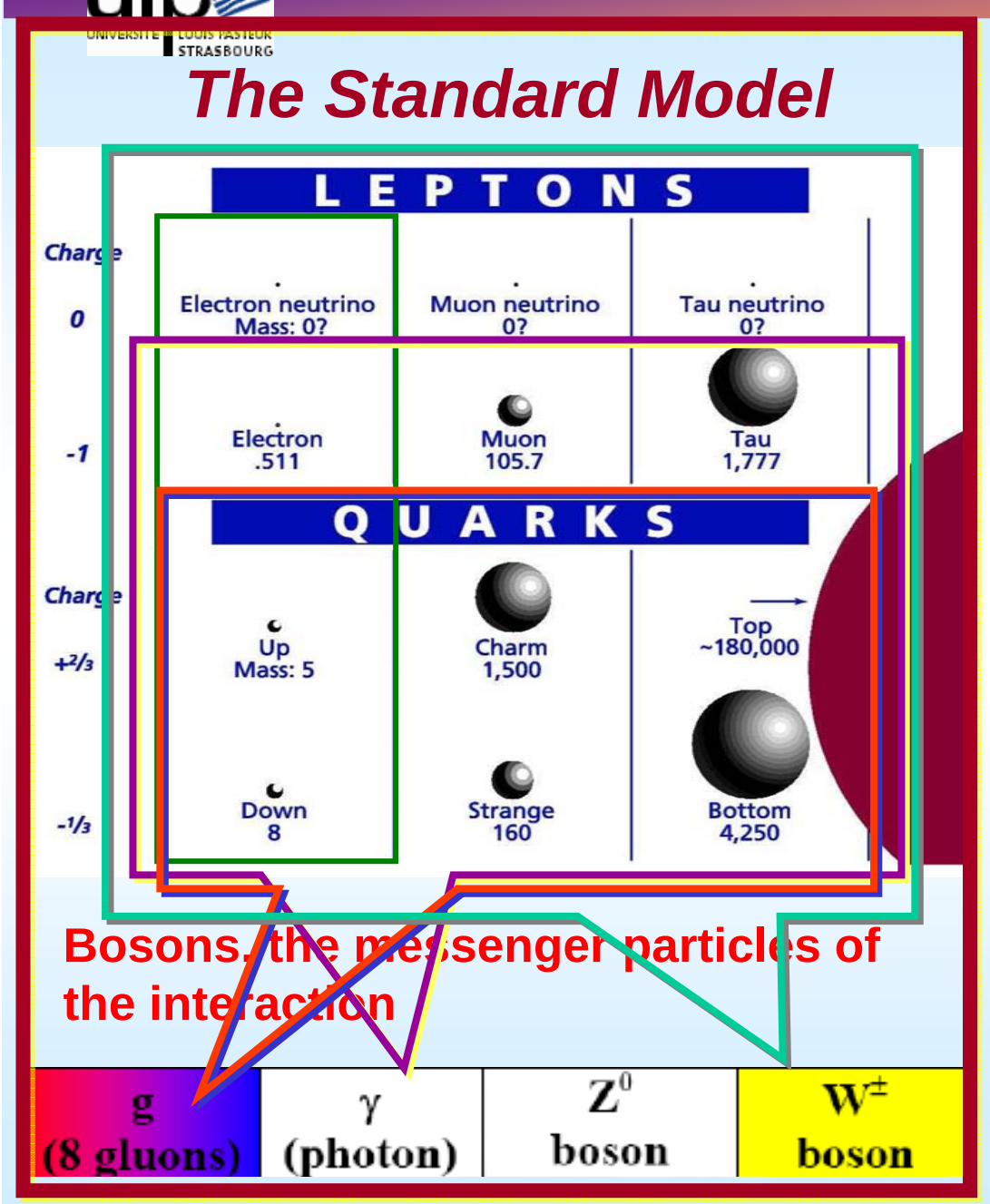
Gigantic Experiments at ever Larger Accelerators

Lecture at the European Summer University 2006
"Particles and the Universe"

- Instruments in Particle and Astrophysics
- Why so large? What do we want to observe and to measure?
- Accelerators and colliders

  "*today*": HERA, TEVATRON, LHC *and* "tomorrow": ILC, CLIC
- Some basics of particle detection
- Detector systems at a collider: the example LHC
- Large collaborations: Where are the students?
- Conclusions or recommendations

The Standard Model



Elementary Particles and their Interactions

Fermions (S=1/2)
3 "families"

Leptons (ν_e, e), (ν_μ, μ) (ν_τ, τ)

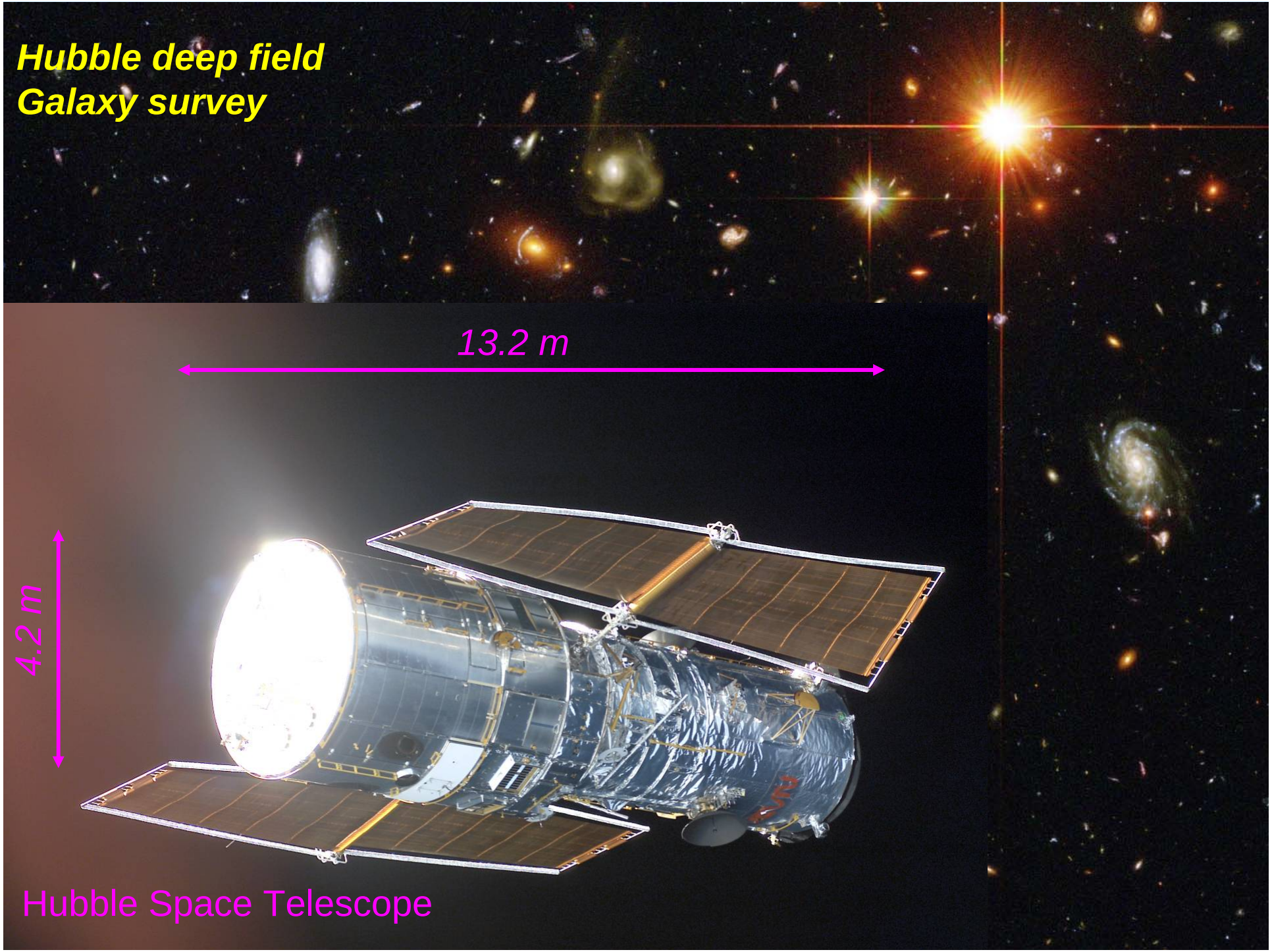
Quarks *(u,d), (c,s), (t,b)*

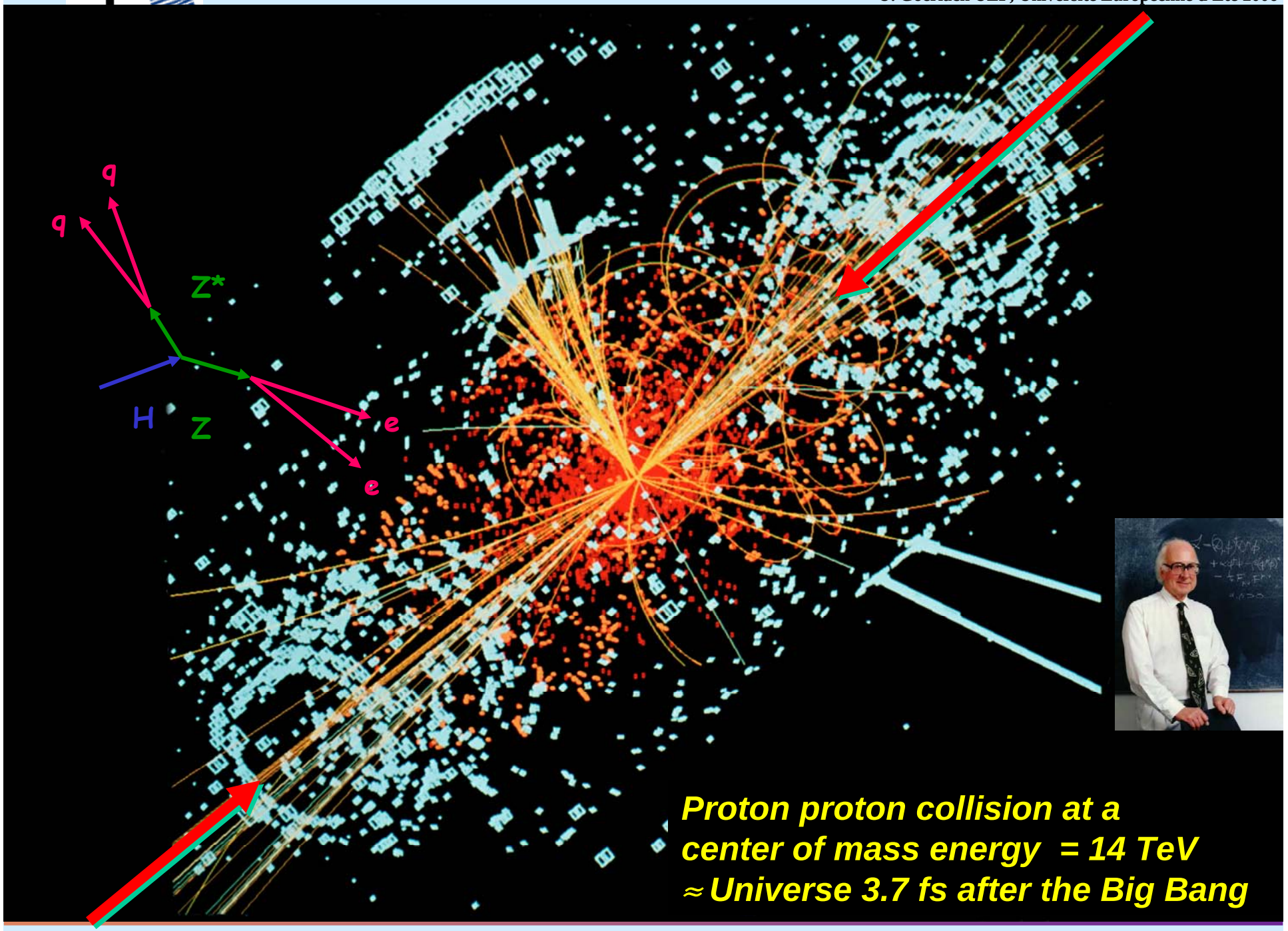
Electromagnetism
(el. charge, photons)

Strong interaction
("colour"-charge, gluons)

Weak interaction
(weak charge, Z^0, $W^\pm$)

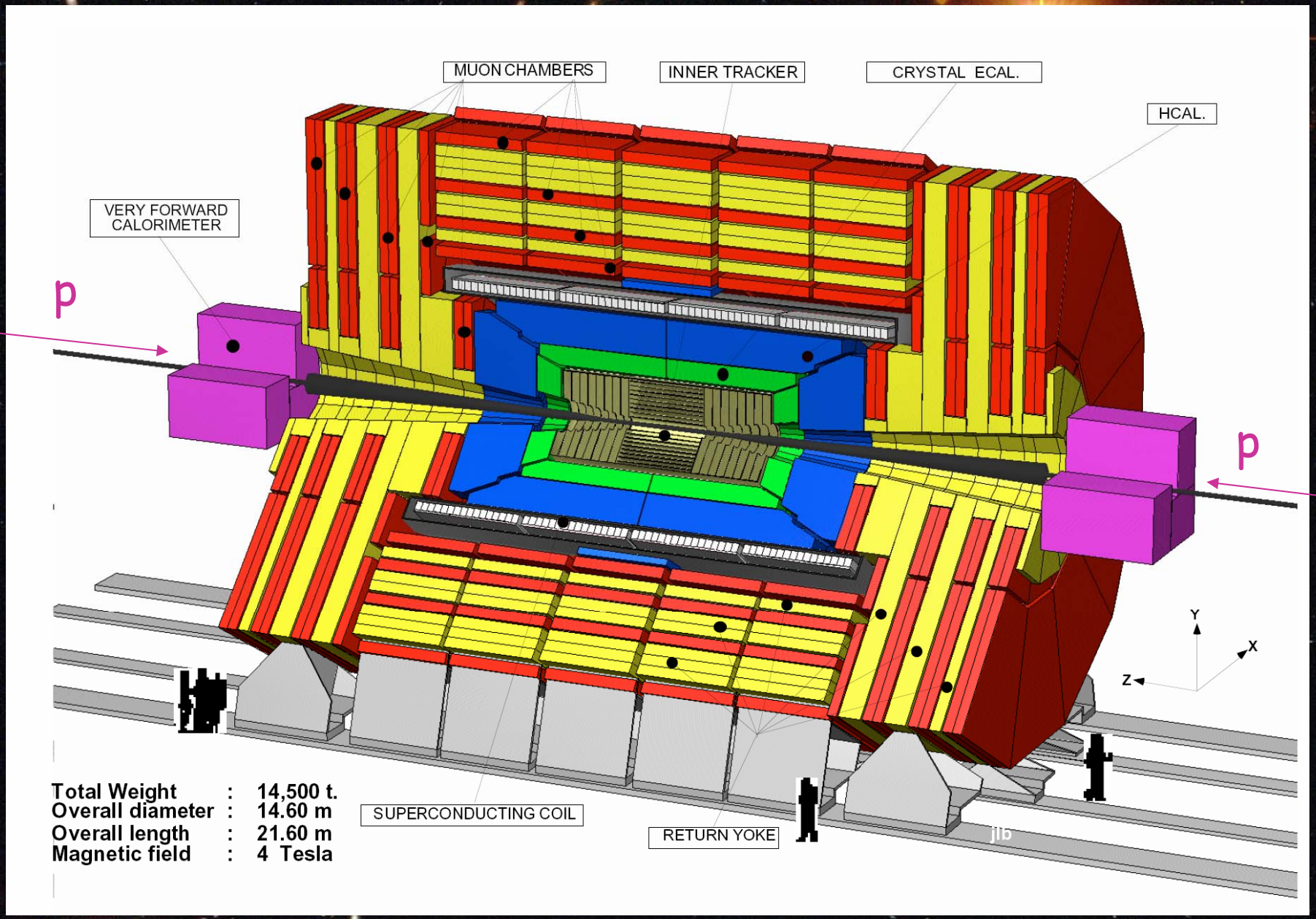
Gravitation (mass, Graviton)


Hubble deep field
Galaxy survey
13.2 m
4.2 m
Hubble Space Telescope

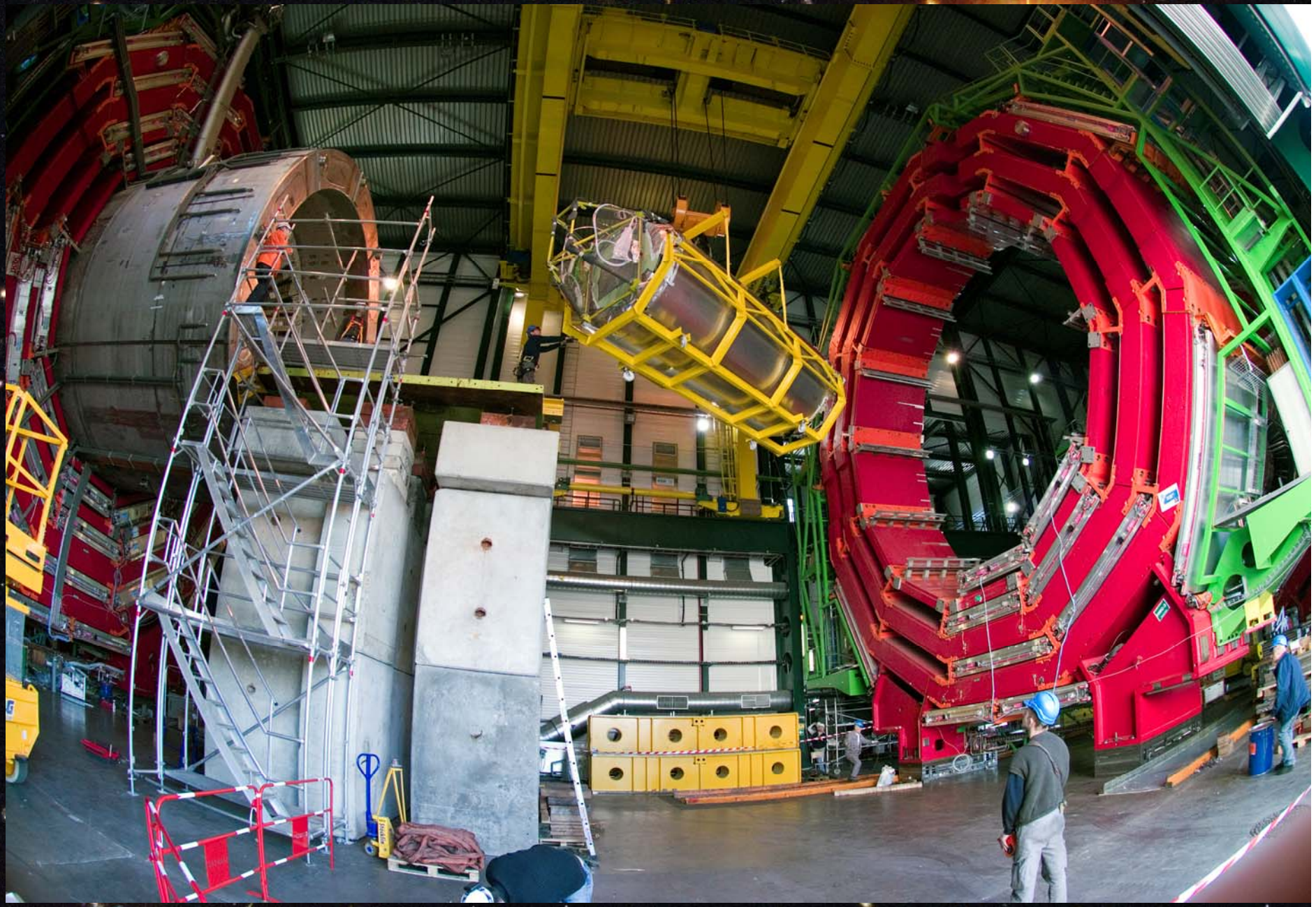


Proton proton collision at a center of mass energy = 14 TeV
≈ Universe 3.7 fs after the Big Bang

Compact Muon Solenoid



Compact Muon Solenoid



Why so large (energy)?

- **De-Broglie wave length:** $\lambda\!\!\!^{-} = \frac{\hbar c}{pc}; \quad \hbar c = 0.197\, GeVfm$

- **To probe the size of elementary particles**

$$\lambda\!\!\!^{-} = 10^{-3}\ fm; \ \Rightarrow\ pc = 0.1 TeV$$

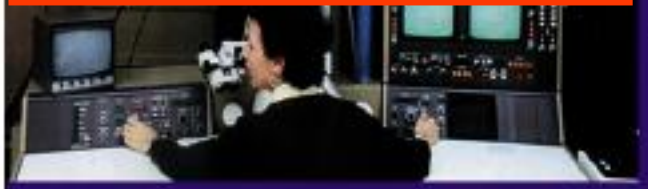
- **Create new objects like the top quark or a Higgs particle**
  - **Mass of top-quark ≈ 175 GeV/c²** $E_{\text{center of mass}} \approx m_{\text{new particle}} c^2$
  - **Mass of Higgs particle between 114 GeV/c² and 1TeV/c²**
  - **New "exotic" particles expected to exist on the TeV scale**
- **What should we accelearate?**
  - **Protons: Example of Tevatron (Fermi lab) and LHC (CERN)**
  - **Electrons. Example of LEP (CERN) and ILC or CLIC (???)**
- **Which intensities do we need?**

  How many collisions per second do we want to (can we) measure?

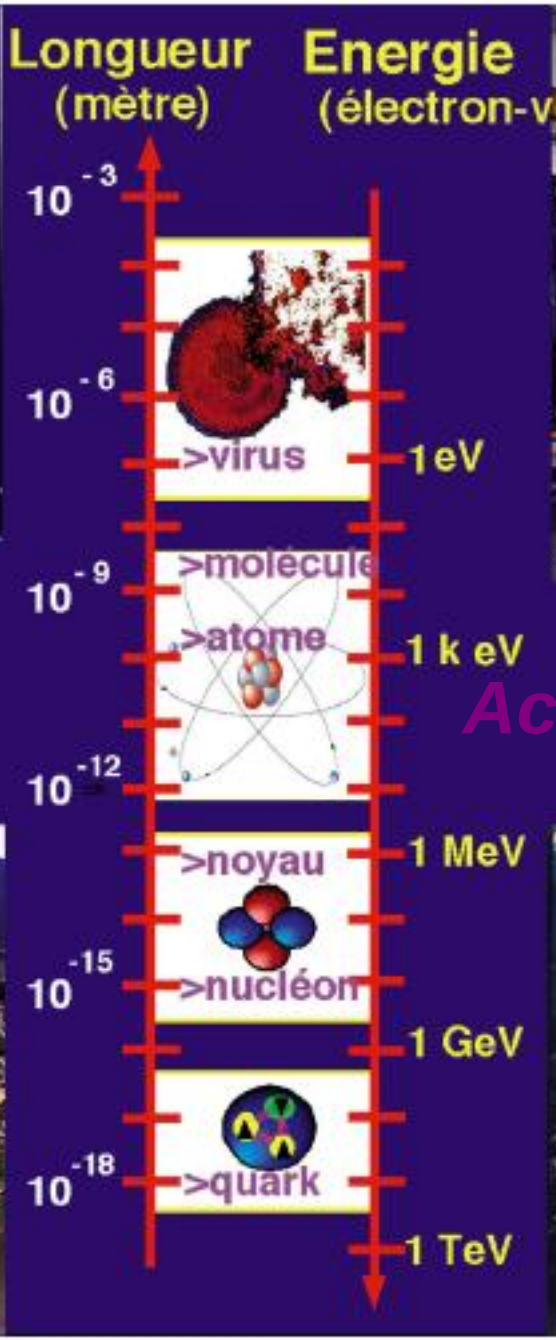
De-Broglie wave length

$$\lambda = \frac{\hbar c}{pc};$$

$$\hbar c = 0.197\,\mathrm{GeV}\cdot\mathrm{fm}$$



Microscope électronique



Cyclotron

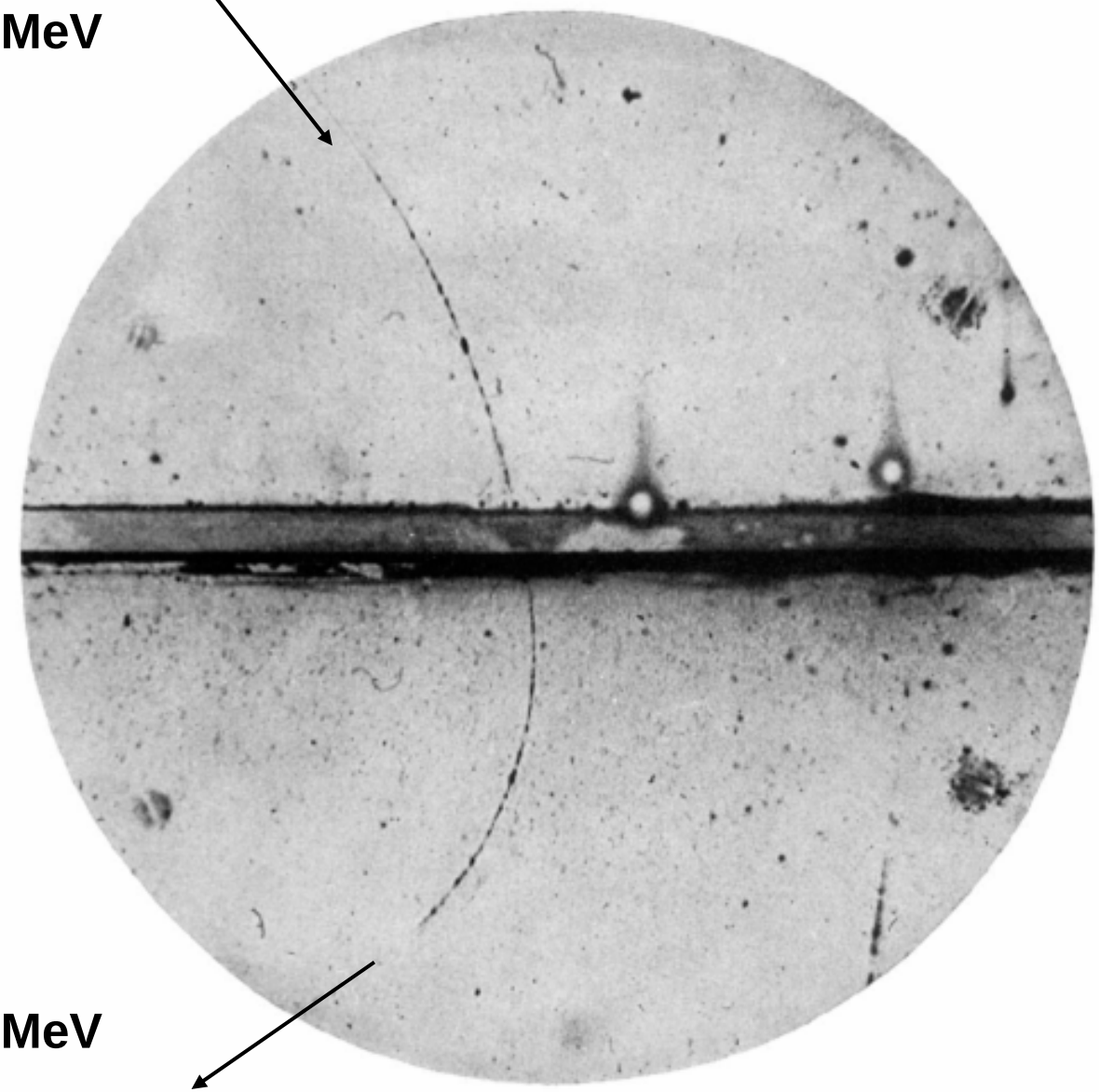
Particle **Accelerators**

Accélérateur linéaire

Synchrotron

What do we want to observe?

- **Elementary particles**
  - Electrons, muons ($c\tau$=659m), taus ($c\tau$=87μm), neutrinos
  - Quarks $\Rightarrow$ jets of many hadrons
- **Decays of particles**
- **The gauge bosons (γ, $W^{\pm}$, Z^0, gluons, ...**
- **Study the interaction at high Q^2 (= very small distances)**
- **Measure precisely the particle 4-vectors (E/c, p) GeV $\rightarrow$ TeV**
  - Energy
  - Momentum
  - Direction
  - Particle identification or mass measurement, life time

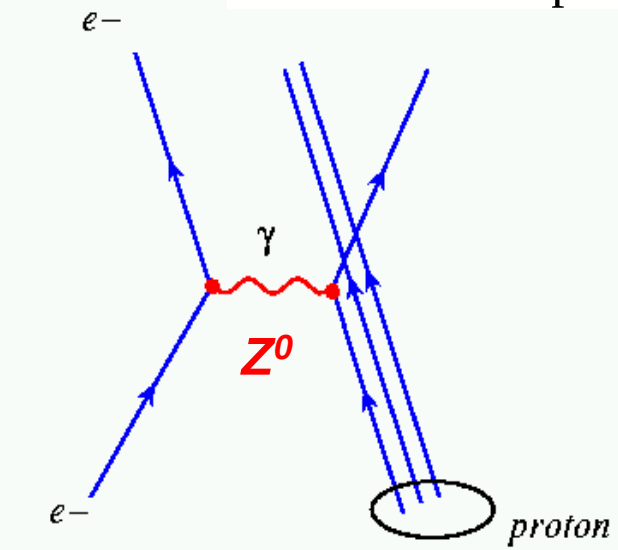


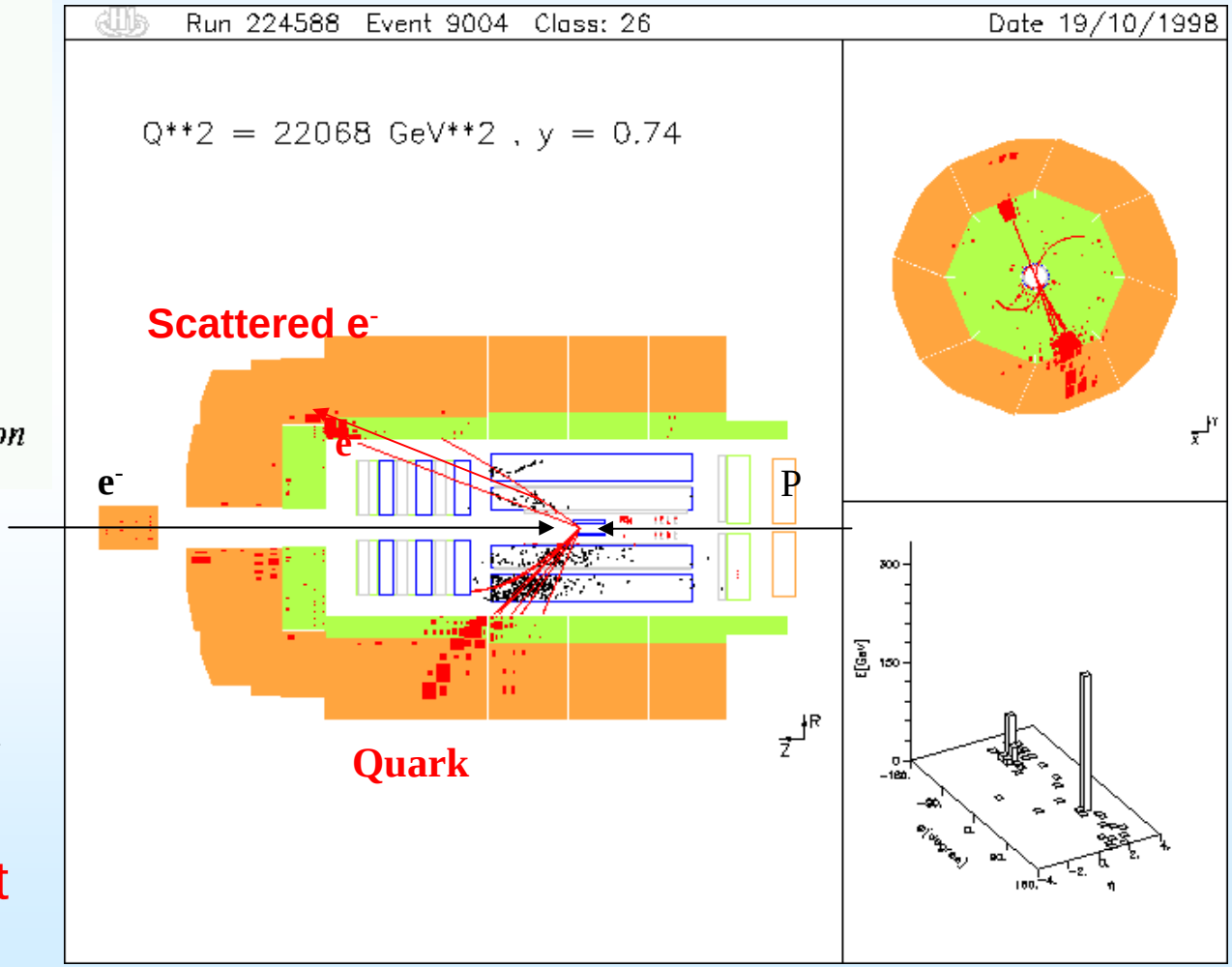
1932 Discovery of the positron by C.D.Anderson

6 mm Pb

Deep inelastic electron-proton scattering

H1 Experiment at the HERA (e-p) collider, DESY - Hamburg



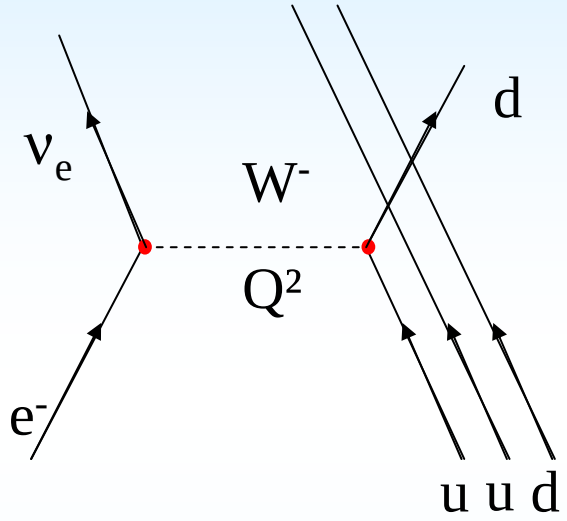


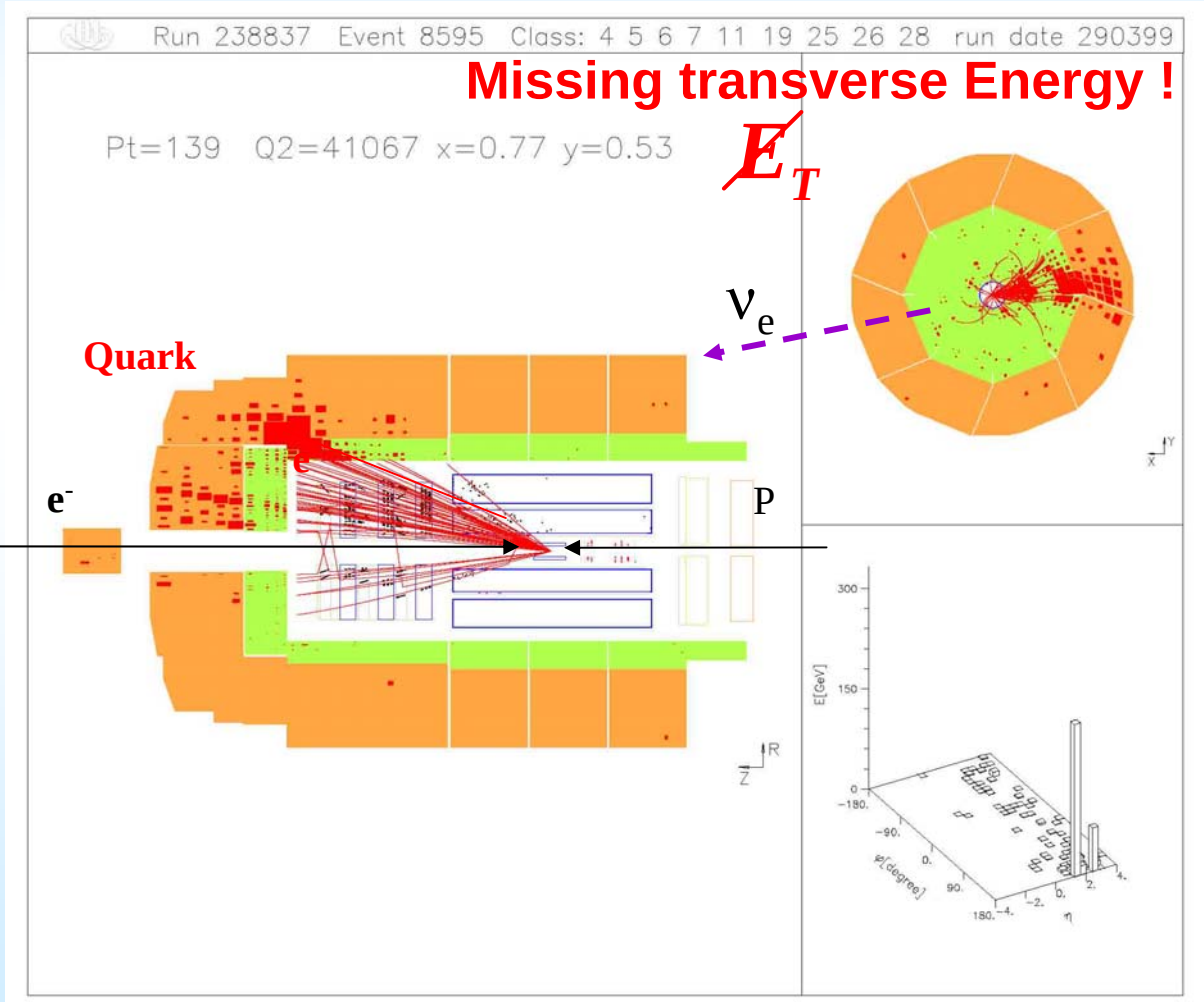
energy (e^-) = 30 GeV
energy (p) = 900 GeV

Neutral current event

Deep inelastic electron-proton scattering

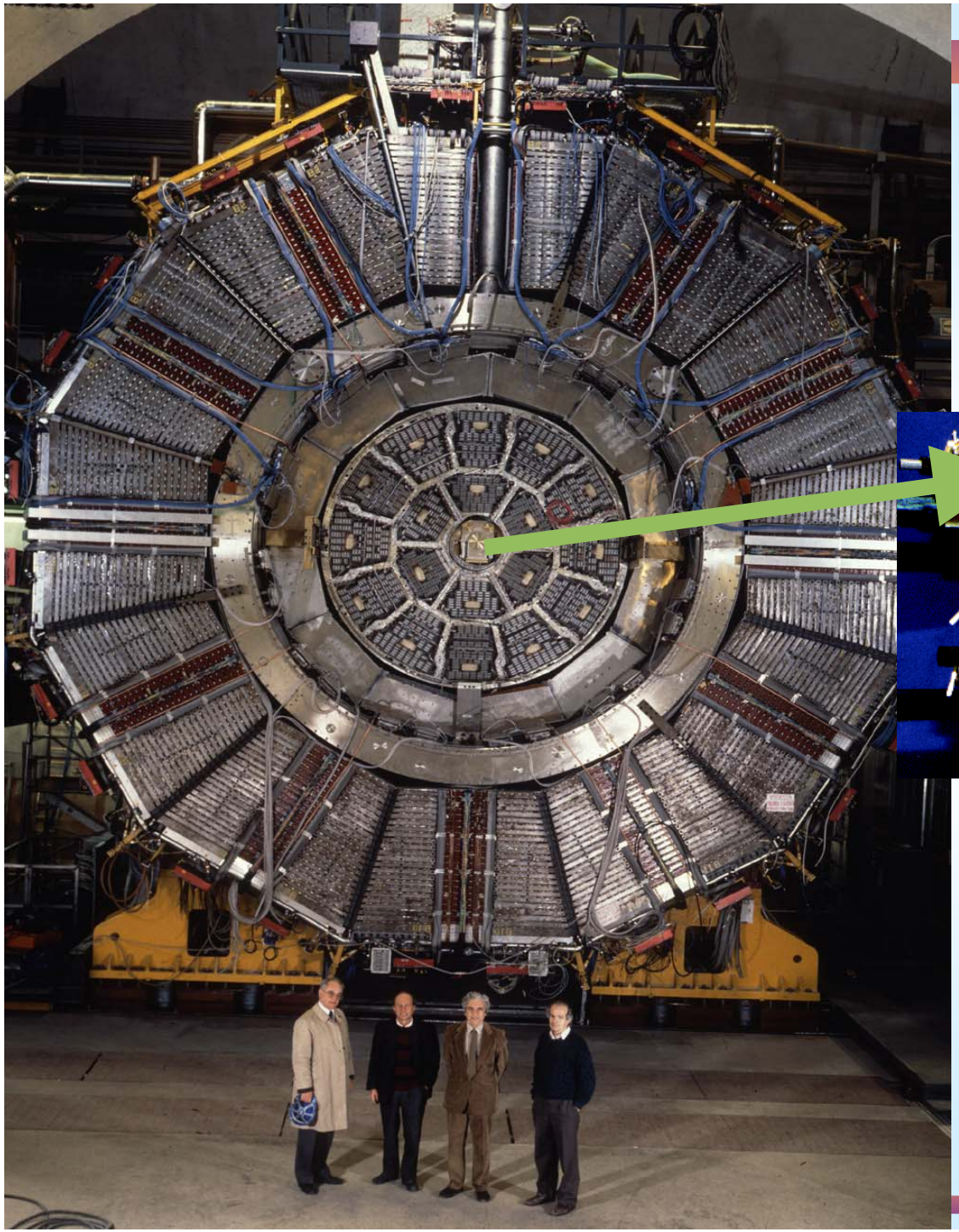
H1 Experiment at the HERA (e-p) collider, DESY - Hamburg

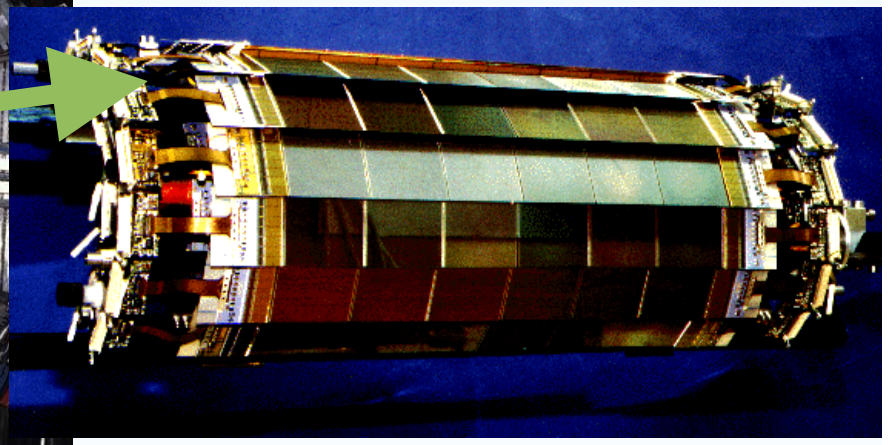




energy (e^-) = 30 GeV
energy (p) = 900 GeV

Charged current event

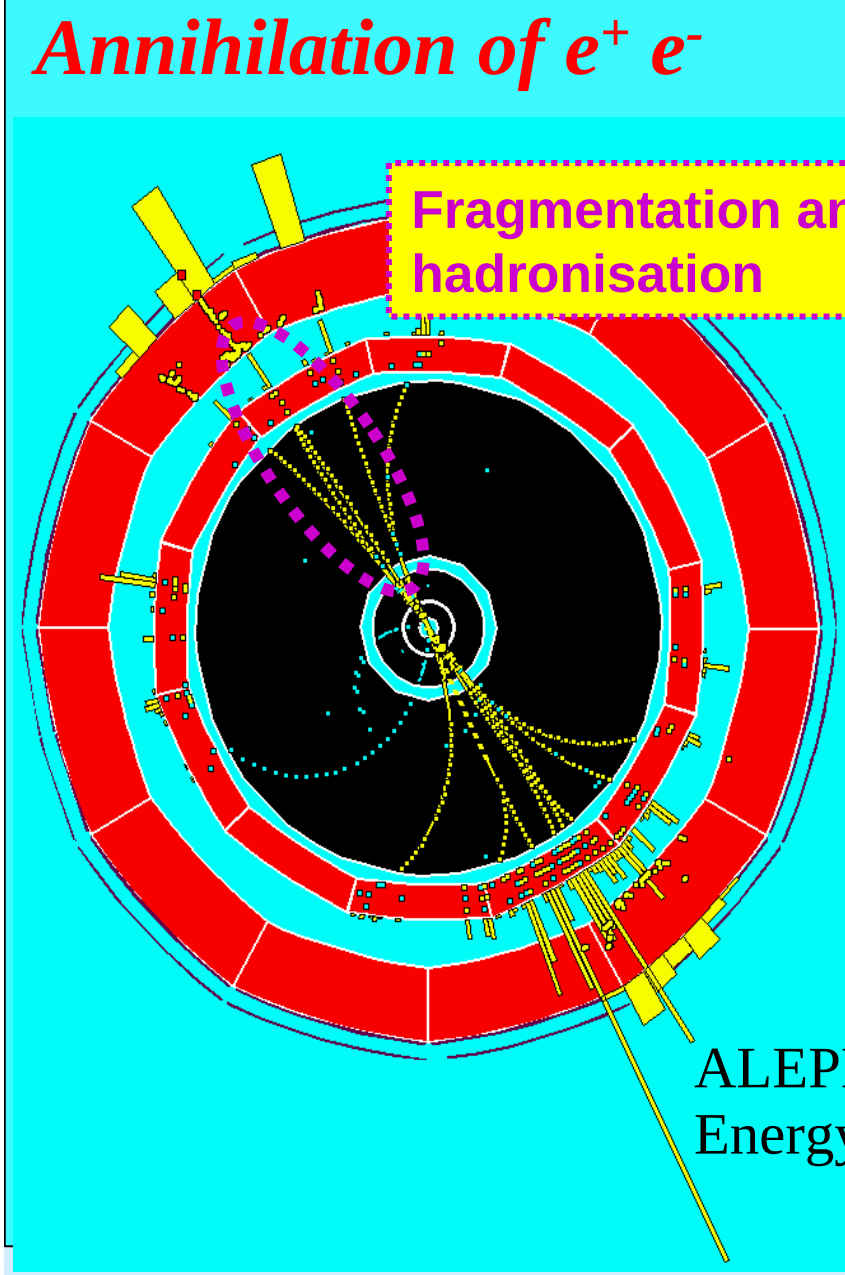


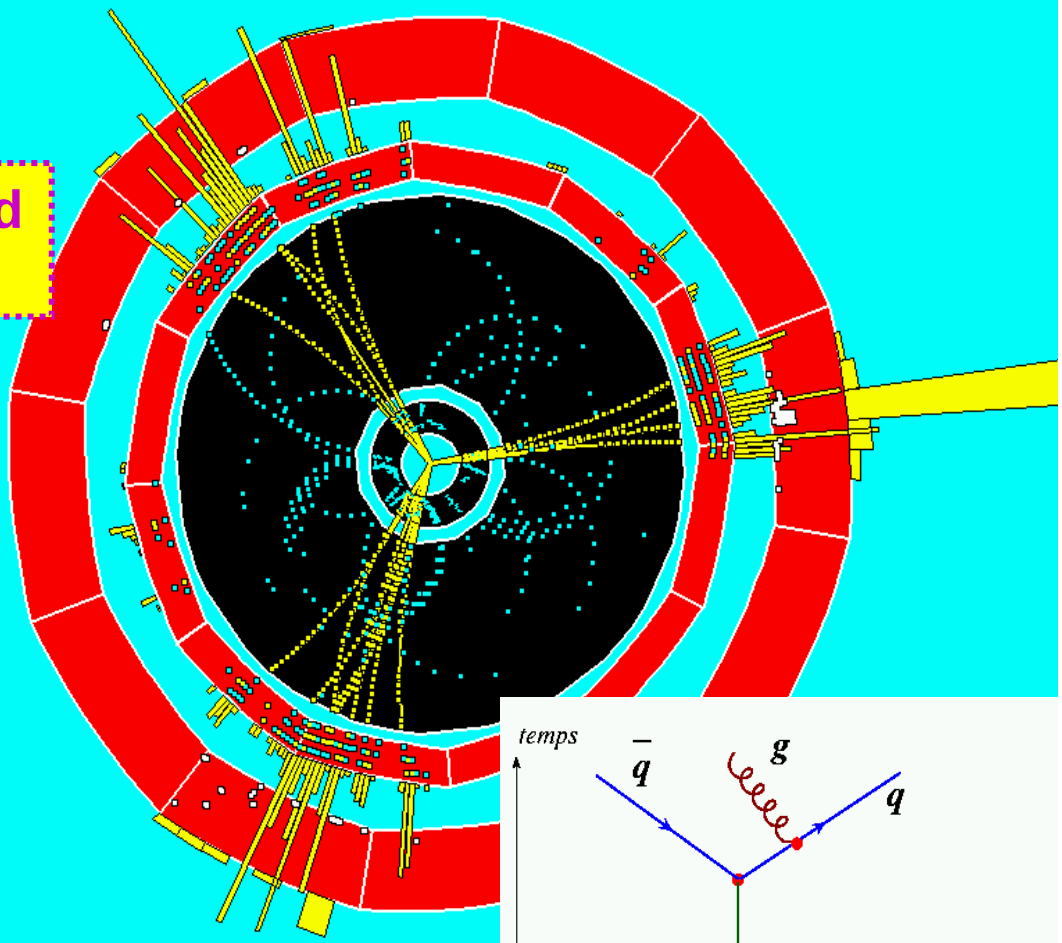


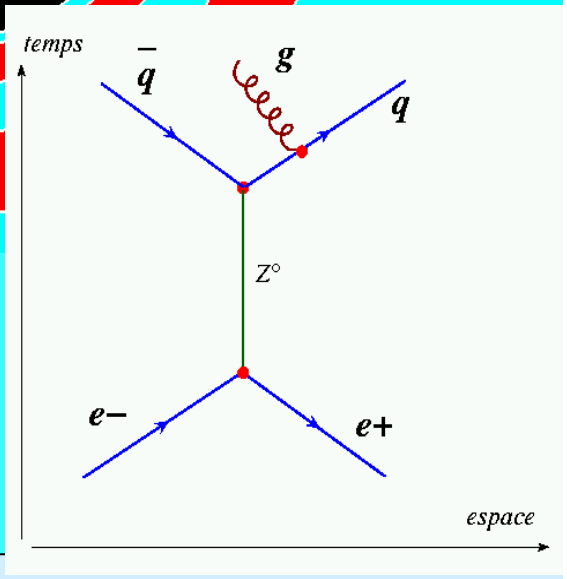
ALEPH at LEP

Annihilation of e^+ e^-

Fragmentation and hadronisation







ALEPH LEP
Energy = 2 × 45.9 GeV

Accelerators

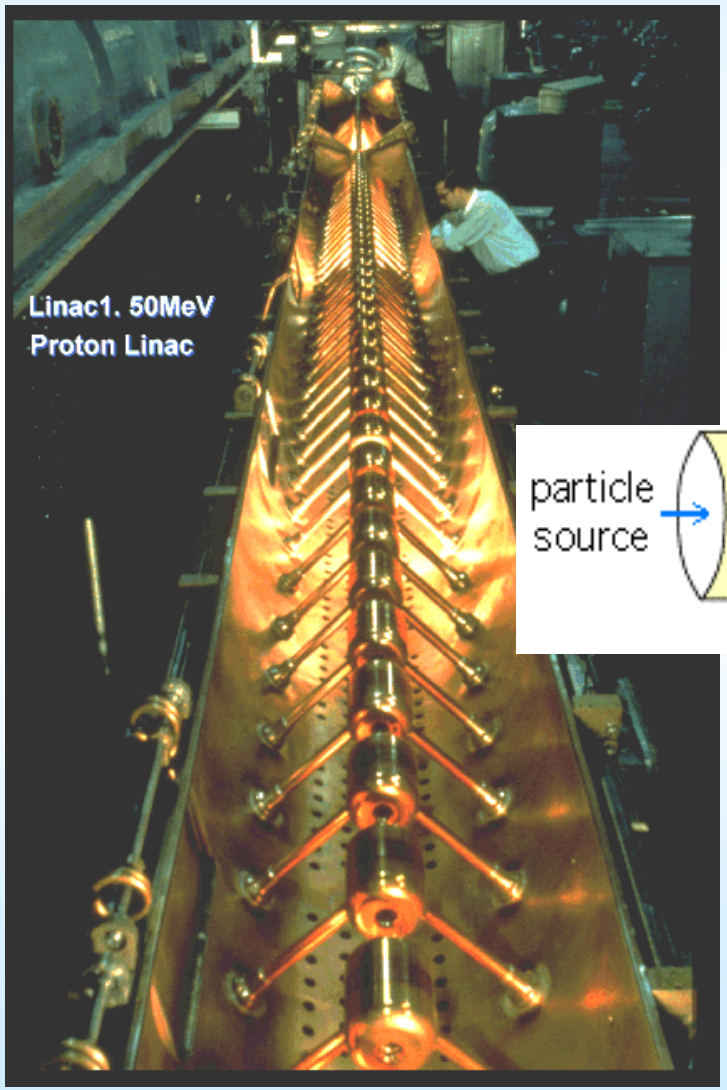
- Electron accelerators
- Proton / hadron accelerators

- Linear machines
- Circular

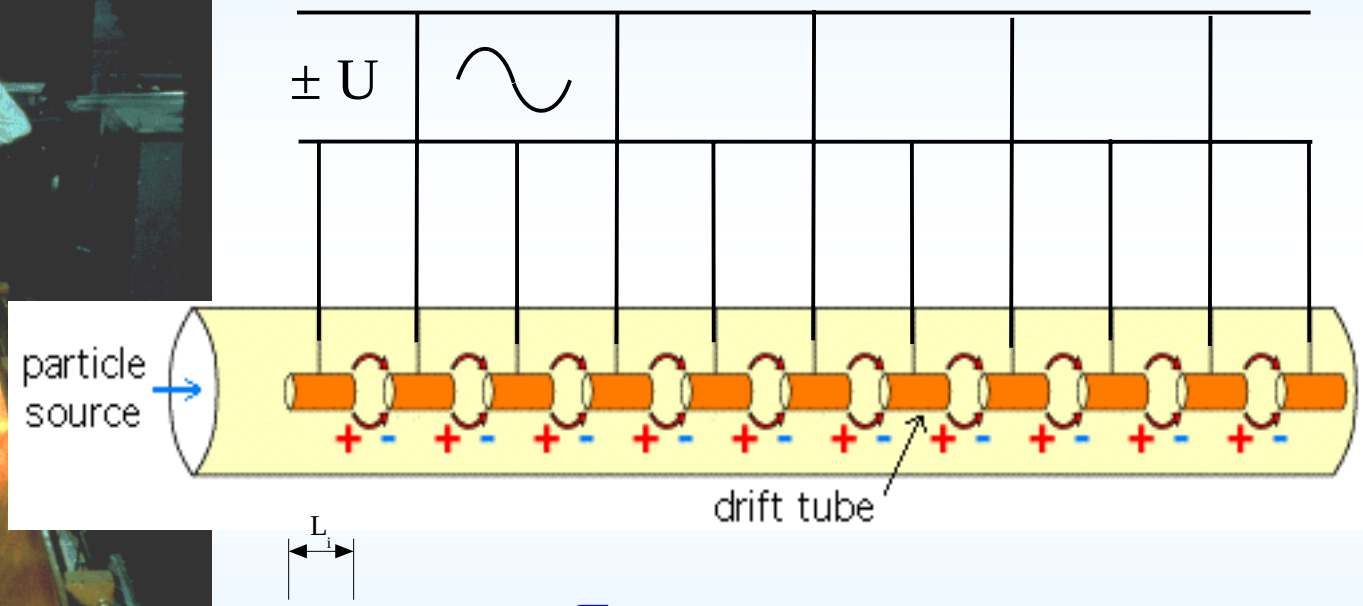
- Fixed Target
- Colliders

Linear accelerator

CERN



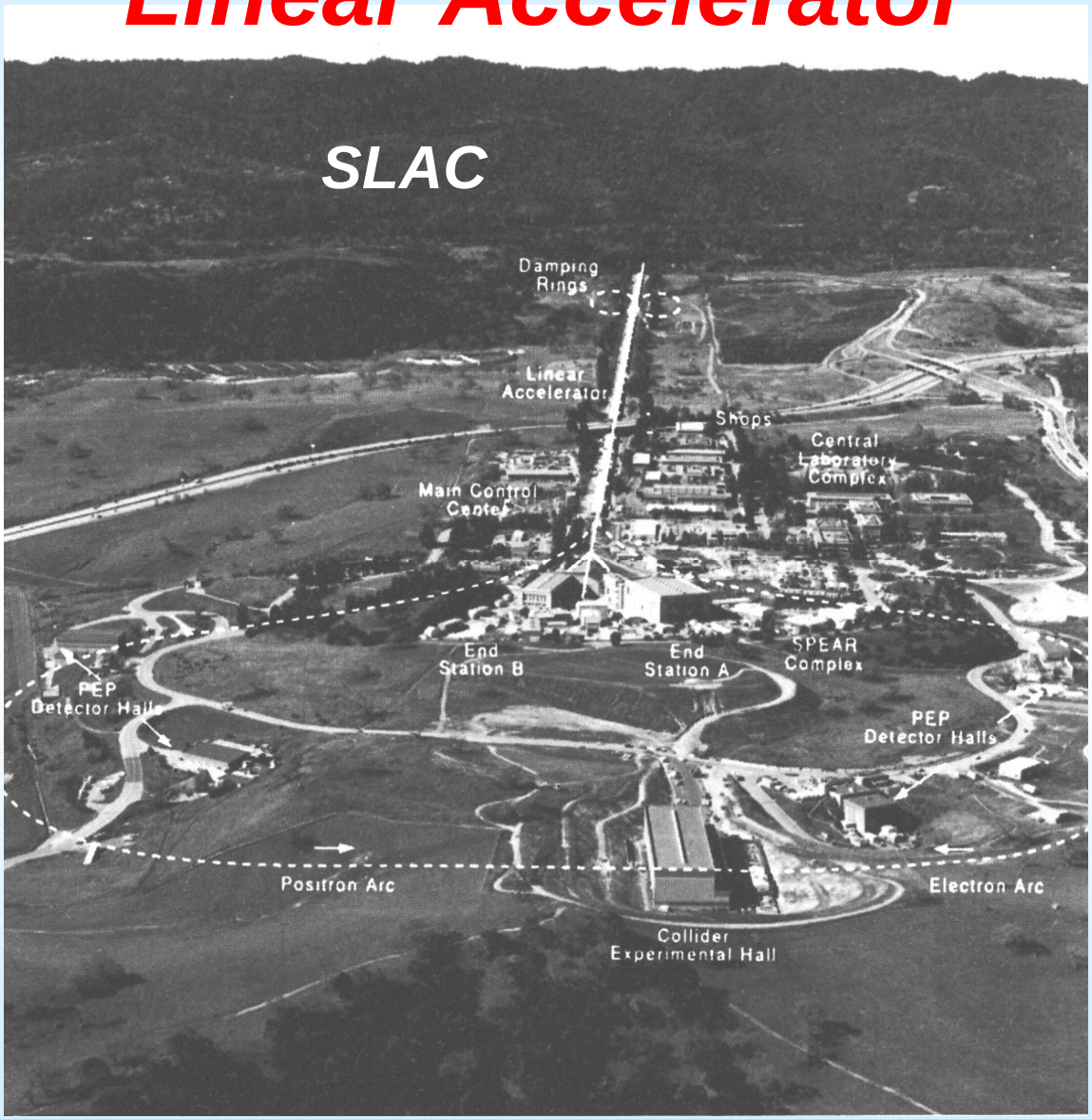
Wideröe Linac

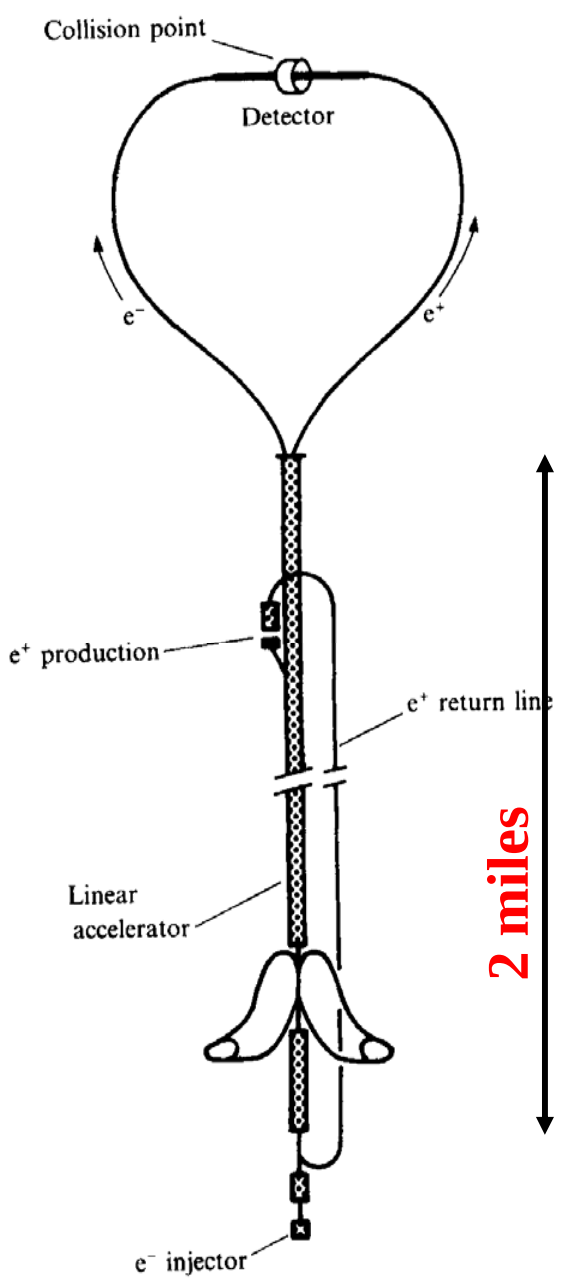


$$L_i = v_i \frac{\pi}{\omega}; \quad E = nZeU;$$

v_i = velocity in section i

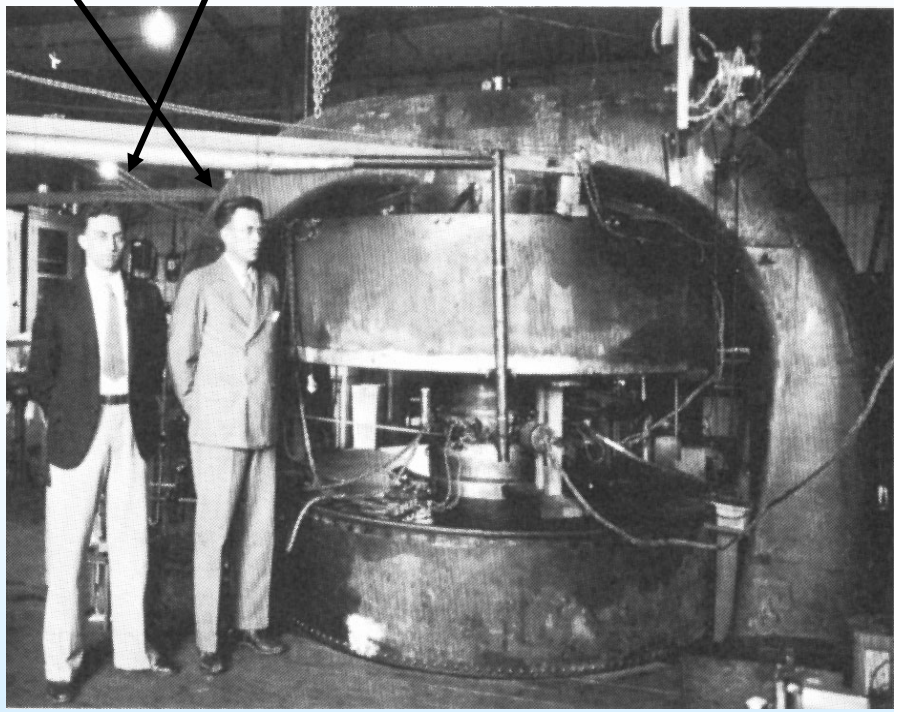
Linear Accelerator





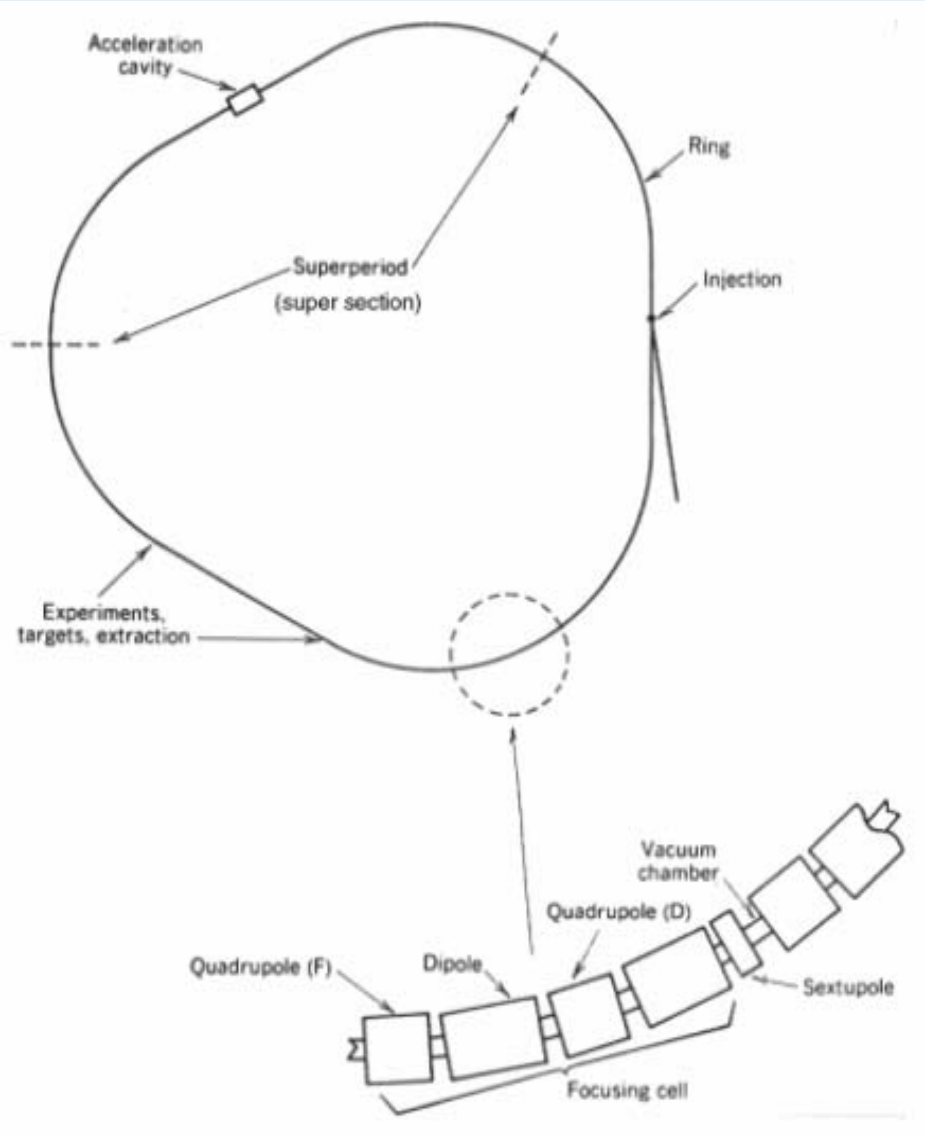
Cyclotron of Lawrence and Livingstone

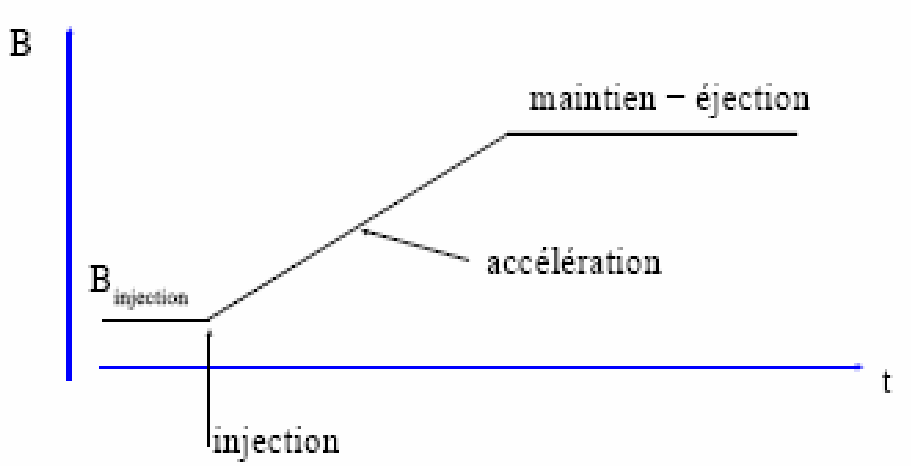
1929



1934 27 inch

Synchrotons





"Fixed Target" and Colliders

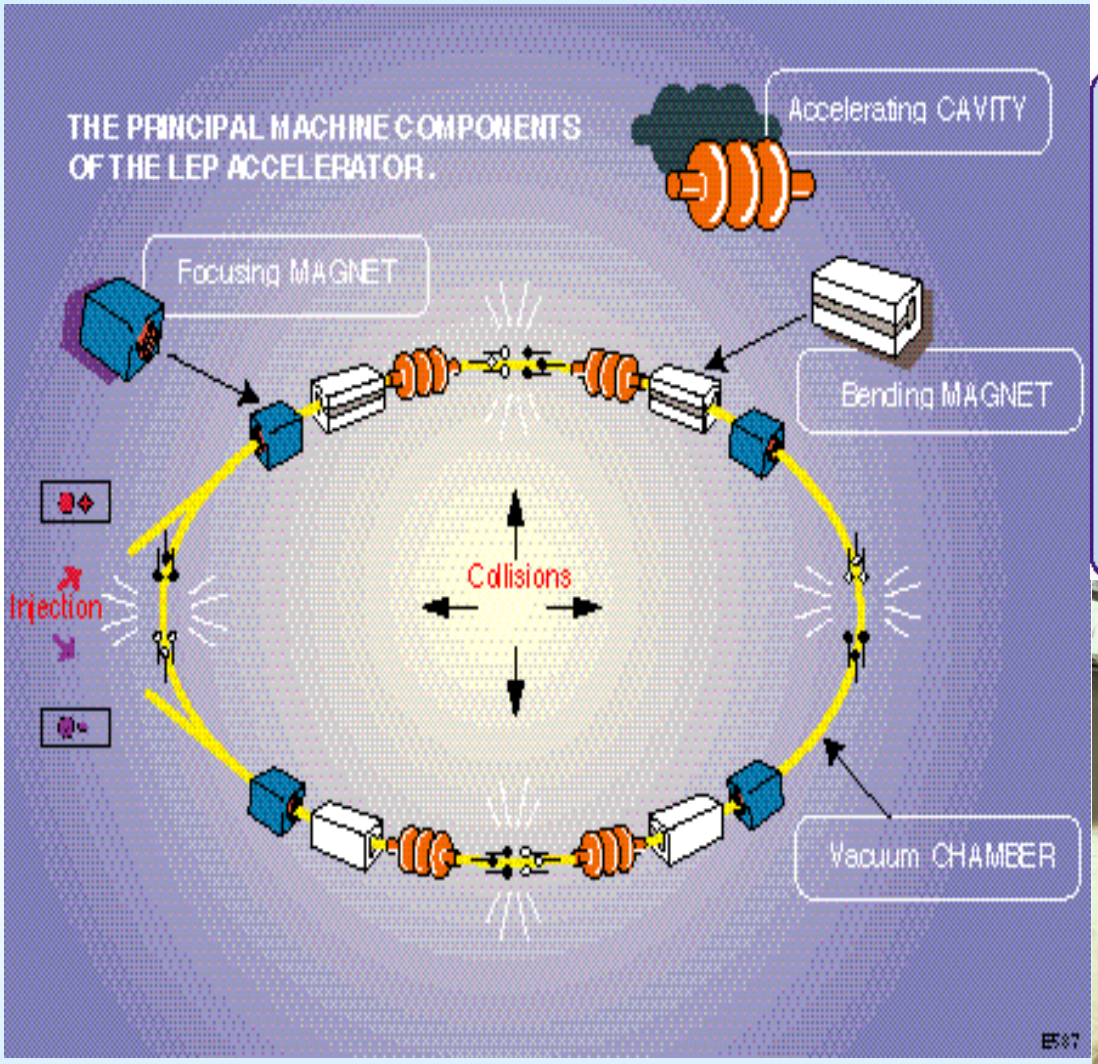
- **Fixed Target:**

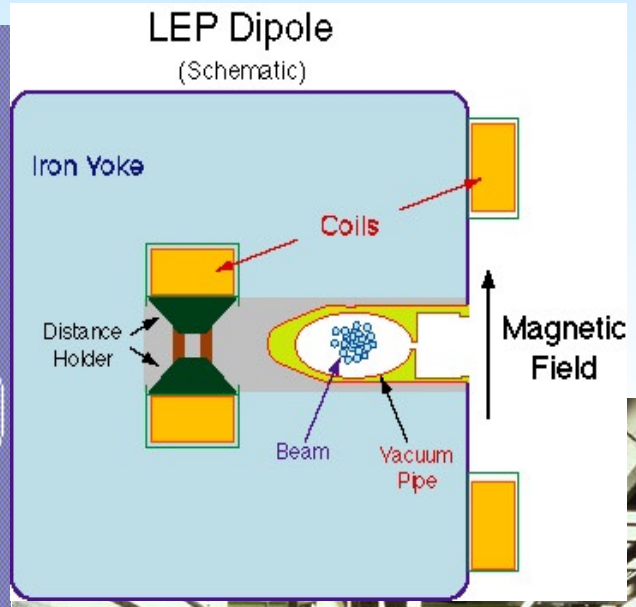
$$E_{CM}^{\text{fixed target}} = \sqrt{2Mc^2E + M^2c^4 + m^2c^4}$$

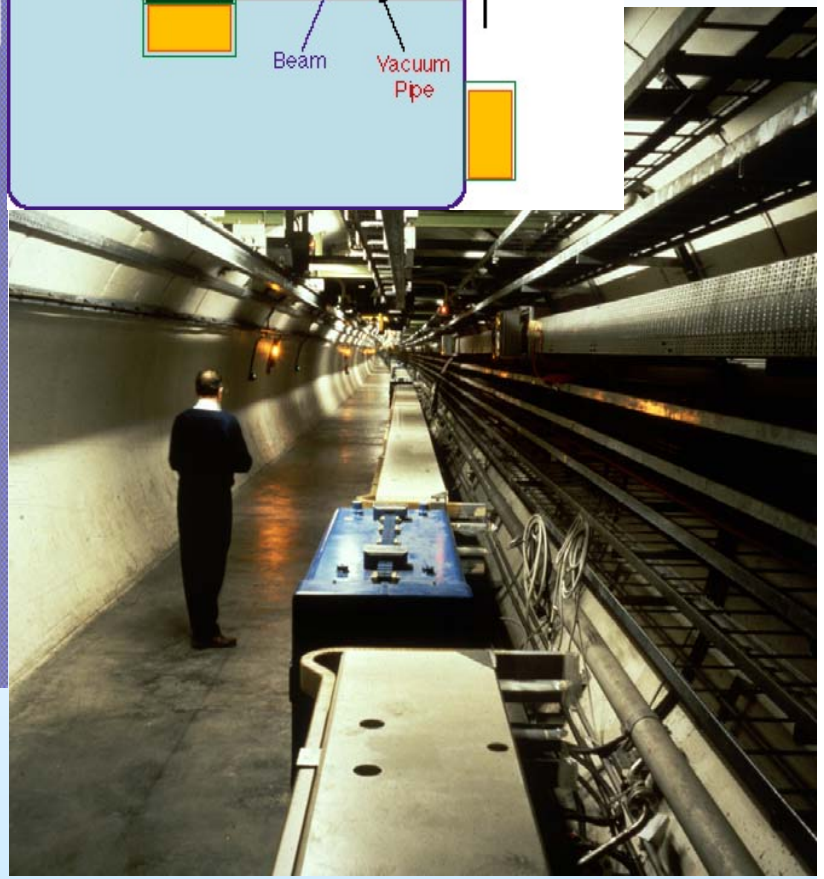
$$\cong \sqrt{2Mc^2E}$$

- **Collider:**

$$E_{CM}^{\text{collider}} = 2E = \sqrt{s}$$





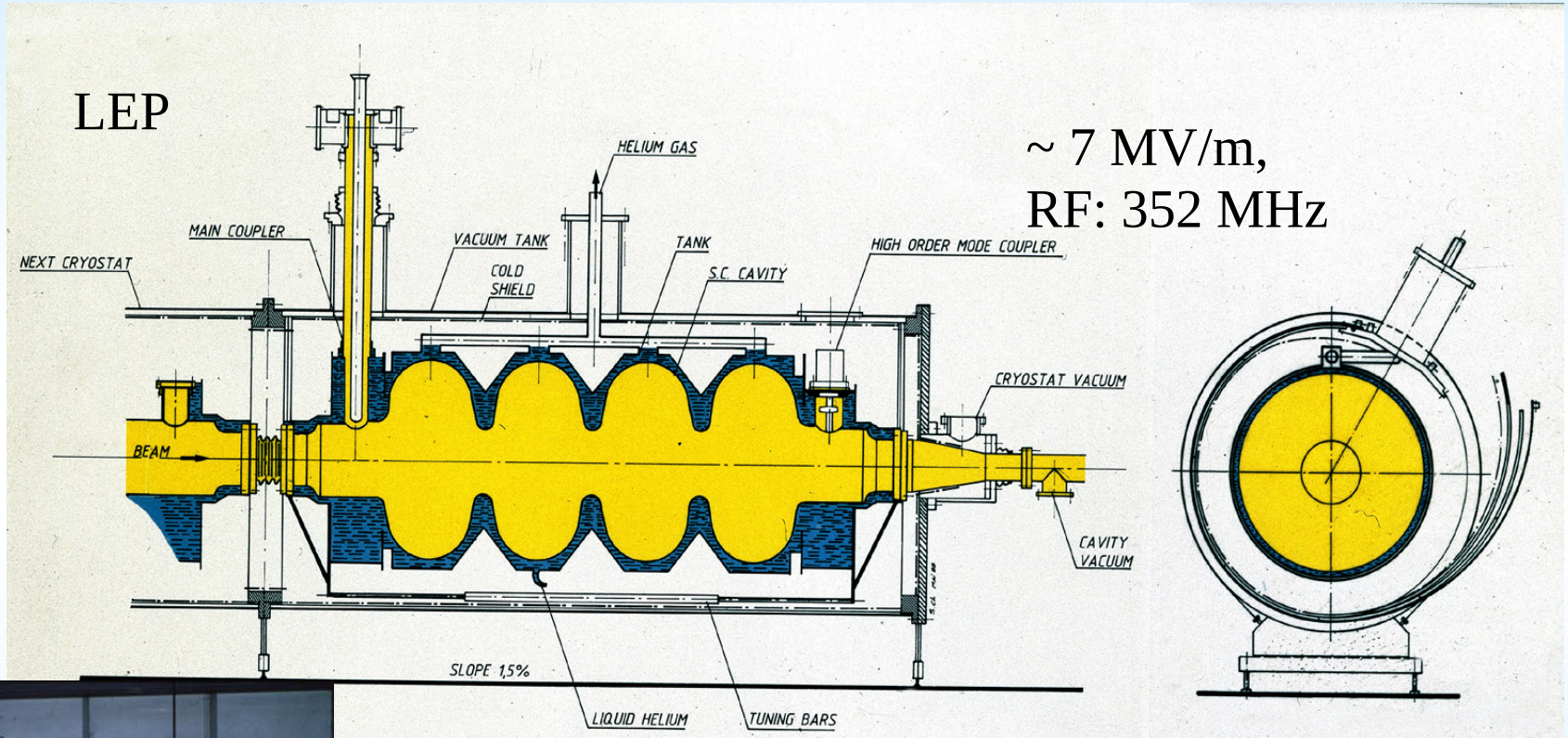


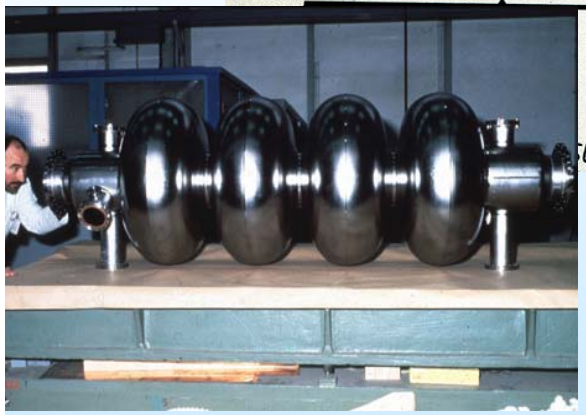
The LEP Collider (e^-,e^+) $\sqrt{s}$ = 90-200 GeV

Normal and Superconducting radio-frequency cavities

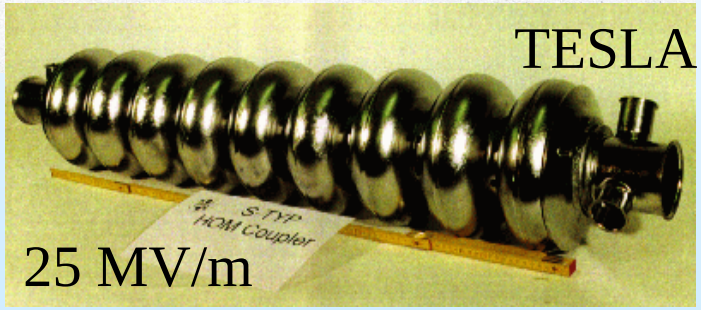
LEP

~ 7 MV/m,
RF: 352 MHz





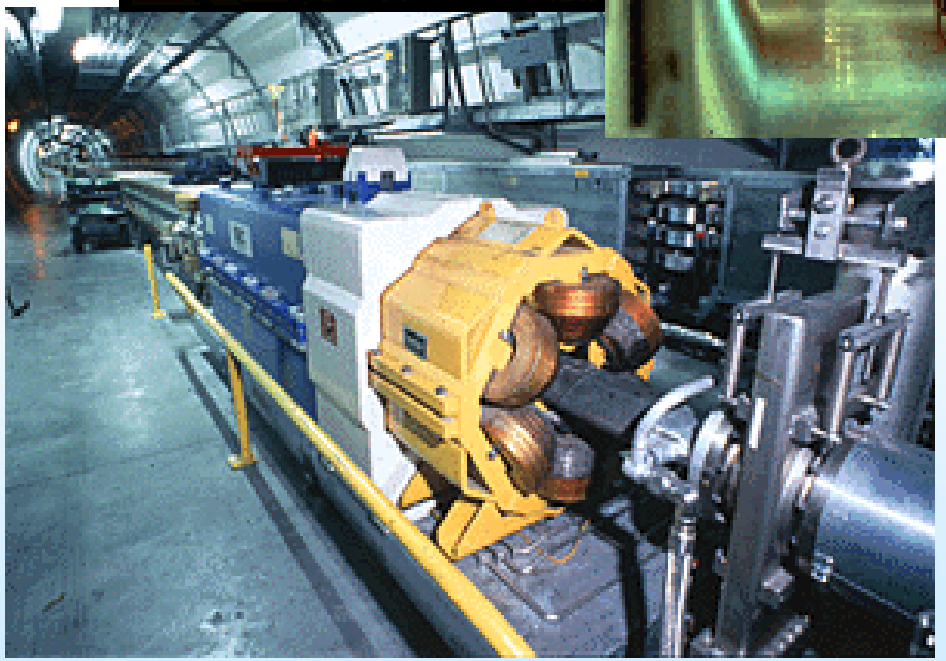
SUPERCONDUCTING CAVITY WITH ITS CRYOSTAT

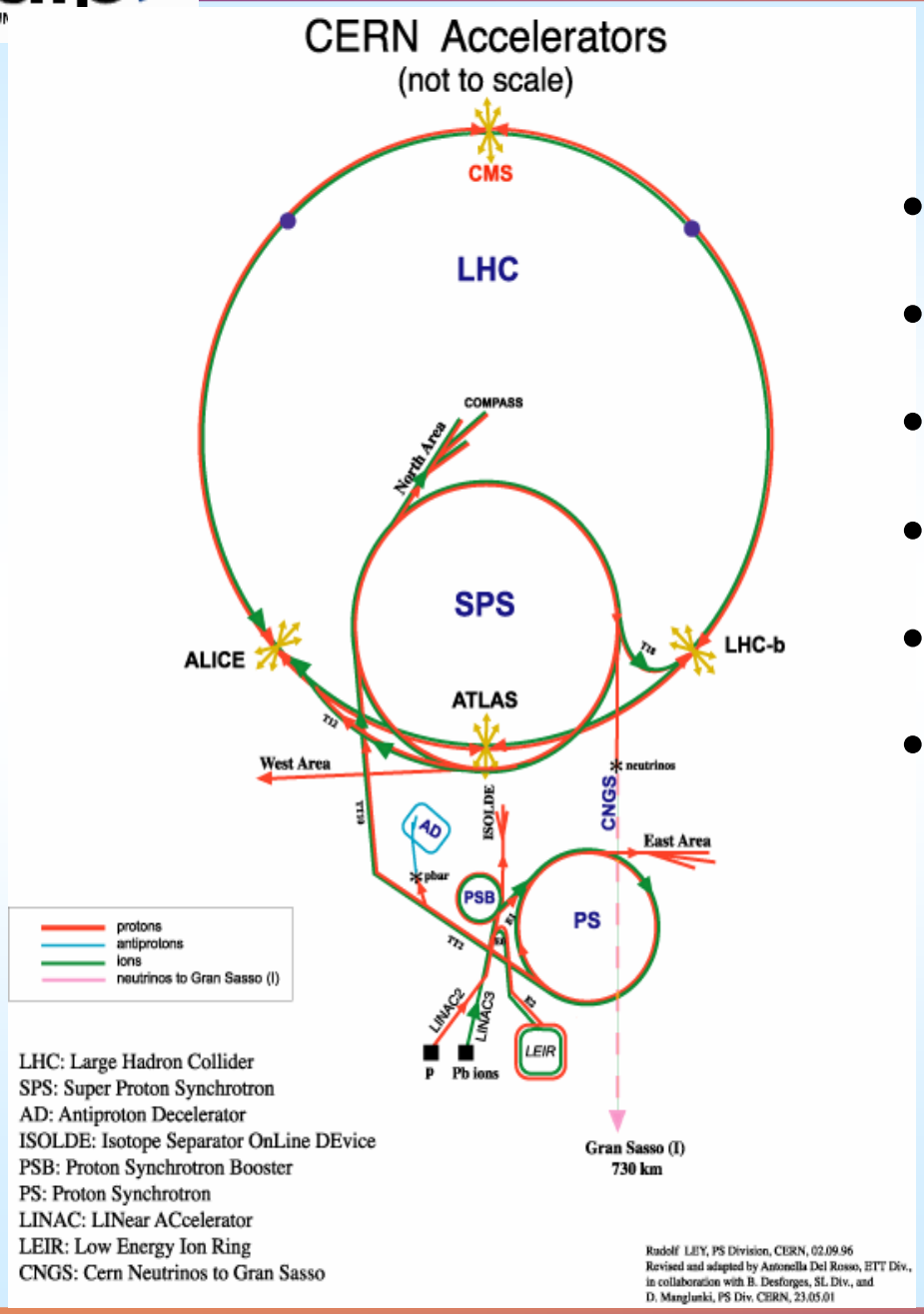


TESLA

25 MV/m

Accélérators at CERN





- Source
- LINAC
- (Booster)
- PS $\rightarrow$ extraction
- SPS $\rightarrow$ extraction
- LEP/LHC

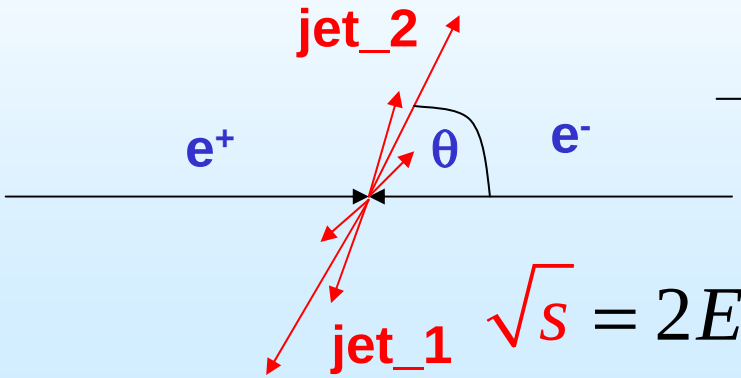
Electrons or Protons ?????

Hadron Collider (p, ions):

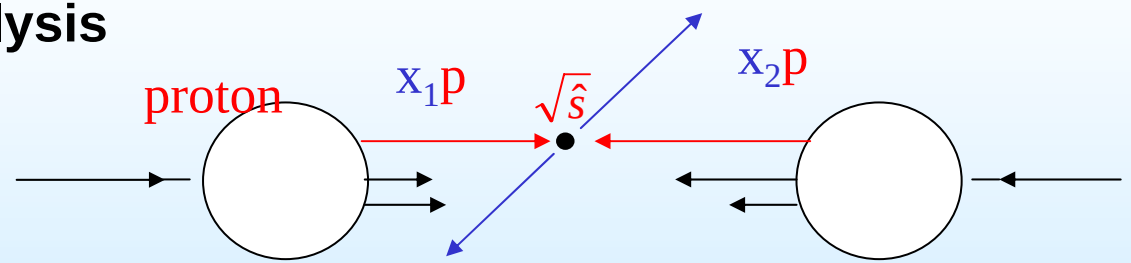
- Higher proton-proton center of mass energy $\sqrt{s} = 2E_{beam}$
- Composite nature of protons ⇒ reduction of partonic Ecm $\sqrt{\hat{s}} \approx \sqrt{\langle x_1 \rangle \langle x_2 \rangle s}$
- Only p_T conservation
- Huge QCD background

Lepton Collider:

- Elementary particles
- Well defined initial state
- Beam polarization
- produces particles "democratically"
- Momentum conservation
- eases decay product analysis



$\sqrt{s} = 2E_{beam}$



$\sqrt{\hat{s}} \approx \sqrt{\langle x_1 \rangle \langle x_2 \rangle s}$

Electrons or Protons ?????
Can we build the machine?

- SUPER-LEP?? (LEP L=27 km E_{cm}=200 GeV)
- Problem: Synchrotron radiation
- Emitted power: scales with E^4 !!

$$P = \frac{2}{3}\frac{r_e c}{\left(m_o c^2\right)^3}\frac{E^4}{\rho^2}$$

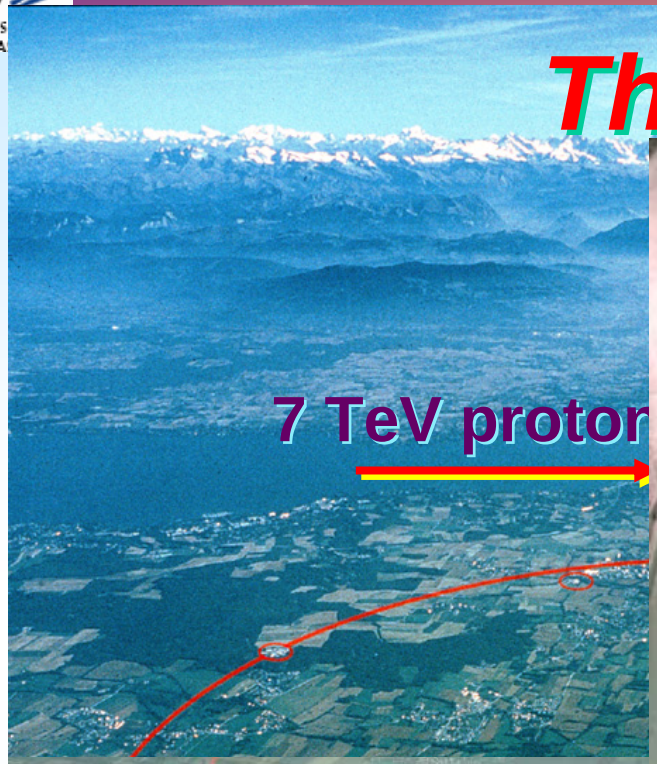
- Energy loss/turn: Energy must be replaced by the RF system !!

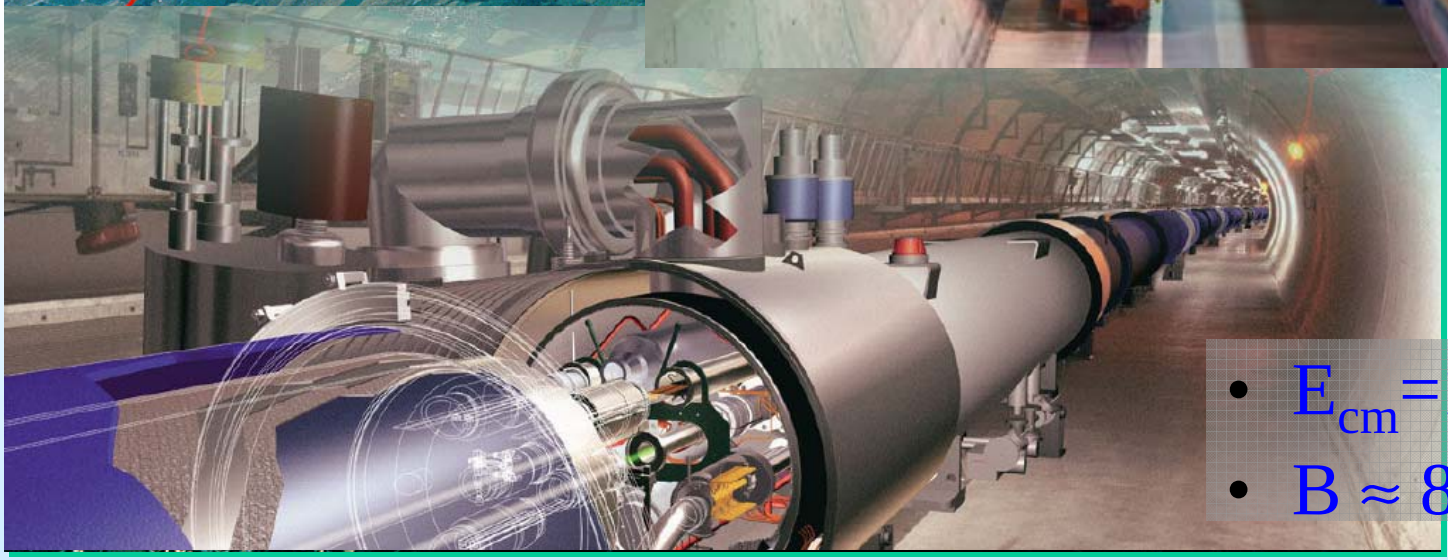
$$U_0 = \frac{4}{3}\pi\frac{r_e}{\left(m_0 c^2\right)^3}\frac{E^4}{\rho}$$

- The size and the optimized cost scale as E^2
- Only solution: LINEAR COLLIDER
- Proton proton collider $\Rightarrow$ LHC

synchroton radiation smaller by $\left(\frac{m_e}{M_p}\right)^4$

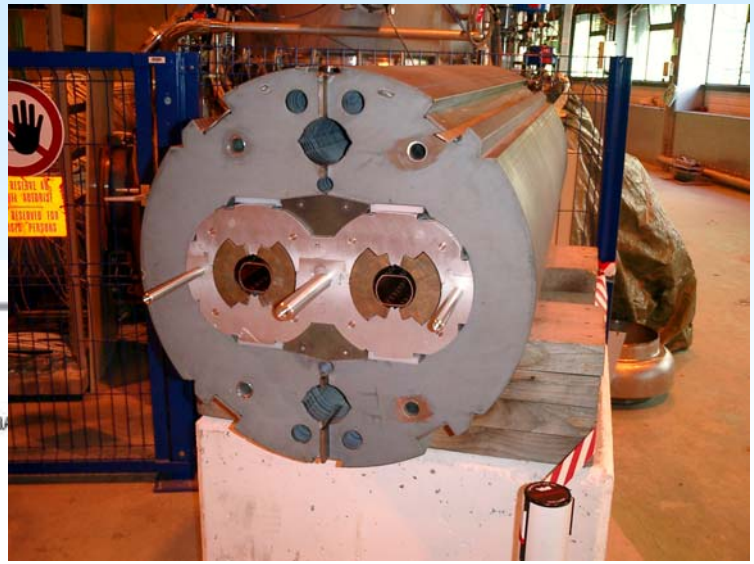
The LHC

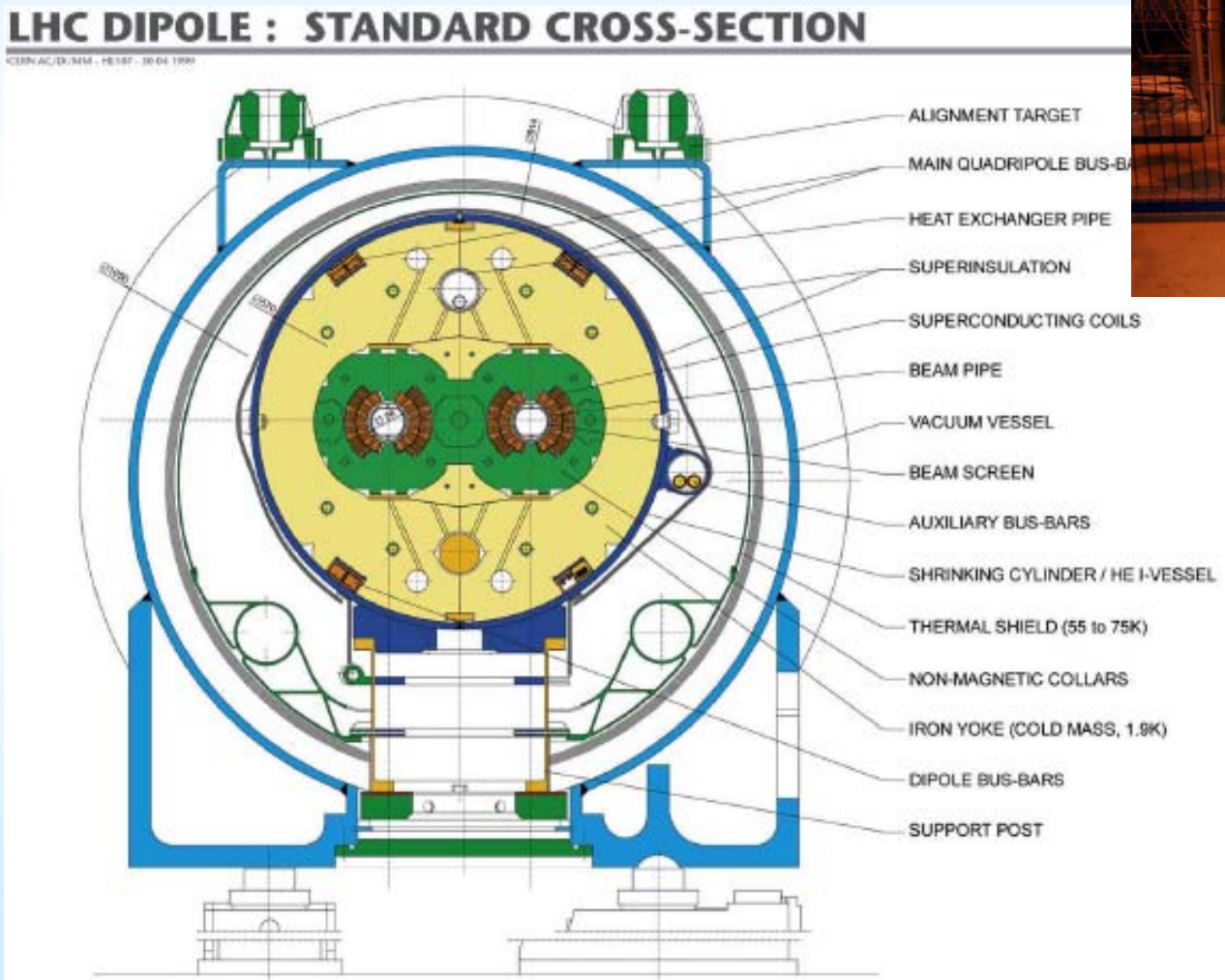




- E_{cm}=14 TeV
- B ≈ 8 Tesla

LHC magnets

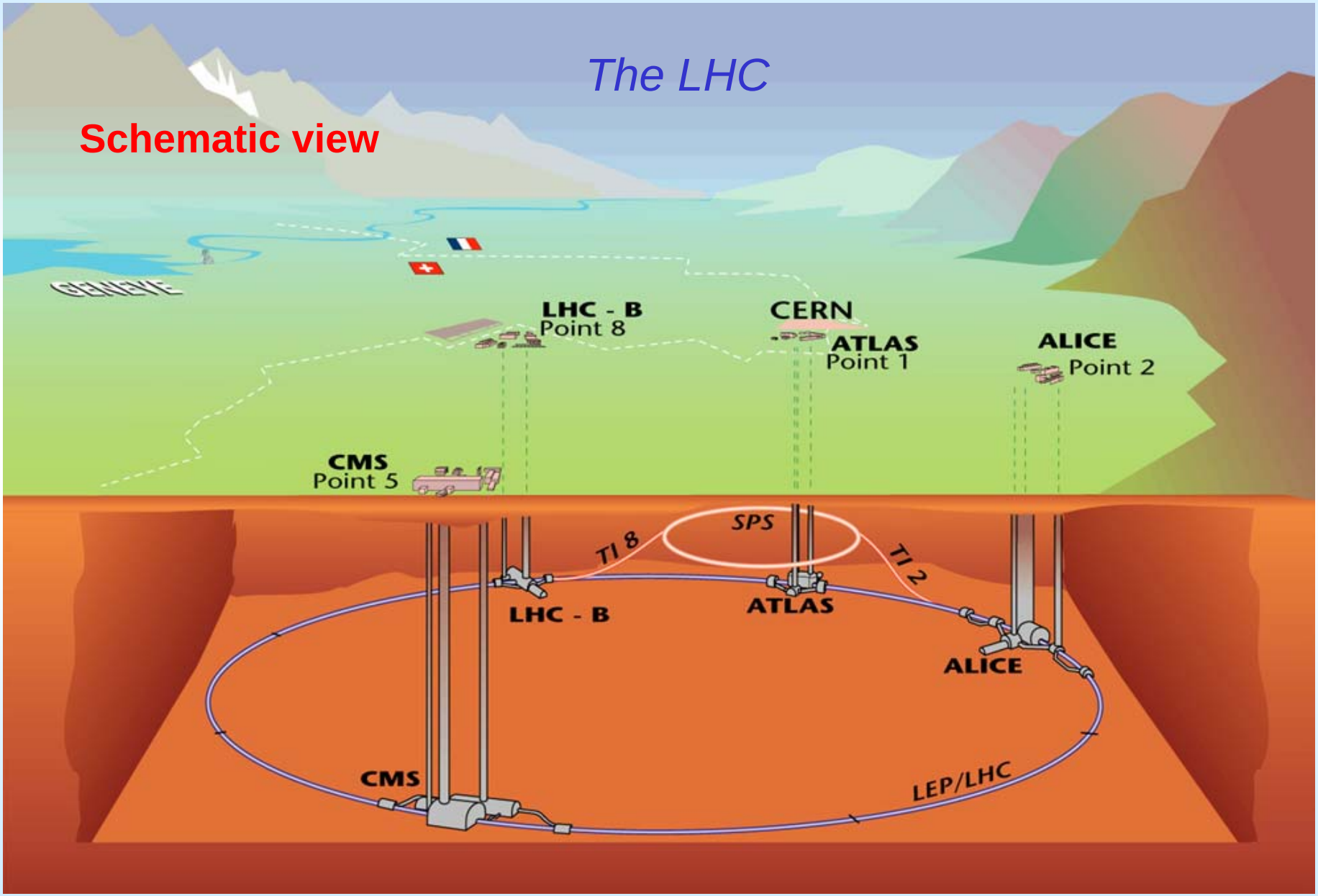


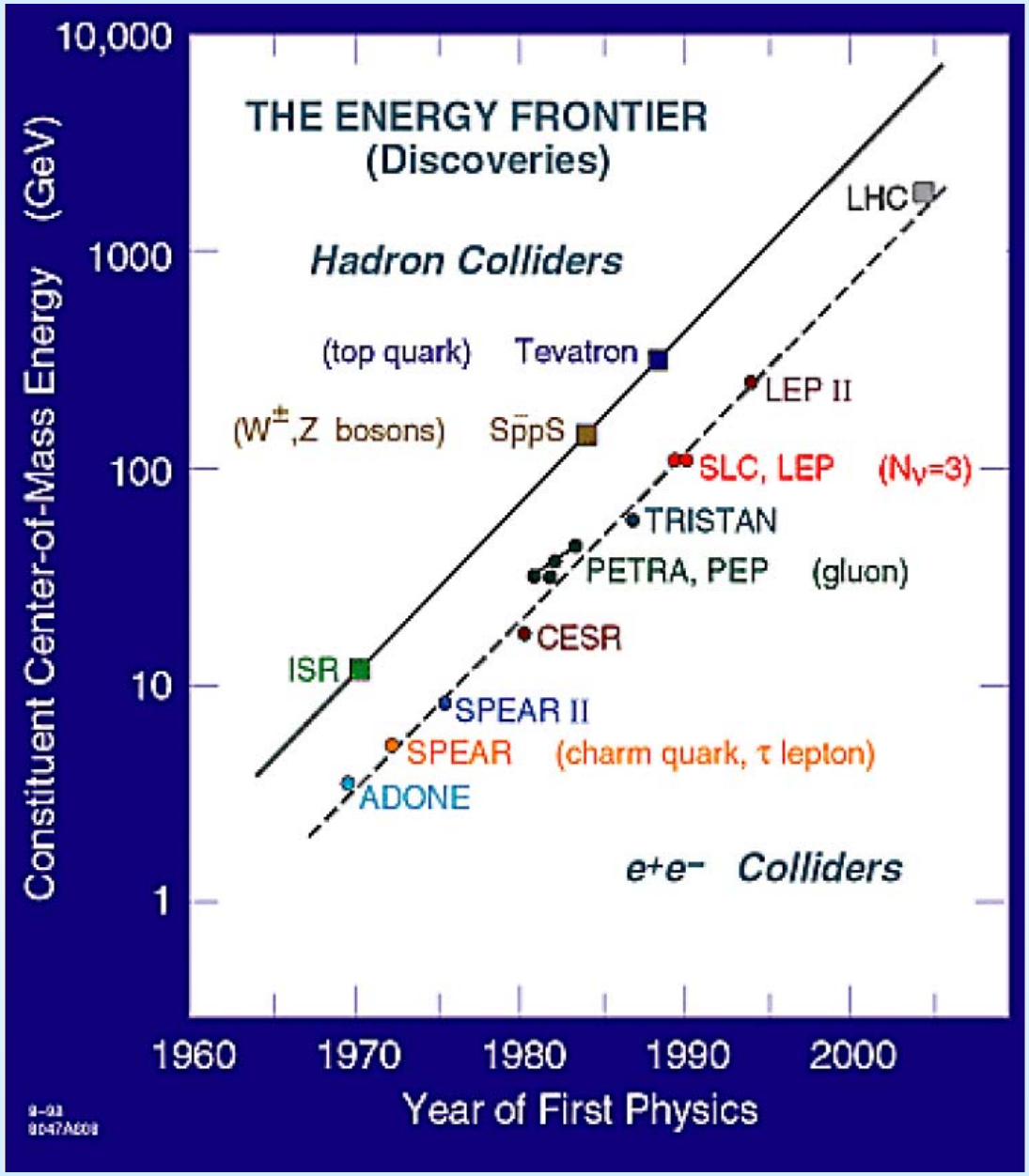


- E_{beam}=7 TeV
- B ≈ 8 Tesla

The LHC

Schematic view





Electron and proton Colliders

Linear Collider projects

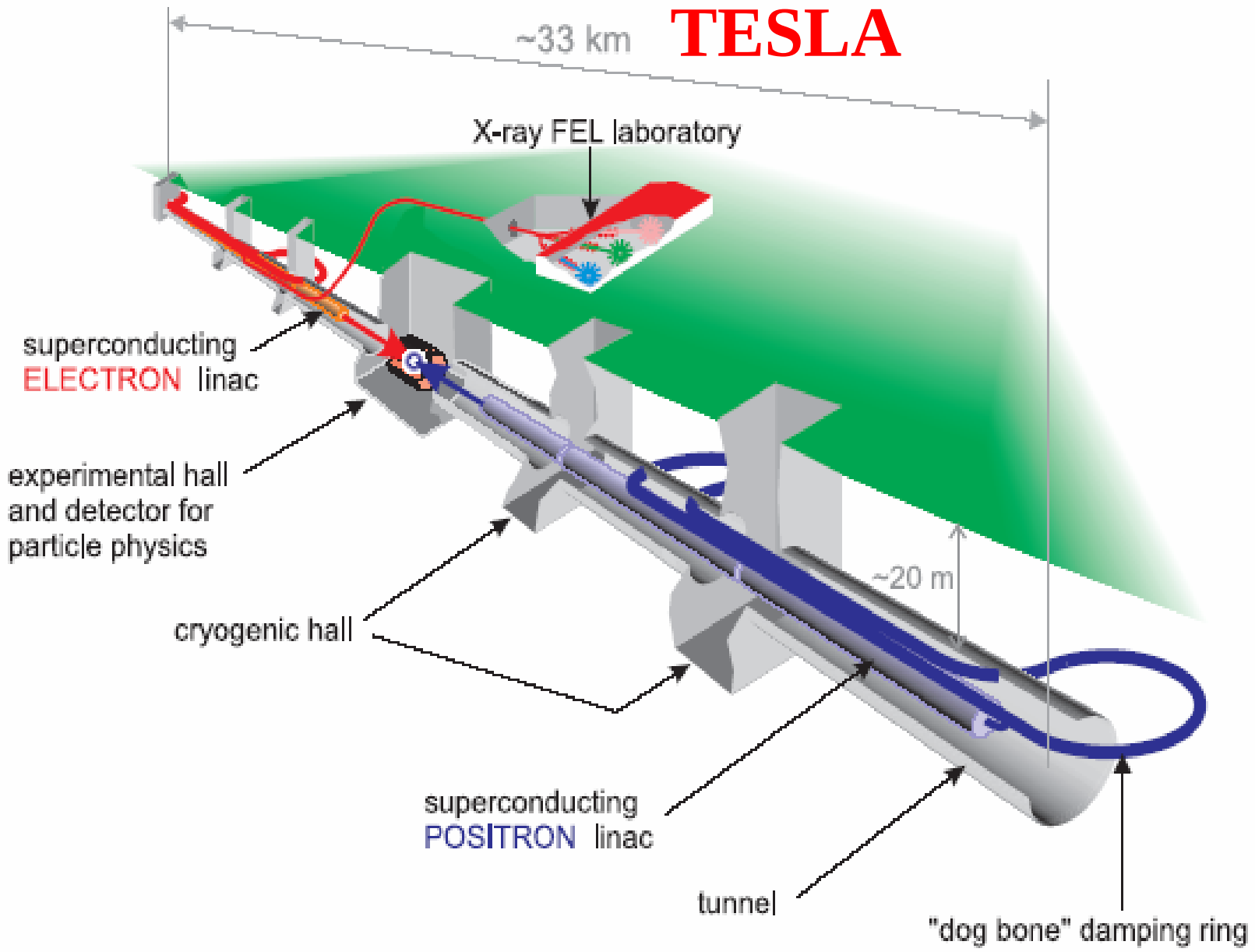
Two projects presently under study:

- ILC (International Linear Collider)
- Technology decision Aug 2004
- Superconducting technology
- 1.3 GHz RF frequency
- ~31 MV/m accelerating gradient
- 500 GeV centre-of-mass energy
- upgrade to 1 TeV possible

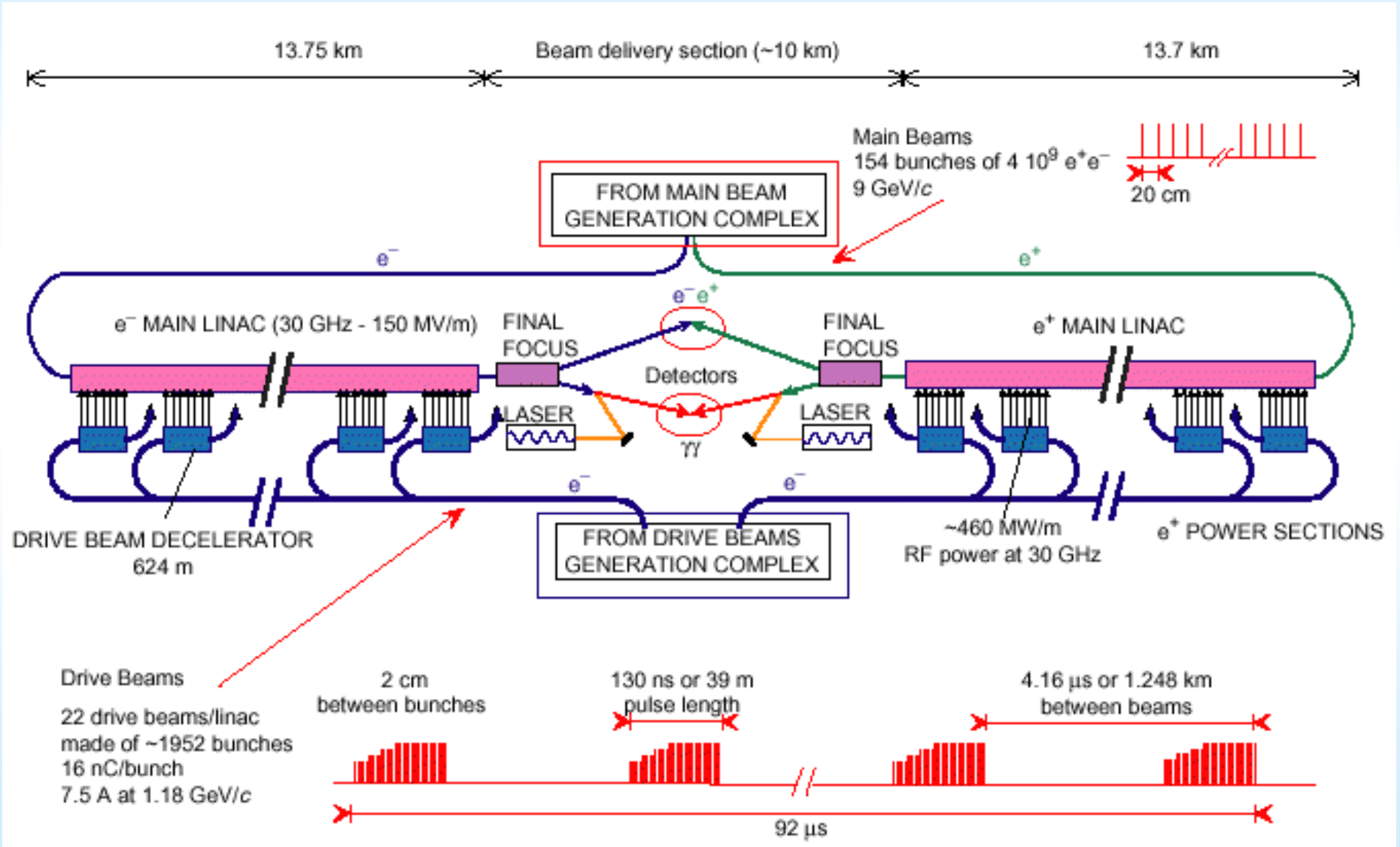
CLIC (Compact Linear Collider)

- normalconducting technology
- multi-TeV energy range (1-5 TeV)

TESLA


~33 km
X-ray FEL laboratory
superconducting
ELECTRON linac
experimental hall
and detector for
particle physics
cryogenic hall
~20 m
superconducting
POSITRON linac
tunnel
"dog bone" damping ring

CLIC

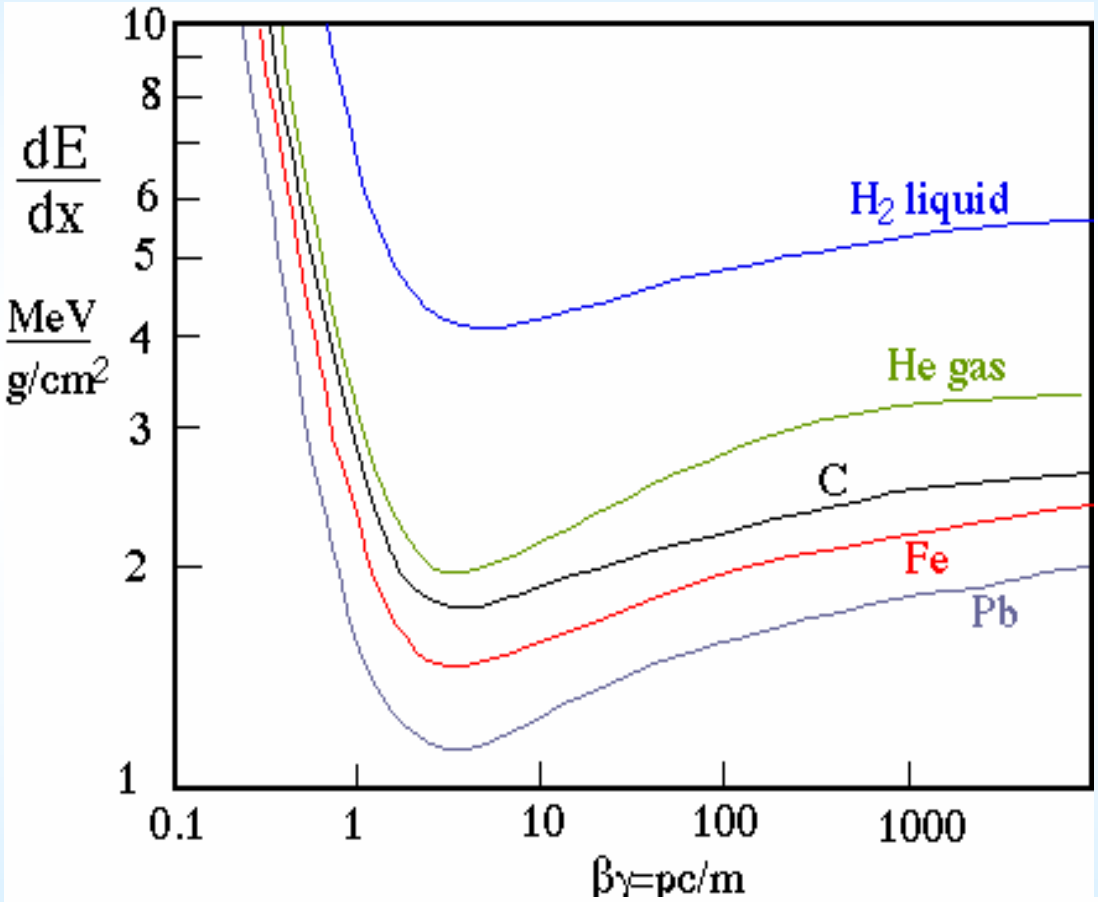

13.75 km
Beam delivery section (~10 km)
13.7 km
Main Beams
154 bunches of 4 10^9 e+e−
9 GeV/c
20 cm
FROM MAIN BEAM GENERATION COMPLEX
e−
e+
e− e+
e− MAIN LINAC (30 GHz - 150 MV/m)
FINAL FOCUS
FINAL FOCUS
e+ MAIN LINAC
Detectors
LASER
LASER
γγ
e−
e−
DRIVE BEAM DECELERATOR
624 m
FROM DRIVE BEAMS GENERATION COMPLEX
~460 MW/m
RF power at 30 GHz
e+ POWER SECTIONS
Drive Beams
22 drive beams/linac
made of ~1952 bunches
16 nC/bunch
7.5 A at 1.18 GeV/c
2 cm
between bunches
130 ns or 39 m
pulse length
4.16 μs or 1.248 km
between beams
92 μs

Some basics of particle detection

- Energy loss of charged particles by ionization
- Bremsstrahlung of electrons and muons
  - Critical energy and radiation length
- Conversion of gammas to electron positron pairs
- $\Rightarrow$ electromagnetique and hadronic showers
  - radiation length and nuclear interaction length
- Cerenkov effect

- Propagation of charged particles in a magnetic field
- Reconstructing their trajectories $p_\perp$ (GeV/c) = 0.3 B ρ
- Measure the energy of electrons, photons and jets
- Detect muons as penetrating particles

Bethe - Bloch formula for the energy loss (by ionisation) of charged particles



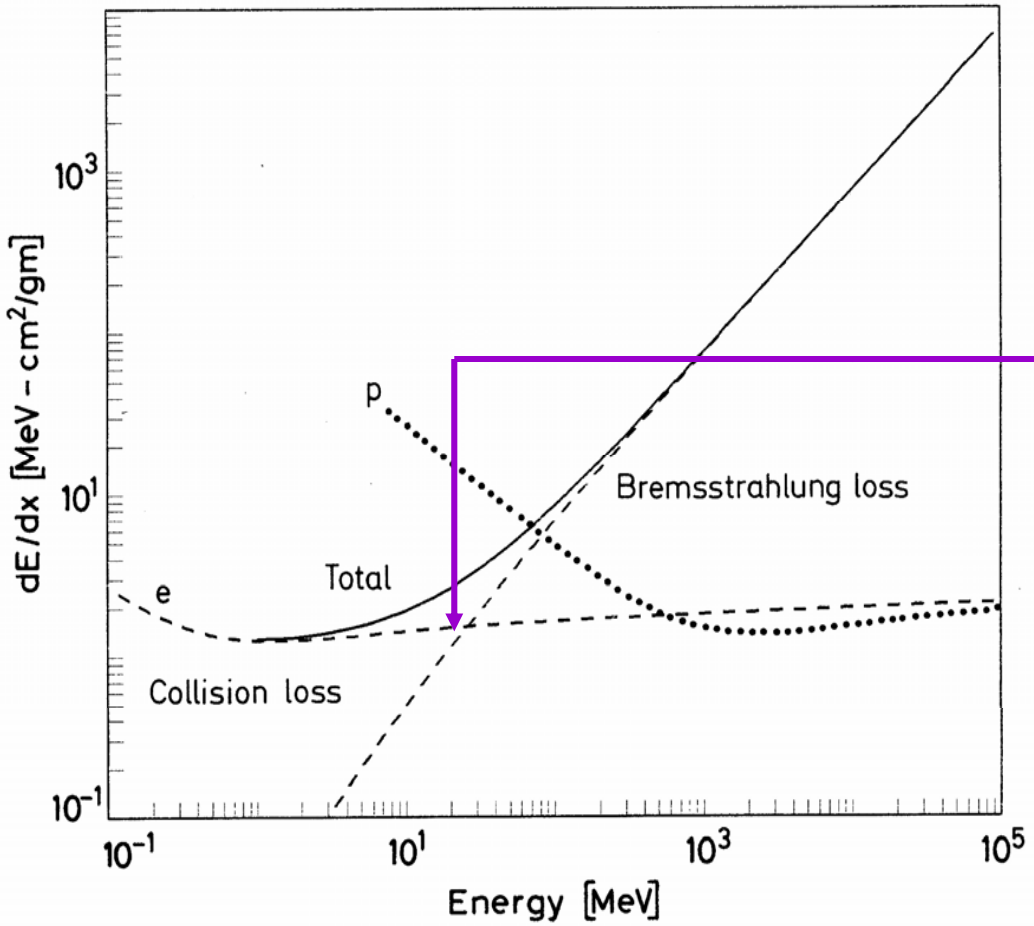
$$-\frac{dE}{dx} = -\frac{1}{\rho}\frac{dE}{ds}$$

$$n_e = N_A \cdot \rho \cdot \frac{Z}{A}$$

$$-\frac{dE}{dx} = 4\pi N r_e^2 m_e z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\left(\frac{2 m_e \beta^2 \gamma^2 T_e^{max}}{I^2}\right) - \beta^2 - \frac{\delta}{2} - \frac{C_e}{Z}\right] \quad (\text{avec} \quad \hbar c = 1)$$

Bremsstrahlung

$$\frac{dE^{rad}}{dx} = -\frac{dE^{e^-}}{dx} = \frac{E^{e^-}}{X_0}$$



X_0 = radiation length

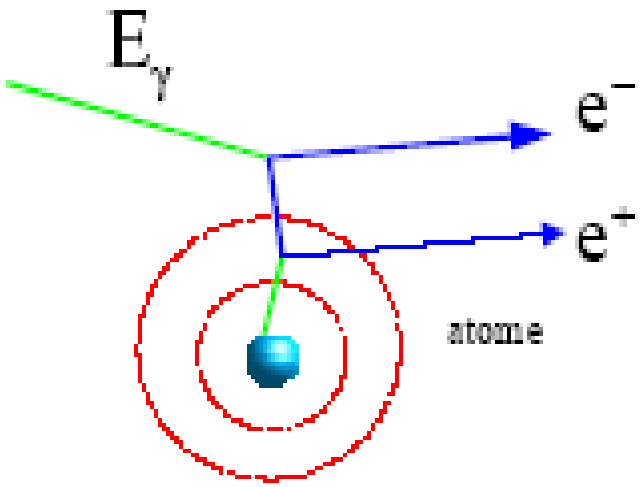
$E_{critical}$

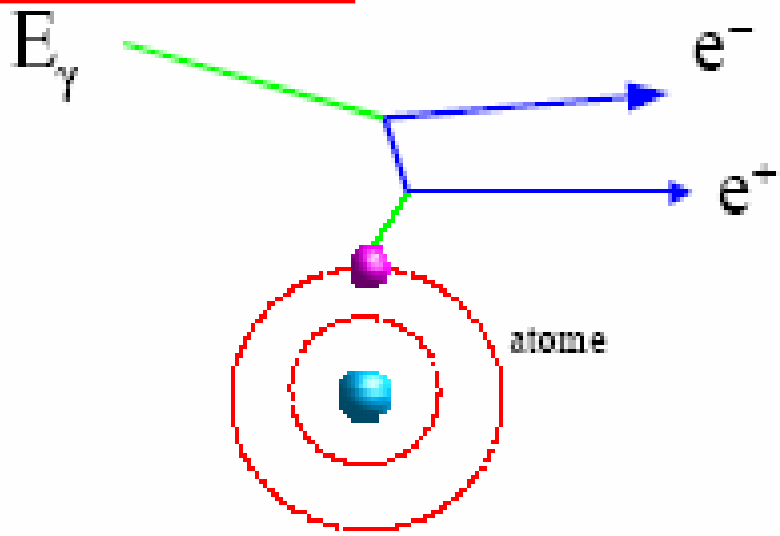
For muons the critical energy is about 200 GeV !

Conversion of photons into electron-positron pairs

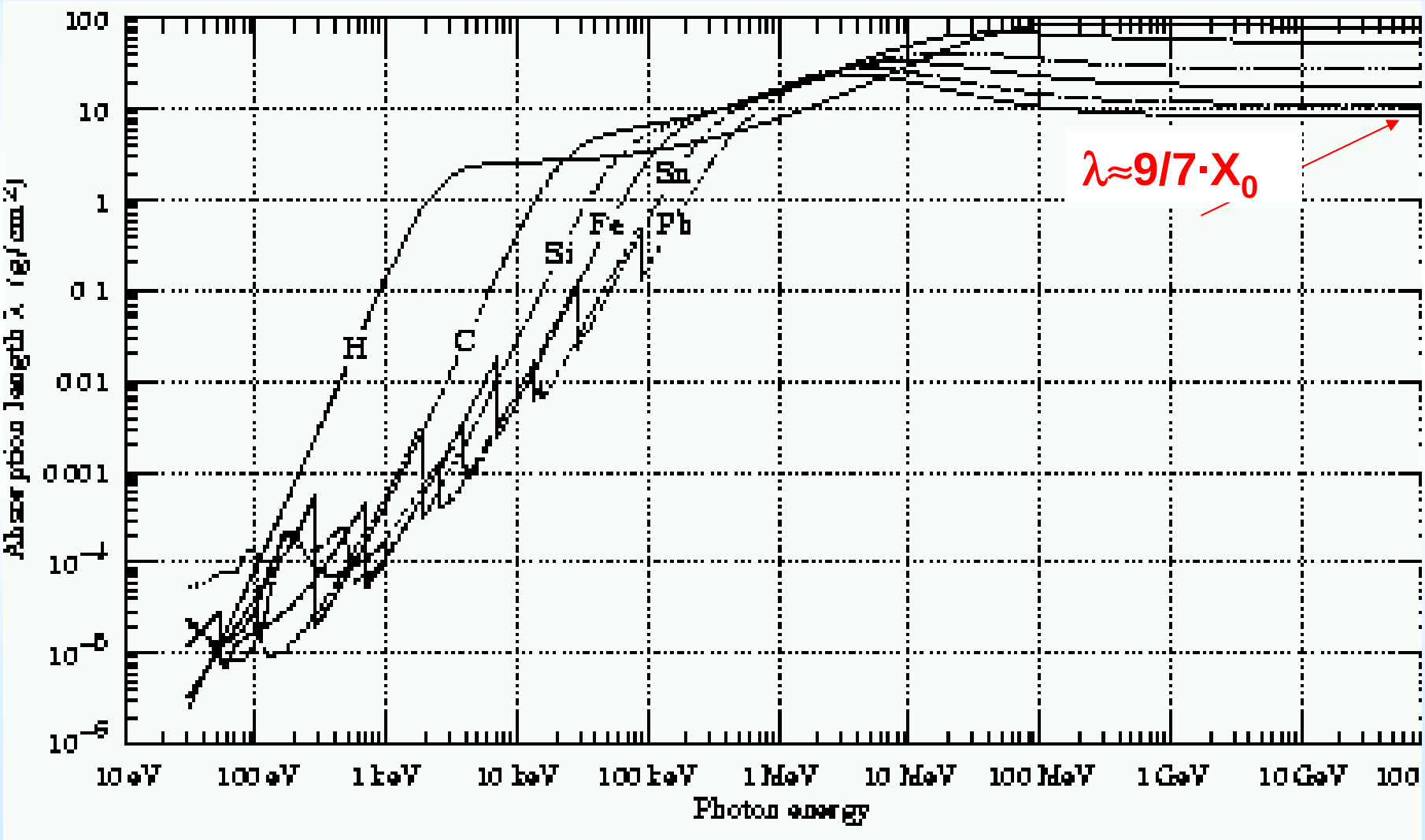
$$\sigma_{pair} \approx \frac{7}{9}\frac{A}{N_A}\cdot\frac{1}{X_0}\,Z(Z+1)$$

$$\mu_{pair} = \frac{N_A}{A}\sigma_{pair} \approx \frac{7}{9}\frac{1}{X_0}\;;\quad \boxed{\lambda_{pair} = \frac{1}{\mu_{pair}} = \frac{9}{7}X_0}$$

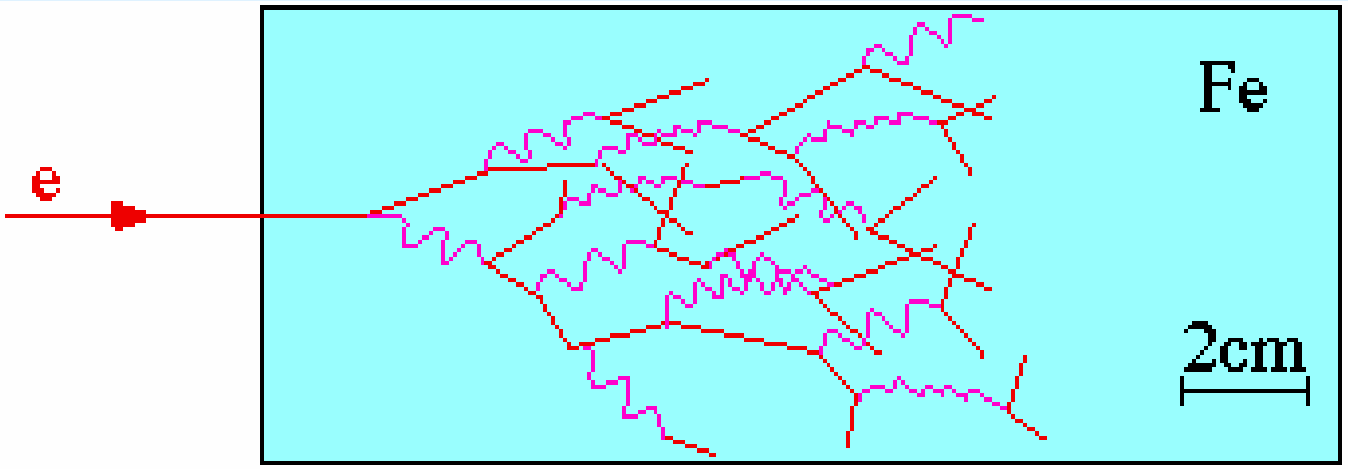




Attenuation length of photons

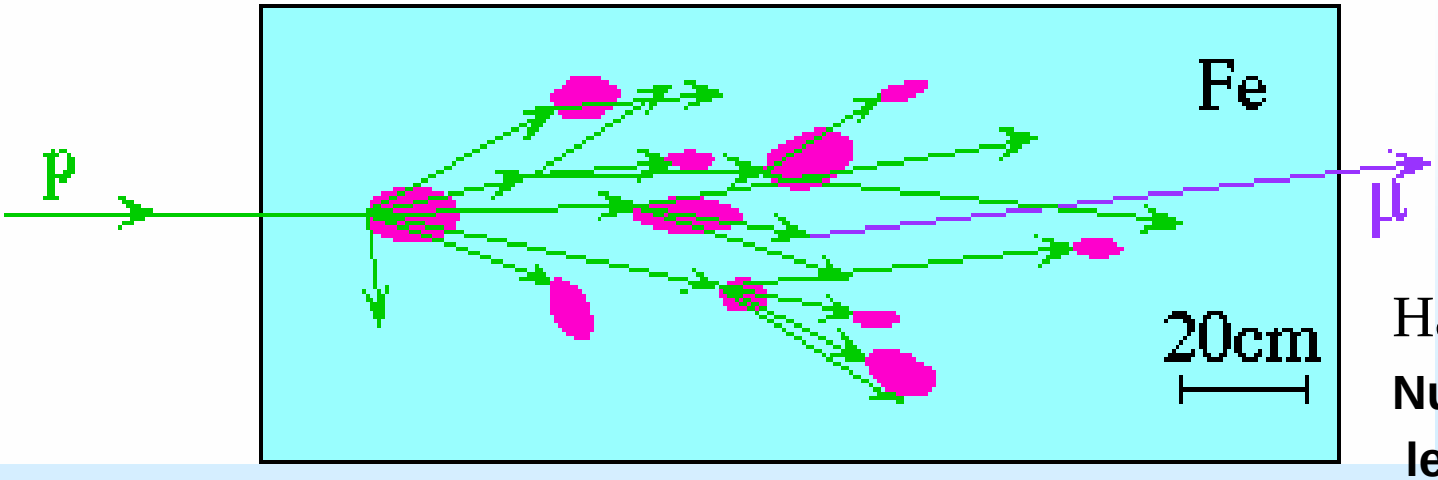


Showers in calorimeters



Electromagnetic shower

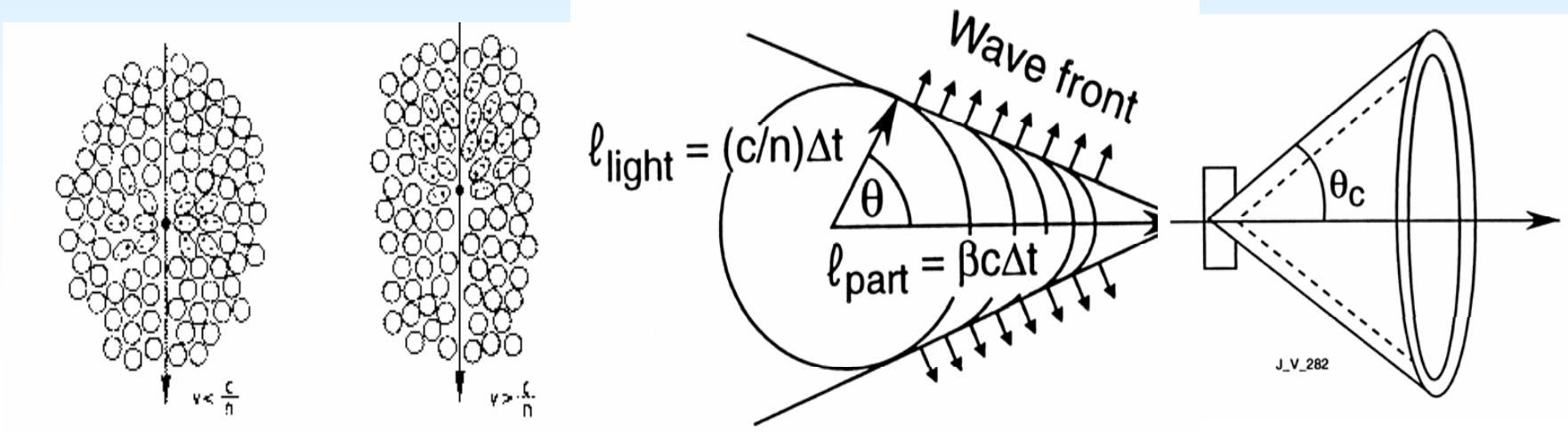
radiation length X_0



Hadronic shower

Nuclear interaction length Λ

Cerenkov effect



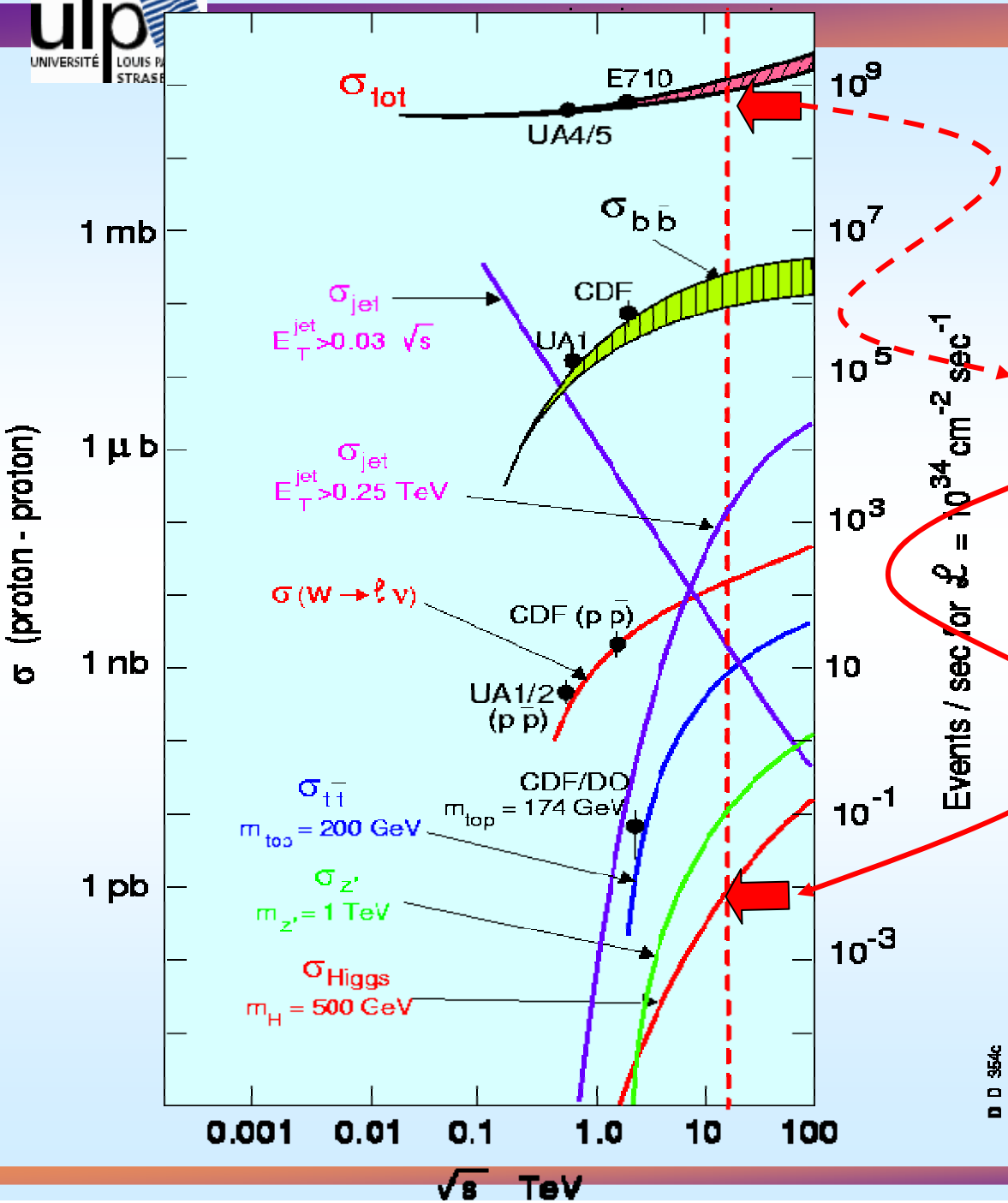
$$\ldots > c/n$$

- **Coherent superposition of light emitted by polorised atoms**
- **UV - visible**
- **Very few photons**
- **Energy loss minimal**
- **Used for particle identification and calorimetry**

$$\cos\theta_C = \frac{c \cdot \Delta t / n}{\beta c \cdot \Delta t} = \frac{1}{\beta n}$$

$$\Rightarrow \beta > \frac{1}{n};$$

$$\lambda \approx 300 - 700\,nm$$



pp Collisions at LHC

$\sigma_{\text{tot pp}} = 40 - 100 mb$

$\sigma_{\text{H(500GeV)}} \approx 1 pb$

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

Beam crossing rate:

40 MHz

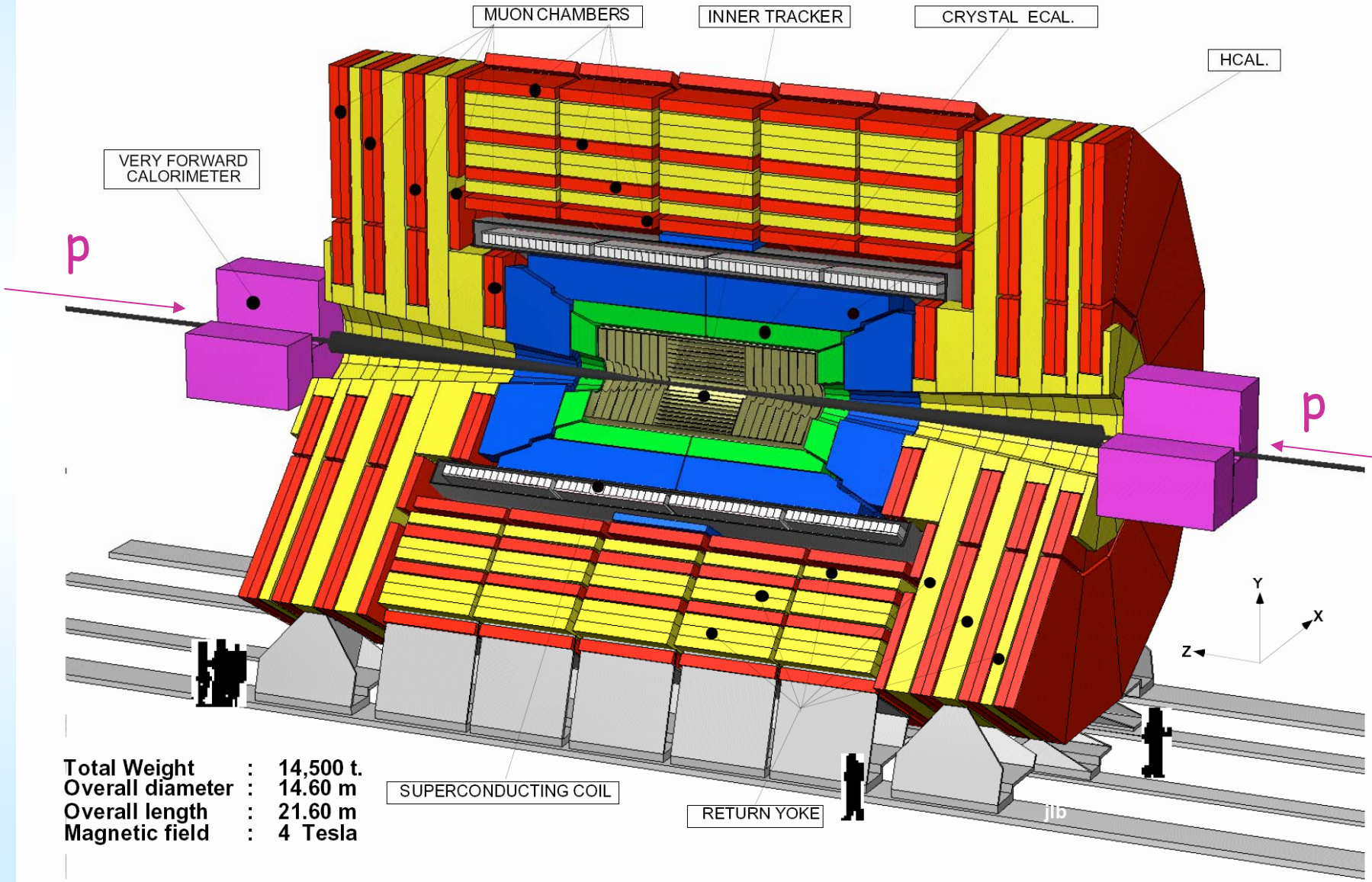
25 interactions

per crossing

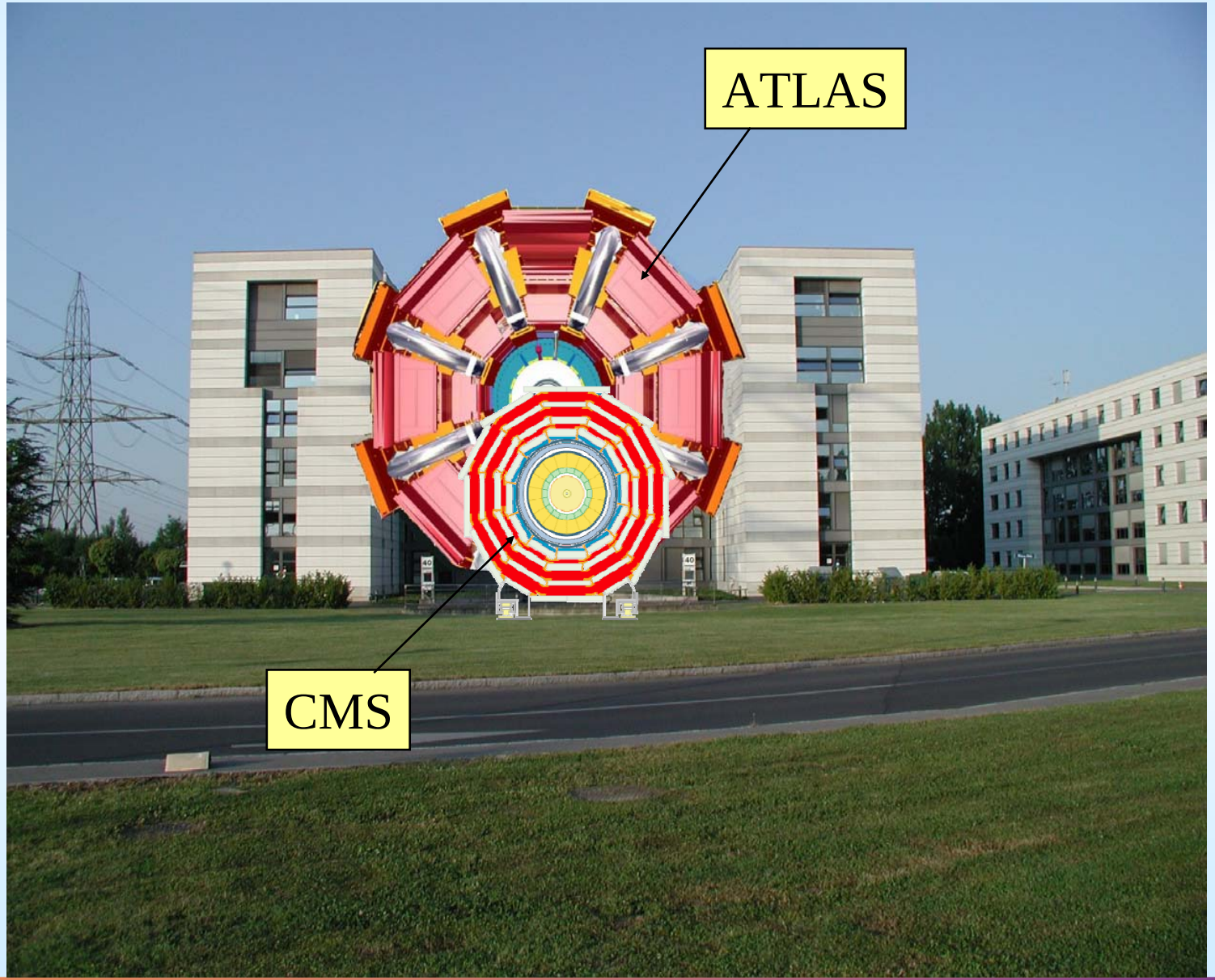
$\dot{N}_{tot} = 10^{9} s^{-1}$

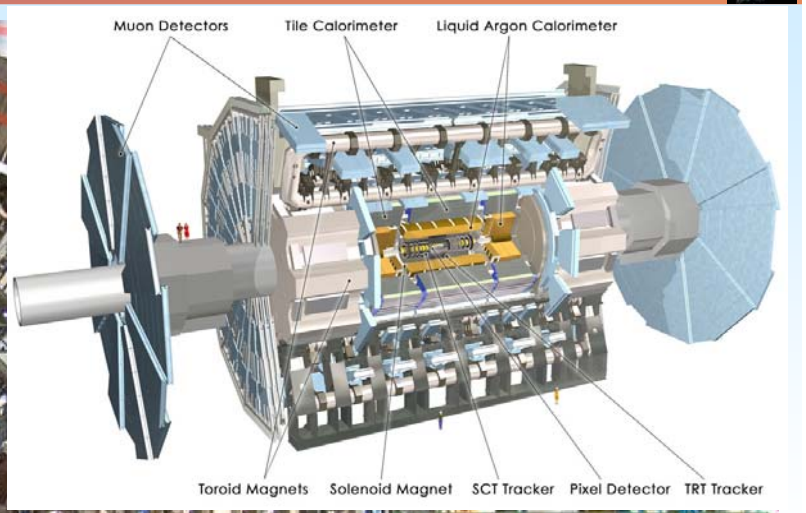
$\dot{N} = 10^{-2} s^{-1}$

Compact Muon Solenoid



The Compact Muon Solenoid





ATLAS DETEKTOR

ATLAS Detector Under construction
October 2005

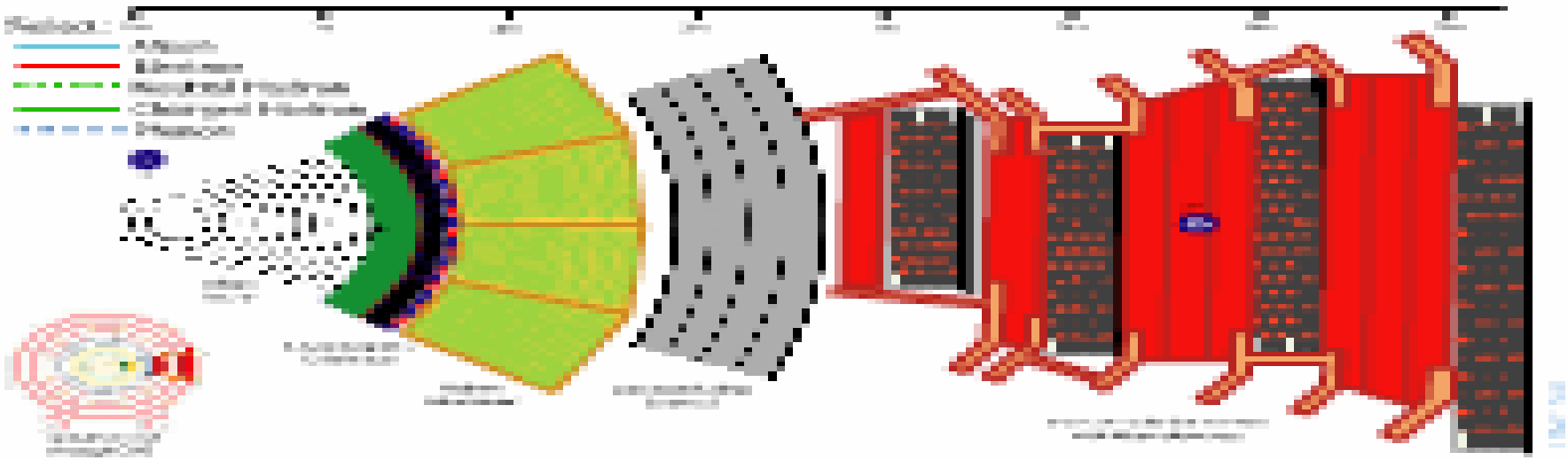
CMS Design Goals

- **A good and redundant *muon system*** (= many layers – if one layer fails we can fall back on the others**)**
- **The best possible *electromagnetic calorimeter***
- **A high quality *central tracking***
- **A *hadronic calorimeter* that has good energy resolution and that is as hermetic as possible**
- **Affordable! (= ~500 MCHF)**

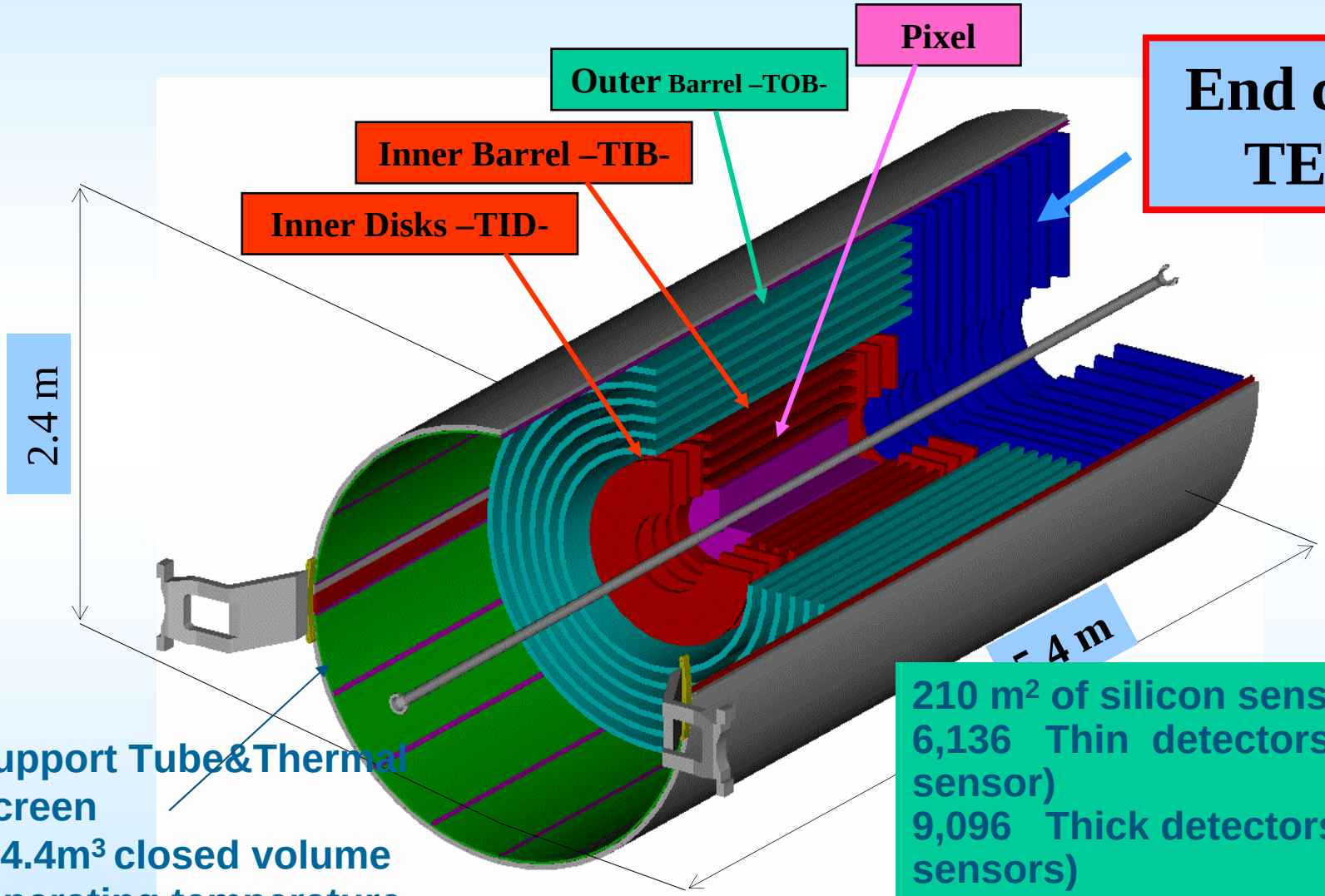
Transverse slice through CMS detector

Click on a particle type to visualise that particle in CMS

Press “escape” to exit



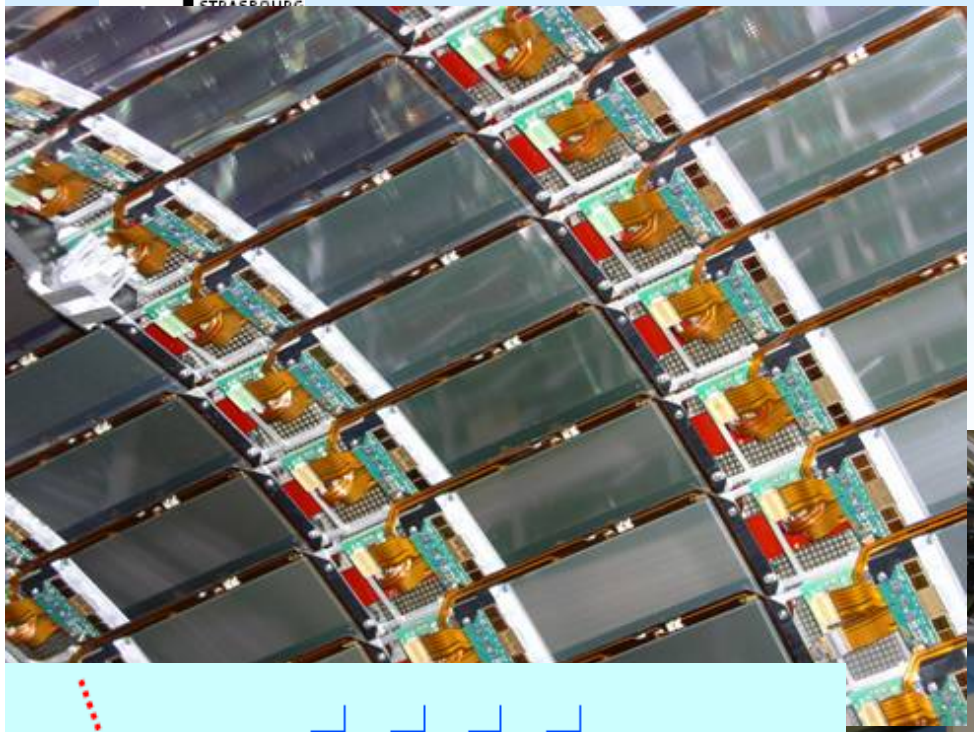
CMS Tracker

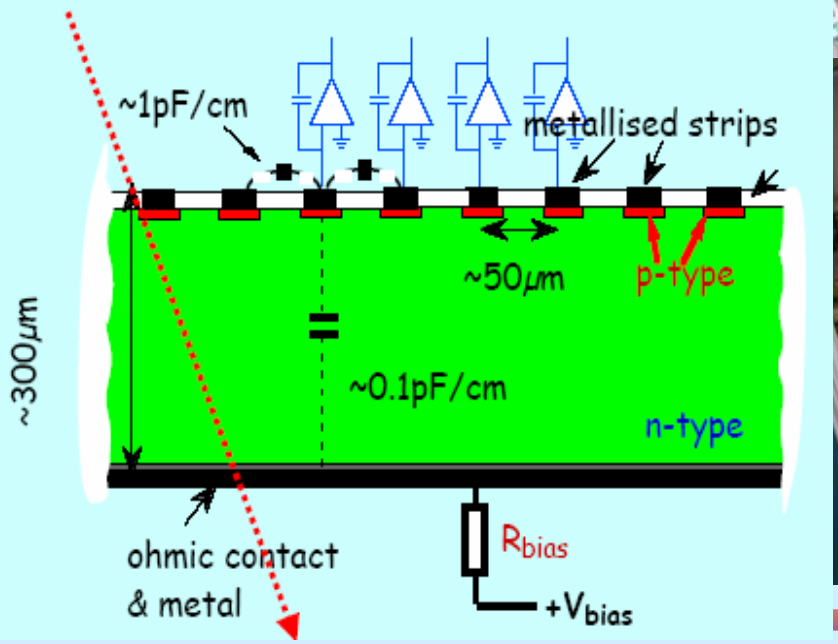


Support Tube&Thermal Screen
- 24.4m³ closed volume
- operating temperature – 10°C

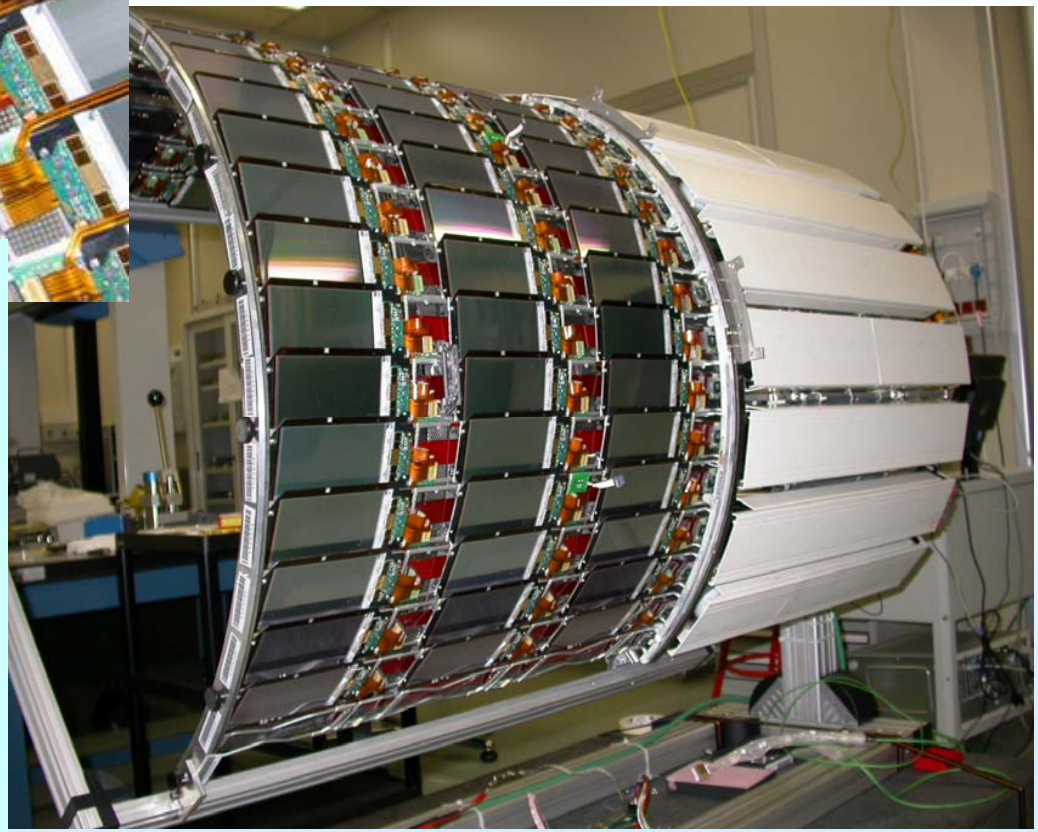
210 m² of silicon sensors
6,136 Thin detectors (1 sensor)
9,096 Thick detectors (2 sensors)
9,648,128 electronics channels

Silicon strip detectors

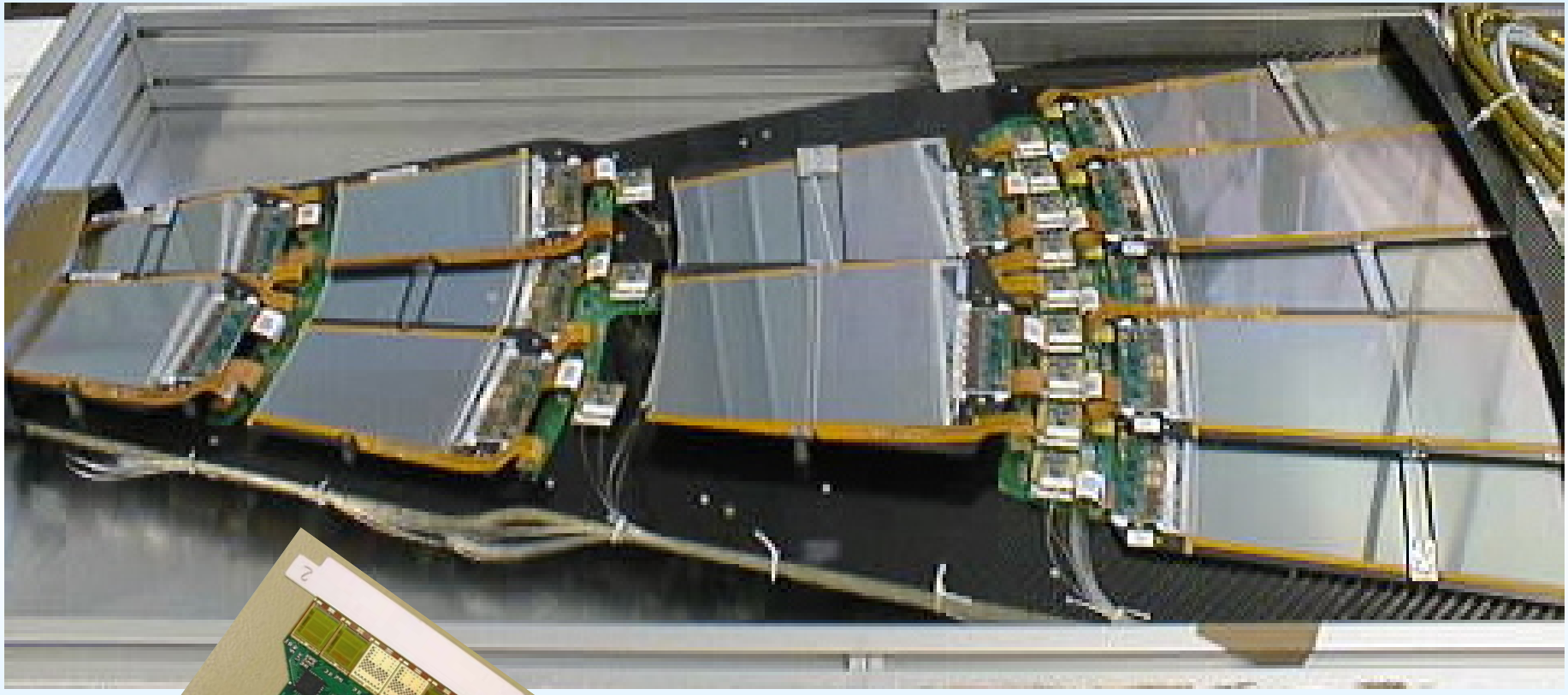


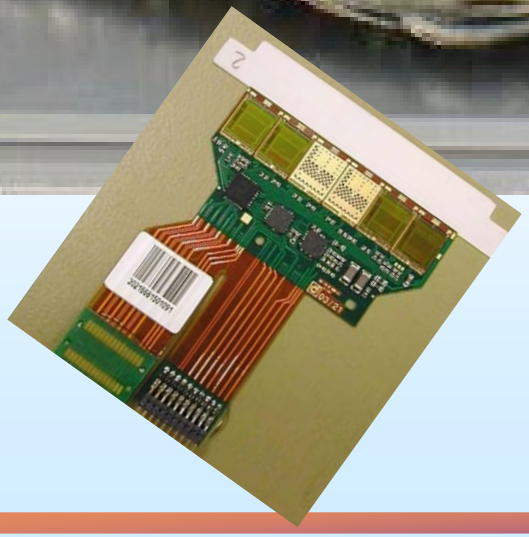


TIB Barrel

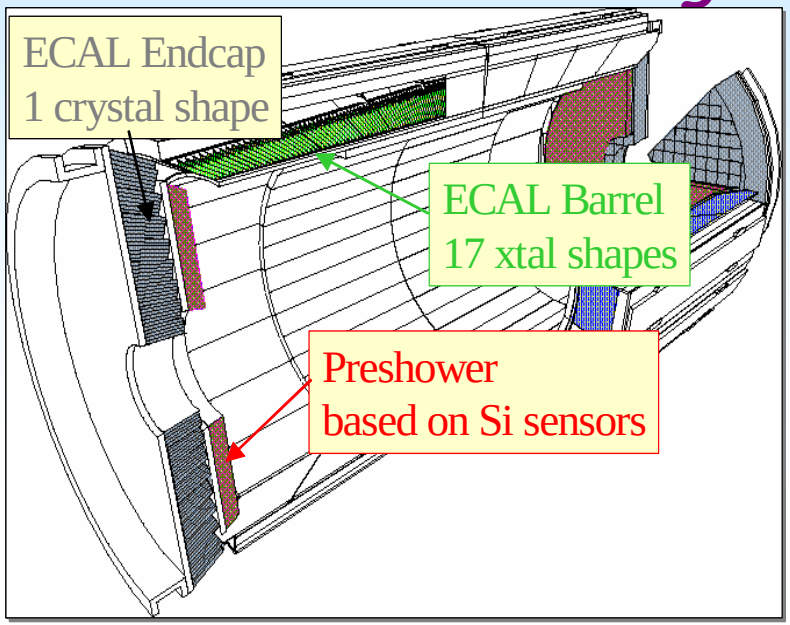


Construction of CMS





The Electromagnetic Calorimeter - ECAL

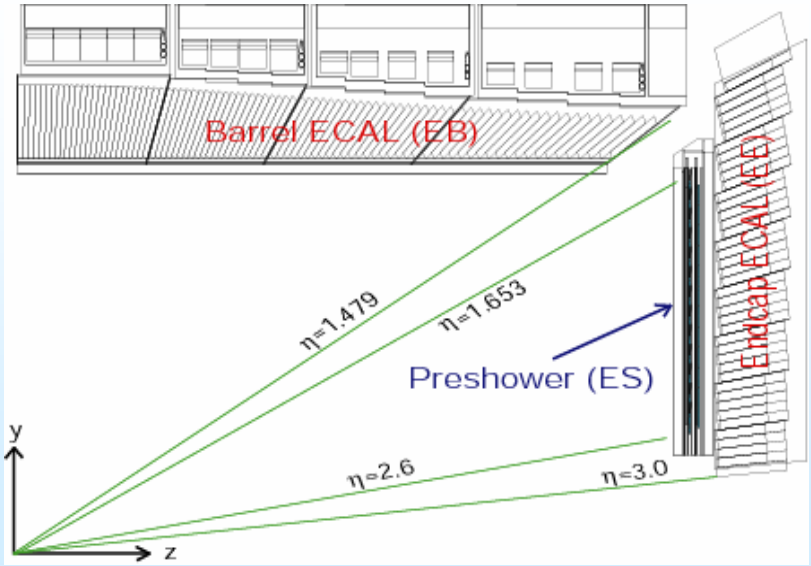


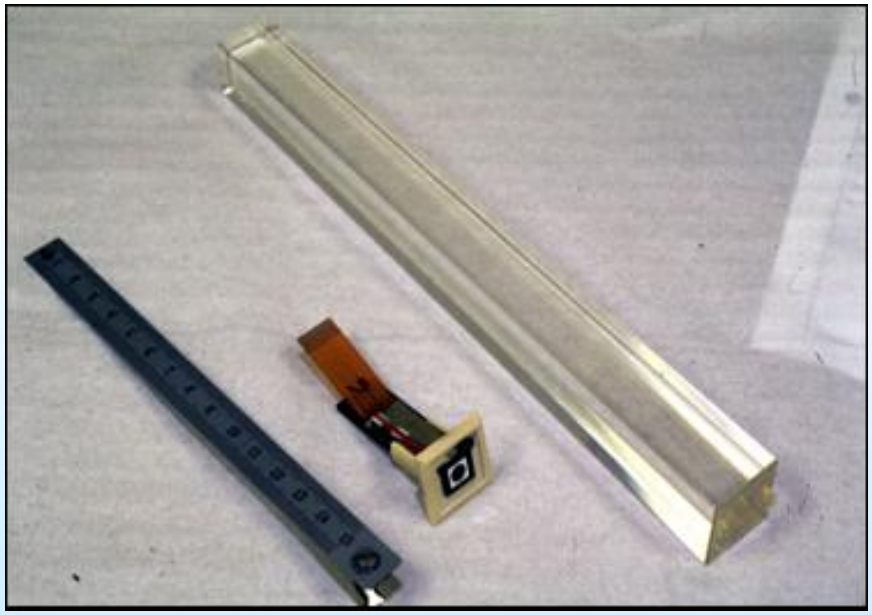
Characteristics of $PbWO_4$

$X_0 = 0.89cm$

$\rho = 8.28 g/cm^3$

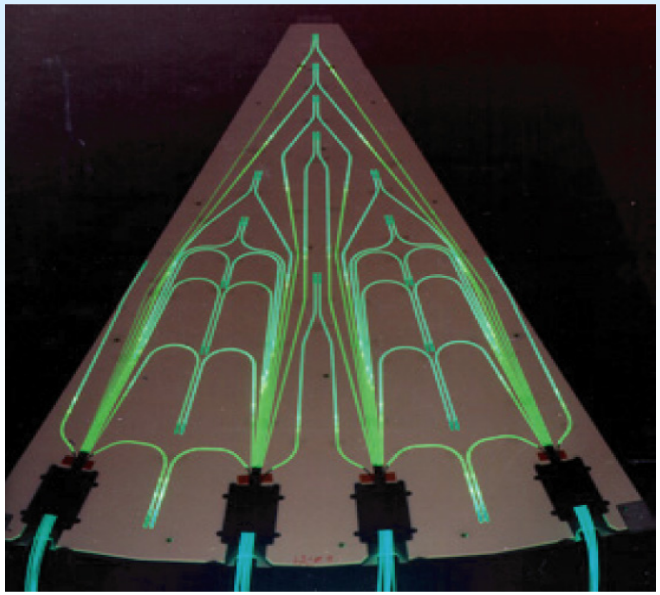
R_M (Molière radius) = 2.2cm



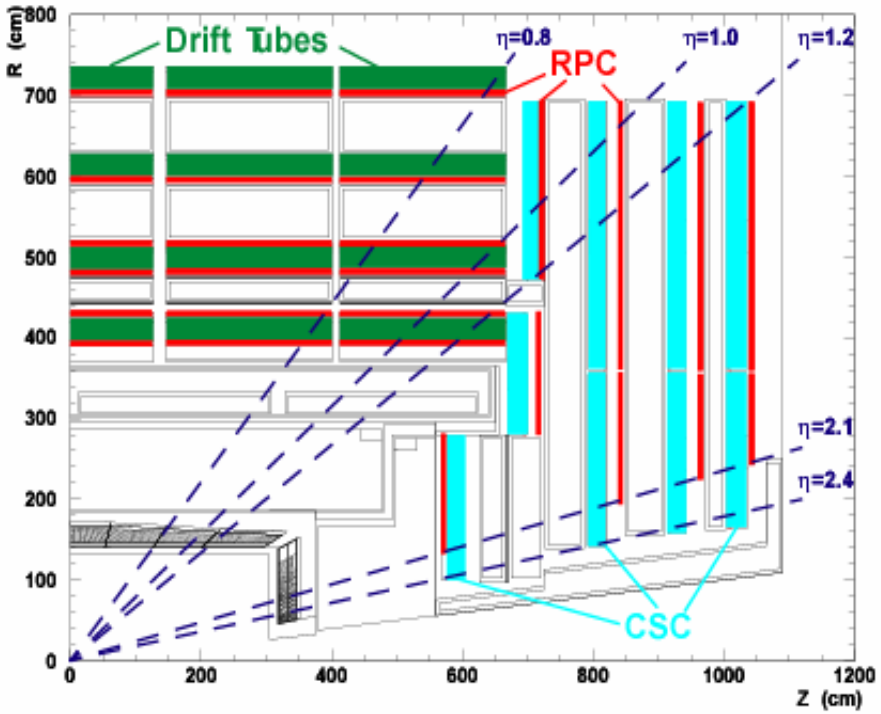


The Hadron Calorimeter - HCAL

- CMS HCAL is constructed in 3 parts:
  - Barrel HCAL (HB)
    - Brass (laiton) plates interleaved with plastic scintillator embedded with wavelength-shifting optical fibres (photo top right)
  - Endcap HCAL (HE)
    - Brass plates interleaved with plastic scintillator
  - Forward HCAL (HF)
    - Steel wedges stuffed with quartz fibres (photo bottom right)
- ~10000 channels total

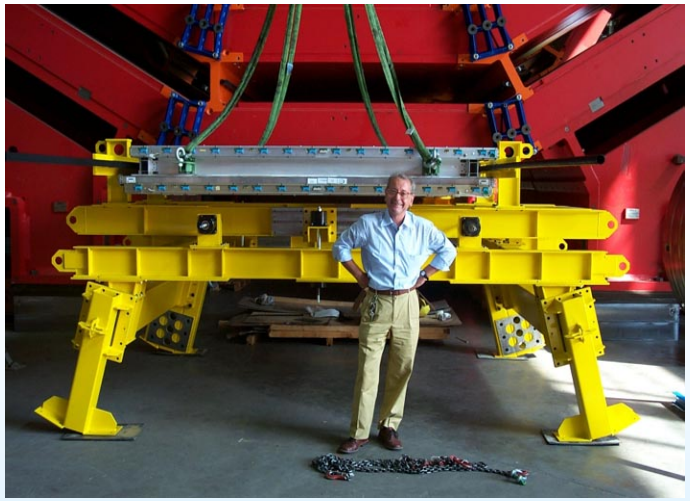


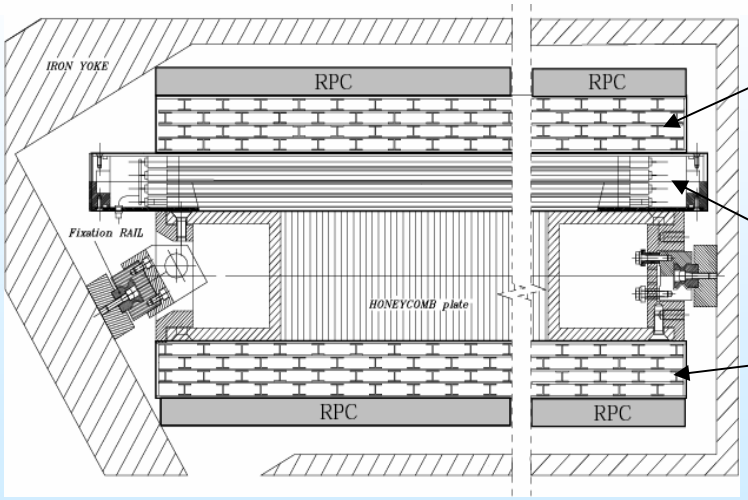
The Muon Chambers



Position measurement:
Drift Tubes (DT) in barrel
Cathode Strip Chambers (CSC) in endcaps

Trigger:
Resistive Plate Chambers (RPCs) in barrel and endcaps





ϕ superlayer of 4 DT layers

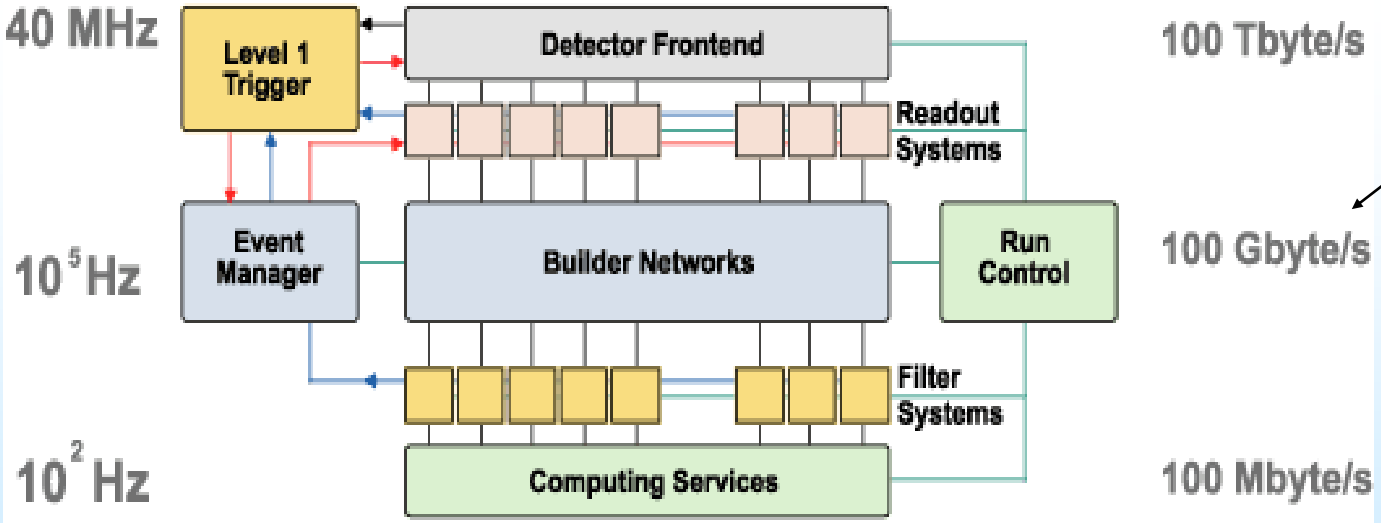
η superlayer of 4 DT layers

ϕ superlayer of 4 DT layers

195000 DT channels
210816 CSC channels
162282 RPC channels

The Trigger and Data Acquisition System (3)

Data Acquisition Main Parameters	
Collision rate	40 MHz
Level-1 Maximum trigger rate	100 kHz
Average event size	1 Mbyte
No. of electronics boards	10000
No. of readout crates	250
No. of In-Out units (200-5000 byte/event)	1000
Event builder (1000 port switch) bandwidth	1 Terabit/s
Event filter computing power	5 10^6 MIPS
Data production	Tbyte/day



Trigger and Data Acquisition baseline structure

~same as whole world's telecom network!

CMS Basic Parameters

Physical Parameters

Length	**21.6m**
Diameter	**14m**
Mass	**12500 Tonnes**
Magnetic field	**4 Tesla**

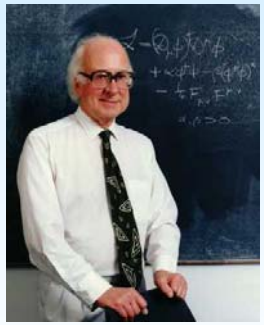
Channel Count

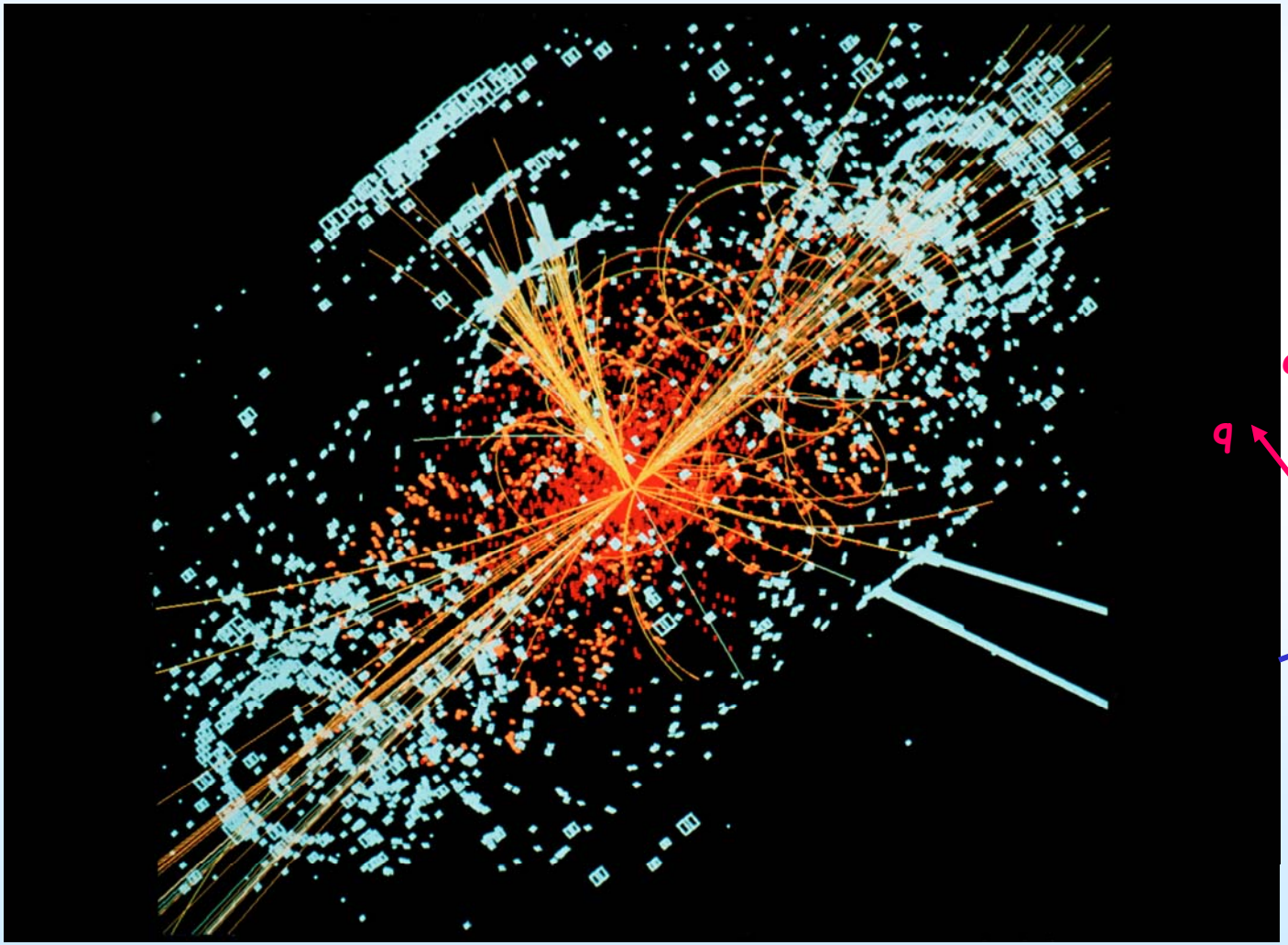
Sub-Detector	*Number of channels*
Pixels	66×10^6
Silicon microstrips	11.4×10^6
ECAL crystals	0.076×10^6
Preshower strips	0.137×10^6
HCAL	0.01×10^6
Muon chambers	0.576×10^6
TOTAL	78.2×10^6

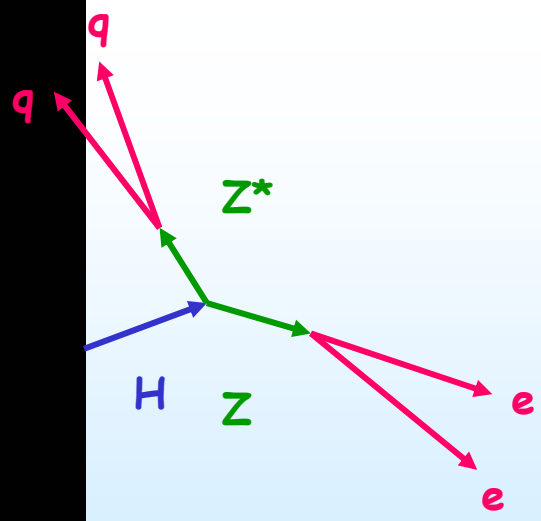
Trigger and Data Acquisition Parameters

Parameter	*Value*
Bunch-crossing frequency	40 MHz
Average # of collisions / bunch-crossing	20
“interaction rate”	$\sim 10^9$
Level-1 trigger rate	100 kHz
Average event size	1 Mbyte
Event builder bandwidth	100 Gbytes/sec
Event filter computing power required	10^6 SI95
Event rate saved to mass storage	100 Hz
Data production	10 Tbytes/day

The scalar Higgs field gives mass to all particles

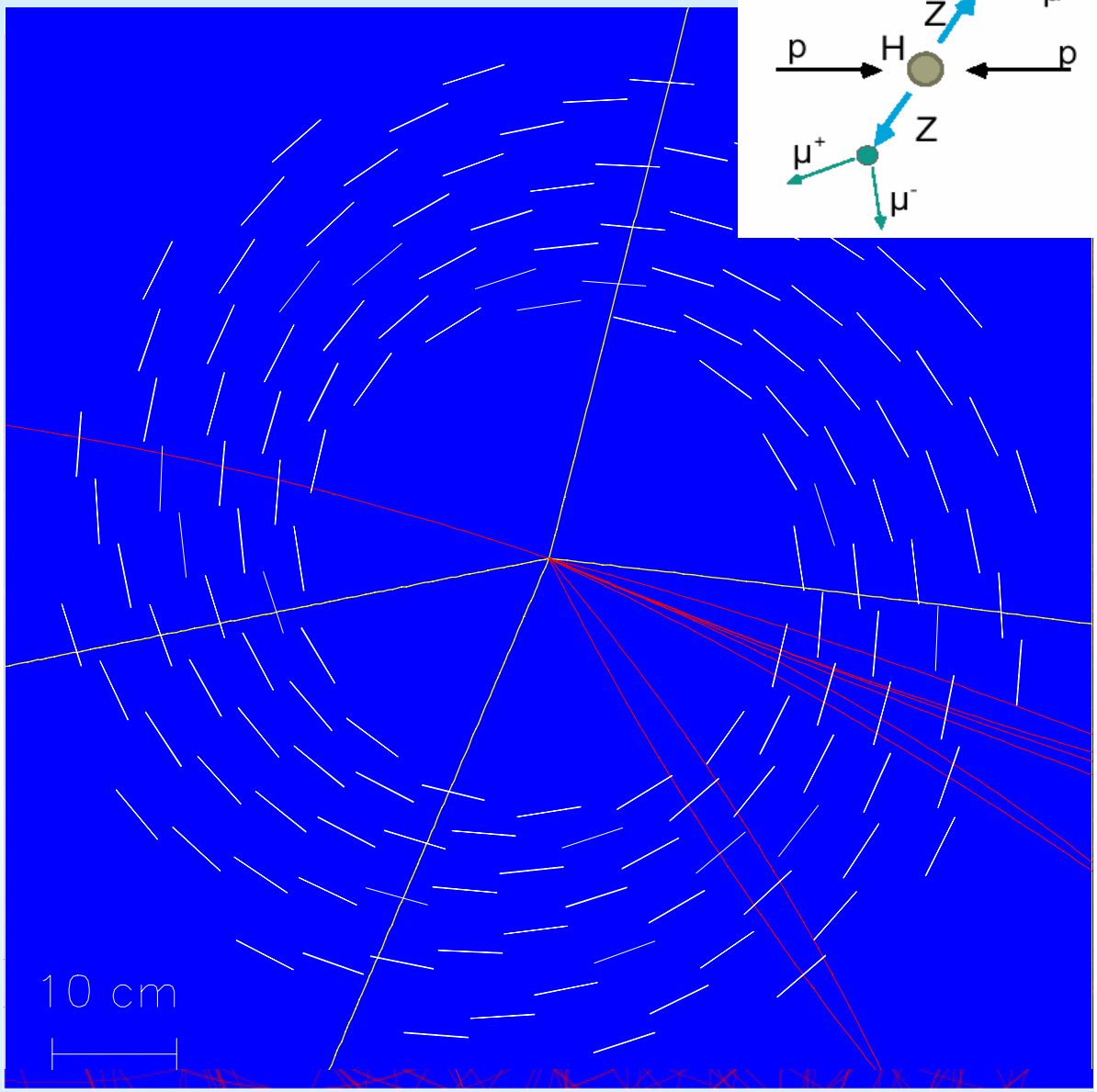






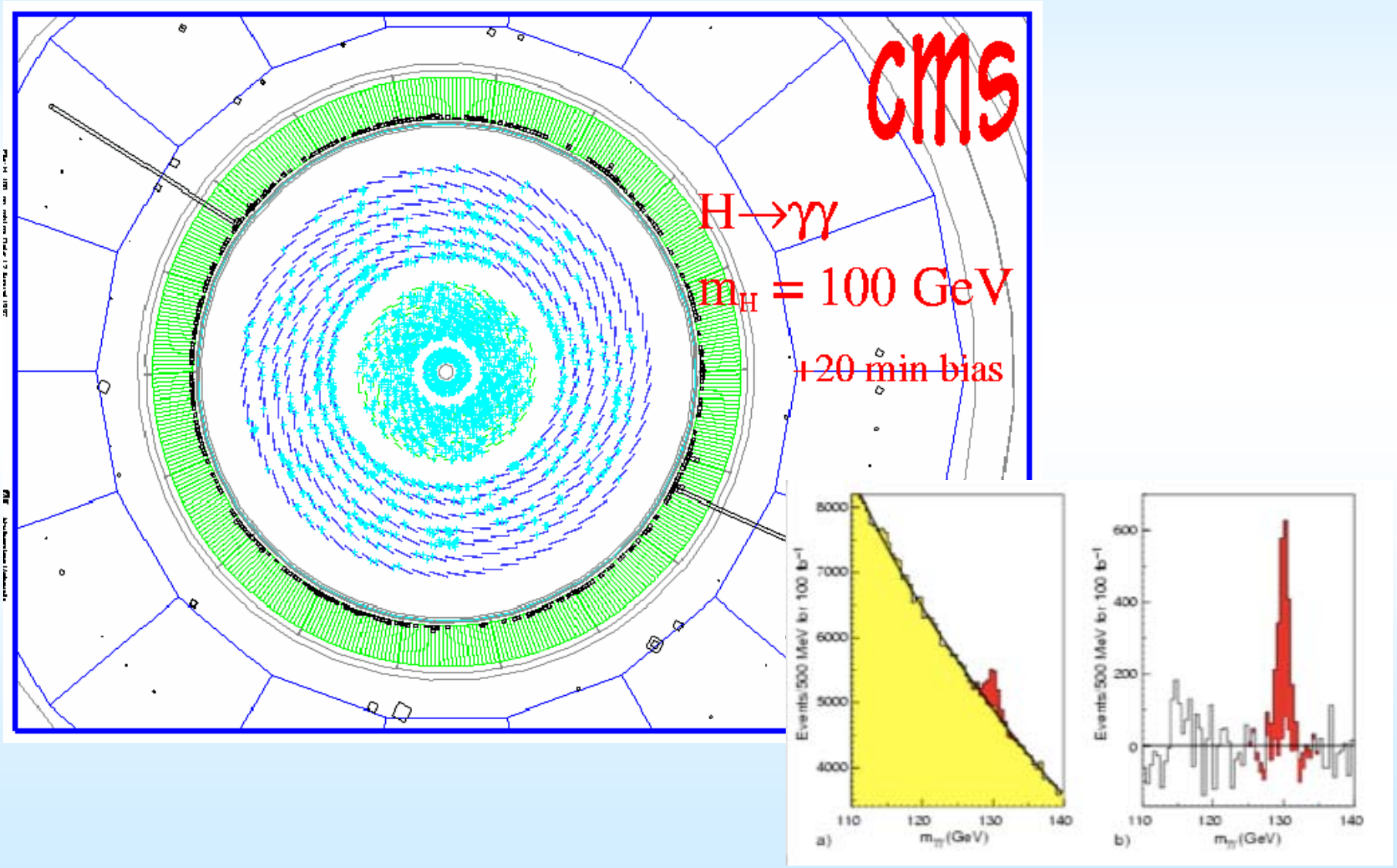
View along beam line of the inner tracking, with a H→ 4μ event superimposed. The μ are very high energy, so leave straight tracks originating from the centre and travelling to the outside

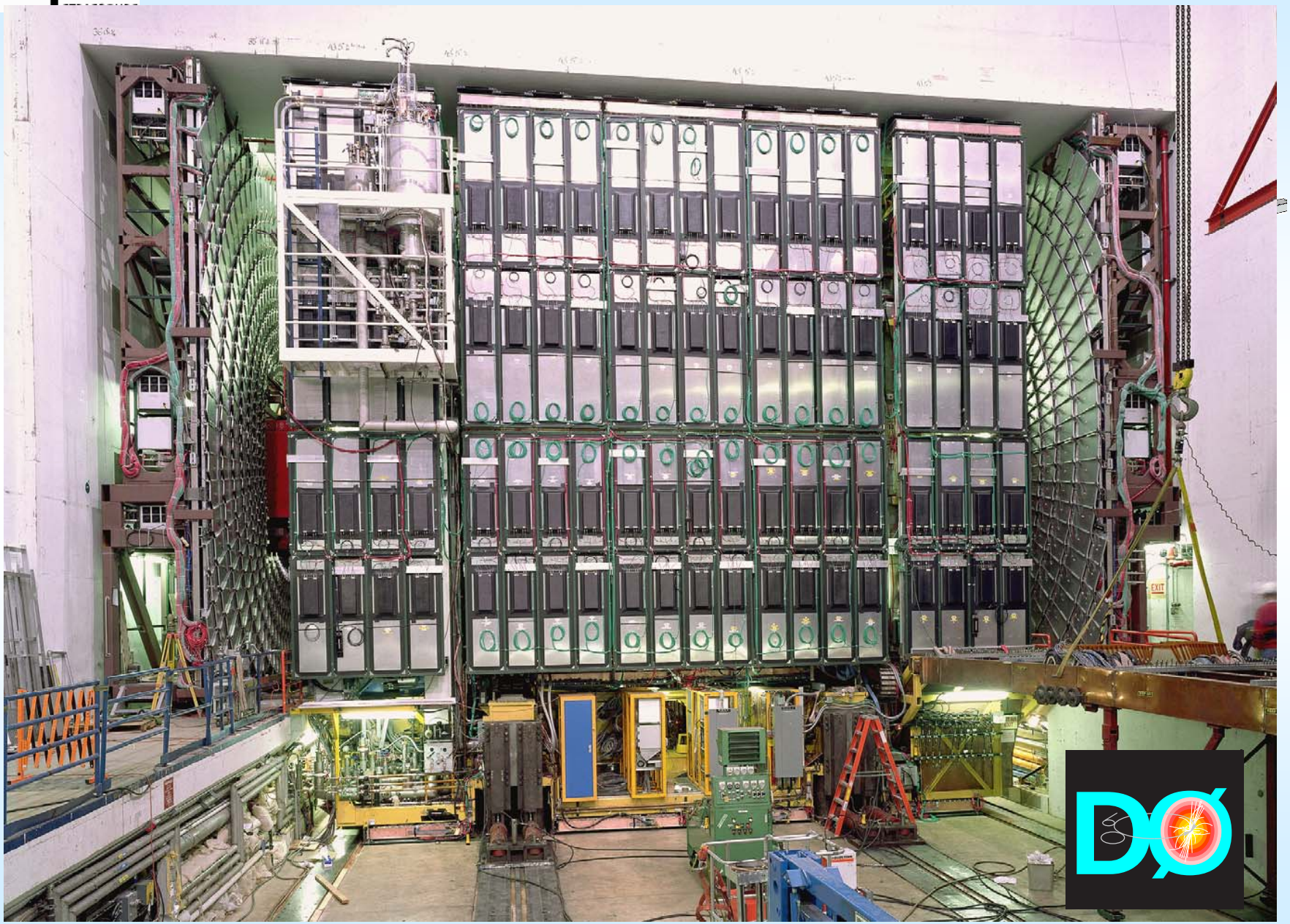
Make a "cut" on the Transverse momentum Of the tracks: p_T>2 GeV



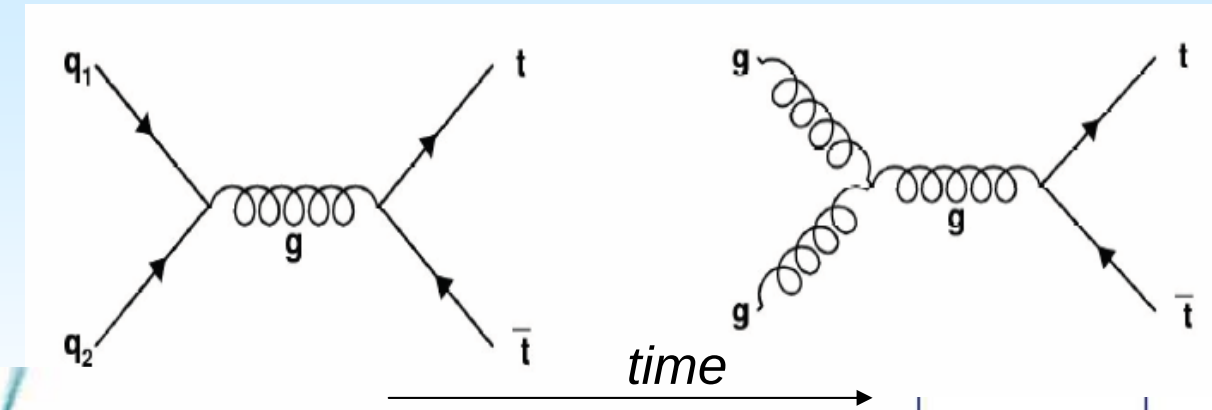
Find 4 straight tracks.

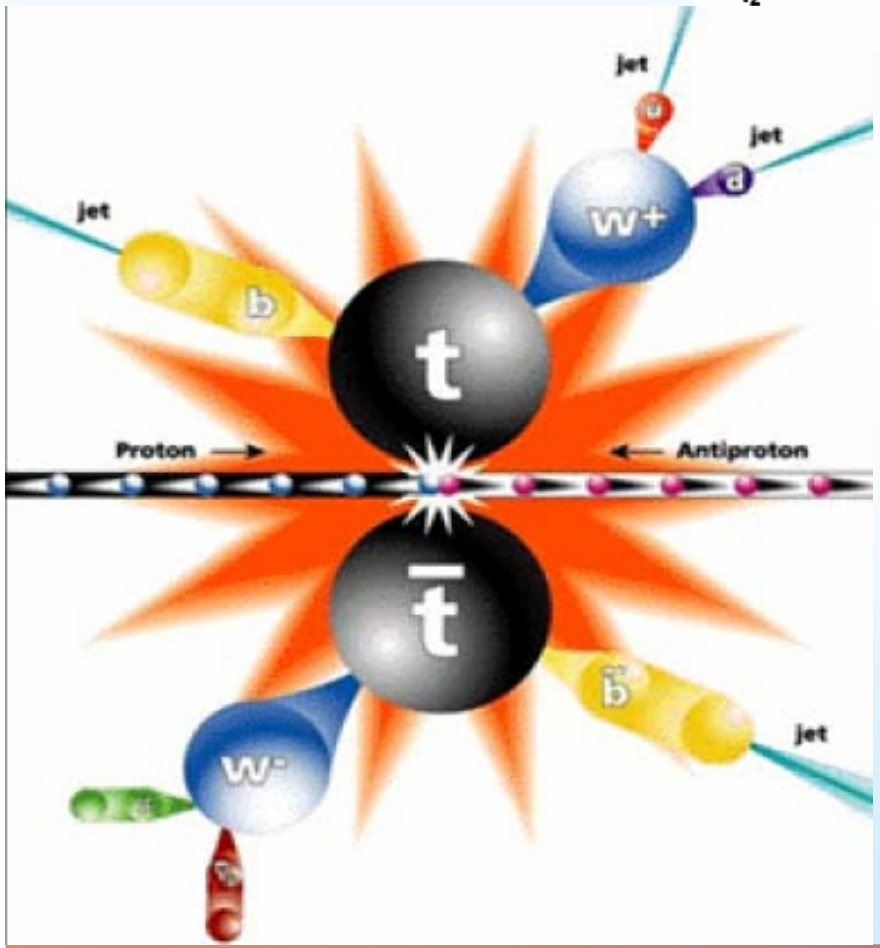
Higgs en $\gamma\gamma$



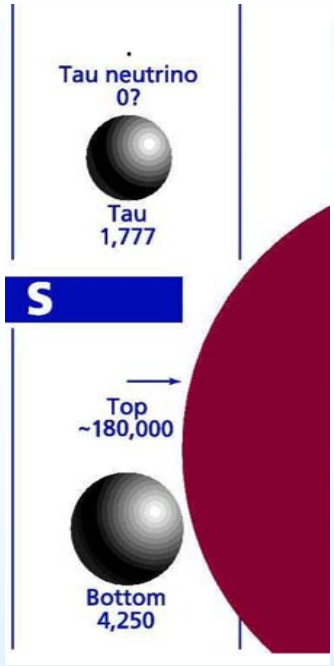

EXIT

The discovery of the Top-Quark





Top mass = 174.3±5.1 GeV/c²



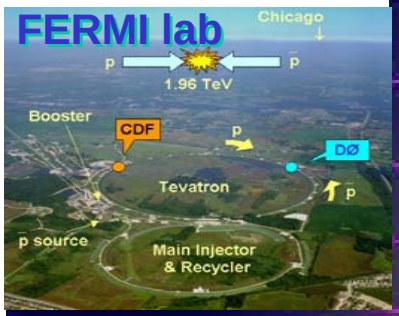
W

$$gg \to t\bar{t};$$

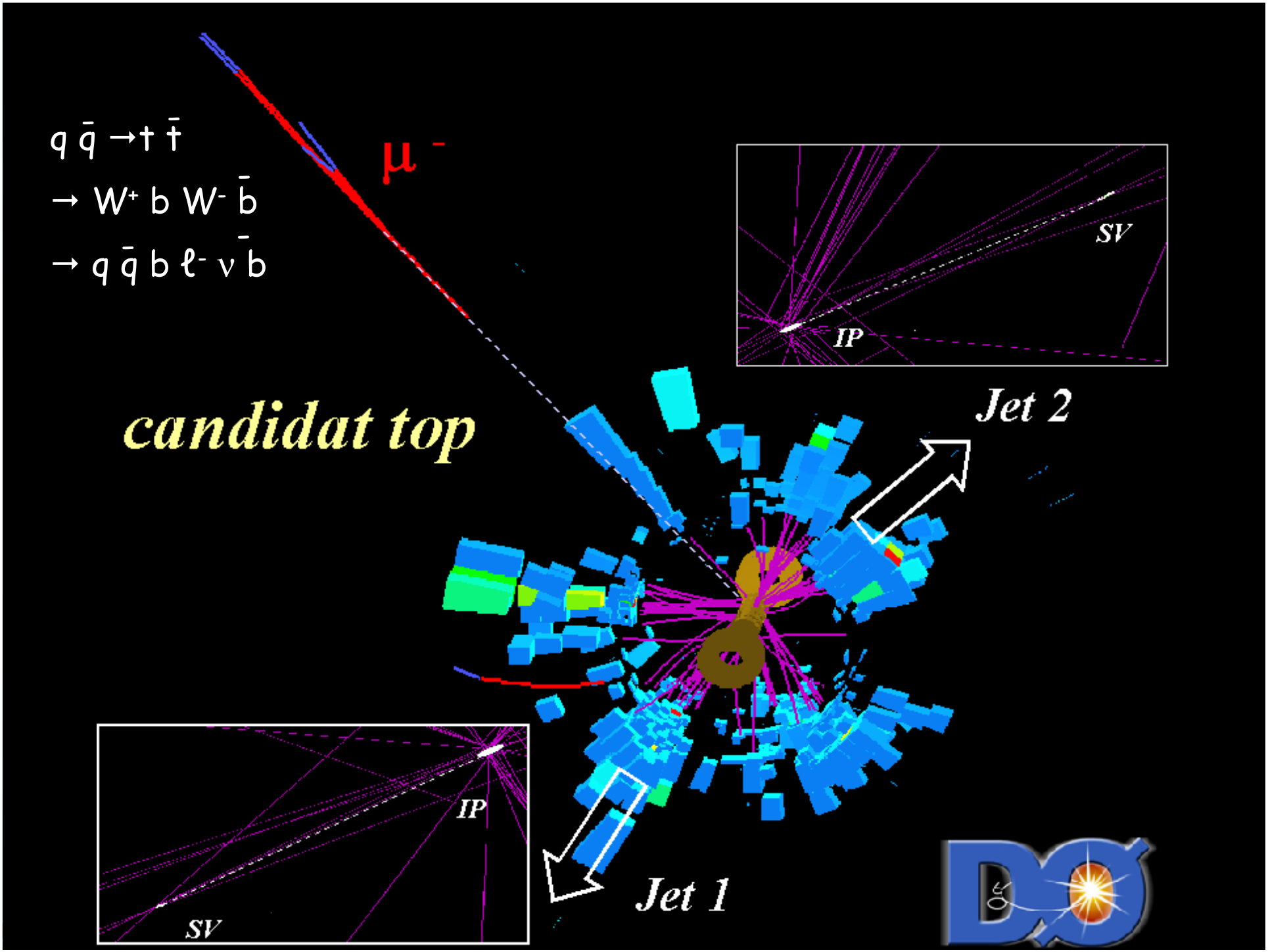
$$t \to bW;$$

$$\begin{bmatrix} W \to l\nu;\ W \to q\bar{q}';\ q \to jet \\ b \to cl\nu;\ b \to jet \end{bmatrix}$$

Production of a Top - anti-Top Pair

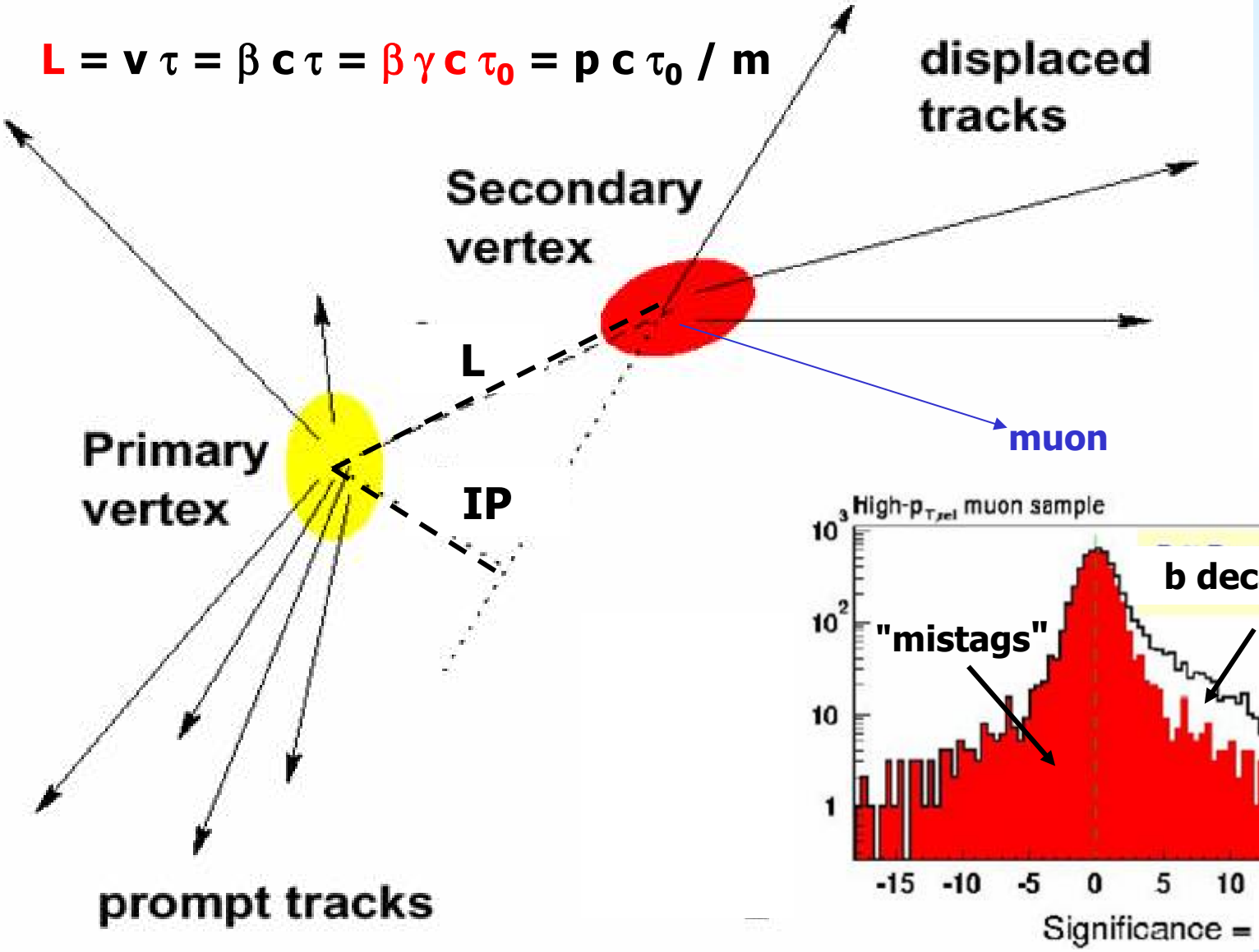


mu+4j+mutag (lepton+jets/tag)


$q\bar{q} \rightarrow t\bar{t}$
$\rightarrow W^+ b W^- \bar{b}$
$\rightarrow q\bar{q} b \ell^- \nu \bar{b}$
μ^-
candidat top
SV
IP
Jet 2
Jet 1
IP
SV

Identification of b jets

$L = v\,\tau = \beta\,c\,\tau = \beta\,\gamma\,c\,\tau_0 = p\,c\,\tau_0 / m$

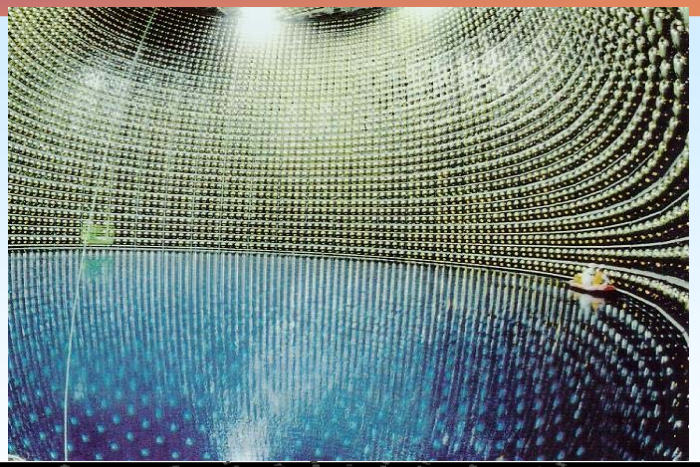


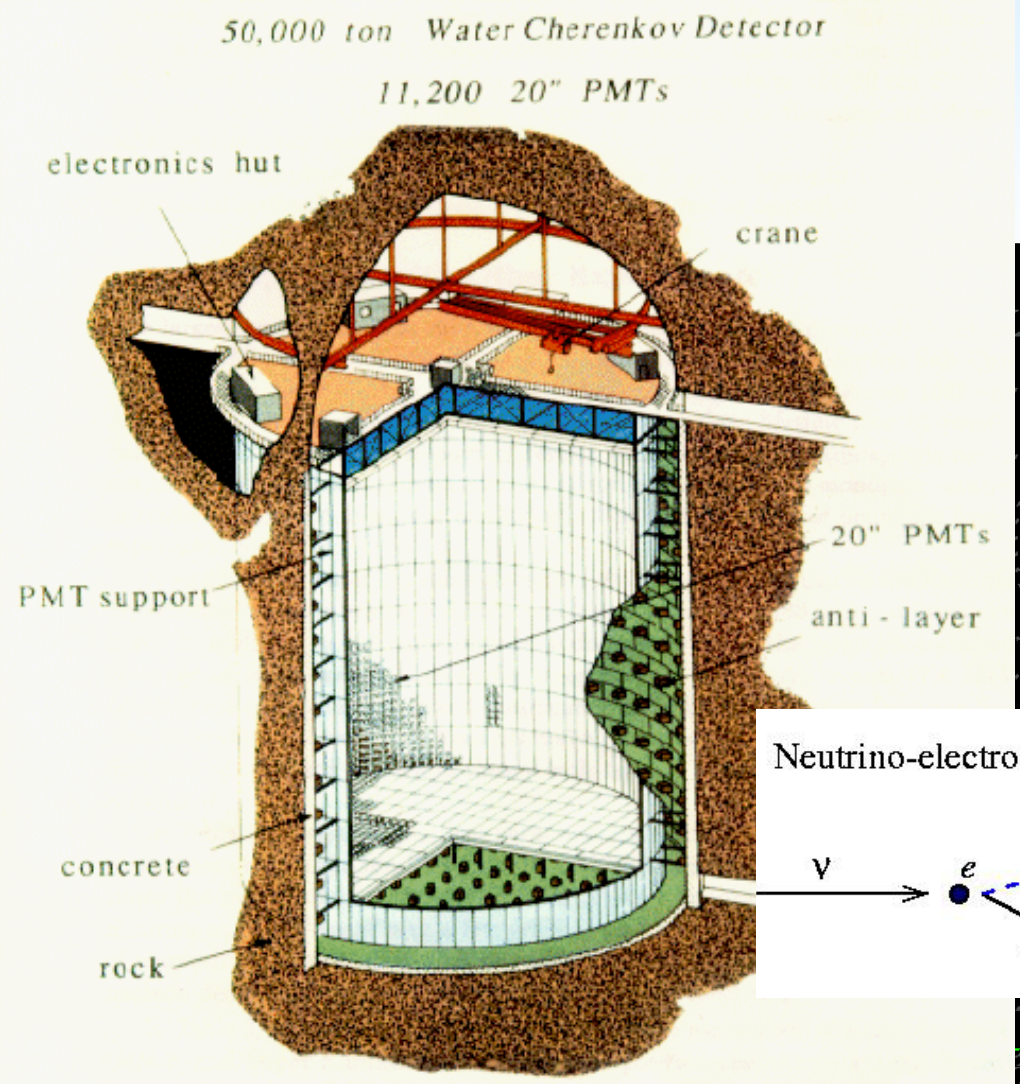
Large colaborations: Where are the students?

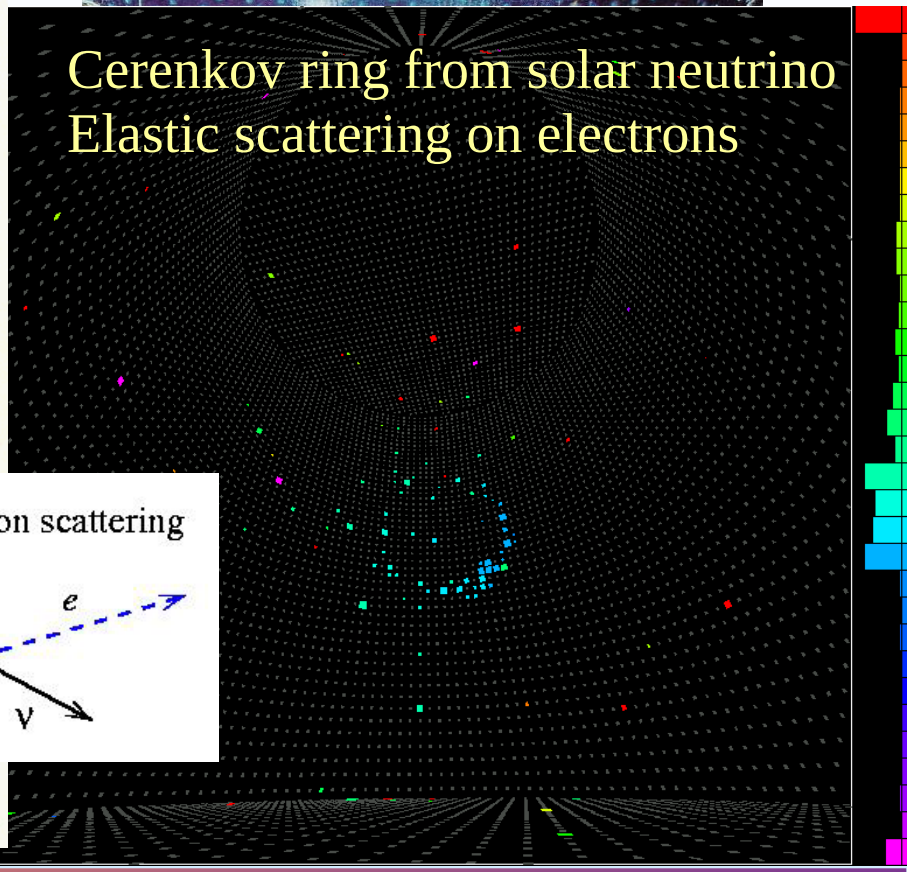
- Sub divided in smaller groups
  - Detector, subdetector
  - Analysis: different topics
  - Students belong to instituts
- International environment
  - Communication skills !
  - Mobility
  - Good students become well known in the collaboration very fast!
- Management
  - Physicists are (generally) not trained for that
    changes with time...
  - Sometimes there are problems, one has to sort them out..
- Students are an extremely important factor
- job opportunities outside particle physics

Astroparticle detectors

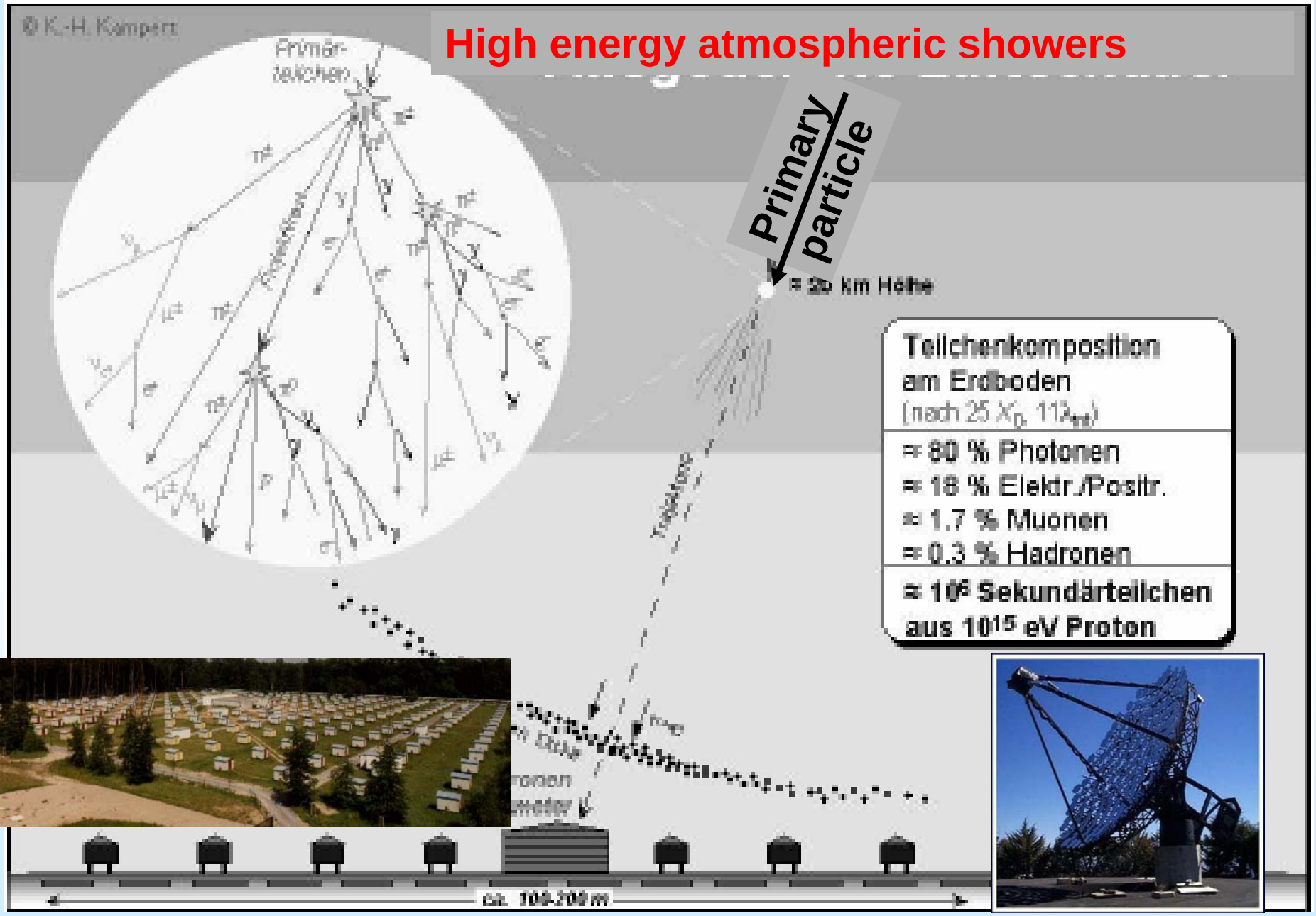
Super-Kamiokande



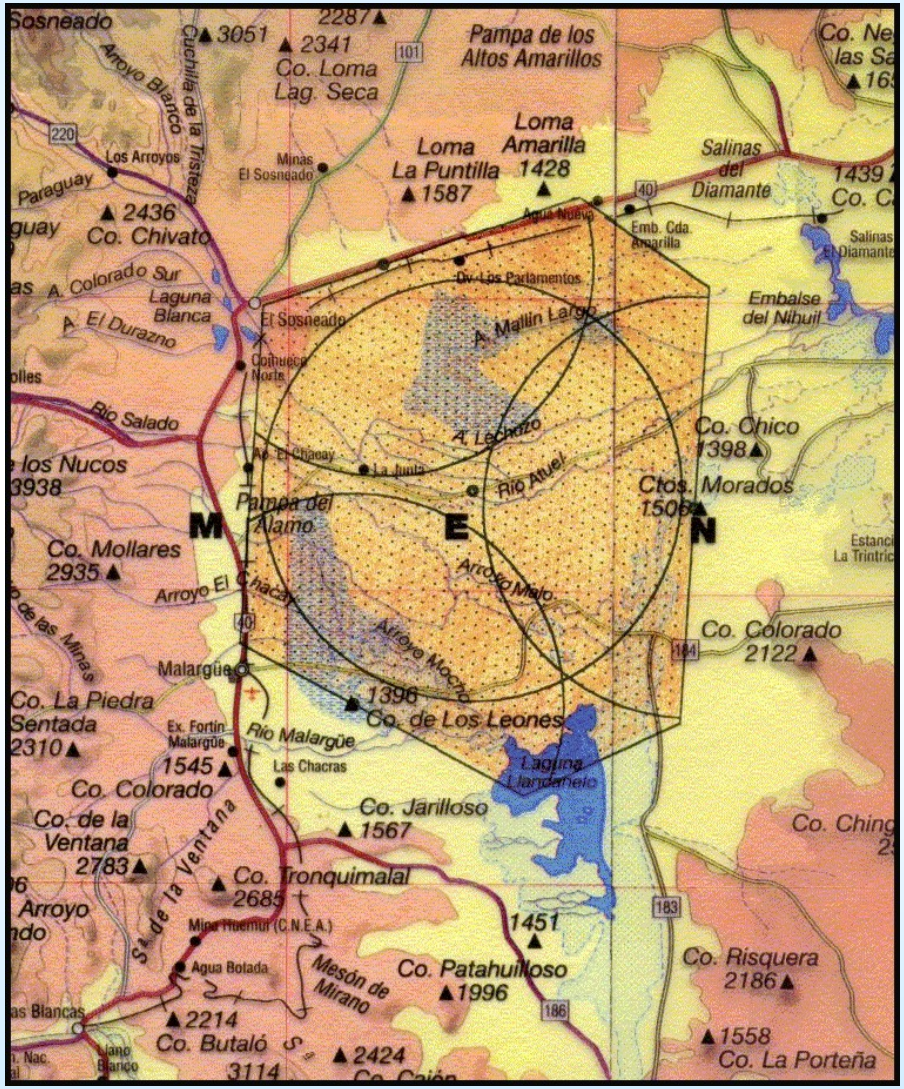




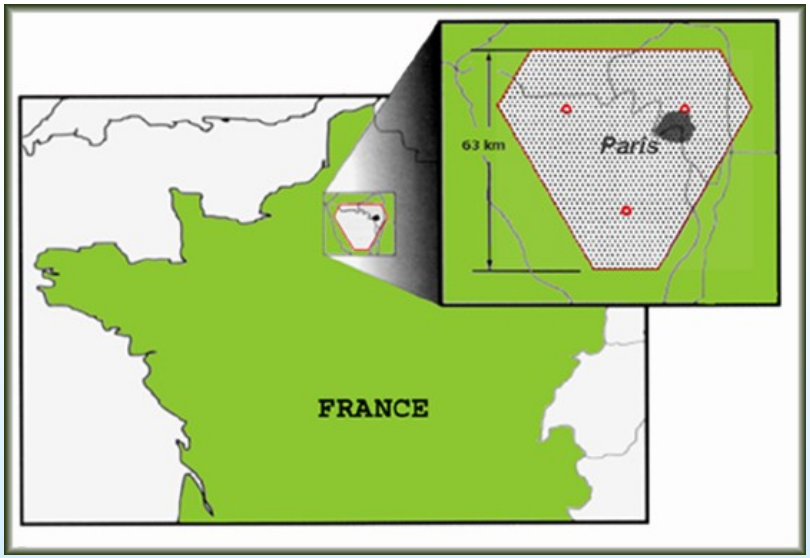
High energy atmospheric showers



Pierre AUGER Observatory– southern site

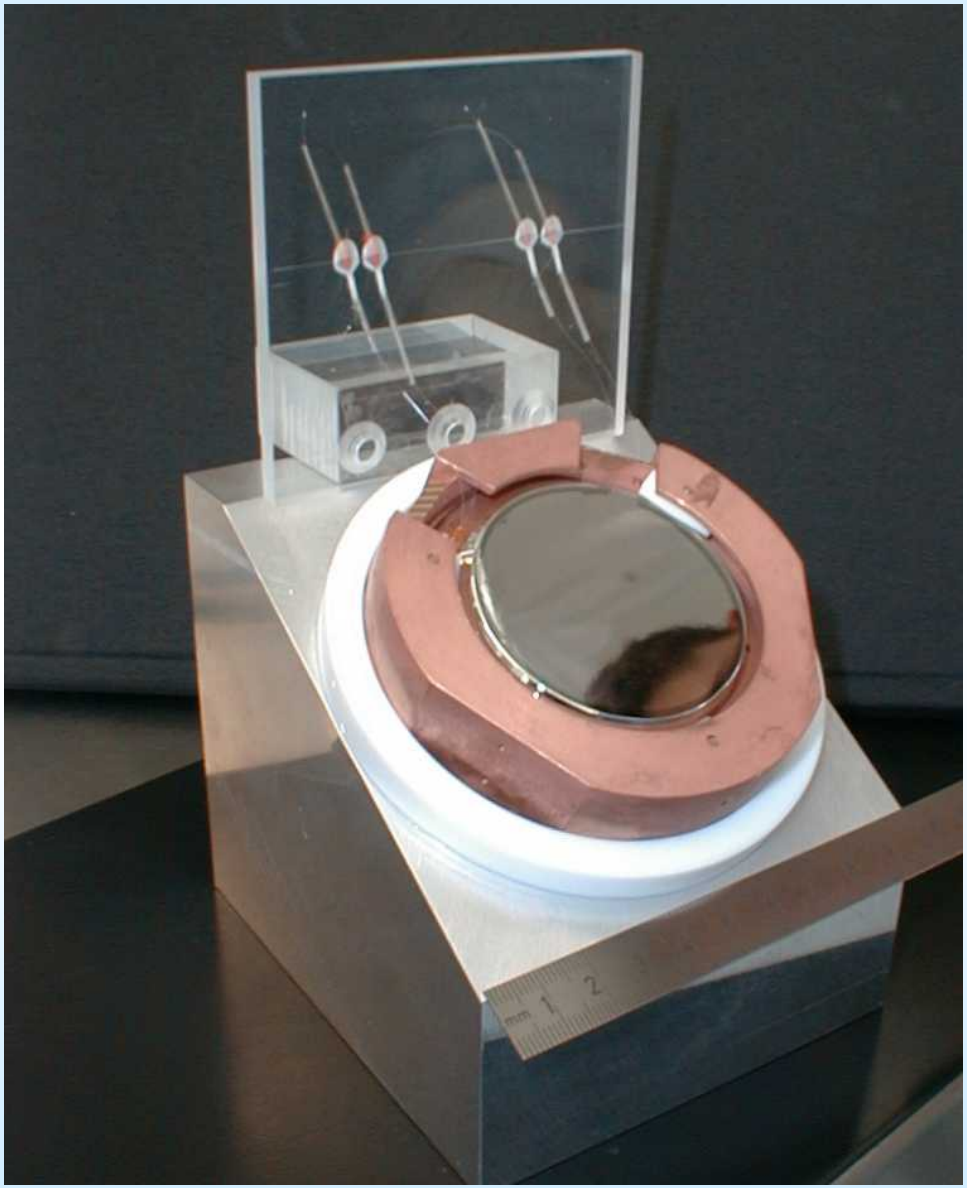


- 1600 detectors at 1,5 km
- 3000 km^2
- 24 telescopes in 4 points



Edelweiss

- Ge Bolometer
- Mass = 70 g



Conclusions

- It is possible to measure and reconstruct the interaction of elementary particles in the very difficult environments of proton proton collisions
- The experiments are large and complex, both in their concept and in the new technologies employed
- They are run by very large collaborations of scientists, engineers and also students over 10-20 years
- Exciting times ahead of us, many opportunities for students
- Many new projects even further in the future are being worked on
- It is fun to work on these experiments and their data