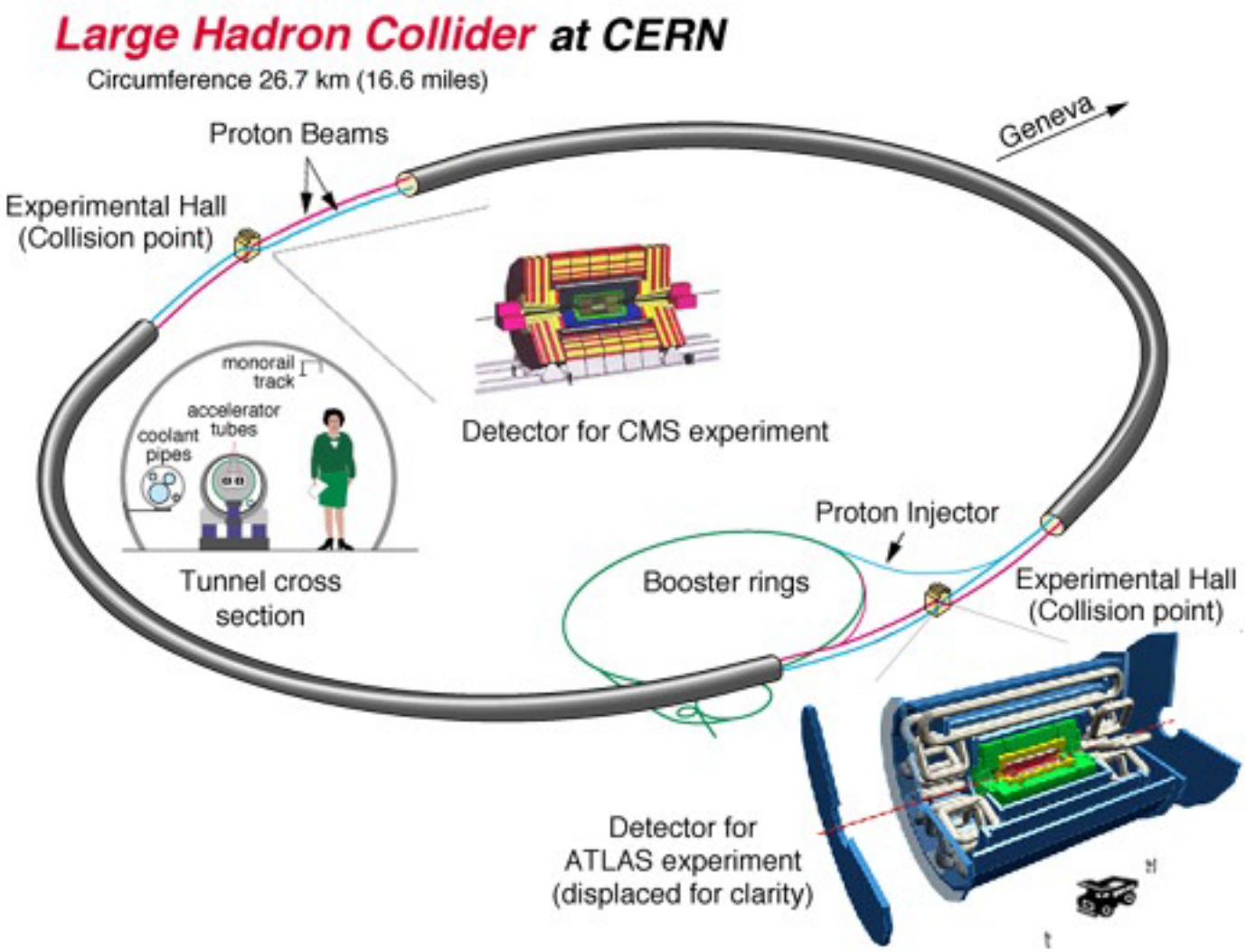
What is the Universe Made Of?

by
Bob Orr

Wanted to talk about the ATLAS experiment at a new large particle accelerator.

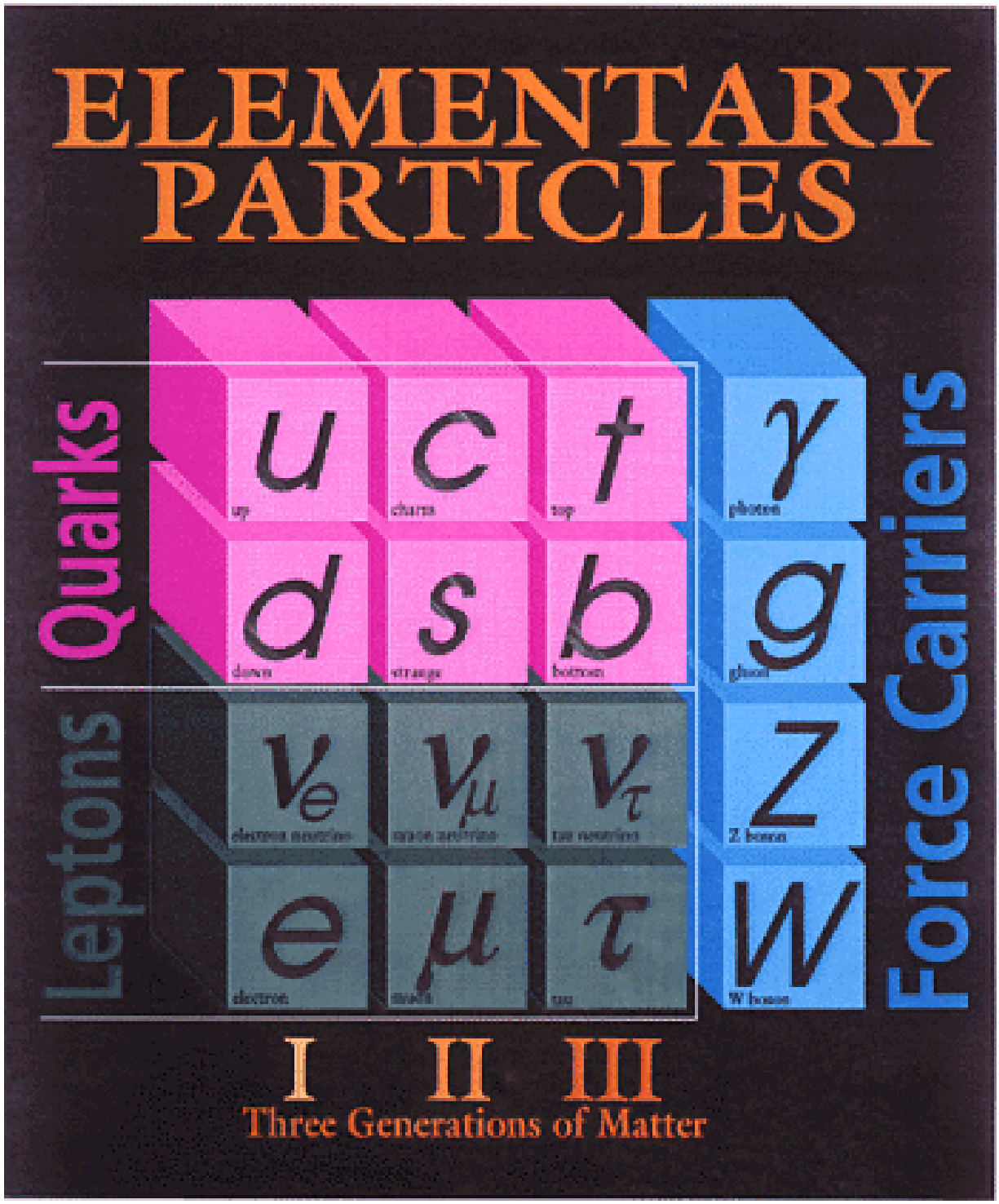
WHY?



Plan of Talk

- What we think visible matter is made of.
- The Standard Model
- Quantum forces
- Gauge Theories & Unification of Forces
- Cosmological Evidence for invisible matter
- Supersymmetry
- Large Hadron Collider
- ATLAS

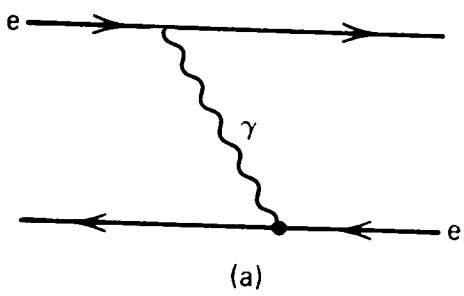
Is the Universe Made of These?

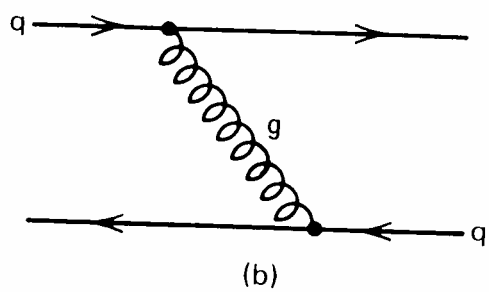


Quantum Forces

- In Quantum Field Theory, particles interact via:.

Exchange of virtual particles





Electrons interact by exchanging:

Virtual Photons

Quarks interact by exchanging:

Virtual Gluons

Real & Virtual Particles

- Interactions of Real particles, conserve

  Energy and Momentum.

- Interactions of Virtual particles, need not conserve these, for short times and distances.

- Hiesenberg's Uncertainty Principle

$$\Delta E \Delta t \approx \hbar$$ Energy & time

$$\Delta p \Delta x \approx \hbar$$ Momentum & position

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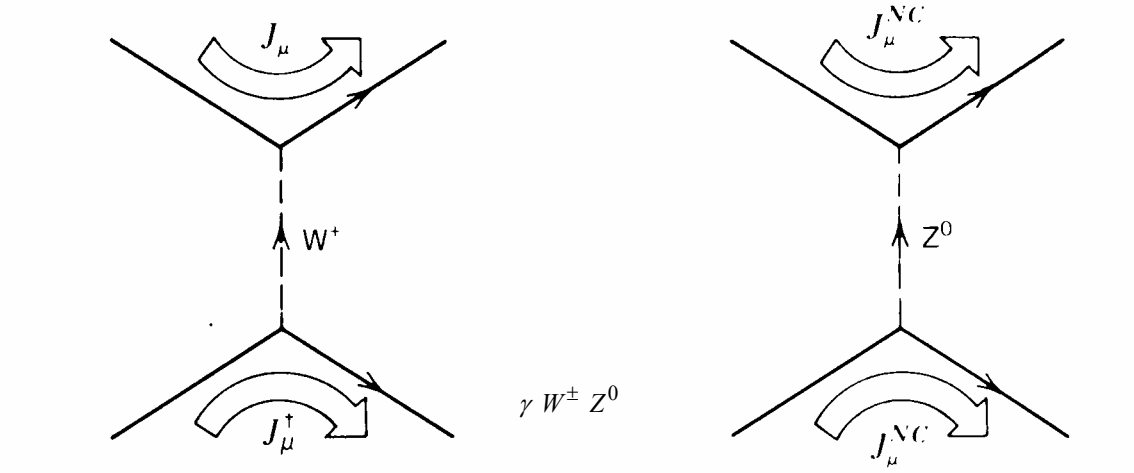
Weak Interaction

- A force very like electromagnetism; but

  acts on Weak Charge



- In Fact, electromagnetism and weak force are aspects of unified electroweak force

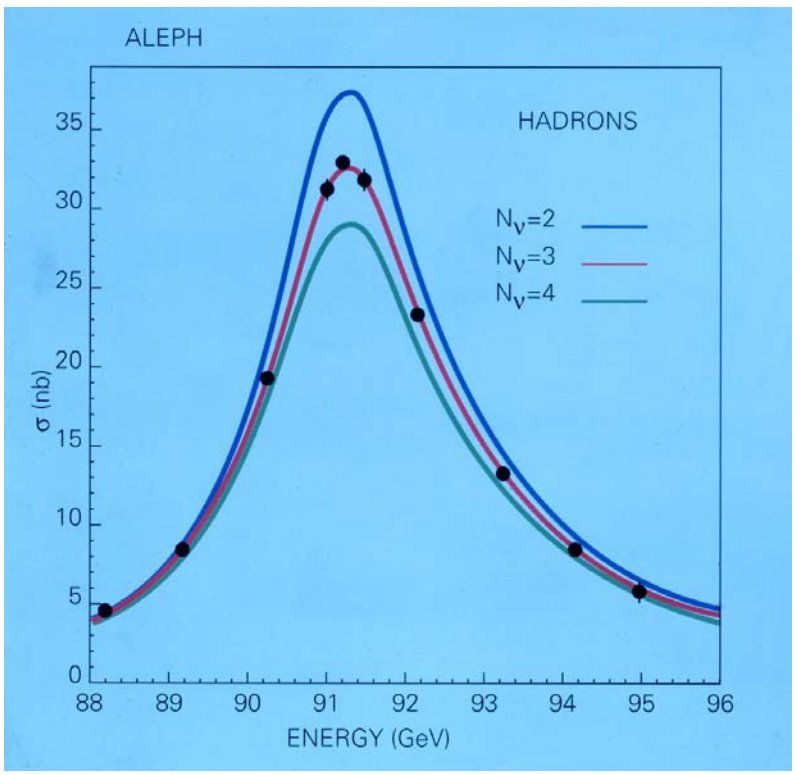
- Electric charge and weak charge are

  related

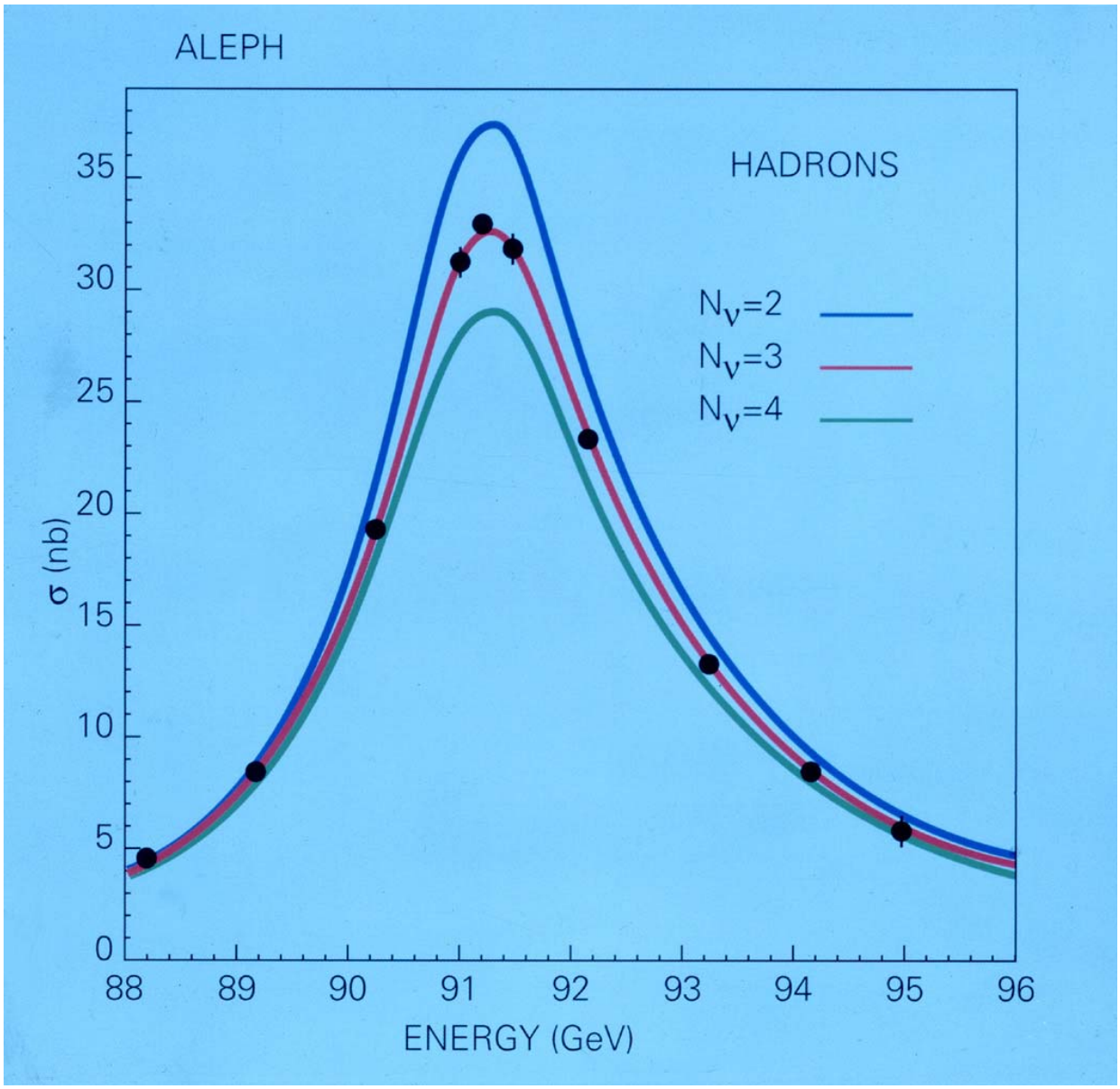
- Three "force carriers" $\gamma\ W^\pm\ Z^0$

Electroweak Force

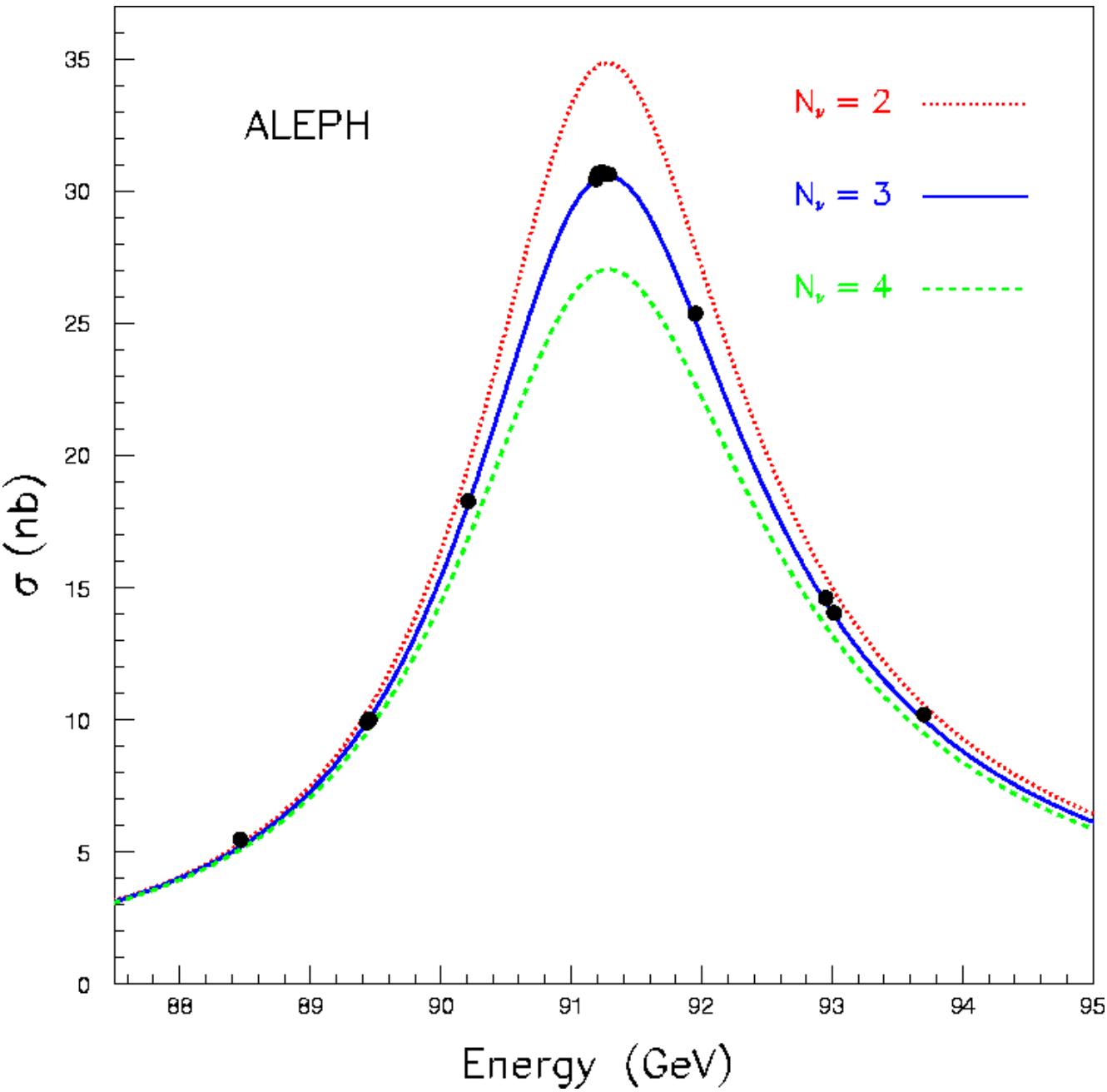
- Photon γ is massless
- $W^{\pm}$ Z^{0} are very massive
- Almost 100 times proton mass



3 Generations



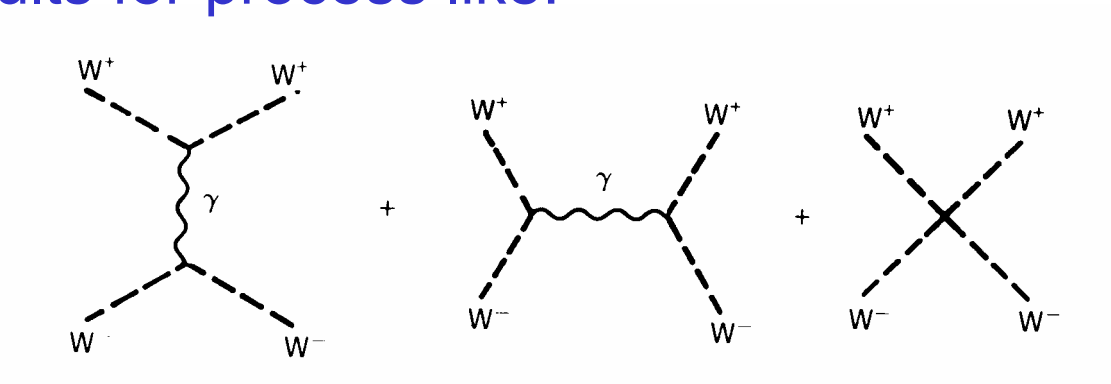
3 Generations



Higgs Boson

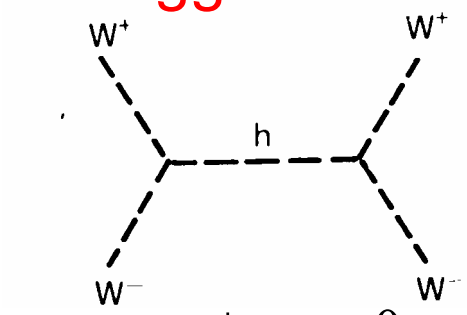
• Electromagnetism on its own can be made to give finite results for all calculations.

• Unified Electroweak theory gives infinite results for process like:



• Become finite if include new particle

Higgs boson



• Higgs makes $W^{\pm}$ Z^{0} massive, and actually generates masses of fundamental particles. It is a quantum field permeating the universe.

How Does Higgs Generate Mass?

- In vacuum, a photon:

  has velocity c and has zero mass

- In glass a photon

  has velocity < c , same as an effective mass

- This is due to photon interacting with

  electromagnetic field in condensed matter

- By analogy can understand masses of particles

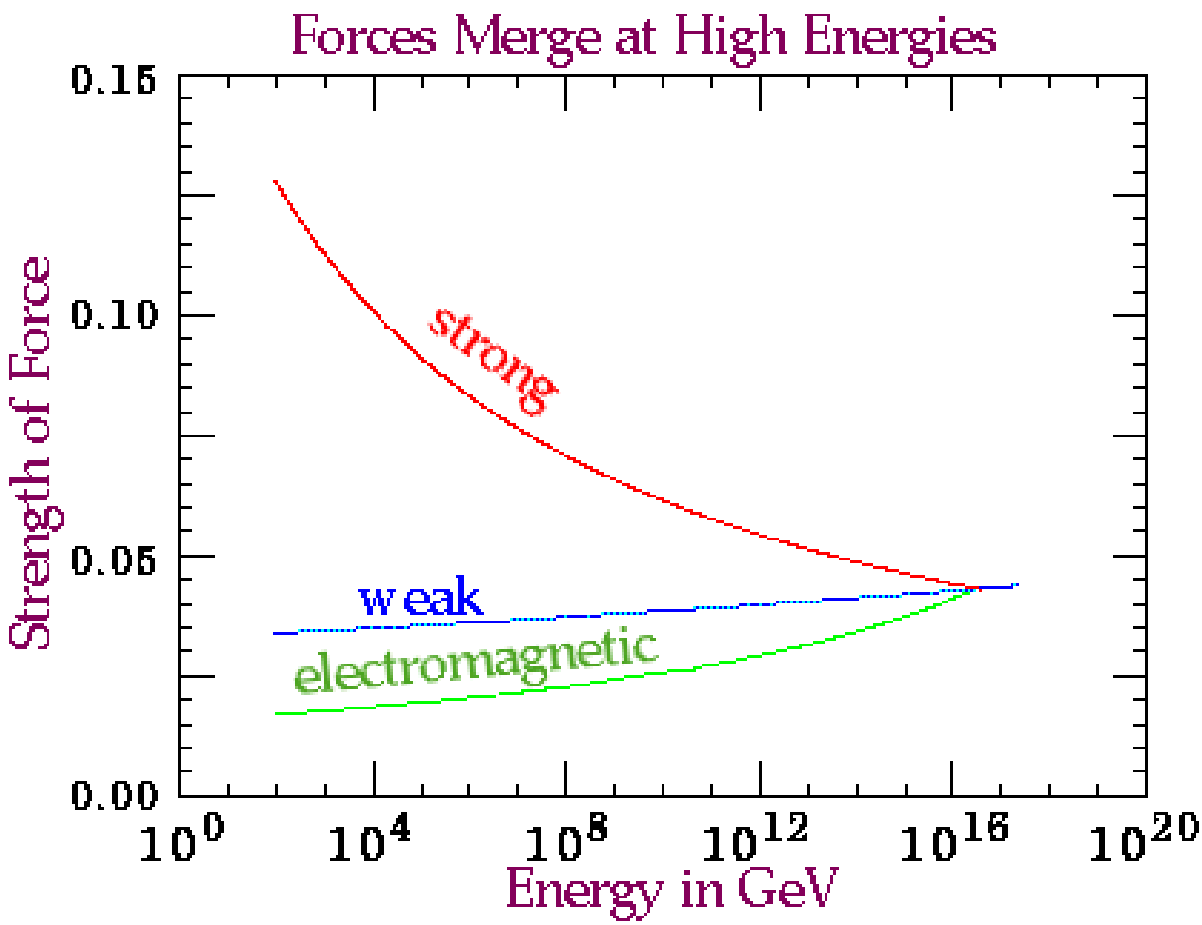
  generated by Higgs Field in vacuum

Grand Unification.

- At a high enough energy

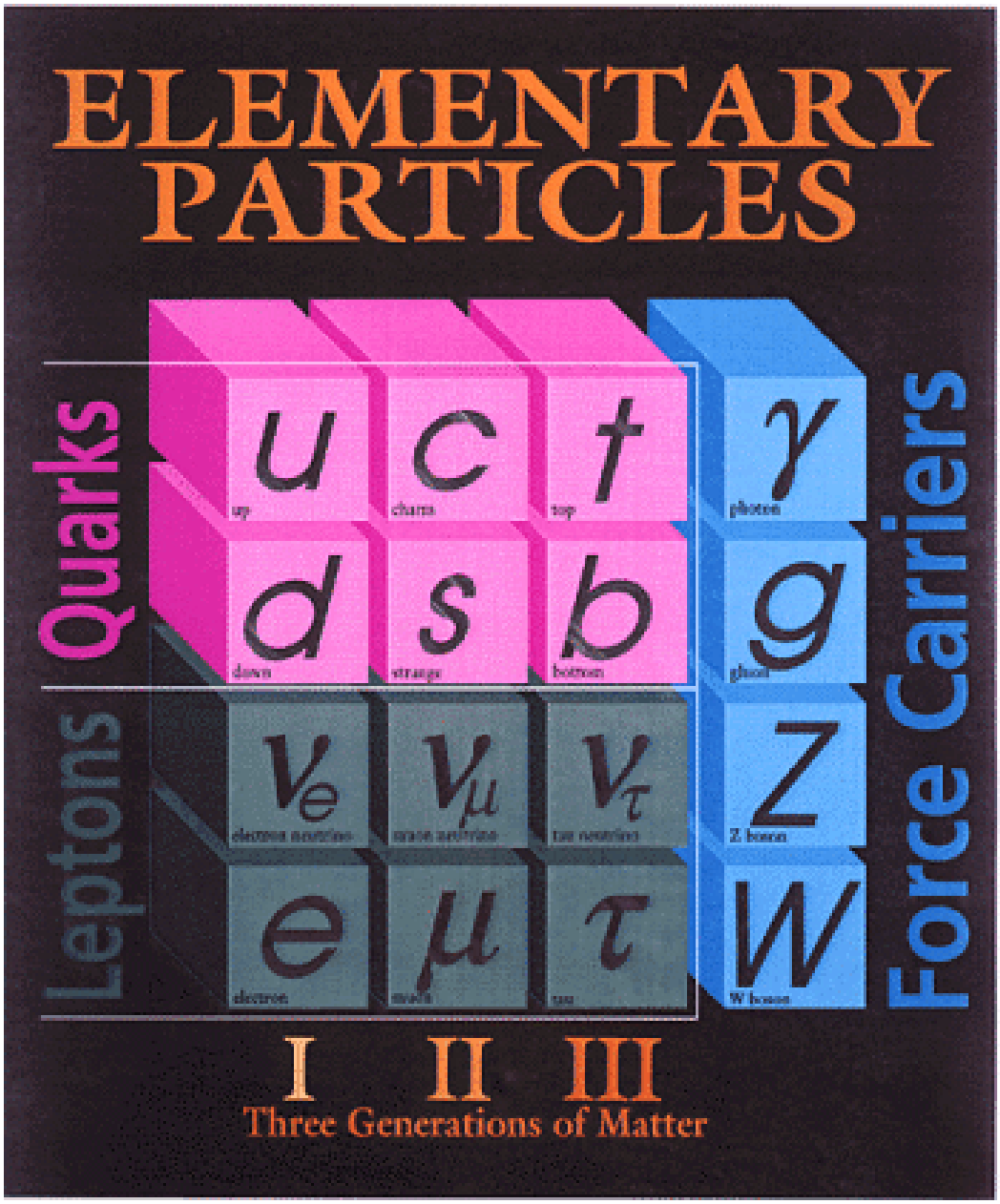
  electromagnetism
  weak force
  strong (colour) force

become aspects of Grand Unified Force

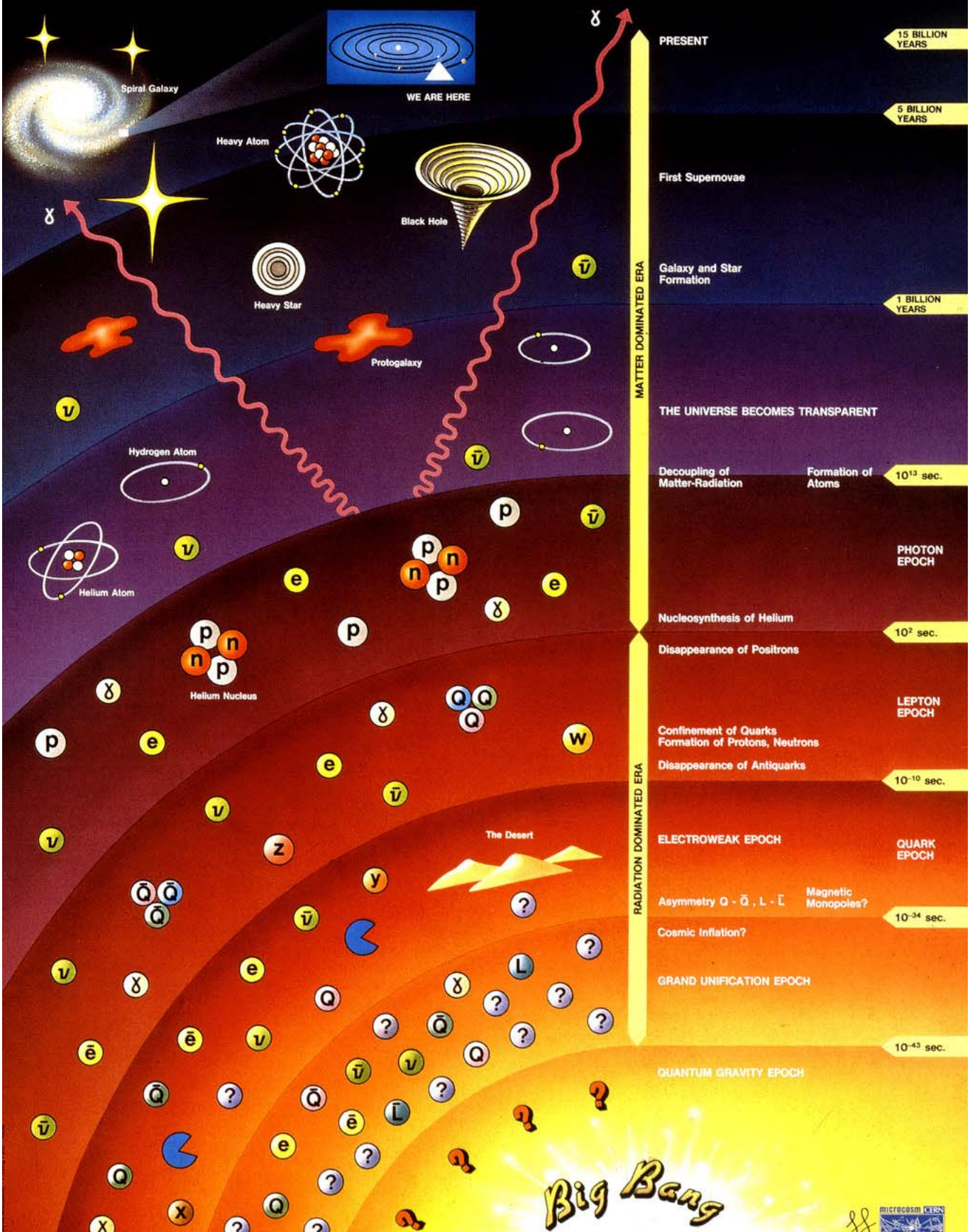


Understand History of Universe?

- What we think (thought?) visible matter is made of.



History of the Universe



microcosm CERN

Hubble's Law & Big Bang.

- Big Bang model came from observation that

  Universe is expanding

- For distant galaxies

  velocity = H_0 x distance

  H_0 is Hubble Parameter

- Whether Universe continues to expand, or starts to contract depends on density of matter and energy in Universe.

Fate of Universe

- If ρ_0, the density of matter and energy is greater that a critical density ρ_c the universe will start to contract.

- If ρ_0 is less than the critical density, the universe will continue to expand.

- Usually measure the density in units of ρ_c

$$\Omega_0 = \frac{\rho_0}{\rho_c} = \frac{8\pi G}{3}\frac{\rho_0}{H_0^2}$$

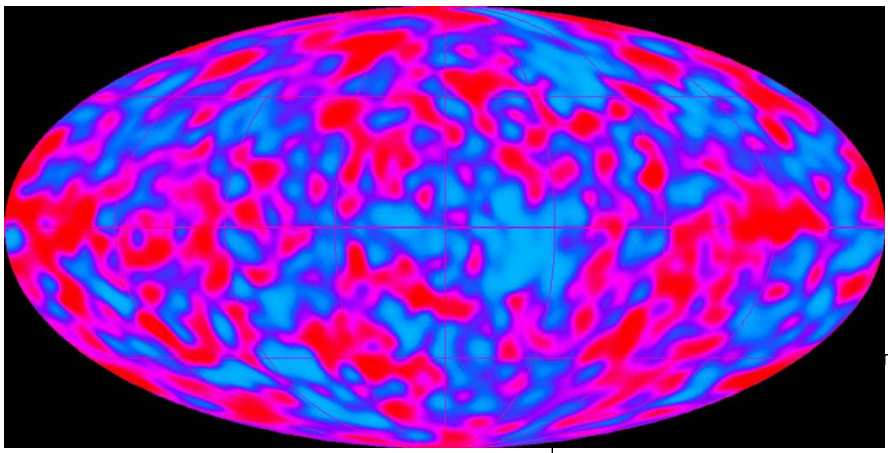
- $\Omega_0 > 1$ spherical space-time: contraction
- $\Omega_0 = 1$ flat space-time: expansion
- $\Omega_0 < 1$ hyperbolic space-time: expansion

Measuring Ω_0

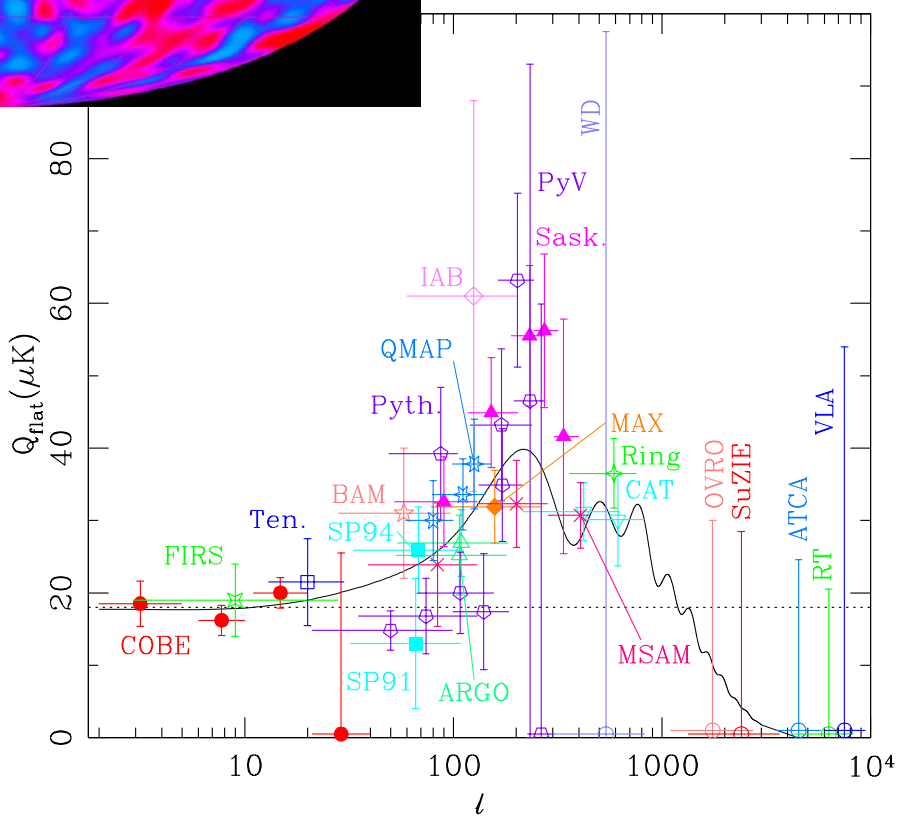
- Amazingly enough can measure total matter/energy density in universe

- Measure temperature fluctuations in remnant of fireball from Big Bang.

$$\Omega_0 = 1$$



Map of sky temp
~ 3 Kelvin



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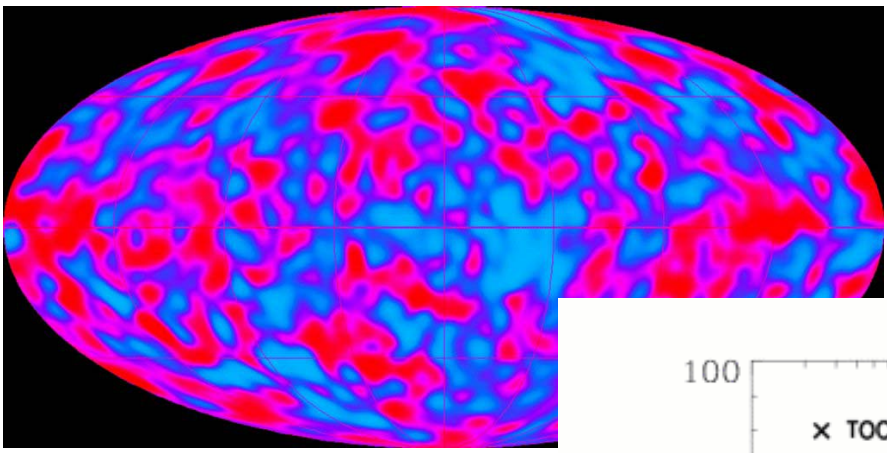

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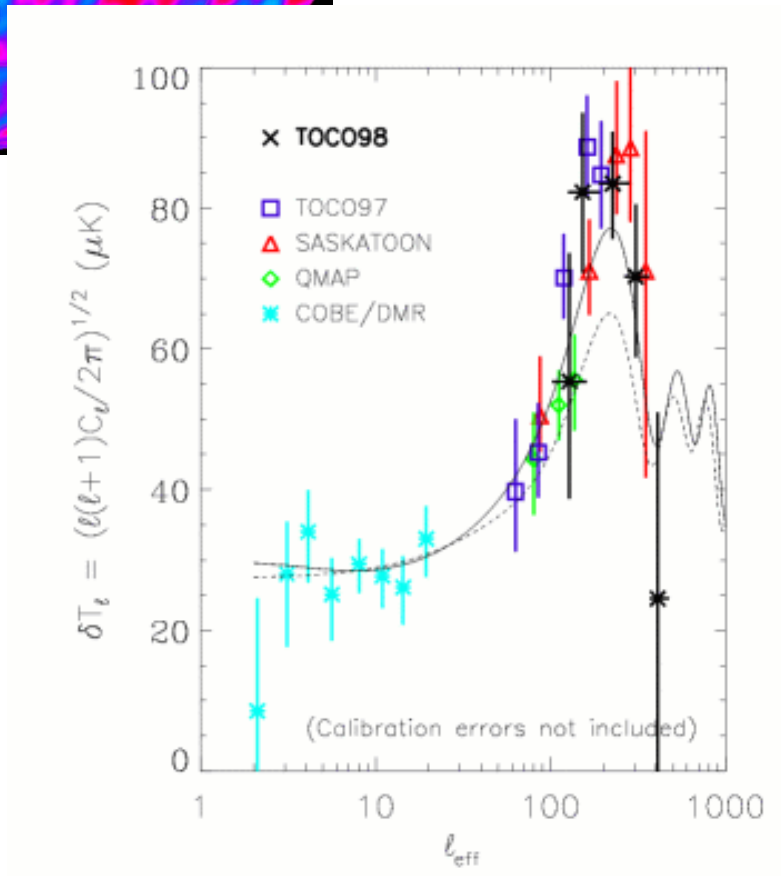

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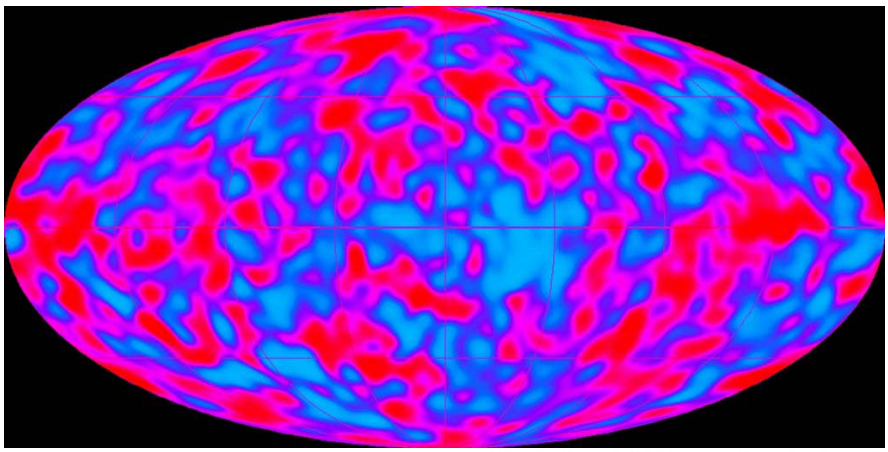

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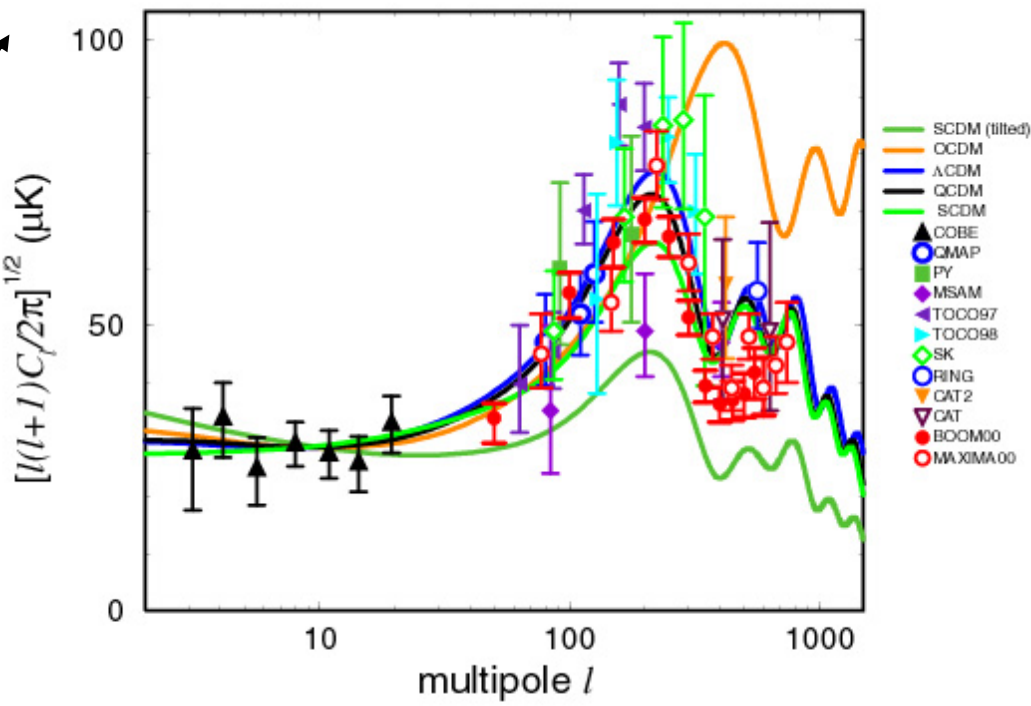


Density of Standard Model Matter

- Referred to as Baryonic Matter
- Density is Ω_B
- If Universe is made of quarks & leptons

$$\Omega_B = \Omega_0 = 1$$

- Ω_B measured from abundance of elements produced in nucleosynthesis of Big Bang.

Deuterium, Helium, Lithium

$$\Omega_B = 0.05$$

$$\Omega_B \neq \Omega_0$$

- Most of Universe is not Standard Model matter. Some kind of Dark Matter

Density of All Matter Ω_M

- Can measure density of all matter, whatever its nature, Ω_M, by looking at gravitational motion:

  rotation curves of galaxies
  motion of galactic clusters

- There is indeed Dark Matter

$$\Omega_M = 0.4 \pm 0.1$$

- So even with this Dark Matter, cannot account for

$$\Omega_0 = 1$$

- Universe must be 60% Dark Energy

Dark Energy Ω_Λ

- If the expansion of the Universe is being slowed down by gravitational attraction; expect that in remote past galaxies were moving apart more rapidly than now.

- Observations of distant supernovae show that in the past galaxies were moving apart more slowly

- Expansion is accelerating

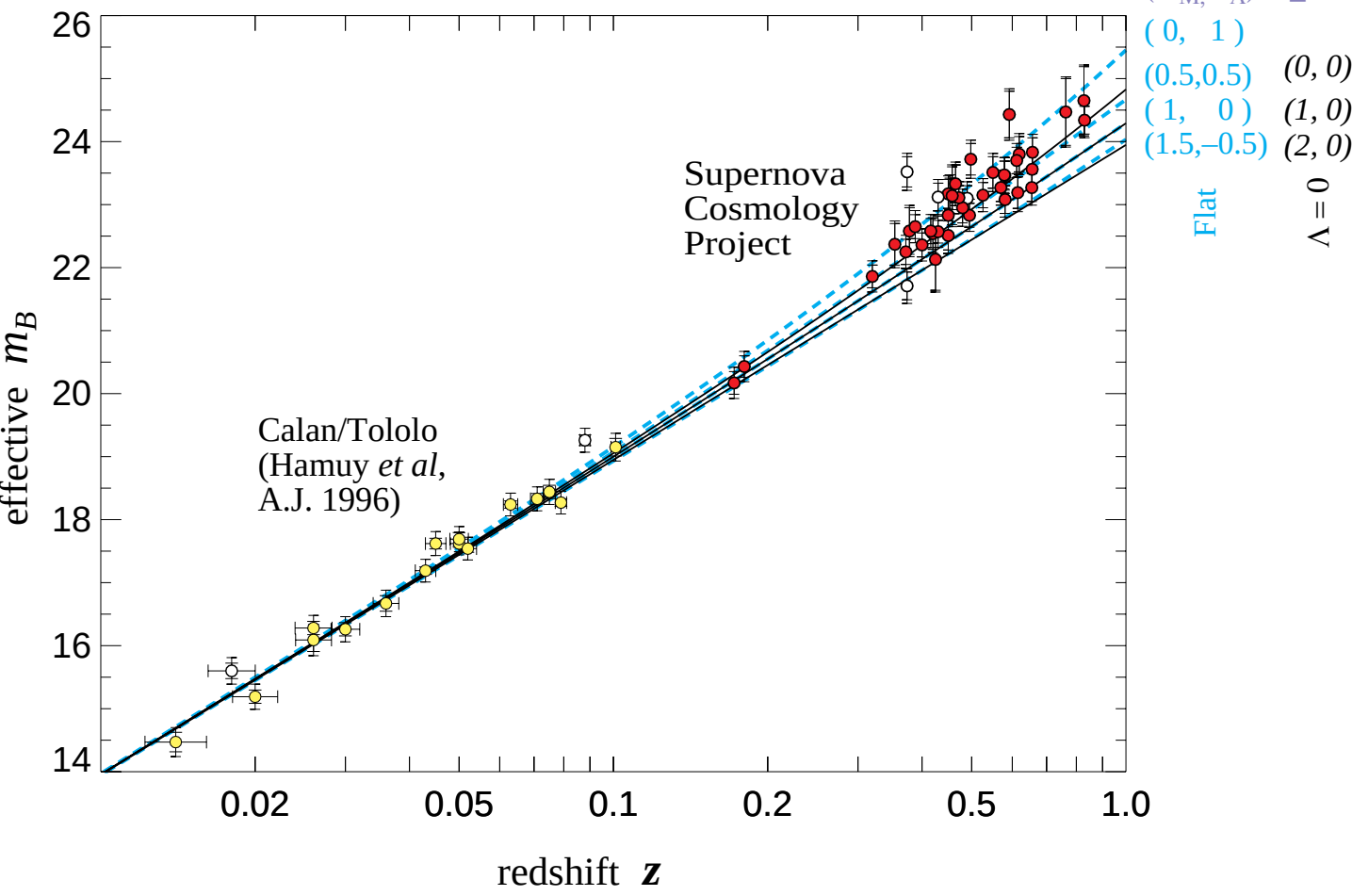
$$\Omega_\Lambda = 0.85 \pm 0.2$$

$$(0.4 \pm 0.1) + (0.85 \pm 0.2) = 1.25 \pm 0.22$$

$$\Omega_M + \Omega_\Lambda = 1$$

- Driven by some quantum field permeating the Universe.

Supernova Cosmology Project
Perlmutter *et al.* (1998)



In flat universe: $\Omega_M = 0.28$ [± 0.085 statistical] [± 0.05 systematic]

Prob. of fit to $\Lambda = 0$ universe: 1%

astro-ph/9812133

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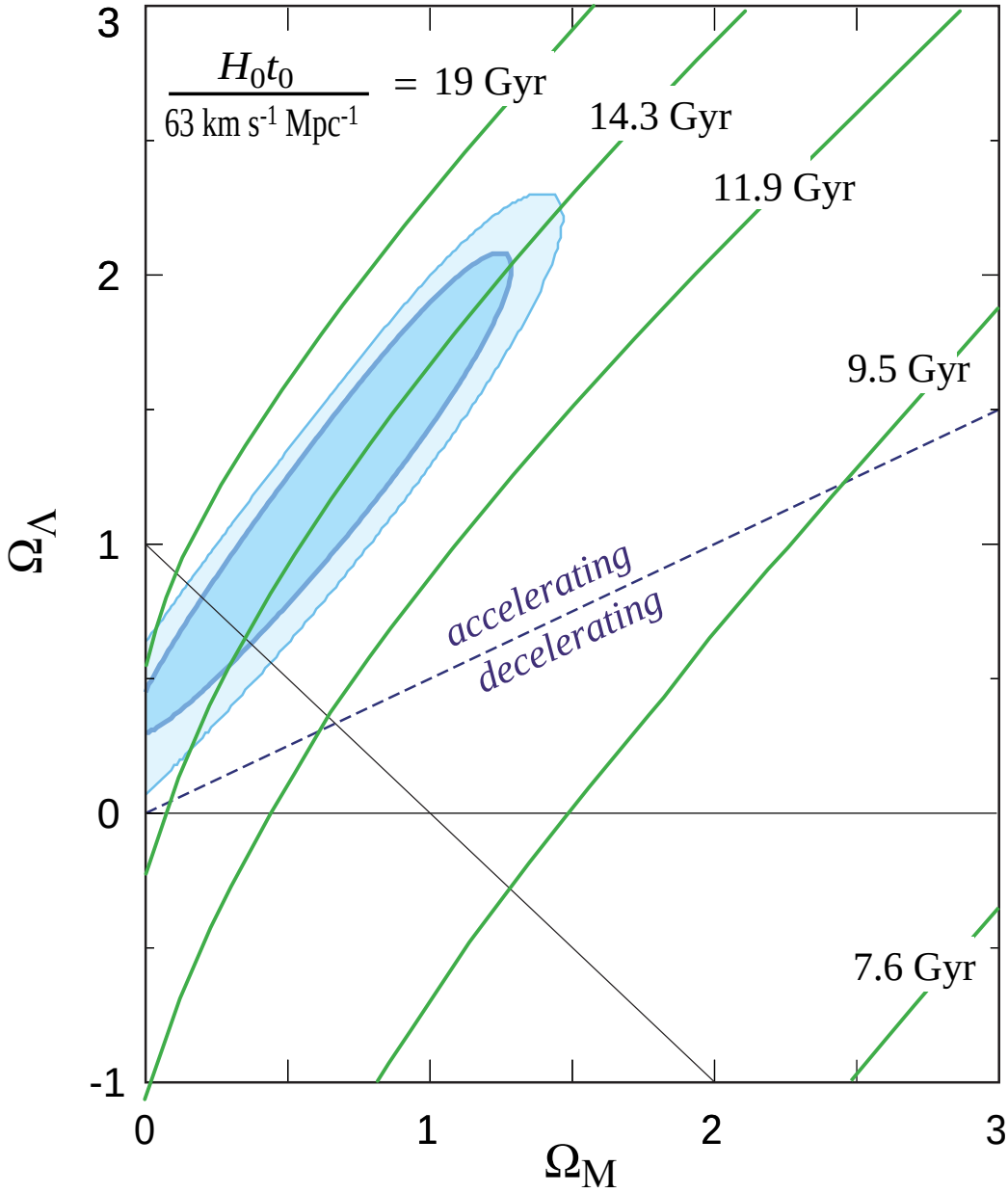


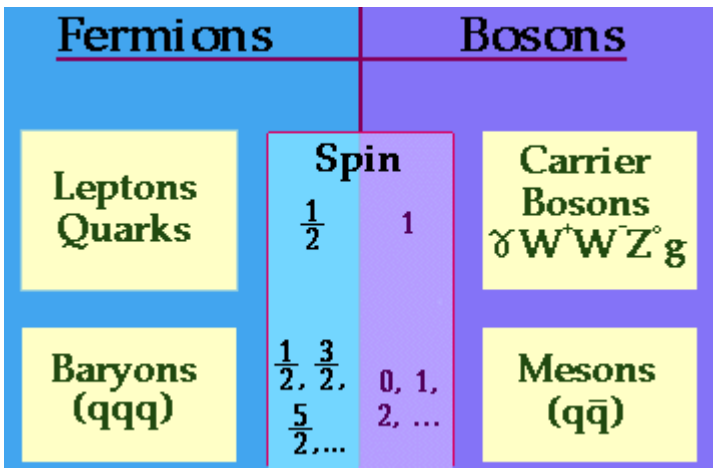
Best fit age of universe: $t_o = 14.5 \pm 1 \ (0.63/h)$ Gyr

Best fit in flat universe: $t_o = 14.9 \pm 1 \ (0.63/h)$ Gyr

www–supernova.LBL.gov

Need for Supersymmetry

- In Grand Unified Theories cannot Unify forces, unless postulate unseen form of matter
  - Higgs mass runs away to Plank Scale
  - Three forces never have same strength
- Unless all particles have supersymmetric sparticle partners (of higher mass)



+

Sleptons Bosinos
Squarks
Spin 1 Spin1/2

SUSY + Dark Matter

- Supersymmetric Particles are unstable

$$Susy \rightarrow Normal + Susy$$

- Eventually decay chain ends in Normal matter + lightest SUSY particle

- Lightest SUSYparticle cannot interact with normal matter

- Lightest SUSY particle good candidate for

Dark Matter

(Caveat - Recent evidence indicates that Dark Matter is Self-Interacting)

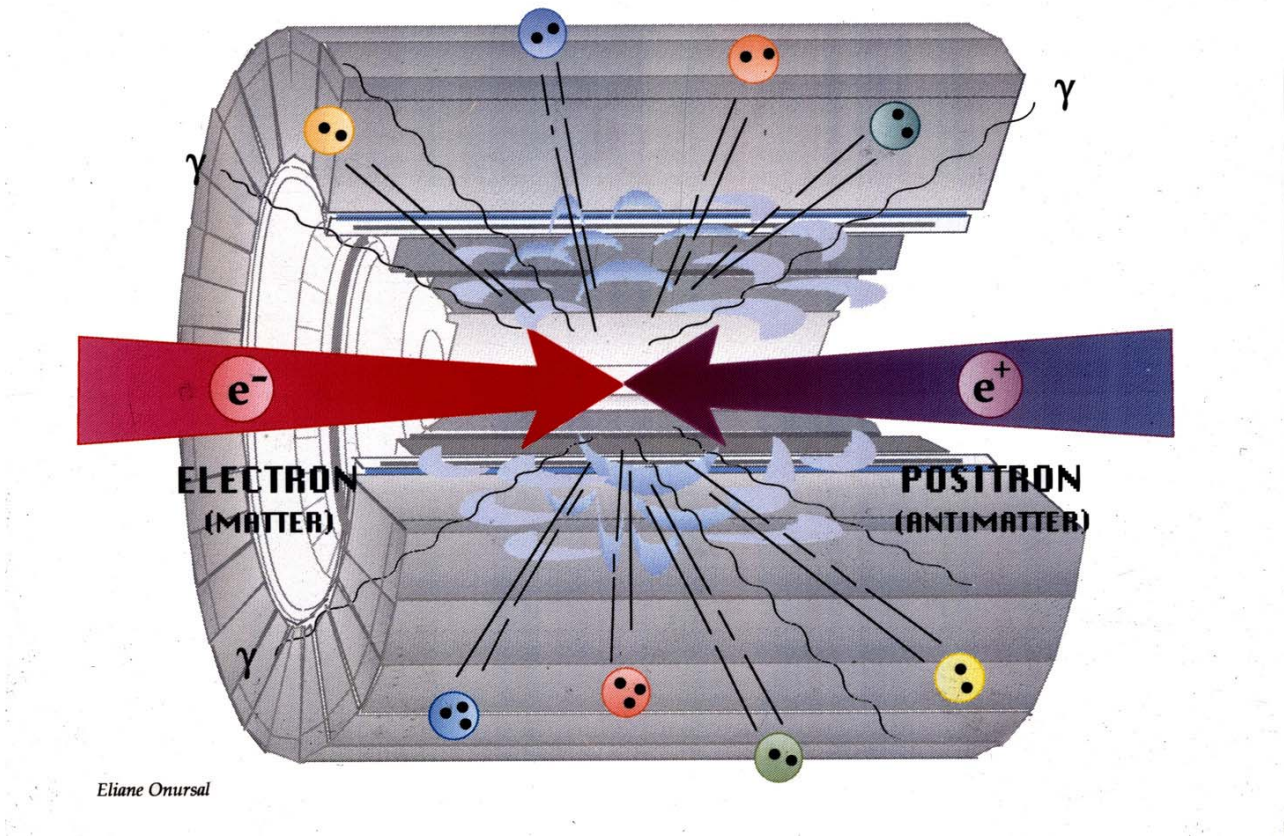
- Hope to produce

(SUSY - antiSUSY) pairs and Higgs
at
Large Hadron Collider

How to Make Matter / AntiMatter?

Colliding high energy beams

Energy of beams transformed into mass of new particles

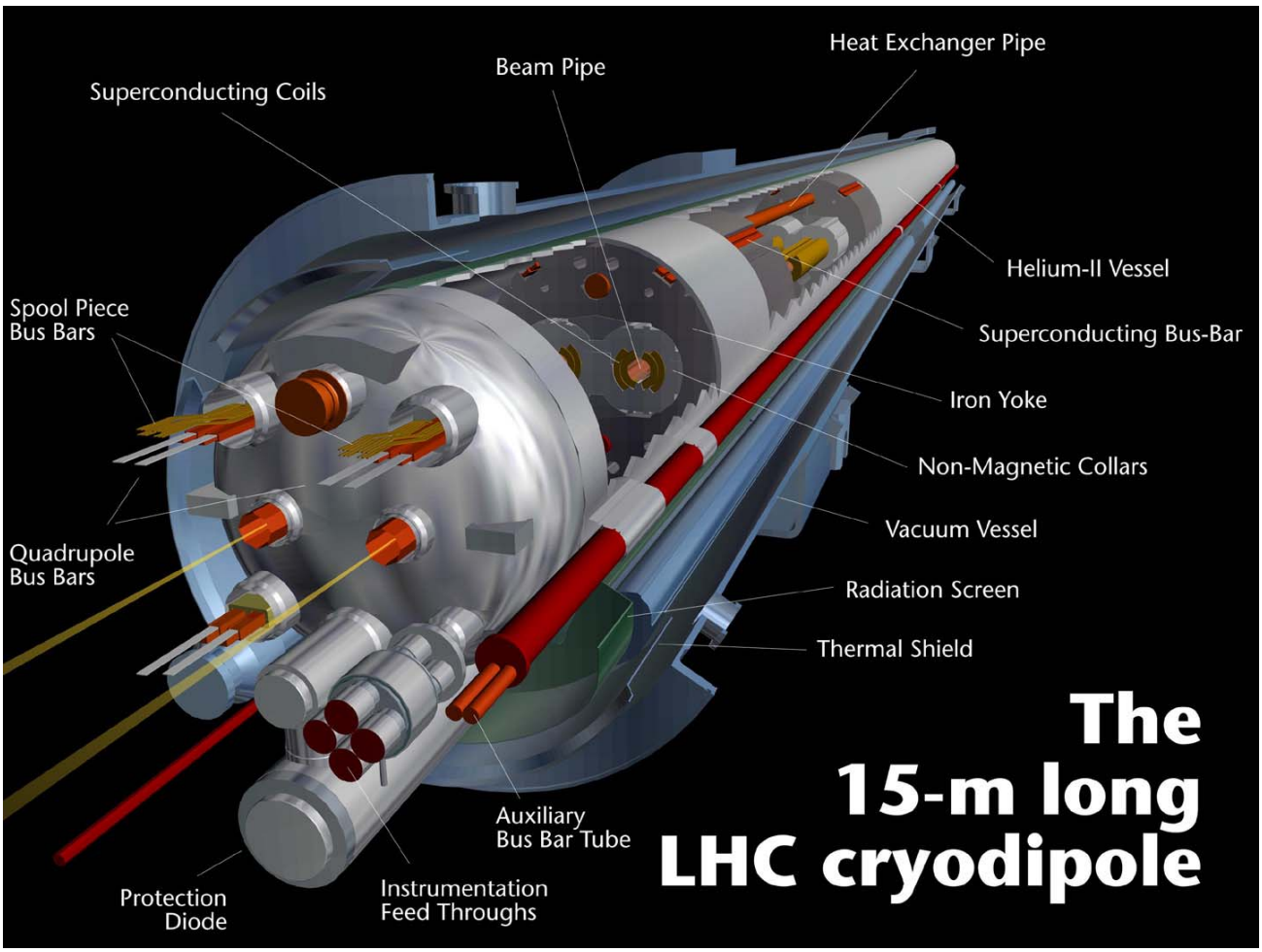


LHC will be proton - proton collider

For SUSY observation must contain ALL visible energy, in order to infer invisible SUSY

Superconducting Magnet

8 Tesla



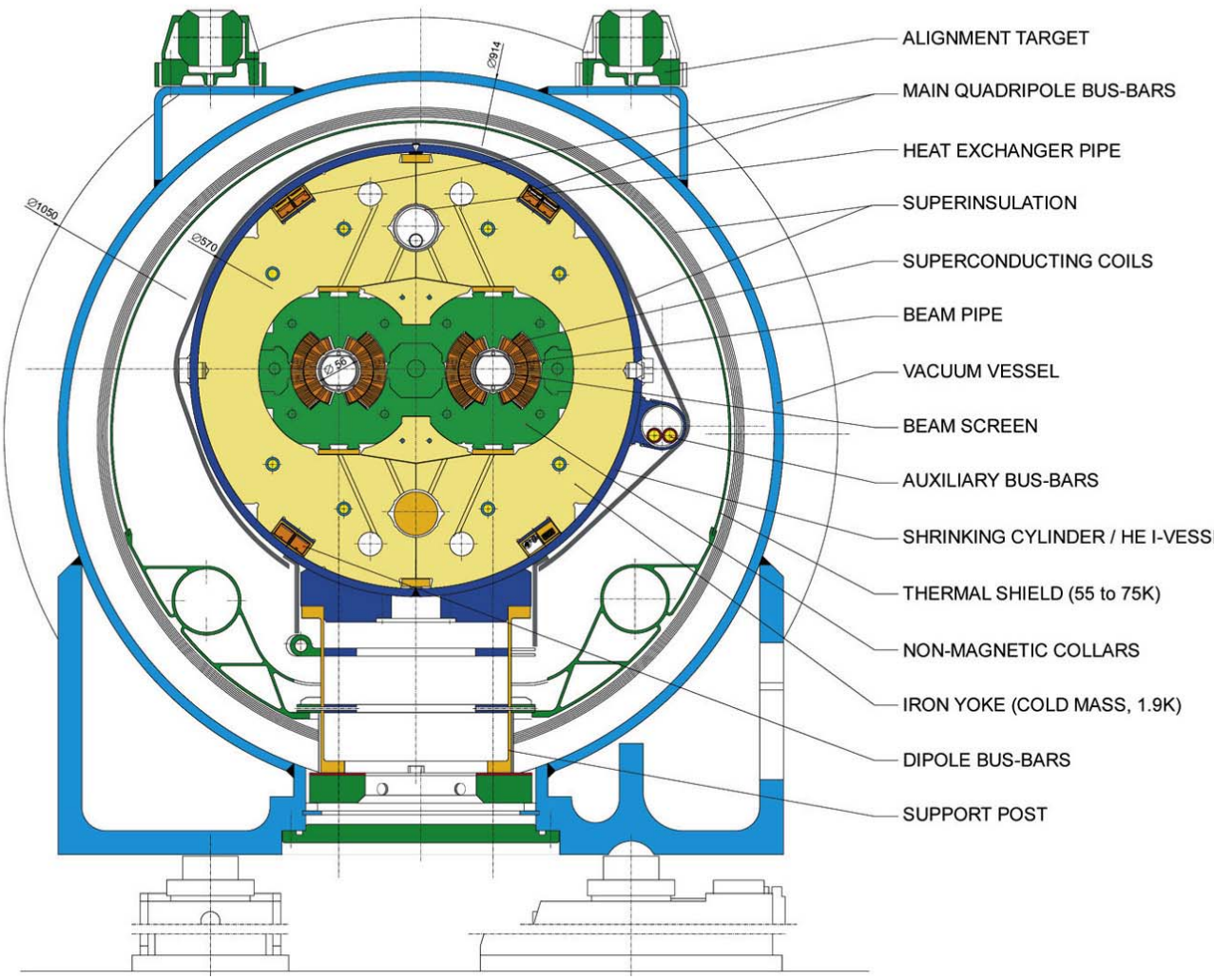
In order to accelerate protons to high energy, must bend them in circular accelerator

7 TeV momentum needs intense magnetic field

LHC Magnet

LHC DIPOLE : STANDARD CROSS-SECTION

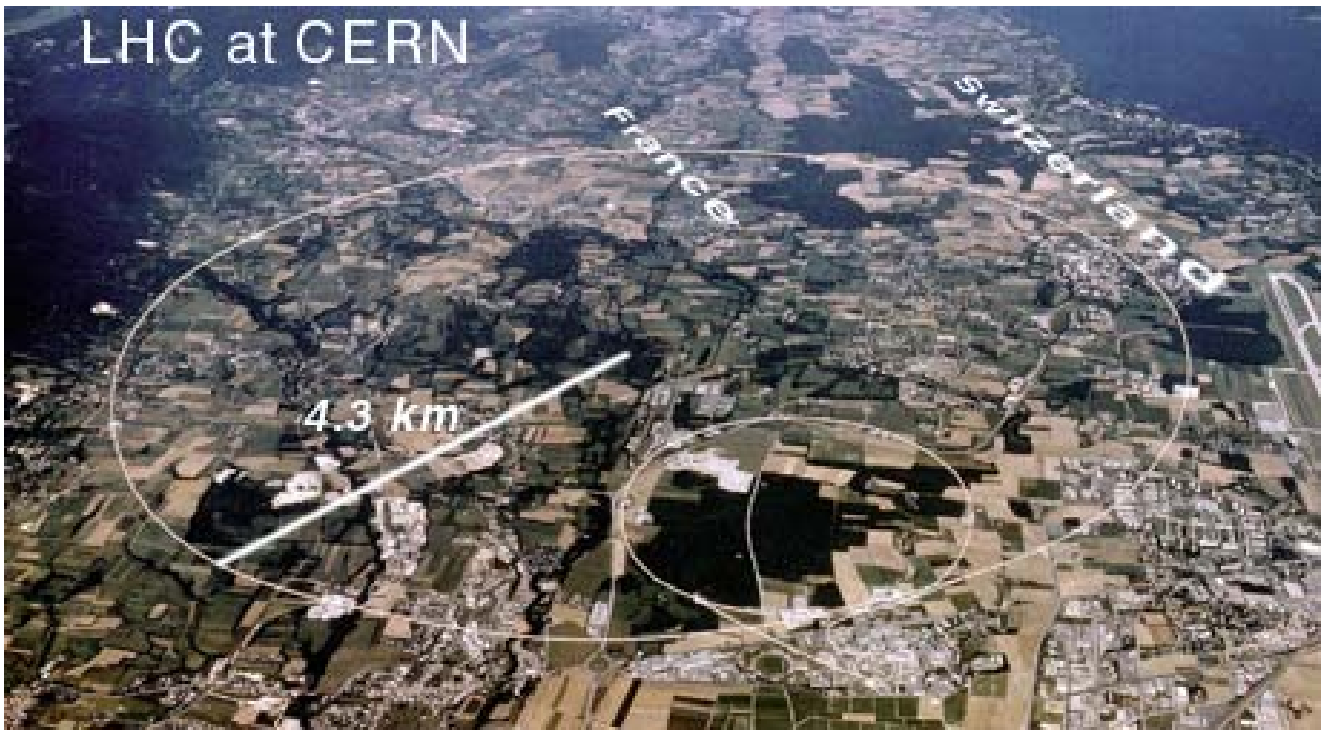
CERN AC/DI/MM - HE107 - 30 04 1999



LHC Tunnel

This is an arc of the circular tunnel
Circumference 26.7 Km

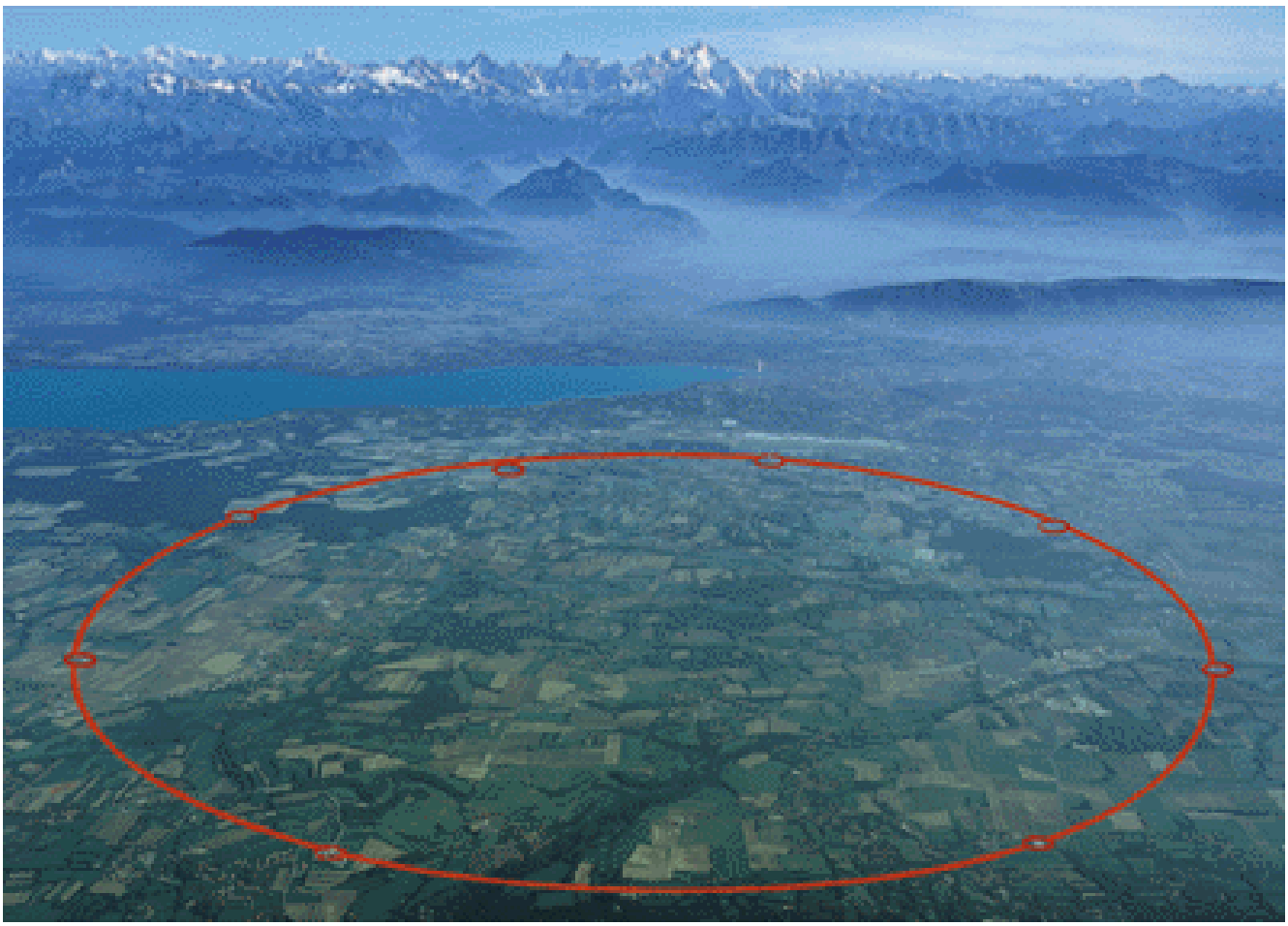
CERN Seen from the Air



- Tunnels of CERN accelerator complex superimposed on a map of Geneva.

- Accelerator is 50 m underground

CERN Seen from the Air



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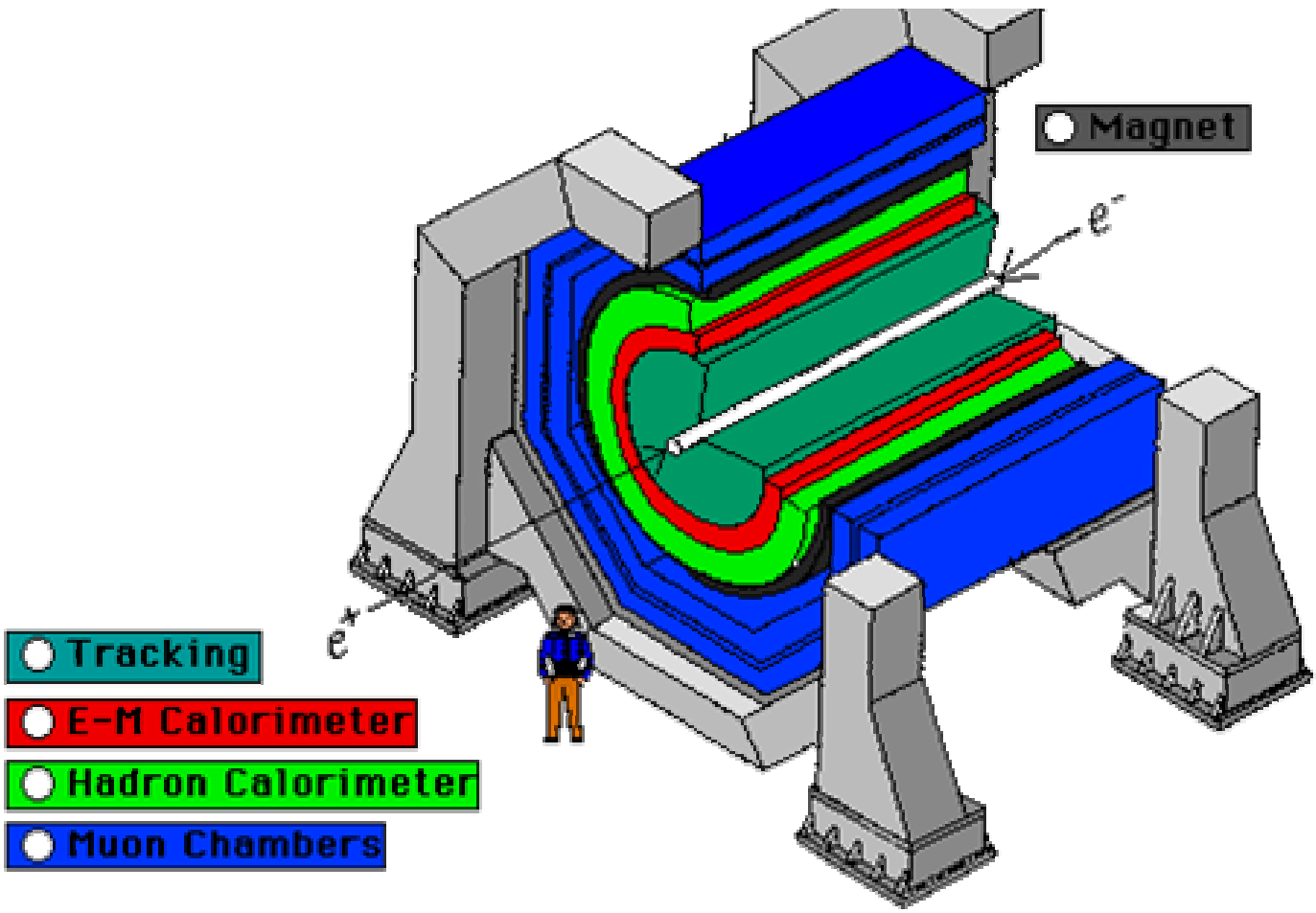
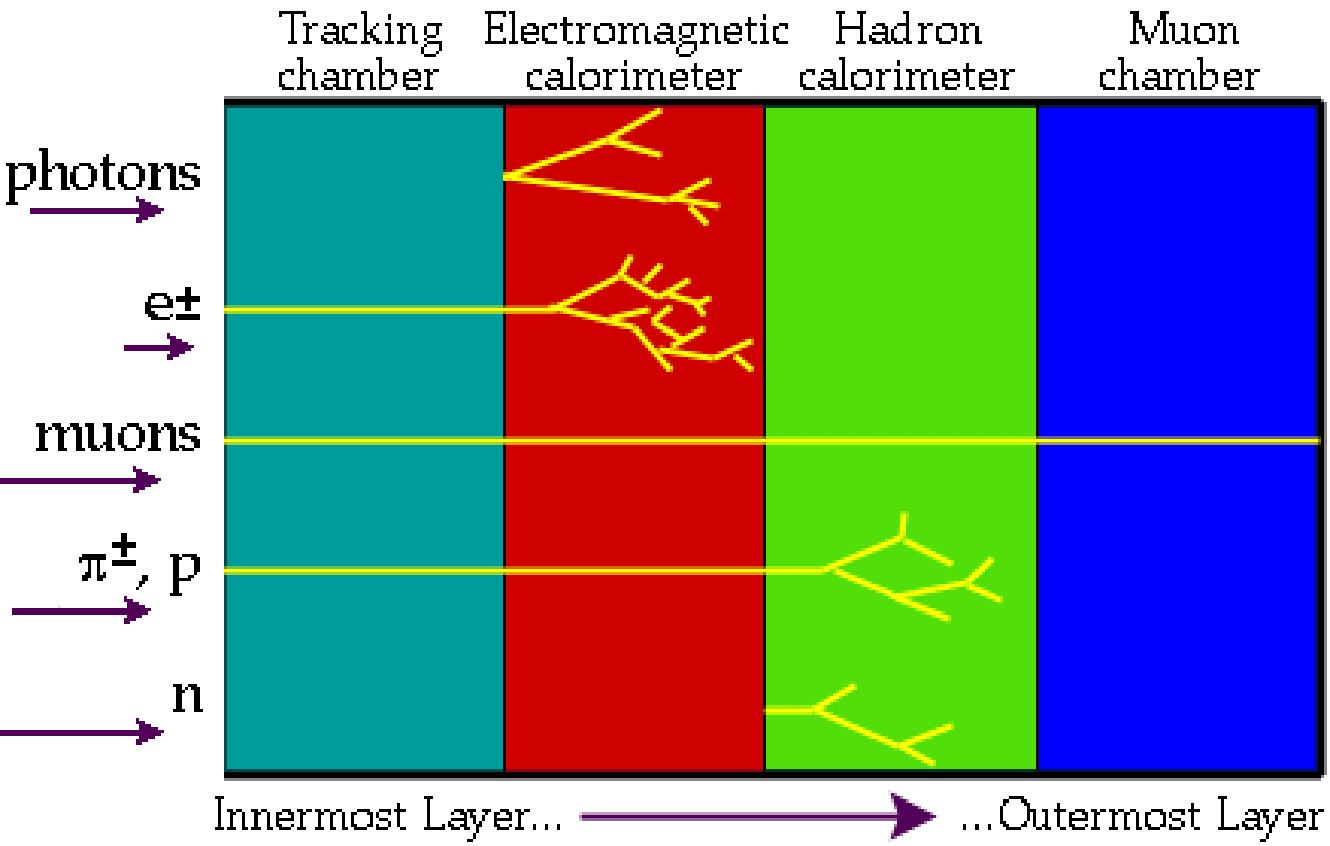
Generic Experiment



Layers of detector systems around collision point

Particle Detection

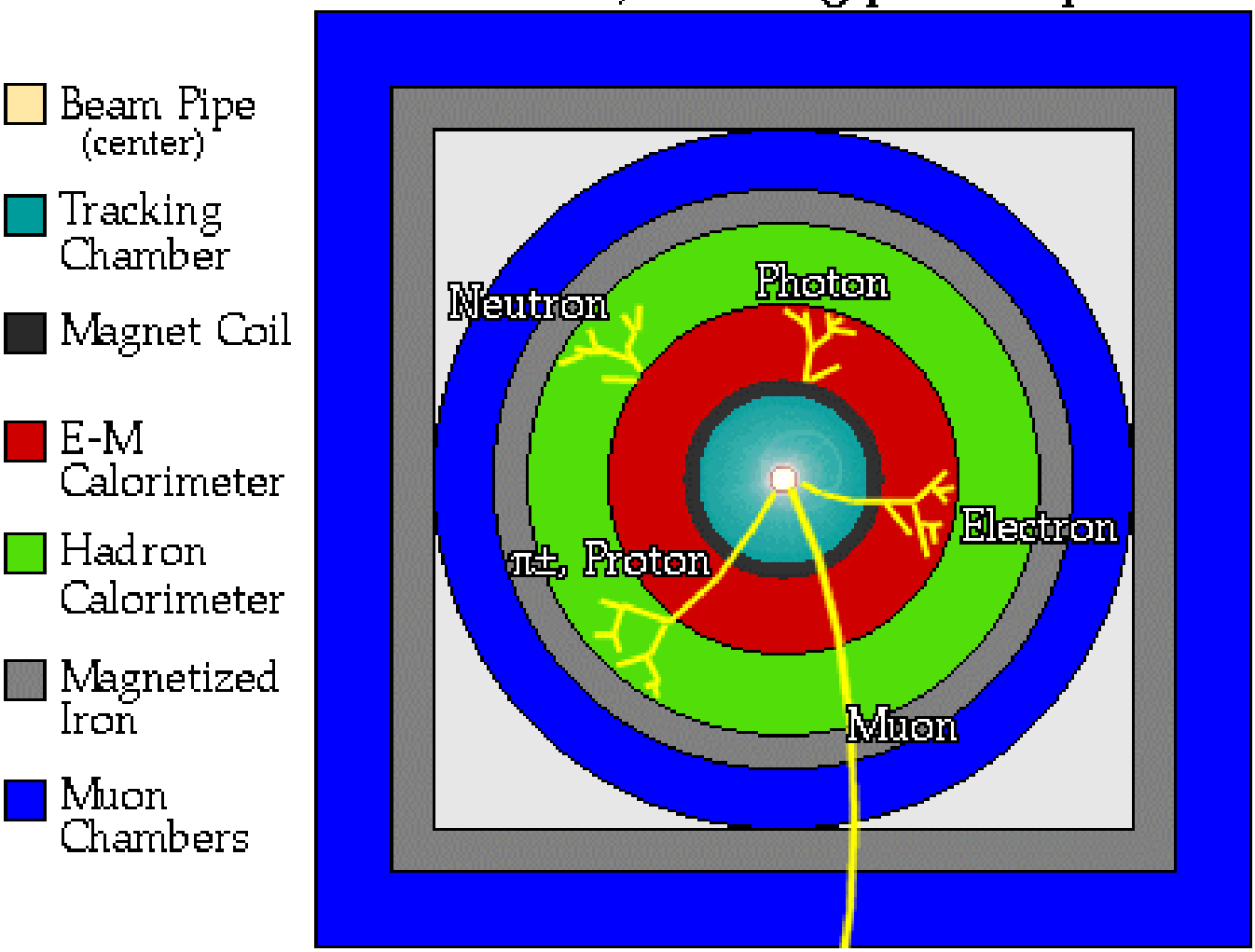


- Different particles detected by different techniques.

- Calorimeter detects ionisation from a shower of secondaries produced by primary particle.

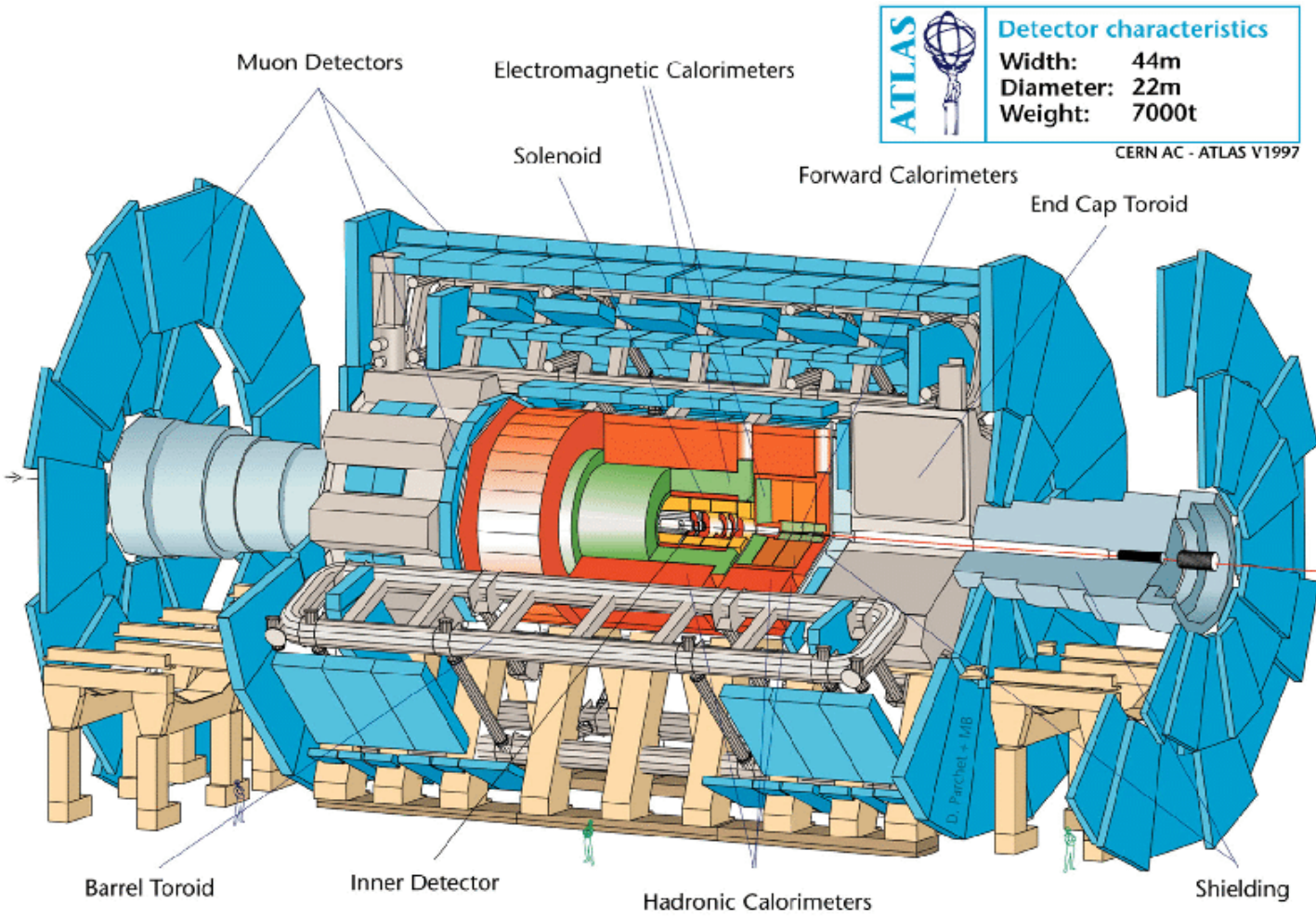
Generic Detector

A detector cross-section, showing particle paths



ATLAS

- Our Detector

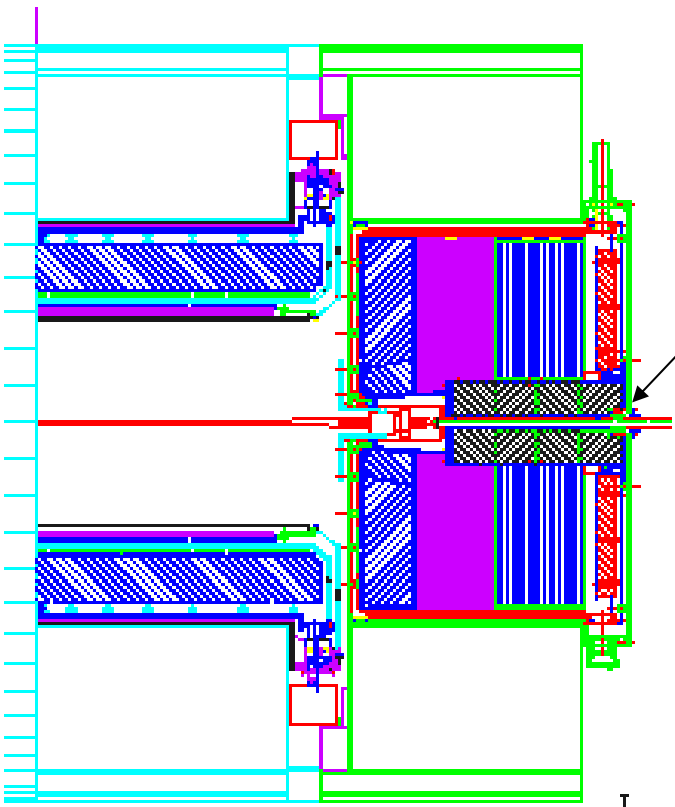


Canada is building

Endcap Calorimeters (TRIUMF Alberta, UVic)

Forward Calorimeters (Toronto Carleton)

Forward Calorimeter



Side view of FCAL

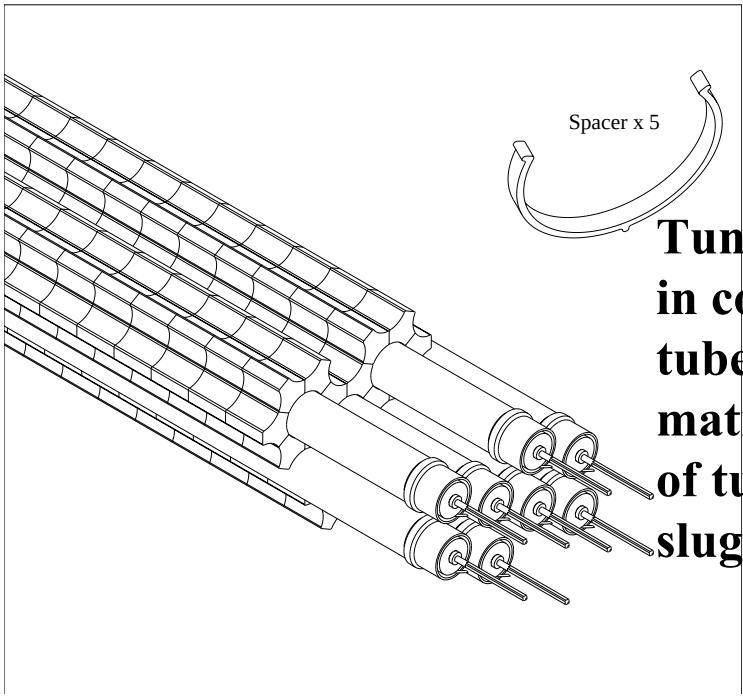
Cryostat

FCAL1 - Cu matrix + rods
2.6λ
FCAL2/3 -W matrix, W rods
Cu skeleton
3.5λ/3.4λ

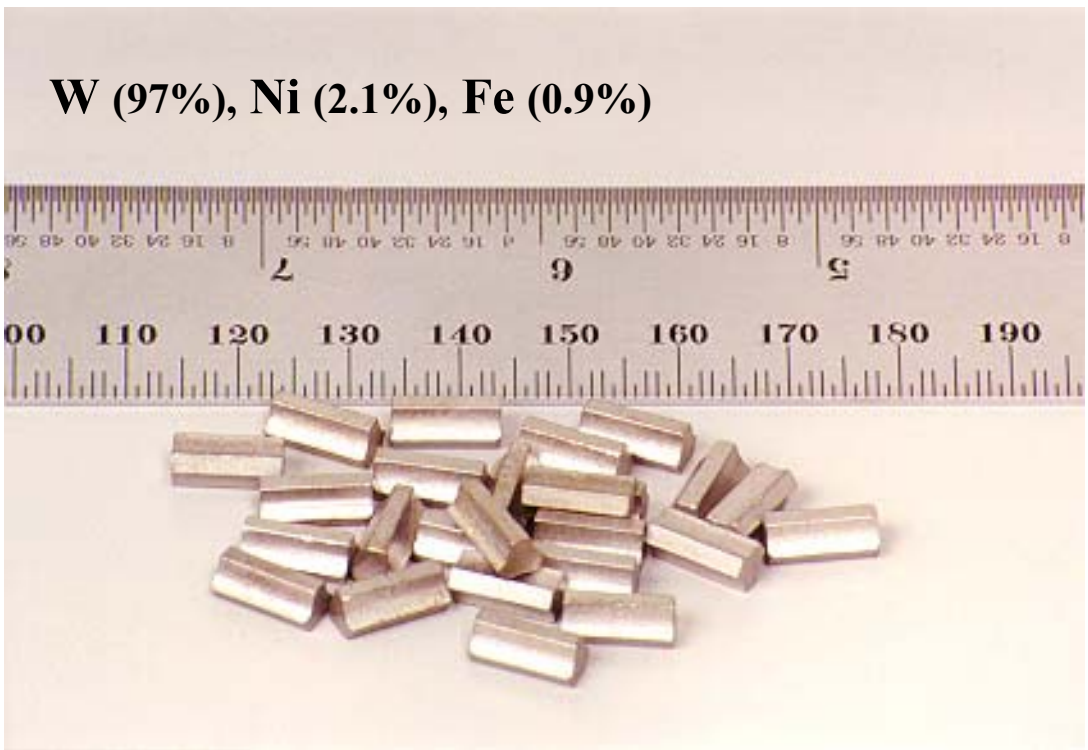
- FCAL is mainly tungsten, uses liquid argon as detecting medium for ionisation from shower

- Close to colliding beams - intense radiation

Hadronic Forward Calorimeter Principle

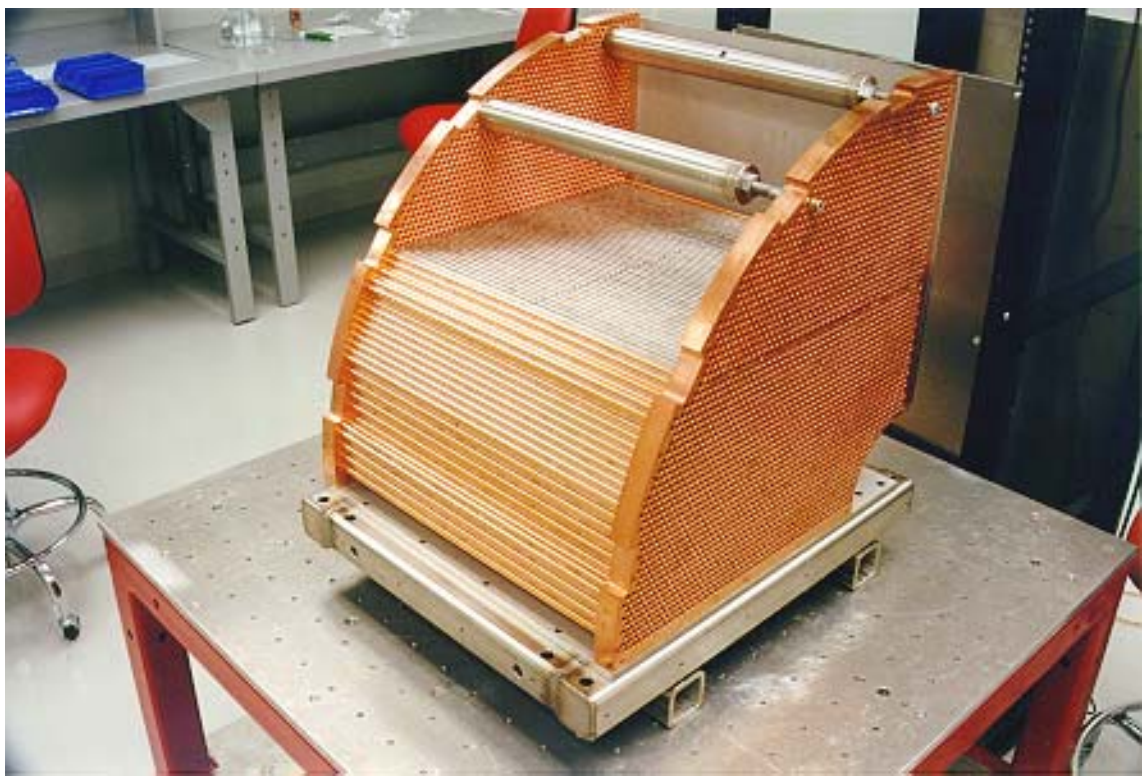


Tungsten rods in copper tubes in a matrix built of tungsten slugs

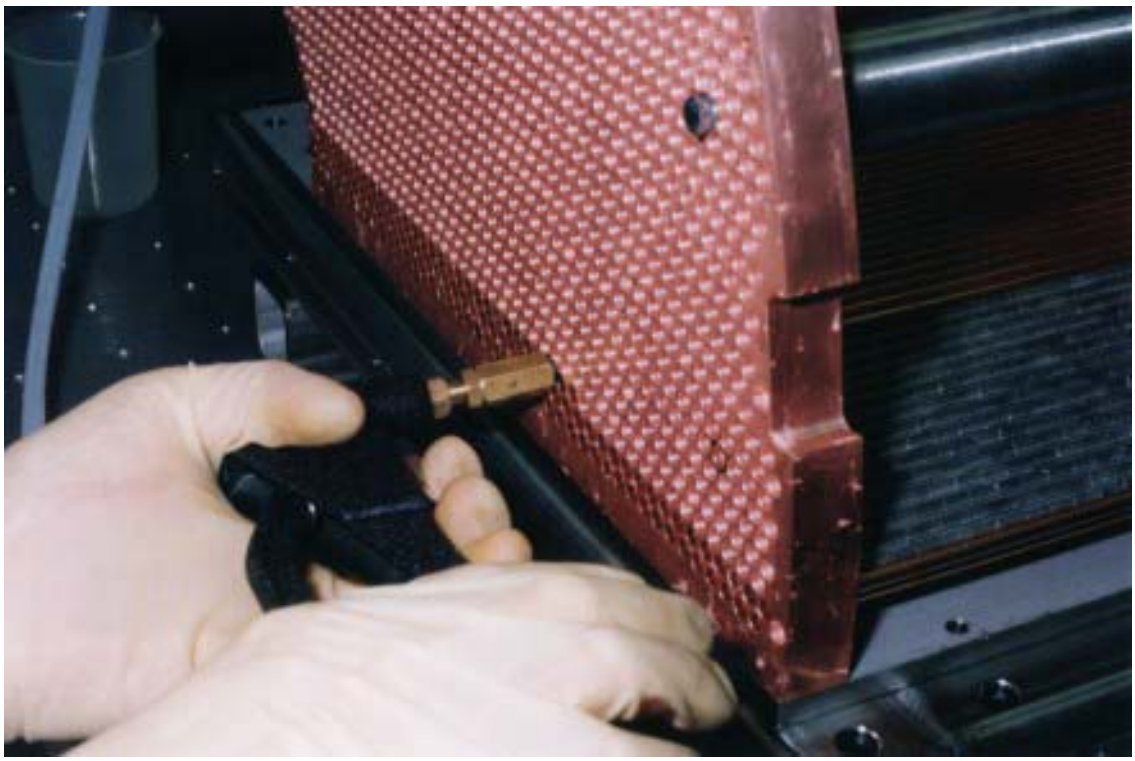


that meet our specifications.

FCAL2 Module 0

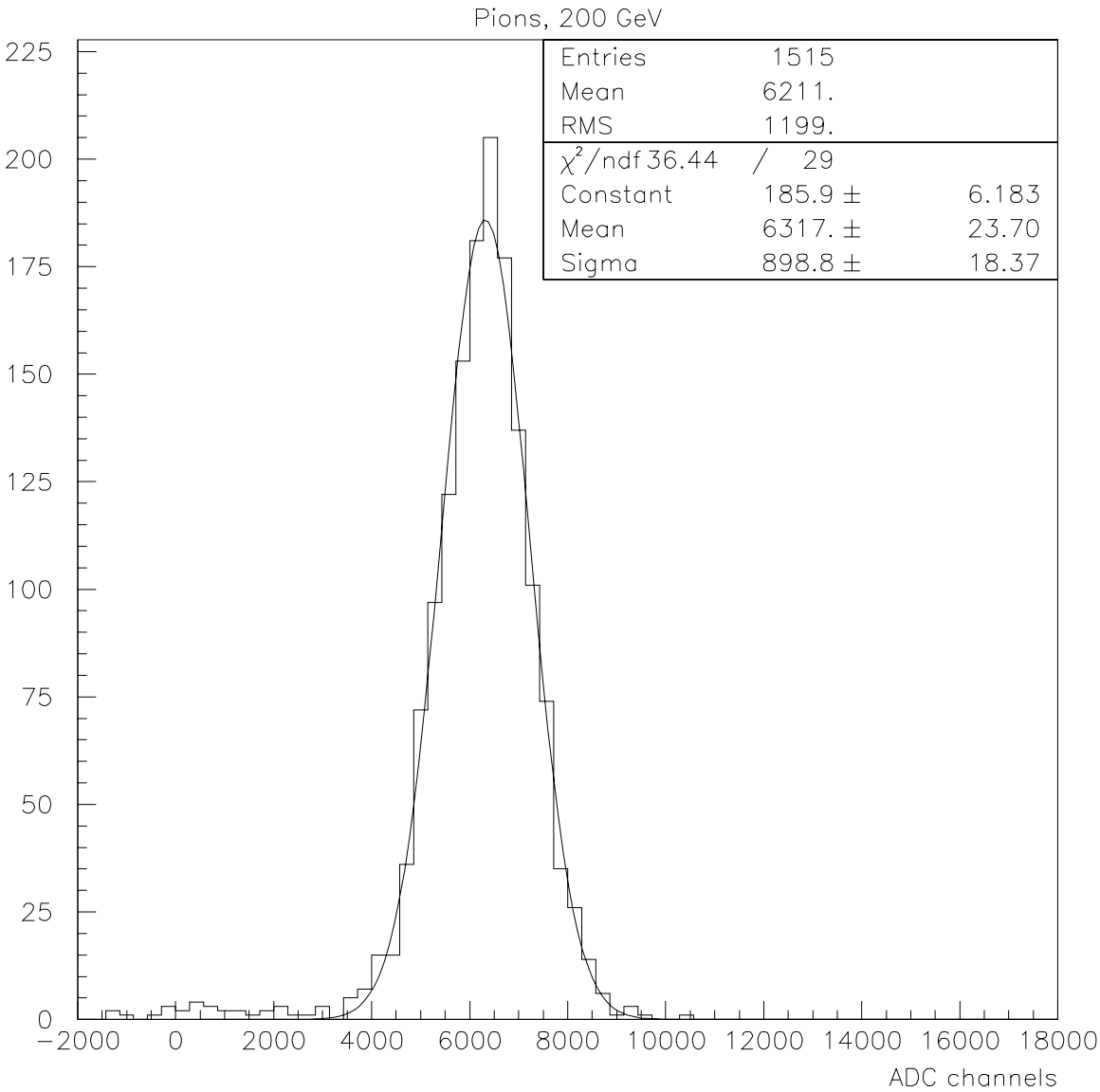


FCAL2 Module 0



FCAL2 Module 0

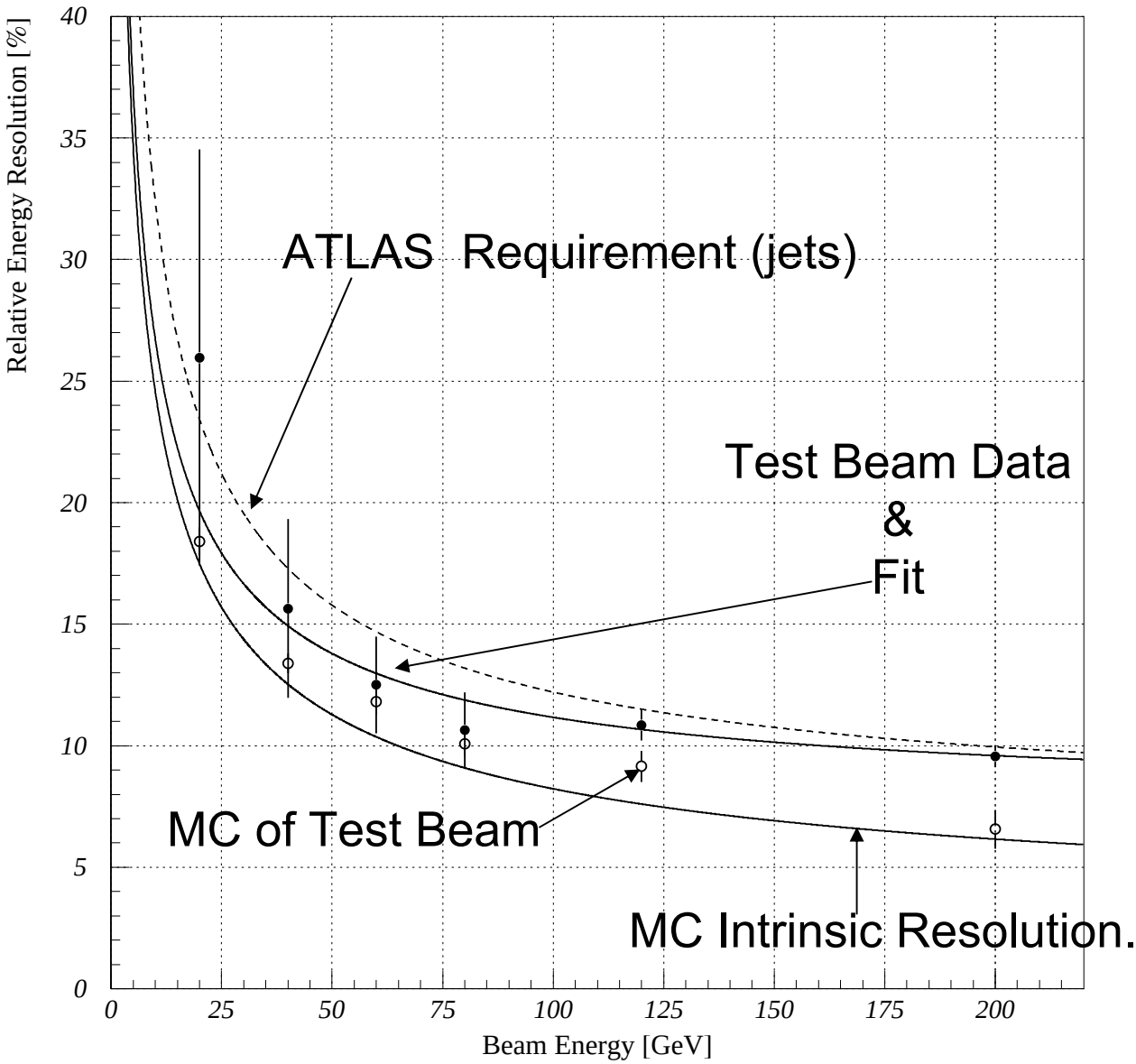
Preliminary Results



Visible energy distribution for 200 GeV pions

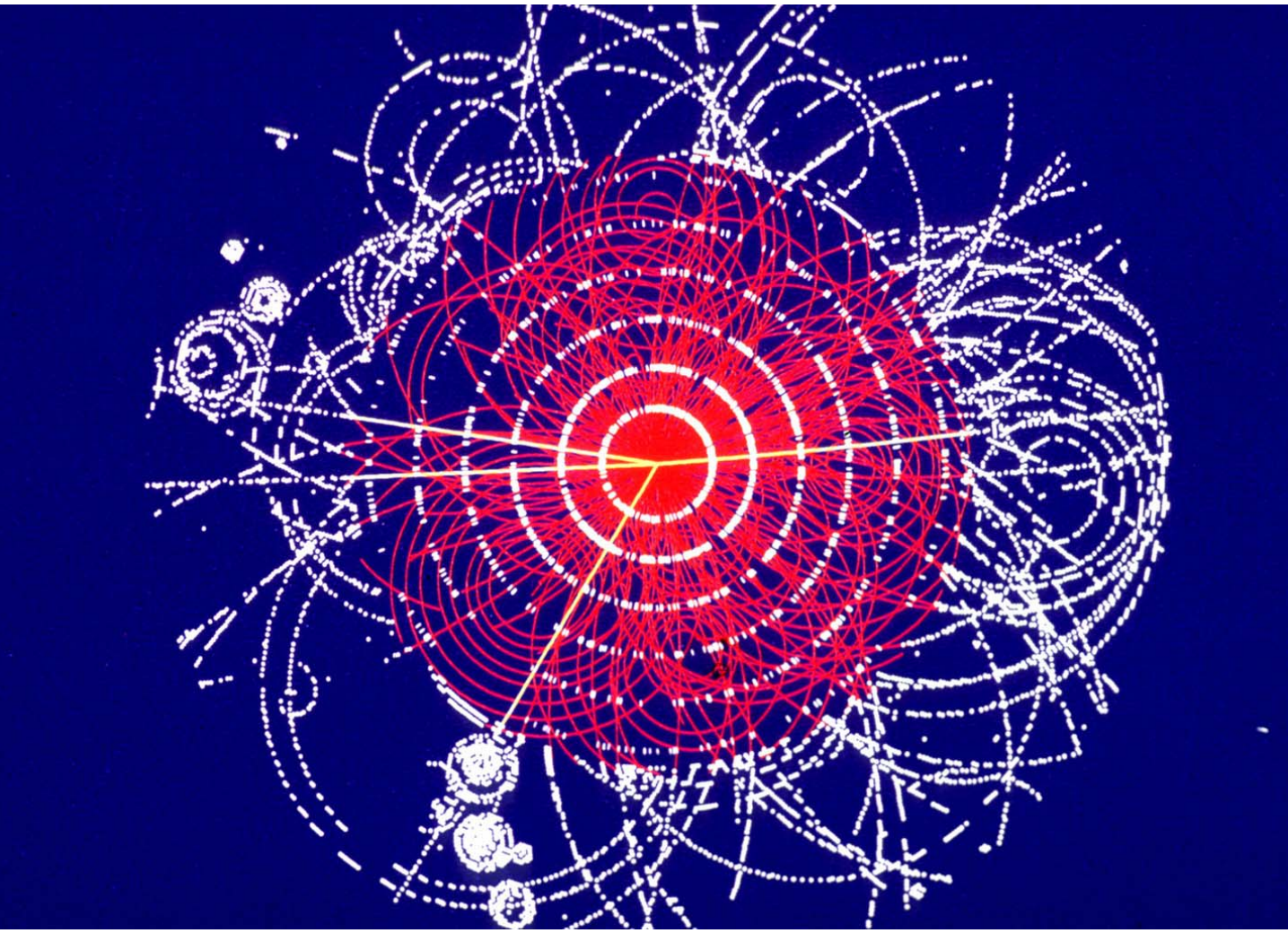
- both modules
- tail catcher energy cut

Preliminary Results



Pion Energy Resolution *cf* Monte Carlo

Higgs Discovery



End on View of a simulated Higgs Boson produced in the ATLAS Detector