Configuration of a muon system for ILC
(based on experience with the D0 muon system)

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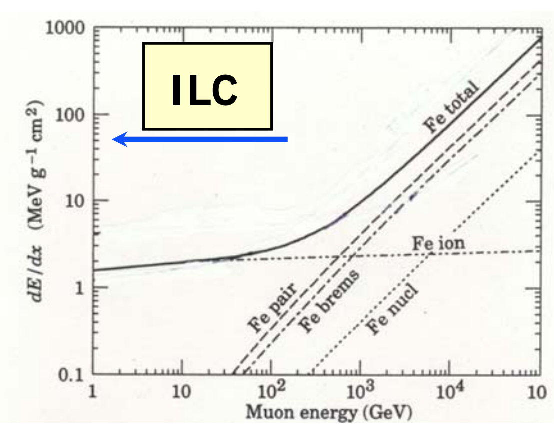
- Why muons?
- D0 muon system
- Possible configurations of a muon system for ILC detector
- Costs
- Lessons from running D0 muon system
- Summary

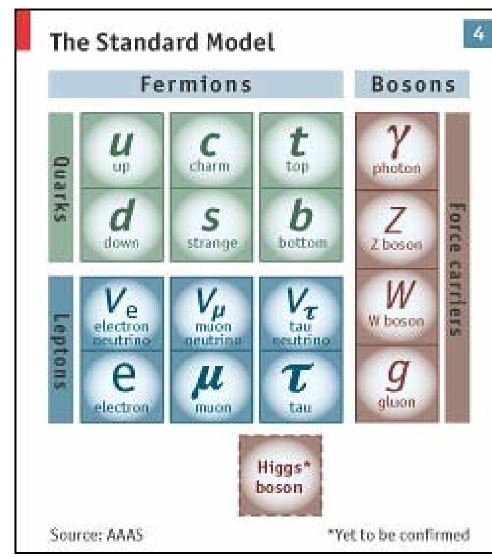
Why muons?

- Muon is one of 3 fundamental charged leptons
- Muon is "stable" (lifetime is more then detector size/c)
  - 2.2μsec or 660 meters $*\gamma$
- In many cases muon provides information directly about hard collision
  - Decay of heavy objects (helped with many discoveries)
  - Not complicated by hadronization
- In detector muon looks like series of densely produced clusters of ionization and can penetrate a lot of material (meters of steel)
  - No hadron interactions
  - Heavy enough not to radiate at typical ILC energies
  - "easy" to trigger and reconstruct
  - Could be detected inside jets

Base for identification



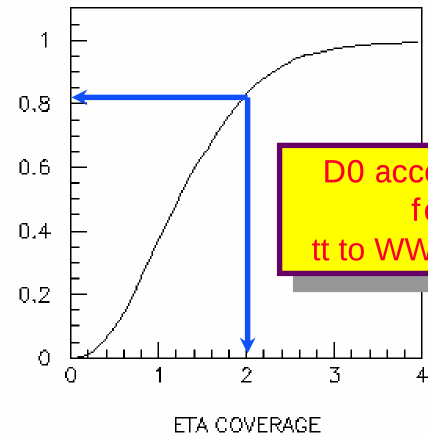
W to μν
Z to μμ
t to Wb to one or more μ
J/Ψ and ϒ to μμ
SUSY, Higgs



Major Specifications for Muon Detectors

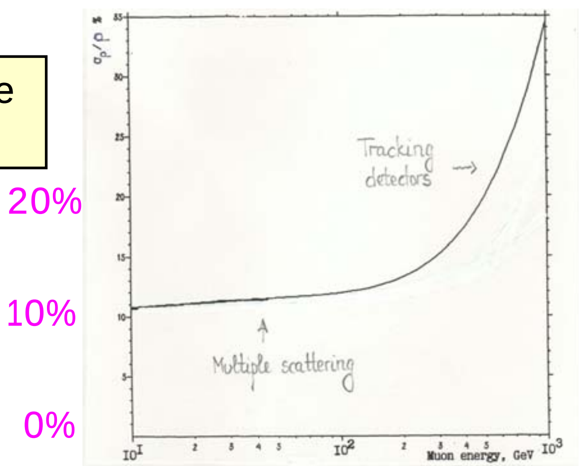
- Solid angle coverage (rapidity coverage)
  - For heavy objects acceptance is proportional to solid angle coverage
  - No “holes”
    - Loss of detection efficiency
    - Loss of missing E_t resolution
  - b/c quark kinematics
    - Advantages in forward coverage
- Momentum resolution (muon system only measurement)

  $\sigma_p/p \sim (p \cdot \sigma_{det})/(B \cdot L_{det}^2)$ & multiple scattering
  - Limited by coordinate accuracy of detectors, magnetic field, lever arm and multiple scattering
  - In most cases muon momentum resolution relies on central tracker for precise momentum determination
- Punchthrough probability
  - ~15+ interaction length (typical for all ILC detectors) of absorber plus directional match of hits reduce non-muon backgrounds to very low level
  - Particle flow calorimetry could provide extra rejection

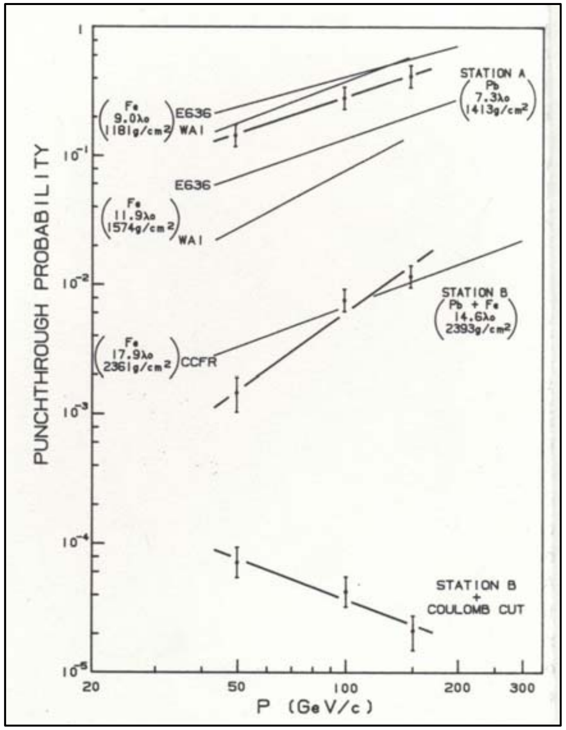


D0 acceptance for tt to WWbb to $\mu\mu$

Muon stand-alone resolution



π punchthrough probability: test beam

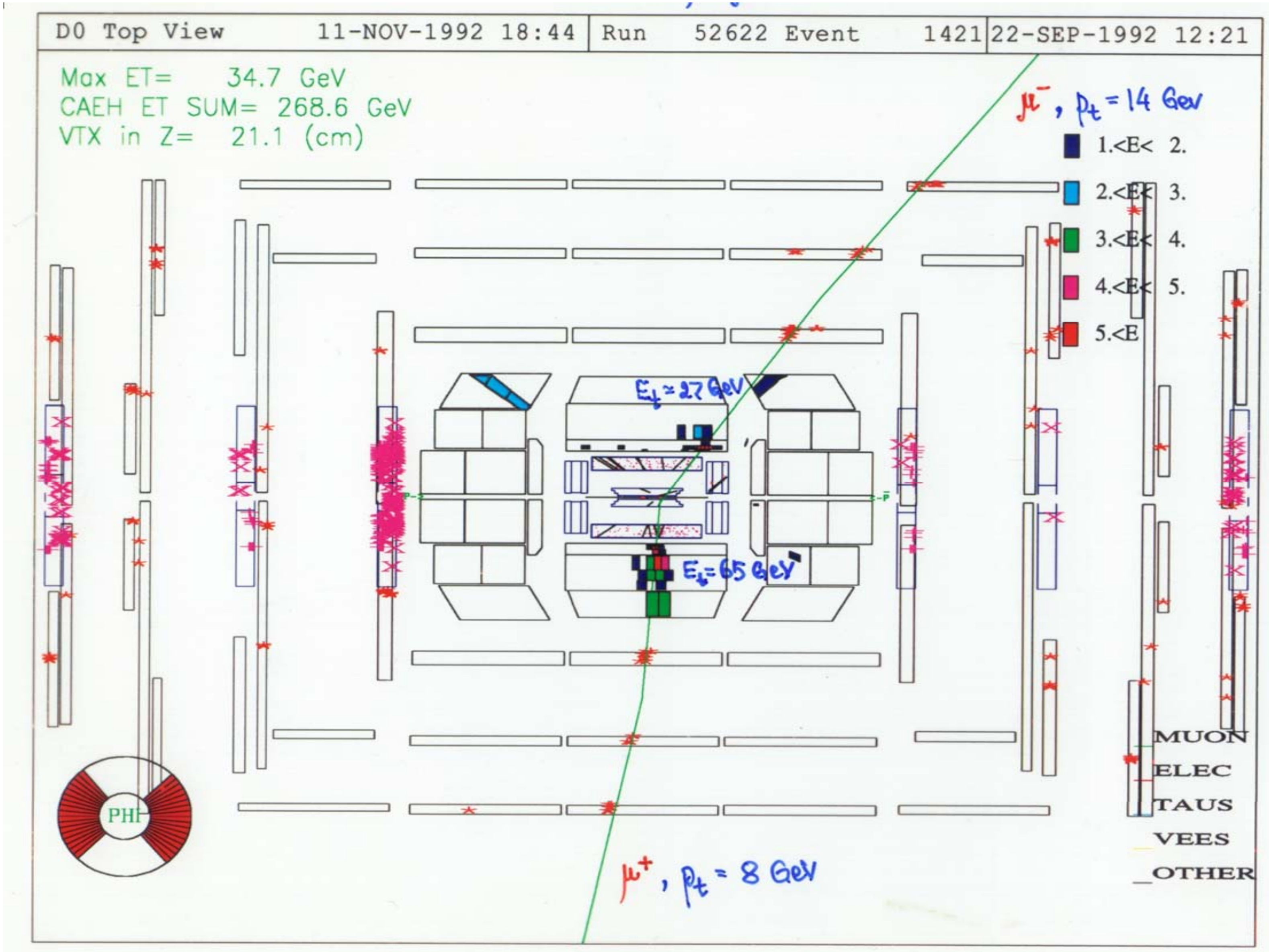


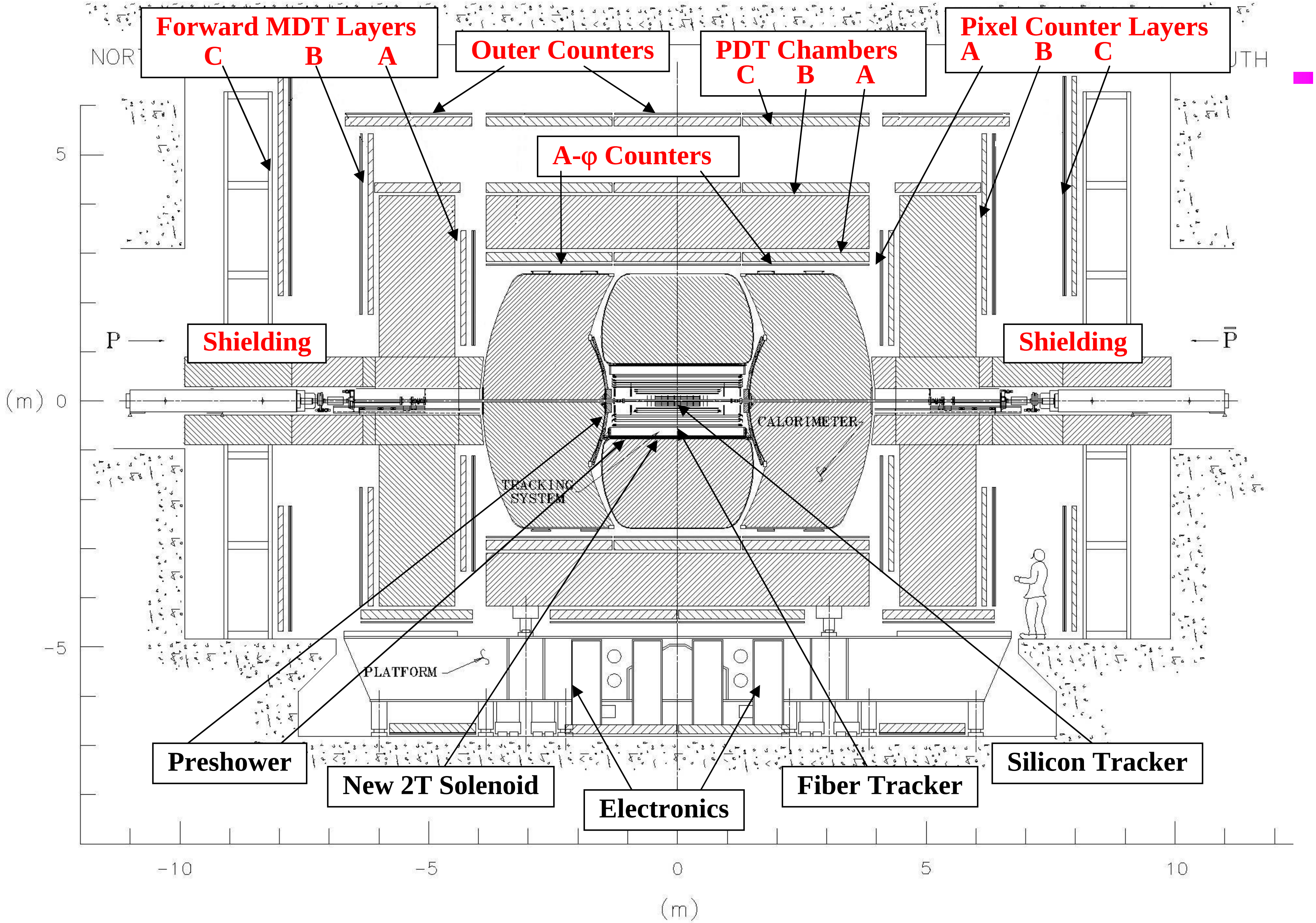
Major Specifications for Muon Detectors

- Appropriate coordinate and time resolution
  - Coordinate resolution: identification vs momentum measurement
    - Defined by multiple scattering: ~1mm for 100GeV/c muon after 1m of steel
  - Bunch synchronization and backgrounds rejection
- Radiation hardness
  - While muon systems are usually located behind considerable amount of material careful studies and monitoring of radiation aging effects is important
- Shielding of muon detectors from accelerator and collisions related backgrounds
  - More later in the talk
- Triggering
  - Less of an issue for ILC vs hadron colliders
- Reliability of muon detectors and electronics
  - Long periods of operation
    - 20+ years
  - Very difficult to access places
    - Hermetic detectors
  - High cost of shutdowns/accesses
- Construction cost and schedule
  - Design, assembly, commissioning
- Reasonable operating costs

Actual detector built is always compromise between above in some cases contradictory requirements and limited resources available

D0 Run I "Typical" Muon Event

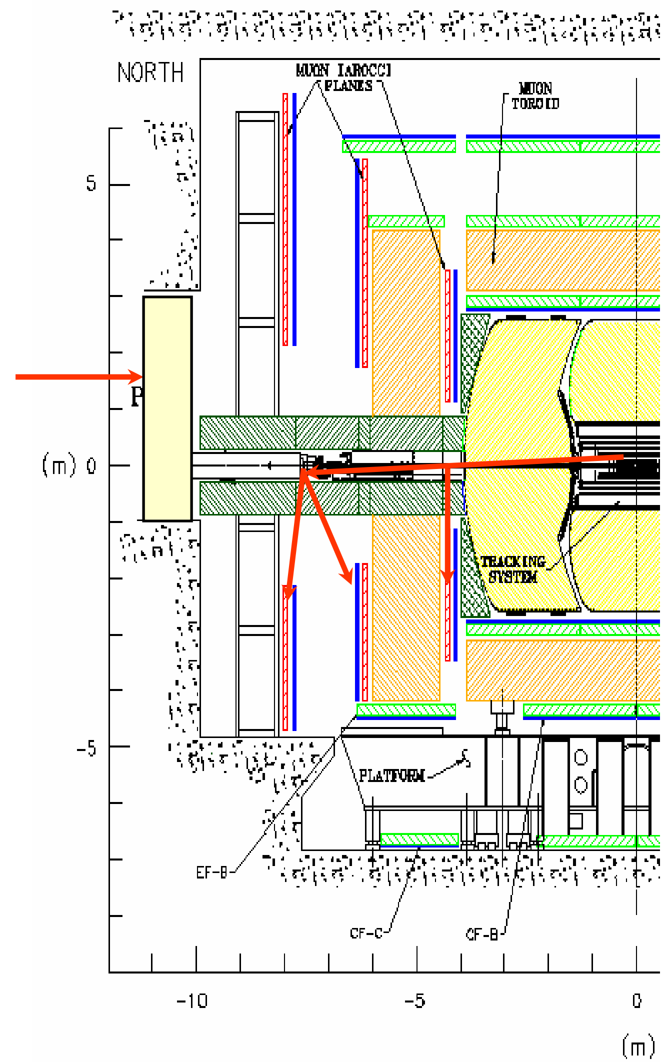




Run II D0 Detector

Muon Detectors Shielding

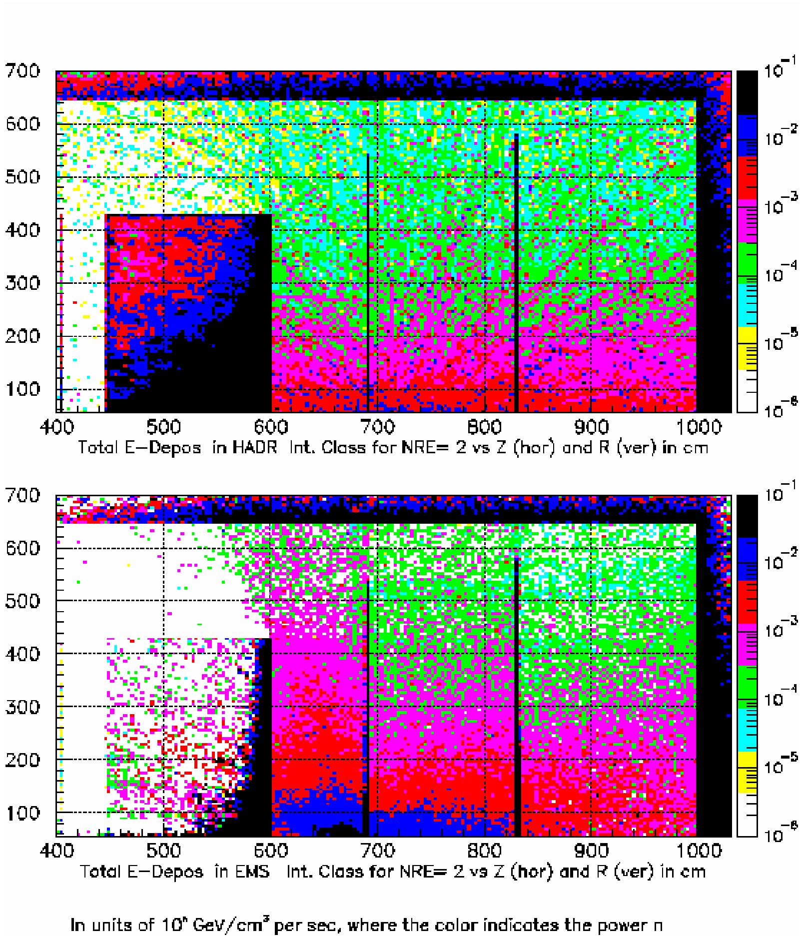
- There are two major sources of backgrounds (non-muon) hits in muon detectors
  - Background particles coming from the accelerator tunnel
  - Background particles originated in interaction region
- Tunnel backgrounds can be substantially reduced by placing shielding around beam pipe
  - And filling the tunnel just before the collision hall
- Calculations based on GEANT/MARS codes demonstrate reduction in particle fluxes for shielded/unshielded detectors by a factor of 50-100 for D0
  - D0 Run II muon detector occupancies are in the 0.05-0.1% level in good agreement with calculations
- ILC muon detector background fluxes
  - With proper shielding(s) in the tunnel muon fluxes are similar to cosmic
    - See Mokhov's talk on Monday
  - Have to carefully estimate hits from neutrons coming from the tunnel/accelerator
    - See Mokhov's talk on Monday
  - IR backgrounds in the forward region have to be estimated
    - Proper shielding might be needed
  - Occupancies from backgrounds below ~1% are usually acceptable



Shielding

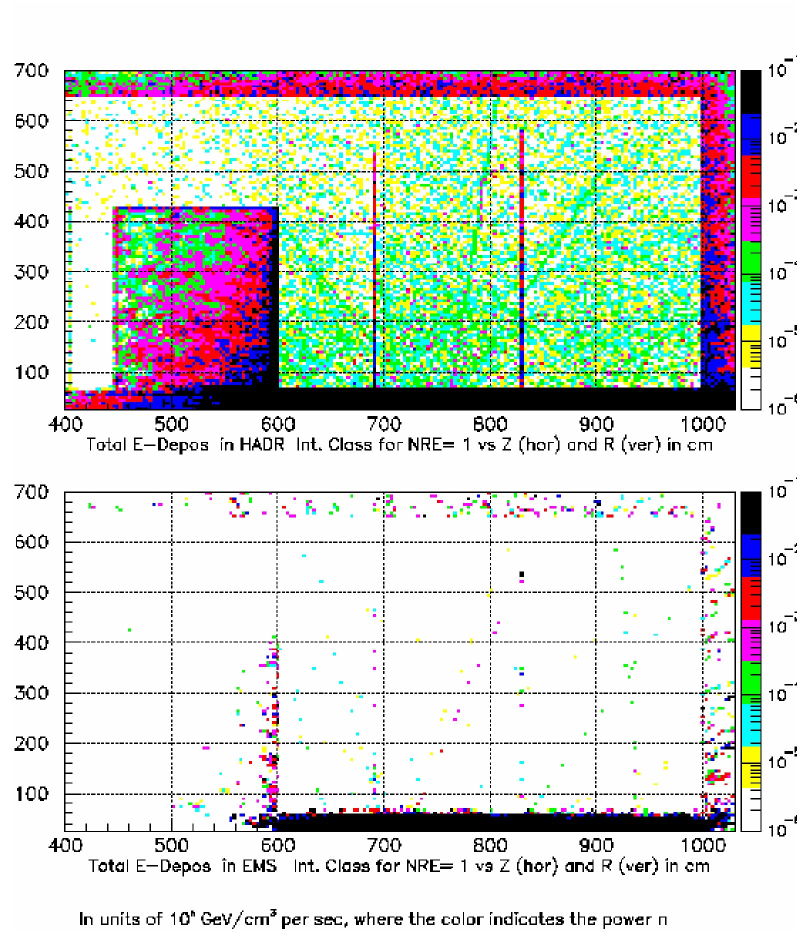
Effect of the D0 muon shielding on background fluxes:

factor of 50-100 reduction



Hadron

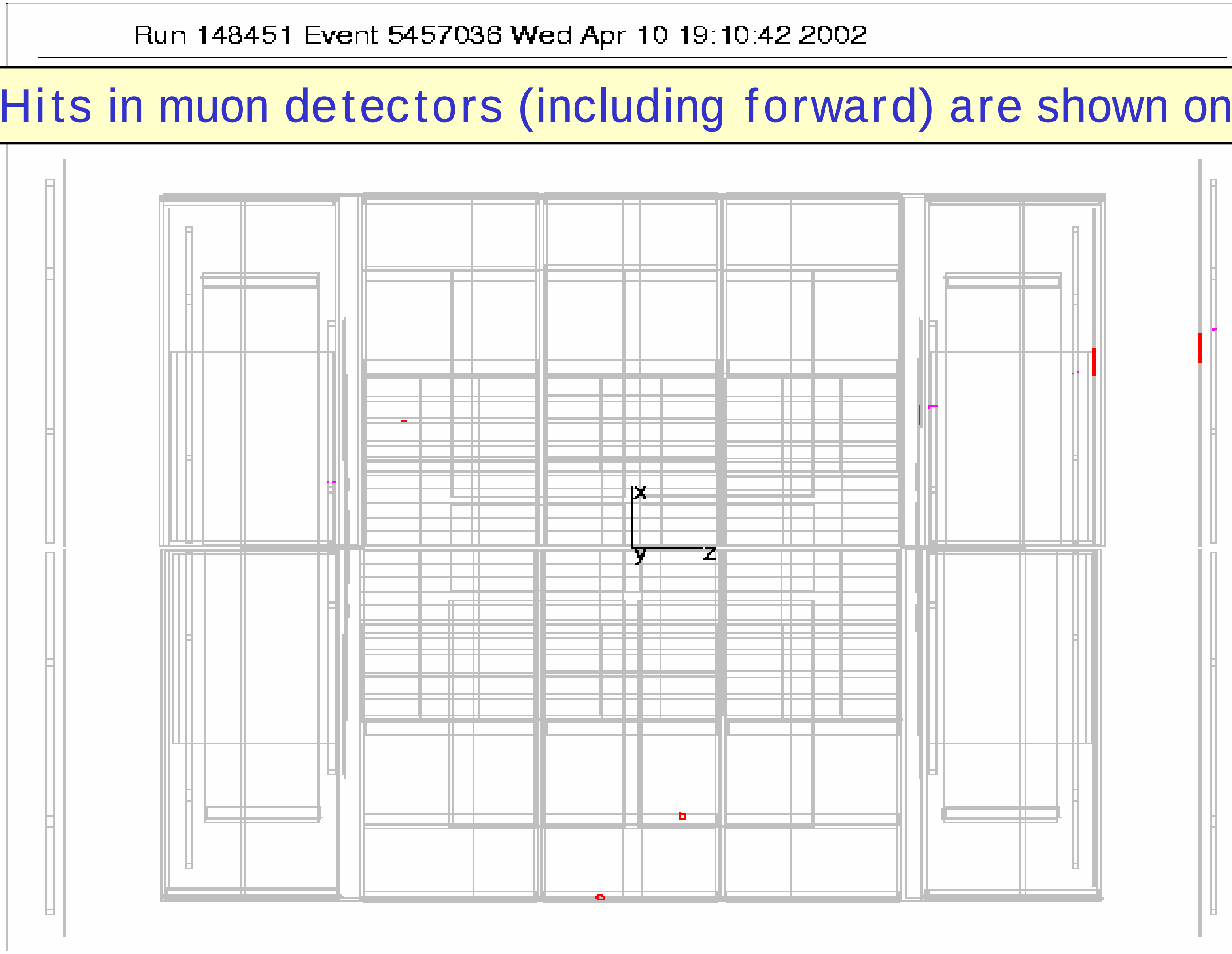
e/gamma



Without Shielding

With Shielding

Single Muon Run II D0 Event

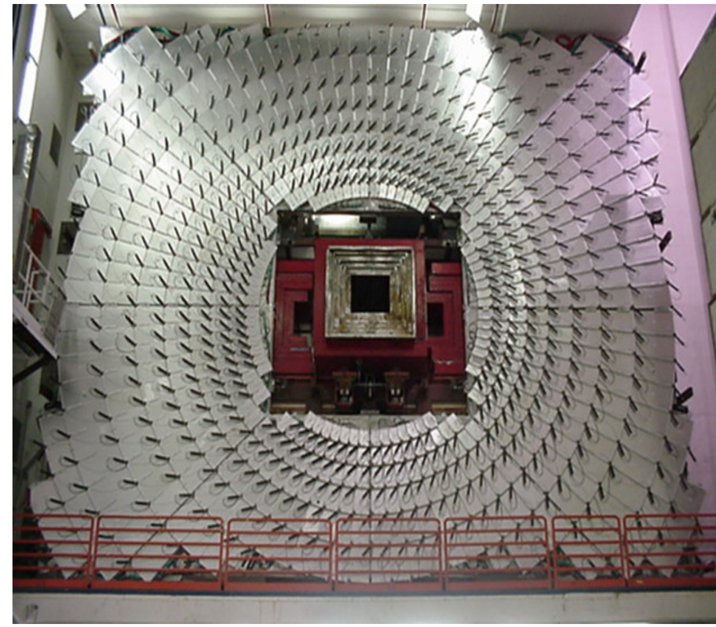


Hits in muon detectors (including forward) are shown only

MARS/GEANT predictions for number of hits (fluxes+detectors sensitivities) are in good agreement with observations – important fact for ILC detectors design

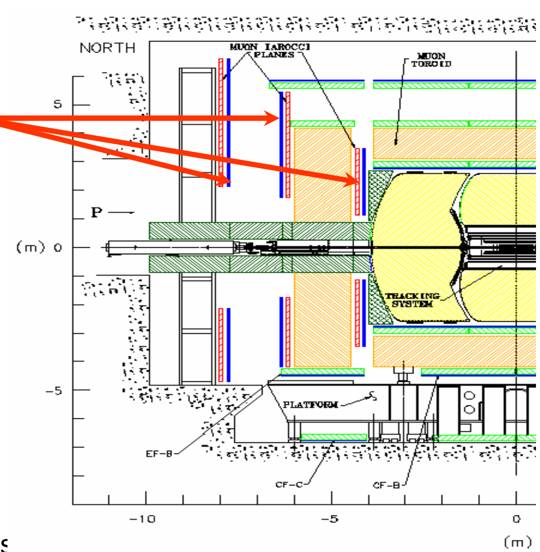
D0 Forward Muon Trigger Scintillation Counters

- 3 planes of ~10x10m^2 (about ILC size) on both sides of the interaction region
- Counters arranged in R-ϕ geometry
- Total number of counters 4608
- Major features
  - Fine segmentation
  - Time resolution of ~1ns to separate muon hits coming from the interaction region from hits from cosmic and accelerator related backgrounds



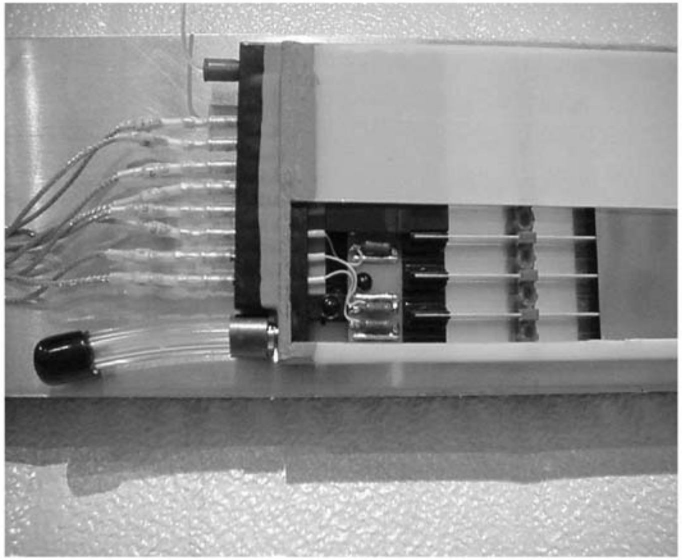
10x10m^2 plane of counters assembled in *"fish scale"* design

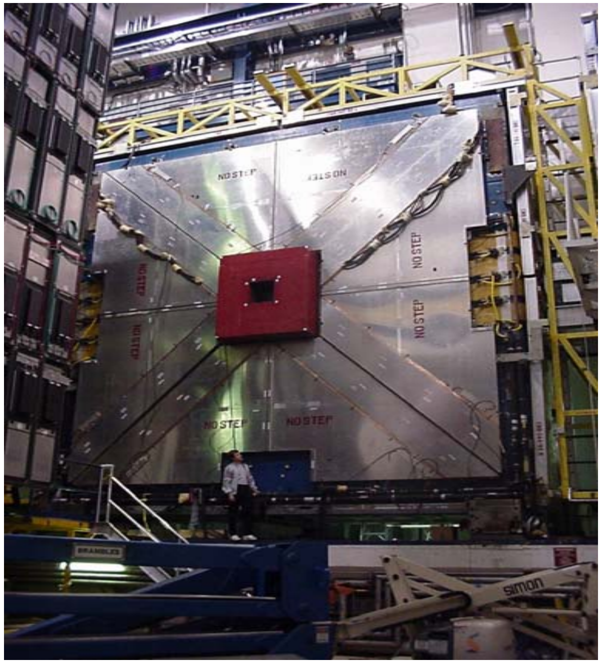
Forward Counters



D0 Forward Muon Tracking Detector

- Forward muon tracking detector is based on mini-drift tubes
  - $1x1cm^2$ drift cell
  - 8 cell aluminum extrusion with 0.7mm thick walls





•Tubes are assembled in 8 octants per layer with wires parallel to magnetic field lines

•Total number of wires in the system is 50,000

• There are 4 planes of wires in a layer before toroid and 3 planes of wires in each of two layers after toroid

- muon track has ~10 hits on average

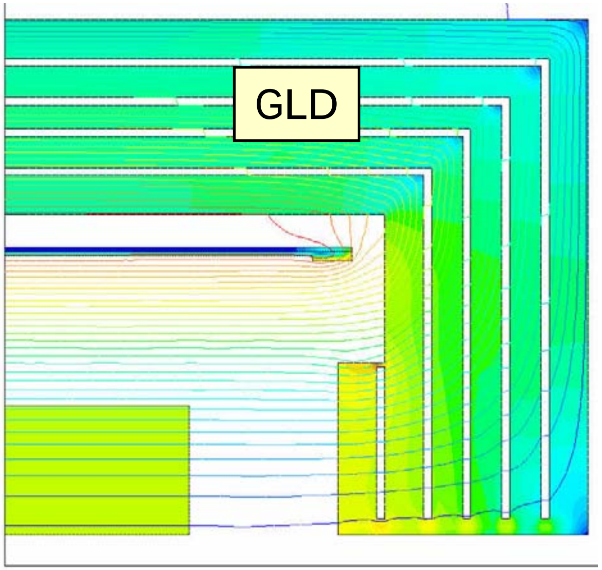
Cosmic Rays and Triggering

- Cosmic rays
  - While flux is “small” sensitive area of the ILC detectors is large and time window is years, so care should be taken to reduce cosmic ray backgrounds
    - ~30Hz single muon trigger rate at D0 is due to cosmic (above ~3GeV/c plus some directional cuts)
    - Most powerful cosmic rejection tools are timing of the hits and precise tracking near vertex
  - Cosmic is good for detectors tests (not only muon system)
  - If ILC detector(s) are deep underground cosmic might be less of an issue/help

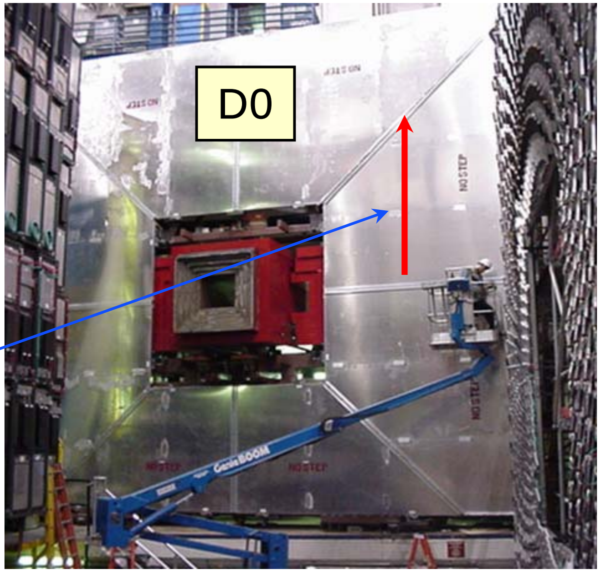
- Triggering
  - While total interaction rate at ILC is very low the beam structure requires understanding of how small number of events with interactions (plus calibration events) are written to tapes
  - ~400ns apart bunches are reasonably easy to separate for almost any type of the muon detectors
  - Bunch trains of ~1ms with ~200ms interval between them define architecture of a trigger/DAQ system

Magnetic Field and Iron

- Return flux steel is used as absorber for muon identification and could be used as magnet for stand-alone muon tracking
  - Total flux is defined by solenoid ~10^2 Tm^2
  - Field in the barrel is ~1T (vs ~2T saturation)
  - Field in the forward direction
    - Very non-uniform
    - Parallel to muon trajectory (no bending power) – this is why D0 uses toroids



How thick iron should be?
Flux return
Punchthrougth
Stand-alone momentum measurement?
Shielding from "outside" backgrounds?
D0 has ~1.5m iron magnet – works fine

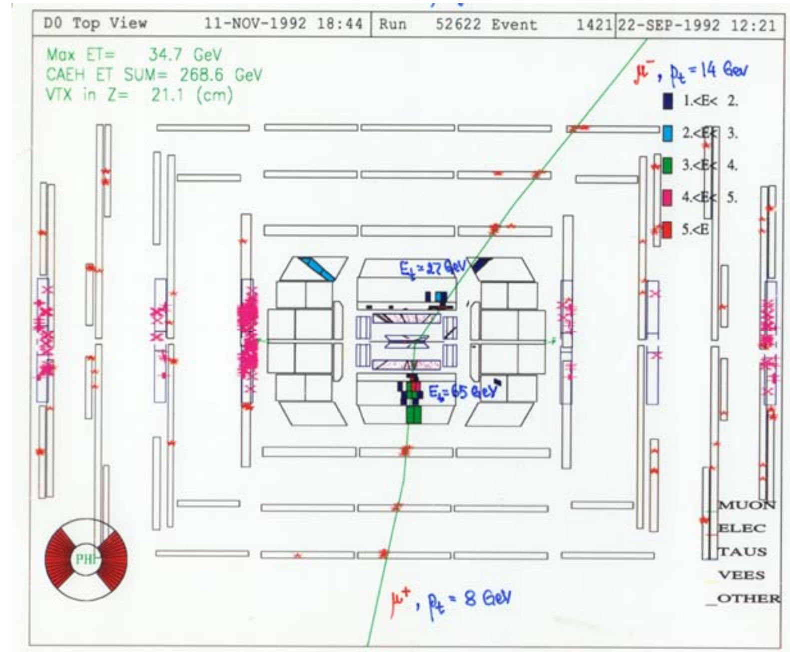


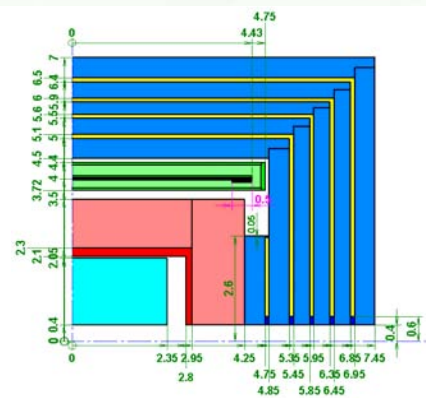
In order to measure muon momentum sensitive elements of the muon detectors should be parallel to the field lines

How Many Muon Detector Layers?

- Definition: one layer provides single muon hit detection (may be in more then one dimension)
- Minimal version
  - Track is measured in central tracker: 4 vector
  - Muon system is used only as "confirmation" after ~15λ
  - ~4+ layers on the outside part of the iron
- Muon system which provides stand-alone triggering/tracking
  - Detectors in multiple iron gaps
  - ~6+ layers sound sufficient
- Tail catcher and muon stand-alone momentum measurement
  - Continuation of digital calorimetry?
  - ~10+ layers

- Optimization based on overall detector design and set of physics processes with some safety margin for backgrounds, issues with detectors, etc. and cost(!) is needed to select optimal design





GLD is between minimal and stand-alone versions

Cost Estimate

- Cost estimate is based on actual costs of the D0 forward muon tracking system as of 2001 with 10 years of inflation extrapolated
  - Detectors (drift tubes, 1x1cm^2) : $1.2M
  - Detectors mounts: $0.7M
  - On-chamber electronics: $1.2M
  - Digitizing and readout electronics: $0.9M
  - Total: $4.0M
- Total cost per m^2 is ~$2k
- “European” cost estimate – no cost for Labs/Univ. physicists/engineers/techs, except for electronics where full assembly cost included
- How this will translates into one layer of GLD (largest sizes of ILC detectors)
  - Total layer area (central and forward) is ~1,200m^2
  - Cost per layer ~$2.5M
- Minimal version (4 layers) ILC muon system cost is ~$10M
- Above cost includes detectors and all electronics, but does not include iron
  - Iron might be re-used: decommissioning detectors/accelerators, battle ships, etc.

D0 Experience – Reliability and Experts

- Muon systems are typically very complex with large sizes and difficult to access areas – reliability is critical
  - How to handle failures have to be addressed on design stage (access, segmentation, etc.)

- One of the most serious reliability issues for D0 muon system was low voltage power supplies!?
  - Modern supplies are more then transformer and four diodes…
    - High tech with very high power produced in small volume
      - Needed for fast high power front-end electronics
    - Never tested by manufacturers for reliability
      - Magnetic fields
      - Radiation doses
  - D0 muon system has ~400 individual low voltage power supplies in the hall
    - ~50 of them in front-end VME crates appeared sensitive to radiation
    - Before modifications D0 was loosing ~1 supply every month

- Availability of experts
  - Collider experiment muon systems are very complex with, unfortunately, relatively poor documentation
  - Construction/operation times are VERY long – 20+ years for D0 already!
  - In many cases departure of expert creates serious problems
    - Sometime it is easier to re-build project from scratch then to do “reverse engineering” (especially in firmware/software)
    - Simple issues might take months (years) to resolve

Critical to develop good documentation and continuity of system support including long term group based commitments

Summary

- Muon systems for ILC detectors are doable
  - And relatively inexpensive
- R&D on muon detectors
  - Optimize performance: time and coordinate resolution, sensitivity to backgrounds, etc.
  - Carefully study and document detector(s) parameters
  - High reliability
  - Reduce cost: detectors, electronics
- Optimization of muon system configuration should be done based on overall ILC detector design and
  - Set of physics benchmarks
  - Realistic description of detectors and electronics
  - Careful estimation (and if possible reduction) of backgrounds
  - Safety margin
  - Cost
  - Availability of groups able to take long term responsibility for the system construction, commissioning and operation