Particle Physics Experiments

Outline:

- particle physics is high energy physics
- accelerators
- detectors
- triggers, data recording
- analysis
- interpretation

- Webpages of interest
  - http://www-d0.fnal.gov (Fermilab homepage)
  - http://sg1.hep.fsu.edu/~wahl/Quarknet/index.html (has links to many particle physics sites)
  - http://www.fnal.gov/pub/tour.html (Fermilab particle physics tour)
  - http://ParticleAdventure.org/ (Lawrence Berkeley Lab.)
  - http://www.cern.ch (CERN -- European Laboratory for Particle Physics)

Experimental particle physics

- particle physics or high energy physics
  - is looking for the *smallest constituents of matter* (the "ultimate building blocks") and for the *fundamental forces* between them;
  - aim is to find *description in terms of the smallest number of particles and forces* ("interactions")
  - at given length scale, it is useful to describe matter in terms of specific set of constituents which can be treated as *fundamental*; at shorter length scale, these fundamental constituents may turn out to consist of smaller parts (be "*composite*").
    - in 19th century, atoms were considered smallest building blocks,
    - early 20th century research: electrons, protons, neutrons;
    - now evidence that nucleons have substructure - quarks;
    - going down the size ladder: atoms -- nuclei -- nucleons -- quarks -- preons ???... ???

Particle physics experiments

- Particle physics experiments:
  - ✻ collide particles to
    - produce new particles
    - reveal their internal structure and laws of their interactions by observing regularities, measuring cross sections,...
  - ✻ colliding particles need to have high energy
    - to make objects of large mass
    - to resolve structure at small distances
  - ✻ to study structure of small objects:
    - need probe with short wavelength: use particles with high momentum to get short wavelength
    - remember de Broglie wavelength of a particle $\lambda = h/p$
  - ✻ in particle physics, mass-energy equivalence plays an important role; in collisions, *kinetic energy converted into mass energy;*
    - relation between kinetic energy K, total energy E and momentum p :

$$E = K + mc^2 = \sqrt{(pc)^2 + (mc^2)c^2}$$

About Units

- Energy - *electron-volt*
  - ✻ 1 electron-volt = kinetic energy of an electron when moving through potential difference of 1 Volt;
    - 1 eV = 1.6×10^{-19} Joules = 2.1×10^{-6} W•s
    - 1 kW•hr = 3.6×10^{6} Joules = 2.25×10^{25} eV

- mass - *eV/c^2*
    - 1 eV/c^2 = 1.78×10^{-36} kg
    - electron mass = 0.511 MeV/c^2
    - proton mass = 938 MeV/c^2
    - professor's mass (80 kg) $\approx$ 4.5×10^{37} eV/c^2

- momentum - *eV/c*:
    - 1 eV/c = 5.3×10^{-28} kg m/s
    - momentum of baseball at 80 mi/hr $\approx$ 5.29 kgm/s $\approx$ 9.9×10^{27} eV/c

How to do a particle physics experiment

- Outline of experiment:
  - get particles (e.g. protons, antiprotons,…)
  - accelerate them
  - throw them against each other
  - observe and record what happens
  - analyse and interpret the data
- ingredients needed:
  - particle source
  - accelerator and aiming device
  - detector
  - trigger (decide what to record)
  - recording device
  - many people to:
    - design, build, test, operate accelerator
    - design, build, test, calibrate, operate, and understand detector
    - analyse data
  - lots of money to pay for all of this

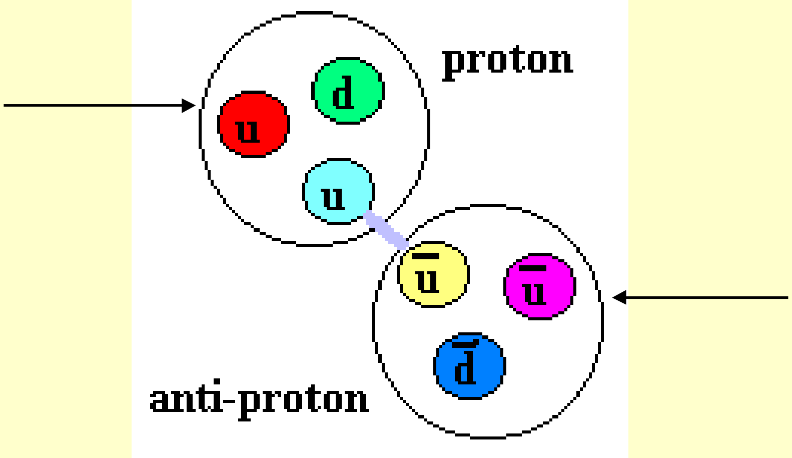
How to get high energy collisions

- Need E_{com} to be large enough to
  - allow high momentum transfer (probe small distances)
  - produce heavy objects (top quarks, Higgs boson)
  - e.g. top quark production: $e^+e^- \to t\bar{t}$, $q\bar{q} \to t\bar{t}$, $gg \to t\bar{t}$, …
- Shoot particle beam on a target (“fixed target”):
  - $E_{com} = 2\sqrt{Emc^2} \sim 20$ GeV for $E = 100$ GeV, $m = 1$ GeV/c^2

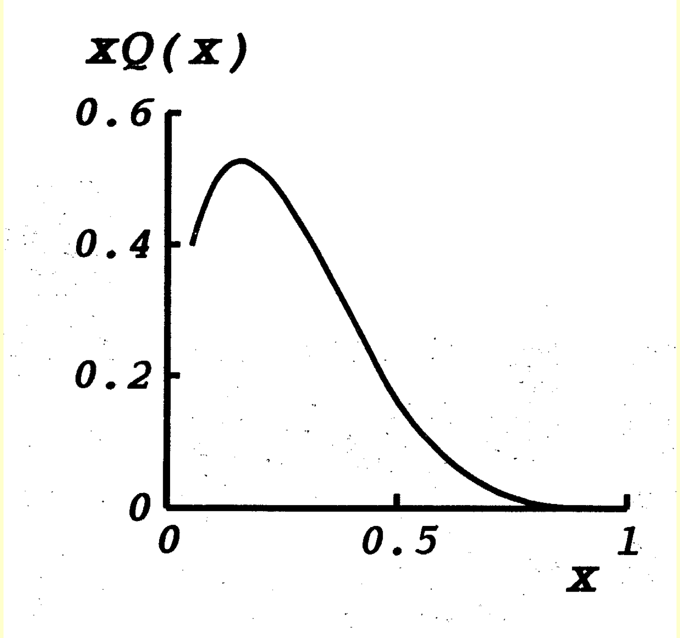
- Collide two particle beams (“collider :
  - $E_{com} = 2E \sim 200$ GeV for $E = 100$ GeV

How to make qq collisions, cont'd

- However, quarks are not found free in nature!
- But (anti)quarks are elements of (anti)protons.
- So, if we collide protons and anti-protons we should get some $q\bar{q}$ collisions.

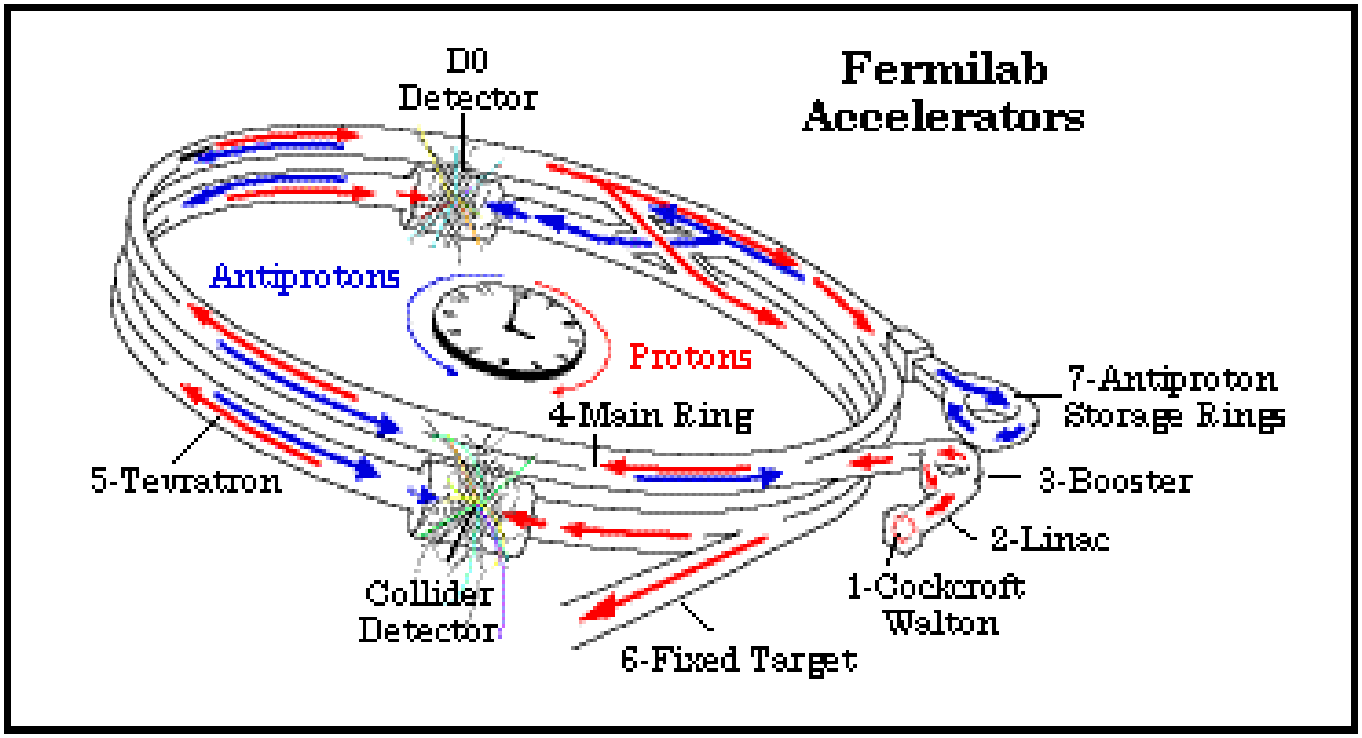


- Proton structure functions give the probability that a single quark (or gluon) carries a fraction x of the proton momentum (which is 900 GeV/c at the Tevatron)

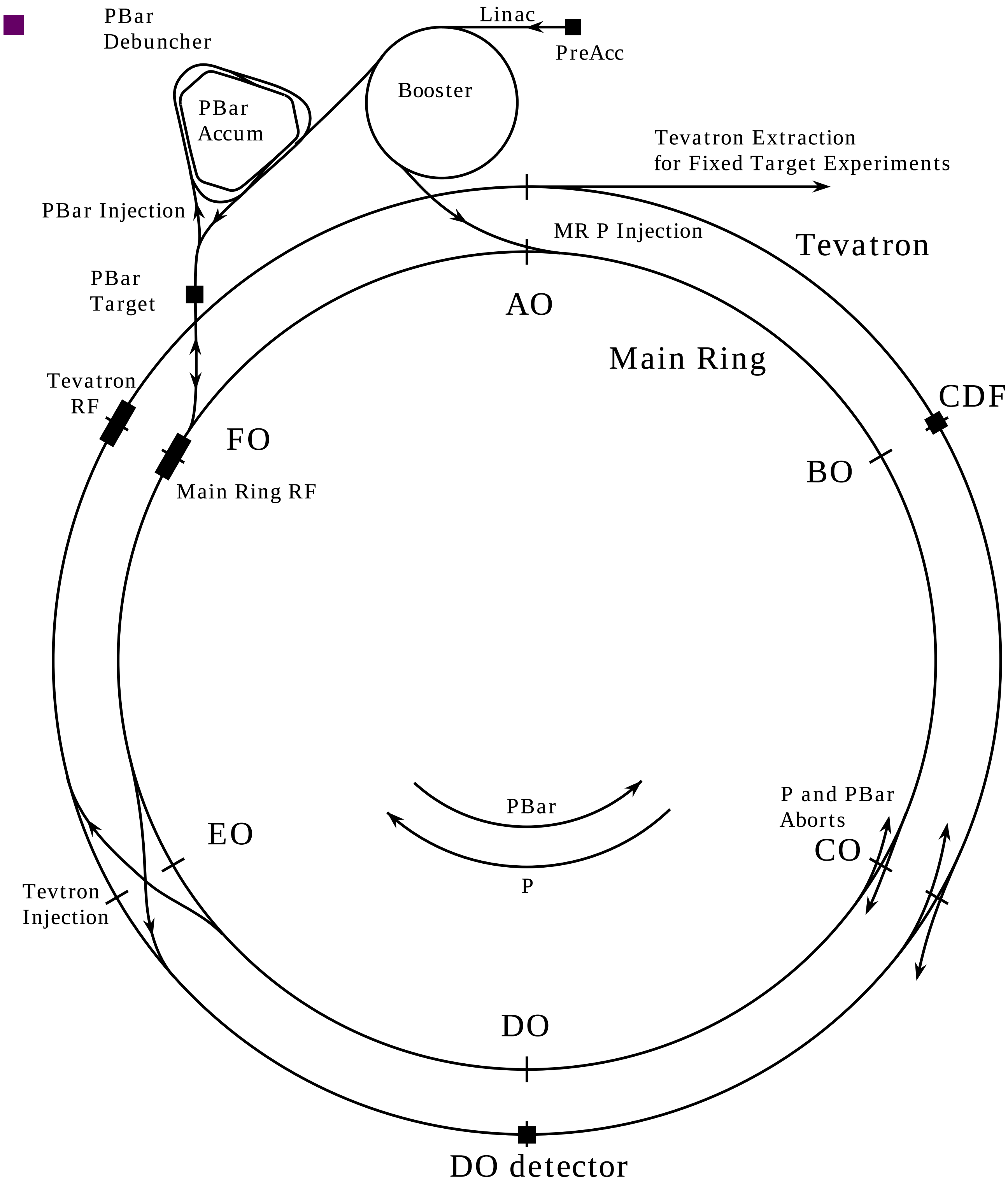


Accelerator

- accelerators:
  - use electric fields to accelerate particles, magnetic fields to steer and focus the beams
  - synchrotron:
    particle beams kept in circular orbit by magnetic field; at every turn, particles "kicked" by electric field in accelerating station;
  - fixed target operation: particle beam extracted from synchrotron, steered onto a target
  - collider operation:
    accelerate bunches of protons and antiprotons moving in opposite direction in same ring; make them collide at certain places where detectors are installed



Fermilab accelerator complex



ACCELERATORS

- are devices to increase the energy of charged particles;
  - use magnetic fields to shape (focus and bend) the trajectory of the particles;
  - use electric fields for acceleration.
- types of accelerators:
  - electrostatic (DC) accelerators
    - Cockcroft-Walton accelerator (protons up to 2 MeV)
    - Van de Graaff accelerator (protons up to 10 MeV)
    - Tandem Van de Graaff accelerator (protons up to 20 MeV)
  - resonance accelerators
    - cyclotron (protons up to 25 MeV)
    - linear accelerators
      - electron linac: 100 MeV to 50 GeV
      - proton linac: up to 70 MeV
  - synchronous accelerators
    - synchrocyclotron (protons up to 750 MeV)
    - proton synchrotron (protons up to 900 GeV)
    - electron synchrotron (electrons from 50 MeV to 90 GeV)
  - storage ring accelerators (colliders)

ACCELERATORS, cont'd

- electrostatic accelerators:
  - ✻ generate high voltage between two electrodes ⇒ charged particles move in electric field,

    energy gain = charge times voltage drop;
  - ✻ *Cockcroft-Walton* and *Van de Graaff* accelerators differ in method to achieve high voltage.
- proton linac (drift tube accelerator):
  - ✻ cylindrical metal tubes (drift tubes) along axis of large vacuum tank
  - ✻ successive drift tubes connected to opposite terminals of AC voltage source
  - ✻ no electric field inside drift tube ⇒ while in drift tube, protons move with constant velocity
  - ✻ AC frequency such that protons always find accelerating field when reaching gap between drift tubes
  - ✻ length of drift tubes increases to keep drift time constant
  - ✻ for very high velocities, drift tubes nearly of same length (nearly no velocity increase when approaching speed of light)

Accelerators, cont'd

- cyclotron
  - ✻ consists of two hollow metal chambers called ("dees" for their shape, with open sides which are parallel, slightly apart from each other ("gap")
  - ✻ dees connected to AC voltage source - always one dee positive when other negative ⇒ electric field in gap between dees, but no electric field inside the dees;
  - ✻ source of protons in center, everything in vacuum chamber;
  - ✻ whole apparatus in magnetic field perpendicular to plane of dees;
  - ✻ frequency of AC voltage such that particles always accelerated when reaching the gap between the dees;
  - ✻ in magnetic field, particles are deflected:
    $p = q \cdot B \cdot R$ p = momentum, q = charge,
    B = magnetic field strength,
    R = radius of curvature
  - ✻ radius of path increases as momentum of proton increases time for passage always the same as long as momentum proportional to velocity
    this is not true when velocity becomes too big (``relativistic change of mass'')

Accelerators: “relativistic effects”

- “relativistic effects”
  - special relativity tells us that certain approximations made in Newtonian mechanics break down at very high speeds;
  - relation between momentum and velocity in “old” (Newtonian) mechanics: $p = m\,v$ becomes
    $p = m_o\,v\,\gamma$, with $\gamma = 1/\sqrt{1 - (v/c)^2}$
    m_o = “rest mass”, i.e. mass is replaced by rest mass times γ
    - “relativistic growth of mass”
  - factor γ often called “Lorentz factor”; ubiquitous in relations from special relativity;
    energy: $E = m_o c^2 \gamma$
  - acceleration in a cyclotron is possible as long as relativistic effects are negligibly small, i.e. only for small speeds, where momentum is still proportional to speed; at higher speeds, particles not in resonance with accelerating frequency; for acceleration, need to change magnetic field B or accelerating frequency f or both;

Accelerators, cont'd

- electron linac
  - ✻ electrons reach nearly speed of light at small energies (at 2 MeV, electrons have 98% of speed of light);
    no drift tubes; use travelling e.m. wave inside resonant cavities for acceleration.
- synchrocyclotron:
  - ✻ B kept constant, f decreases;
- synchrotron :
  - ✻ B increases during acceleration,
    f fixed (electron synchrotron)
    or varied (proton synchrotron);
    radius of orbit fixed.

Particle detectors, cont'd

- Scintillator:
  - energy liberated in de-excitation and capture of ionization electrons emitted as light - ``scintillation light''
  - light channeled to photomultiplier in light guide (e.g. optical fibers);
  - scintillating materials: certain crystals (e.g. NaI), transparent plastics with doping (fluors and wavelength shifters)
- proportional tube:
  - metallic tube with thin wire in center, filled with gas, HV between wall (-, "cathode") and central wire (+,"anode"); ⇒ strong electric field near wire;
  - charged particle in gas ⇒ ionization ⇒ electrons liberated;
  - electrons accelerated in electric field ⇒ can liberate other electrons by ionization which in turn are accelerated and ionize ⇒ "avalanche of electrons" moves to wire ⇒ current pulse; current pulse amplified ⇒ electronic signal:
  - gas is usually noble gas (e.g. argon), with some additives e.g. carbon dioxide, methane, isobutane,..) as "quenchers";

Particle detectors, cont'd

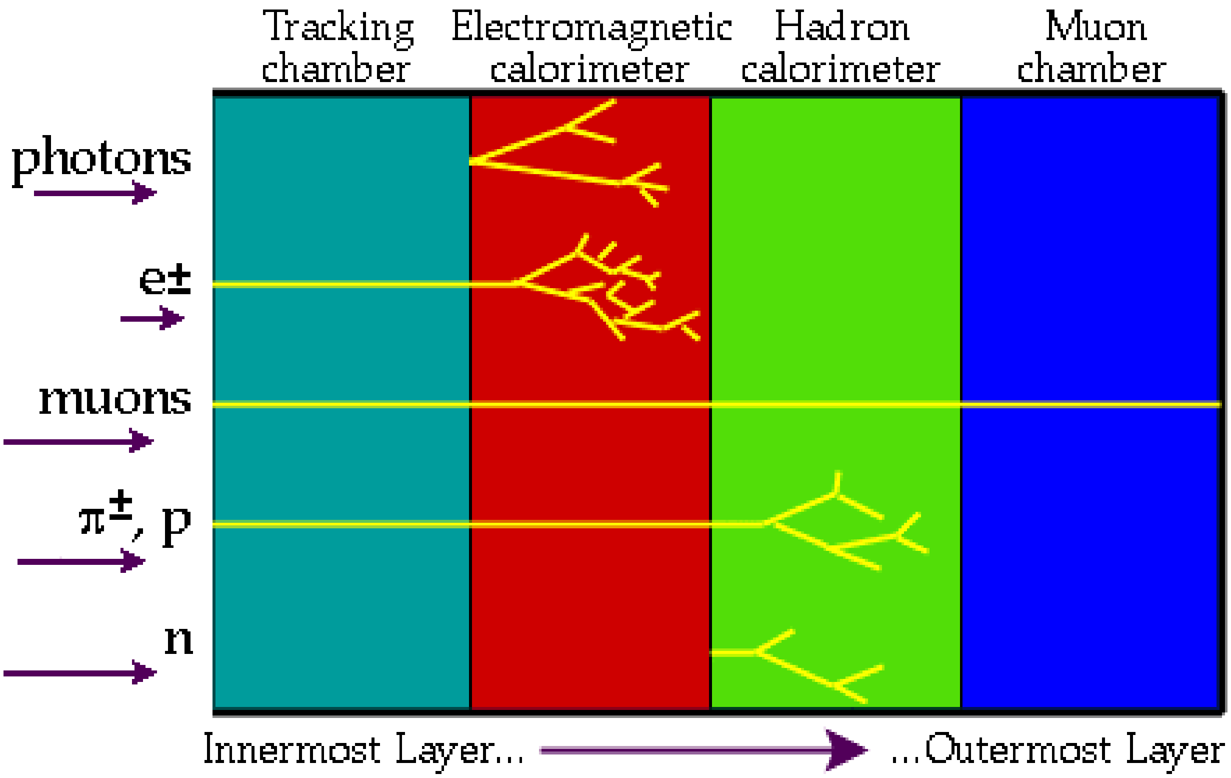
- multi wire proportional chamber:
  - ✻ contains many parallel anode wires between two cathode planes (array of prop.tubes with separating walls taken out)
  - ✻ operation similar to proportional tube;
  - ✻ cathodes can be metal strips or wires ⇒ get additional position information from cathode signals.
- drift chamber:
  - ✻ field shaping wires and electrodes on wall to create very uniform electric field, and divide chamber volume into "drift cells", each containing one anode wire;
  - ✻ within drift cell, electrons liberated by passage of particle move to anode wire, with avalanche multiplication near anode wire;
  - ✻ arrival time of pulse gives information about distance of particle from anode wire; ratio of pulses at two ends of anode wire gives position along anode wire;

Particle detectors, cont'd

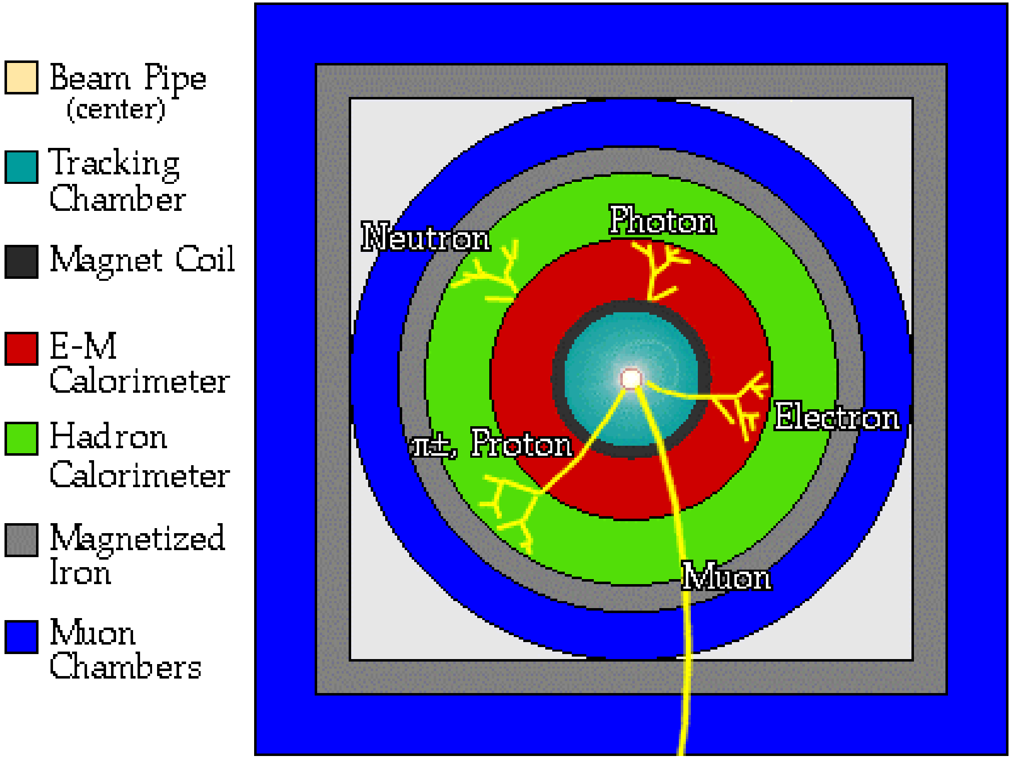
- Cherenkov detector:
  - measure Cherenkov light (amount and/or angle) emitted by particle going through counter volume filled with transparent gas liquid, aerogel, or solid ⇒ get information about speed of particle.
- calorimeter:
  - "destructive" method of measuring a particle's energy: put enough material into particle's way to force formation of electromagnetic or hadronic shower (depending on kind of particle)
  - eventually particle loses all of its energy in calorimeter;
  - energy deposit gives measure of original particle energy.
- Note:

  many of the detectors and techniques developed for particle and nuclear physics are now being used in medicine, mostly diagnosis, but also for therapy.

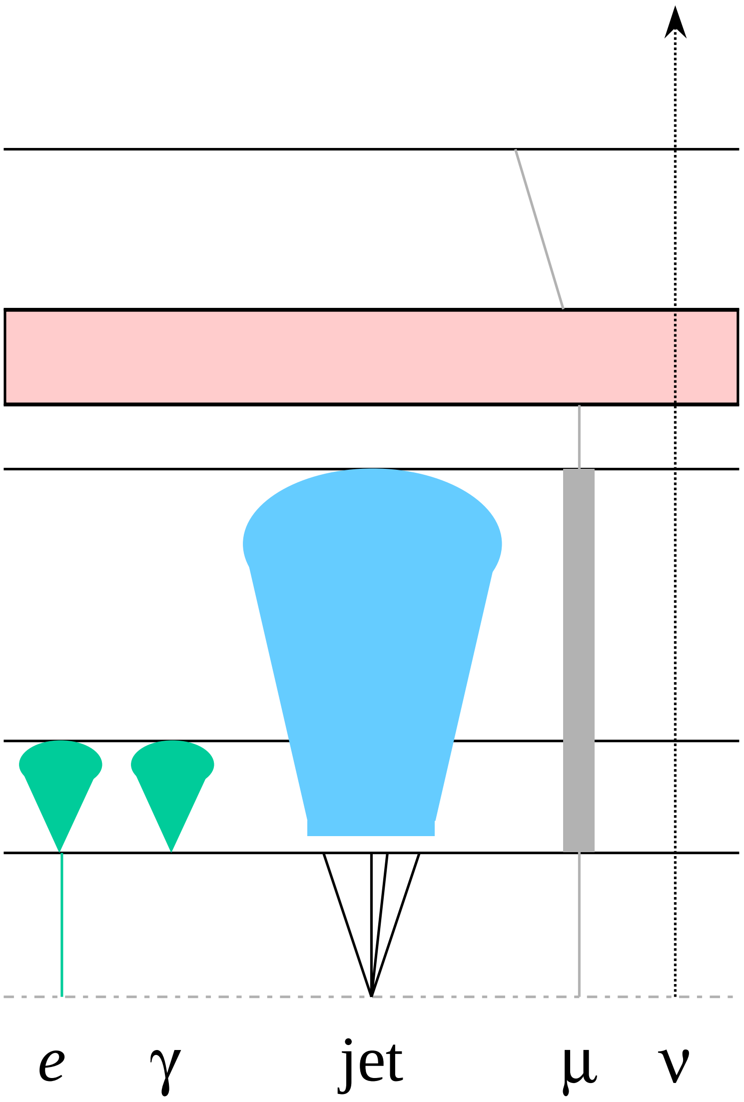
Identifying particles



A detector cross-section, showing particle paths



Particle Identification



Muon B&C

Magnet

Muon A-Layer

Hadronic
Layers

Calorimeter

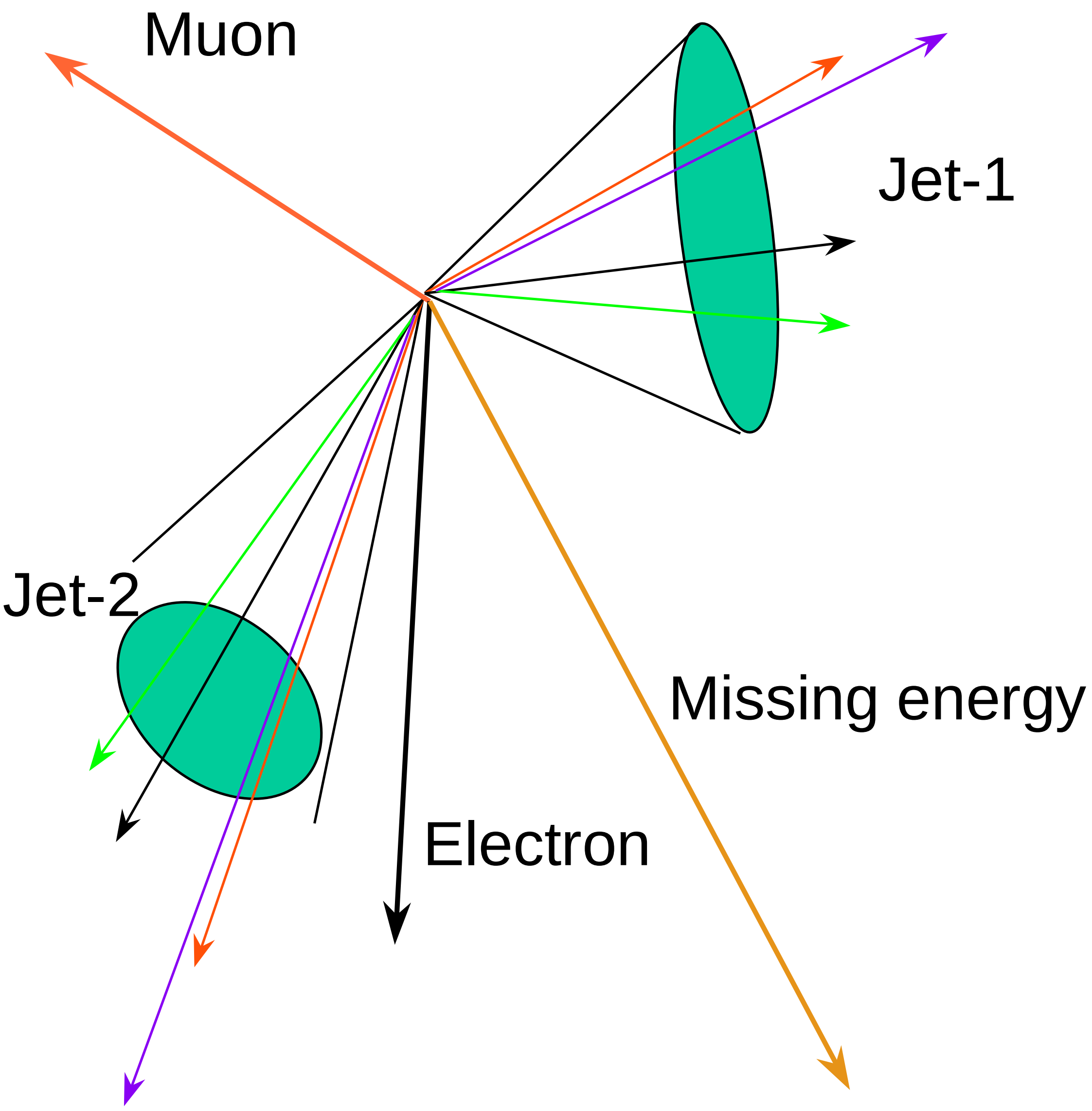
EM Layers

Central Tracking

Beam Axis

What do we actually "see"

$$t\bar{t} \rightarrow e\mu + jets$$



Detectors

- Detectors
  - use characteristic effects from interaction of particle with matter to detect, identify and/or measure properties of particle; has "transducer" to translate direct effect into observable/recordable (e.g. electrical) signal
  - example: *our eye is a photon detector;*
  - *"seeing"* is performing a *photon scattering experiment:*
    - light source provides photons
    - photons hit object of our interest -- some absorbed, some scattered, reflected
    - some of scattered/reflected photons make it into eye; focused onto retina;
    - photons detected by sensors in retina (photoreceptors -- rods and cones)
    - transduced into electrical signal (nerve pulse)
    - amplified when needed
    - transmitted to brain for processing and interpretation

Particle interactions with matter

- ✻ electromagnetic interactions:
  - excitation
  - ionization
  - Cherenkov radiation
  - transmission radiation
  - bremsstrahlung
  - photoelectric effect
  - Compton scattering
  - pair production
- ✻ strong interactions:
  - secondary hadron production,
  - hadronic showers

- ✻ detectors usually have some amplification mechanism

Interaction of particles with matter

- when passing through matter,
  - particles interact with the electrons and/or nuclei of the medium;
  - this interaction can be *electromagnetic* or *strong interaction*, depending on the kind of particle; its effects can be used to detect the particles;
- possible interactions and effects in passage of particles through matter:
  - **excitation** of atoms or molecules (e.m. int.):
    - charged particles can excite an atom or molecule (i.e. lift electron to higher energy state);
    - subsequent de-excitation leads to emission of photons;
  - **ionization** (e.m. int.)
    - electrons liberated from atom or molecule, can be collected, and charge is detected
  - **Cherenkov radiation** (e.m. int.):
    - if particle's speed is higher than speed of light in the medium, e.m. radiation is emitted -- "Cherenkov light" or Cherenkov radiation, which can be detected;
    - amount of light and angle of emission depend on particle velocity;

Interaction of particles with matter, cont'd

- **transition radiation** (e.m. int.):
  - when a charged particle crosses the boundary between two media with different speeds of light (different "refractive index"), e.m. radiation is emitted -- "transition radiation"
  - amount of radiation grows with (energy/mass);
- **bremsstrahlung** (= braking radiation) (e.m. int.):
  - when charged particle's velocity changes, e.m. radiation is emitted;
  - due to interaction with nuclei, particles deflected and slowed down emit bremsstrahlung;
  - effect stronger, the bigger (energy/mass) ⇒ electrons with high energy most strongly affected;
- **pair production** (e.m. int.):
  - by interaction with e.m. field of nucleus, photons can convert into electron-positron pairs
- **electromagnetic shower** (e.m. int.):
  - high energy electrons and photons can cause "*electromagnetic shower*" by successive bremsstrahlung and pair production
- **hadron production** (strong int.):
  - strongly interacting particles can produce new particles by strong interaction, which in turn can produce particles,... "*hadronic shower*"

Examples of particle detectors

- photomultiplier:
  - photomultiplier tubes convert small light signal (even single photon) into detectable charge (current pulse)
  - photons liberate electrons from photocathode,
  - electrons "multiplied" in several (6 to 14) stages by ionization and acceleration in high electric field between "dynodes", with gain ≈ 10^4 to 10^{10}
  - photocathode and dynodes made from material with low ionization energy;
  - photocathodes: thin layer of semiconductor made e.g. from Sb (antimony) plus one or more alkali metals, deposited on glass or quartz;
  - dynodes: alkali or alkaline earth metal oxide deposited on metal, e.g. BeO on Cu (gives high secondary emission);

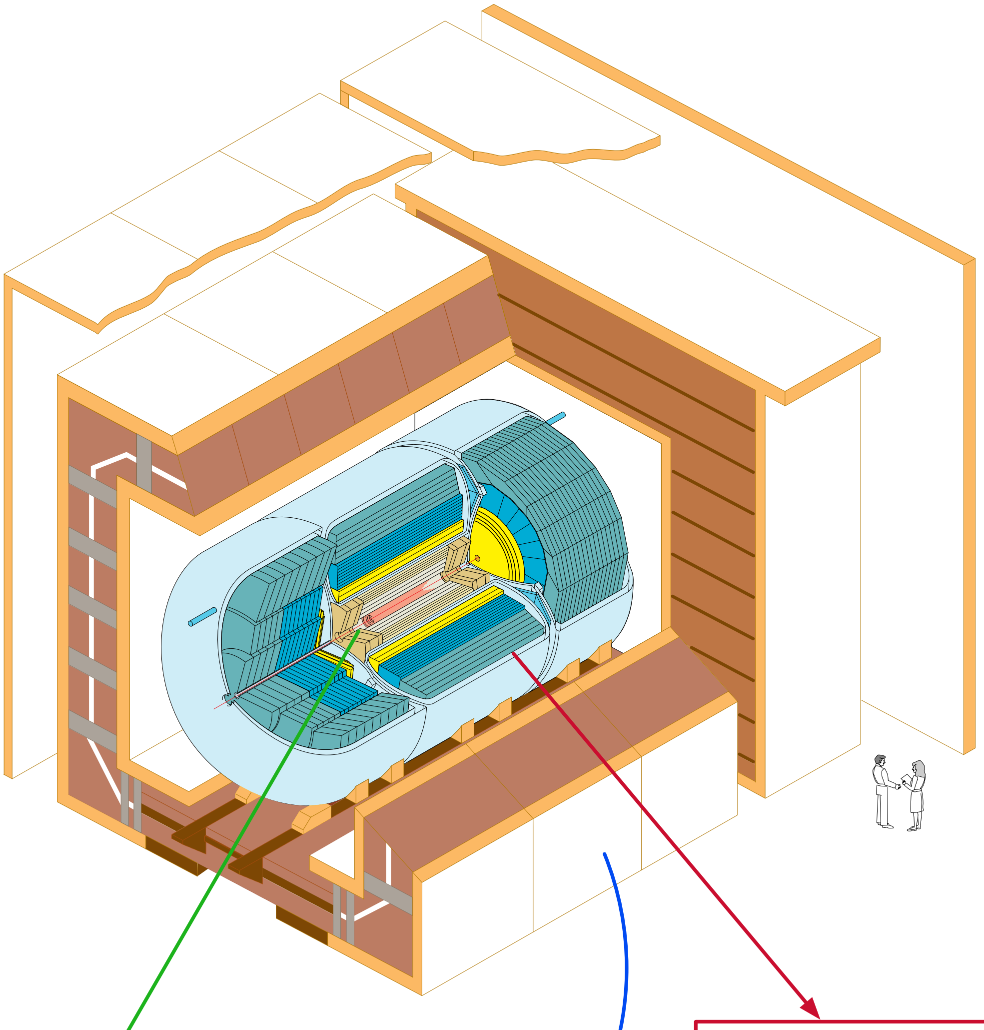
Examples of particle detectors

- Spark chamber
  - ✻ gas volume with metal plates (electrodes); filled with gas (noble gas, e.g. argon)
  - ✻ charged particle in gas ⇒ ionization ⇒ electrons liberated;
    ⇒ string of electron - ion pairs along particle path
  - ✻ passage of particle through "trigger counters" (scintillation counters) triggers HV
  - ✻ HV between electrodes ⇒ strong electric field;
  - ✻ electrons accelerated in electric field ⇒ can liberate other electrons by ionization which in turn are accelerated and ionize ⇒ "avalanche of electrons", eventually formation of plasma between electrodes along particle path;
  - ✻ gas conductive along particle path
    ⇒ electric breakdown ⇒ discharge ⇒ spark
  - ✻ HV turned off to avoid discharge in whole gas volume

Examples of particle detectors, contd

- Scintillation counter:
  - energy liberated in de-excitation and capture of ionization electrons emitted as light - "scintillation light"
  - light channeled to photomultiplier in light guide (e.g. piece of lucite or optical fibers);
  - scintillating materials: certain crystals (e.g. NaI), transparent plastics with doping (fluors and wavelength shifters)
- Geiger-Müller counter:
  - metallic tube with thin wire in center, filled with gas, HV between wall (-, "cathode") and central wire (+,"anode"); ⇒ strong electric field near wire;
  - charged particle in gas ⇒ ionization ⇒ electrons liberated;
  - electrons accelerated in electric field ⇒ liberate other electrons by ionization which in turn are accelerated and ionize ⇒ "avalanche of electrons"; avalanche becomes so big that all of gas ionized ⇒ plasma formation ⇒ discharge
  - gas is usually noble gas (e.g. argon), with some additives e.g. carbon dioxide, methane, isobutane,..) as "quenchers";

The D0 detector



TRACKING

σ(z vertex)=6 mm
$\sigma(r\phi)$ = 60 μm (VTX)
= 180 μm (CDC)
= 200 μm (FDC)

MUON

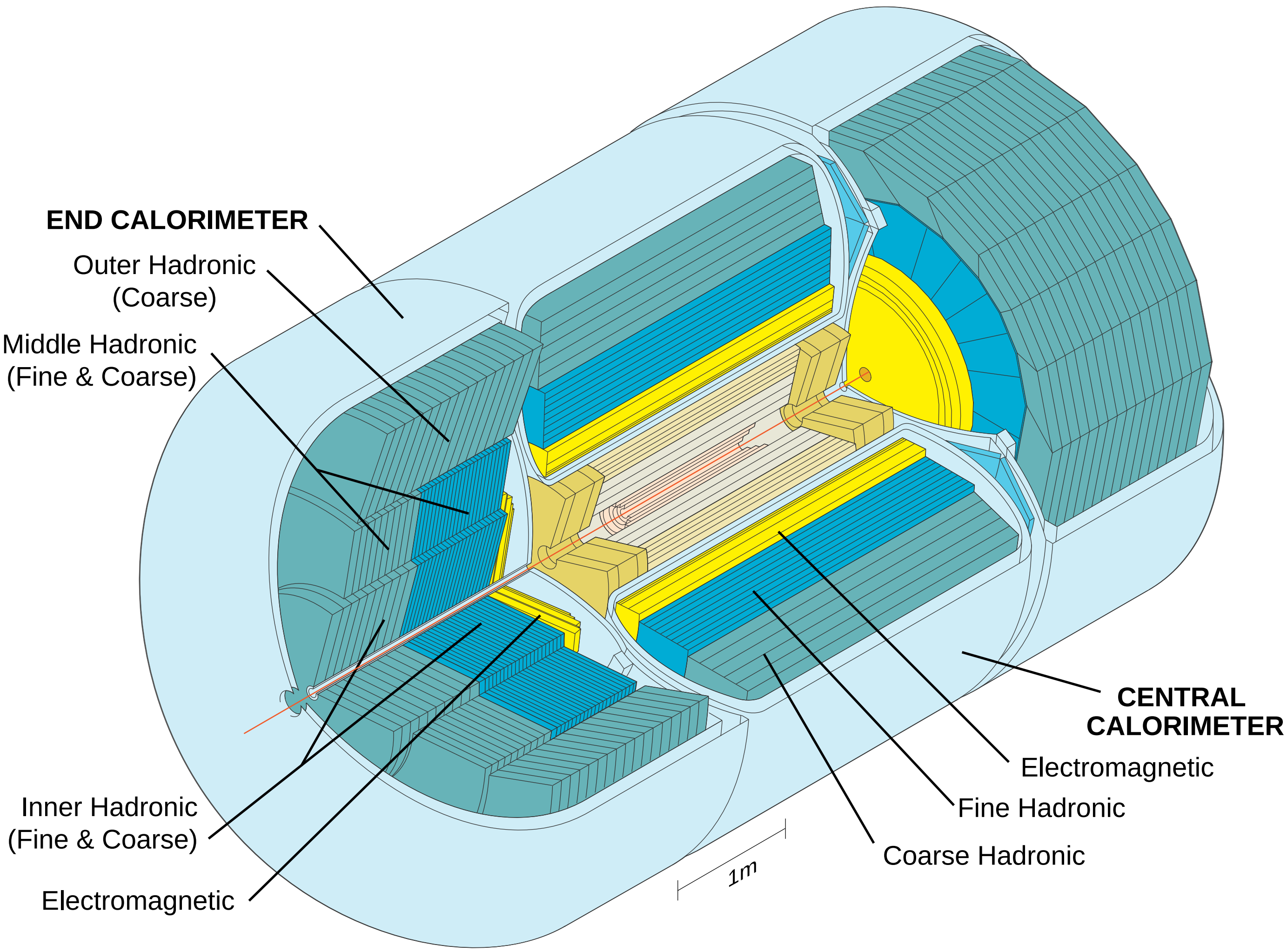
$|\eta| < 3.3$

$$\frac{\delta \mathbf{p}}{\mathbf{p}} = 0.2 \oplus 0.01p$$

CALORIMETRY

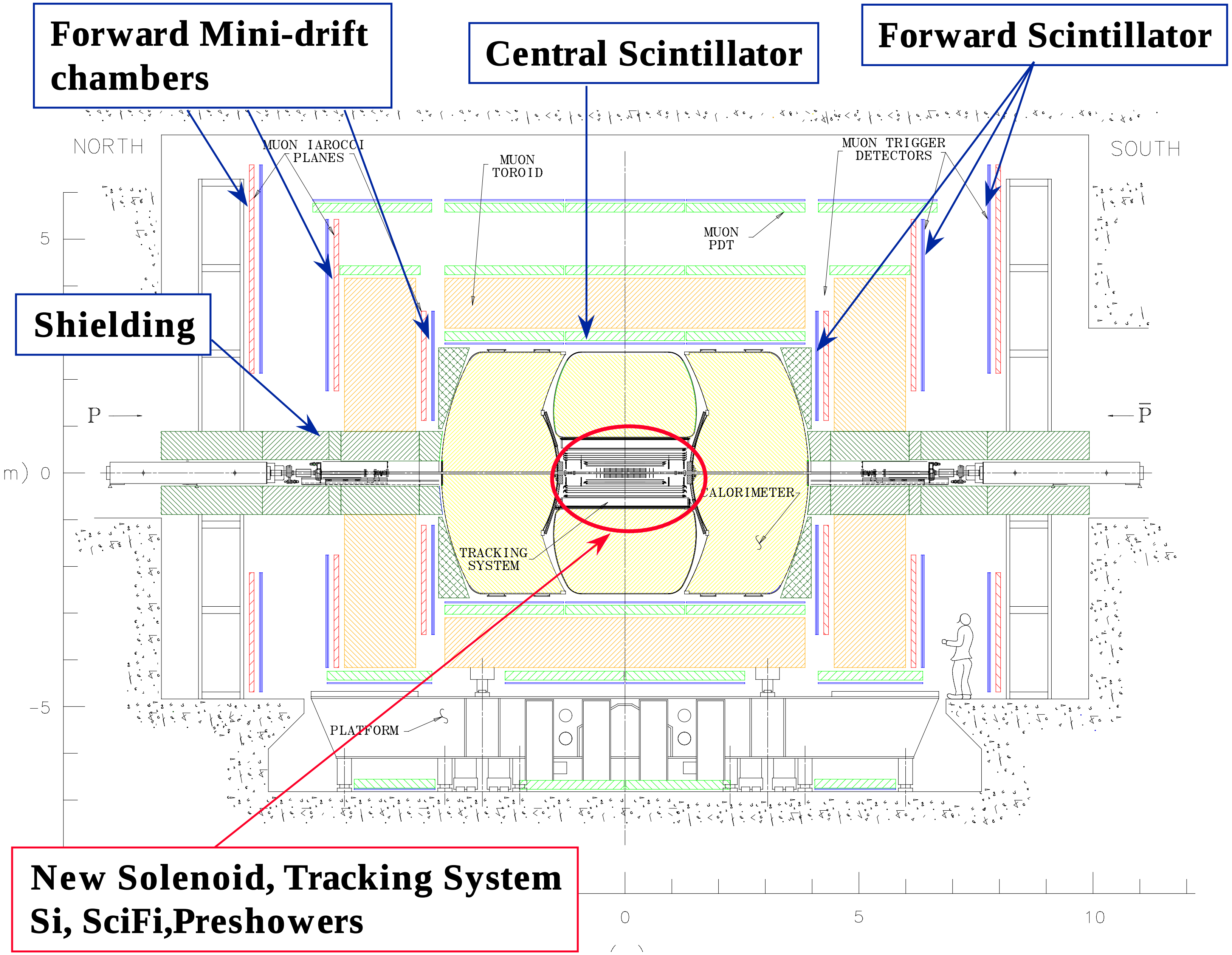
$|\eta|<4$
$\Delta\eta \times \Delta\phi = 0.1 \times 0.1$
$\sigma(EM) = 15\% / \sqrt{E}$
$\sigma(HAD) = 50\% / \sqrt{E}$

DØ Calorimeter



- Uranium-Liquid Argon sampling calorimeter
  - Linear, hermetic, and compensating
- No central magnetic field!
  - Rely on EM calorimeter

DØ Upgrade



Forward Mini-drift chambers

Central Scintillator

Forward Scintillator

Shielding

New Solenoid, Tracking System Si, SciFi,Preshowers

+ New Electronics, Trig, DAQ

DØ Upgrade Tracking

- Silicon Tracker
  - ✻ Four layer barrels (double/single sided)
  - ✻ Interspersed double sided disks
  - ✻ **793,000 channels**
- Fiber Tracker
  - ✻ Eight layers sci-fi ribbon doublets (z-u-v, or z)
  - ✻ 74,000 830 μm fibers w/ VLPC readout

•Preshowers

Central

•Scintillator strips

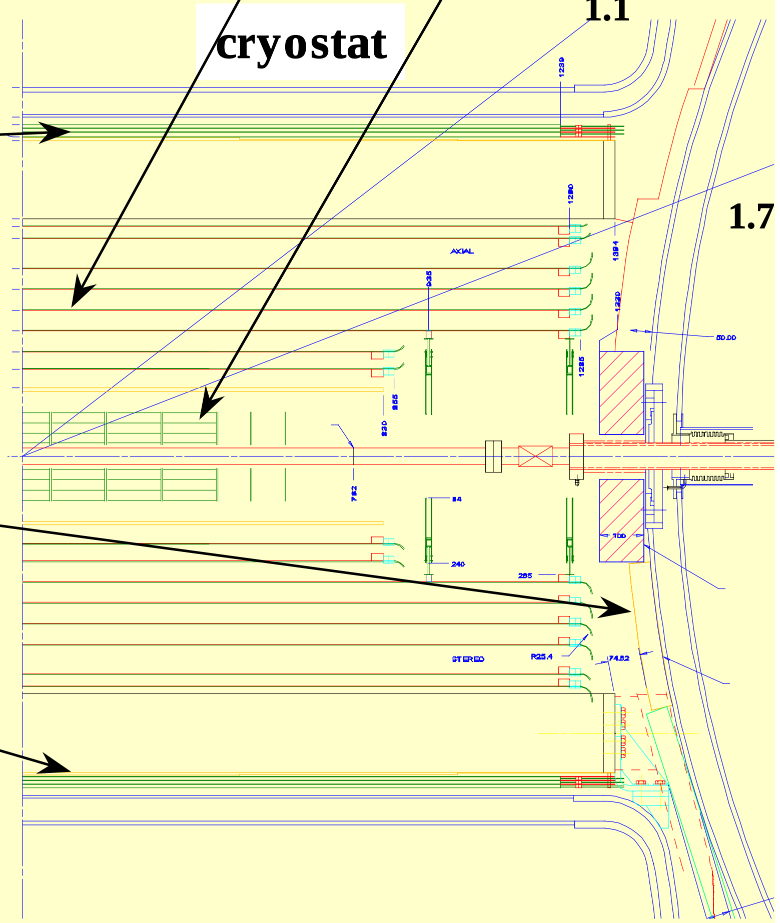
- 6,000 channels

Forward

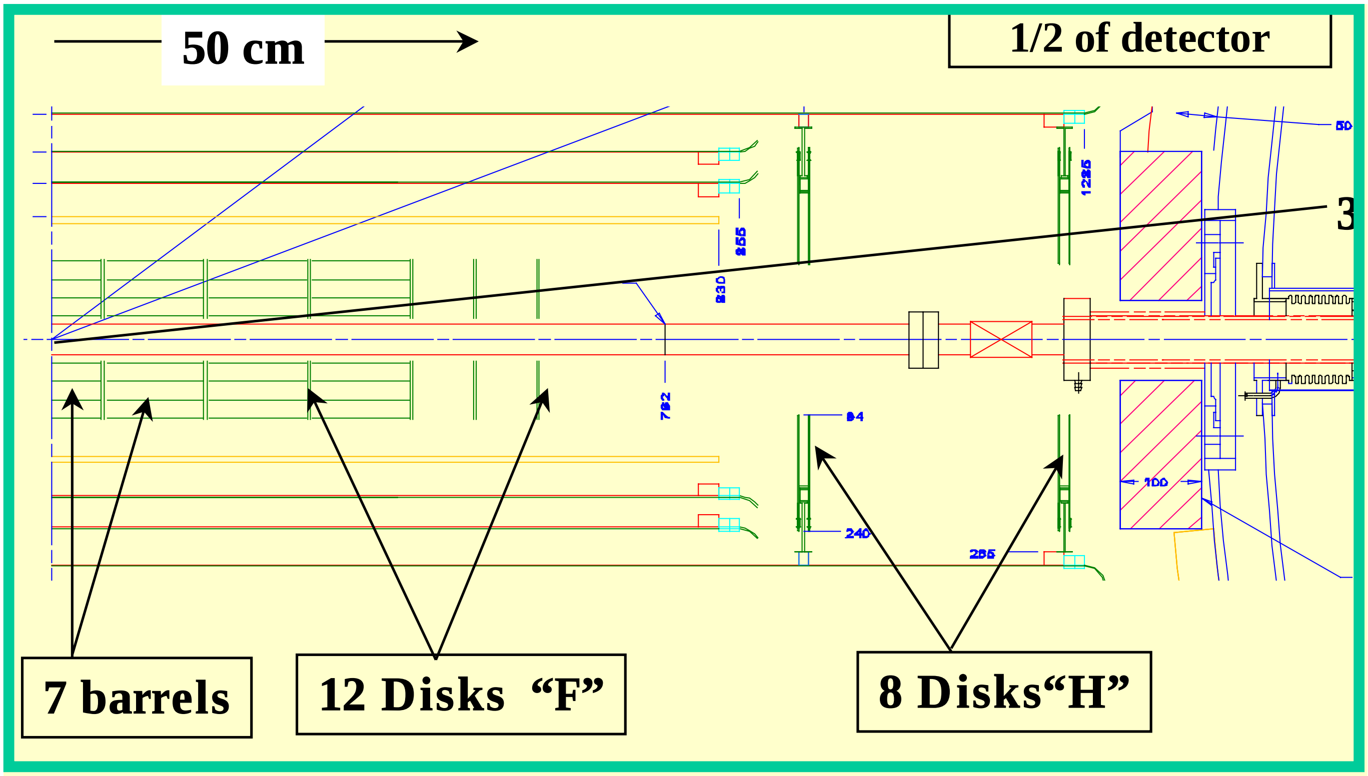
- Scintillator strips
- 16,000 channels

Solenoid

-2T superconducting



Silicon Tracker



50 cm

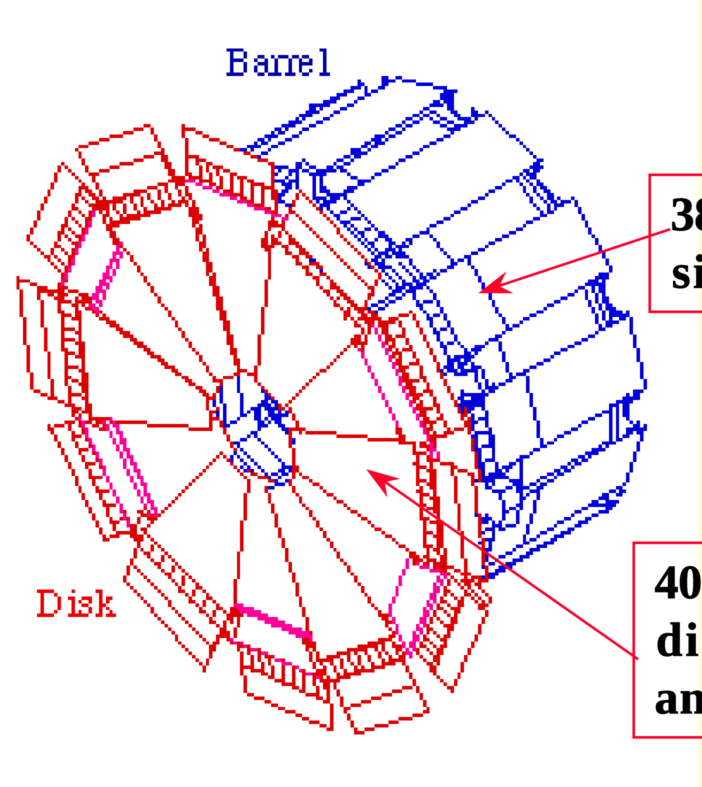
1/2 of detector

7 barrels

12 Disks "F"

8 Disks"H"

1/7 of the detector (large-z disks not shown)

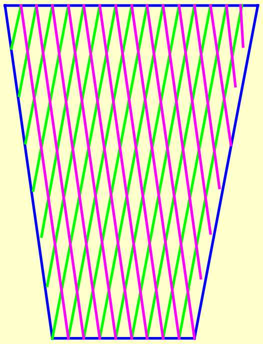


387k ch in 4-layer double sided Si barrel (stereo)

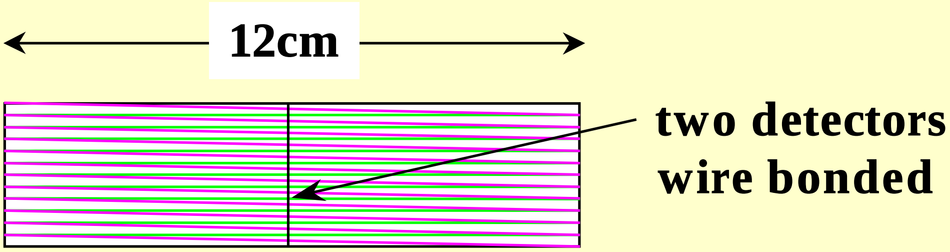
405k ch in interspersed disks (double sided stereo) and large-z disks

Silicon Tracker -Detectors

- Disks
  - ✻ "F" disks wedge (small diameter):
    - 144 double sided detectors, 12 wedges = 1disk
    - 50μm pitch, +/-15 stereo
    - 7.5cm long, from r=2.5 to 10cm, at z=6,19,32,45,50,55 cm
  - ✻ "H" disk (large diameter):
    - 384 single sided detectors
    - 50 μm pitch
    - from r=9.5-20 cm, z= 94, 126 cm



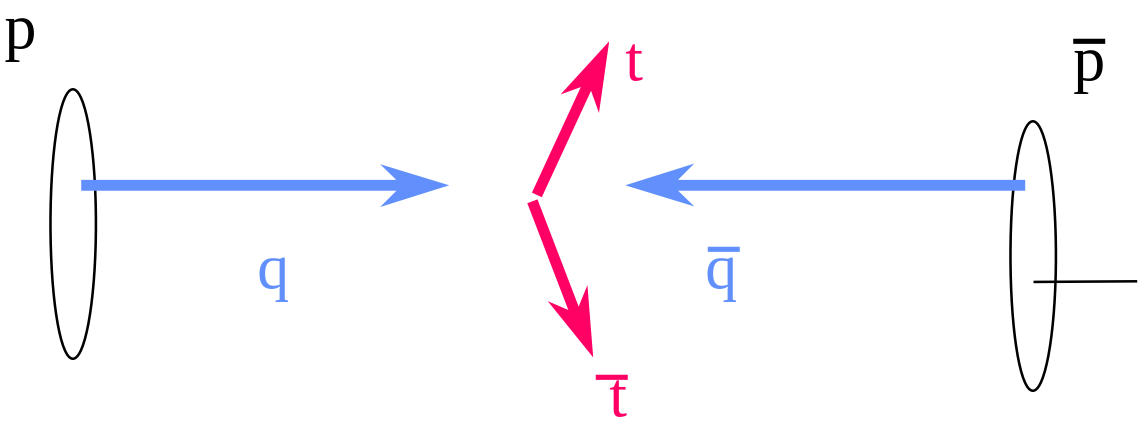
- Barrels
  - ✻ 7 modular, 4 layer barrel segments
  - ✻ single sided:
    - layers 1 , 3 in two outermost barrels.
  - ✻ double sided:
    - layers 1, 3 have 90° stereo (mpx'd 3:1)
      50 & 100μm pitch, 2.1 cm wide
    - layers 2,4 have small angle stereo (2°)
      50 & 62.5μm pitch, 3.4 cm wide



Trigger

- Trigger = device making decision on whether to record an event
- why not record all of them?
  - we want to observe "rare" events;
  - for rare events to happen sufficiently often, need high beam intensities ⇒ many collisions take place
  - e.g. in Tevatron collider, proton and antiproton bunches will encounter each other every 132ns
  - at high bunch intensities, every beam crossing gives rise to collision ⇒ *about 7 million collisions per second*
  - we can *record about 20 to (maybe) 50 per second*
- why not pick 10 events randomly?
  - We would miss those rare events that we are really after:
    e.g. top production: ≈ 1 in 10^{10} collisions
    Higgs production: ≈ 1 in 10^{12} collisions
  - ⇒ would have to record 50 events/second for 634 years to get one Higgs event!
  - Storage needed for these events:
    $\approx 3 \times 10^{11}$ Gbytes
- Trigger has to decide fast which events not to record, without rejecting the "goodies"

Sample cross sections



Process	**σ(pb)**		**events**
collision	**8×10^{10}**		**8 trillion**
2 jets	**3×10^{6}**		**300 million**
4 jets	**125,000**		**12,500,000**
6 jets	**5,000**		**500,000**
W	**25,000**	**x 100 pb^{-1}**	**2,500,000**
Z	**11,000**		**1,100,000**
WW	**10**		**1000**
tt	**5**		**500**
Higgs	**0.1**		**10**

Luminosity and cross section

- Luminosity is a measure of the beam intensity
  (particles per area per second)
  ($L \sim 10^{31}/\mathrm{cm}^2/\mathrm{s}$)

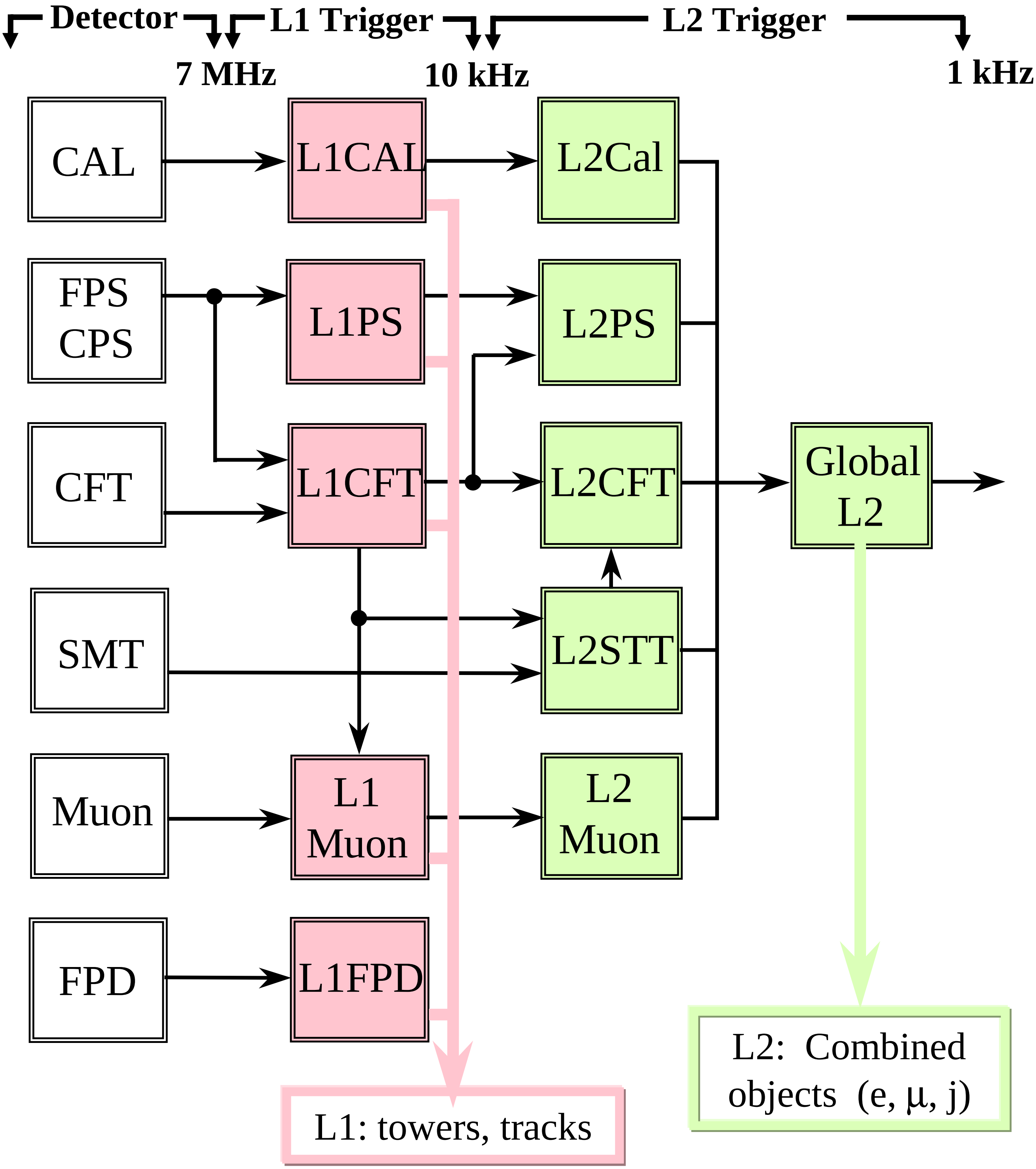
- "integrated luminosity"
  is a measure of the amount of data collected (e.g. ~100 pb^{-1})

- cross section σ is measure of effective interaction area, proportional to the probability that a given process will occur.
  - 1 barn = 10^{-24} cm^2
  - 1 pb = 10^{-12} b = 10^{-36} cm^2 = 10^{-40} m^2

- interaction rate:

$$dn/dt = L \times \sigma \quad \Rightarrow \quad n = \sigma \int L dt$$

Trigger Configuration



Detector

L1 Trigger

L2 Trigger

7 MHz

10 kHz

1 kHz

CAL

FPS
CPS

CFT

SMT

Muon

FPD

L1CAL

L1PS

L1CFT

L1
Muon

L1FPD

L2Cal

L2PS

L2CFT

L2STT

L2
Muon

Global
L2

L1: towers, tracks

L2: Combined
objects (e, μ, j)