A Window on the TeraScale
ATLAS & the LHC

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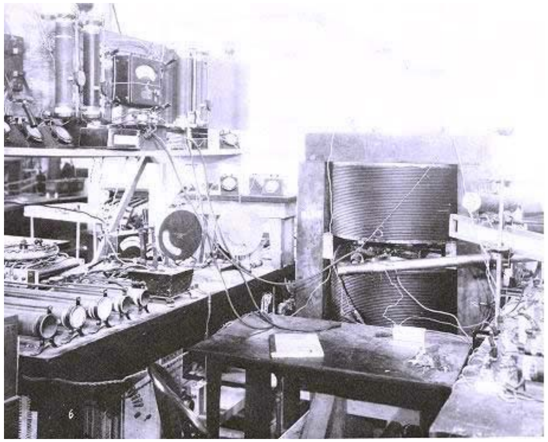


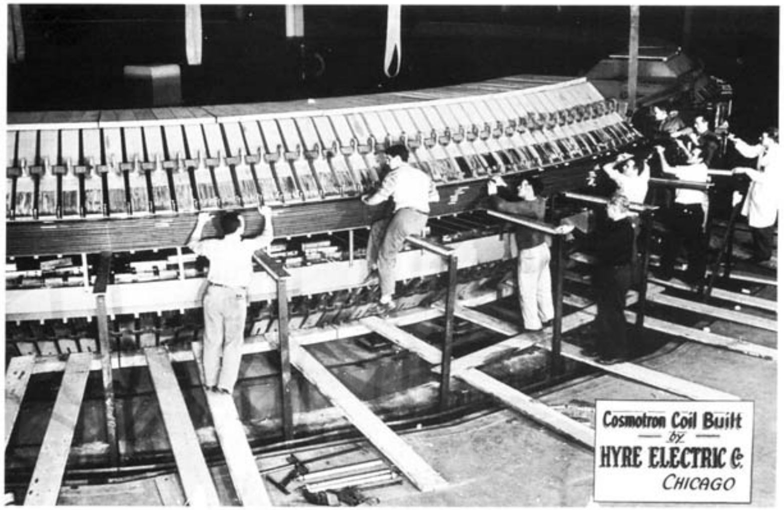
Berkley 1930
1 MeV

Geneva 2007
14 TeV

"Oh – it will cost a billion dollars, ten billion volts 'twill give,
It will take five thousand scholars seven years to make it live.
All the generals approve it, all the money's now at hand,
And to help advance our program, teaching students now we've banned."

"We have chartered transportation, we provide a weekly dance.
Our motto's integration, there is nothing left to chance.
This machine is just a model for a bigger one of course.
That's the future road for physics, as I'm sure you'll all endorse."

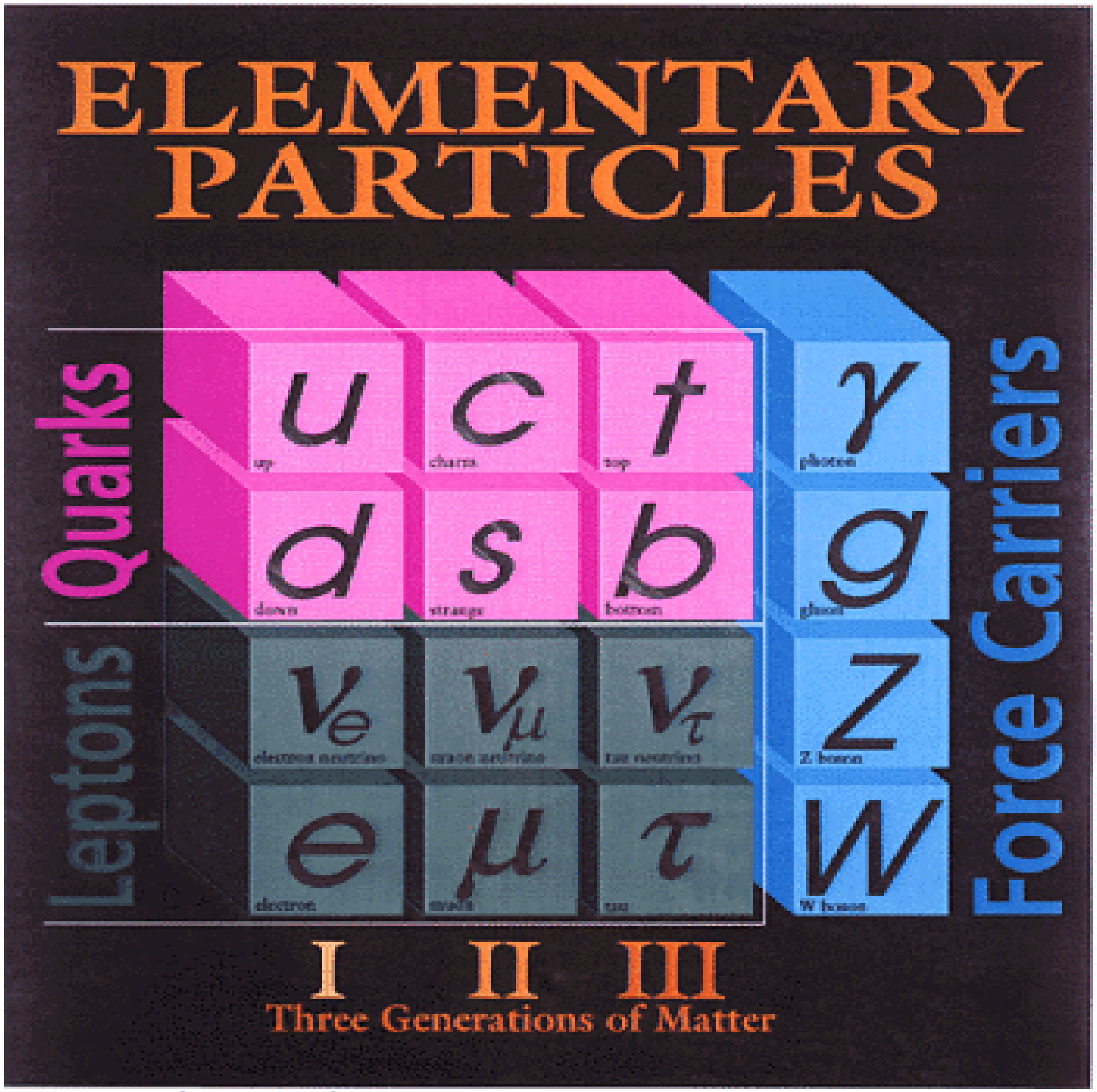
Take Away Your Billion Dollars
by Arthur Roberts (1946)
sung by Arthur Roberts
and the Chorus of the
Iowa State University Department of Physics



Cosmotron – 3 GeV - 1952

LHC – Summer 2007

Is the Universe Made of These?

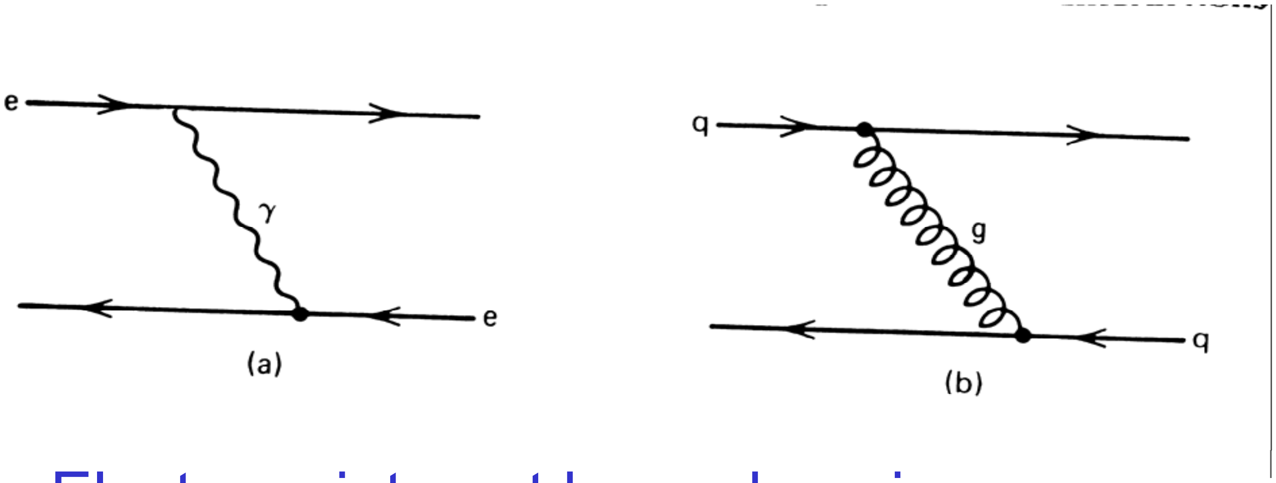


Proton = (u u d) – held together by gluons
Neutron = (u d d)

Quantum Forces

- In Quantum Field Theory, particles interact via:

Exchange of virtual particles



Electrons interact by exchanging:

Virtual Photons - EM Force

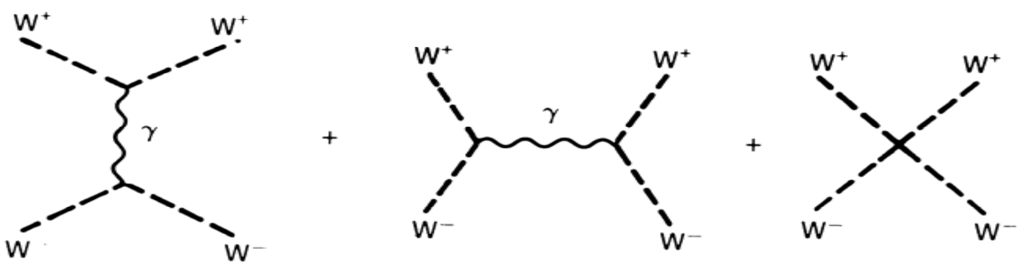
Quarks interact by exchanging:

Virtual Gluons – Color Force

Higgs Boson

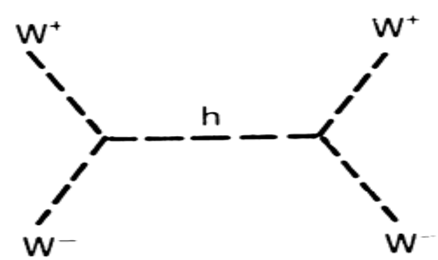
- Electromagnetism on its own can be made to give finite results for all calculations.

- Unified Electroweak theory gives infinite results for process like:



- Become finite if include new particle

Higgs



Spontaneous Symmetry Breaking

Renormalizable Gauge Theory

- 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

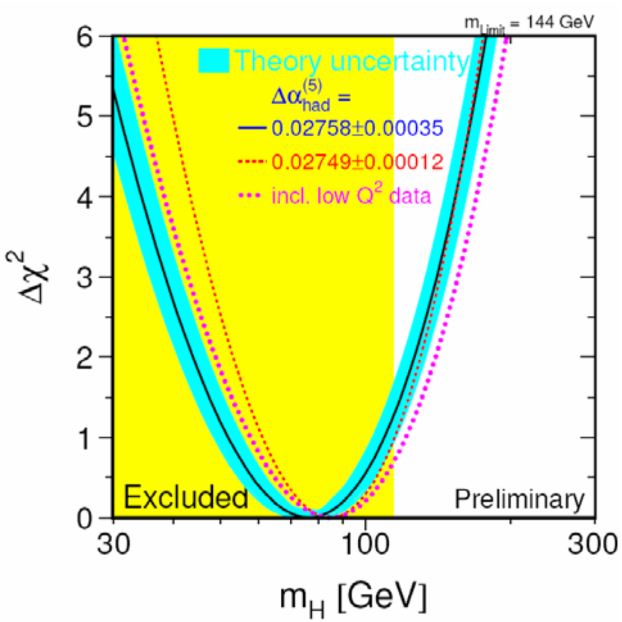
Refractive Index

- 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

What we know about the Higgs Boson today

- Mass not predicted by theory, except that $m_H <$ ~1000 GeV
- $m_H > 114.4$ GeV from direct searches at LEP
- Indirect limits from electroweak precision measurements (LEP, Tevatron and other experiments….)



Results of the precision el.weak measurements:
(all experiments, July 2007):

M_H = 80 (+36) (-26) GeV/c^2

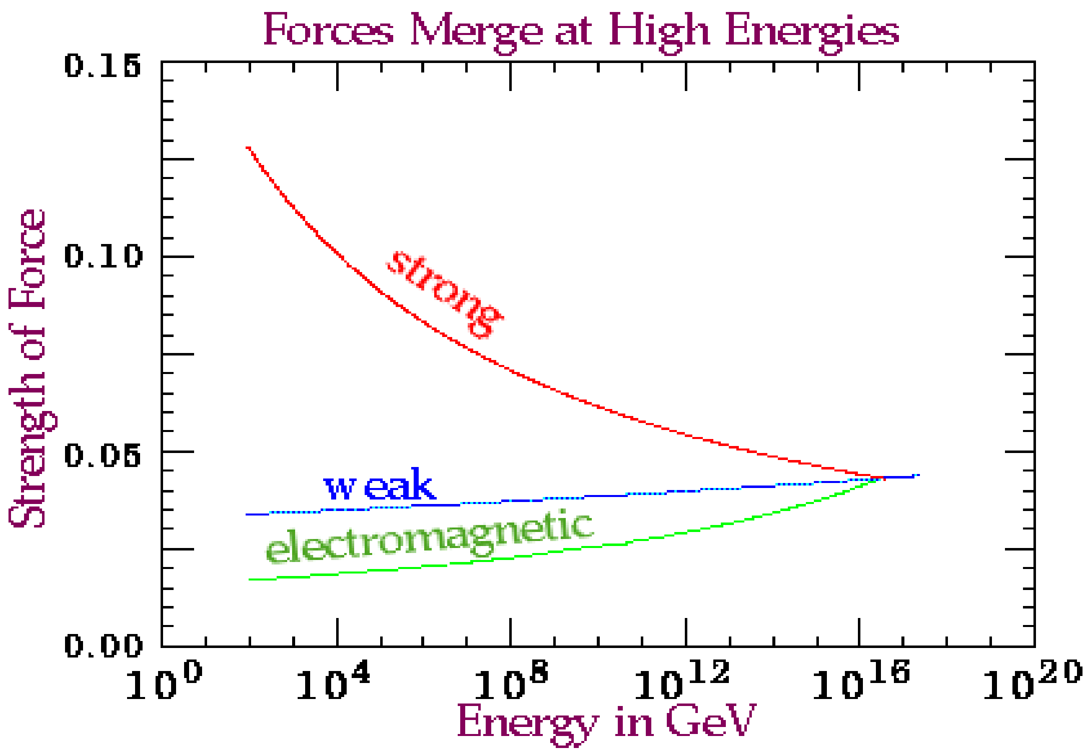
$M_H <$ 144 GeV/c^2 (95 % CL)

→ Higgs boson could be around the corner

Grand Unification.

- At a high enough energy
  - electromagnetism
  - weak force
  - strong (colour) force

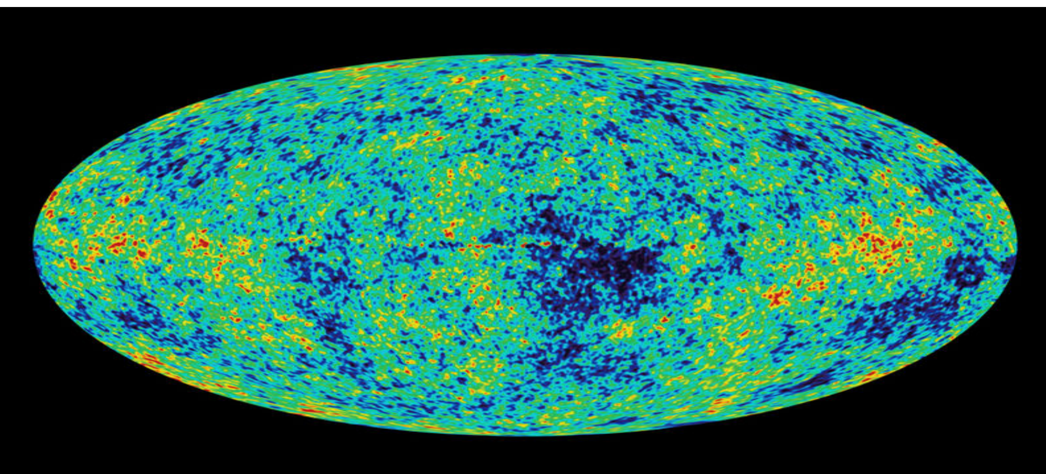
become aspects of Grand Unified Force

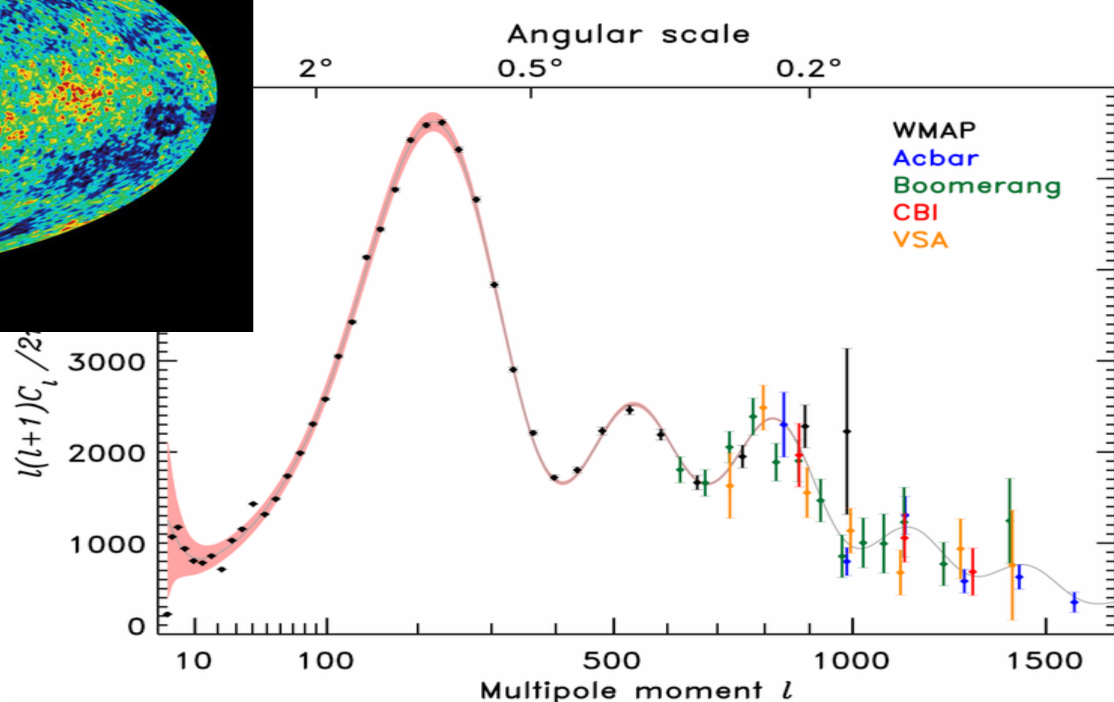


Measuring $\Omega_0 = \rho_0 / \rho_C$

- Amazingly enough can measure
  - Total matter/energy density in universe
  - Seems equal to critical density for flat space/time
- Measure temperature fluctuations in remnant of fireball from Big Bang.

$$\Omega_0 = 1.003 \pm 0.013$$





Map of sky temp
~ 3 Kelvin

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

$$\Omega_B = 0.044$$

$$\Omega_B \neq \Omega_0$$

- 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

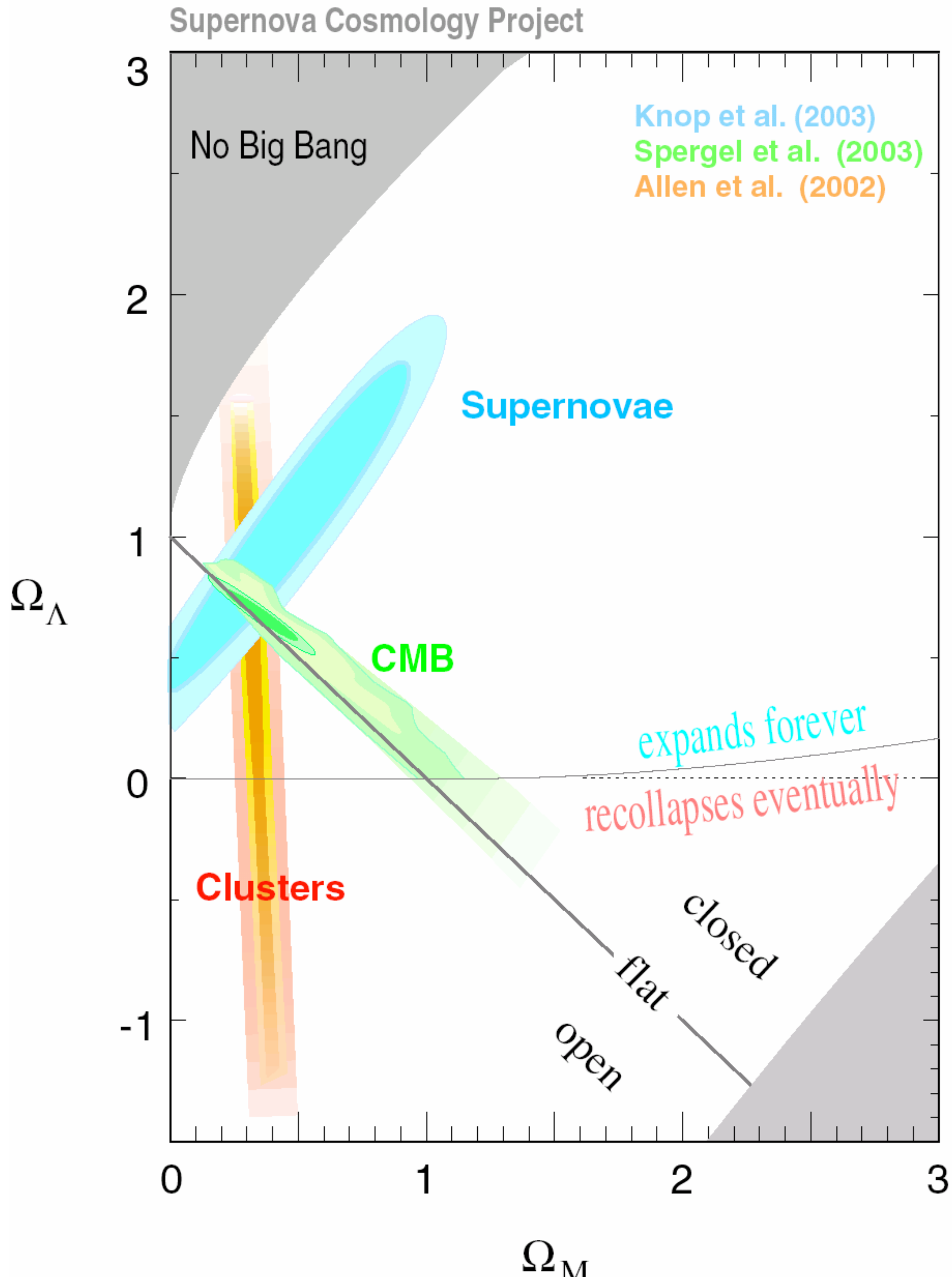
Fit to global parameters of Universe

$$\Omega_M = 0.26 \pm 0.012$$

- There is indeed Dark Matter

$$\Omega_0 = 1$$

- So even with this Dark Matter, cannot account for
- Universe must be 75% Something Else

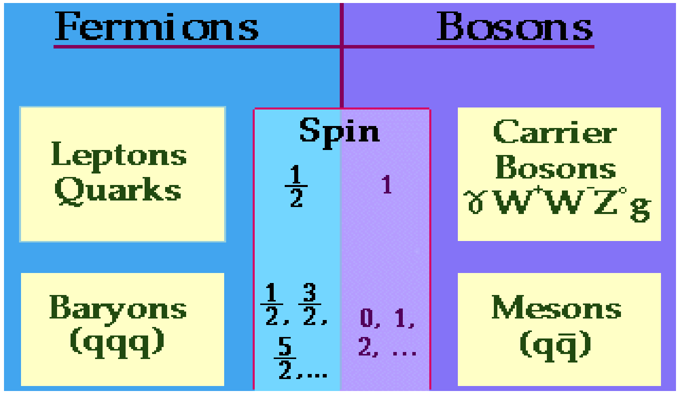


Supernova Cosmology Project
Knop et al. (2003)
Spergel et al. (2003)
Allen et al. (2002)
No Big Bang
Supernovae
CMB
Clusters
expands forever
recollapses eventually
closed
flat
open
3
2
1
0
-1
0
1
2
3
Ω_Λ
Ω_M

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

Squarks

Spin 1

Bosinos

Spin1/2

SUSY + Dark Matter

- Supersymmetric Particles are unstable

$$Susy \rightarrow Normal + Susy$$

- Eventually decay chain ends in Normal matter + lightest SUSY particle
- Lightest SUSY particle cannot interact with normal matter
- Lightest SUSY particle good candidate for

Dark Matter

- Hope to produce

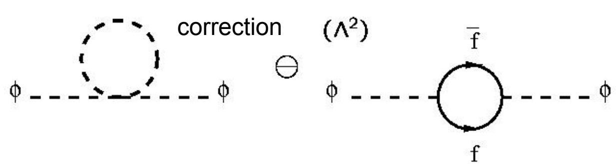
(SUSY - antiSUSY) pairs and Higgs

at

Large Hadron Collider

Why do we like SUSY so much?

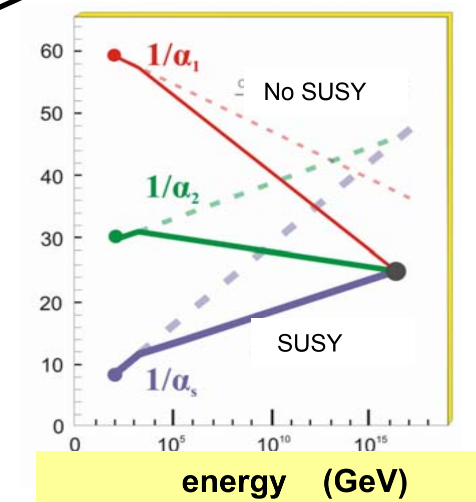
1. Quadratically divergent quantum corrections to the Higgs boson mass are avoided (fermion loops cancel boson loops)



$$\Delta m_H = f(m_B^2 - m_f^2)$$

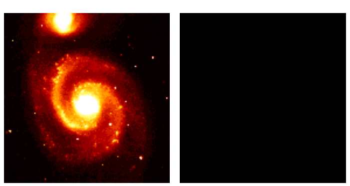
(Hierarchy or naturalness problem)

$m_{SUSY} \sim 1$ TeV



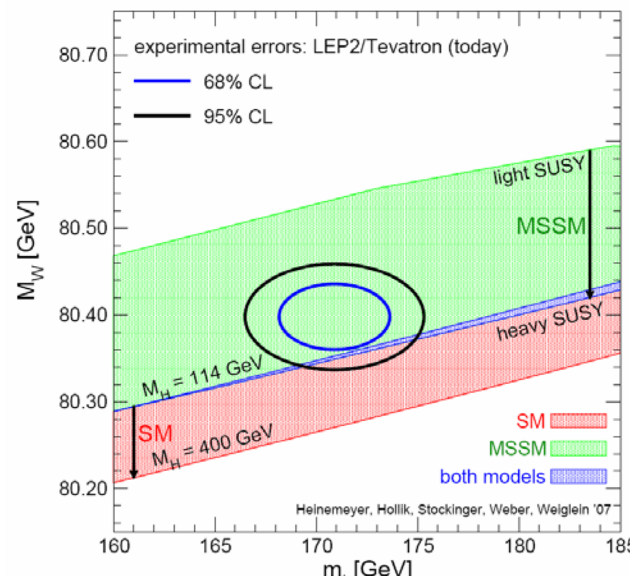
2. Unification of coupling constants of the three interactions seems possible

3. SUSY provides a candidate for dark matter,



The lightest SUSY particle (LSP)

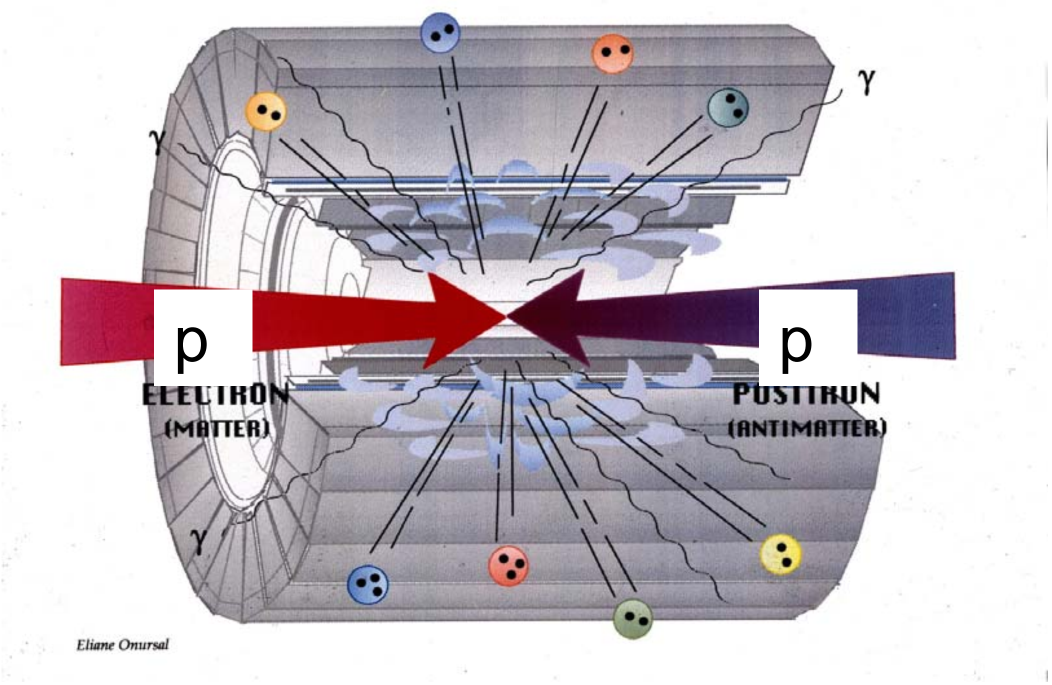
4. A SUSY extension is a small perturbation, consistent with the electroweak precision data



How to Make Matter / AntiMatter?

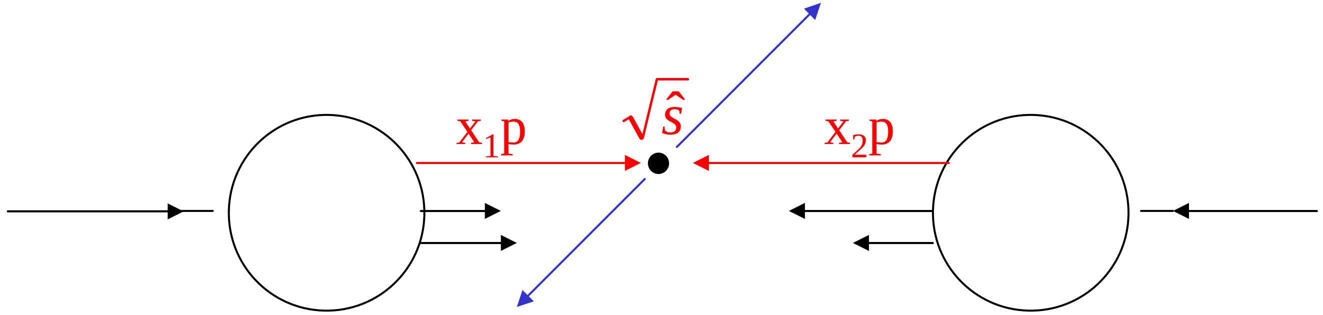
Colliding high energy beams

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

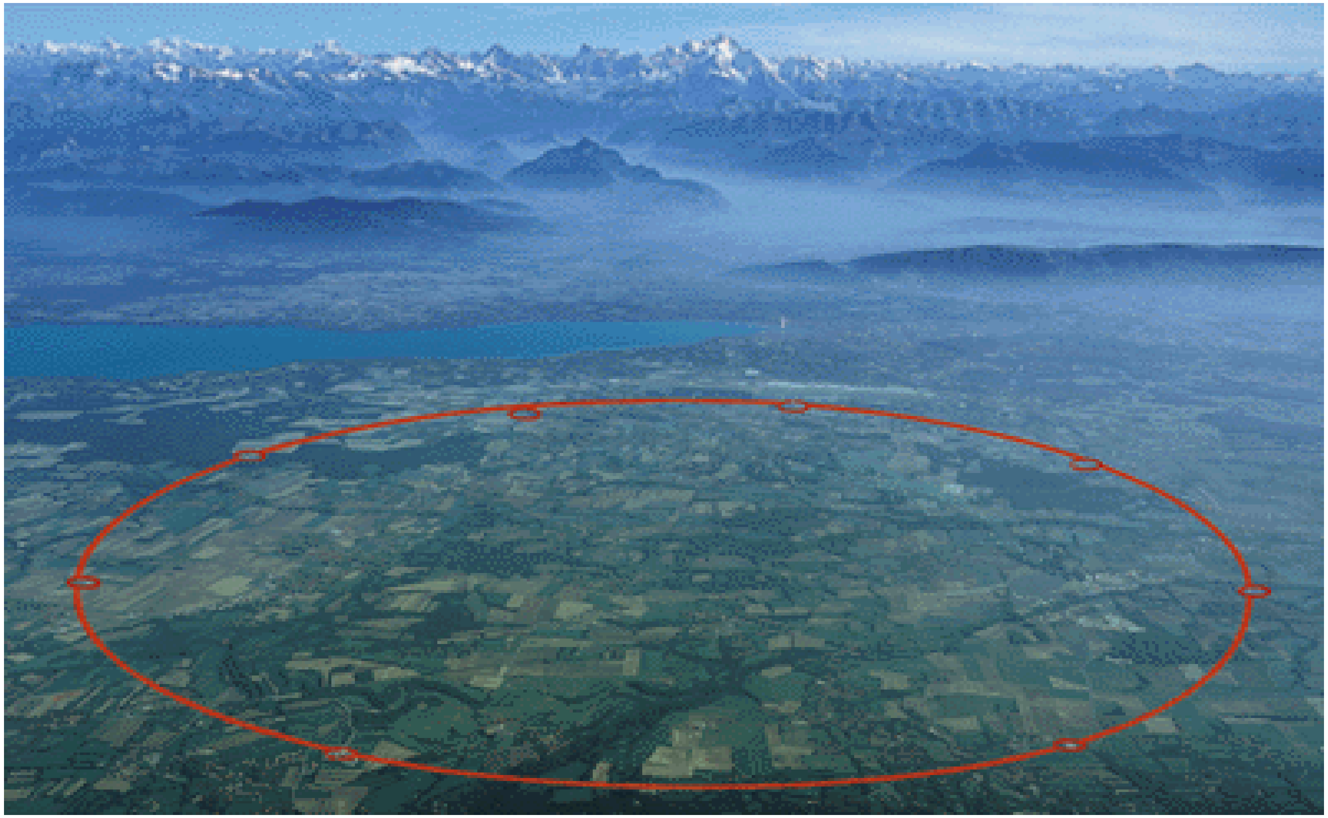
- Monochromatic proton beam is a beam of quarks and gluons, with a wide band of energy.
- Occasionally hard scattering (" head on") between constituents of incoming protons occurs.



p ≡ momentum of incoming protons = 7 TeV

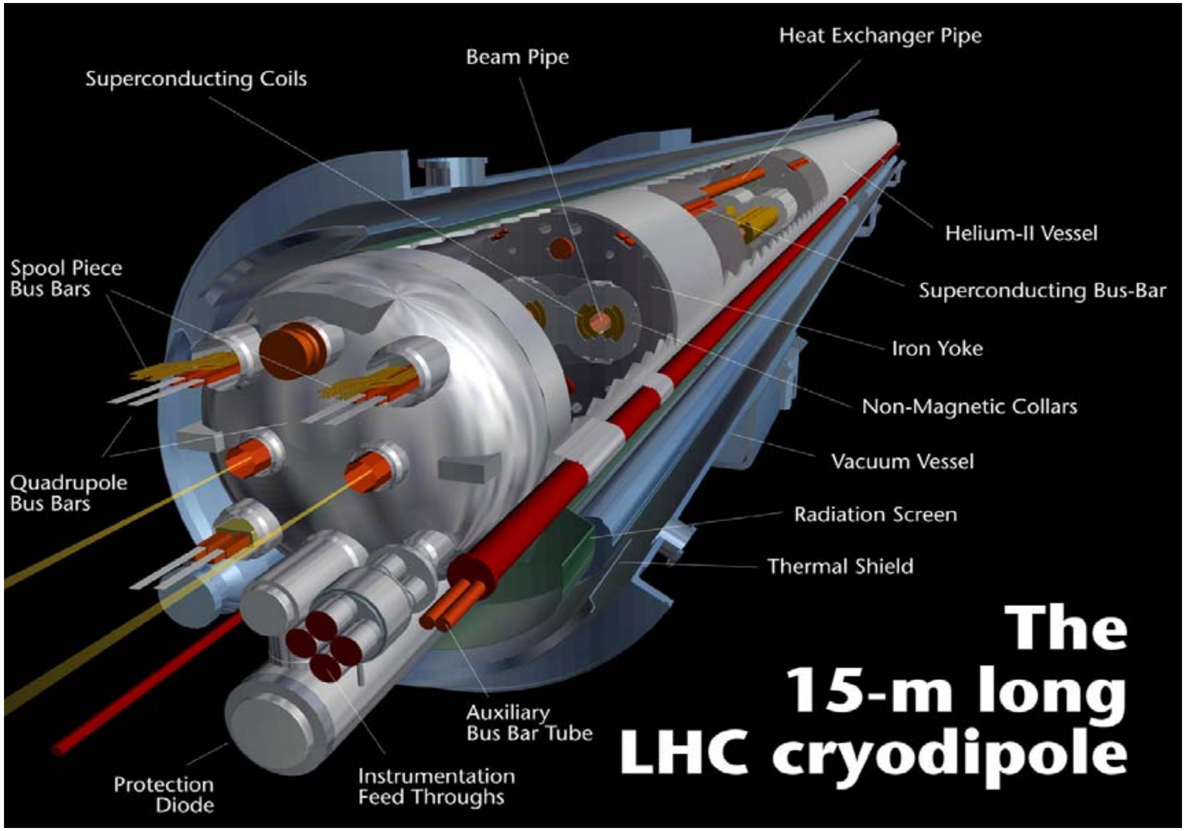
Interactions at small distance
→ large momentum transfer
→ massive particles are produced.

CERN Seen from the Air



- Tunnels of CERN accelerator complex superimposed on a map of Geneva.
- Accelerator is 50 m underground
- 25 km in circumference

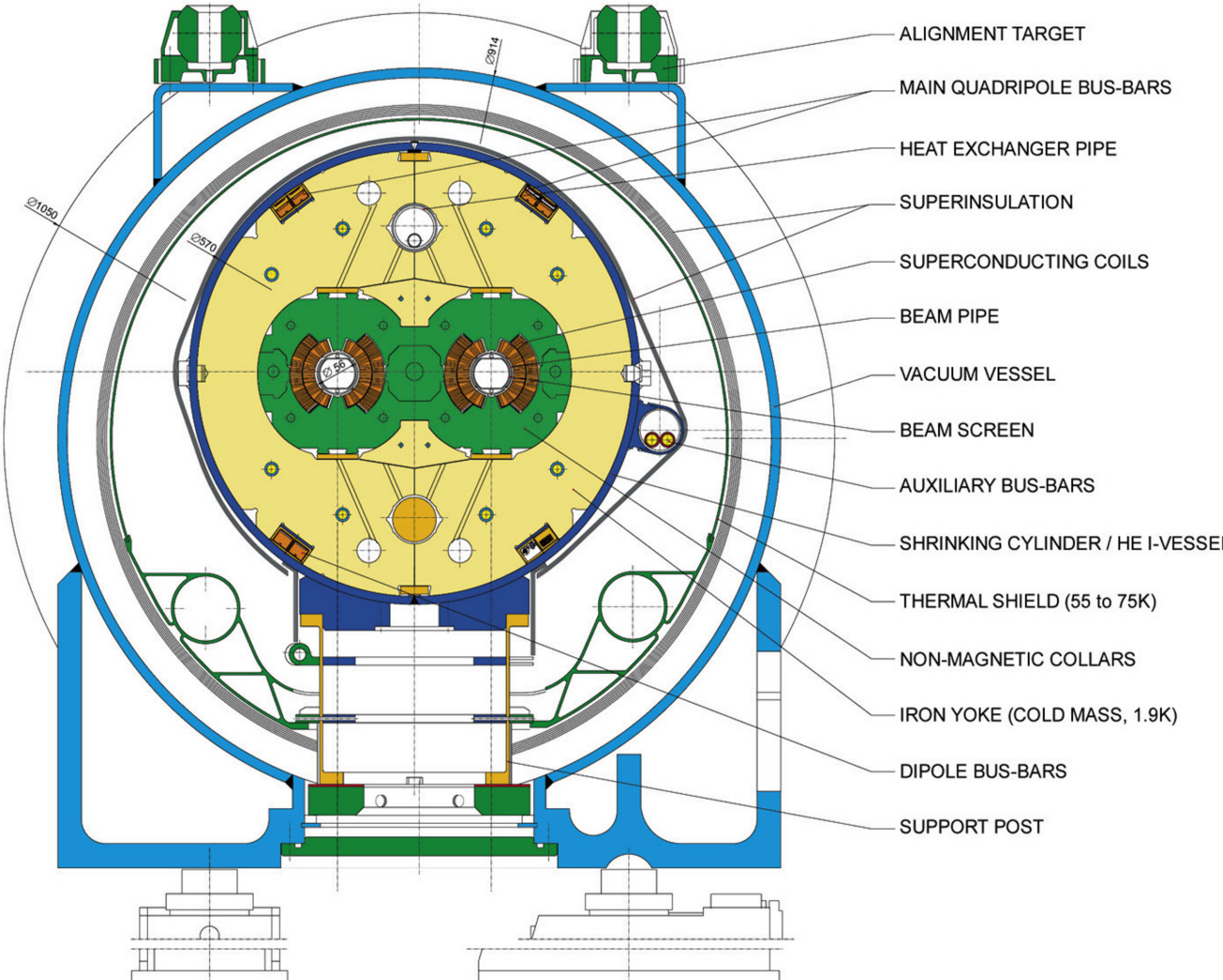
Superconducting Magnet
8 Tesla



- In order to accelerate protons to high energy, must bend them in circular accelerator
- 7 TeV momentum needs intense magnetic field

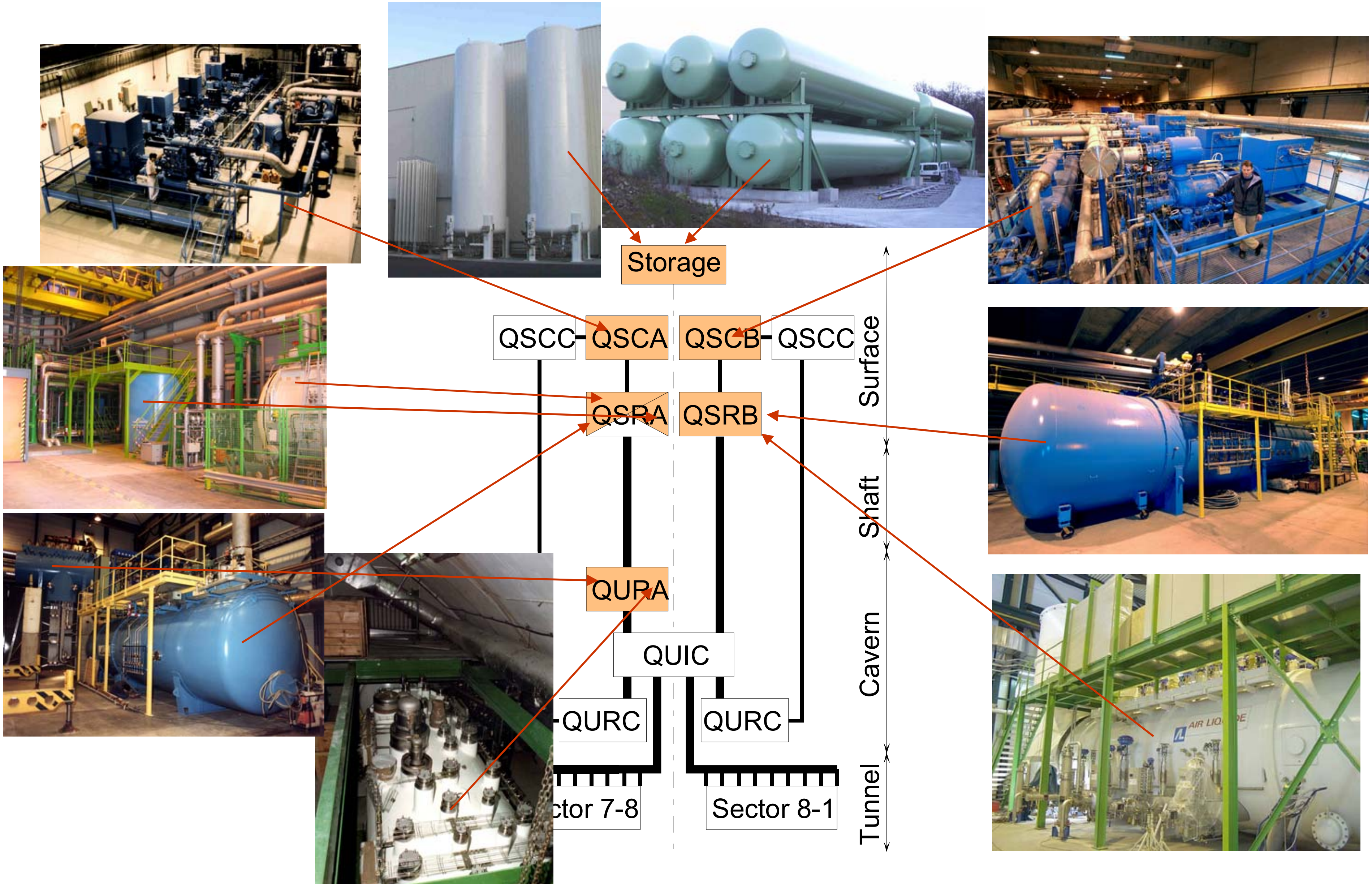
LHC DIPOLE : STANDARD CROSS-SECTION

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



Dipole Magnet

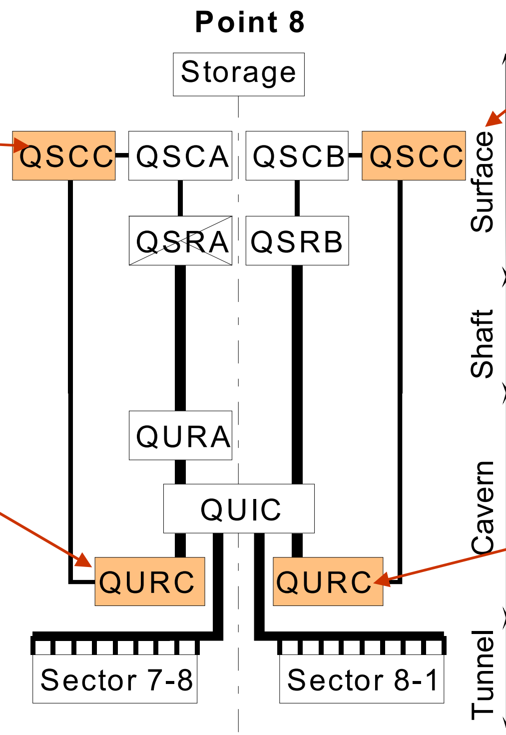
Infrastructure and Refrigerators at 4.5 K



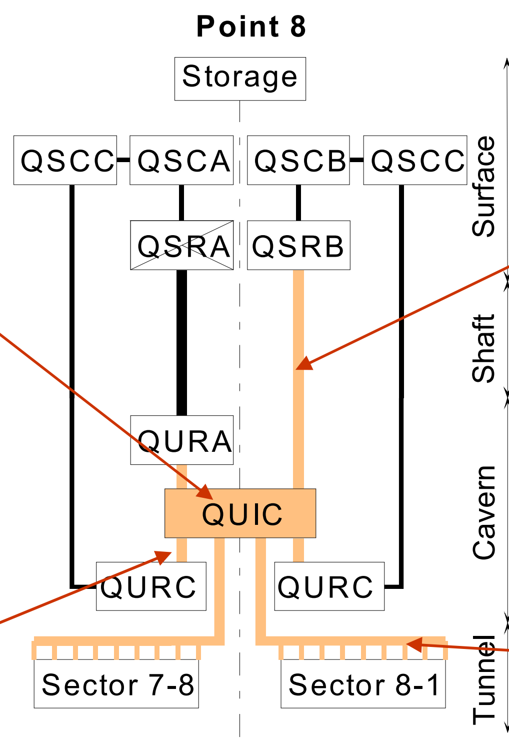
Refrigeration Units at 1.8 K

Air Liquide

IHI Linde

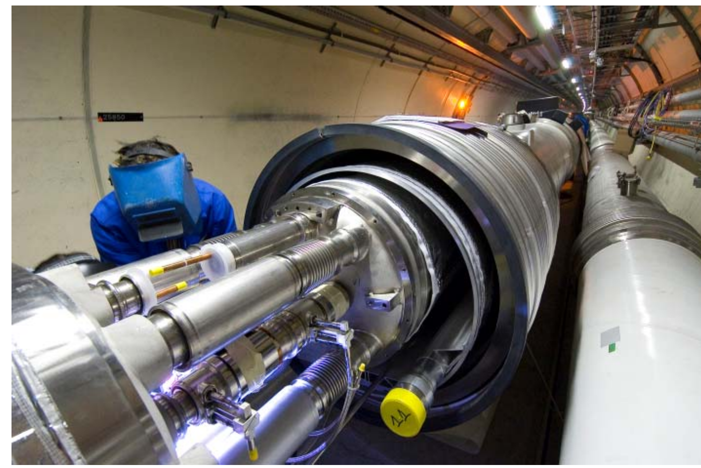


Cryogenic Distribution

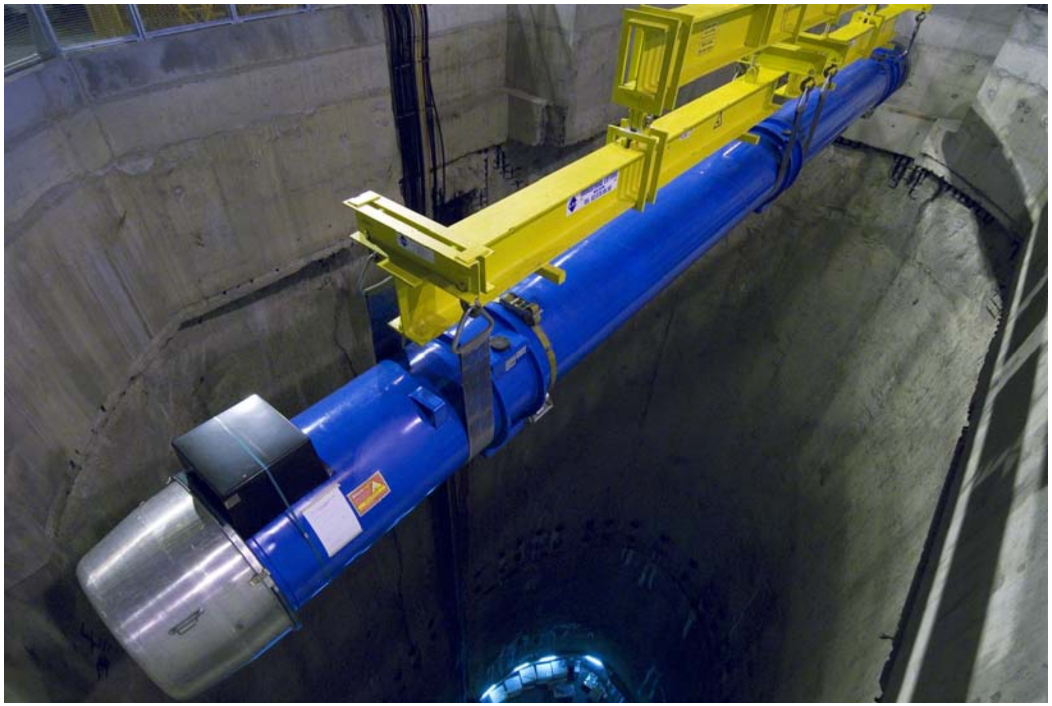


CERN
Hardware
Commissioning
Panel n° 1
First cool down of the QRL
Access forbidden
Entering this zone is a
PROFESSIONAL FAULT
Last updated
15:03
Call
for information
ATTENTION
Site sous
surveillance

Underground

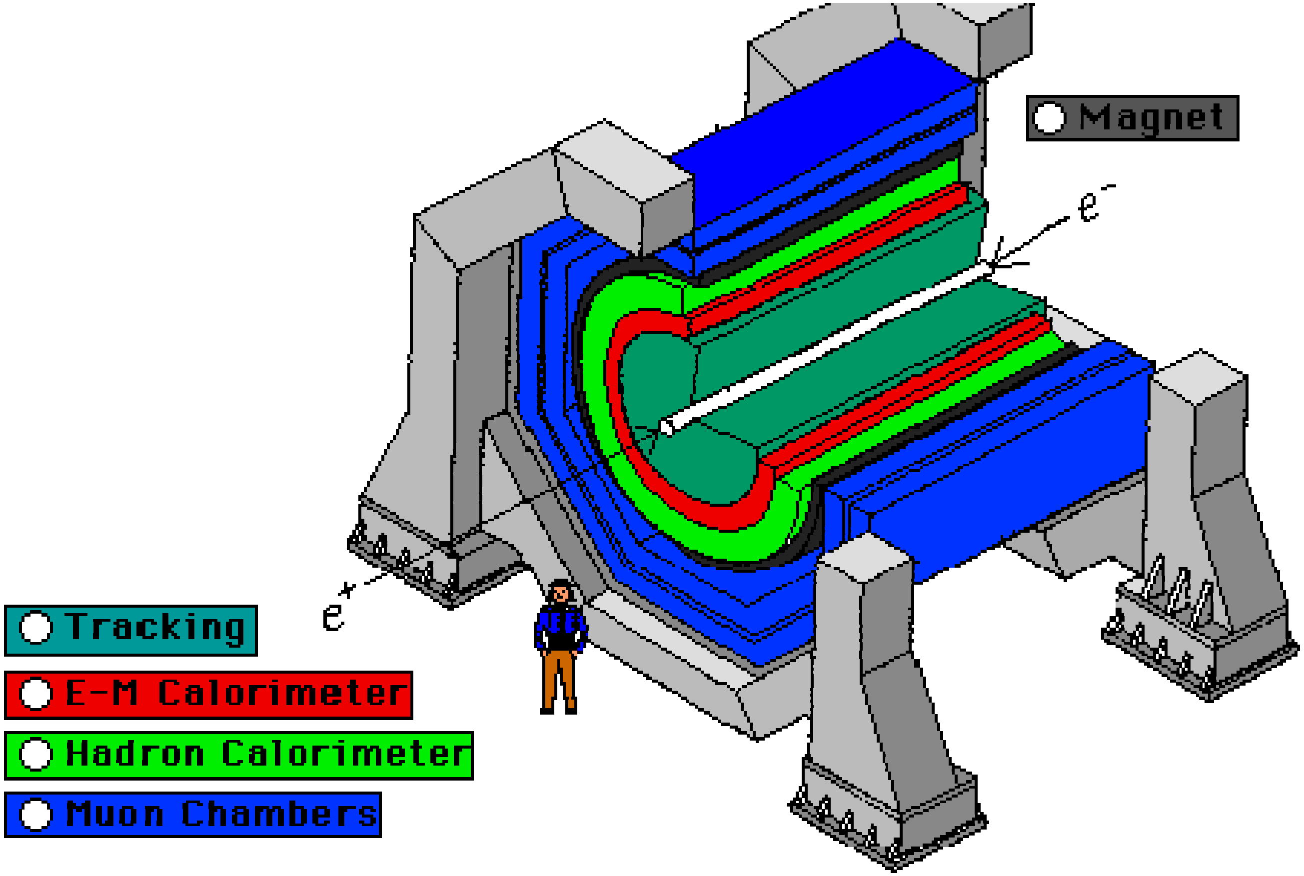


Descent of the Last Magnet, 26 April 2007

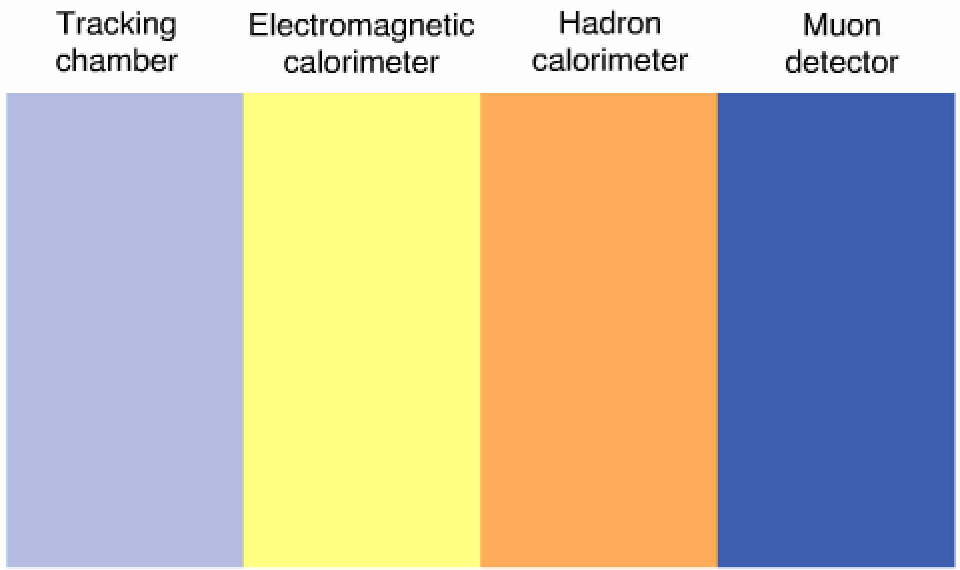


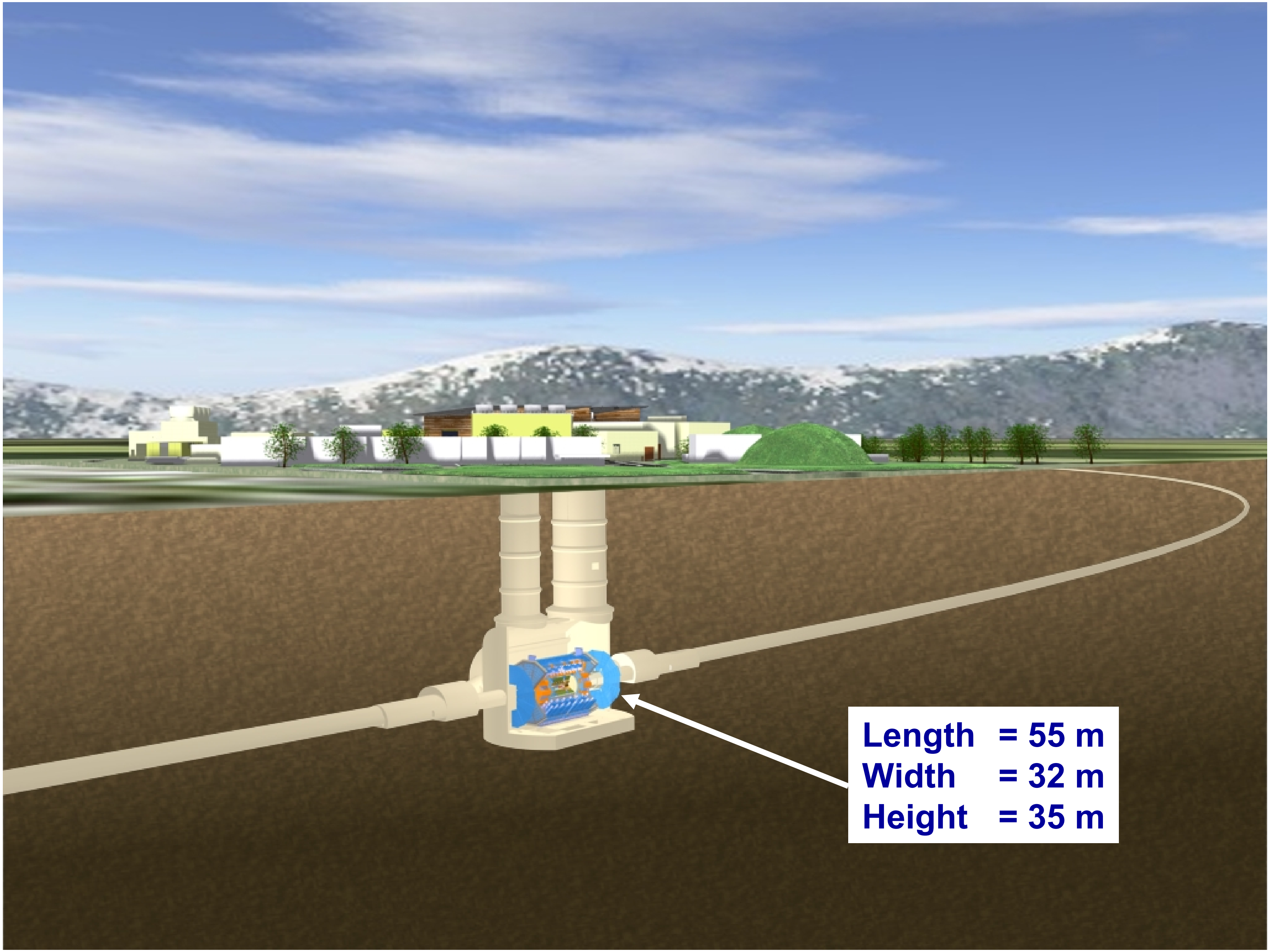
300 m underground at 2 km/h!

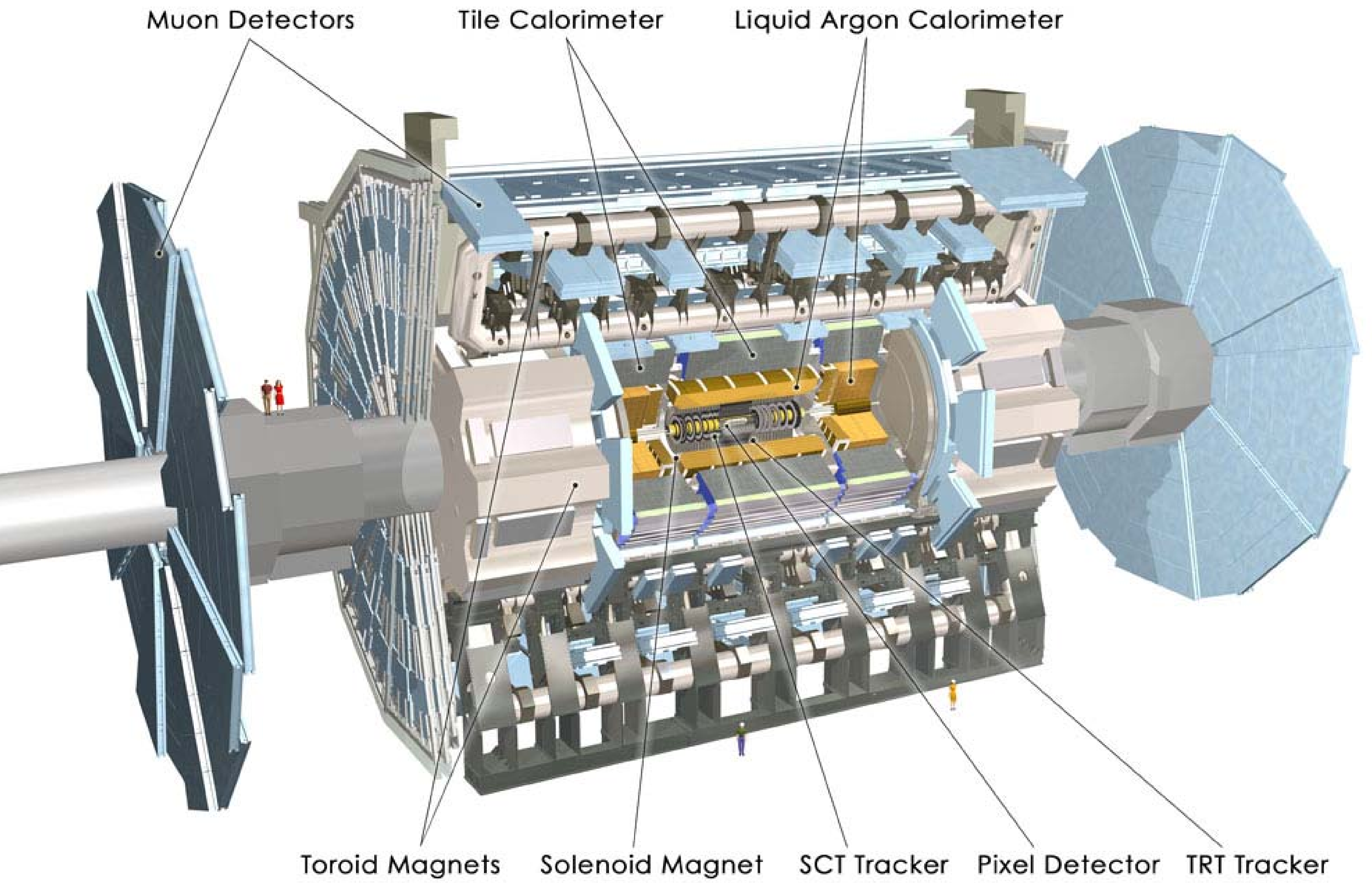
Generic Experiment

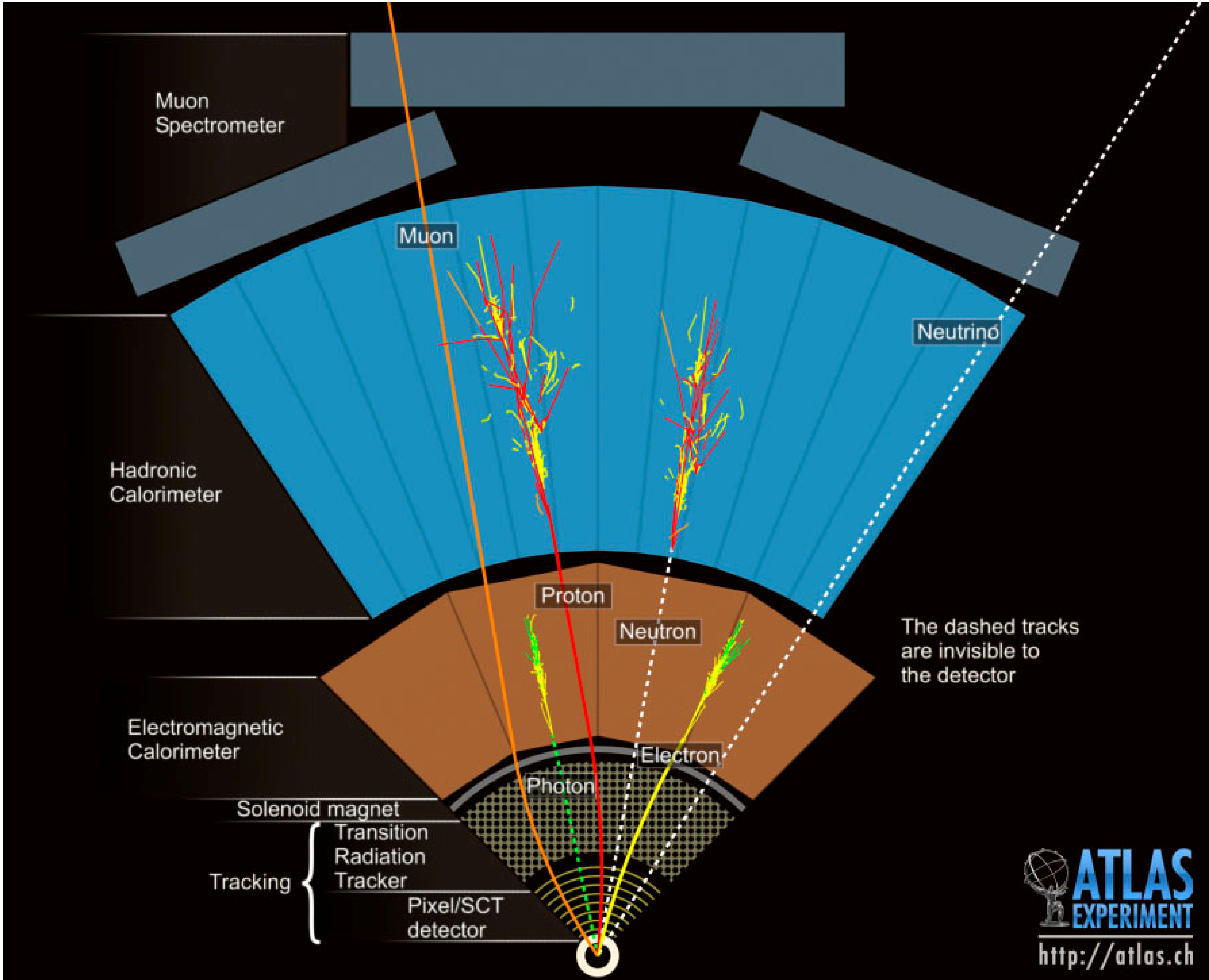


Layers of detector systems around collision point

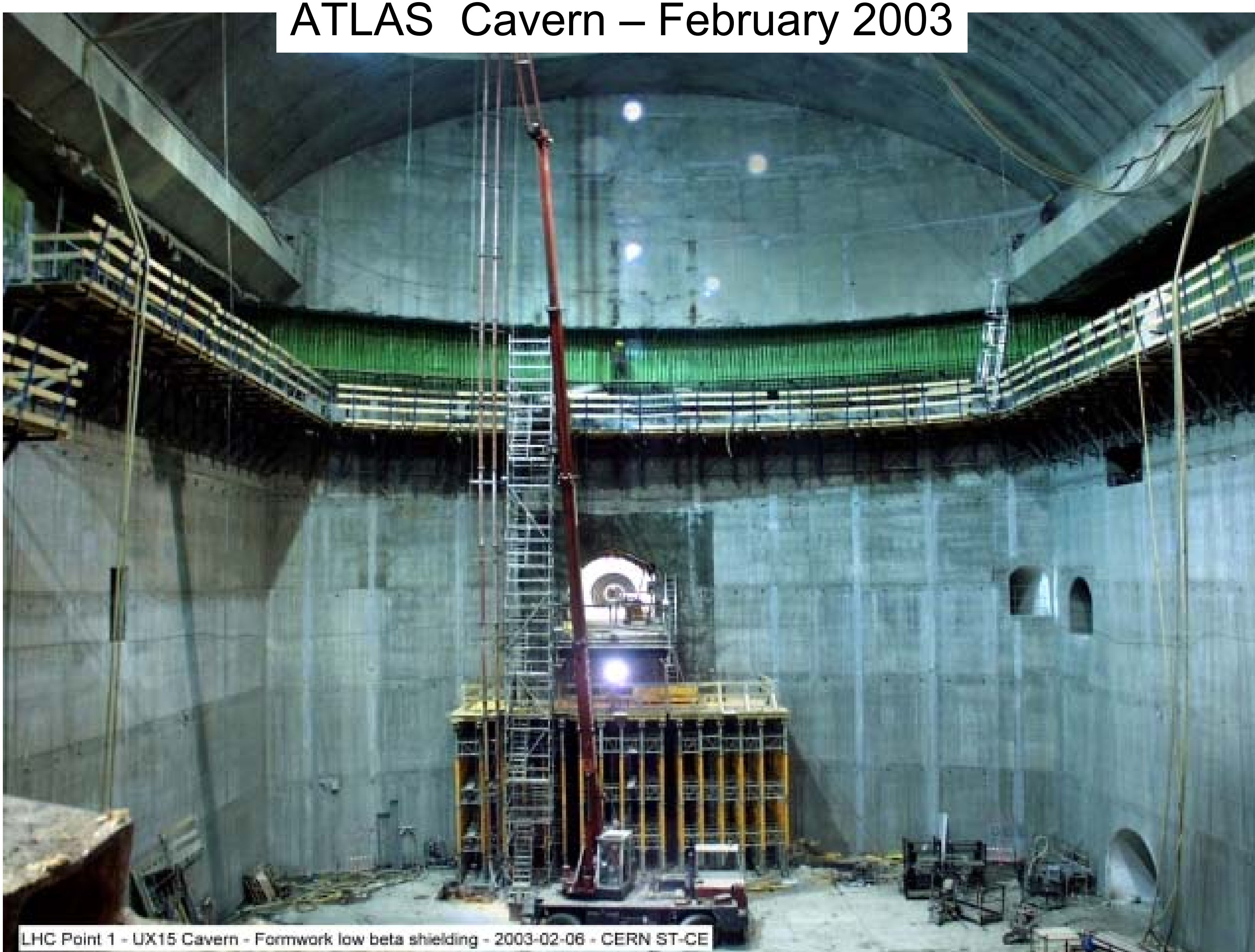

Tracking chamber
Electromagnetic calorimeter
Hadron calorimeter
Muon detector


Length = 55 m
Width = 32 m
Height = 35 m


Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker

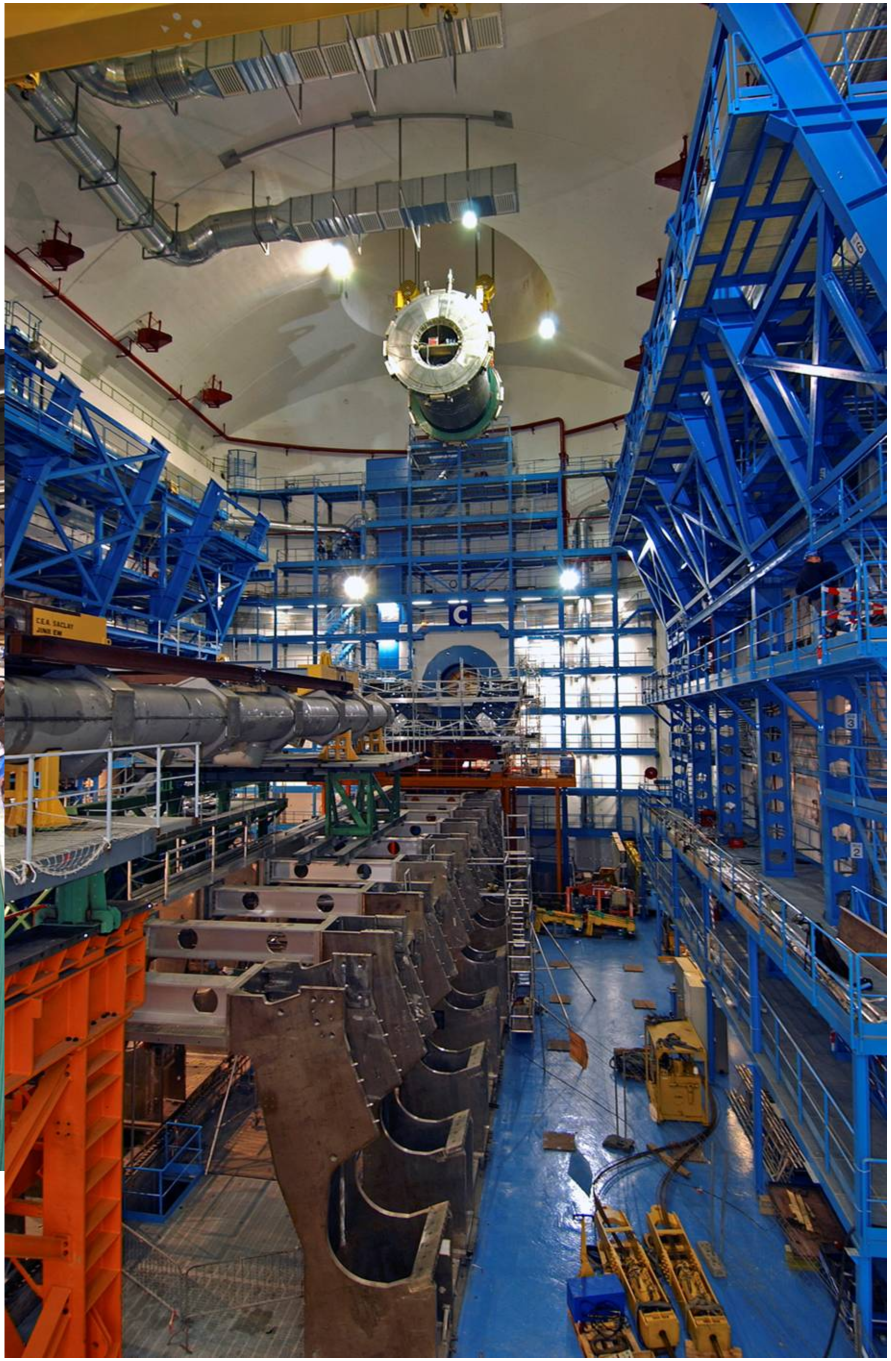

Muon
Spectrometer
Muon
Neutrino
Hadronic
Calorimeter
Proton
Neutron
The dashed tracks
are invisible to
the detector
Electromagnetic
Calorimeter
Electron
Photon
Solenoid magnet
Transition
Radiation
Tracker
Tracking
Pixel/SCT
detector
ATLAS
EXPERIMENT
http://atlas.ch

ATLAS Cavern – February 2003

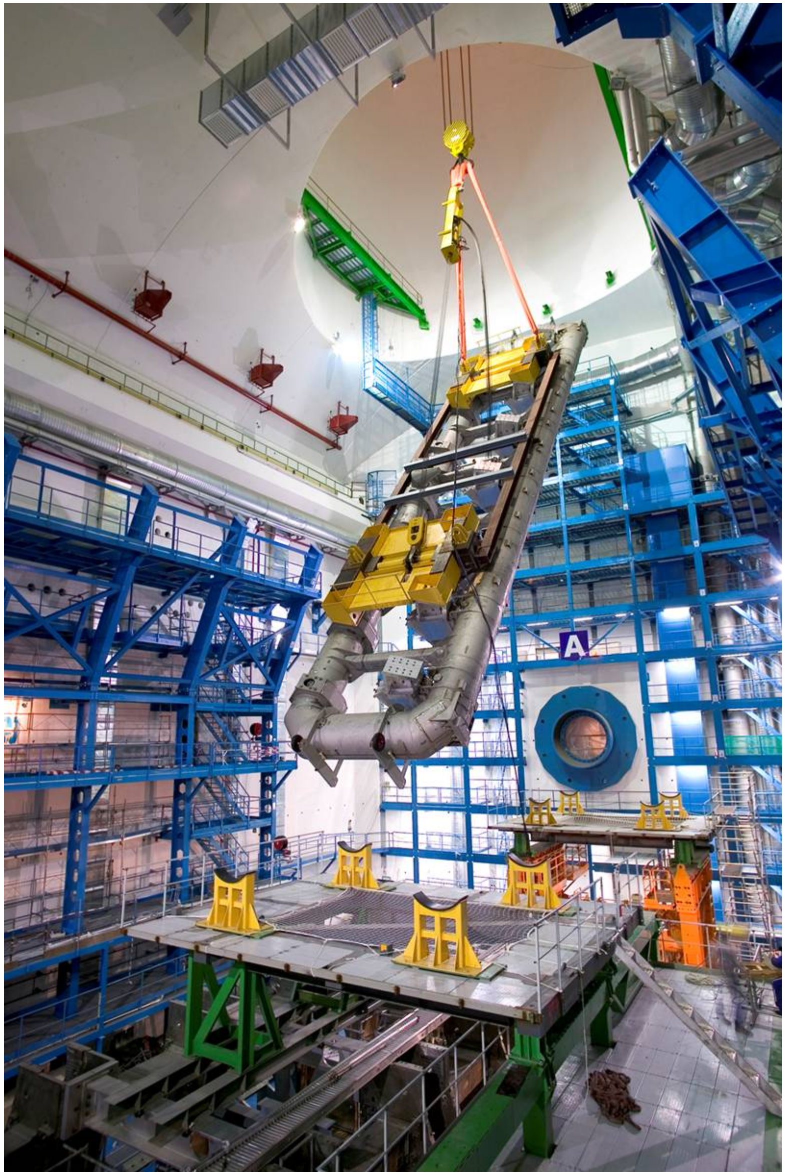


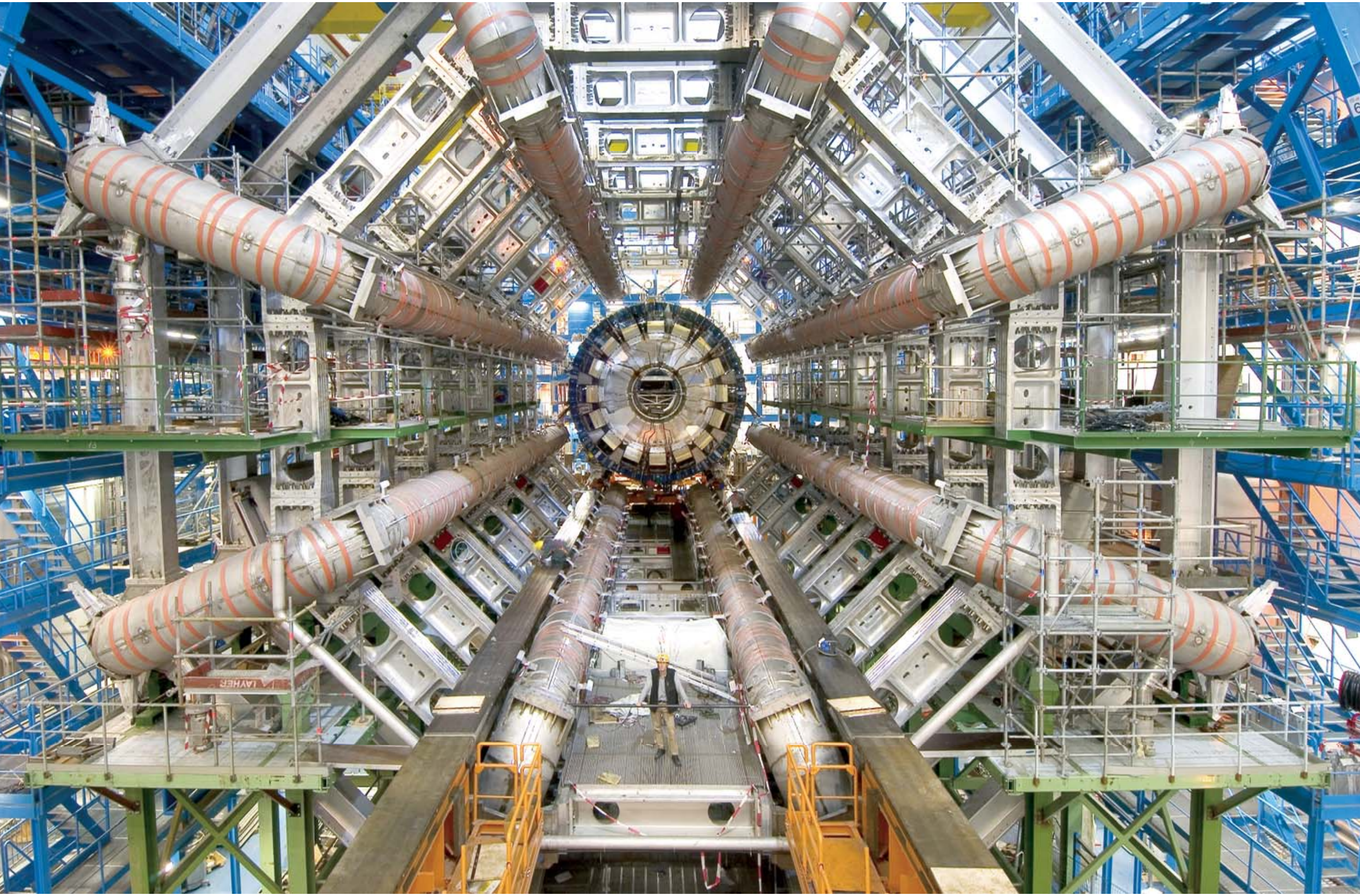
ATLAS Cavern – November 2004

Installation of the Barrel Cryostat on 28th October 2004 in the pit onto the lower part of the Barrel Tile Calorimeter

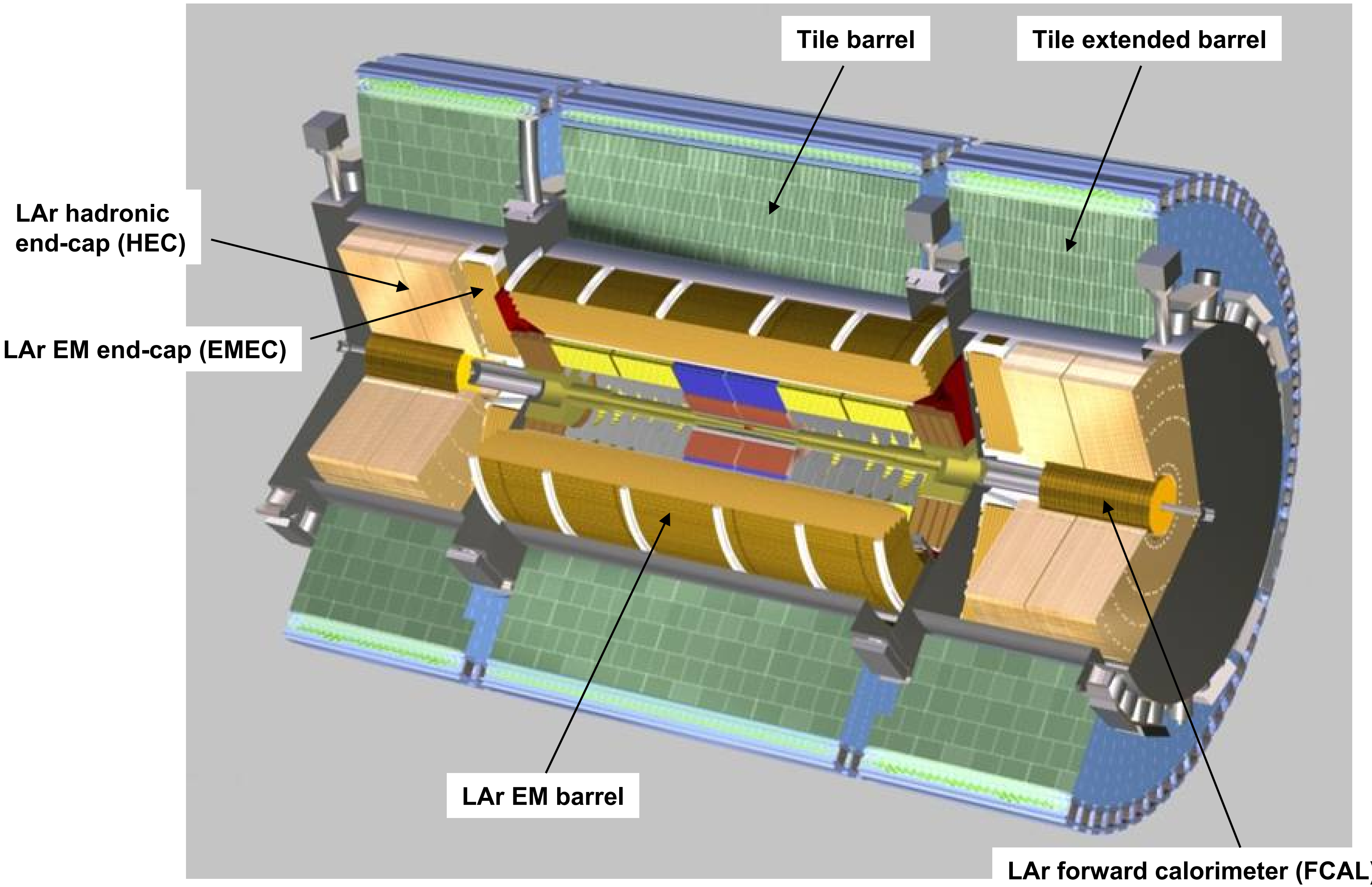


BT-1 installation in the cavern

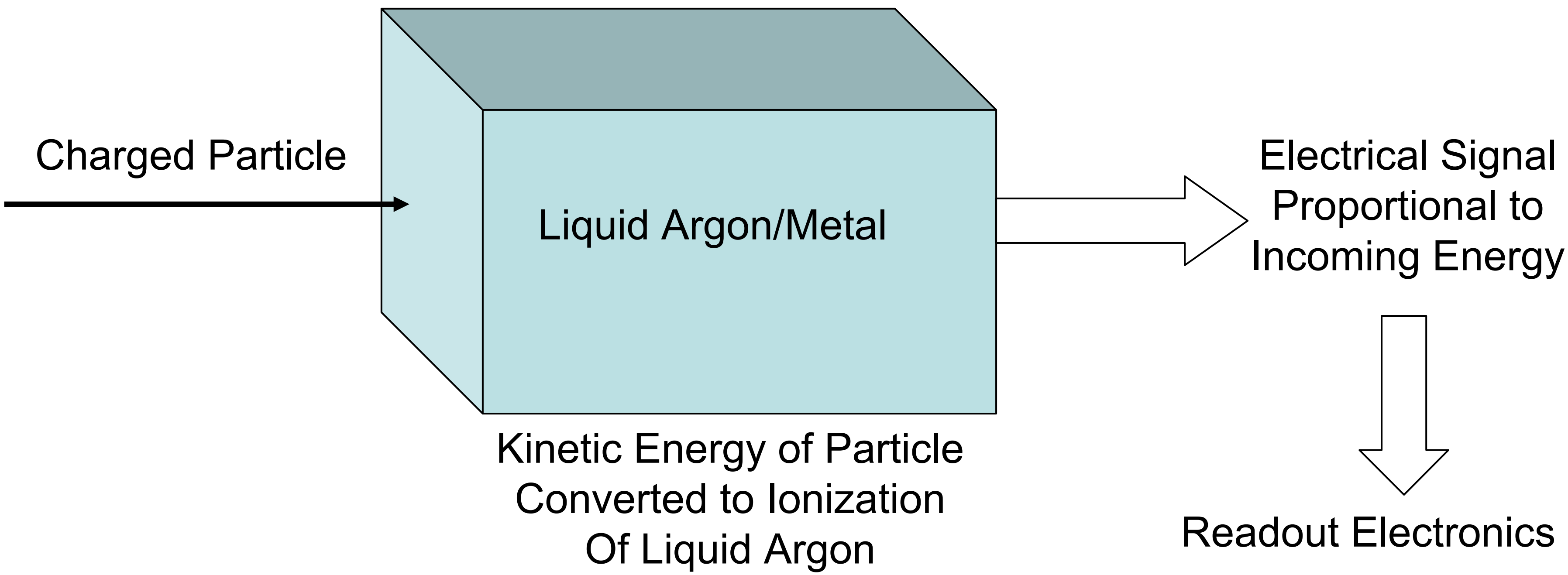




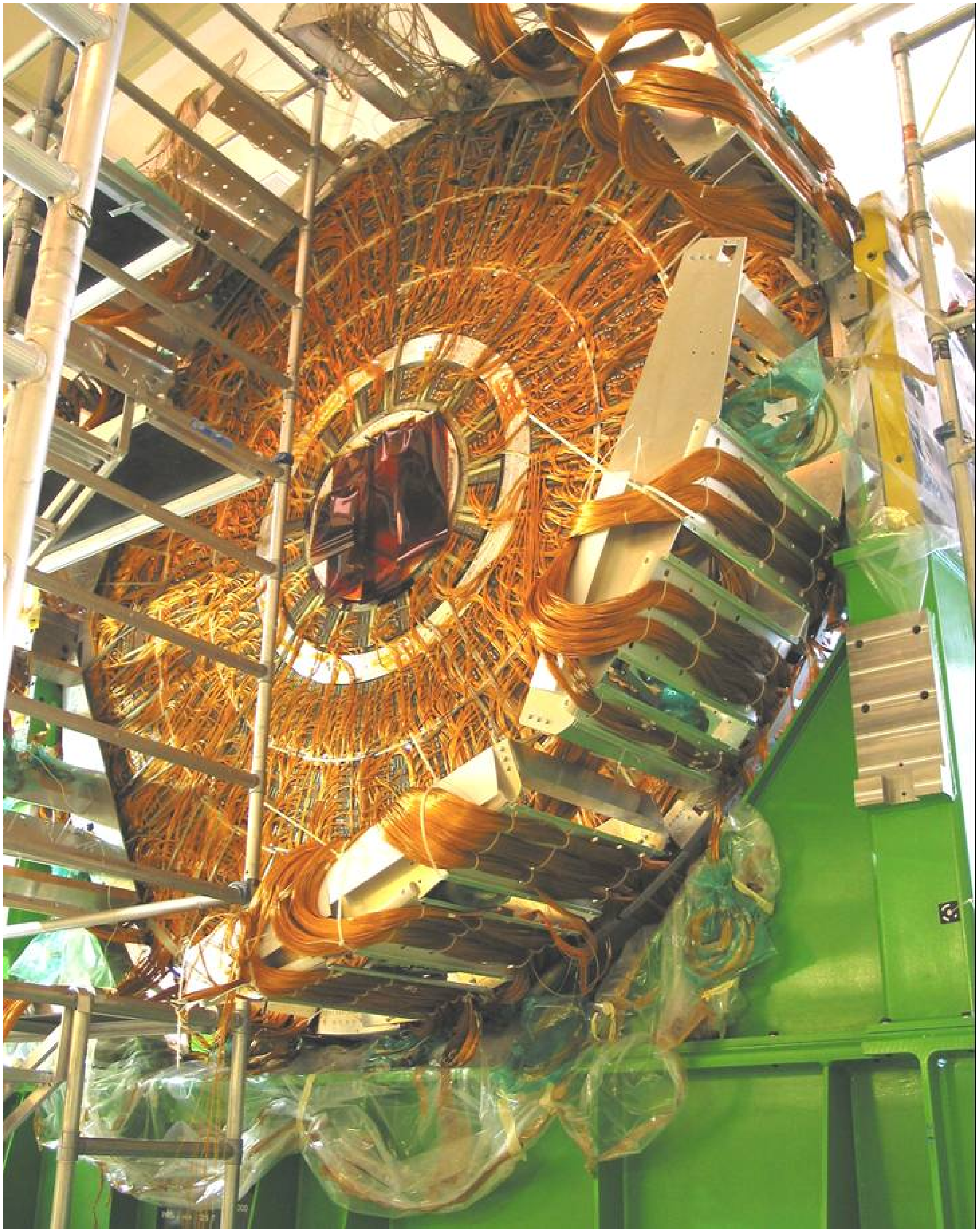
LAr and Tile Calorimeters

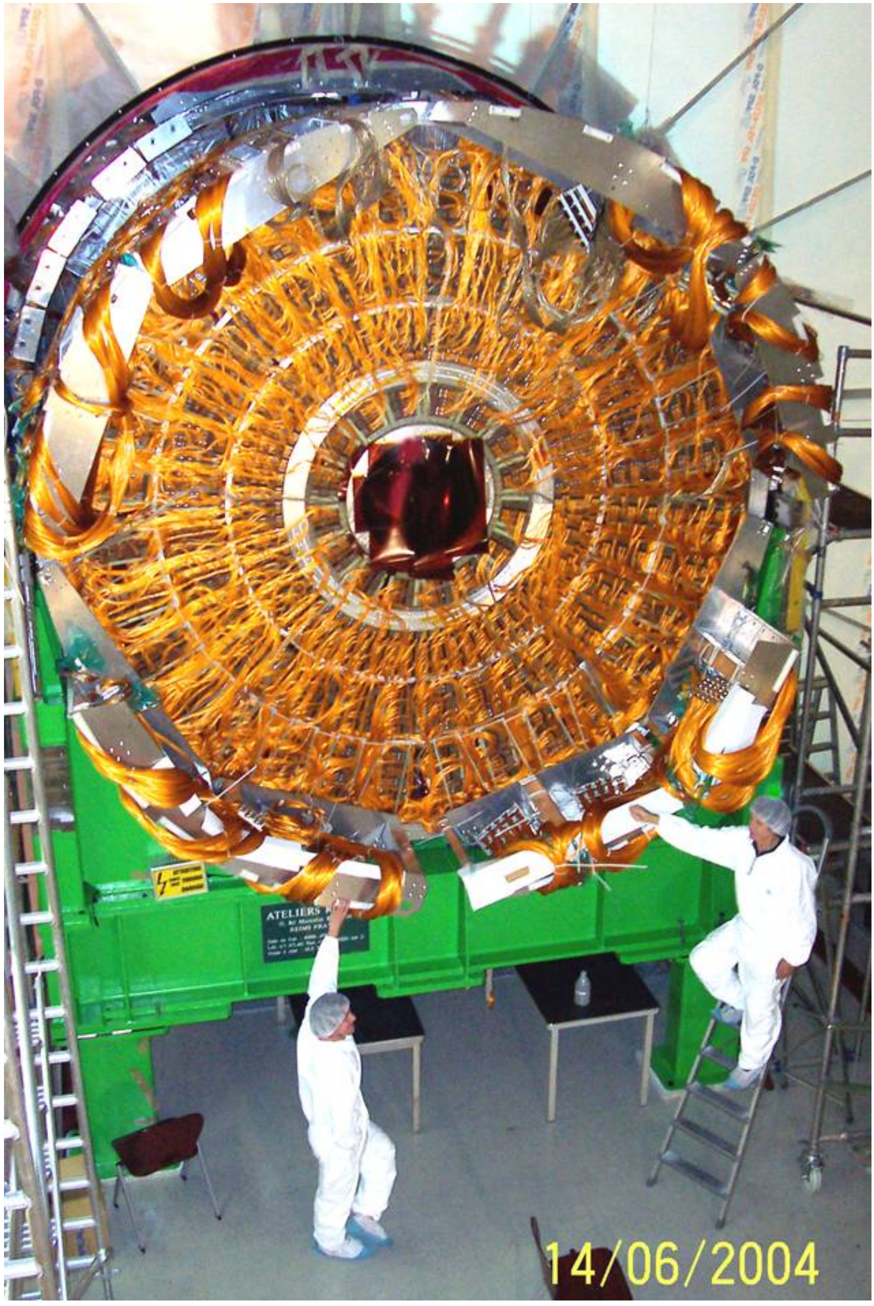


Why Is It Called a Calorimeter?

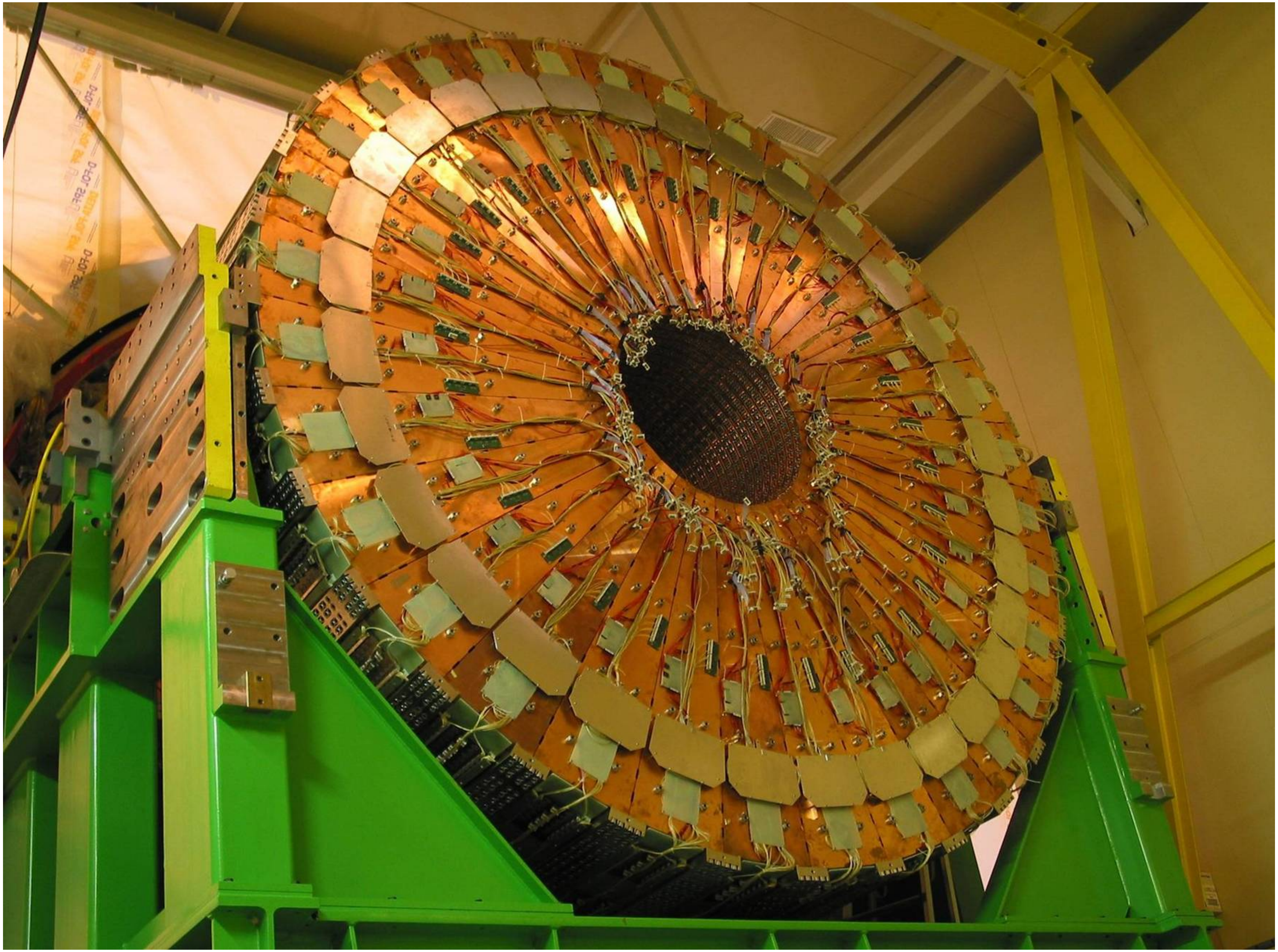


EM EndCap A wheel on the insertion stand, May - June 2004





HEC 2 A-wheel on the insertion stand, Aug. 2004

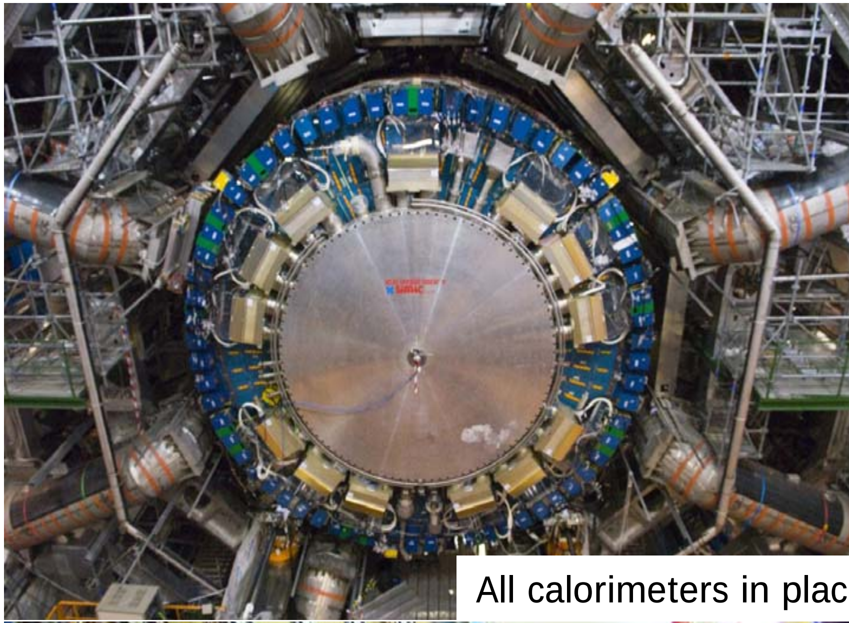


LAr Forward Calorimeters

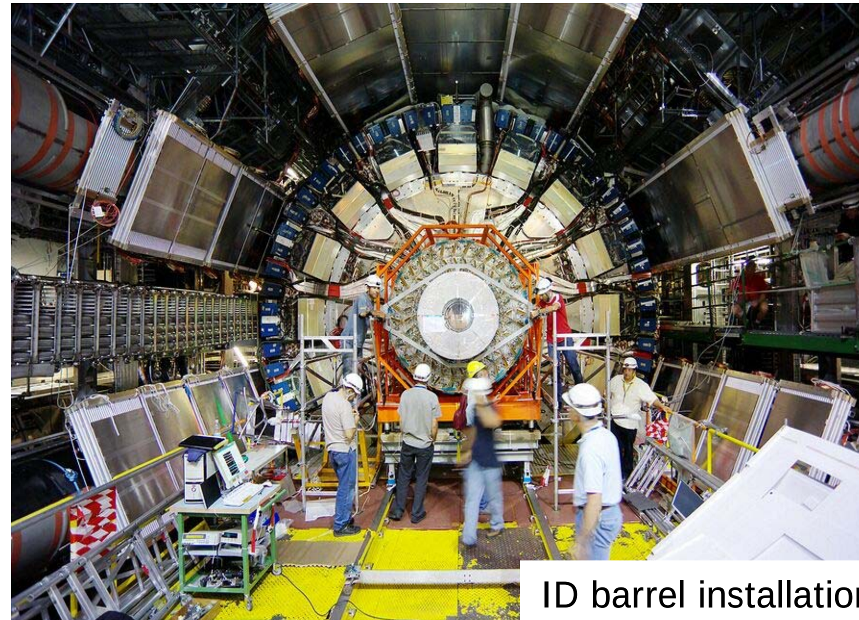
• FCAL C assembly into tube – Fall 2003

HEC – FCAL Assembly

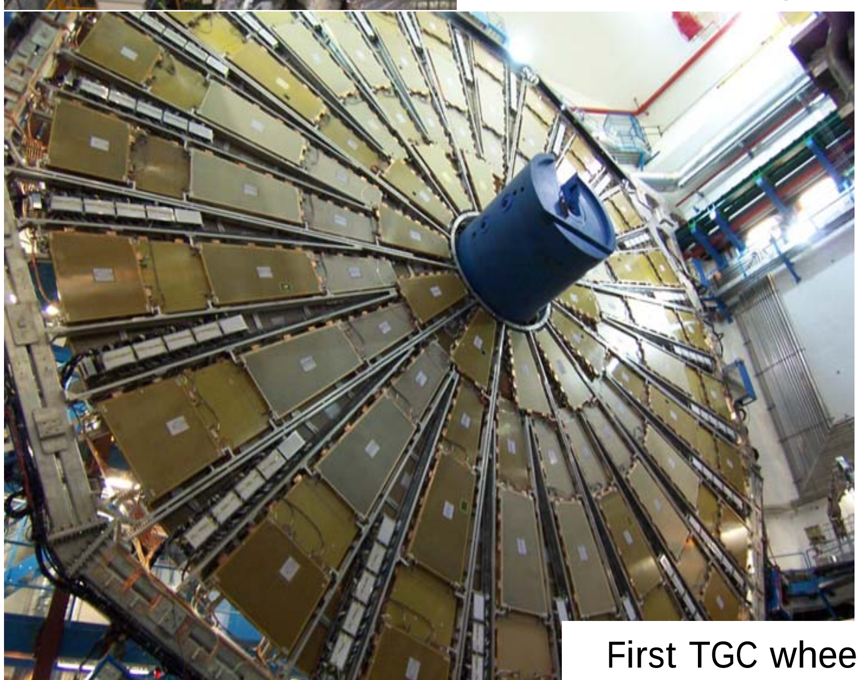
ATLAS Detector construction in UX15



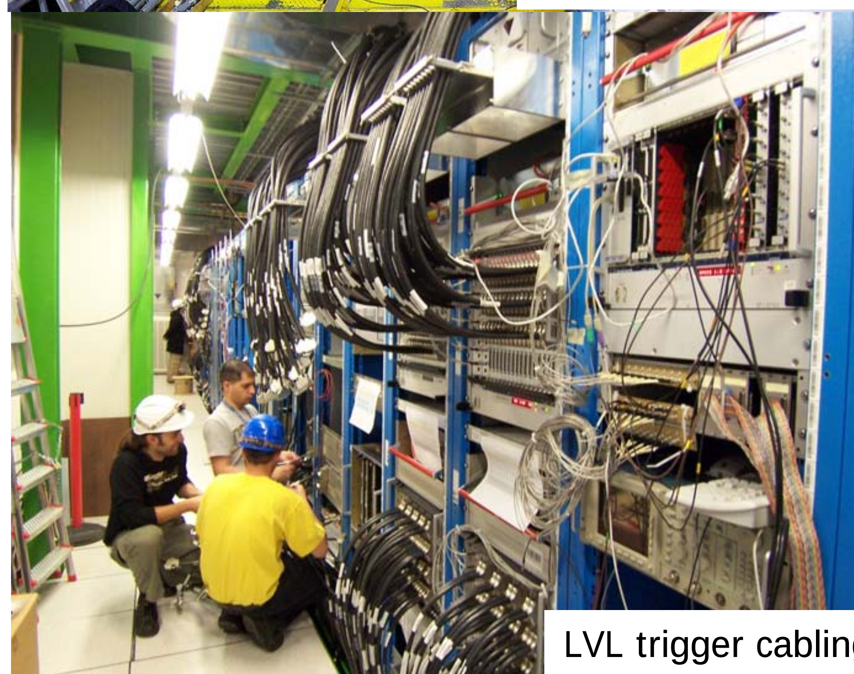
All calorimeters in place



ID barrel installation

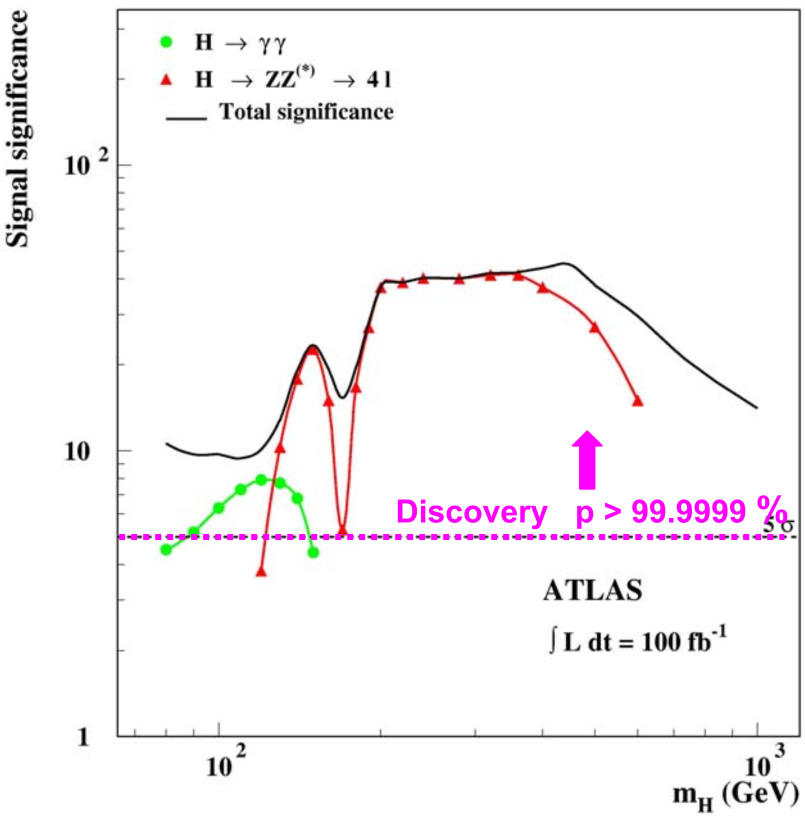


First TGC wheel



LVL trigger cabling

If the Standard Model Higgs particle exists,
it will be discovered at the LHC



The full allowed mass range from the LEP limit

(~114 GeV)

up to theoretical upper bound of

~1000 GeV

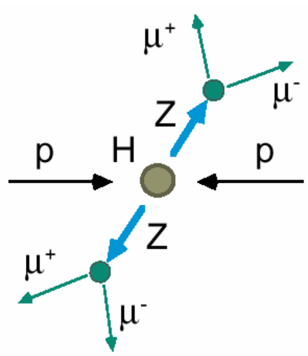
can be covered using the two “safe” channels

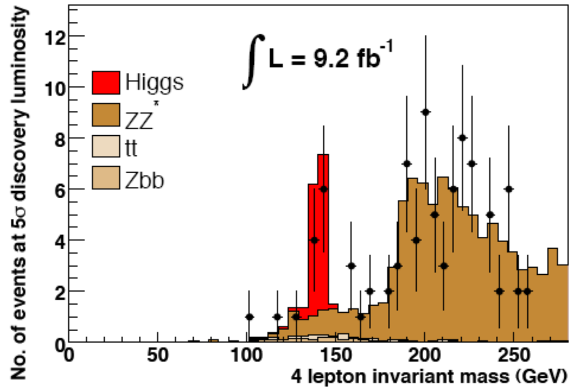
$H \rightarrow ZZ \rightarrow \ell\ell\ \ell\ell$

and

$H \rightarrow \gamma\gamma$

$H \rightarrow ZZ^{(*)} \rightarrow \ell\ell\ell\ell$





Background: Top production

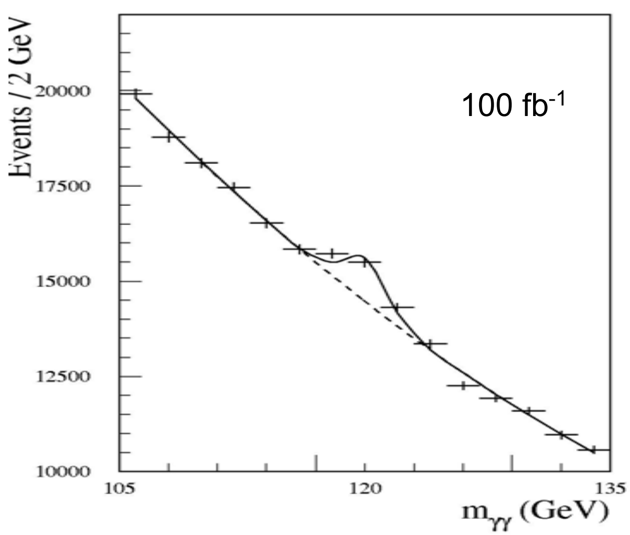
$tt \rightarrow Wb\ Wb \rightarrow \ell\nu\ \ell\nu\ \ell\nu\ \ell\nu$

Associated production Z bb

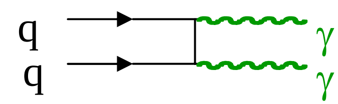
$Z\ bb \rightarrow \ell\ell\ell\ell$

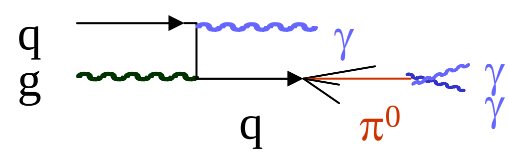
Discovery potential in mass range from ~130 to ~600 GeV/c^2

$H \rightarrow \gamma\gamma$



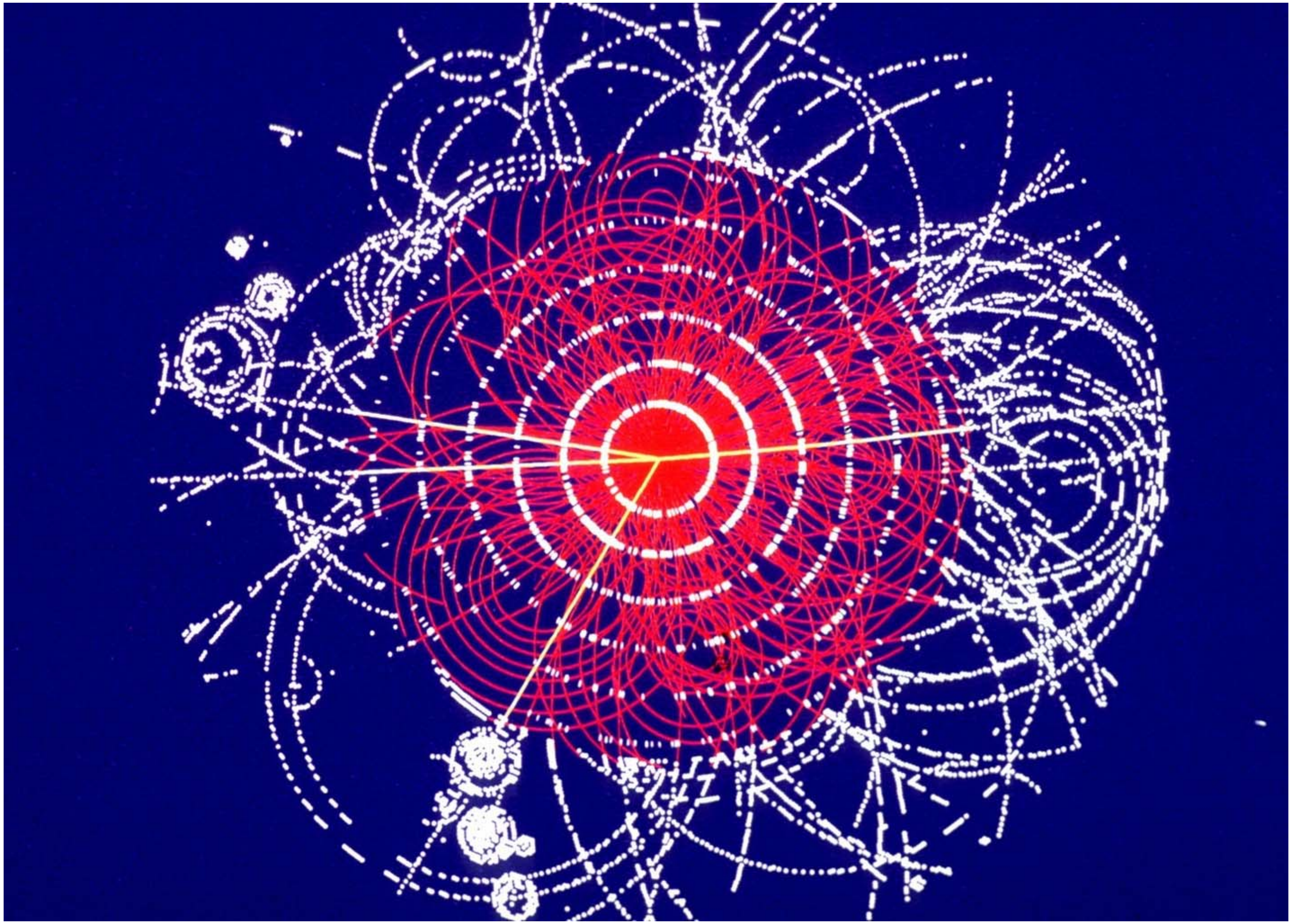
Background:



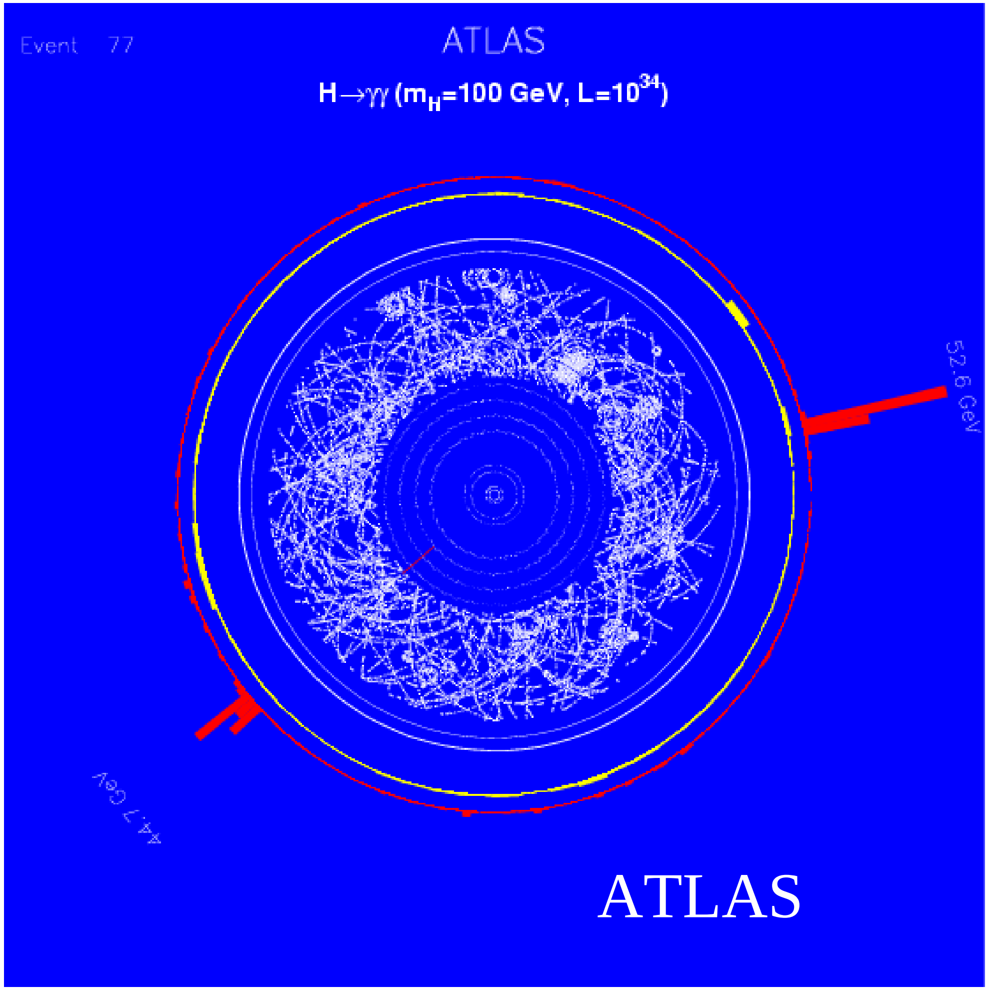


Excellent EM Calorimeter

Simulated H $\rightarrow$ ZZ $\rightarrow$ $\ell\ell\ell\ell$ event



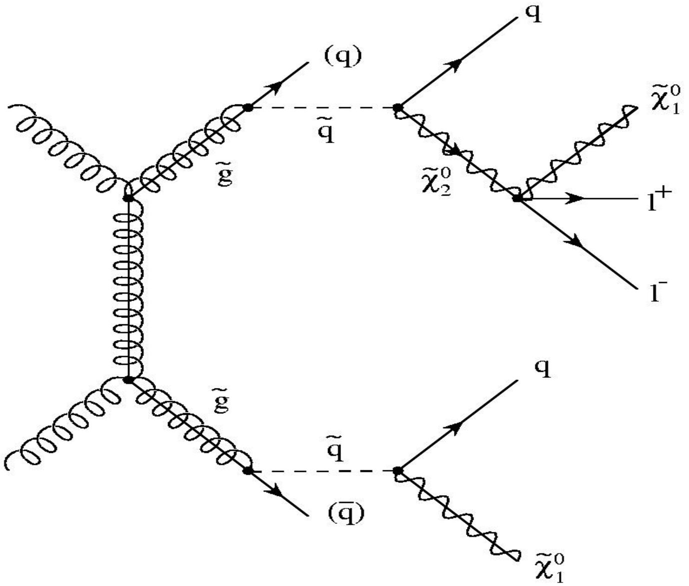
Simulated H → γγ event in ATLAS



Search for Supersymmetry at the LHC

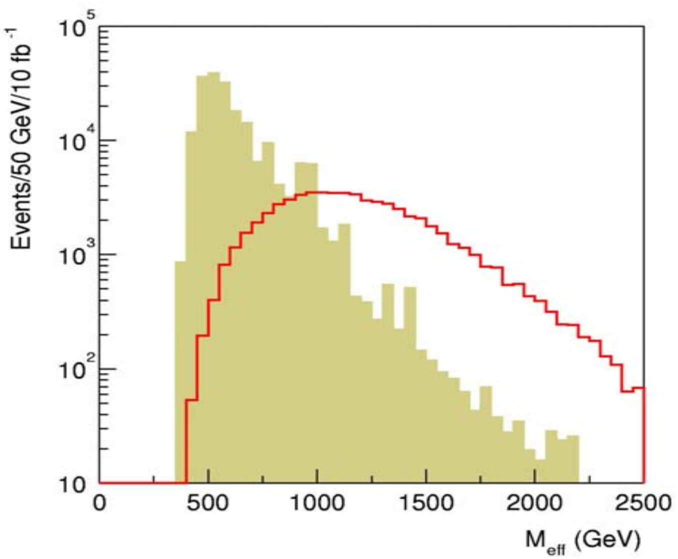
- If SUSY exists at the electroweak scale, a discovery at the LHC should be easy
- Squarks and Gluinos are strongly produced
- They decay through cascades to the lightest SUSY particle (LSP)

  - Look for deviations from the Standard Model
    Example: Multijet + ETmiss signature



$\Rightarrow$ combination of
Jets, Leptons, E_T^{miss}

$$M_{eff} = E_T^{miss} + P_T^1 + P_T^2 + P_T^3 + P_T^4$$



LHC reach for Squark- and Gluino masses:

1 fb^{-1}	$\Rightarrow$	M ~ 1500 GeV
10 fb^{-1}	$\Rightarrow$	M ~ 1900 GeV
100 fb^{-1}	$\Rightarrow$	M ~ 2500 GeV

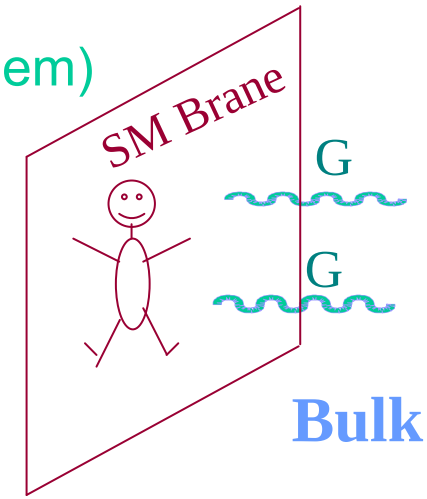
TeV-scale SUSY can be found quickly


Theorists have thought of large number of possible phenomena beyond the Standard Model

Can LHC Probe Extra Dimensions ?

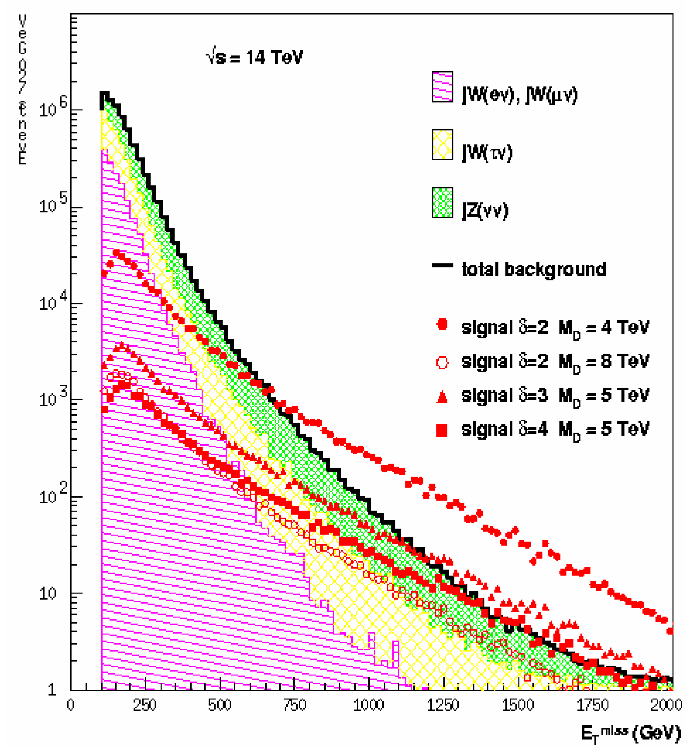
- Models with extra dimensions
- Explain the weakness of gravity (or hierarchy problem) by extra dimensions
- New physics can appear at the TeV-mass scale,

  Example: Search for direct Graviton production



$$g\,g \rightarrow g\,G\ ,\ q\,g \rightarrow q\,G\ ,\ q\,\overline{q} \rightarrow G\,g$$

$$q\,\overline{q} \rightarrow G\,\gamma$$



$\Rightarrow$ Jets or Photons with E_T^{miss}

$$G_N^{-1} = 8\pi R^{\delta} M_D^{\,2+\delta}$$

δ : # extra dimensions

M_D = scale of gravitation

R = radius (extension)

The Large Hadron Collider

- The most difficult and ambitious high-energy physics project ever attempted.
- It has a crucial role in physics
- It can say the final word about
    - SM Higgs mechanism
    - Low-energy SUSY and other TeV-scale predictions
- It will most almost certainly change our understanding of Nature

REMOVED ON FIRST PASS

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

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

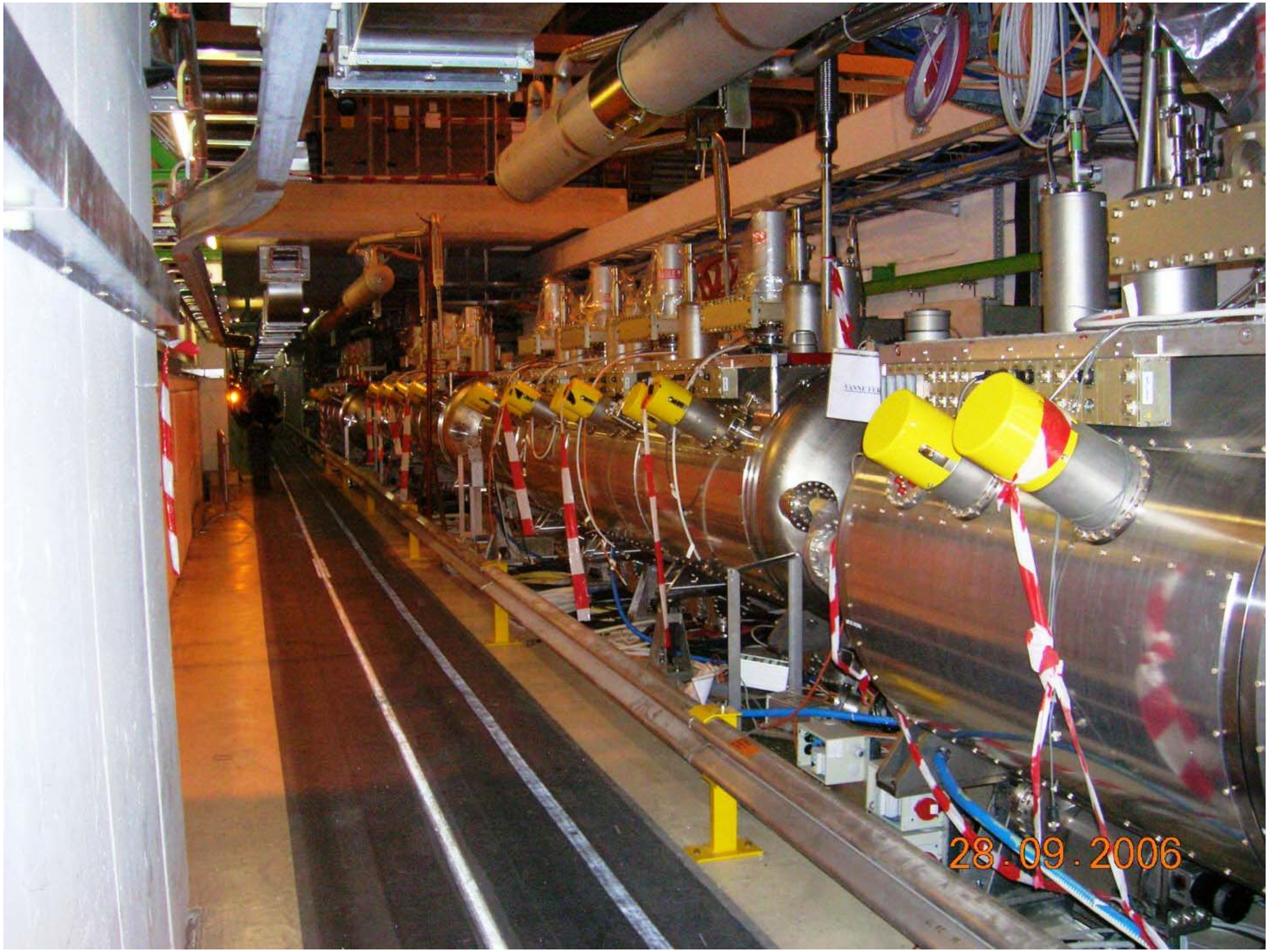
- $\Omega_0 > 1$ spherical space-time: contraction
- $\Omega_0 = 1$ flat space-time: expansion
- $\Omega_0 < 1$ hyperbolic space-time: expansion

March 2006

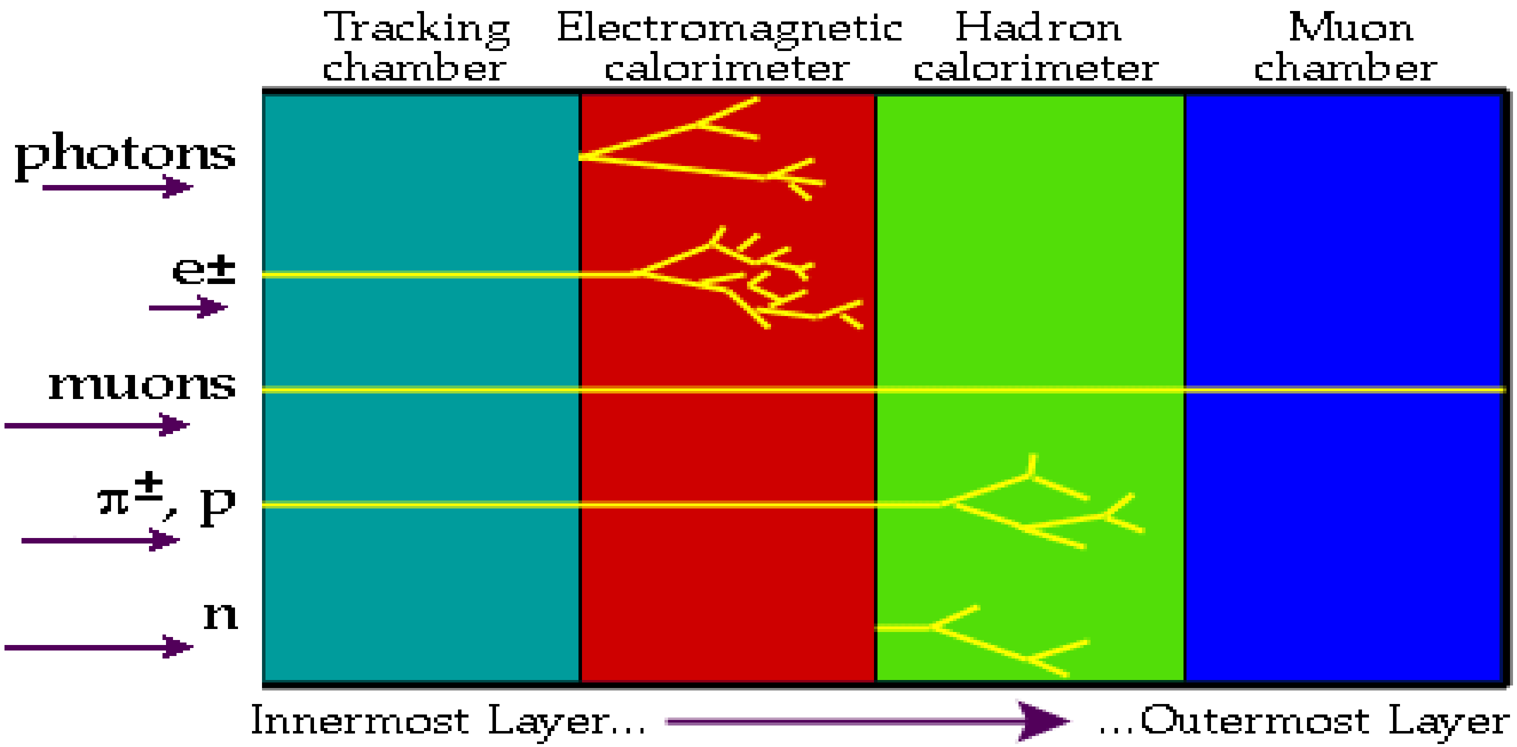
Cryogenic Magnet Test Station

LHC Tunnel

RF Modules

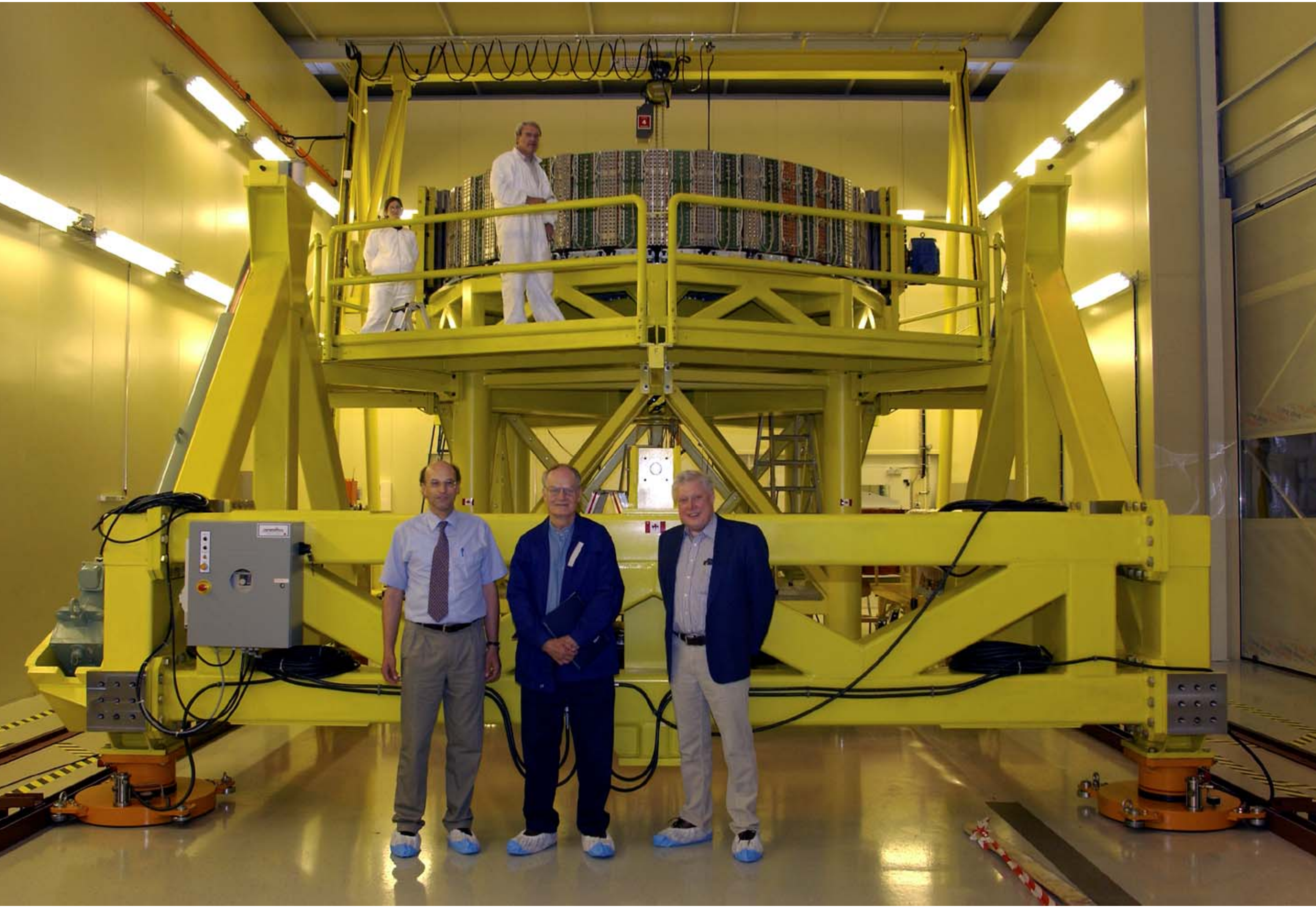


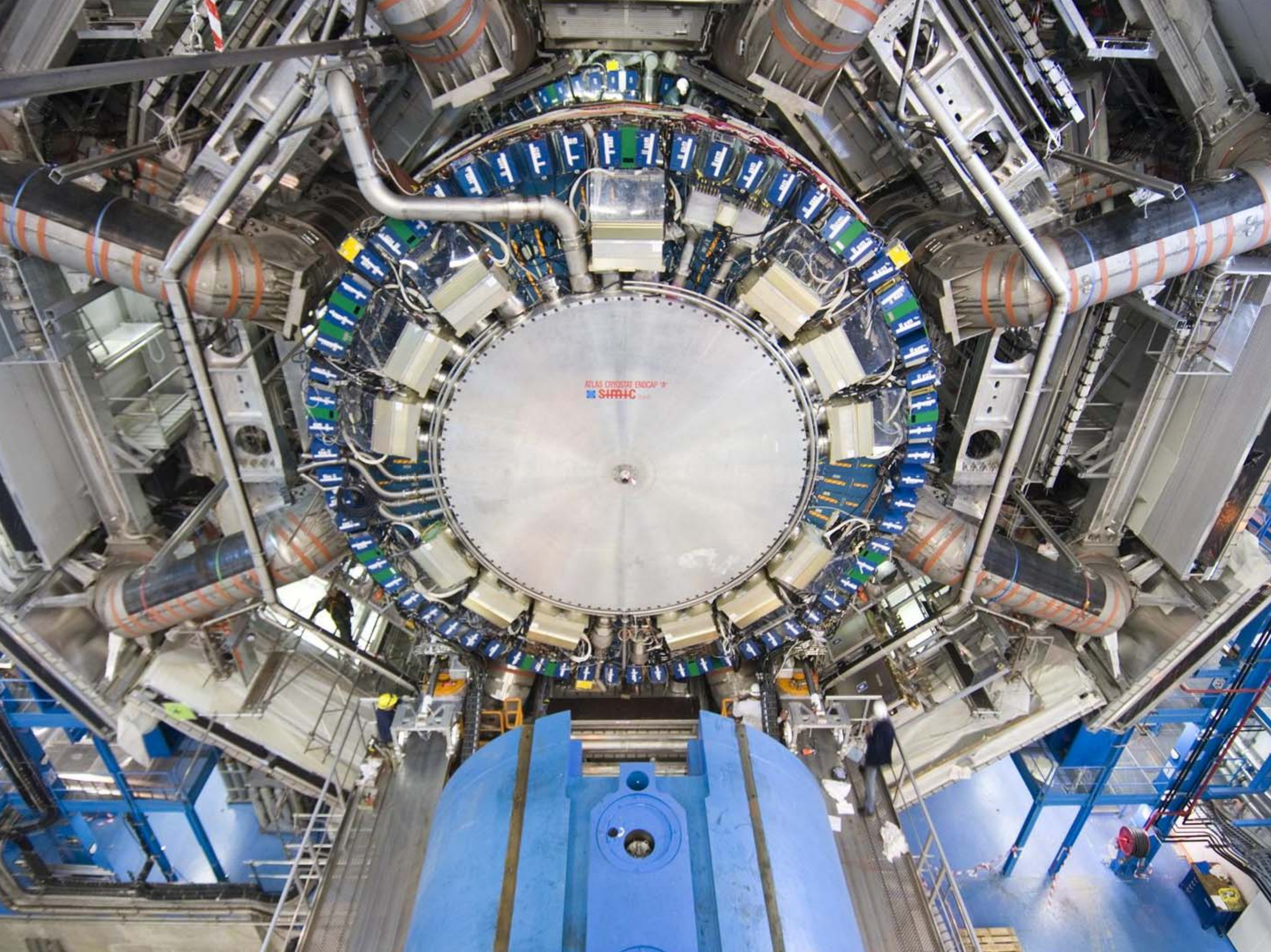
Particle Detection



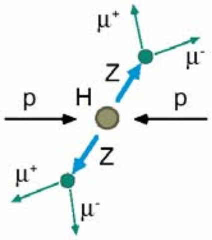
- Different particles detected by different techniques.

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





$H \rightarrow ZZ^{(*)} \rightarrow \ell\ell\ell\ell$



Signal: σ BR = 5.7 fb (m_H = 100 GeV)

Background: Top production

$tt \rightarrow Wb\ Wb \rightarrow \ell\nu\ c\ell\nu\ \ell\nu\ c\ell\nu$

σ BR ≈ 1300 fb

Associated production Z bb

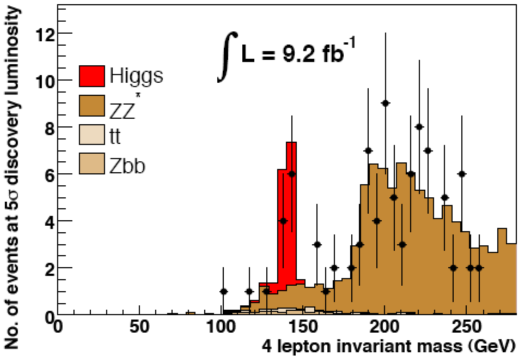
$Z\ bb \rightarrow \ell\ell\ c\ell\nu\ c\ell\nu$

Background rejection: Leptons from b-quark decays

→ non isolated

→ do not originate from primary vertex

(B-meson lifetime: ~ 1.5 ps)



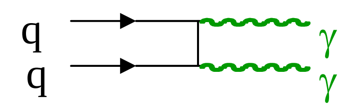
Dominant background after isolation cuts: ZZ continuum

Discovery potential in mass range from ~130 to ~600 GeV/c²

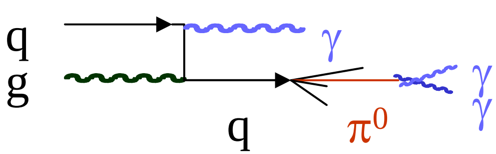
$H \rightarrow \gamma\gamma$

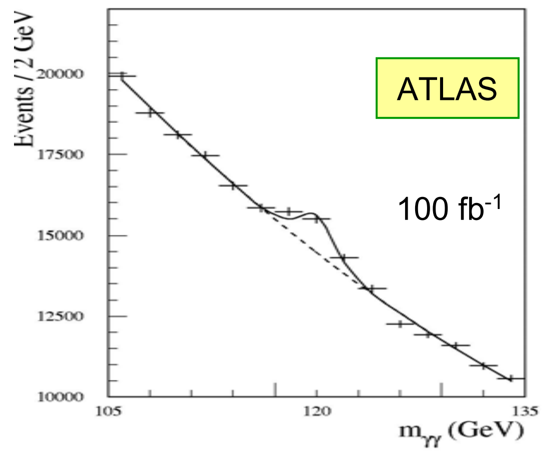
Main backgrounds:

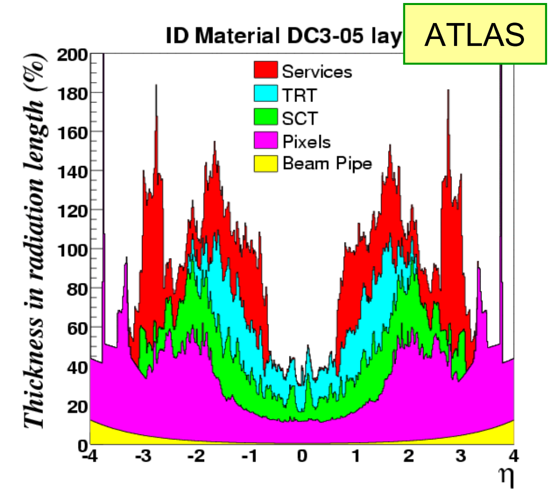
$\gamma\gamma$ irreducible background



γ-jet and jet-jet (reducible)



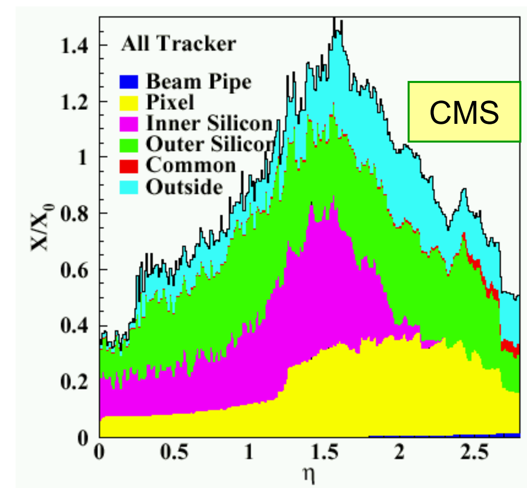




$\sigma_{\gamma j+jj} \sim 10^6 \, \sigma_{\gamma\gamma}$ with large uncertainties

$\rightarrow$ need $R_j > 10^3$ for $\varepsilon_\gamma \approx 80\%$ to get $\sigma_{\gamma j+jj} \ll \sigma_{\gamma\gamma}$

- Main exp. tools for background suppression:
  - photon identification
  - γ / jet separation (calorimeter + tracker)
  - note: also converted photons need to be reconstructed (large material in LHC silicon trackers)



CMS: fraction of converted γs

Barrel region:	42.0 %
Endcap region:	59.5 %

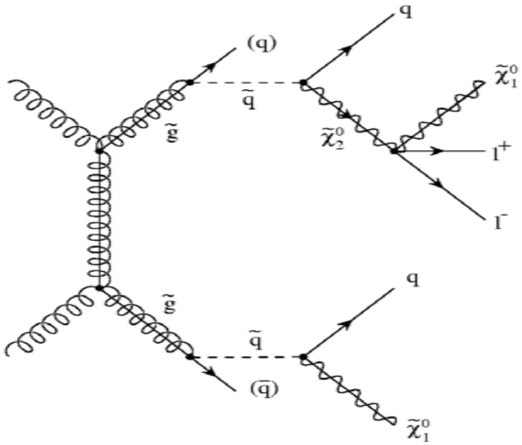
$\rightarrow$ most demanding channel for EM calorimeter performance : energy and angle resolution, acceptance, γ /jet and γ / π^0 separation

Search for Supersymmetry at the LHC

- If SUSY exists at the electroweak scale, a discovery at the LHC should be easy

- Squarks and Gluinos are strongly produced

  They decay through cascades to the lightest SUSY particle (LSP)



$\Rightarrow$ combination of
Jets, Leptons, E_T^{miss}

1. Step: Look for deviations from the Standard Model
   Example: Multijet + E_T^{miss} signature

2. Step: Establish the SUSY mass scale use inclusive variables, e.g. effective mass distribution

3. Step: Determine model parameters (difficult)
   Strategy: select particular decay chains and use kinematics to determine mass combinations

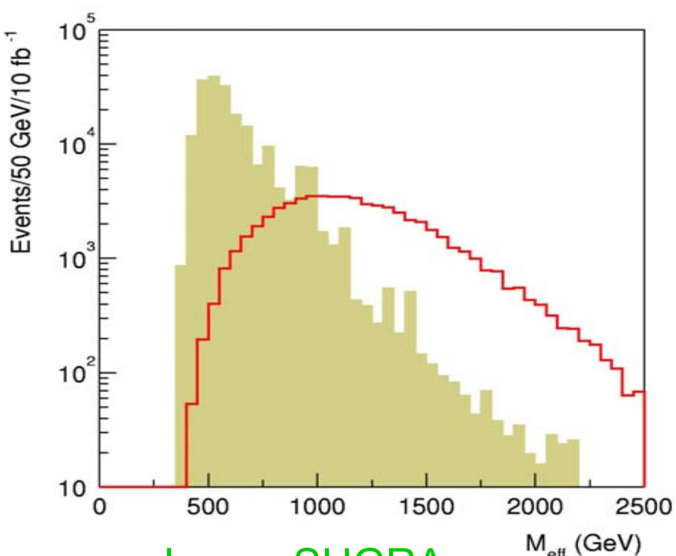
Squarks and Gluinos

- Strongly produced, cross sections comparable to QCD cross sections at the same mass scale

- If R-parity conserved, cascade decays produce distinctive events: multiple jets, leptons, and E_T^{miss}

- Typical selection: $N_{jet} > 4$, $E_T > 100, 50, 50, 50$ GeV, $E_T^{miss} > 100$ GeV

- Define: $M_{eff} = E_T^{miss} + P_T^1 + P_T^2 + P_T^3 + P_T^4$ (effective mass)



example: mSUGRA
m_0 = 100 GeV, $m_{1/2}$ = 300 GeV
tan β = 10, $A_0 = 0$, $\mu > 0$

LHC reach for Squark- and Gluino masses:

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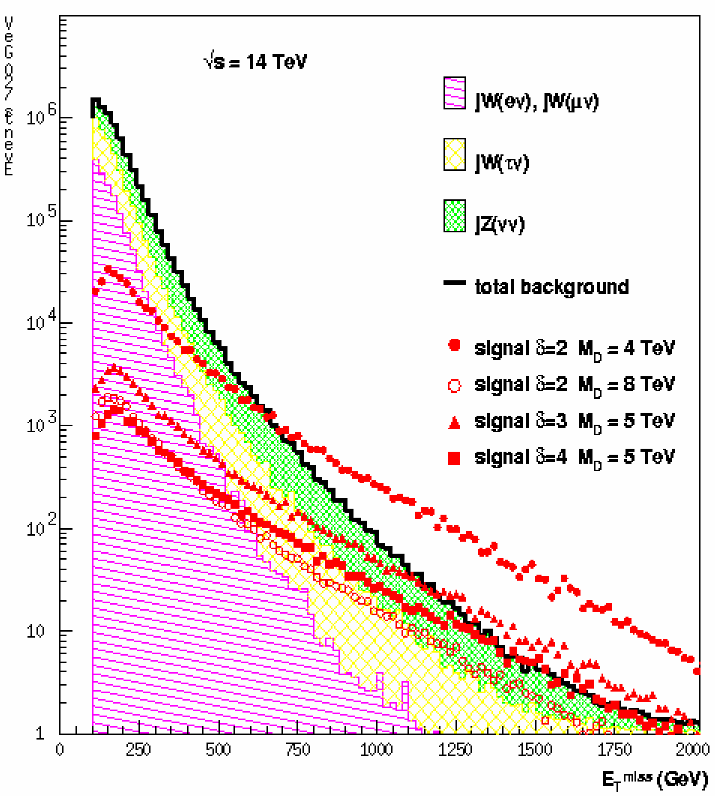
100 fb^{-1}	$\Rightarrow$	M ~ 2500 GeV

TeV-scale SUSY can be found quickly !

Search for escaping gravitons:

Jet + E_T^{miss} search:



$$G_N^{-1} = 8\pi R^\delta M_D^{2+\delta}$$

δ : # extra dimensions
M_D = scale of gravitation
R = radius (extension)

M_D^{max}	=	9.1,	7.0,	6.0 TeV
	for			
δ	=	2,	3,	4

<u>**Main backgrounds:**</u>
jet+Z(→νν), jet+W→jet+(e,μ,τ)ν

„LHC experiments are also sensitive to this field of physics“ → robust detectors