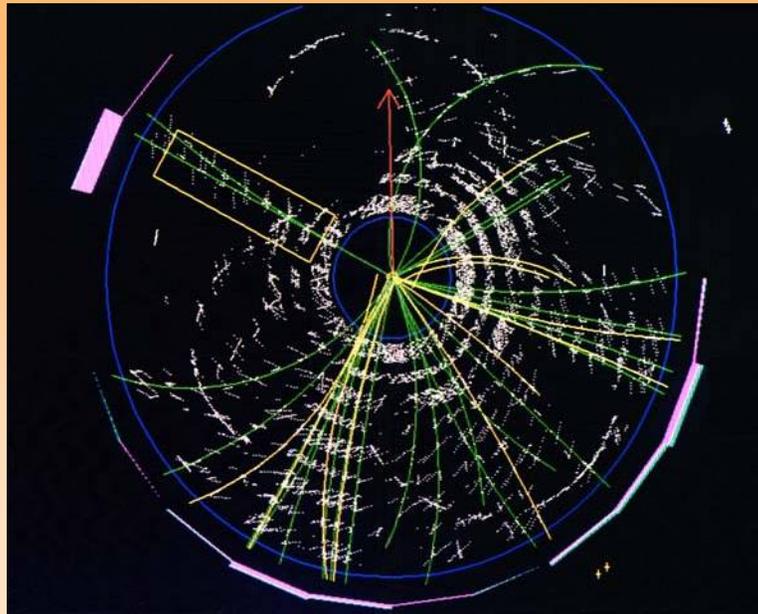


Particle Physics Detectors

Lecture 2 of 2

Robert Roser

Fermi National Accelerator Laboratory



Shameless Promotion...

A Special Lunch Hour Lecture

Monday, August 14th

1:00

Taking the next career step...

Finding a job!

RECAP...

- Detector design is driven by the physics
- Before one can successfully design a detector, one needs to think through the entire physics analysis of interest
- Designers have to keep 5 important points in mind
 - The size and characteristics of the collision hall
 - The total cost/budget
 - The time it takes to read out the detector
 - The state of technology when the experiment “goes live”
 - What level of risk can you accept?

RECAP (2)

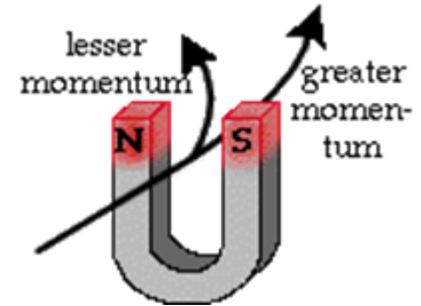
- There is no single “correct” answer to the above constraints
- Detector designers perform a difficult and almost impossible optimization task
- In the end, detectors are an amazing blend of science, engineering, management and human sociology

Tracking

Call 'em Spectrometers

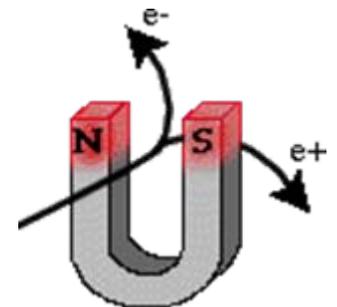
- a “*spectrometer*” is a tool to measure the momentum spectrum of a particle in general
- one needs a magnet, and tracking detectors to determine momentum:

$$\frac{d\mathbf{p}}{dt} = \frac{q}{c} \mathbf{v} \times \mathbf{B}$$



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

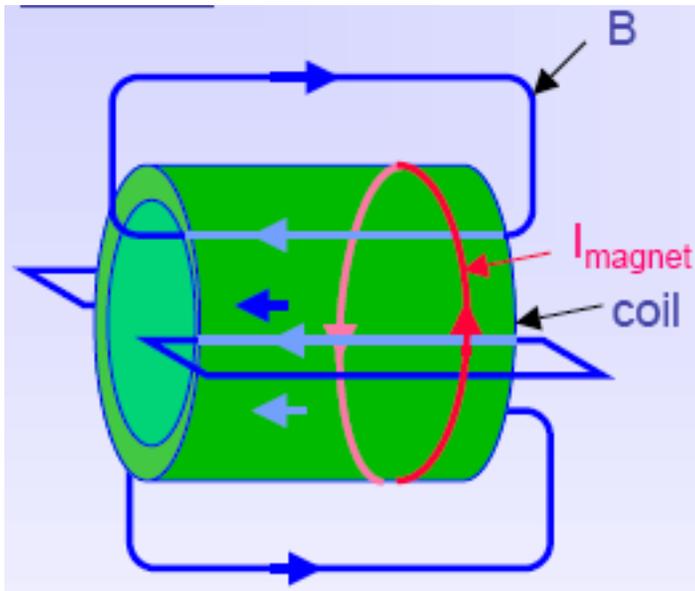
- **Approximately:** $p = 0.2998 B \rho$ T - m
 $\rho =$ radius of curvature



Magnets for 4π Detectors

Solenoid

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

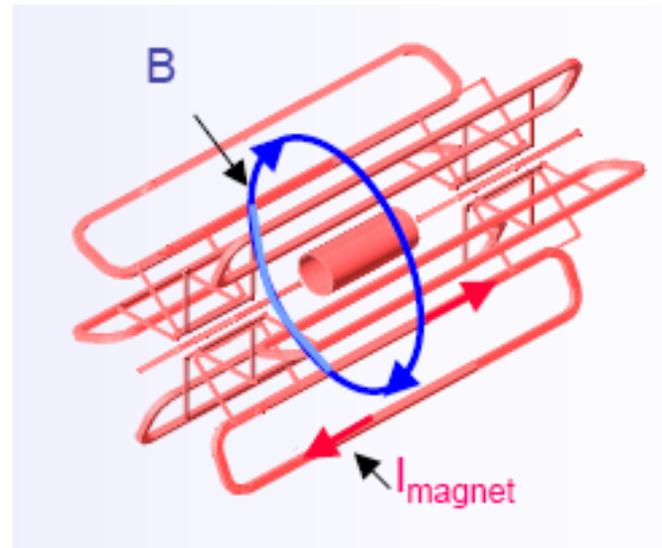


Examples:

- 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

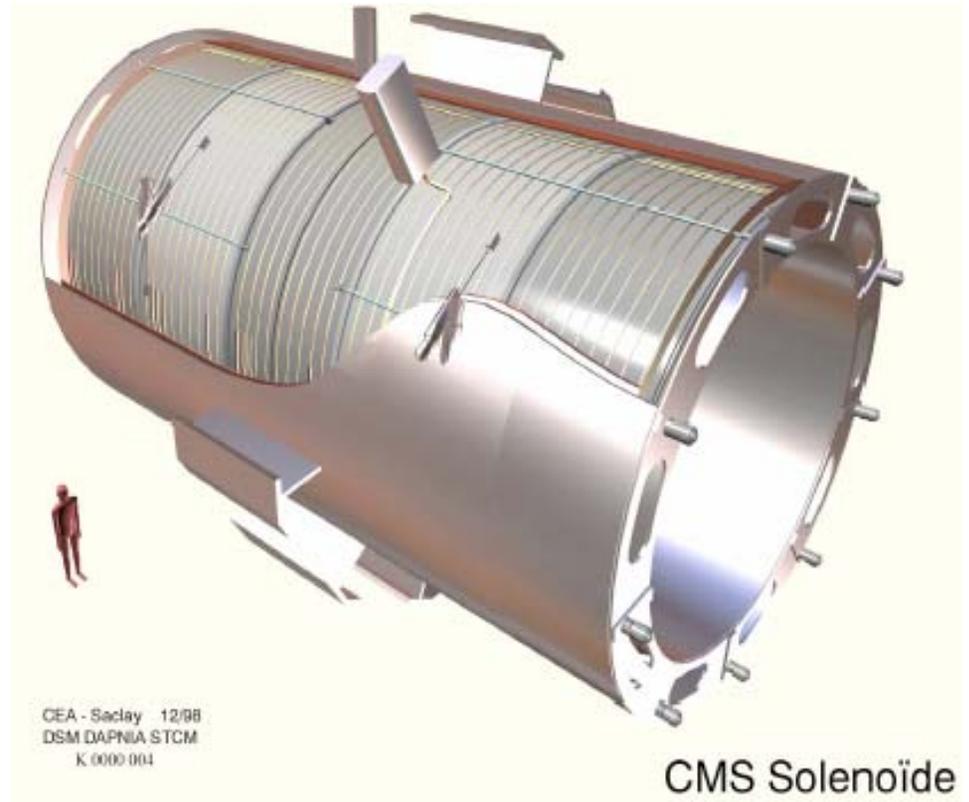


Example:

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

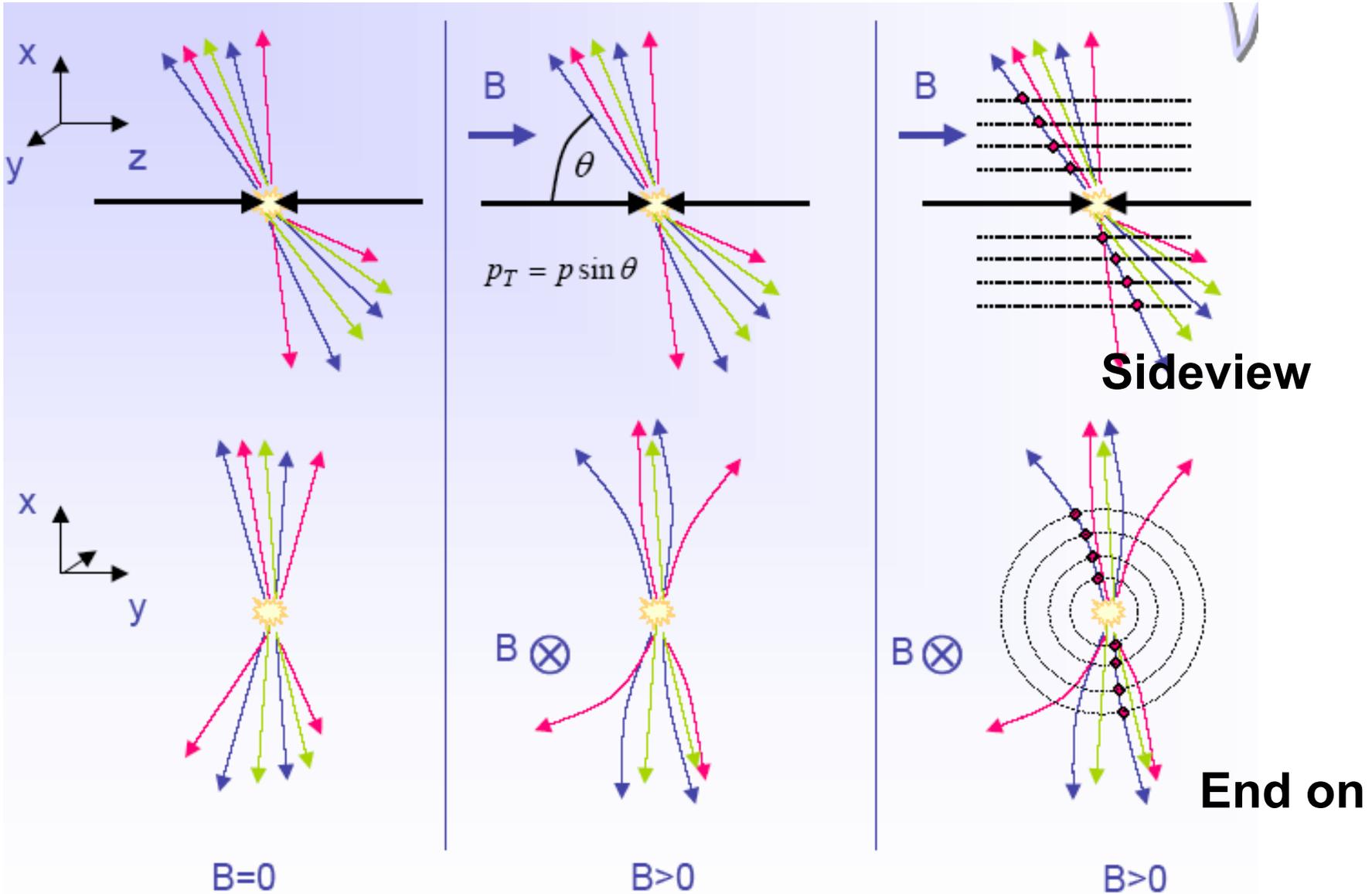
Charge and Momentum

Two ATLAS toroid coils



Superconducting CMS Solenoid Design

Charge and Momentum



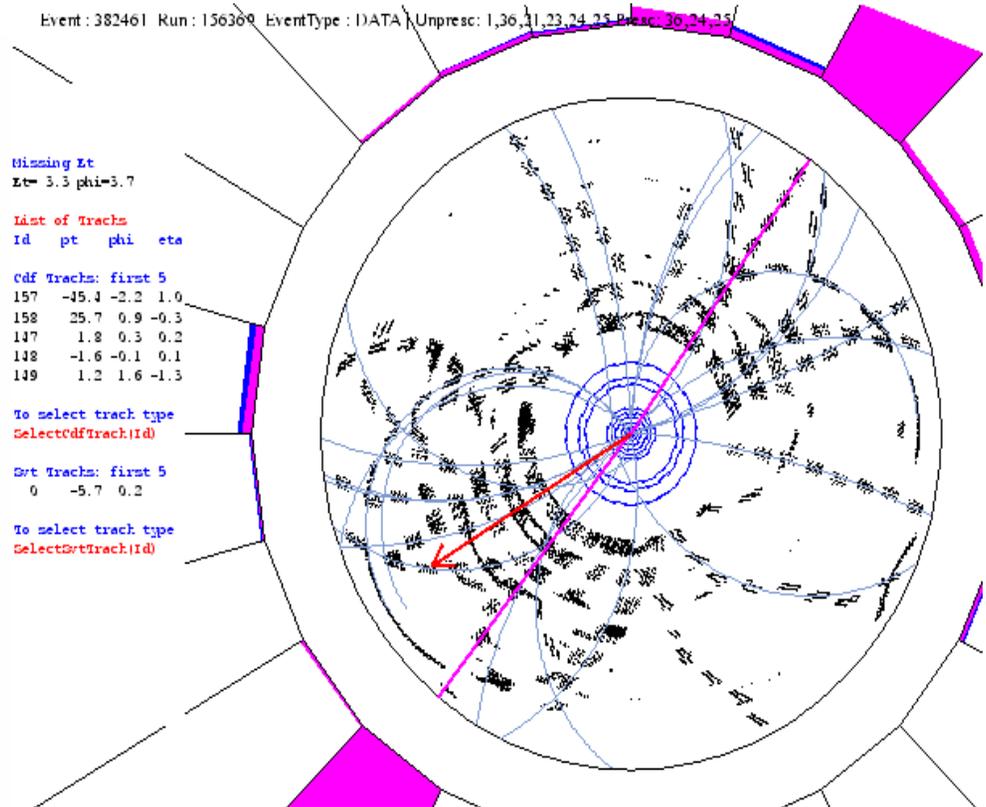
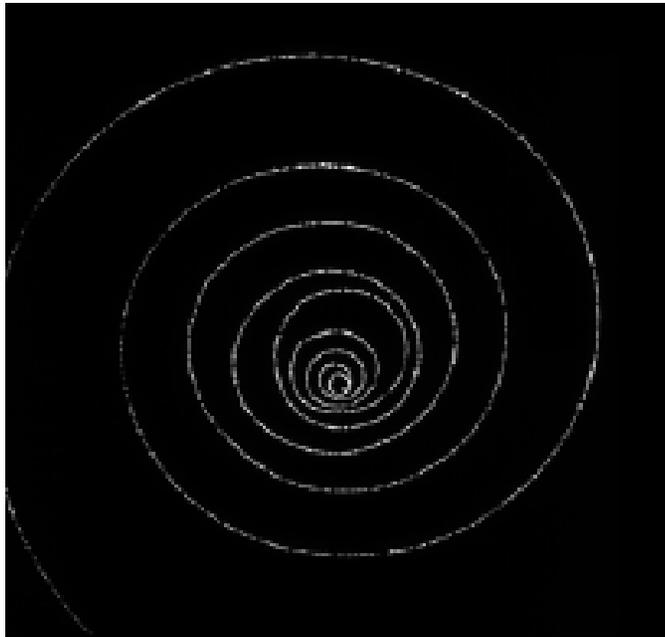
The Art of Tracking

(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...

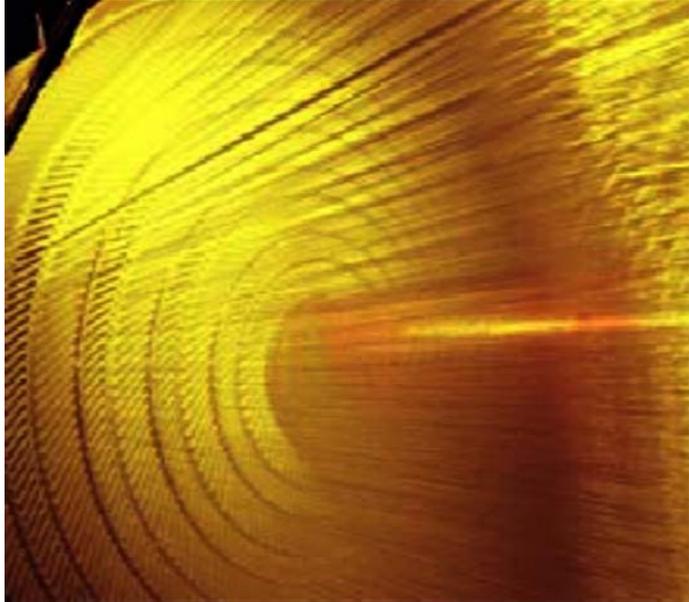


Specifications (Design)

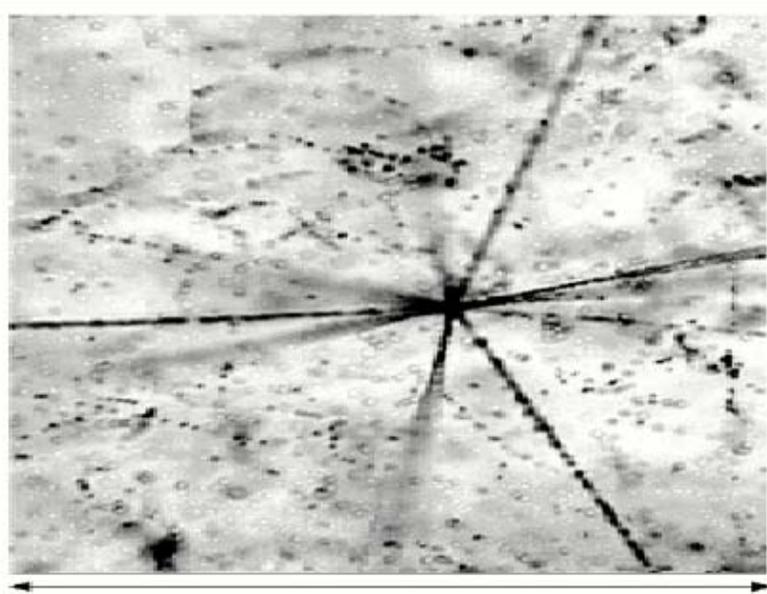
- Performance based upon reconstruction of track parameters
- Defined in terms of:
 - parameters of the system (layout, magnetic field, etc)
 - performance of position sensing elements.
 - Initially evaluate with simple parametric analyses.
- Full simulation
- Performance of position sensing elements
 - 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



1.1 cm x 5.2 cm

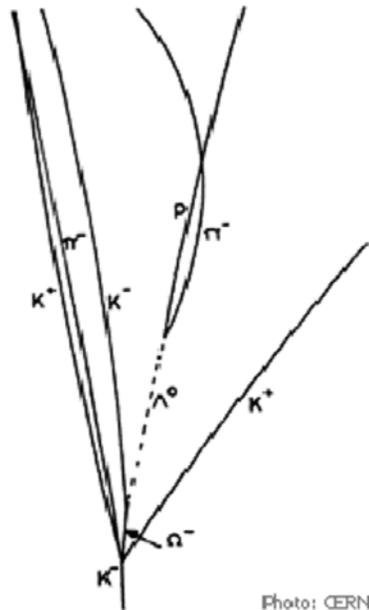
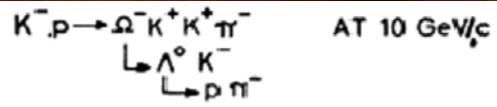
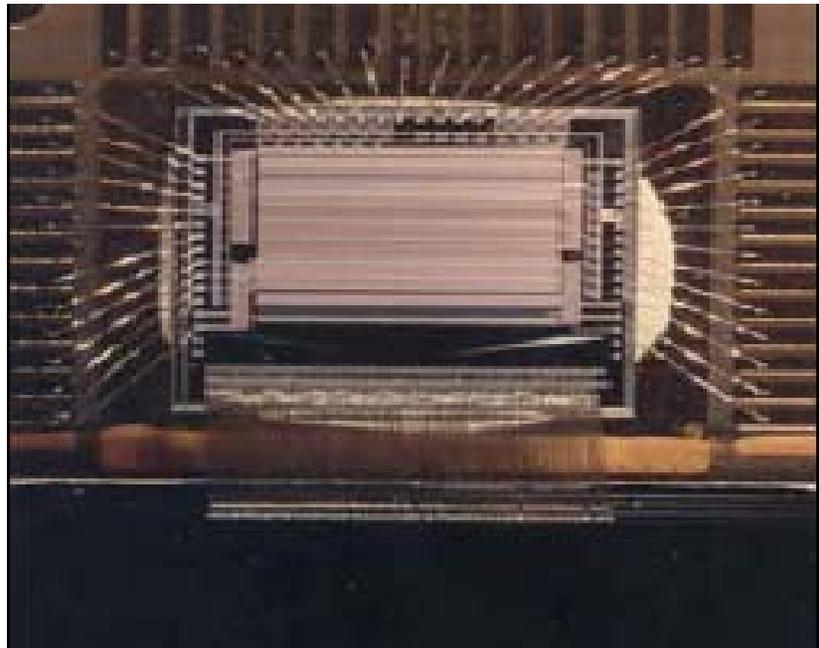
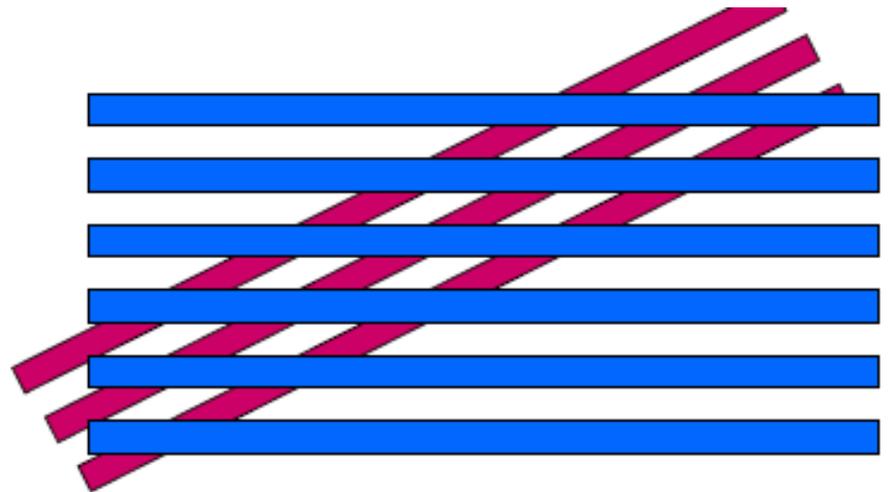
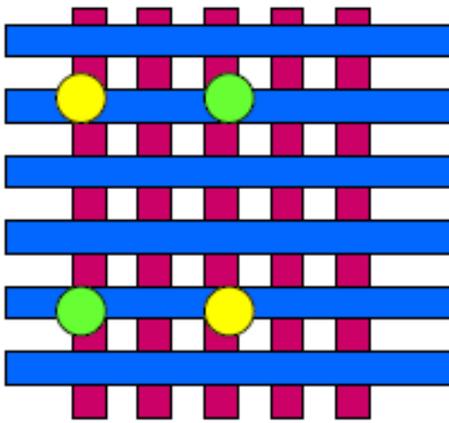


Photo: CERN

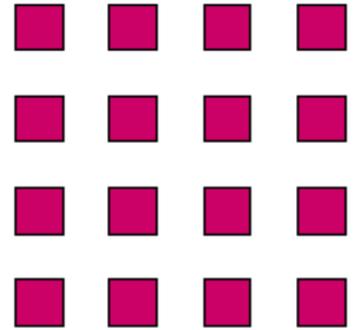


The problems with 2 dimensions

- crossed array of n elements each on pitch p gives equal resolution on both coordinates.
 - m hits $\rightarrow m^2$ 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 $1/\sin(\alpha)$



Hello Pixels!



- Pixel structure: $n \times m$ 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

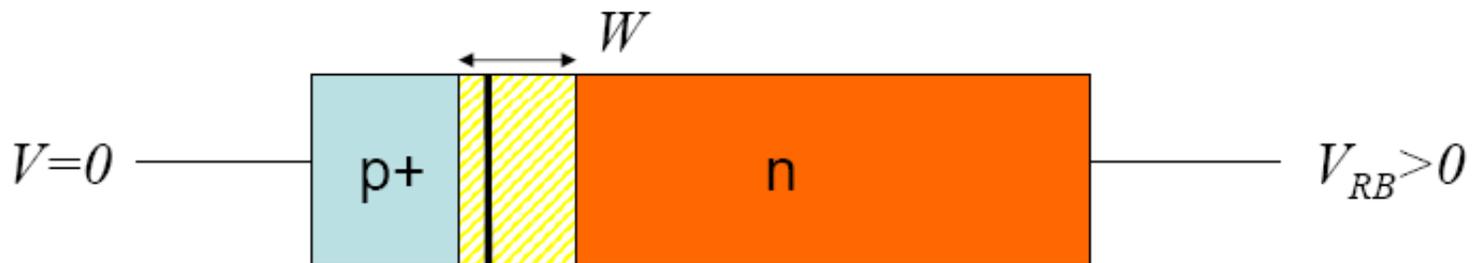
- Semiconductor band structure → energy gap
- Asymmetric diode junction: example p(+) into contact with n ($N_A \gg N_D$)
- Space charge region formed by diffusion of free charges, can be increased with “reverse bias”

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

μ = electron mobility, $\varepsilon = 11.9\varepsilon_0$

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

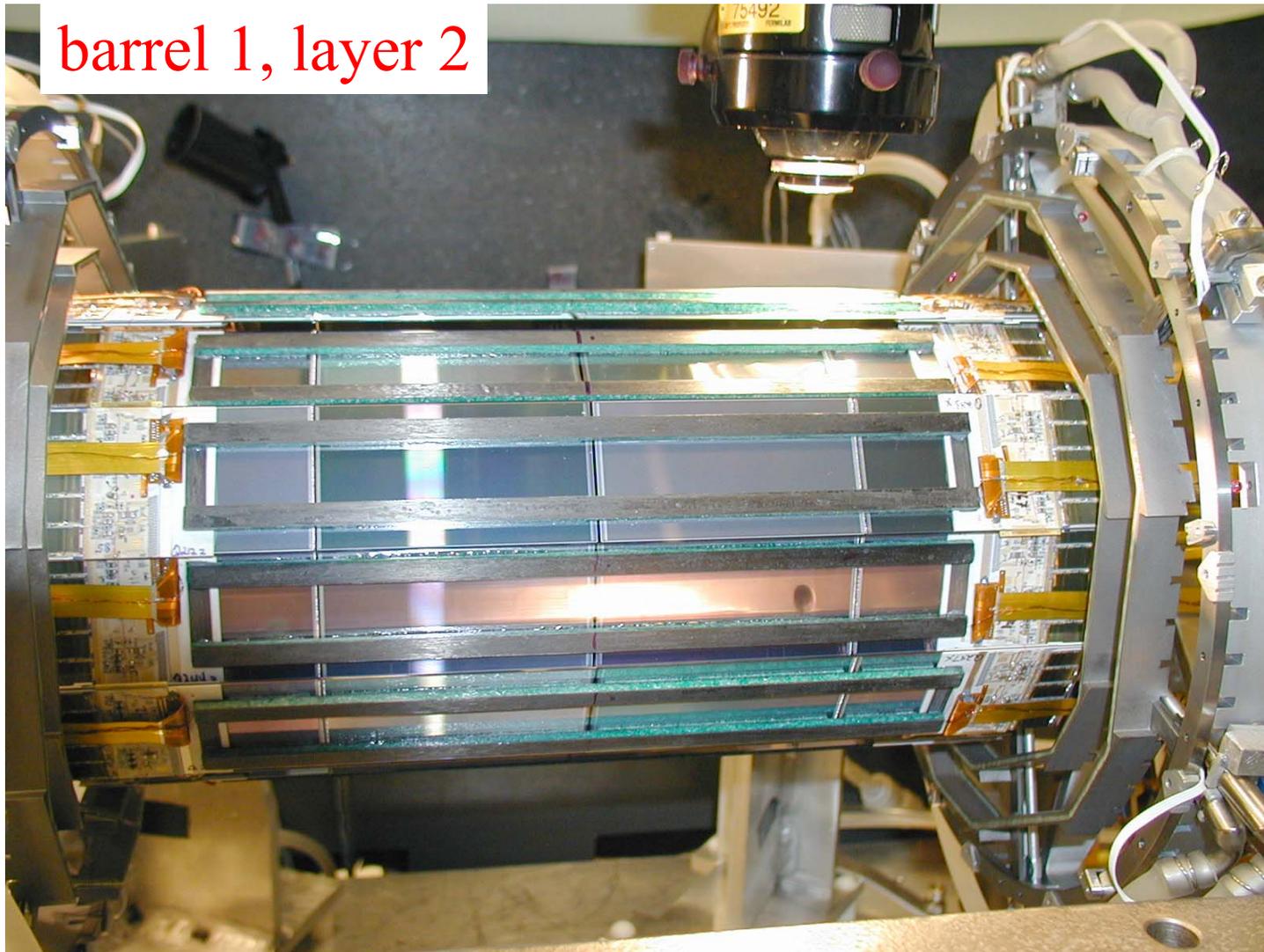
V_{BI} = built in potential ($\sim 0.8 \text{ V}$) V_{RB} = applied reverse bias



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

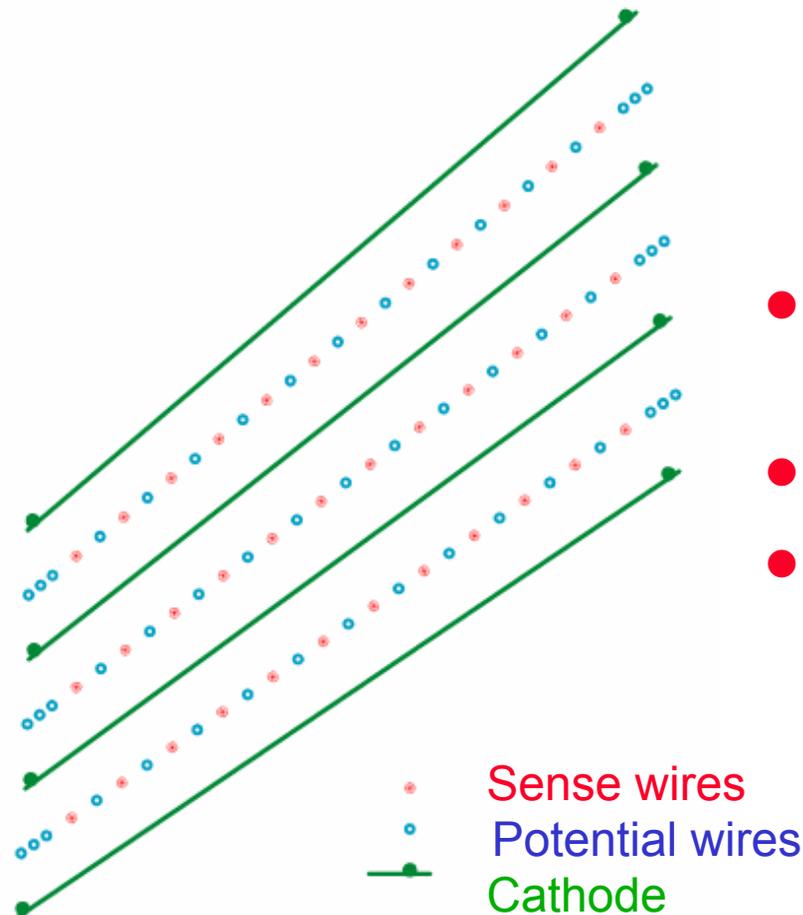
Radiation Environment

- 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/cm²
 - Compare to:
 - space (~ 1 MRad)
 - nuclear weapons ($\sim 10^{13}$)

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 $^{\circ}$ 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

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:
 - $W \rightarrow \mu\nu$, $Z \rightarrow \mu\mu$
 - $t \rightarrow bW \rightarrow b\mu\nu$
- **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, $c \Gamma = 0.7 \text{ km}$
- Decay path

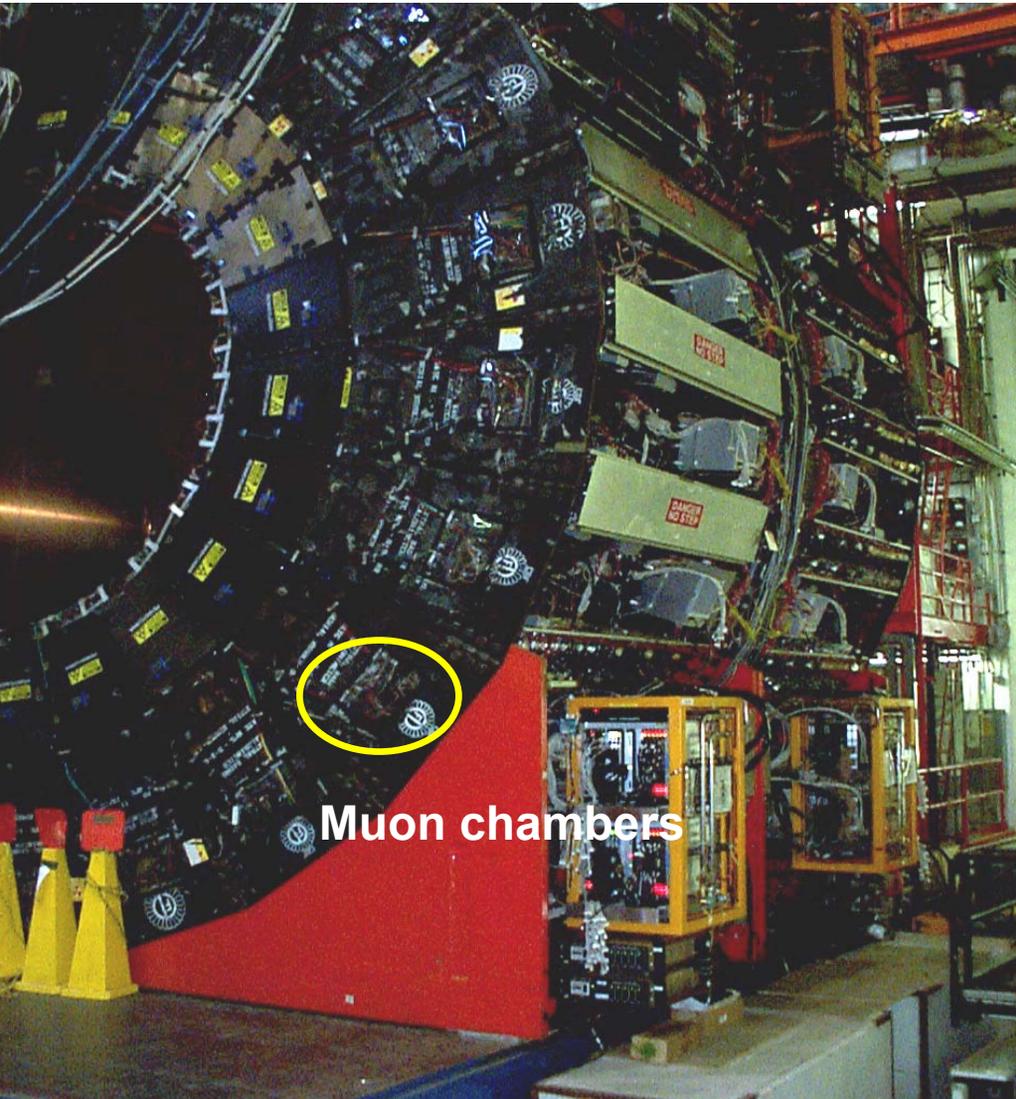
P, GeV/c	Decay Path in (km)	type
1	7	cosmics
10	70	b-quarks
100	700	Muon collider

- For most high energy physics applications muon can be considered “stable” particle

Muon Energy Loss

- Muon Energy loss is defined by electromagnetic 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

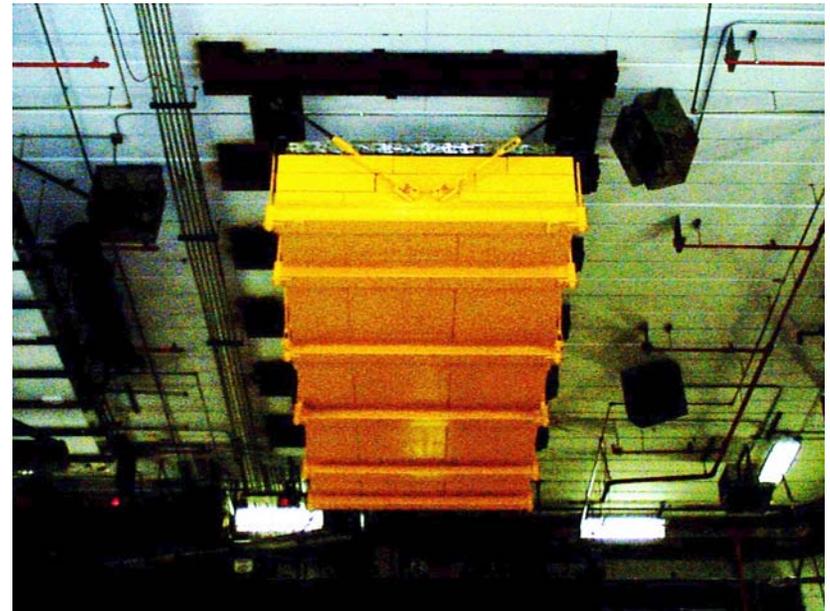


- What people worry about when designing muon systems...
 - Punch-through probability
 - Momentum (angular) resolution

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

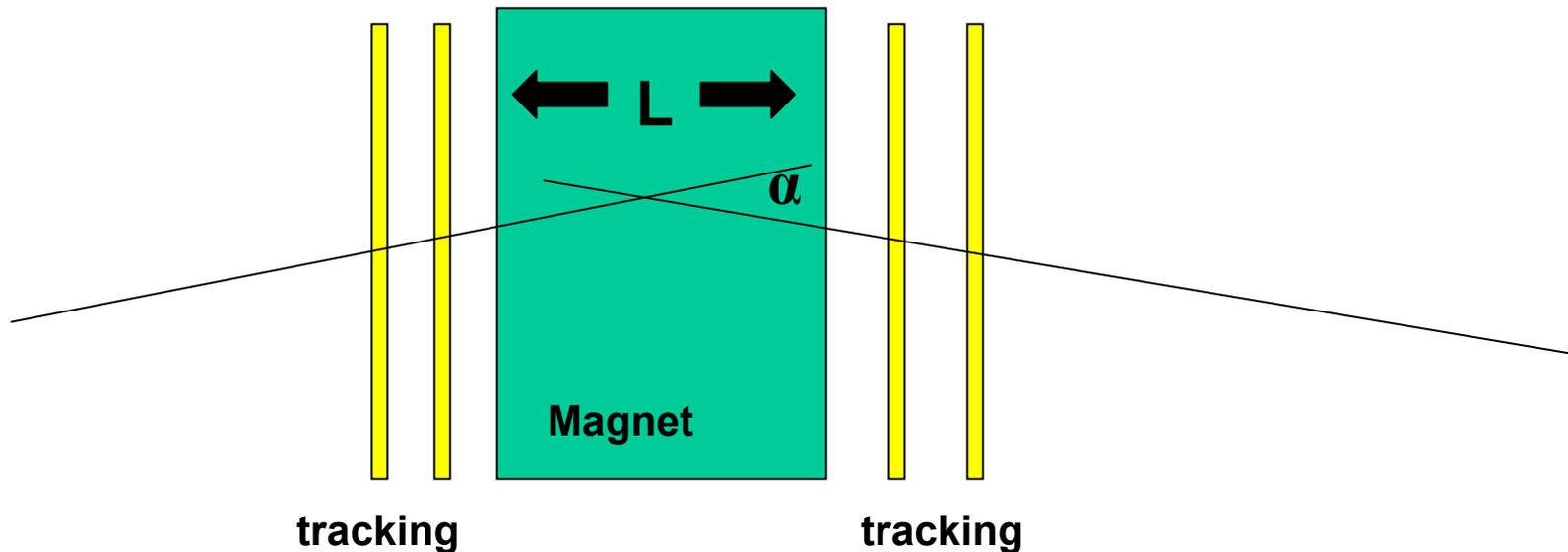
Very High Energy Muons

- At energies above $\sim 0.5\text{TeV}$, muons start to lose 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 $\sim 2\text{T}$

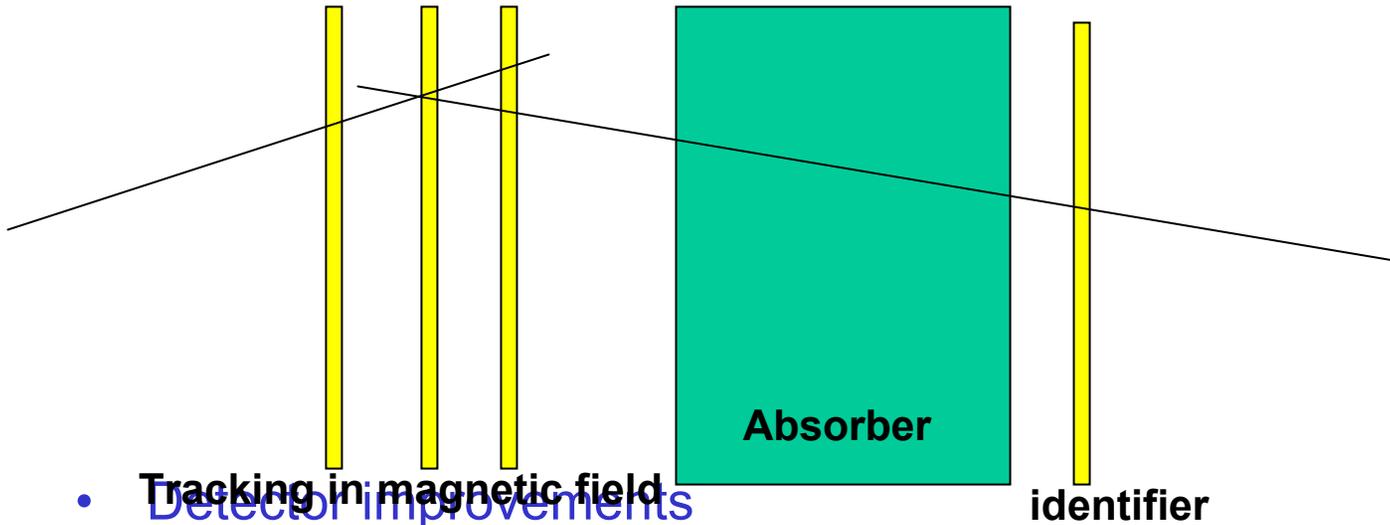
$$P(\text{GeV}/c) = 0.3B(\text{T})L(\text{m})/\alpha(\text{rad})$$



- 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)

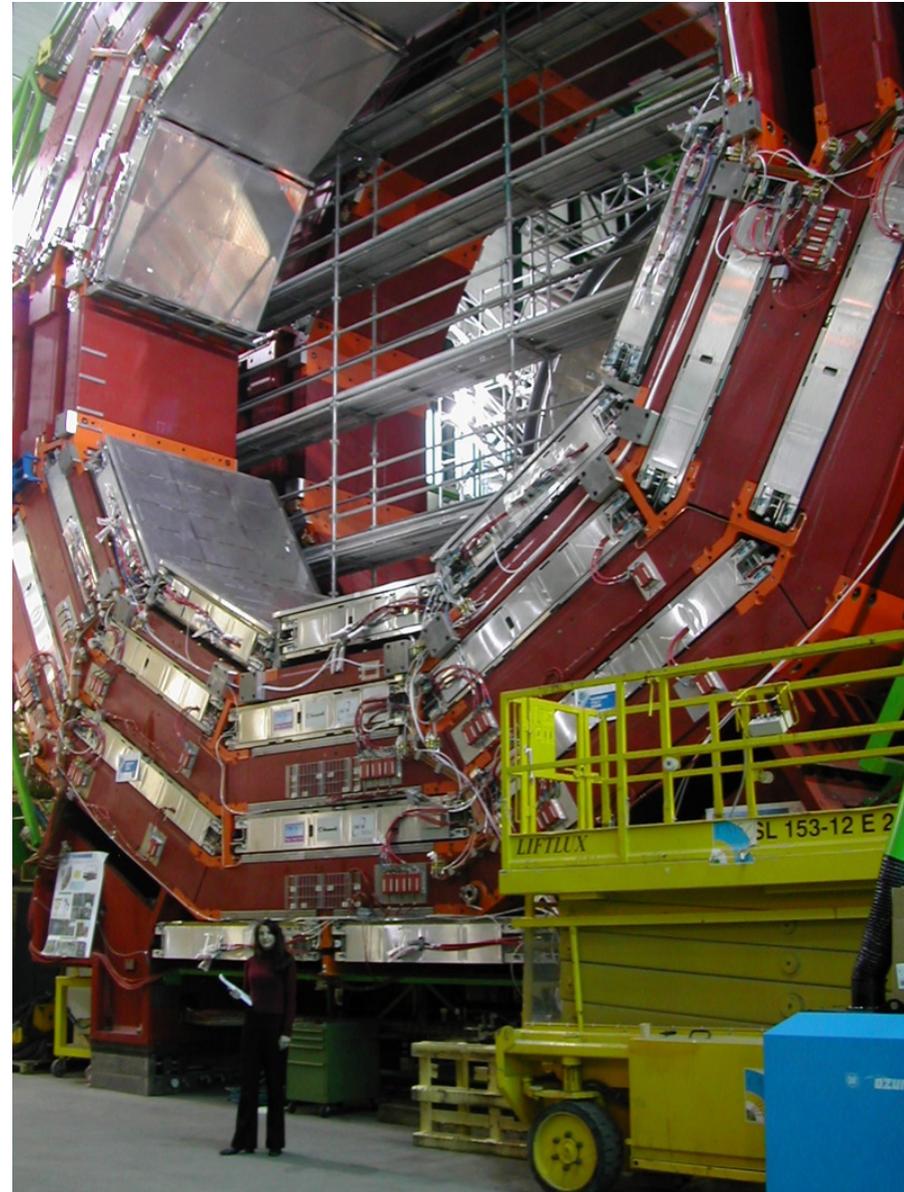
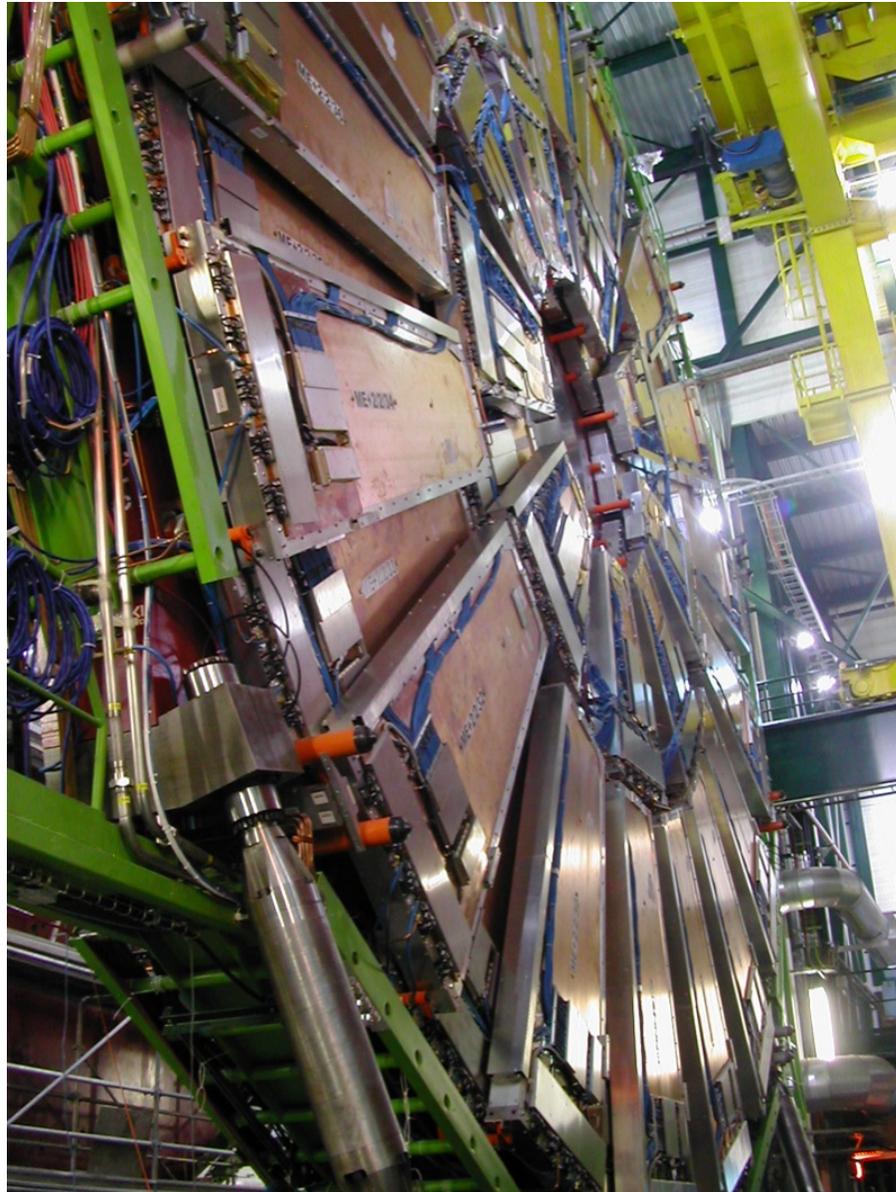


- Increase intrinsic accuracy
- Increase lever arm

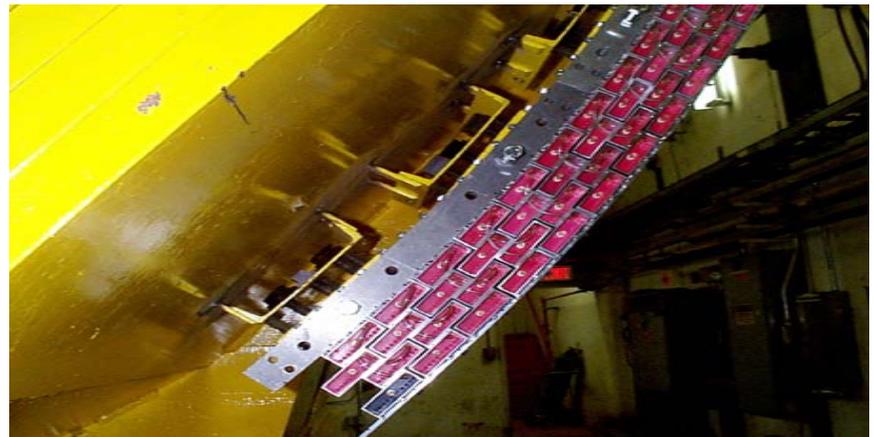
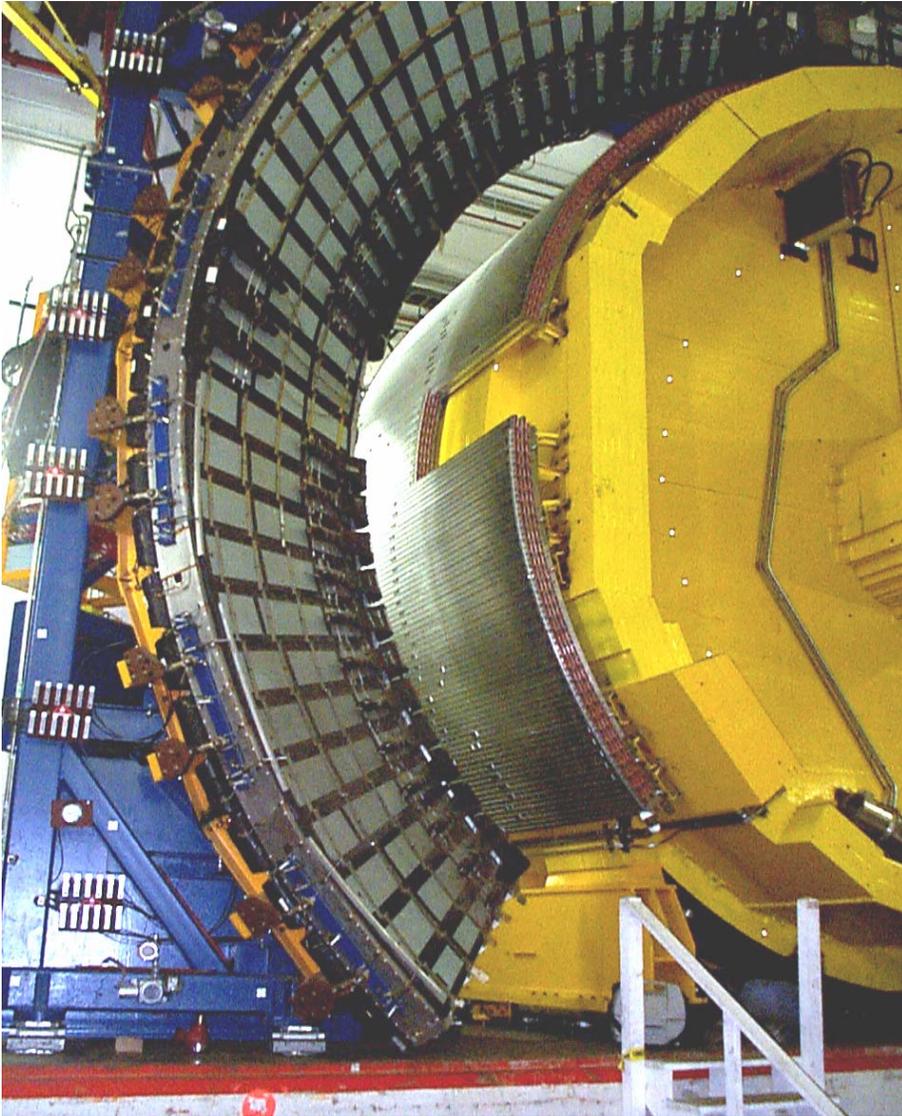
Instrumentation of Muon Detectors

- **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 $\sim 2\text{T}$
 - cryo and/or high energy consumption
- **magnetized iron toroids:**
 - hundreds m^3 volume
 - saturation at $\sim 2\text{T}$
 - 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 ($\sim 10^3 \text{ m}^2$) 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...

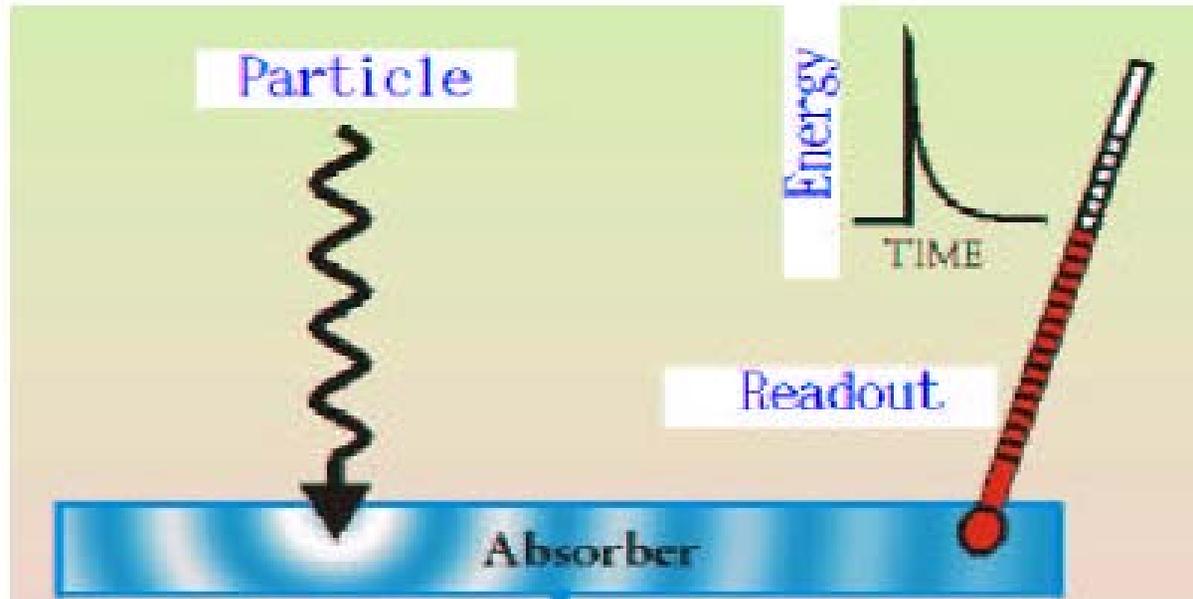
- Typically used before and after absorber for muon ID, bunch tagging, and triggering. Rarely is it used for momentum measurement
- Typical sizes are 1cm(thick) by 10-50cm(width) by N meters (length)
- Muon deposits a few mev of energy into a counter – which converts into several hundred photo electrons
- Attributes
 - Fast (1ns resolution)
 - Easy to make – custom sizes are not a problem
 - Inexpensive to operate but expensive per m²

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 ($\sim 10^6$ occurs near the anode wire providing detectable signals ($\sim 1 \mu\text{A}$))
 - Can get much higher precision than just wire spacing by determining the drift time.

Calorimeters

Calorimeter Basics

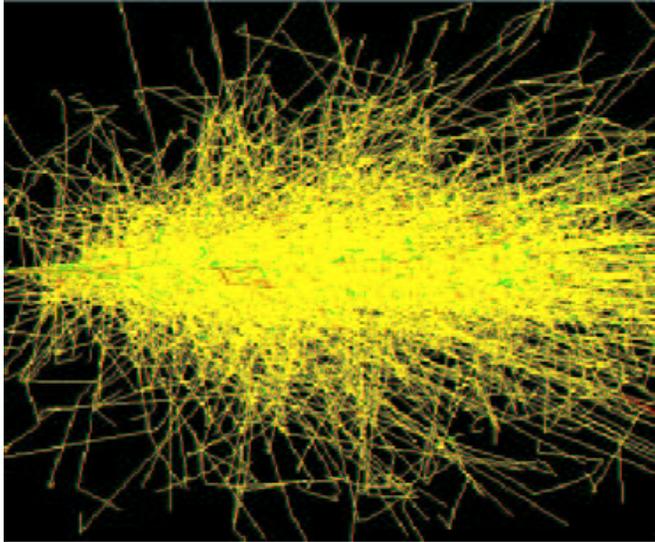


- Particles: e, photons, and hadrons
- Absorber: particles interact → shower cascades
 - e, photons: electromagnetic cascades
 - Hadrons: nuclear interaction cascades
- Readout: measures the excitation of absorber matter by the cascade
- Need thick absorber to contain cascade so that readout response is proportional particle energy
- muons: total absorption calorimetry is impractical

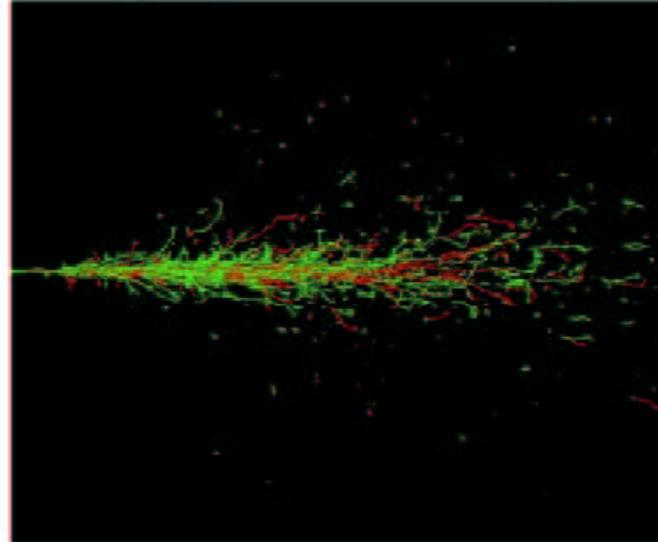
Electromagnetic Cascades

EGS Simulation of 1 GeV Electron shower in 15 cm of copper

All particles are shown



Only electrons are shown



- Dominant energy loss mechanisms:

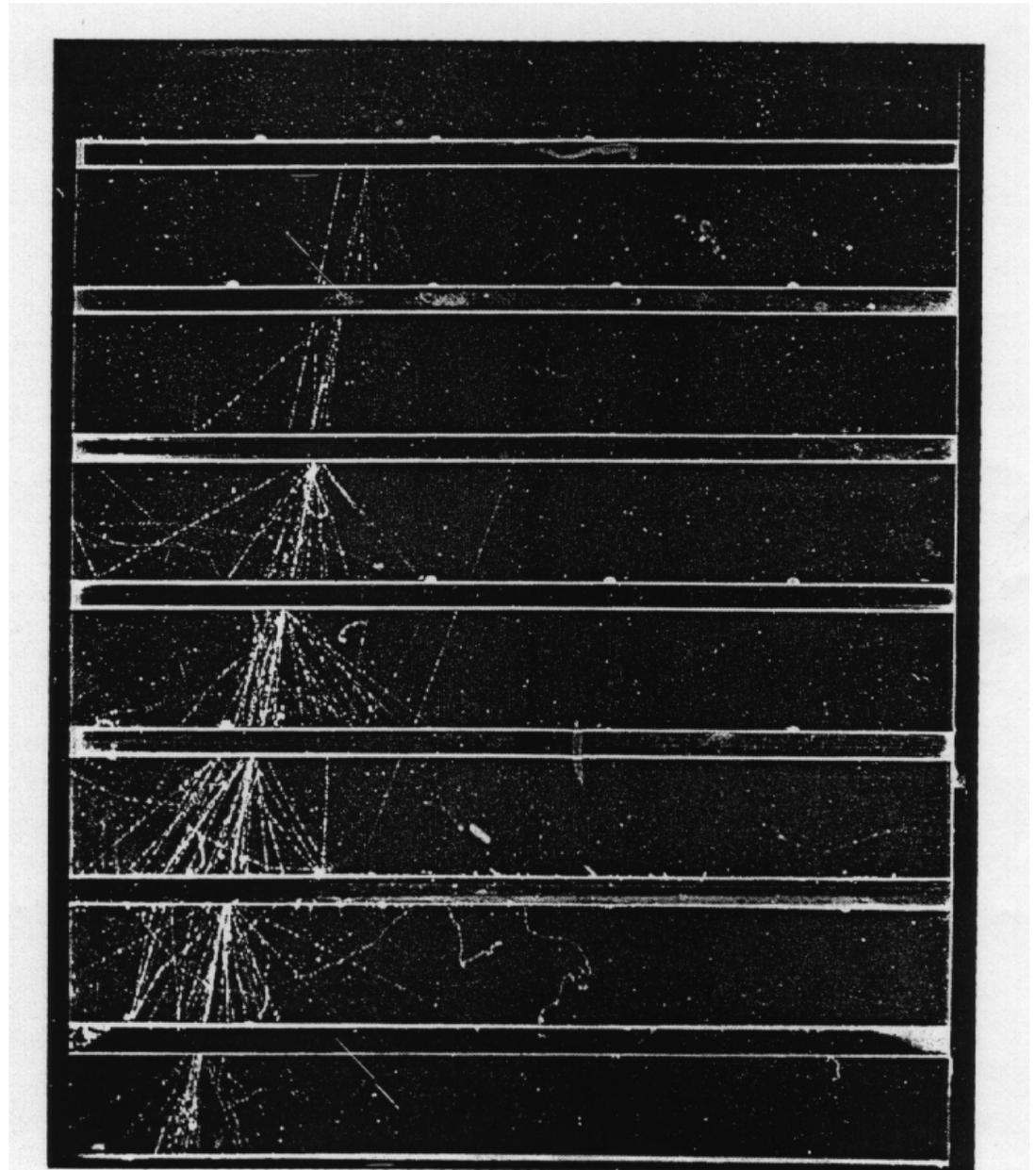
- e^\pm : ionization and bremsstrahlung
- Photon: photoelectric effect, Compton scattering, and pair production

- Cascade parameters

- X_0 . Radiation length: mean distance for e^\pm to lose all but $1/e$ of its energy by brem
- E_c . Critical energy: energy at which the e^\pm brem and Ionization rates are equal

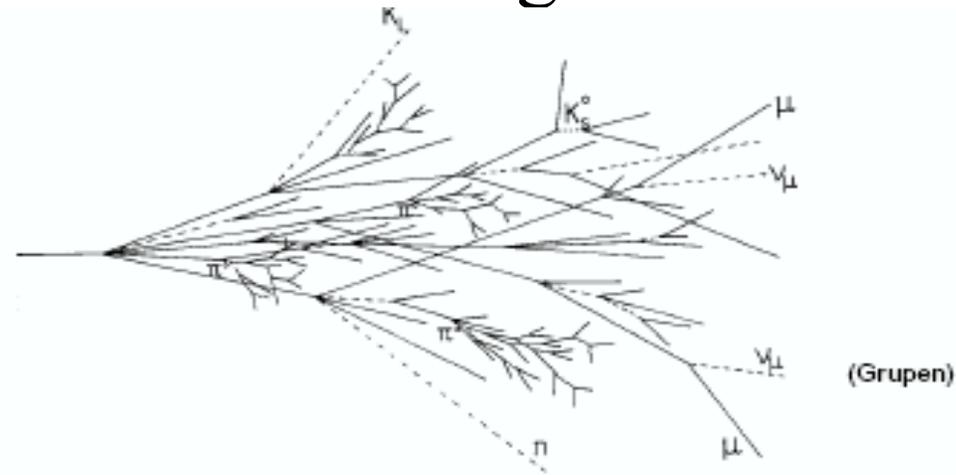
Electromagnetic Showers

**Cloud chamber
photo of
electromagnetic
cascade between
spaced lead
plates.**



Hadronic Cascades

- Various processes involved. Much more complex than electromagnetic cascades.



Hadronic

+

electromagnetic
component



charged pions, protons, kaons
Breaking up of nuclei
(binding energy),
neutrons, neutrinos, soft γ 's
muons \rightarrow invisible energy

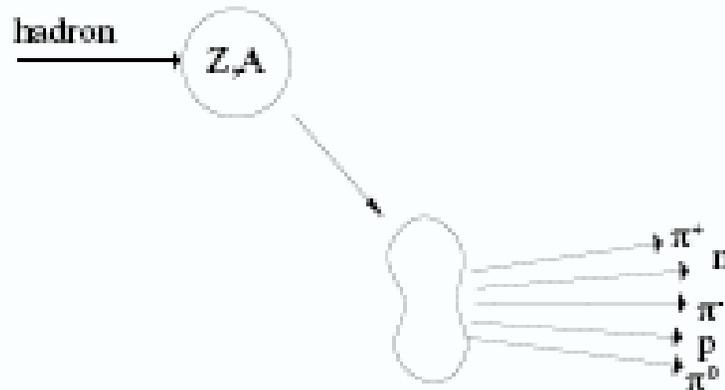


neutral pions $\rightarrow 2\gamma \rightarrow$
electromagnetic cascade
 $n(\pi^0) \approx \ln E(\text{GeV}) - 4.6$
example 100 GeV: $n(\pi^0) \approx 18$

Large energy fluctuations \rightarrow limited energy resolution

Nuclear Interactions

The interaction of energetic hadrons (charged or neutral) is determined by **inelastic nuclear processes**.



multiplicity $\propto \ln(E)$

$p_t \approx 0.35 \text{ GeV}/c$

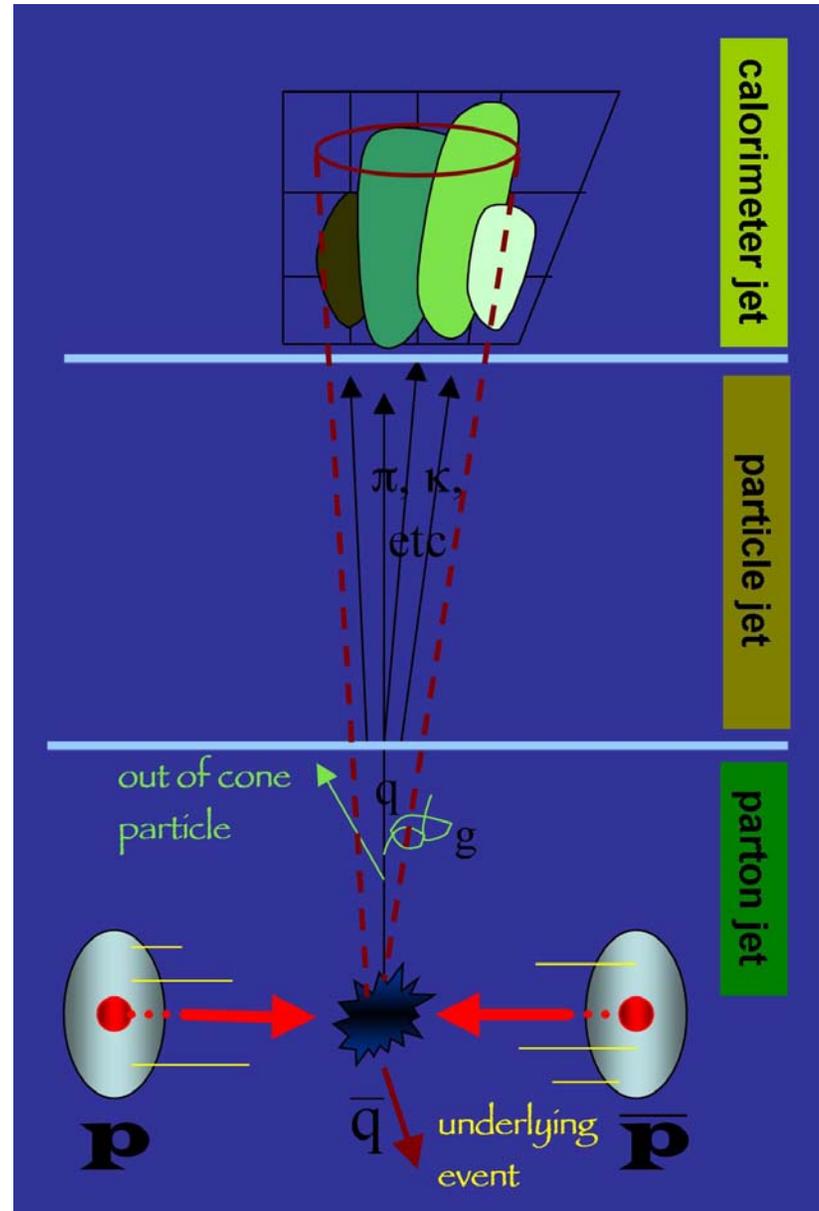
Excitation and finally breakup up nucleus \rightarrow nucleus fragments + production of secondary particles.

For high energies ($>1 \text{ GeV}$) the cross-sections depend only little on the energy and on the type of the incident particle (p, π, K, \dots).

Partons \rightarrow Particles \rightarrow Jets

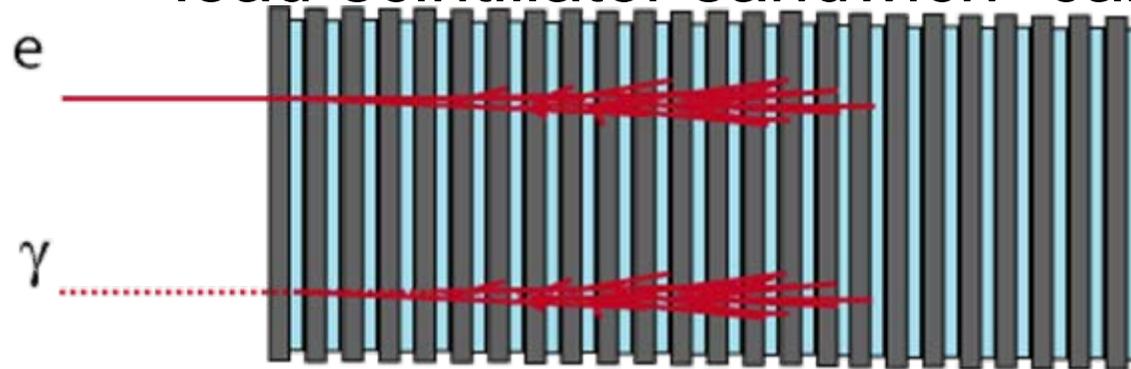
Processes creating jets are very complicated, and consist of parton fragmentation, then both electromagnetic and hadronic showering in the detector.

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



Electromagnetic Calorimeter Types

- “lead-scintillator sandwich” calorimeter



Energy resolutions:

$$\otimes E/E \sim 20\%/\sqrt{E}$$

- exotic crystals (BGO, PbW, ...)



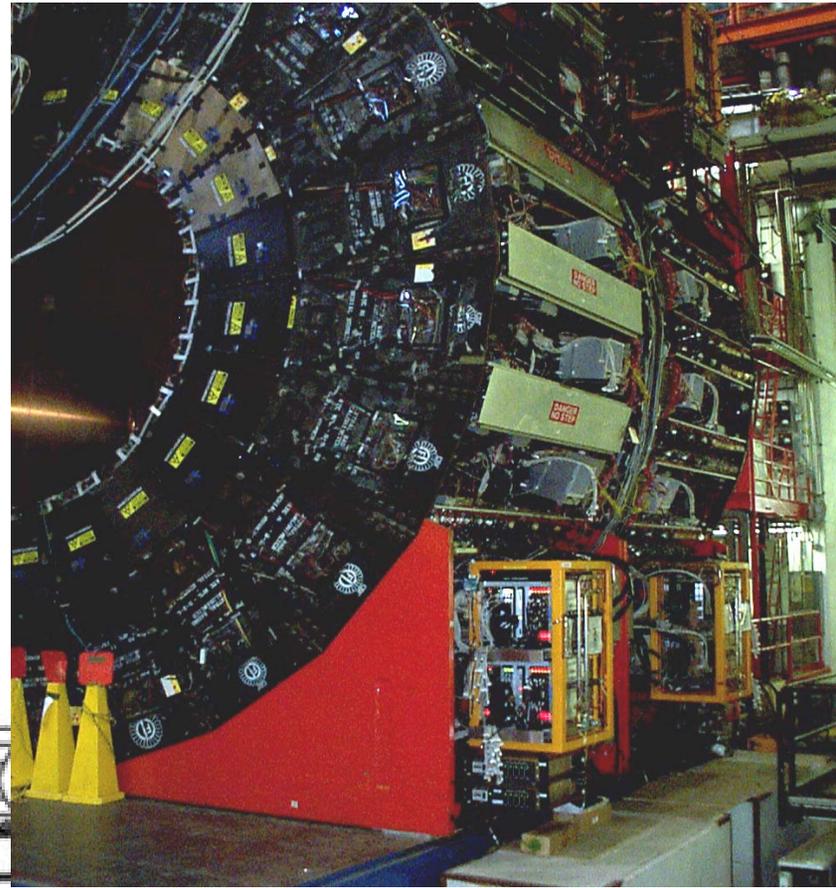
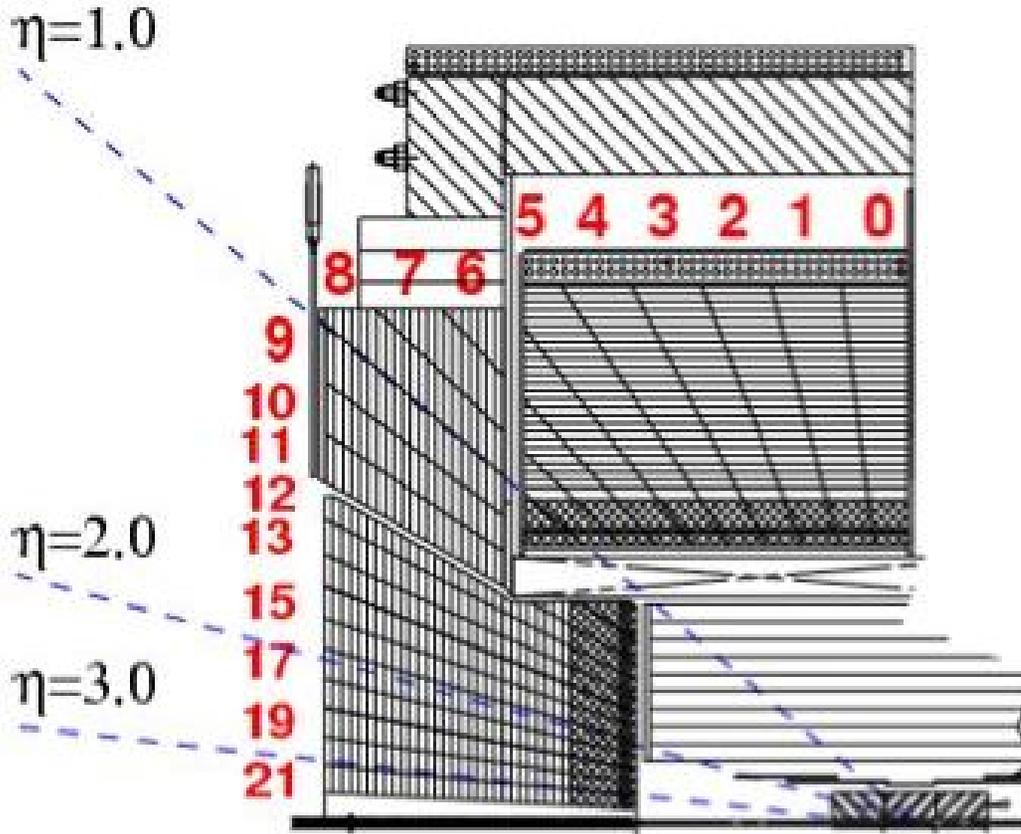
$$\otimes E/E \sim 1\%/\sqrt{E}$$

- liquid argon calorimeter

$$\otimes E/E \sim 18\%/\sqrt{E}$$

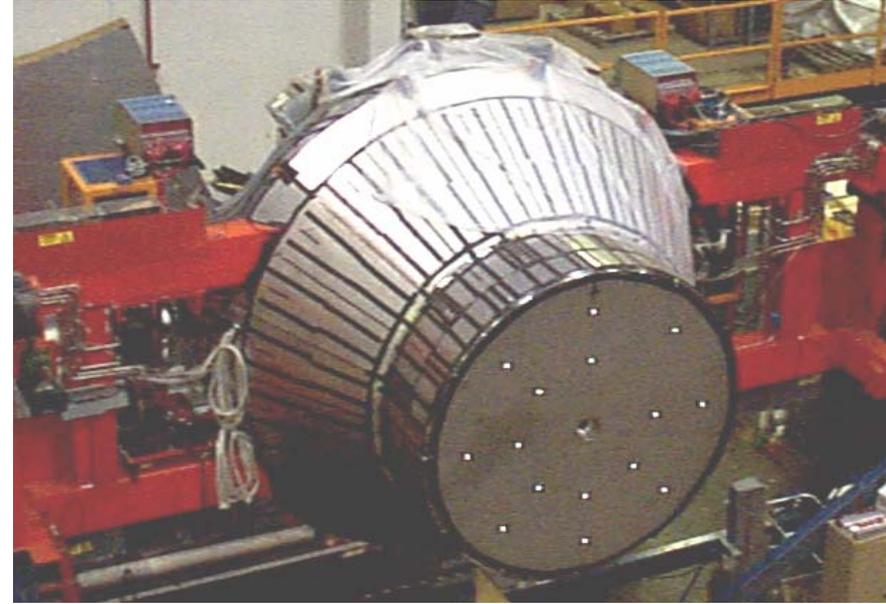
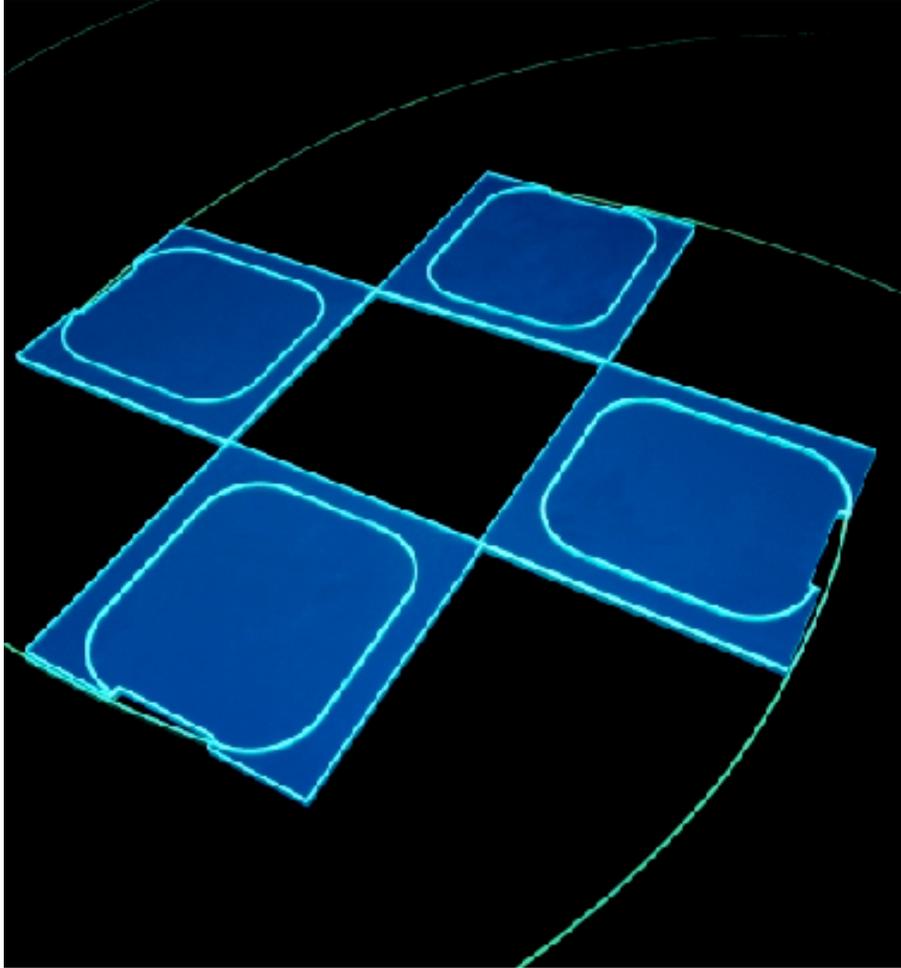
CDF Sampling Calorimeter

- calorimeter is arranged in projective “towers” pointing at the interaction region
- most of the depth is for the hadronic part of the calorimeter



CDF Endplug Calorimeter

4 scintillating tiles of the CMS Hadron calorimeter

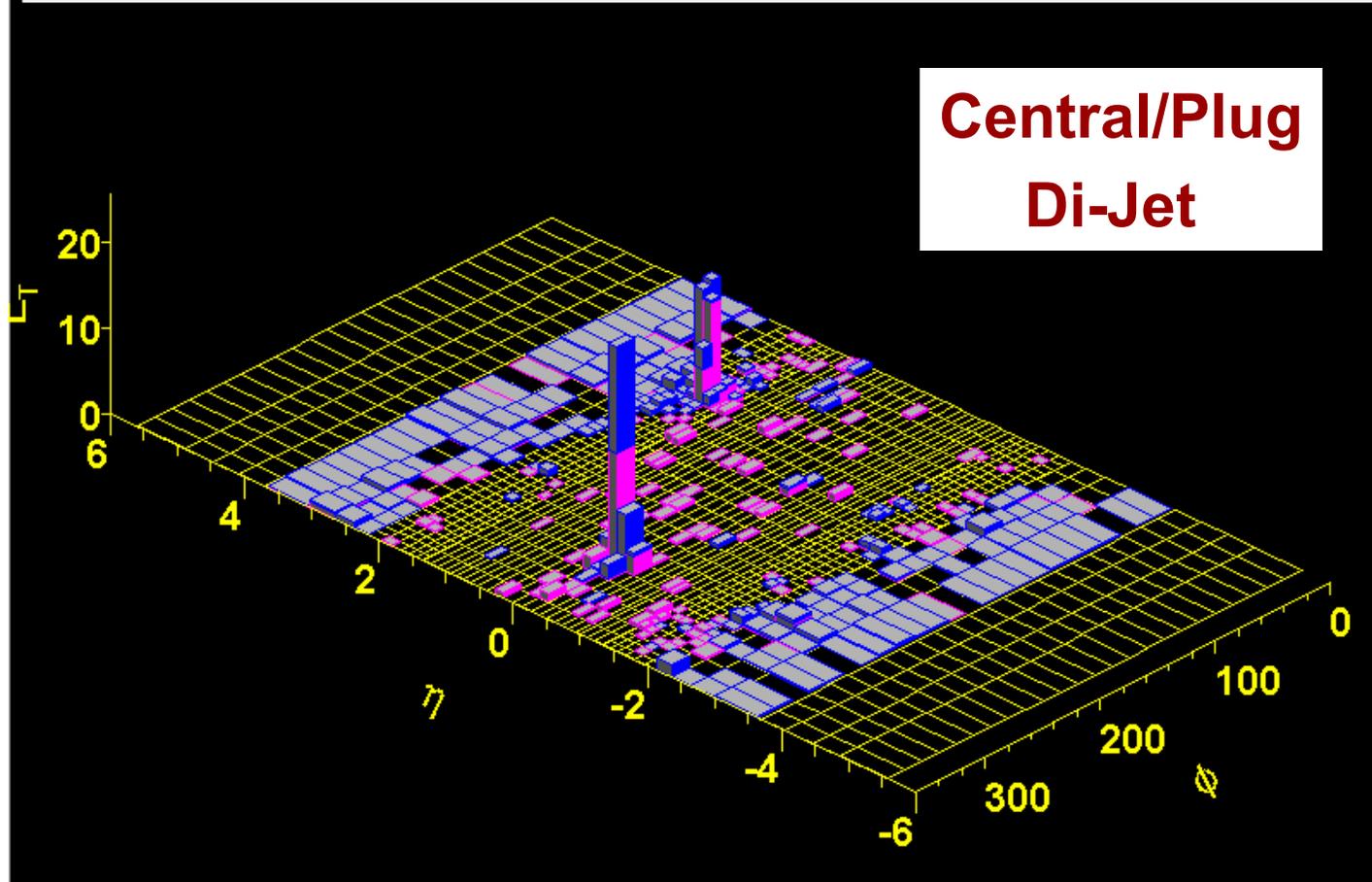


CMS Hadron Calorimeter



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



Unfolded Top/anti-Top Candidate

e + 4 jet event

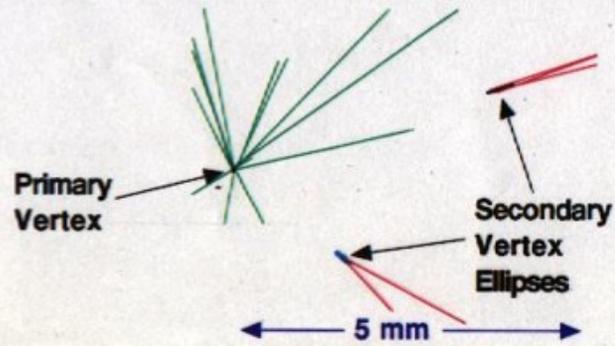
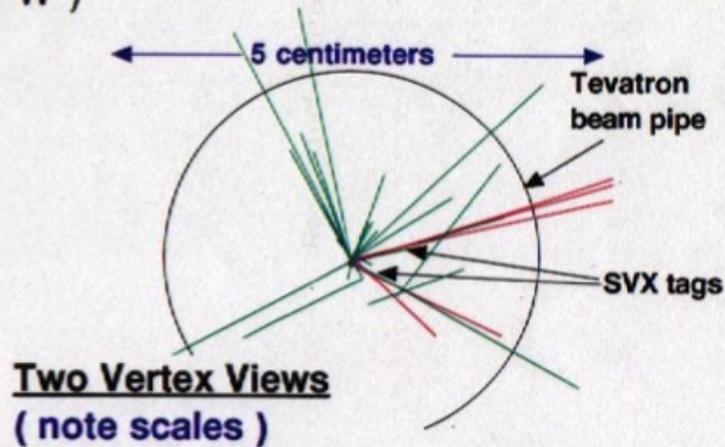
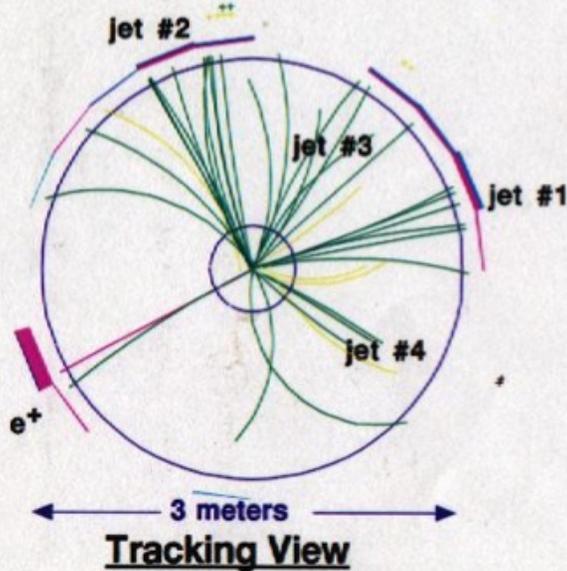
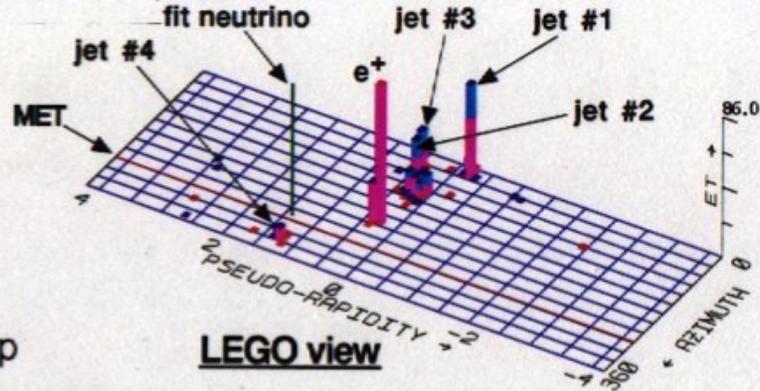
40758_44414

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)

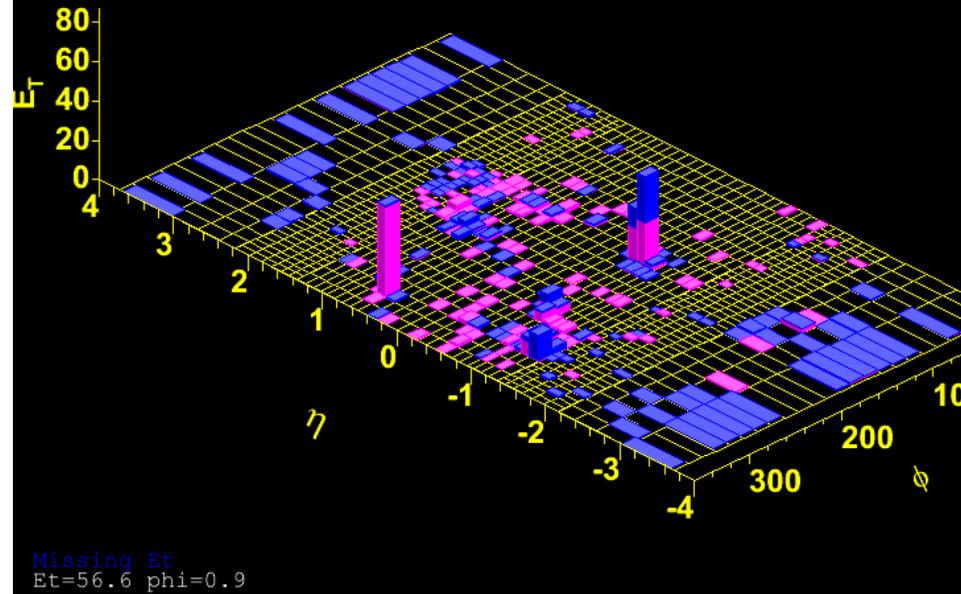


Run 1
Event

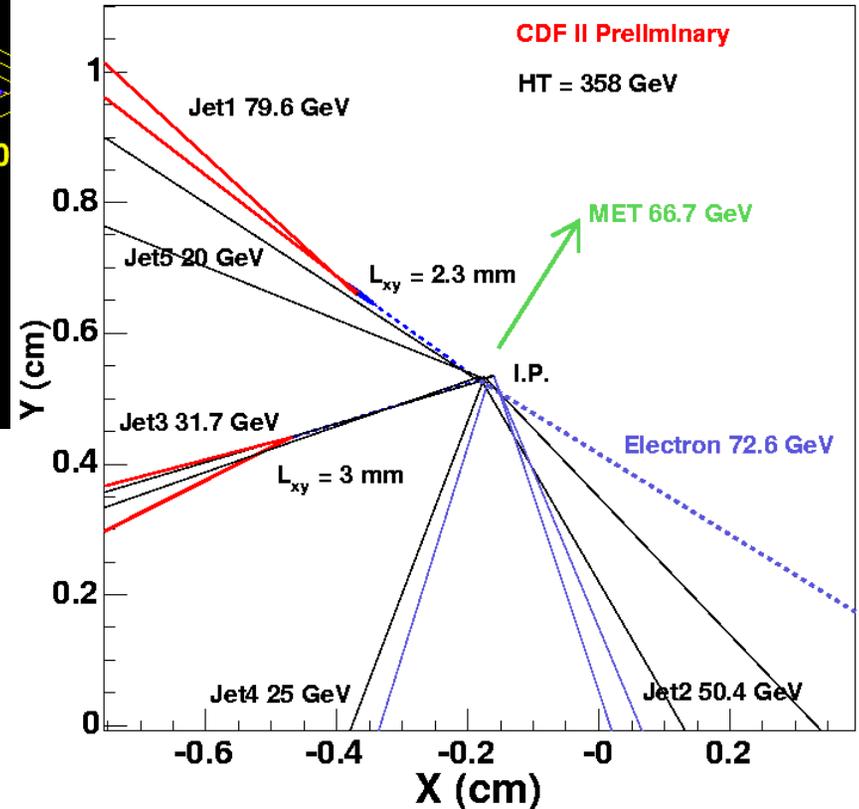
Unfolded Top/anti-Top Candidate

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,

Run 2 Event

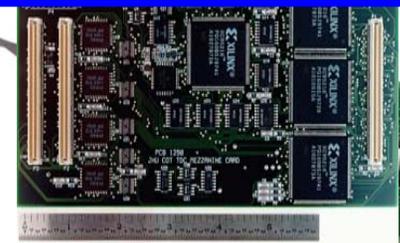


Missing E_T
 $E_T=56.6$ $\phi=0.9$



The Detector is NOT
complete...

XTC Mezzanine - Michigan



DIRAC



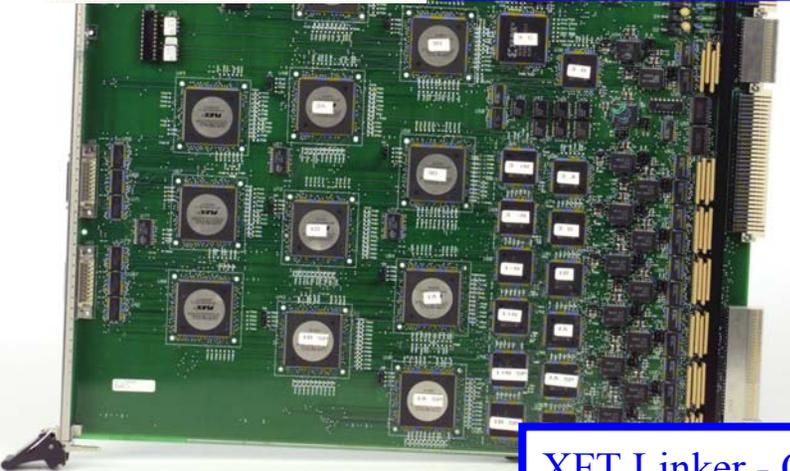
CRATESUM



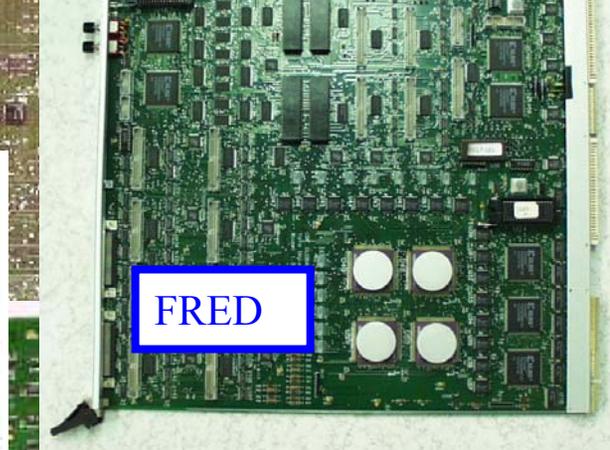
XFT FINDER - FNAL



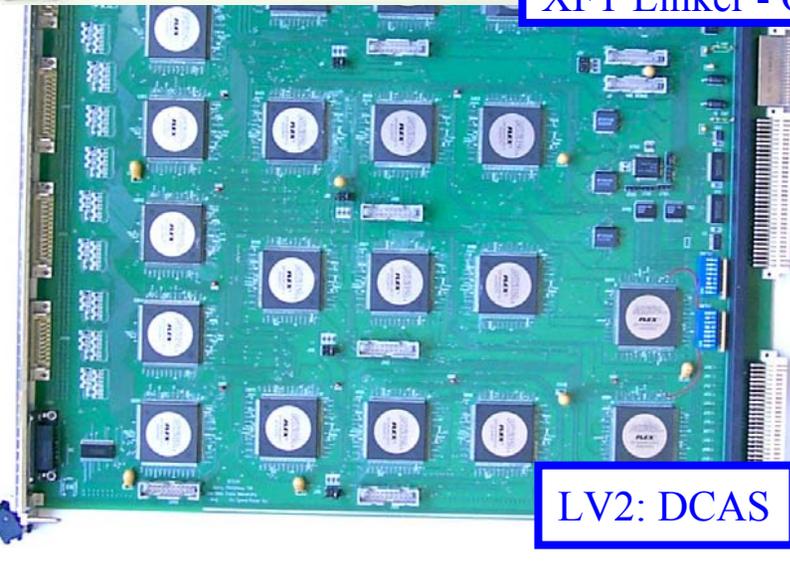
PreFRED



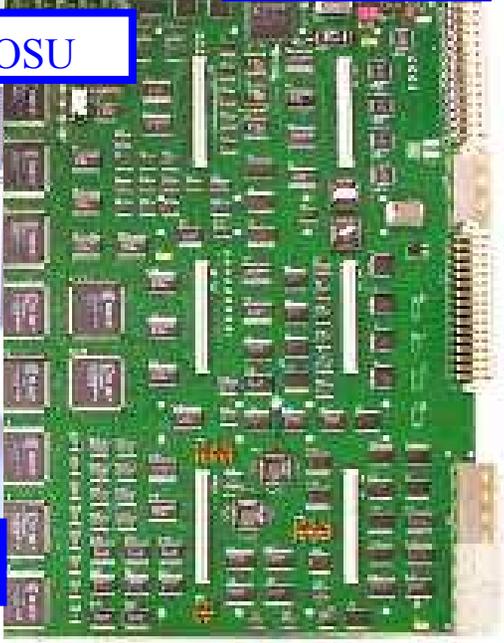
XFT Linker - OSU



FRED



LV2: DCAS

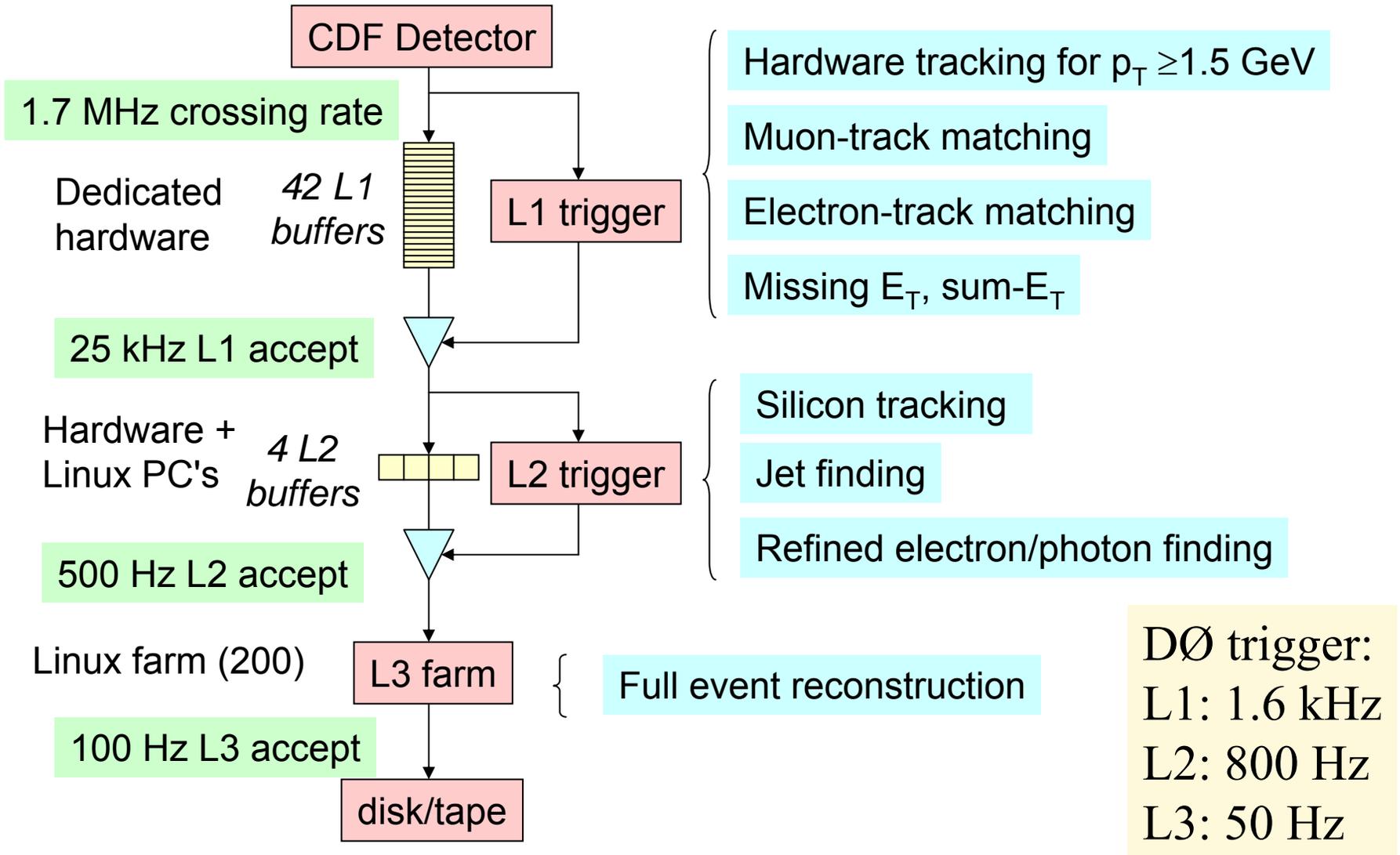


LV2: LOCUS



Triggering at hadron colliders

The trigger is the key at hadron colliders

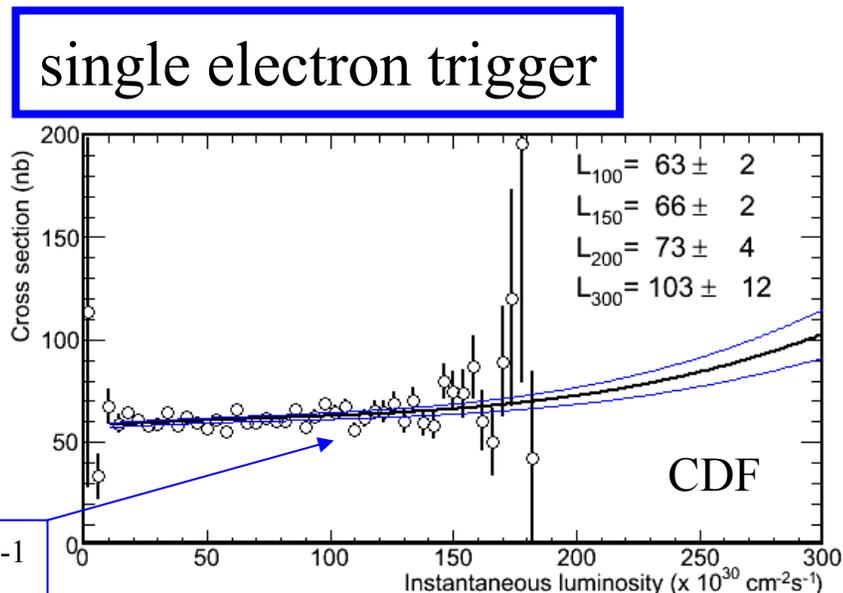


Typical Triggers and their Usage

- **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: $W \rightarrow \text{taunu}$
 - **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
 - $ZH \rightarrow \nu\nu b\bar{b}$

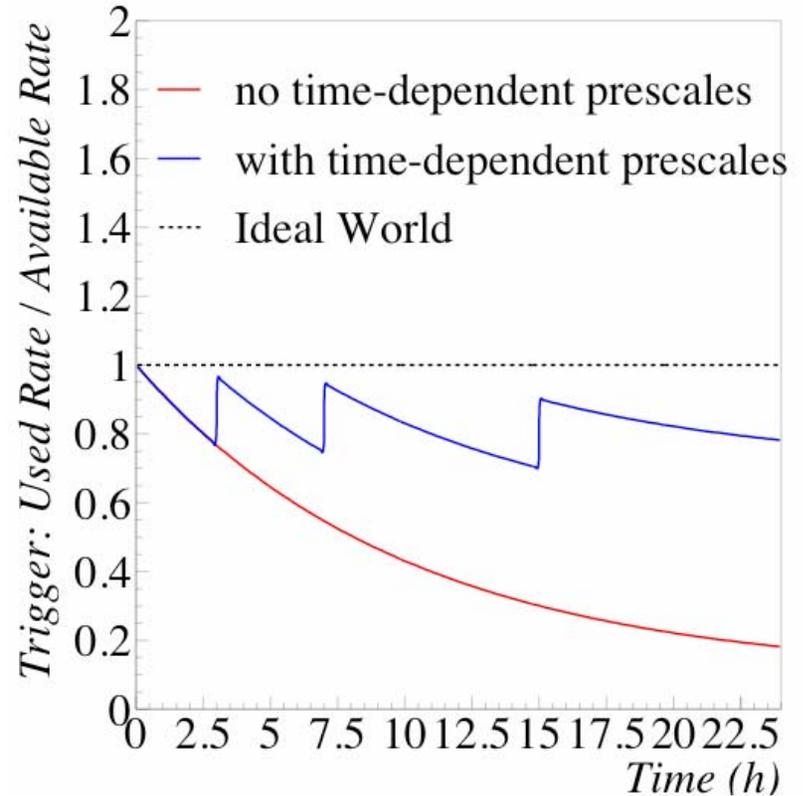
Rate = 6 Hz at $L = 100 \times 10^{30} \text{ cm}^{-2}/\text{s}^{-1}$

- **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



Trigger Operation

- Aim to maximize physics at trigger level:
 - Trigger cross section:
 - N_{event}/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

- I did not discuss the important role computing has with Detectors...
- Data Acquisition
- Full event reconstruction as the final trigger stage
- Offline data processing, event reconstruction, and production of analysis data sets
- For CDF to collect data (not analyze, just collect) – it takes ~400 computers.

SIMULATION

A Few Comments on Monte Carlo

- Critical for **understanding the acceptance and the bckg's**
 - Speed: CDF ~ 10 s per event, DØ ~ 3 m 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)

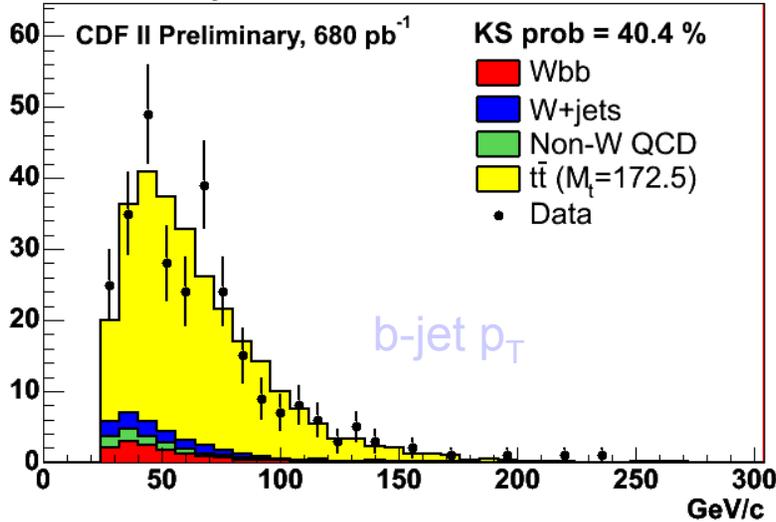
- **Neither physics nor detector simulation can generally be trusted!**

- 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

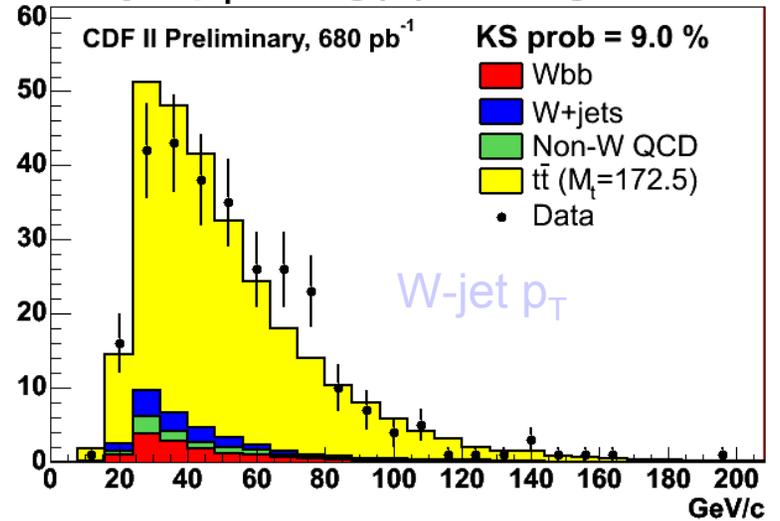
A Few Comments on Monte Carlo

- It is important that the detector builders work closely with those who are writing the MC simulation.
- Accurate simulations mean its not just about the detector geometry
- important to model the support structure, cable plant, etc – all of the material needs to find its way into the simulation.....
- Typically one starts to verify and tune simulation by trying to get MC detector components to agree with testbeam data.
- From that, one starts to use the data...
 - Vertex smearing
 - Beam position
 - Underlying event
 -

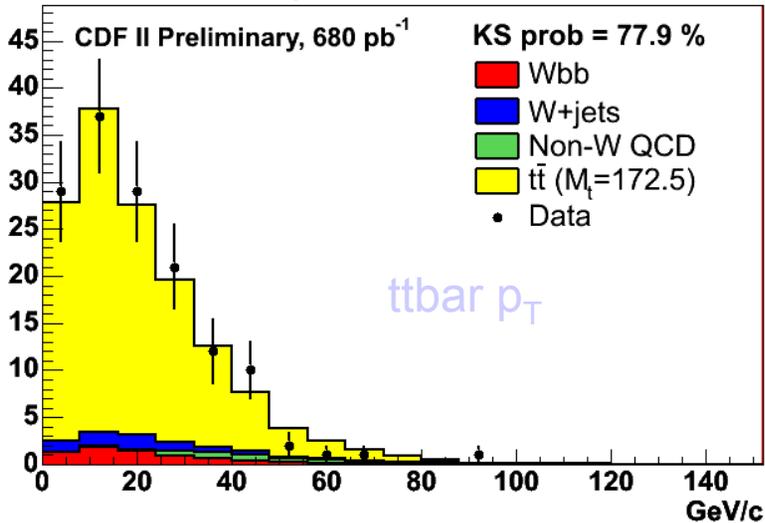
b-jet p_T , 1-tag(T) + 2-tag events



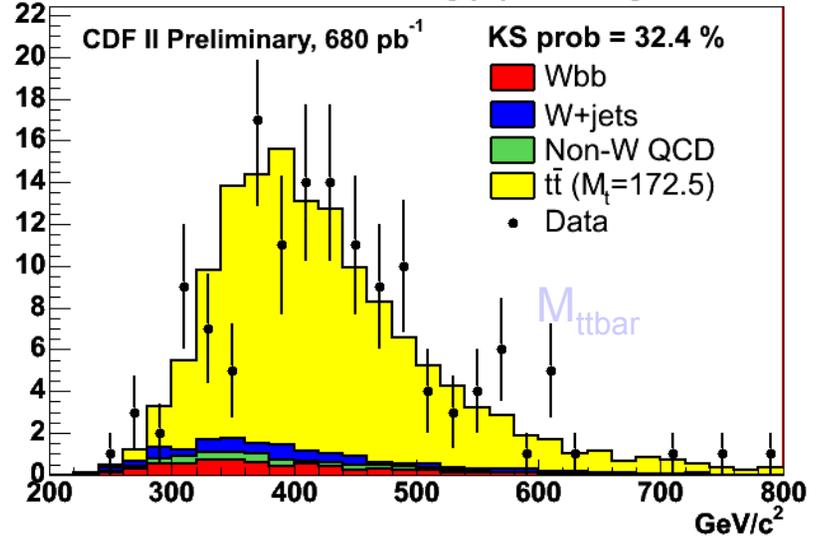
W-jet p_T , 1-tag(T) + 2-tag events



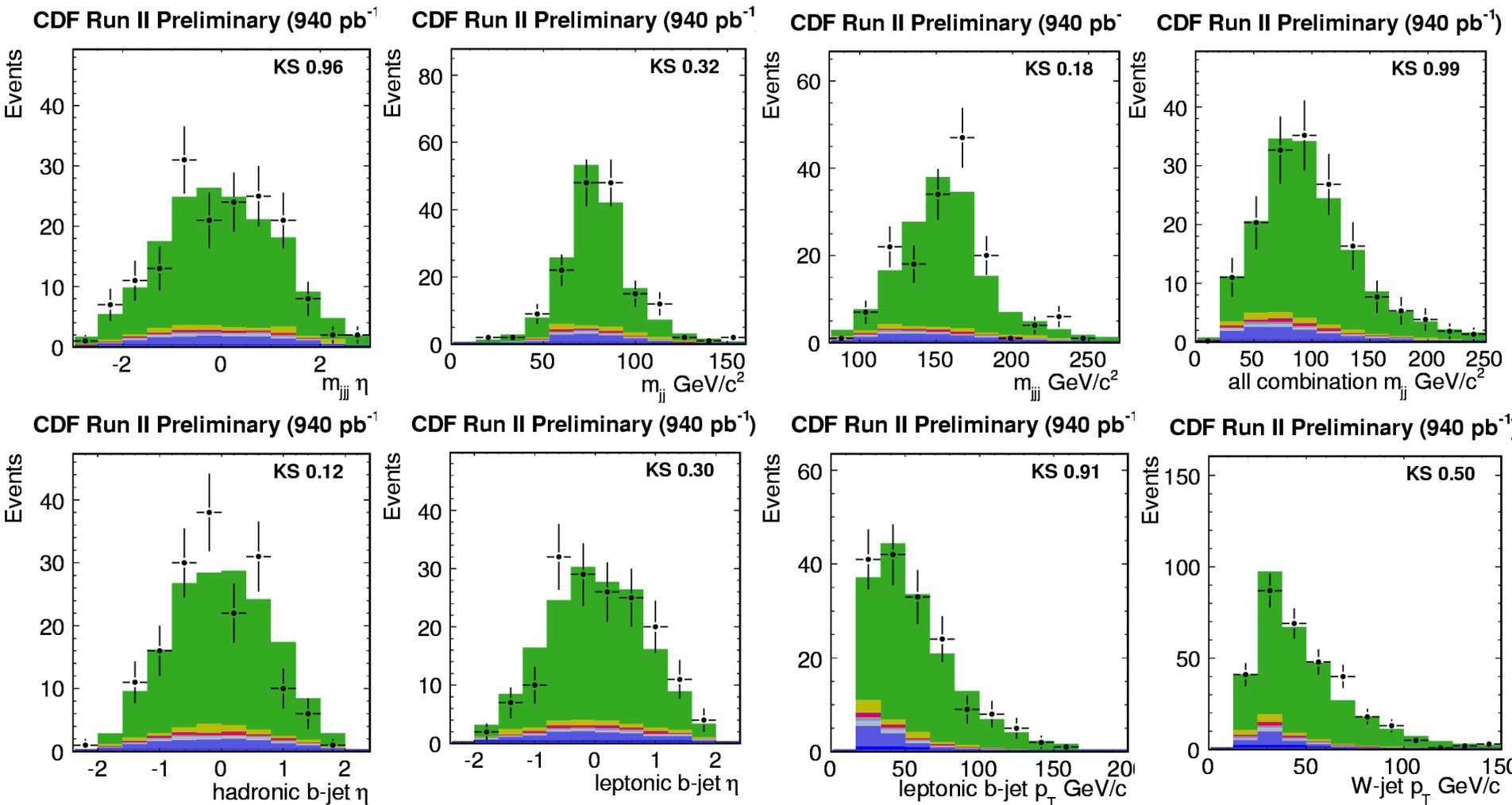
Reco $t\bar{t}$ bar p_T , 1-tag(T) + 2-tag events



Reco $t\bar{t}$ bar 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**
- **...**