Muons: Lecture #2

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Lecture Organization

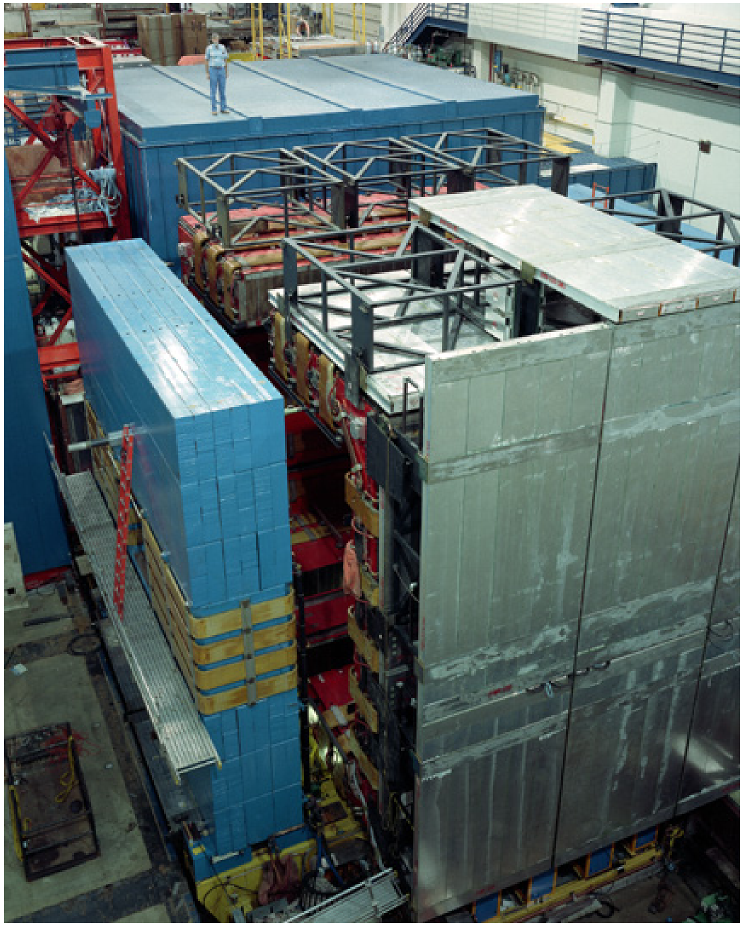
- Lecture #1
  - Why muons?
  - Sources of muons
  - Muon detection and reconstruction
    - With examples of muon detectors
- Lecture #2
  - Alignment
  - Muon ID
    - Using muon system features and other subdetectors to
      - Further discriminate muons from backgrounds
      - Identify different sources of muons
    - Efficiency measurement
  - Triggering
    - Particular considerations for muons
  - Commissioning

Alignment of muon detector elements

- In order to measure muon tracks with high precision, exact location of wires (cells) is required:
  - temperature variations
  - movement (“sink”) of heavy objects
  - Movement when magnets are energies
  - 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

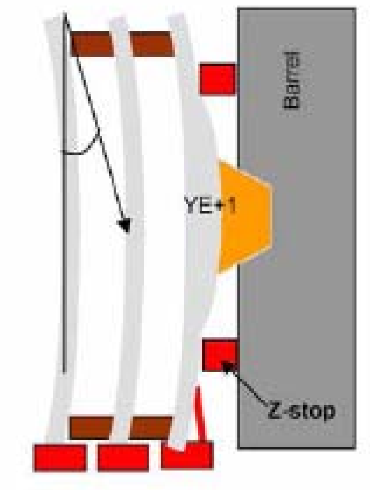
Example of alignment: DØ

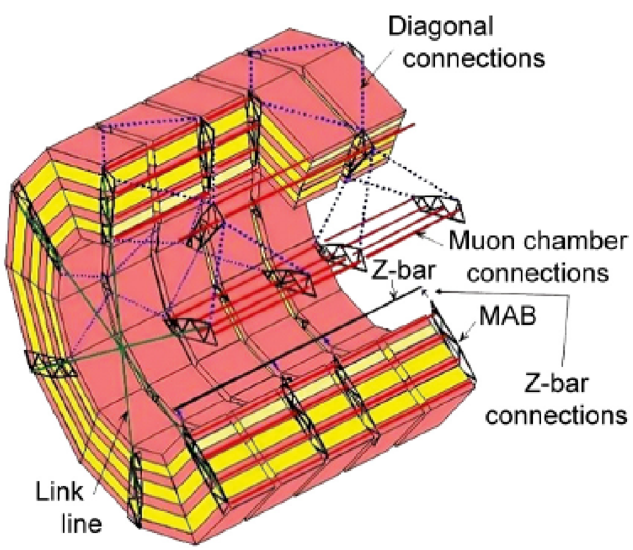
- Wires aligned to a precision of **~1mm** over ~8 m distances
- Survey information
  - Chamber survey during construction
    - Wire locations relative to fiducial marks
  - Optical survey after construction
    - Chamber location on large pieces of iron
    - Location of iron relative to central tracker
  - Electronic sensors
    - Proximity of iron pieces relative to each other, used during opening and closing to get iron back to previous position
- Checked with $W \rightarrow \mu\nu$ events



Example of alignment: CMS

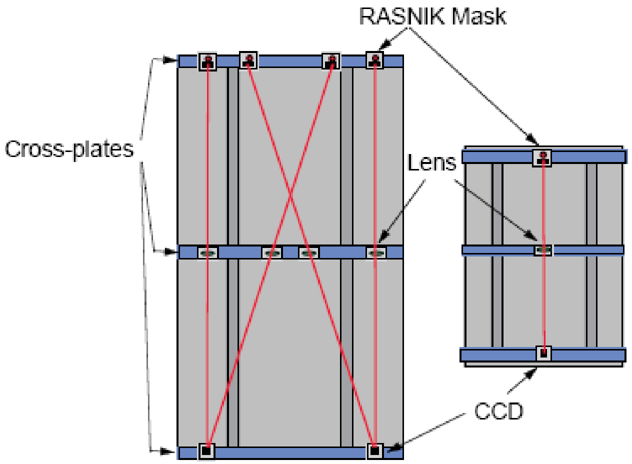
- Requirements:
  - 75-200 μm in end cap region
  - 150-350 μm in barrel
- Over distances of ~10 m
- Magnetic distortion: displacements at the level of more than a cm in some regions when solenoid is energized
  - Clearly, static survey is inadequate
- Continuous local alignment systems for barrel and end cap systems, plus a link system to relate muon and central track
- 10,000 LEDs, 150 laser beams, 900 photodectectors, 600 analog sensors



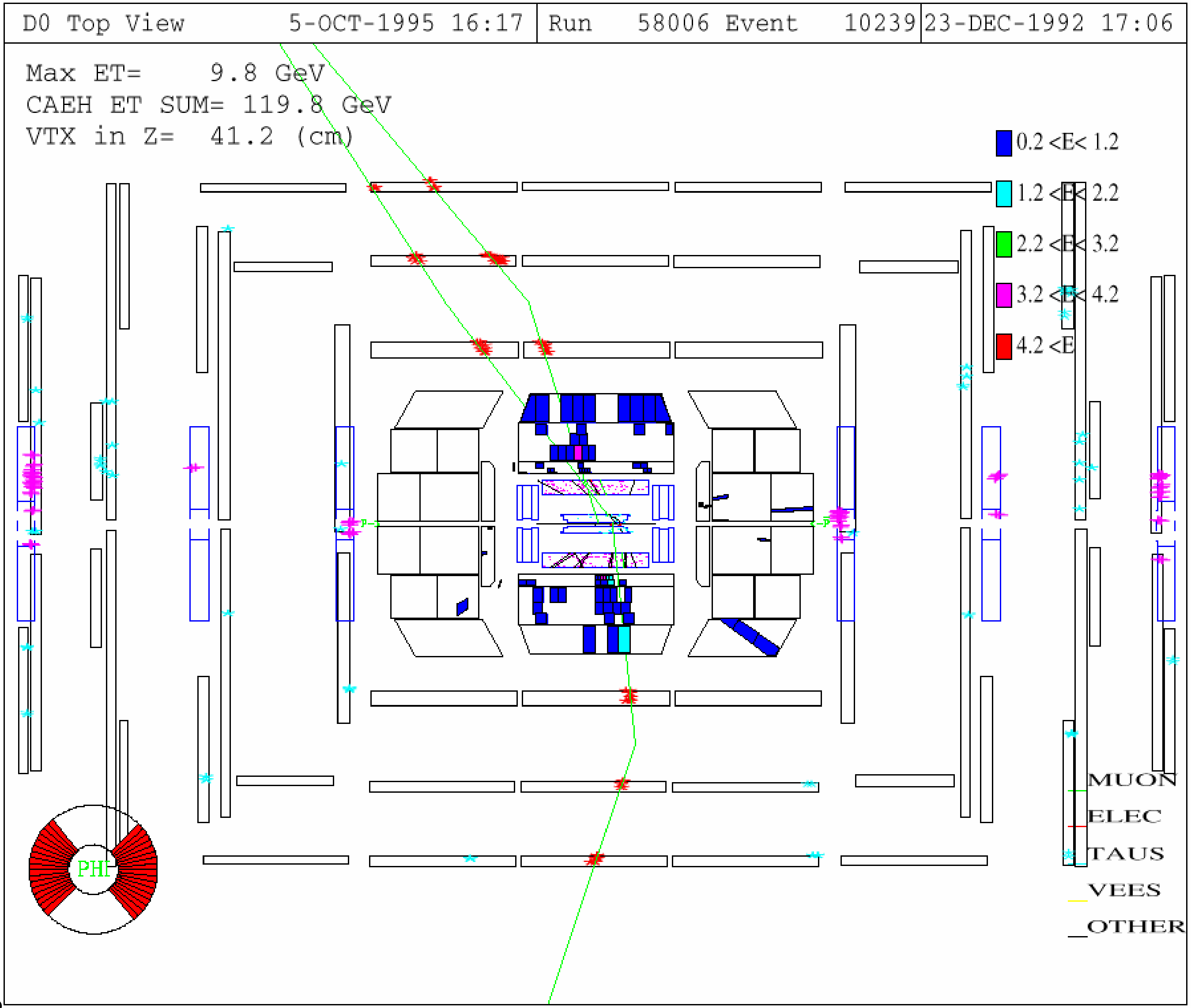


Example of alignment: ATLAS

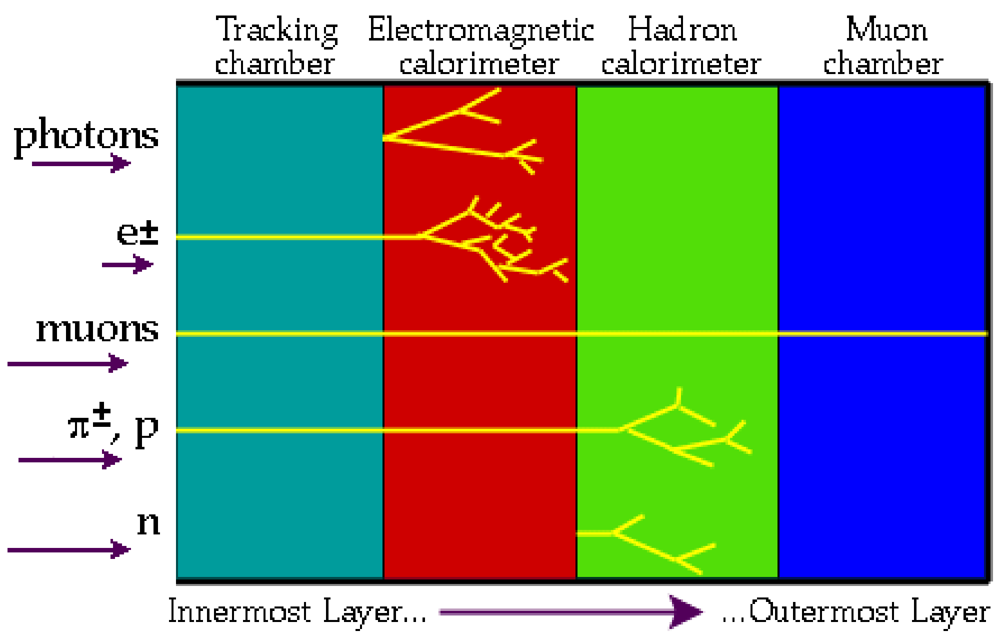
- Requirements
  - 30 μm accuracy
  - Over distances of ~20 m
- MDT = "monitored drift tubes"
  - Refers to constant position monitoring
- ~5000 alignment sensors
  - 10 μm precision
  - Example: RASNIK monitors for in-plane measurement of chambers

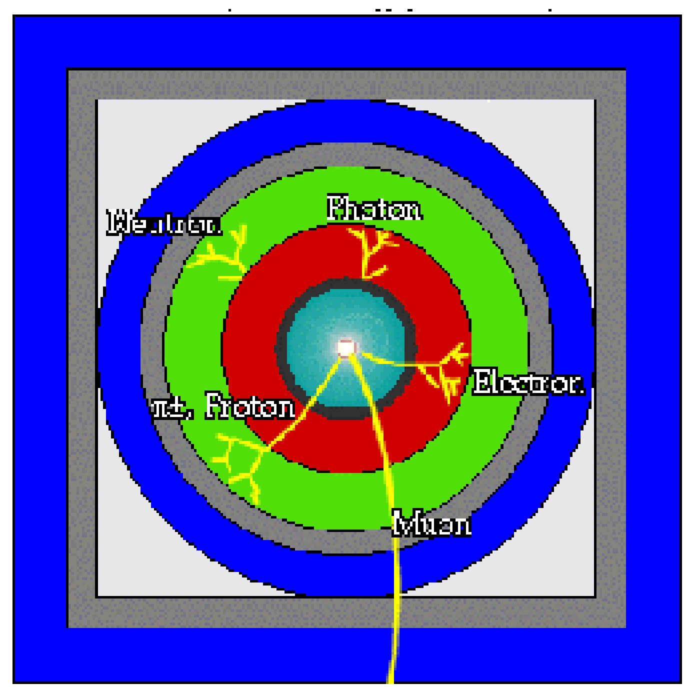


Identifying Muons



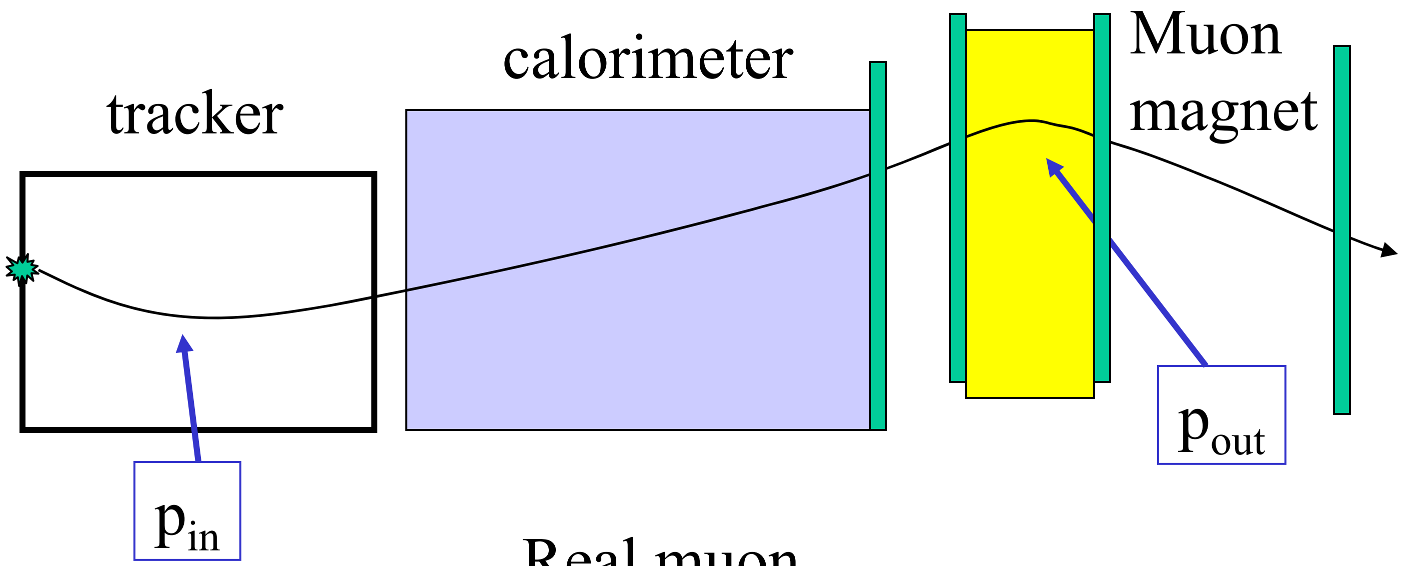
A Generic Detector System





Tracking chambers ⇒ trajectory of charged particles
Calorimeters ⇒ measure energy
  Electromagnetic: e, photon
  Hadronic: pion, K, proton,neutrons…
Muon Chambers ⇒ measure muon trajectory
Magnets ⇒ charged particles bend in magnetic fields. Bend depends on charge and momentum

Muon Signal

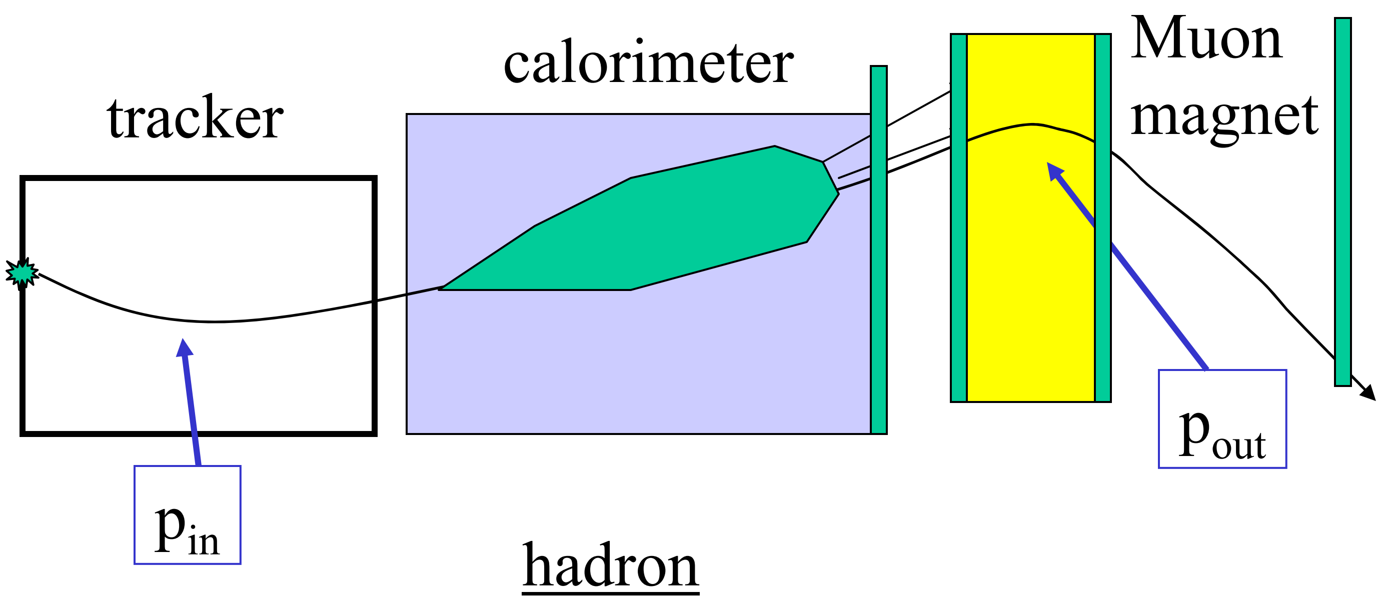


Real muon

$p_{in} \approx p_{out} + E_{loss}$ (muon ID tool)

Better resolution comes from tracker; p_{out} dominated by multiple scattering (or showering)

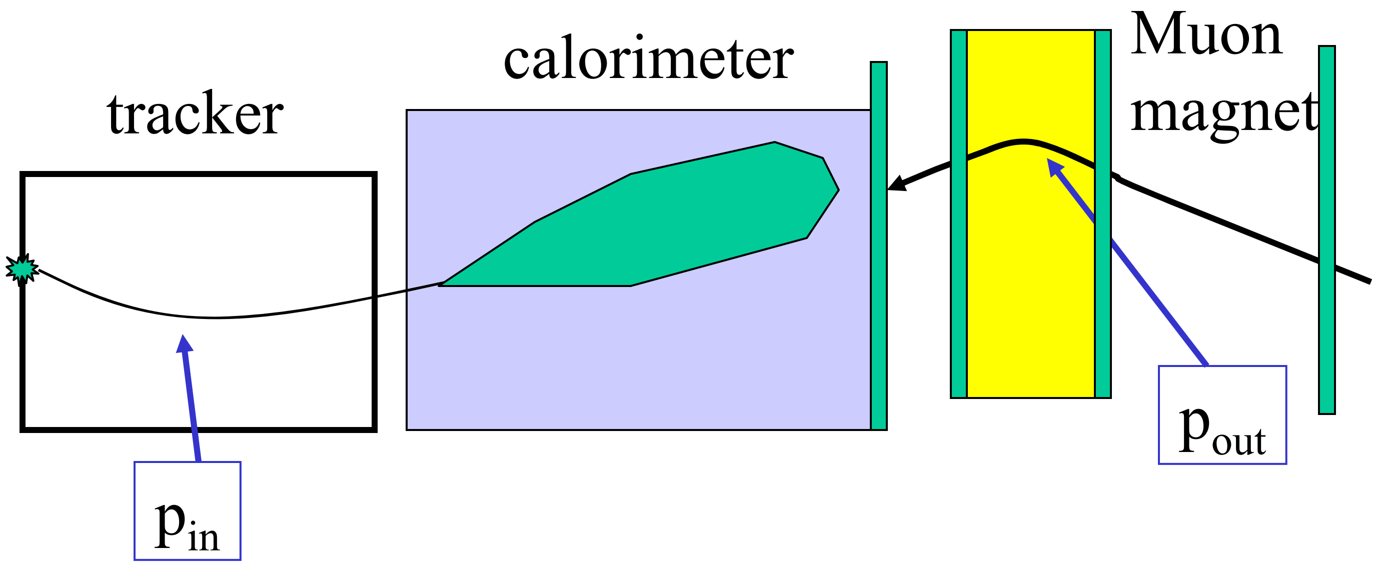
Muon background 1: punchthrough/decay



$p_{in} >> p_{out} + E_{loss}$

Outer decay/p.t. track points back to parent hadron, but momenta do not match.

Muon background 2: halo/backscatter

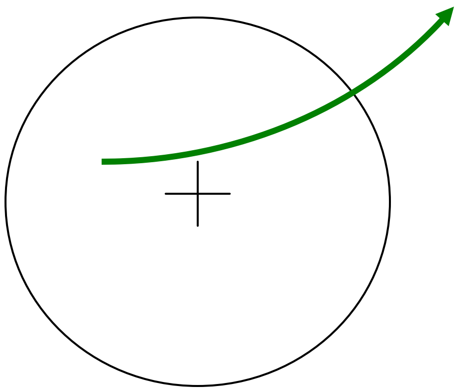


p_{in} ? $p_{out}+E_{loss}$

Good timing (scintillator) can get rid of most of these

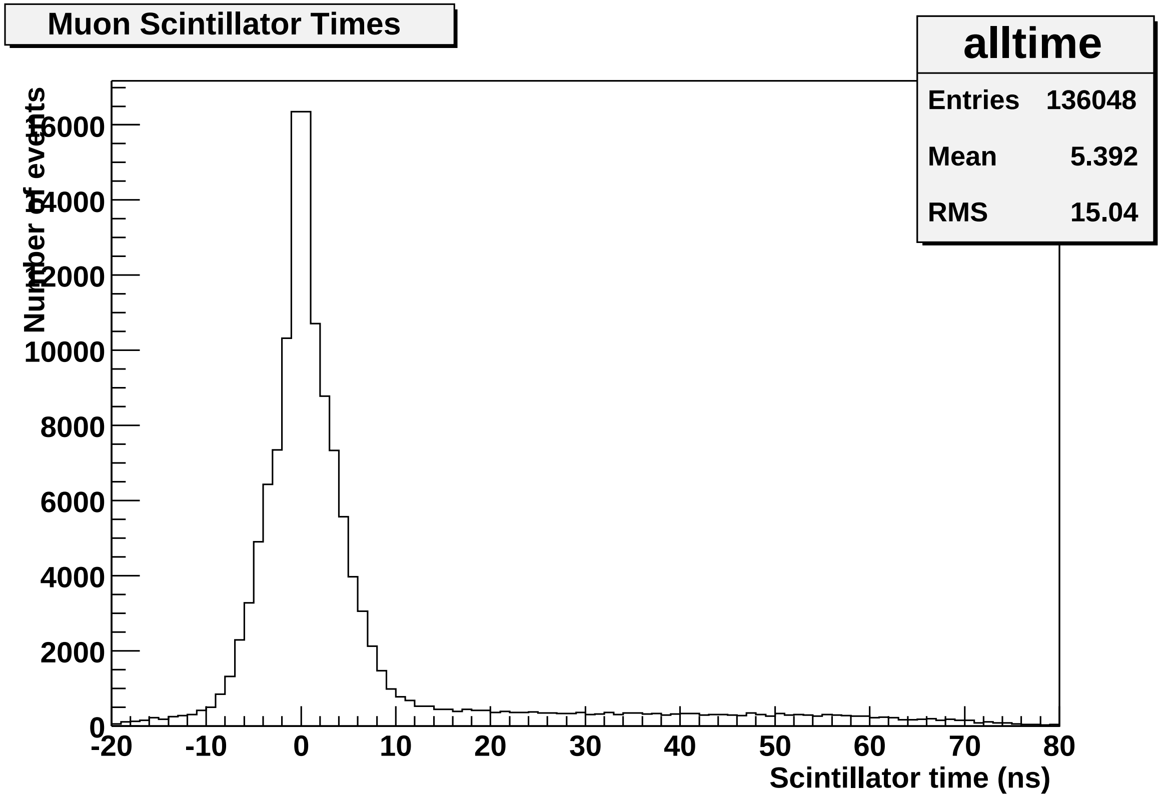
Common tools to reject fake/mismeasured muons

- Number of muon hits and fit quality (chisquared)
  - Rejects combinatorics, poorly measured muons
- Impact parameter to vertex
  - Rejects most cosmic rays, beam halo
  - Careful, can also reject muon from long-lived decays
- Spatial matching with central track
  - Improves momentum determination
  - Rejects combinatorics
- Timing (time of flight)
  - Rejects most cosmics rays, some beam halo
  - Careful, can reject hypothetical massive stable charged particles



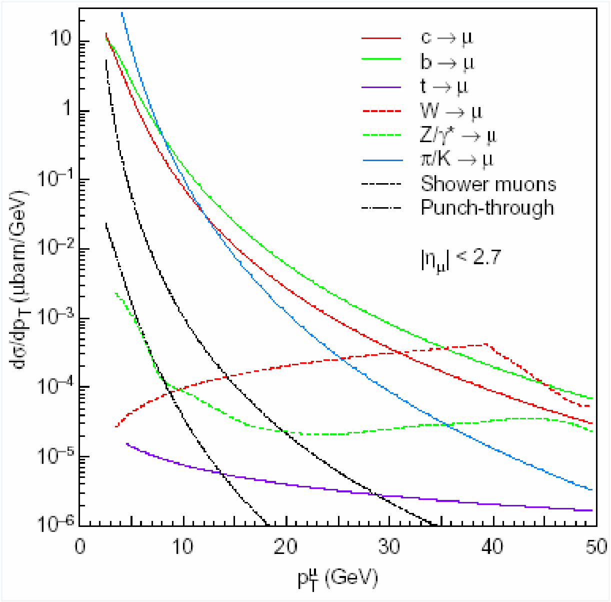
Background: Cosmic Ray Muons

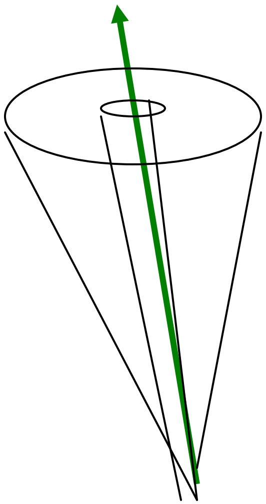
- Cosmic ray muons arrival times are uncorrelated with beam crossings → flat background in time
  - Cut on tight timing window around t = 0 using fast counters
- Also require track point to the primary vertex



Isolated muons

- Usual way to select muons from decays of W, Z, etc. (as opposed to b/c decays)
  - Isoloation in calorimeter and/or tracker
- Keep in mind this is rejecting real muons
- Common styles of isolation
  - Upper limit on calorimeter energy in hollow cone around muon
  - Upper limit on sum of track p_T in a hollow cone around muon
  - Minimum separation between muon and nearest jet





Measuring muon ID efficiency with data

- Common method is “tag and probe” with events from dimuon decays of know resonances (J/ψ or Z, usually)

Tag muon: passes strict ID requirements

Require invariant mass of tag+probe to match resonance (J/ψ, Z) mass

$$\varepsilon = \frac{\#\,\text{probes passing ID}}{\text{total}\,\#\,\text{probes}}$$

Probe muon: reconstructed, but not necessarily passing strict ID cuts

- Cannot be used to measure reconstruction efficiency, because method requires both muons to be reconstructed
  - With good enough momentum quality to ensure that the muons come from the selected resonance
- To remove trigger bias, typically require a single muon trigger satisfied by tag muon

Isolated muons – questions and caveats

- Should isolation energy threshold be fixed, or proportional to the muon energy?
  - Both are used
- When using jet isolation, what if the jet is not reconstructed, or falls below threshold?
  - Difficult to use for low momentum muons
  - Creates dependence on jet reconstruction algorithm
- Isolation efficiency will tend to decrease with increasing instantaneous luminosity unless there are specific precations
  - Luminosity dependent thresholds? Ugly, but can work
- Efficiency can depend strongly on event type
  - Can't necessarily expect the same efficiency for $W \to \mu\nu$ and for t-tbar$\to \mu\nu$ jjjj
  - Great caution is required when including isolation in a trigger

Measuring muon reconstruction efficiency with data

- Again, "tag and probe":

Tag muon: passes strict ID requirements

Require invariant mass of tag+probe to match resonance (J/ψ, Z) mass

Probe track: not necessarily matched with a muon

$$\varepsilon = \frac{\#\,\text{probes passing ID}}{\text{total}\,\#\,\text{probes}}$$

- Typically need to require probe track to be isolated – otherwise, large combinatoric background

Tag and probe efficiencies: caveats

- Sample used to measure efficiency with tag and probe must be similar to your intended signal sample
  - Same run range, to account for any time variations
  - Same luminosity profile, in case any ID requirements depend on luminosity
- Tag and probe assumes uncorrelated efficiencies for the tag and probe muons, and this is often not quite the case
  - Example #1: If ID requirements include isolation, events with lots of extra jets will be suppressed by the tag requirements, thus leading to an overestimate of the probe efficiency
    - Usually need to correct for this, with Monte Carlo studies or event topology studies
  - Example #2: Inefficiencies which effect the whole muon system, e.g. readout failure, would not show up as inefficiencies with this method

Determining background from data

- Typical example: Studying a signal where you expect muons to be isolated (e.g. $W \to \mu\nu$) and you want to estimate your background from b/c decays
  - N = number of events selected before the isolation cut
  - N_{iso} = number of events selected after isolation cut
  - ε_S and ε_b are the efficiencies to pass the isolation cut for signal and background muons, repsectively
  - S and B are the number of signal and background events in your sample before the isolation requirement

$$N = S + B$$

$$N_{iso} = \varepsilon_s S + \varepsilon_b B$$

$$\Rightarrow B = \frac{\varepsilon_s N - N_{iso}}{\varepsilon_s - \varepsilon_b}$$

This works if you can determine ε_S and ε_b from appropriate test samples, e.g.
• $Z \to \mu\mu$ for ε_S and a low missing ET event sample for ε_b

Efficiencies from data vs. MC

- Advantages to data-based efficiency determinations
  - Includes effects that are not included in MC or are difficult to model
    - Real channel-to-channel behavior
    - Underlying events and multiple interactions
    - Cosmic rays and beam halo
  - Naturally provides systematic uncertainties on the efficiencies
- Advantages to MC-based efficiency determinations
  - Incorporates possible physics/kinematic/topological dependencies
  - No need to worry about background contamination of signal sample
- Common to use hybrid approach: effic from MC with corrections and uncertainties from data

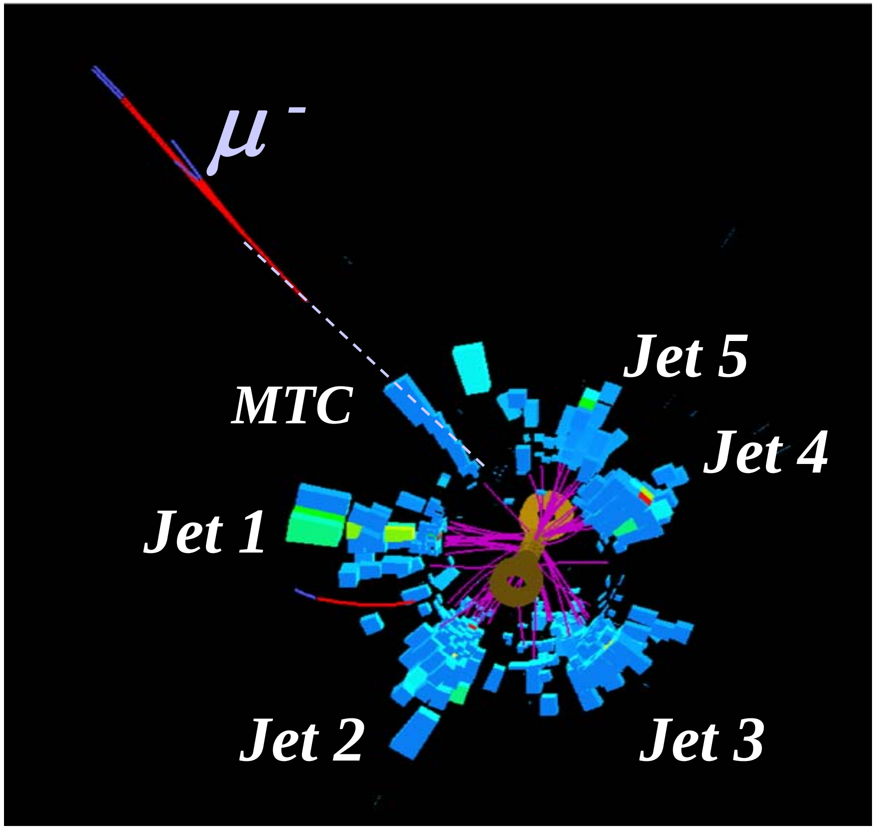
Very High Energy Muons

- Above energies of about 0.35 TeV, muons start to create γ's and e+e- pairs which create electromagnetic showers in material
  - Can destroy usual signal of isolated muon
  - Can fake the signature of an electron or a photon
- Options
  - Use calorimeter information to reject such muons, and give up trying to measure them
    - Won't work if energy loss occurs in passive material (e.g. muon iron)
  - Restrict momentum information to that from inner detector (before shower)
    - Still potential problems with failing isolation criteria
- Never a large issue at the Tevatron (except with cosmic rays): interesting challenge for the LHC experiments

Muon tracks in the calorimeter

- Another possible ID tool is the MIP trace of the muon in the calorimeter
- Requires
  - Low threshold on calorimeter cells to measure single MIP deposit
  - Low noise, not too many underlying events
- Easier to see in the back of the calorimeter, where most soft hadrons to not penetrate

A DØ t-tbar to μ+jets Candidate Event



A few words on commissioning muon systems

- Cosmic rays are a blessing here – a constant source of muons for chamber/counter testing
  - But very low rate once detector is deep underground
- Beam halo can also be a blessing – horizontal muons from upstream
- Challenges
  - Getting the relative timing of different chambers aligned properly
    - Easier with beam, but usually one can’t wait that long
  - Getting a consistent understanding of geometry for the hardware and the reconstruction
    - Event display can be very useful here
  - Anticipating time structure of real data
    - sometimes get bursts of data that hare hard to understand
  - Integrating with other systems and global DAQ
    - Always takes longer than anticipated

A few remarks on triggering

- An inclusive single muon trigger is a real workhorse
  - Essential for $W \rightarrow \mu\nu$
  - Needed for $Z \rightarrow \mu\mu$ if you want to use tag-and-probe to measure efficiencies
    - Dimuon trigger would bias the probe muon
  - Challenge is the real rate of inclusive muons, dominated by heavy flavor