The Quest for 10^{-20} meters

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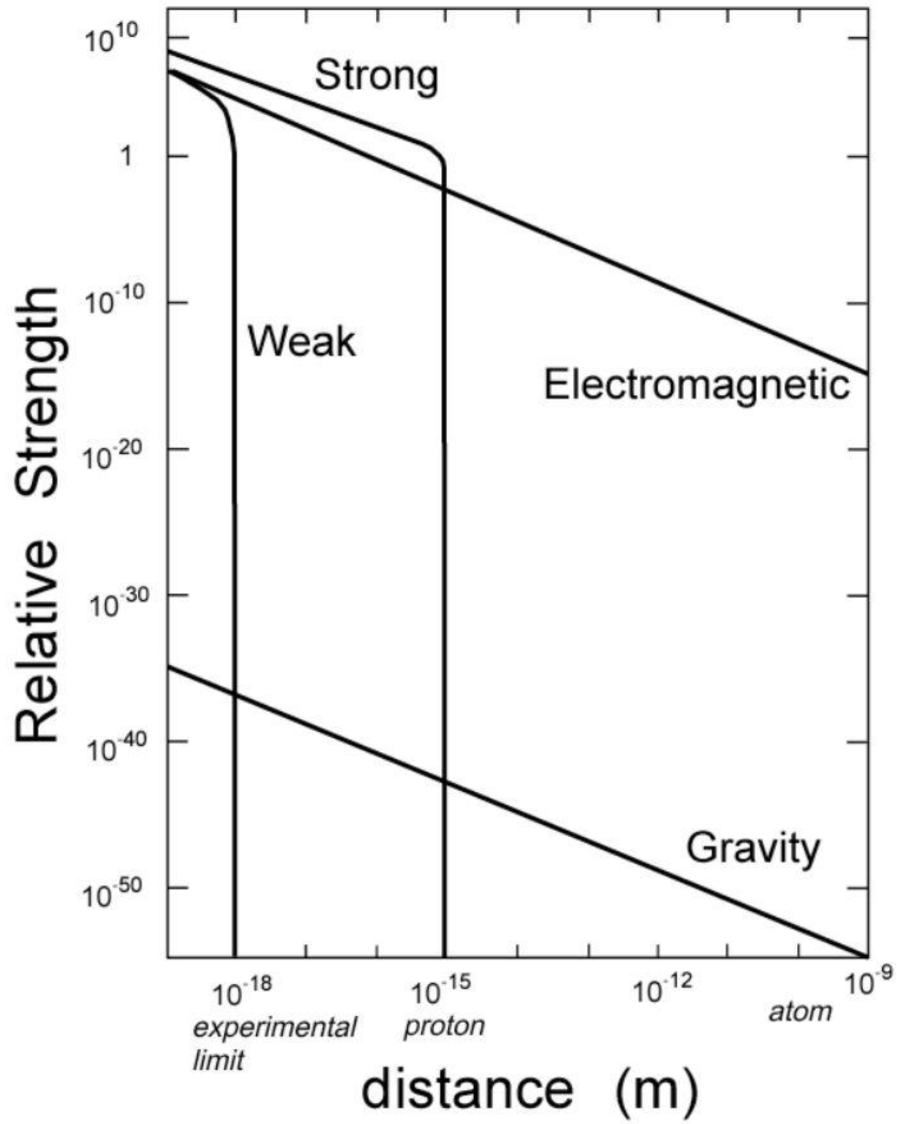
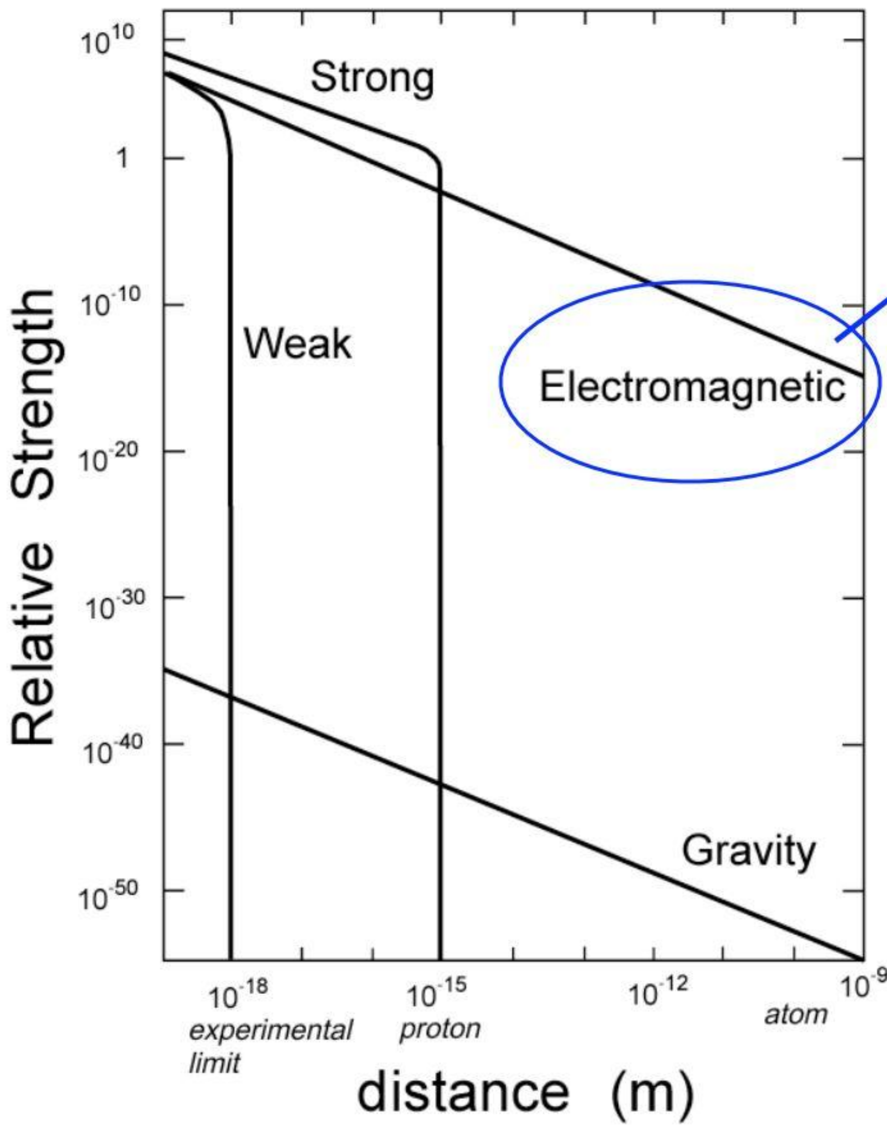
* UMD Class of 1973

The forces vs. distance



The forces vs. distance



$$F_E = \frac{1}{4\pi\epsilon_0}\frac{q^2}{r^2} = k\frac{e^2}{r^2}$$

$$k = \frac{1}{4\pi\epsilon_0} = 8.99 \times 10^9\ \mathrm{N \cdot m^2/C^2}$$

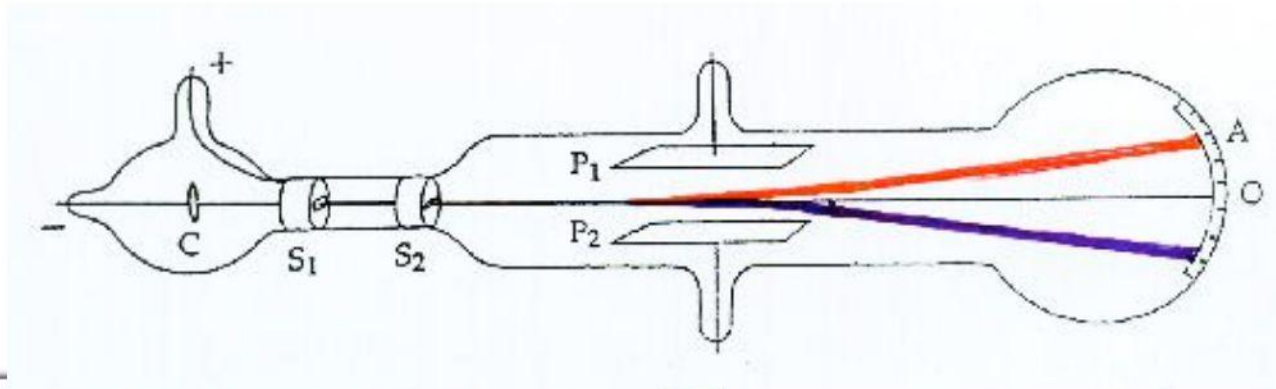
$$ke^2 = 1.44\ \mathrm{eV \cdot nm}$$

$$\hbar c = 197\ \mathrm{eV \cdot nm}$$

$$\alpha = \frac{ke^2}{\hbar c} = \frac{1}{137}$$

Discovery of the electron (J.J. Thompson, 1897)

birth of the spectrometer



Note: electron deflection (and thus, e/m result) depends on speed which is hard to measure!

$v = E/B$
if EM forces balance

Classical electron radius

We have "big trouble" with classical physics when the electrostatic potential energy exceeds the electron mass energy!

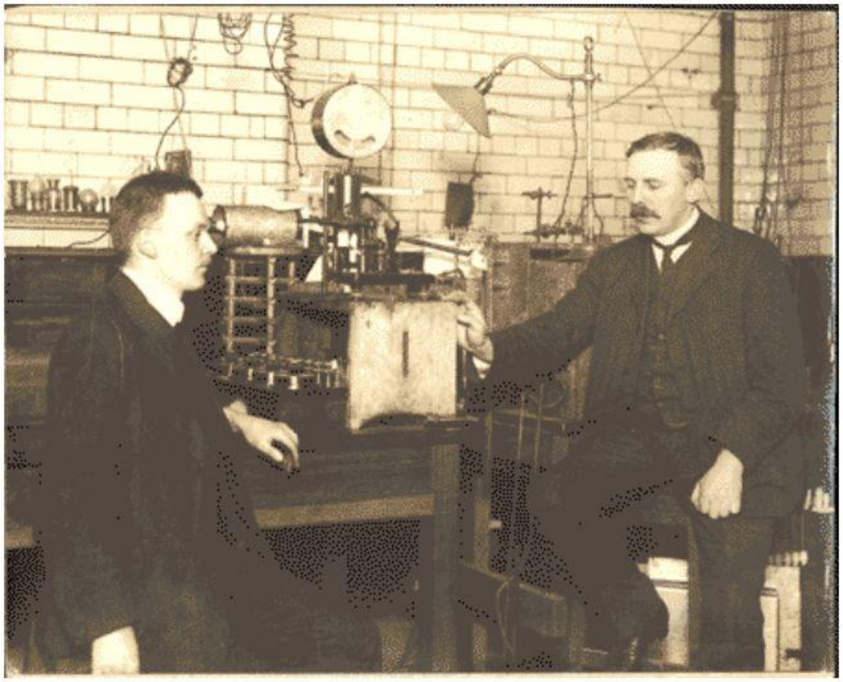
$$\frac{ke^2}{r} > mc^2 \qquad \text{(yikes !)}$$

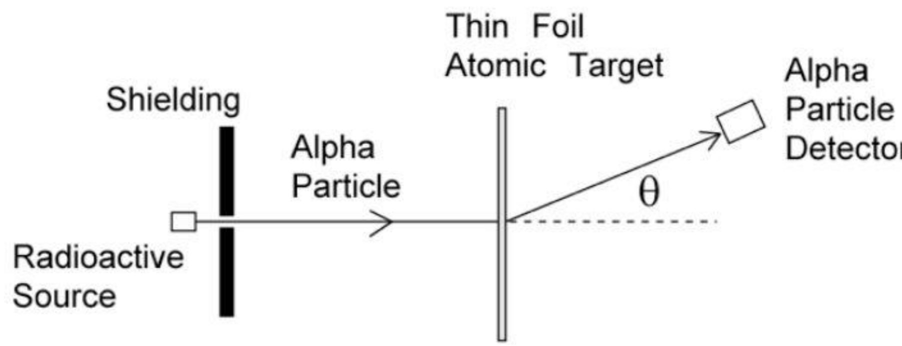
This problem occurs when

$$r < \frac{ke^2}{mc^2} = \frac{1.44 \text{ ev}\cdot\text{nm}}{0.511 \text{ MeV}} \approx 3 \times 10^{-15} \text{ m}$$

(Note: history will repeat itself, more later.)

Rutherford scattering (1909)





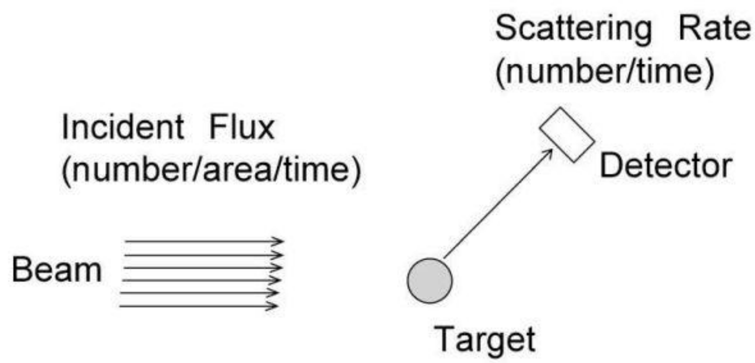
The detector consisted of Hans Geiger looking through a microscope and counting light flashes... This experience, no doubt, is what led him to invent the Geiger counter!

Cross Section

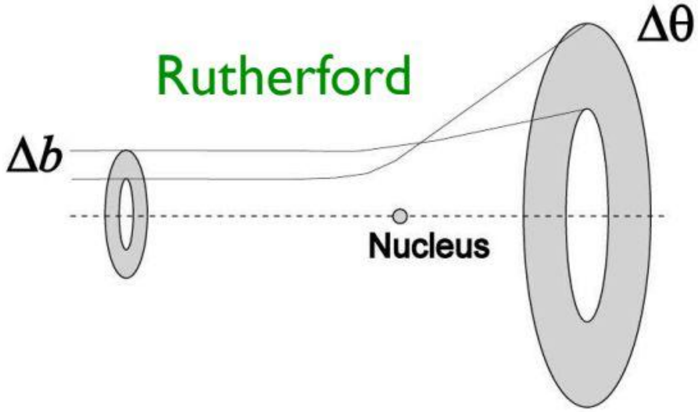
$$\sigma = \frac{\text{transition rate}}{\text{incident flux}}$$

effective area of the target

also called luminosity



Rutherford



often measured as differential, e.g. $d\sigma/d\theta$

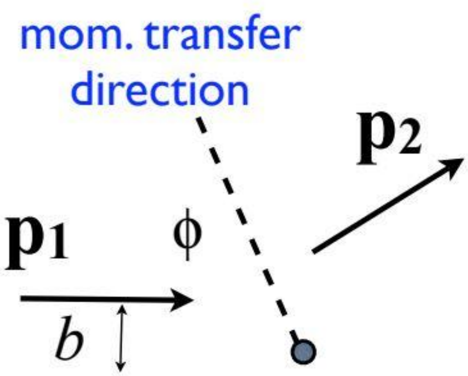
Rutherford formula (non-relativistic electromagnetic interaction):

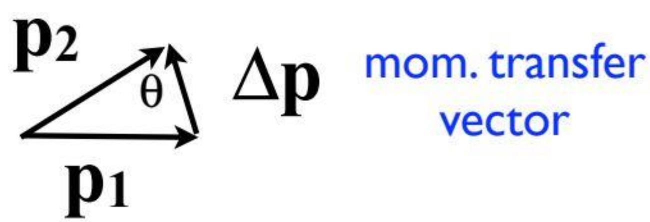
$$\frac{d\sigma}{d\cos\theta} = 2\pi Z^2\alpha^2\left(\frac{\hbar c}{E_\mathrm{k}}\right)^2\frac{1}{(1-\cos\theta)^2}$$

explanation:

$$\Delta p^2 = (\vec{\mathbf{p}}_1 - \vec{\mathbf{p}}_1)^2 = p_1^2 + p_2^2 - 2p_1p_2\cos\theta$$

$$\Delta p^2 = 2p^2(1-\cos\theta) \qquad \Delta p = mv\sqrt{2(1-\cos\theta)}$$





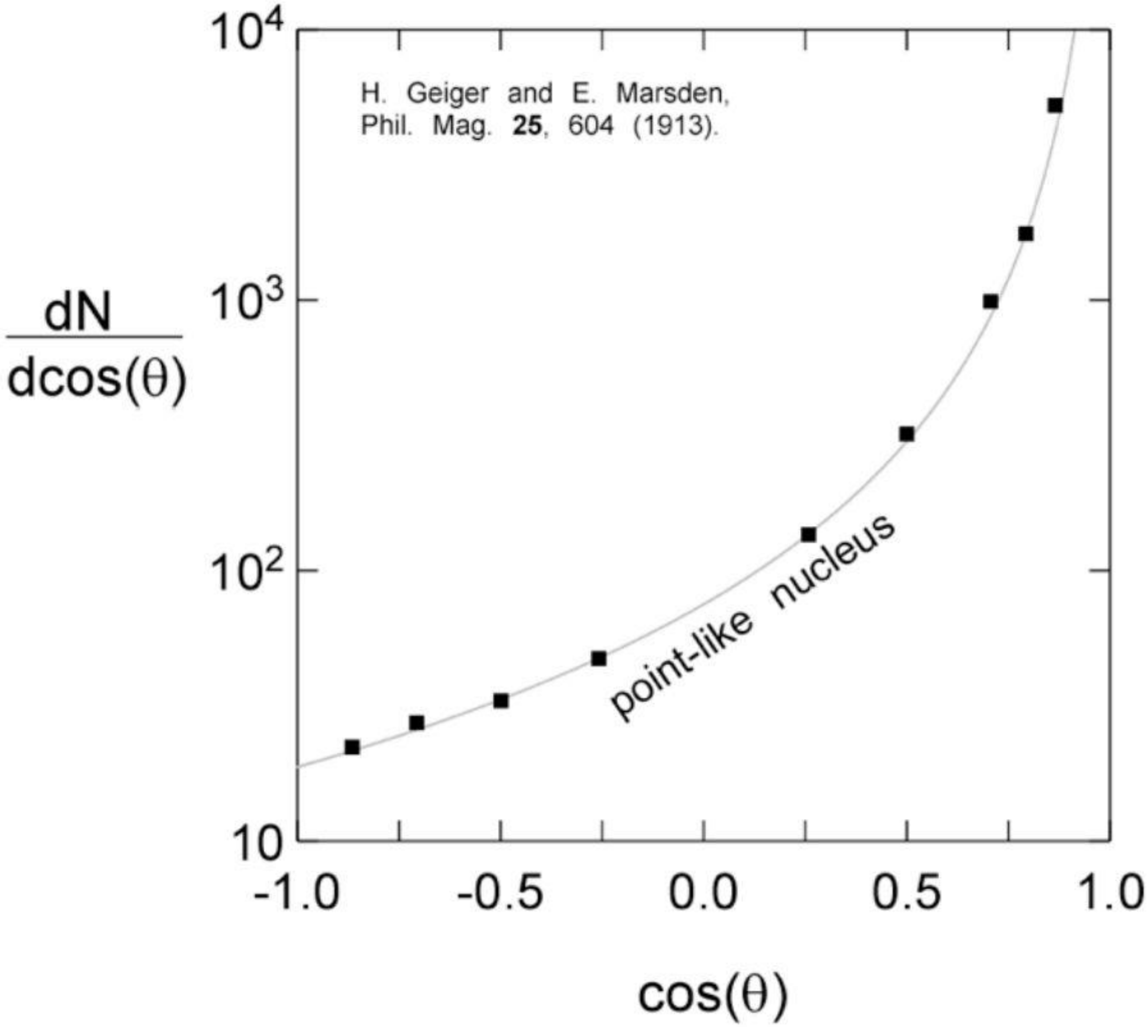
$$\Delta p = \int dt F\cos\phi \sim \frac{1}{b}$$

$$d\sigma = 2\pi b db$$

$$\frac{d\sigma}{d\cos\theta} \sim \frac{1}{(1-\cos\theta)^2}$$

Rutherford scattering

EM interaction: $$\frac{d\sigma}{d\cos\theta} \sim \alpha^2 \left(\frac{\hbar c}{E_k}\right)^2 \frac{1}{(1-\cos\theta)^2}$$



Can ONLY happen if:

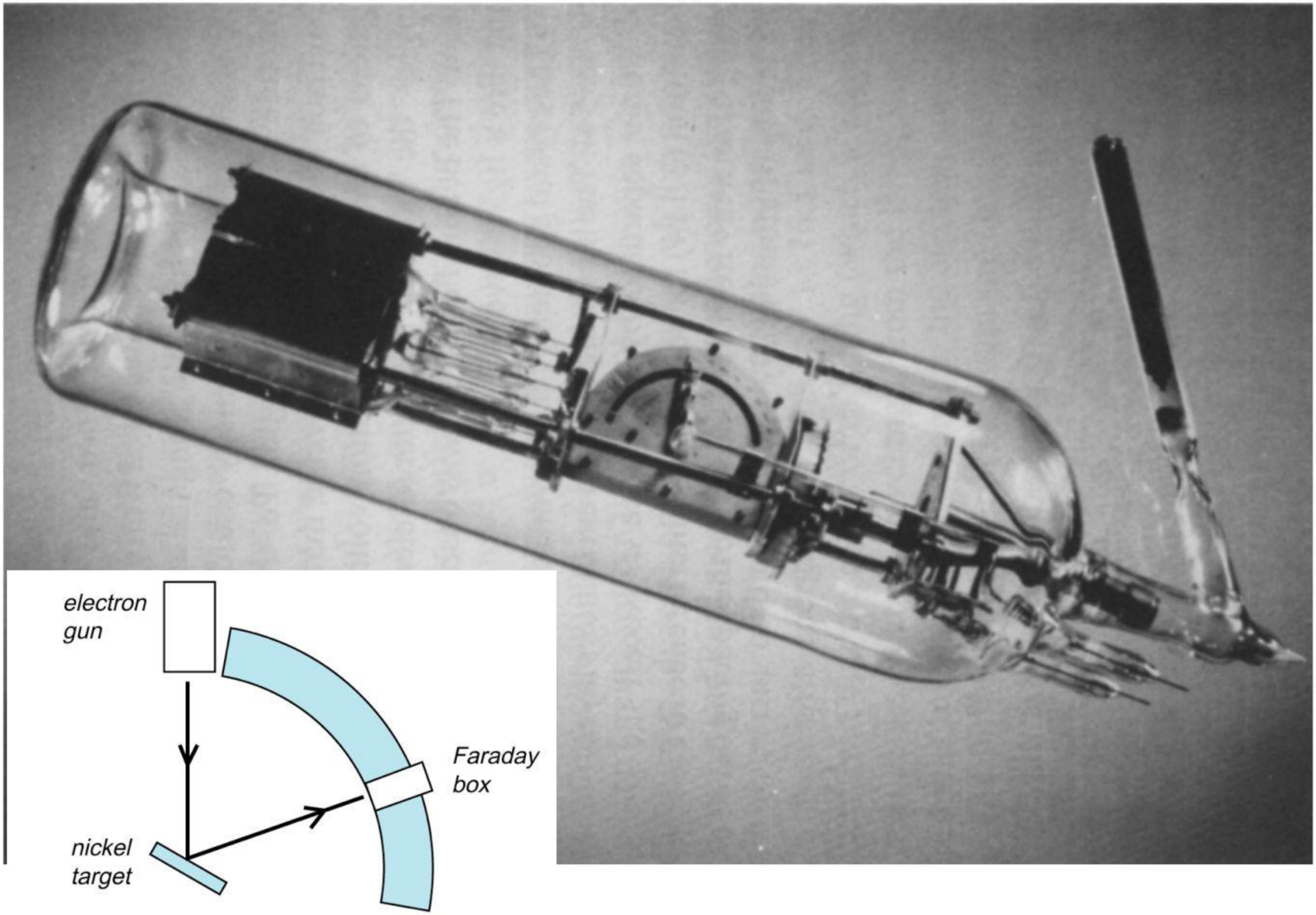
force ~ $1/r^2$
nucleus is pointlike
photon exchanged is $J = 1$ and $mc^2 = 0$
($v = c$ for photon)

Discovery of electron waves

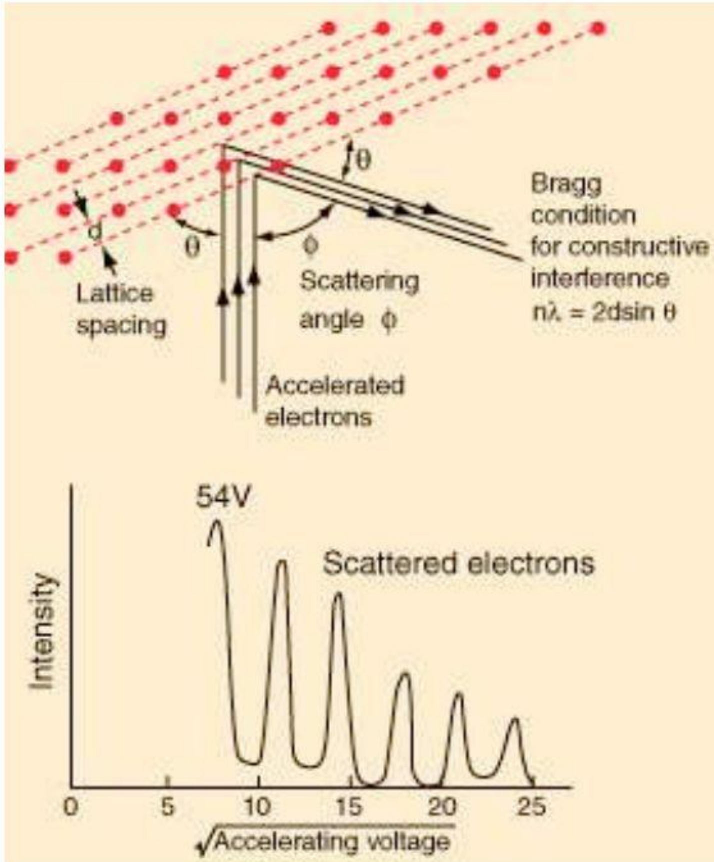
(Davisson and Germer, 1927)

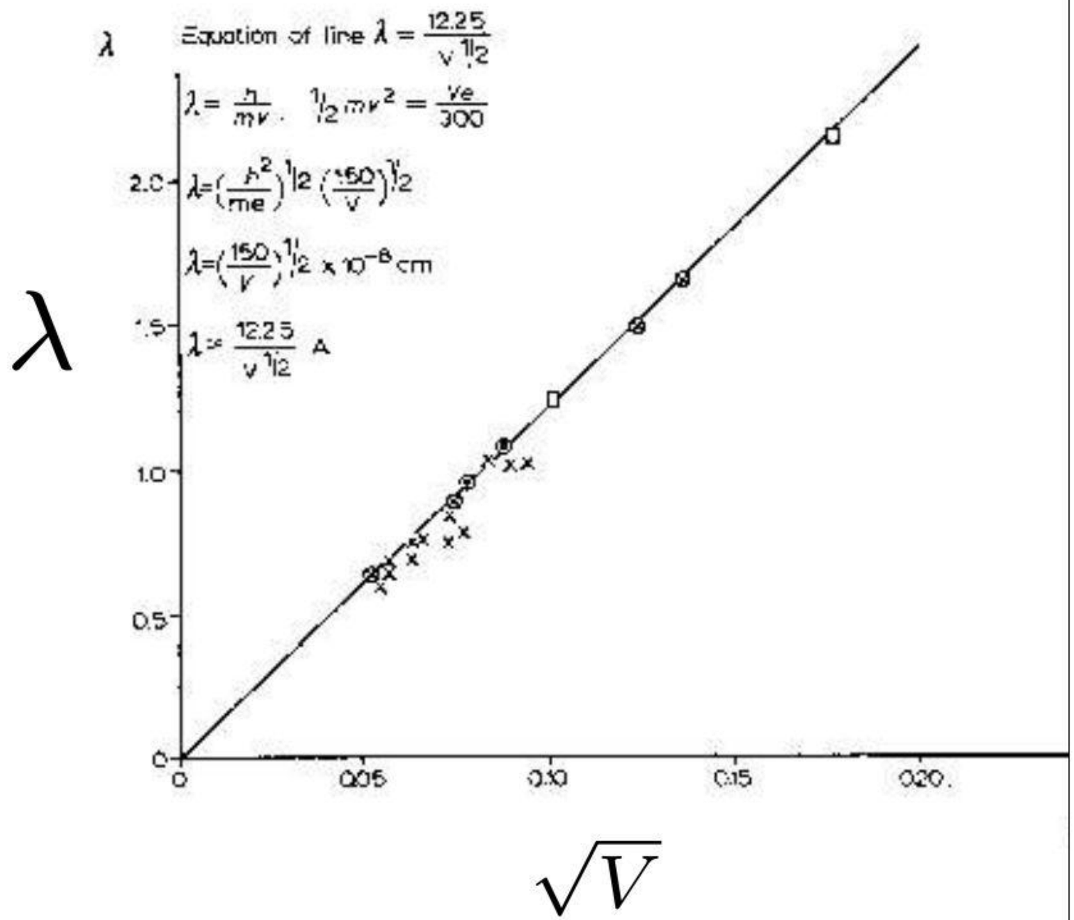
“We have become accustomed to think of the atom as rather like a solar system... There is a cer tain small probability, or at least there might seem to be, that the electron will strike into the atom in or near the surface of the metal, be swung about cometwise and sent flying out of the metal without loss of energy. The direction taken by such an electron as it leaves the metal should be a matter of private treaty between the electron and the individual atom. One does not see how neighboring atoms can have any voice in the matter.”

Davisson-Germer spectrometer



Discovering that λ = h/p   deBroglie hypothesis





$$\lambda = \frac{h}{p} = \frac{hc}{\sqrt{2mc^2 eV}} = \frac{1.23\ \text{nm}{\cdot}\text{V}^{1/2}}{\sqrt{V}}$$

Recall the electron energy crisis...

We have found an elegant solution...

The electron in an atom is SLOW.

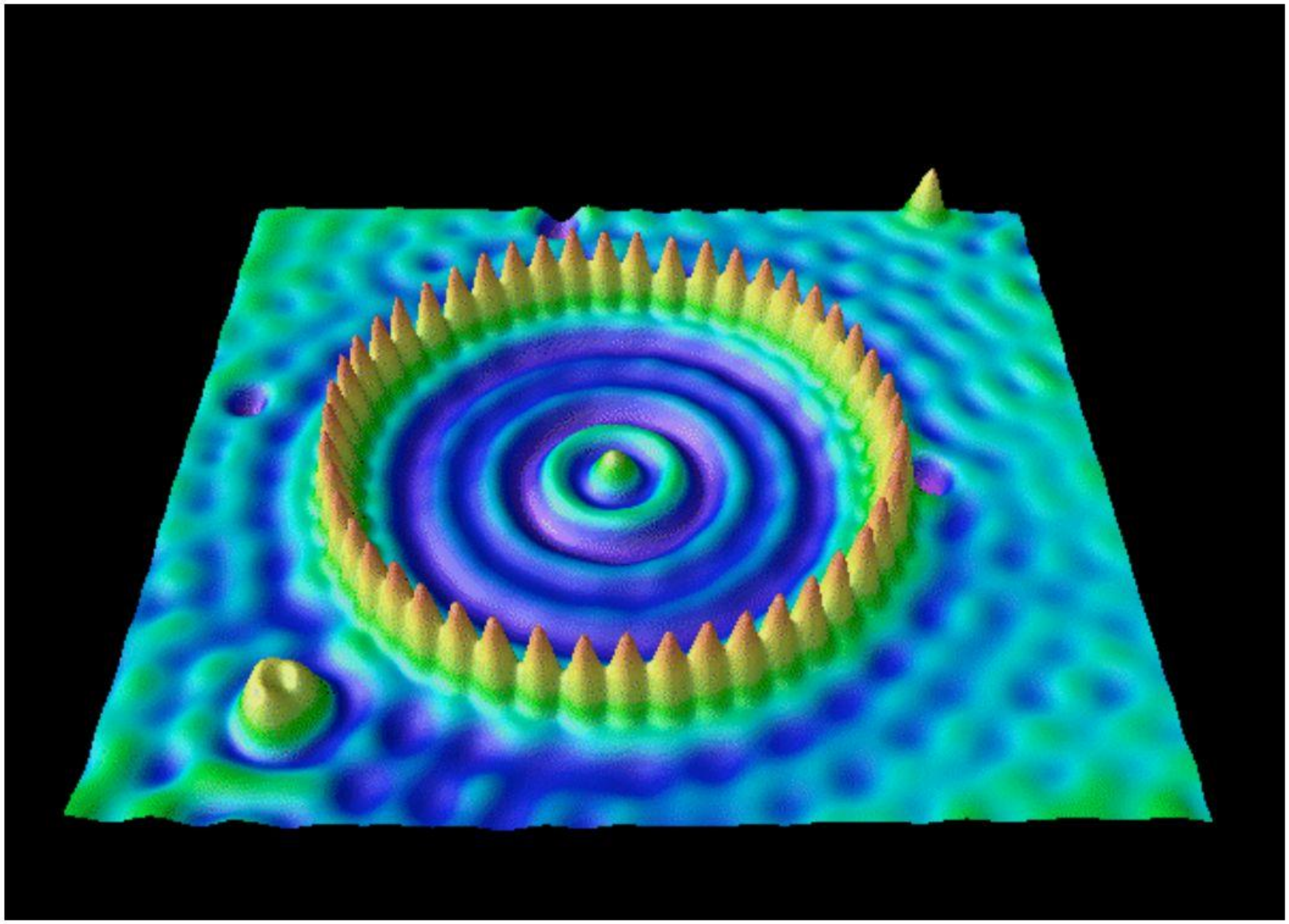
$$v \approx \alpha c$$

Slow means big thanks to QM

The electron has no structure but it has a size

$$\lambda = \frac{h}{p} = \frac{hc}{pc} \approx \frac{hc}{\alpha m c^2} = \frac{1240 \text{ ev}\cdot\text{nm}}{(\frac{1}{137})(5.11\times10^{-5} \text{ eV})} \approx \ 0.3 \text{ nm}$$

Electron waves seen with a scanning tunneling microscope



Wavelength of Rutherford's alpha particles

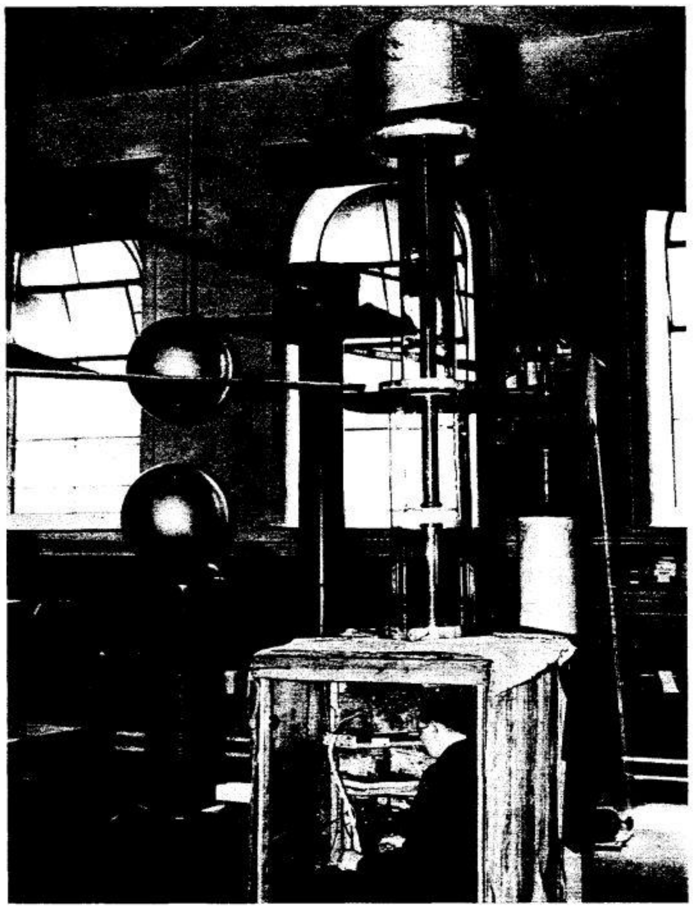
The kinetic energy of the alpha particles was 5.5 MeV

$$\lambda = \frac{h}{p} = \frac{hc}{\sqrt{2mc^2 E_\mathrm{k}}} = \frac{1240 \text{ eV}\cdot\text{nm}}{\sqrt{(2)(3730 \text{ MeV})(5.5 \text{ MeV})}} \approx \quad 6 \text{ fm}$$

Luckily, the alpha particles were the same size as the nucleus that they were used to discover... of course, they came from a nucleus, in fact they were a helium nucleus (which Rutherford could not have known!)

Cracking the nucleus

Crockoft and Walton (1932)



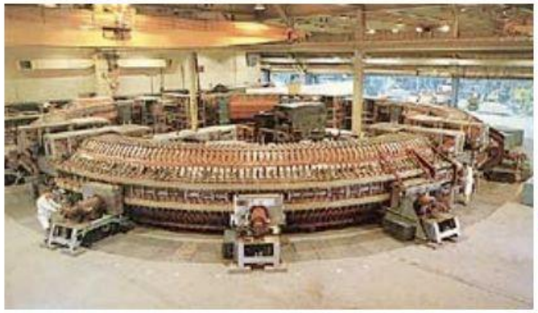
$$p + {}^{7}\mathrm{Li} \rightarrow \alpha + \alpha$$

“Almost at once at an energy of 125 kilovolts, Dr. Walton saw the bright scintillations characteristic of α par ticles... We then confirmed by a primitive coincidence experiment carried out with two zinc sulphide screens and two obser vers tapping keys, that the α par ticles were emitted in pairs. Our resolving time was a second or so- somewhat longer than the resolving time of modern coincidence circuits which operate in units of millimicroseconds.”

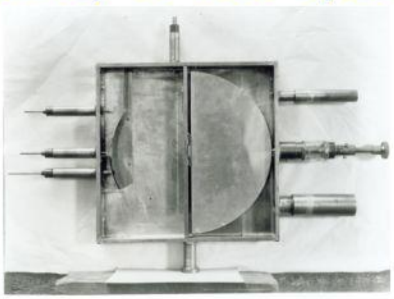
Livingston plot

growth of accelerator technology

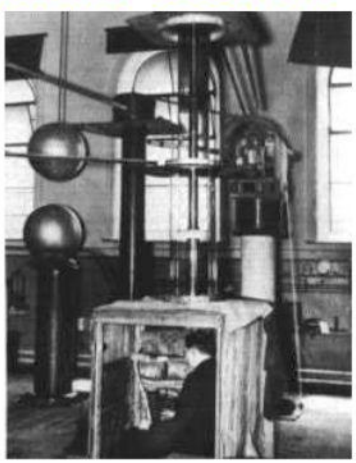
Brookhaven Cosmotron

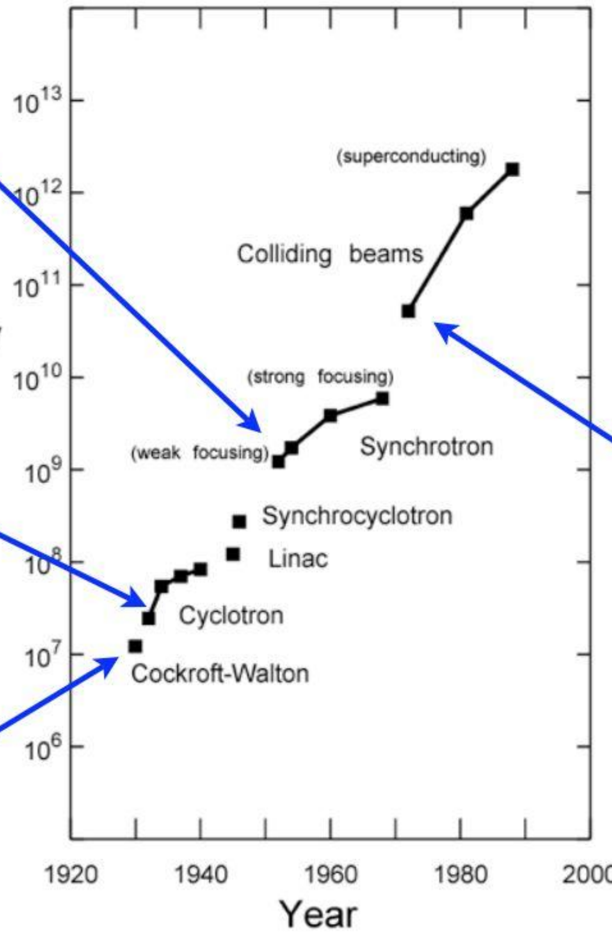


Berkeley 11 inch Cyclotron



Cavendish Cockroft-Walton





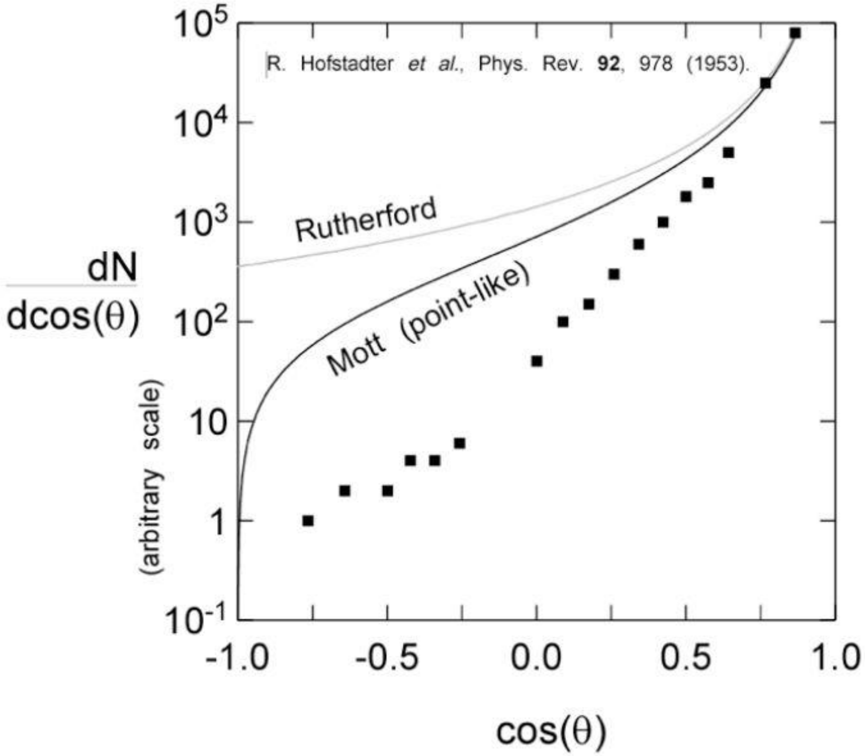
M. Stanley Livingston
(1905-1986)

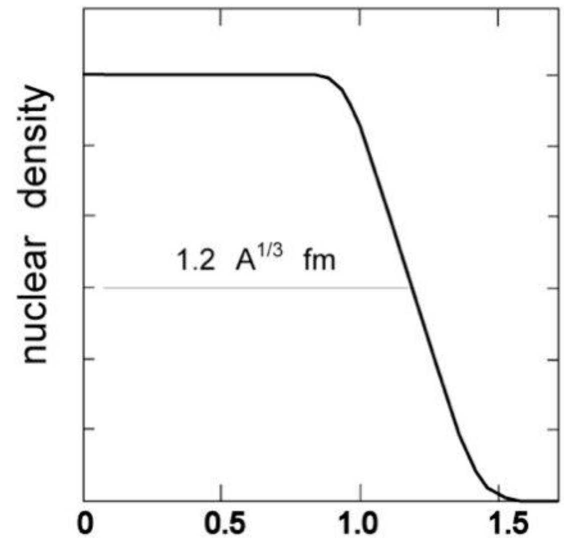
SLAC SPEAR

x10 energy every 6 years

Inside the nucleus $eN \rightarrow eN$

125 MeV electrons hitting gold, Hofstadter (1953)





Point-like cross section modified by electron magnetic moment and nuclear recoil

$$[\frac{d\sigma}{d\cos\theta}]_{\text{Mott}} = [\frac{d\sigma}{d\cos\theta}]_{\text{Ruth}} \frac{1+\cos\theta}{2[1+(1-\cos\theta)E_{\text{k}}/Mc^2]}$$

Yesterday's probe...
becomes tomorrow's target

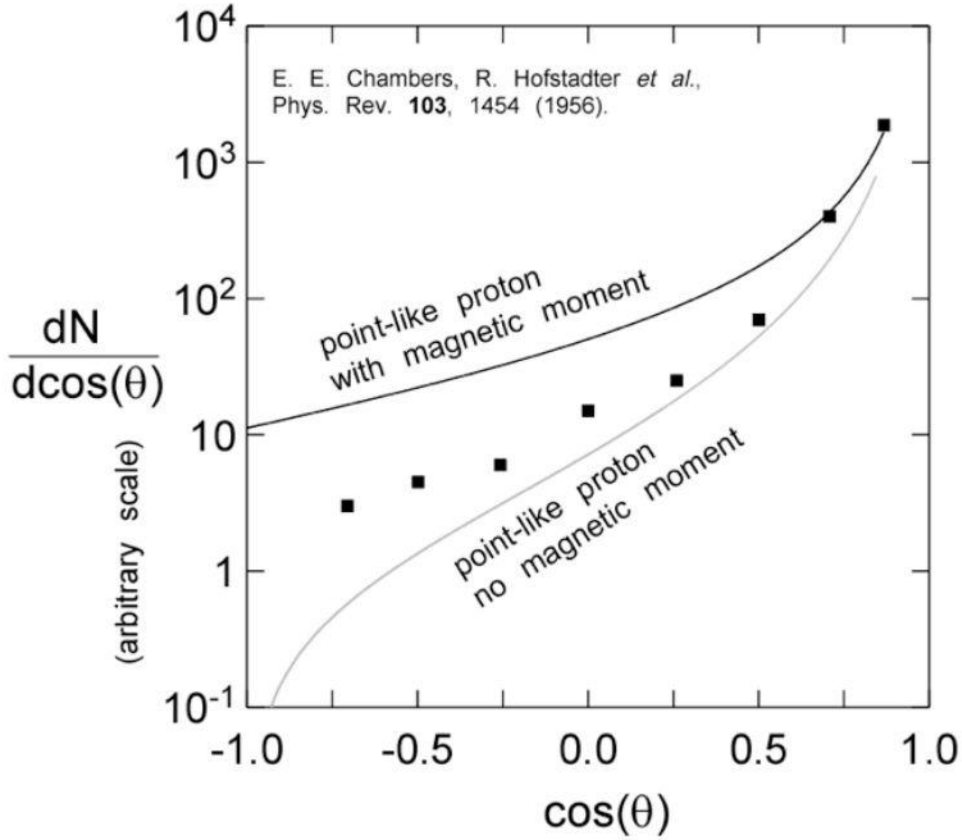
$\alpha \rightarrow p,n \rightarrow q \rightarrow ?$

"I was more thrilled by seeing the structure in the alpha particle than by almost anything else, because Rutherford used the alpha particle in figuring out the scheme of construction of the atom."

Robert Hofstadter

Inside the proton $ep \rightarrow ep$

550 MeV electrons hitting protons, Hofstadter (1956)



$$\left[\frac{d\sigma}{d\cos\theta}\right]_{\text{proton}} = \left[\frac{d\sigma}{d\cos\theta}\right]_{\text{Mott}} |F(\theta)|^2$$

The function F is called the form factor; it contains the information on how the charge distribution inside the proton differs from a "point."

Inside the proton (cont.)

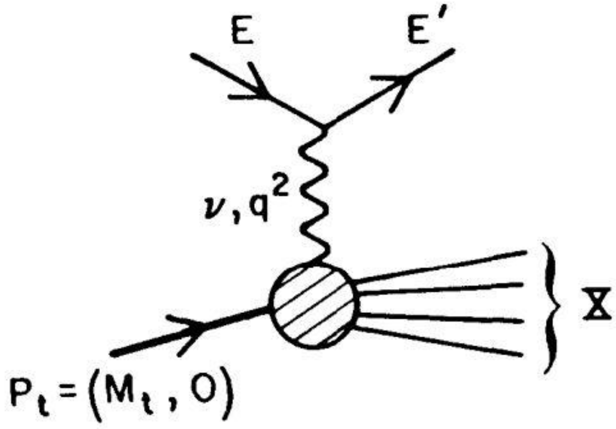
Stanford Linear Accelerator Center: End Station A

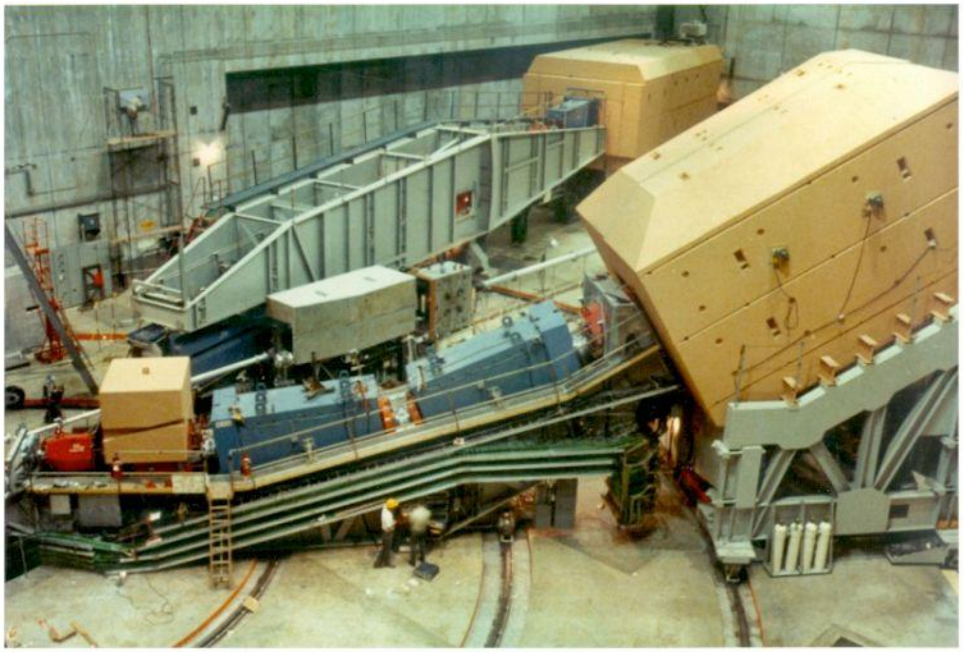
10 GeV electrons 1968

e+p → e+X

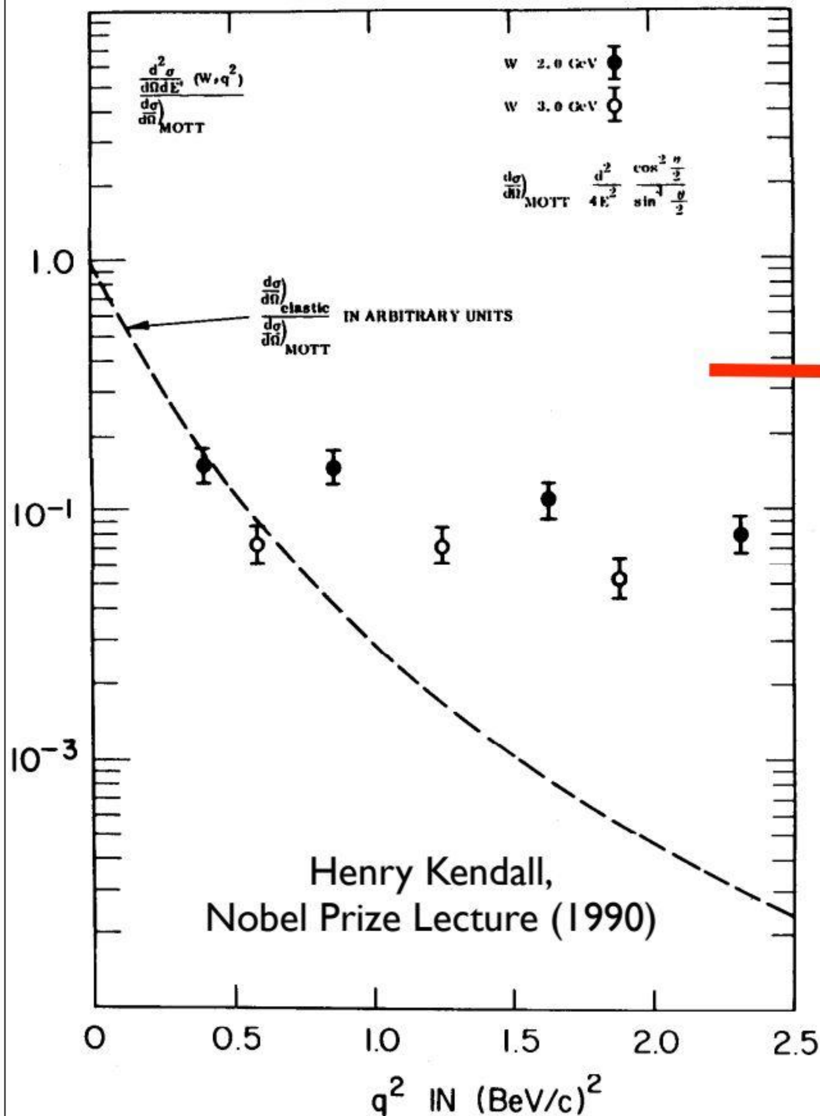
First evidence for scaling

$$q^2 = 2EE'(1 - \cos\theta)$$

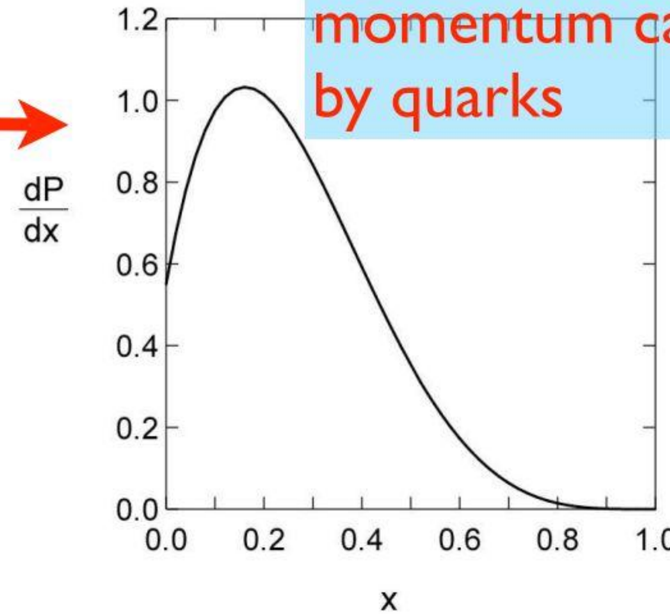




$$q^2 = 2EE'(1 - \cos\theta)$$



fraction of proton momentum carried by quarks



$$x = \frac{q^2}{2m_{\mathrm{p}}(E - E')}$$

These results were inconsistent with the current expectations of most physicists at the time.

Feynman x

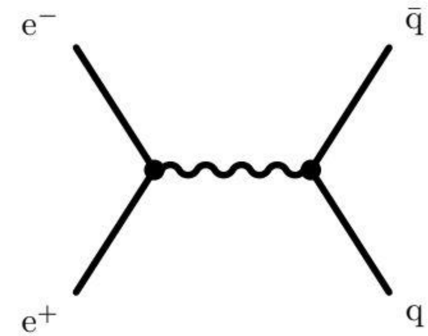
parton momentum fraction

"I am more sure of the conclusions than of any single argument which suggested them to me for they have an internal consistency which surprises me and exceeds the consistency of my deductive arguments which hinted at their existence."

Richard Feynman, "Very High Energy Collisions of Hadrons," *Phys. Rev. Lett.* **24**, 1415 (1969)

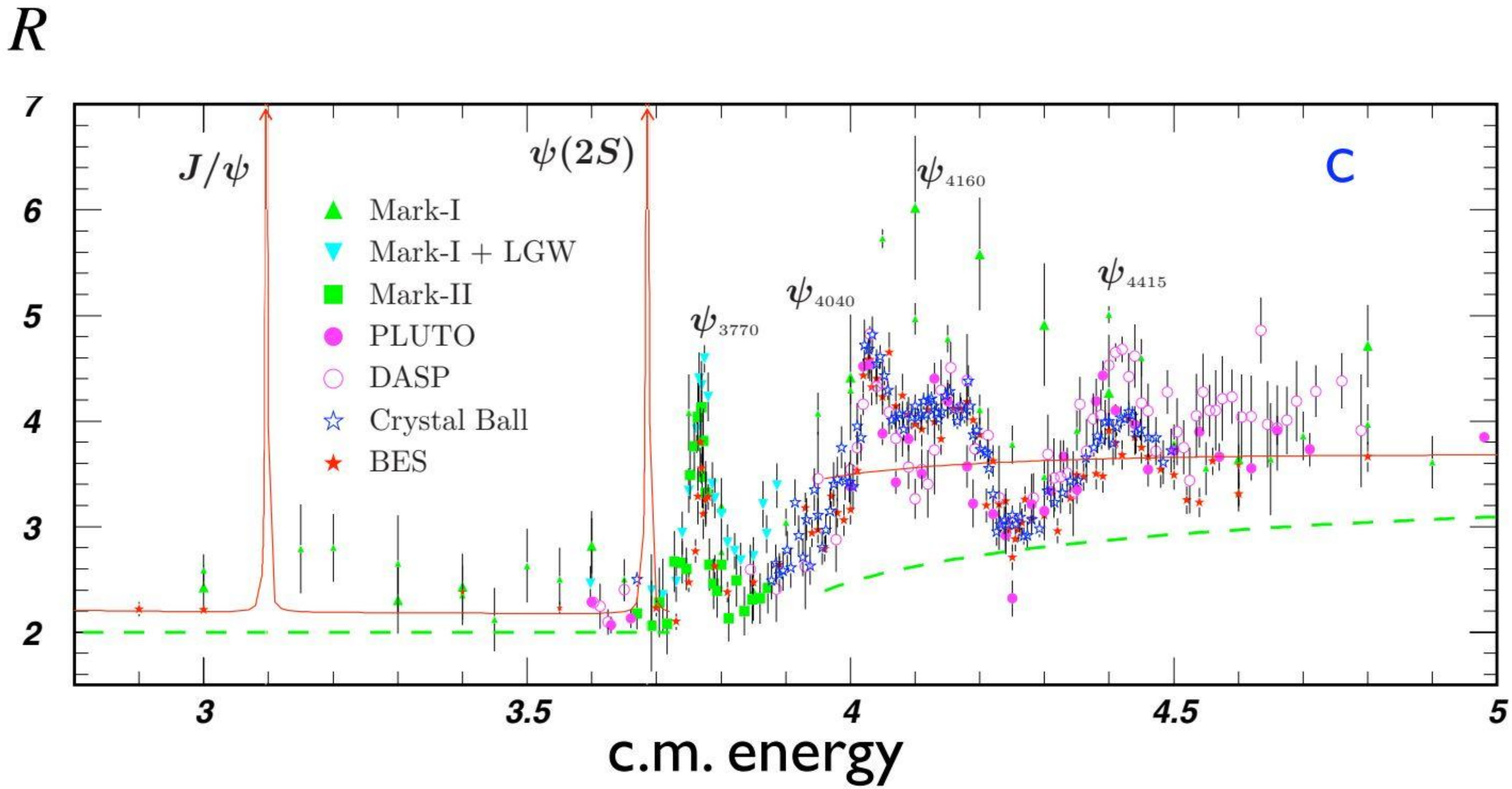
Predicting R London conference (July 1974)

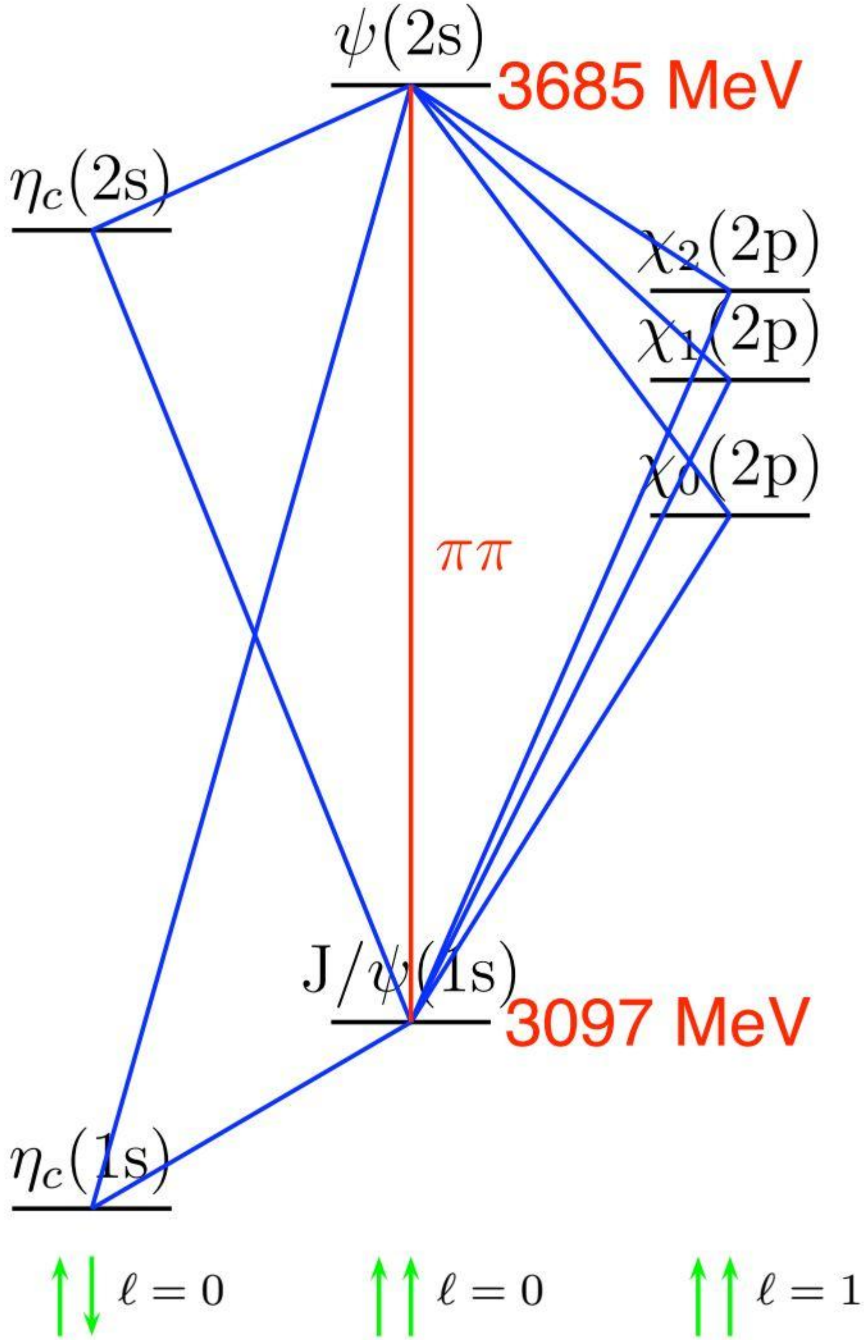
$$R = \frac{\sigma_{e^+e^-\to \text{hadrons}}}{\sigma_{e^+e^-\to\mu^+\mu^-}}$$



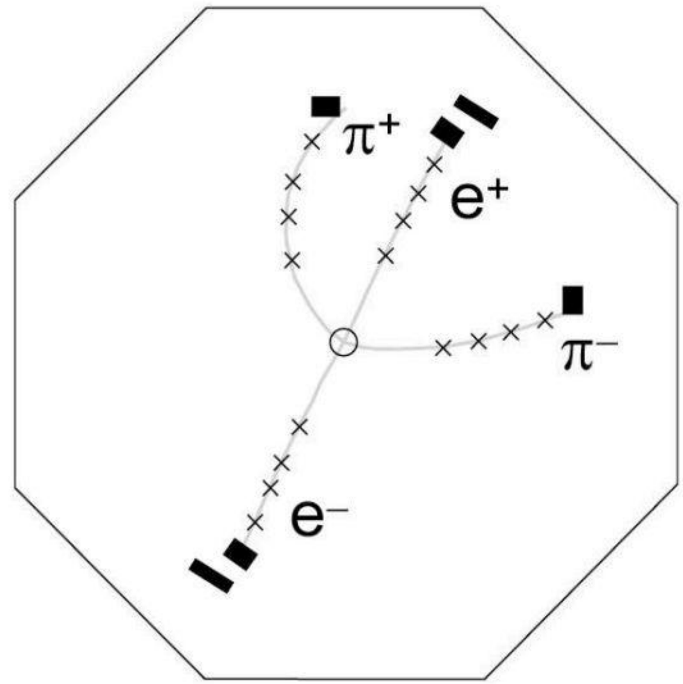
0.36	Bethe-Salpeter bound quarks	6	Han-Nambu with charm
2/3	Gell-Mann Zweig quarks	6.69 - 7.77	Broken scale invariance
0.69	vector meson dominance I	8	Tati quarks
1	composite quarks	8	trace anomaly II
10/9	Gell-Mann Zweig with charm	9	gravitational cut-off
2	colored quarks	9	broken scale invariance
2.5-3	vector meson dominance II	16	$SU_{12} \times SU_2$
2-5	vector meson dominance III	35 1/3	rm $SU_{16} \times SU_1 6$
3 1/3	colored charmed quarks	5000	high-Z quarks
4	Han-Nambu quarks	70,383	Schwinger's quarks
5.7	trace anomaly	∞	∞ partons

e^+e^- collisions (c quark region)



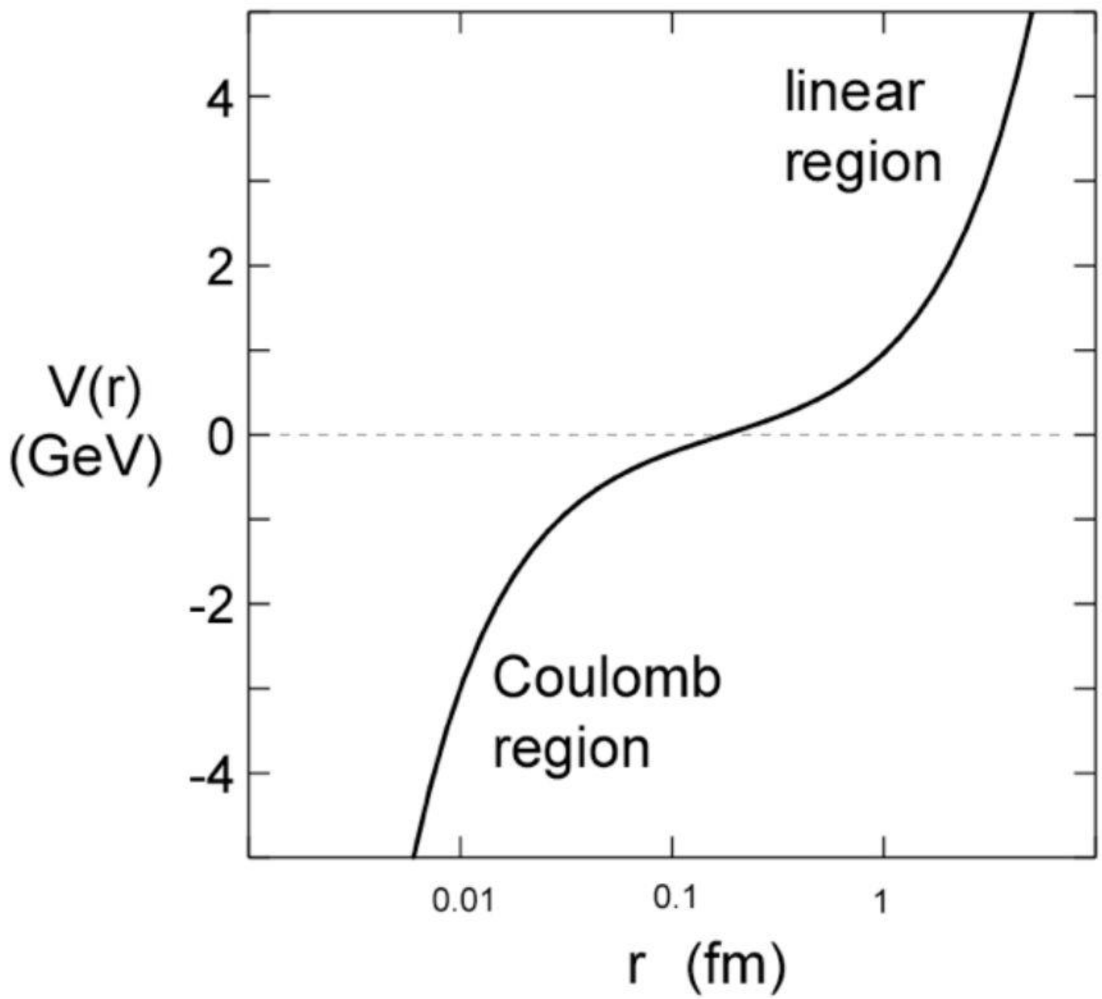


$$e^+e^- \to \psi' \to \pi^+\pi^-\psi$$
$$\to e^+e^-$$



Strong interaction potential

$$V = \frac{-\kappa_1}{r} + \kappa_2 r$$



from observed energy levels:

$\kappa_1 \approx 0.05\ \mathrm{GeV \cdot fm}$

$\kappa_2 \approx 1\ \mathrm{GeV/fm}$

Speed of the quarks

$\lambda \approx 2\ \mathsf{fm}$ particle in a box

$$pc = \frac{hc}{\lambda} = \frac{1.24\ \mathsf{GeV{\cdot}fm}}{2\ \mathsf{fm}} = 0.6\ \mathsf{GeV}$$

$$E = \sqrt{(mc^2)^2 + (pc)^2} = \sqrt{(1.5\ \mathsf{GeV})^2 + (0.6\ \mathsf{GeV})^2} = 1.6\ \mathsf{GeV}$$

$$v/c = pc/E = (0.6\ \mathsf{GeV})/(1.6\ \mathsf{GeV}) \approx 0.4$$

not a turtle but not speed of light either

Hadron jets are they the same as from e^+e^- ?

my first publication

Observation of the production of jets of particles at high transverse momentum and comparison with inclusive single particle reactions,
Mar 1977. Phys. Rev. Lett. **38**, 1447 (1977)

my thesis

Experimental tests of quantum chromodynamics in high p_T jet production in 200 GeV/c hadron-proton collisions,
May 1979. Phys. Rev. Lett. **43**, 565 (1979).

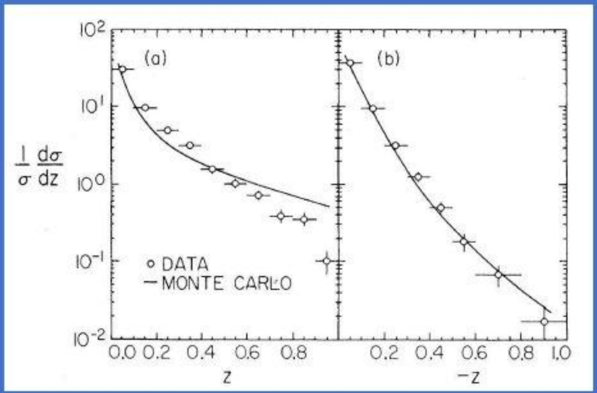
Nuclear Physics B171 (1980) 1–37

(full thesis)

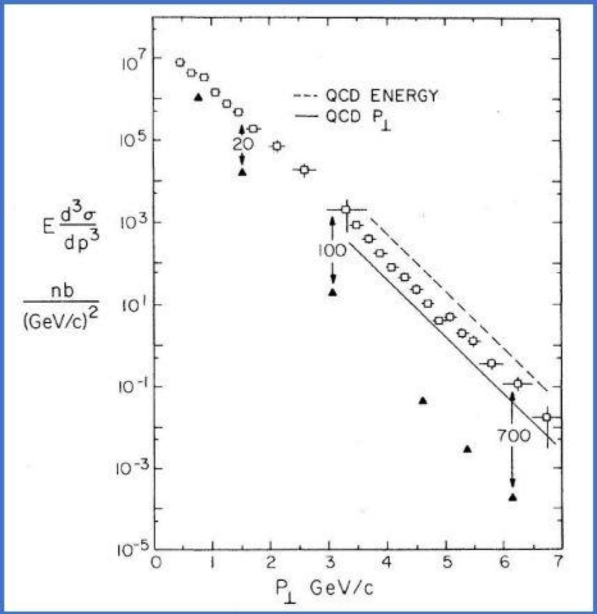
JET PRODUCTION IN HIGH-ENERGY HADRON-PROTON COLLISIONS*

E260 First calorimeter jet trigger (1977)

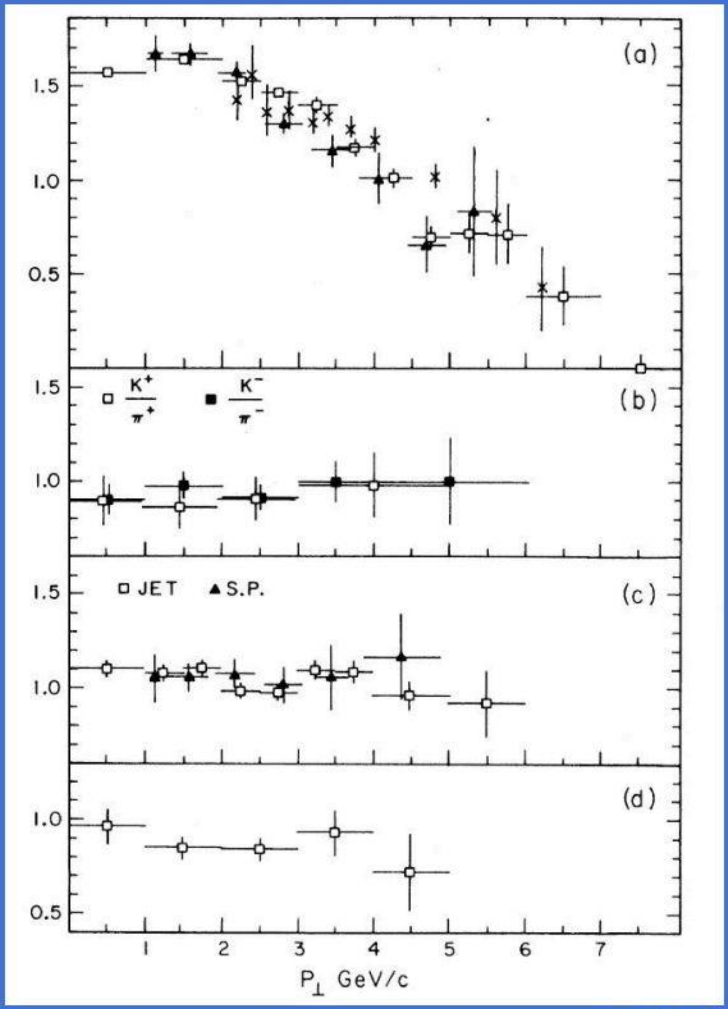
Field-Feyman fragmentation



QCD calculation (G. Fox)



$\sigma(\mathrm{pp} \to \mathrm{jet})/\sigma(\pi\mathrm{p} \to \mathrm{jet})$



A better microscope: proton-antiproton collider

Antiproton cooling (CERN)

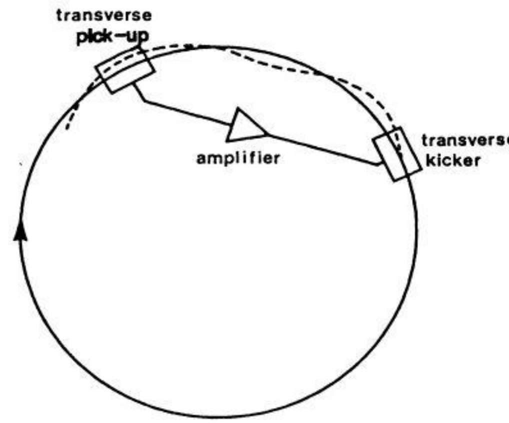


FIG. 2. Cooling of the horizontal betatron oscillation of a sin
gle particle.

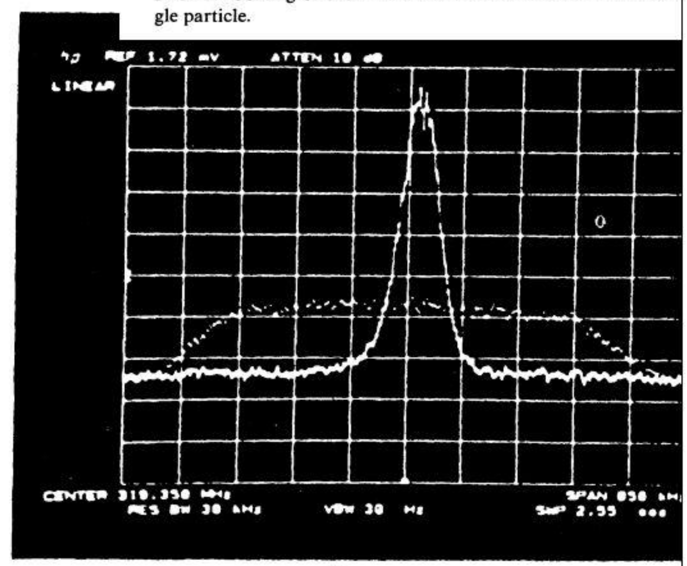
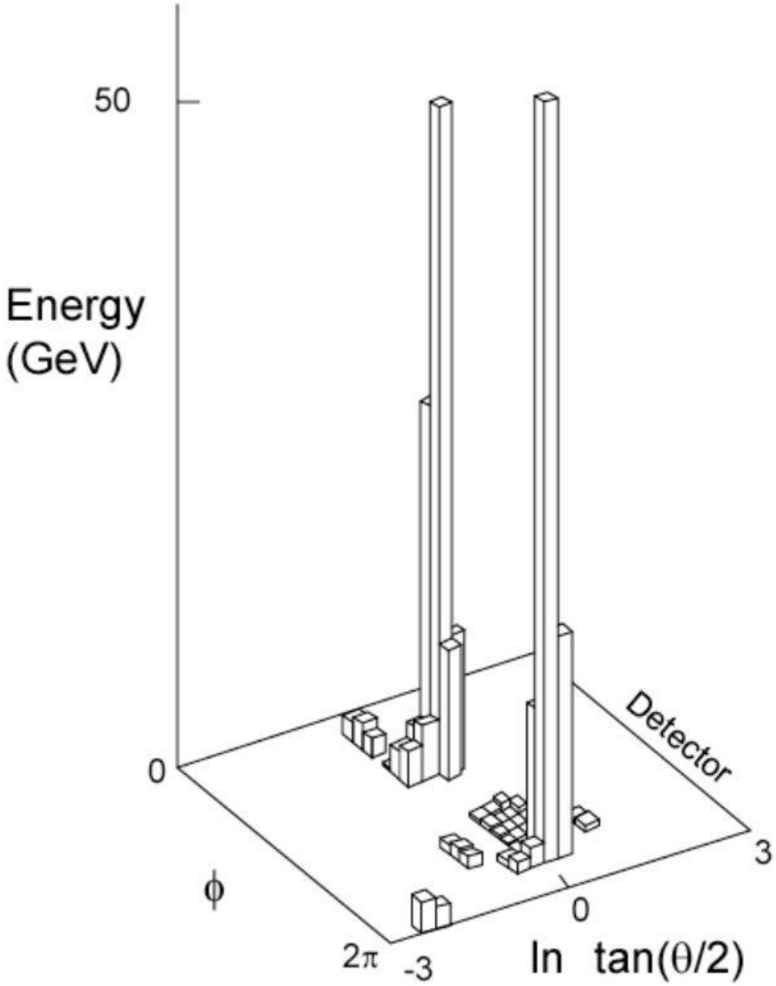
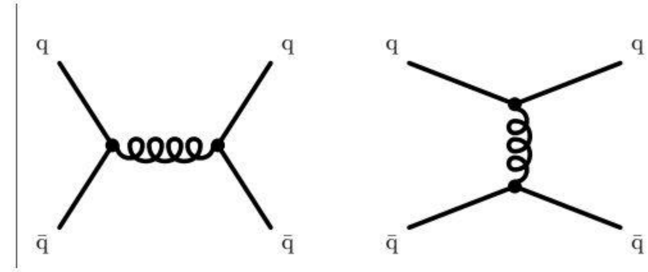
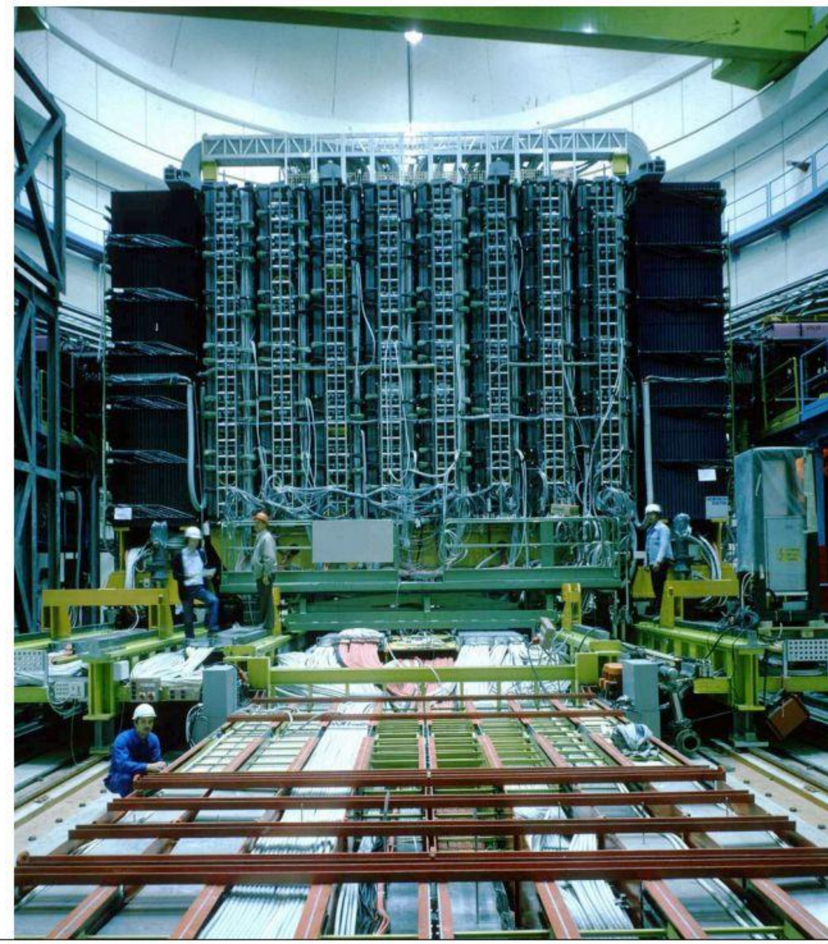


FIG. 13. Precooling 6×10^{6} $\bar{p}$'s in 2 seconds. Long
Schottky band at the 170th harmonic (314 MHz) bef
after cooling.

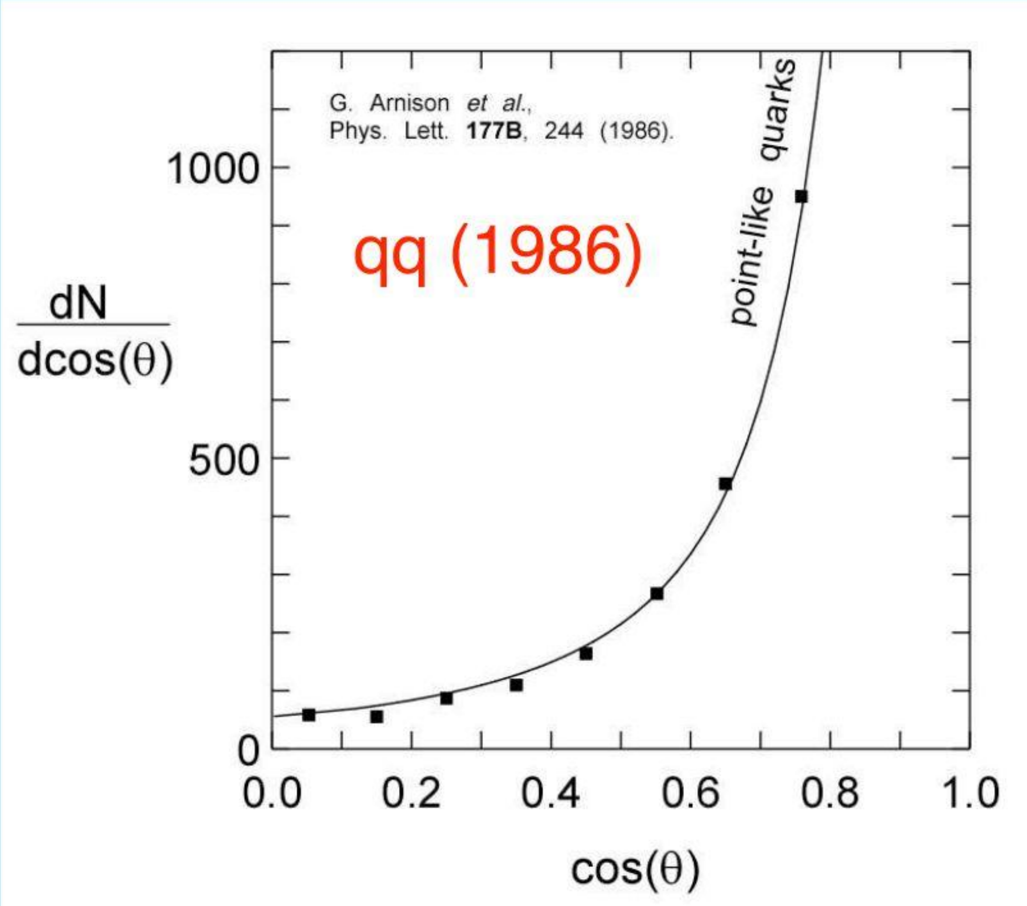
Quark Scattering







Scattering quarks (1986)

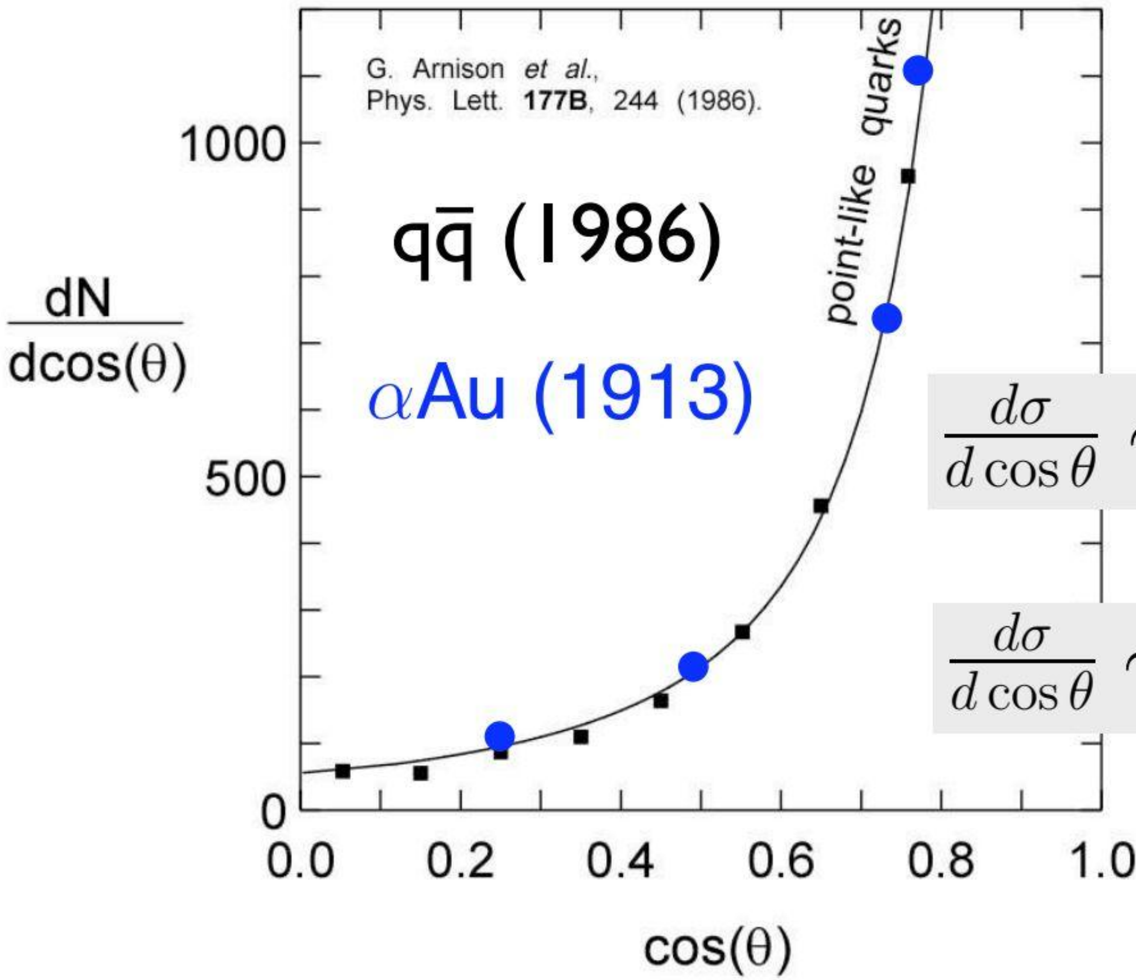


$$\frac{d\sigma}{d\cos\theta} \sim \alpha_s^2\left(\frac{\hbar c}{E_{\mathrm{CM}}}\right)^2 \frac{1}{(1-\cos\theta)^2}$$

demonstrating:

- $1/r^2$ strong force
- spin 1 gluon
- pointlike quarks

Rutherford scattering



Electromagnetism

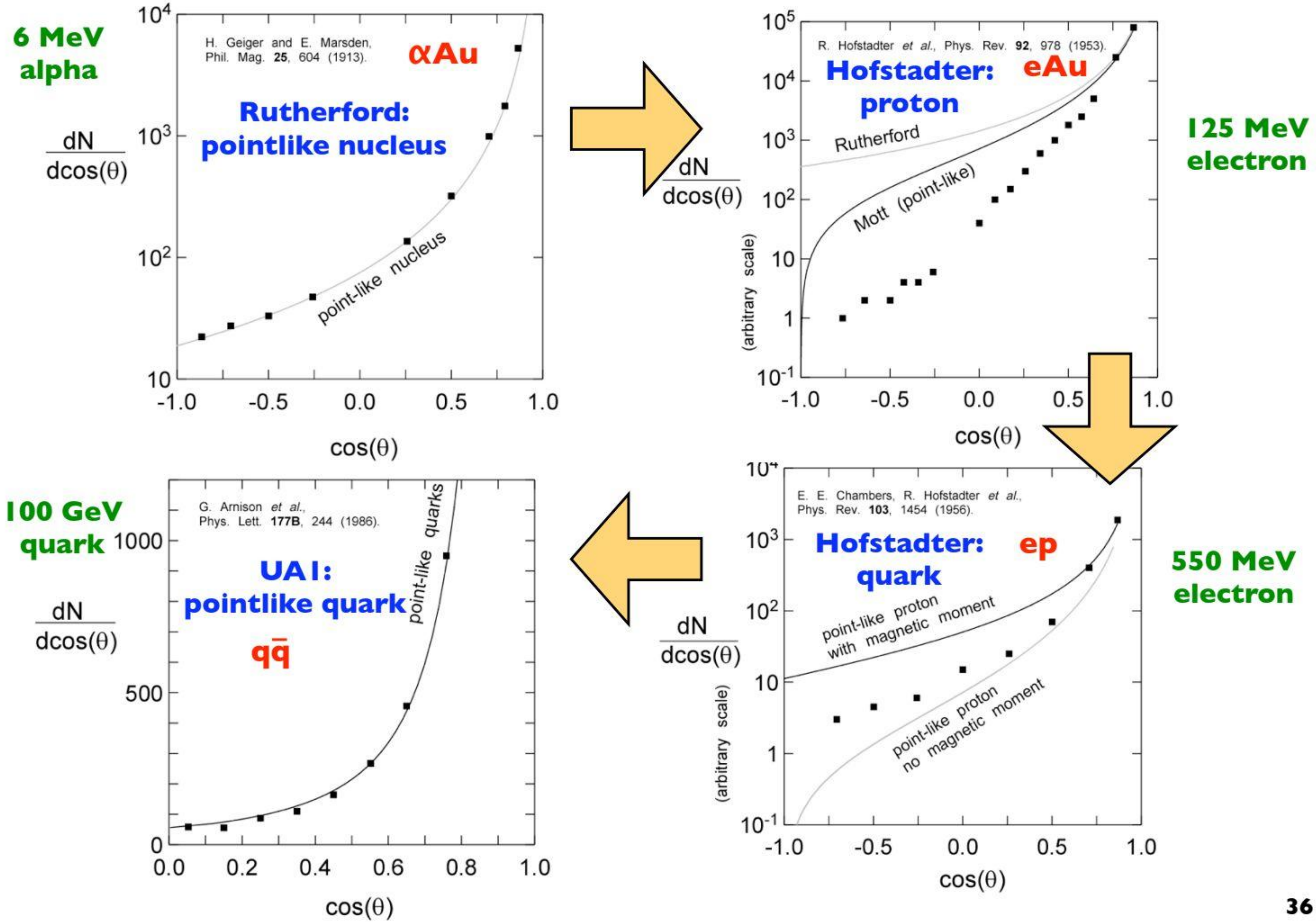
$$\frac{d\sigma}{d\cos\theta} \sim \alpha^2\left(\frac{\hbar c}{E_\mathrm{k}}\right)^2\frac{1}{(1-\cos\theta)^2}$$

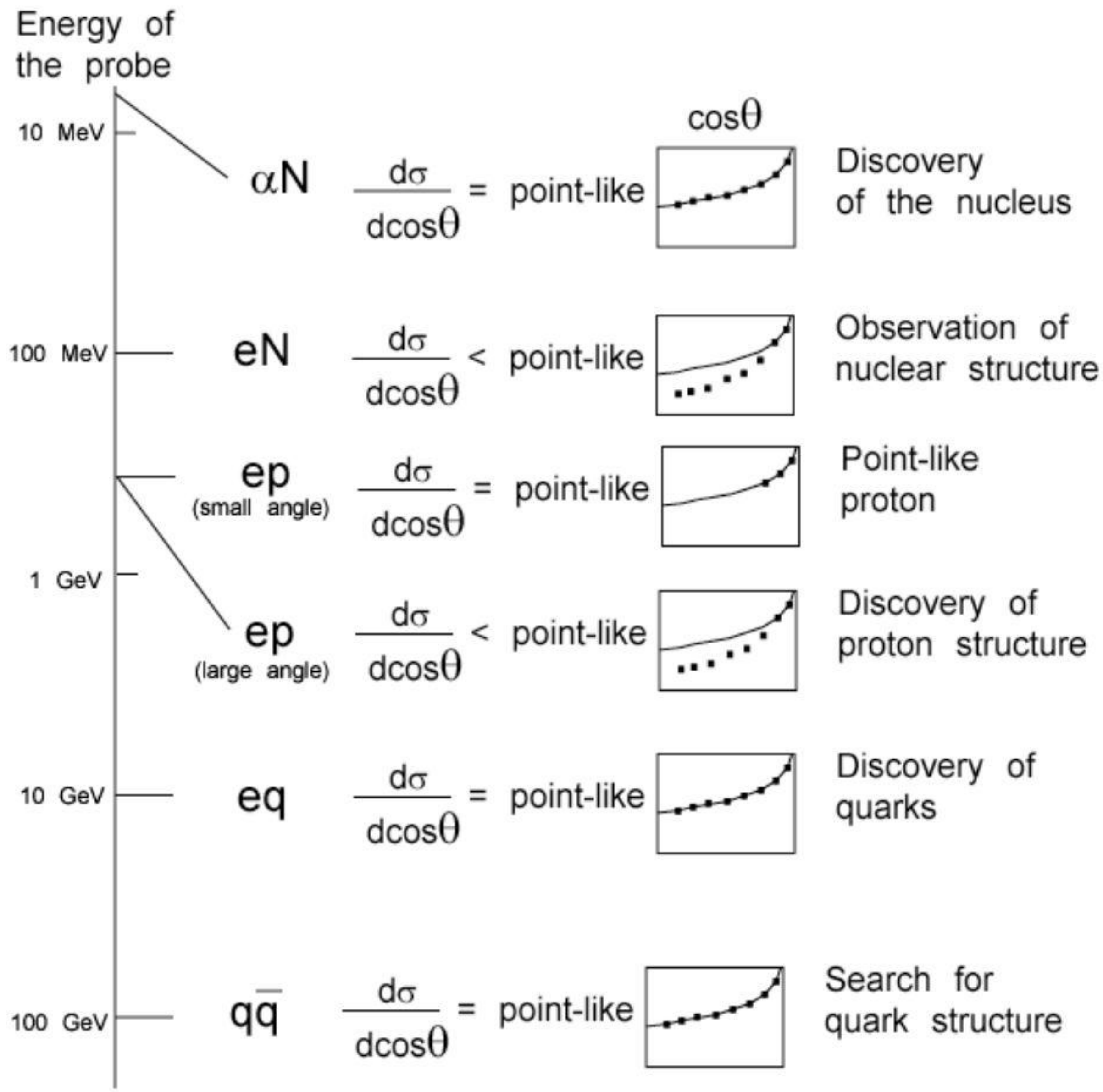
QCD

$$\frac{d\sigma}{d\cos\theta} \sim \alpha_s^2\left(\frac{\hbar c}{E_\mathrm{CM}}\right)^2\frac{1}{(1-\cos\theta)^2}$$

History of compositeness

J. Rohlf: Modern Physics from α to Z^0



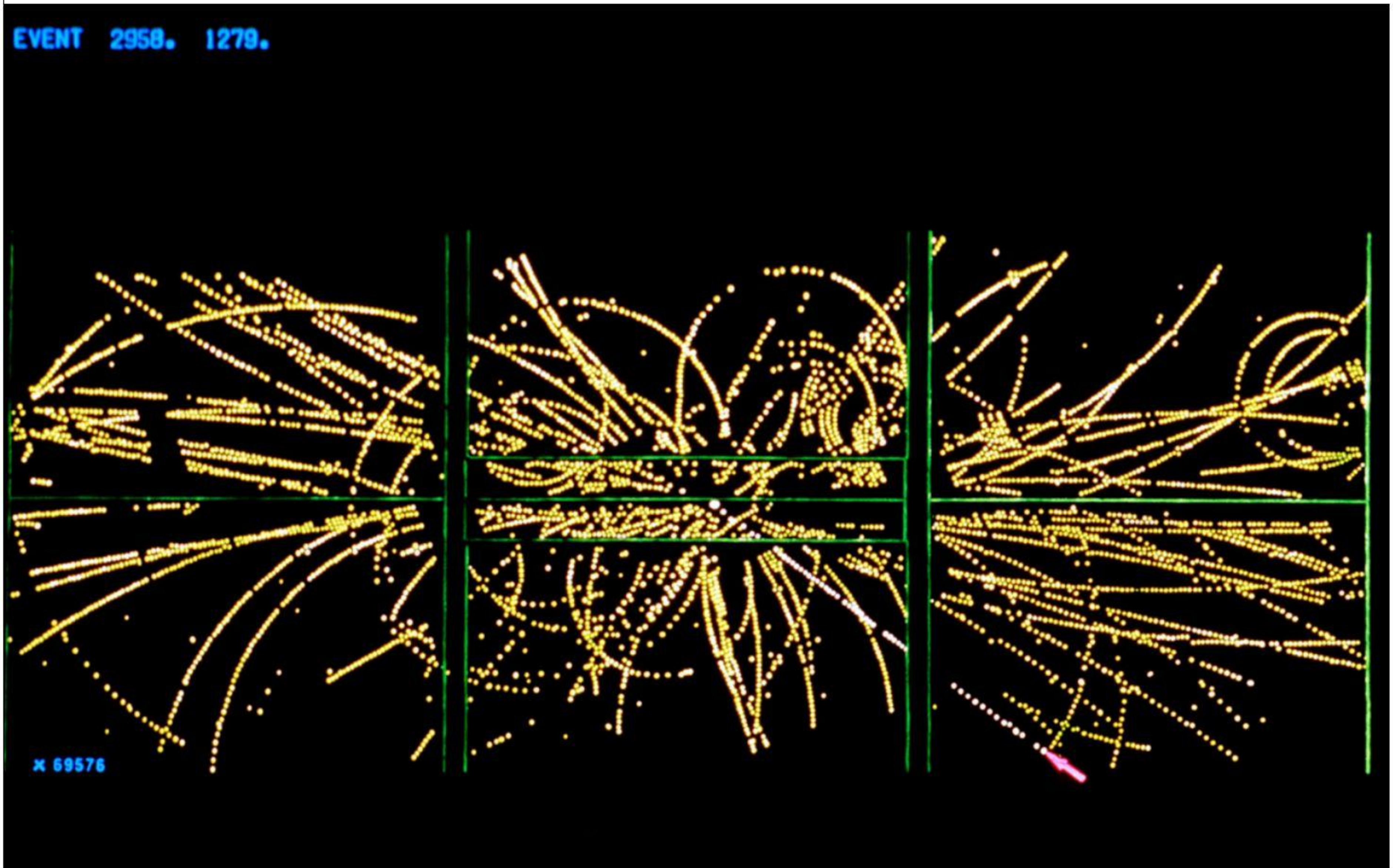

Energy of the probe
10 MeV
100 MeV
1 GeV
10 GeV
100 GeV
cosθ
αN $\frac{d\sigma}{d\cos\theta}$ = point-like
Discovery of the nucleus
eN $\frac{d\sigma}{d\cos\theta}$ < point-like
Observation of nuclear structure
ep (small angle) $\frac{d\sigma}{d\cos\theta}$ = point-like
Point-like proton
ep (large angle) $\frac{d\sigma}{d\cos\theta}$ < point-like
Discovery of proton structure
eq $\frac{d\sigma}{d\cos\theta}$ = point-like
Discovery of quarks
$q\bar{q}$ $\frac{d\sigma}{d\cos\theta}$ = point-like
Search for quark structure

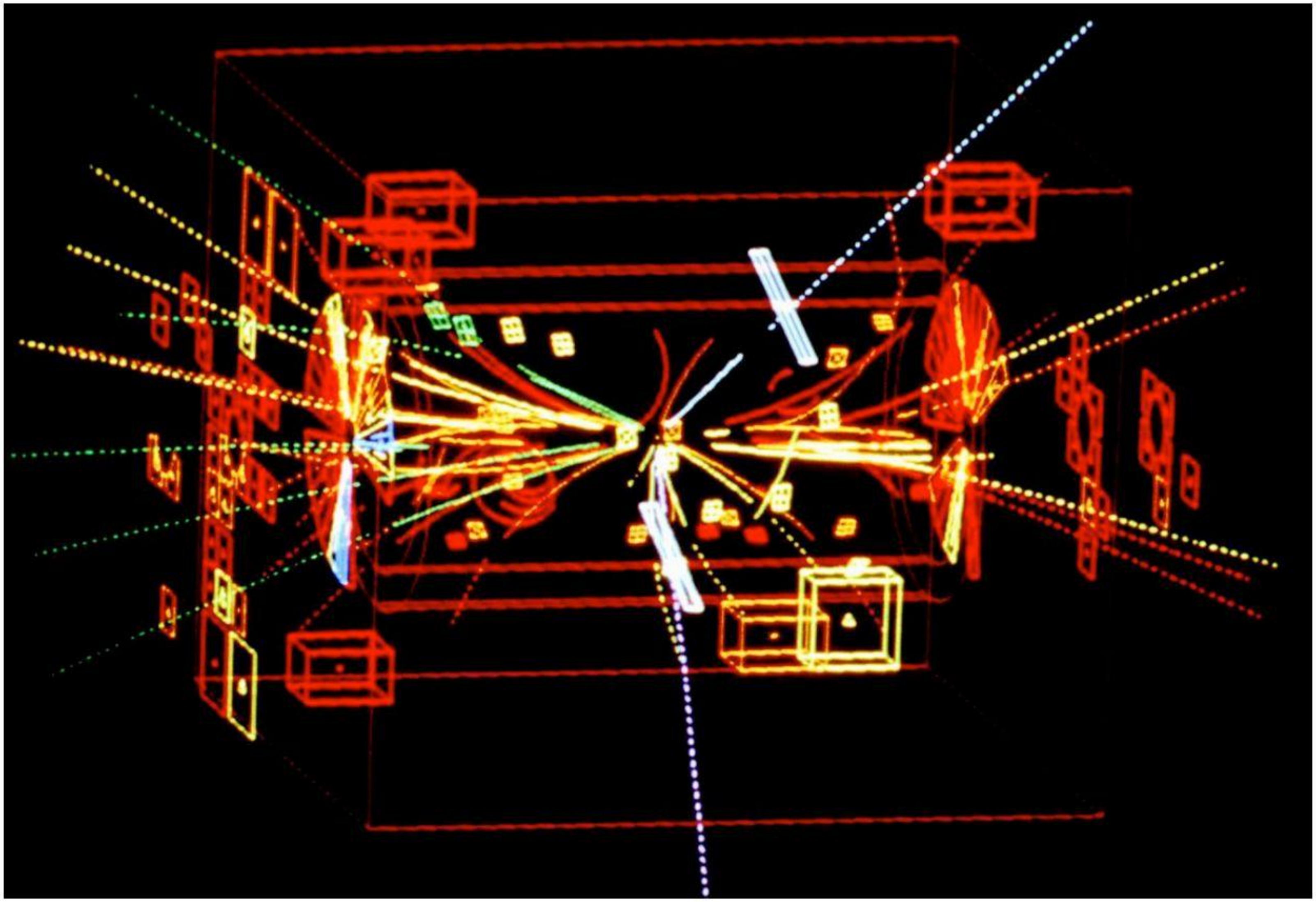
Producing the W and Z^0

With constituent collisions at 100 GeV, we have probed nature to distances of

$$d \simeq \frac{\hbar}{p} = \frac{0.2\ \mathrm{GeV}\cdot\mathrm{fm}}{100\ \mathrm{GeV}} = 2 \times 10^{-18}\ \mathrm{m}$$

At this energy, the W and Z^0 are produced as free particles.


EVENT 2958. 1279.
x 69576



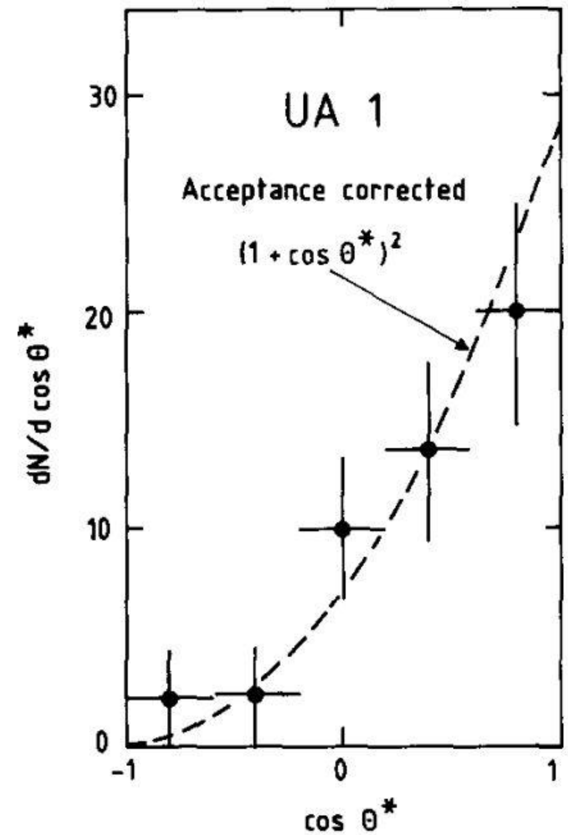


Fig. 8. The angular distribution of the electron emission angle θ^* in the rest frame of the W after correction for experimental acceptance. Only those events in which the electron charge is determined and the kinematic ambiguity (see text) has been resolved have been used. The later requirement has been corrected for in the acceptance calculation.

$$P = \frac{2ke^2\gamma^4 c}{3r^2}$$

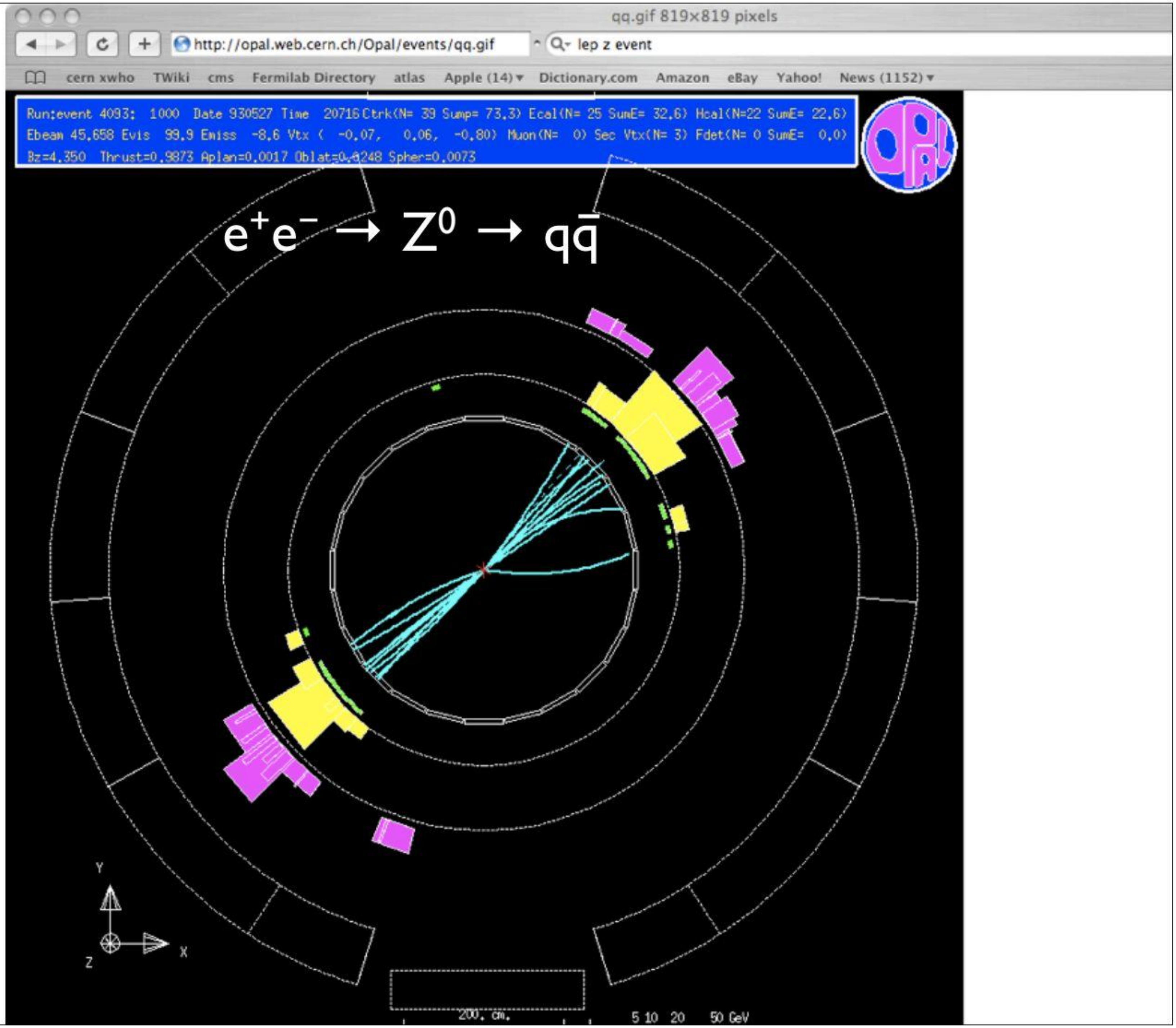
radiated power from circular orbit

"It is apparent that as the velocity is increased there will come a point at which energy is radiated away just as rapidly as it is supplied by the accelerator. Thus, there exists a practical upper limit for the energy of electrons that can be achieved in a circular machine. This limit apparently is in the energy range 10-20 GeV."

Classical Electromagnetic Radiation

Marion and Heald (1980)

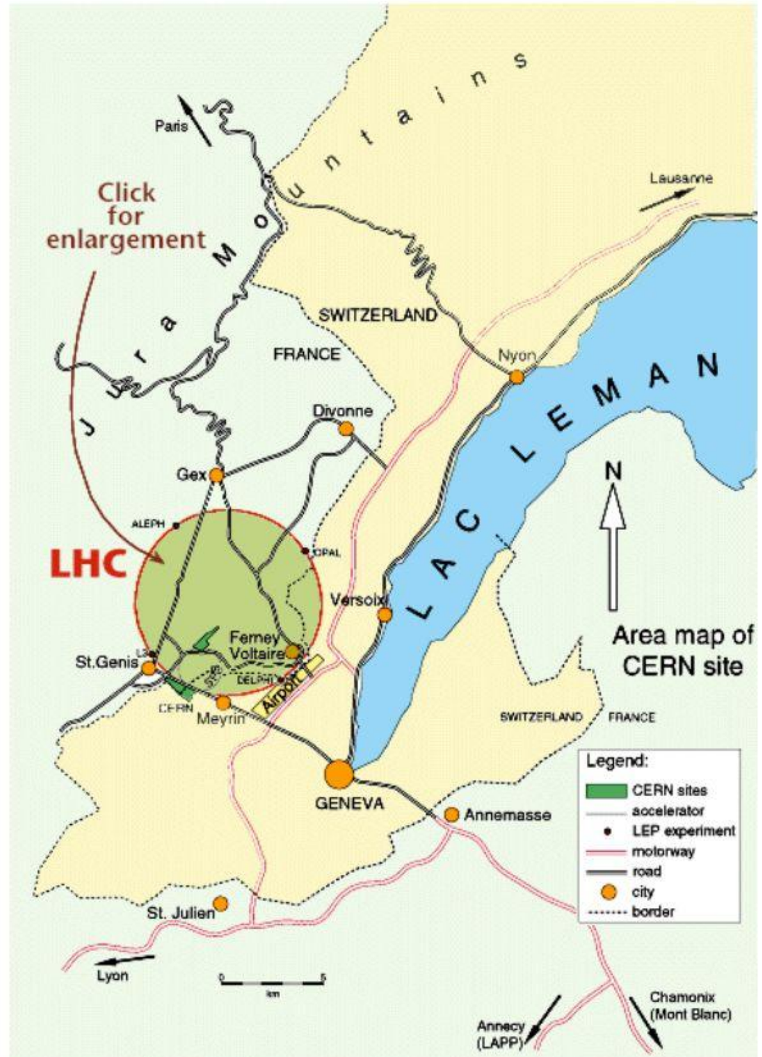
$e^+e^- \rightarrow Z^0 \rightarrow q\bar{q}$



LHC Geographical Situation

electron machines:
limited by
synchrotron radiation

proton machines:
limited by
magnet technology



Recall the crisis of the classical electron radius, the failure of electromagnetics at a distance of 1 fm... the solution of which appeared at a much larger distance scale (0.1 nm). Now we come to the current version...

$$\boxed{\alpha_{\mathrm{W}} \simeq \alpha\left(\frac{E}{m_{\mathrm{W}}c^2}\right)^2}$$

Our understanding of the weak force fails when

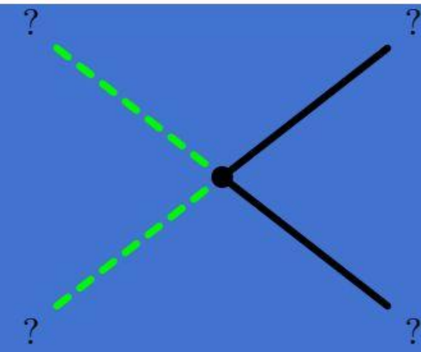
$$\boxed{\alpha_{\mathrm{W}} \simeq 1.7\ \mathrm{TeV}}$$

Our current understanding of the weak force is analogous to the understanding of electrodynamics in 1920... Some new physics must (!) appear on the TeV scale (or below), corresponding to 10^{-19} m.

Supercollider physics

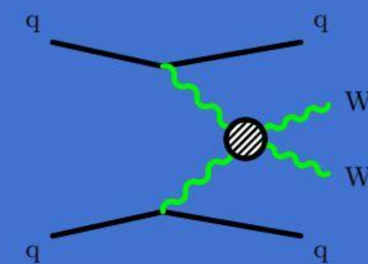
Big Picture

FIRST look at the TeV/c^2 mass scale to find a clue to the hierarchy problem... *What lies between the weak scale and the Planck mass?*



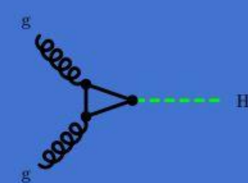
Medium Picture

EXPLORE the mechanism for electroweak symmetry breaking... *How do the* W/Z^0 *interact at high energies?*



Small Picture

NAIL down the elusive Higgs boson...



Large Hadron (proton) Collider

$\vec{p}\ \overleftarrow{p}$

Basic Parameters of the LHC

circumference	26,659 m
dipole field	8.33 T
energy per beam	7 TeV
number of dipoles	1232
total number of magnets	9994
operating temperature	1.9 K
power consumption	120 MW
revolution frequency	11.2455 kHz
revolution period	88.9 μs
radio frequency (RF)	400.8 MHz
RF electric field	5.5 MV/m

0.5 amp proton currents!

Proton speed

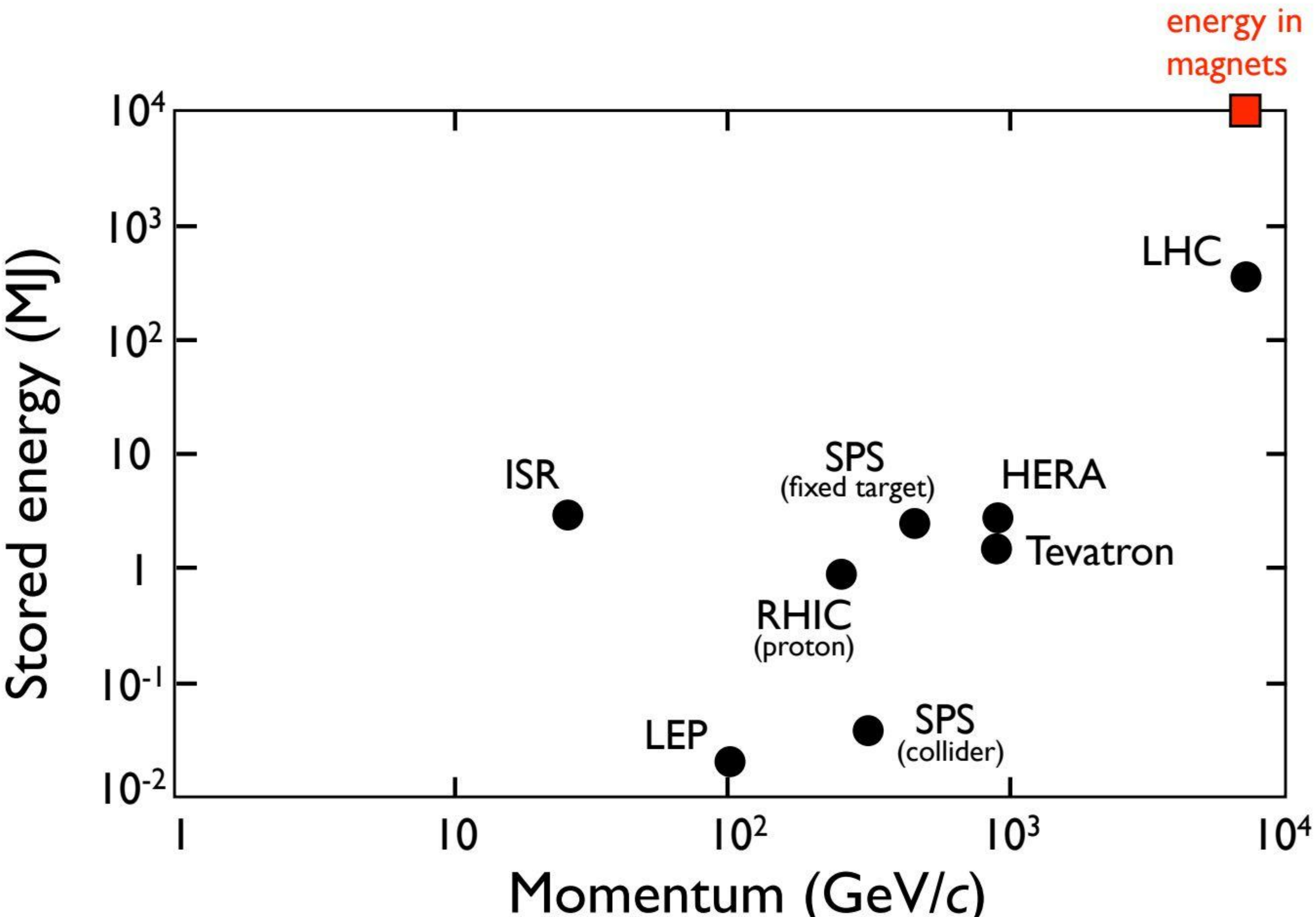
$$\gamma = \frac{1}{\sqrt{1-v^2/c^2}} = E/m$$

$$1 - v^2/c^2 = m^2/E^2$$

$$v = c\sqrt{1 - m^2/E^2}$$

$$v \approx c(1 - m^2/2E^2) = c - 2.7 \text{ m/s}$$

$$E_{\mathrm{s}} = E_{\mathrm{p}} n_{\mathrm{b}} N_{\mathrm{b}} = (7 \times 10^{12}\ \mathrm{eV})(1.6 \times 10^{-19}\ \mathrm{J/eV})(2808)(1.1 \times 10^{11}) = 350\ \mathrm{MJ}.$$

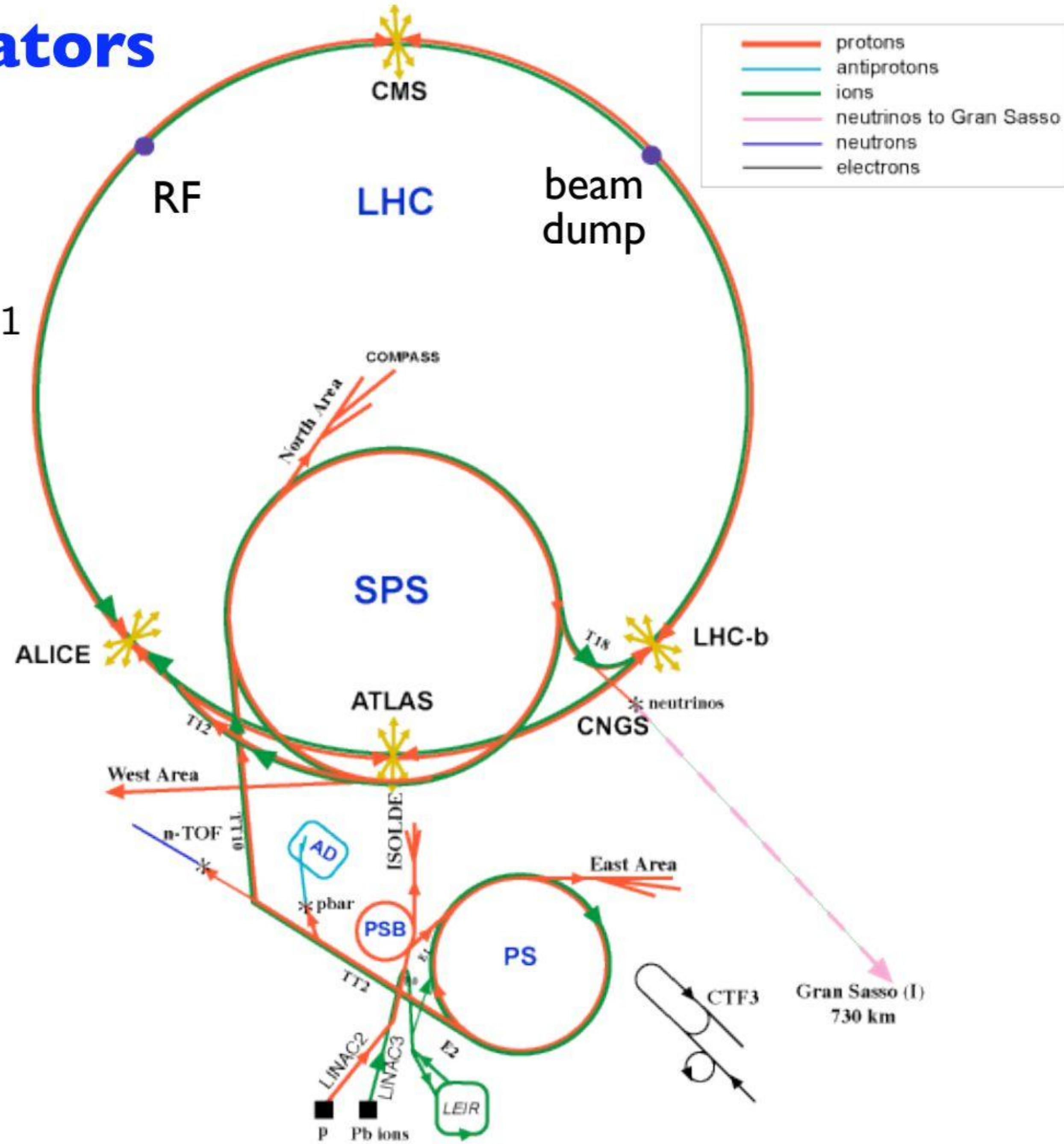


CERN Accelerators

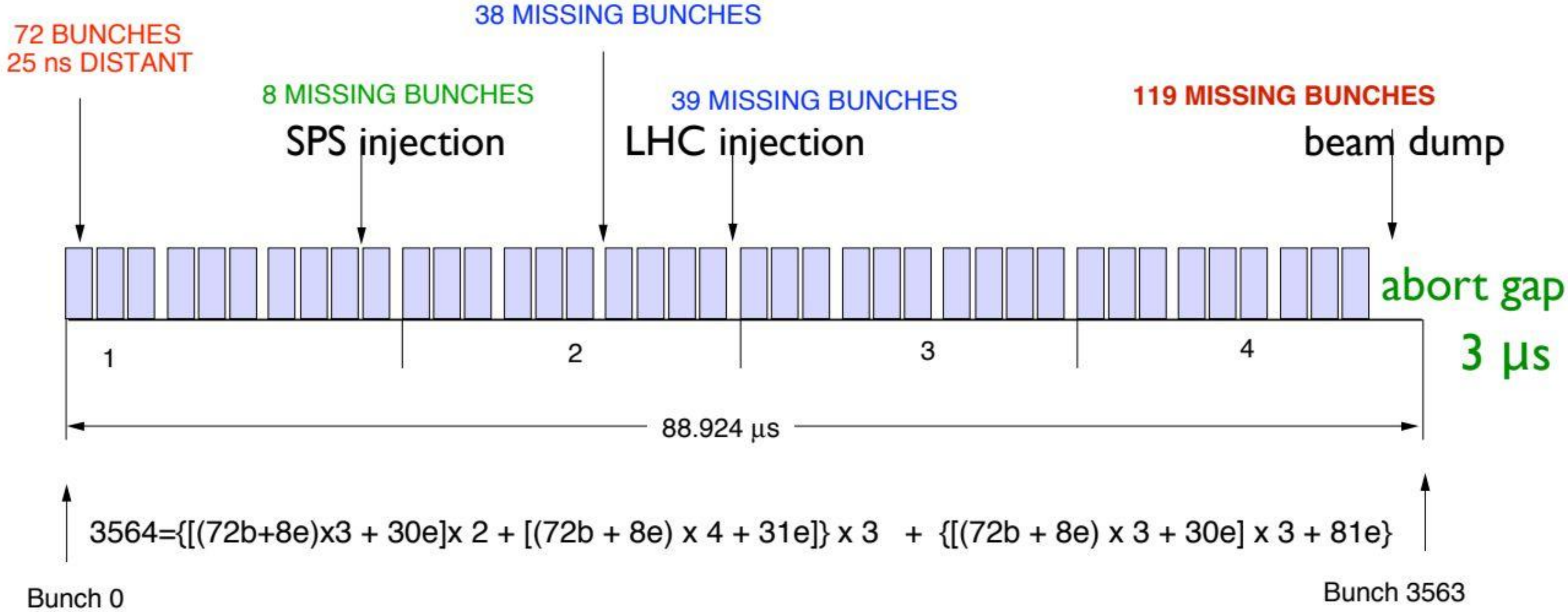
pp collisions:

$\sqrt{s} = 14\ \text{TeV}$

$L = 10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$



LHC Bunch Structure



Harmonic 84 = PS orbit is divided into 84 time slices or "buckets"

PS SPS LHC

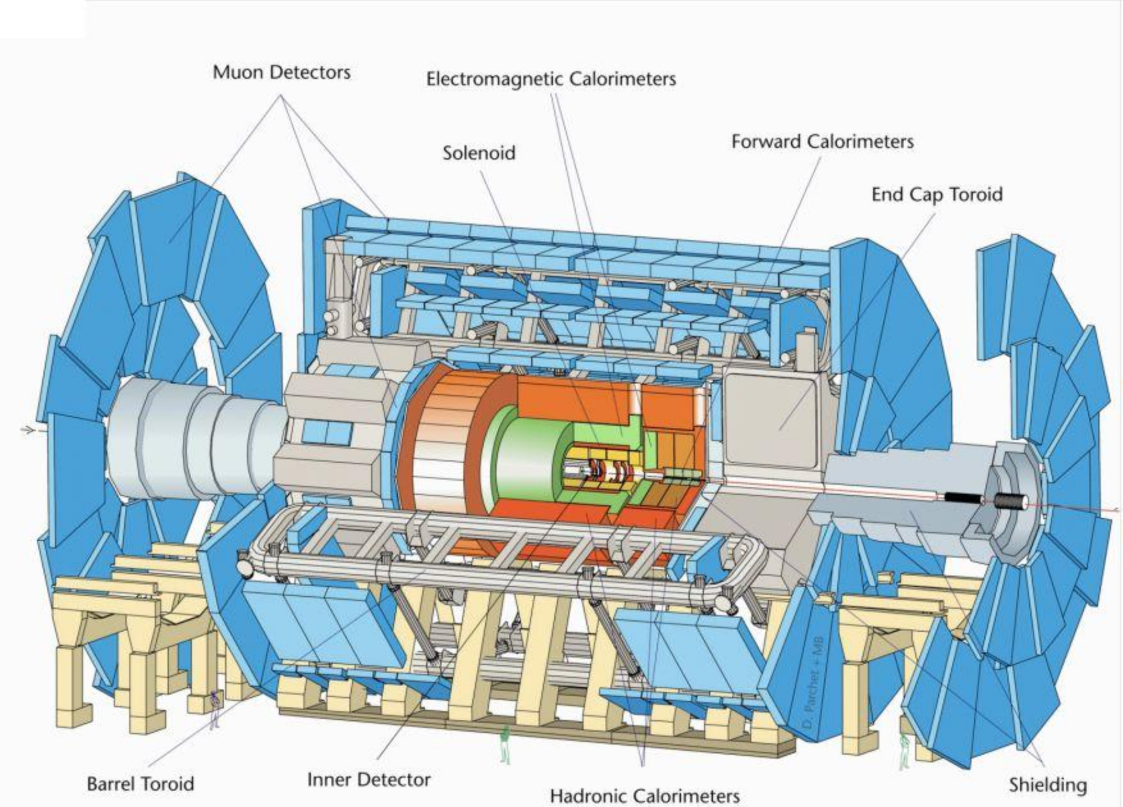
$$(84)(11)\left(\frac{27}{7}\right) = 3564$$ # of buckets in LHC

$$\frac{88924 \text{ ns}}{3564} = 24.95 \text{ ns}$$ bucket size in LHC

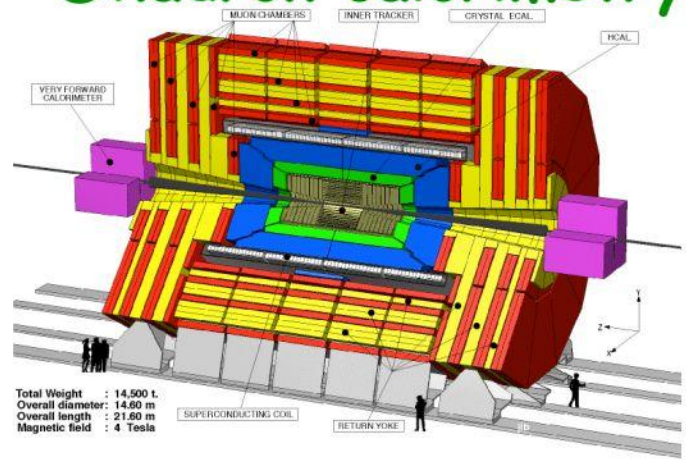
only 2808 buckets in known pattern have protons

40.079 MHz crossing frequency

Detectors: Overview

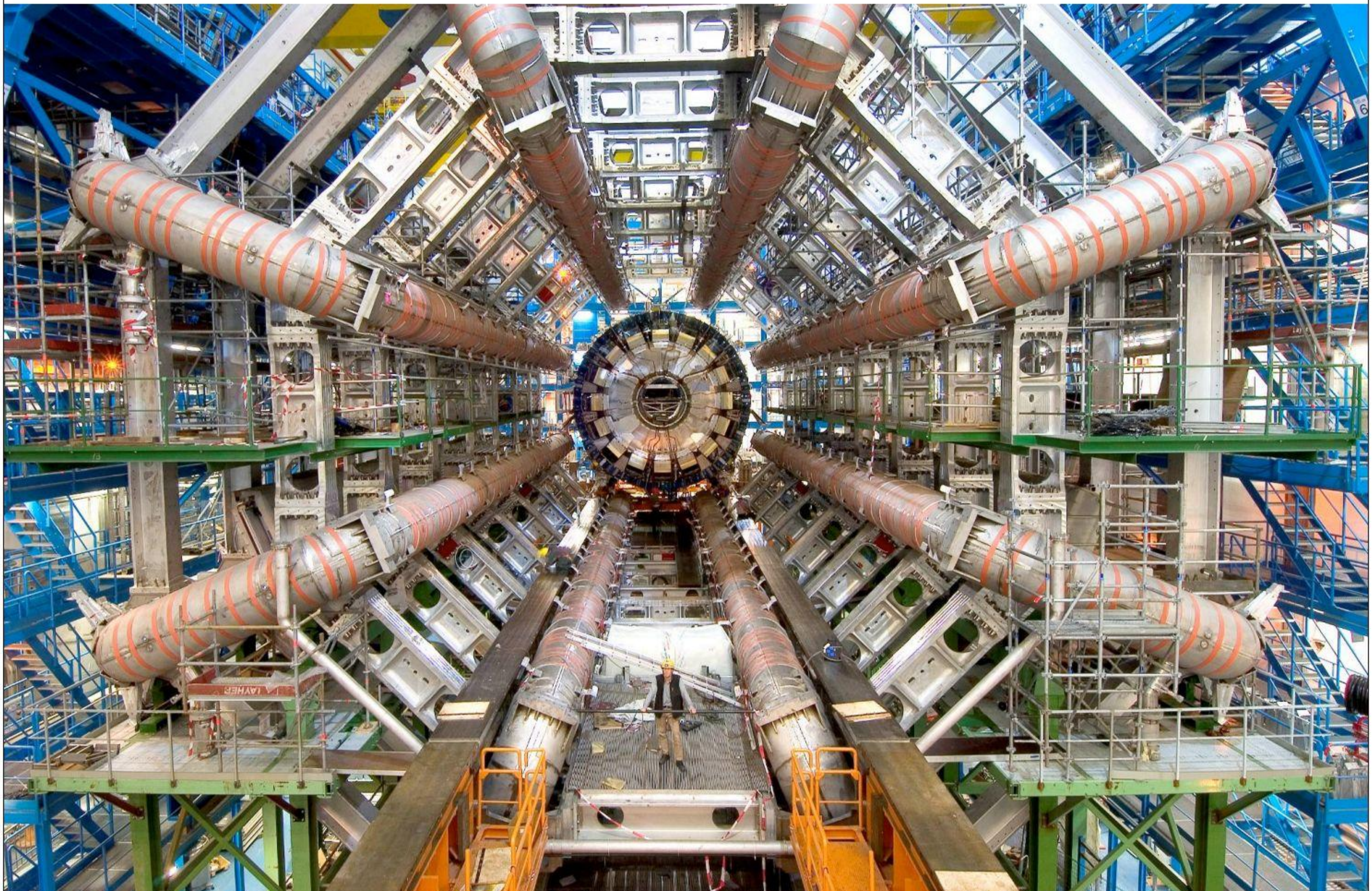


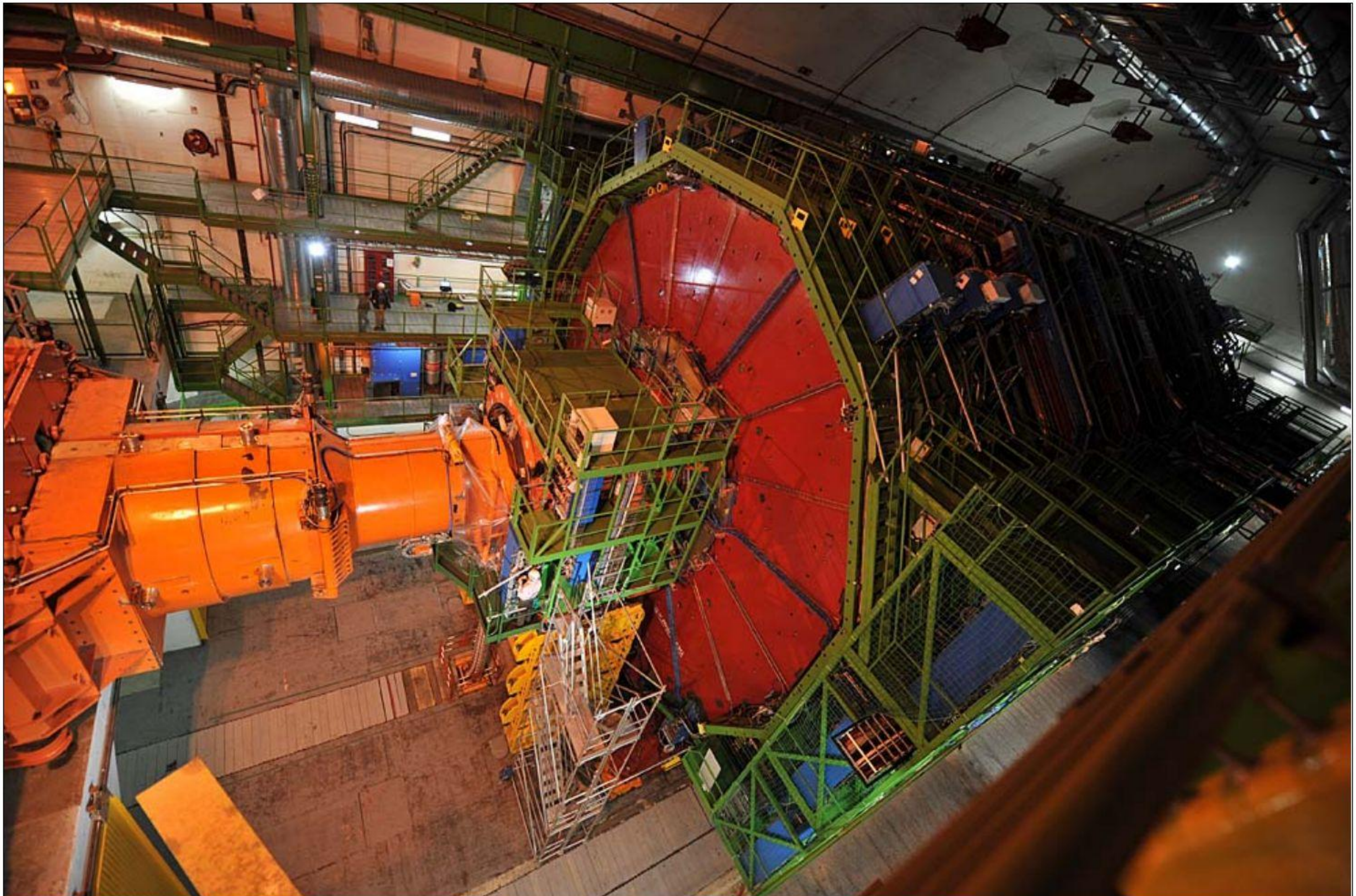
- muon detectors
- tracking in B field
- EM calorimetry
- hadron calorimetry



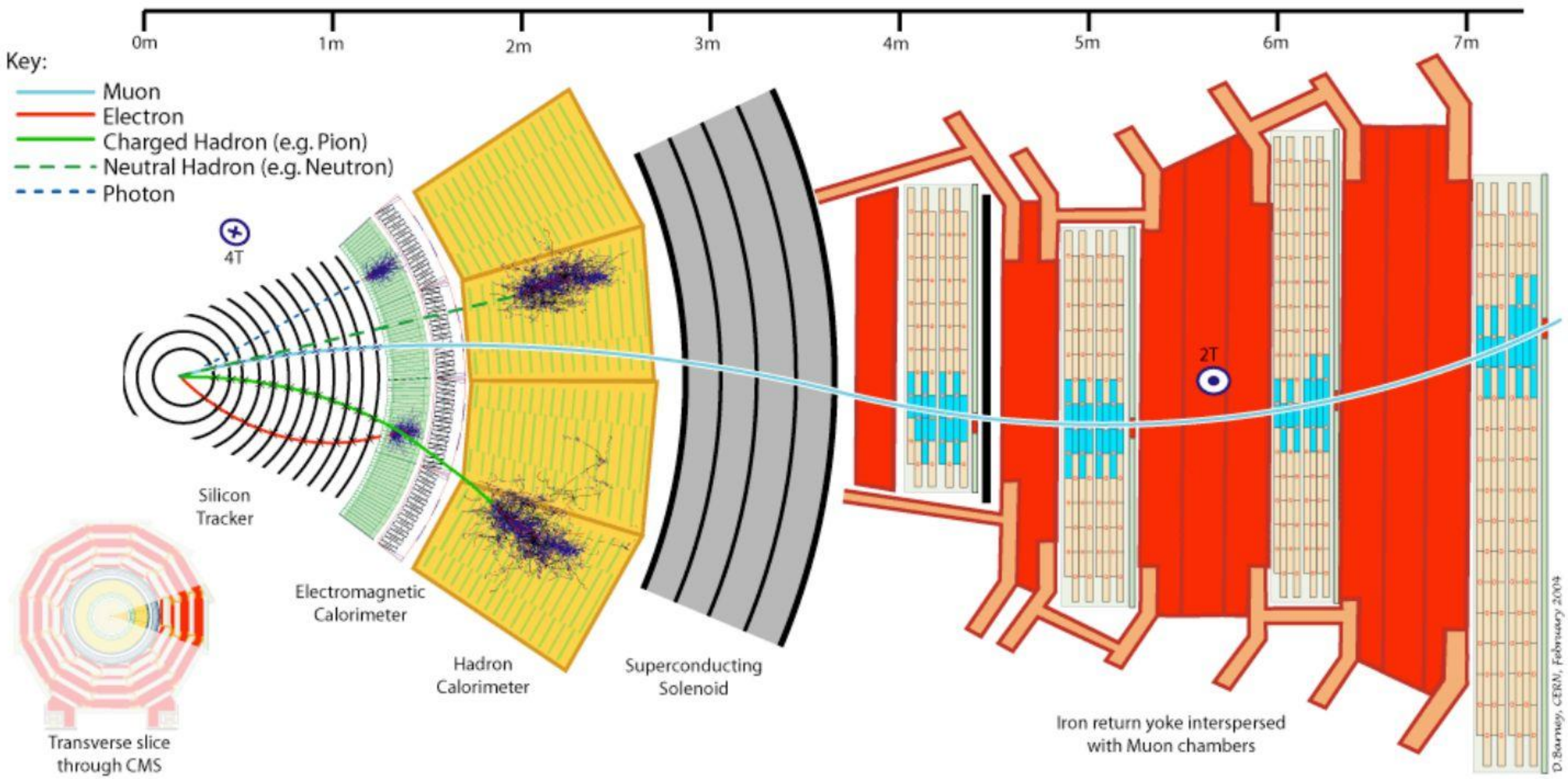
A Toroidal Large hadron collider AparatuS (ATLAS)
7 kTons 0.5 T toroid,
2 T solenoid, $(25\ \mathrm{m})^2 \times 46$ m
magnet=40% of $$,
good stand-alone muon res.

Compact Muon Solenoid (CMS) 14 kTons
4 T solenoid,
$(15\ \mathrm{m})^2 \times 22$ m
magnet=25% of $$,
high res.tracker & ECAL

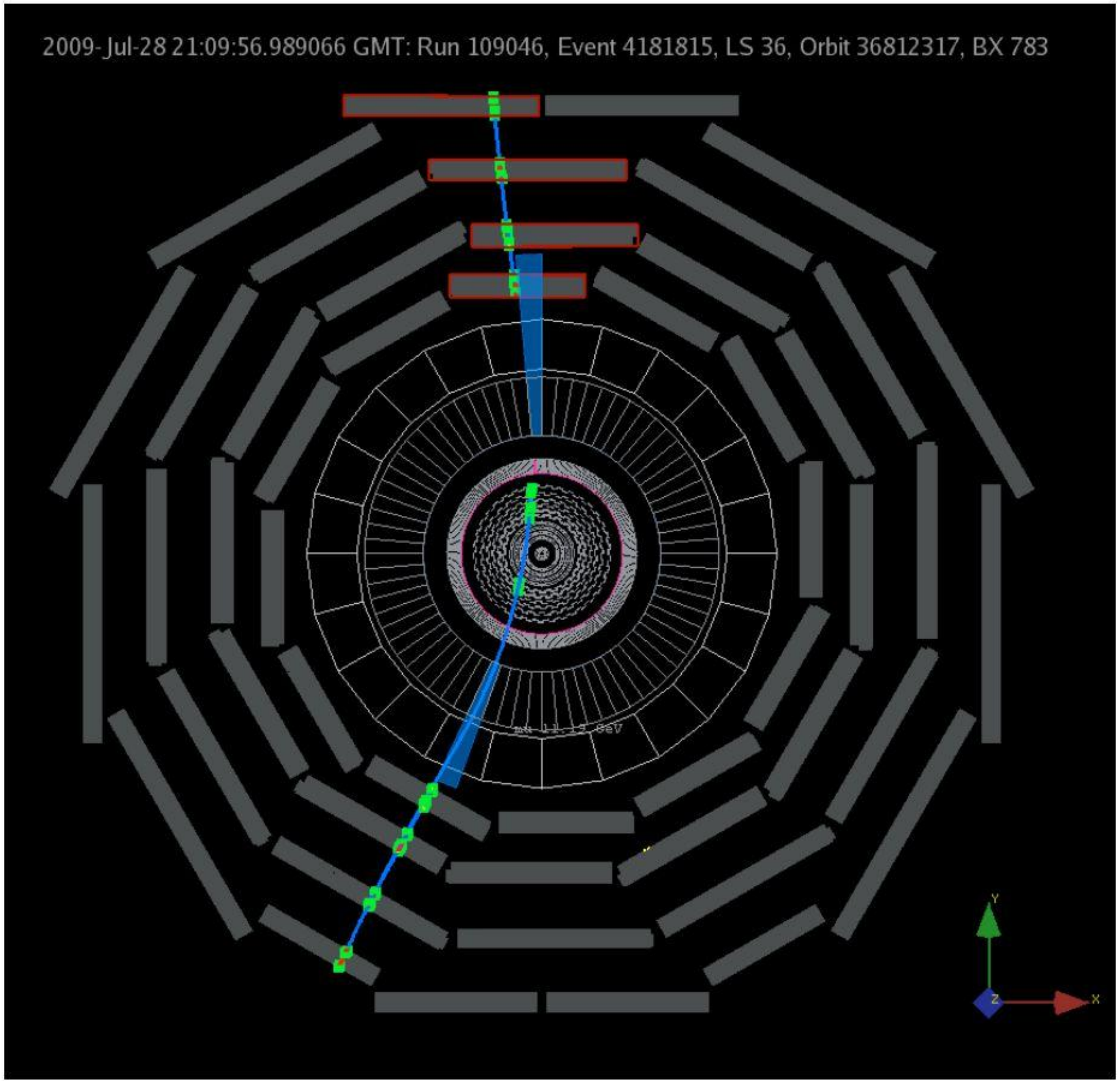




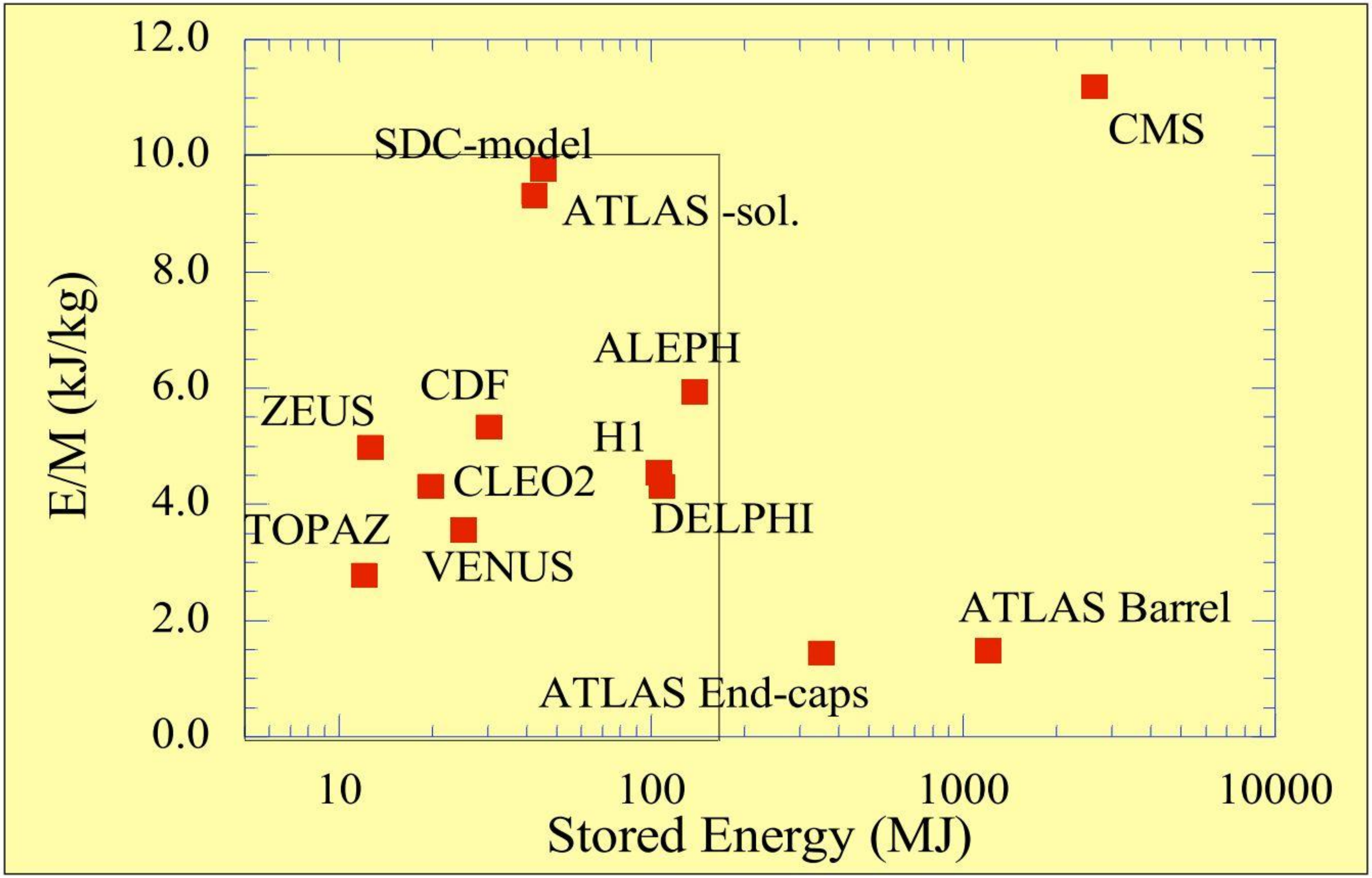
CMS Slice


0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

CRAFT09 Cosmic Muon event

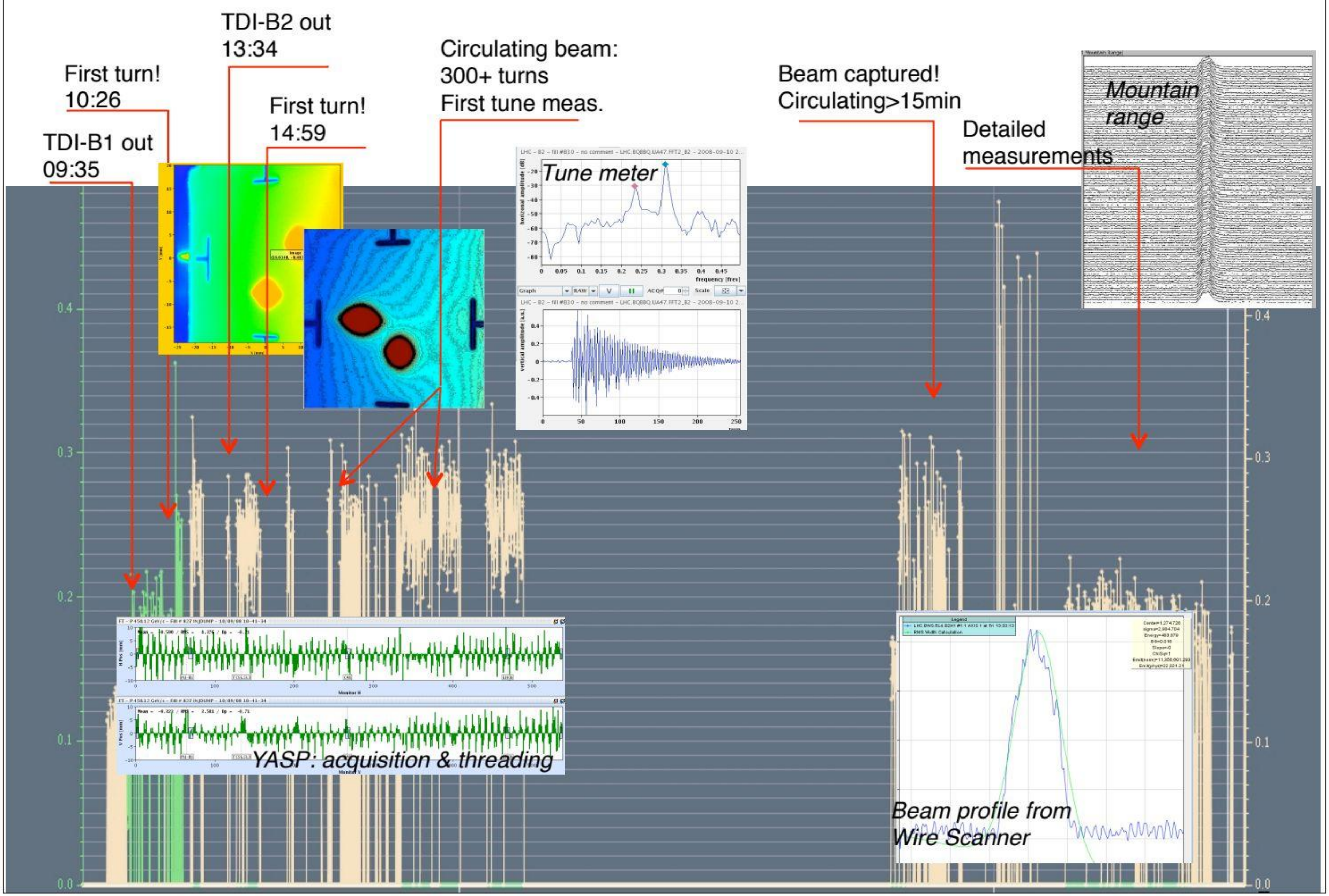


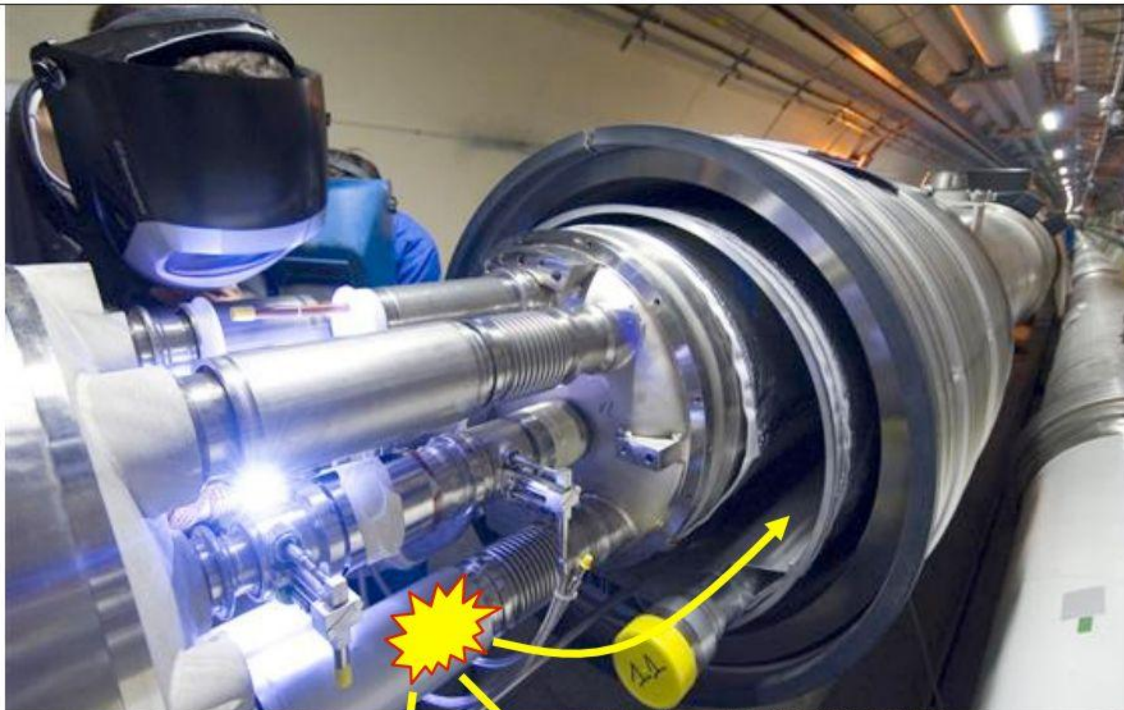
Specific Energy (kJ/kg of cold mass)



BEAM COMMISSIONING IN 2008: SEPTEMBER 10

60 HOURS OF BEAM OPERATION

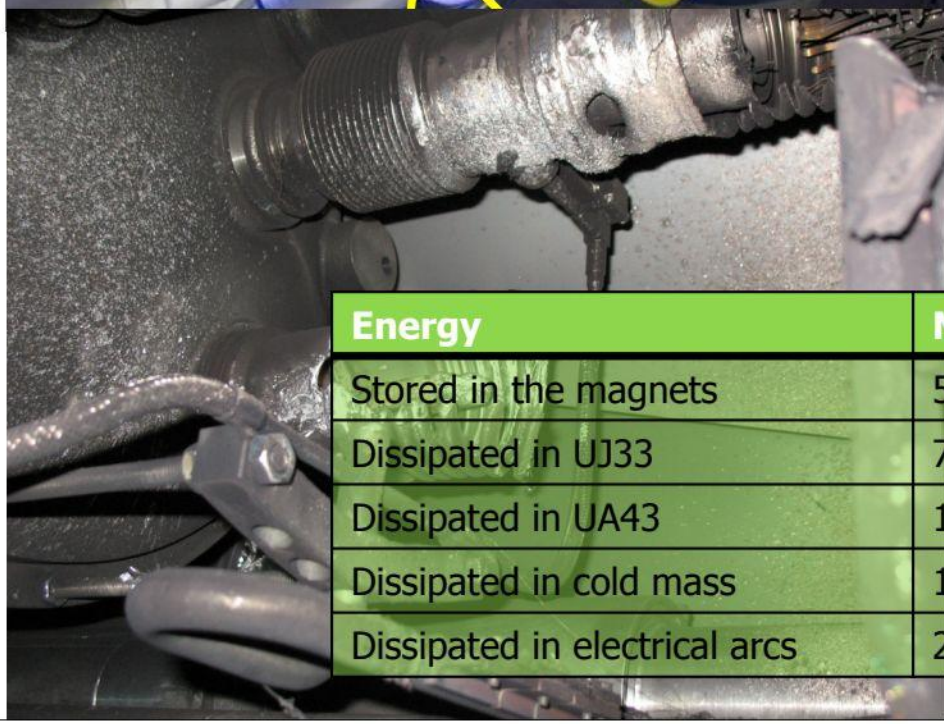


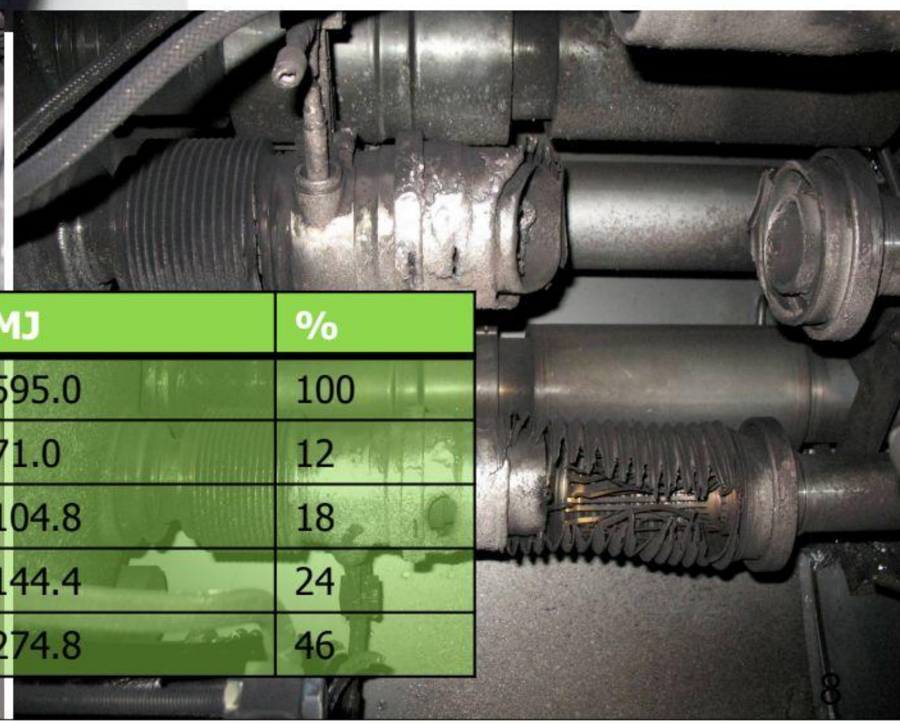


THE DYNAMICS

Electrical arc developed which punctured the helium enclosure, producing helium release into the insulation vacuum

Large pressure wave travelled along the accelerator in both directions



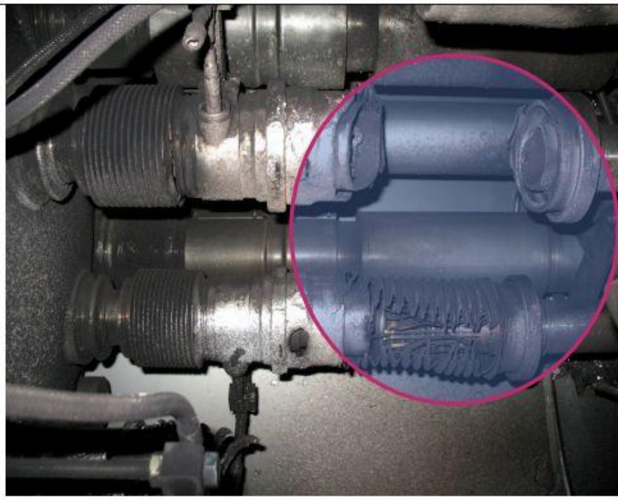


Energy	MJ	%
Stored in the magnets	595.0	100
Dissipated in UJ33	71.0	12
Dissipated in UA43	104.8	18
Dissipated in cold mass	144.4	24
Dissipated in electrical arcs	274.8	46

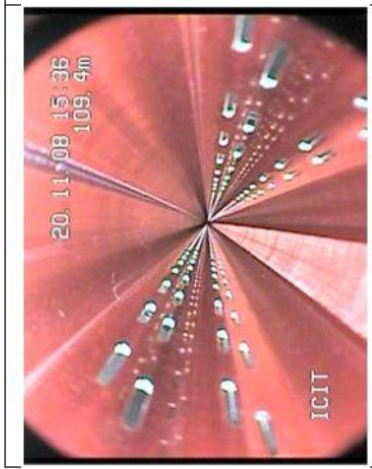
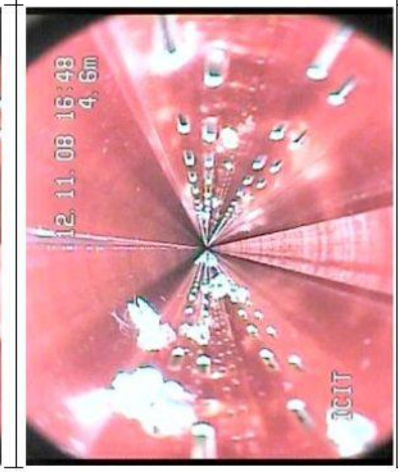
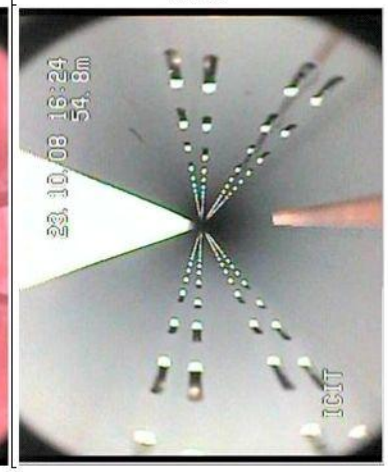
COLLATERAL DAMAGE: MAGNET DISPLACEMENTS

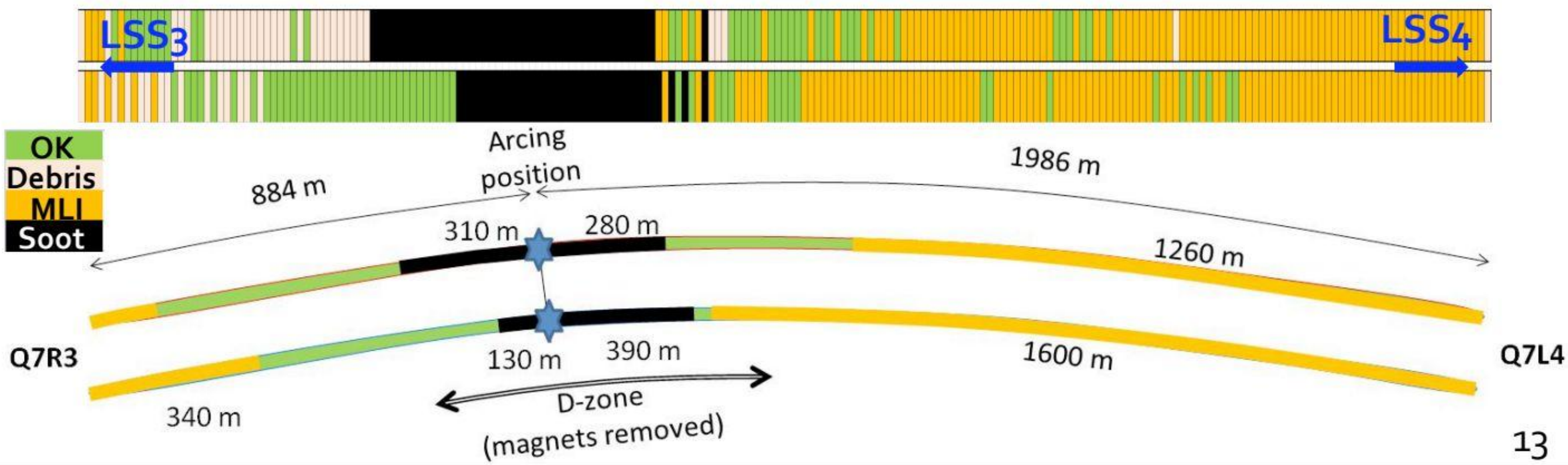
COLLATERAL DAMAGE: SECONDARY ARCS

COLLATERAL DAMAGE: BEAM VACUUM



The beam pipes were polluted with thousands of pieces of MLI and soot, from one extremity to the other of the sector

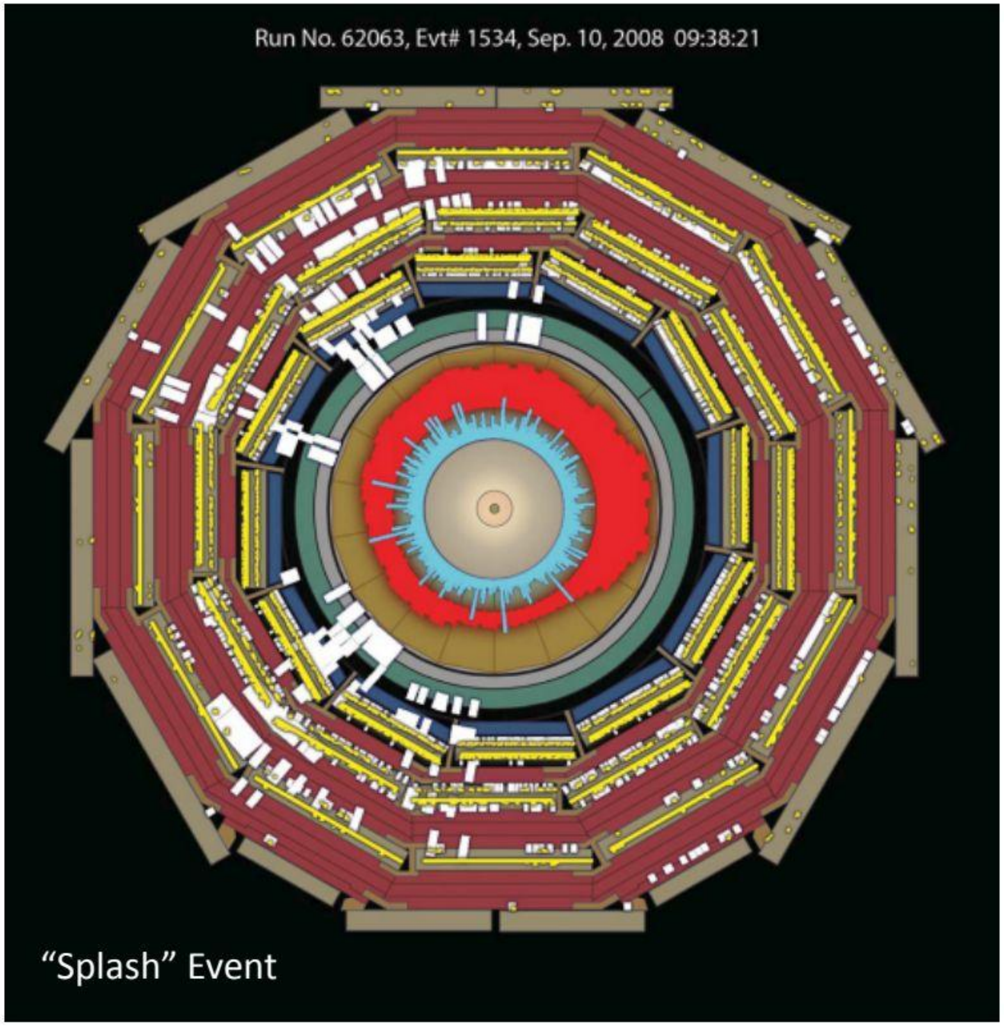
Beam Screen (BS) : The red color is characteristi c of a clean copper surface	BS with some contaminati on by super-isolati on (MLI multi layer insulati on)	BS with soot contaminati on. The grey color varies depending on the thickness of the soot, from grey to dark.
		

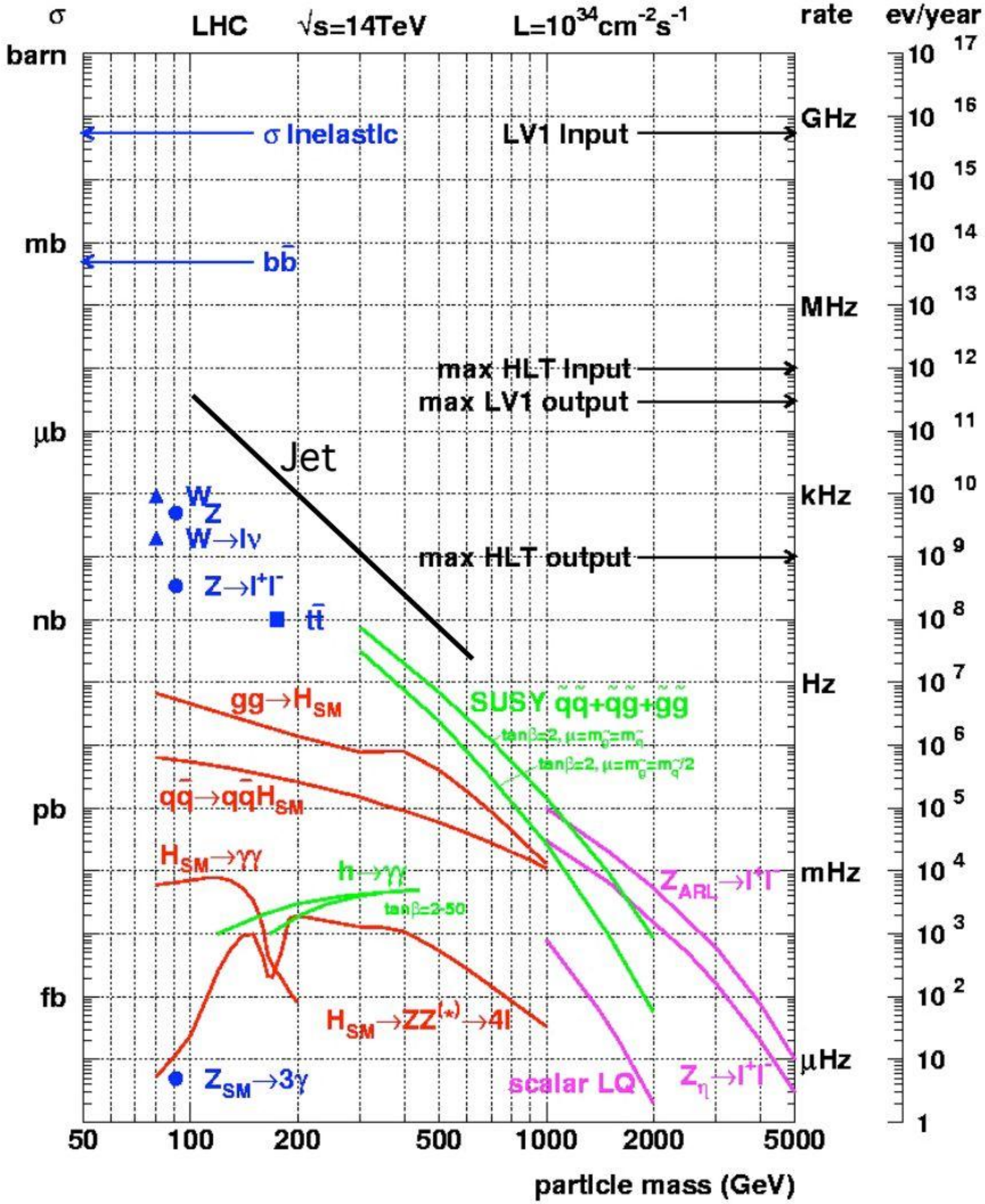


First LHC Beam in 2008

Data-taking with LHC beam.

- **Wed, 10 Sept. 2008**
  - "Splash" events observed when beam (450 GeV, 4×10^9 p) struck collimators 150m upstream of CMS
  - Halo muons observed once beam (uncaptured and captured) started passing through CMS





Data Recording Rate

L1 hardware
leptons, jets, MET
→100 kHz

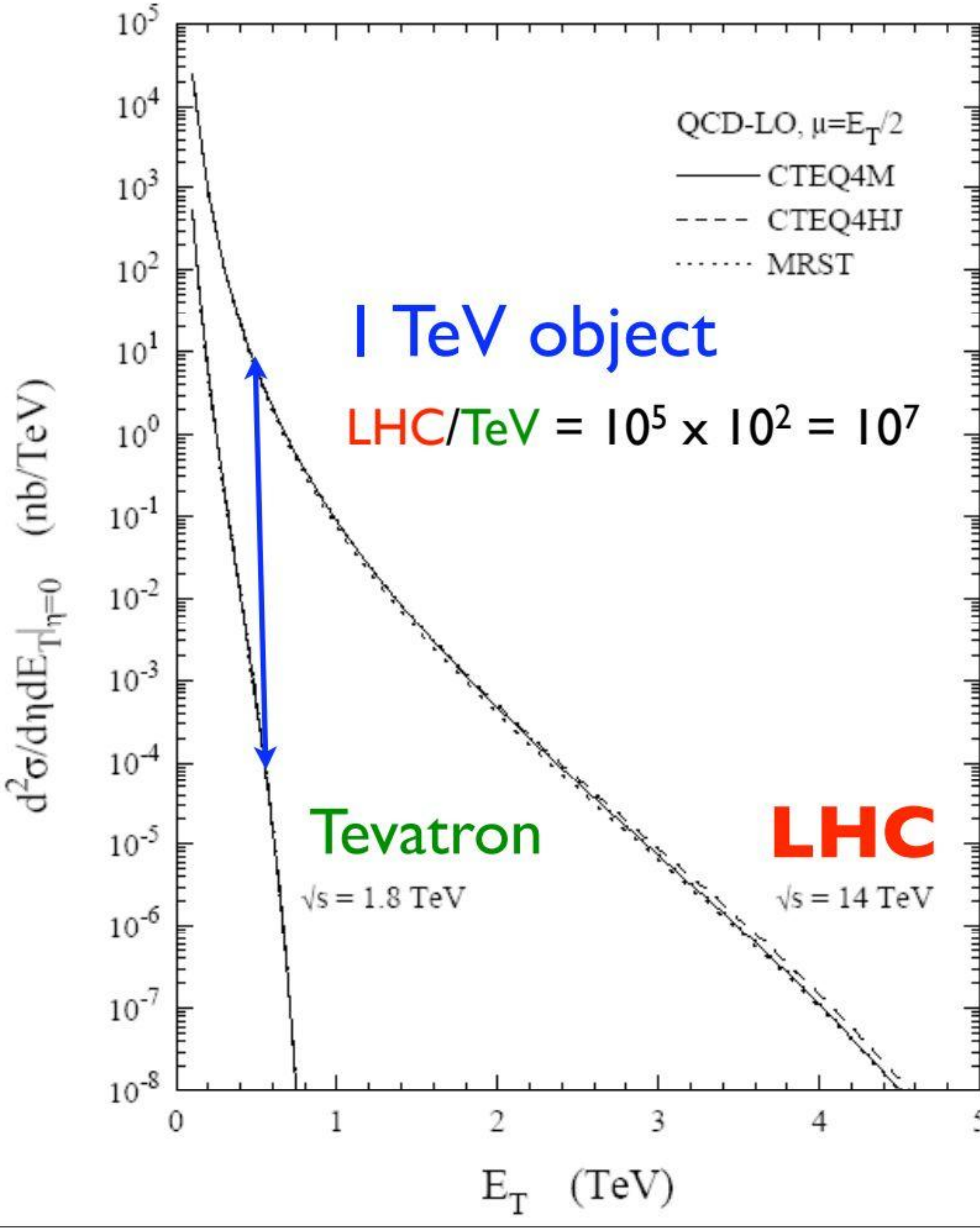
HLT software
→100-200 Hz

$(500\ s^{-1})(2\ \text{MByte}) =$ GByte/s

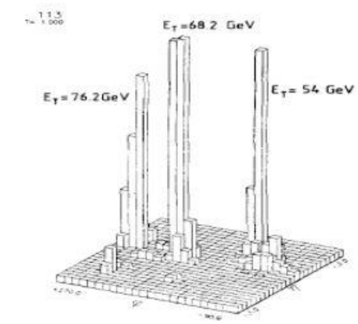
1 CD per second

10^{17} bits per year

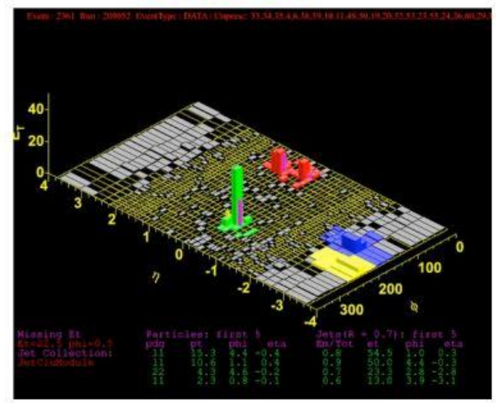
Jet Cross Section

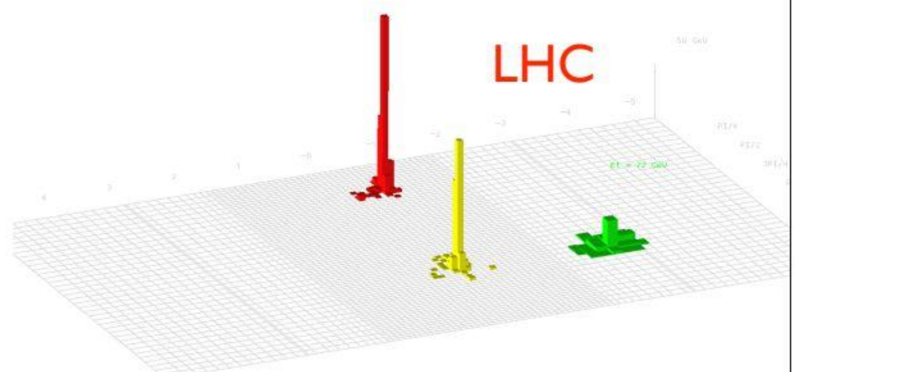


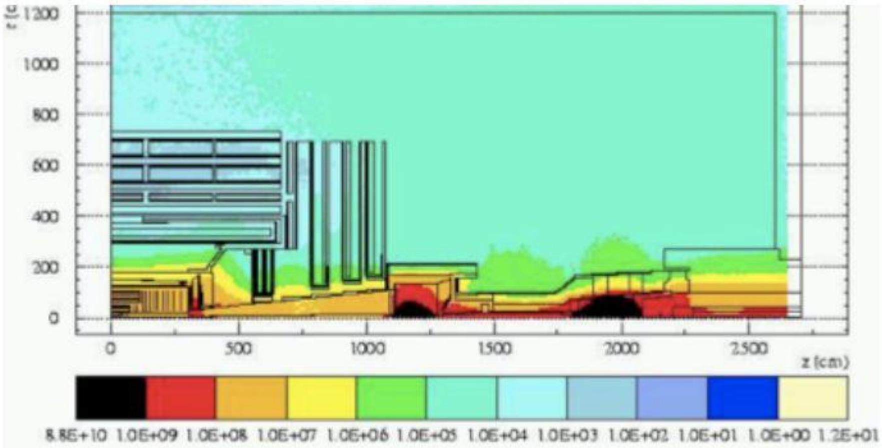
CERN SPS



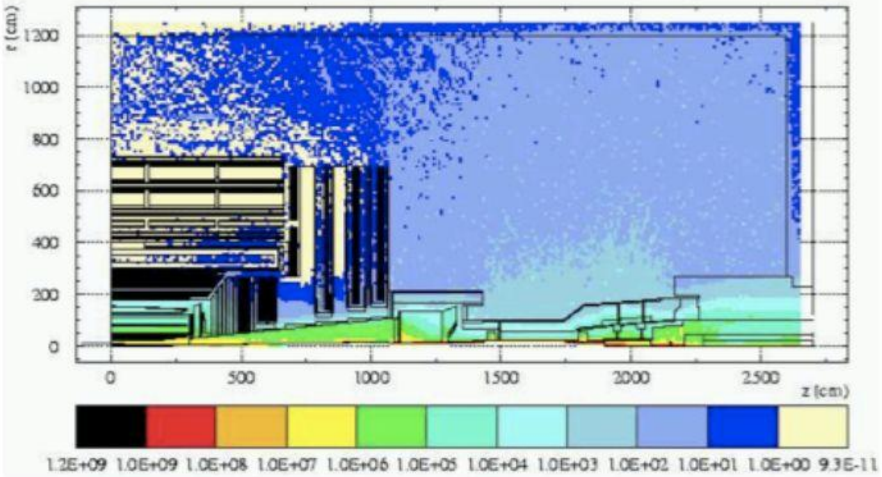
Tevatron







neutron flux

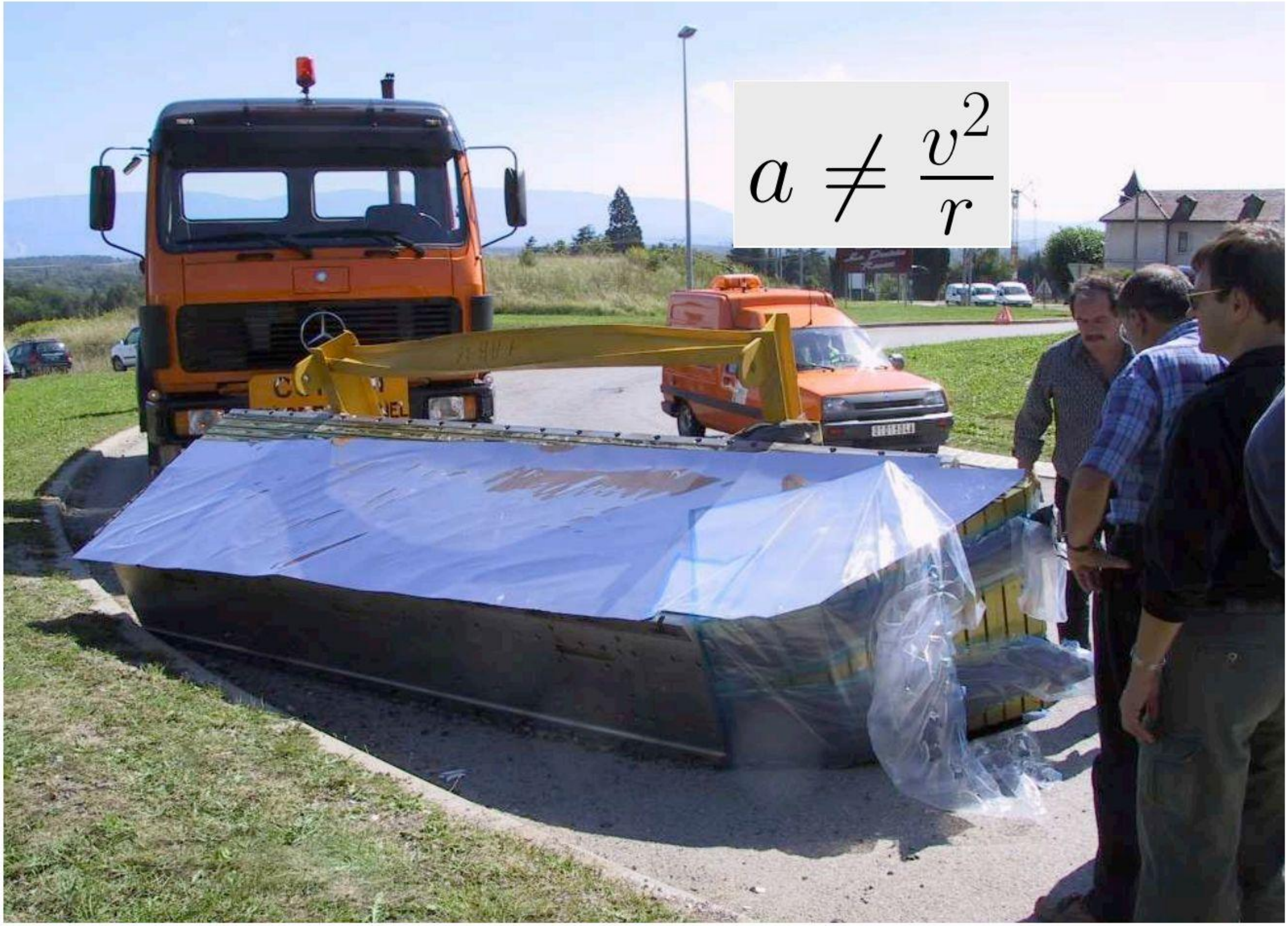


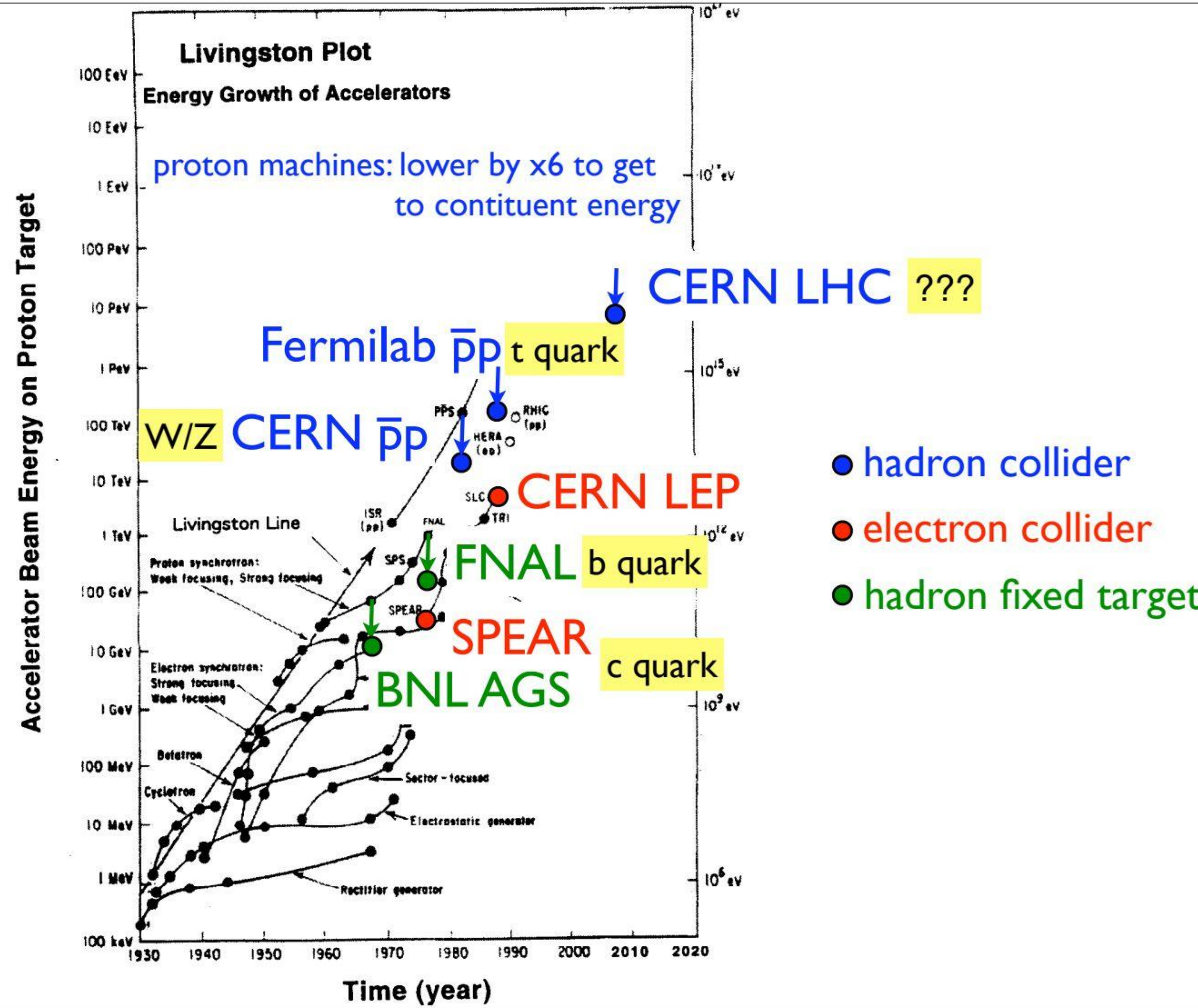
dose (Gy=J/kg absorbed)
2500 fb^{-1}

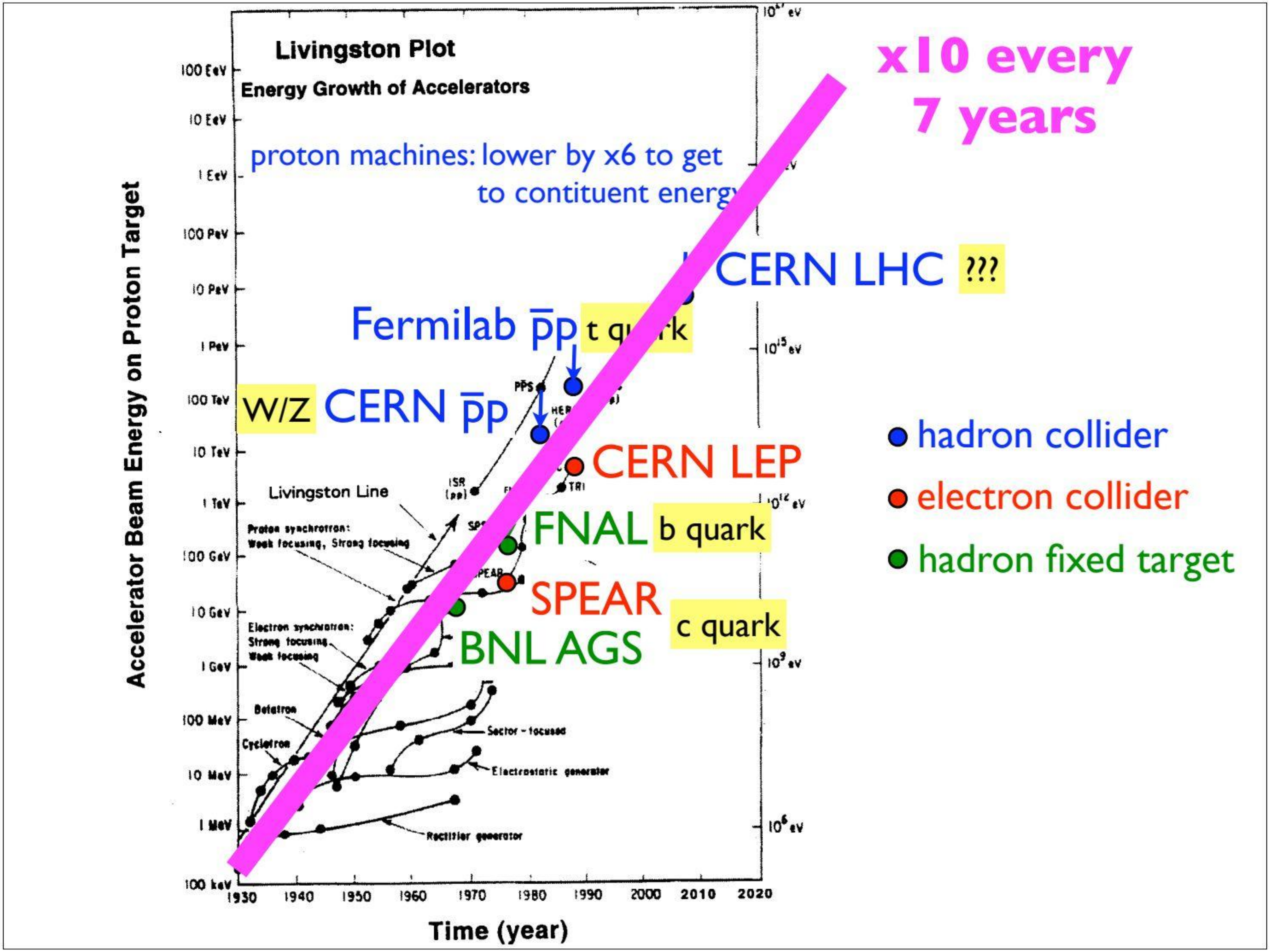
$$d \sim \frac{\hbar}{p} \simeq \frac{0.2\ \mathrm{GeV{\cdot}fm}}{2\ \mathrm{TeV}} = 10^{-19}\ \mathrm{m}$$

The LHC is going to take us down to a distance scale of 10^{-19} m. We expect to settle once and for all the existence (or not) of the higgs boson. Most of all, we hope to see something nobody has thought of yet.

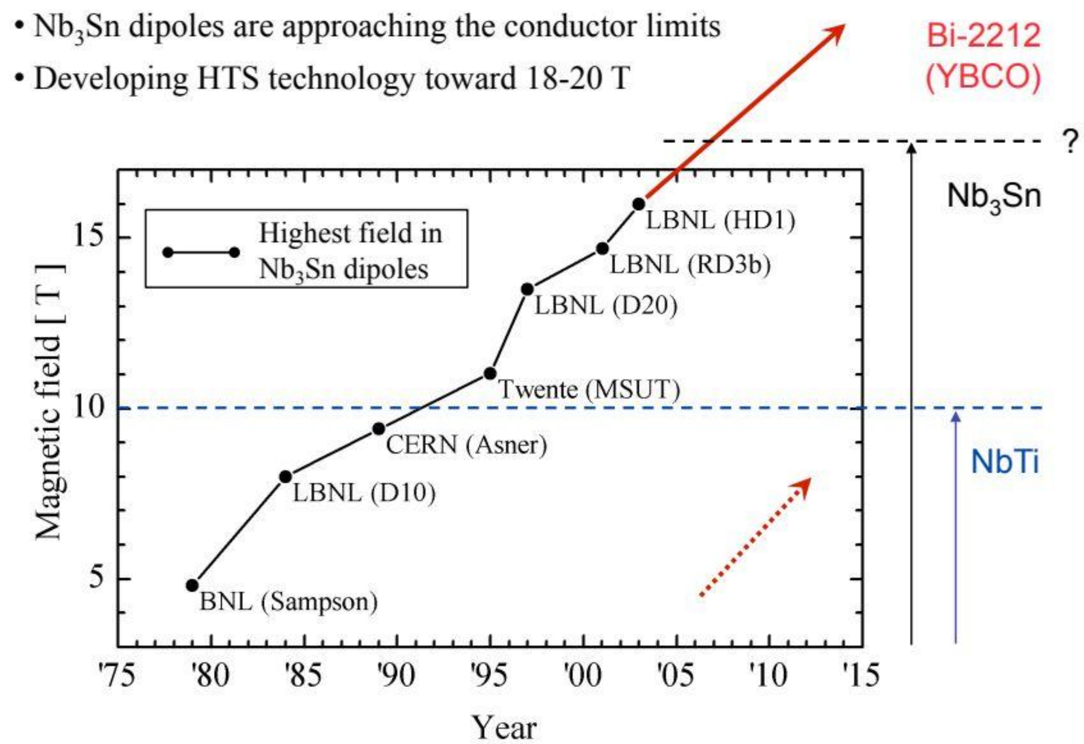
Physics will not go as planned...




Livingston Plot
Energy Growth of Accelerators
proton machines: lower by x6 to get to contituent energy
CERN LHC
???
Fermilab p̄p
t quark
W/Z
CERN p̄p
CERN LEP
FNAL
b quark
SPEAR
c quark
BNL AGS
Livingston Line
Proton synchrotron: Weak focusing, Strong focusing
Electron synchrotron: Strong focusing, Weak focusing
Betatron
Cyclotron
Sector - focused
Electrostatic generator
Rectifier generator
Accelerator Beam Energy on Proton Target
Time (year)
hadron collider
electron collider
hadron fixed target


Livingston Plot
Energy Growth of Accelerators
proton machines: lower by x6 to get to contituent energy
x10 every 7 years
CERN LHC ???
Fermilab p̄p t quark
W/Z CERN p̄p
CERN LEP
FNAL b quark
SPEAR c quark
BNL AGS
hadron collider
electron collider
hadron fixed target
Livingston Line
Proton synchrotron: Weak focusing, Strong focusing
Electron synchrotron: Strong focusing, Weak focusing
Betatron
Cyclotron
Sector - focused
Electrostatic generator
Rectifier generator
Accelerator Beam Energy on Proton Target
Time (year)

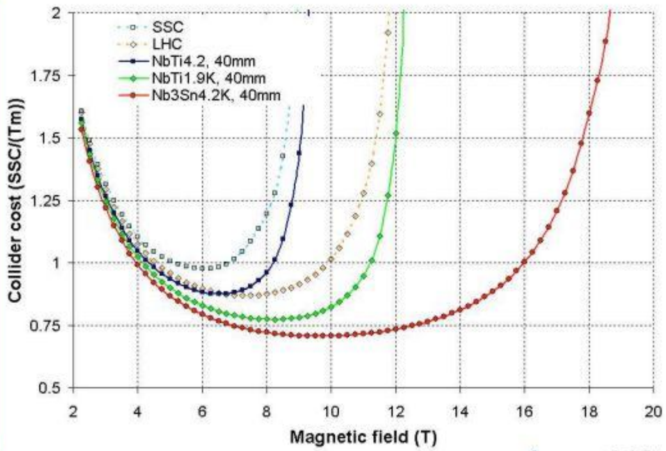
Progress in Maximum Dipole Field

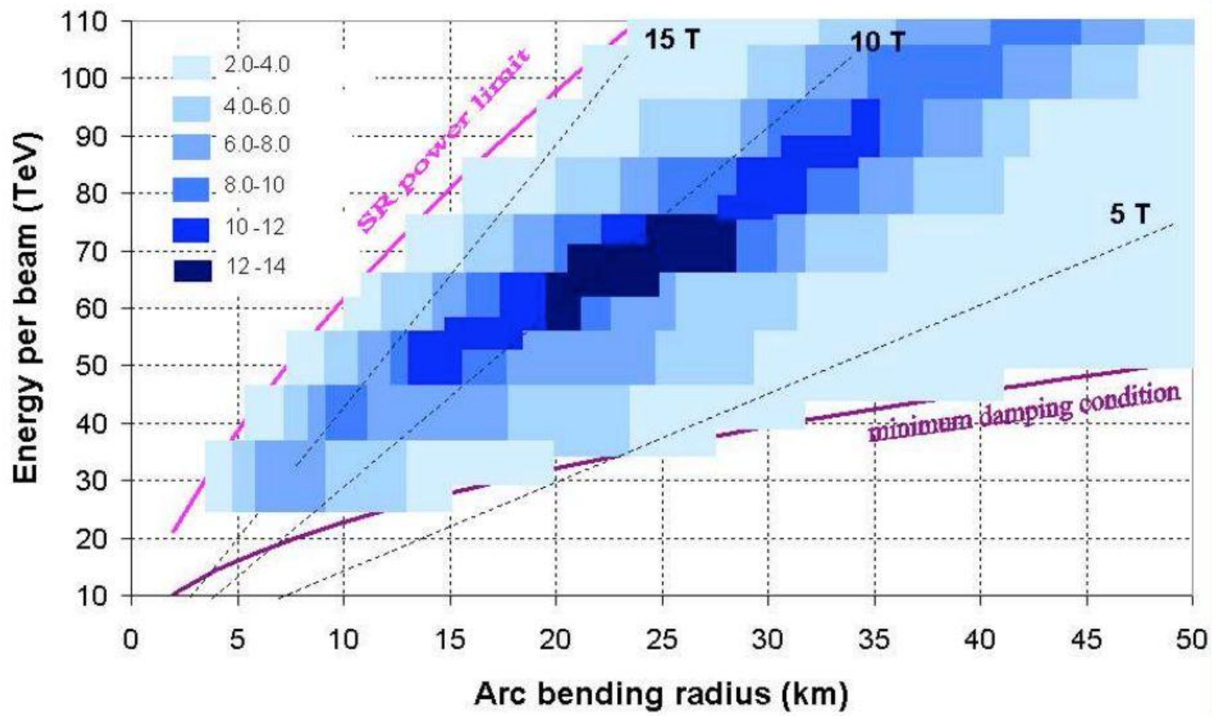


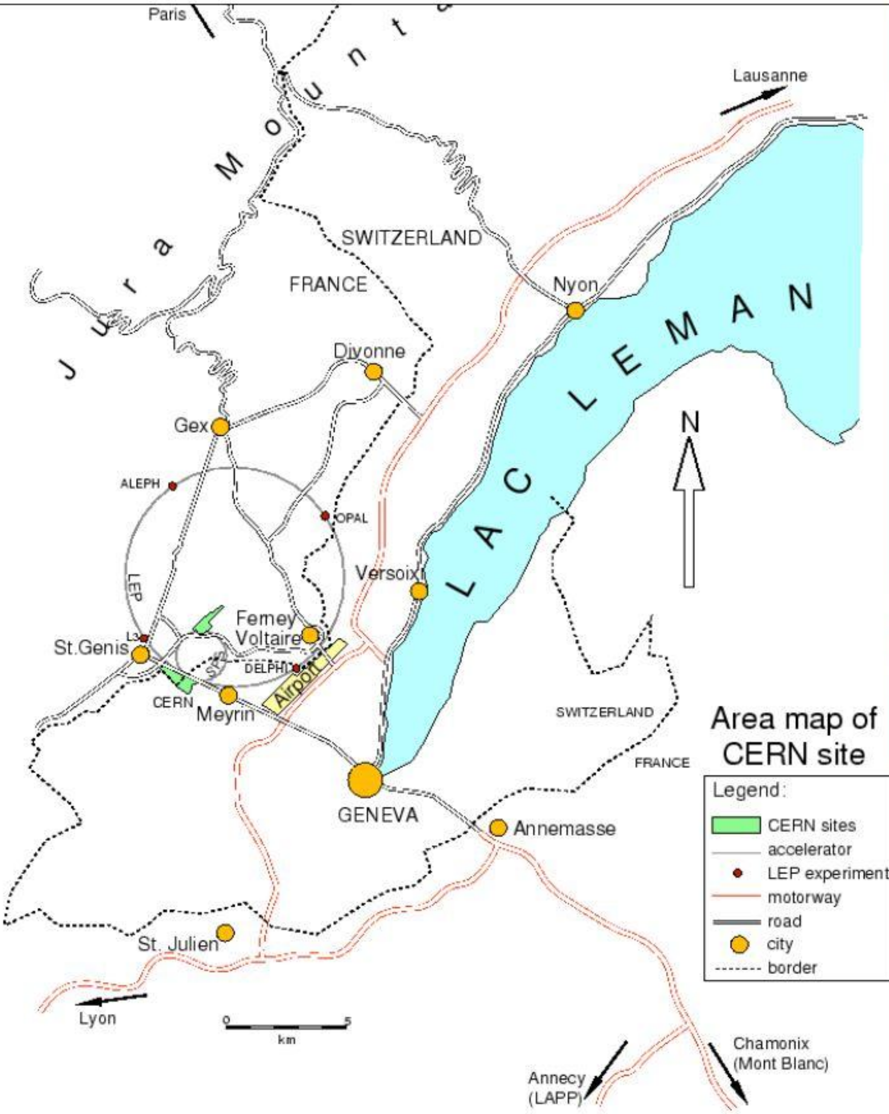
G. Sabbi, Berkeley, 26 Sept. 2009

Note: radius of CERN tunnel is (using $p = erB$)

$$pc/B = erc = e(\frac{26\times10^3\ \mathrm{m}}{2\pi})(3\times10^8\ \mathrm{m/s})(\frac{\mathrm{V}}{\mathrm{T\cdot m^2/s}}) \sim \ 1\ \mathrm{TeV/T}$$

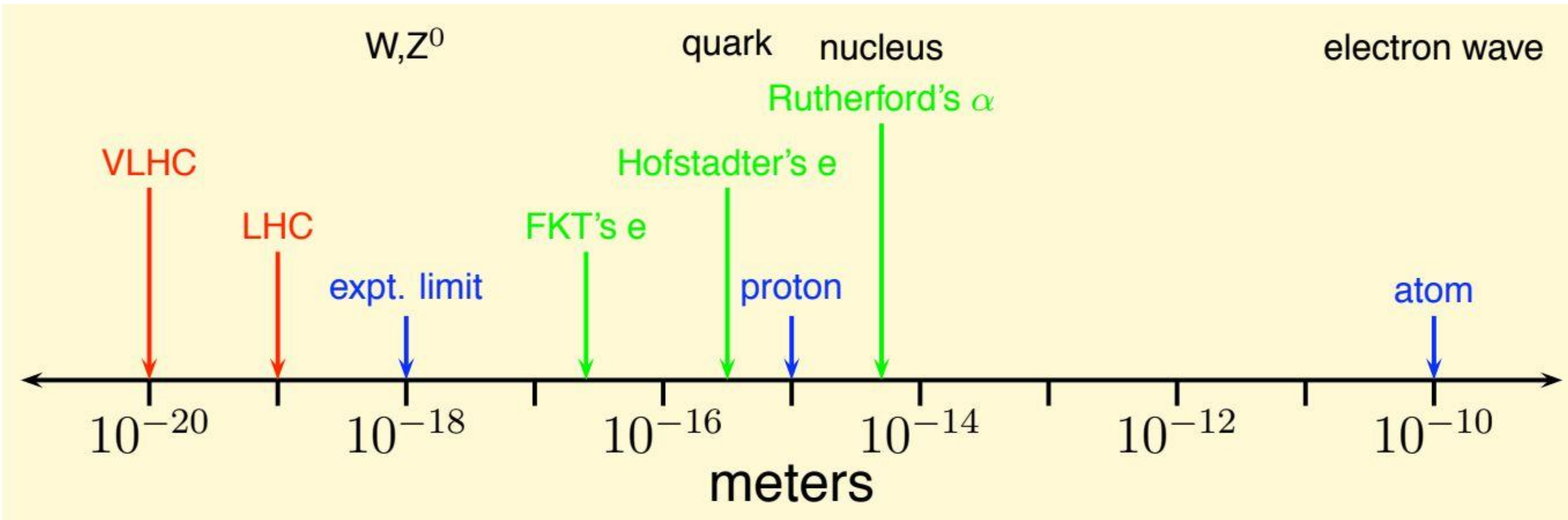

SSC
LHC
NbTi4.2, 40mm
NbTi1.9K, 40mm
Nb3Sn4.2K, 40mm
Collider cost (SSC/(Tm))
Magnetic field (T)


2.0-4.0
4.0-6.0
6.0-8.0
8.0-10
10-12
12-14
SR power limit
15 T
10 T
5 T
minimum damping condition
Energy per beam (TeV)
Arc bending radius (km)


Area map of
CERN site
Legend:
CERN sites
accelerator
LEP experiment
motorway
road
city
border
Paris
Lausanne
Jura Mountains
SWITZERLAND
FRANCE
Nyon
Divonne
Gex
ALEPH
OPAL
LEP
Versoix
LAC LEMAN
N
Ferney
Voltaire
St.Genis
L3
DELPHI
Airport
CERN
Meyrin
SWITZERLAND
FRANCE
GENEVA
Annemasse
St. Julien
Lyon
0
5
km
Annecy
(LAPP)
Chamonix
(Mont Blanc)


FRANCE
Biel
Neuchâtel
BERN
JURA
Fribourg
Lac de
Neuchâtel
Lausanne
Lake
Geneva
Geneva
Dufourspitze

Summary


W,Z^0
quark
nucleus
electron wave
Rutherford's α
VLHC
Hofstadter's e
LHC
FKT's e
expt. limit
proton
atom
10^{-20}
10^{-18}
10^{-16}
10^{-14}
10^{-12}
10^{-10}
meters