Detection of Muons

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Outline:

- Muon
- Muon identification
- Muon interaction with matter
- Elements of muon spectrometers
  - absorbers and magnets
  - tracking detectors
- Examples of muon detection systems

Muon

- **Discovered by Anderson and Nedermeir in 1936 in cosmic rays. Till 1947 (pion discovery) was considered Yukawa particle, but very low interaction rate was a puzzle**
- **Since that time muon parameters are well defined**
  - Charge +/- 1
  - Mass 105.658389 MeV
  - Lifetime 2.19703 msec
  - Decay (100%) enn
  - No strong interaction
- **Major sources of muons**
  - cosmic (decays of pions p->mn)
    - $\sim 10^2$ muons/m^2.sec, E>1GeV
  - accelerators
    - low P_t muons product of mesons decay, 100m long 40GeV/c pion beam line
      - ~2% of pions will decay
      - muon energy is between E_{beam} and $E_{beam}/2$
    - high P_t muons product of heavy objects decays: b , W/Z, etc.

Why we would like to detect muons?

- **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:**
  - T **->**mm
  - **W->**mn **, Z ->** mm
  - **t -> bW ->** mm
- **Many of new particles searches contain muon(s) as final detectable particles**

Particle Identification Methods

- **Detection of muons consists of two major steps:**
  - identification
  - 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:**

$$m = p(\beta^{1}-1)^{1/2}$$

- **Velocity is measured by:**
  - Time of flight
  - Cherenkov, TRD

Identification (cont)

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

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

- Details and definitions of "large amount of absorber", "minor energy losses", etc. will be discussed in this Lecture

Muon Lifetime

- **Muon lifetime is 2.2 μsec, τc=0.7km**

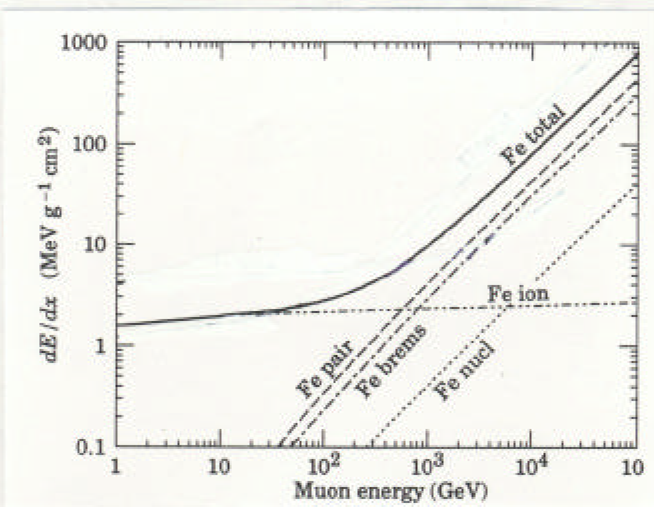
- **Decay path:**

p, GeV/c	Decay path, km	
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 Losses

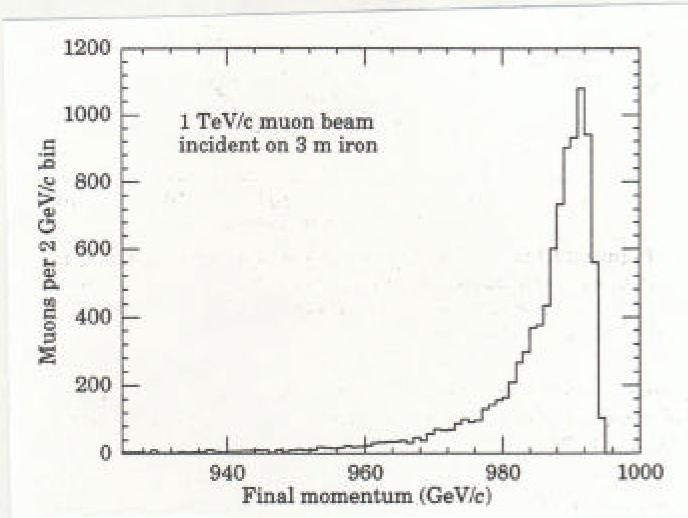
- Muon energy loss is defined by electro-magnetic interactions:
  - ionization
  - e+e- pair production
  - bremsstrahlung
  - photo nuclear reactions



- Below ~200GeV muon energy losses are mainly due to ionization. The average loss is about 2MeV/g cm^2 or 1.4GeV/m of steel

Muon Energy Losses

- dE/dx energy loss curves describe average energy losses. Fluctuations of energy losses are described by Landau distribution (~20% width):



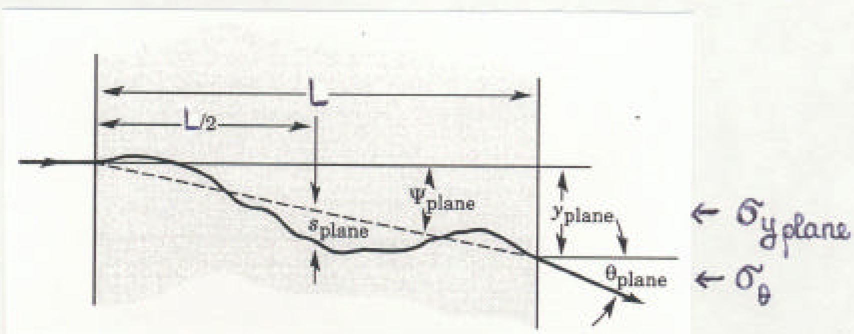
- Muon with energy above ~0.2TeV behaves similar to electron: create clouds of em showers along its trajectory

Multiple Scattering

- Muon changes its direction due to electromagnetic interactions:

$$\sigma_\theta = (14MeV/c)(L/L_{rad})^{1/2}/p$$

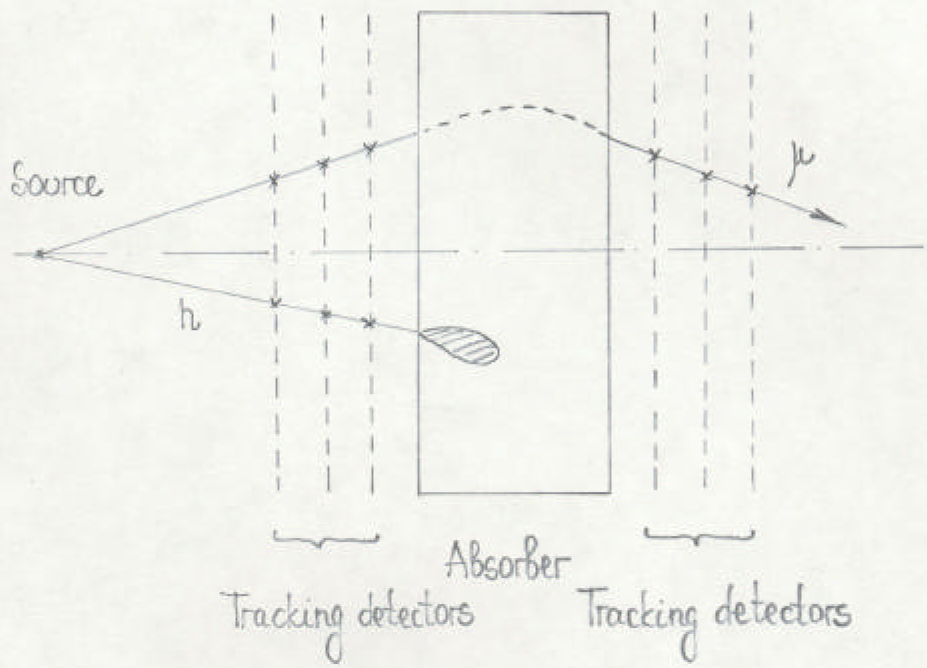
- Let's consider example of 50GeV/c muon passing via 2m of steel



$$\sigma_{y_{plane}} = 0.6cm\ (L_{rad}=1.76cm)$$

- Above formula is good approximation for small angle scattering. Monte Carlo and more complex expressions used for high accuracy calculations

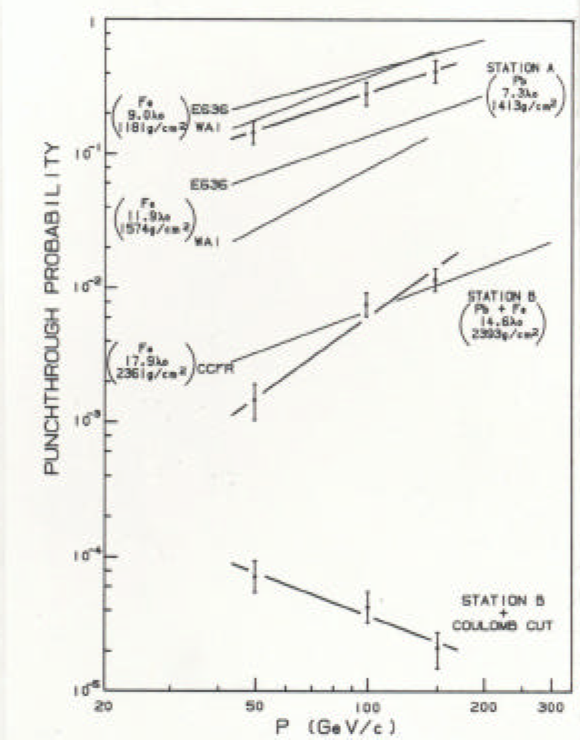
Muon Detector Layout



- **Major parameters of muon detector:**
  - **punchthrough probability**
  - **momentum (angular) resolution**

Hadron Punchthrough

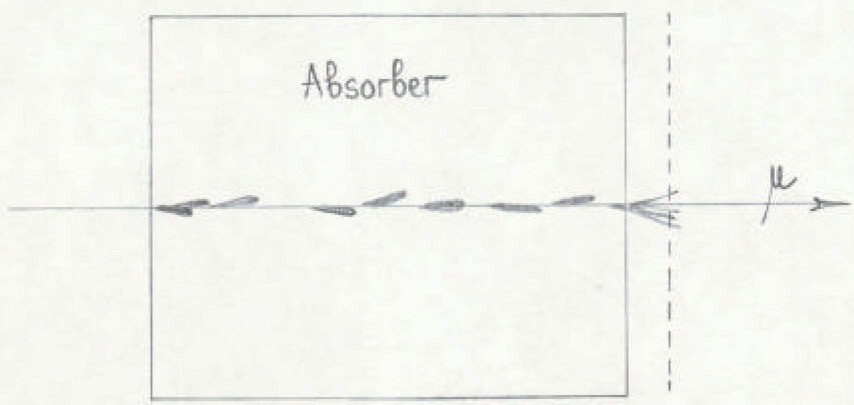
- Hadrons create showers in absorber. If the absorber is too thin shower can "leak" through, so that charged particle(s) is detected after absorber
- Monte Carlo calculations and test beam measurements are used to estimate punchthrough probability



- Methods to minimize punchthrough:
  - tracking before/after absorber
  - momentum measurement before/after absorber
  - timing

Very High Energy Muons

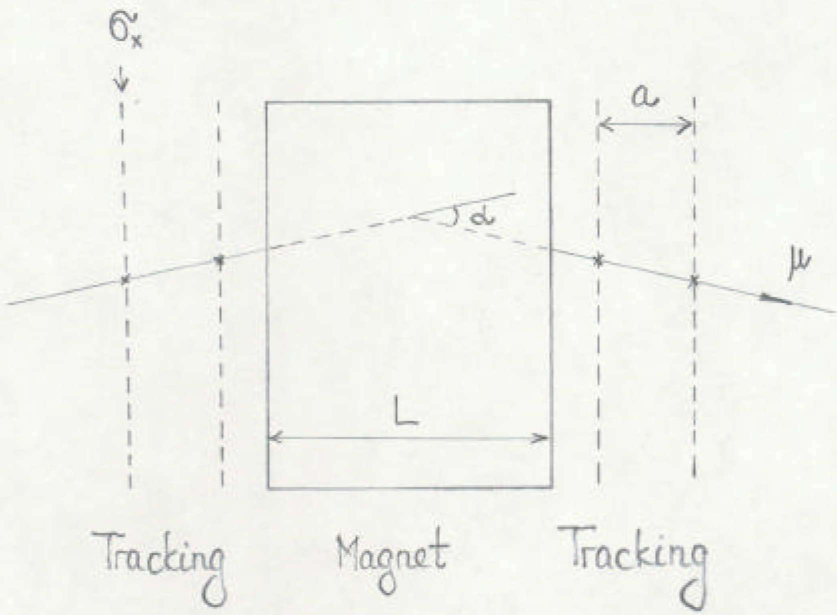
- At energies above ~0.5TeV muons start to loose energy due to radiation (gamma, e+e-), as a result muon track is accompanied by em showers:



- Major problem due to radiation is occupancy of tracking detectors
- Ways to reduce em backgrounds:
  - multi hit detectors/electronics
  - air gap between absorber and tracking detector
  - increase in number of detector planes

Momentum Resolution of Muon Spectrometer

- Muon track can be bent "inside" magnetized iron and steel can be easily magnetized up to ~2T:



$$p\,(GeV/c) = 0.3\ B(T)\ L(m)/\alpha(rad)$$

- Determination of momentum is limited by bending angle measurement:
  - accuracy of tracking detectors
  - multiple scattering

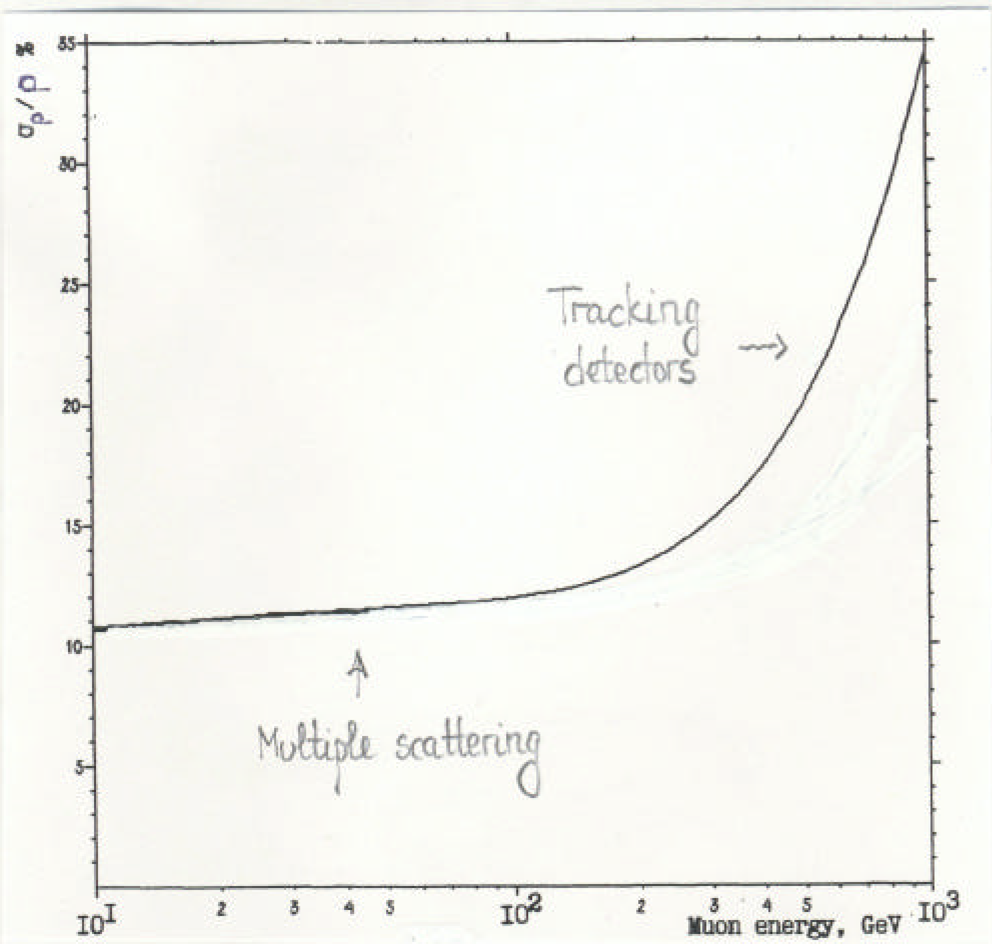
Momentum Resolution

- **Formula for momentum resolution:**

$$\sigma_p/p \sim \frac{1}{B \cdot L} \left\{ \left(14\,\text{MeV} \cdot \sqrt{\frac{L}{L_{Rad}}}\right)^2 + \left(p \cdot \frac{2\sigma_x}{a}\right)^2 \right\}^{1/2}$$

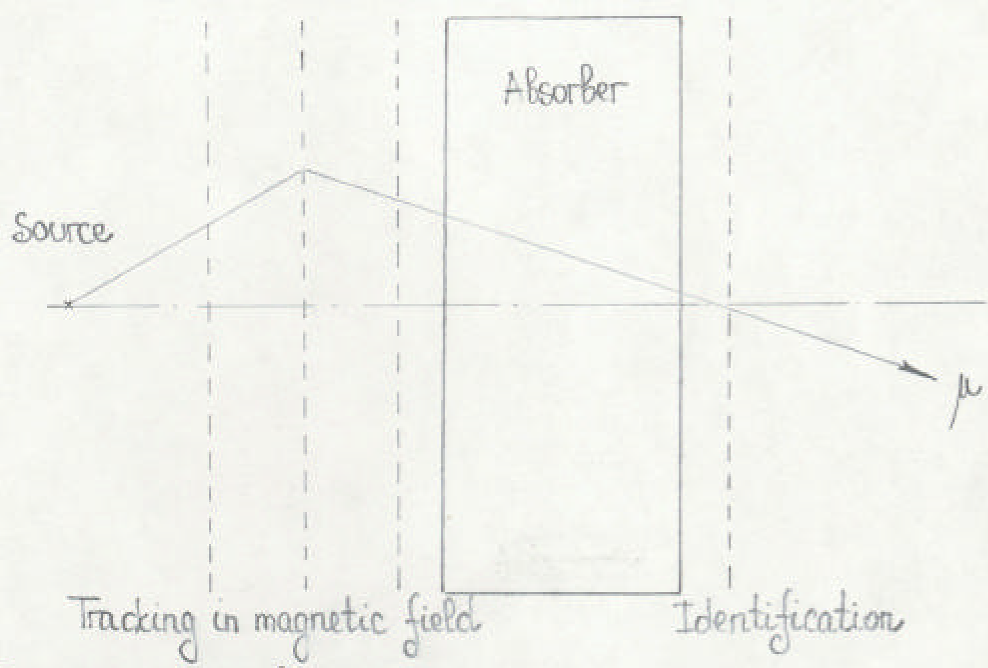
Multiple scattering — Tracking detectors

- **Example of muon momentum resolution for L=2m, σ_x=0.5mm and a=2m**



How to Improve σ_p/p

- Reduce multiple interaction term by bending muon in air, not in iron:
  - after target (fixed target)
  - in the central tracker (colliders)
  - in large air core magnets (colliders)



- Improve detectors:
  - 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.
- **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

Tracking Detectors

- There are two major requirements for 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

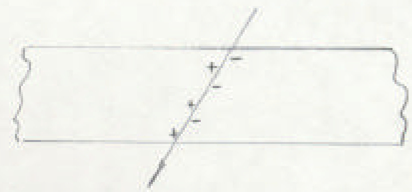
- Used before/after absorber for muon identification/triggering, rarely for momentum measurement
- Typical size 0.1m x 1m x 1cm
- Muon deposits ~2MeV of energy in a counter, which converts into 20-200 photo electrons for a typical phototube
- Major parameters of scintillation counters:
  - very fast s_t ~1ns
  - easy to make of any size
  - inexpensive in operation
  - due to high muon energy deposition less sensitive to backgrounds

  …but

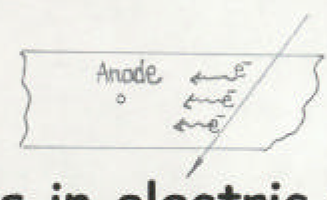
  - expensive per m^2
  - coordinate resolution is s_x>1cm

Gas Detectors

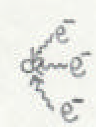
- Gas wire detectors are most commonly used for muon tracking:
  - drift tubes
  - cathode strip chambers (CSC)
- One of the best references is F. Sauli, Preprint CERN 77-09, 1977
- Principle of gas avalanche detectors operation:



  - muon creates one electron-ion pair per 30eV of deposited energy, 100 pairs per cm of gas



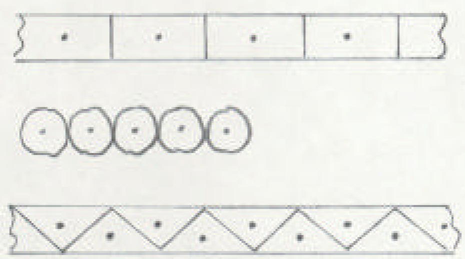
  - electrons in electric field drift to the small diameter anode wire



  - gas amplification (~10^6) occurs near anode wire providing detectable signals (~$1\mu A$)

Drift Tubes

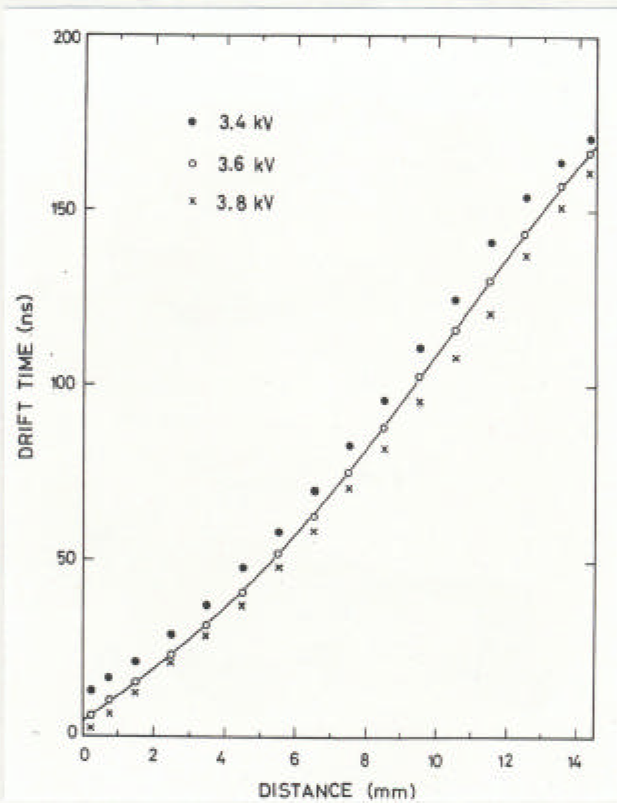
- Drift tube tracking detector consists of array of cells with anode wire in the center:
  - sizes ~1-10cm^2
  - total number of cells ~10^4-10^5
  - individual chamber (up to 10m long) consists of ~10^2-10^3 cells



- Advantages of such scheme:
  - broken wire is localized inside cell
  - detector is made of simple repetitive cells with properties defined by individual cell
  - cell walls create self supporting detector element

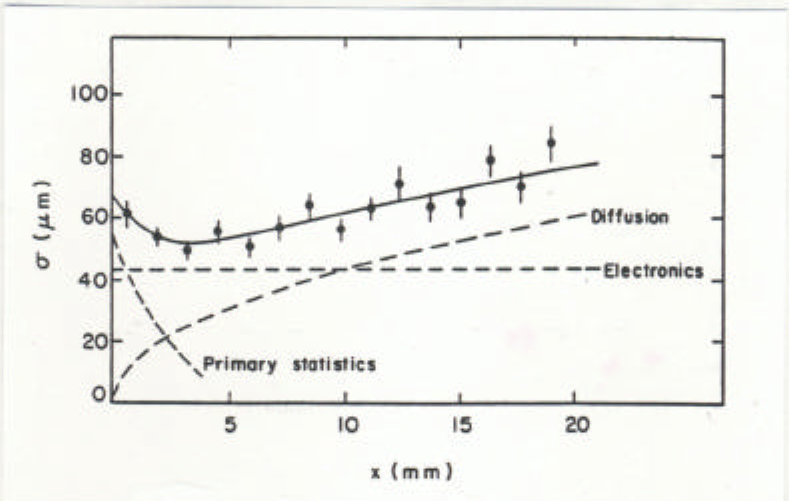
Drift Tubes (cont)

- In order to define muon location with high precision electron drift time is measured
- Determination of drift time to distance relation is done by Monte Carlo and/or test beam measurements



Drift Tubes (cont)

- Factors limiting coordinate resolution of drift detectors:
  - electronic noise
  - electron-ion pairs statistics
  - diffusion



- Drift tubes coordinate resolution:
  - typical ~ 0.2mm
  - best ~ 50μm
- In addition to physics limitations "mechanics" of the detector could affect coordinate resolution: wires location

Alignment of Tracking Detectors

- In order to measure muon tracks with high precision, exact location of wires (cells) is required:
  - temperature variations
  - movement ("sink") of heavy objects
  - complications due to detectors sizes and lack of space (hermeticity)
- Major ways of alignment:
  - passive - detectors location is determined before the run by (optical) survey and these data are used for data analysis: ~0.5-1mm
  - active - continuing monitoring of chambers locations by system of sensors (lasers beams, etc.): <0.1mm
  - self calibration - muon tracks are used to determine final location of detector elements

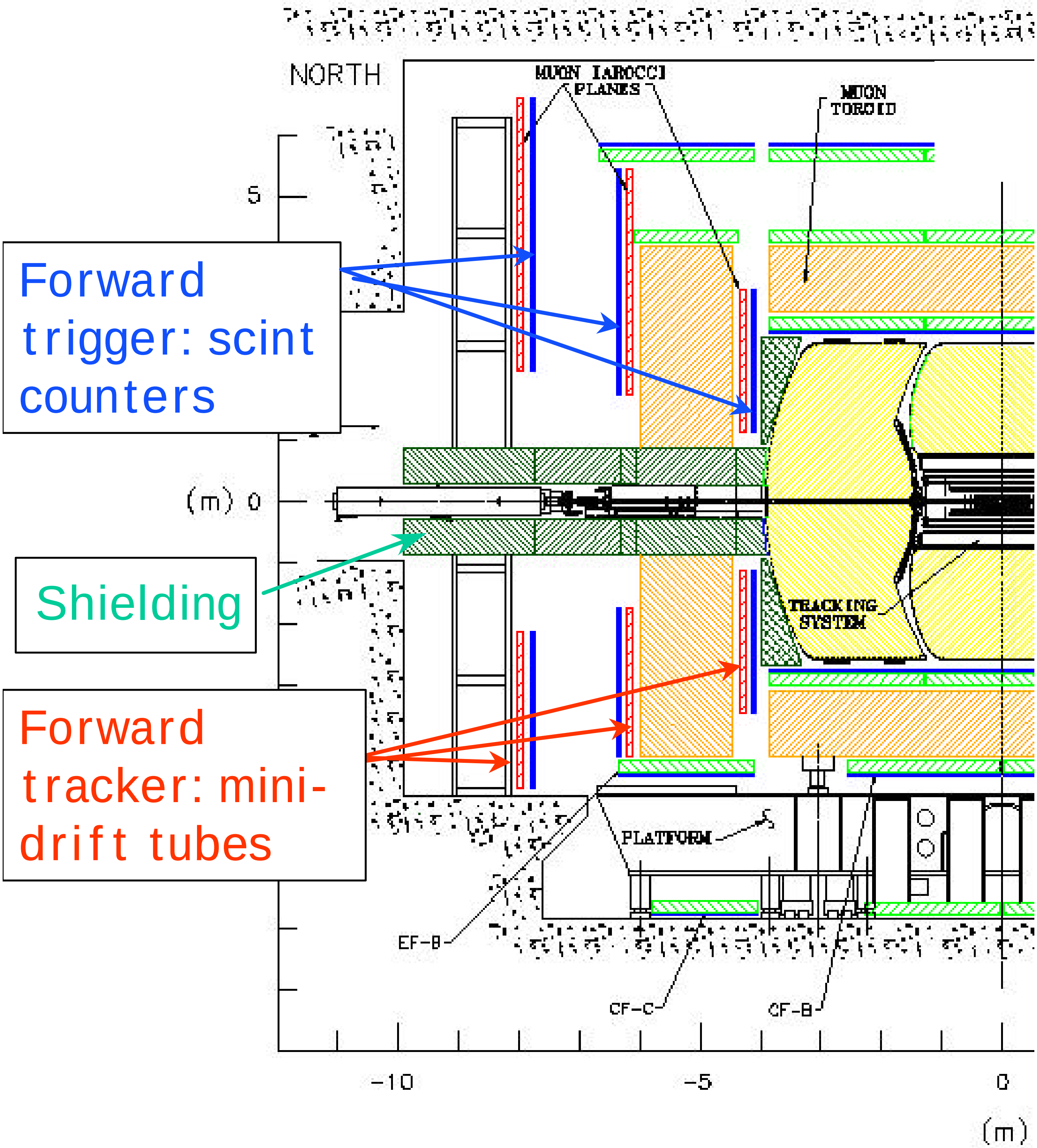
Shielding of Muon Detectors

- During HEP experiments in addition to "useful" particles large amount of background particles are created:
  - particles coming from accelerator beam losses
  - spectators interactions (showers) with accelerator and detector equipment
  - neutrons
- Muon detectors are sensitive to backgrounds because:
  - have large area
  - gas detectors have low (~1keV) threshold
- Most common way is to install thick shielding to absorb backgrounds:
  - steel to catch hadrons
  - poly to absorb neutrons
  - lead to reduce gamma fluxes
- Even moderate shielding could provide factor of ~10^2 reduction in number of background hits

D0 Muon System

- **Absorbers:**
  - calorimeter and steel toroid: 15 l
  - punchthrough less then 10^{-5}
- **Detectors:**
  - tracking: drift tubes with 1mm resolution, 3 layers
  - trigger: scintillation trigger counters, time resolution 1ns
- **Momentum resolution (muon system only):**
  - multiple scattering limit is 18%
  - s_p/p is ~50% at 200GeV/c

D0 Muon System Upgrade



Muon Detection - Summary

- Muon detection is based on ability of muon to penetrate thick absorbers with minor energy losses
- Muon spectrometer momentum resolution is limited by multiple scattering in absorber and coordinate accuracy of tracking detectors:

$$s_p/p = (s_{ms}^2 + (s_x p/b)^2)^{1/2}$$

- Due to the size of muon systems ($\sim 10^3 m^2$) scintillation counters and/or gas detectors are used
- Backgrounds estimation is important and shielding installation may be necessary
- Precision determination of detectors location is achieved via alignment
- For very high energy muons (above 0.2TeV) electromagnetic radiation becomes an issue