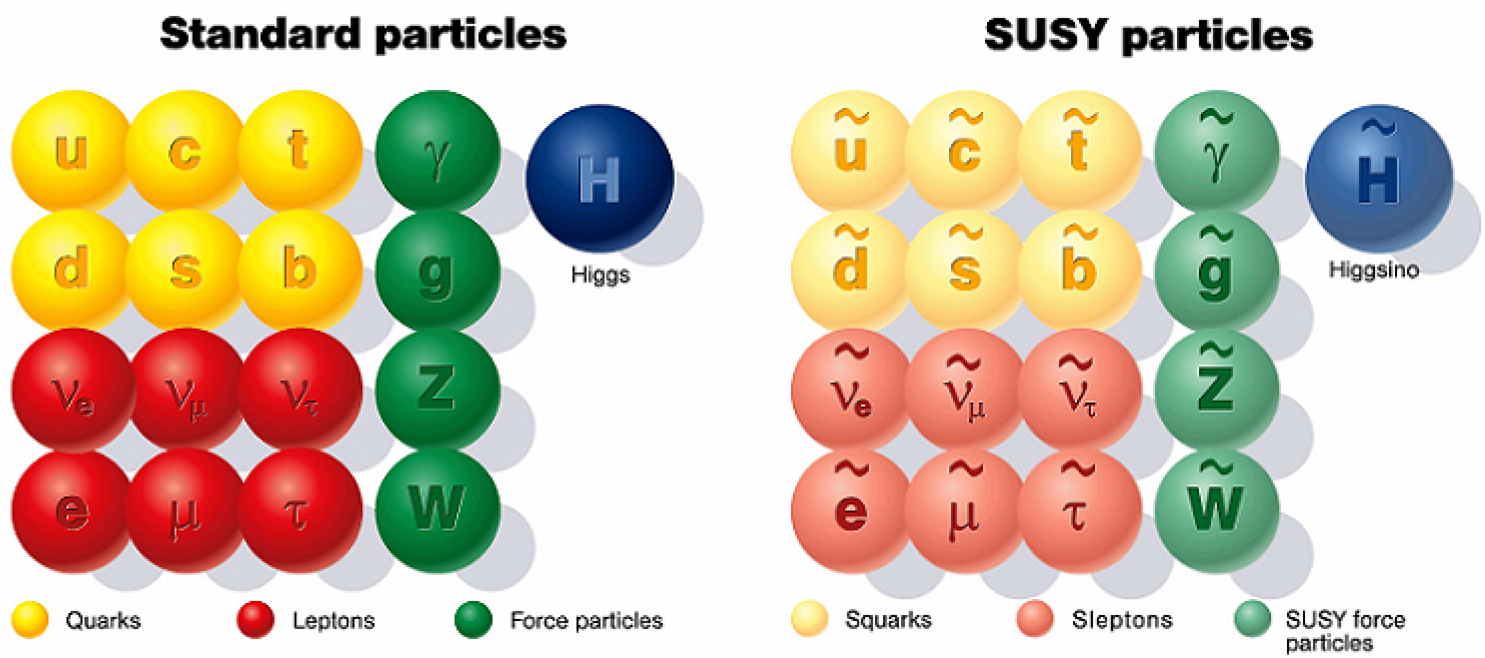


Electromagnetic Waves

velocity = constant

(Lorentz, … , Einstein)

Supersymmetry

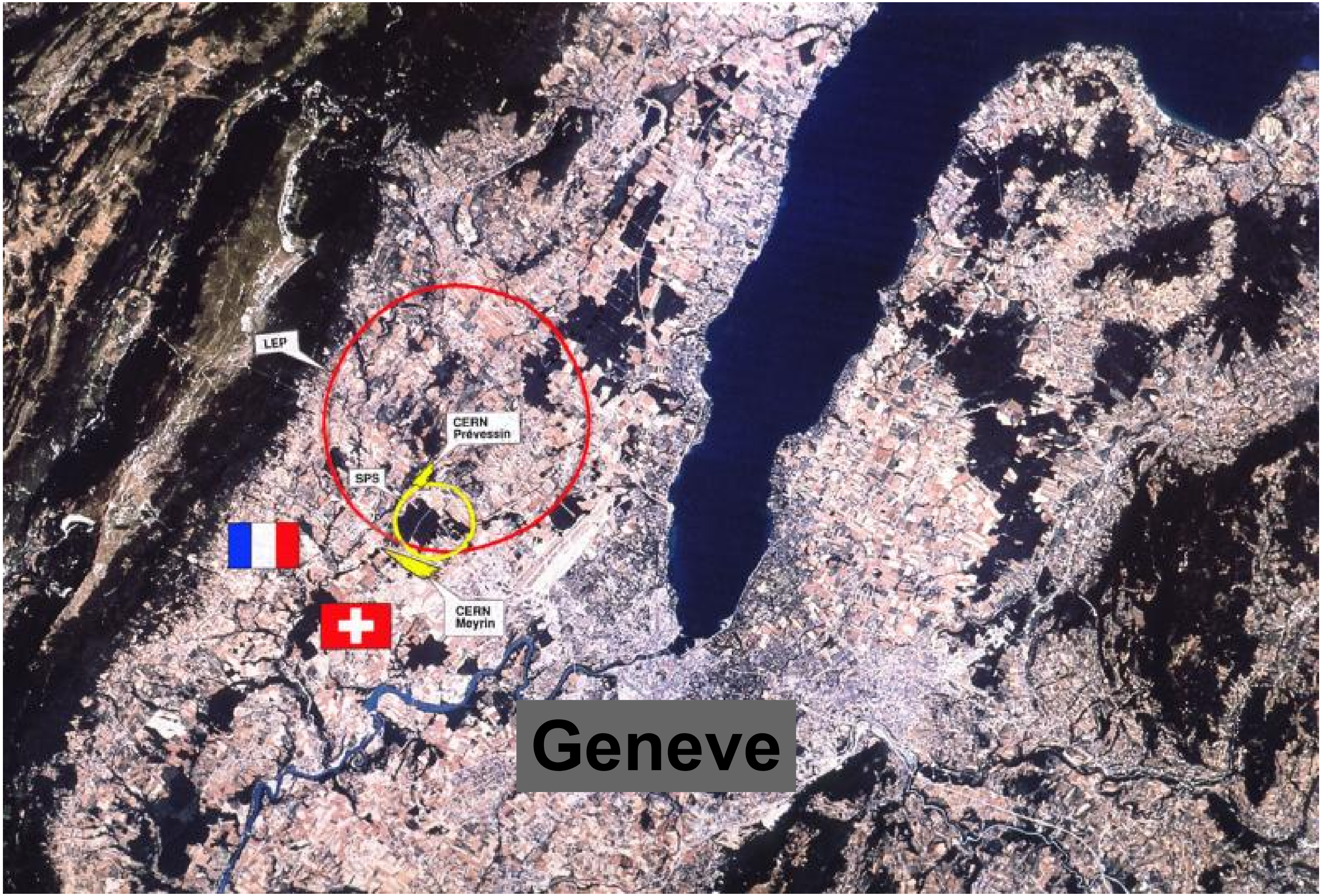


Every SM particle gets a *super*-partner to cancel inconvenient divergences.
Superpartners of fermions are bosons (add an "s": selectron, squark...)
Superpartners of bosons are fermions (add an "ino": wino, gluino, photino...)

Dark matter candidates!

Superpartners more massive than SM, but should be around ~TeV or so...
Hunting grounds of the LHC!

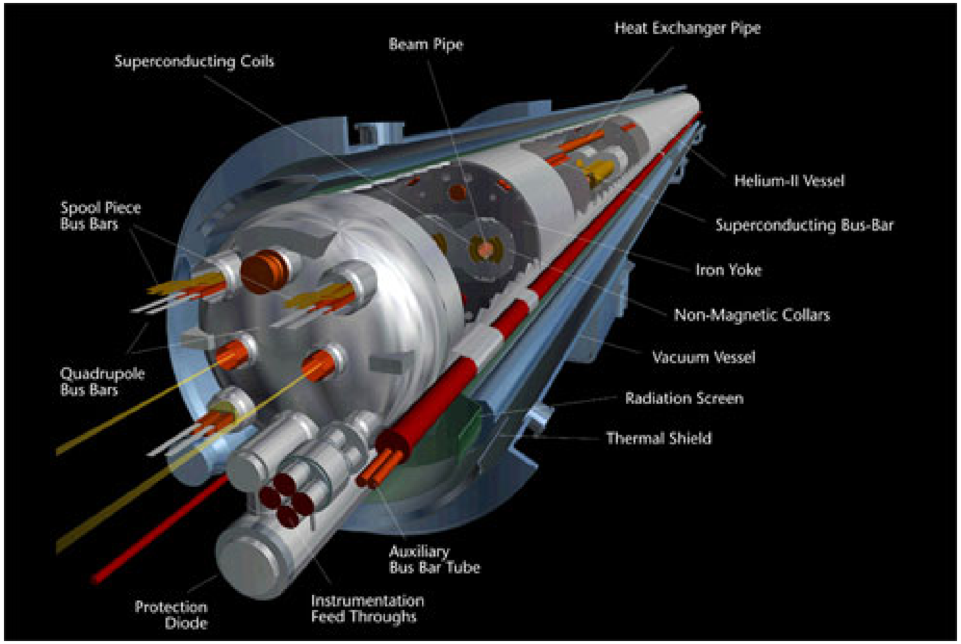
The Large Hadron Collider



Large Hadron Collider

Radio Frequency Klystron Cavities

1232 Super Conducting Dipole Magnets



T = 1.9 K I = 12000 Amps

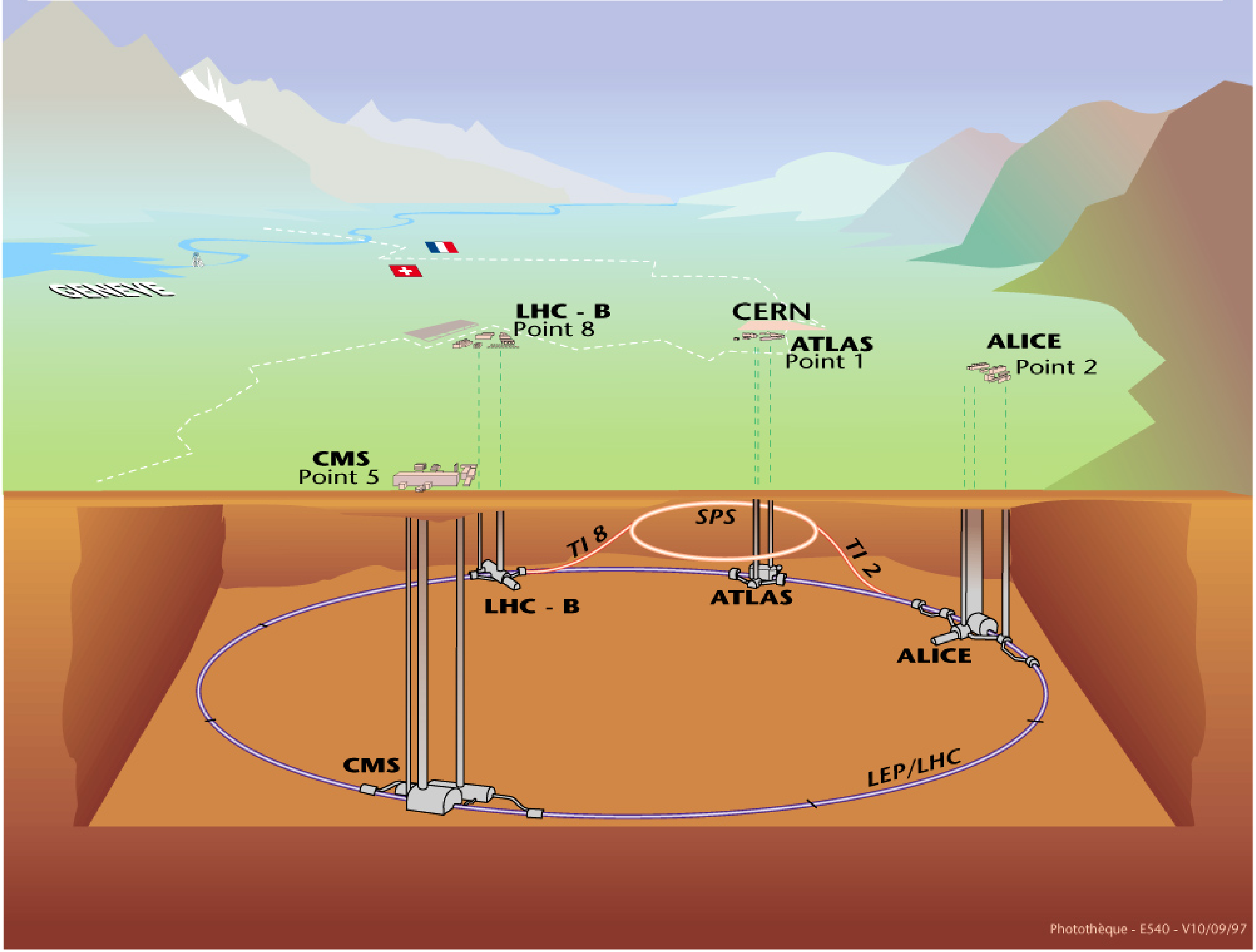
B = 8.3 Tesla E = 7 MJ / Dipole

½ nanogram in Beam –

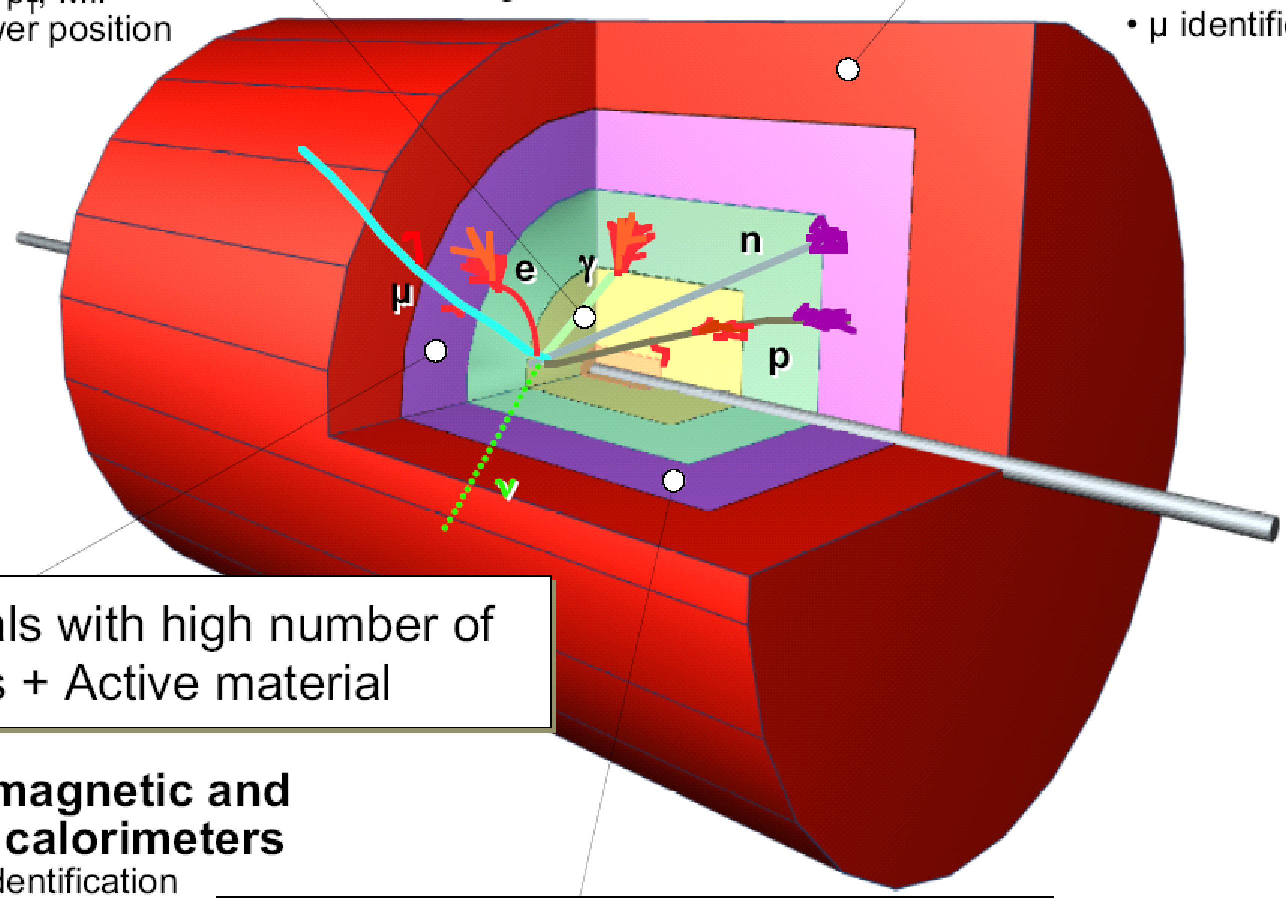
Kinetic Energy of 100,000 Ton

. ircraft Carrier at Cruising Speed

Vue d'ensemble des expériences LHC.

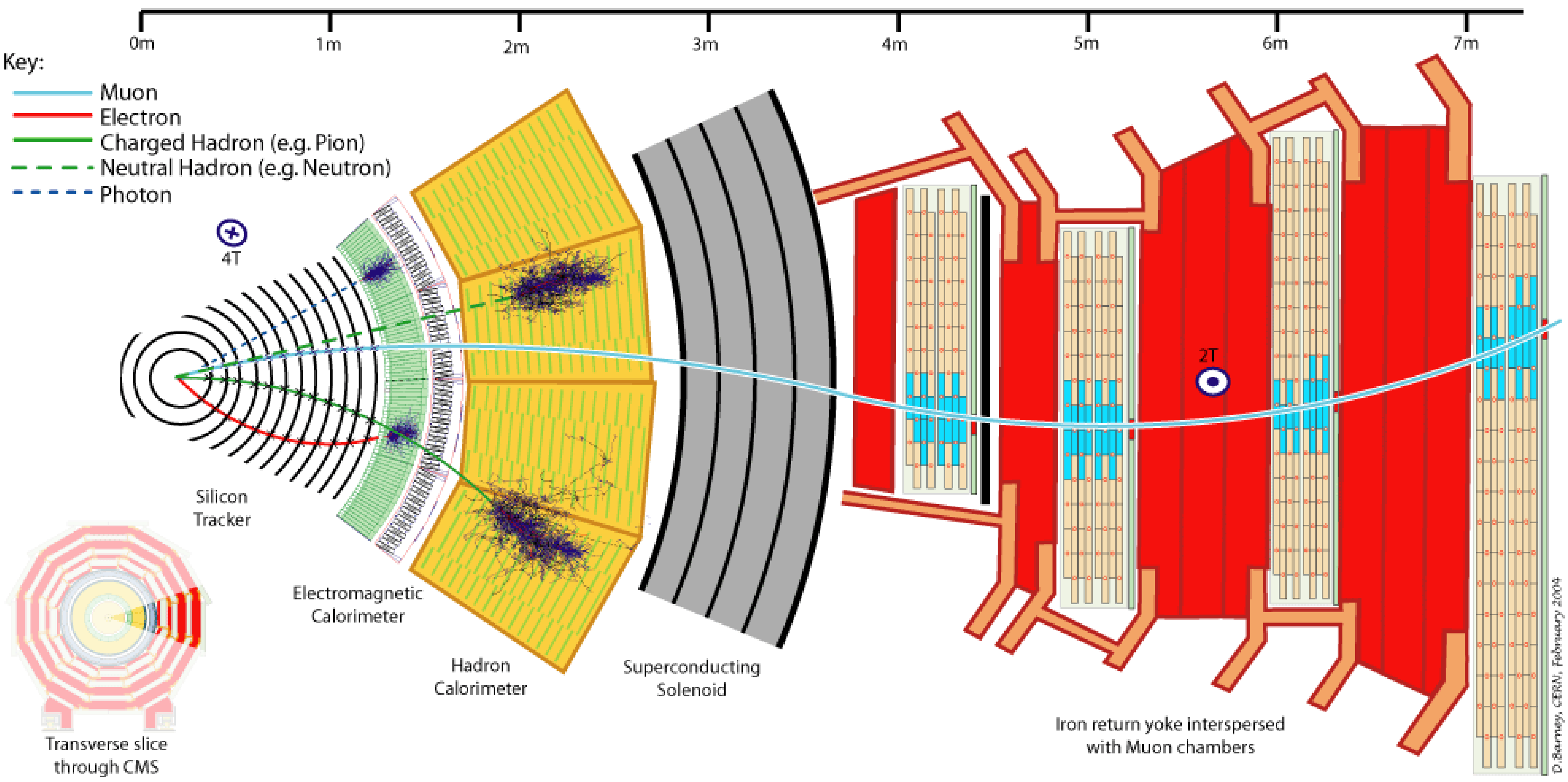


High Energy Collider Detectors

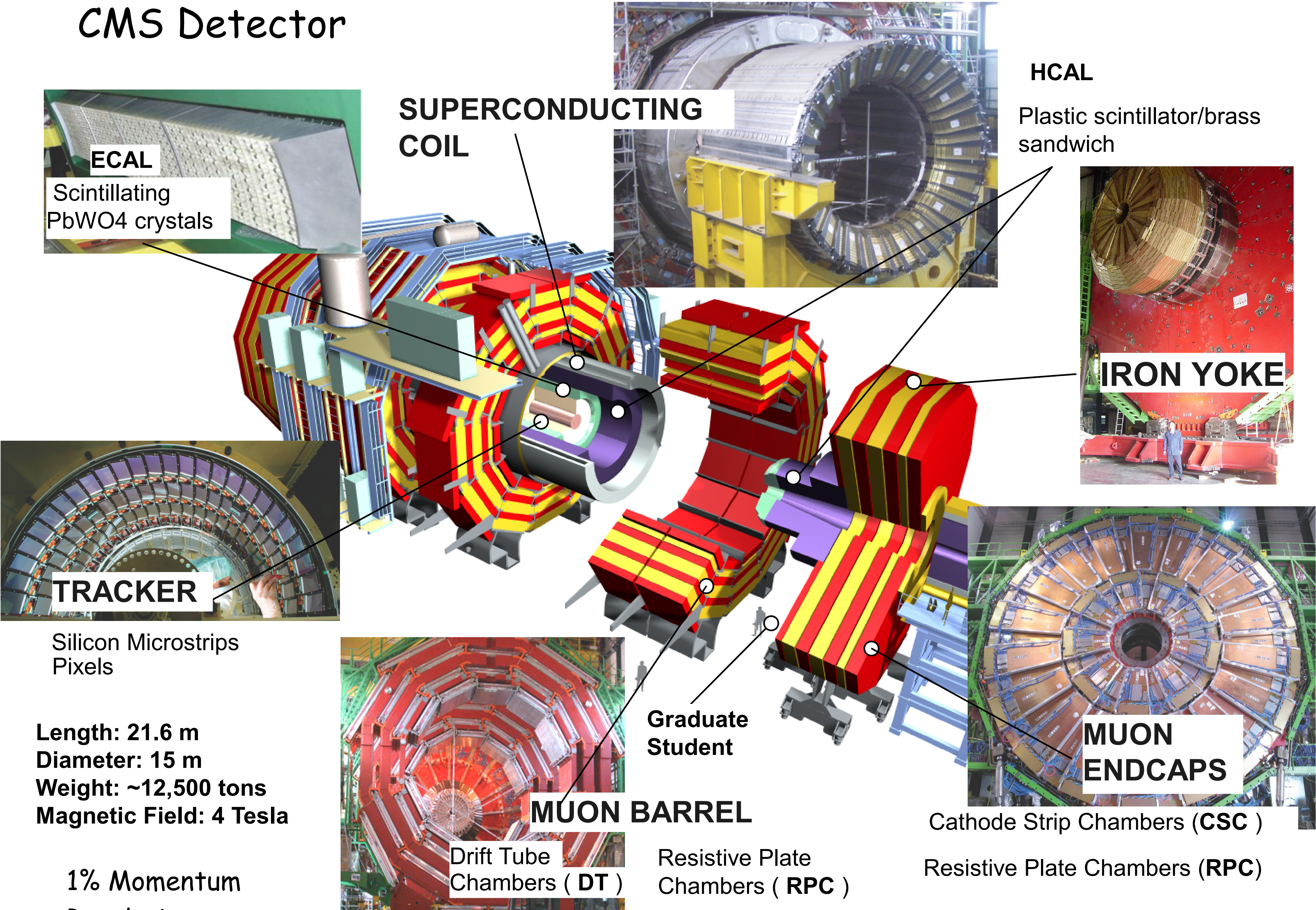


CMS Detector Transverse Slice

Particle Identification



CMS Detector

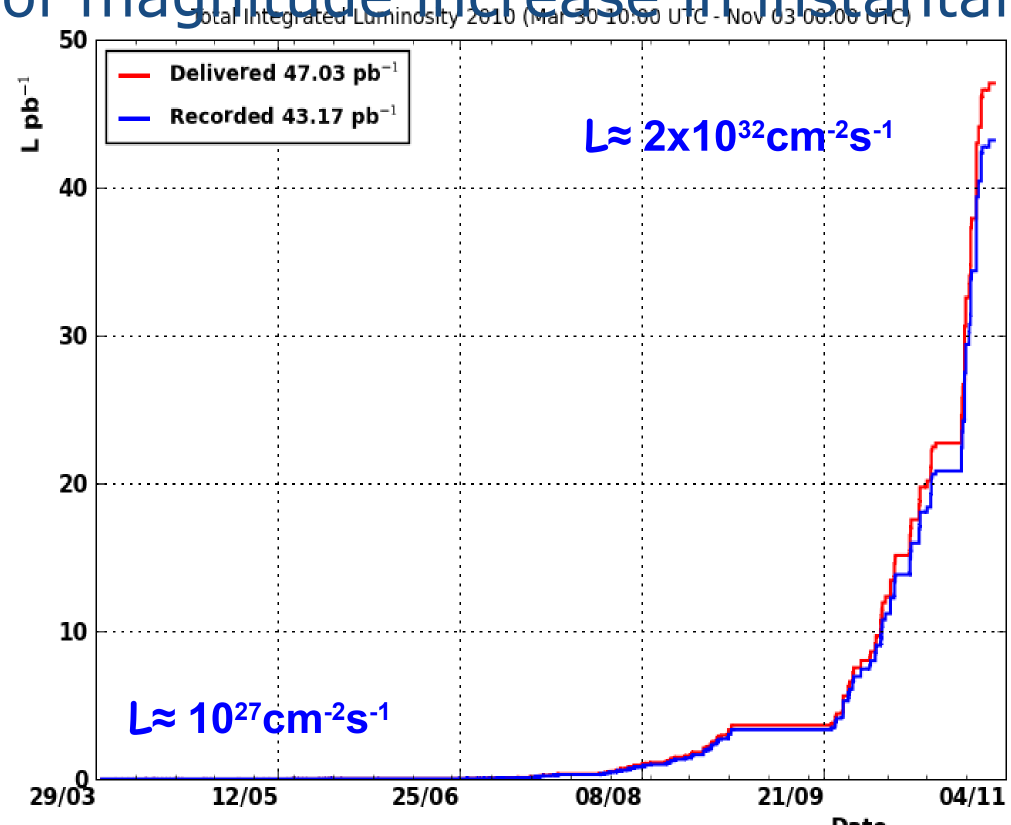


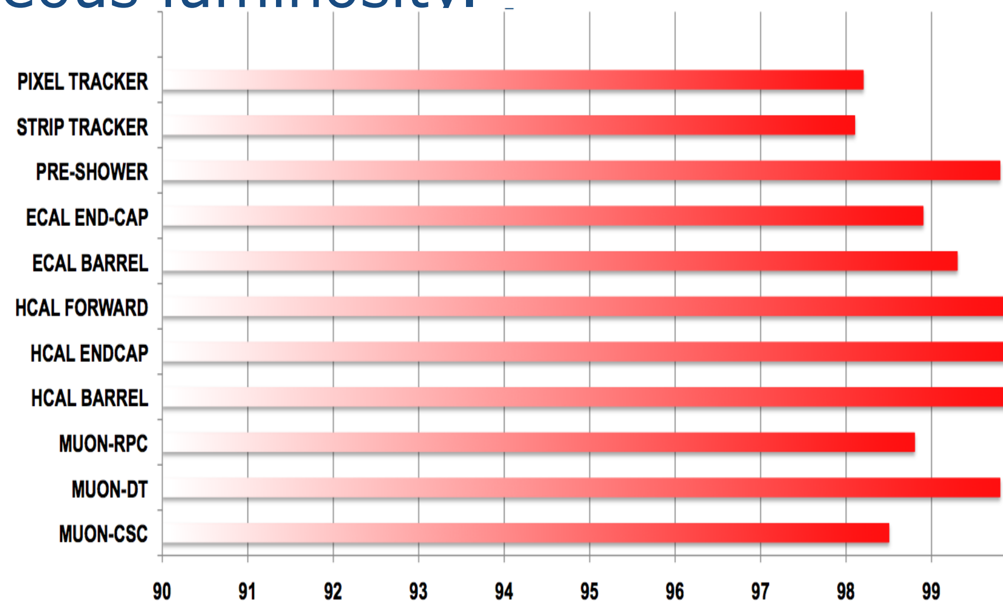
Length: 21.6 m
Diameter: 15 m
Weight: ~12,500 tons
Magnetic Field: 4 Tesla

1% Momentum Resolution

LHC and CMS operations in 2010.

About **47pb^{-1}** delivered by LHC and **~43pb^{-1}** of data collected by CMS. Overall data taking efficiency **~92%. 6pb^{-1}** of data integrated in a good fill**.** Excellent performance in coping with more than 5 order of magnitude increase in instantaneous luminosity.



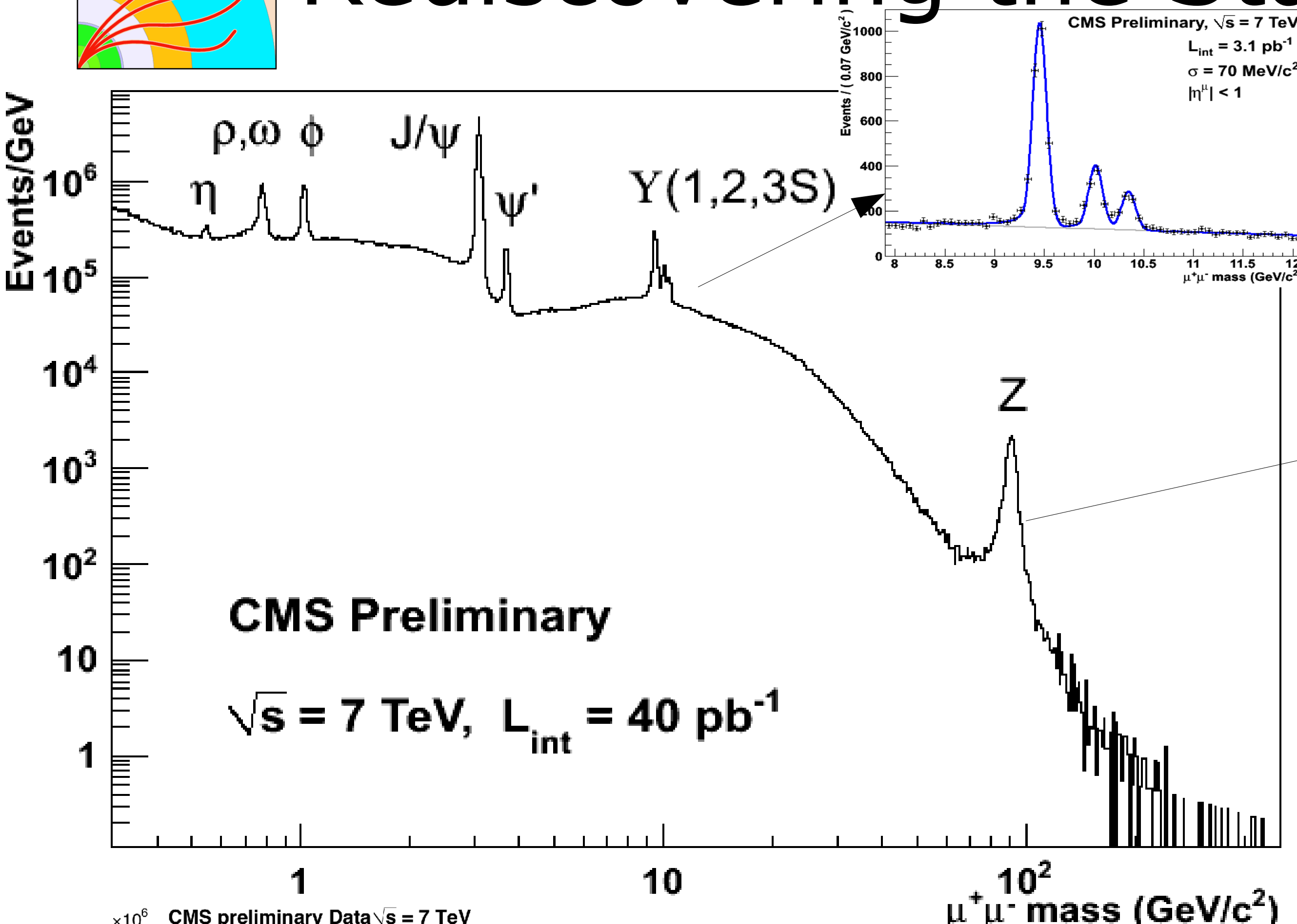


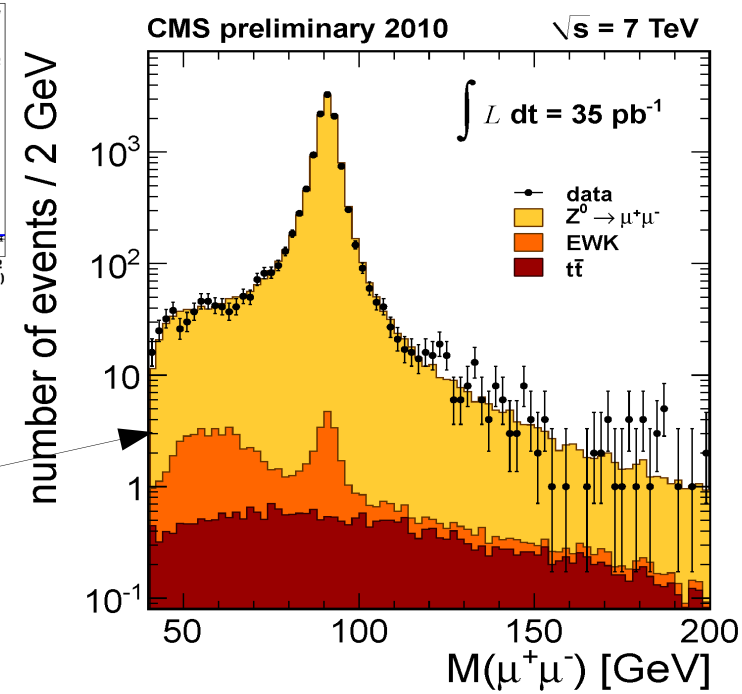
	MUON-CSC	MUON-DT	MUON-RPC	HCAL BARREL	HCAL ENDCAP	HCAL FORWARD	ECAL BARREL	ECAL END-CAP	PRE-SHOWER	STRIP TRACKER	PIXEL TRACKER
Series1	98.5	99.8	98.8	99.9	100	99.9	99.3	98.9	99.8	98.1	98.2

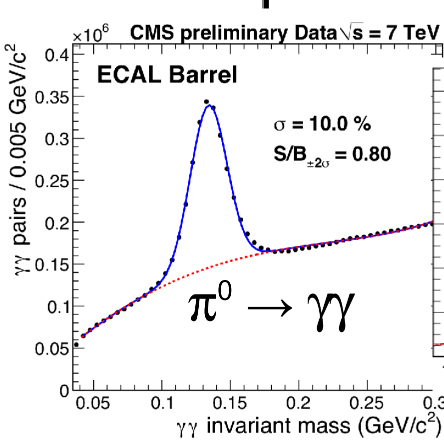
Average fraction of operational channels per CMS sub-system still **~99%. A few problems here and there.** Last few days of pp running tested **50ns** filling scheme. Vacuum (e-cloud) worse than at 150ns. **75ns** vacuum much better. **800 bunches OK.**

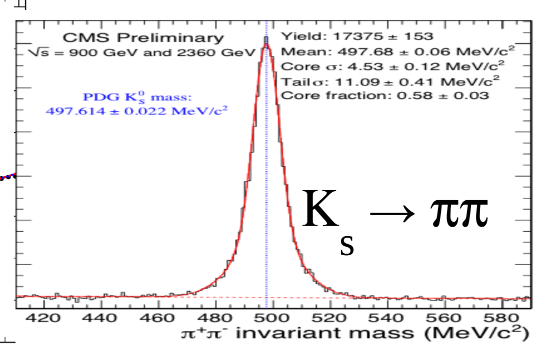
From G. Tonneli talk, 6 Dec 2010

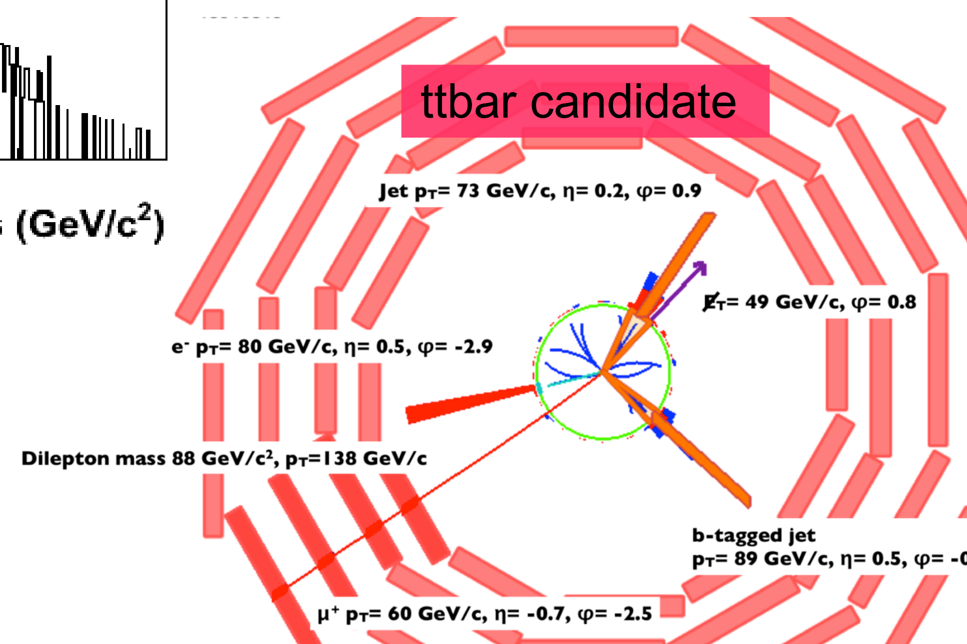
Rediscovering the Standard Model











Standard Model Versus New Physics Processes

Yesterday's Discovery
Today's Background
Tomorrow's Calibration

100,000,000 Top Quarks / yr Design Luminosity

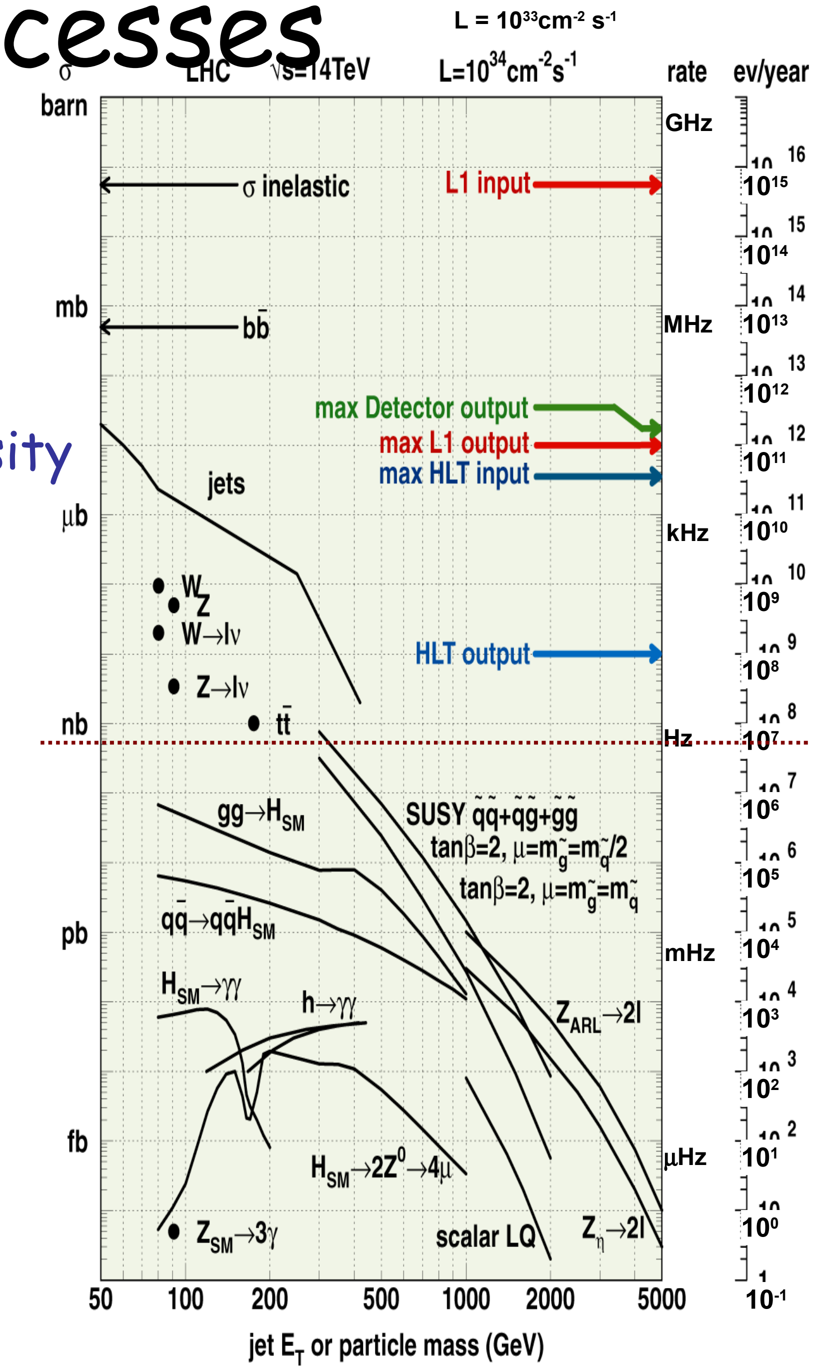
Opportunity for Precision Top Physics …

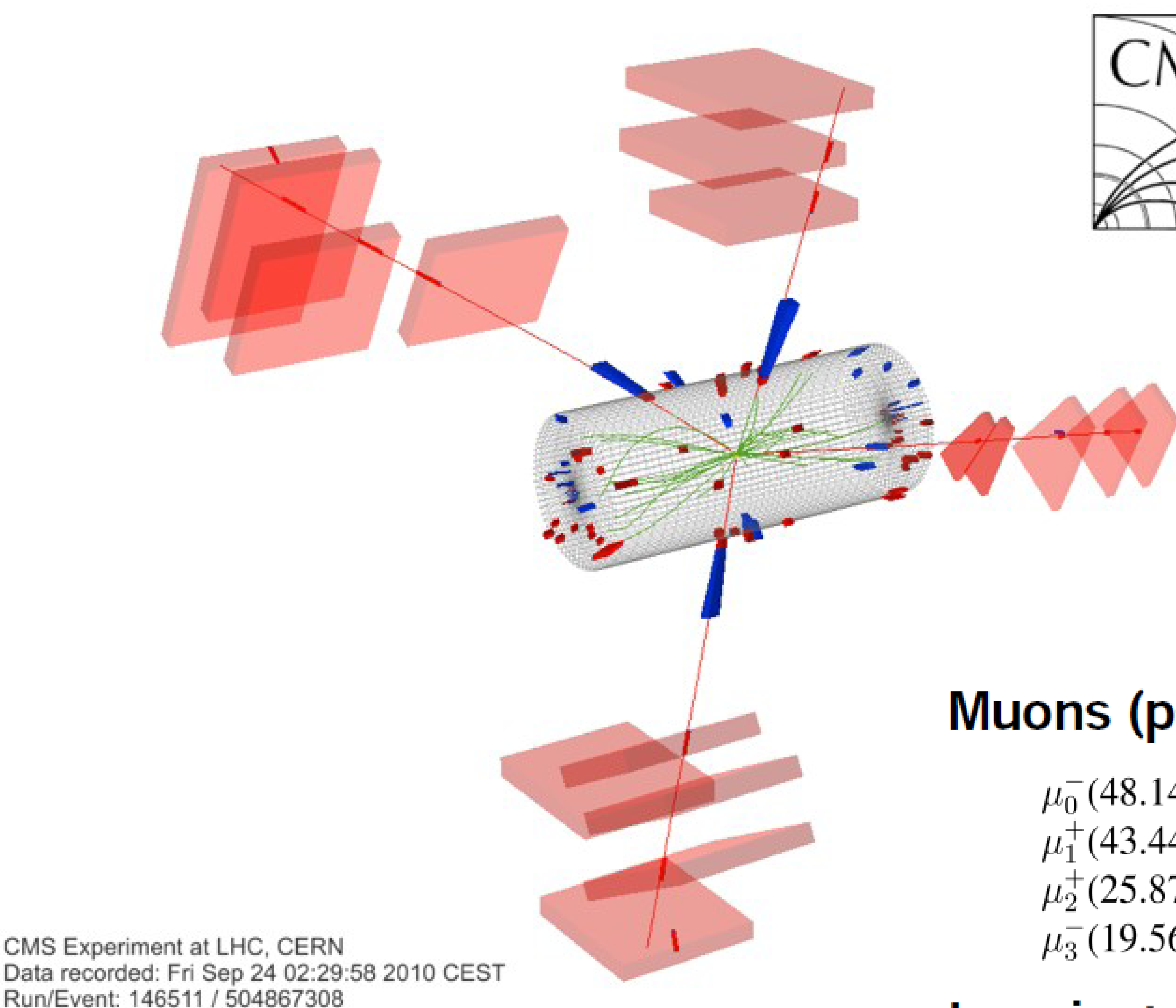
<u>Huge</u> Background to New Physics Searches

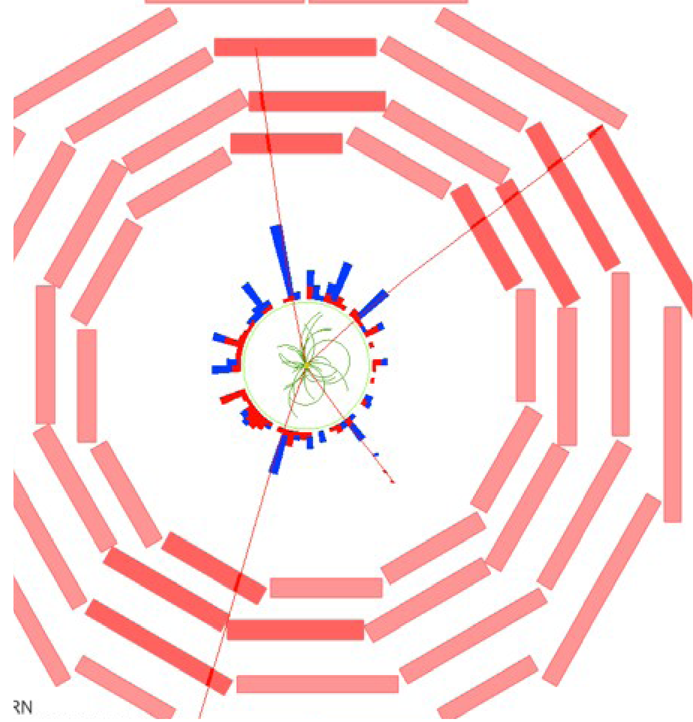
May Have to Enhance Recorded S/B by $10^{(4-5)}$
Skill of the Physics Analysis

Typically Look in Low Background Channels

– *But what if nature doesn't live there?*







Muons (p_T [GeV], η, φ [rad])

μ_0^-(48.1422, -0.412532,-1.92555)
μ_1^+(43.4421, 0.204654, 1.79493)
μ_2^+(25.8769, -0.782084, 0.774588)
μ_3^-(19.5646, 2.01112, -0.980597)

Invariant Masses

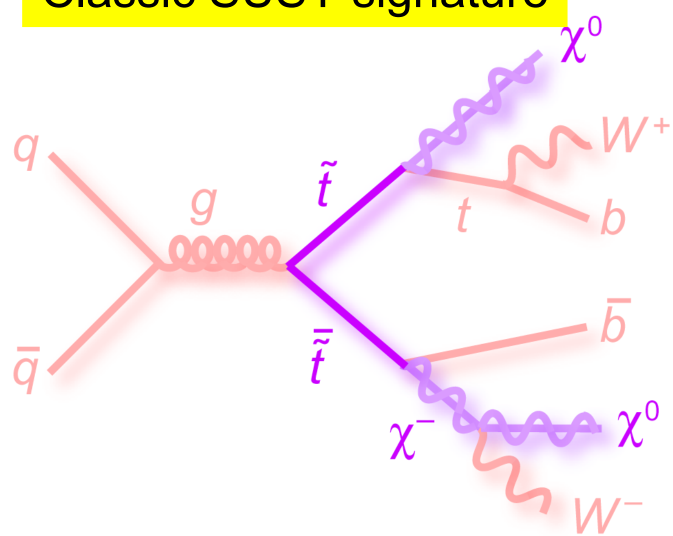
$\mu_0 + \mu_1$: 92.15 GeV (total(Z) p_T 26.5 GeV, ϕ -3.03),
$\mu_2 + \mu_3$: 92.24 GeV (total(Z) p_T 29.4 GeV, ϕ +.06),
$\mu_0 + \mu_2$: 70.12 GeV (total p_T 27 GeV),
$\mu_3 + \mu_1$: 83.1 GeV (total p_T 26.1 GeV).

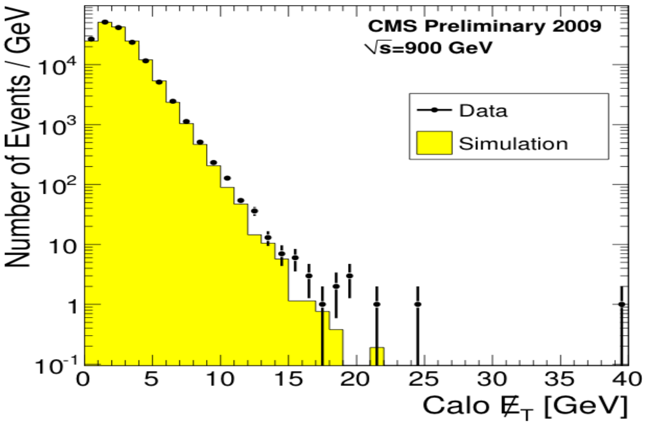
Invariant Mass of 4μ: 201 GeV

Beautiful ZZ event seen in CMS data. First found by RU postdoc R. Gray.

Multilepton SUSY Search

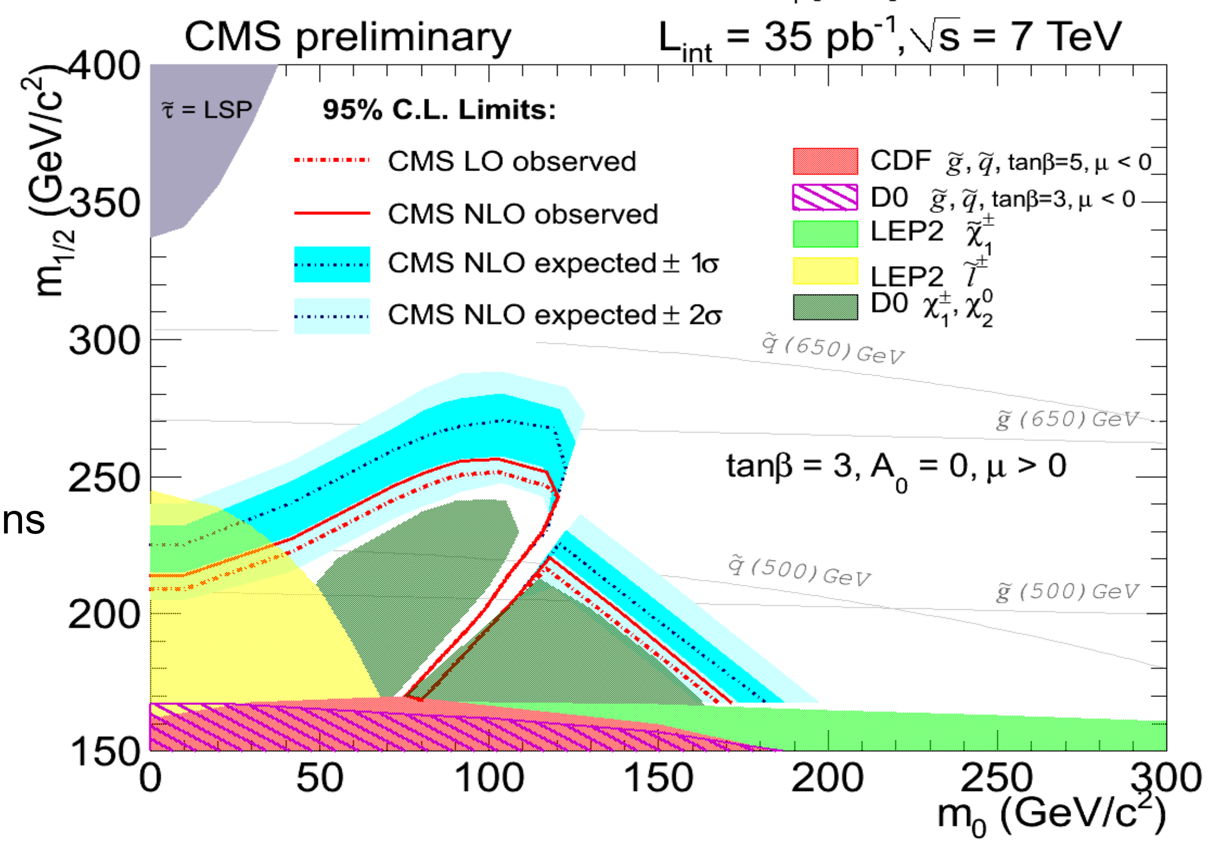
Classic SUSY signature



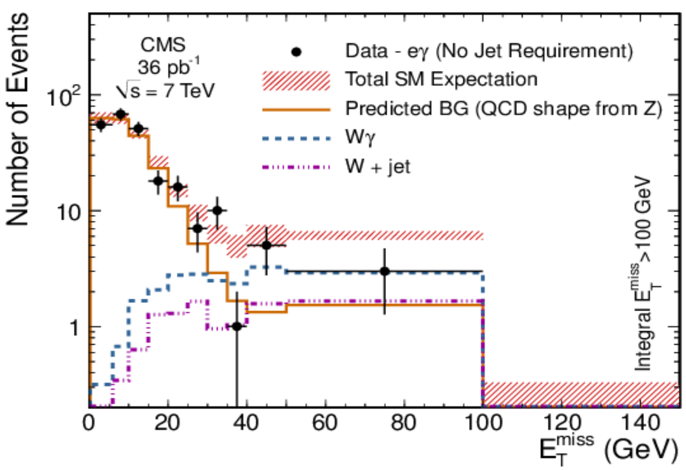


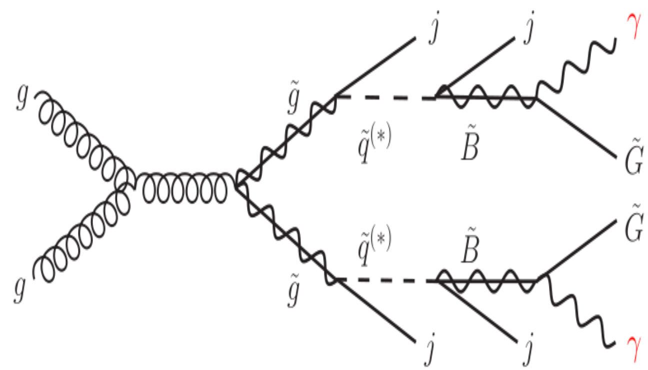
Many other models for new physics have multiple leptons as decay signatures.

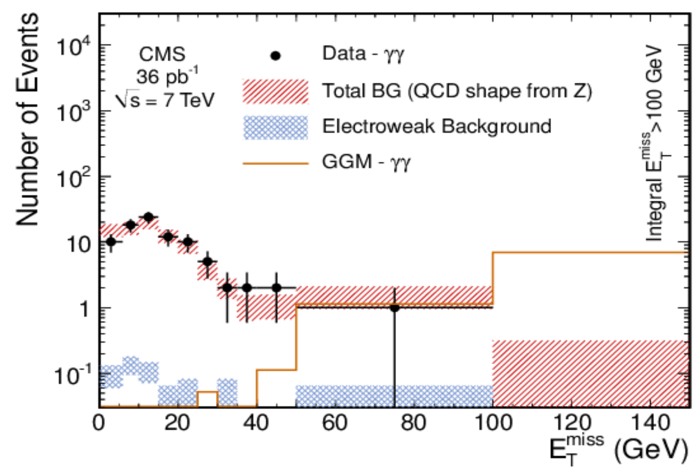
This one analysis also puts bounds on **Slepton Co-NLSP** (where the sleptons are close in mass to the lightest SUSY Particle) models with **leptonic R-Parity volations.** Both of these give 4 leptons In the final state.

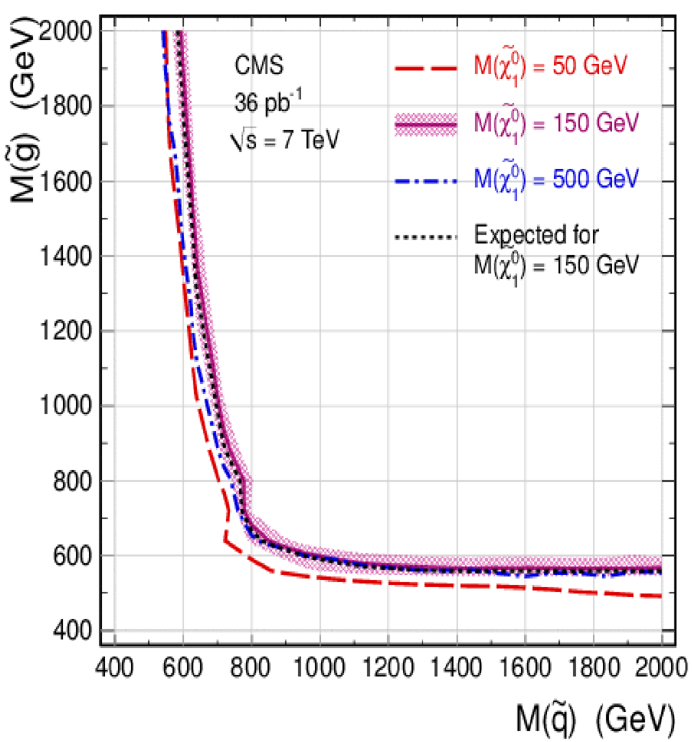


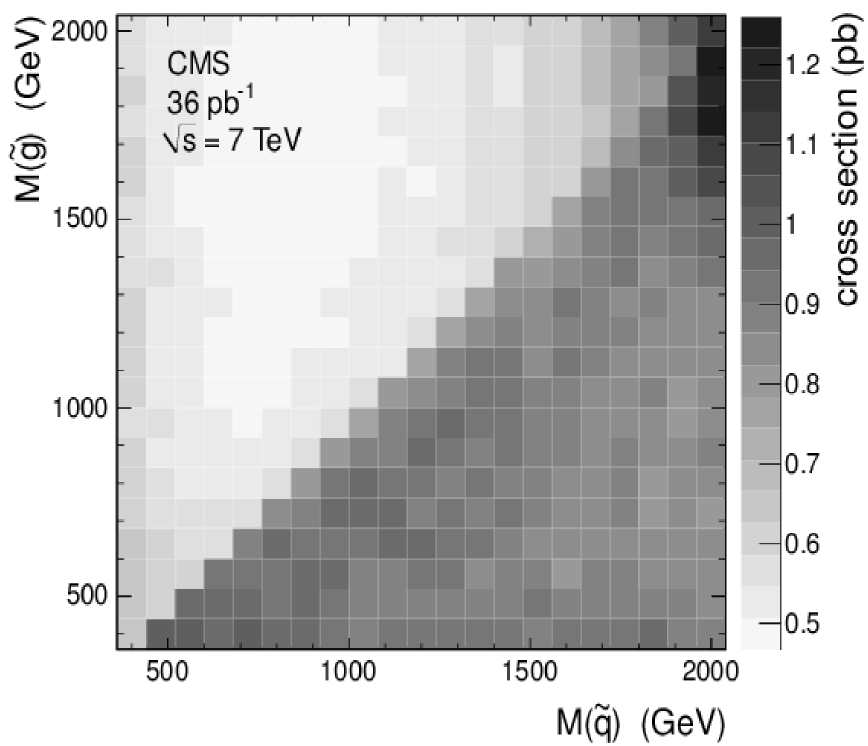
Diphoton + missing momentum



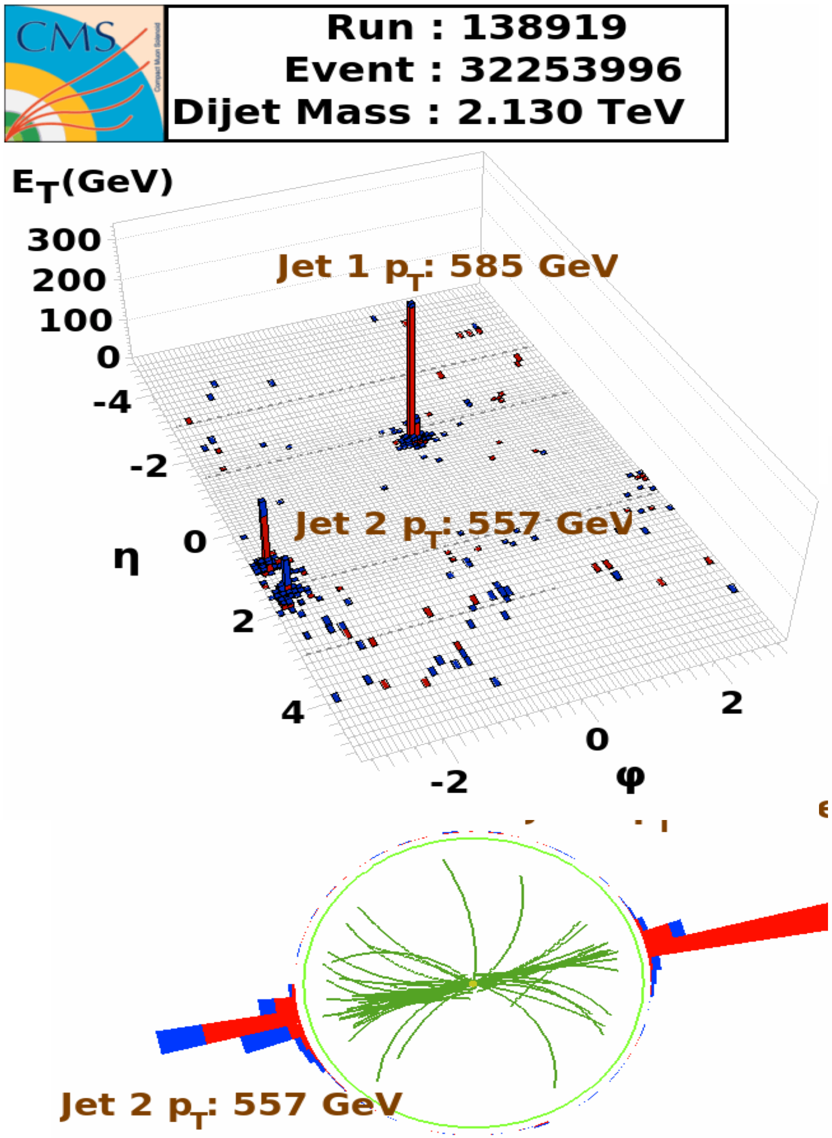


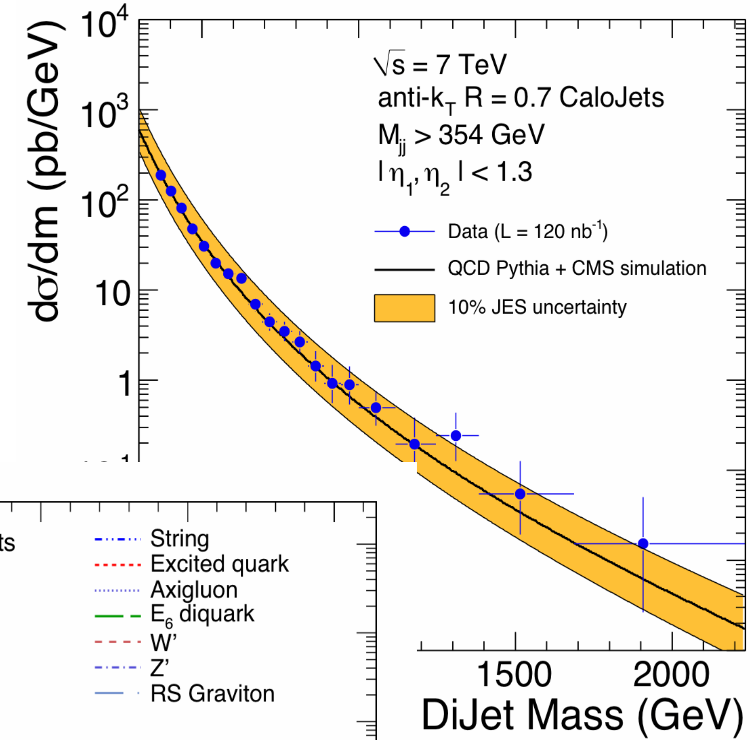


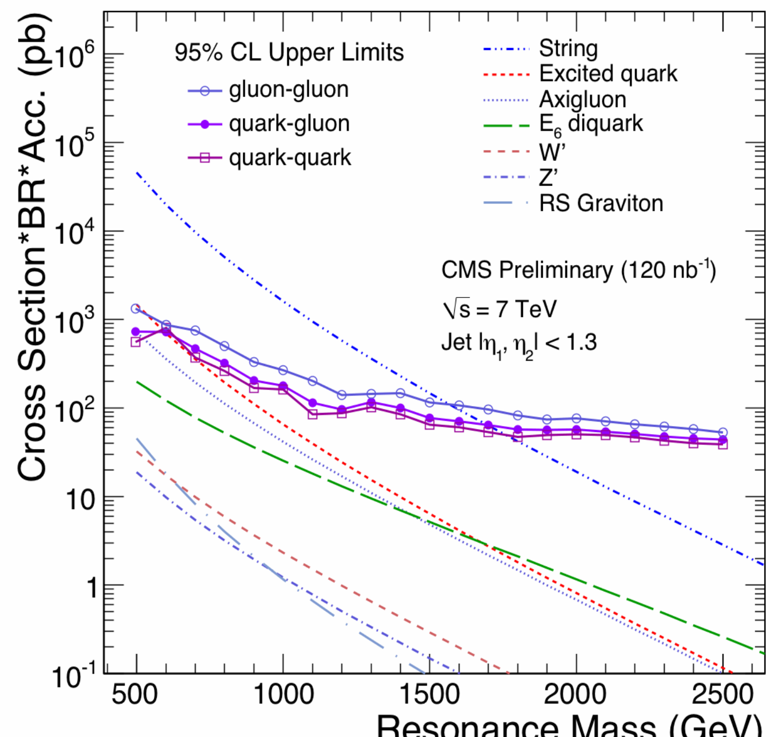




Jet Physics







Highest mass dijet event

Summary

- The energy frontier has always been surprising.
  - No one expected the nucleus, heavy leptons, mesons, partons, charm...

- Incredibly beautiful data coming out of LHC detectors.
  - *Almost makes you forget how long it took...*
  - Granularity of CMS/ATLAS much finer than CDF/D0 → entirely new physics techniques.

- We have entered the era of new physics. The 2011-2012 run is being called the "discovery run".
  - Is there a higgs? Will we create Dark Matter?
  - Whatever happens, it probably will not be what we expect.
    - Will SUSY etc go the way of S-Matrix theory?

- To the students in the audience: JOIN US!