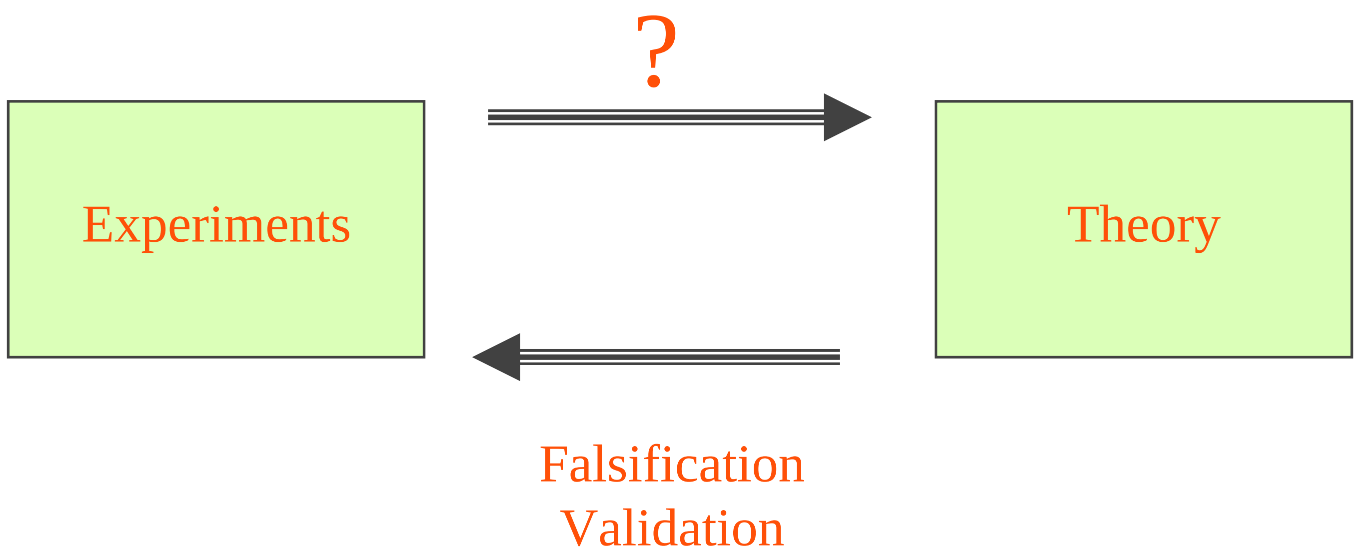
How a particle experiment is designed

How physicists go from the "basic ideas of measuring some quantities" to the "design and constructions of large scale experiments".



Theory and experiments

- Exp: Particles have masses: …..why ?
- Theo: Mass is given by the interaction with the Higgs field
- Exp: Find the Higgs Boson

- Exp: There are 3 Forces: ……why ?
- Theo: Super Symmetry unifies the Forces
- Exp: Find the signals of Super Symmetry

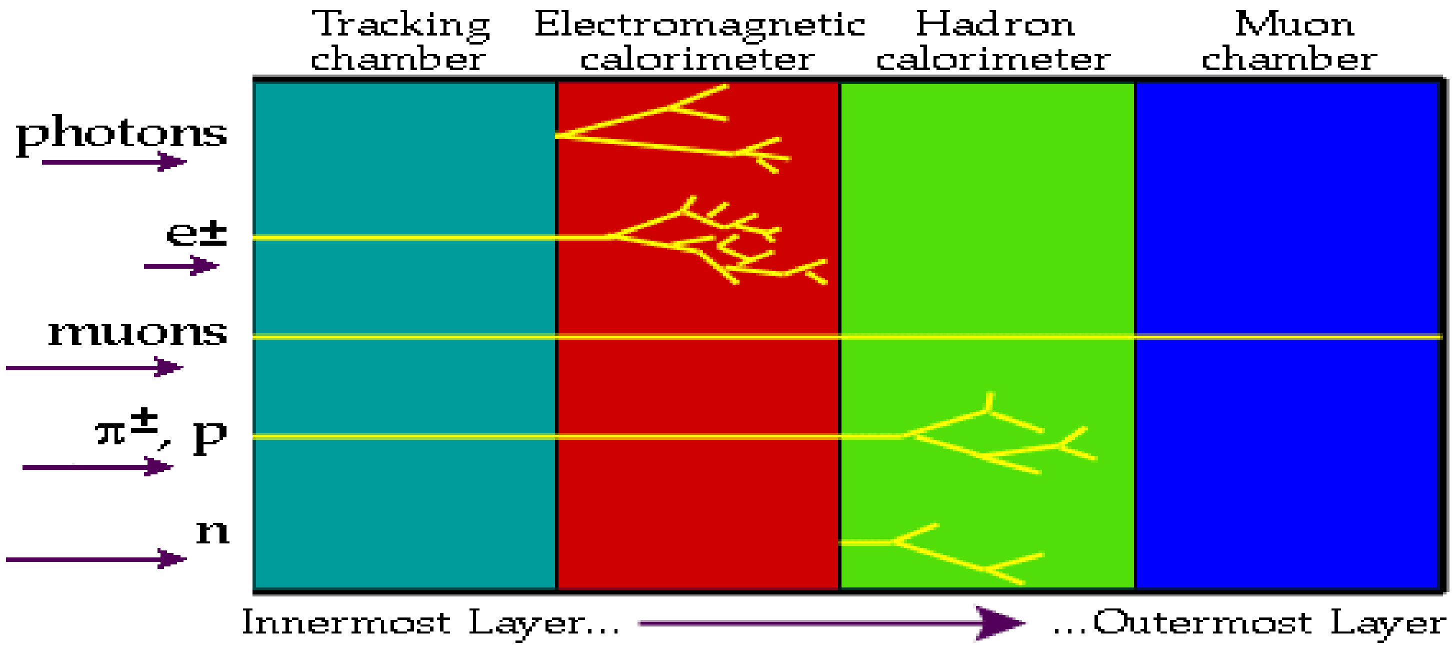
Two classes of experiments

- “Small” and beautiful : experiments designed to measure typically “one quantity” exploring the “very rare” or “very precise” : they need high intensity beams and/or very high precision

- LARGE and exciting: experiments that explore the high energy frontier. They are typically multi-purpose experiments. They also need high intensity beams

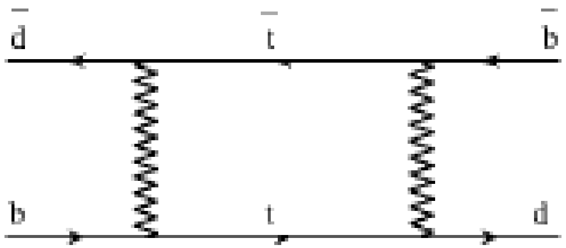
General Principle for particle detection

Visible particles are measured by the various subdetectors and identified from their characteristic pattern .



Quest for precision

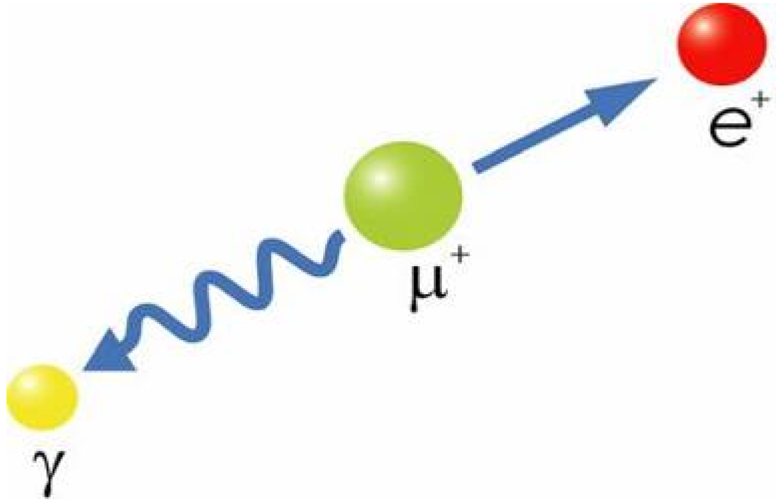
Non decupling : heavy particles contribute to "low" energy phenomena through "loops"



Measuring some quantities with high precision and comparing the result with the prediction of theory one may falsify/validate the theory

MEG EXPERIMENT

http://meg.web.psi.ch/



Clear 2-body decay

- Back to Back
- $E_e = E_\gamma = 52.8$MeV

Backgrounds

- Accidental overlap of
  - e^+ from Michel decay : $\mu \rightarrow e \nu_e \nu_\mu$
  - γ from radiative decay,
    e^+-annihilation in flight
- Radiative μ^+ decay: $\mu \rightarrow e \nu_e \nu_\mu \gamma$

MEG: Physics Motivations

$\mu \rightarrow e\gamma$: Lepton Flavor Violating process

Forbidden in the SM

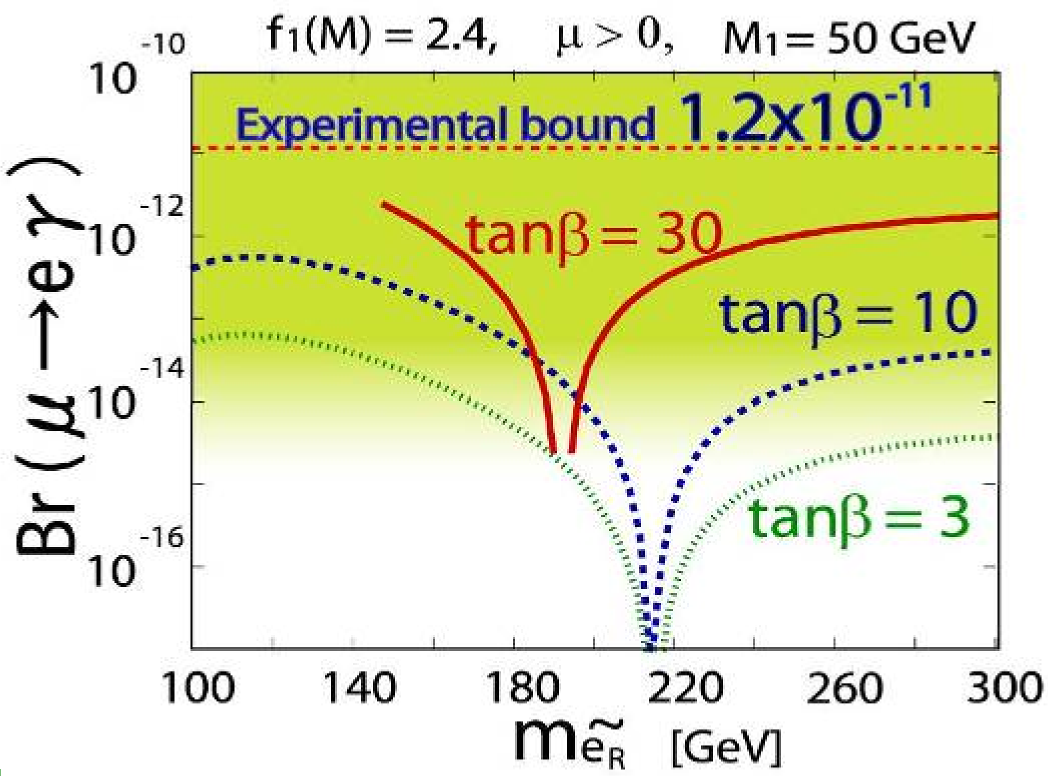
Sensitive to new physics

- ✓SUSY GUT
- ✓SUSY Seesaw

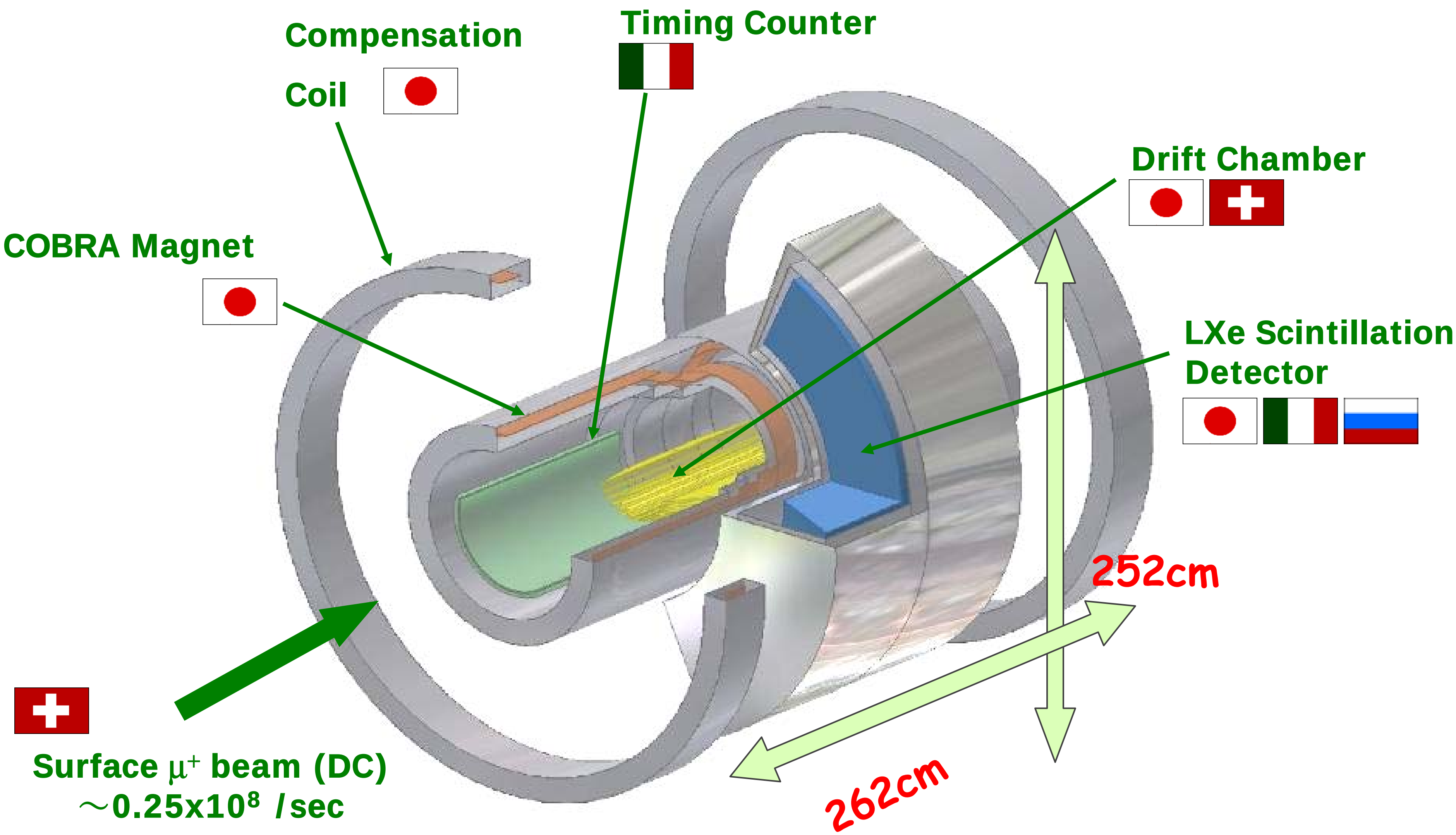
Sensitivity

- – down to $\sim 10^{-14}$
- – Present limit $< 1.2 \times 10^{-11}$ (MEGA)

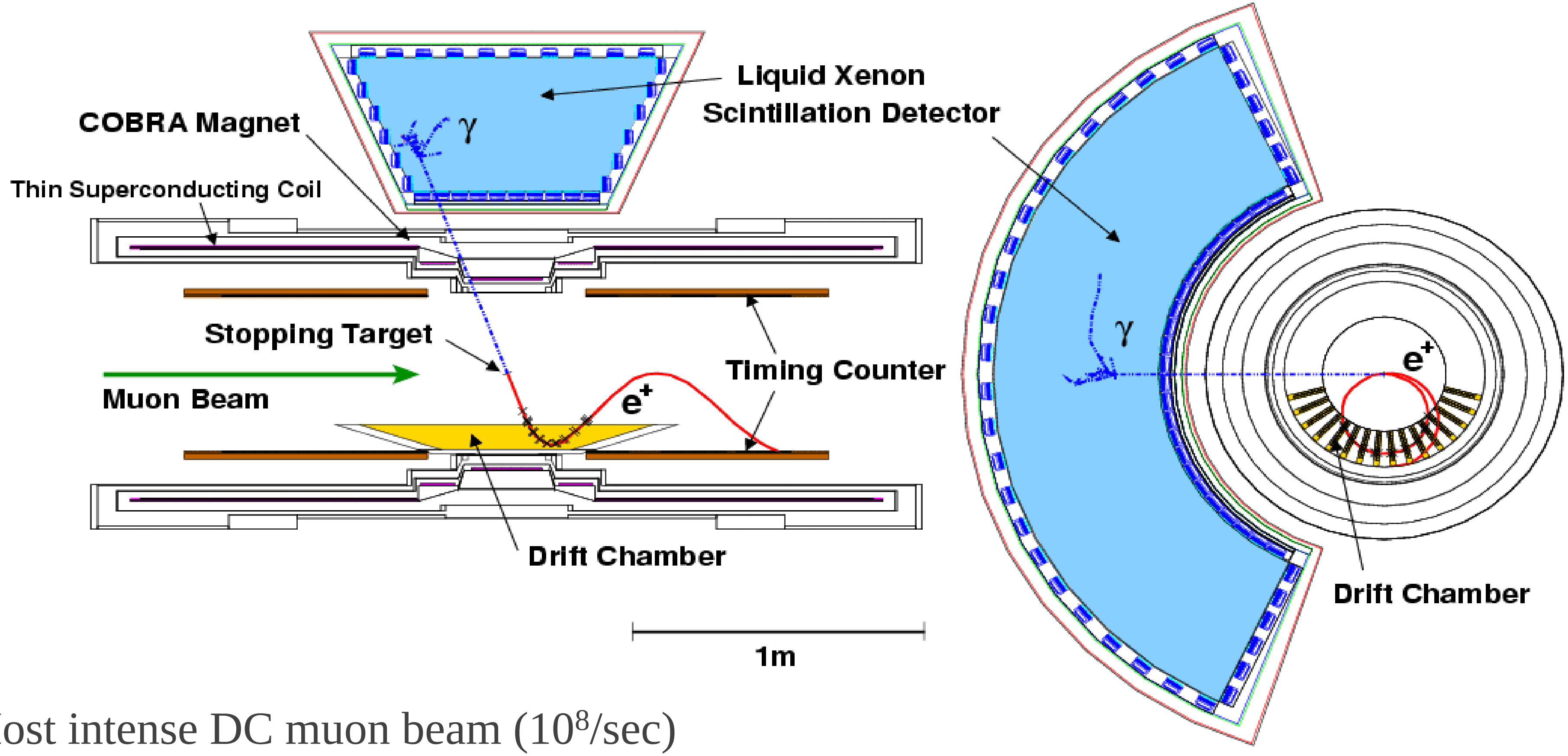
J.Hisano *et al.*,
Phys.Lett.**B391** (1997) 341



The MEG Detector



MEG : design of the experiment



Most intense DC muon beam (10^8/sec)

Gradient magnetic field e^+ spectrometer

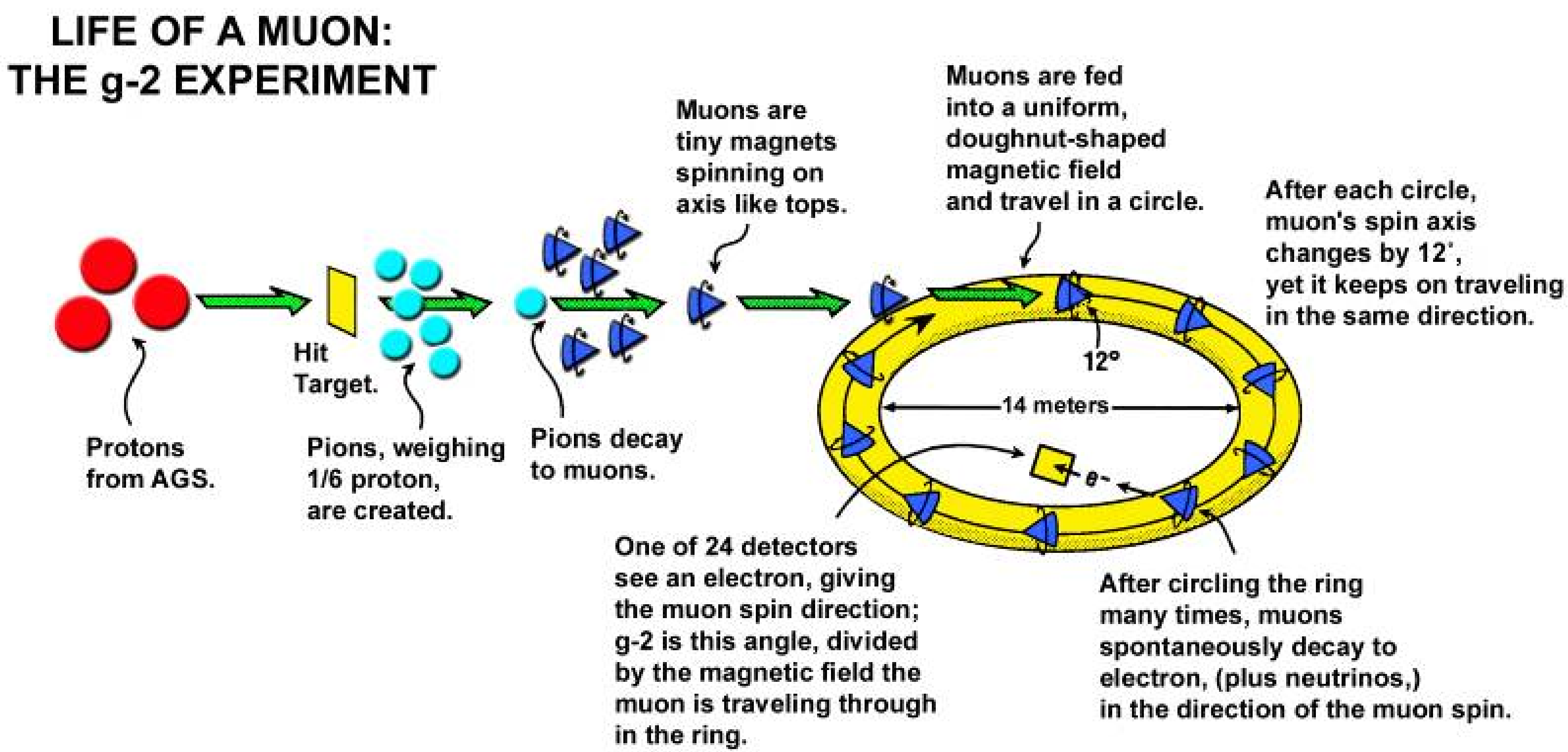
Liquid Xe scintillation γ-ray detector

The MEG Experiment

- Approved at Paul Scherrer Institut, Switzerland in 1999
- Start physics run from 2006
- Initial aim at 10^{-13}, eventually down to 10^{-14}

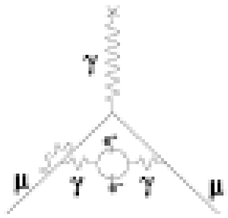
g-2 experiment

http://www.g-2.bnl.gov/index.shtml

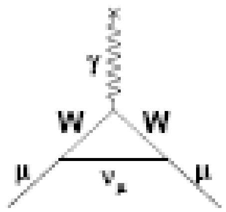


g-2: physics motivations

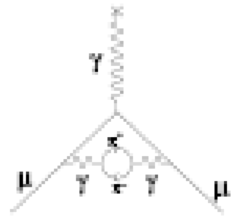
Muon interaction with the photons of the magnetic field is sensitive to new physics through loops



Higher Order QED



Electroweak



Hadronic VP

+ ? ? ?

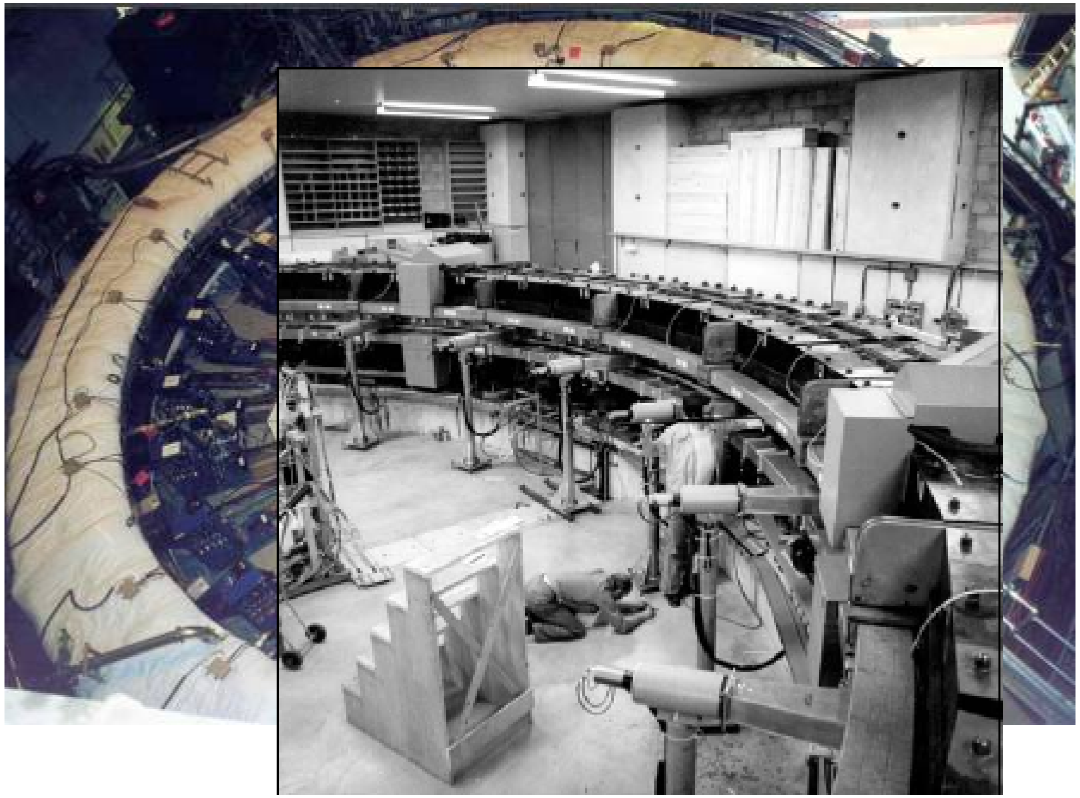
Discrepancy between experiment and theory indicates new physics

g-2: design of the experiment

$$a_\mu = \frac{g-2}{2}$$

- $\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = \frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)(\vec{\beta} \times \vec{E})\right]$
  - Choosing $\gamma = \sqrt{\frac{1}{a_\mu} + 1} \approx 29.3$ ($p_\mu = 3.09$ GeV) cancels the $\vec{\beta} \times \vec{E}$ term

$$a_\mu = \frac{\omega_a}{\frac{e}{m_\mu c}\langle B \rangle}.$$



g-2: results

fit $N(t) = N_0\, e^{-t/\tau} \times [1 + A\cos(\omega_a t + \phi)]$

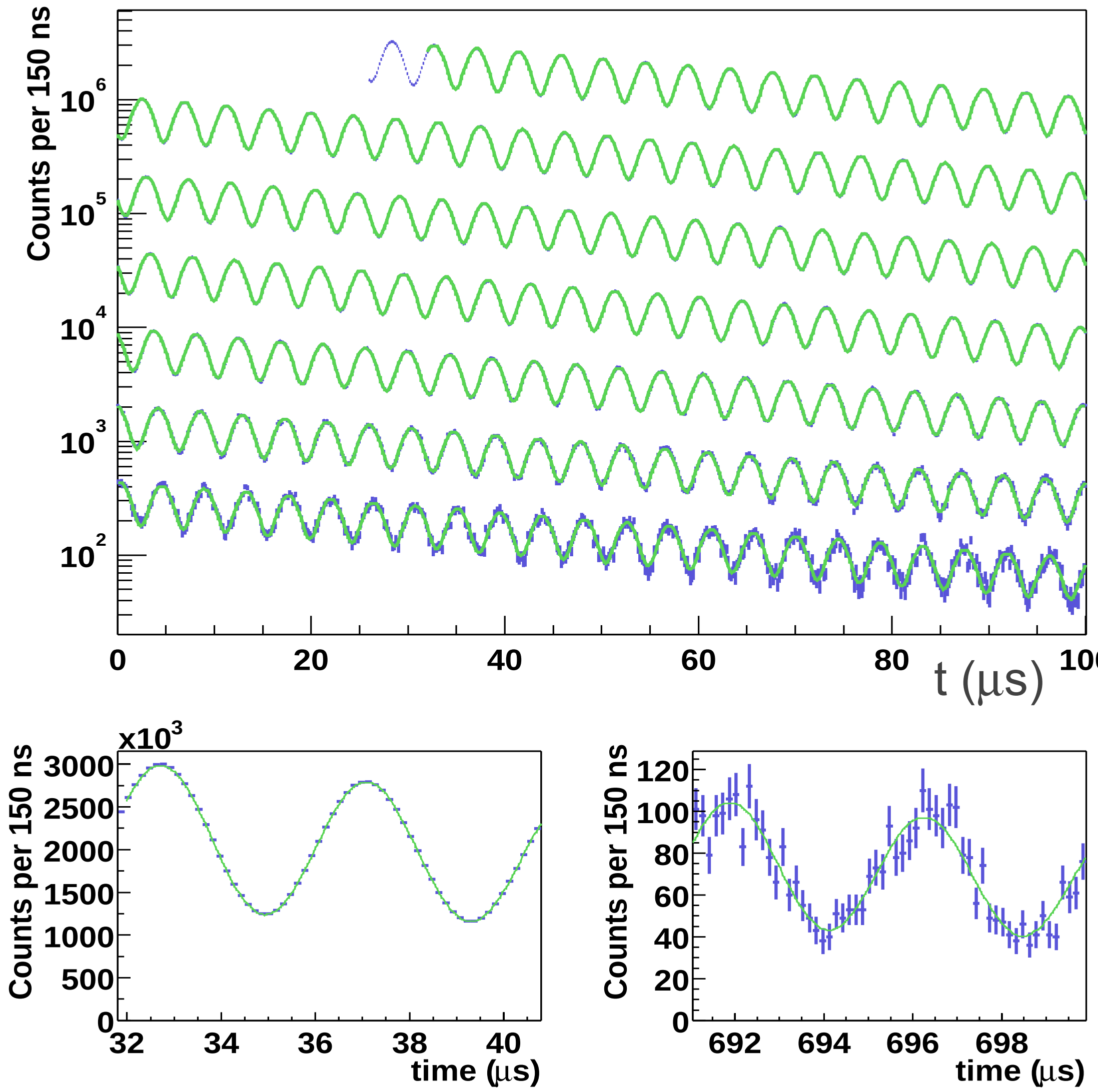
measure ‹B› with NMR

$\omega_a / \langle B \rangle \rightarrow$

$a_\mu = (11{,}659{,}208 \pm 5 \pm 3)\ 10^{-10}$

0.5 ppm = 15 times better than earlier exp.

hep-ex/0501053



g-2: comparison with theory

Contributions $\times 10^{10}$

QED	11,659,471.94	0.14
Had LO (*)	693.4	6.4
Had LBL	12.0	3.5
Had HO	-10.0	0.6
weak	15.4	0.22
Total	11,659,182.7	7.3
exp	11,659,208	6
Exp-the	25.3	9.4

- 2.7 σ $\rightarrow$ new physics ?
  SUSY,
  leptoquark,
  μ substructure,
  anomalous W coupling

(*) Using e^+e^- data + KLOE (not τ)

g-2: the collaboration

Page 1 of 2

The Muon (g-2) Collaboration

Co-Spokesmen: B. Lee Roberts (BU), Vernon Hughes (deceased) (Yale)

Resident Spokesman: Bill Morse (BNL)

Project Manager: Gerry Bunce (BNL)

E. Benedict, R.M. Carey, W. Earle, E. Efstathiadis, M.F. Hare, E. Hazen, X. Huang, F. Krienen, A. Lam Ng, I. Logashenko, J.P. Miller, V. Monich, J. Ouyang, J. Paley, Q. Peng, O. Rind, B.L. Roberts, L.R. Sulak, A. Trofimov, G. Varner, W.A. Worstell - Boston University

J. Benante, G.W. Bennett, H.N. Brown, G. Bunce, J. Cullen, G.T. Danby, J. Geller, H. Hseuh, J.W. Jackson, L. Jia, S. Kochis, R. Larsen, Y.Y. Lee, M. Mapes, W. Meng, J.L. Mi, W.M. Morse, D. Nikas, C. Özben, C. Pai, C. Pearson, I. Polk, R. Prigl, S. Rankowitz, J. Sandberg, Y.K. Semertzidis, R. Shutt, L. Snydstrup, A. Soukas, J. Stehle, A. Stillman, T. Tallerico, M. Tanaka, F. Toldo, D. Von Lintig, D. Warburton, K. Woodle - Brookhaven National Laboratory

Y. Orlov - Cornell University

D. Winn - Fairfield University

K.P. Jungmann - Kernfysisch Versneller Instituut, Rijksuniversiteit Groningen

J. Gerhäuser, A. Grossmann, G. zu Putlitz, P. von Walter - University of Heidelberg

B. Bunker, P.T. Debevec, W. Deninger, F. Gray, D.W. Hertzog, T.D. Jones, C.J.G. Onderwater, C. Polly, S. Sedykh, M.

http://www.g-2.bnl.gov/collab.html 7/3/2005

Sossong, D. Urner - University of Illinois

U. Haeberlen - MPI für Med. Forschung

M.A. Green - Lawrence Berkeley National Laboratory

B. Bousquet, P. Cushman, L. Duong, S. Giron, J. Kindem, I. Kronkvist, R. McNabb, D. Miller, C. Timmermans, T. Qian, D. Zimmerman - University of Minnesota

A. Chertovskikh, V.P. Druzhinin, G.V. Fedotovich, D. Grigoriev, V.B. Golubev, B.I. Khazin, A. Maksimov, Yu. Merzliakov, N.M. Ryskulov, S. Serednyakov, Yu.M. Shatunov, E. Solodov - Budker Institute of Nuclear Physics, Novosibirsk

K. Endo, H.Hirabayashi, S. Kurokawa, A. Yamamoto - KEK

Y. Mizumachi, M. Iwasaki, M. Kawamura - Tokyo Institute of Technology

H.E. Ahn, M. Deile , H. Deng, S.K. Dhawan, A. Disco, F.J.M. Farley, X. Fei, M. Grosse-Perdekamp, V.W. Hughes, D. Kawall, J. Pretz, S.I. Redin, E.P. Sichtermann, A. Steinmetz - Yale University

About 100 people

Experiment approved in 1988

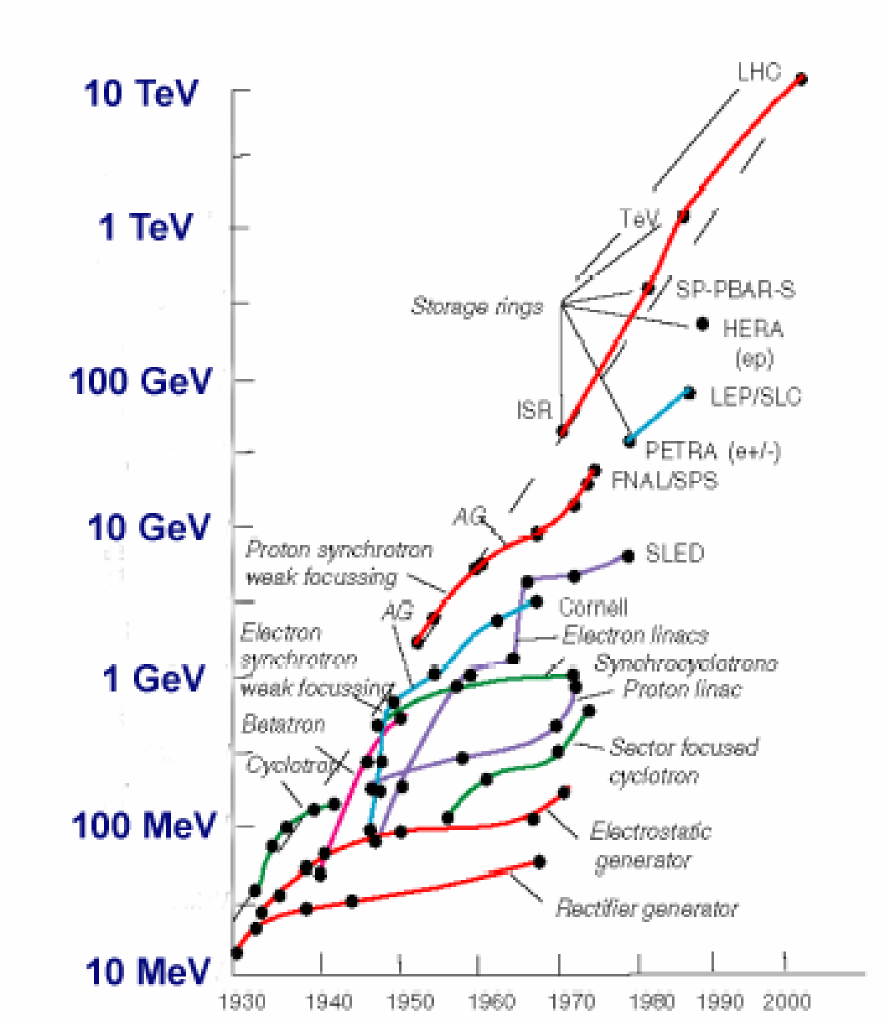
Final result in 2004

Quest for Energy

$$\lambda = \frac{hc}{2\pi}\frac{1}{E}$$

$$\lambda(fm) \approx \frac{0.2}{E(GeV)}$$

Increasing energy you probe Nature at smaller distances and you may cross the threshold of new phenomena



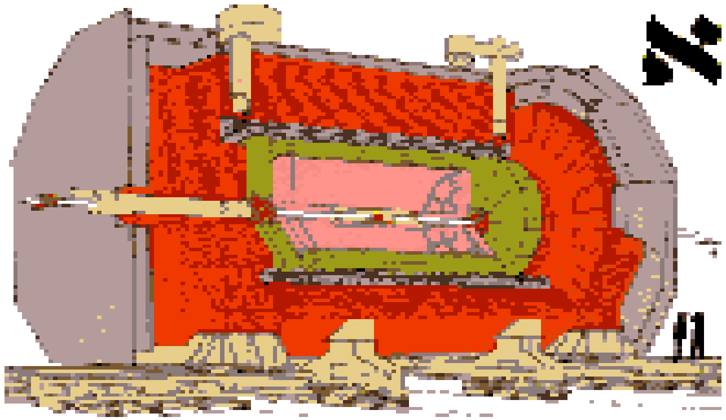
Large Scale Facilities

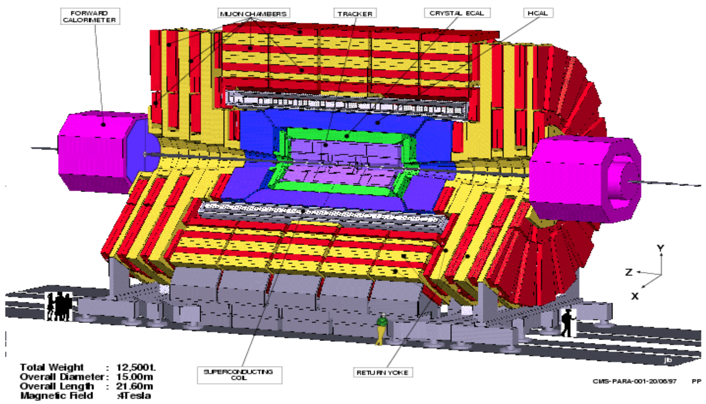
27 km Tunnel instrumented with high technology devices

Multi Billion projects

N-decades projects

Large scale experiments





ALEPH EXP at LEP

1980 : first meetings

1982 : Experiment Approved

1989 : First Collisions

2000: Last run

>2005: Last publication

CMS EXP at LHC

1991 : first meetings

1994 : Experiment Approved

2007 : First Collisions

2010 : Design Luminosity

>2014: Luminosity upgrade

Main Physics Motivations

LEP

- Precise Measurements of the properties of the Z and W bosons
- Search for new particles
- B physics

LHC

- Search for the Higgs Boson
- Search for new particles
- Top physics

General Purpose Detectors

When it became more and more likely, early in 1980, that an electron–positron collider, energetic enough to produce the as yet undiscovered Z boson, would be constructed at CERN, some of us got together to initiate discussions on a possible experiment. Some of us who collaborated in the CDHS neutrino experiment were joined by colleagues from Orsay, Pisa, Munich (Max Planck) and Rutherford Labs.

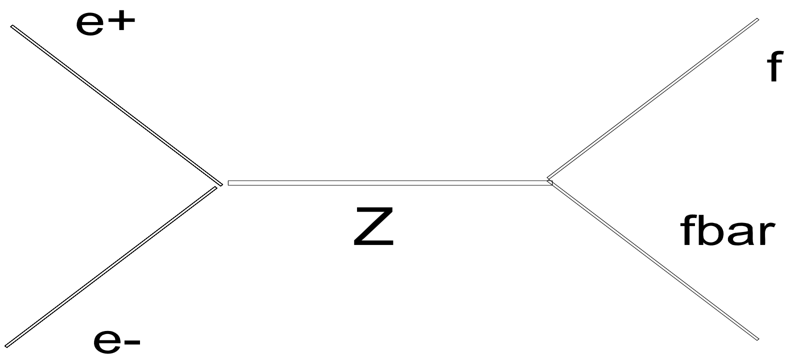
The first question we asked ourselves was: 'Can we think of a focused experiment, requiring a specialized rather than general-purpose detector?'

The answer was a clear no, and in fact, no special purpose detector was ever built at LEP. So we started to think of a general-purpose, 4π detector, such as had been developed at the DESY Petra and the SLAC PEP colliders, but clearly more ambitious in all aspects: tracking resolution, angular coverage, calorimetry, and particle identification.

Jack Steinberger – Nobel Laureate and first spokesman of the Aleph Experiment

High Q2 Reactions

High Q2 reactions involve partons (quarks and leptons)



	Quarks		Leptons	
Famiglia 3	t Top	b Bottom	τ Tau	ν_τ Tau-neutrino
Famiglia 2	c Charm	s Strange	μ Muon	ν_μ Muon-neutrino
Famiglia 1	u Up	d Down	e Electron	ν_e Electron-neutrino

Measure the properties (parameters) of the partons in the final state

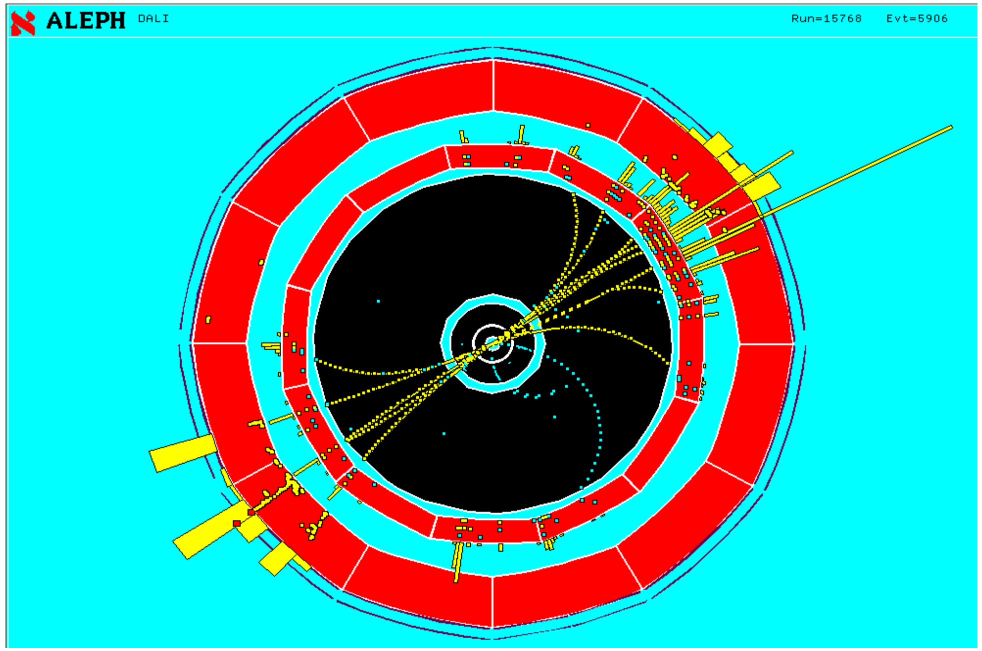
- Charge
- Direction
- Flavor
- Energy
- Spin

Quarks and Hadronization

Quarks hadronize producing JETS

The jet retains the direction and energy of the parent parton

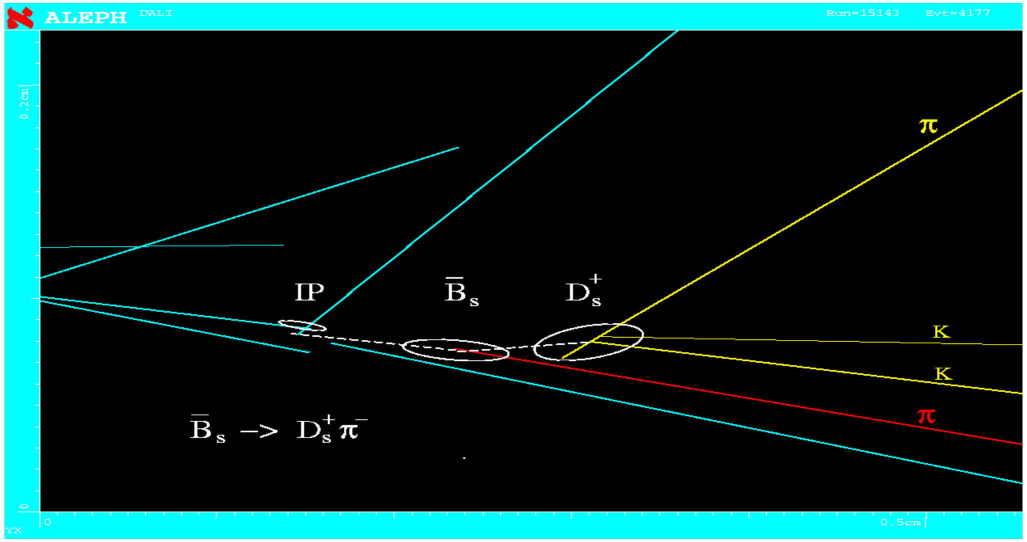
The visible final state is constituted by *stable* hadrons ($c\tau\gamma$ >> meters) π^+, π^-, k+,k-, k0, p+ p-,n nbar…….
π^0 decays promptly into two photons



Z--> q qbar

The challenge is to reconstruct the parton parameters from the Jet parameter

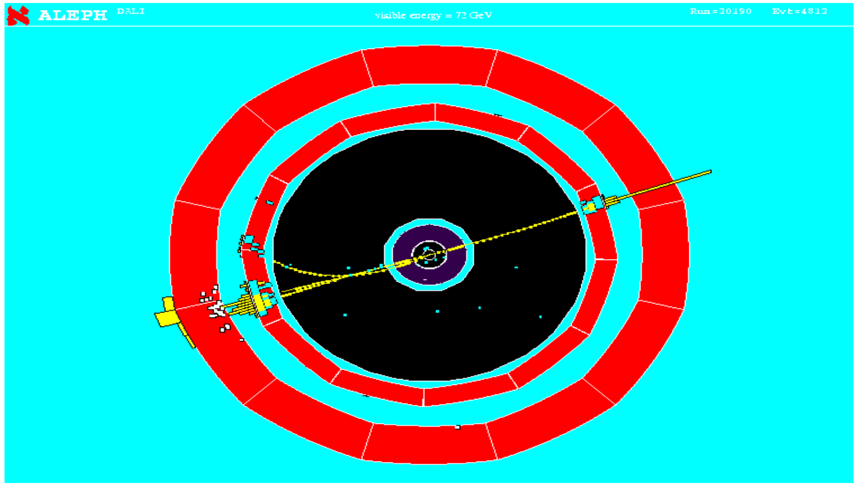
Decays



Z-->b bbar

In the hadronization process (few fermi) of heavy quarks also heavy hadrons are produced. They decay weakly (few mm) and only the decay products are detected

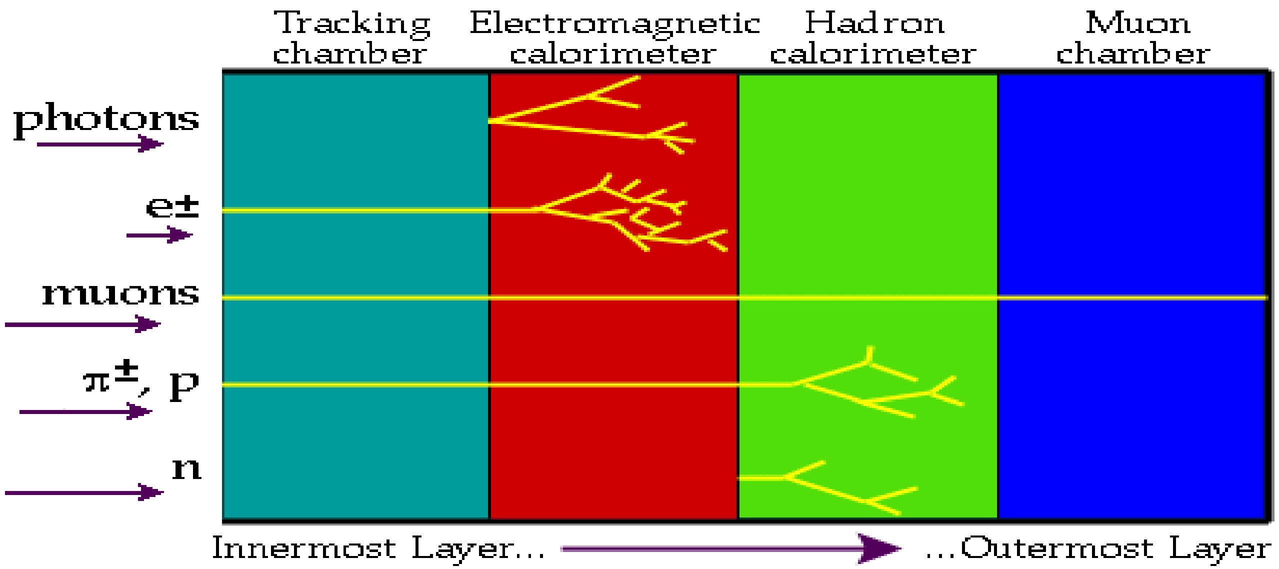
Also τ leptons decay with cτγ few mm



Z--> τ+τ–

General Principle

Visible particles are measured by the various subdetectors and identified from their characteristic pattern .

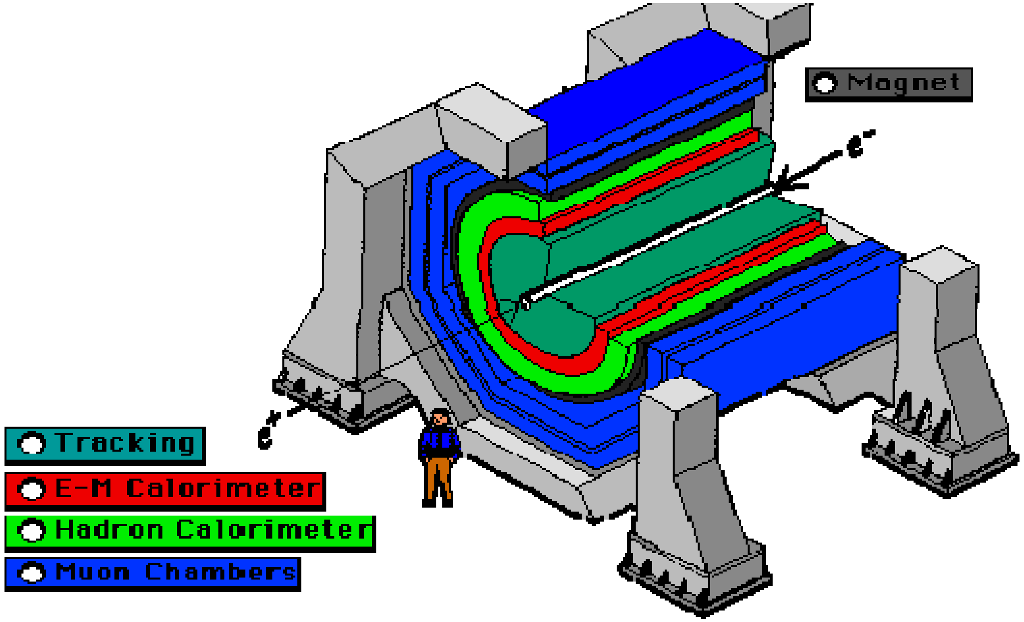


The parameters of the quarks are reconstructed from the hadronic jets.

The flavor of the quark is determined reconstructing the hadronic decays of heavy mesons or detecting their detached decay vertex

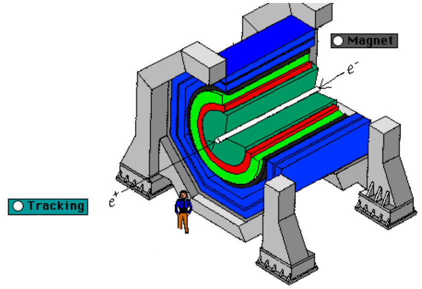
END OF FIRST LECTURE

General Principle

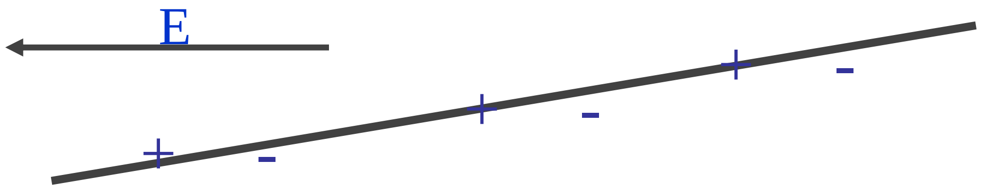


Collider detectors look all similar since they must perform in sequence the same basic measurements.

The dimension of the detector are driven by the required resolution . The calorimeter thickness change only with the logarithm of the energy: for this reason the dimension of the detectors change only slightly with the energy.



Charged particle trajectories

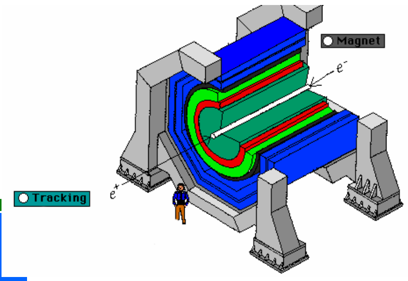


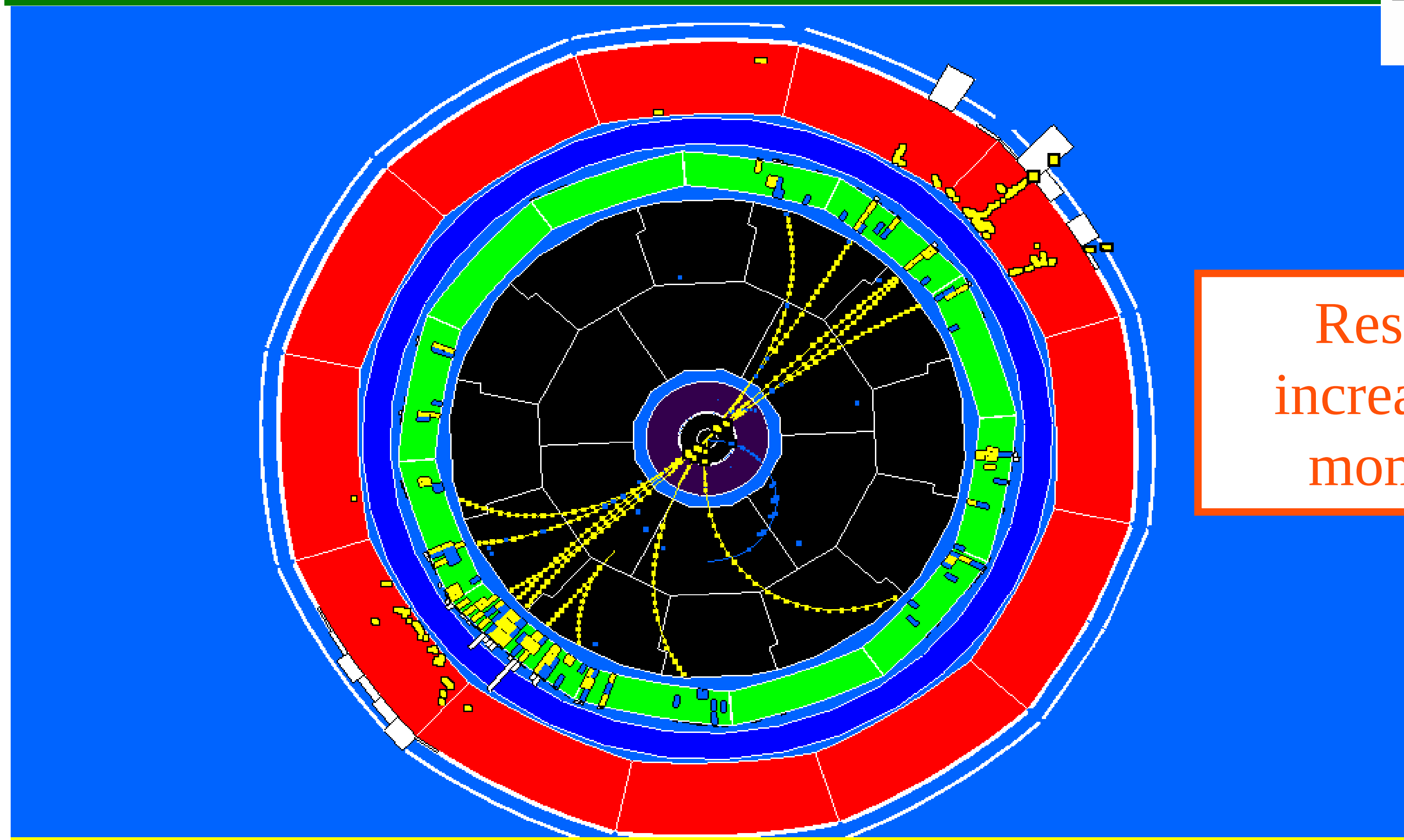
Charged particles ionize and their trajectories can be reconstructed detecting the ionization electrons on charge sensitive detectors.

The measurement of the trajectory in a magnetic field gives

- Direction at the origin
- Sign of the charge Q of the particle
- Pt/abs(Q), Pt= component of the momentum perpendicular to the magnetic field

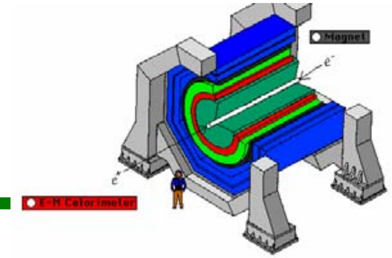
Magnetic field is along the beam axis





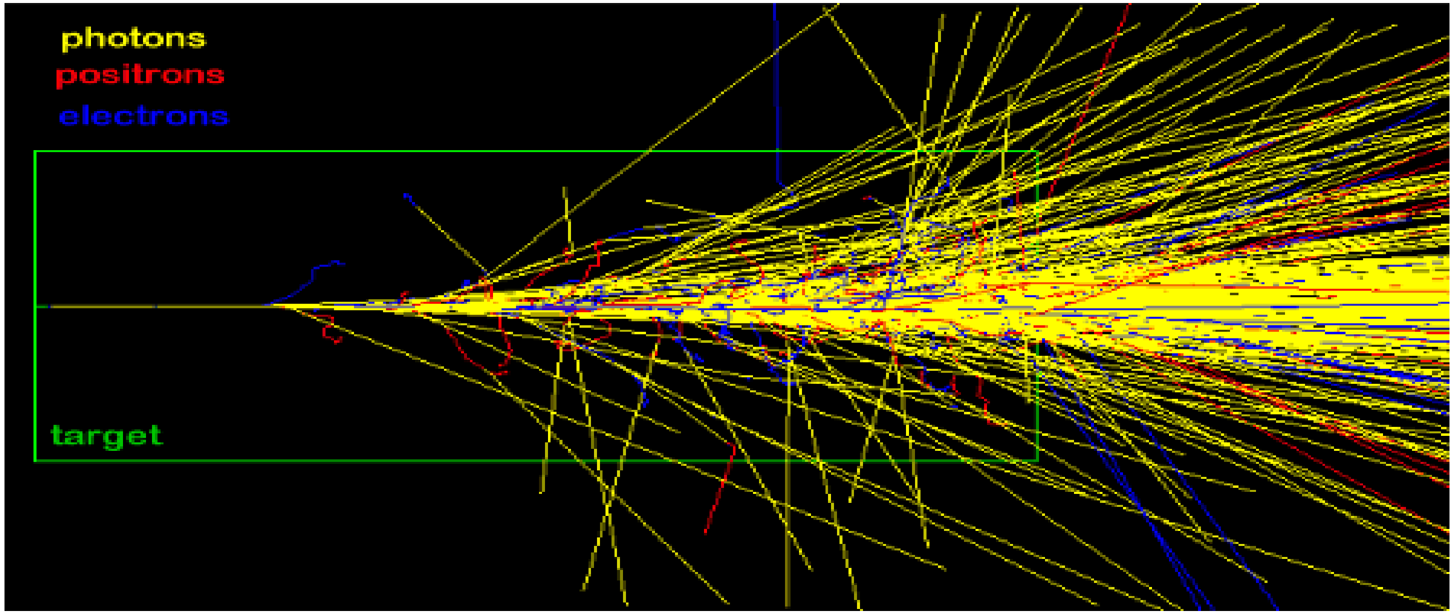
Resolution increases with momentum

$$\frac{\Delta p}{p} \approx 0.25 \left(\frac{\Delta s}{100\ \mu m} \right)^{1} \left(\frac{1m}{L} \right)^{2} \left(\frac{1T}{B} \right)^{1} \left(\frac{p}{100\ GeV} \right)$$



Photon Detection

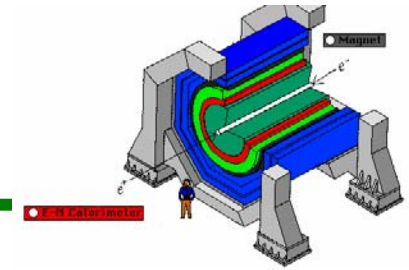
Massive shower in a tungsten cylinder (outlined in green) produced by a single 10 GeV incident electron.



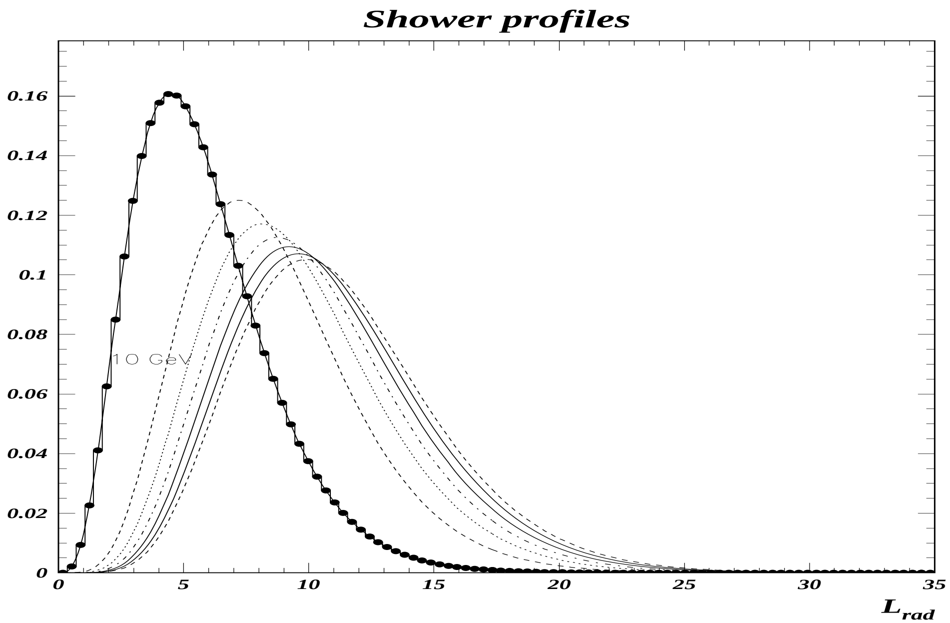
Photons and electrons interact in matter producing showers of neutral and charged particles.

The number of secondary particles is proportional to the energy.

Radiation length



The physical size of the shower is described by the Radiation Length Xo
Dense material have Xo ~ 1 cm



Shower profiles for

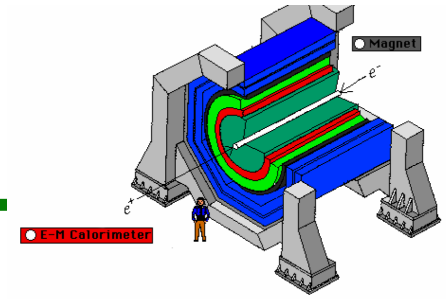
10, 100, 200, 300… GeV

electrons

The length of the shower increases with the log of the energy

The lateral size does not depend on the energy (90% in 2-3 cm)

Energy resolution



In order to absorb high-energy photon/electron the calorimeter must integrate 15-25 Xo.

The energy resolution has a statistical term that d
number of secondary charged particles, which in
to the energy

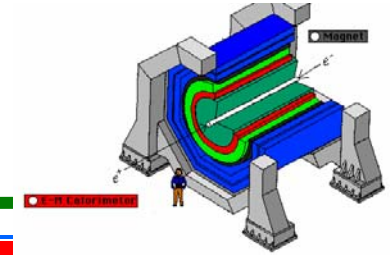
Resolution decreases with Energy

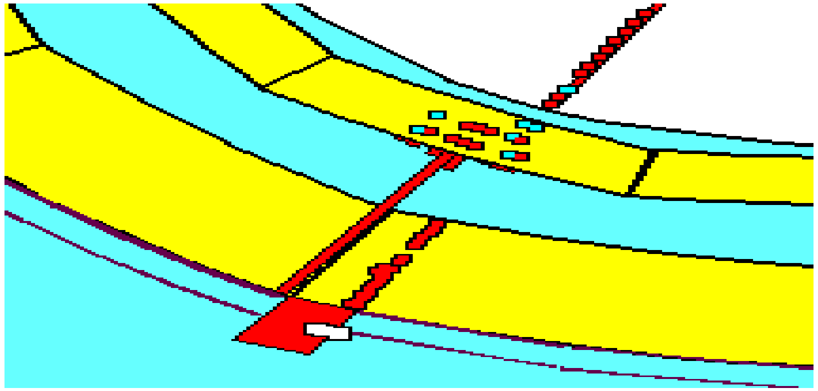
$$\frac{\Delta E}{E} \approx \frac{(3-30)\%}{\sqrt{E(GeV)}} \oplus O(1\%)$$

The size of the statistical term depends on the technique used in the calorimeter

At high momentum Energy resolution for an electron in the calorimeter is better than momentum resolution in the tracker

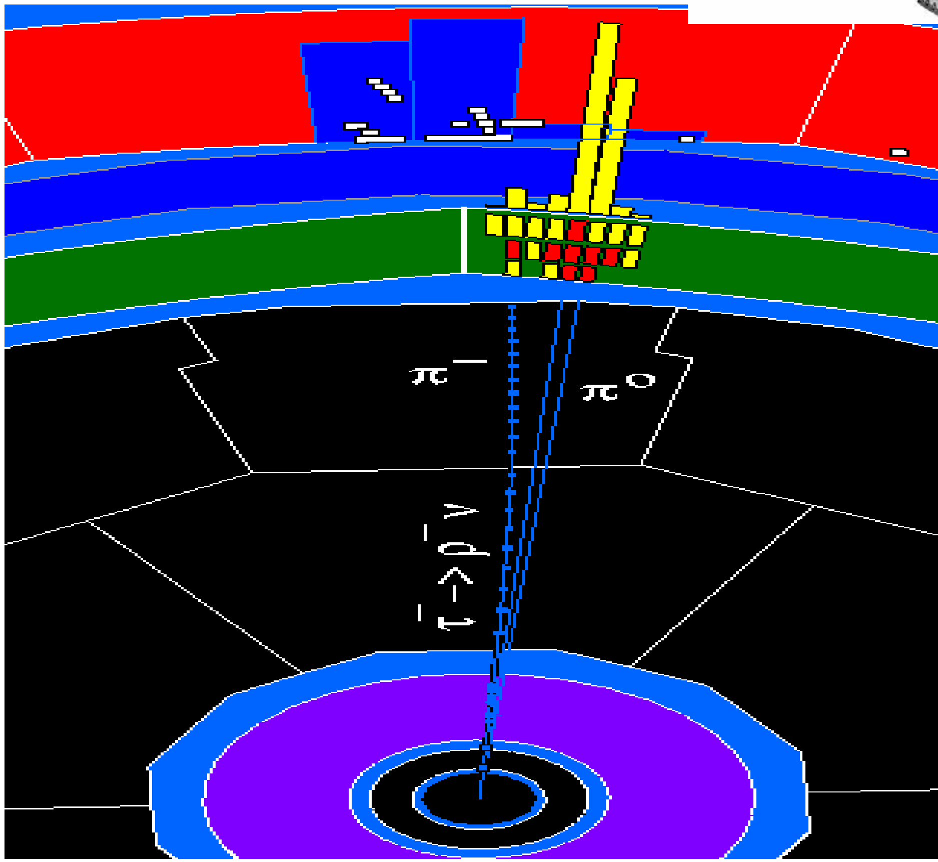
Granularity





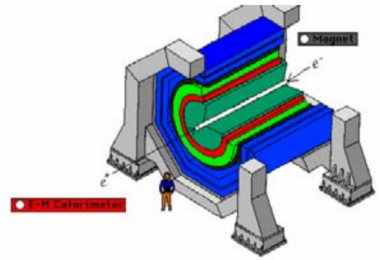
High granularity is needed to separate showers induced by nearby particles.

The angular separation is limited by the lateral size of the shower and by the distance of the calorimeter from the interaction point



Photons are identified as compact showers not associated to charged particles

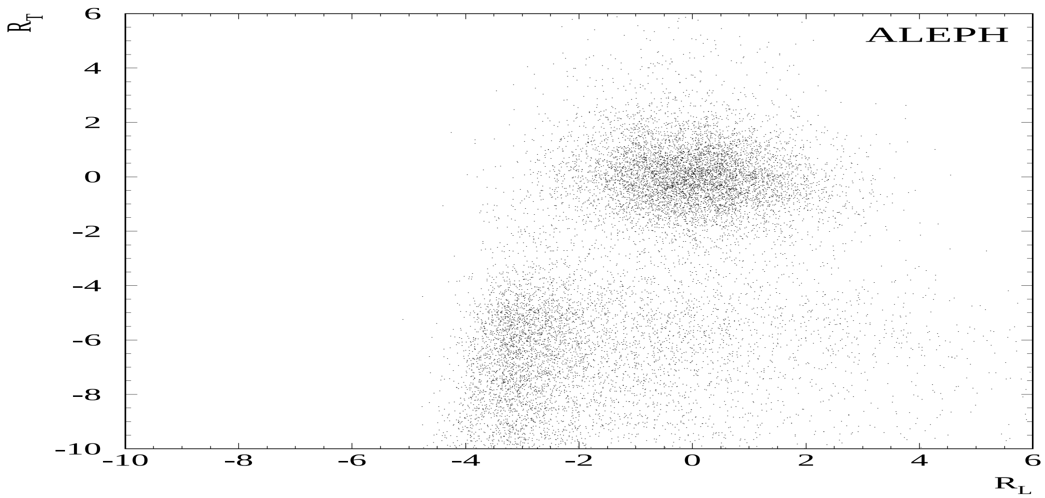
Electron identification



Electrons can be identified (wrt to charged hadrons) comparing the momentum measured in the tracker and the energy measured in the calorimeter.

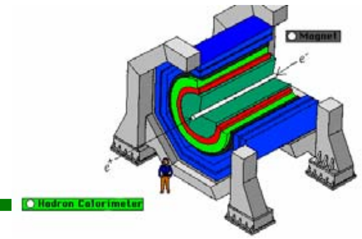
Extra separation is obtained by exploiting the longitudinal shower profile

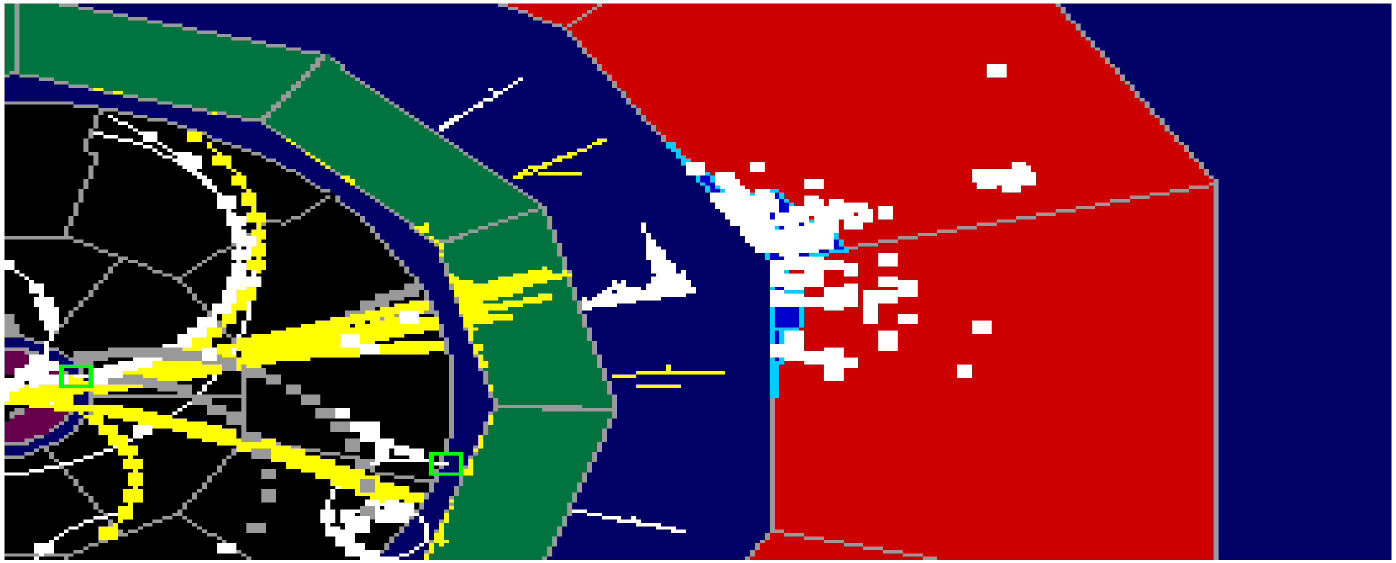
Match energy and momentum



Longitudinal shape of the shower

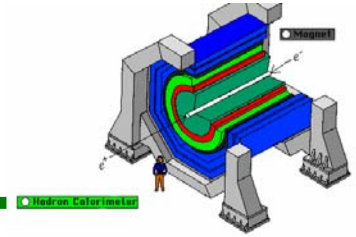
Hadronic energy





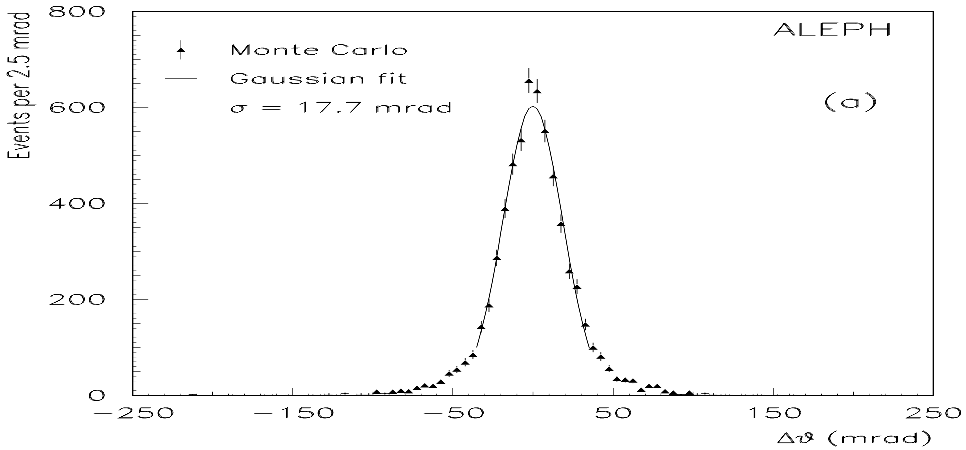
Hadrons interact in the Electromagnetic calorimeter producing hadronic showers that are not absorbed since the hadronic interaction length is much larger than a radiation length (11 cm vs 0.5 cm in lead).

The hadronic shower is absorbed in the Hadron calorimeter: typically 1-2 meters of heavy material (iron, copper) interleaved with detecting elements.



Jet parameters

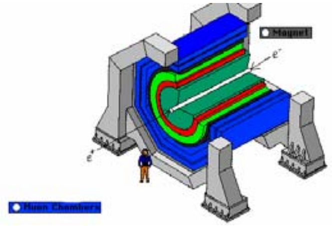
Careful analysis of the charged particles trajectories and their match with clusters measured in the calorimeters allows a good definition of the jet energy and direction.

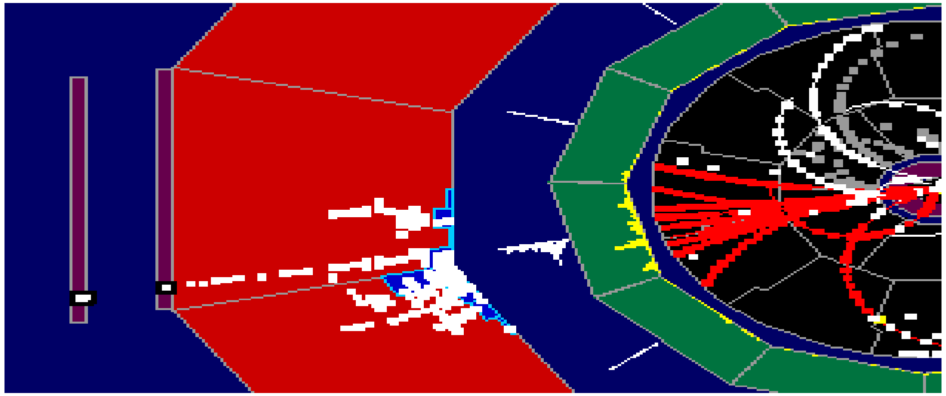


Jet direction is reconstructed in ALEPH with a resolution of about 20 mrad

In Aleph
Energy resolution was $0.6/\sqrt{E\,(Gev)}$

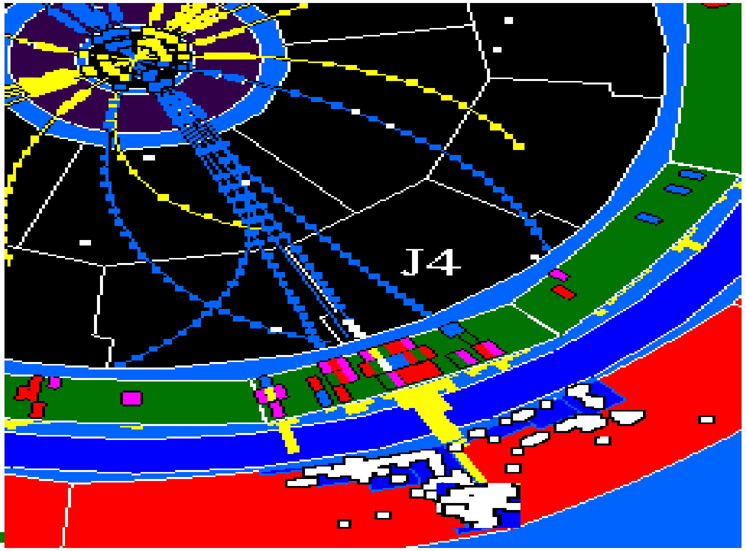
Muon identification





Muons have no hadronic interaction and very long electromagnetic interaction length.

They cross the detector almost undisturbed and are identified by their penetration through the calorimeters



With small probability hadronic showers PUNCH THROUGH the hadron calorimeter and fake a muon

Detector Design one example: The Aleph TPC

When ALEPH was proposed, there was no large TPC working to design specifications:

Recommendation by the LEPC

Following the letter of intent in March 1982 (on the left is the first transparency of Jacques' presentation to the LEPC), Aleph was recommended by the LEPC at its meeting on 16 November 1982 (see the DG's letter opposite).

The LEPC required a technical report to be produced by 25 April 1983 where a number of technical and financial issues had to be addressed and specified the following:

Milestones:

– TPC: a prototype of at least a 1.5 m long drift length, with magnetic field (later known as TPC 90)

Design & Construction of the ALEPH TPC

1982-1985 Prototypes and Detector design

Small group ~ 15 physicists + engineering support

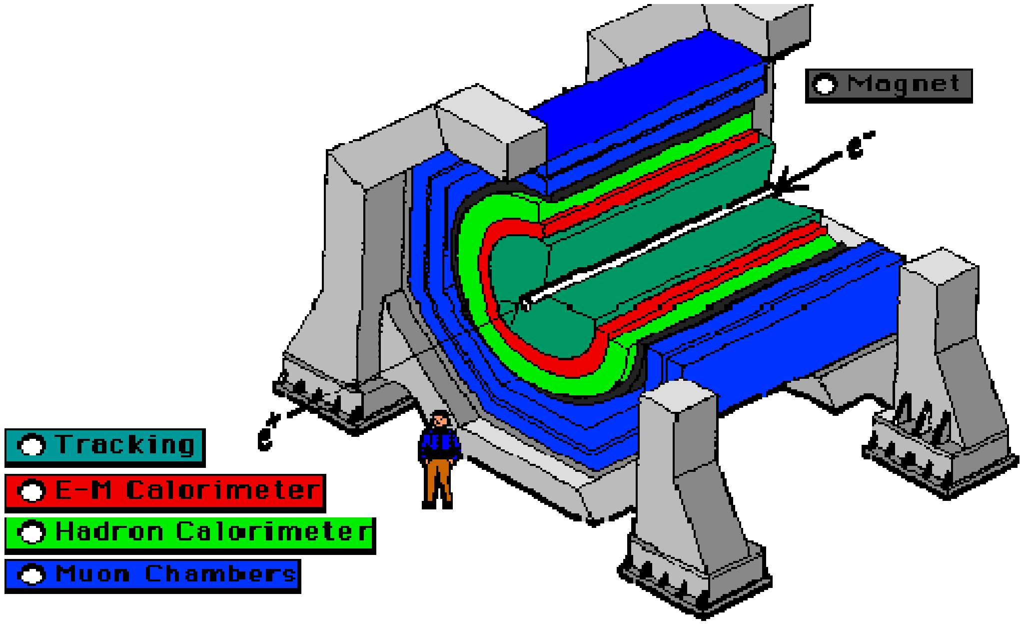
1985- 1987 Detector Construction

Project managing, quality control, mainly engineer work

1987-1989 Detector Commissioning

Larger group ~ 30 physicist + engineering support

General Principle



Collider detectors look all similar since they must perform in sequence the same basic measurements.

The dimension of the detector are driven by the required resolution . The calorimeter thickness change only with the logarithm of the energy: for this reason the dimension of the detectors change only slightly with the energy.

However…..

Though the general principles for the design of a "general purpose detector" for LEP and LHC are very similar…….

….. the detector technologies exploited for the two machines are different because of the very relevant differences in the initial state.

LEP vs LHC

LEP
e+ e- collisions

• 4 x 4 bunches in the machine colliding every 25 μs

•Rate of events with tracks in the detector ~ 10 Hz

•Rate of interesting events (Z peak) 1 Hz

•Typical multiplicity 20 tracks

LHC
p p collisions

• 2800x2800 bunches in 2 beam pipes. Collisions every 25 ns

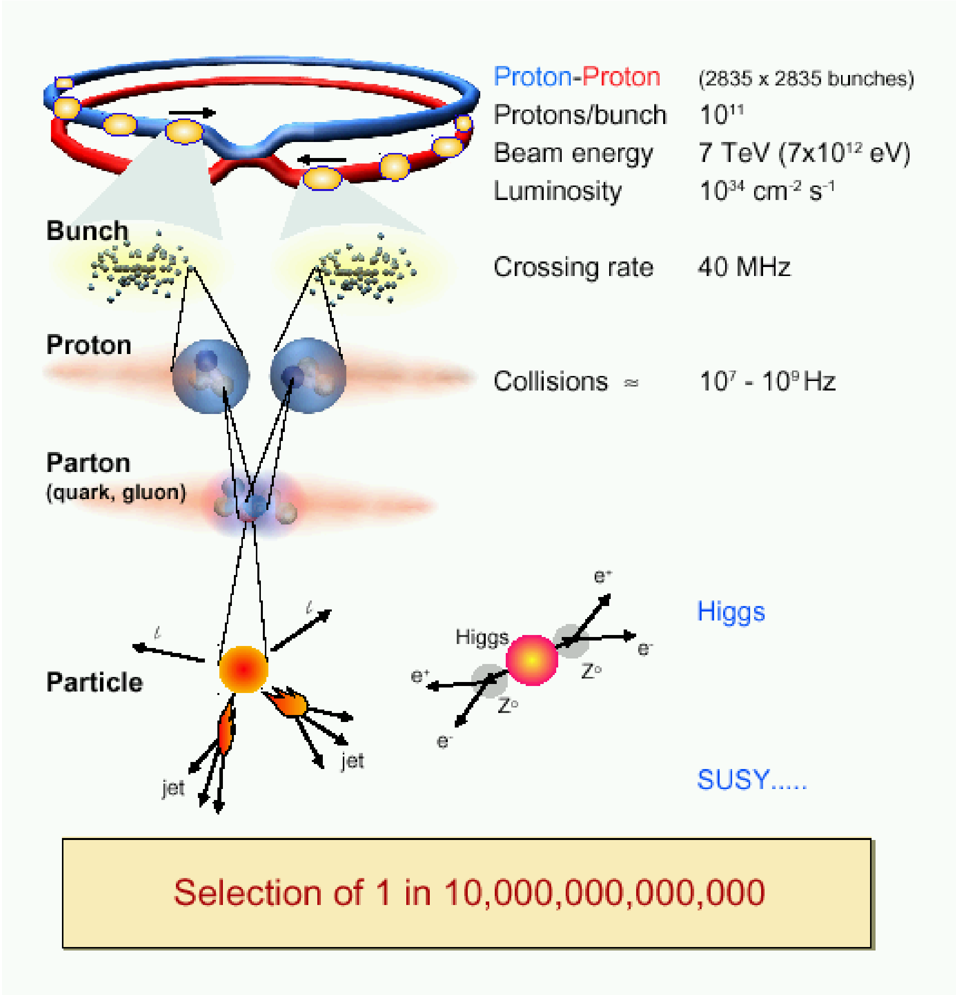
•Rate of events with tracks in the detector ~ 40 MHz

•Rate of interesting events (t-tbar or Z→μμ)10 Hz

•Rate of interesting events (Higgs 500 GeV) 0.01 Hz

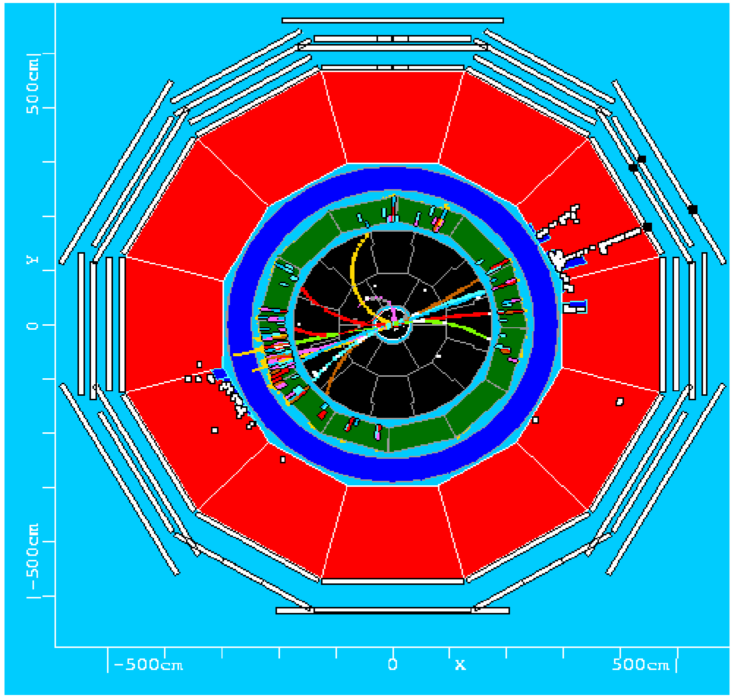
•Typical multiplicity 700 tracks

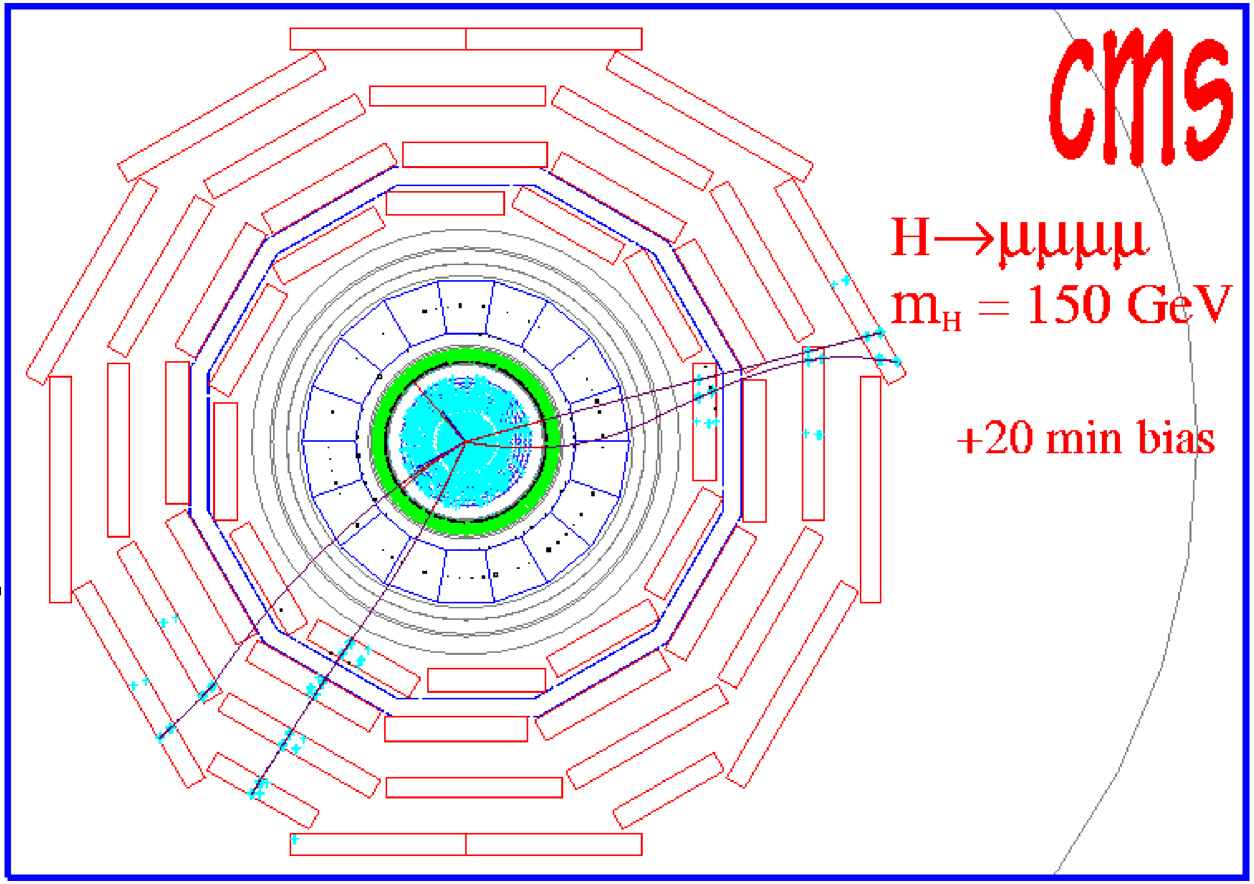
Collisions at LHC



LEP vs LHC

About on scale





LEP vs LHC

LEP No radiation hard	LHC Radiation hard
• Trigger very simple	• Trigger very difficult
• Tracking with gas detector collection time 40 μs, 0.05 Xo	•Tracking with silicon detectors collection time 25 ns, 1 Xo
• Calorimeters: quite standard	•Calorimeters: coverage 10 units of rapidity. Response time 25 ns.
• Muons: only identification	•Muons: independent measurement of momentum in magnetic field

The Aleph Collaboration

Aleph collaboration in 1986

- About 400 physicists
- 11 years of data taking
- About 2300 Internal Notes
- About 300 papers
- About 50 Abstracts per Conference (peak)
- About 250 Thesis

•http://aleph.web.cern.ch/aleph/

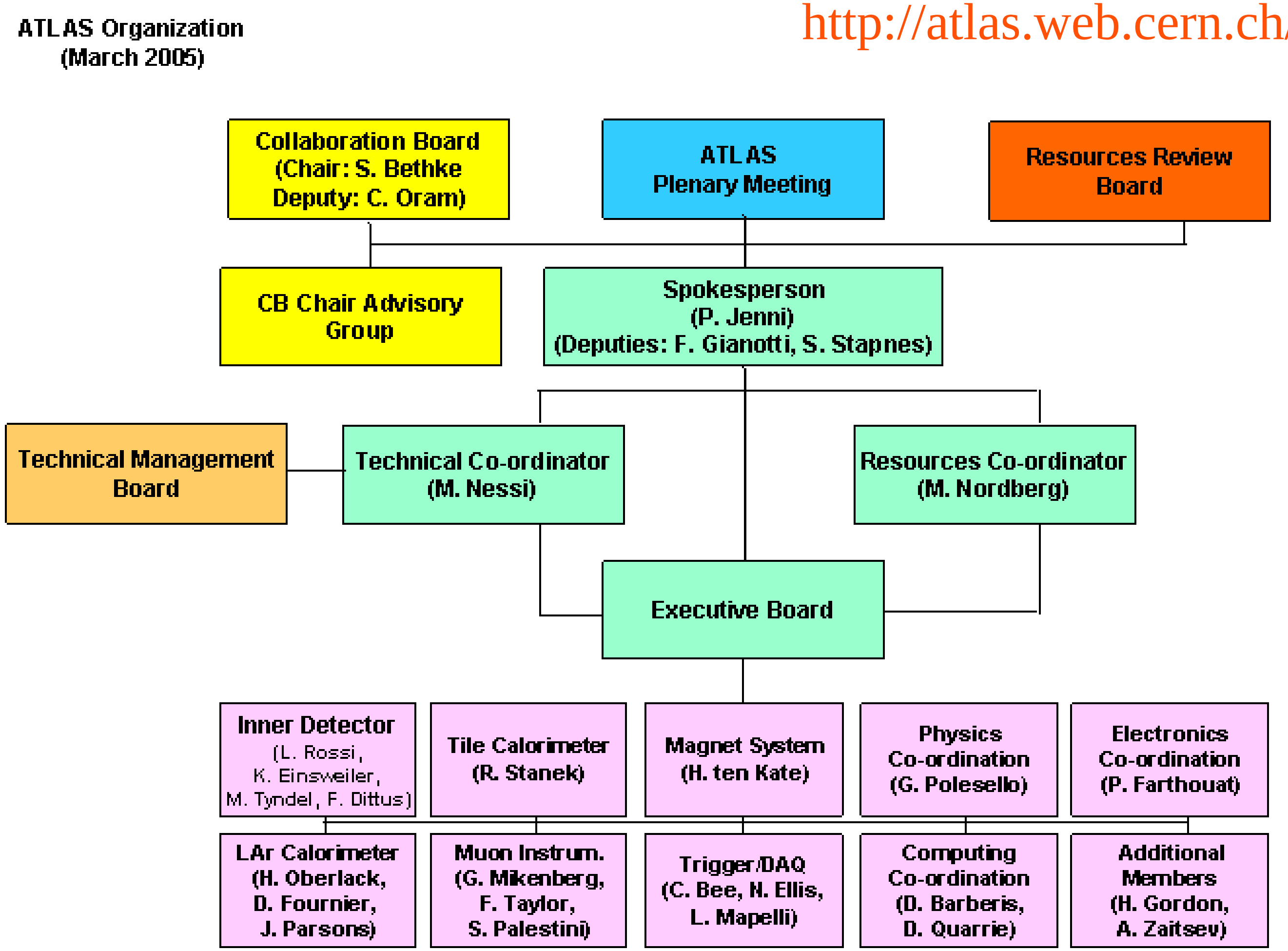
The ATLAS Collaboration

- About 1770 Scientific Authors
- Data Taking will start 2007
- About 250 Notes
- About 200 Thesis

•http://atlas.web.cern.ch

ATLAS Organization

http://atlas.web.cern.ch/Atlas/index.html



ATLAS physics organization

CERN – European Laboratory for Particle Physics

Physics

Where - (directory tree) - phys_groups.html

Who - (questions/comments) - Giacomo

When - last modified - Friday, July 01, 2005 2:08:59 PM

Physics groups

- B physics
- Top
- Standard Model
- Higgs
- SUSY
- Exotics
- Heavy Ions
- Monte Carlo generator

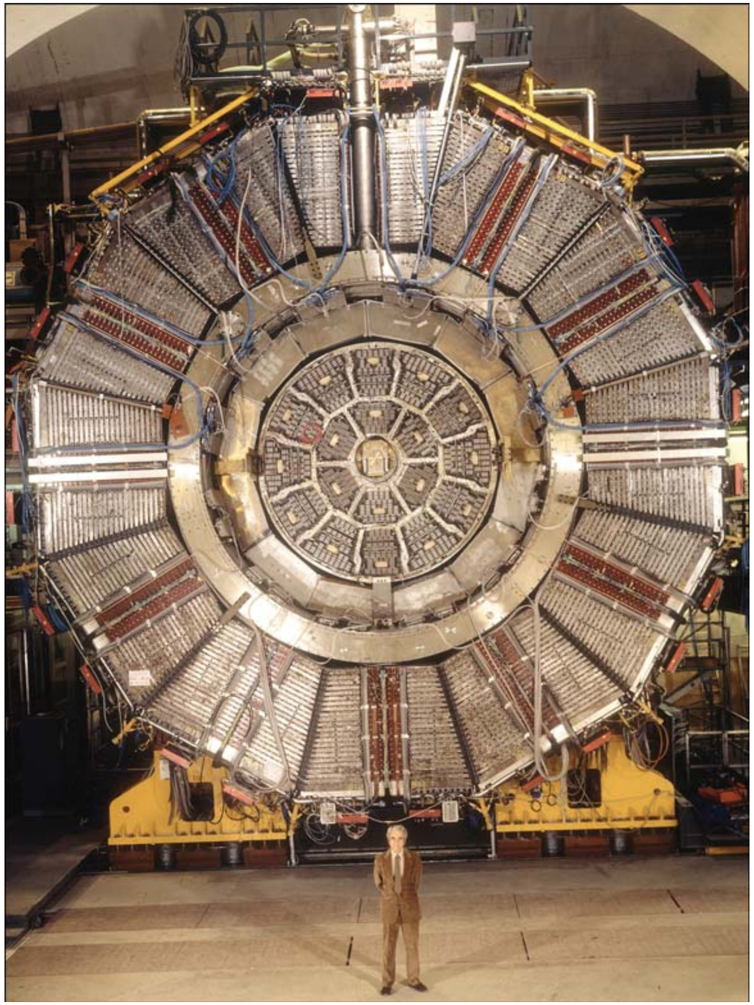
Combined performance groups

- e/gamma
- Jets/ETmiss
- b-tagging
- Muon

Useful links to other groups

- Physics Event Selection Algorithms (PESA)
- Computing
- Luminosity
- Background

How to “steer” a large collaboration



Jack Steinberger - Nobel laureate and first spokesman of The Aleph experiment