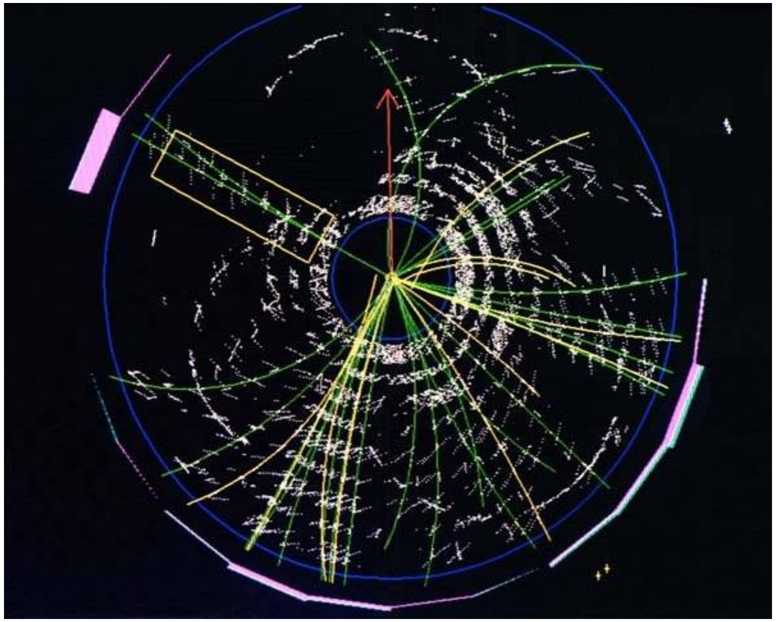
Particle Physics Detectors



Based on the slides prepared by

Robert Roser

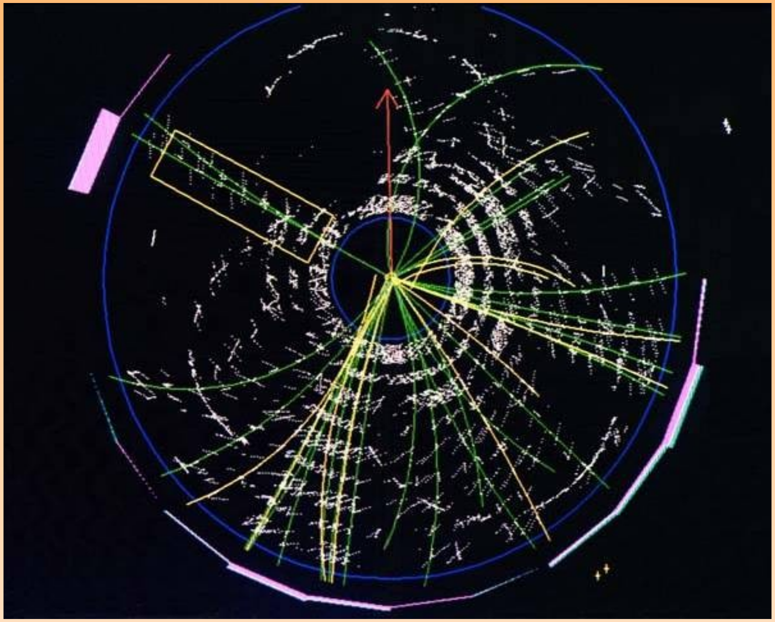
Fermi National Accelerator Laboratory

Particle Physics Detectors

Lecture 1 of 2

Robert Roser

Fermi National Accelerator Laboratory



A Different Kind of Lecture..

Vertex Resolution

$x1, x2 =$ measurement planes

$y1\ , y2 =$ measured points, with errors δy

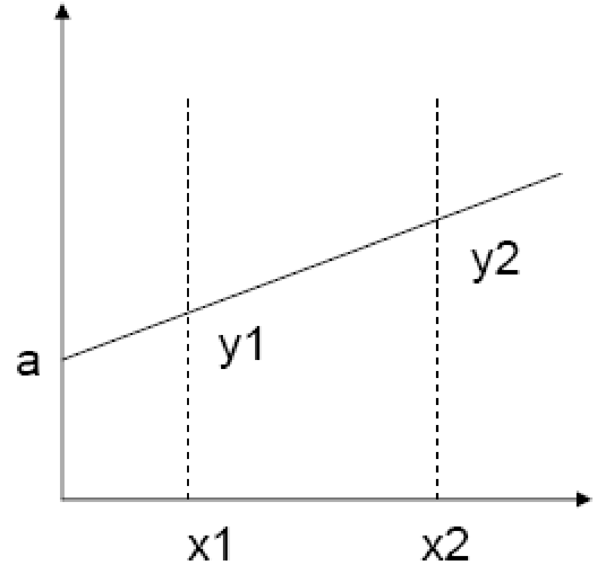
$y = a + bx$

$$b = \text{slope} = \frac{y1 - y2}{x1 - x2} = \frac{y1 - y2}{\Delta x}$$

$$a = \text{intercept} = \frac{1}{2}(y1 + y2) - \frac{1}{2}(y1 - y2)\left(\frac{x1 + x2}{\Delta x}\right) = \overline{y} - b\overline{x}$$

$$(\delta b)^2 = \left(\frac{\partial b}{\partial y1}\right)^2 (\delta y)^2 + \left(\frac{\partial b}{\partial y2}\right)^2 (\delta y)^2 \Rightarrow \delta b = \frac{\sqrt{2}\delta y}{\Delta x}$$

$$\delta a = \frac{\delta y}{2}\sqrt{1 + \frac{8\overline{x}}{\Delta x}}$$



for good resolution on angles (ϕ and θ) and intercepts (d, z_0)

- Precision track point measurements
- Maximize separation between planes for good resolution on intercepts
- Minimize extrapolation - first point close to interaction

Trying Something Different

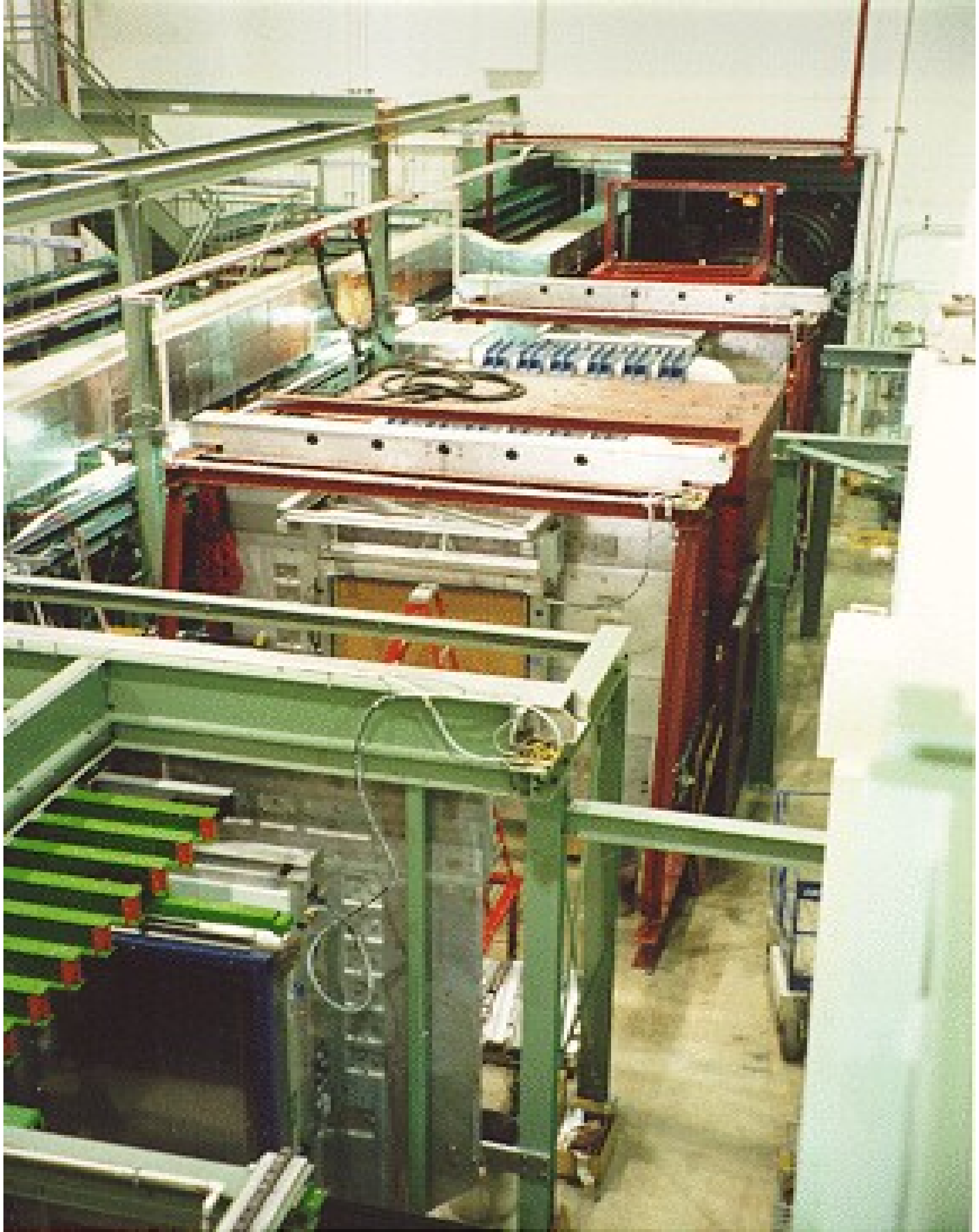
- Lectures are too short to go through the details of silicon, tracking, calorimeters, luminosity….
- Each topic could be the subject of a several hour lecture
- Instead, I will try approach detectors from a designers perspective
- How do you design an experiment
  - What goes into the decisions that are being made?
  - Why does each detector look the way it does?
  - Try to give you an appreciation for what these designers have to do.

Particle Detectors
come in
all sorts of
shapes and sizes

Fixed Target Neutrino Experiment, Fermilab

Fermilab E706

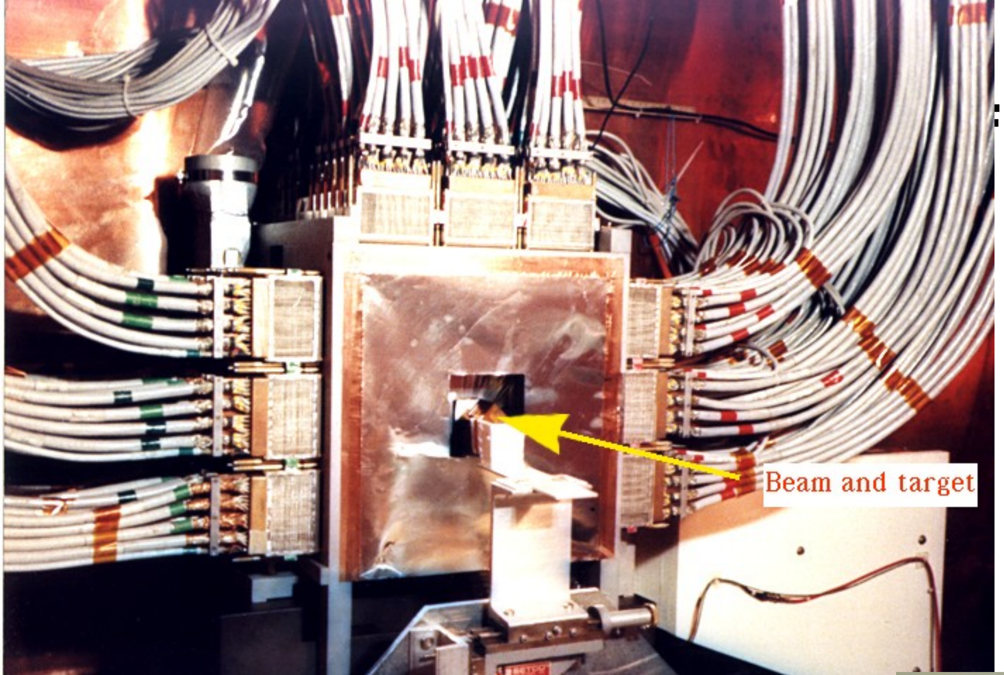
KTEV Hall



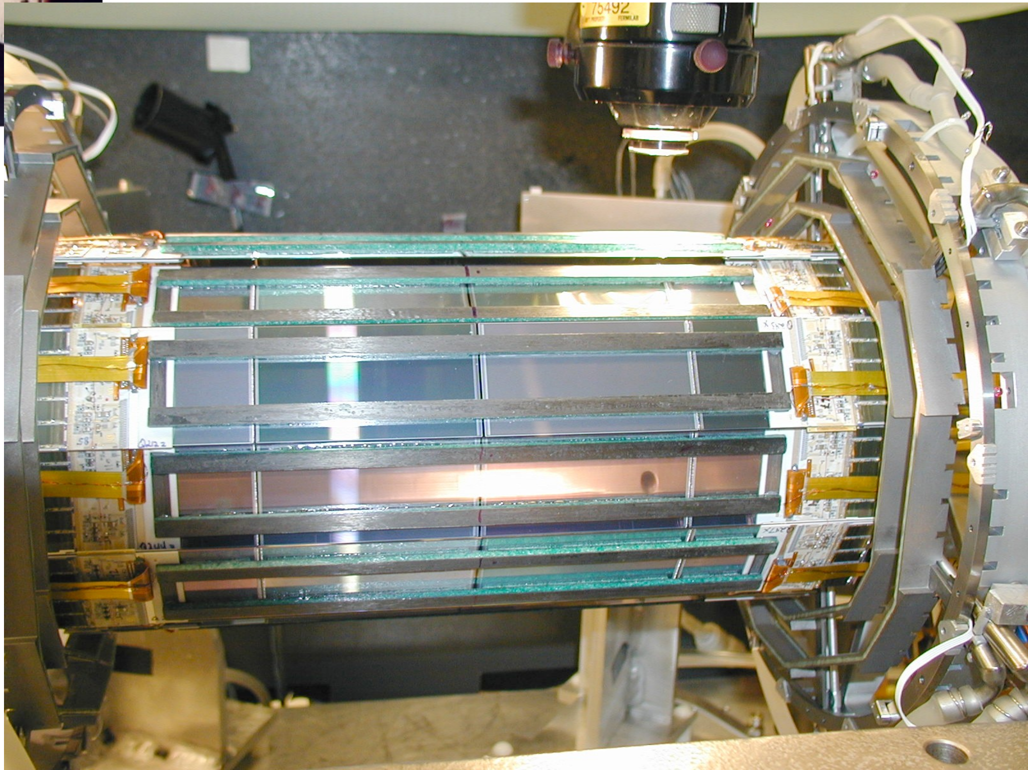
Miniboone, Fermilab

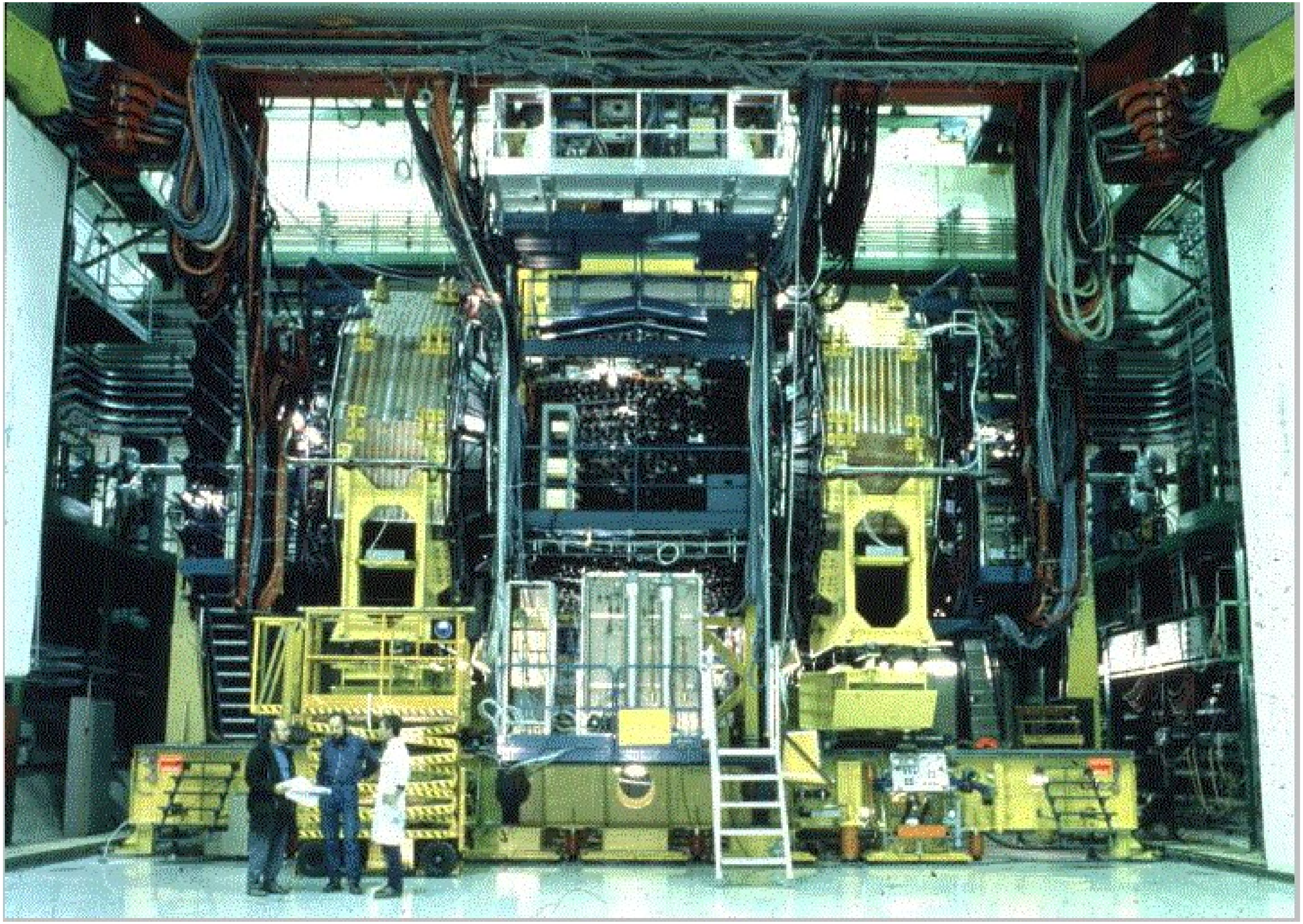
CDMS Fridge and Coldbox in the mine

FNAL E687 Microstrip Detector



FNAL CDF Silicon under assembly





UA2, CERN

Aleph at LEP (CERN)

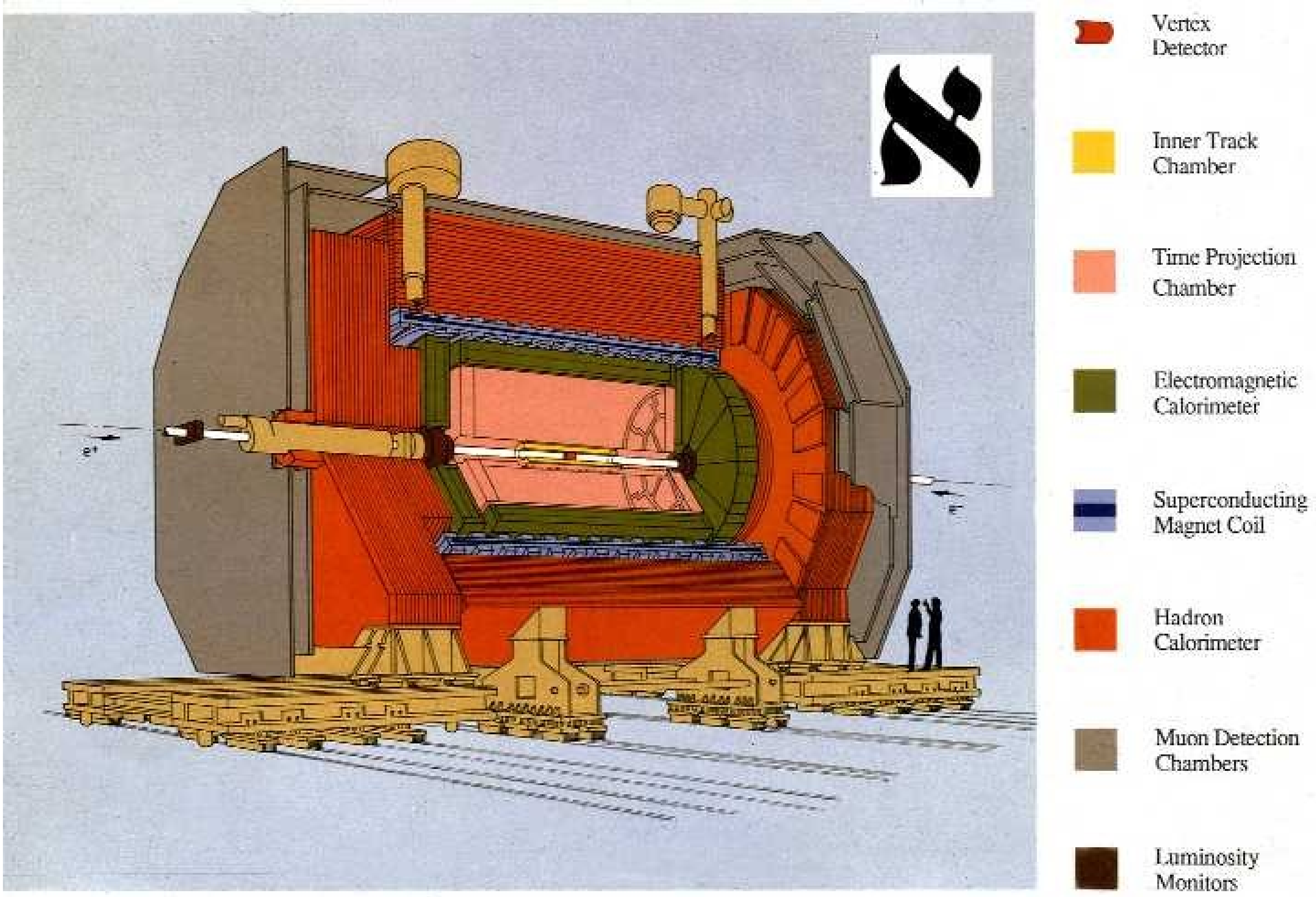
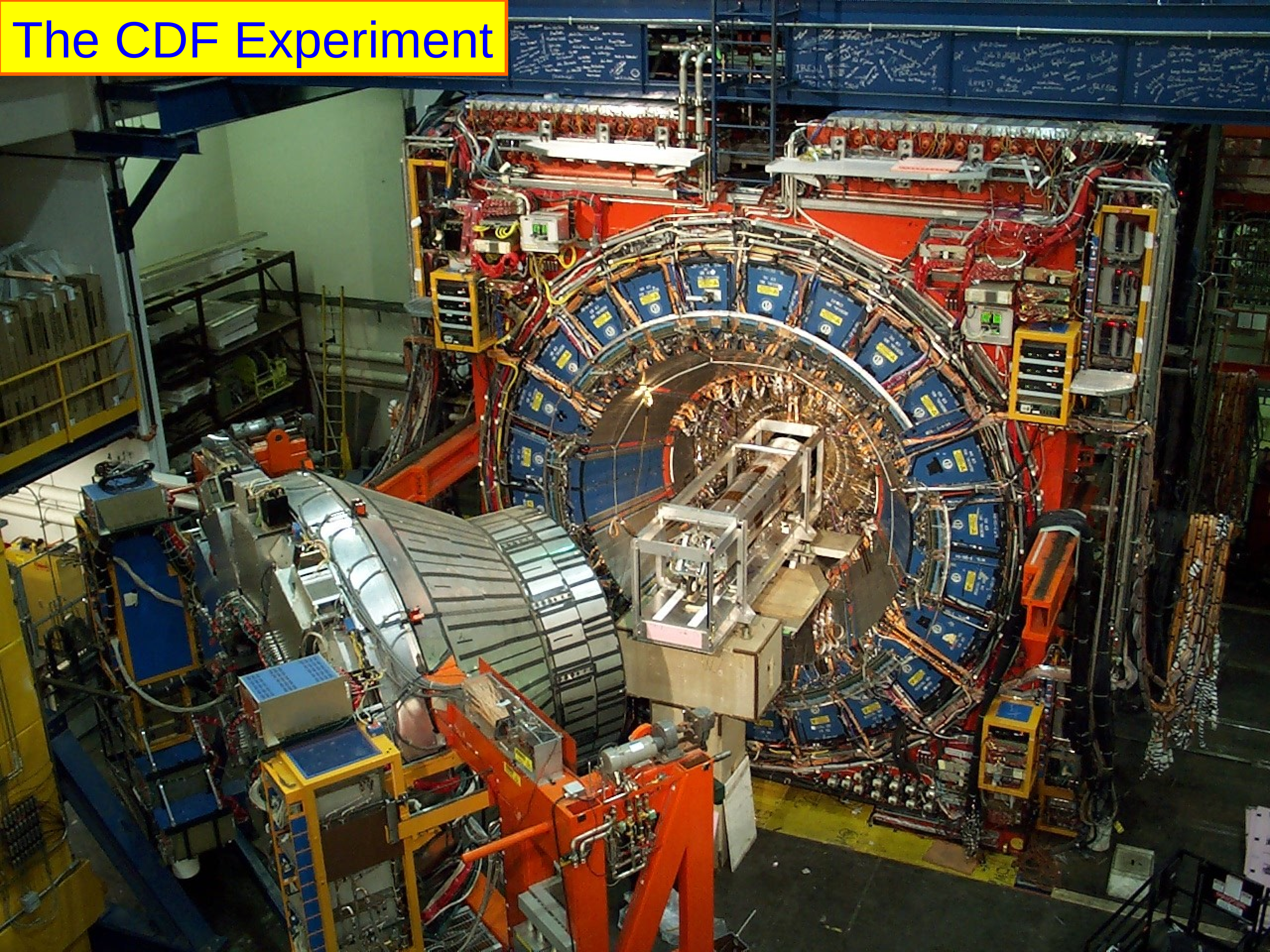
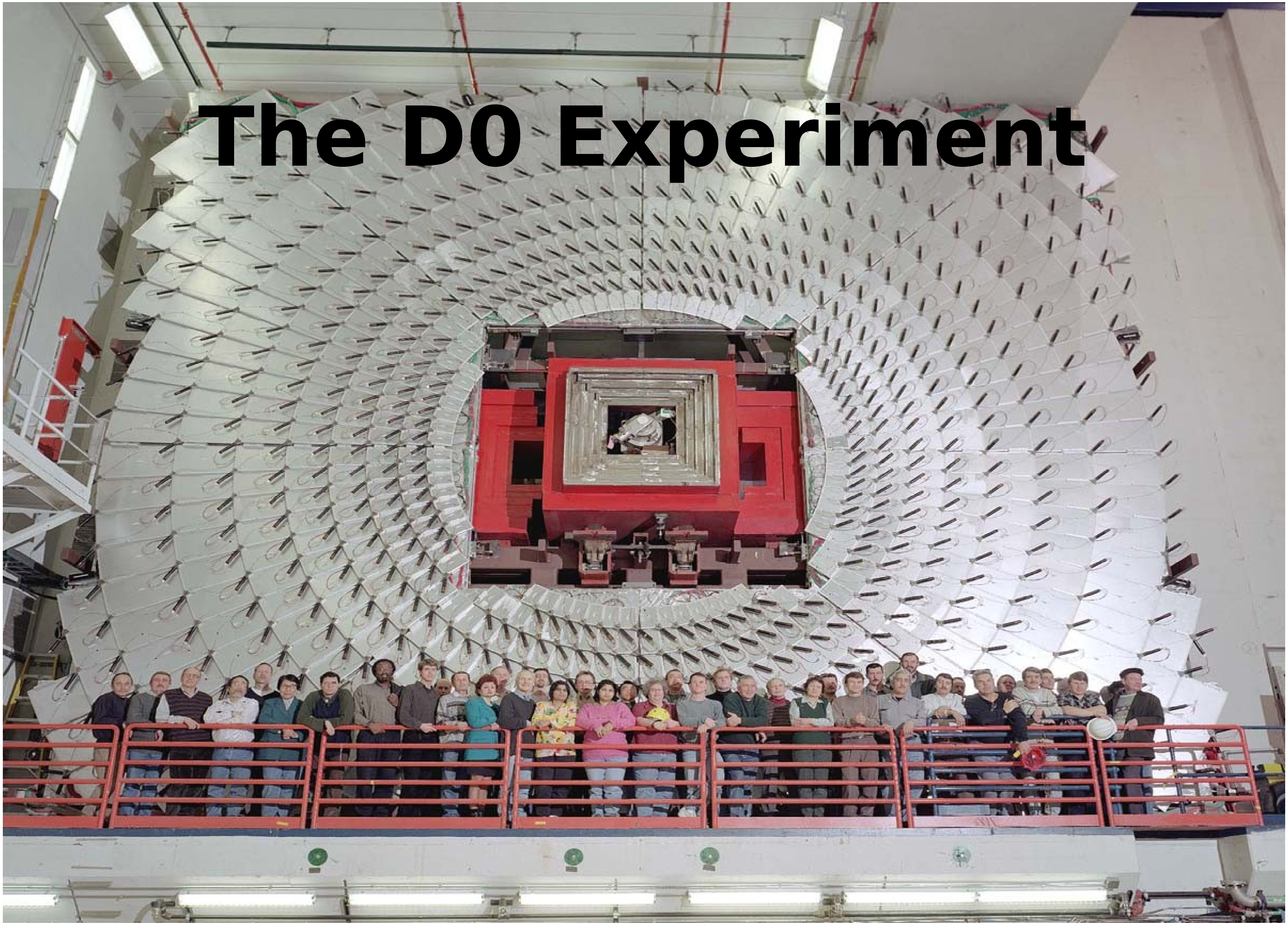


Fig. 1 - The ALEPH Detector

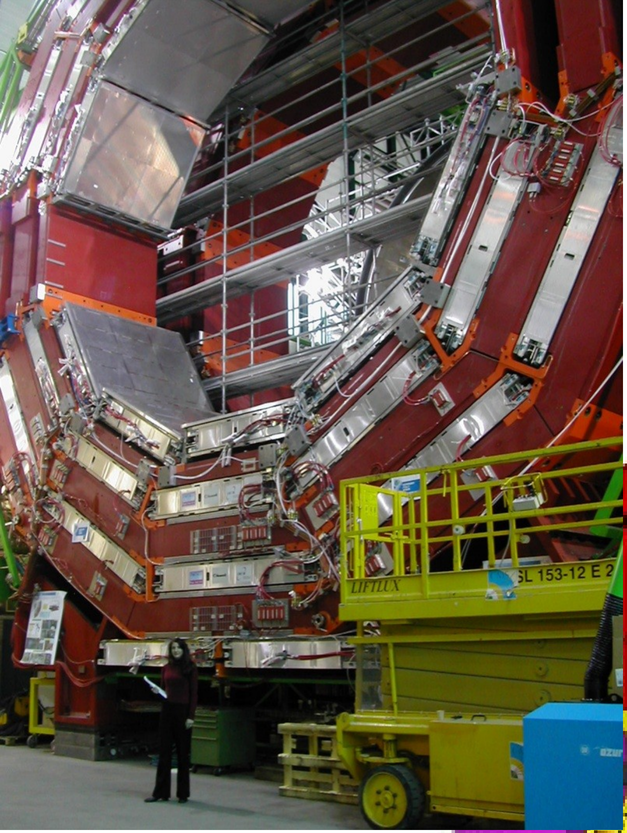
The CDF Experiment

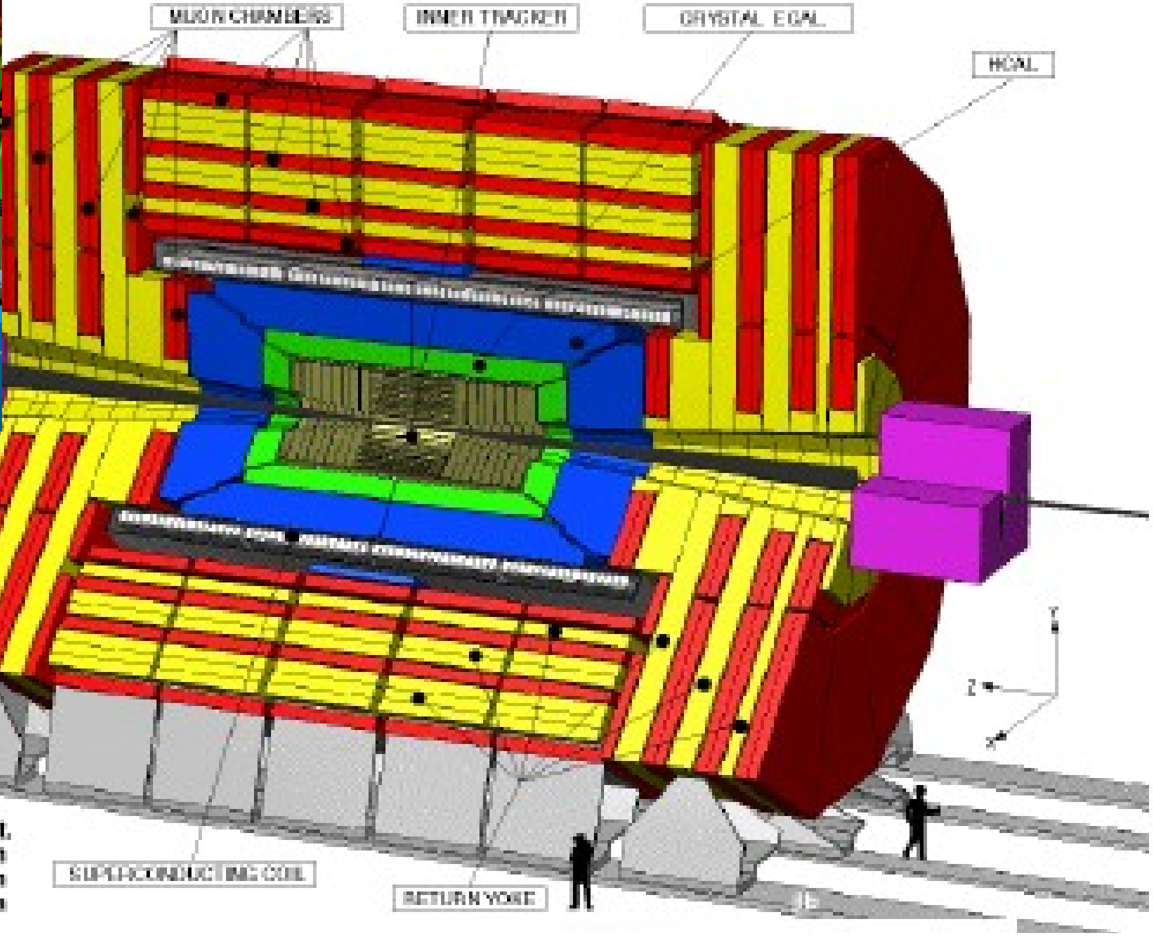


The D0 Experiment

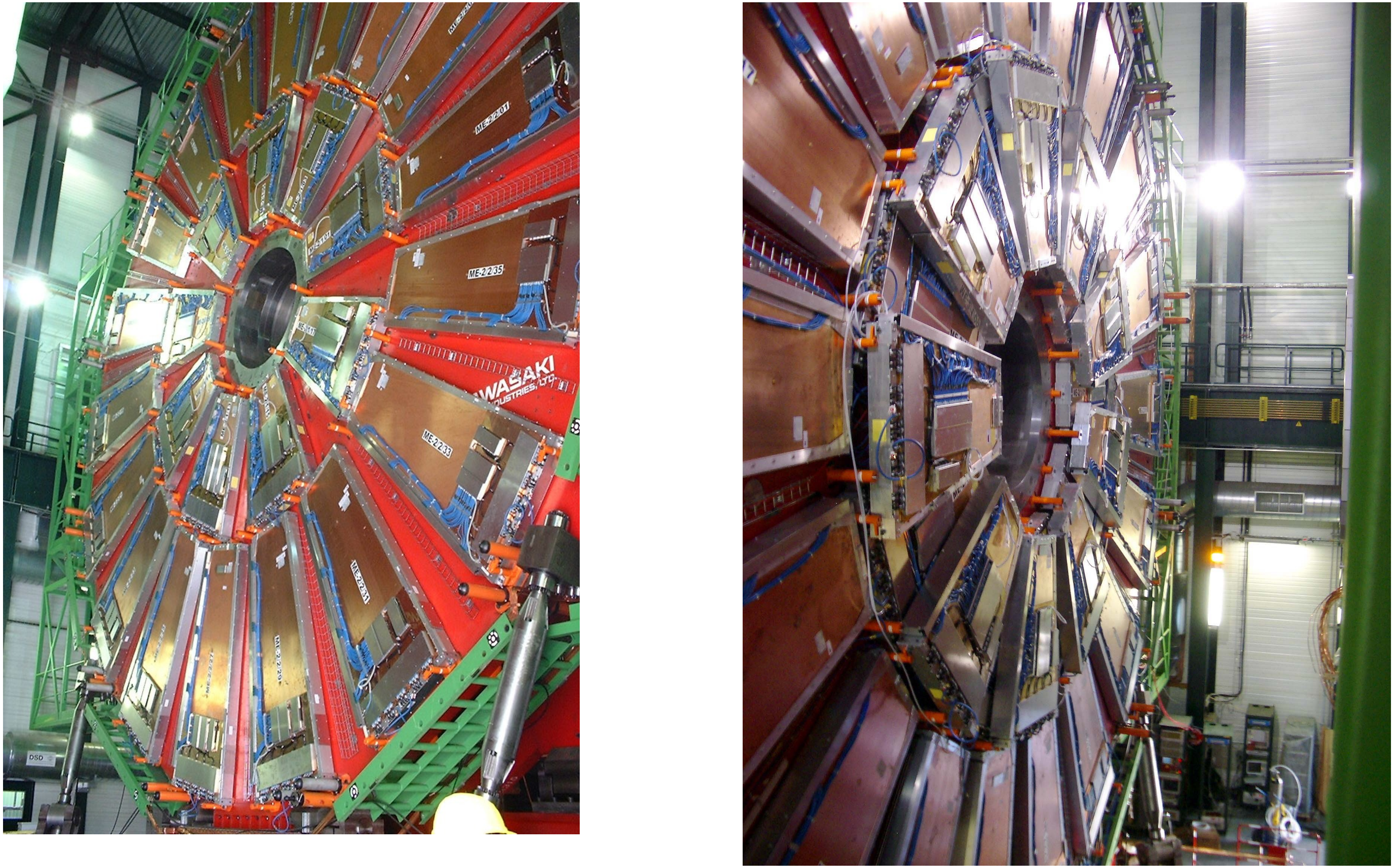


CMS


SL 153-12 E 2
LIFTLUX

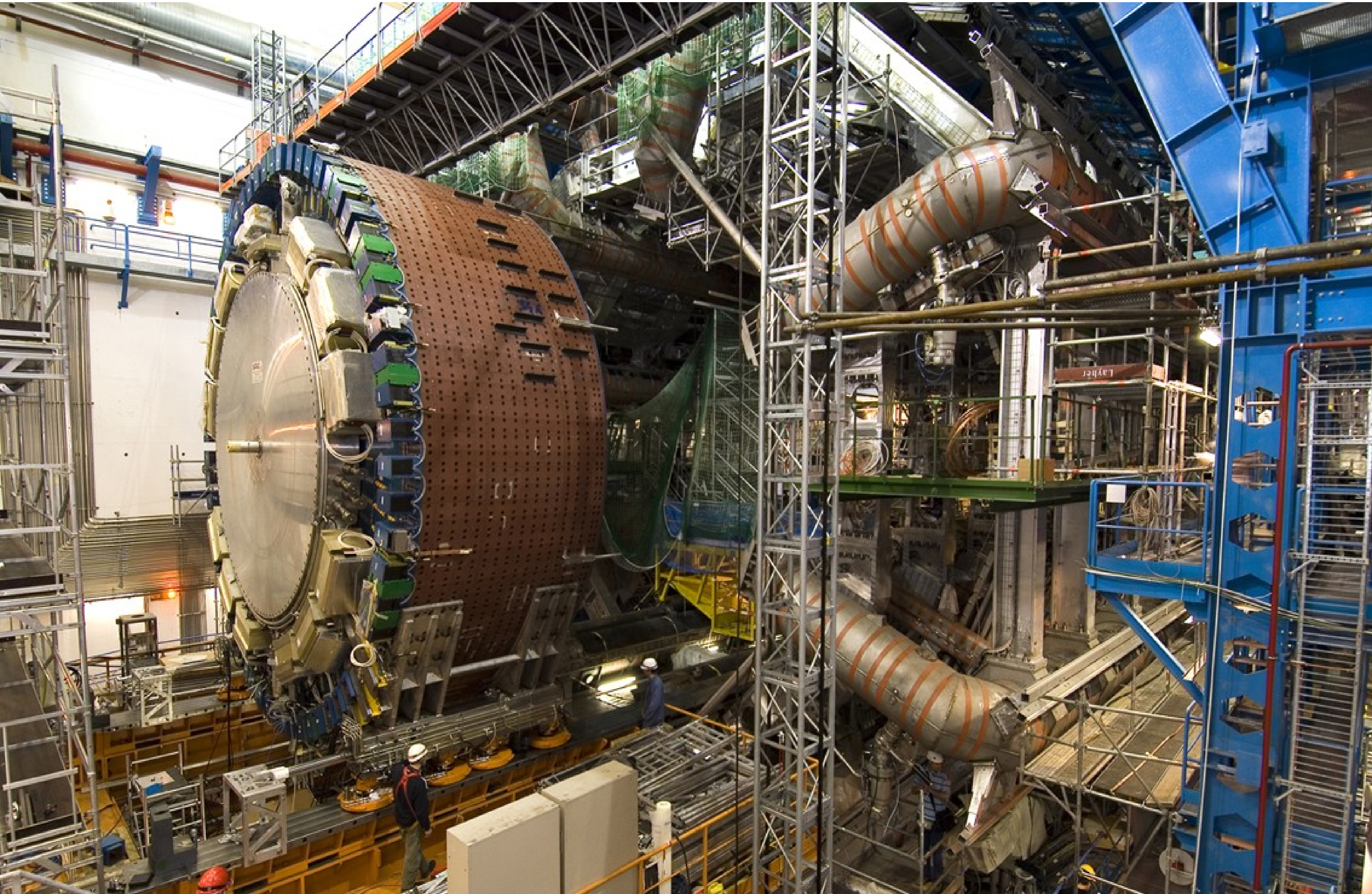

MUON CHAMBERS
INNER TRACKER
CRYSTAL ECAL
HCAL
SUPERCONDUCTING COIL
RETURN YOKE
Y
Z
X
Total Weight : 14,500 t.
Overall diameter: 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

CMS



CMS (SX5)

ATLAS



The Cold Truth!

Detectors have to work near the beam…

LHC can be intimidating

Putting the LHC Stored Energy in Perspective

USS New Jersey (BB-62)
16”/50 guns firing

(Watts = joules/sec)

- LHC stored energy at design ~700 MJ
  - Amount of Power created if that energy is deposited in a single orbit: ~10 TW (world energy production is ~13 TW)
- Battleship gun kinetic energy ~300 MJ

Why not start with 10^{34} (m^{-2} s^{-1}) on Day One?

Luminosity Equation: $$L = \frac{fE}{\varepsilon_n} \frac{n_b N_p^2}{\beta^{*}}$$

- Quantities we cannot easily change:
  - f: revolution frequency of the LHC
    - set by radius and c
  - E: beam energy
    - set by physics goals
  - ε_n: beam emittance at injection
    - set by getting the beam into the LHC

- Quantities we can easily change
  - n_b: number of bunches
    - Factor of 3 lower initially
  - β^* : strength of final focus
    - Factor of ~2 possible
  - N_p: protons per bunch
    - Can be as small as we want
    - Initially, can be within a factor of ~2 of design

This works out to 4 x 10^{32} on Day One

Prudence and Luminosity Profile

- There is a HUGE amount of stored energy in the LHC at design
- Safety/sanity requires that we operate with less stored energy until we have plenty of experience with beam aborts
  - This means less intense proton beams
  - This means substantially lower luminosity
    - luminosity goes as the square of stored energy
  - LHC Physicists (especially those involved with the silicon) will probably insist on many successful unintentional store terminations before agreeing to putting more beam into the machine
- Expect that the luminosity will grow slowly
  - If we are not absolutely confident in our ability to tolerate an unintentional store termination, luminosity will grow even more slowly

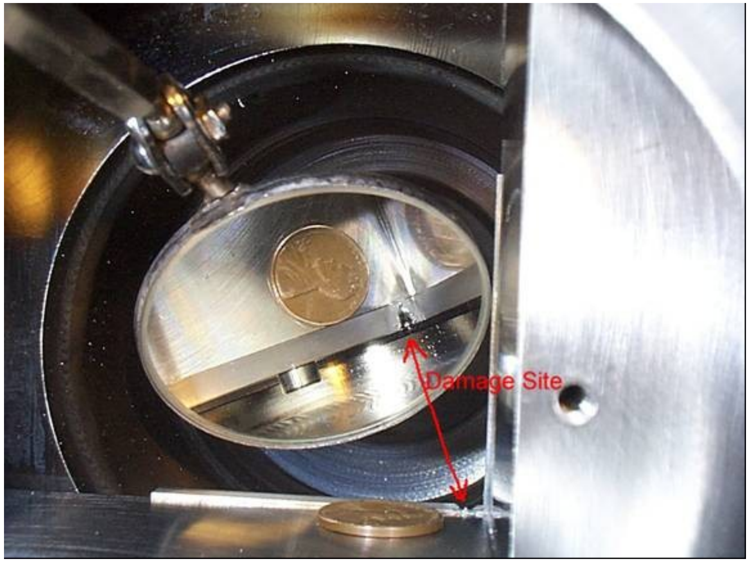
"Accidents Can Happen"

Elvis Costello – Armed Forces

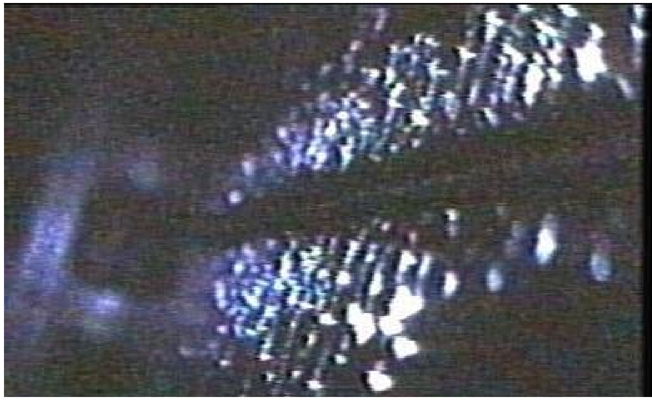
Each proton bunch is like a bullet!

Tevatron Beam Incident caused by a device moving toward the beam too quickly and too close!

Primary collimator



Secondary collimator



LHC beam power = 350 x Tevatron!

monitoring, shielding, collimators, diagnostic tools,
a well engineered abort system as well as
communication between machine and experiment teams
is essential to avoid the above...

What is 1 fb^{-1}?

- 1 fb^{-1} = 10^{14} collisions
  - 2 nanograms of matter produced in collisions (about the same mass as a cell)
- 1 fb^{-1} = 10^{7} seconds of running at 10^{32}
  - More likely 5 x 10^{6} seconds at 2 x 10^{32}
- Note that the Tevatron hit the 1 fb^{-1} milestone in 2006, 20 years after the first collisions
  - Probably 75% of the collisions it will ever produce will be in the last few years of operation

Starting to Design an Experiment

It starts with the Physics

- Experiments in particle physics are based upon three basic measurements.
  - Energy flow and direction: calorimetry
  - Particle identification (e,μ,π,K,ν…)
  - Particle momentum: tracking in a magnetic field
- Ability to exploit increased energy and luminosity are driven by detector and information handling technology.

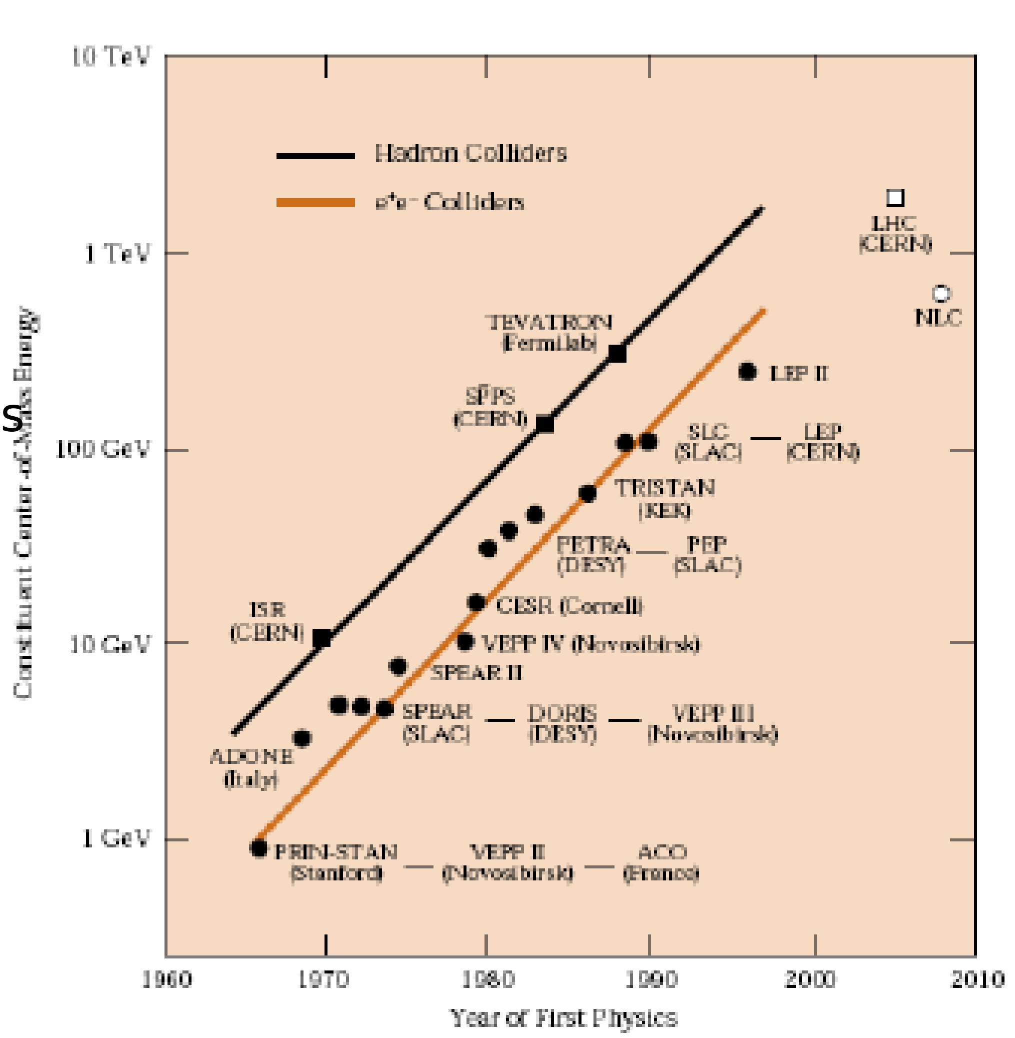
Searching for Particles

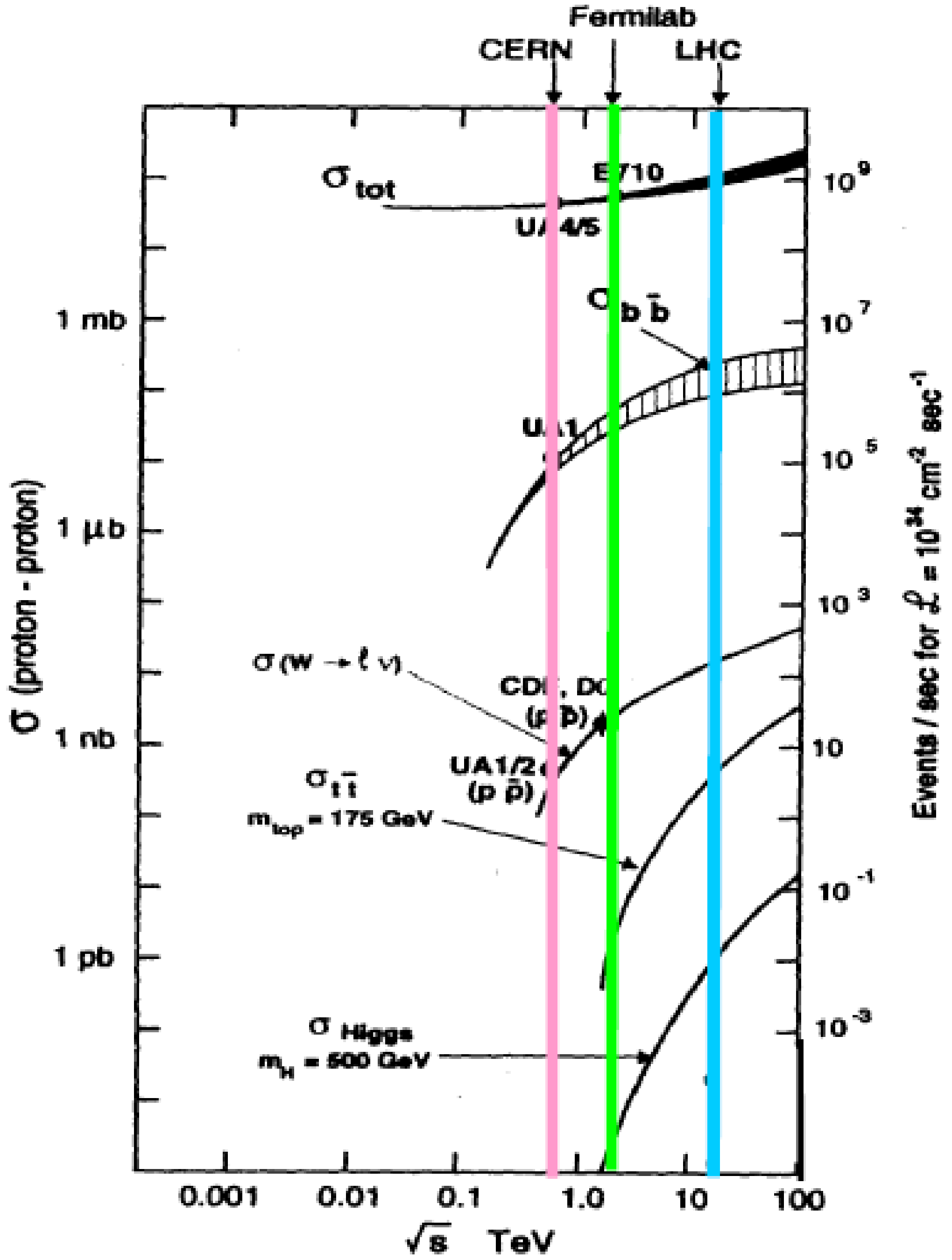
- Event rates are governed by
  - Cross section $\sigma(E)[cm^2]$ –physics
  - Luminosity $[cm^{-2}s^{-1}] = N_1N_2f / A$
    - N_1N_2= particles/bunch
    - f = crossing frequency
    - A = area of beam at collision
    - $N_{events} = \sigma \int Ldt$
    - Acceptance and efficiency of detectors
- Higher energy: threshold, statistics
- Higher luminosity: statistics

Experimental Program (history)

- Series of accelerators with increasing energy and luminosity
- 25 years: domination of colliders
- Proton colliders
  - “broadband” beams of quarks and gluons, -

  “search and discovery” and precision measurements
- Electron colliders
  - “narrowband” beams, clean, targeted experiments and precision measurements

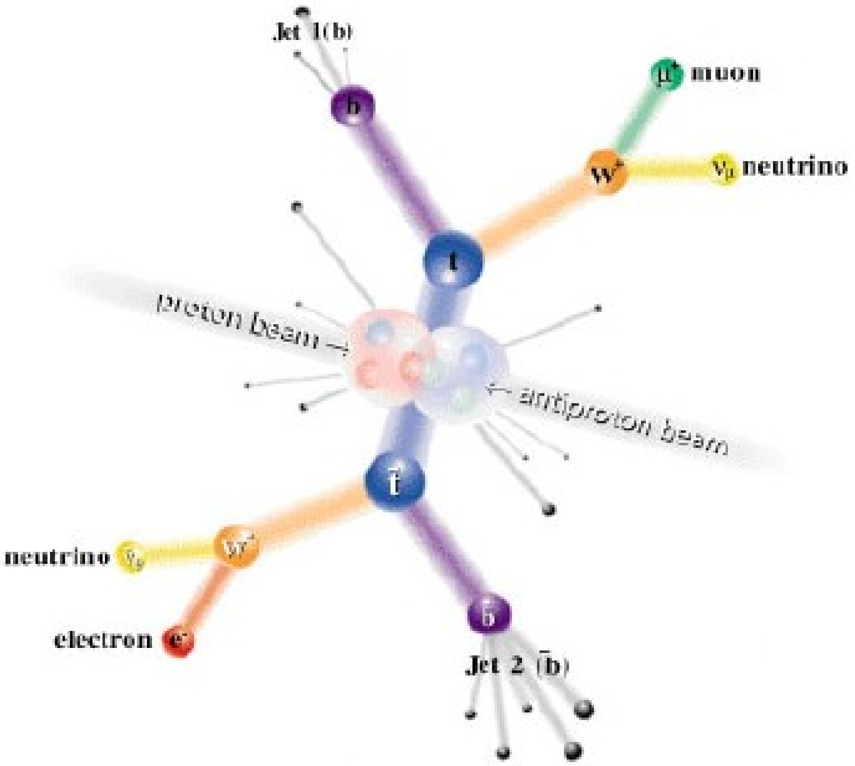



Fermilab
CERN
LHC
σ tot
E710
UA4/5
σ $b\bar{b}$
UA1
σ (W → ℓ ν)
CDF, D0
(p $\bar{p}$)
UA1/2
(p $\bar{p}$)
σ $t\bar{t}$
m top = 175 GeV
σ Higgs
m H = 500 GeV
1 mb
1 μb
1 nb
1 pb
σ (proton - proton)
10^9
10^7
10^5
10^3
10
10^{-1}
10^{-3}
Events / sec for $\mathcal{L} = 10^{34}\ cm^{-2}\ sec^{-1}$
0.001
0.01
0.1
1.0
10
100
√s TeV

Hadron Collider History

Machine	C.M.S. Energy	Luminosity	Year	Role	Detector Innovations
ISR	31 GeV	2 x 10^{32}	1970's	Exploratory, IVB search	High rate electronics
SppS	640 GeV	6 x 10^{30}	'80 -'88	W, Z, jets	Hermetic and projective calorimeters, magnetic tracking
Tevatron	1.9 TeV	10^{30}-10^{32}	'85 -'08	Top quark	Precision tracking, advanced triggers
LHC	14 TeV	10^{33}-10^{35}	'08 - ?	Higgs,…?	Fast detectors, radiation resistances

Proton Colliders…



- Most interesting physics is due to hard collision of quark(s) or gluon(s)
- That production is central (and rare) and “jet” like
- Remaining “spectators” scatter softly, products are distributed broadly about the beam line and dominate the average track density

How do you design a detector?

Global Detector Systems

Overall Design Depends on:

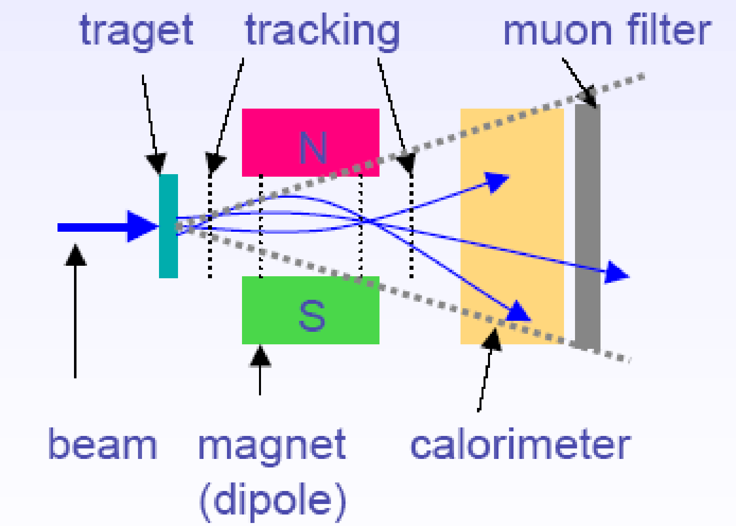
- –**Number of particles**
- –**Event topology**
- –**Momentum/energy**
- –**Particle identity**

}

No single detector does it all…

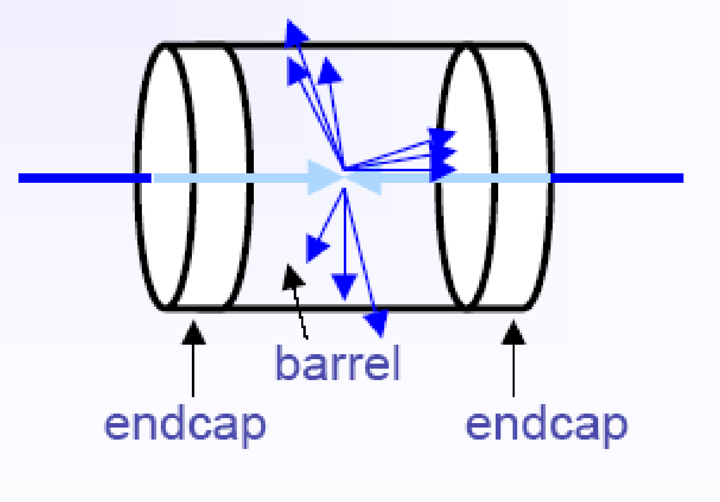
→ Create detector systems

Fixed Target Geometry



- •Limited solid angle (dΩ) coverage (forward)
- •Easy access (cables, maintenance)

Collider Geometry



- •“full” solid angle dΩ coverage
- •Very restricted access

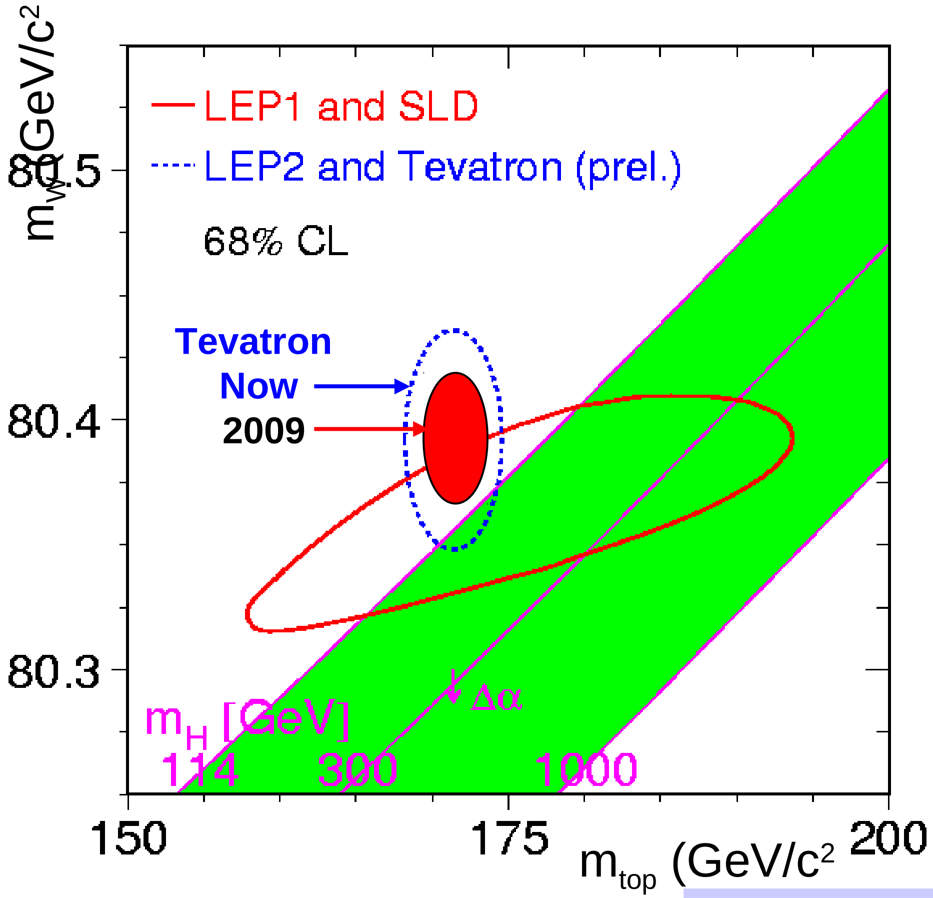
It starts with the Physics

- What is the physics measurement that is driving the experiment?
- What are the final states – how will you measure them? Examples include
  - Pizero ID (separation of two photons?)
  - J/Psi – good tracking
  - Light quarks – good calorimeter
  - b and c quarks (tagging)
- What level of precision are you after?
  - Precision has a cost; dollars, complexity, and readout speed

It continues with the Physics

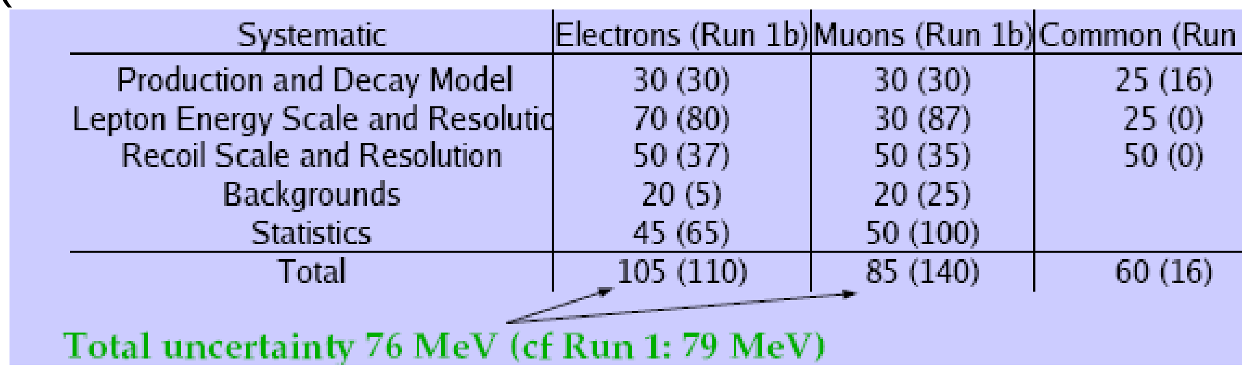
- Can you trigger on the physics process of interest?
  - Separate the unique signature of the physics of interest from the literally billions of collisions that go on each day
- What is the rate?
  - Drives both the trigger and data acquisition system
  - Do you need to worry about “dead-time”?
  - How will you calibrate your detector?
  - How will you measure the various detector efficiencies

Measuring the W Mass



- Can I design an experiment using CDF/D0 components in the LHC era to improve the W Mass?
  - Can you trigger on the physics process of interest?
  - Find new triggers/detectors to control the systematic errors
  - Get a better handle on the backgrounds, recoil products?

CDF Run 1 Systematics



Systematic	Electrons (Run 1b)	Muons (Run 1b)	Common (Run
Production and Decay Model	30 (30)	30 (30)	25 (16)
Lepton Energy Scale and Resolutic	70 (80)	30 (87)	25 (0)
Recoil Scale and Resolution	50 (37)	50 (35)	50 (0)
Backgrounds	20 (5)	20 (25)	
Statistics	45 (65)	50 (100)	
Total	105 (110)	85 (140)	60 (16)

Total uncertainty 76 MeV (cf Run 1: 79 MeV)

Still the Physics

- Lots of things to think about to decide up-front before you ever start to think about the types of detectors, shapes and sizes…
  - It starts with the idea but one needs to think through all the way through the final analysis and level of precision to insure that the detector system proposed is up for the challenge!

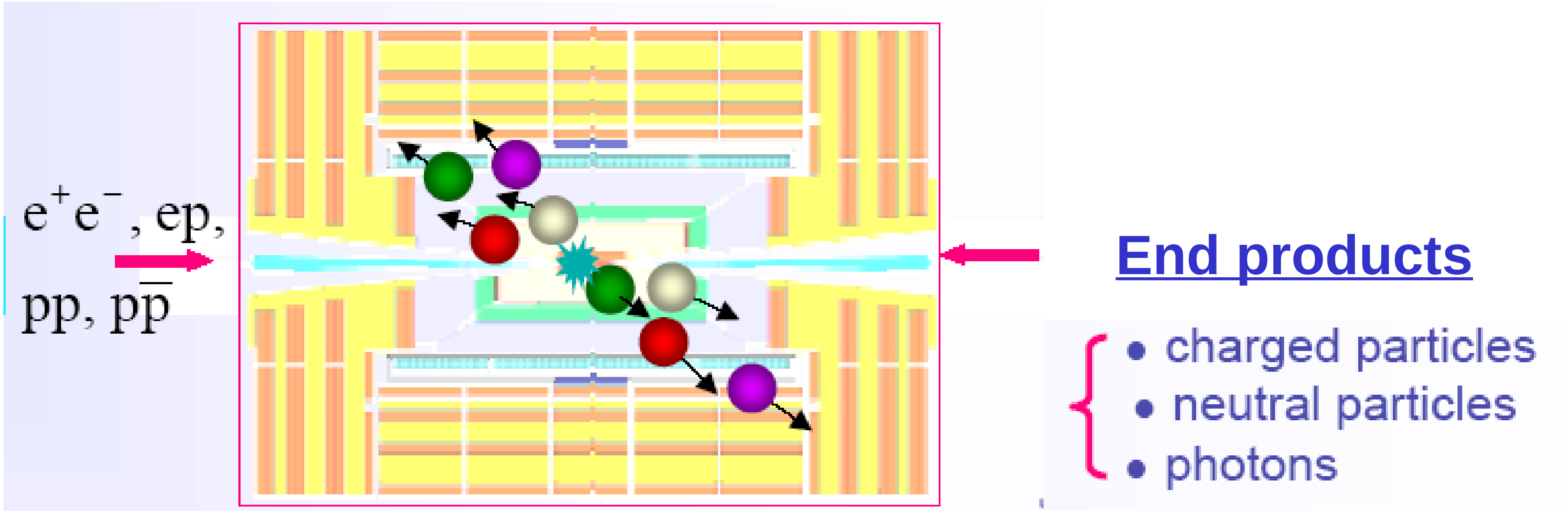
The tools of Particle Physics

- Conservation of Energy
- Conservation of Momentum
- $E = M c^2$
- Of course there are other equations that help but these are the core principles upon which we work.

How do we use this tool kit?

- Given the physics equations, what should we design our detector to measure?
  - Position of the particles
  - Energy of the particles
  - Momentum of the particles
- Other properties that might be nice to know (or even essential depending on the measurement)
  - Exact location of the collision point
  - Charge of the decay products
  - Initial energy of the incident particles
  - Polarization of incoming particles
  - ID of the incident Partices
  - And others…

Ideal Detectors



End products

- charged particles
- neutral particles
- photons

An "ideal" particle detector would provide…

- **Coverage of full solid angle, no cracks, fine segmentation**
- **Measurement of momentum and energy**
- **Detection, tracking, and identification of all particles (mass, charge)**
- **Fast response: no dead time**

However, practical limitations: Technology, Space, Budget, and engineering prevent perfection…

Detector Design Constraints

- There are 4 things to keep in mind when designing a detector.
  - Size of the collision hall and specific characteristics of the building
    - Floor space
    - Weight?
    - How far underground?
    - Crane coverage?
    - Accessability of detector components
    - Gasses, cryogens, flammability, explodability, and ODH issues
    - Available AC power
    - Cooling

Detector Design Constraints

- Total construction cost
  - How much $$$ do you have to work with
  - How many physicists are available to participate in construction (how big is your collaboration?)
  - When do you want to be ready for collisions?
  - How "hard" will you be pushing current technology –
    - how much financial and schedule contingency is required? (more below)
  - An honest assessment of how well the collaborations skills and interests align to the work that lies ahead
- Amount of time it takes to read the detector out after a collision – or reversed, how quickly do you need to read out the detector
  - Sets the drift time tracking chambers,
  - Integration time in calorimeters
  - Digitization time
  - Logging Time

Detector Design Constraints

- What is the current technology and where do we expect technology to be when the experiment is ready to take data
  - Most experiments these days take a long time. The time between “the expression of interest” to “ready for collisions” is measured in years
  - All of the technology required for the experiment to work does not have to be “ready” (commercial) at the proposal stage
  - Typically time for R&D
  - Moore’s law for computing is often relied upon

RISK!

- Is the level tolerable
  - Can’t push the envelope of technology for every detector
    - Will guarantee a blown schedule and cost over runs
    - Need to use new technologies judiciously
    - New Technology should not be used as a “carrot” to draw in collaborators that might otherwise pass.

The Bottom Line!

- There is no single “correct” answer to the above constraints
  - Every experiment finds its own “way”
- Detector designers perform a difficult and almost impossible optimization task

Detectors are an amazing blend of science, engineering, management and human sociology

By the Way…

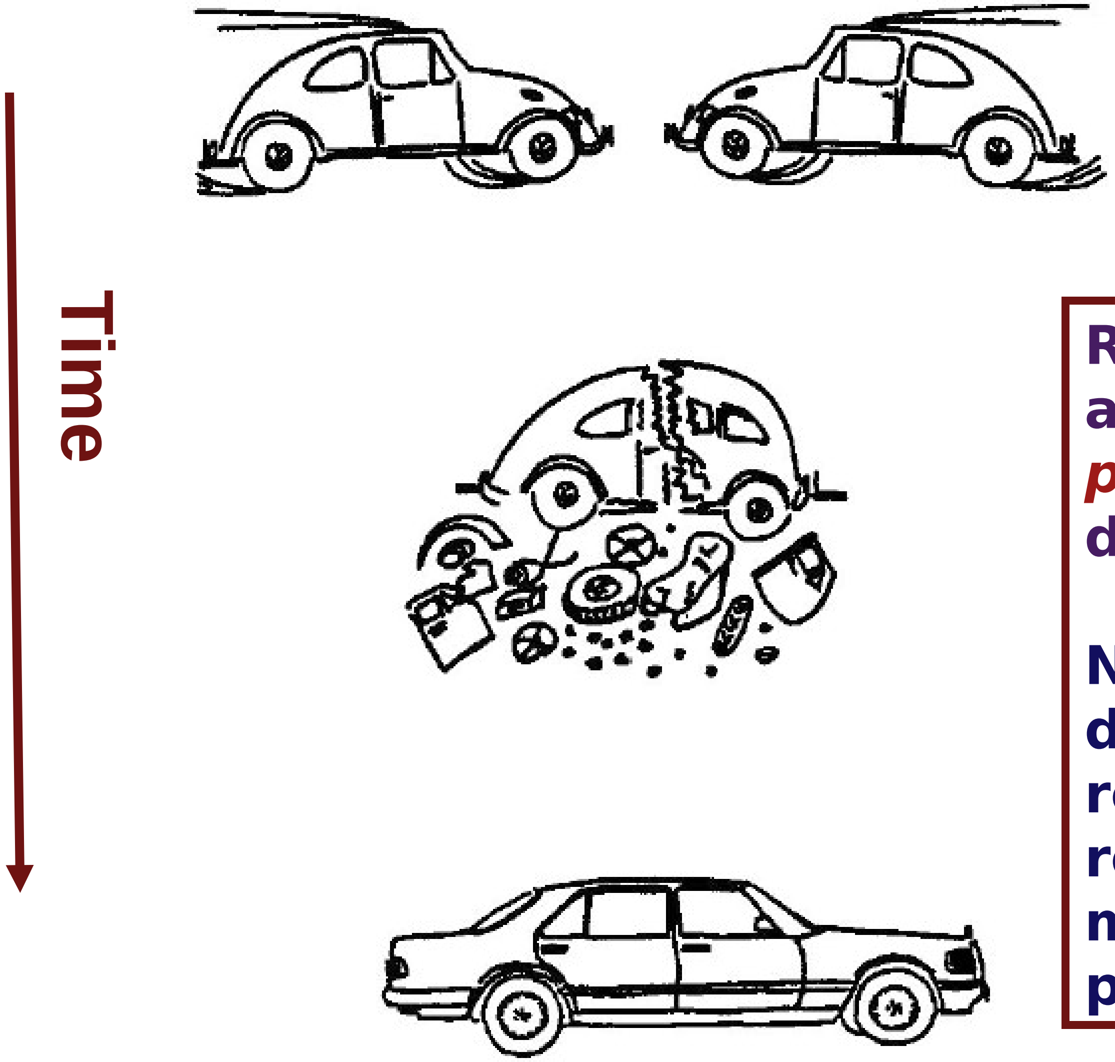
- These constraints are not unique to particle physics
  - one would face the same issues in designing a boat to compete, for instance, in the America’s Cup!

REALITY SETS IN!

We can’t build a perfect detector

- A perfect detector has no “holes”
  - Reality is that in order to read the detector, we need to get the signals out.   This is done with cables. Cable paths force us to have “seams” in the detector where we don’t know what is happening
- A perfect detector is identical in every direction with respect to the collision point
  - We need to support these detectors which means that the material is not isotropic.
- A perfect detector is 100% efficient

Rare Collision Events



Rare Events, such as *Higgs production*, are difficult to find!

Need good detectors, triggers, readout to reconstruct the mess into a piece of physics.

Cartoon by Claus Grupen, University of Seigen

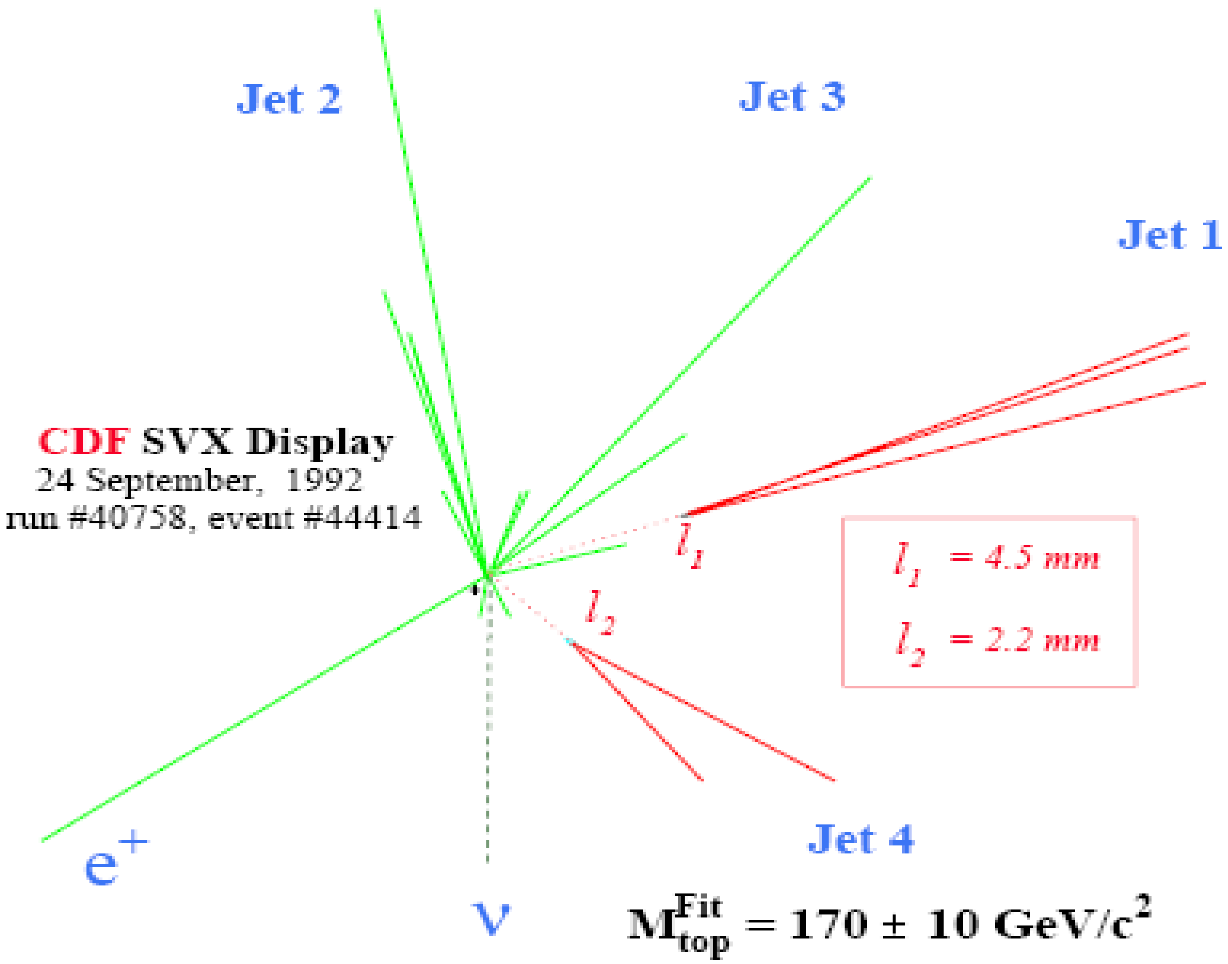
Experimental Trigger

- Need to decide what characteristics in an event means the event is interesting
  - high Pt tracks
  - lots of energy in the calorimeter
  - missing energy (energy inbalance)
  - Displaced vertex
  - High energy muon, photon, electron,…
- A trigger by its nature bias' the data
- You have to make sure you understand exactly what you are doing to correct the data for this bias.

We can’t collect data from every Event!

- Take CDF as an example…
  - We have a collision every 396 nano seconds ~ once every 10^{-6} seconds
  - We can only write data to tape at ~100 hz
  - While we write data to tape, the detector is “dead”
  - Deadtime can be avoided with proper buffering
  - Deadtime is NOT evil – it just needs to be controlled.
- Not all collisions are interesting!
- Name of the game is “live-time” -- required in order to look for rare processes
- Develop an electronics based “trigger” in order to solve this problem

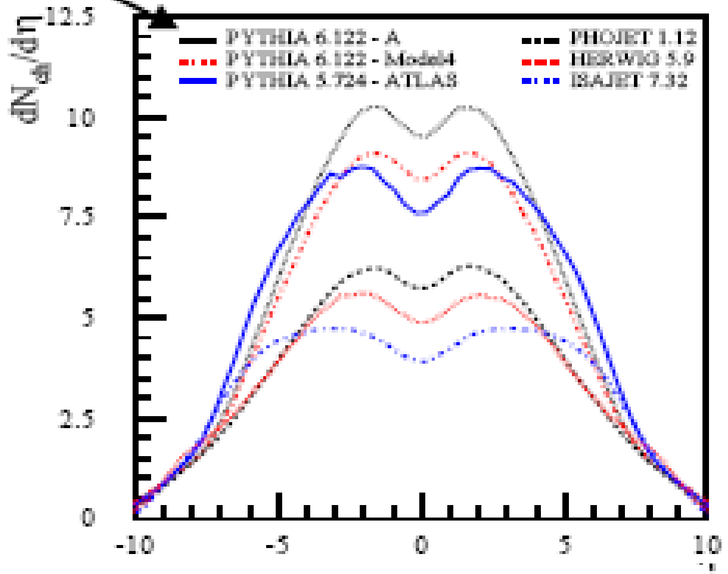
CDF’s 1st Top Event… (run 1)

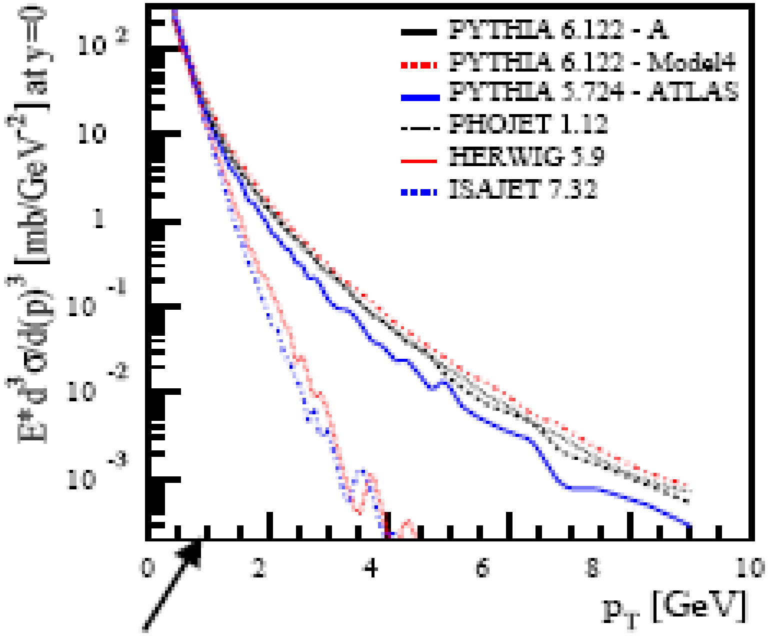


The LHC

- High luminosity means multiple interactions
    - At design luminosity, LHC experiments will face roughly 25 minimum bias events per bunch crossing
- Parton distributions mean no beam energy constraint
    - Conservation only in the transverse plane
- Initial state radiation (qcd)
    - Even more activity

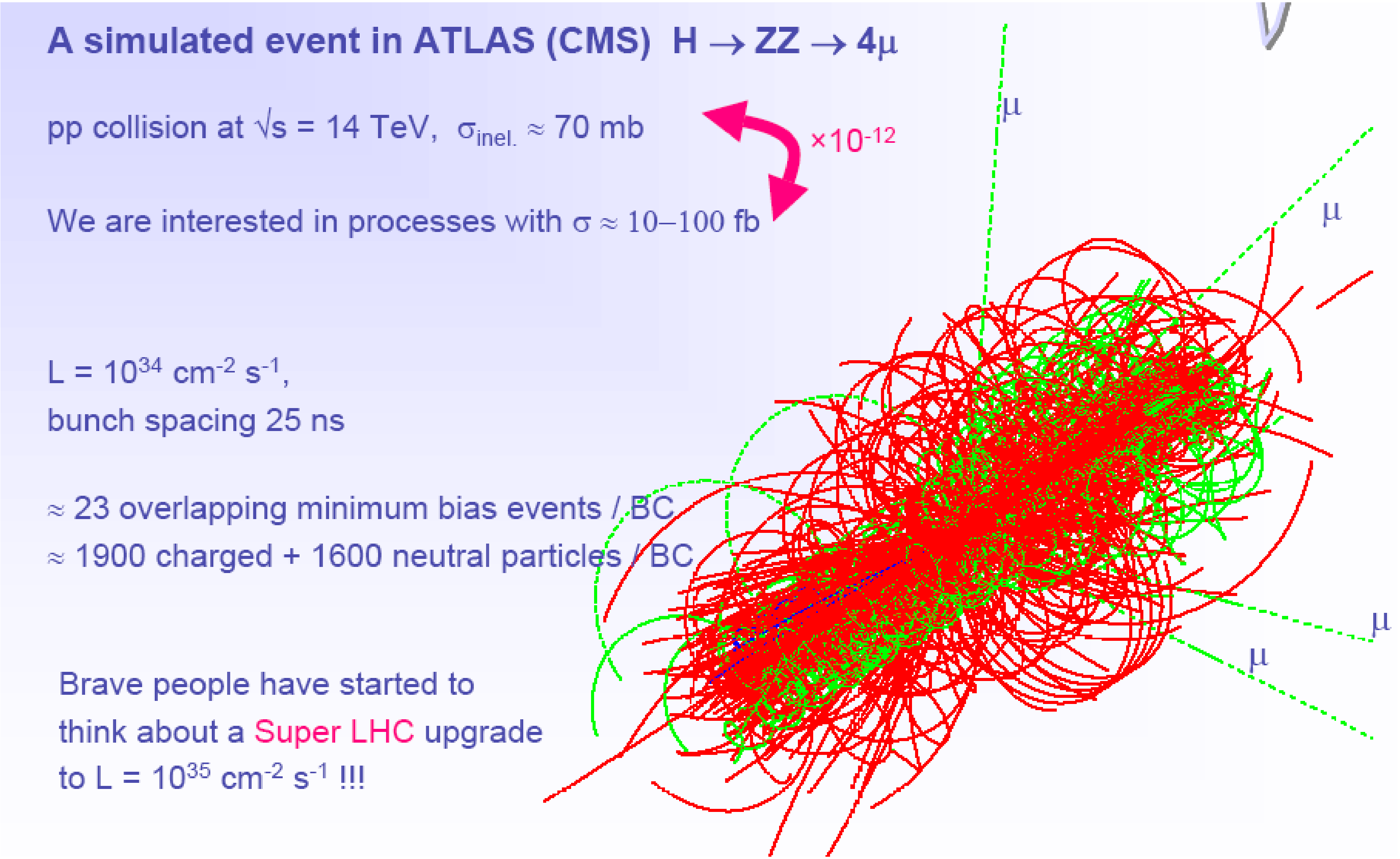
Charged particle versus pseudorapidity in LHC minimum bias events





p_T distribution of Charged particles in LHC minimum bias events

Complicated Collisions



A simulated event in ATLAS (CMS) $H \rightarrow ZZ \rightarrow 4\mu$

pp collision at $\sqrt{s}$ = 14 TeV, $\sigma_{inel.} \approx$ 70 mb

$\times 10^{-12}$

We are interested in processes with $\sigma \approx 10-100$ fb

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

bunch spacing 25 ns

$\approx$ 23 overlapping minimum bias events / BC

$\approx$ 1900 charged + 1600 neutral particles / BC

Brave people have started to think about a Super LHC upgrade to $L = 10^{35}$ cm^{-2} s^{-1} !!!

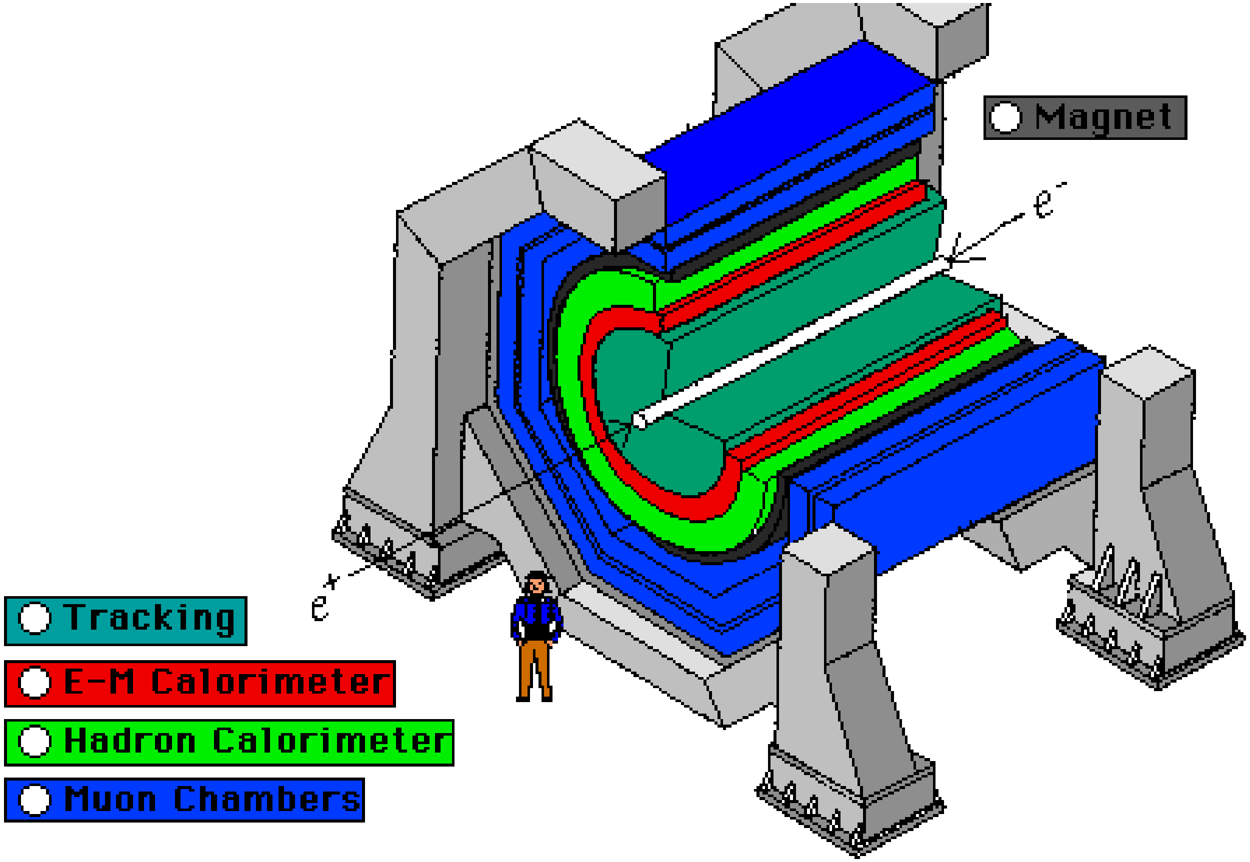
Lets Get Down To Business…

Individual Detector Types

odern detectors consist of many different pieces of quipment to measure different aspects of an event.

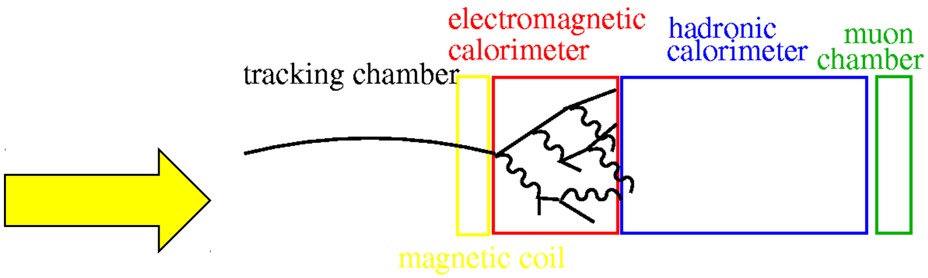
Measuring a particle’s properties:

1. **Position**
2. **Momentum**
3. **Energy**
4. **Charge**
5. **Type**

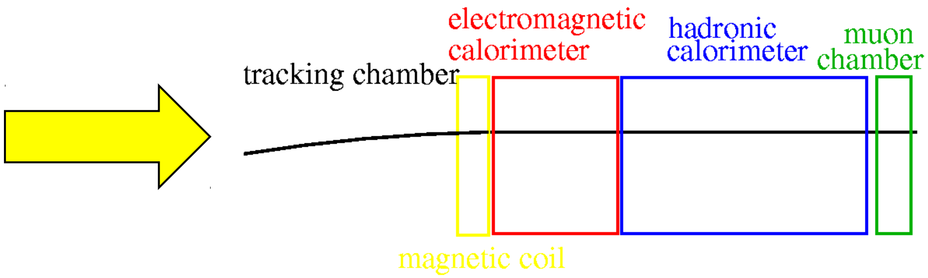


Lepton Identification

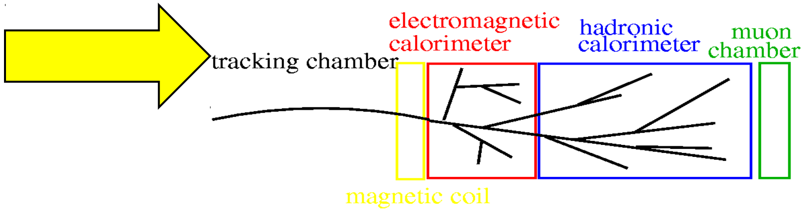
- Electrons:
  - compact electromagnetic cluster in calorimeter
  - Matched to track



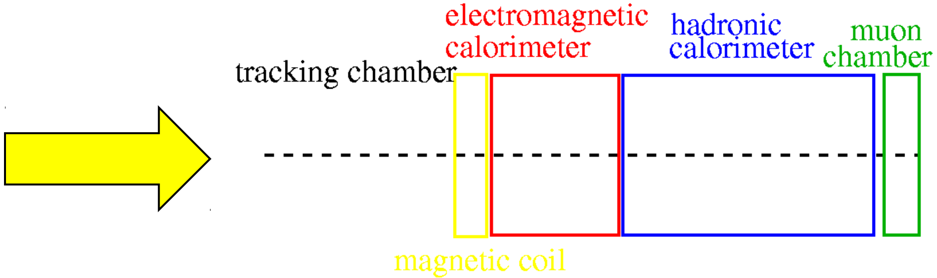
- Muons:
  - Track in the muon chambers
  - Matched to track



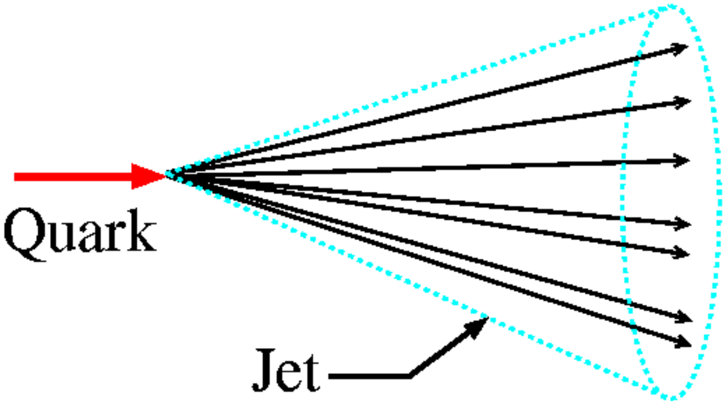
- Taus:
  - Narrow jet
  - Matched to one or three tracks

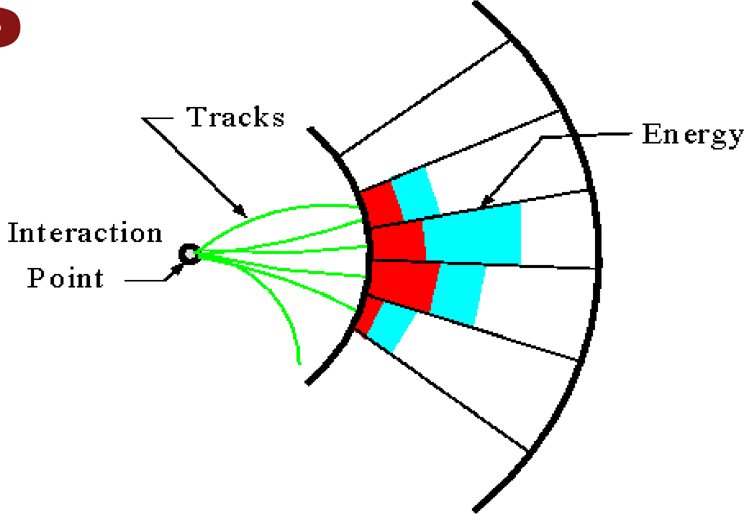


- Neutrinos:
  - Imbalance in transverse momentum
  - Inferred from total transverse energy measured in detector



"Jets"

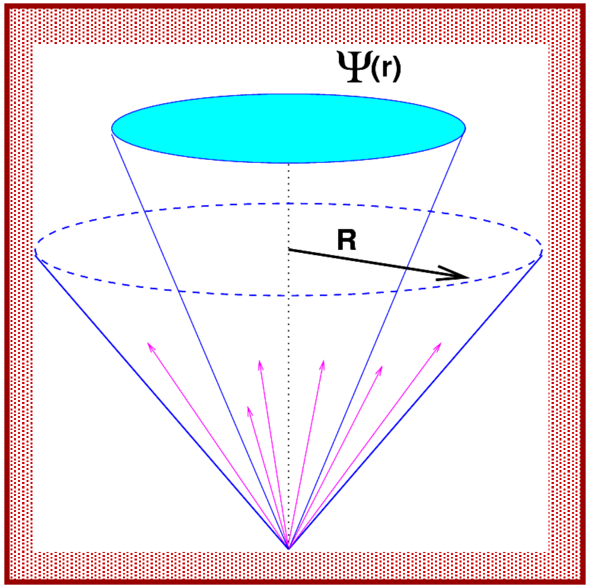




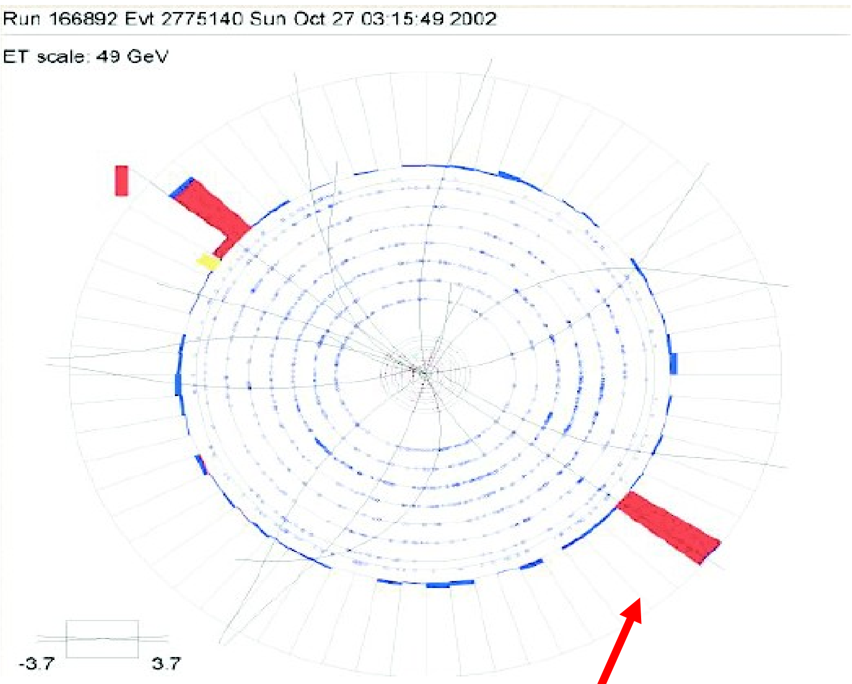
Jet (jet) *n.* a collimated spray of high energy hadrons

Quarks fragment into many particles to form a jet, depositing energy in both calorimeters.

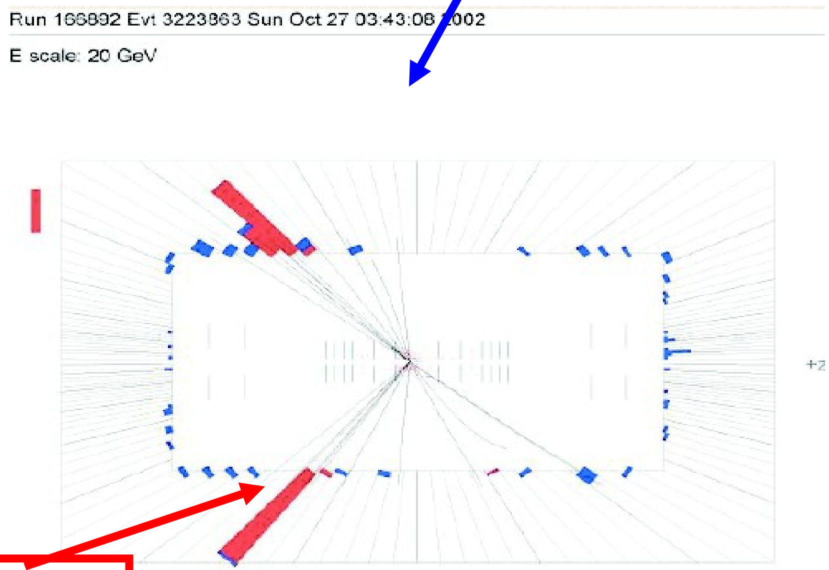
Jet shapes narrower at high E



Electrons and Jets



Hadronic Calorimeter Energy

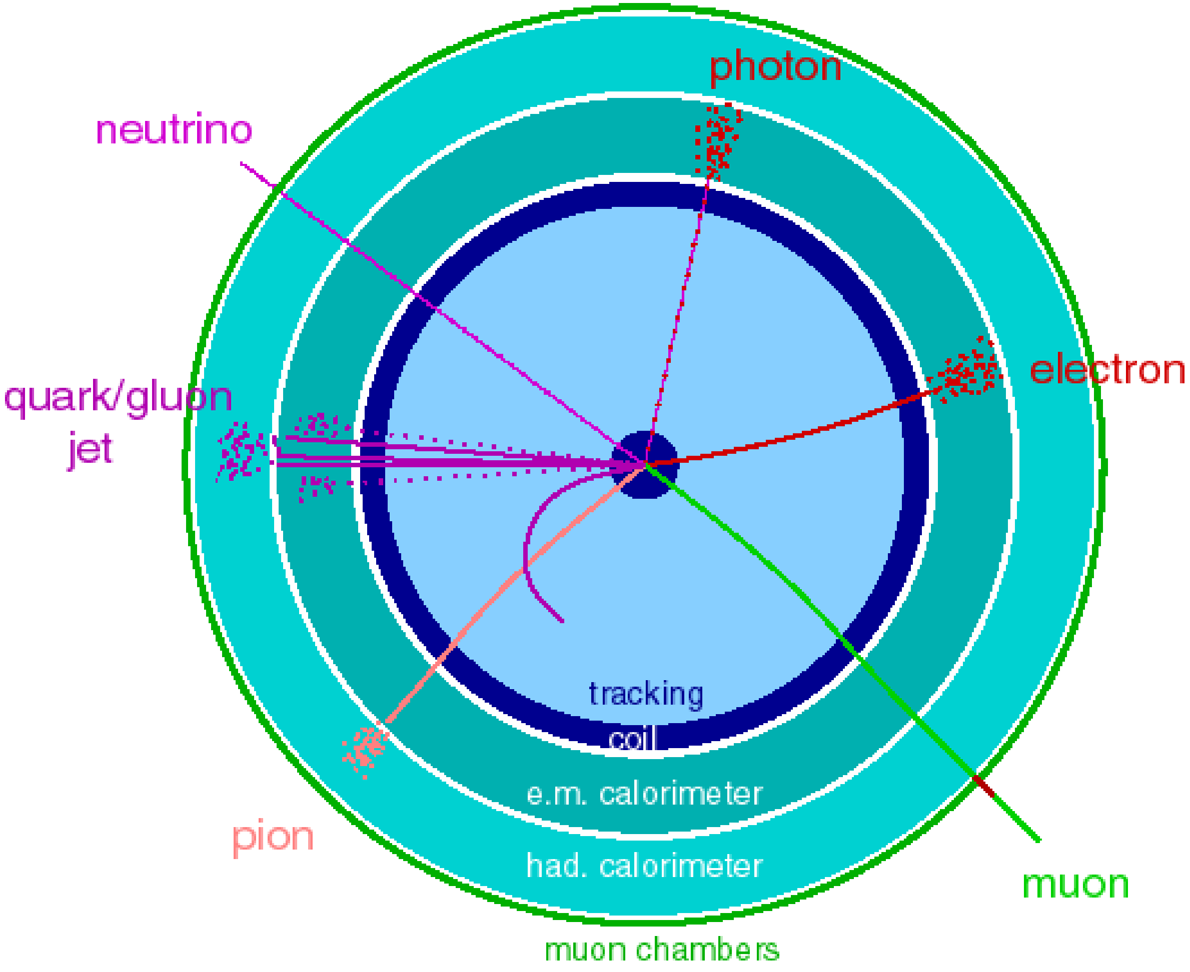


Electromagnetic Calorimeter Energy

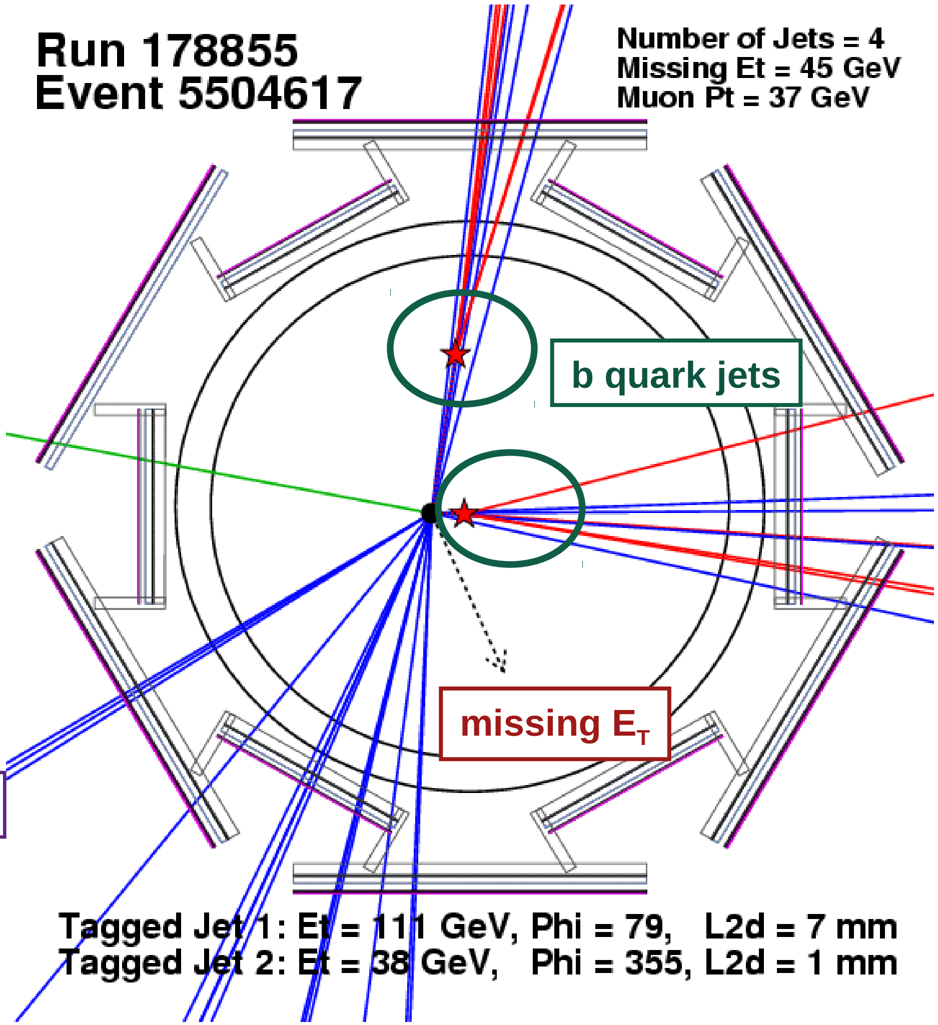
- Jets can look like electrons, e.g.:
  - photon conversions from π^0's: ~13% of photons convert (in CDF)
  - early showering charged pions
- And there are lots of jets!!!

Modern Collider Detectors

- the basic idea is to measure charged particles, photons, jets, missing energy accurately
- want as little material in the middle to avoid multiple scattering
- cylinder wins out over sphere for obvious reasons!



CDF Top Pair Event



Run 178855
Event 5504617

Number of Jets = 4
Missing Et = 45 GeV
Muon Pt = 37 GeV

Tagged Jet 1: Et = 111 GeV, Phi = 79, L2d = 7 mm
Tagged Jet 2: Et = 38 GeV, Phi = 355, L2d = 1 mm

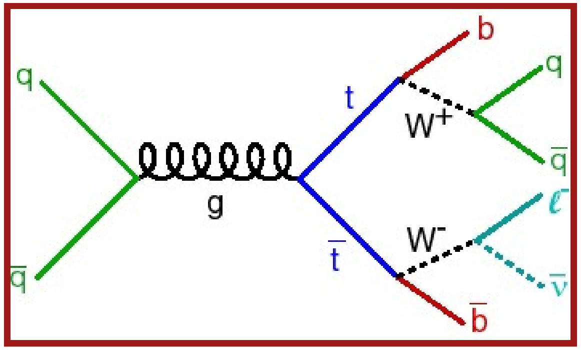
high p_T muon

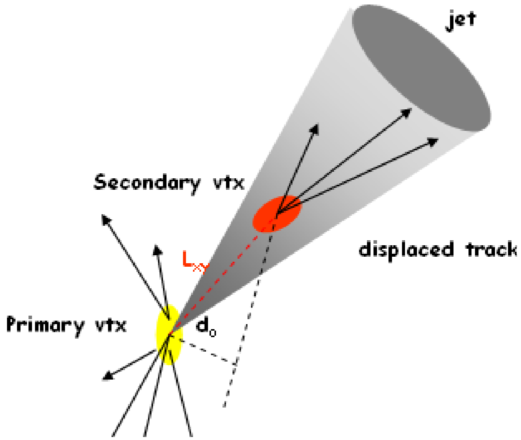
b quark jets

missing E_T

q jet 1

q jet 2



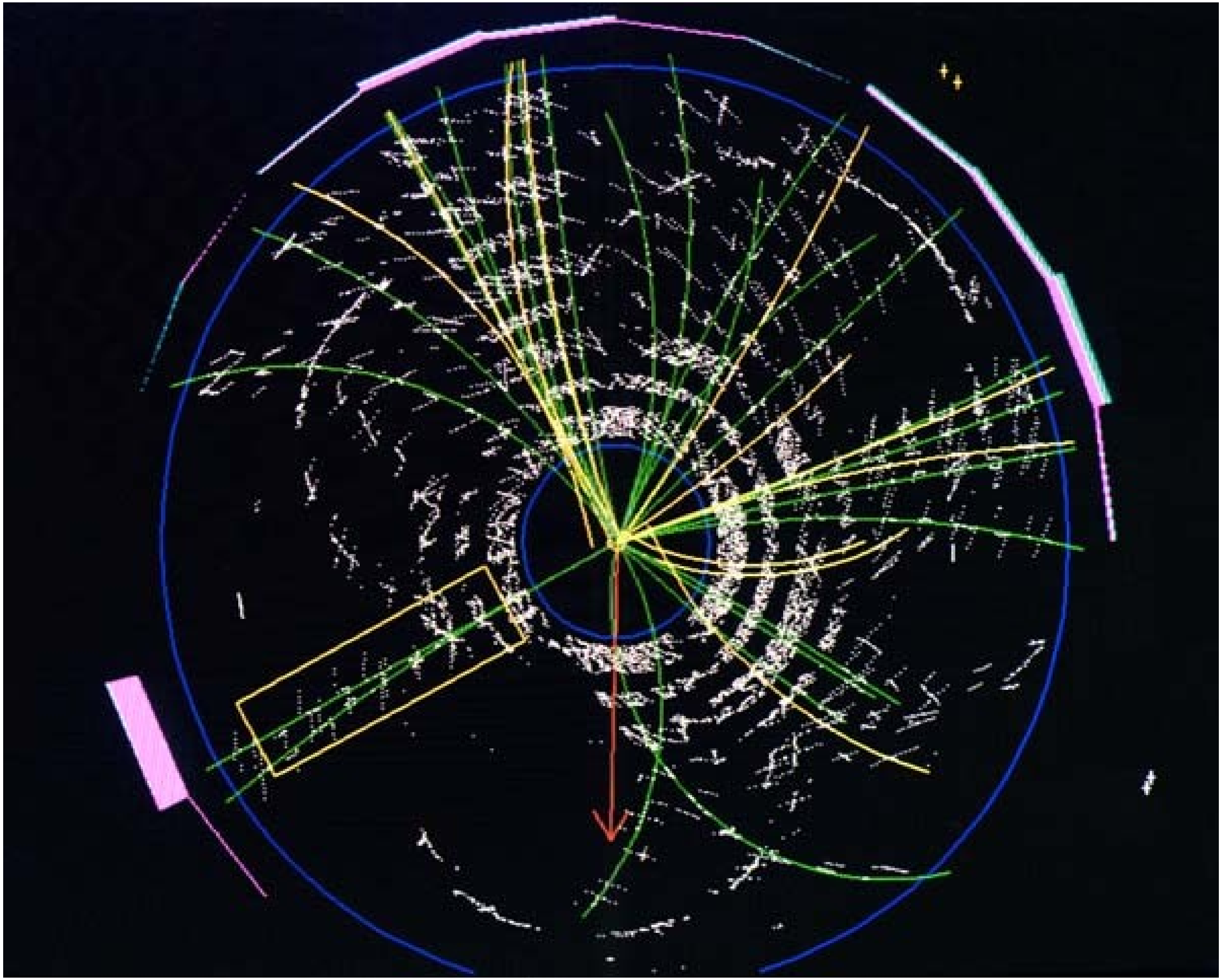


b-quark lifetime:

$c\tau \sim 450\mu m$

→ b quarks travel ~3 mm before decay

CDF Top Pair Event

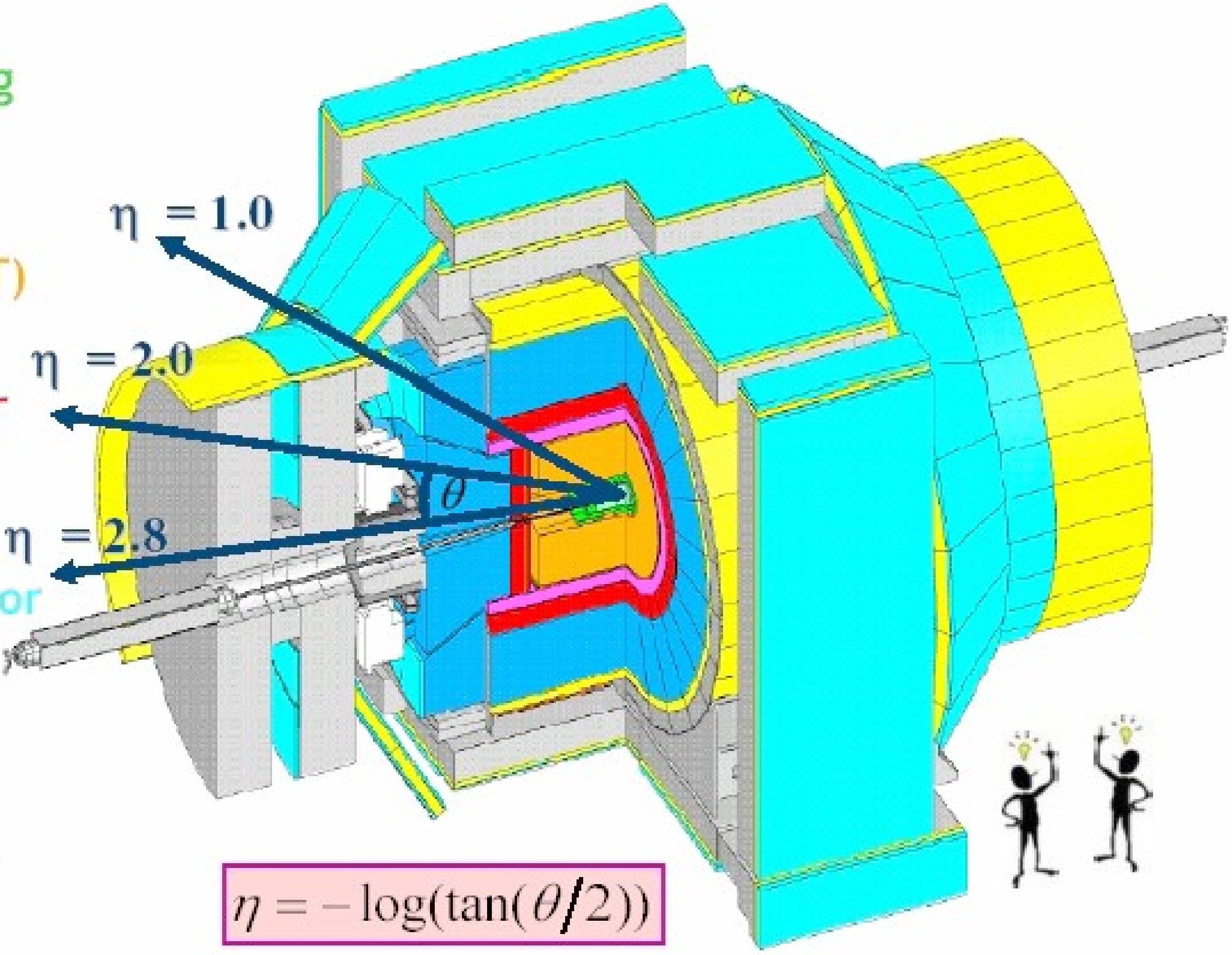


Particle Detection Methods

Signature	Detector Type	Particle
et of hadrons	Calorimeter	u, c, t→Wb, d, s, b, g
Missing' energy	Calorimeter	ν_e, ν_μ, ν_τ
lectromagnetic shower, X_o	EM Calorimeter	e, γ, W→eν
urely ionization nteractions, dE/dx	Muon Absorber	μ, $\tau \rightarrow \bar{\mu}\nu\nu$
Decays,c$\tau \geq 100\mu$m	Si tracking	c, b, τ

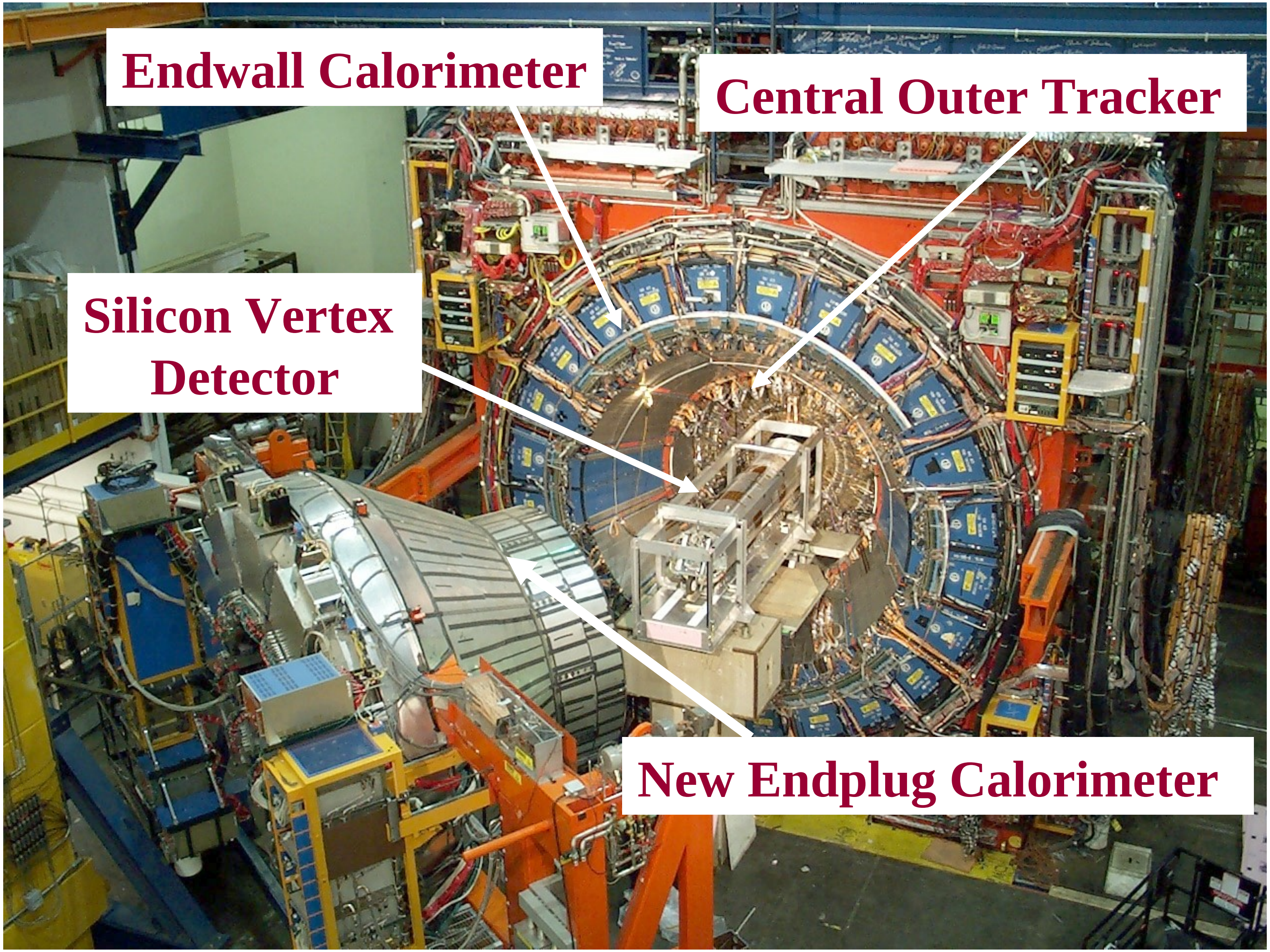
CDF Schematic

- ■ Silicon tracking detectors
- ■ Central drift chambers (COT)
- ■ Solenoid Coil
- ■ EM calorimeter
- ■ Hadronic calorimeter
- ■ Muon scintillator counters
- ■ Muon drift chambers
- ■ Steel shielding



$$\eta = -\log(\tan(\theta/2))$$

CDF Run 2 Detector



Endwall Calorimeter

Central Outer Tracker

Silicon Vertex Detector

New Endplug Calorimeter

Particle Identification Methods

onstituent	Si Vertex	Track	PID	Ecal	Hcal	Muon
electron — —	primary	▯	▪	▪		
Photon γ —	primary	—	—	▪	—	
u, d, gluon —	primary	▪	—	▪	▪	
Neutrino ν —	—	—	—	—	—	
s ▪ —	primary	▪	▪	▪		
c, b, τ	secondary	▪	▪	▪	▪	

PID = Particle ID
(TOF, Č, dE/dx)

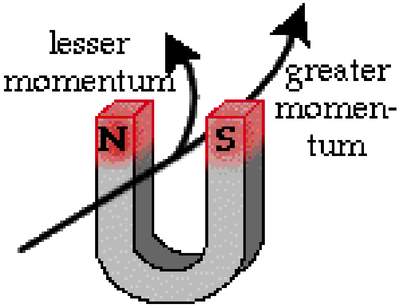
MIP = Minimum
Ionizing Particle

Tracking

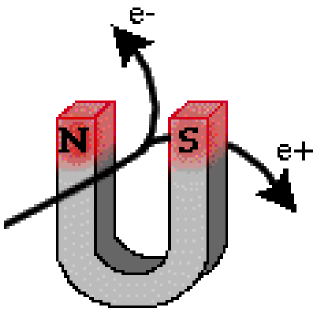
Call ‘em Spectrometers

- a “*spectrometer*” is a tool to measure the momentum spectrum of a particle in general
- one needs a magnet, and tracking detectors to determine momentum:

$$\frac{dp}{dt} = \frac{q}{c} v \times B$$



- helical trajectory deviates due to radiation E losses, spatial inhomogeneities in B field, multiple scattering, ionization



- Approximately:

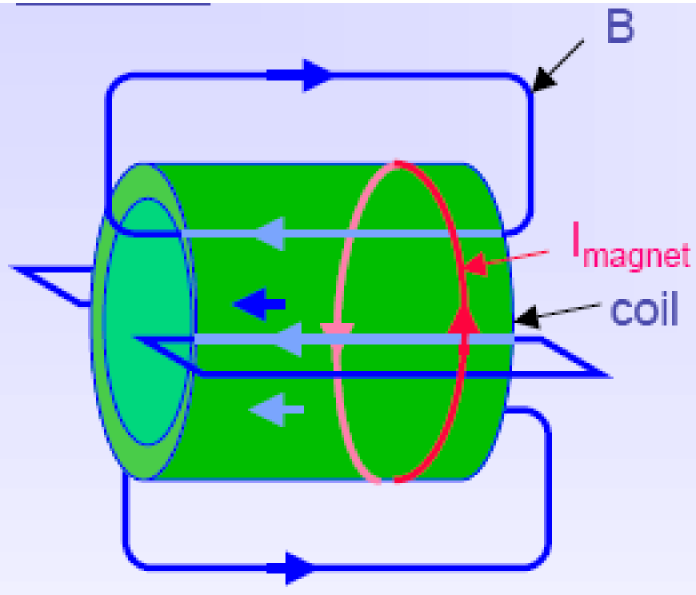
$$p = 0.2998\, B\rho \quad \text{T-m}$$

ρ = radius of curvature

Magnets for 4π Detectors

Solenoid

- + Large homogeneous field inside
- - Weak opposite field in return yoke
- - Size limited by cost
- - Relatively large material budget

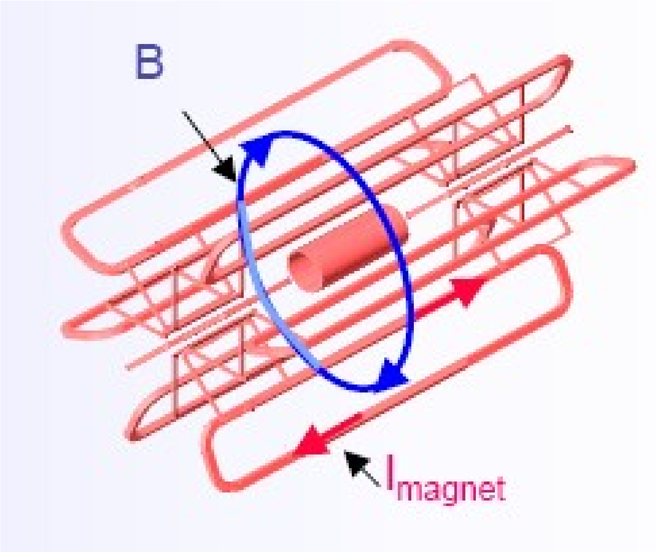


Examples:

- Delphi: SC, 1.2 T, 5.2 m, L 7.4 m
- CDF: SC, 1.4T, 2 m, L 6m
- CMS: SC, 4 T, 5.9 m, L 12.5 m

Toroid

- + Field always perpendicular to p
- + Rel. large fields over large volume
- + Rel. low material budget
- - Non-uniform field
- - Complex structural design

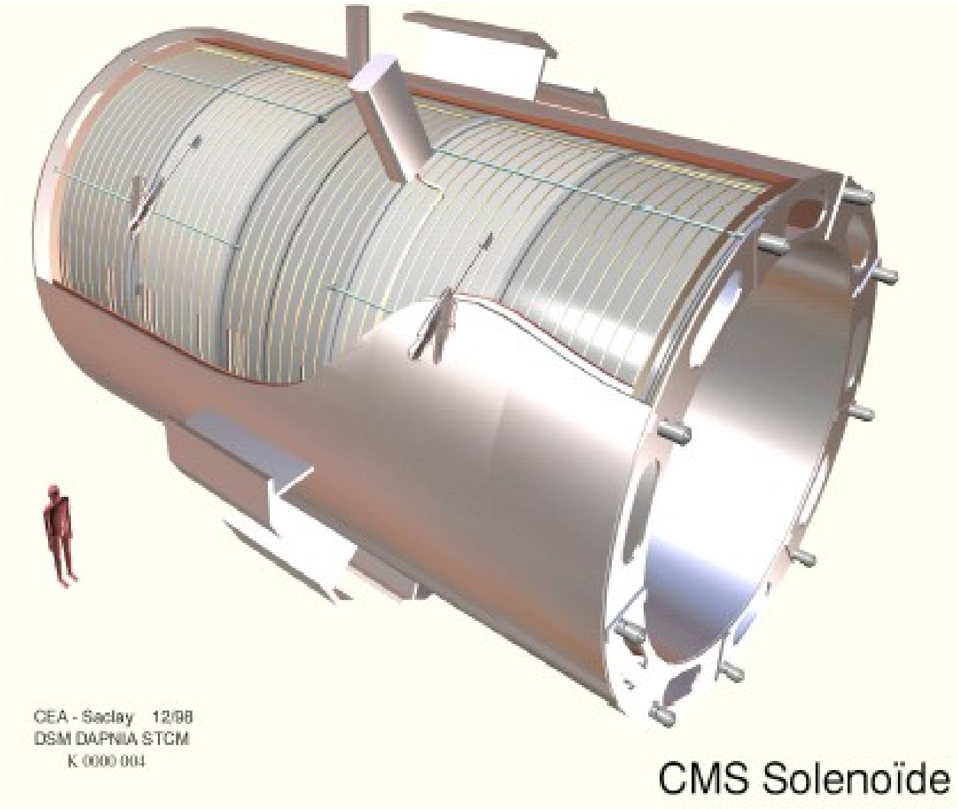


Example:

- ATLAS: Barrel air toroid, SC, ~1 T, 9.4 m, L 24.3 m

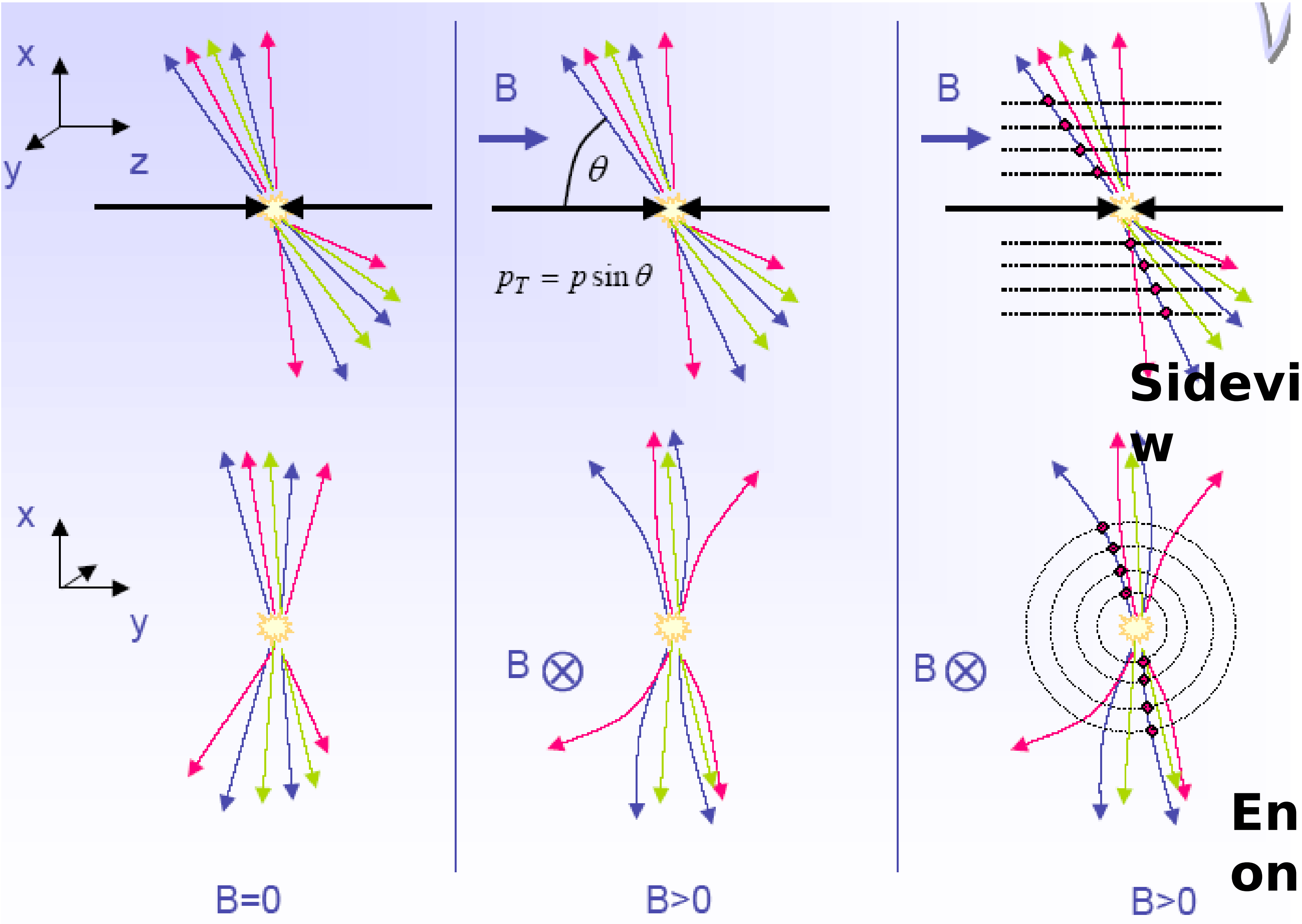
Charge and Momentum

Two ATLAS toroid coils



Superconducting CMS Solenoid Design

Charge and Momentum



Sideview

End on

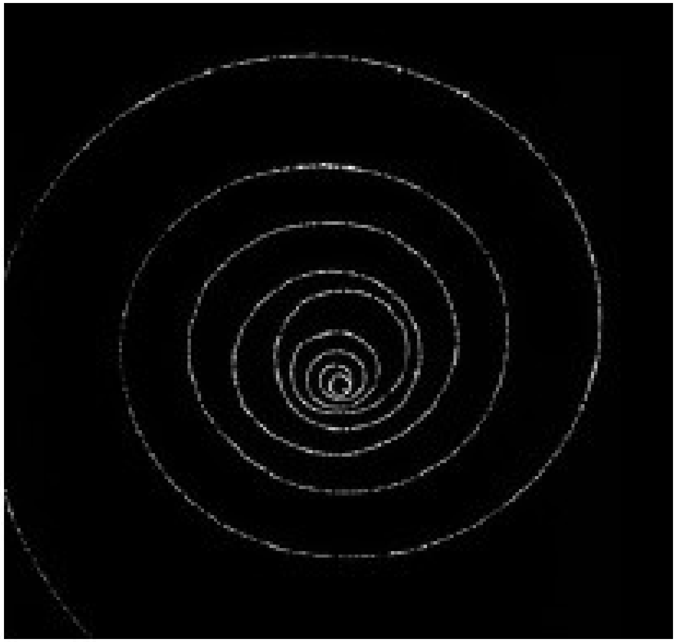
The Art of Tracking

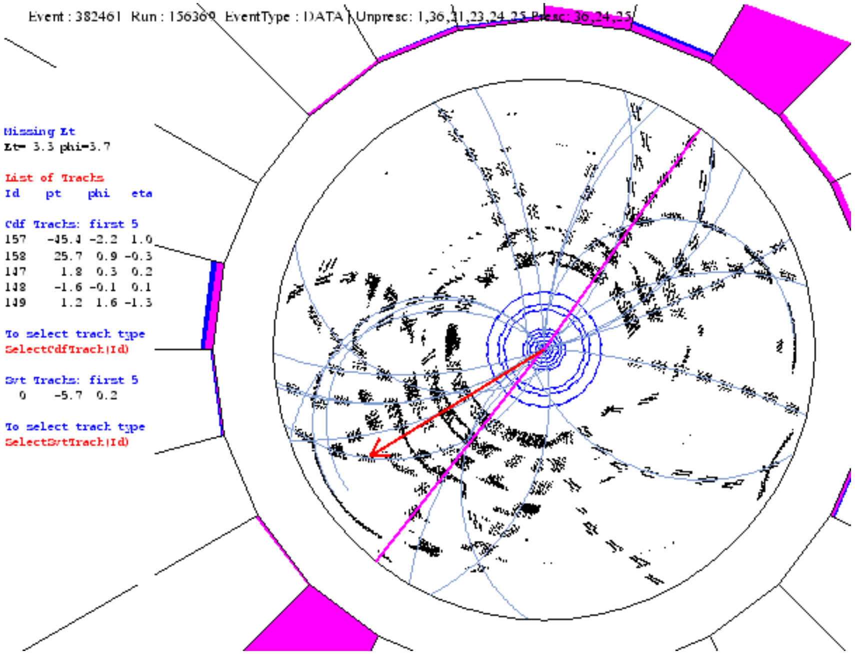
(Zen and motorcycle maintenance)

- Tracking is simply the process of sampling a particle's trajectory in space and determining its parameters. Namely:
  - Momentum
  - Direction
  - Decay points
  - Charge
- At High energy
  - Only a small fraction of energy deposited in instrument
- Ideally, the trajectory should be disturbed minimally by this process.

Method

- Charged particles ionize matter along their path.
- Tracking is based upon detecting ionization trails.
- An “image” of the charged particles in the event is created…





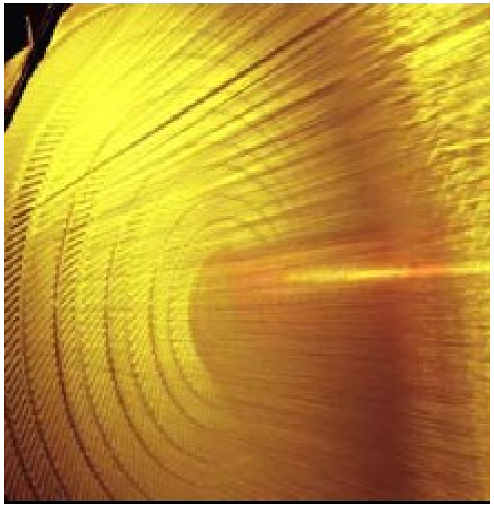
```
Event : 382461  Run : 156369  EventType : DATA  Unpresc: 1,36,31,23,24,25 Presc: 36,24,25

Missing Et
Et= 3.3 phi=3.7

List of Tracks
Id    pt    phi   eta

Cdf Tracks:  first 5
157    -45.4 -2.2  1.0
158     25.7  0.9 -0.3
147      1.8  0.3  0.2
148     -1.6 -0.1  0.1
149      1.2  1.6 -1.3

To select track type
SelectCdfTrack(Id)

Svt Tracks:  first 5
  0     -5.7  0.2

To select track type
SelectSvtTrack(Id)
```

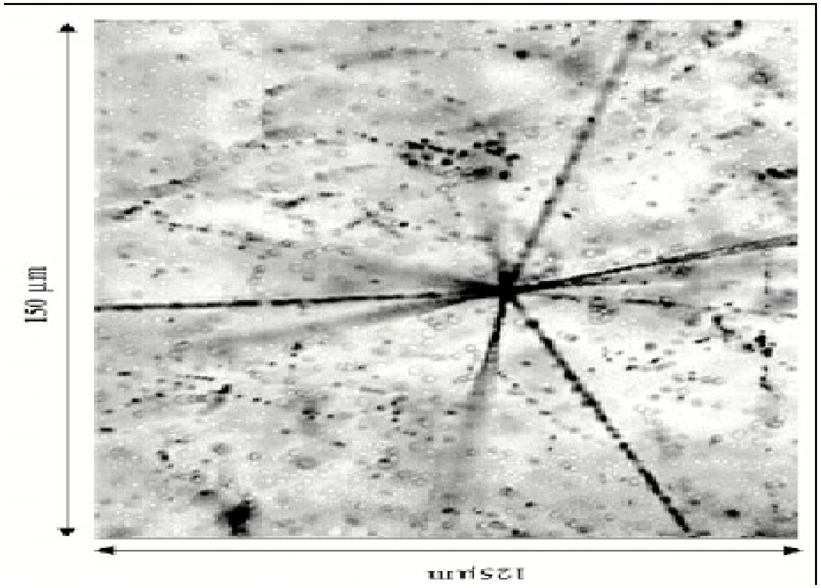
Specifications (Design)

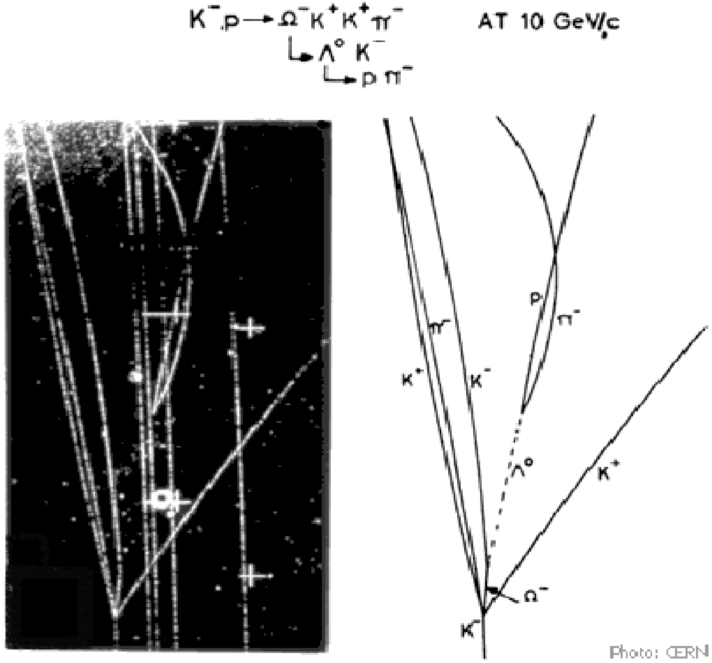
- Performance based upon reconstruction of track parameters
- Defined in terms of:
  - parameters of the system (layout, magnetic field, etc)
  - performance of position sensing elements.
  - Initially evaluate with simple parametric analyses.
- Full simulation
- Performance of position sensing elements
  - hit resolution, timing resolution, effects of data transmission
  - defined by physics of detecting medium/process and general considerations such as segmentation and geometry.

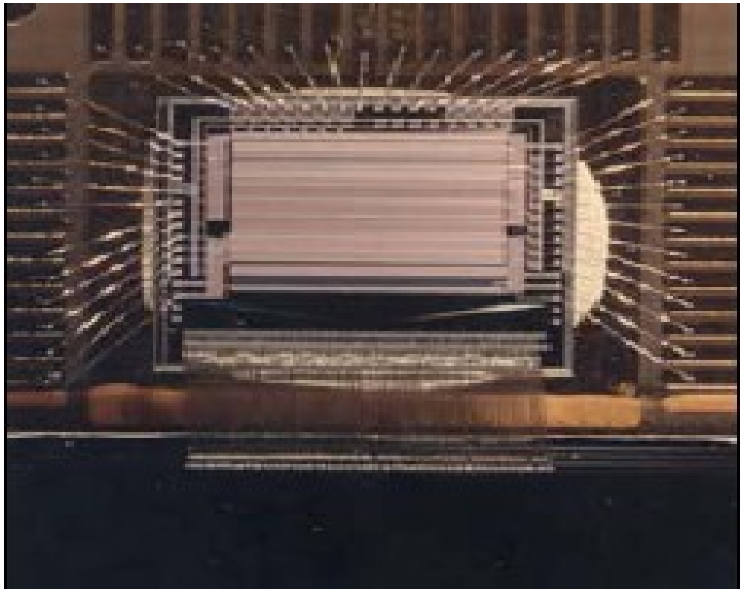
Technology

- Old:
  - Emulsions, cloud, and bubble chambers
  - Continuous media
  - Typically gave very detailed information but were slow to respond and awkward to read out
- New:
  - Electronic detectors, wire chambers, scintillators, solid state detectors
  - Course to very finely segmented
  - Fast, can be read out digitally, information content is now approaching the “old” technology



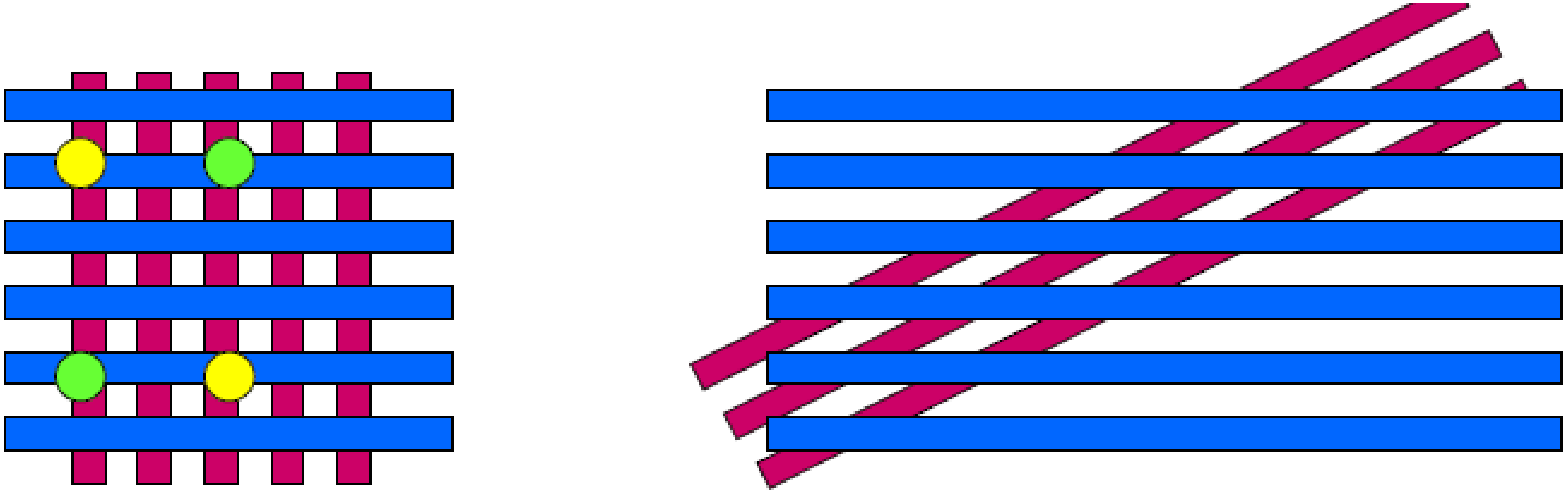

150 µm
125µm


K⁻p → Ω⁻K⁺K⁺π⁻
↳ Λ° K⁻
↳ p π⁻
AT 10 GeV/c
π⁻
K⁺
K⁻
p
π⁻
Λ°
K⁺
Ω⁻
K⁻
Photo: CERN

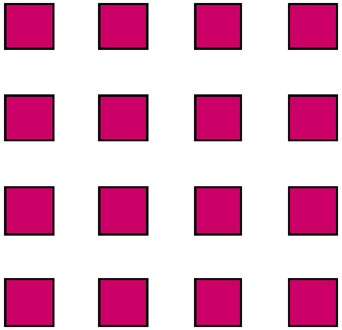


The problems with 2 dimensions

- crossed array of n elements each on pitch p gives equal resolution on both coordinates.
  - m hits → m^2 combinations with $m^2 - m$ false combinations
- Small angle stereo geometry, angle α
  - False combinations are limited to the overlap region but resolution on second coordinate is worse by 1/sin(α)



Hello Pixels!



- Pixel structure: *n* x *m* channels
  - Ultimate in readout structure
  - Expensive in material, system issues, technology
- Pixels and strips can also be thought of as 2 extremes of a continuum (super-pixels, short-strips,.....)
  - Some potential for optimizations of performance vs. complexity but needs to be analyzed on a case by case basis
- Novel 2D structures with 1D readout which rely on assumptions about hit characteristics

Semi Conductor Devices

- Since mid-80’s use of position sensitive “silicon detectors” became widespread
- Can resolve track positions to ~10 microns
- Used to measure momentum and identify secondary vertices due to decays of primary particles
- Handle high particle rates and radiation dose

Silicon Detectors

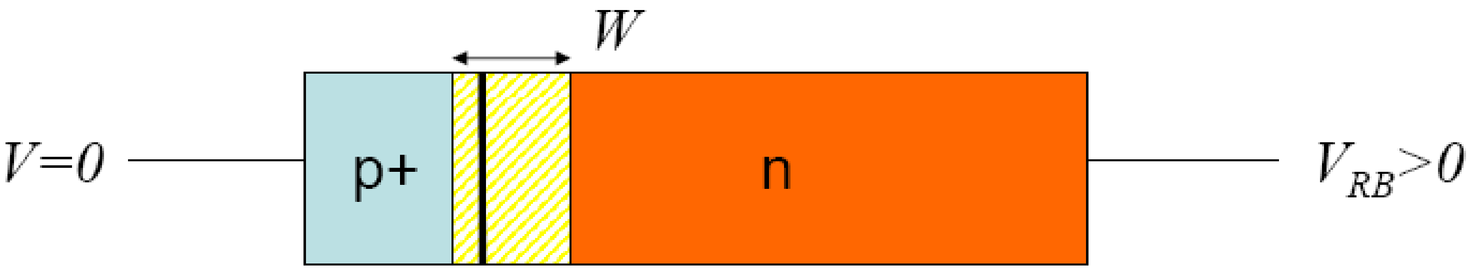
- Semiconductor band structure →energy gap
- Asymmetric diode junction: example p(+) into contact with n ($N_A >> N_D$)
- Space charge region formed by diffusion of free charges, can be increased with “reverse bias”

$$\text{junction width}: W = \sqrt{2\mu\rho\varepsilon(V_{BI}+V_{RB})} = 0.5\mu m\sqrt{\rho(V_{BI}+V_{RB})}$$

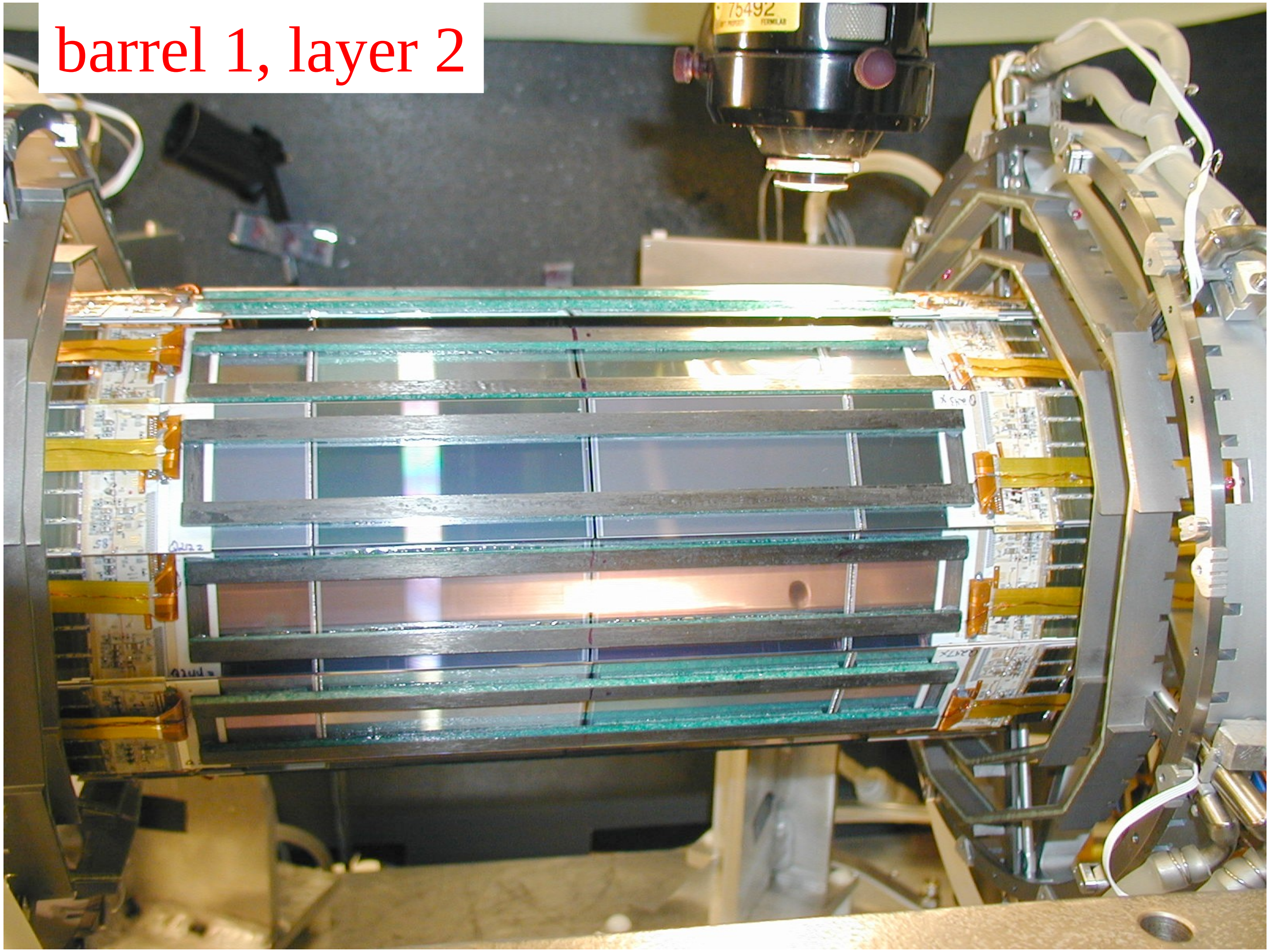
$$\mu = \text{electron mobility}, \varepsilon = 11.9\varepsilon_0$$

$$\rho = \text{resistivity of n type material} = \frac{1}{e\mu N_D} \approx 1-10k\Omega\, cm$$

$$V_{BI} = \text{built in potential} (\sim 0.8\,\text{V}) \qquad V_{RB} = \text{applied reverse bias}$$



CDF SVXII Barrel Assembly
First production Barrel



barrel 1, layer 2

Radiation Environment

- Primary source is collision products
  - High energy charged particles
  - Neutrals from interactions
  - Beam “halo” has minimal affect at the Tevatron
- Additional component due to “accidents”
  - Kicker “prefires”
  - Poor collimator placement
- Collisions occur over extended line – many cm

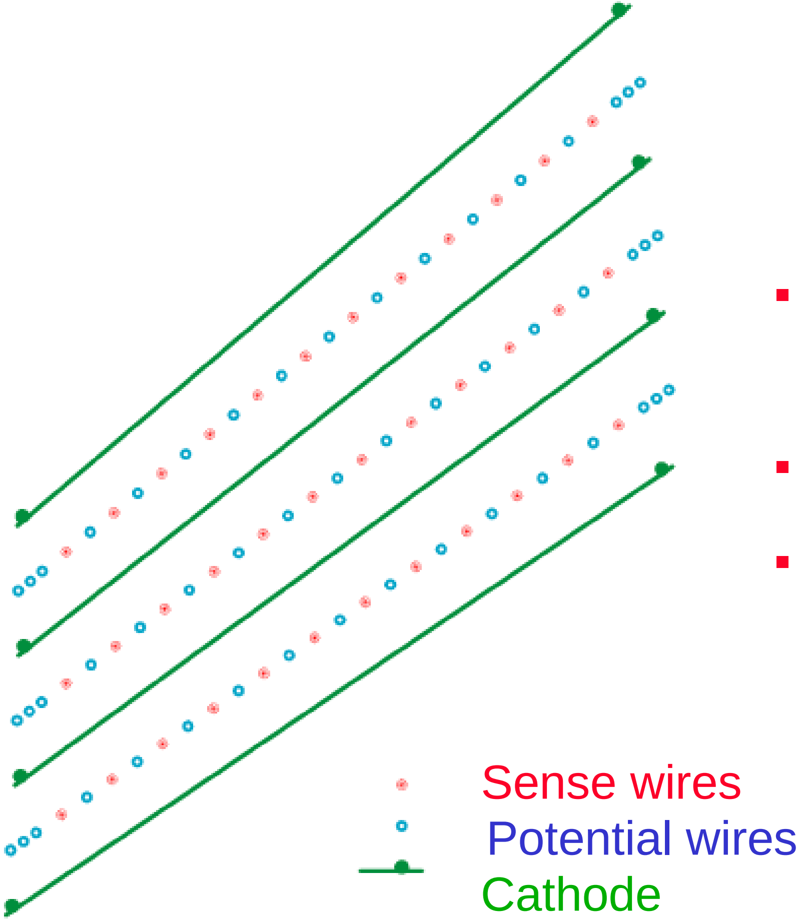
Radiation Environment

- Primary field falls with radius as $\sim r^{-(1-2)}$
  - The inner layers are most vulnerable
- Fluence and dose have increased $>10^4$ since mid-80's
  - Near future detectors expect unprecedented dose
    - 100 Mrad absorbed energy (units)
    - 10^{15}-10^{16} particles/cm^2
  - Compare to:
    - space (~1 MRad)
    - nuclear weapons (~10^{13})

Radiation Effects

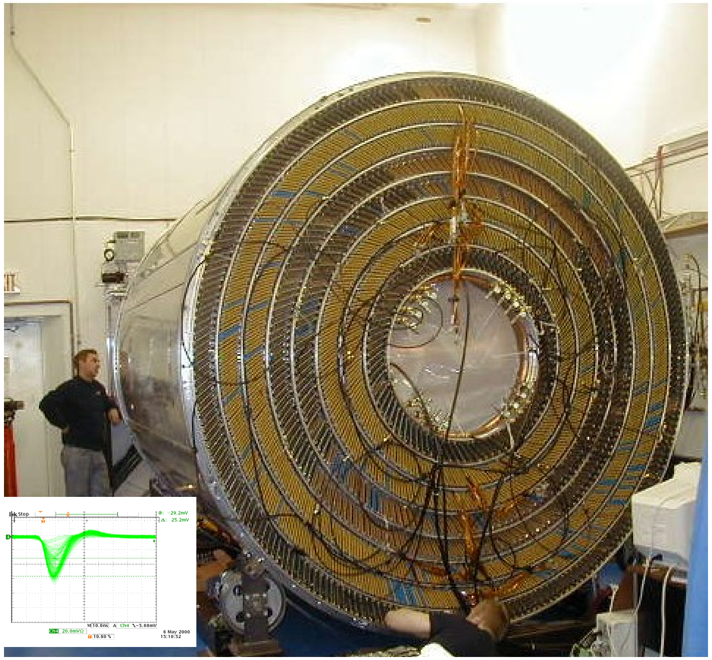
- Incident particle interacts with atomic electrons
- Measure in energy absorbed (rads(Si))
- e/h pairs created, recombine or trap
- Transient effect
  - Actual signal formation
  - Single event upset condition in circuits
    - Single event upsets not just for silicon on detectors, but for any silicon based electronics located on the detector
- Detectors: surface effects

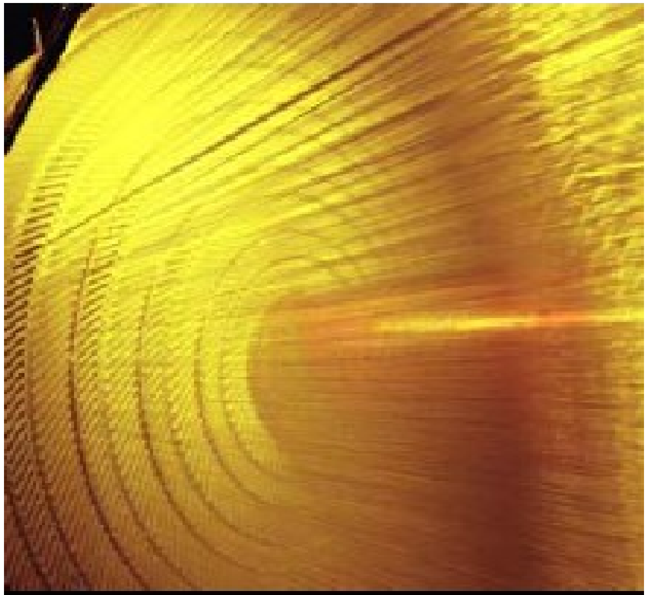
Central Outer Tracker (COT) Construction



- Basic Cell :
  - 12 sense ,17 potential wires
  - 40 μ diameter gold plated W
  - Cathode: 350 A gold on 0.25 mil mylar
- Drift trajectories very uniform over most of the cell (3.5 cm-->0.88 cm)
- cell tilted 35^{o} for Lorentz angle
- Novel Construction:
  - Use winding machine
  - 29 wires/pc board, precision length
  - Snap in assembly fast vs wire stringing
  - 30,240 sense wires vs 6156 in CTC
  - Total wires 73,000 vs 36,504 in CTC

Central Outer Tracker





Muons

Whats up with the Muon?

- **Muons are easy to detect with high accuracy and low backgrounds: no strong interaction**
  - **Long lifetime**
  - **Lepton decay channels for many of heavy objects are clean and have low backgrounds:**
    - **W-> μν, Z -> μμ**
    - **t -> bW -> bμν**
- **Many of new particles searches contain muon(s) as final detectable particles**
- **Everyone loves muons!**

Muon Particle ID Methods

- **Detection of muons consist of two major steps:**
  - **identification that the object is a muon**
  - **muon parameters measurement**
- **The direct way for identification is to compare parameters of particle in question with known values:**
  - **Mass**
  - **Charge**
  - **Lifetime**
  - **decay modes**
- **Typical method for a few GeV muons is to measure momentum and velocity of a particle:**
- **Velocity is measured by:**
  - **Time of flight**
  - **Cherenkov, TRD**

Muon Particle ID Methods

- **For high energy (above a few GeV), muons identification is based on low rate of interaction of muons with matter**

- **Bottom Line:**
  If charged particle penetrates large amount of absorber with minor energy losses and small angular displacement -- such particle is considered a muon

Muon Lifetime

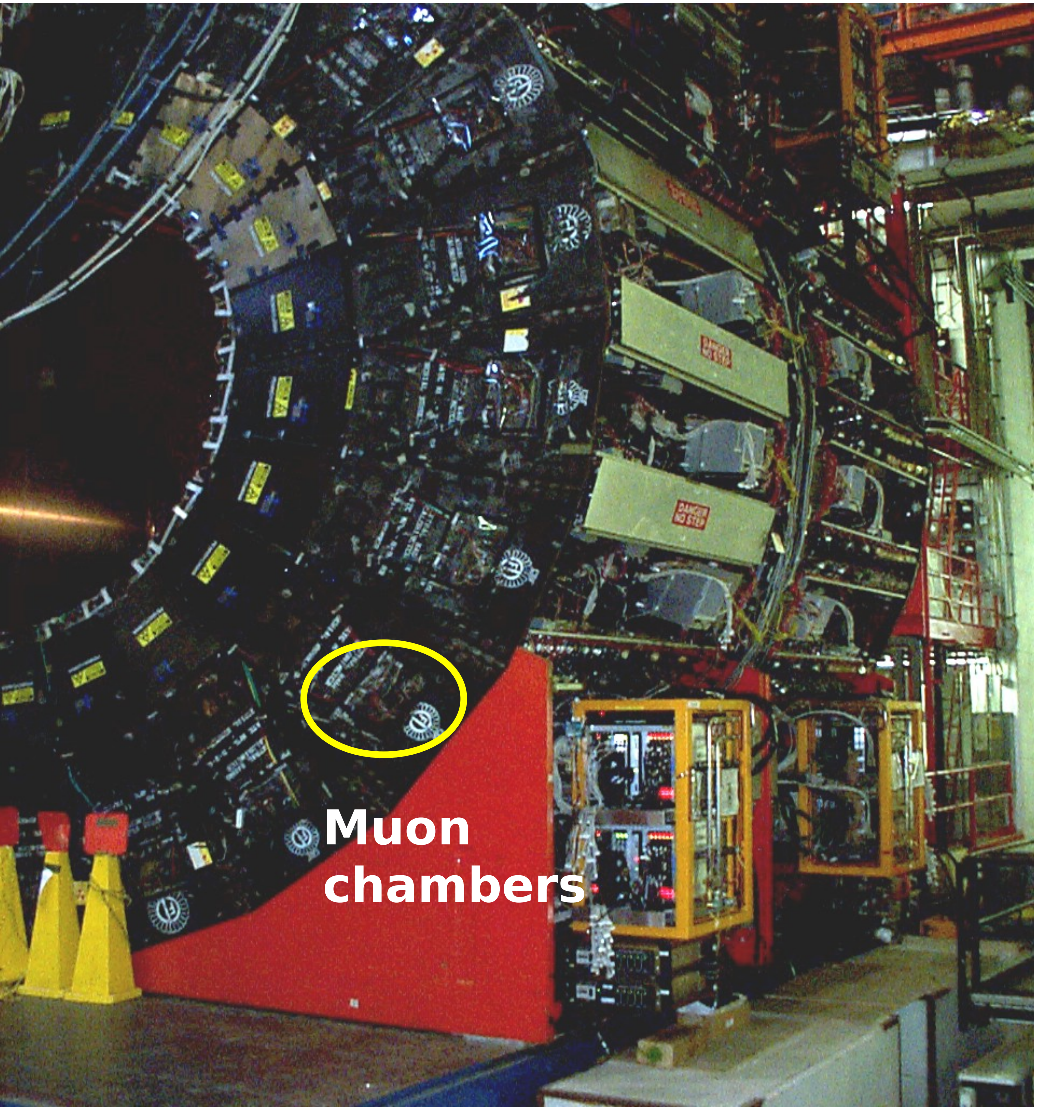
- **Muon lifetime is 2.2 msec, c Γ=0.7km**
- **Decay path**

P, GeV/c	Decay Path in (km)	type
1	7	cosmics
10	70	b-quarks
100	700	Muon collider

Muon Energy Loss

- Muon Energy loss is defined by electro-magnetic interactions
  - Ionization
  - e^+e^- pair production
  - Bremsstrahlung
  - Photo nuclear reactions
- Below ~200 GeV, muon energy losses are mainly due to ionization – the average loss about 2 MeV/gcm^2 or 1.4 GeV/m steel

Muon Detector Layout

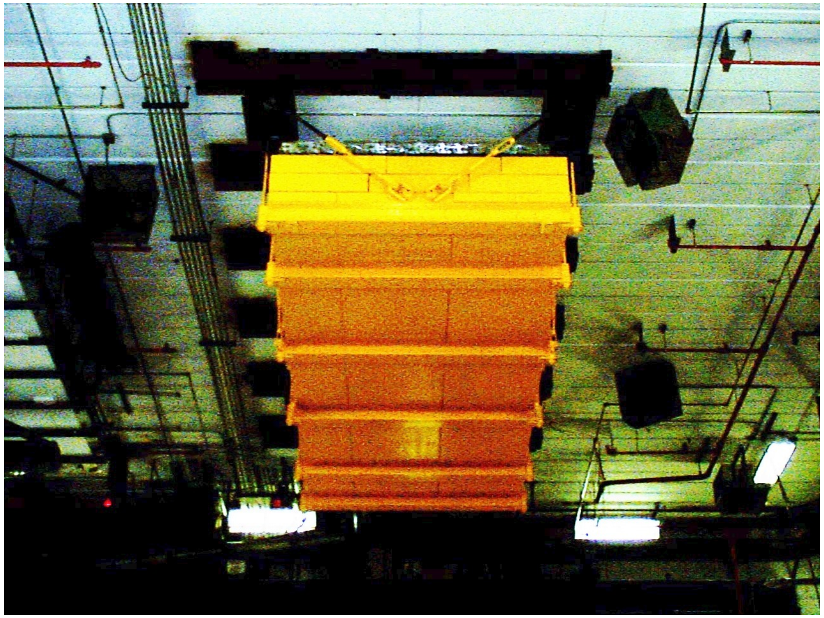


- What people worry about when designing muon systems…
  - Punch-through probability
  - Momentum (angular) resolution

CDF Central Calorimeter arch
pulled out for repairs

CDF’s Solution

- More Steel and More chambers!!!



Hadron Punch-through

- Hadrons create showers in absorber. If the absorber is too thin, the shower can "leak" through such that charged particles are then detected after the absorber
- Monte Carlo calculations and test beam measurements are used to estimate the punch-through probability
- Methods to minimize punch-through
  - Tracking before/after absorber
  - Momentum measurement before/after absorber
  - timing

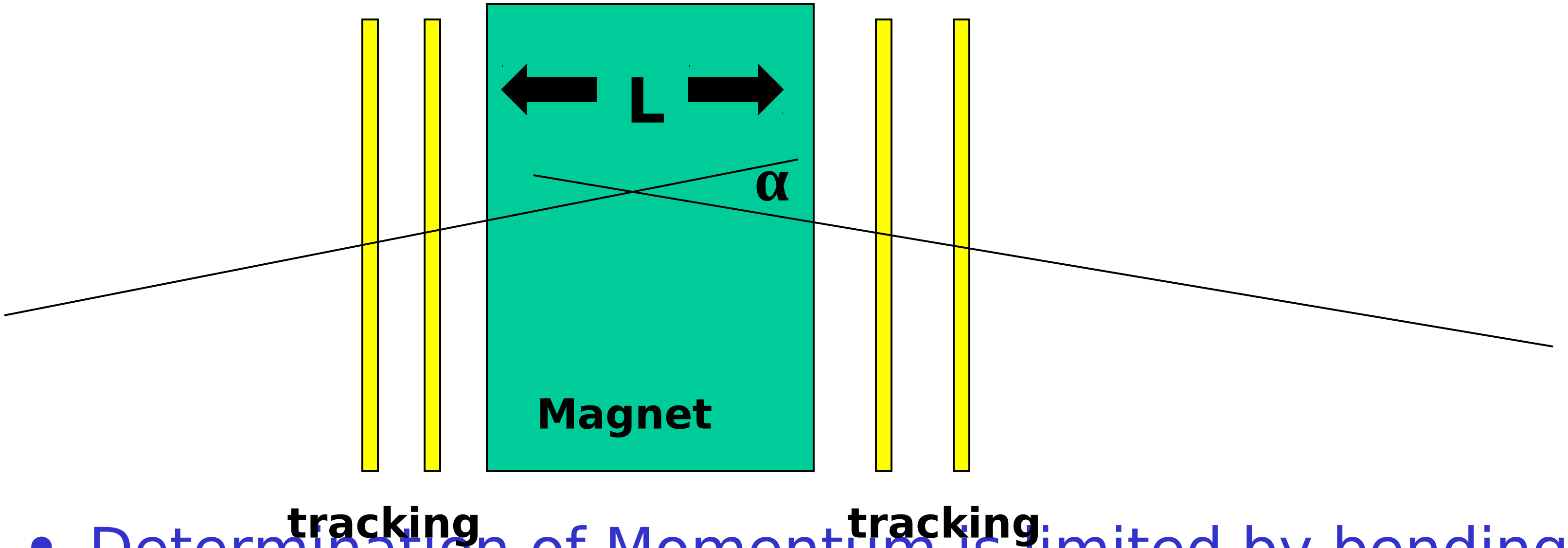
Very High Energy Muons

- At energies above ~0.5TeV, muons start to loose energy due to radiation (gamma, e+e-); as a result the muon track is accompanied by em showers...
- Major problem due to radiation is occupancy of the tracking detectors
- Ways to reduce em backgrounds
  - Multi hit detectors/electronics
  - Air gap between absorber and tracking detector
  - Increased number of detector planes

Momentum Resolution

- Muon track can be bent “inside” magnetized iron and steel. Both can be easily magnetized up to ~2T

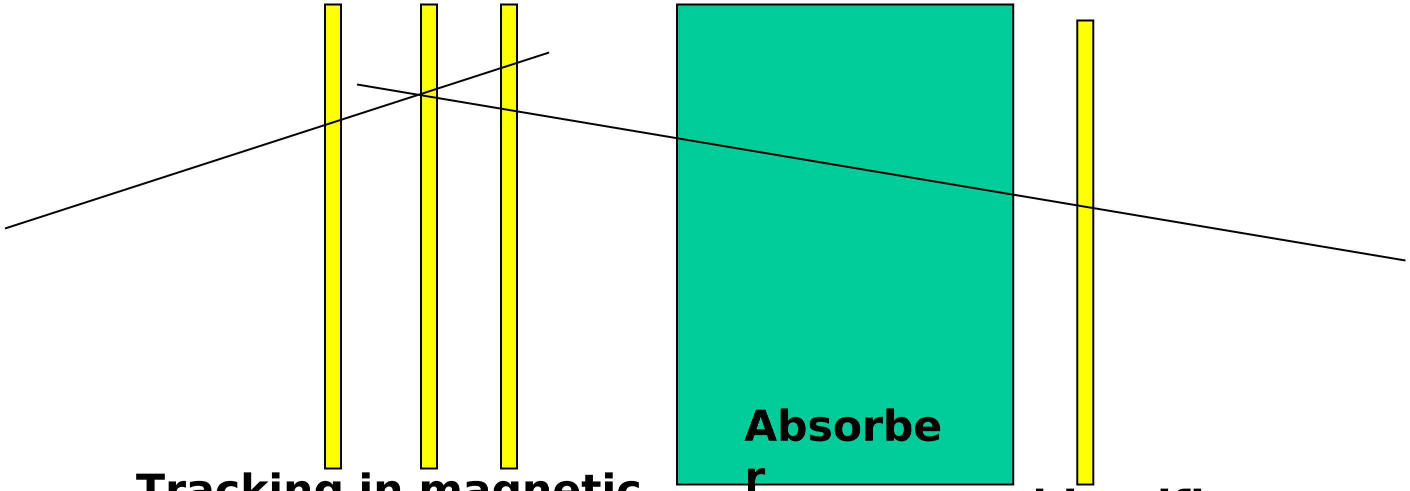
  $P(\mathrm{GeV}/c) – 0.3B(\mathrm{T})L(\mathrm{m})/\alpha(\mathrm{rad})$



- Determination of Momentum is limited by bending angle measurement
  - Accuracy of tracking detection
  - Multiple scattering

How to Improve Resolution

- Reduce multiple interaction term by bending muon in air, not iron
  - After collision target (in fixed target expts)
  - Using solenoid of central tracker (colliders)
  - In large air core magnets (colliders)



Tracking in magnetic field

Absorber

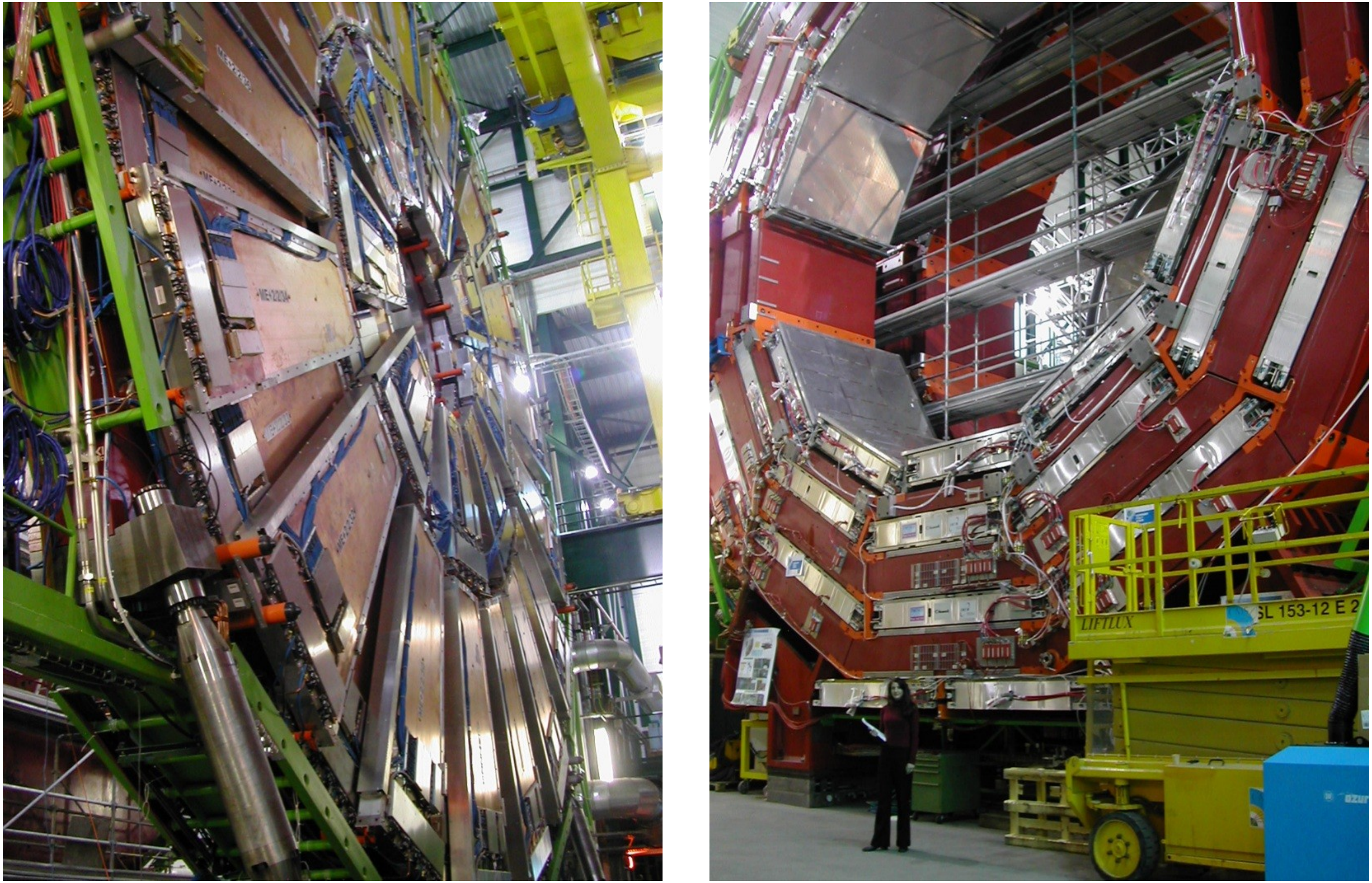
identifier

- Detector improvements
  - Increase intrinsic accuracy
  - Increase lever arm

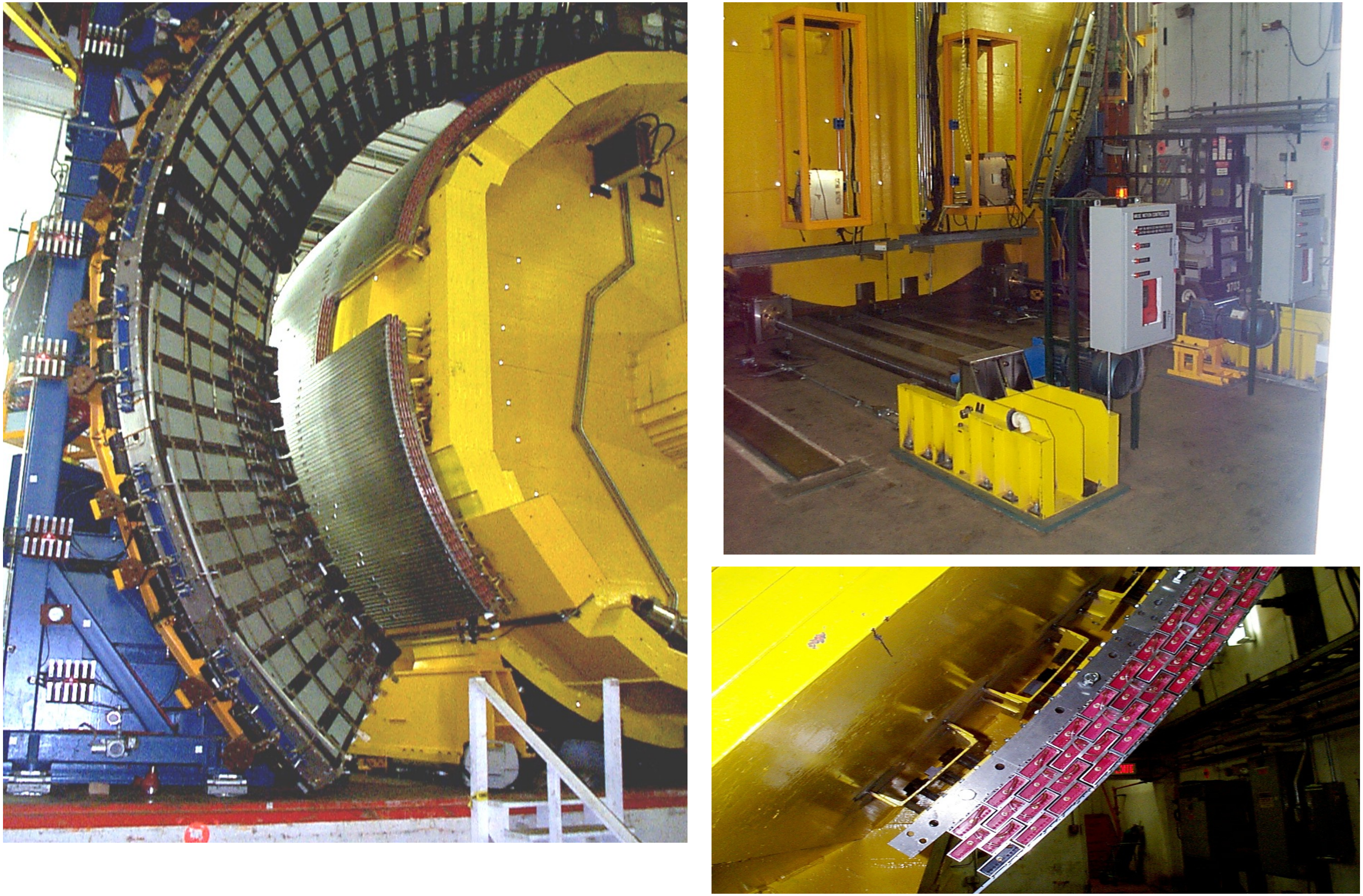
Instrumentation of Muon Detectors

- **Major parts of muon detector:**
  - absorber/magnet
  - tracking detectors
  - (electronics, DAQ, trigger, software)
- **Absorbers:**
  - most common is steel: high density (smaller size)
  - not expensive, could be magnetized concrete, etc depending on space
- **Magnets:**
  - dipole magnets in fixed target or solenoid magnets in colliders:
  - “a few” m^3 in volume
  - field ~2T
  - cryo and/or high energy consumption
- **magnetized iron toroids:**
  - hundreds m^3 volume
  - saturation at ~2T
  - low power consumption
- **air core super conducting magnets:**
  - field similar to iron magnets, but no multiple scattering
  - cryo and complex design

CMS Muon Chambers



Some CDF Muon Detectors



Considerations for Tracking Detectors

- **muon tracking detectors:**
  - **coordinate accuracy**
  - **large (~10^3 m^2) area**
- **Other considerations include:**
  - **resolution time**
  - **sensitivity to backgrounds**
  - **segmentation (triggering)**
- **aging**
- **cost**
- **Two most common types of detectors:**
  - **scintillation counters**
  - **gas wire detectors**

Scintillation Counters…

- Typically used before and after absorber for muon ID, bunch tagging, and triggering. Rarely is it used for momentum measurement
- Typical sizes are 1cm(thick) by 10-50cm(width) by N meters (length)
- Muon deposits a few mev of energy into a counter – which converts into several hundred photo electrons
- Attributes
  - Fast (1ns resolution)
  - Easy to make – custom sizes are not a problem
  - Inexpensive to operate but expensive per m^2

Gas Detectors

- Most commonly used for muon tracking
  - Drift tubes
  - Cathode strip chambers
- Principle of gas avalanche detector operations
  - Muon creates on electron-ion pair per 30 ev of deposited energy; typically 100 pairs per cm of gas
  - Electrons inside the electric field drift to the small diameter anode wire
  - Gas amplification (~10^6 occurs near the anode wire providing detectable signals (~1 µA)
  - Can get much higher precision than just wire spacing by determing the drift time.

Calorimeters

A Brief Introduction

Energy of a particle or group of particles is necessarily measured destructively. We must completely stop the particle in our detectors to measure its full energy.

The energy is deposited in a localized space, so that *position* can be determined with accuracy dependent on transverse energy fluctuations and detector design.

Accuracy of energy measurement comes from a:

- **Constant term: Uniformity of the detector medium, and a**
- **Stochastic term: Level of active sampling wrt total detector volume**

Calorimetry can thus provide momentum of a particle redundantly to the inner tracking measurements, useful in cleaning up backgrounds.

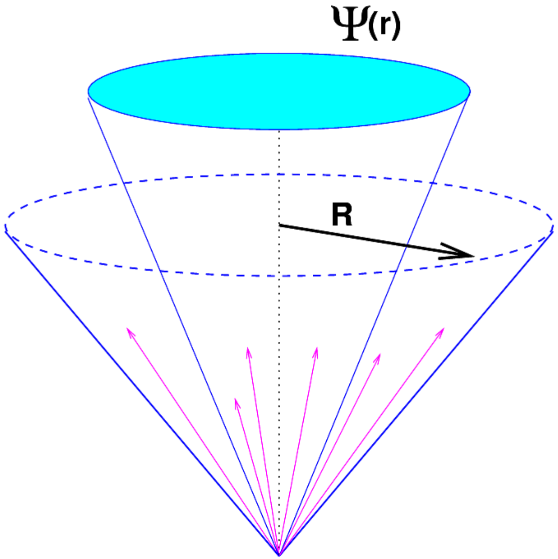
Multipurpose Calorimeters

Calorimeter use widespread, essential to most experiments.

Neutral particles (γs, neutrons) are only detected by this. Why?

Sampling calorimeters are sometimes used as ν detectors.

Triggers for jets: as collision energies increase, particle multiplicity increases, and we get highly collimated sprays of secondary particles in a localized angular distributions.

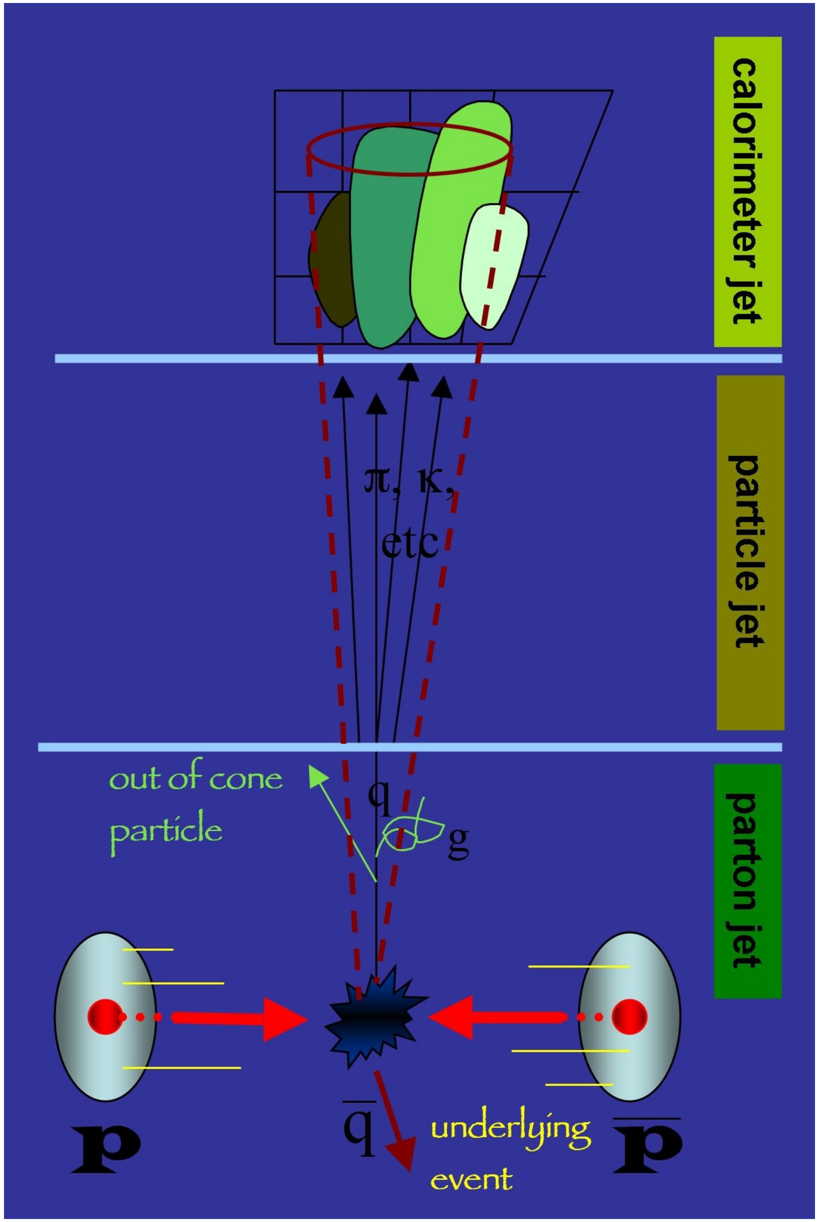


Can be made modular, and to cover large solid angles. Size scales as ln(E), but B-field tracking goes like $E^{1/2}$.

Partons → Particles → Jets

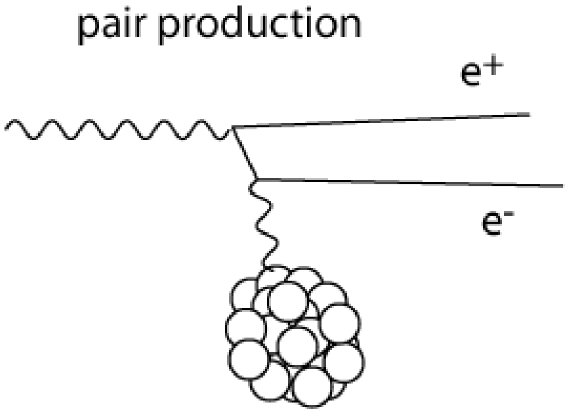
Processes creating jets are very complicated, and consist of parton fragmentation, then both electromagnetic and hadronic showering in the detector.

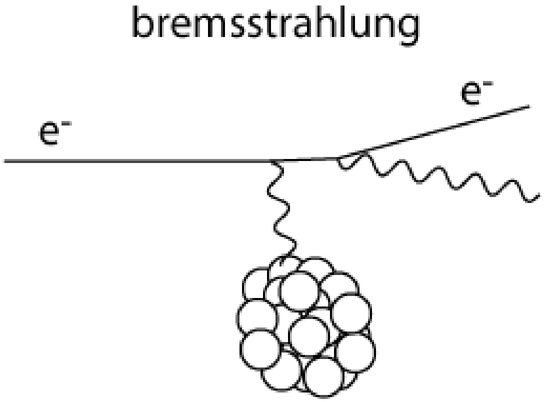
Reconstructing jets is, naturally, also very difficult. Jet energy scale and reconstruction is one of the largest sources of systematic error.



Electron and γ Interactions

At E > 10 MeV, interactions of γs and e^-s in matter is dominated by e^+e^- pair production and Bremsstrahlung.





At lower energies, Ionization becomes important.

The ratio of the energy loss for these processes is:

$$R = \left(\frac{dE}{dx}\right)_{Brem} \Big/ \left(\frac{dE}{dx}\right)_{ion} \sim \frac{ZE}{580\ MeV}$$

Critical Energy:

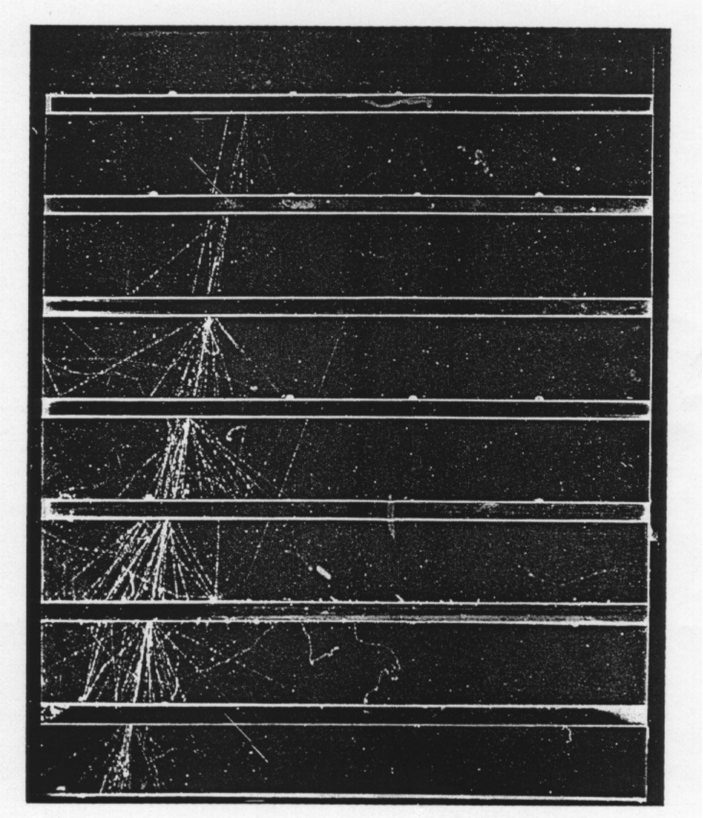
When energy loss due to Brem and energy loss due to ionization are =.

$$E_c = \frac{580\ MeV}{Z}$$

Electromagnetic Showers

An alternating sequence of interactions leads to a cascade:

- **Primary γ with E_0 energy pair-produces with 54% probability in layer X_0 thick**
- **On average, each has $E_0/2$ energy**
- **If $E_0/2 > E_c$, they lose energy by Brem**
- **Next layer X_0, charged particle energy decreases to $E_0/(2e)$**
- **Brem of avg energy between $E_0/(2e)$ and $E_0/2$ is radiated**
- **Mean # particles after layer $2X_0$ is ~4**
- **Radiated γs pair produce again**



Cloud chamber photo of electromagnetic cascade between spaced lead plates.

After n generations ($dx= nX_0$), 2^n particles, avg energy $E_0/2^n$ for shower.

Cascade stops: e^- energy → critical energy $E_c= E_0/2^n$.

Number of generations: $n=\ln(E_0/E_c)/\ln 2$.

Number of particles at shower maximum: $N_p = 2^n = E_0/E_c$.

EM Shower Properties

Typical properties of electromagnetic showers:

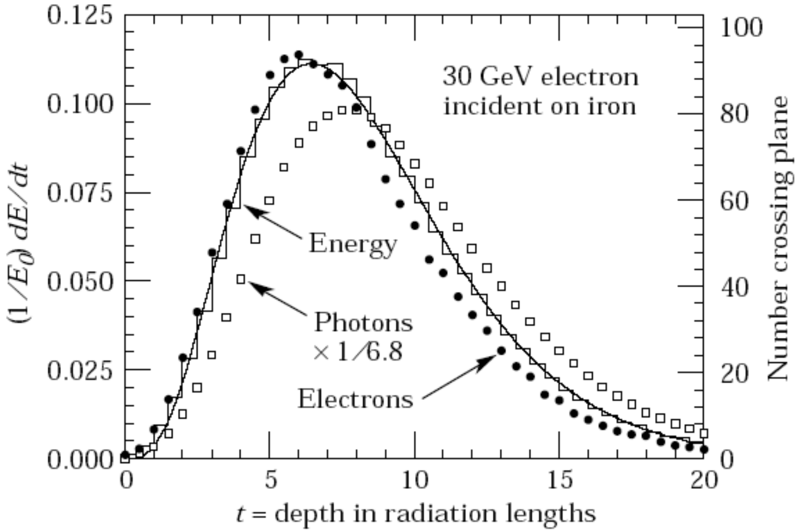
- **# particles at shower maximum N_p proportional to E_0**
- **Track length (depth) of e^- and e^+ proportional to E_0**
- **Depth for maximum X_{max} increases logarithmically:**

Longitudinal energy deposition:

$$\frac{dE}{dt} = E_0 c t^{\alpha} \exp(-\beta t), \text{ where } t = X / X_0 \text{ and}$$

$$\beta » 0.5, \alpha » \beta t_{\max}, \text{ and } c = \beta^{\alpha+1} / G(\alpha+1)$$

vary logarithmically with energy



Longitudinal energy deposition for e^- in lead, fit to gamma function

Transverse shower dimension: multiple scattering of low energy e^-:

Moliere Radius: $R_M = 21 \text{ MeV} * X_0 / E_c$

Radial distribution in R_M independent of material used!

99% of energy is inside a radius of 3 R_M.

Energy Resolution

Energy resolution of ideal detector of infinite dimensions is limited by statistical fluctuations.

Example: For E_c=11.8 MeV and detection cut-off E_k=0.5 MeV and a track length of 176 cm/GeV, best resolution ~ $s(E)/E=0.007/\sqrt{E(GeV)}$

Losses of Resolution:

- **Shower not contained in detector → fluctuation of leakage energy; longitudinal losses are worse than transverse leakage.**
- **Statistical fluctuations in number of photoelectrons observed in detector. If** $\alpha_p = N_p / E_0$ **is # photoelectrons per unit primary particle E,**

$$\left[s(E)/E\right]_{PE} = 1/\sqrt{\alpha E_0}$$

- **Sampling fluctuations if the counter is layered with inactive absorber.**

- **If active area is gas or liquid argon, low E e- move at large angles from the shower axis, Landau tail leads to “path length fluctuations”.**

Electromagnetic Calorimeter Types

Homogeneous “shower counters”:

Best performance from organic scintillating crystals. Example of NaI(Tl) have achieved ~ $s(E)/E=0.028/[E(GeV)]^{-0.25}$. Also use lead glass, detects Cerenkov light of electrons, limited by photoelectron statistics.

Sampling calorimeters:

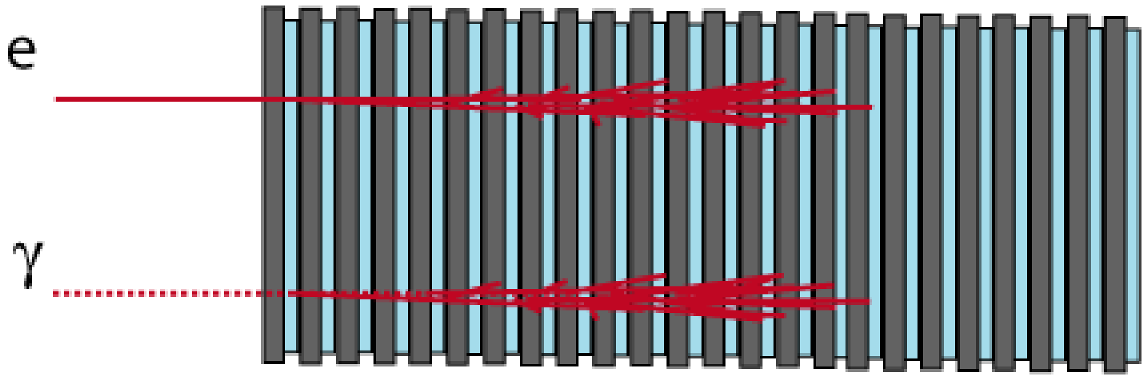
Layers of inactive absorber (such as Pb) alternating with active detector layers, such as scintillator or liquid. Resolutions ~7%/√E or so.

Liquid noble gases:

Counters based on liquid noble gases (with lead plates, for example) can act as ionization chambers. L Ar - Pb versions obtain ~10%/ √E. Ionization read out by electrodes attached to plates (no PMTs!). Disadvantage: slow collection times (~1 μs).

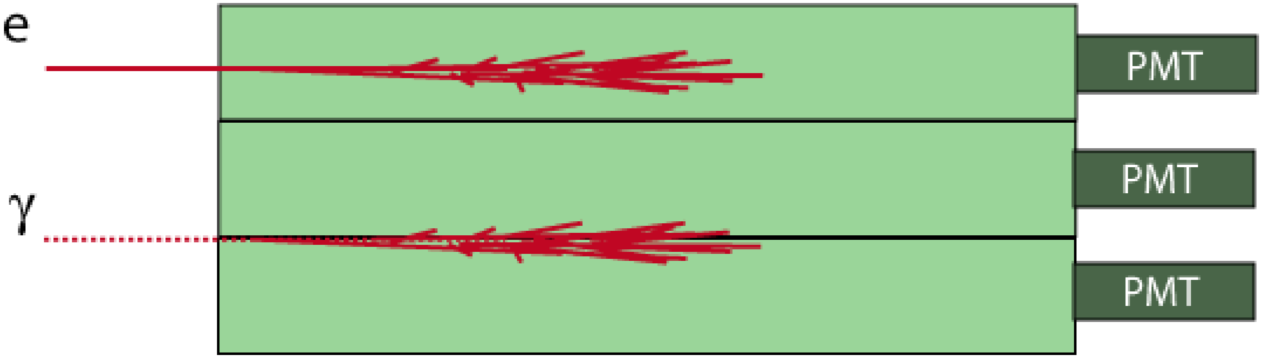
Variations in the 1990s: ‘Accordion’ for fast readout (front/back readout) and L Kr homogeneous detector (energy&time resolution).

Electromagnetic Calorimeter Types



Energy resolutions:

$\sigma(E)/E \sim 20\%/\sqrt{E}$



$\sigma(E)/ E \sim 1\%/\sqrt{E}$

$\sigma(E)/ E \sim 18\%/\sqrt{E}$

Hadron Calorimeters

When a strongly interacting particle above 5 GeV enters matter, both inelastic and elastic scattering between particles and nucleons occur.

Secondary hadrons → examples: π and K mesons, p and n.
Energy from primary goes to secondary, then tertiary, etc.

Cascade only ceases when hadron energies small enough to stop by ionization energy loss or nuclear absorption.

Hadronic Shower: spatial scale for shower development given by nuclear absorption length λ_N. Compare X0 for high-Z materials, we see that the size needed for hadron calorimeters is large compared to EM calorimeters.

material	X_0 (g/cm^2)	λ_n (g/cm^2)
H_2	63	52.4
Al	24	106
Fe	13.8	132
Pb	6.3	193

Compensating Calorimeters

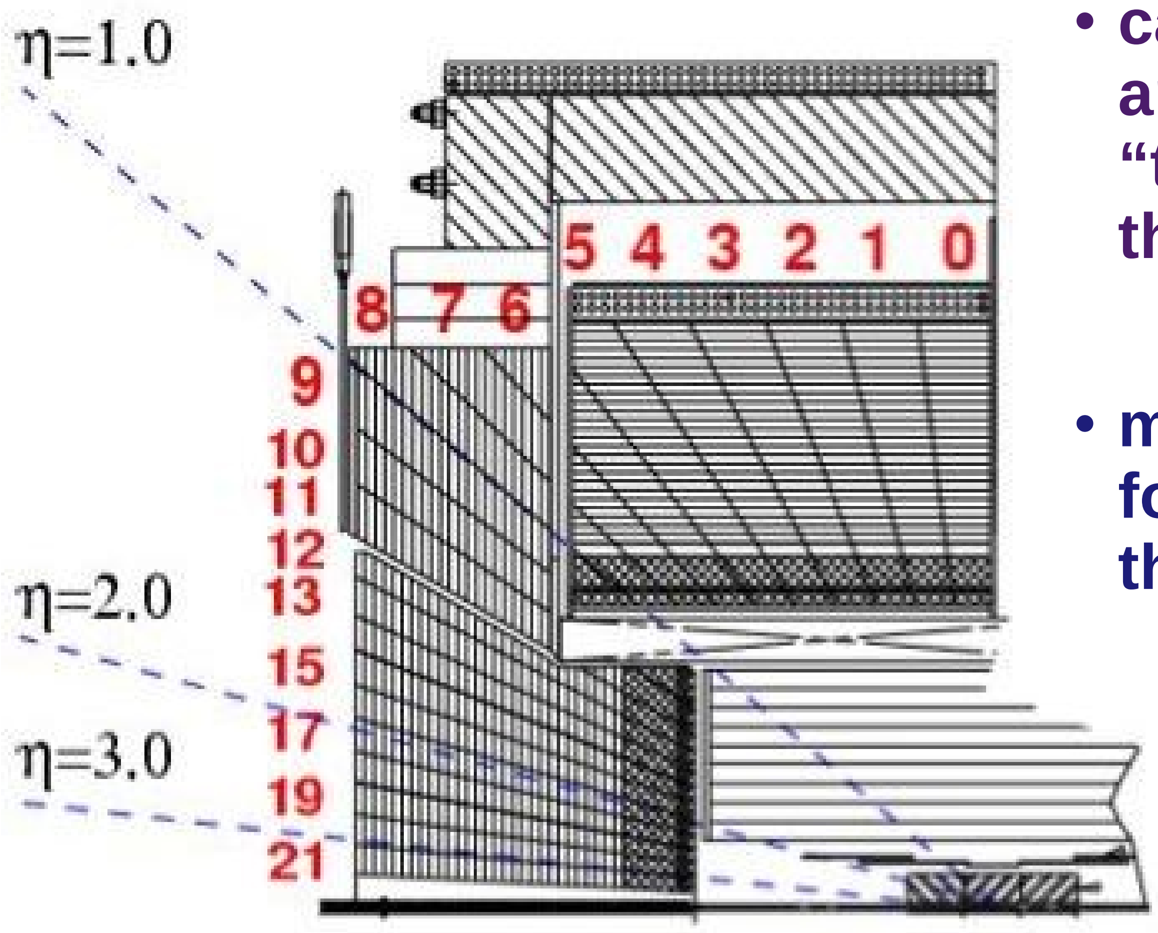
Improvements in energy resolution can be achieved if showers induced by electrons and hadrons of same energy produce same visible energy (detector response).

Requires the losses to be "compensated" in some way.

Three methods:

- **Energy lost by nuclear reactions made up for by fission of ^{238}U, liberating n and soft γ–rays. Can get response close to equal: proton-rich detector em shower decreases, had shower increases due to more nuclear reactions.**
- **If have lots of H2, compensation achieved with high absorber material: in inelastic collision of hadrons w/ absorber nuclei, neutrons are produced → recoil protons, larger signal.**
- **Reduce fluctuation in EM component: weight individual counter responses, and even response out across the board.**

CDF Sampling Calorimeter



- calorimeter is arranged in projective "towers" pointing at the interaction region

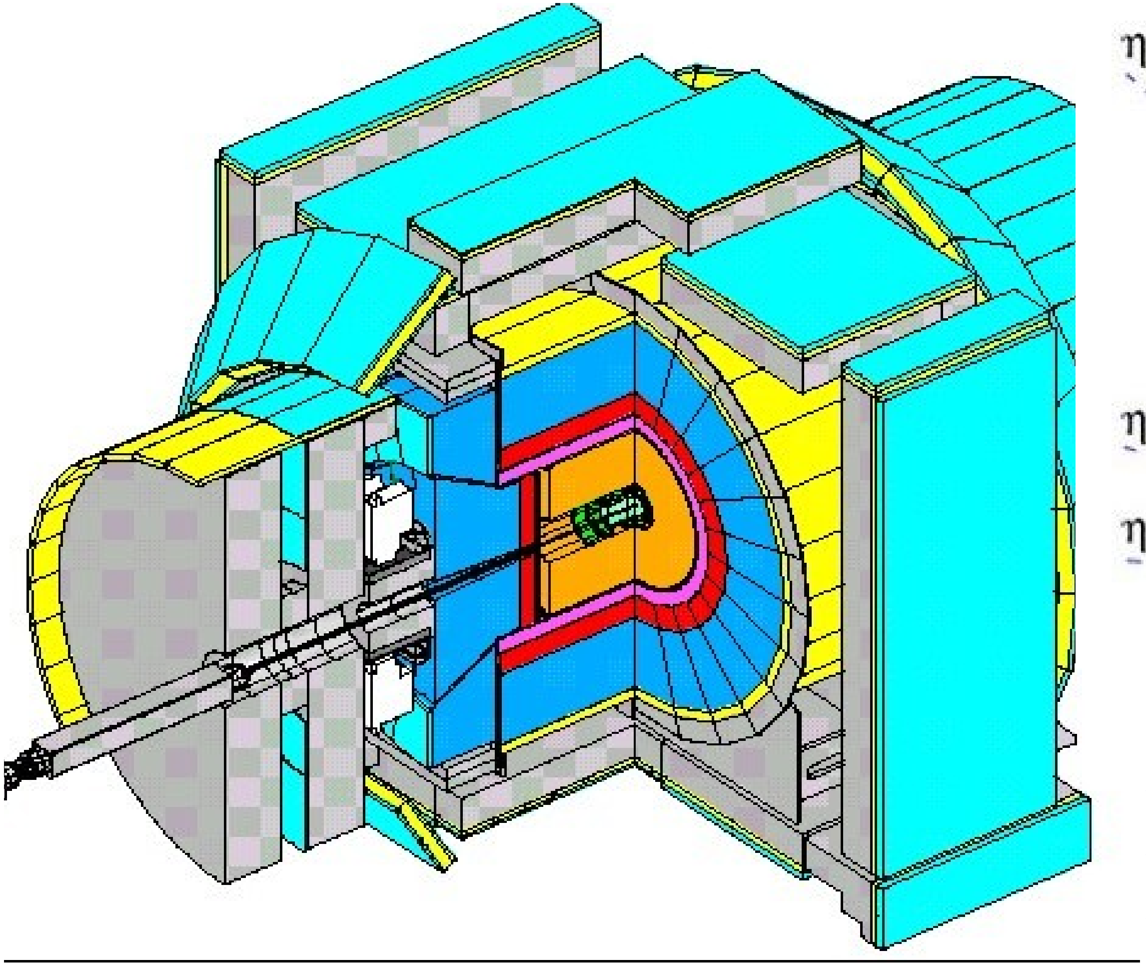
- most of the depth is for the hadronic part of the calorimeter

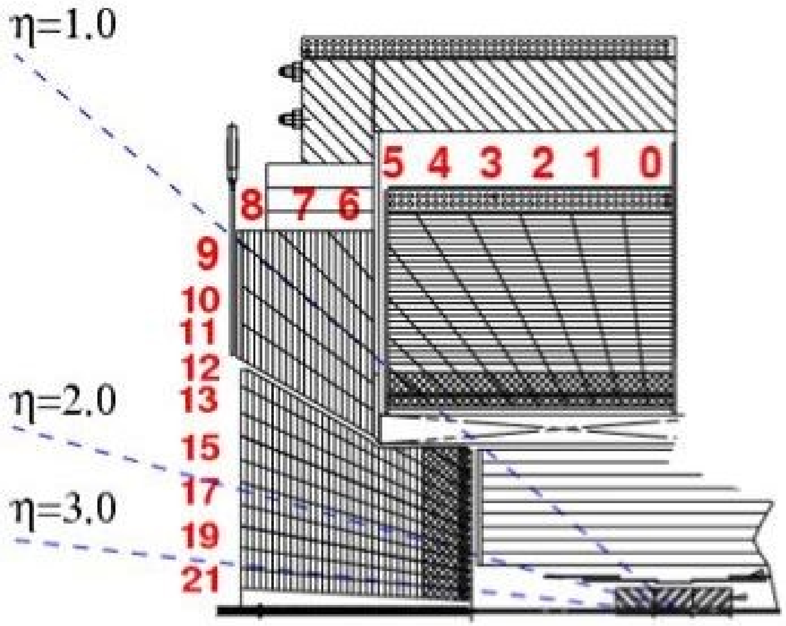
CMS Hadron Calorimeter

Not Covered

- **Shower shapes in hadron calorimeters**
- **Fluctuations in hadronic energy measurements**
- **Position resolution in the calorimeters**
- **Shower maximum detectors**
- **New calorimeter designs for ILC with silicon, tracking for “particle-flow” algorithms.**

Geometry of CDF

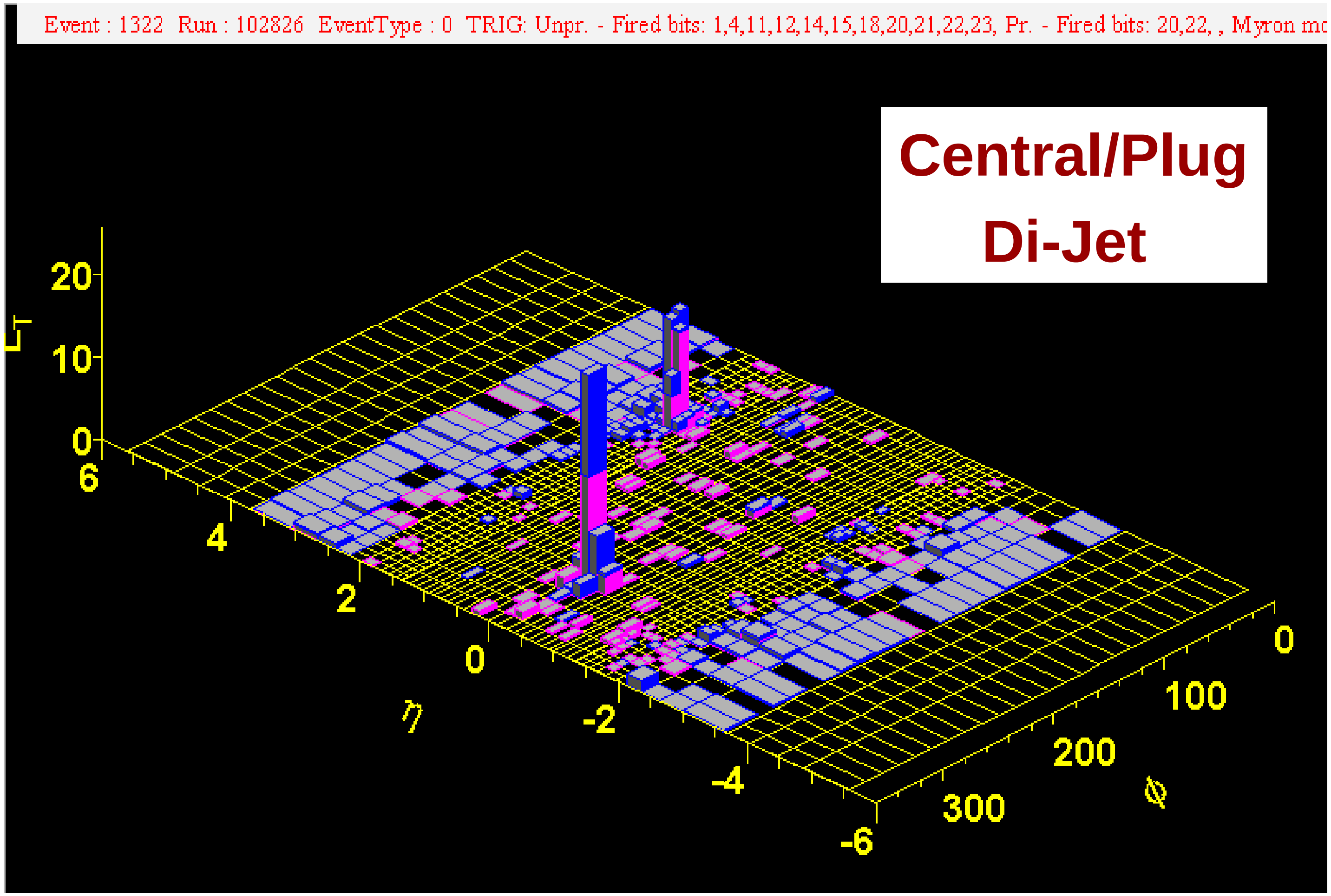




- calorimeter is arranged in projective "towers" pointing at the interaction region

- most of the depth is for the hadronic part of the calorimeter

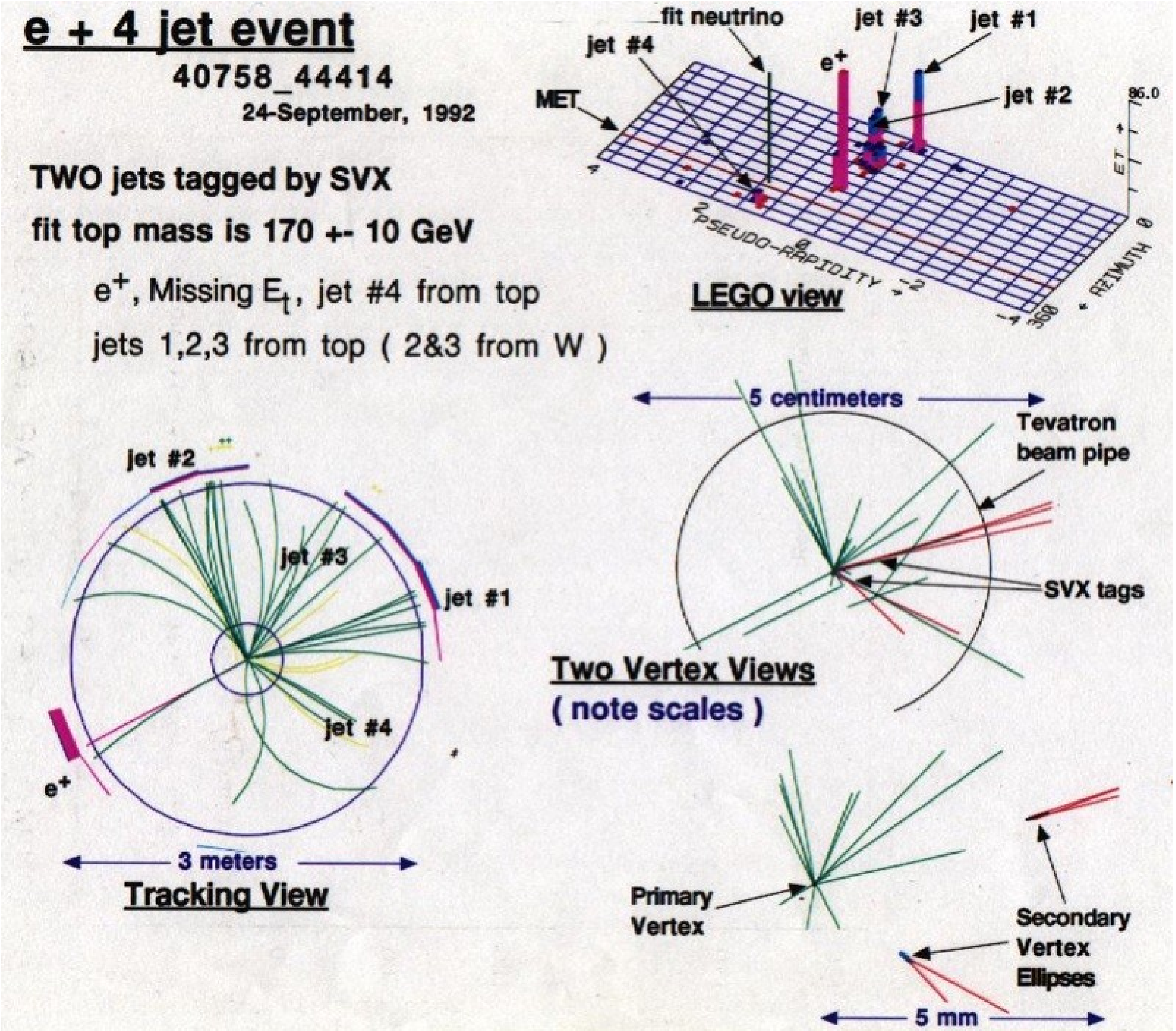
QCD Di-Jet Event, Calorimeter Unfolded



Event : 1322 Run : 102826 EventType : 0 TRIG: Unpr. - Fired bits: 1,4,11,12,14,15,18,20,21,22,23, Pr. - Fired bits: 20,22, , Myron mc

Central/Plug
Di-Jet

Unfolded Top/anti-Top Candidate



e + 4 jet event

40758_44414

24-September, 1992

TWO jets tagged by SVX

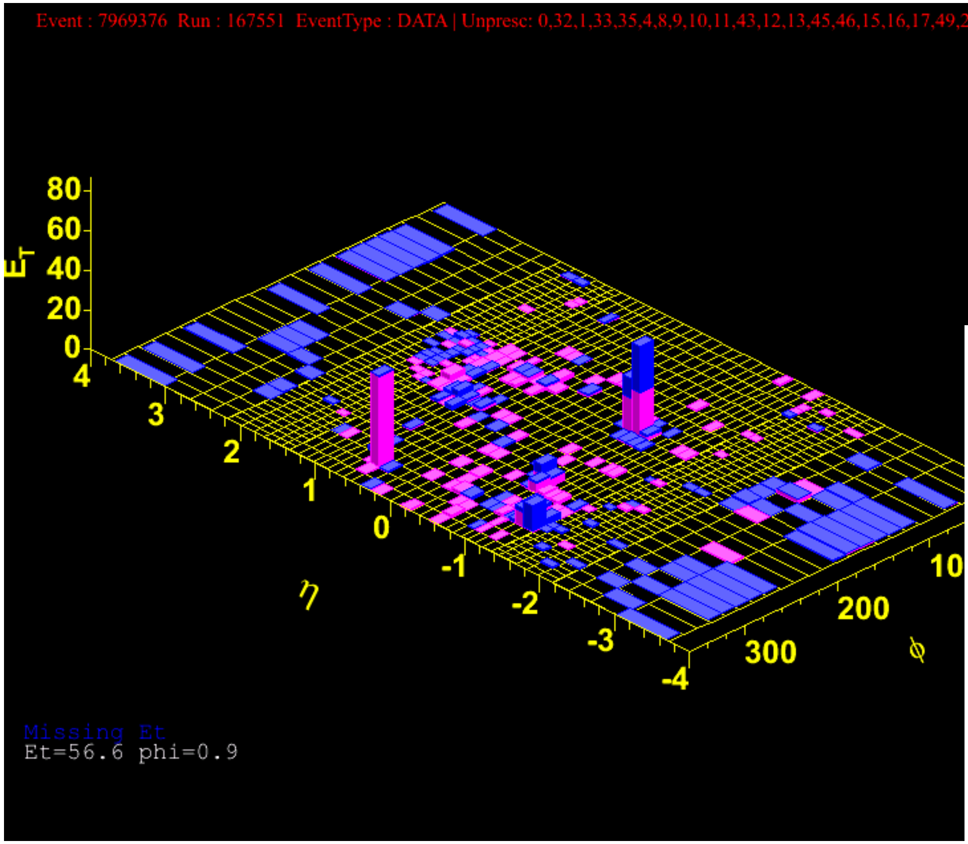
fit top mass is 170 +- 10 GeV

e$^+$, Missing E$_t$, jet #4 from top

jets 1,2,3 from top (2&3 from W)

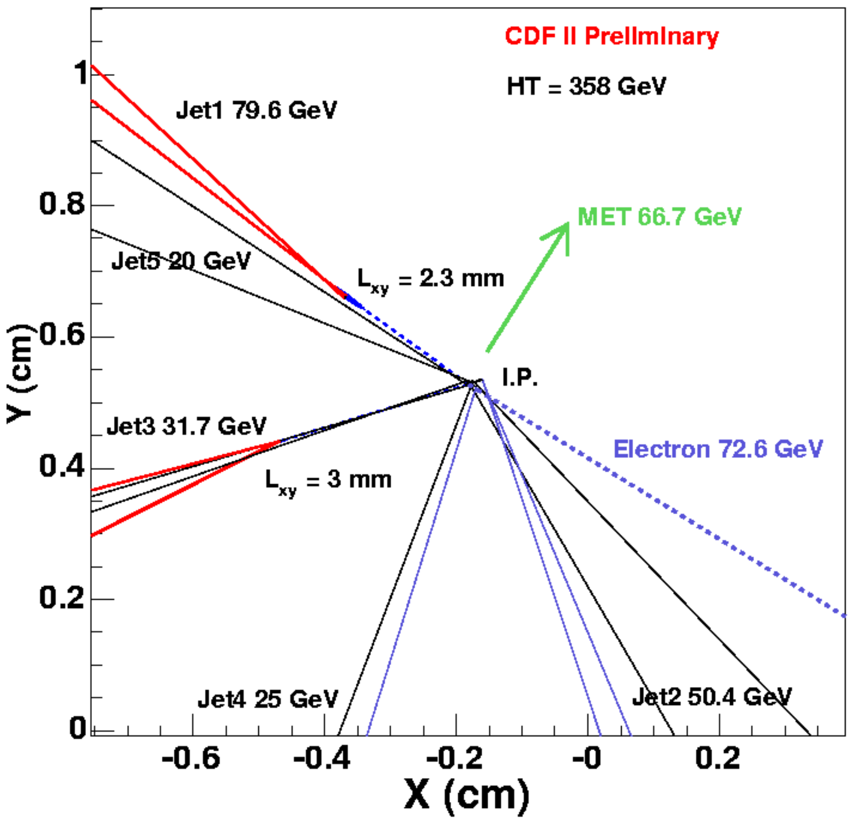
Run 1 Event

Unfolded Top/anti-Top Candidate

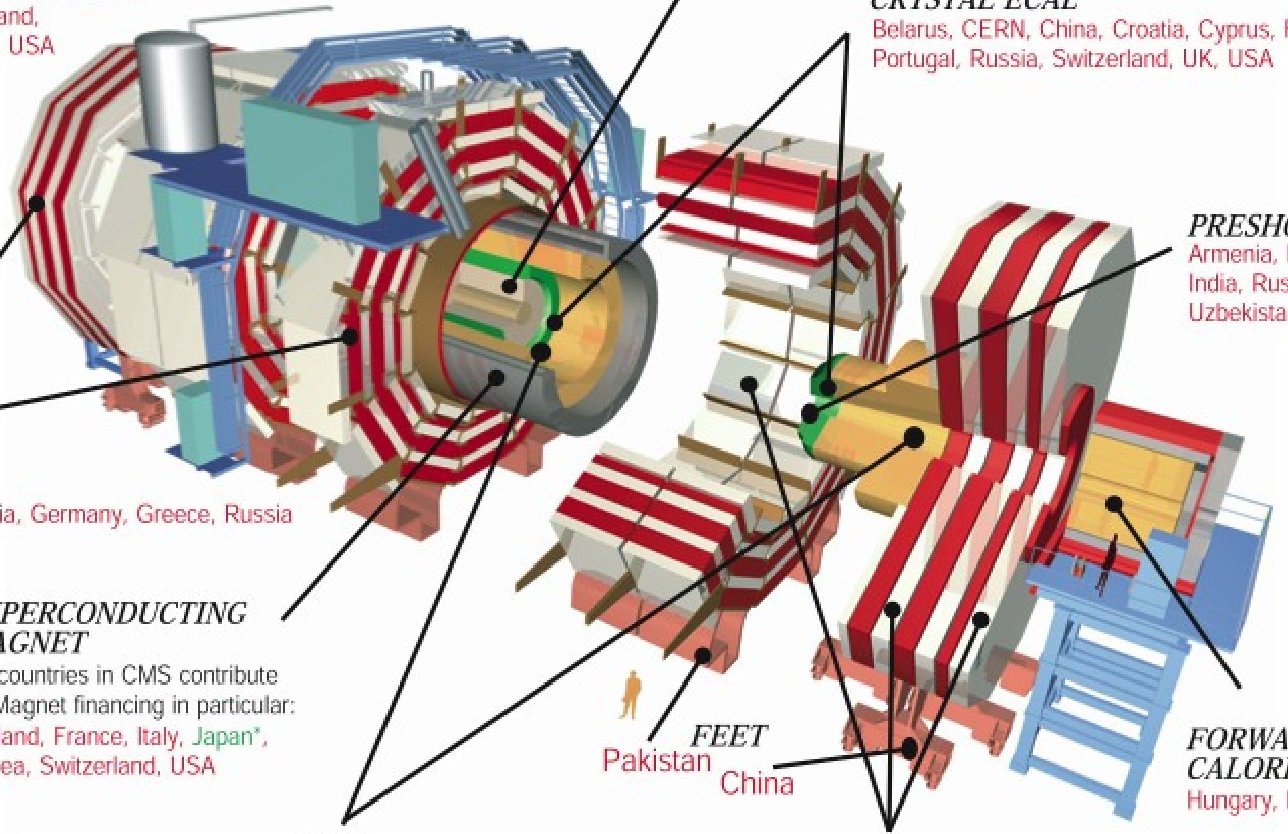

Event : 7969376 Run : 167551 EventType : DATA | Unpresc: 0,32,1,33,35,4,8,9,10,11,43,12,13,45,46,15,16,17,49,21,22,23,55,25,26,

Missing Et
Et=56.6 phi=0.9

Run 2 Event



CMS at CERN



TRIGGER & DATA ACQUISITION
Austria, CERN, Finland, France, Greece, Hungary, Italy, Korea, Poland, Portugal, Switzerland, UK, USA

TRACKER
Austria, Belgium, CERN, Finland, France, Germany, Italy, Japan*, Switzerland, UK, USA

CRYSTAL ECAL
Belarus, CERN, China, Croatia, Cyprus, France, Italy, Japan*, Portugal, Russia, Switzerland, UK, USA

PRESHOWER
Armenia, Belarus, CERN, Greece, India, Russia, Taiwan (PC), Uzbekistan

RETURN YOKE
Barrel: Czech Rep., Estonia, Germany, Greece, Russia
Endcap: Japan*, USA

SUPERCONDUCTING MAGNET
All countries in CMS contribute to Magnet financing in particular:
Finland, France, Italy, Japan*, Korea, Switzerland, USA

FEET
Pakistan
China

FORWARD CALORIMETER
Hungary, Iran, Russia, Turkey, USA

HCAL
Barrel: Bulgaria, India, Spain*, USA
Endcap: Belarus, Bulgaria, Russia, Ukraine
HO: India

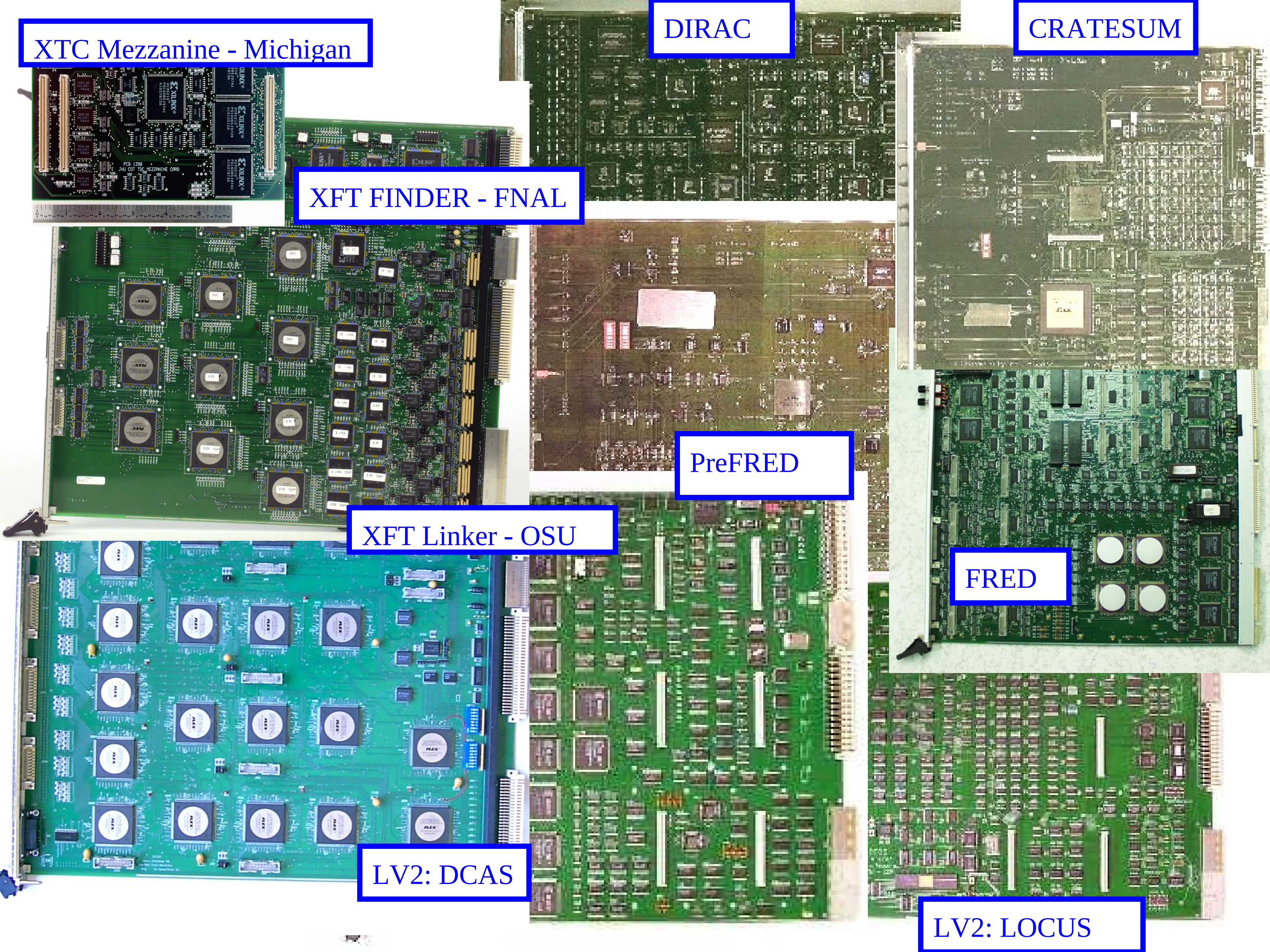
MUON CHAMBERS
Barrel: Austria, Bulgaria, CERN, China, Germany, Hungary, Italy, Spain,
Endcap: Belarus, Bulgaria, China, Korea, Pakistan, Russia, USA

* Only through industrial contracts

Total weight : 12500 T
Overall diameter : 15.0 m
Overall length : 21.5 m
Magnetic field : 4 Tesla

S = Solenoid!

The Detector is NOT complete…



XTC Mezzanine - Michigan

DIRAC

CRATESUM

XFT FINDER - FNAL

PreFRED

FRED

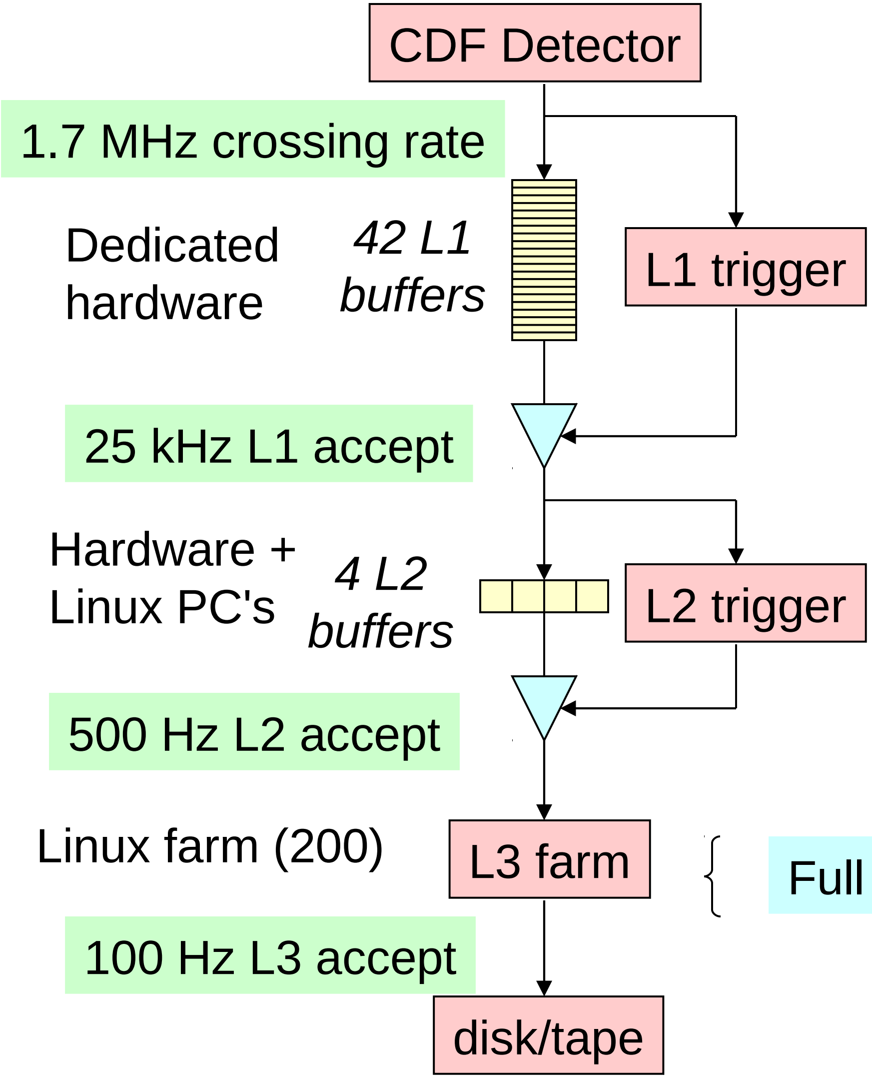
XFT Linker - OSU

LV2: DCAS

LV2: LOCUS

Triggering at hadron colliders

The trigger is the key at hadron colliders



CDF Detector

1.7 MHz crossing rate

Dedicated hardware

42 L1 buffers

L1 trigger

- Hardware tracking for $p_T \geq 1.5$ GeV
- Muon-track matching
- Electron-track matching
- Missing E_T, sum-E_T

25 kHz L1 accept

Hardware + Linux PC's

4 L2 buffers

L2 trigger

- Silicon tracking
- Jet finding
- Refined electron/photon finding

500 Hz L2 accept

Linux farm (200)

L3 farm

- Full event reconstruction

100 Hz L3 accept

disk/tape

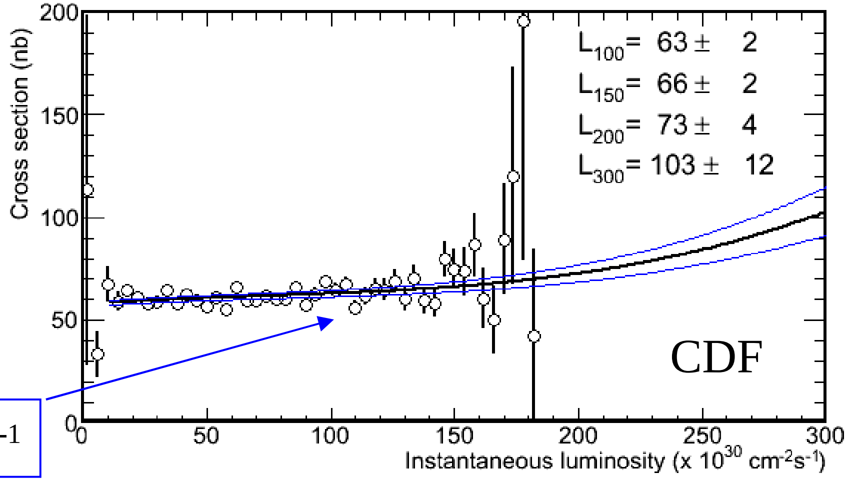
DØ trigger:
L1: 1.6 kHz
L2: 800 Hz
L3: 50 Hz

Typical Triggers and their Usage

- Unprescaled triggers for primary physics goals
- Examples:
  - Inclusive electrons, muons p_T>20 GeV:
    - W, Z, top, WH, single top, SUSY, Z',Z'
  - Dileptons, p_T>4 GeV:
    - SUSY
  - Lepton+tau, p_T>8 GeV:
    - MSSM Higgs, SUSY, Z
    - Also have tau+MET: W->taunu
  - Jets, E_T>100 GeV
    - Jet cross section, Monojet search
    - Lepton and b-jet fake rates
  - Photons, E_T>25 GeV:
    - Photon cross sections, Jet energy scale
    - Searches (GMSB SUSY)
  - Missing E_T>45 GeV
    - SUSY
    - ZH->vvbb

- Prescale triggers because:
  - Not possible to keep at highest luminosity
  - Needed for monitoring
  - Prescales depend often on Lumi
- Examples:
  - Jets at E_T>20, 50, 70 GeV
  - Inclusive leptons >8 GeV
  - B-physics triggers
  - Backup triggers for any threshold, e.g. Met, jet ET, etc…
    - At all trigger levels

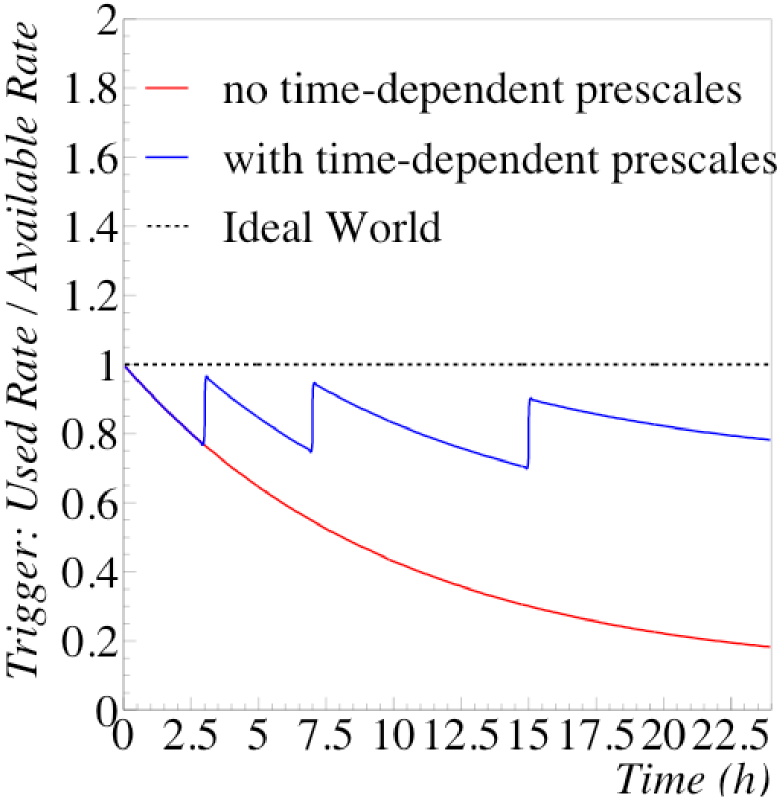
single electron trigger



Rate= 6 Hz at L=100×10^{30} cm^{-2}/s^{-1}

Trigger Operation

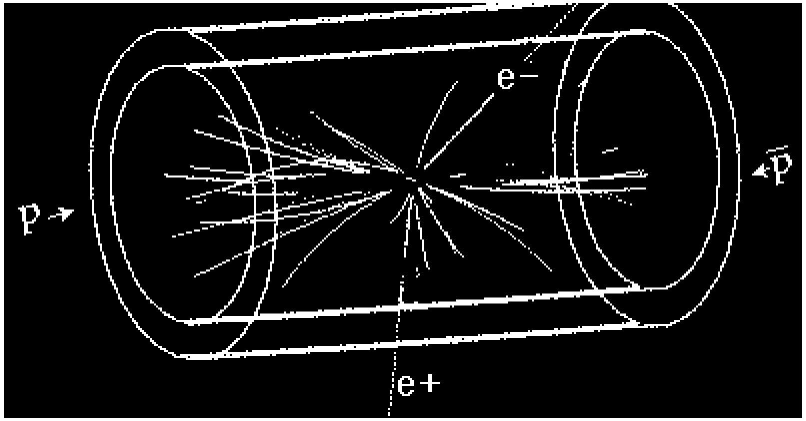
- Aim to maximize physics at trigger level:
  - Trigger cross section:
    - Nevent/nb^{-1}
    - Independent of Luminosity
  - Trigger Rate:
    - Cross Section x Luminosity
- Luminosity falls within store
  - Rate also falls within store
  - 75% of data are taken at <2/3 of peak luminosity
- Use sophisticated prescale system to optimize bandwidth usage
  - A good trigger = more physics!



	CDF	DØ
L1 bits	64	128
L2 bits	125	>128
L3 bits	173	418

The Computer is our friend

- Detectors record millions of points of data during collision events. For this reason, it is necessary to let a computer look at this data, and figure out the most likely particle paths and decays, as well as anomalies from the expected behavior



- A computer reconstruction of a proton-antiproton collision event that produced an electron-positron pair as well as many other particles

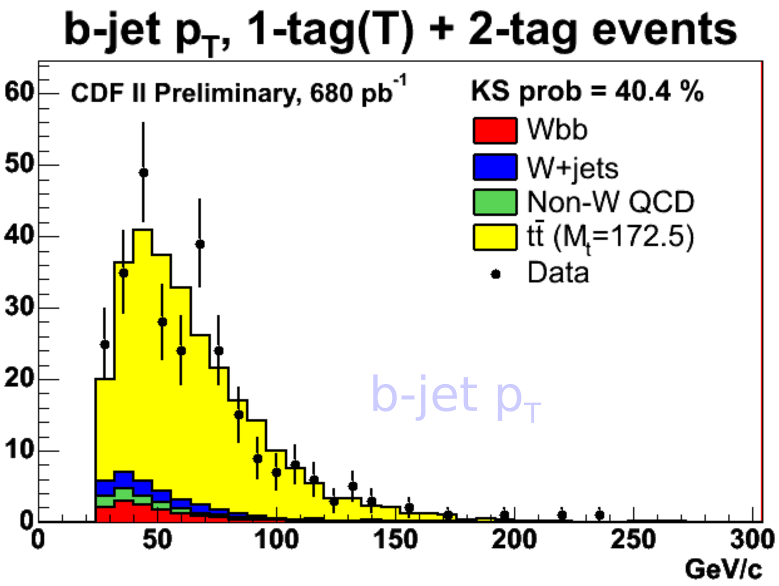
SIMULATION

A Few Comments on Monte Carlo

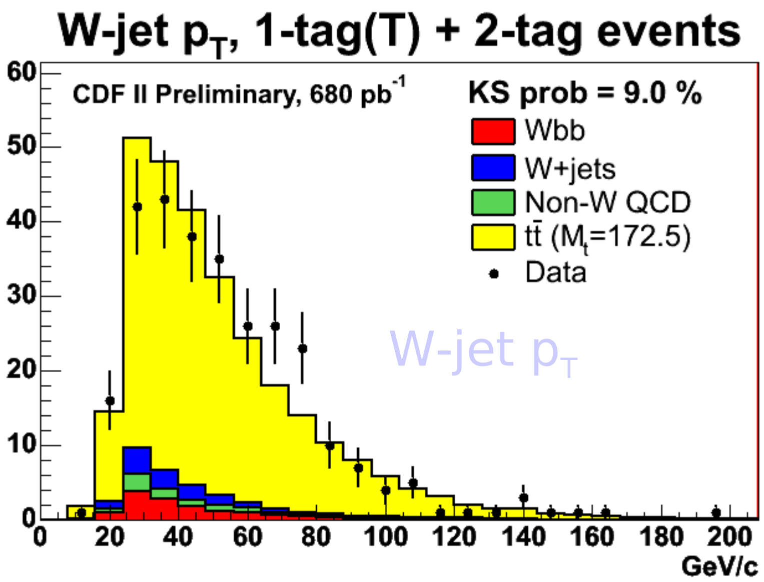
- Critical for understanding the acceptance and the bckg's
  - Speed: CDF ~10s per event, DØ ~ 3m per event
- Two important pieces:
  - Physics process simulation:
    - PYTHIA, HERWIG
      - Working horses but limitations at high jet multiplicity
    - "ME generators": ALPGEN, MADGRAPH, SHERPA, COMPHEP,…
      - Better modeling at high number of jets
      - Some processes only available properly in dedicated MC programs
        - e.g. $W\gamma$ or single top
    - NLO generators (MC@NLO)
      - Not widely used yet but often used for cross-checks

A Few Comments on Monte Carlo

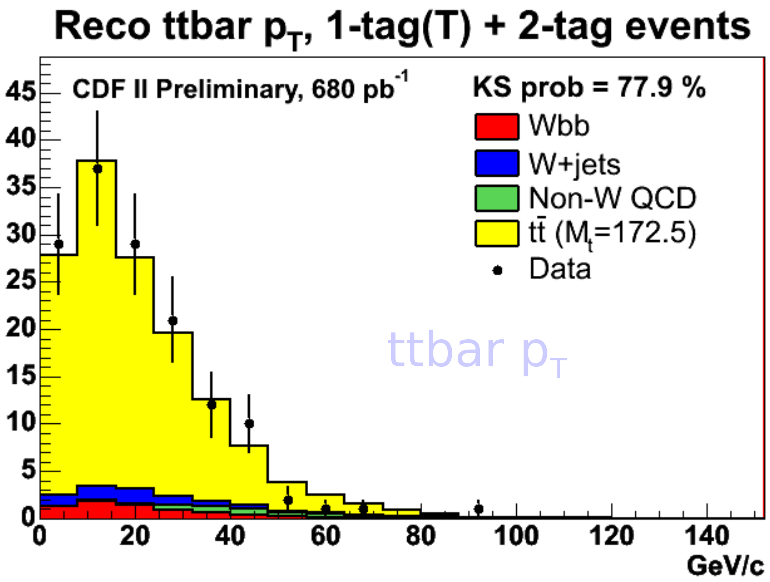
  - Detector simulation:
    - GEANT, fast parameterizations (e.g. GFLASH)
- Neither physics nor detector simulation can generally be trusted!
    - Most experimental work goes into checking whether the Monte Carlo is right and appropriate
    - Even for mature experiments, this takes many months for each analysis



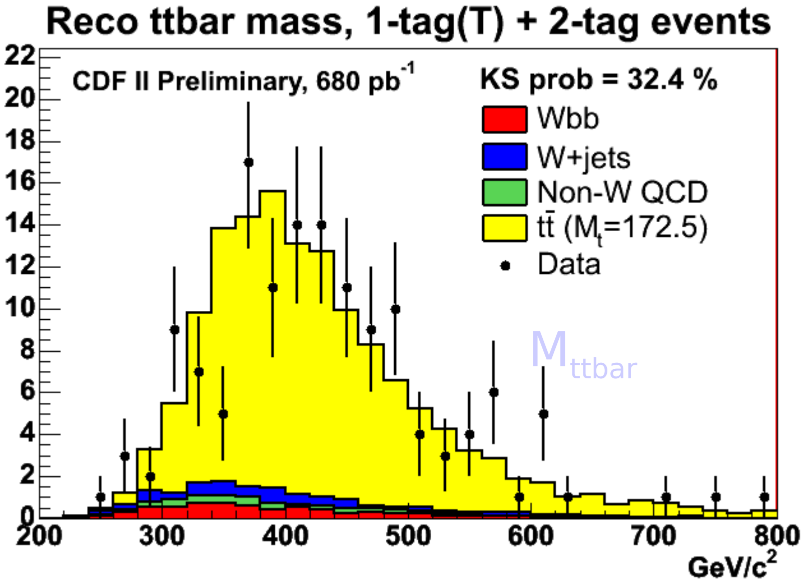
b-jet p_T, 1-tag(T) + 2-tag events



W-jet p_T, 1-tag(T) + 2-tag events

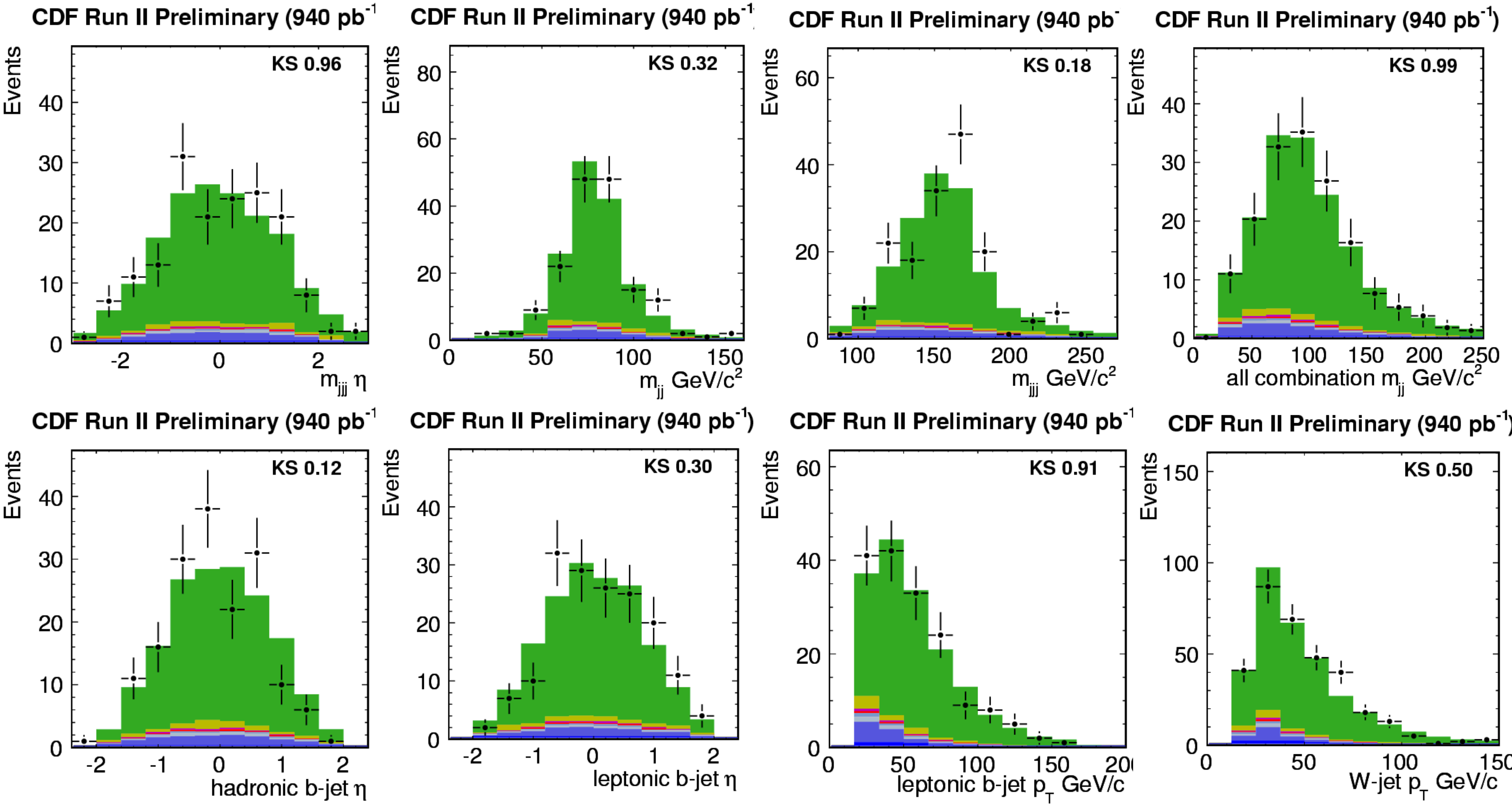


Reco ttbar p_T, 1-tag(T) + 2-tag events



Reco ttbar mass, 1-tag(T) + 2-tag events

Top Mass: MC/Data Comparison



- Good agreement between data and Monte Carlo

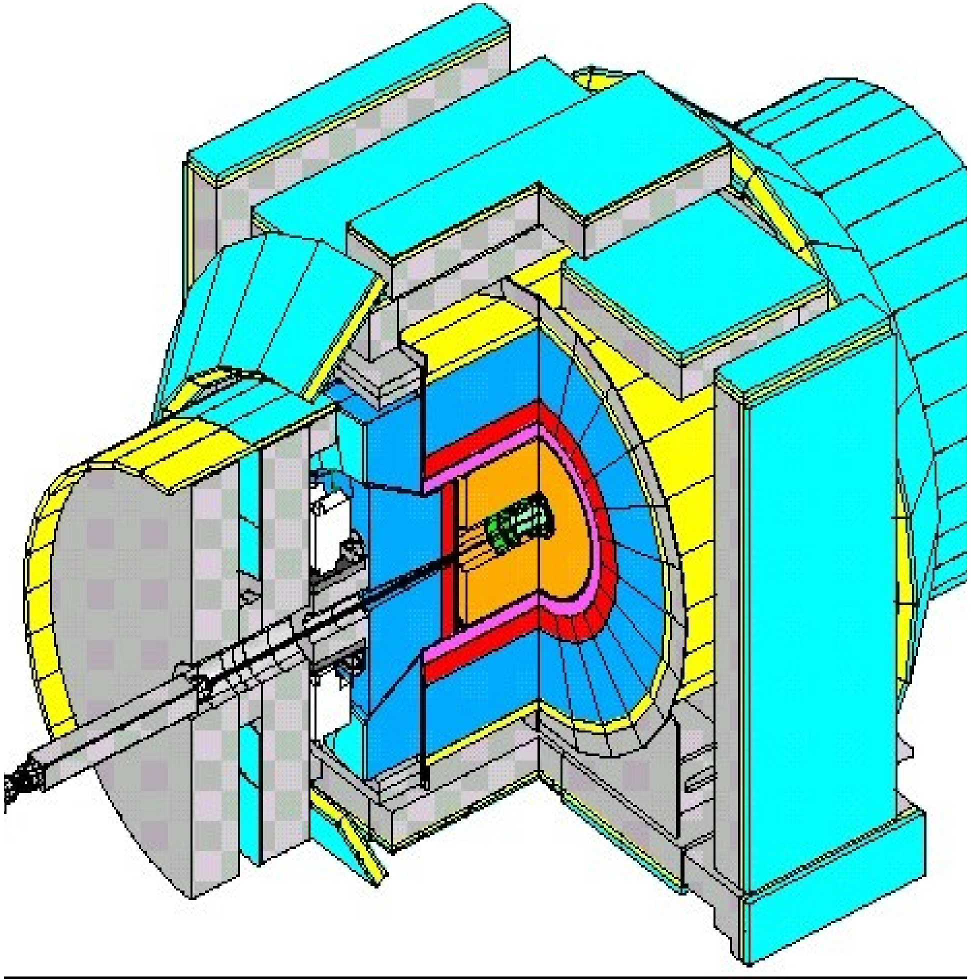
BACKUP

CMS Spectrometer Details

- 12,500 tons (steel, mostly, for the magnetic return and hadron calorimeter)
- 4 T solenoid magnet
- 10,000,000 channels of silicon tracking (no gas)
- lead-tungstate electromagnetic calorimeter
- 4π muon coverage
- 25-nsec bunch crossing time
- 10 Mrad radiation dose to inner detectors
- …

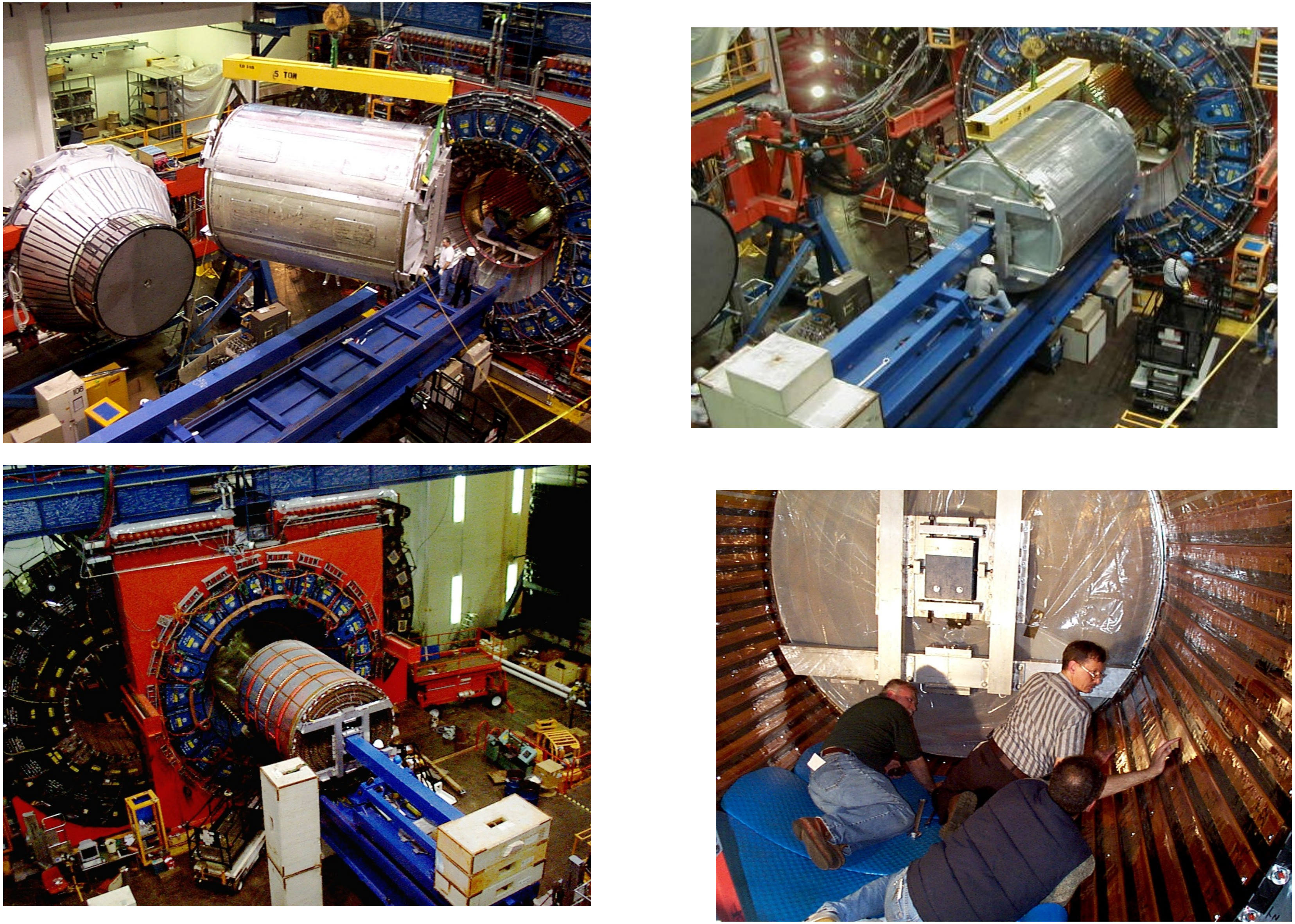
Detector Systems

CDF II Detector cross section

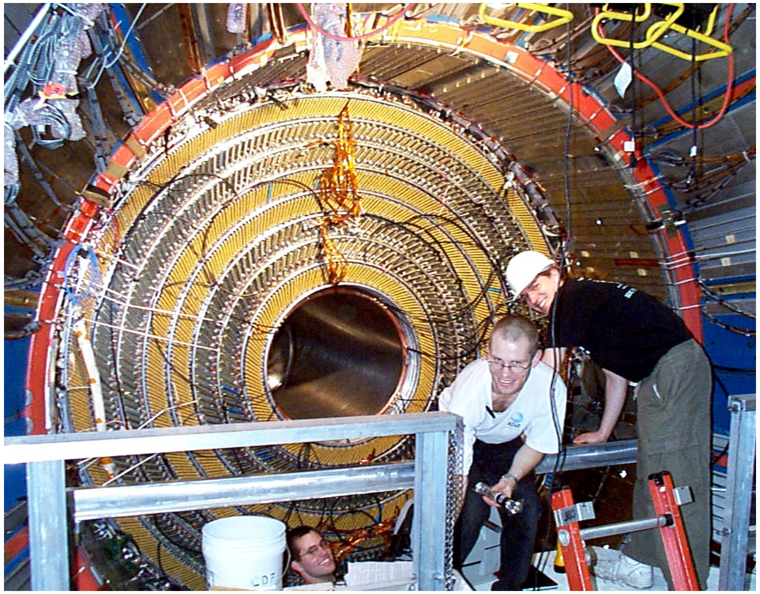


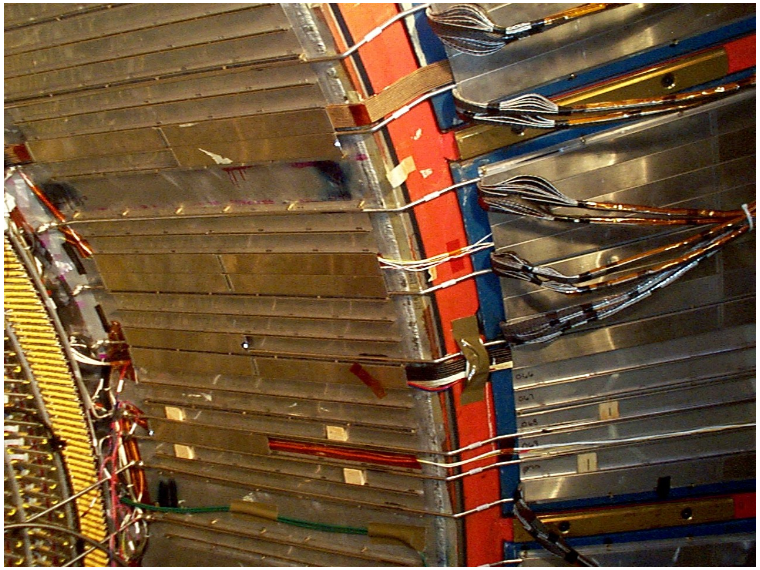
- **Tracking**
  - **Silicon Vertex Detector**
  - **Intermediate Silicon Layers**
  - **Central Outer Tracker**
- **Calorimeters**
- **Front End Electronics**
- **Trigger**
- **Data Acquisition**
- **Muon systems**
- **Infrastructure**
- **Offline Software**

COT Installation



COT Installation Cont…

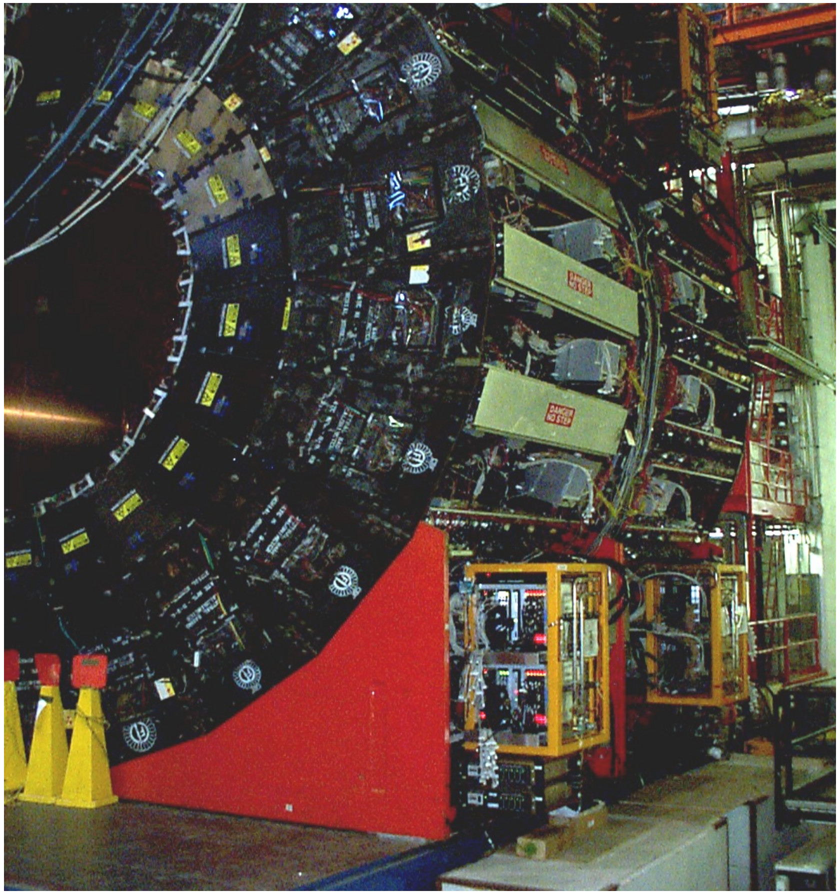


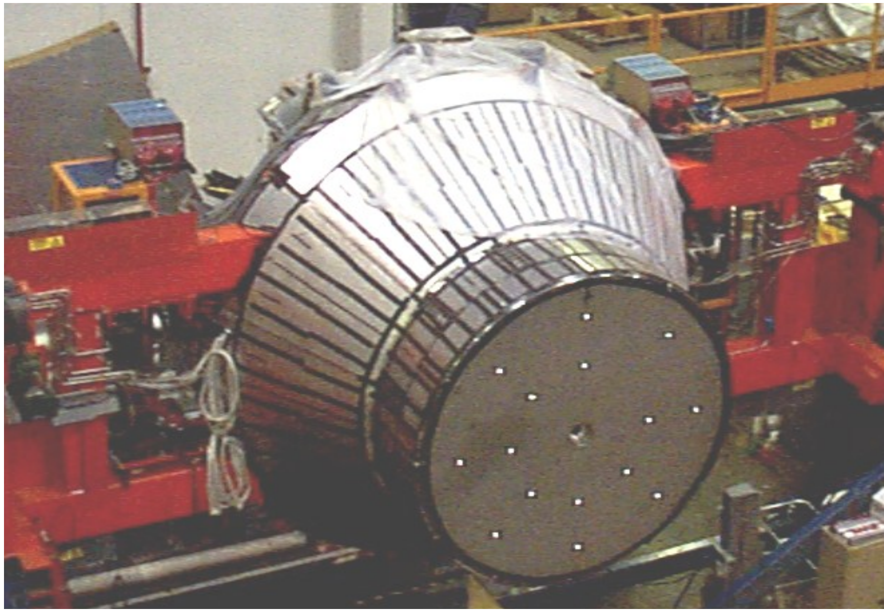


Calorimeters

Central Calorimeter

Retained from original CDF.
All New cables and Electronics

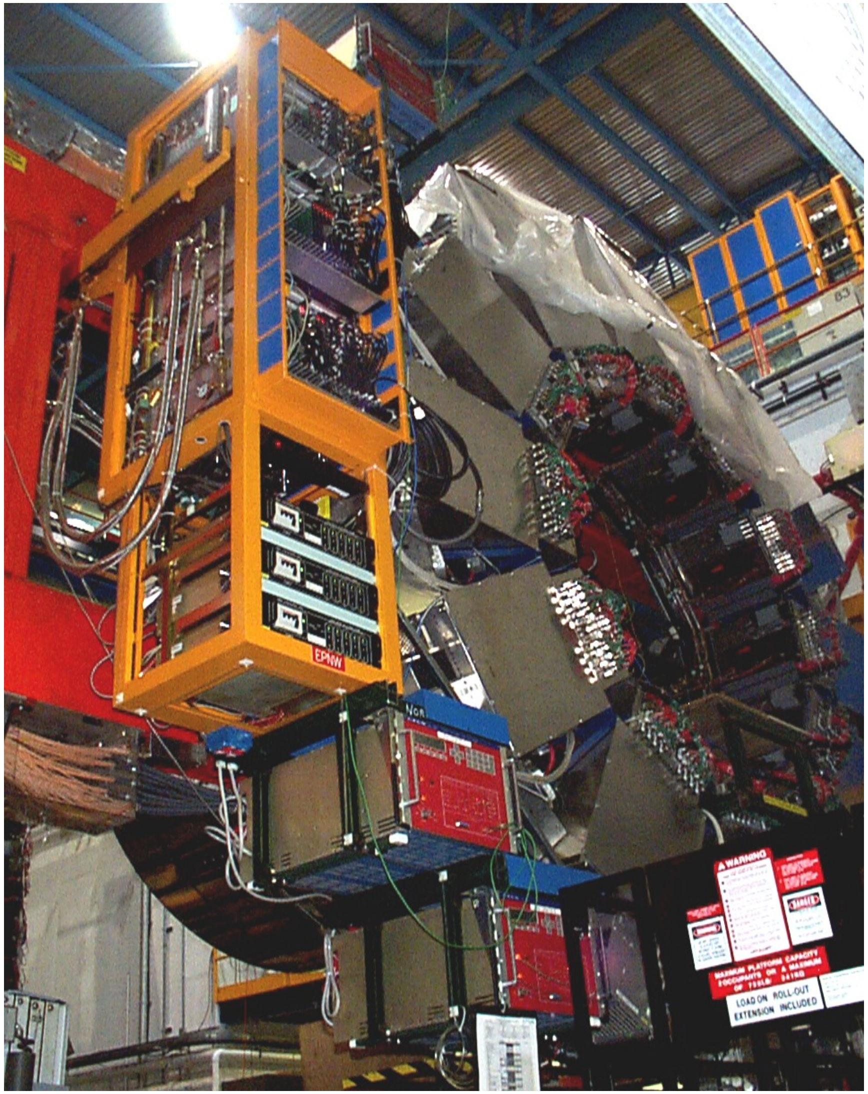




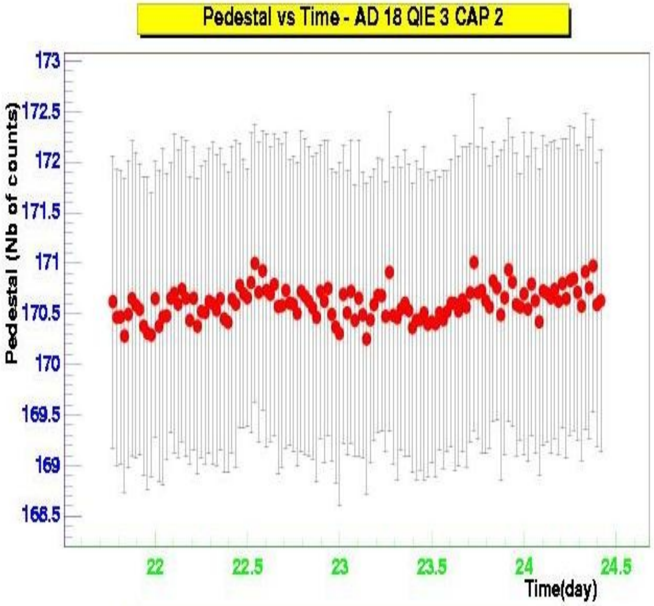
Endplug Calorimeters

- scintillating tiles read out with WLS fibers.

Calorimeter Electronics

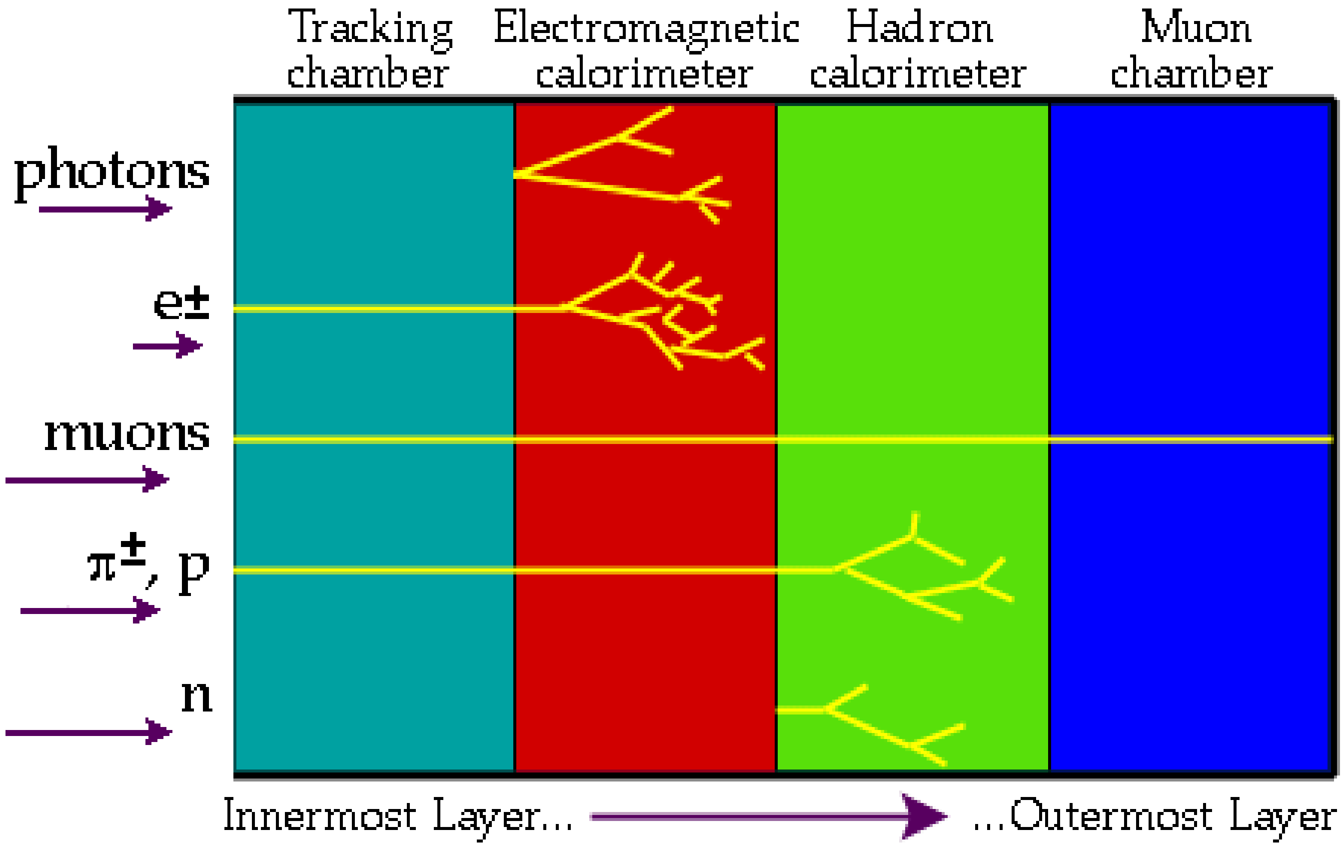


Detector Stability vs Time



- 3 crates of electronics and power supplies
- Fans, cooling water, power, cables, heat exchangers, monitoring

Particle Decay Signatures



Particles are detected via their interaction with matter.

Many types of interactions are involved, mainly electromagnetic.
In the end, always rely on ionization and excitation of matter.