Collider Detectors

Giorgio Chiarelli
Istituto Nazionale di Fisica Nucleare
Sezione di Pisa

TRIUMF Summer Institute

This lectures

Collider Physics made a big impact on our understanding of the elementary particles and fundamental interactions

- ☞ Detectors played a fundamental role

With the startup of the LHC this role will be strenghtened

- ☞ The topic is wide and I chose to concentrate on hadron colliders as hadron collisions are a more challenging enivoronment and what applies in an hadron collider can be (usually) be done in e^+e^- colliders. Usually it is not the other way around

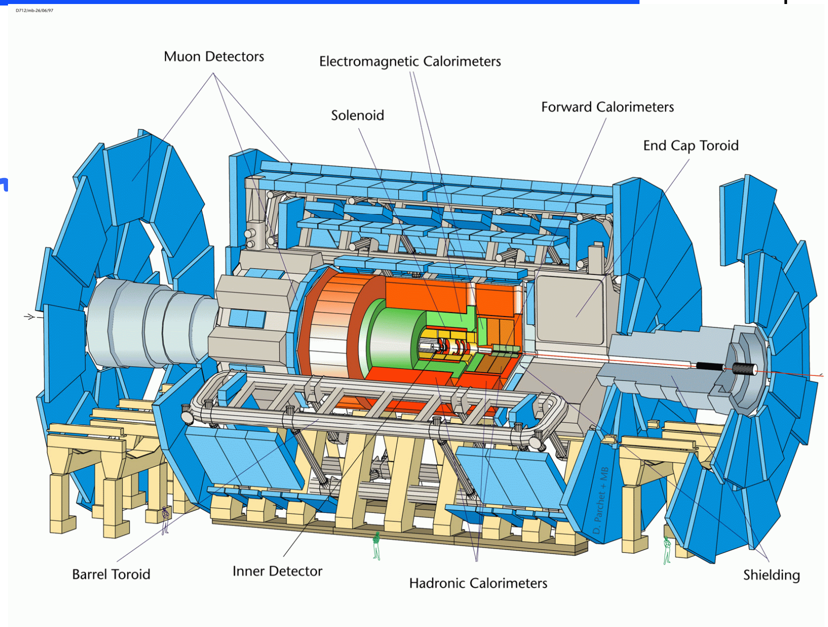
- ☞ Three lectures: past/present/future
  - ⇨ Not completely disjoint..

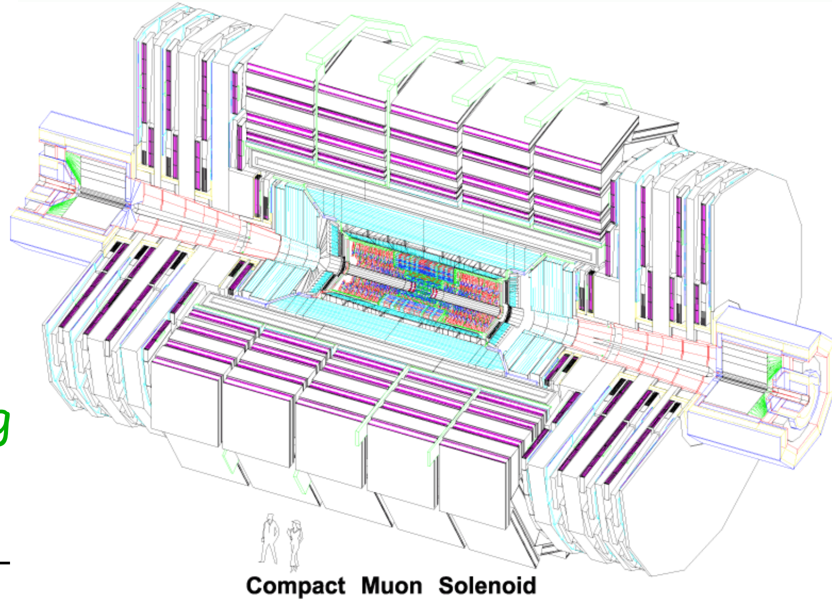
Collider detectors

We live in an era of a paradigmatic approach to a detector for physics at a collider

- ☞ 4 π as much as possible
- ☞ Magnetic spectrometer
  - ⇨ Good tracking system
- ☞ Hermetic calorimeter
  - ⇨ Possibly e/π compensation
- ☞ Muon id
- ☞ Secondary vertex detections

- ☞ Fast online decision
  - ⇨ Trigger
    - → Mandatory in hadron collisions
    - → Becoming more important at Hig Intensity Facilities (HIF)





Scheme of a "typical" detector

"Onion" structure

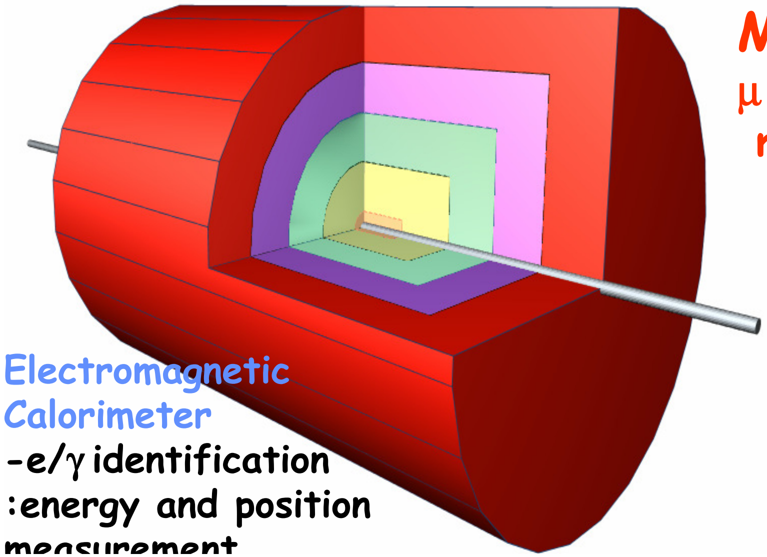
☞ Several layers, each one with a specific role

Backward and forward openings

☞ As small as background from beam allows, to leave room for outgoing beam

☞ Cylindrical geometry

⇨ Typically a number of cylinders one inside the other. End caps ("plugs") backward and forward



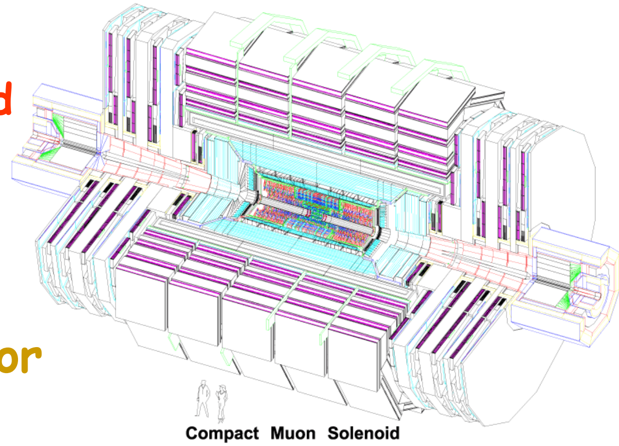
Electromagnetic Calorimeter

-e/γ identification

:energy and position measurement

Muon detector

μ identification and measurement



Central detector

- Tracking
- Sign of tracks
- Flavour tagging

Deconstructing a collider detector

Main components

- A tracking system
  - Role: reconstruct charged particles paths
    - Infer charge, momentum if within a magnetic field (spectrometer)
  - Can be complemented by a microvertex detector to identify tracks generated from secondary vertices
- A calorimetric system
  - One calorimeter designed to measure energies of EM interacting particles (e, γ..)
  - One calorimeter designed to measure hadronic interacting particles (p, π, n, K…)
- A muon detection system
  - *Self explaining*
- Trigger/DAQ and analysis chain

System issues

A collider detector is a remarkably complicated object

- ☞ Many subdetectors
  - ⇨ Some with specialized role
- ☞ Non trivial interactions among them
- ☞ Problems must be addressed (and worked out) in advance (at project stage)
  - ⇨ Limited or no access to some parts of the system
- ☞ Operational issues and Q&A often more relevant to good behaviour of the detectors than usually understood
- ☞ Very limited access to most of the detector after startup of data taking

The early days

It is interesting to see when the concept of colliders appeared

- ☞ Mid '50 of the past century
  - ⇨ Hadron collisions (….)
    - → Midwestern research (then URA…Fermilab will come)
- ☞ Late '50:
  - ⇨ e^+e^- collisions (Bruno Tousheck, Frascati)
    - → First actual collider
- ☞ What kind of physics was being pursued?
  - ⇨ Hadron collisions:
    - → *Soft* collisions
  - ⇨ e^+e^- colliders:
    - → ee→hadrons
- ☞ Detectors: small fraction of the solid angle

Two paths...one physics

Through the sixties zoo of particles

- SM emerges in the early seventies
  - November (1974) Revolution
    - J/Psi discovery
      - Lasting as long as October?
- Detectors at hadron colliders still looking at small fractions of the angular space
  - Originally designed for *soft* collisions were badly suited for high Pt physics

- One hadron colliders (ISR)
- Several e^+e^- colliders (SLAC, LNF, DESY, then KEK to name a few)
  - Flurries of proposal for new detectors

...and hadrons?

hadron collisions at the ISR (1967-1980)

☞ Two (continuous) proton beams colliding with an angle

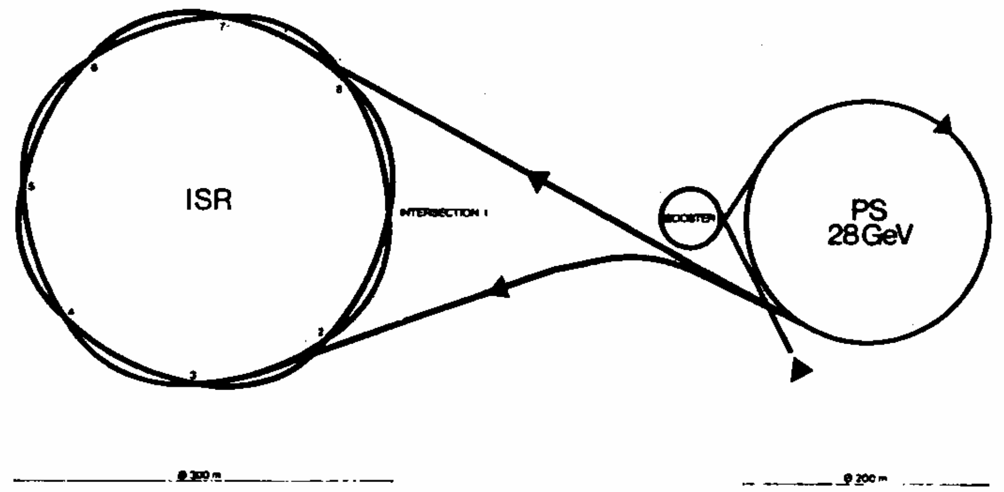
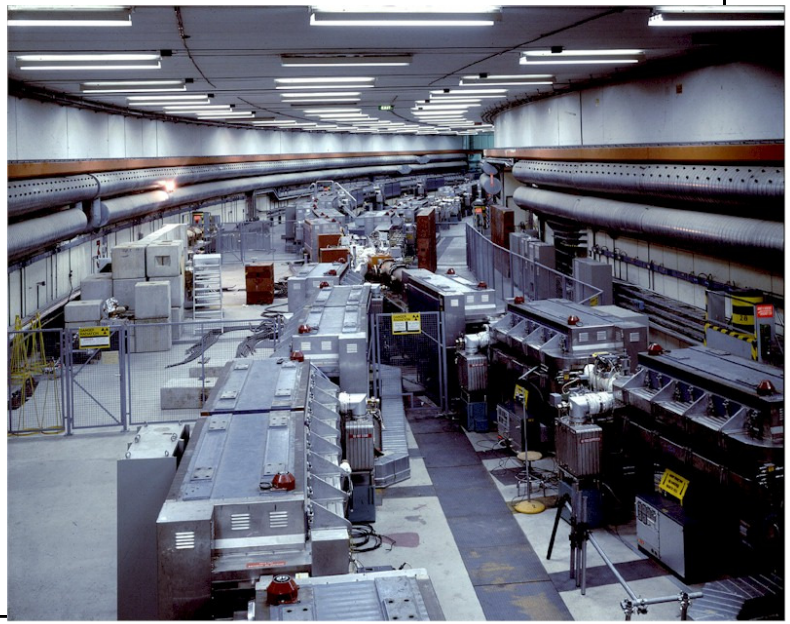
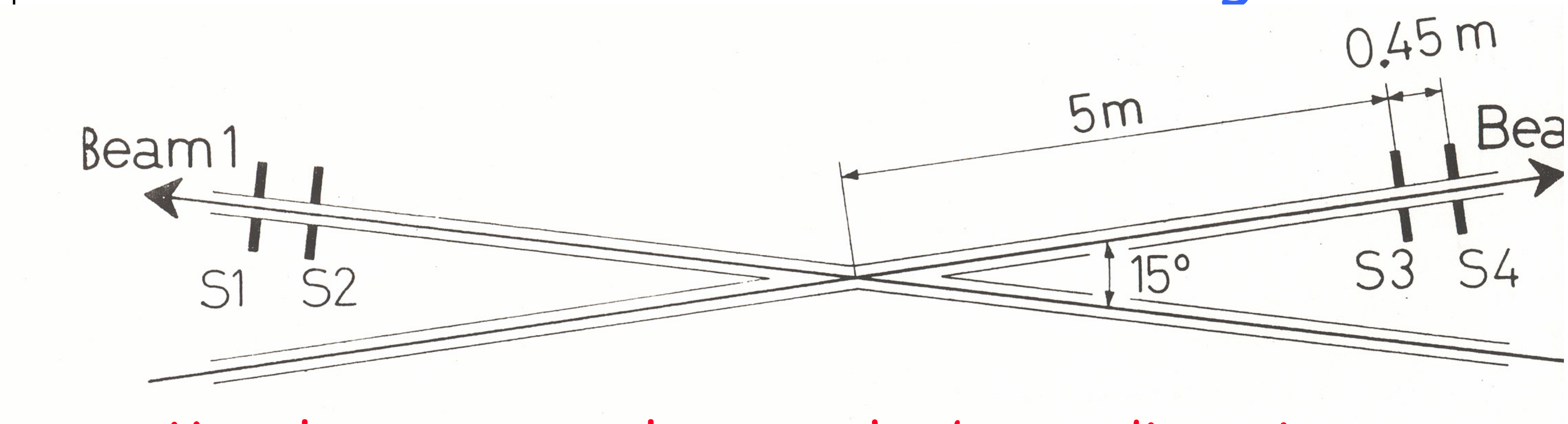


Fig. 2.1. Schematic view of the PS and ISR rings.



ISR -2

At the beginning experiments were designed to cover small fractions of solid angle:



Mostly counters close to the beam direction

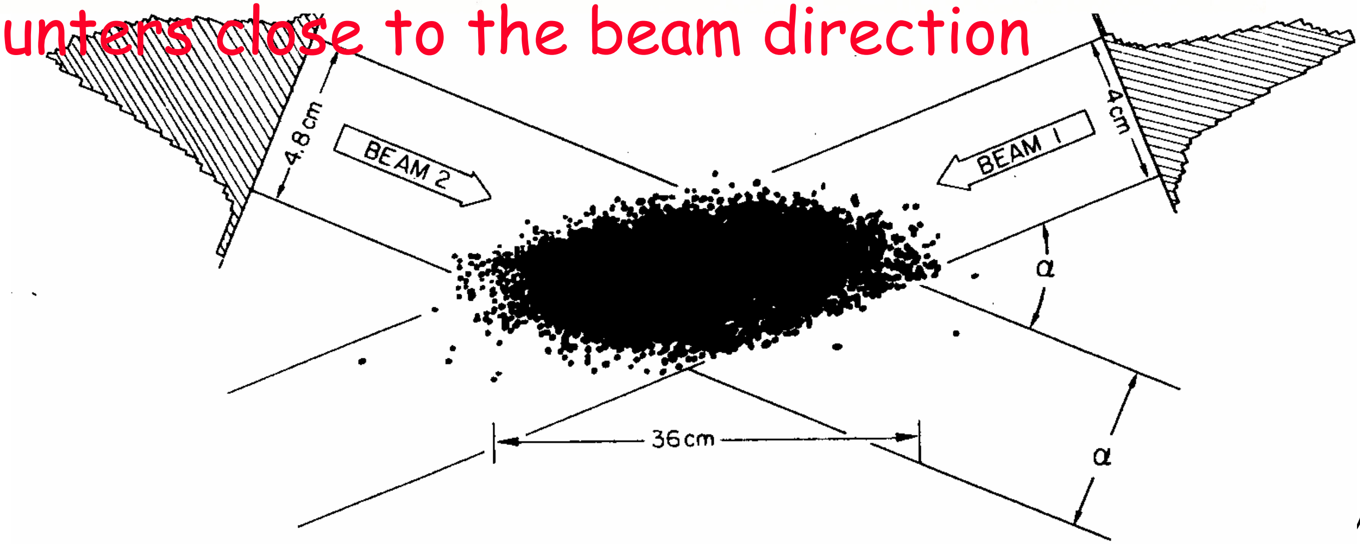


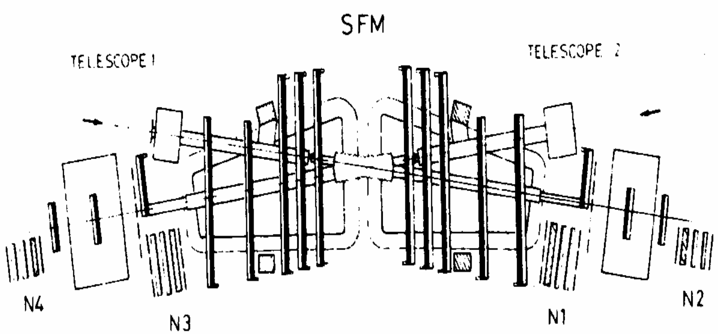
Fig. 2.4. Horizontal distribution of 65 000 reconstructed events. Also shown are the single beam profiles (R602).)

"New" Physics

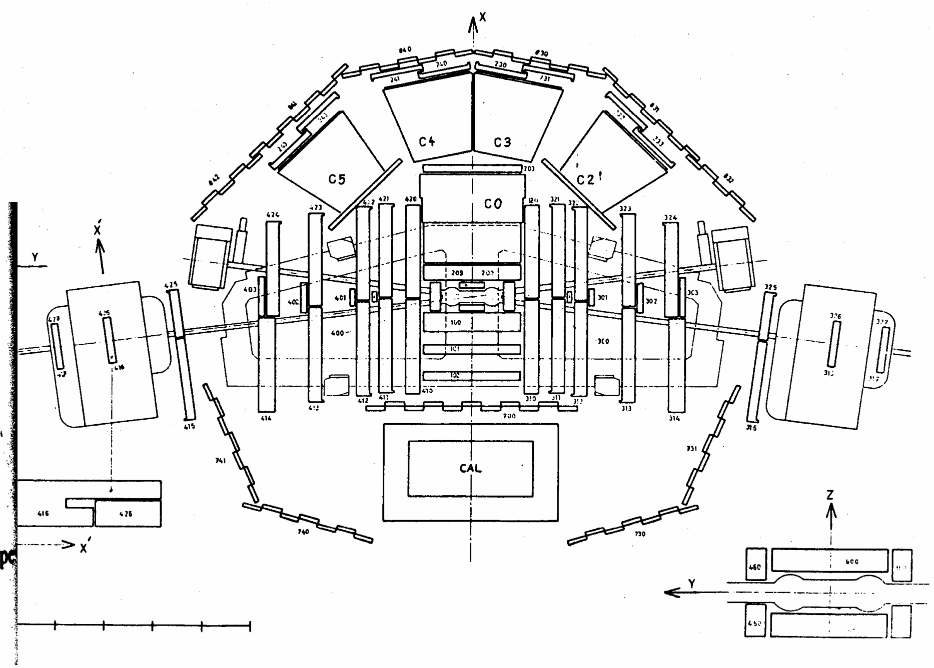
After Nov. 1974 quickly changed to observe what is happening at 90 wrt beam axis

- Most ambitious:
  - Split Field Magnet (the largest ISR detector)
- Originally built in a traditonal fashion (study of small angle physics)

Observation of J/psi at 90



detector as used in the CHOV experiment (R401). N, Neutron detectors. Compensator chambers and Trigger/Monitor hodoscope
avy lines.



More from the ISR

First attempt to detect the Z0 decaying in two muons (R 209)

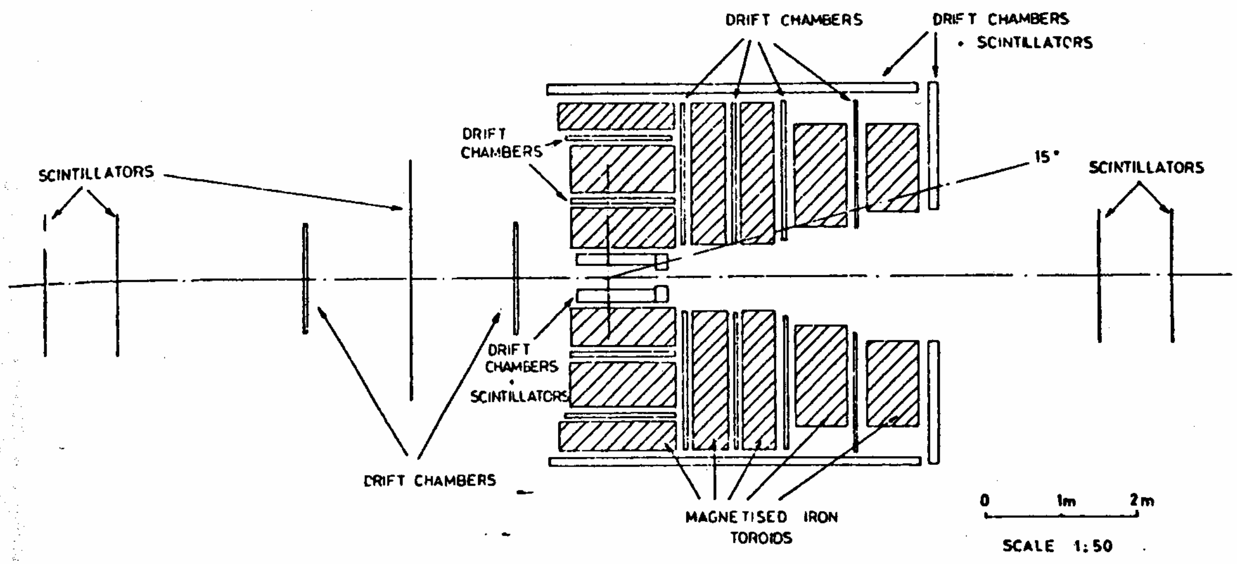


Fig. 11.5. Experiment R209: high mass muon pairs and associated hadrons.

The New Physics

With the rise of the Standard Model leptons became (as elementary brick) the main objects

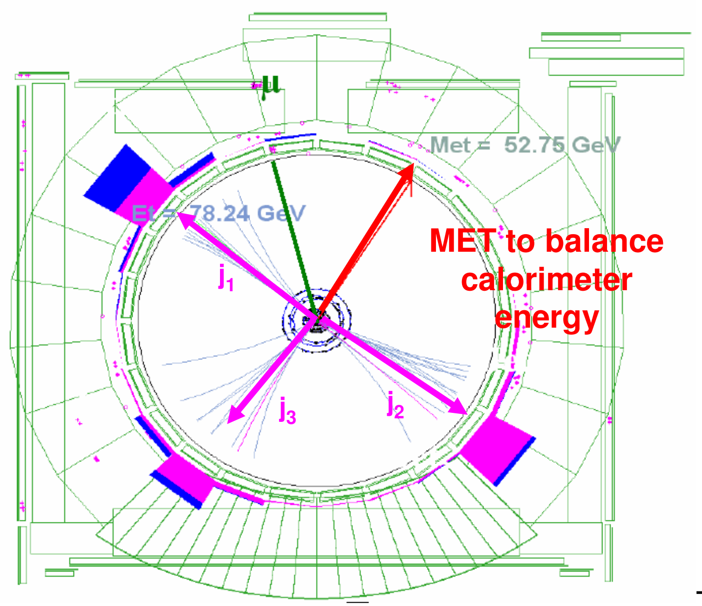
- ☞ For e and μ
  - ⇨ Use of known properties and techinques
- ☞ For quarks and neutrinos
  - ⇨ Their *signature*
    - → Quarks
      - Shower of particles
    - → Neutrinos
      - Non interacting particles

Neutrinos?

In an hadron hadron collision the longitudinal momentum of the colliding component is not balanced (previous pciture)

The transverse component is approximately balanced

- A neutrino, which is a non interacting particle, will be identified by "missing transverse energy"
  - UA1/UA2



Two birds with one stone

A quark hadronizes in a shower of neutral and charged particles

- ☞Charged can be (in principle) individually measured in a magnetic spectrometer
- ☞Neutral can be only measured by their energies

As the relevant quantities are related to the *quark* properties, one can infer its direction and energy by measuring the (collective) properties (energy and direction) of the shower of particles it generates

- ☞Calorimeters were already in use (for example in neutrino physics) to measure the energy released by showers of particles

Energy Measurement: Calorimeters

- Instrumented block of material where incident electrons, photons, hadrons are absorbed and part of their energy is transformed in a measurable quantity

- The interaction of an incident particle with the material produces, through either electromagnetic or strong processes, secondary particles which themselves interact and origin a shower of progressively lower energy particles.

- Part of the deposited energy is collected in form of electric charge or light. When designing a calorimeter care is taken to make the response as linear with the incident energy as possible.

Calorimetry -II

These devices are classified:

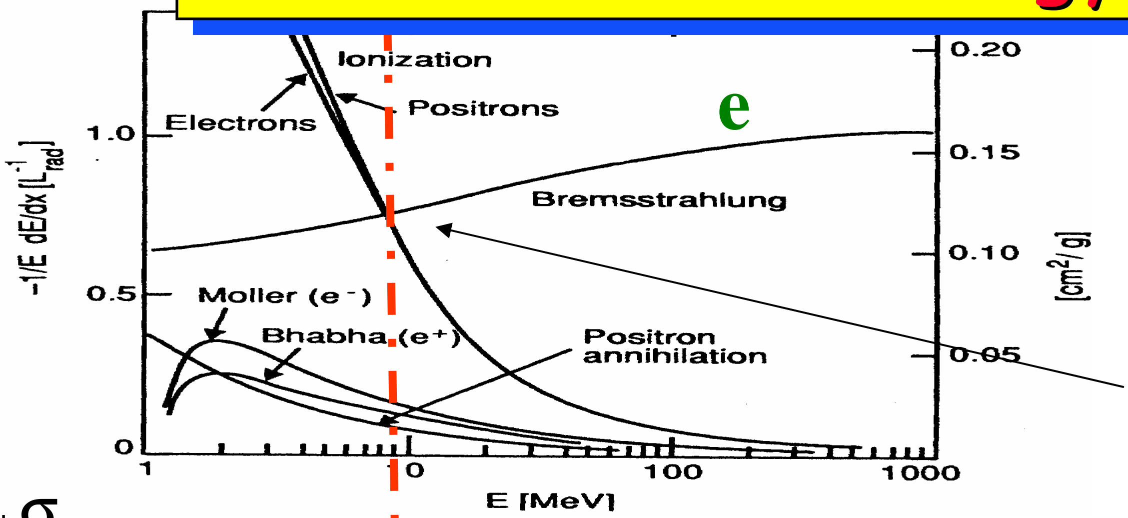
According to the kind of particles are planned for:

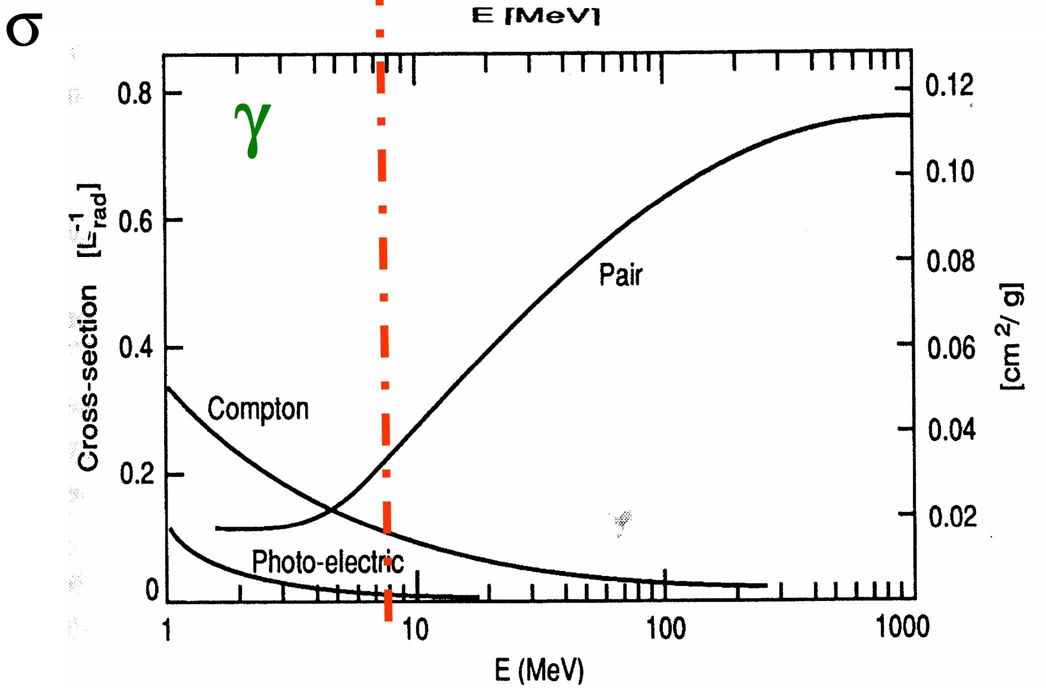
electromagnetic calorimeters: detect (mainly) electrons and photons through electromagnetic interactions (Bremsstrahlung, e^+e^- production, etc.)
hadronic calorimeters: detect (mainly) hadrons through strong and electromagnetic interactions

And by the construction technique:

homogeneous calorimeters: only one type of material acting as absorber and active medium. Ex: ICs, BGO, etc
sampling calorimeters: alternating layers of absorber (Pb, Fe, Cu,..) where the shower is generated and active medium where the signal is detected.

Fractional energy loss $e^{\pm}$





Rad Length : $X_0 \sim Z^{-1}(Z+1)^{-1}$

$E_{el} = E_0\, e^{-X/X0}$

$N\gamma = N_0\, e^{-\frac{7}{9}\frac{X}{X0}}$

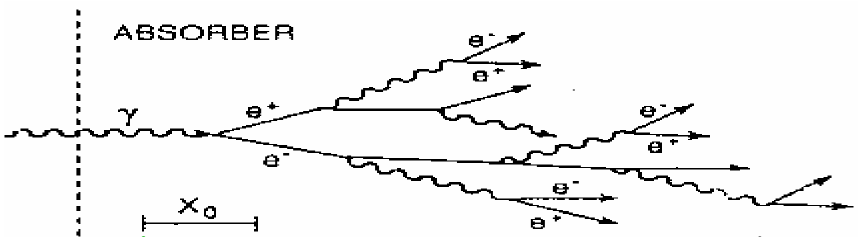
Critical Energy ε

The energy at which the energy loss by ionization equals the energy loss by radiation

ε ~ 560/ Z (MeV)

Ex: For Pb ~ 7 MeV

Electromagnetic Cascade



The em shower properties are understood in term of two scaling variables:

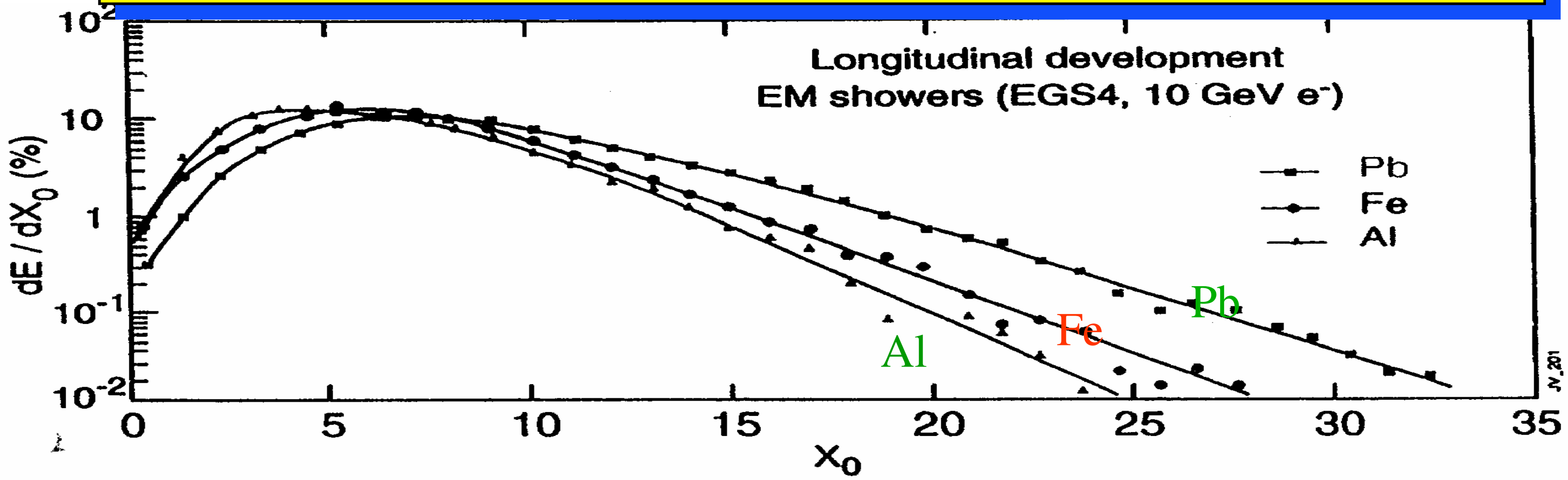
$t = X/X_0$ and $y = E/\varepsilon$

At each X_0 the number of particle increses by m. After t one has $n(t) = m^t$ The multiplication process stops when the energy of the degraded particles is about the critical energy ε

$N_{mx} = E/\varepsilon = y = m^{tmx}$ $t_{Mx} \sim \ln(E/\varepsilon)$

The depth of the shower increses only with the ln(E) Good!

Em shower longitudinal development



$t_{max}(X_0) \sim \ln \frac{E_0}{\varepsilon} \pm 0.5$ +/- for γ/e

$t_{95\%}(X_0) \sim t_{max} + 0.08 Z + 9.6$

Ex: 100 GeV : $t_{95\%}$ = 26 X_0 in Pb.

1 TeV $t_{95\%}$ = 28 X_0 in Pb

At LHC an em calo should have ≥ 25 X_0

Em Lateral shower profile

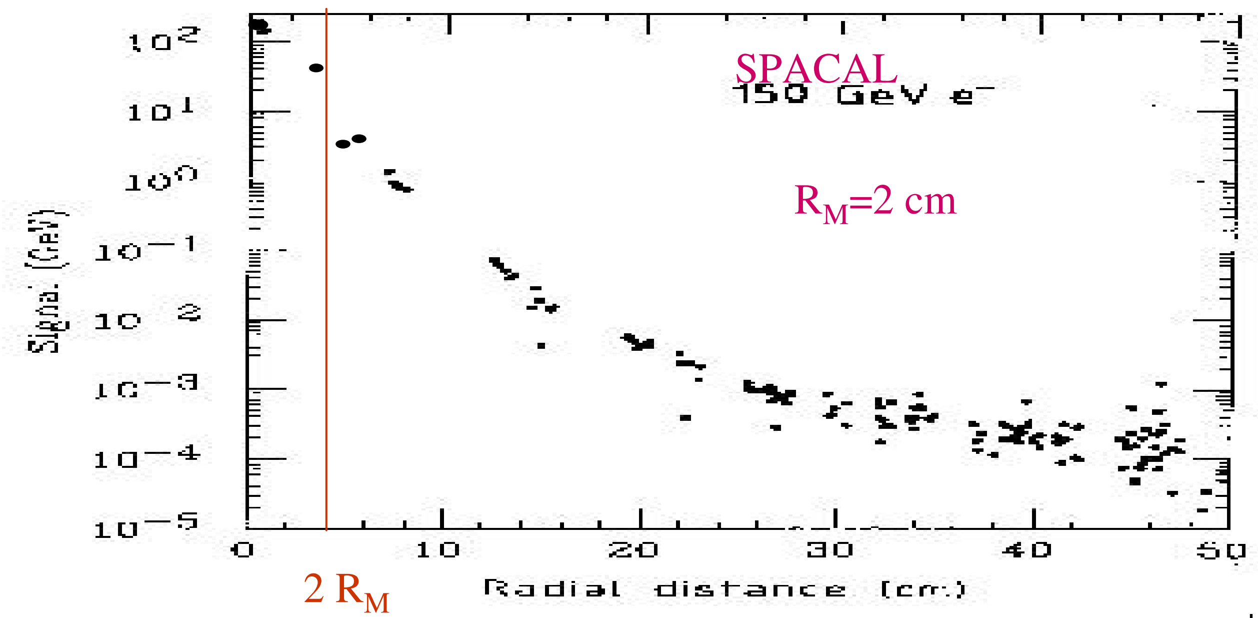
Soft particles undergo multiple Coulomb scattering in the calorimeter material and can travel at large angle from the shower axis.

The characteristic quantity is the Molière Radius

$$R_M\ (g/cm^2) \sim 21\ \text{MeV}\ \frac{X_0}{\varepsilon}$$

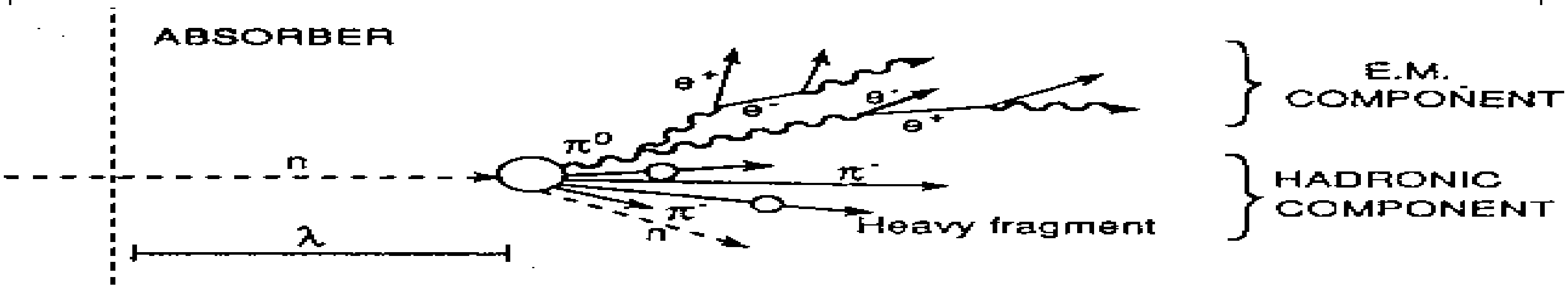
Transverse size: 95% of shower contained in 2 R_M

Most calorimeters :
R_M ~ cm
ok showers are narrow.
This set the granularity to measure shower profile



Hadronic Calorimeter

The principles of an hadronic calorimeter is similar to an em one. An hadron interacts in the material and produces charged and neutral hadrons (mainly π_0) and nuclear fragments. The process goes on up to an energy of secondary hadrons below the threshold energy for π production (~ 240 MeV) .
This energy is equivalent to the critical energy for an em showers



em O(50%) ; $h^{\pm}$ O(25%) ; Not visible (n, heavy fragments) O(25%) ; escape (ν) O(2%). Large fluctuations

Hadronic shower properties

The scaling variable is $t = x/\lambda$

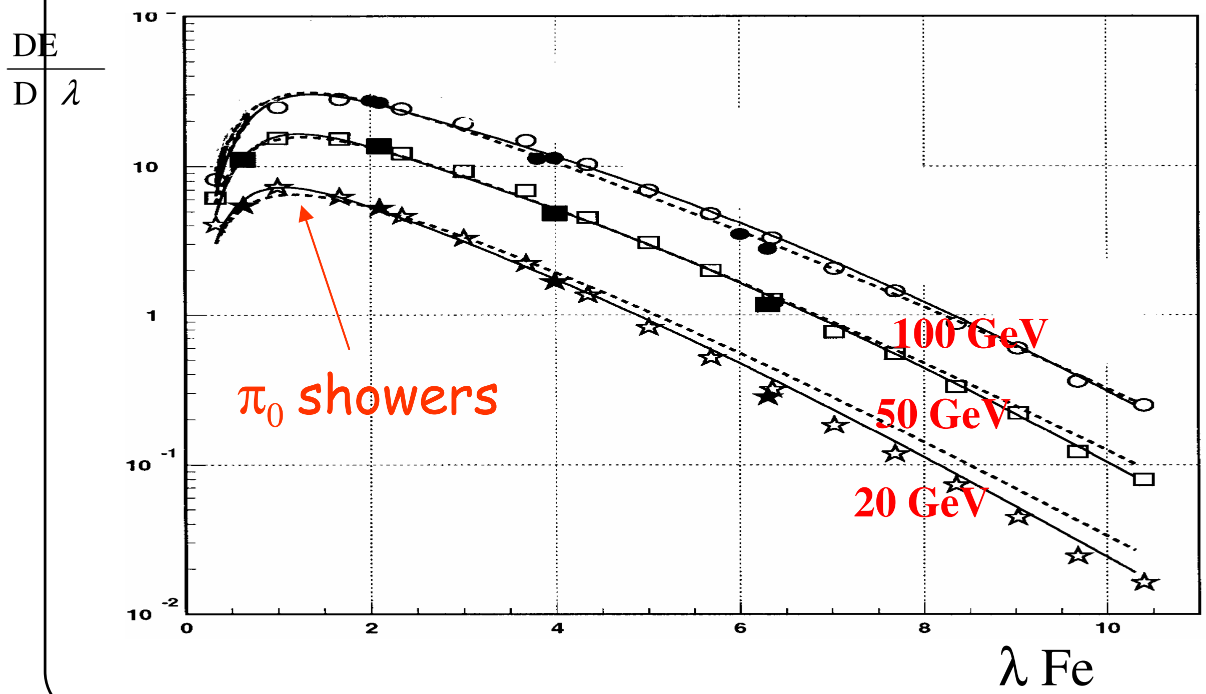
λ = interaction length ≡ mean free path between two inelastic nuclear interactions $\lambda \approx 35\ g\ cm^{-2}\ A^{1/3}$ e.g. λ = 17 cm (Fe) , 10 cm (U) ,9.6 cm (W).

Fenomenologically:

Shower maximum: $t_{max} \approx 0.2 \ln E(GeV) + 0.7$

$t_{95\%} = t_{max} + 2\lambda E^{0.13}$

Ex: π 100GeV : $t_{max} = 1.6$; $t_{95\%} = 7$

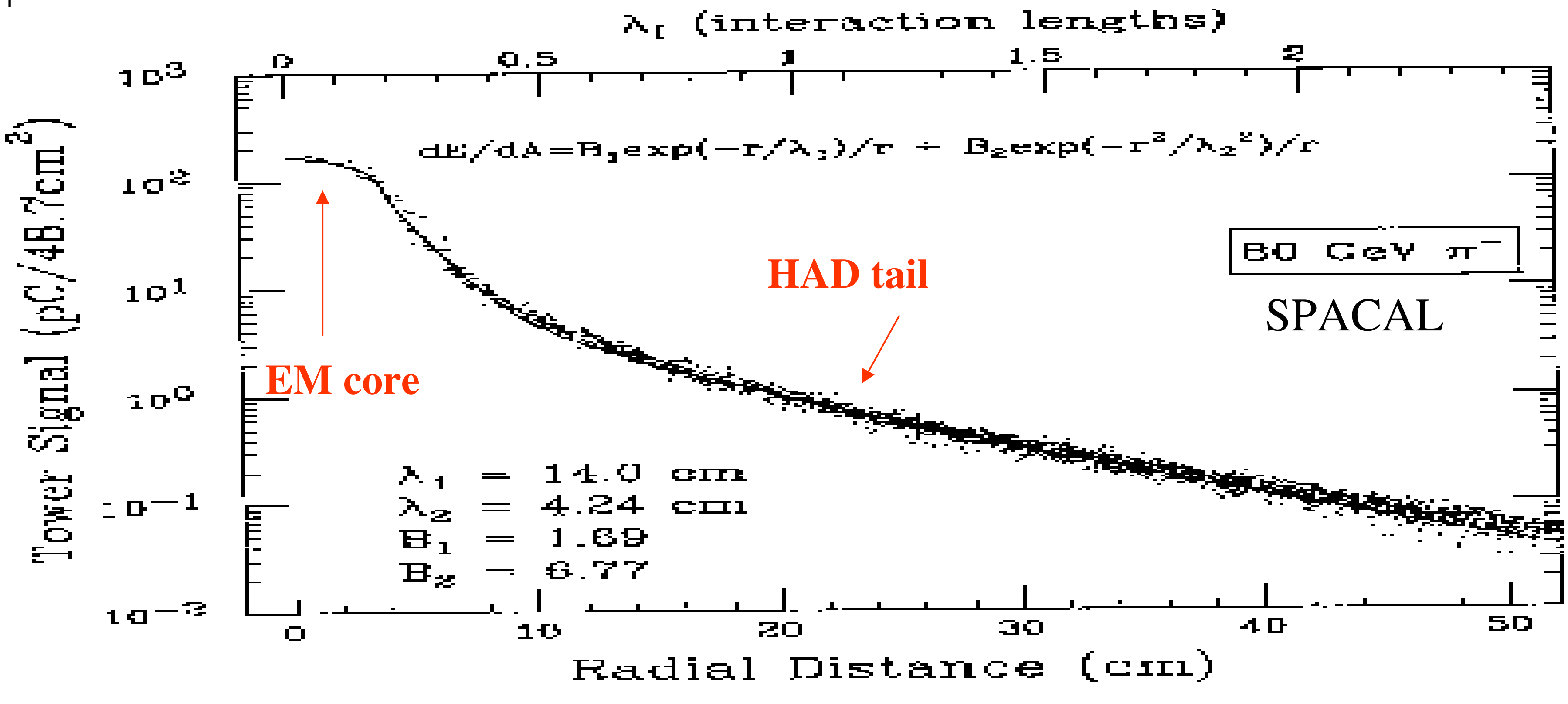


This means a > 1m thick calo. Sampling only possible

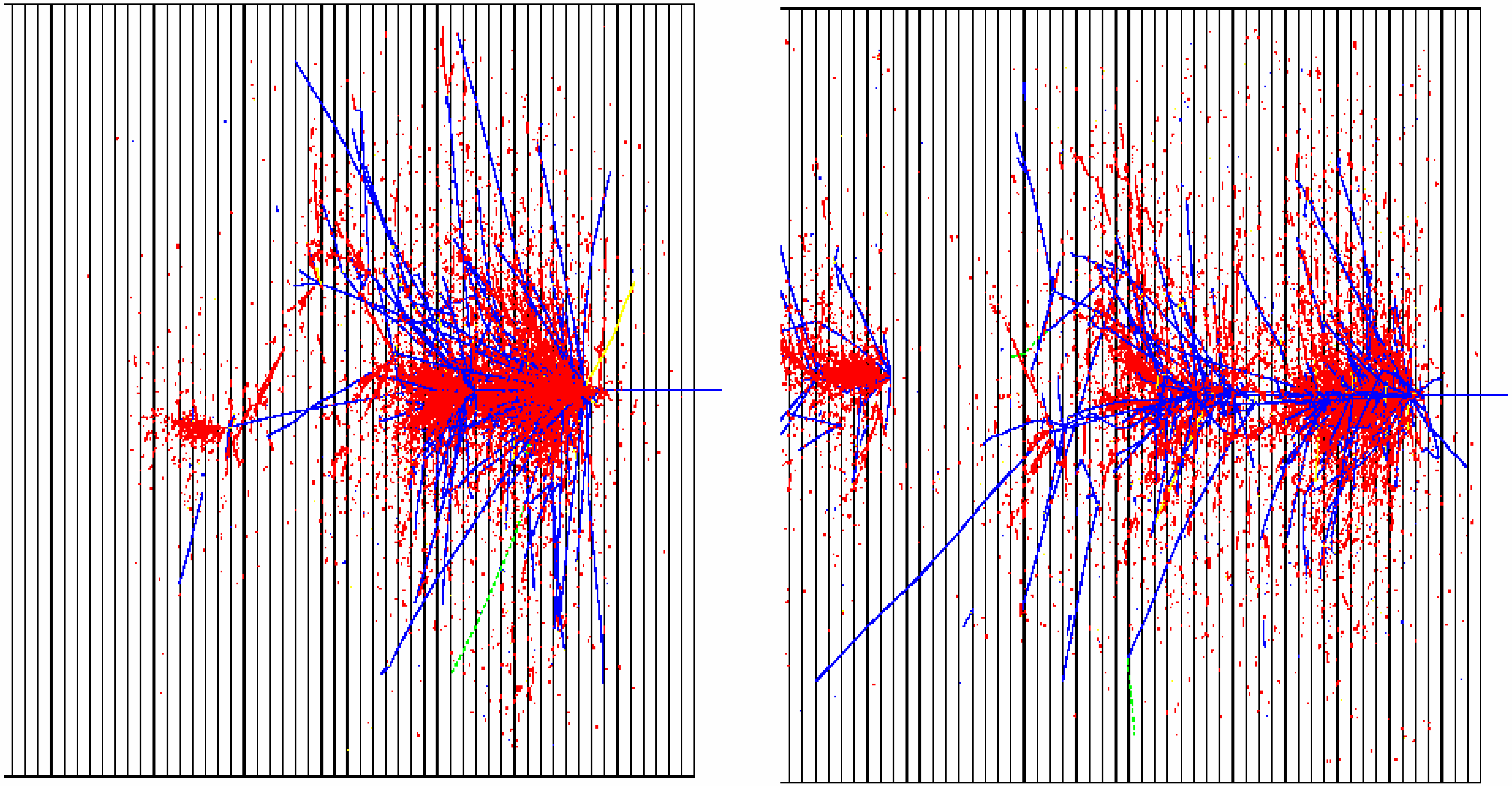
π in prototype of ATLAS Fe-Sci Tile calorimeter
Closed symbols: test-beam data
Open symbols: MC

Lateral shower profile

The mean transverse momentum of the secondary hadrons is about 300 MeV, same order of magnitude of the production threshold energy (~ 240 MeV) . Consequently the lateral shower width should be of the order of λ which set the cell granularity



150 GeV Pion Showers in Cu



red - e.m. component
blue - charged hadrons

Energy Measurement and resolution

A fraction of the energy of the em particle goes to ionization. This fraction is proportional to the incident energy.

The number of tracks generated in a shower is E/ε and the total track lenght T is

$$T_0 \approx X_0 \frac{E_0}{\varepsilon}$$

The intrinsic resolution of an ideal calorimeter, is due to fluctuations in T_0 since the cascade process is random in nature

$$\sigma(E) \sim \sqrt{T_0} \Rightarrow \frac{\sigma(E)}{E} \sim \frac{1}{\sqrt{T_0}} \sim \frac{a}{\sqrt{E}}$$

Since in a sampling calorimeter the tracks in the sensible device are only a part their resolution is worse than in an homogenous one.

Energy resolution: real calorimeter

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

a : stochastic term

Intrinsic fluctuations from shower physical development as previously discussed

b: Noise term

It is the term introduced by the read out chain: photomultipliers, preamps etc. It is constant and important at low energies

c: Constant term

includes any instrumental effect which produces response variations in the detector like : detector geometry, imperfections in the mechanics or readout, temperature gradients, non-uniform aging,, radiation damage. It dominates at high energy and define the " construction quality of the calorimeter"

Energy resolution: real Calorimeter

d. Longitudinal leakage

A shower has a long tail of soft particles and since a calo cannot be infinitely long part of the energy is lost. The leakage is more important at high energy and is corrected by SW

e. Upstream E losses:

Usually there are materials in front of the calorimeter. (Ex: Atlas has at least 1 X_0 (magnet) + 0.5 X_0 (tracker) at η=0). Electrons have brems and photon may convert. Part of the energy is lost and can be recovered measuring the energy deposited by the shower in a thin detector (preshower) in front of the calorimeter and applying a SW weight

f. Inactive regions:

There are always dead regions to allow for services and transition regions between detectors. At LHC tipical region is the crack between Barrel and EC. Here the measurement is usually strongly degraded. At the Tevatron we have cracks in many places…between wedges (at CDF), at the cryostat (D0), "chimney" (for cables) at CDF..

A calorimetric detector

The use of sampling calorimeters allows (in a relatively easy fashion) to measure EM energies with

$$\frac{\Delta E}{E} = \frac{15\%}{\sqrt{E(GeV)}} \equiv 1.5\% \; at \; E = 100\, GeV$$

- ☞ In a tracker in which $\Delta PT/P_T^2 = 10^{-3}$ momentum of an electron with E=100 GeV would be measured with a 10% accuracy
  - ⇨ Without taking into account the bremmstrahlung

Quarks appears as shower of particles

- ☞ Resolution for hadrons

$$\frac{\Delta E}{E} = \frac{70\%}{\sqrt{E(GeV)}} \equiv 7\% \; at \; E = 100\, GeV$$

- ☞ Missing energy UA1: $\Delta E_{x,y} = 0.4\sqrt{\Sigma_i |E|^i_T}$

Speed and calorimetry

Plastic scintillator provides trigger thanks to its quick response

- ☞ UA calorimeters, made of sandwiches of lead(iron)-scintillators are automatically Ok from the point of view of timing
  - ⇨ They also provide the possibility to create a "topological" trigger in which "showers" of particles are selected (jets)
  - ⇨ Ditto for high energy electrons
  - ⇨ MIP signal for muons

- ☞ Nowday triggers are very complicated objects but in many aspects calorimeters are still the cornerstone

The new age

UA1 and UA2 built in the early eighties

- ☞UA1 as a magnetic spectrometer (dipole)
- ☞UA2 without magnet and less hermeticity
  - ⇨Jet thought to be a key to new physics and worry of magnetic field sweeping away relevant particles
    - →Some success at the begining
    - →Weaker choice on the medium/long run
- ☞UA1 got the NP

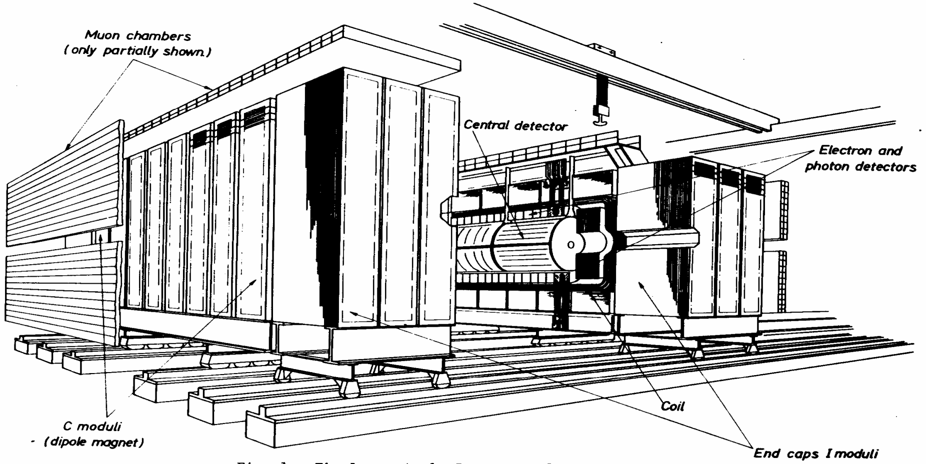
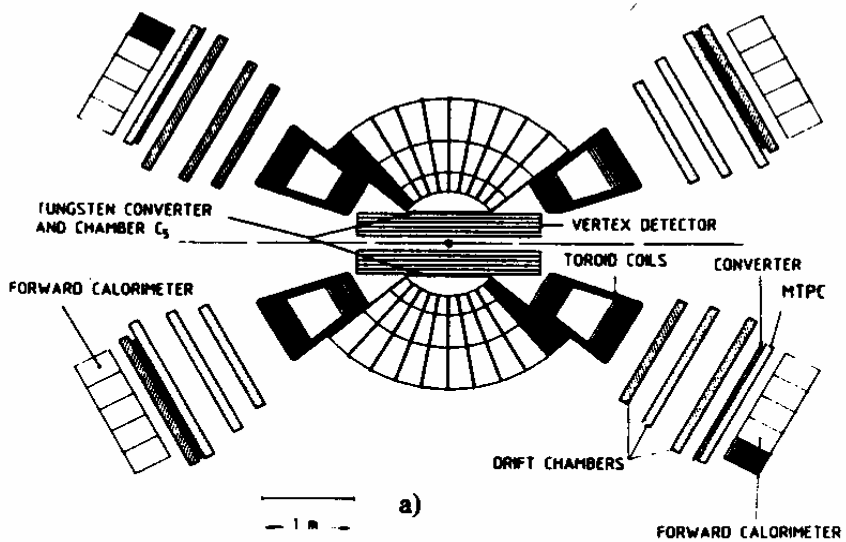


Fig. 1. The Large Angle Detector of the UA1 Apparatus.



UA2 and UA1

UA1 magnetized calorimeter

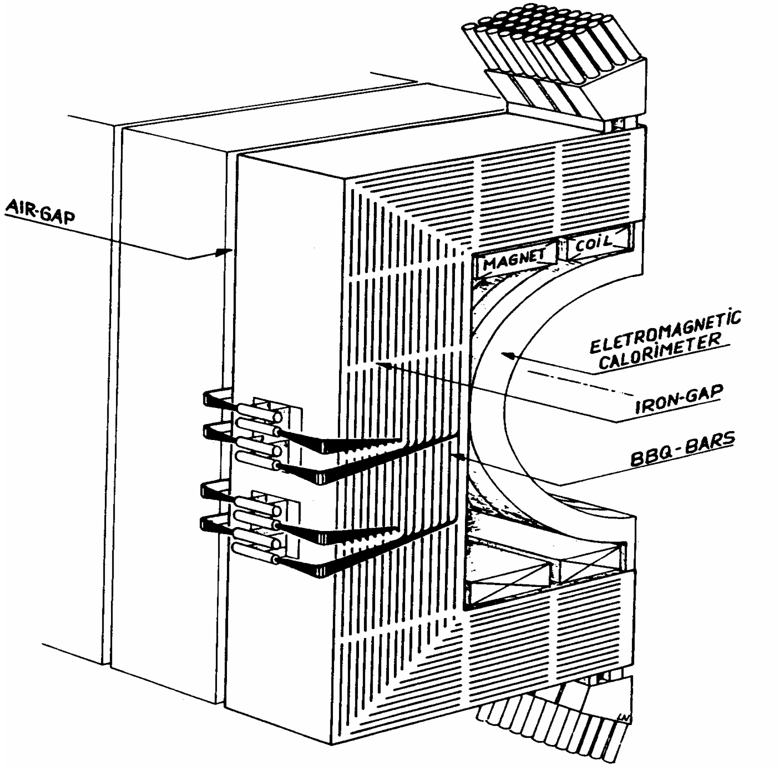
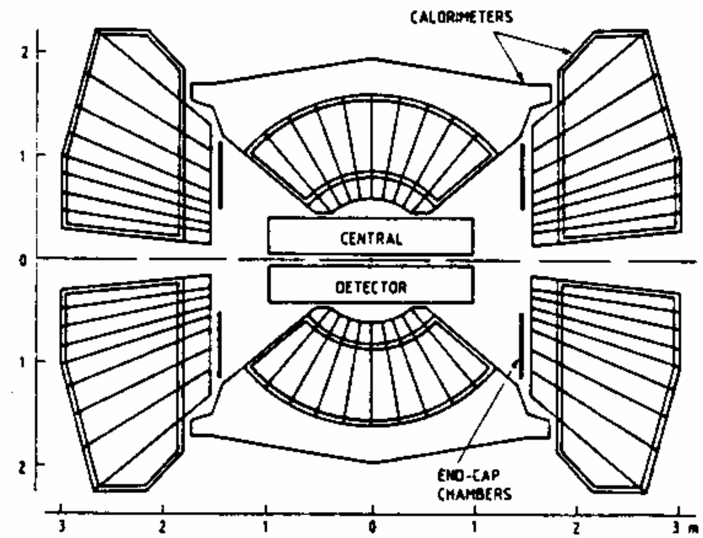


Fig. 2. One of the 16 "C" models comprising the magnet yoke and hadron calorimeter.

UA2' cross section



b)

Projective towers

UA2 was the first experiment to use *projective* calorimetric towers

- ☞Pointing to the IP

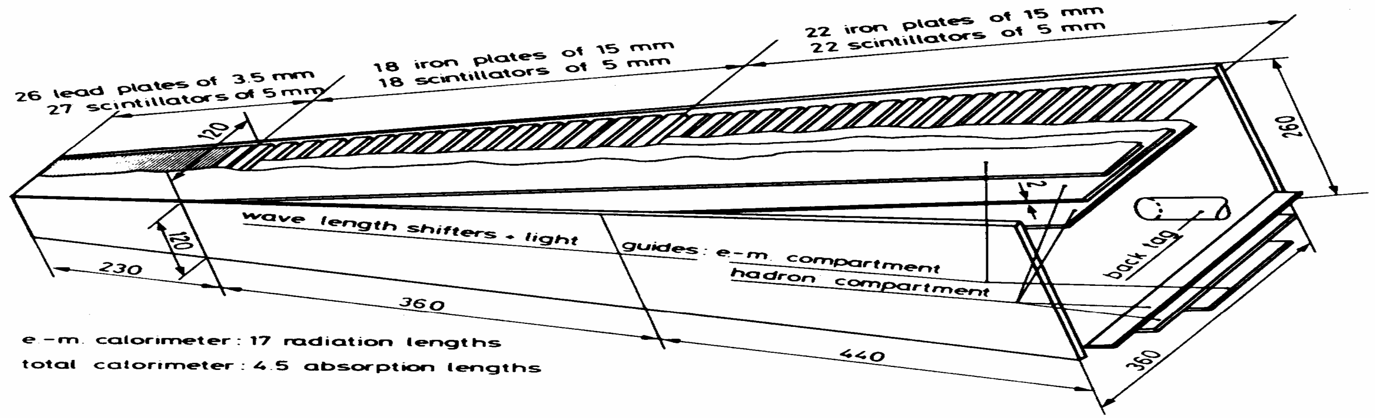


Fig. 6 : Central calorimeter cell.

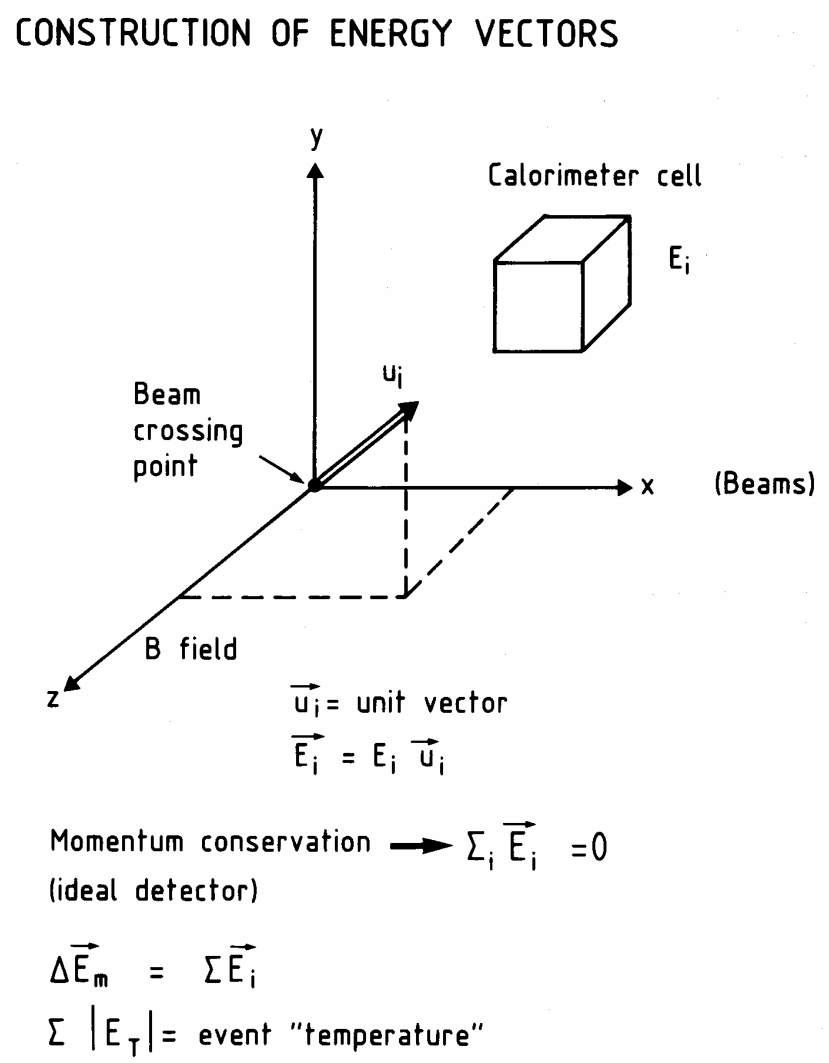
- ☞three compartments
  - ⇨Pb-scintillator sandwich 17 X0 thick (e.m. calorimeter)
  - ⇨two Fe-scintillator sandwiches 4,5 λ thick (hadron calorimeter)

UA1..

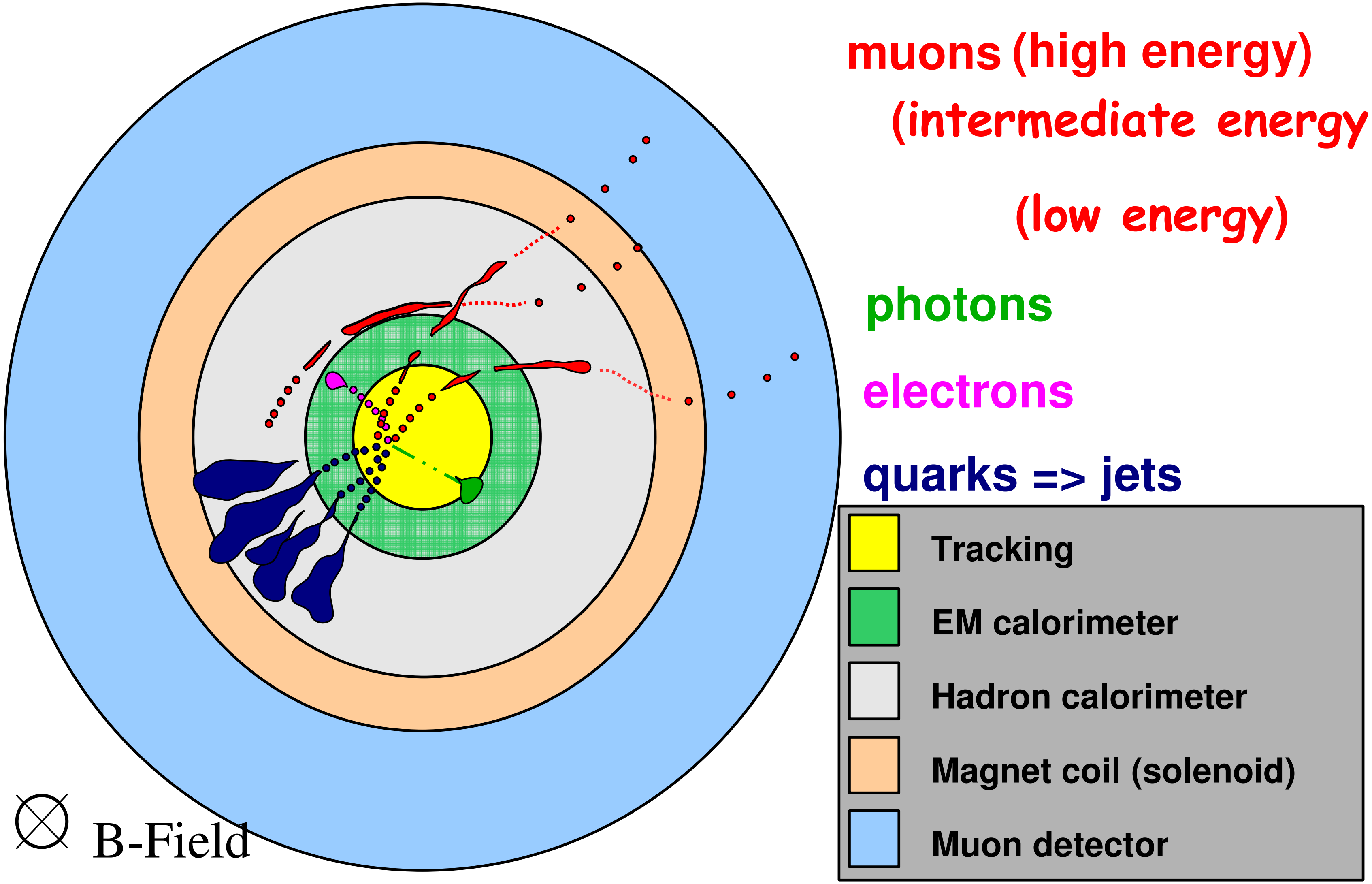
Neutrino transverse energy in UA1:

- The entire calorimeter was used to measure the transverse momentum of the escaping neutrinos.
- A transverse energy vector was associated to each cell and the total "transverse energy vector" was computed.
  - ⇨ The neutrino transverse momentum was obtained as

$$\vec{E}_{t,\nu} = -\sum \vec{E}_{t,cells}$$



Working principles of a detector at an hadron collider



Let's see a movie..

Working principles as they operate at
CMS

The big jump: from Sp$\bar{p}$S to the Tevatron

From cms energy of 546 to 1800 GeV it is a big jump in energy

Even more relevant the change in rate of interactions

- ☞ An optimal exploitation of those changes required a change philosophy
  - ⇨ Move analysis as much as possible from offline to online
    - → Define physics objects and processes of interests
      - Anything which is not logged is lost forever

$$\langle n_{\mathrm{int}} \rangle = L \times \sigma$$

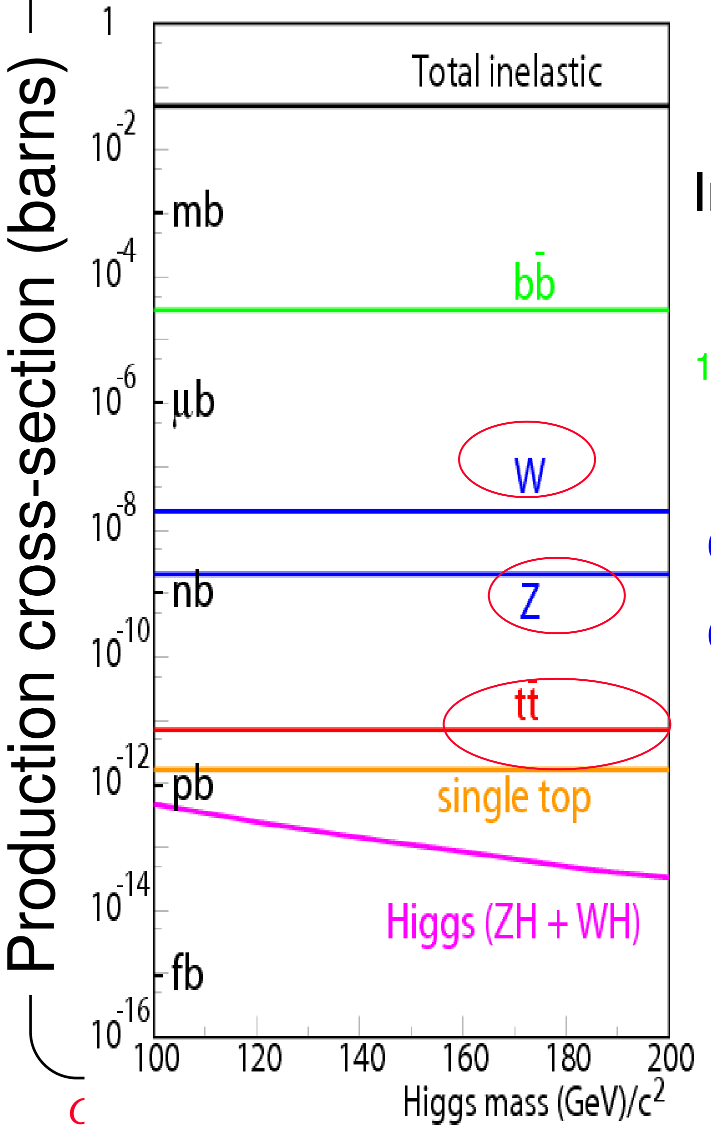
Tevatron parameters

$$L = \frac{10^{-6} fBN_p N_{pb} (6\beta_r \gamma_r)}{2\pi\beta^* (\varepsilon_p + \varepsilon_{pb})} H(\sigma_l / \beta^*)(10^{31} cm^{-2} s^{-1})$$

	Run I (6x6)	Start run II(36x36)	Run 2 now	units
Protons/bunch	230	200	250	10^9
Pbar/bunch	55	26	30	10^9
Total Pbar	330	900	1080	10^9
Peak Pbar prod. rate	20	50	230 rec.	10^9/hour
Pbar:AA→ low β		0.30	0.80	
P emittance	23	20	20	π mm-mr
Pbar emittance	13	18	5-7	π mm-mr
Bunch length (p, rms)	.60	0.37	0.28	m
Bunch length (pbar, rms)	.60	0.37	0.28	m
Typical lum.	1.6	3.2	25-28	$10^{31}cm^{-2}s^{-1}$
Integrated L	3.2	5-6.7	45	pb^{-1}/week

Running with 36x36 bunches ($\beta_r\gamma_r$=1045, B=36, f=47.7 KHz)

The environment (Tevatron)



In 1 fb^{-1}

1×10^{11}

6×10^6

6×10^5

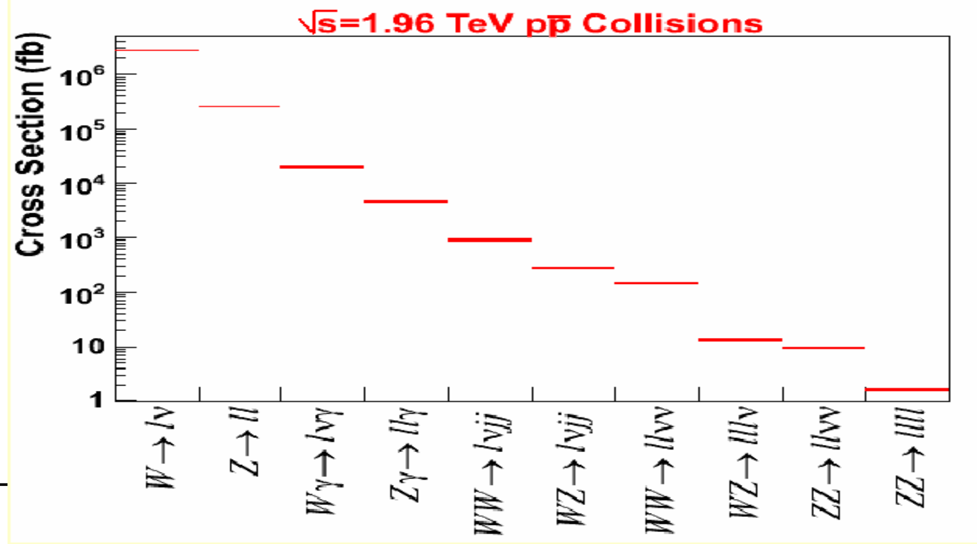
14,000

5,000

100 ~ 10

Taking data at $L=2 \times 10^{32} cm^{-2} s^{-1}$…implies

- Several interactions per x-ing
  - ⇨ Tough life
- We can walk down the stair on the left
  - ⇨ if our triggers are able to select the needle in the haystack



Physics at a hadron collider…

…Trigger is everything!

High p_T lepton
High E_T jet, photon
High Missing E_T (MET)

Look at all collisions
Select interesting events (≈100 Hz)
For later offline analysis

1/60,000 selected

Process	Cross-section	Event Rate
Inelastic $p\bar{p}$	60 mb	6 MHz
$\bar{p}p \to b\bar{b}$ (b p_T>6 GeV, $\lvert\eta\rvert$<1)	10 μb	1 kHz
$\bar{p}p \to WX \to \ell\nu X$	5 nb	0.4 Hz
$\bar{p}p \to ZX \to \ell\ell X$	0.5 nb	0.04 Hz
$\bar{p}p \to t\bar{t} \to WWbb \to \ell\nu bbX$	2 pb	0.0002 Hz
$\bar{p}p \to WH \to \ell\nu bb$ (if M_H=120GeV)	15 fb	0.0000015 Hz

Assuming L =100x10^{30} cm^{-2}s^{-1}, ℓ=e or μ

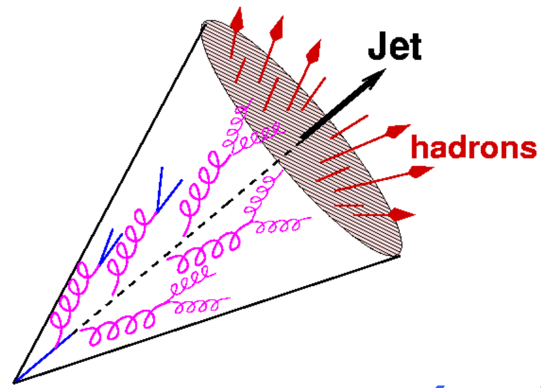
Collisions at hadron colliders

Hard scattering is only part of it

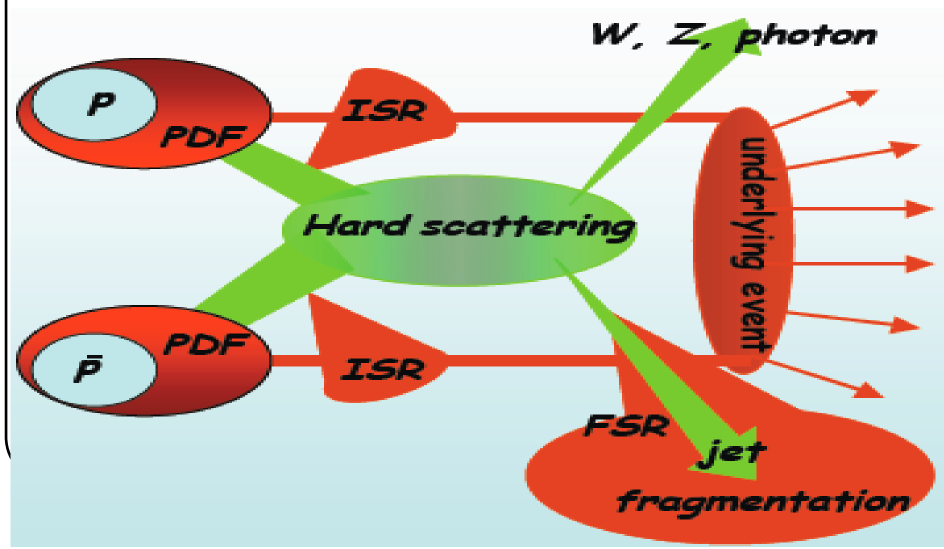
Parton Distribution Functions (PDF): fraction of (anti)proton momentum carried by ingoing partons

Underlying Event (UE): remaining debris of the collisions

- Initial and Final State Radiation (ISR, FSR): extra gluons emitted in initial/final state.
- Jets: quarks/gluons fragmentation and recombinations in hadrons



All those processes (and more) interacts with our measurements



Basic idea for CDF-I

Build a spectrometer
- ☞ Magnetic field
- ☞ Very good momentum resolution

Build a calorimeter
- ☞ Circa 1981…how are jets?
  - ⇨ Projective towers to reconstruct jets
    - → Heavy flavout ID? Leptonic decays?

Lepton ID
- ☞ Electrons, muons, neutrinos
  - ⇨ Where is tau? What is tau?

Particle Id?
- ☞ No way

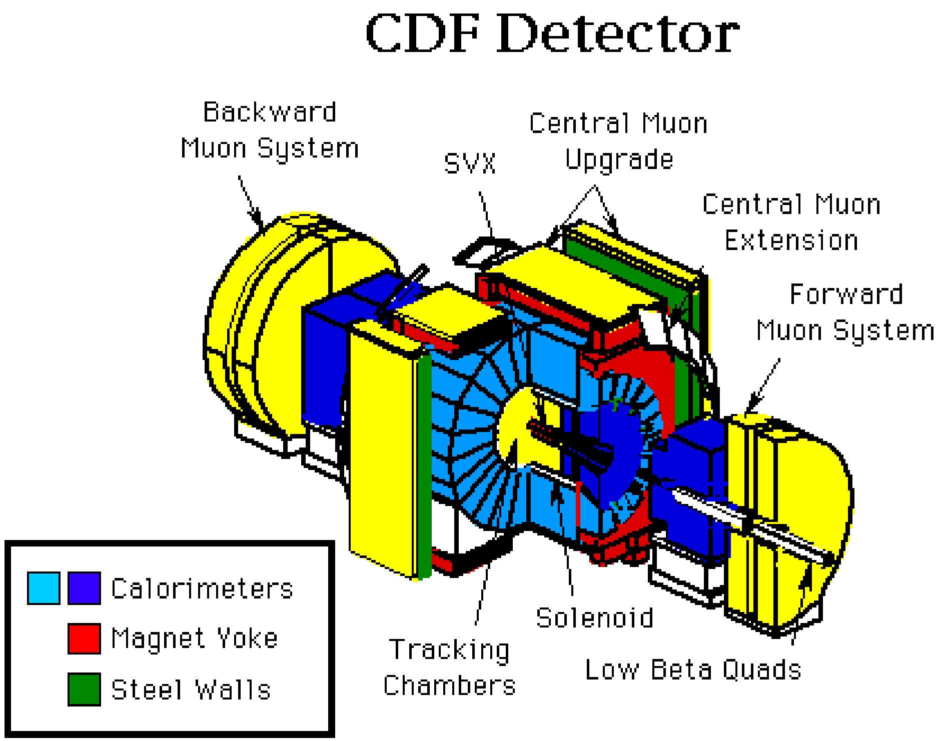
Three trigger levels
- ☞ L1, L2 hardware, L3 semplified version of offline running on a farm of processors (VAX cluster)

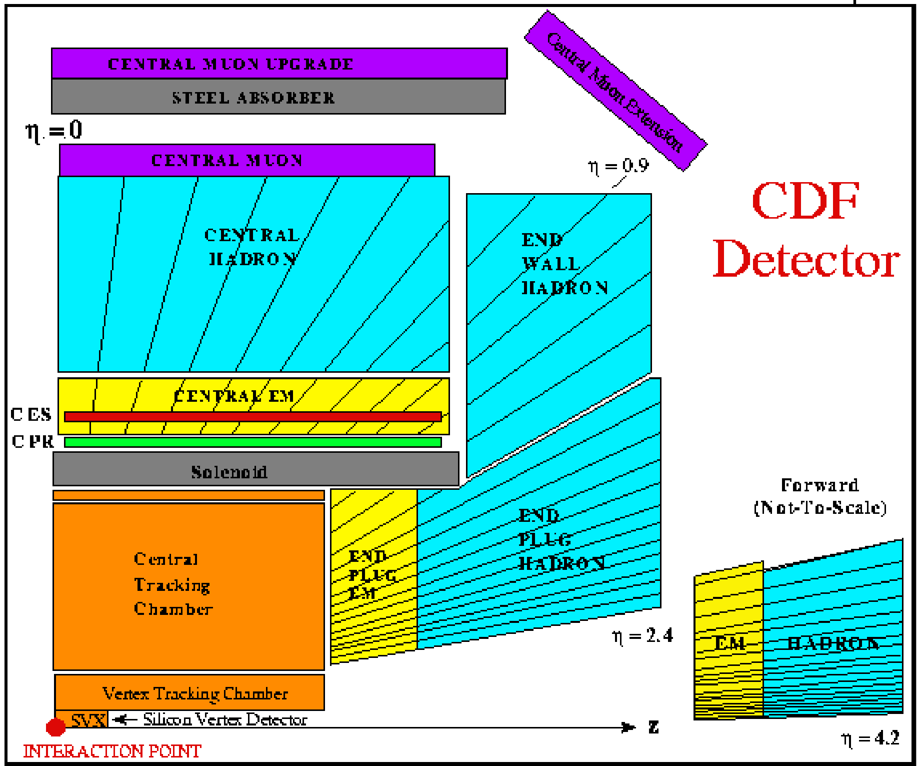
Secondary vertices
- ☞ Last moment appearance in the TDR (the few, the happy few…)

More than 25 years ago!

A scuccessfull experiment: 1985-1996
- ☞ >100 articles, many new particles, top quark discovery..

CDF during Run I



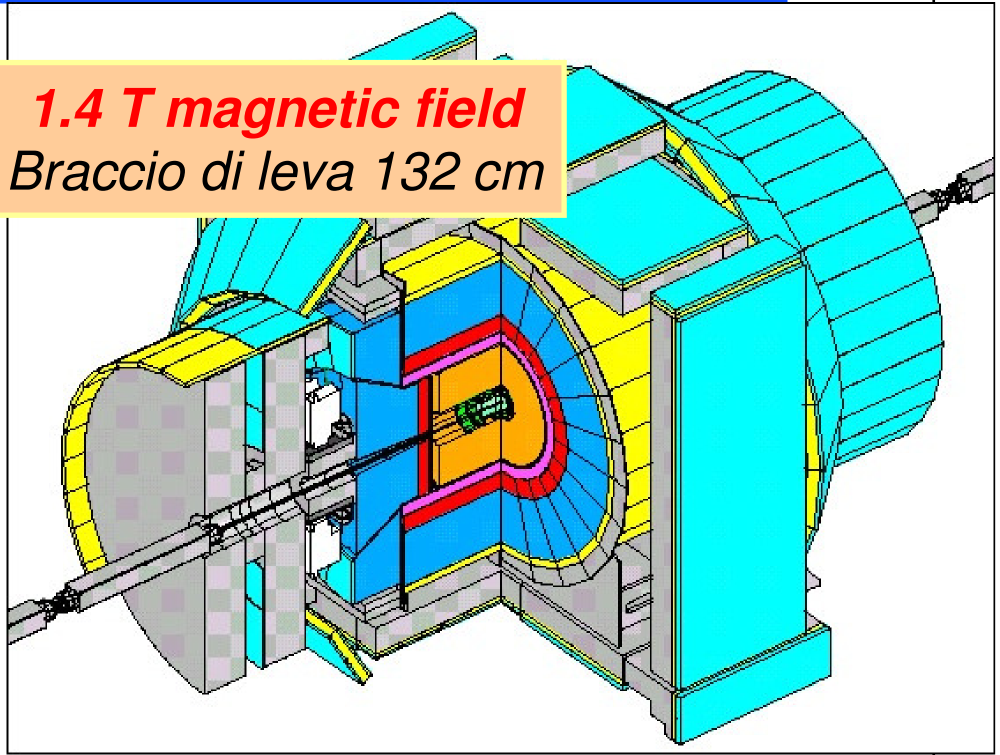


4 layer Si strip detector: 60% acceptance, σ_D = 13 μm
CTC large drift chamber: B=1.4 T, N_{axial} = 60, N_{stereo} = 24, $\Delta p_t/p_t < 0.001\ p_t$
Projective towers calorimeters: $\Delta\eta \times \Delta\phi = 0.1 \times 0.3$, lead/steel-scintillator(PWC)
Central muon chambers: $|\eta| < 1$
Forward calorimeters and muon up to $\eta = 4.2$

CDF II

FE electronics, DAQ and trigger rebuilt

- ☞ New track-trigger L1
- ☞ New L2 trigger on sec.vertices (SVT)
- ☞ New Time of Flight



Tracking system (COT)

- ☞ $\delta p_T/p_T = 0.0005 \times p_T$ [GeV]

Em calorimeter

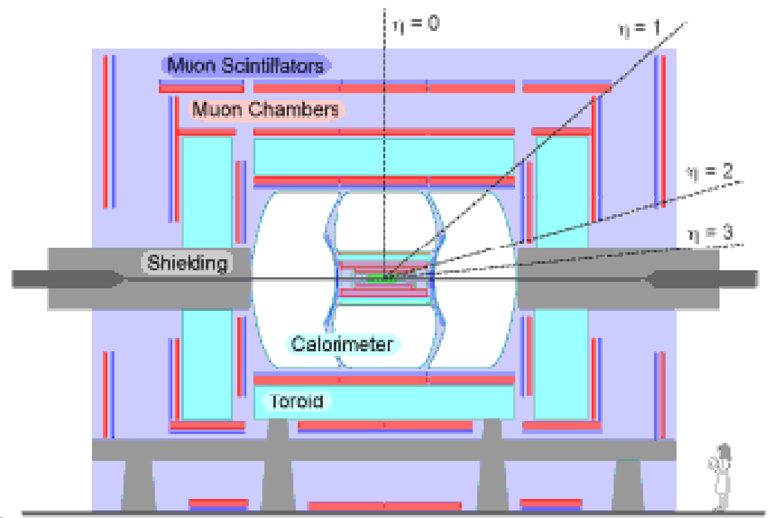
- ☞ $\delta E_T/E_T \sim 13.5\% / \sqrt{E_T} \oplus 1.5\%$ [GeV, $|\eta| < 1.1$]

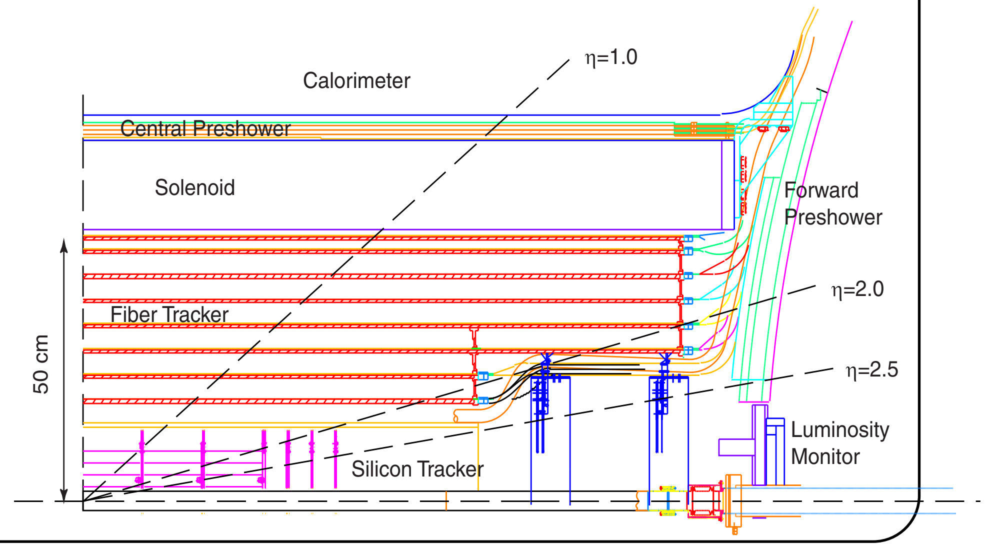
- New tracking system based on silicon sensors 7(8) $|\eta| < 2.8$ coverage
- New drift chamber COT $N_{axial} = 48$, $N_{stereo} = 48$, $\Delta p_t/p_t < 0.001\, p_t$
- New Plug calorimeter (larger coverage and using scintillator)
- Extension of muon chamber coverage $|\eta| < 1.5$ – some are new
- Removed forward calorimeters

D0 upgrade

D0: change of philosophy
- Precision silicon vertexing
- Outer Fiber Tracker (r=0.5m)
- 2.0 T solenoid
- EM+HAD Calorimetry
- muon chambers (|η| < 2.0)

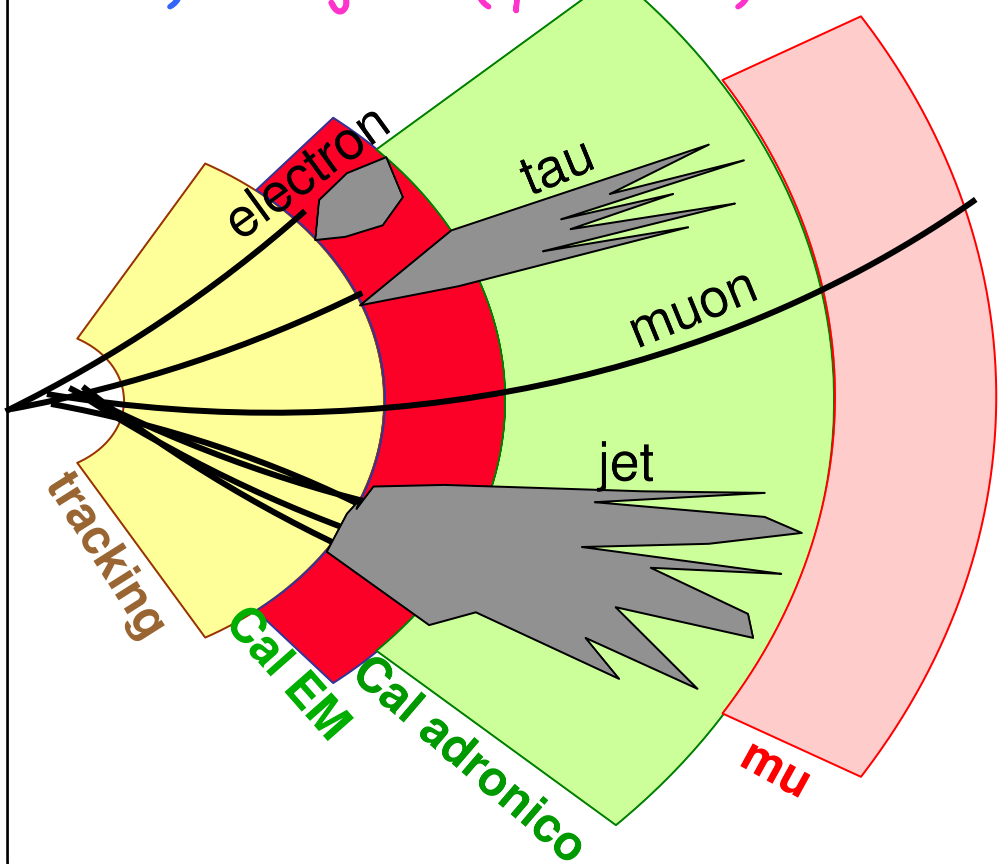
A full magnetic spectrometer
- ☞ Tracking system
  - ⇨ Limited P_T resolution
  - ⇨ 8 layers
    - → Potential problems at high L
- ☞ Improved muon coverage
- ☞ "L00" layer added

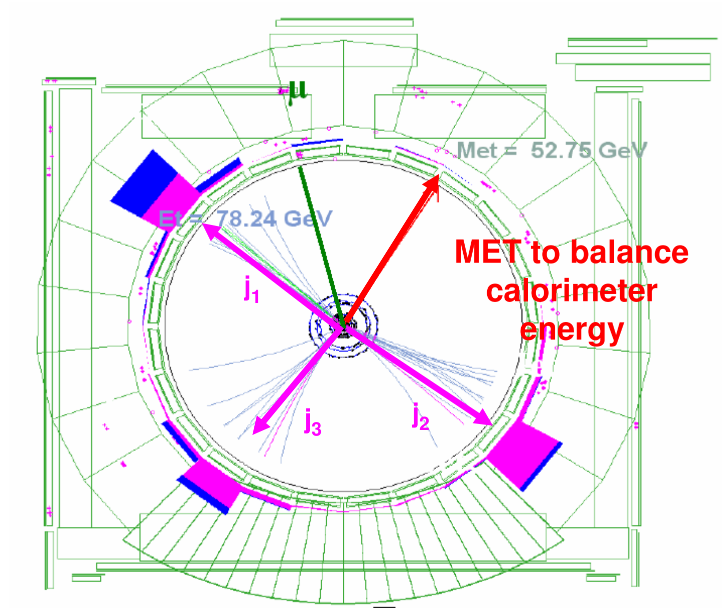




Tevatron Experimental Signatures

EWK and Top Physics are based (mostly) on high p_T leptons (e, μ, τ, ν) and jets (quarks…)





Presence of neutrinos is signalled by Missing Transverse Energy (MET) (missing in calo)