HEP Experiments at Particle Accelerators

Primary Consideration:

What Physics do we expect to do?

⇒ what particles to accelerate and collide?
what energy?
Beam intensities / luminosity?

Lepton colliders: leptons are elementary particles.
So, you can tune the CM energy
if you know what you are looking for

Hadron Colliders: Hadrons are composite.
So the CM energy of component elementary particles,
i.e., quarks and gluons vary from collision to
collision.

→ Broad range of C.M. energies accessible
→ often helpful in many searches
→ But not a very clean environment
lots of soft stuff from remnants
of collisions
→ Harsh radiation environment for
detectors.

Time Structure of Accelerator Beams

Particles are accelerated by electric fields generated by an RF system. This requires particles to be bunched (packed into bunches). There is a time-structure for the beam.

FT experiments:

An experiment received beam only for a fraction of the total time; this is called the duty cycle of the machine. ← Measure of the efficiency of an accelerator

Tevatron FT: Duty cycle $\sim 20s/60s \simeq 33\%$

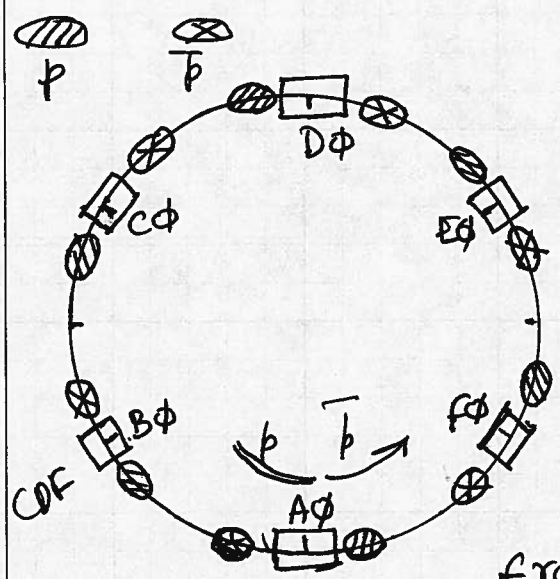
spill time

40s for acceleration and extraction of the beam.

The data-acquisition (DAQ) system at Fixed Target experiments must be organized in such a way that the data are collected rapidly during the spill time. Much of the filtering, recording and monitoring can be done in between spills.

Time Structure at Colliders

In the colliders / storage rings, the two beams are filled, accelerated to nominal energy once and allowed to circulate and collide with each other for several hours ($\gtrsim$ 24 hours at the Tevatron).



Many bunches in the ring

$6p \times 6\bar{p}$ provides 6 interaction or collision regions.

But, in unused interaction regions the beams are prevented from colliding (and wasting of beam) by separating the ~~beams~~ / bunches using electrostatic separators.

Run 1 ← $6 \times 6 \Rightarrow 20\,\mu s / 6 = 3.3\,\mu s$

In Run 2~~A~~, we have $36p \times 36\bar{p}$ bunches

The bunch-spacing is dictated by the accumulator RF timing structure

~4 bunches in ~1.6 μs

$\Rightarrow$ ~396 ns $\Rightarrow$ 400 ns

~~Actual~~ Quoted bunch-spacing 396 ns

Some Relevant Accelerator Parameters

	Tevatron	LHC	SLHC
E_{CM}	1.96 TeV	14 TeV (?)	14 TeV
Lum	$> 2.0 \times 10^{32}\ cm^{-2}s^{-1}$	$10^{34}\ cm^{-2}s^{-1}$	$10^{35}\ cm^{-2}s^{-1}$
α (beam crossing ∠)	0	300 μrad	50-500 μrad
t_b (Bunch-spacing)	396 ns	25 ns	25 ns
N_b (Number of bunches)	36 × 36	2808 × 2808	
Lum. region	0.54 m	0.085 m	0.085 m
σ_x (trans)	30 μm	15 μm	15 μm
σ_b (long)	38 cm	7.6 cm	7.5 cm
σ_{inel}	~60 mb	~80 mb	~80 mb
$\langle n_v \rangle$	~6-7	~20	~200

LUMINOSITY

Fixed Target Experiments:

No. of interactions,

$N_{ev} \propto \sigma$, the interaction cross section

$\propto N_0$, the beam flux

$\propto N_t$, No. of target atoms / unit area

$$N_t = \frac{N_A \cdot \rho \cdot l}{A} \; ; \; F = \frac{1}{N_t}$$

$$N_{ev} = N_0 \cdot N_t \cdot \sigma = \frac{N_0}{F} \cdot \sigma$$

$$F = \text{Target Constant} = \frac{A}{N_A \cdot \rho \cdot l} \simeq 2.3 \times 10^{-24} \, cm^2$$

~~(fixed~~

$= 2.3 b$

for liquid hydrogen target ($\rho = 0.071 g/cc$) and length $= 10$ cm

$$\boxed{N_{ev}/_{sec} = L * \sigma}$$

$$L = \frac{N_0/sec}{F} = \text{Luminosity}.$$

for $F = 2.3 b$, $N_0 = 10^{10}$ particles / sec

$$L = \frac{10^{10}}{2.3 \times 10^{-24} cm^2} = 4.3 \times 10^{+9} \times 10^{+24} \, cm^{-2} s^{-1}$$

$$= 4.3 \, nb^{-1} s^{-1}$$

$\therefore$ A cross section of 1 nb will yield 4.3 events / sec.

Collider Luminosity

The Instantaneous Luminosity

$$L = \frac{3\gamma \cdot f_0\, n_b \cdot N_p \cdot N_{\bar{p}}}{\pi \beta^* (\epsilon_p + \epsilon_{\bar{p}})} H(\sigma_z/\beta^*)$$

$$\longrightarrow \quad L = \frac{N_p \cdot N_{\bar{p}} \cdot n_b \cdot f}{4\pi \sigma_t^2}$$

For Tevatron,

$N_p \sim 3 \times 10^{11}$, $N_{\bar{p}} \sim 10^{11}$, $n_b = 36$, $f = 47\,kHz$

$\sigma_t = 30\,\mu m$

$$L = \frac{3\times10^{11} * 10^{11} * 36 * 47\times10^{3}\ s^{-1}}{4\pi\ (30\times10^{-4})^2\ cm^2}$$

$$\simeq \frac{\cancel{9}\times 5 \times 10^{26}}{\cancel{9}} \times 10^{6}\ cm^{-2}\,s^{-1}$$

$$\sim \underline{5\times10^{32}\ cm^{-2}\,s^{-1}}$$

Currently, $L \sim 3.5 \times 10^{32}\ cm^{-2}\,s^{-1}$.

$$\mathcal{L} = \int L\,dt = \int 3\times10^{32}\ cm^{-2}s^{-1} * dt$$

Seconds in a year

Run efficiency * lum lifetime.

$$= 10^{32} * 3\times10^{7} * 0.5\ cm^{-2}$$

$$= 1.5 * 10^{39}\ cm^{-2}$$

$$= \underline{\underline{1.5\ fb^{-1}}}/year \qquad 10^{-24}\ cm^{2} = 1\ b$$

$$10^{-39}\ cm^{2} \leftarrow 10^{-24}\times10^{-15}\ cm^{2} \leftarrow 1\ fb$$

Currently, averaging $\sim 2.5\ fb^{-1}/year$.

Total Run 1 luminosity $\sim \underline{\underline{125\ pb^{-1}}}$

Event Rates at the Collider

$$N_{obs} = \sigma(p\bar{p} \to X_1 X_2 ..) \cdot \int \mathcal{L}\, dt \cdot \epsilon$$

Cross section
≡ Probability for the process
units: barn $= 10^{-24}\,cm^2$

Efficiency & Detection
≡ Detector Acceptance
* various efficiencies

E.g.,
$\sigma_{p\bar{p} \to t\bar{t}}(\sqrt{s} = 1.96\,TeV) \sim 8\,pb$

Luminosity integrated over time

Currently
Run II $\int \mathcal{L}\, dt \sim 6.2\,fb^{-1}$

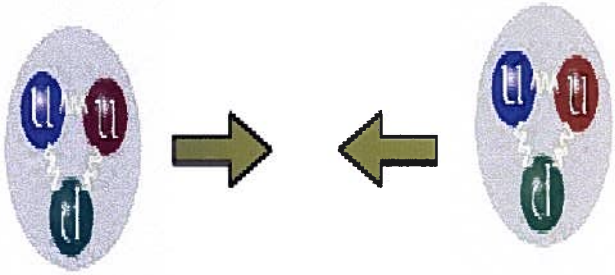
Size of the data set

$\mathcal{L}$ is in units $cm^{-2}\,s^{-1}$

$\mathcal{L}_{Tev} \simeq 9 \times 10^{32}\,cm^{-2}\,s^{-1}$

In principle,
$\sigma * BR$

Branching Ratio to particular final states.



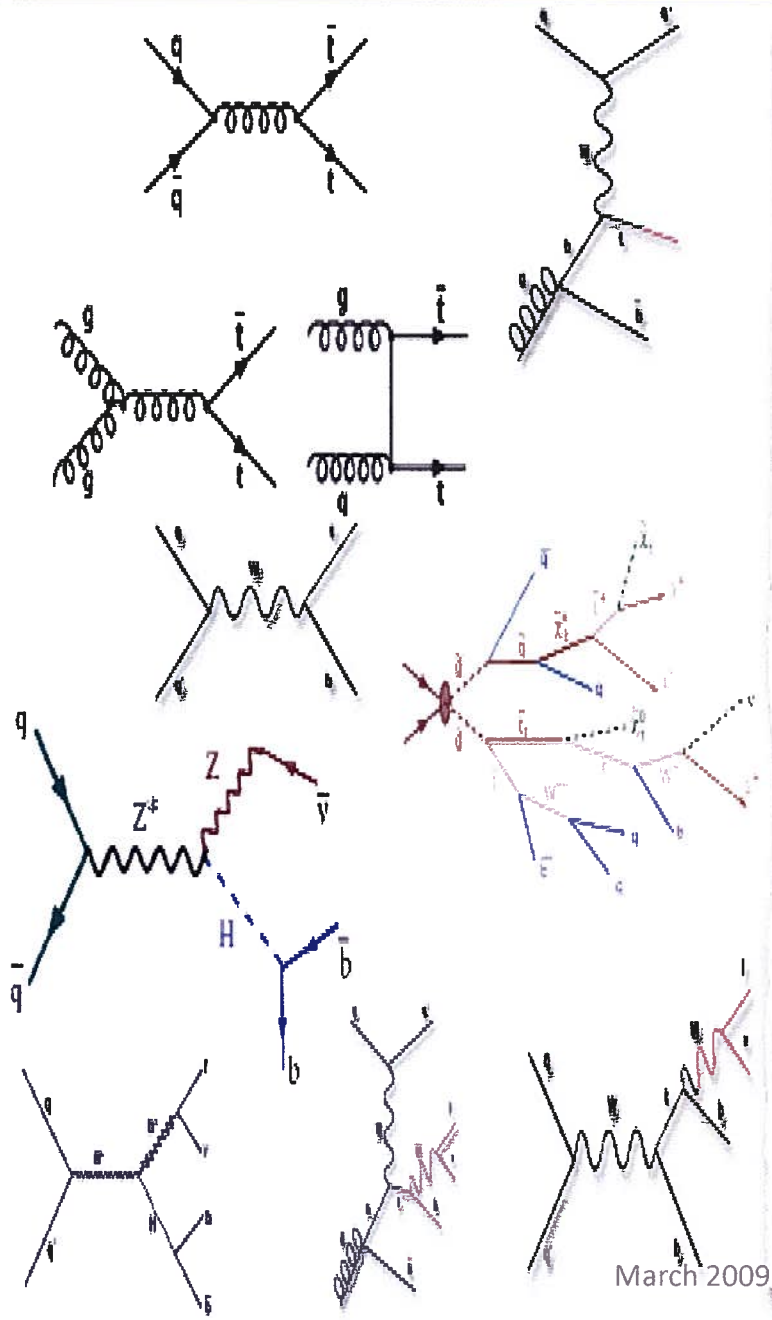
Hadron Colliders

protons are 3-quark baryons + X

hadrons = composite particles:

- mesons = made of a quark and an antiquark
- baryons = made of 3 quarks

We can make a lot of stuff at the Tevatron



"Particles, particles, particles"

Event Rates / fb^{-1}

$\sigma(t\bar{t}) \sim 8\,pb$

$N = L\sigma = 1000\,pb^{-1} * 8\,pb$

$\int L\,dt$

$= 8000$ $t\bar{t}$ events in $1\,fb^{-1}$

$\sigma(W+X) \sim 2\,nb$

$N = 1000 * 10^3 \times 2$

$= 2 \times 10^6$ W's / $1\,fb^{-1}$

for $M_H = 115\,GeV/c^2$

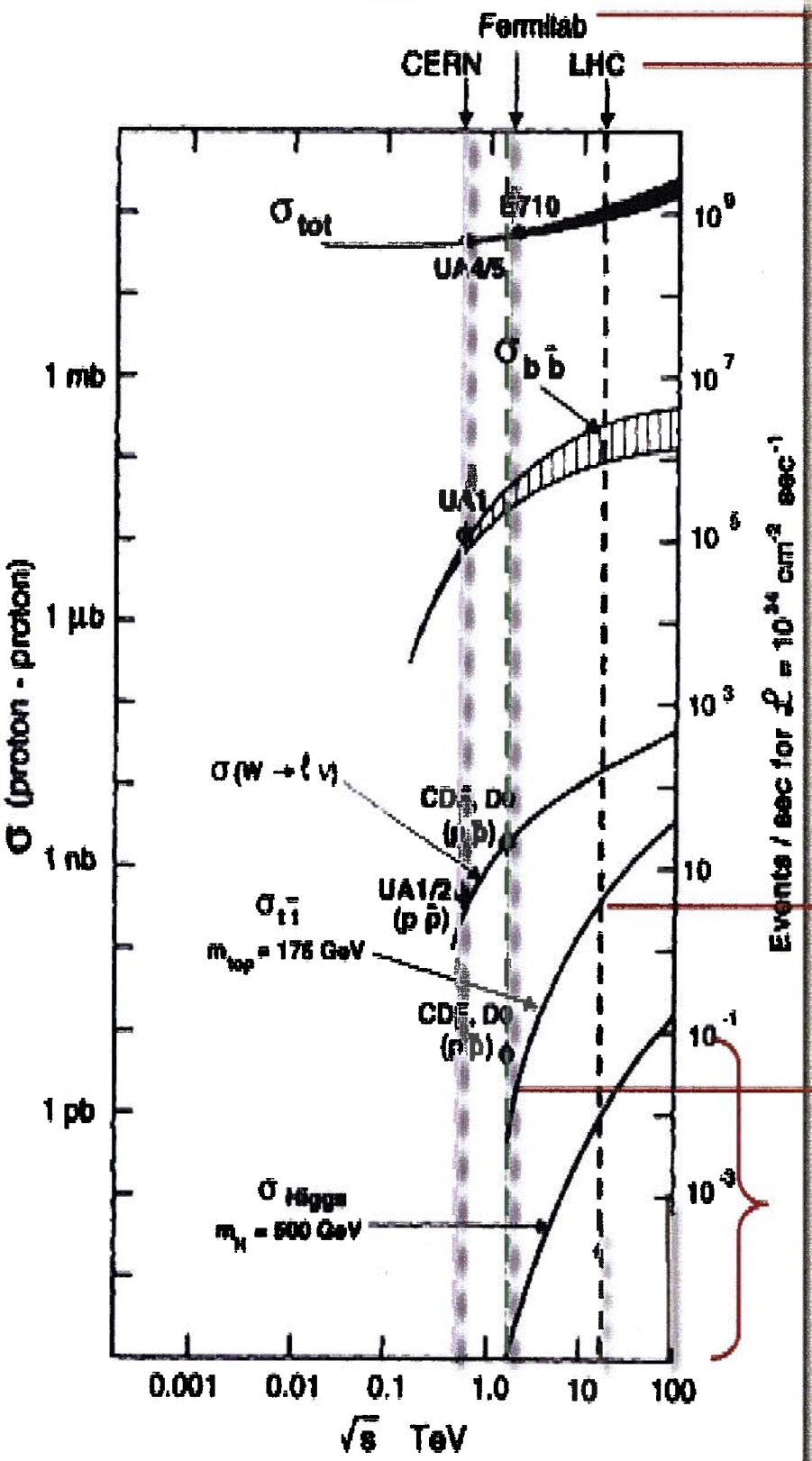
$\sigma_{WH} * BR(WH \to l\nu b\bar{b}) \simeq 50\,fb$

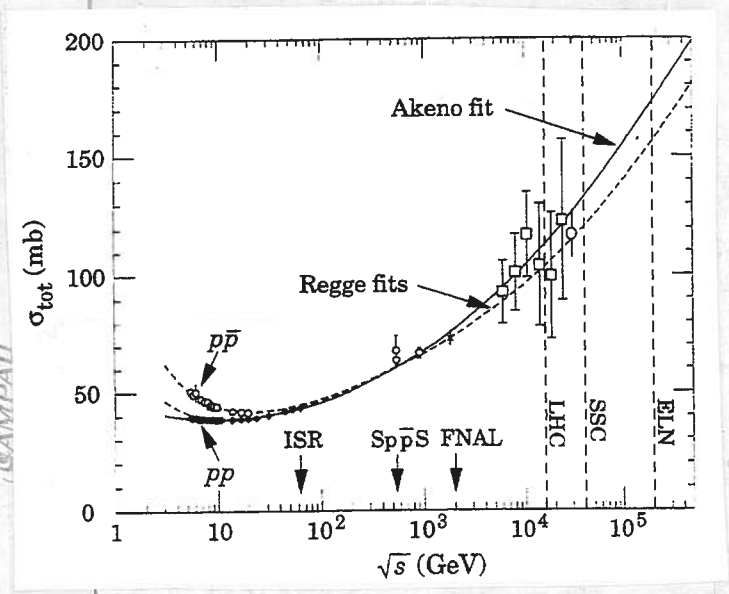
$N = 1\,fb^{-1} * 50\,fb$

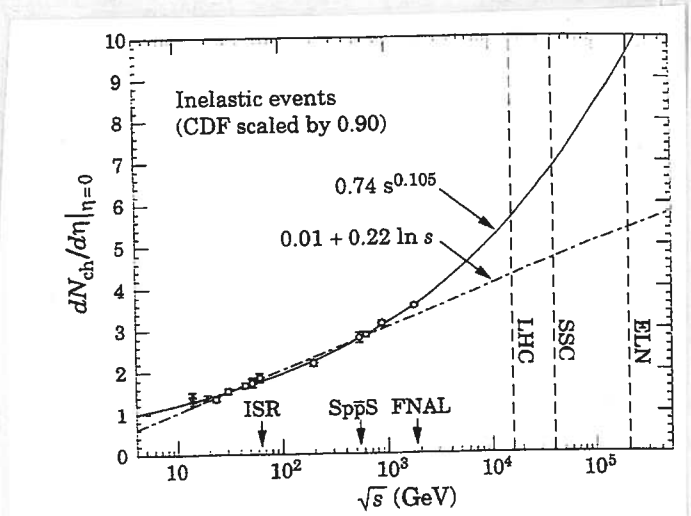
$= 50$ event / fb^{-1}

$\therefore$ we ~~would~~ have 300 such events in our data if $M_H = 115\,GeV/c^2$

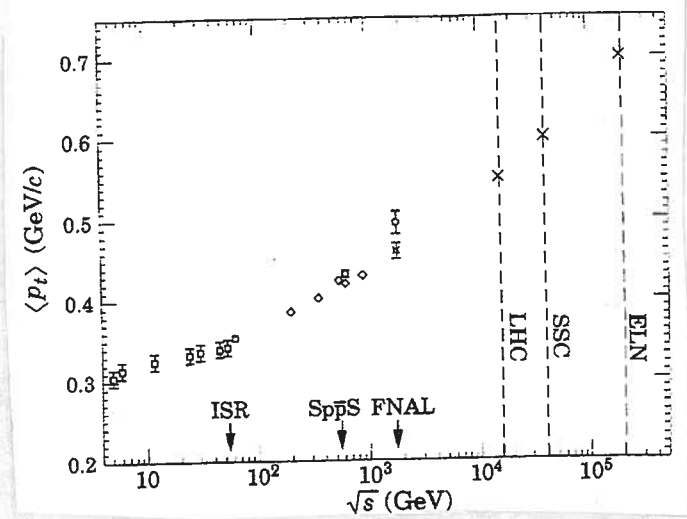
Cross sections vs energy







G. 2. Data and extrapolations of $dN_{ch}/d\eta|_{\eta=0}$.



$$\sigma_{tot} \sim \tfrac{3}{4}\sigma_{inel} + \tfrac{1}{4}\sigma_{el}$$

$$\langle p_t \rangle \simeq 0.44 + .07 \log\sqrt{s}$$

Detector Design

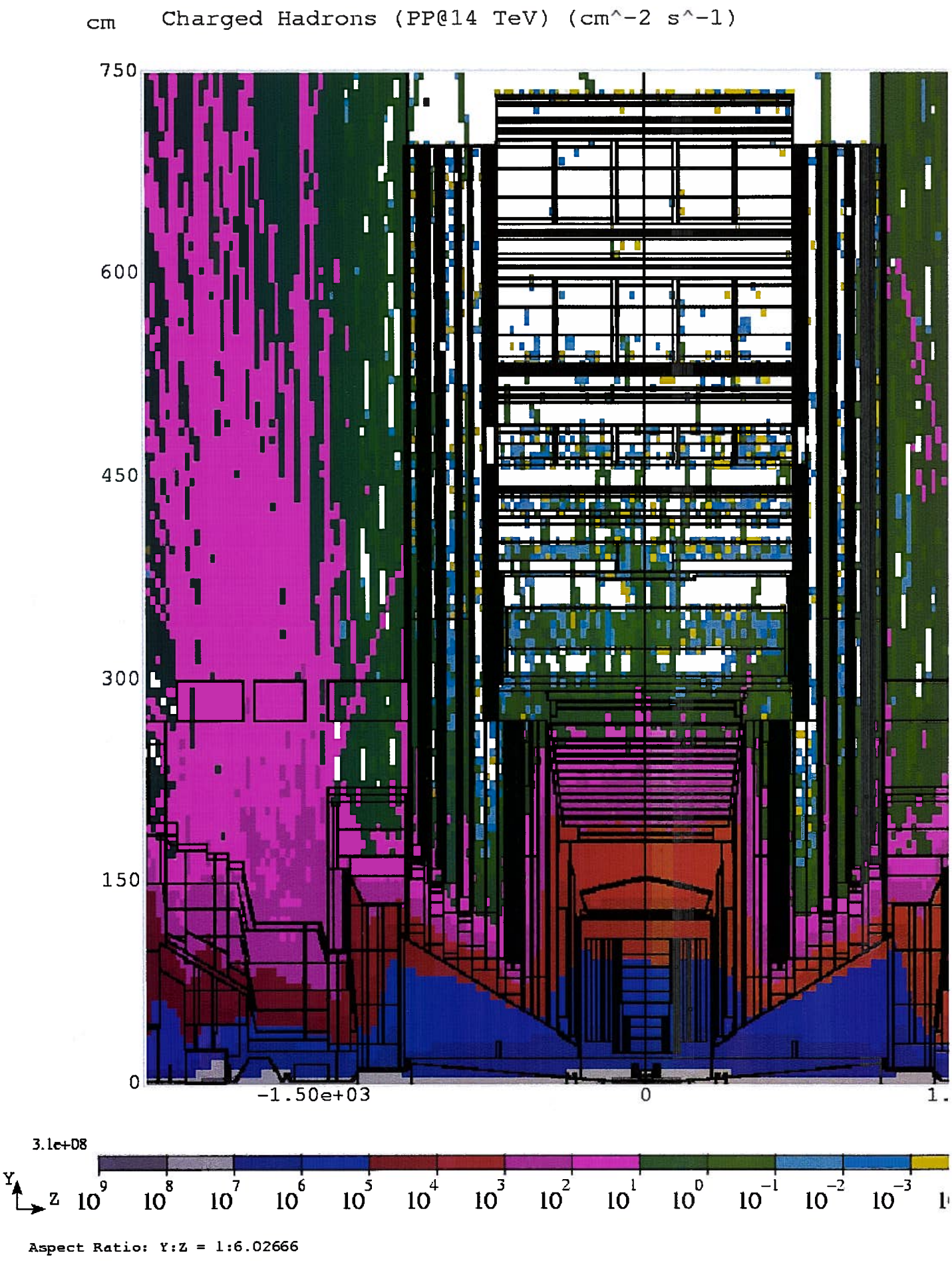
* What particles do we want to measure, identify?
* What momentum/energy ranges?
* What precision for measurements?
* Measure
  - trajectory, charge, momentum, velocity, energy

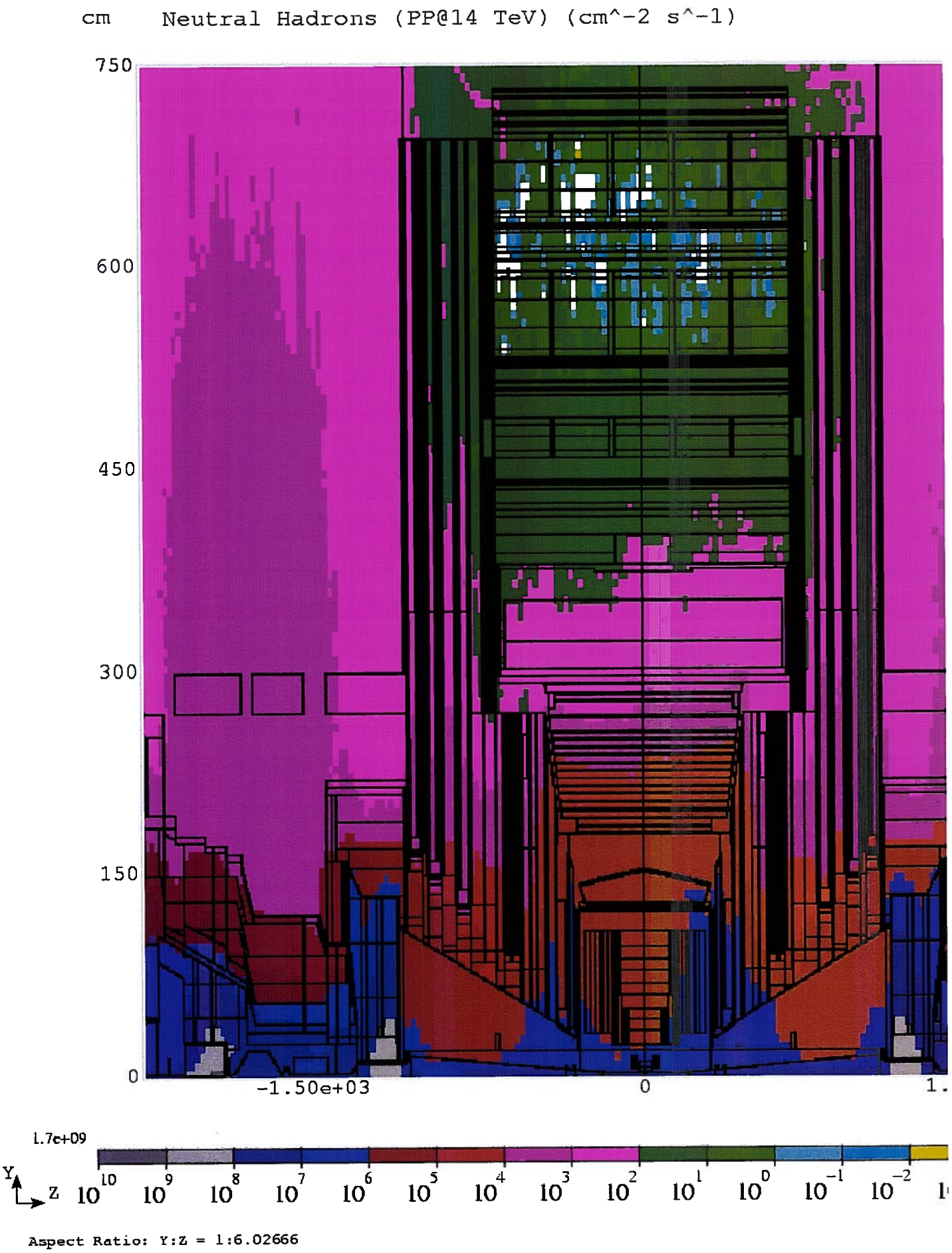
Some basic points –

- Cost of the experiment ~scales with volume, number of electronic channels
- Collider detectors have to be hermetic but easy to dismount/service
- Have as little material as possible in front of the calorimeter but as much as possible in front of the muon chambers
- Design individual detectors (trackers, calorimeter) etc to get required resolution in vertex position, track hit position, momentum, energy, etc.
- Simulation of detector performance!!
- Simulation of radiation environment!

+ Simulation of physics too!

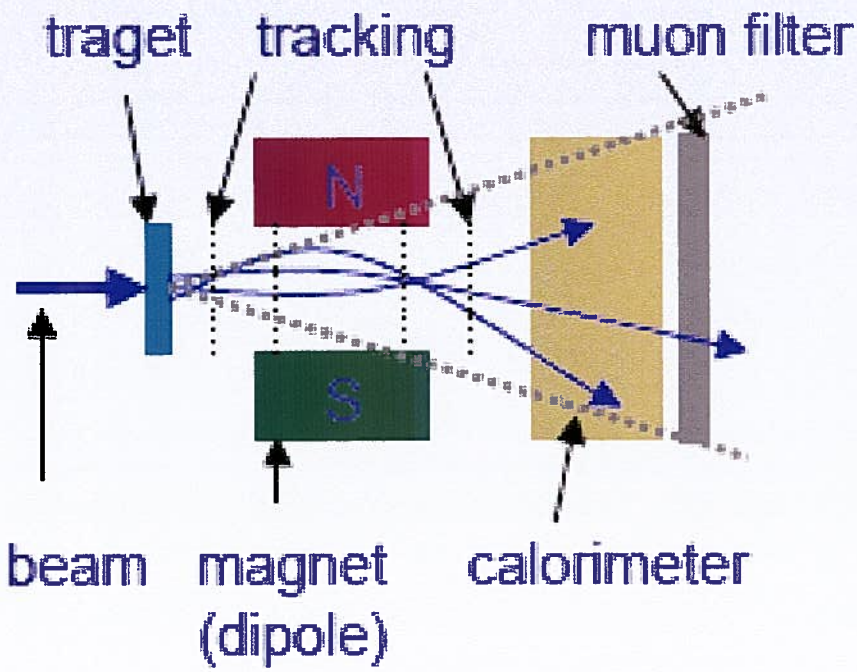
GEANT


cm
Charged Hadrons (PP@14 TeV) (cm^-2 s^-1)
750
600
450
300
150
0
-1.50e+03
0
1.
3.1e+08
Y
Z
10^9 10^8 10^7 10^6 10^5 10^4 10^3 10^2 10^1 10^0 10^-1 10^-2 10^-3
Aspect Ratio: Y:Z = 1:6.02666


cm
Neutral Hadrons (PP@14 TeV) (cm^-2 s^-1)
750
600
450
300
150
0
-1.50e+03
0
1.
1.7e+09
Y
Z
10^10 10^9 10^8 10^7 10^6 10^5 10^4 10^3 10^2 10^1 10^0 10^-1 10^-2
Aspect Ratio: Y:Z = 1:6.02666

Fixed target geometry

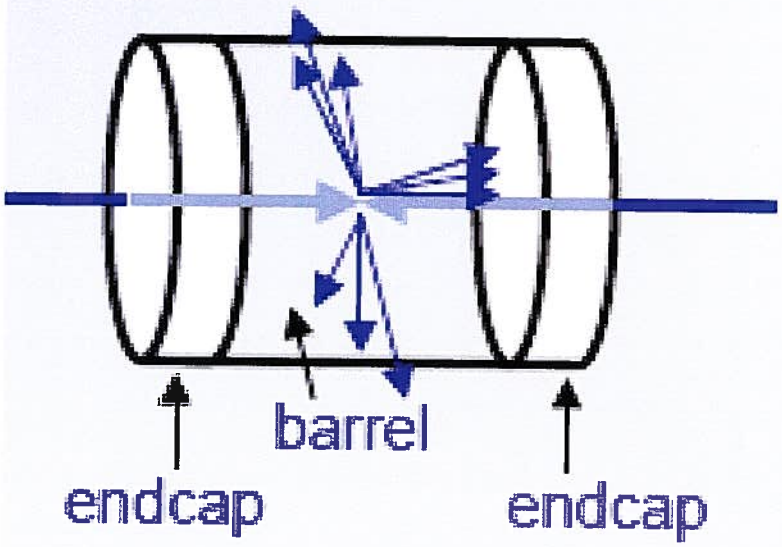
"Magnet spectrometer"



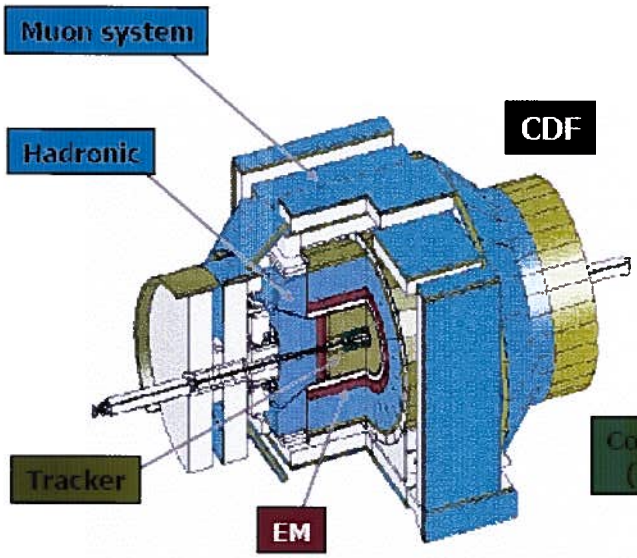
- Limited solid angle dΩ coverage
- rel. easy access (cables, maintenance)

Collider Geometry

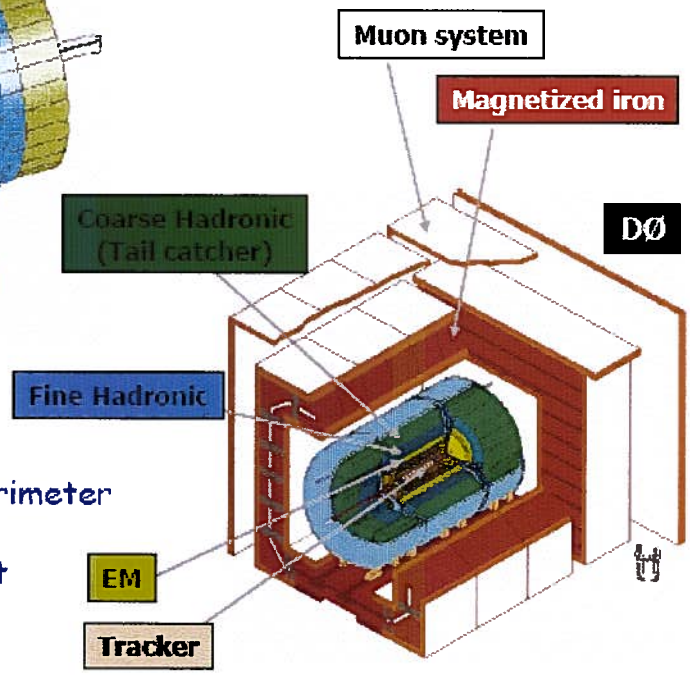
"4π multi purpose detector"



- "full" $d\Omega$ coverage
- very restricted access

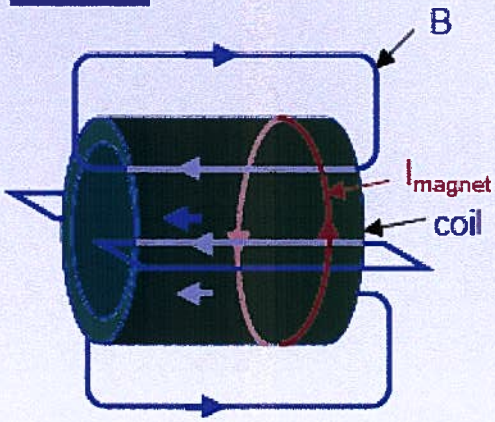


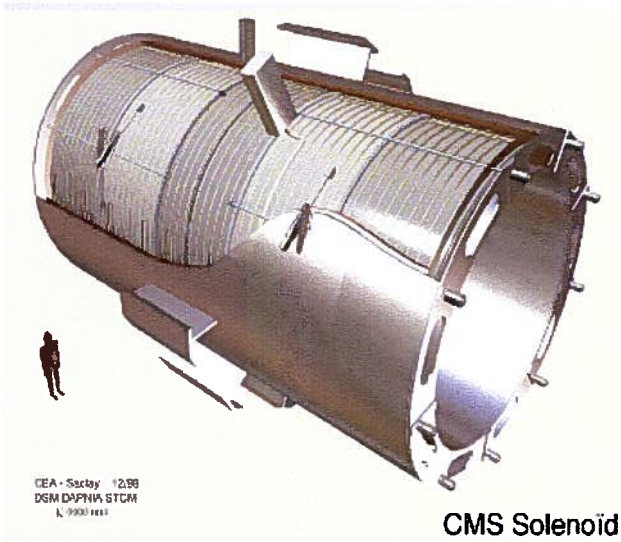
Arrays of sensitive instrumentation
> Million electronic channels each



- "Transparent" central tracking in a magnetic field
- Energy measurement of photons, electrons and hadrons in the calorimeter (most particles absorbed)
- Muons measured in the outermost magnetic spectrometer
- Missing energy (neutrinos) from measuring everything else

solenoid



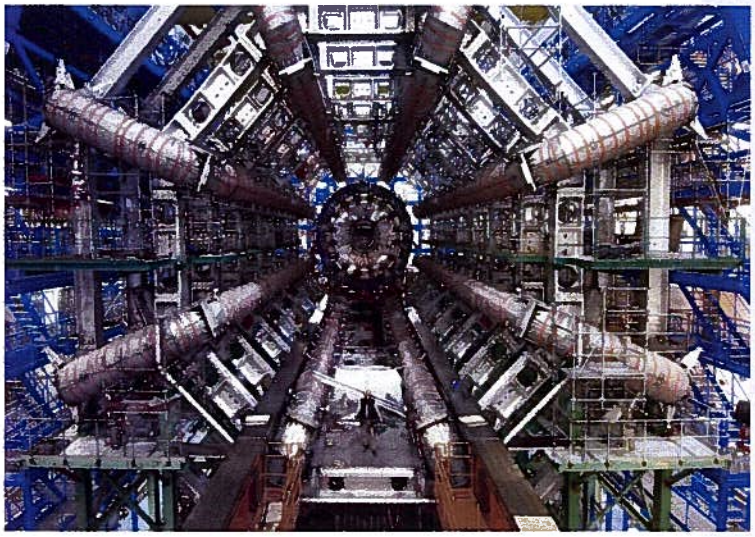


CMS Solenoïd

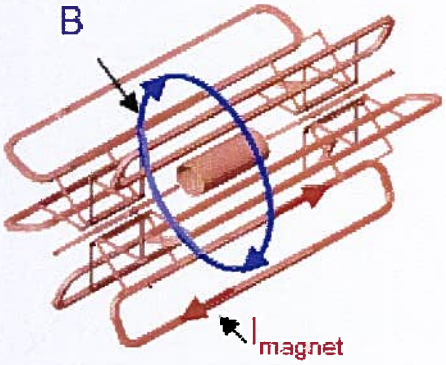
+ Large homogenous field inside coil
- weak opposite field in return yoke
- Size limited (cost)
- rel. high material budget

Examples:

- DELPHI: SC, 1.2T, Ø5.2m, L 7.4m
- L3: NC, 0.5T, Ø11.9m, L 11.9m
- CMS: SC, 4.0T, Ø5.9m, L 12.5m



toroid

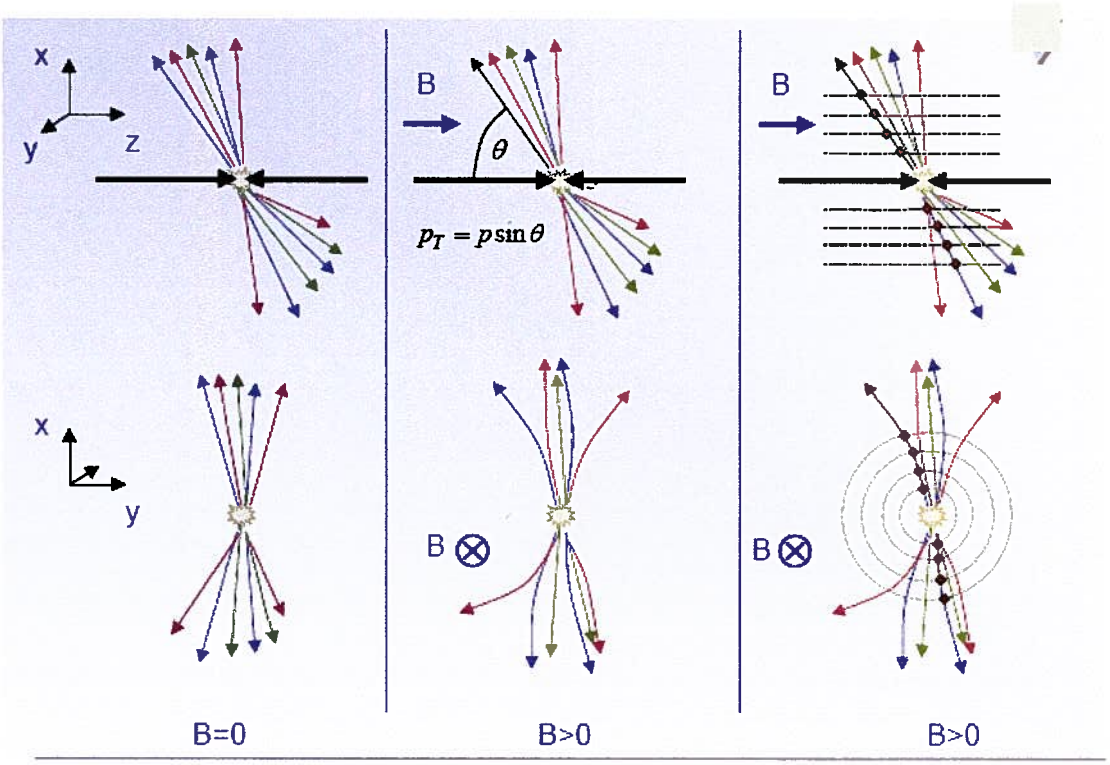


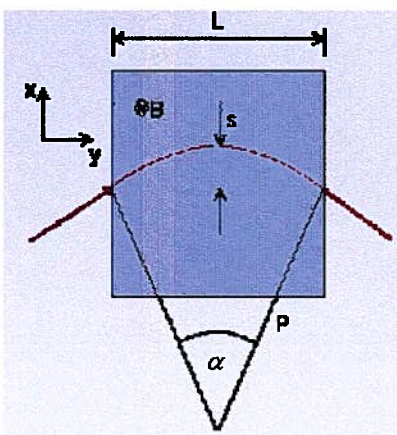
+ Field always perpendicular to $\vec{p}$
+ Rel. large fields over large volume
+ Rel. low material budget
- non-uniform field
- complex structure

Example:

- ATLAS: Barrel air toroid, SC, ~1T, Ø9.4, L 24.3m

Momentum measurement in B field





We measure only p-component transverse to B field !

$$p_T = qB\rho \quad \rightarrow \quad p_T\,(\mathrm{GeV/c}) = 0.3B\rho \quad (\mathrm{T\cdot m})$$

$$\frac{L}{2\rho} = \sin\alpha/2 \approx \alpha/2 \quad \rightarrow \quad \alpha \approx \frac{0.3L\cdot B}{p_T}$$

$$s = \rho(1-\cos\alpha/2) \approx \rho\frac{\alpha^2}{8} \approx \frac{0.3}{8}\frac{L^2B}{p_T}$$

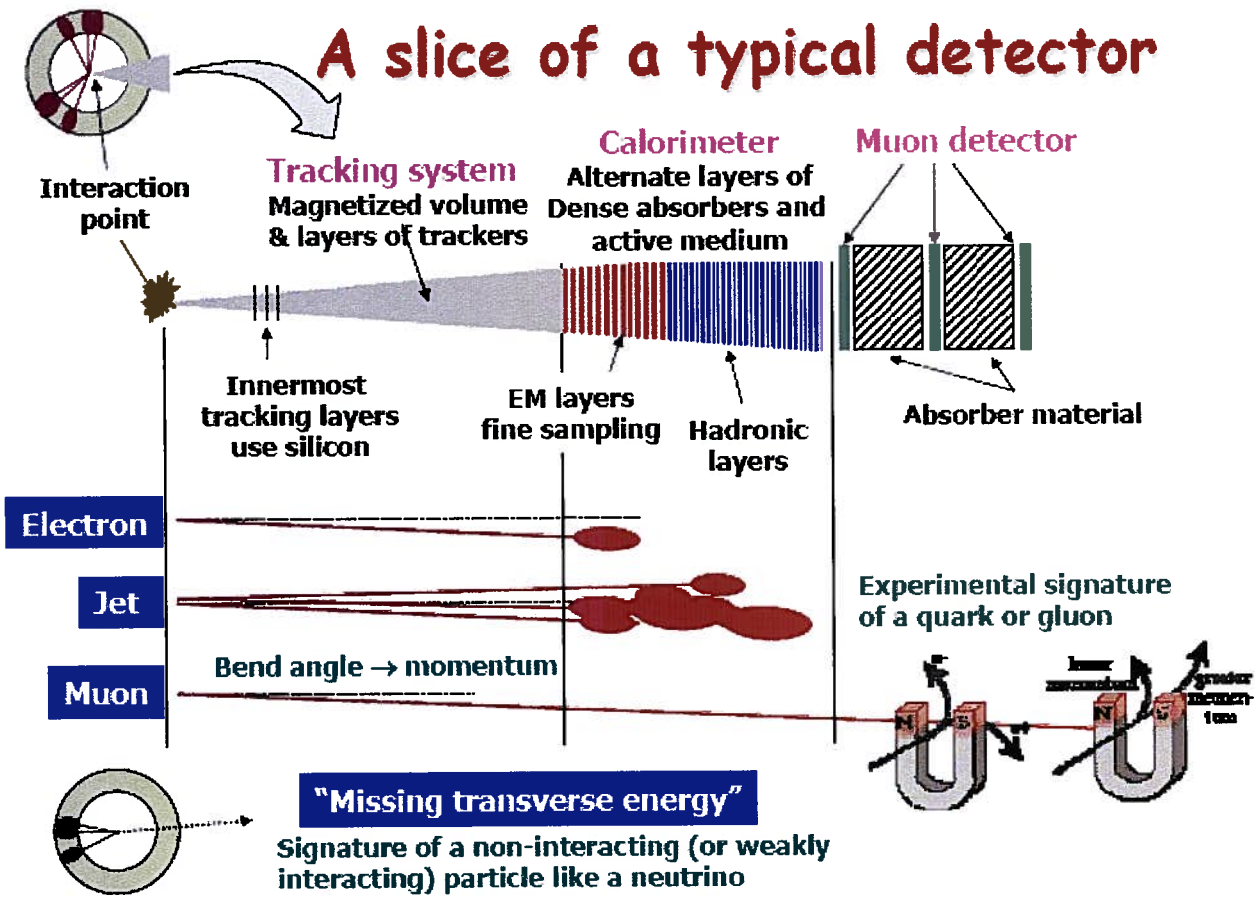
the sagitta s is determined by 3 measurements with error *s(x)*:

$$s = x_2 - \frac{x_1+x_3}{2} \qquad \left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma(s)}{s} = \frac{\sqrt{\frac{3}{2}}\sigma(x)}{s} = \frac{\sqrt{\frac{3}{2}}\sigma(x)\cdot 8p_T}{0.3\cdot BL^2} \qquad \boxed{\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} \propto \frac{\sigma(x)\cdot p_T}{BL^2}}$$

for N equidistant measurements, one obtains (R.L. Gluckstern, NIM 24 (1963) 381)

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma(x)\cdot p_T}{0.3\cdot BL^2}\sqrt{720/(N+4)} \qquad \text{(for N} \geq \sim 10)$$

A slice of a typical detector

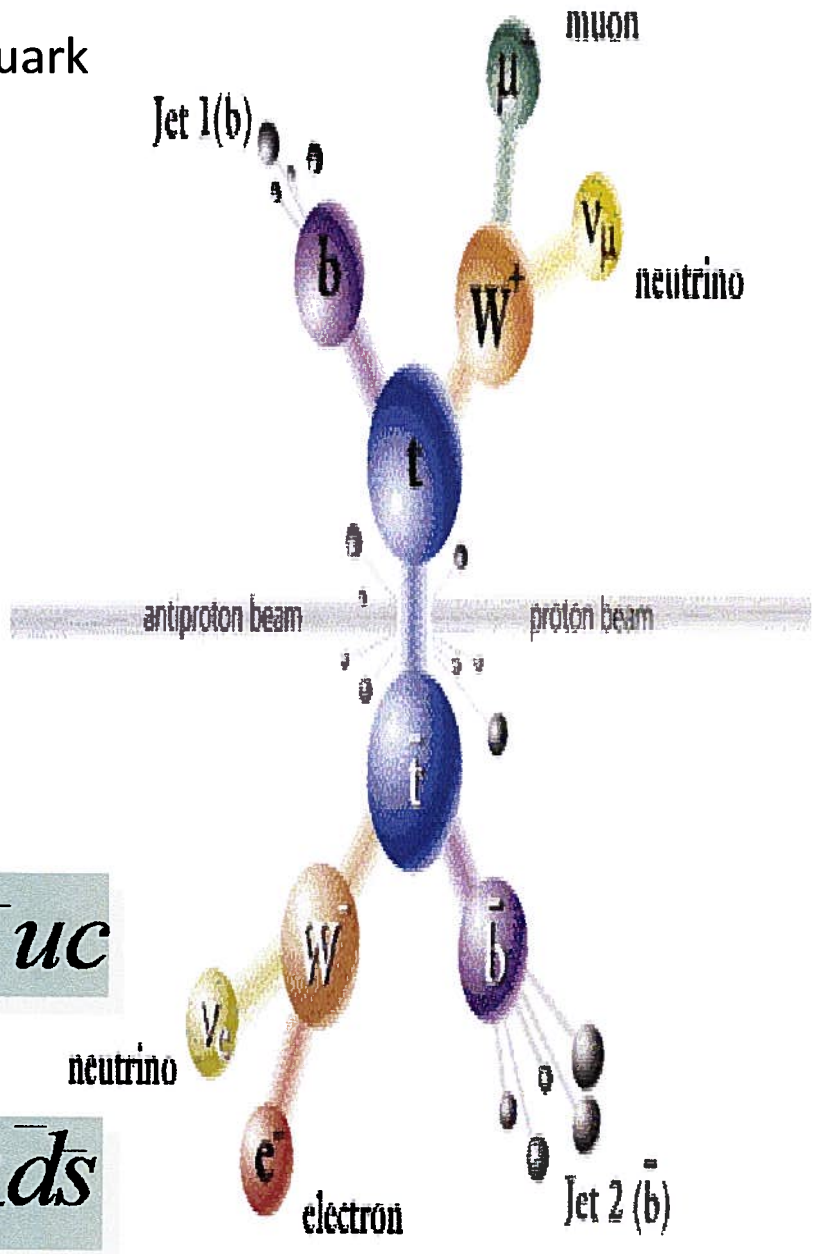


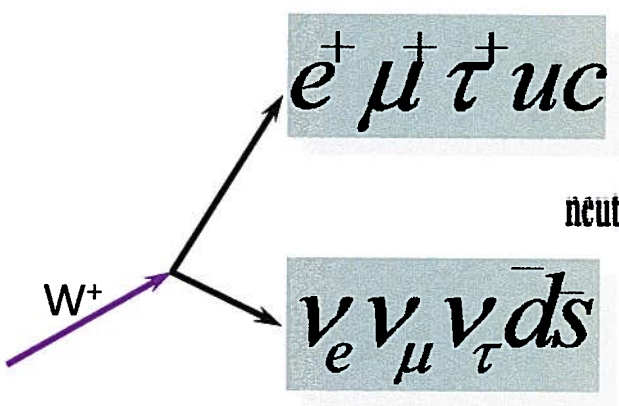
Pushpa Bhat

The Top Quark

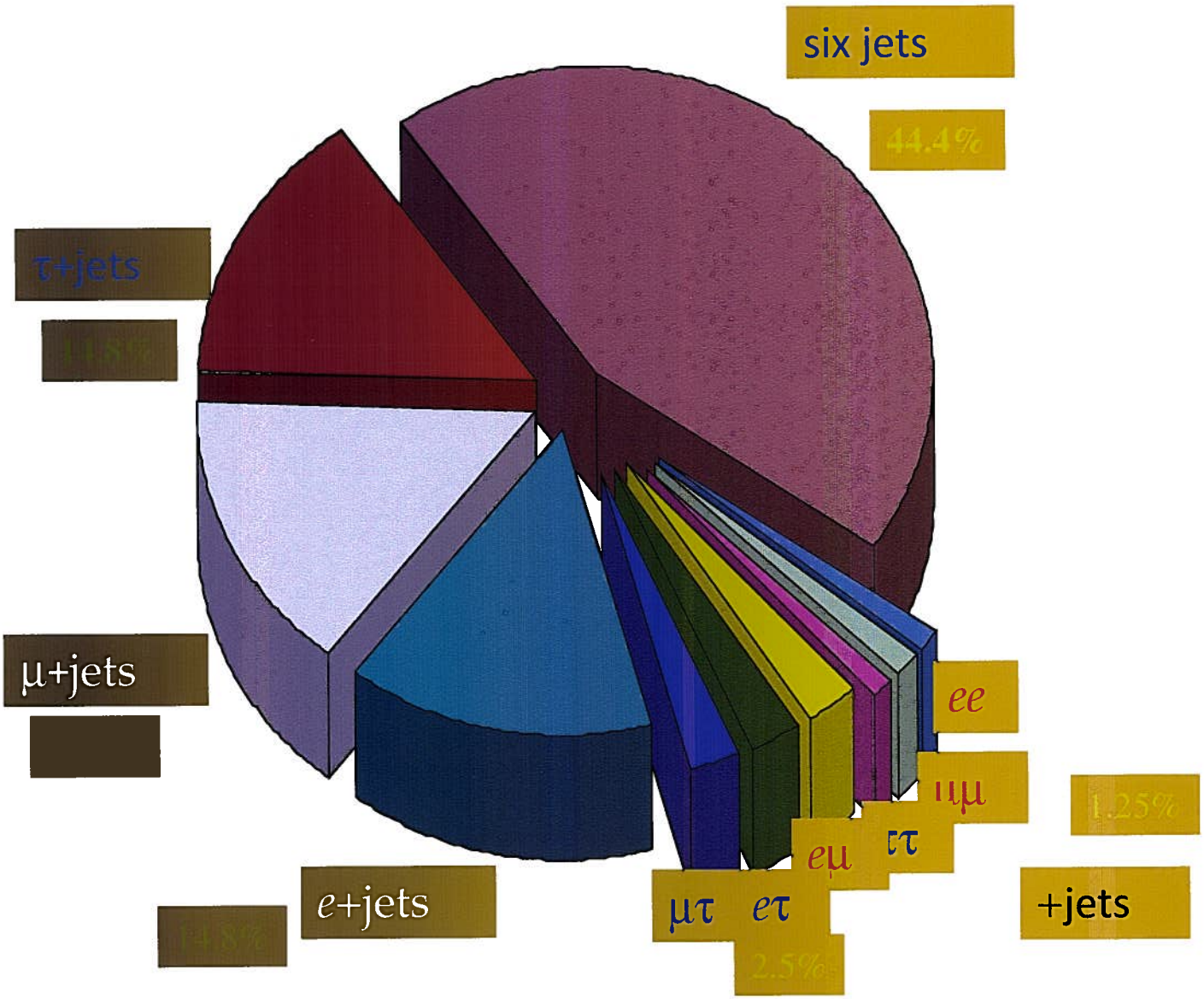
Top decays to a
W boson and a b-quark

Very heavy
(~175 GeV)
Extremely short-lived!
Lifetime ~ 10^{-25} s!

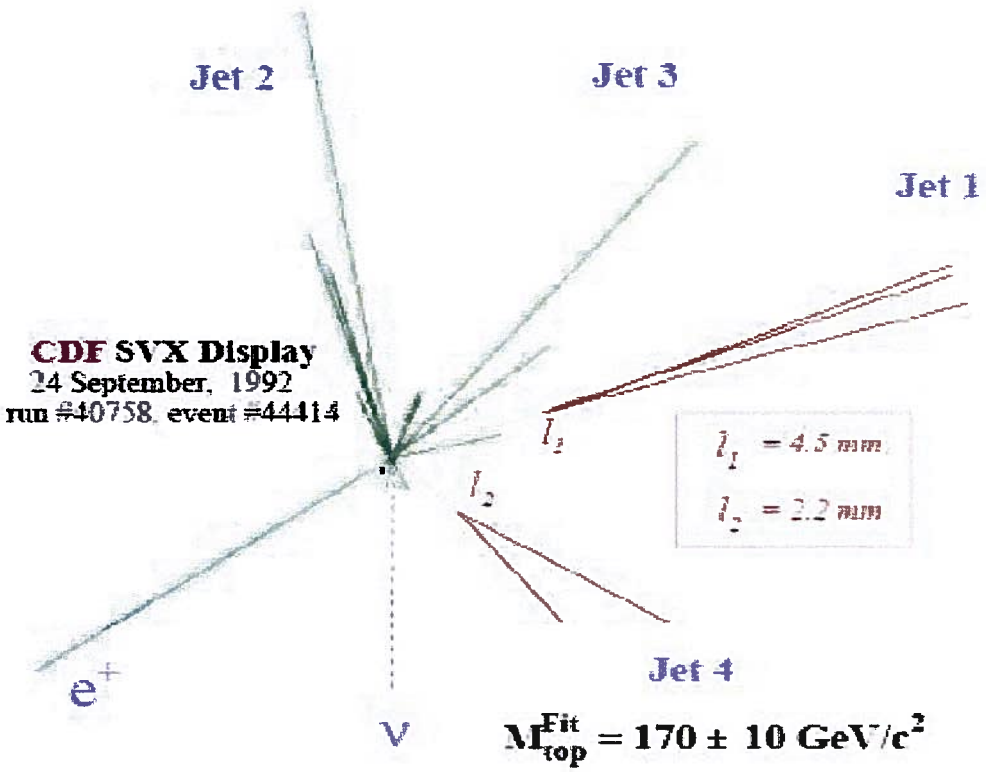




Top Quark Decay Modes



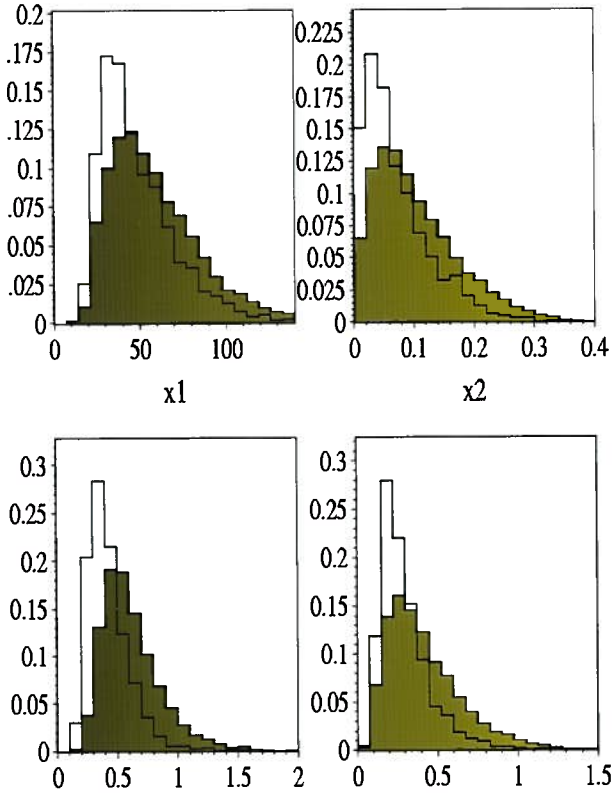
CDF's 1st Top Event... (run 1)



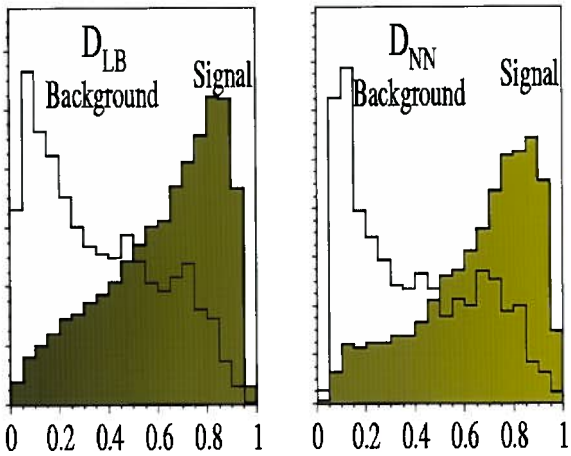
Measuring the Top Quark Mass (1997)

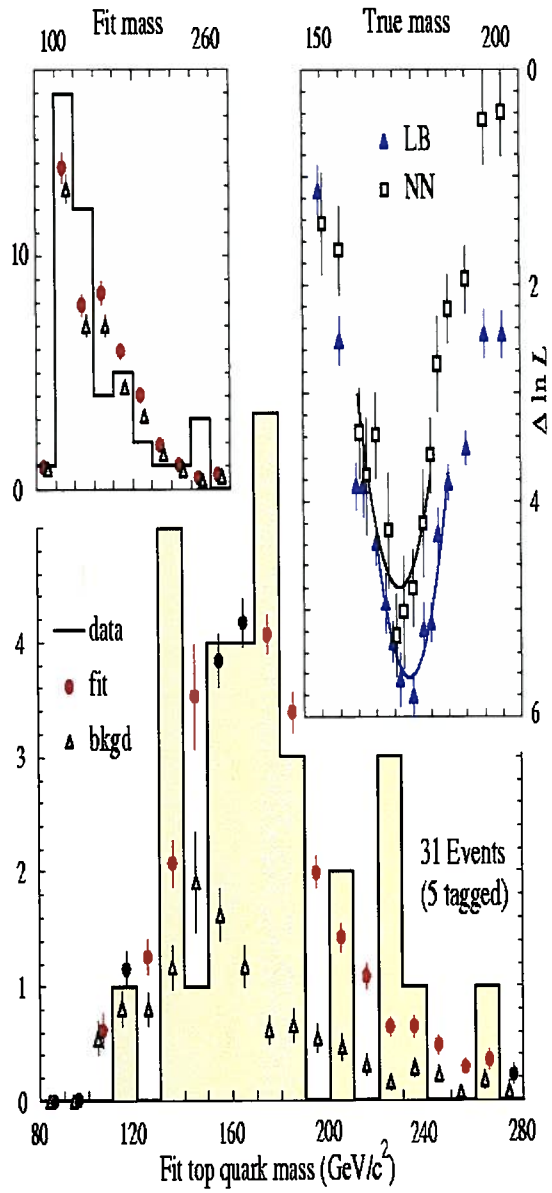
Discriminant variables

DØ Lepton+jets



The Discriminants

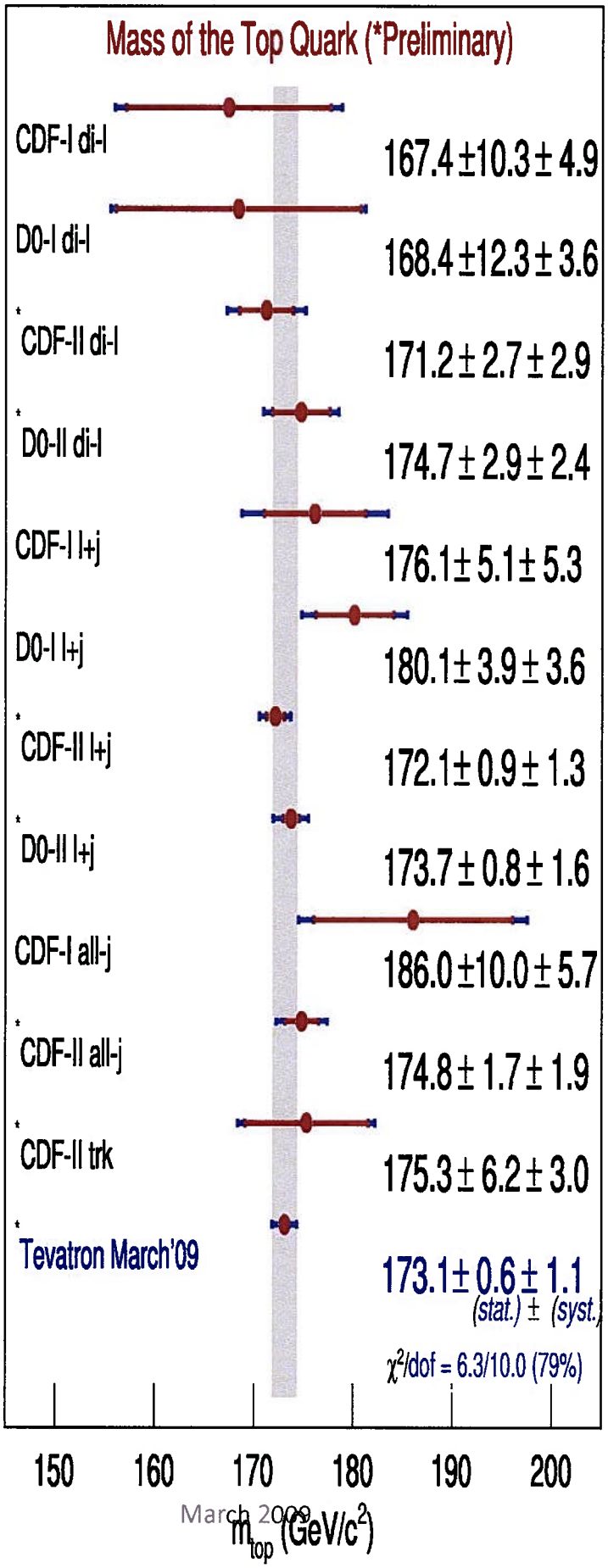




Fit performed in 2-D: ($D_{LB/NN}$, m_{fit})

m_t = 173.3 ± 5.6(stat.) ± 6.2 (syst.) GeV/c²

2009


Mass of the Top Quark (*Preliminary)
CDF-I di-l
167.4±10.3±4.9
D0-I di-l
168.4±12.3±3.6
*CDF-II di-l
171.2±2.7±2.9
*D0-II di-l
174.7±2.9±2.4
CDF-I l+j
176.1±5.1±5.3
D0-I l+j
180.1±3.9±3.6
*CDF-II l+j
172.1±0.9±1.3
*D0-II l+j
173.7±0.8±1.6
CDF-I all-j
186.0±10.0±5.7
*CDF-II all-j
174.8±1.7±1.9
*CDF-II trk
175.3±6.2±3.0
*Tevatron March'09
173.1±0.6±1.1
(stat.) ± (syst.)
χ²/dof = 6.3/10.0 (79%)
150
160
170
180
190
200
m_top (GeV/c²)

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

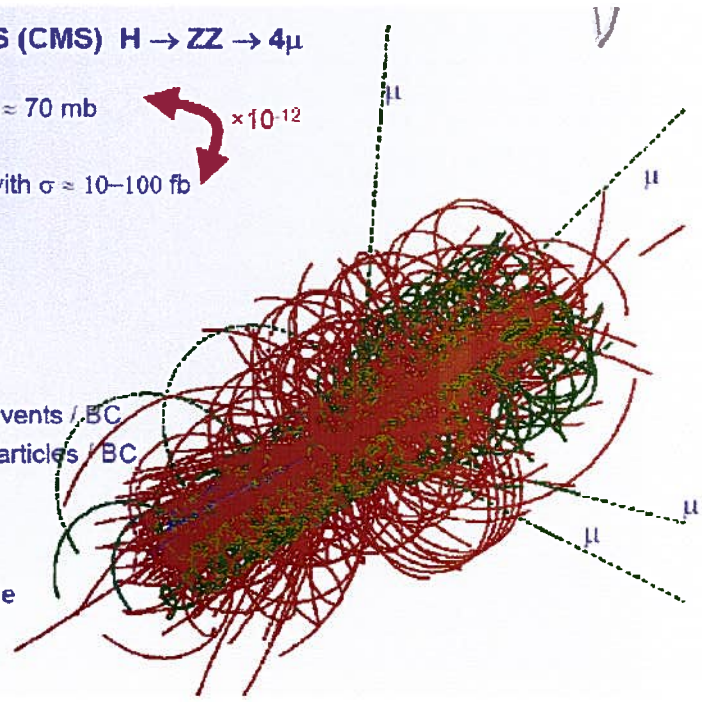
$\times 10^{-12}$

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

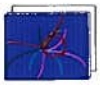
$L = 10^{34}$ cm^{-2} s^{-1},
bunch spacing 25 ns

≈ 23 overlapping minimum bias events / BC
≈ 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} !!!



CMS Experiment



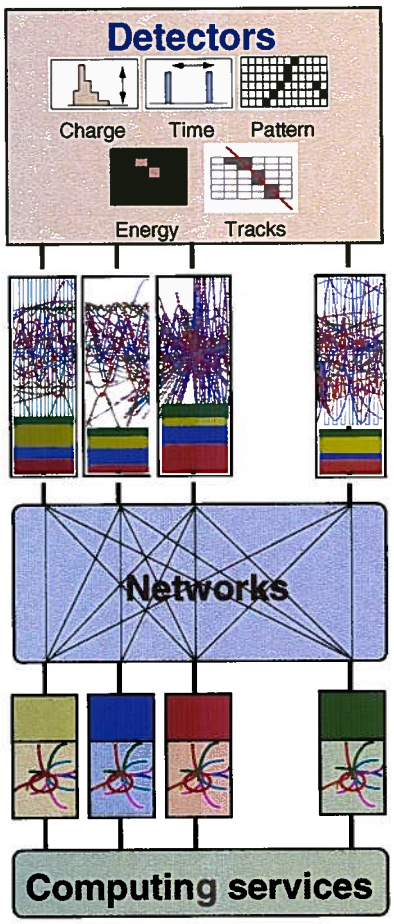
40 MHz
COLLISION RATE

100 kHz
LEVEL-1 TRIGGER

1 Terabit/s
(50000 DATA CHANNELS)

500 Gigabit/s

Gigabit/s SERVICE LAN



16 Million channels
3 Gigacell buffers

1 Megabyte EVENT DATA

200 Gigabyte BUFFERS
500 Readout memories

EVENT BUILDER. A large switching network (512+512 ports) with a total throughput of approximately 500 Gbit/s forms the interconnection between the sources (Readout Dual Port Memory) and the destinations (switch to Farm Interface). The Event Manager collects the status and request of event filters and distributes event building commands (read/clear) to RDPMs

5 TeraIPS

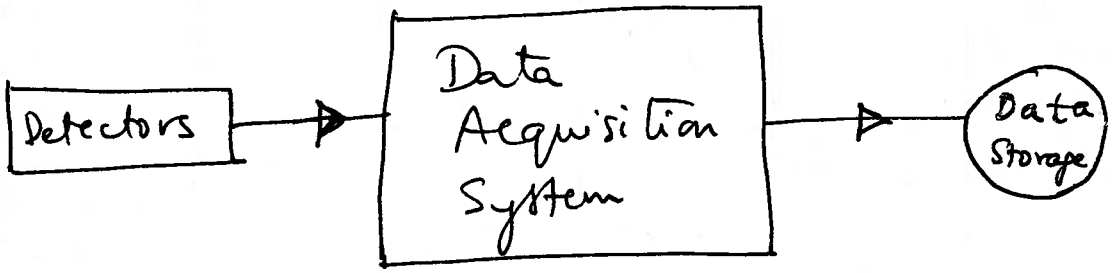
EVENT FILTER. It consists of a set of high performance commercial processors organized into many farms convenient for on-line and off-line applications. The farm architecture is such that a single CPU processes one event

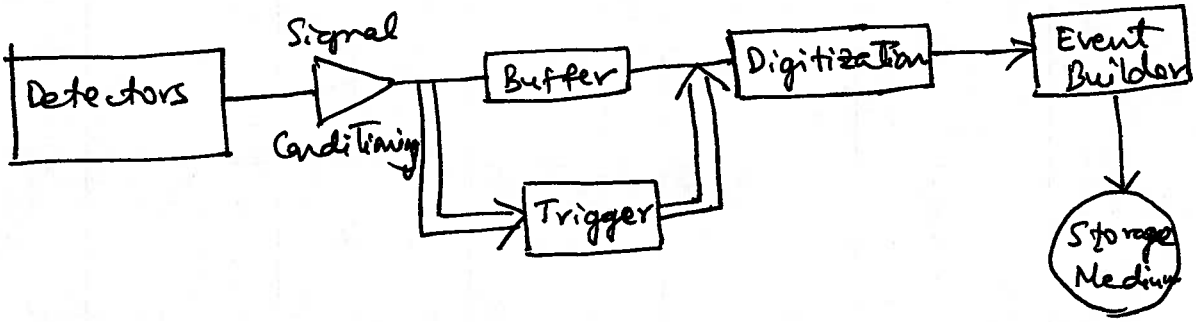
Petabyte ARCHIVE

DAQ Design Criteria and Goals :

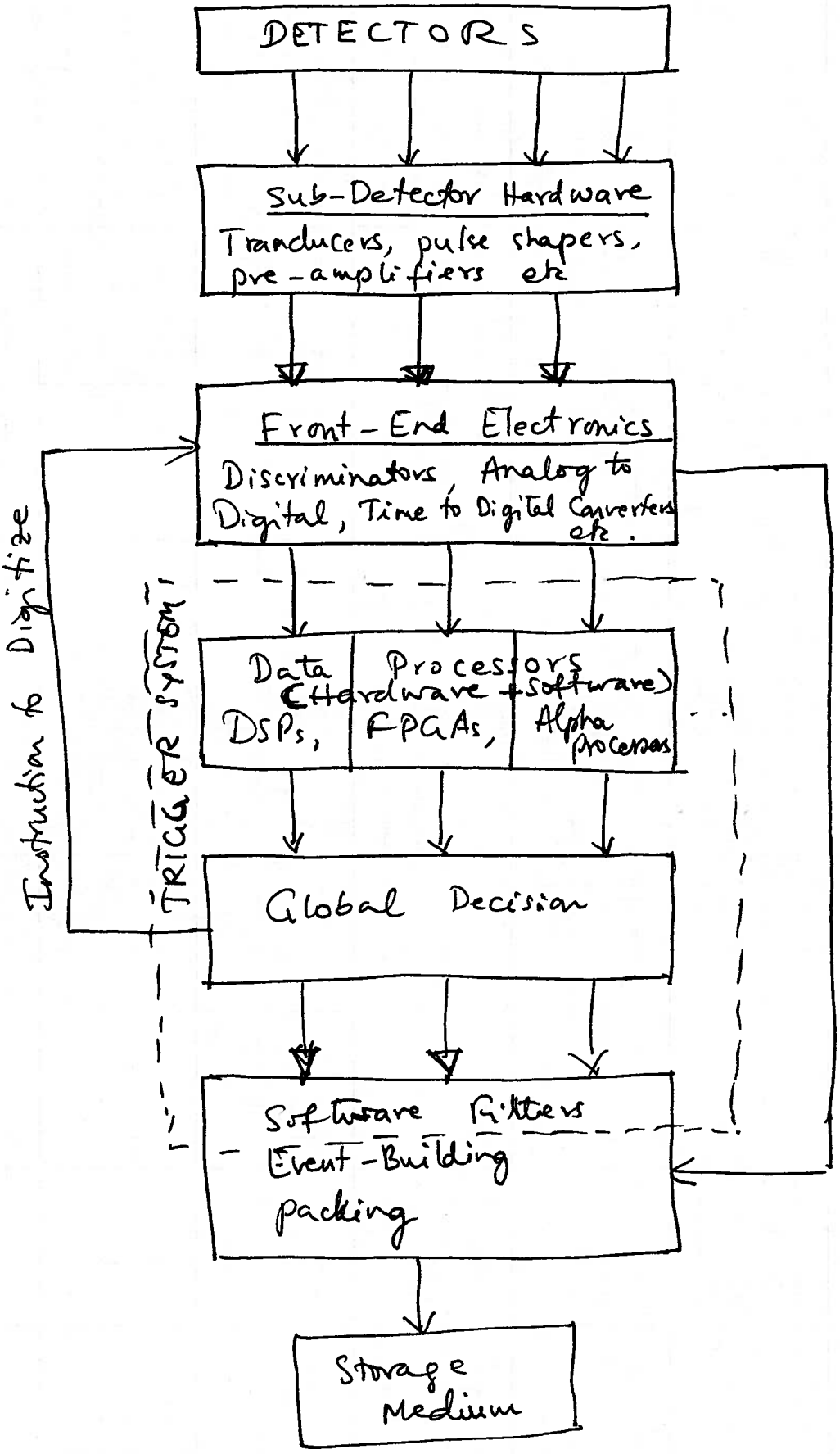
- "Measure" signal adequately to permit reconstruction of events
  - Processing for each element must consider the resolution and dynamic range of the signals
- Minimize dead-time (preferably dead-timeless) and minimize loss of information (preferably no loss)
  - Provide adequate pipelining and buffering
- Provide proper calibration of all detector systems
- Provide adequate monitoring
  - temperatures, pressures, gas purity, ... etc
  - also detector performance (including trigger performance)
- Provide adequate diagnostics and alarms to detect component failure and timely repair
-

Basic components of a DAQ system





Data-Flow Scenario



On-line Data Handling Tasks

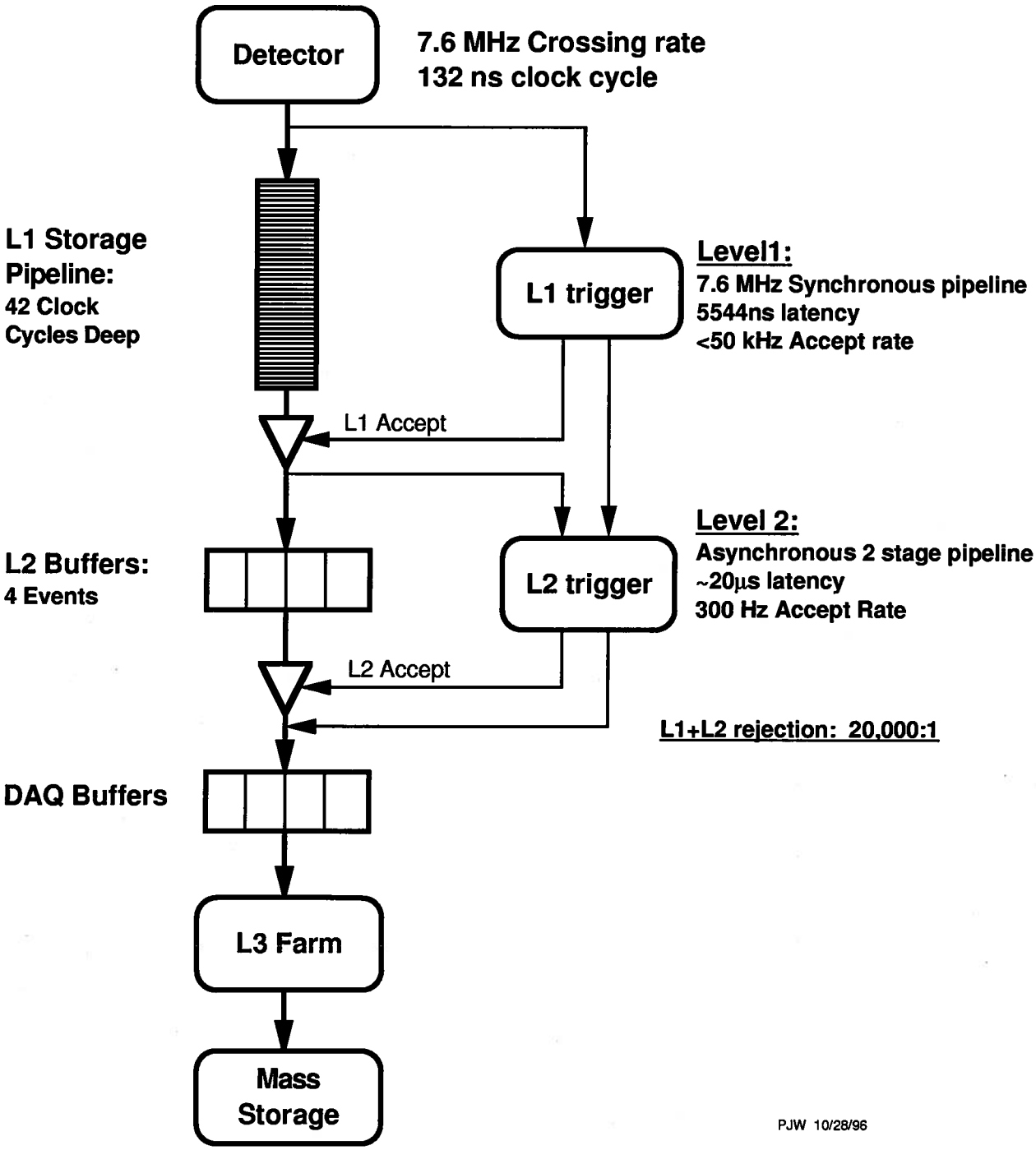
Electronics Engineering → Computer Engineering

- Amplification of signals
- Pulse-shaping / Signal conditioning
- Digitization
  - Measurement of amplitudes of signals from calorimeters, $\frac{dE}{dx}$, ..
  - Measurement of drift times, time of flight ..
- Multiplexing
  - Sharing of electronics or data communication resources (or even computational resources)
  - to be designed as to avoid undesirable deadtime.
- Data Processing / Manipulation
  - Computing derived quantities from measurements
  - making logical decisions & data communication
- Data Sparsification or Compression
  - Read-out only channels with signals (zero-suppression)
  - Packing of data, data reduction
- Data Correction
  - Applying calibration, (off-sets, scaling etc.)
- Data Recording

Triggering / On-line Data Selection

- The goal of a trigger system is to select interesting events with high efficiency for recording and suppress background events.
- Should have capability to handle very high rates
- Carried out by a large, complex array of sophisticated electronics circuits and computers that examine the information flowing in and decide whether an event is worthy of further consideration.
- Usually multi-level, hierarchical triggers. At each level, "go" or "no-go" decision is made to proceed to additional, more sophisticated processing of information at next level.
- A properly designed trigger system, will allow all (or most) of the interesting events (signals of rare events and new phenomena) to survive the highest level trigger and be permanently recorded for offline analysis.
- The number of events from input to output is reduced by several orders of magnitude.

Dataflow of CDF "Deadtimeless" Trigger and DAQ



PJW 10/28/96

Real-Time Data Handling and Data Acquisition

- Once upon a time, data was recorded off-line!
  Data acquisition could wait for days, months or years!
  - Expose nuclear emulsions to particle beams
  - Take bubble chamber photographs of interactions

  → Then scan "off-line" and record data.

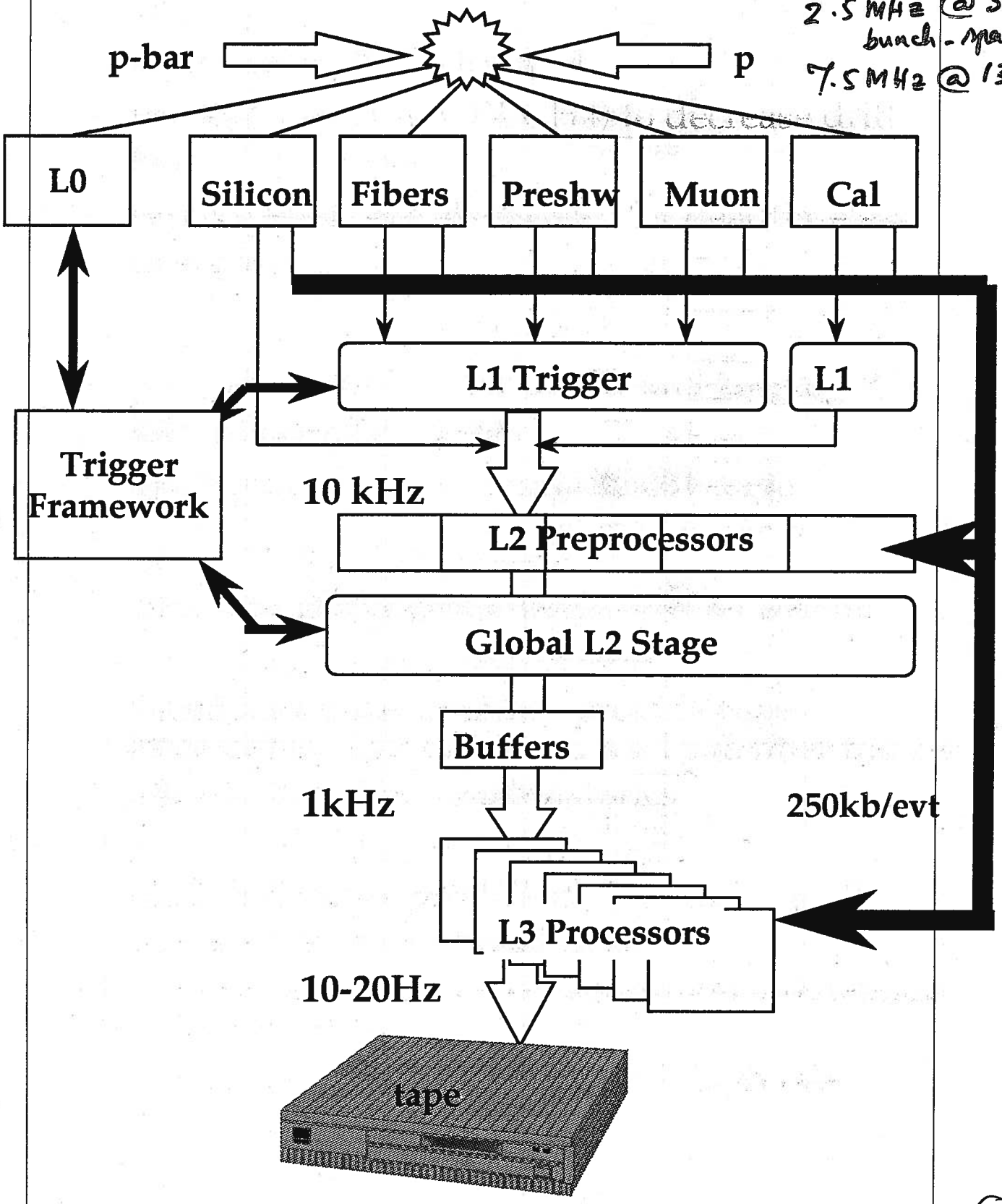
- In the not-so-distant past, we wrote data to storage media based on simple interaction criteria
  - Then we organized, reduced and analyzed data completely off-line.

- Today, not only do we need to record data on-line, but, data analysis has to start when a high energy event occurs.

  The electronic data from the detectors has to be transformed into useful "physics" information in real-time, reduce the data volume by several orders of magnitude and record interesting events for offline analysis

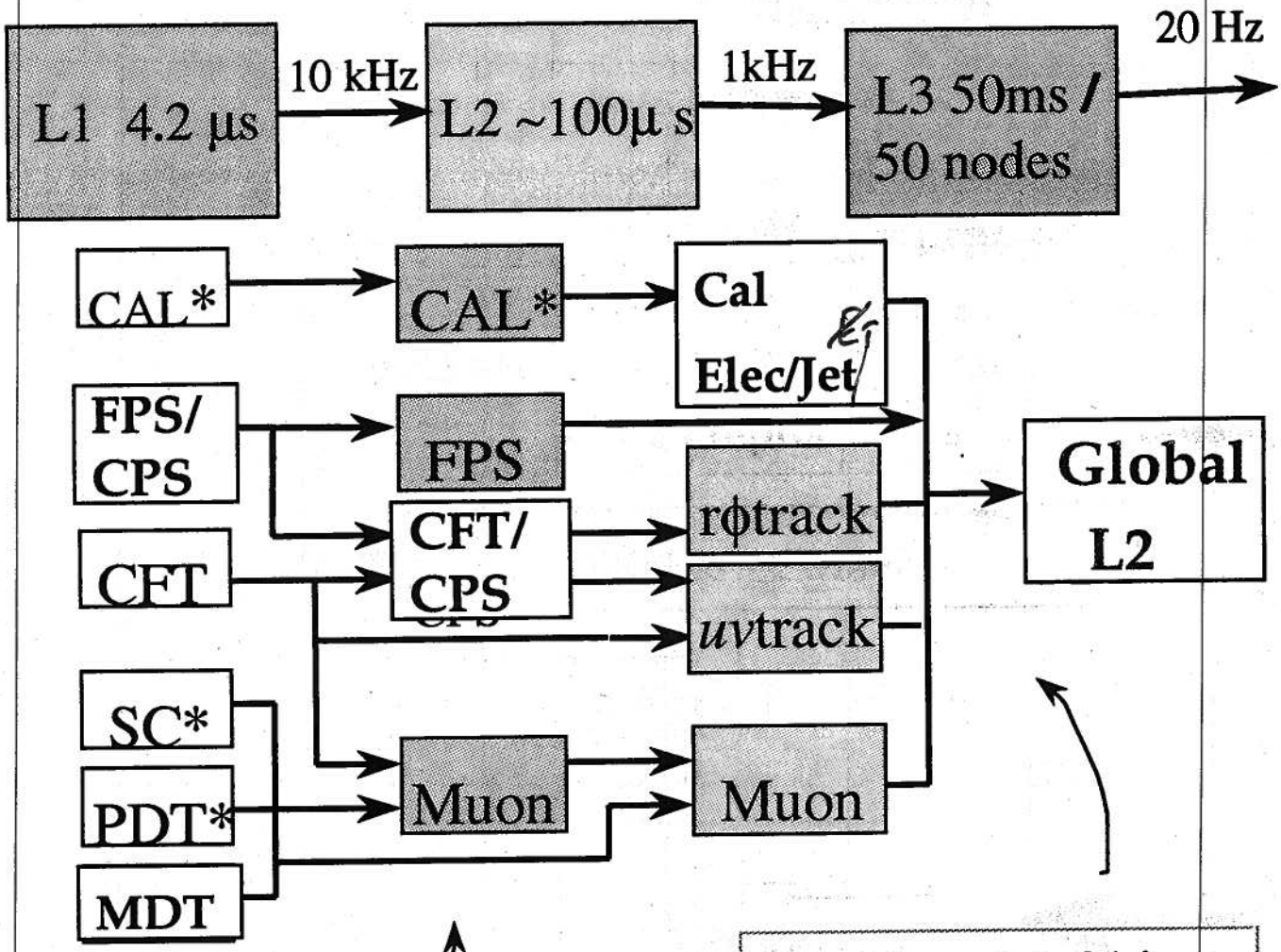
Trigger Architecture

Collision Rate:
2.5 MHz @ 396 ns
bunch-spacing
7.5 MHz @ 132 ns



L1/L2 Trigger Elements

- Trigger: reduce inelastic trig rate by 10^6
- Maintain Run I eff., accept. for high p_t e,μ,jet

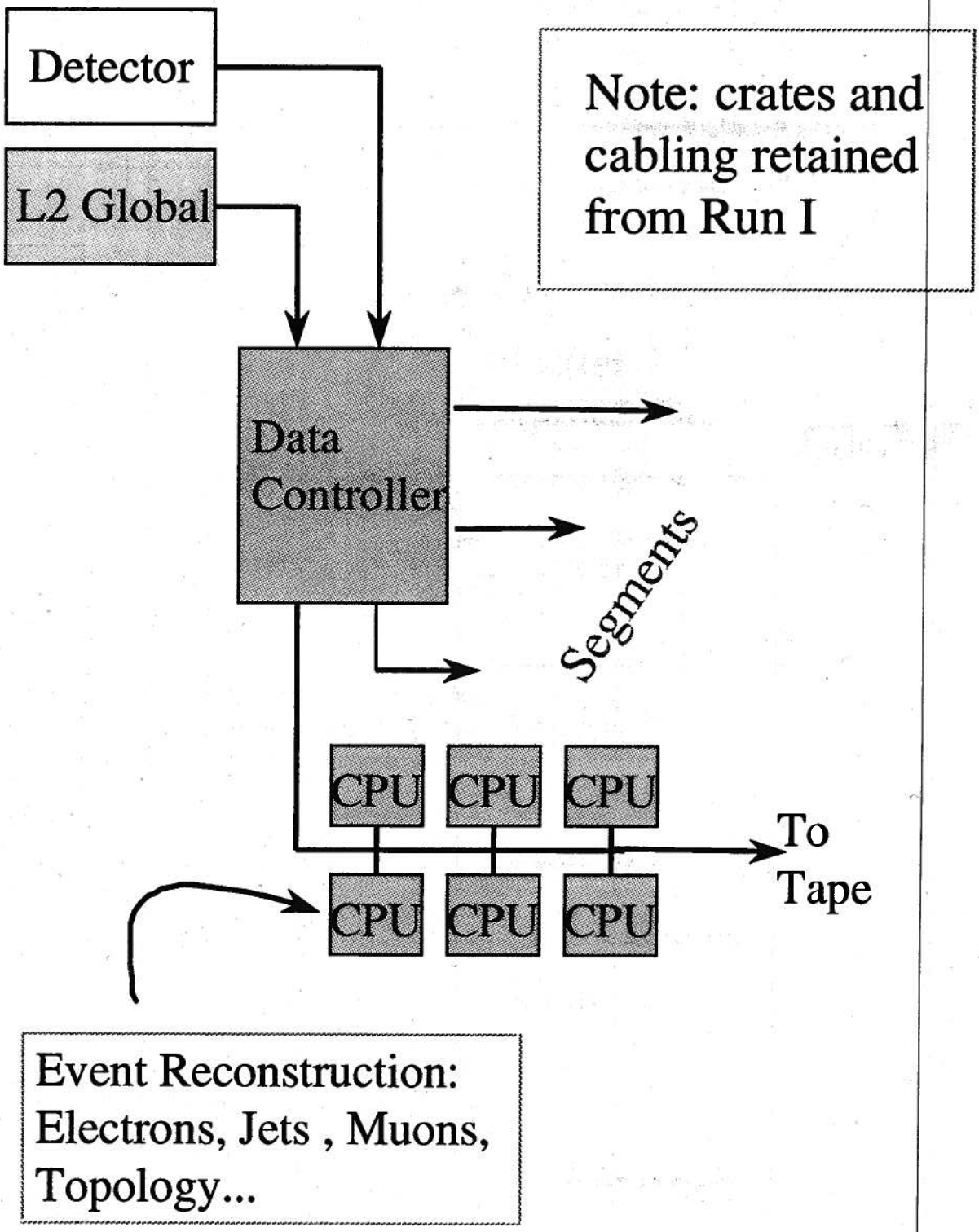


Combines L1 Objects into electrons, muons jets, ...

Looks for E_T, tracks consistent with electrons muons, jets

* Retained from Run I

L3 Farm


Detector
L2 Global
Note: crates and cabling retained from Run I
Data Controller
Segments
CPU
CPU
CPU
CPU
CPU
CPU
To Tape
Event Reconstruction: Electrons, Jets , Muons, Topology...

Triggers can be set on any measured or computed quantity.

Trigger on:

- event vertex
- inelastic interactions
- secondary vertices
- heavy ionization
- charged particle multiplicity
- various particle types (presence of)
  - electrons, muons, taus, jets, ν ($\not{E}_T$)
- momenta of particles
  - high p_T leptons
- large missing energy
- Combination of the above
- any derived / computed quantity in the trigger system (say invariant mass)

On-line Computing System

Responsible for tasks such as configuration, calibration, monitoring, diagnostics for DAQ and front-end and trigger electronics.

Run-Control is an important sub-system

- Primary user-interface to the DAQ system
  - starting and stopping runs, viewing the system
- Initialization of all front-end and trigger hardware
- Configuration of the DAQ system
- Automatic start-up of event monitor tasks
  → Examines
- Procedures to perform calibration
- Monitoring of system performance
- Reporting of errors and recovery action if feasible.