PANIC11
Pedagogical Lectures for Students

Tools of Particle Physics II

Particle Detectors

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Overview

- Basics of particle detection in high energy physics.
- Particle identification techniques.
- Examples of particle detection systems:
    - Direct dark matter search underground.
    - Antimatter/dark matter searches/measurements in space.
    - Neutrino oscillation detectors.
    - Collider detectors.
- I will talk about experiments I have worked with and therefore know best.

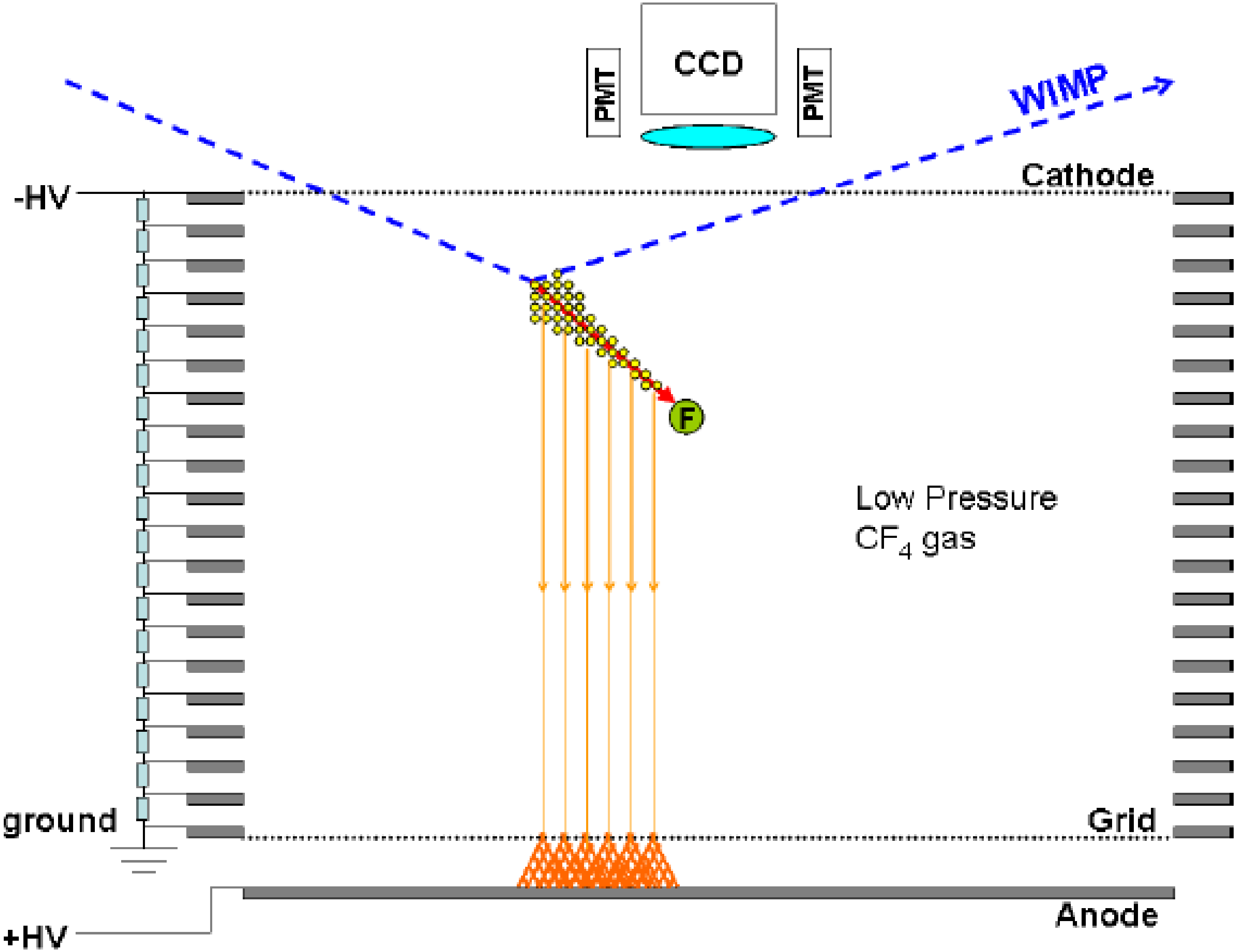
The Basics I – interactions with matter

- Fast ($v \approx c$), singly charged particles lose about *dE/dx* = 2 MeV/(g/cm^2) of energy in matter due to electronic excitation & ionization (density x thickness in cm = # of g/cm^2). Slow particles have larger values of dE/dx.
- Electrons (> 10 MeV or so) radiate photons, and photons (> 10 MeV or so) make electron-positron pairs, each in about a *radiation length* X_0, causing *Electromagnetic Showers.*
- Hadrons (e.g. protons, neutrons, pions) interact with nuclei in an interaction length λ_I, causing nuclei to break up into big chunks, or knocking nucleons out, or producing pions and kaons, all of which contribute to *Hadronic Showers*.
- Muons do not undergo either kind of shower (too heavy for EM shower, not strongly interacting so no hadronic shower).
- Neutrinos do not interact very often in collider experiment detectors. But they will interact with very massive specialized detectors near reactors or intense specialized proton beams/targets, or in massive detectors deep underground.
- Nobody knows how dark matter interacts with regular matter. However there are many attempts to look for dark matter assuming various possible mechanisms.

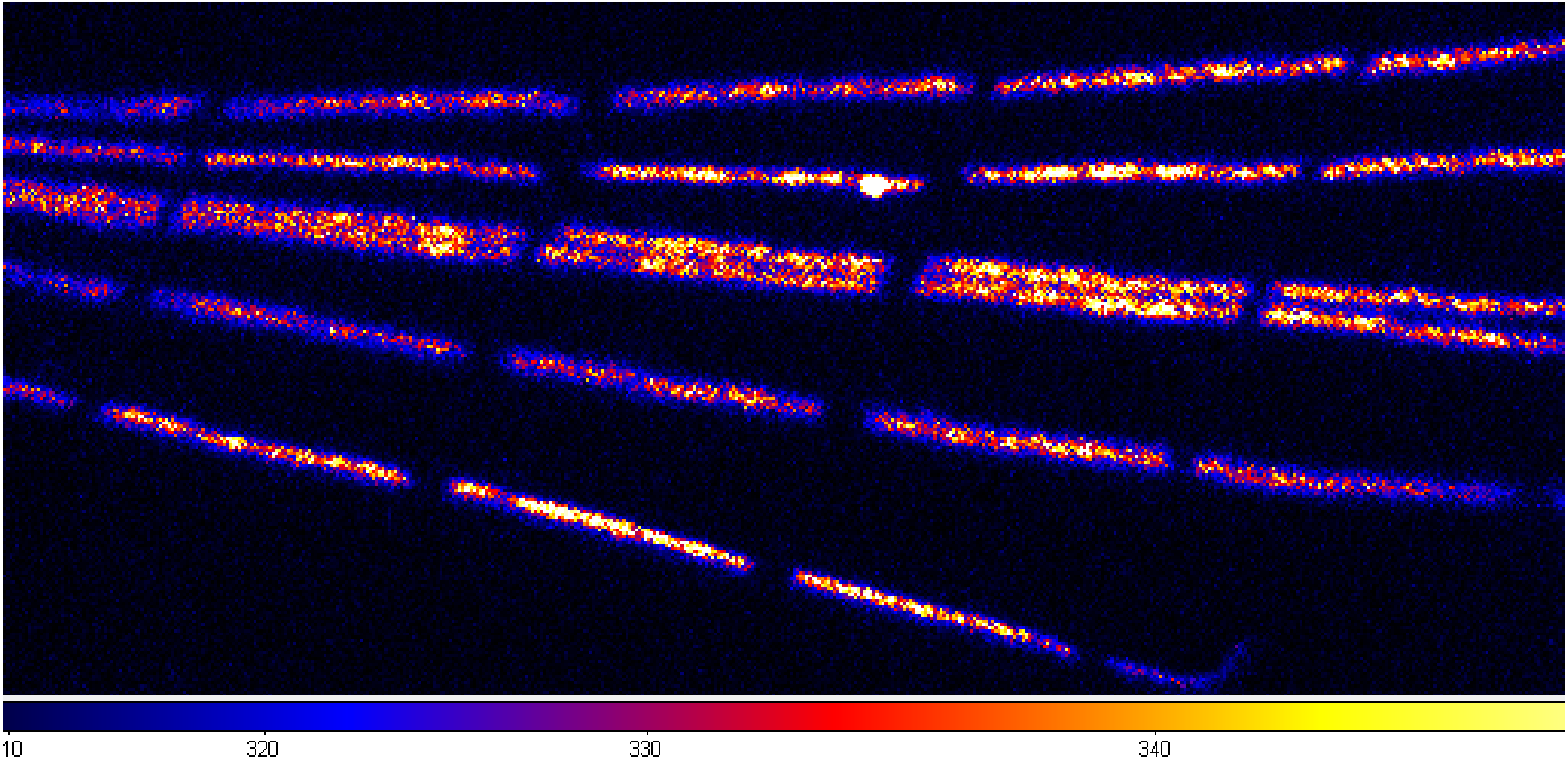
The Basics II - types of particle detectors

- Scintillators – organic or inorganic solids, liquids or gases; absorbed energy induces light emission, detected by phototubes, photodiodes or ccd's (scintillating fibers can be used for particle tracking).
- Cerenkov detector – light emitted in transparent medium by charged particle moving faster than light in the medium (sensitive to velocity and particle pathlength); can be used to measure total light, or characteristics of Cerenkov rings.
- Transition radiation detectors – x-rays emitted by charged particle passing between two different dielectric layers (sensitive to Lorentz factor).
- Ionization detectors – ionization in gases or liquids collected at electrodes for energy measurements and/or particle tracking (multi-wire-proportional-chambers, drift chambers, time-projection-chambers).
- Solid state diode detectors – can be used in variety of segmentations for measurements of total energy deposition and/or precision particle tracking (ccds, pixels, silicon strips); electron hole pairs drift through depletion zone in medium in much the same way as electrons and ions drift through gaseous ionization detectors.

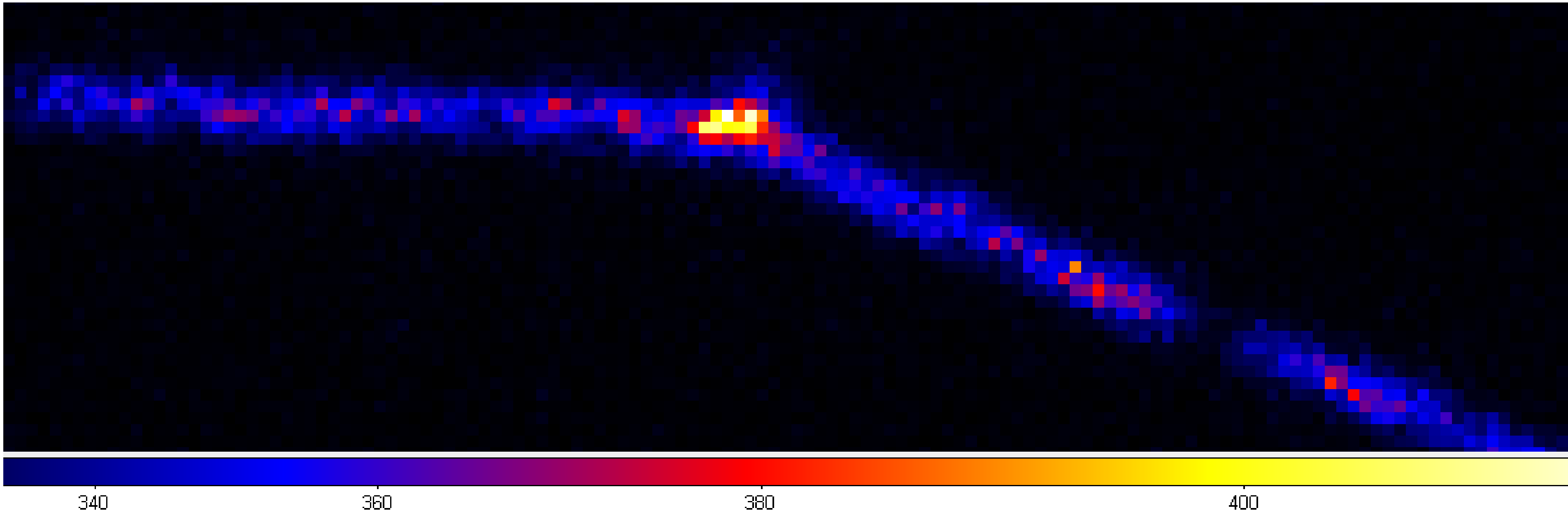
Examples from a direction-sensitive dark matter detector.



Six alpha particle tracks (5 MeV, energy ≈ 1 MeV as shown) .
Gas is CF_4 at 40 torr pressure (1 atm = 760 torr).
Field of view is 8 cm wide (full α range is 25 cm).
Color scale: 300 = 0 photons/pixel, 350 = 40 photons/pixel.
Each pixel corresponds to 180 microns in real space.
Note Bragg peak of energy loss, and scattering near end of range.



Rutherford scattering event.
40 keV nucleus recoils, depositing 20 keV of energy.
This (if you subtract the part due to the alpha particle) is what a dark matter event would look like.



Many talks on dark matter detectors will be given at this conference: ADMX, ZEPLIN, COUPP, EDELWEISS, CUORE, DMTPC, CDMS, MiniCLEAN, LUX.

How to measure energy and momentum

- Electrons, photons
  - Measure ionization or excitation of matter in an electromagnetic shower. This is an *electromagnetic calorimeter*.
- Protons, neutrons, pions
  - Measure ionization or excitation of matter in a hadronic shower. This is a *hadronic calorimeter*.
- Muons
  - Measure curvature of muons in magnetic field.
- Neutrinos or dark matter
  - At collider, assume energy and momentum conservation and identify *missing energy*.
  - For direct/indirect detection experiments, measure energies of recoils or reaction products which gives some information.

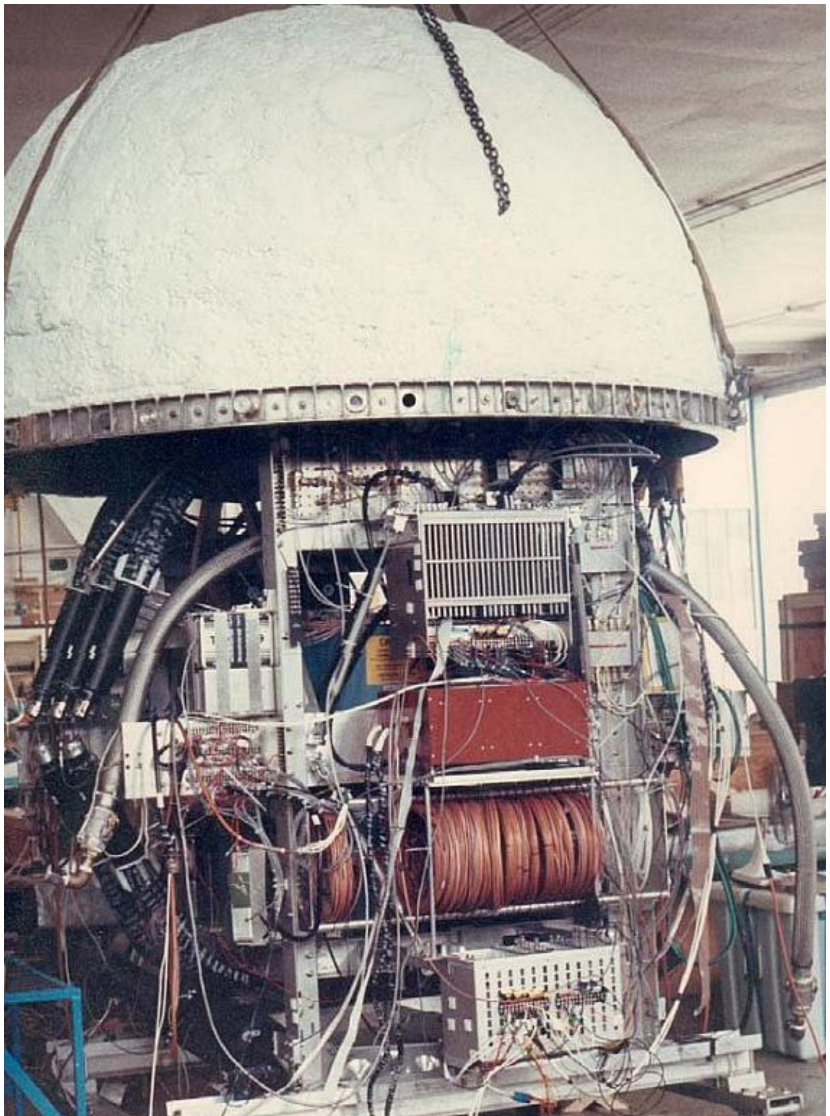
How do we measure quark energy and momentum?

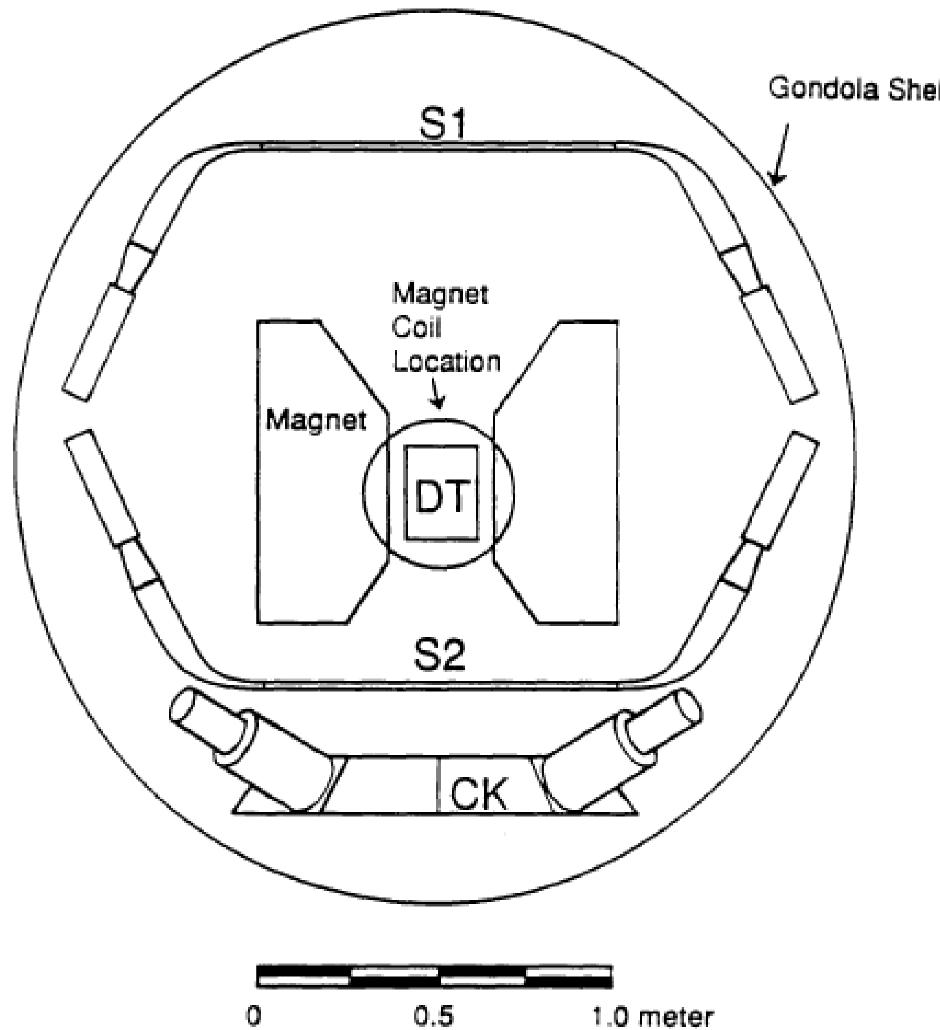
- Quark –antiquark pairs can be made in fundamental processes, or quarks can be knocked out of nucleons in violent, *high* p_T, qcd interactions.
- Free, fractionally charged quarks are not observed – as they move through small distances they are *dressed* with newly made quark-antiquark pairs that produce hadrons with integral electric charge and no *color*.
- An energetic initial quark becomes a *jet*, consisting of a spray of particles.
- The energy of jets can be measured in *hadron calorimeters*.

How do we identify particles?

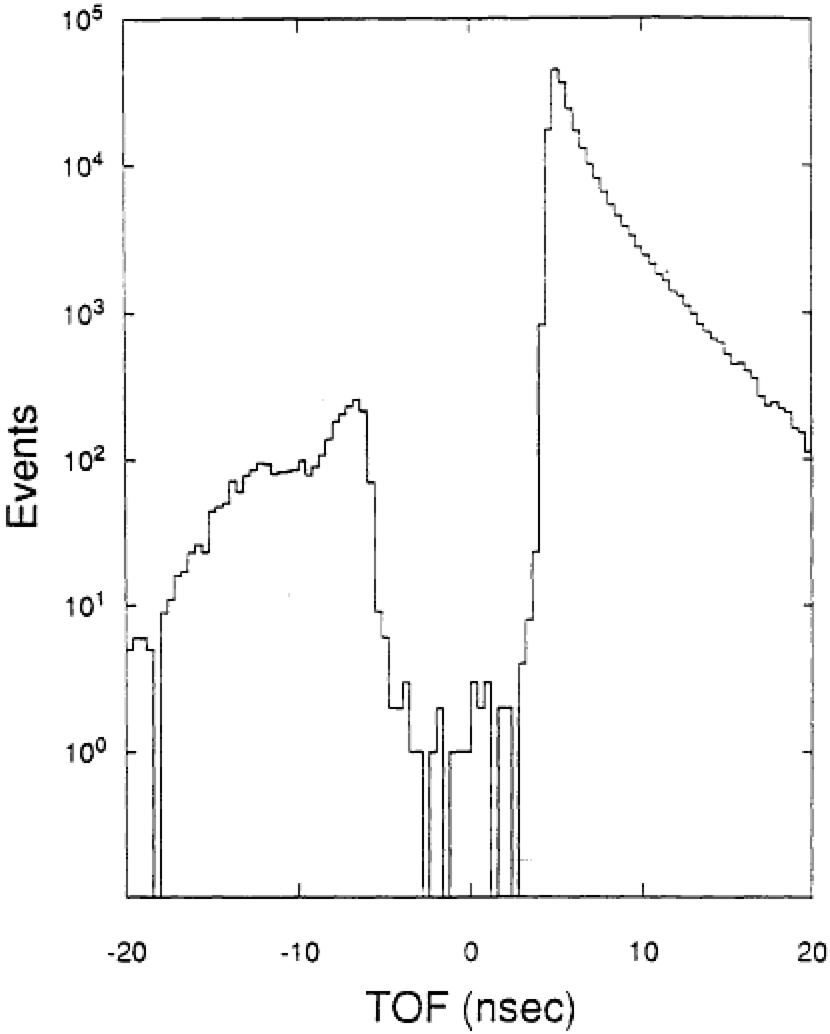
- This means determining mass, charge and energy.
- For example we could use scintillators to measure dE/dx and time-of-flight to find charge magnitude. We could use a magnetic field and particle tracking device to measure charge sign, and momentum per charge. With velocity measurements (TOF, Cerenkov radiation, transition radiation, or the relativistic rise of dE/dx), we could measure mass.

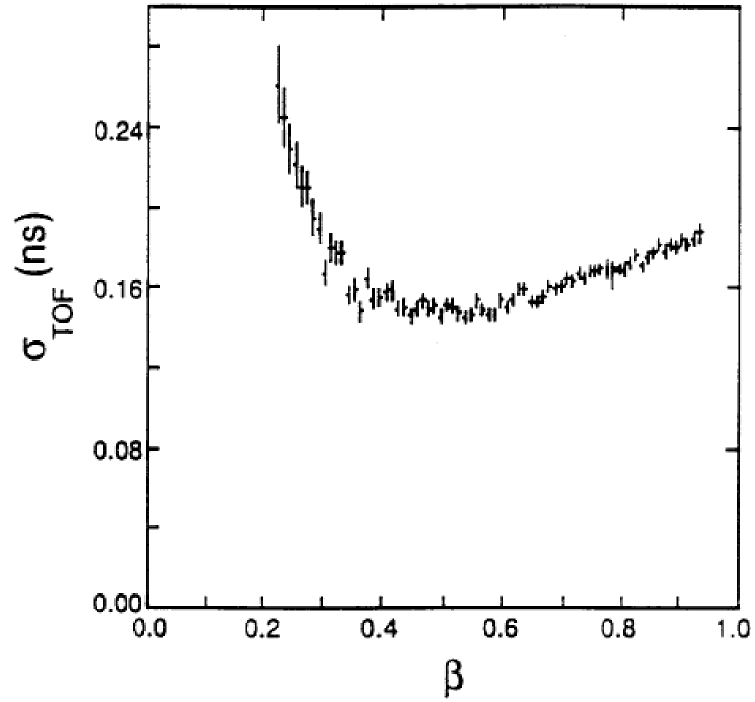
Example: *PBAR* searched for cosmic antiprotons in 1987 from a balloon over Canada with a superconducting magnetic spectrometer.

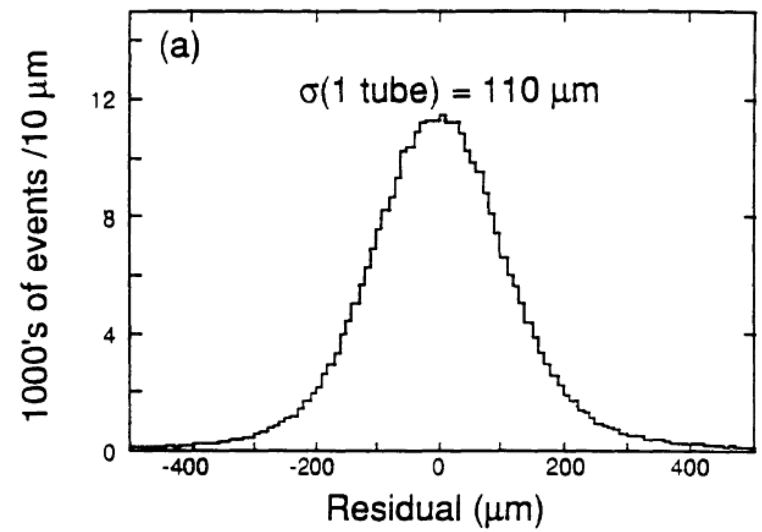




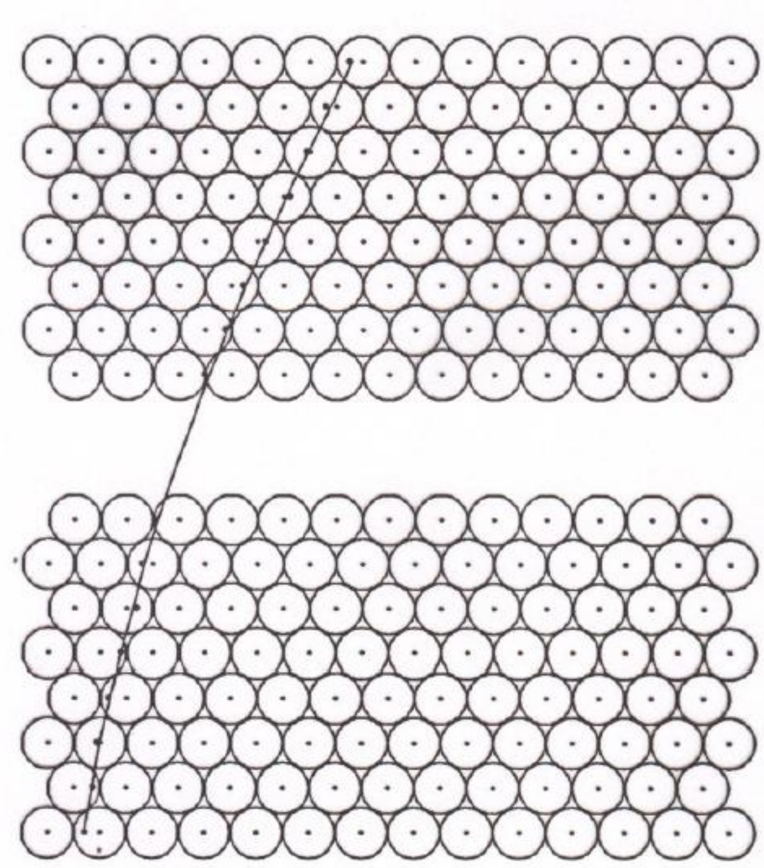
PBAR used state-of-the-art detectors to be the first high precision high energy physics experiment done in space.



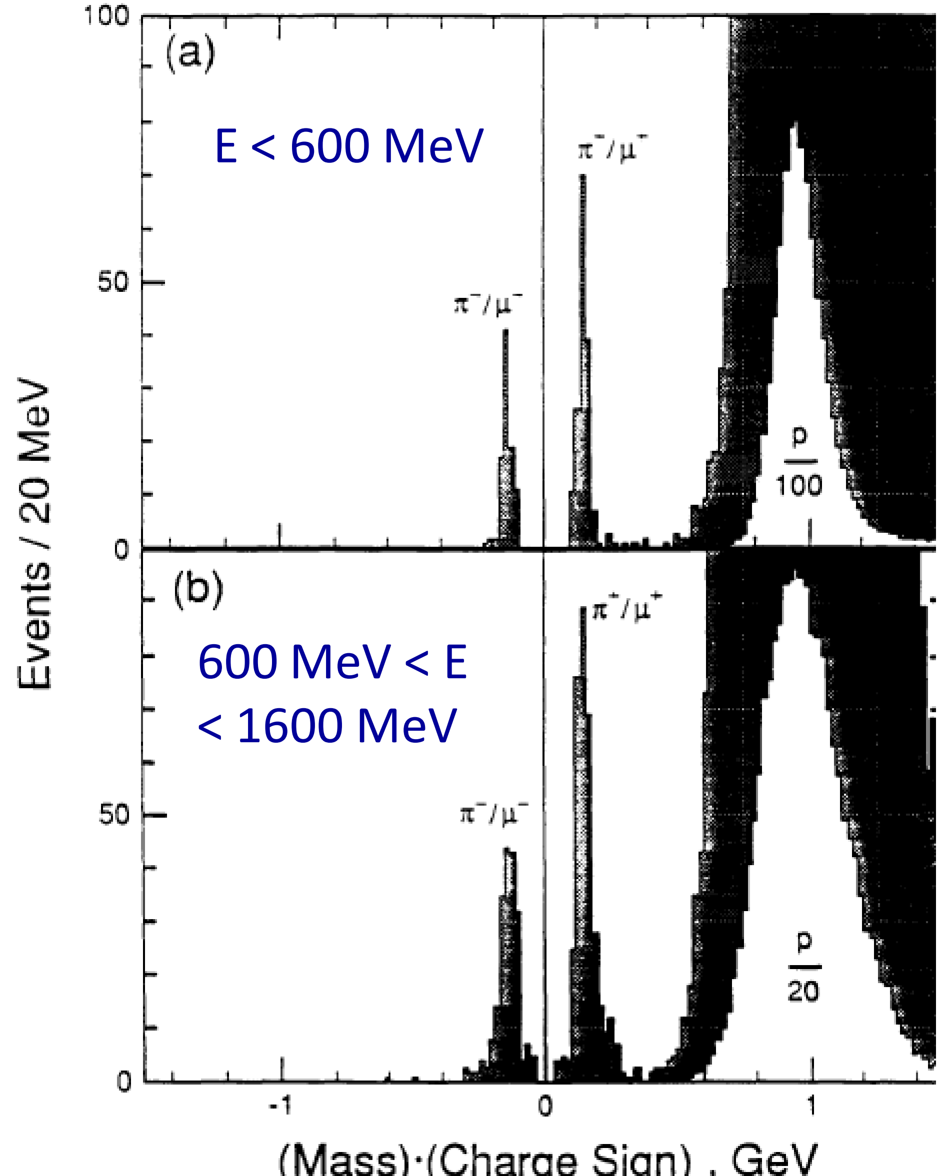




124,000 protons
No antiprotons



$$\frac{dE}{dx} \approx K\frac{Q^2}{v^2} \quad m = \frac{p}{v\gamma}$$

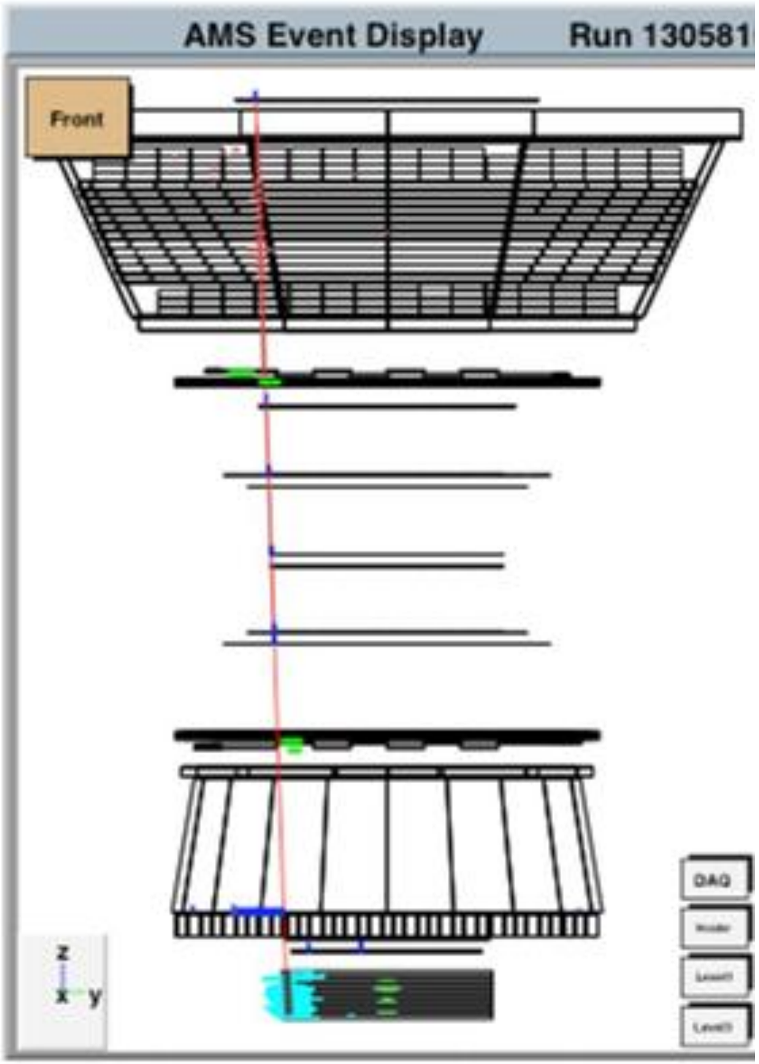


PBAR being launched from Prince Albert, Saskatchewan in 1987

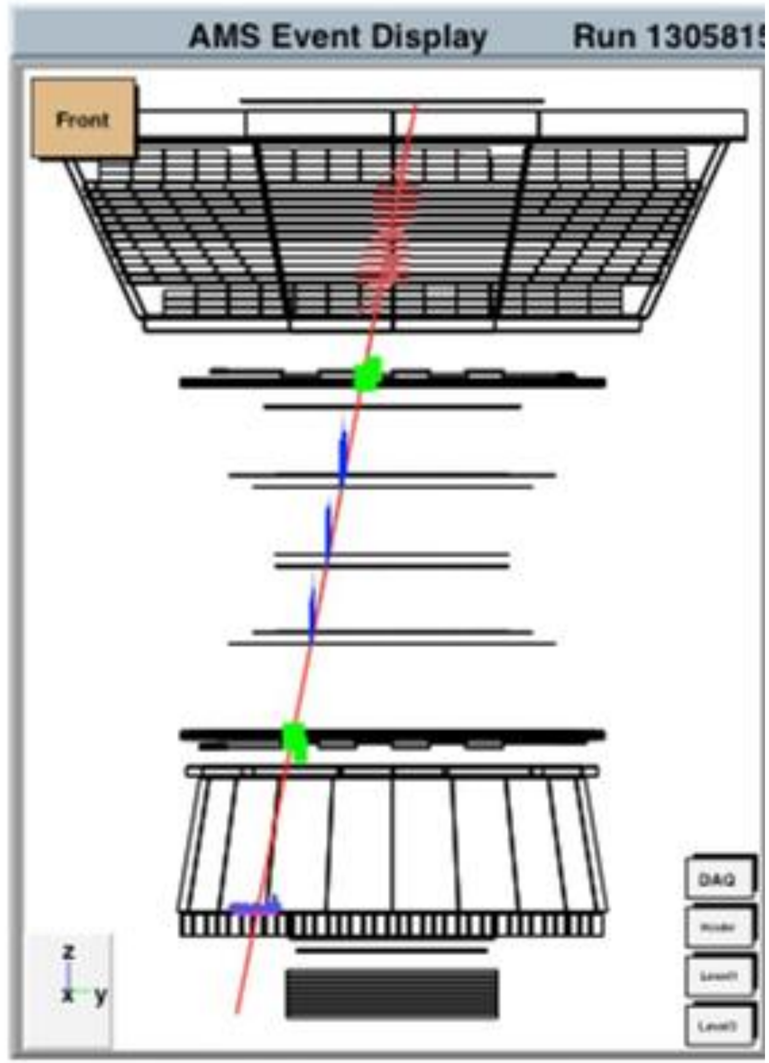
Pamela and AMS are space based magnetic spectrometers currently taking data to search for antimatter and dark matter. An update on AMS will be given at this conference on Wednesday morning.

AMS-02 moved to Space Station in May 2011

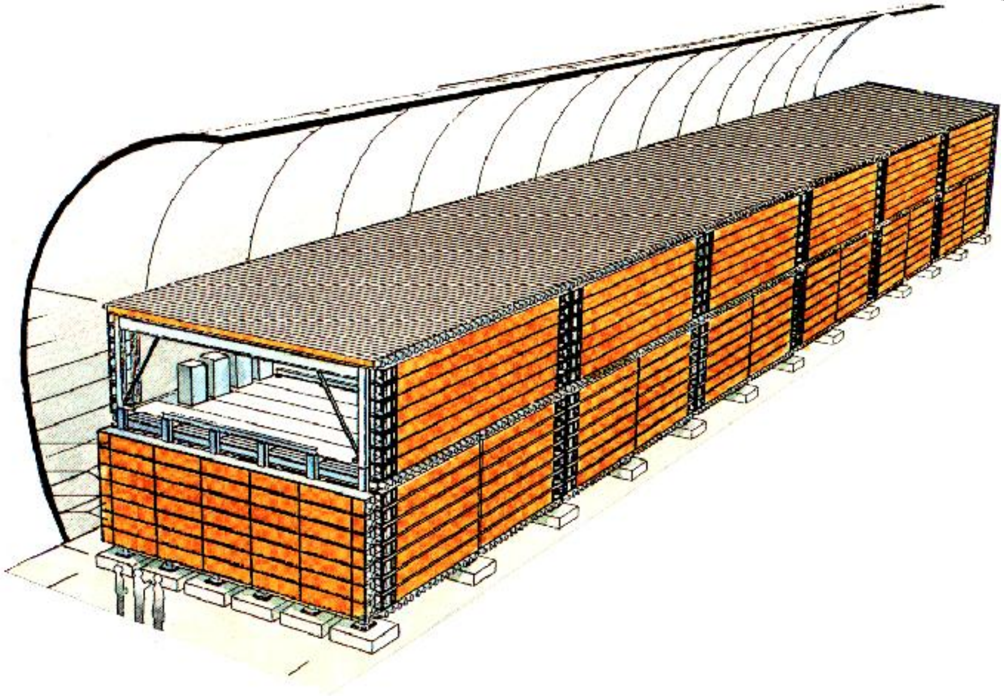
20 GeV electron

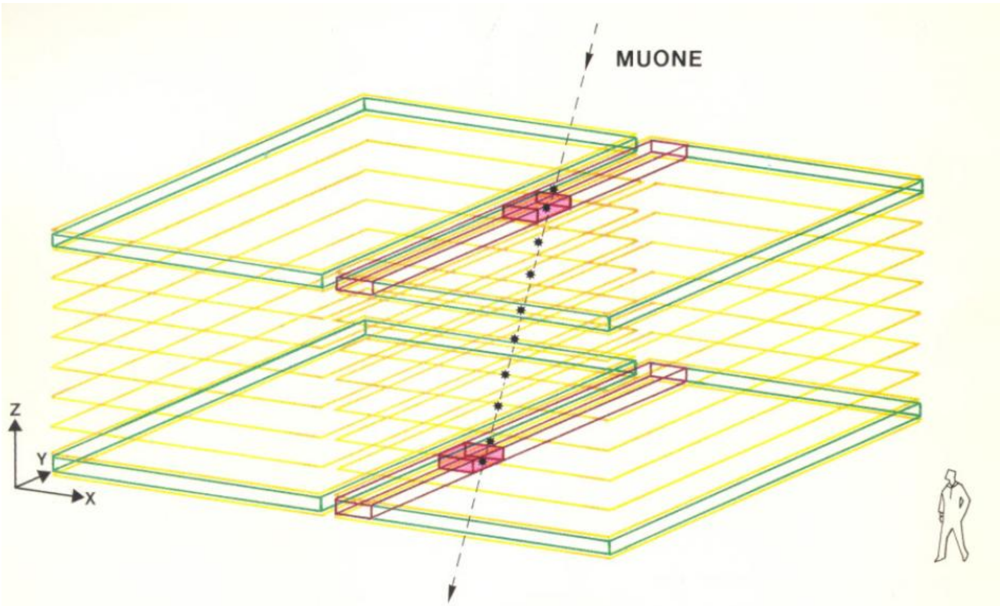


42 GeV carbon



Neutrino physics and rare particle searches





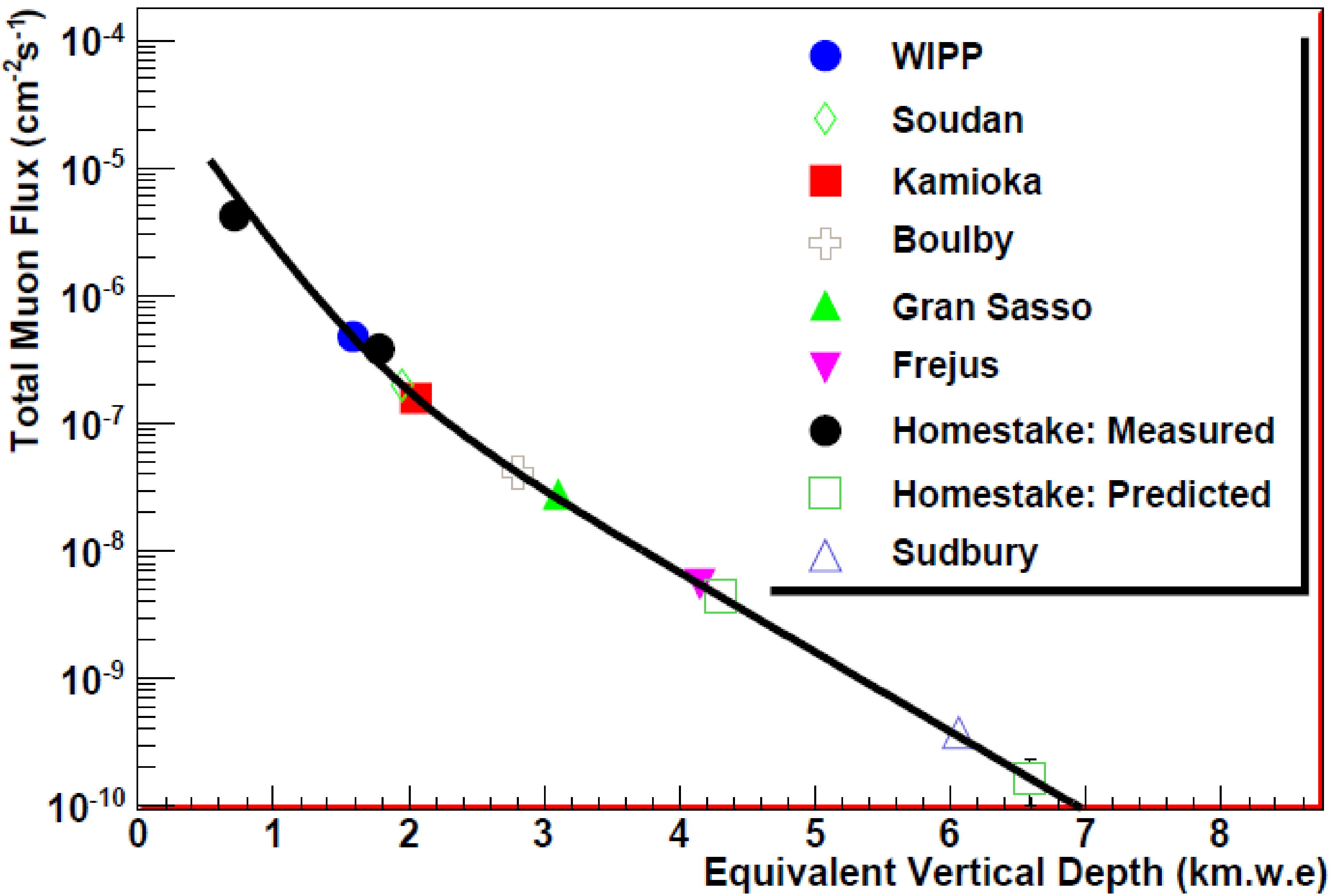
THE MACRO DETECTOR

12 m horizontal
76.6 m in length
9.3 m height.

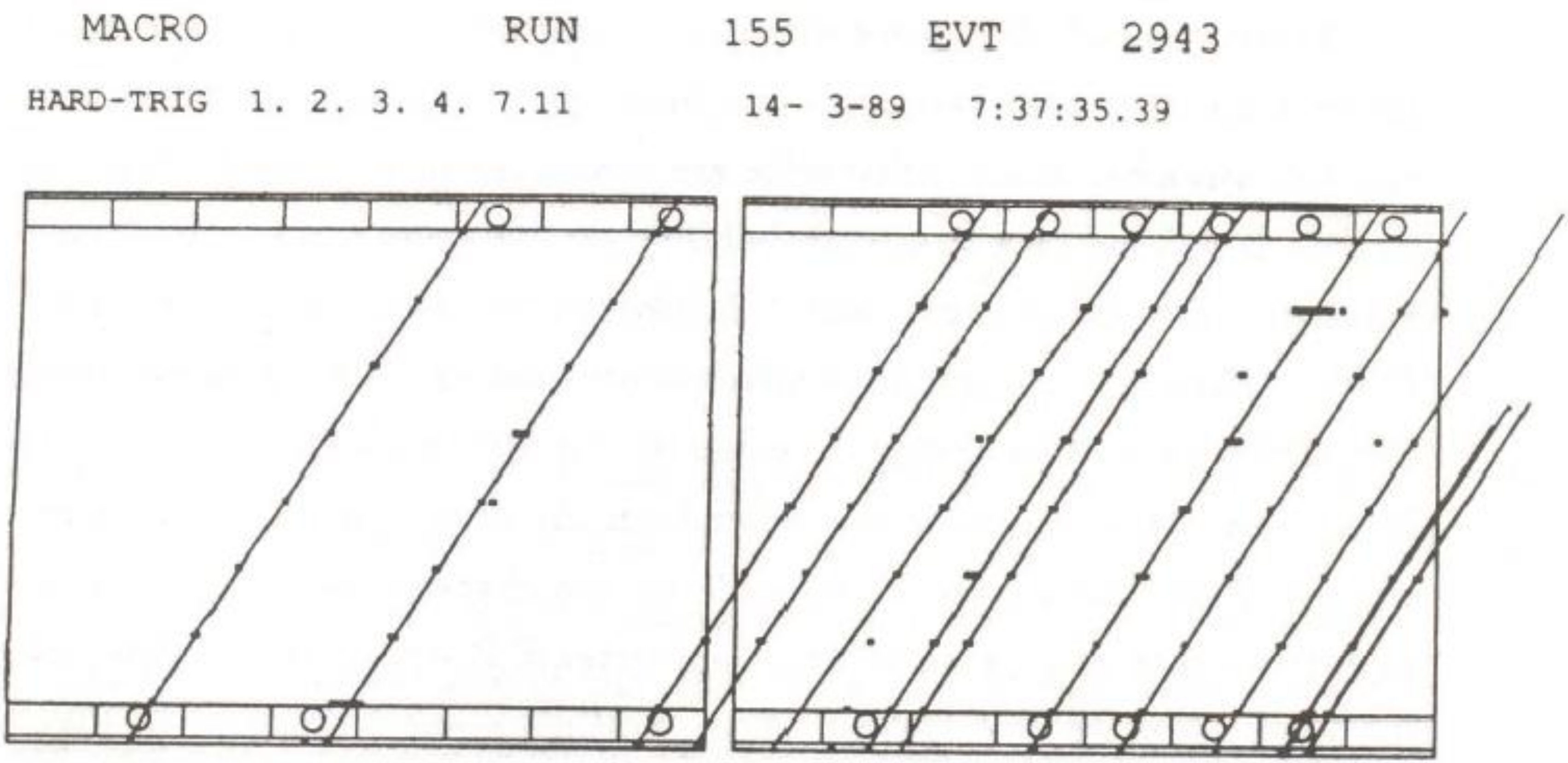
- Built 1989 -1994
- Built to look for Grand Unified Theory Magnetic Monopoles, neutrinos, cosmic ray muons
- 600 tons of liquid scintillator for monopole detection and muon time of flight
- 14 layers of Iarocci tubes separated by crushed rock for muon tracking and monopole identification

Gran Sasso, 80 miles from Rome

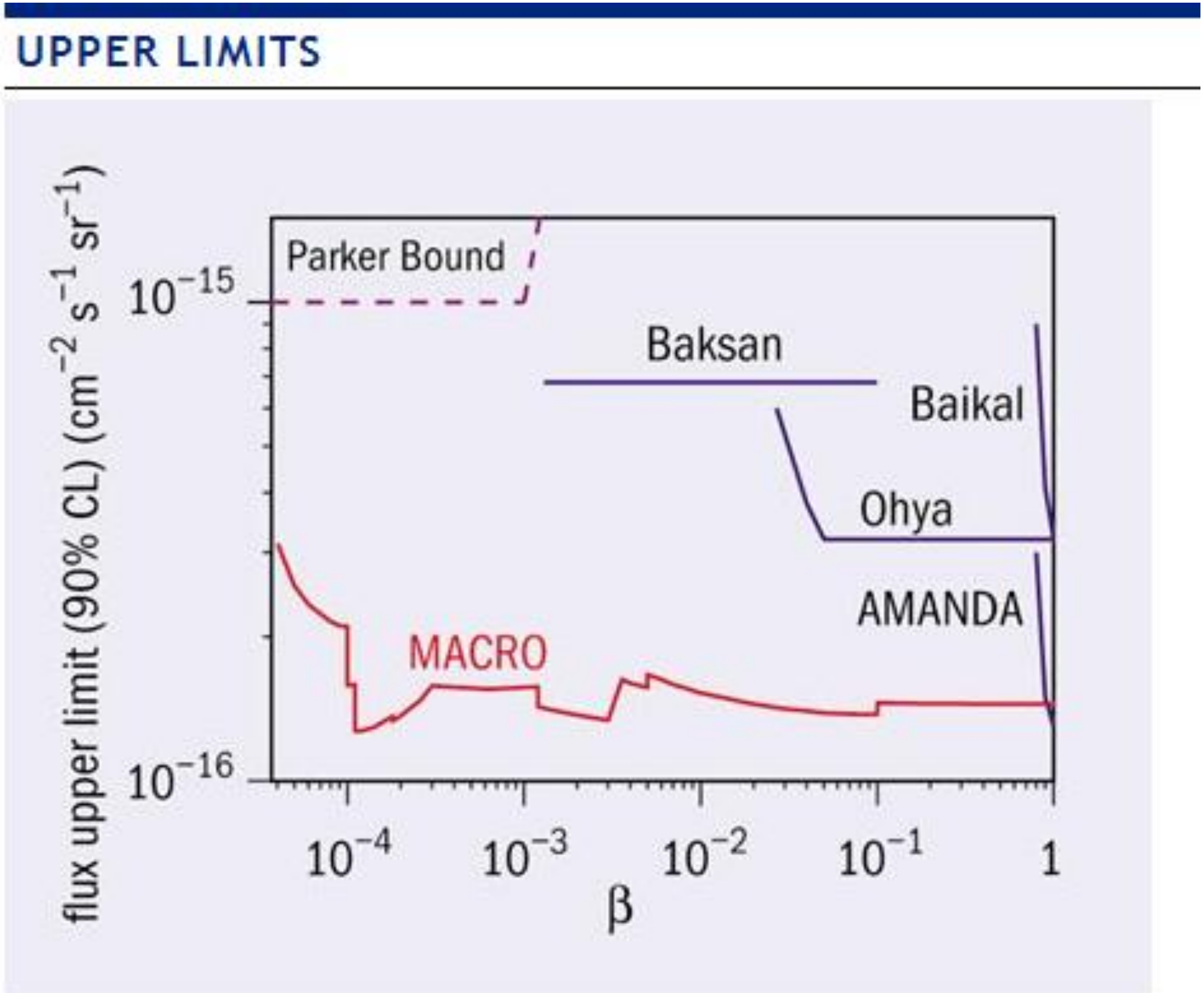
Muon flux is greatly reduced underground. At sea level, muon flux = 0.02/(cm^2 s)



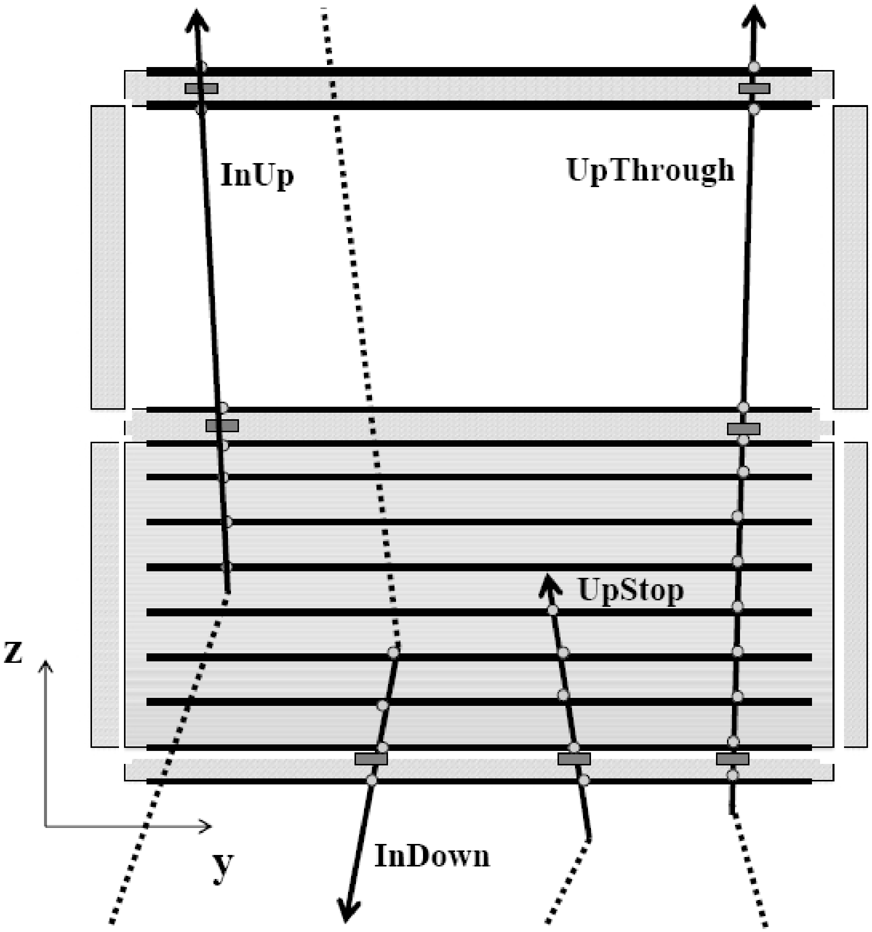
12 muon event: about 10% of time, muon accompanied by delta ray from rock; avg muon energy about 1/2 TeV

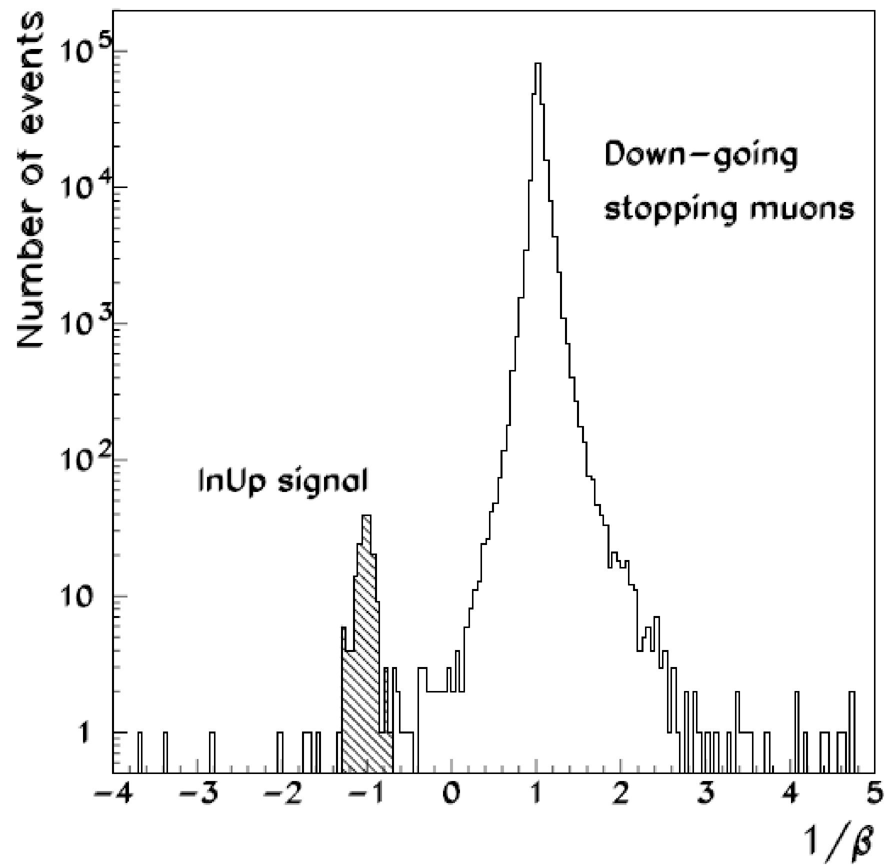


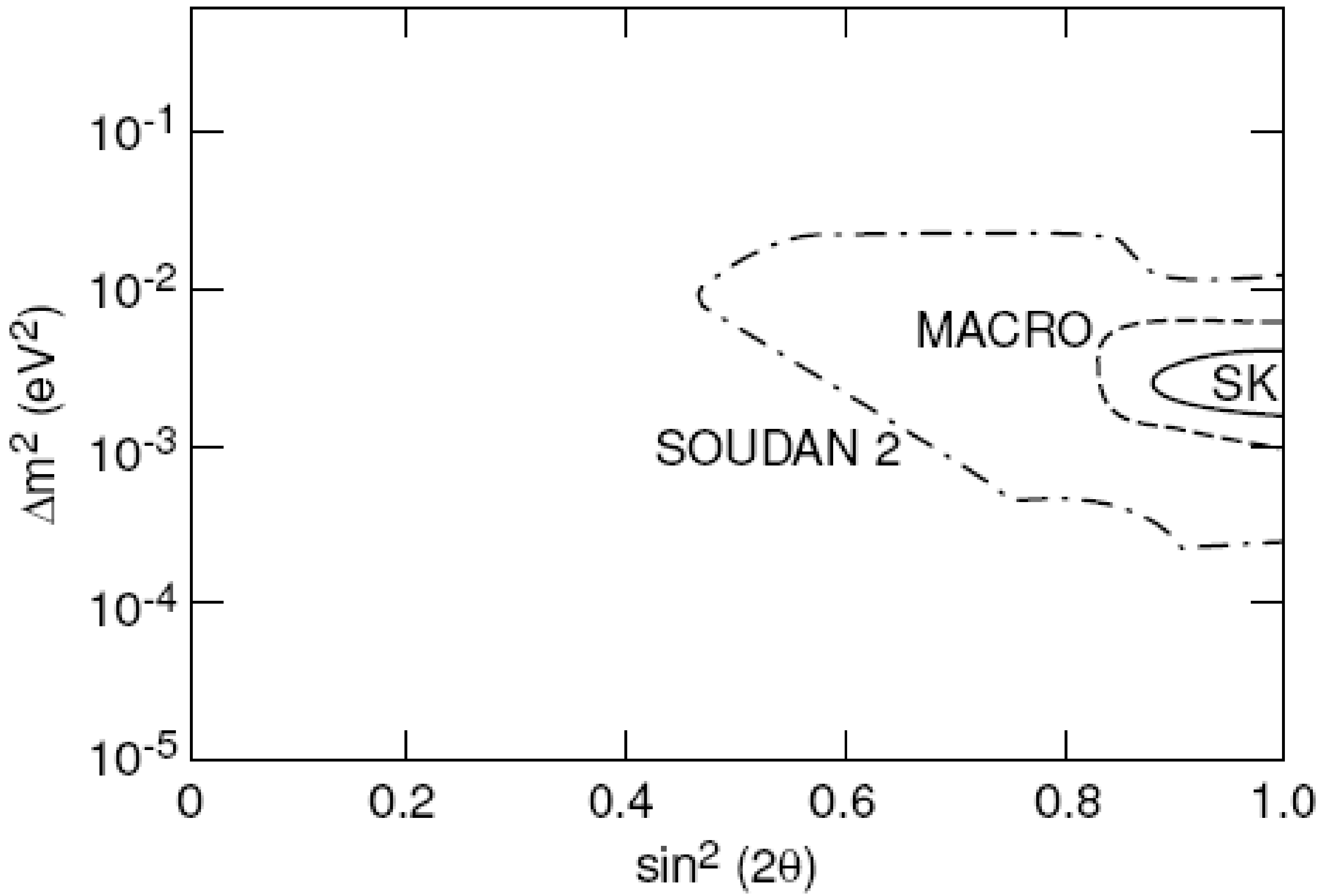
MACRO set best limits on massive magnetic monopoles and electrically charged particles.



Atmospheric neutrino studies with MACRO

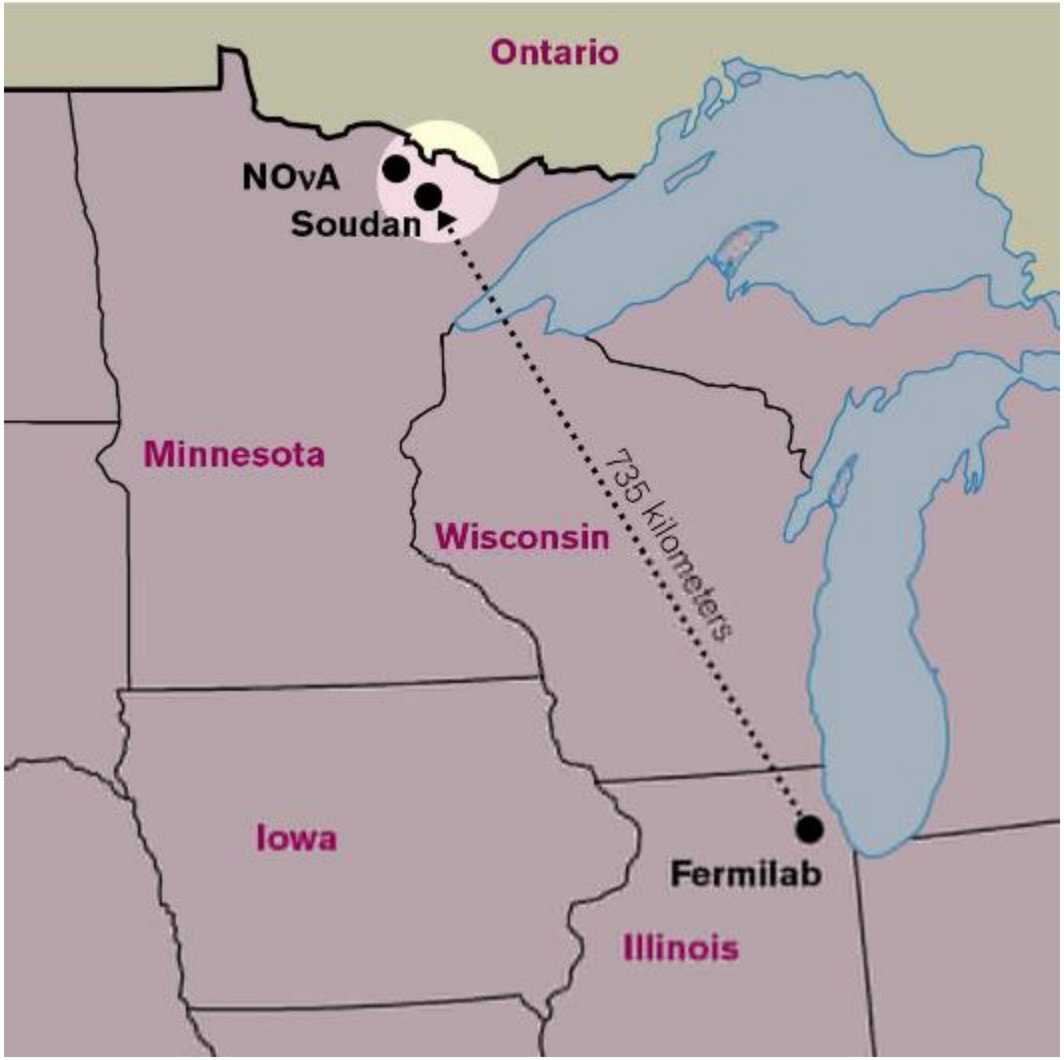




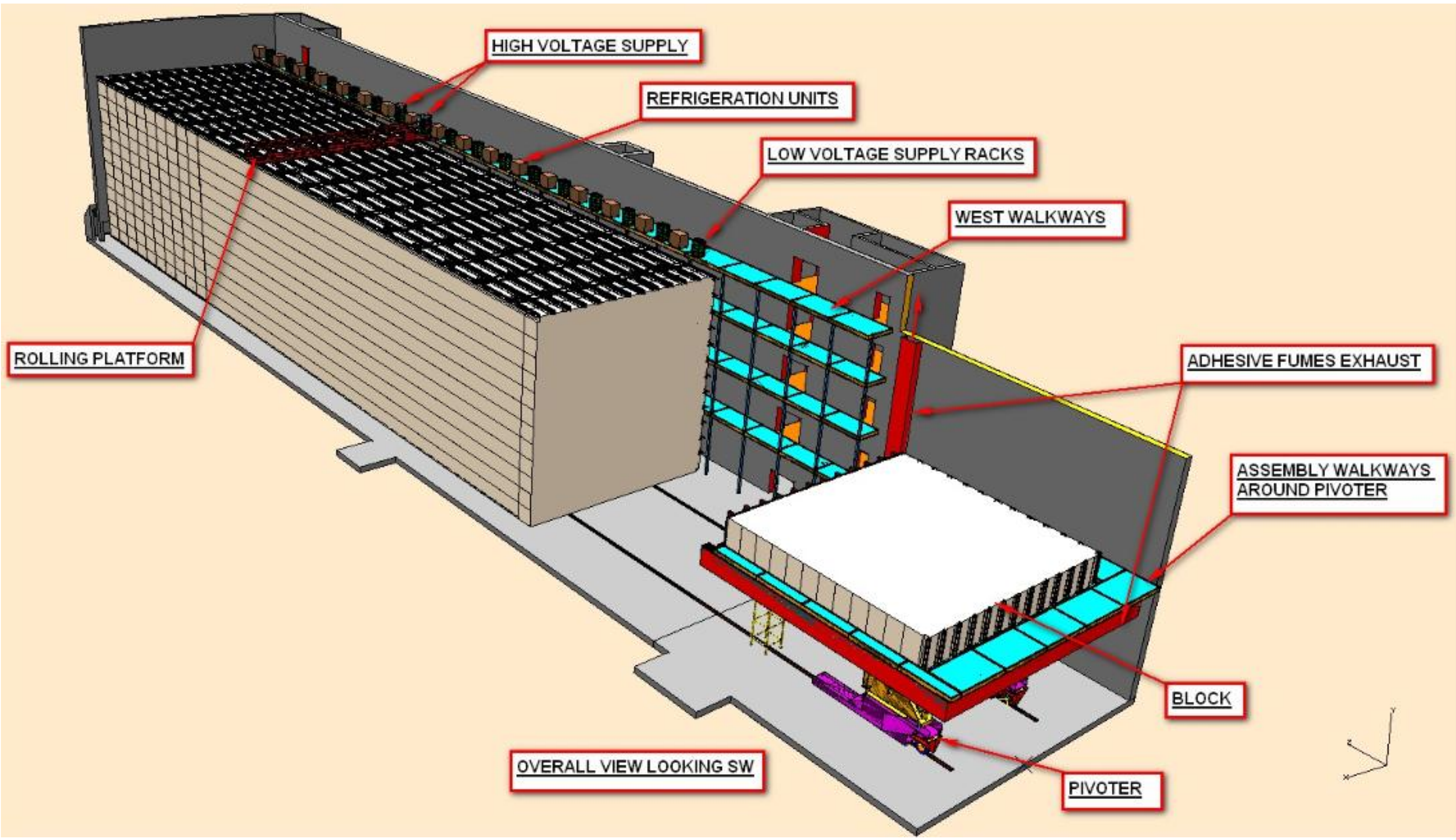


10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Δm^2 (eV^2)
MACRO
SK
SOUDAN 2
0
0.2
0.4
0.6
0.8
1.0
$\sin^2 (2\theta)$

NOvA, one of many new neutrino experiments that will soon turn on (others have turned on already). These will refine our knowledge of neutrino mixing. An immediate goal is to observe and determine properties of $\nu_\mu \to \nu_e$ (recently observed in T2K).

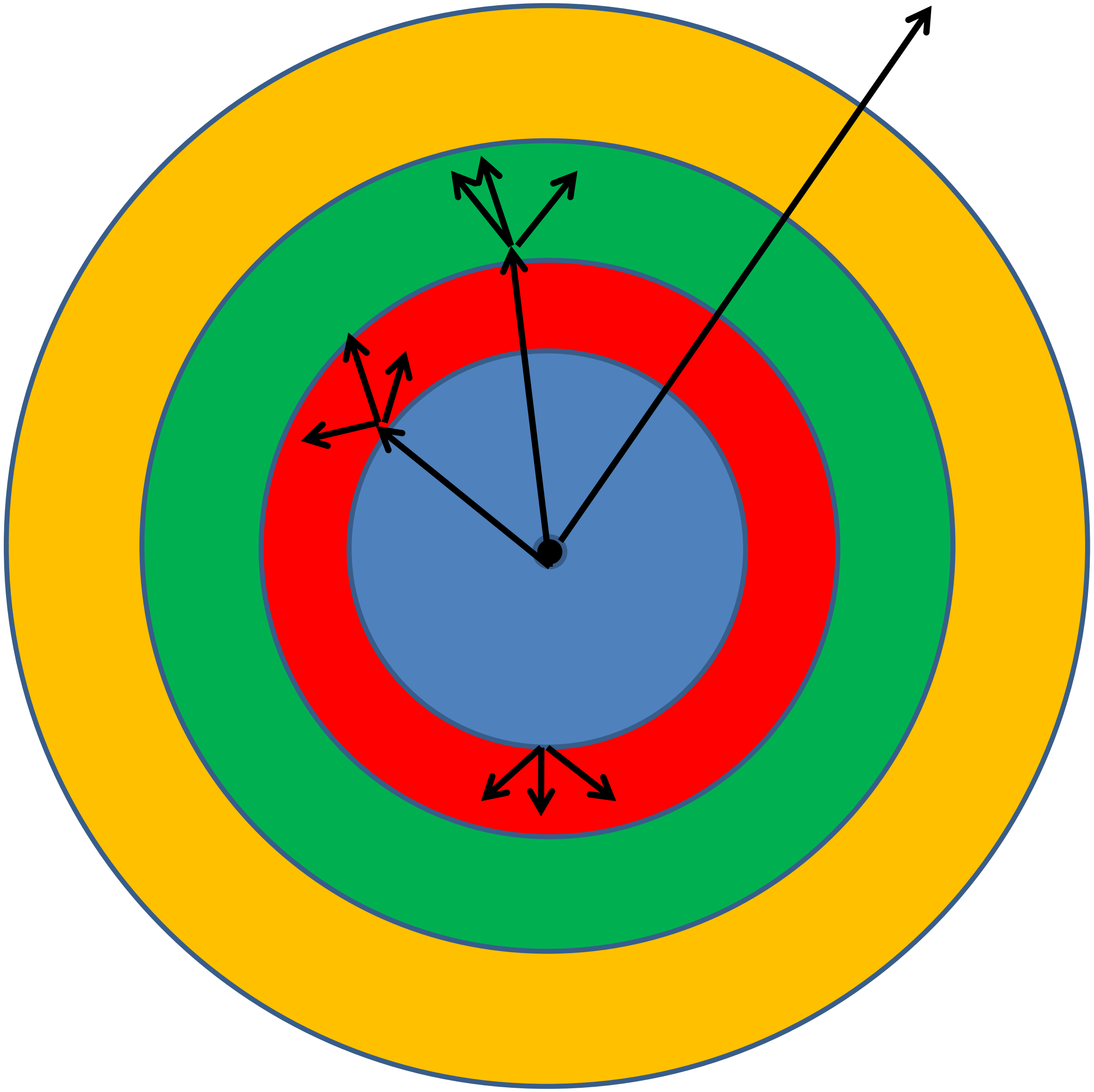


The NOvA experiment uses two detectors: a 222 metric-ton near detector at Fermilab and a much larger 15 metric-kiloton liquid scintillator far detector (25 times more scintillator mass than MACRO) in Minnesota just south of the U.S.-Canada border.



A number of talks on neutrino oscillation experiments will be given at this conference, including T2K, IceCube, MiniBooNE, Double Chooz, Borexino, NOvA, Daya Bay, Minos.

Particle collider experiments



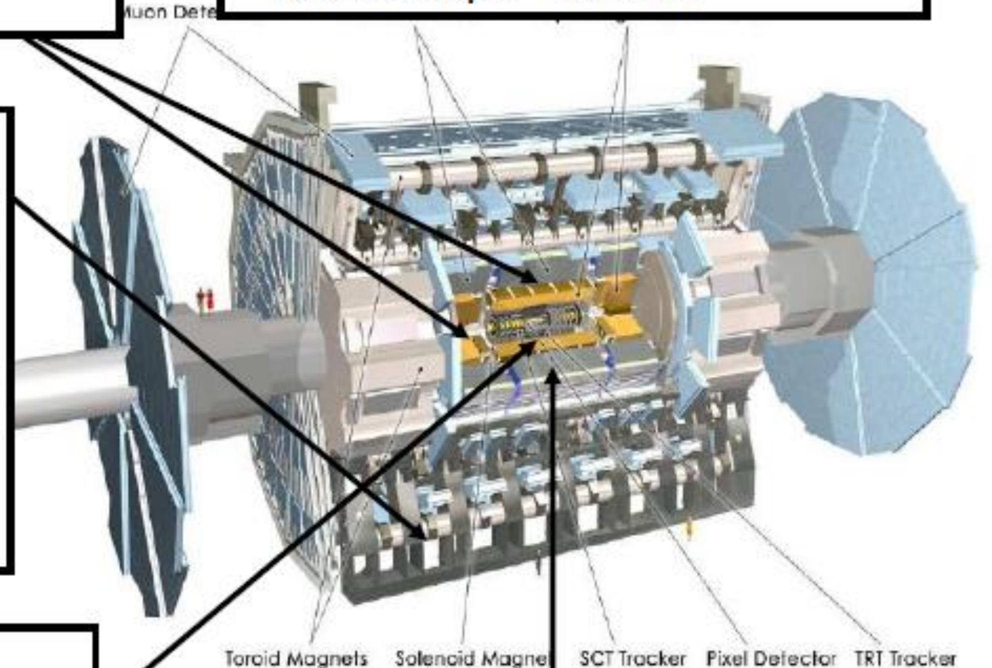
- Particles move into slide and out of slide, colliding in center
- Blue is inner tracker
- Red is EM Cal
- Green is Hadron Cal
- Orange is muon spectrometer

ATLAS Detector

EM Calorimeter: $|\eta| < 4.9$
- Barrel/Endcap: accordion-shaped Pb/LAr
- 3 longitudinal layers at $|\eta|<2.5$
- $\sigma_E/E = 10\%/\sqrt{E} \oplus 24.5\%/E \oplus 0.7\%$

Trigger/DAQ:
- Input rate ~1 GHz
- Rate to tape ~400 Hz

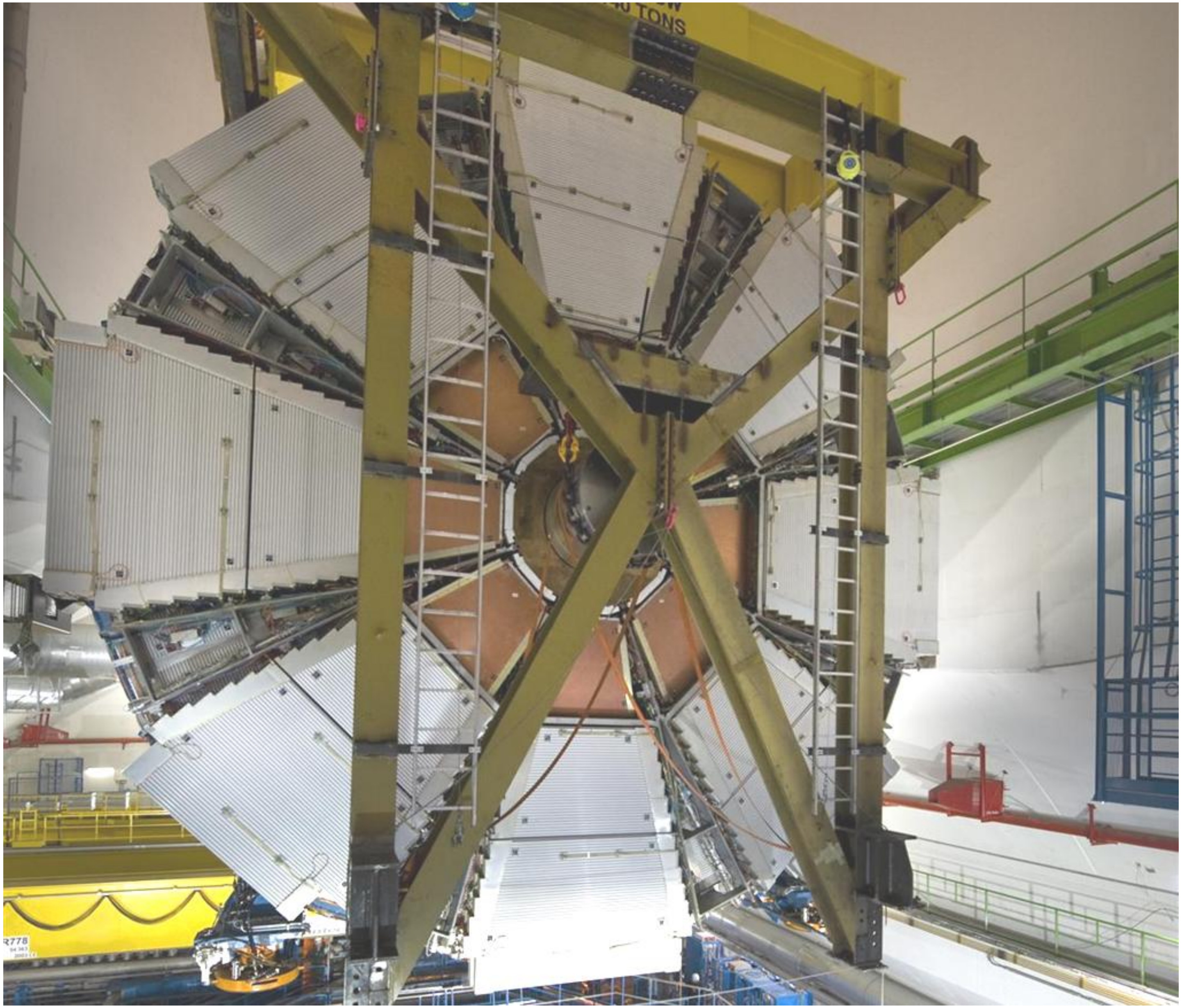
Muon Spectrometer : $|\eta| < 2.7$
- In air-core toroid with gas detectors
- Barrel: Resistive Plate Chambers & Cathode Strip Chambers
- Endcap: Thin Gap Chambers and Monitored Drift Tubes
- Standalone: $\sigma(p)/p$=3%(0.1TeV)-10%(1TeV)



Inner Detector: $|\eta| < 2.5$
- 3 layers of Pixel Detector
- 4 layers of Semi-Conductor Tracker
- 73-layer Transition Radiation Detector (TRT) [only within $|\eta|<2.0$]
- In 2T solenoidal magnetic field
- $\sigma(p_T)/p_T = (0.034 p_T/\mathrm{GeV} \oplus 1.5)\%$

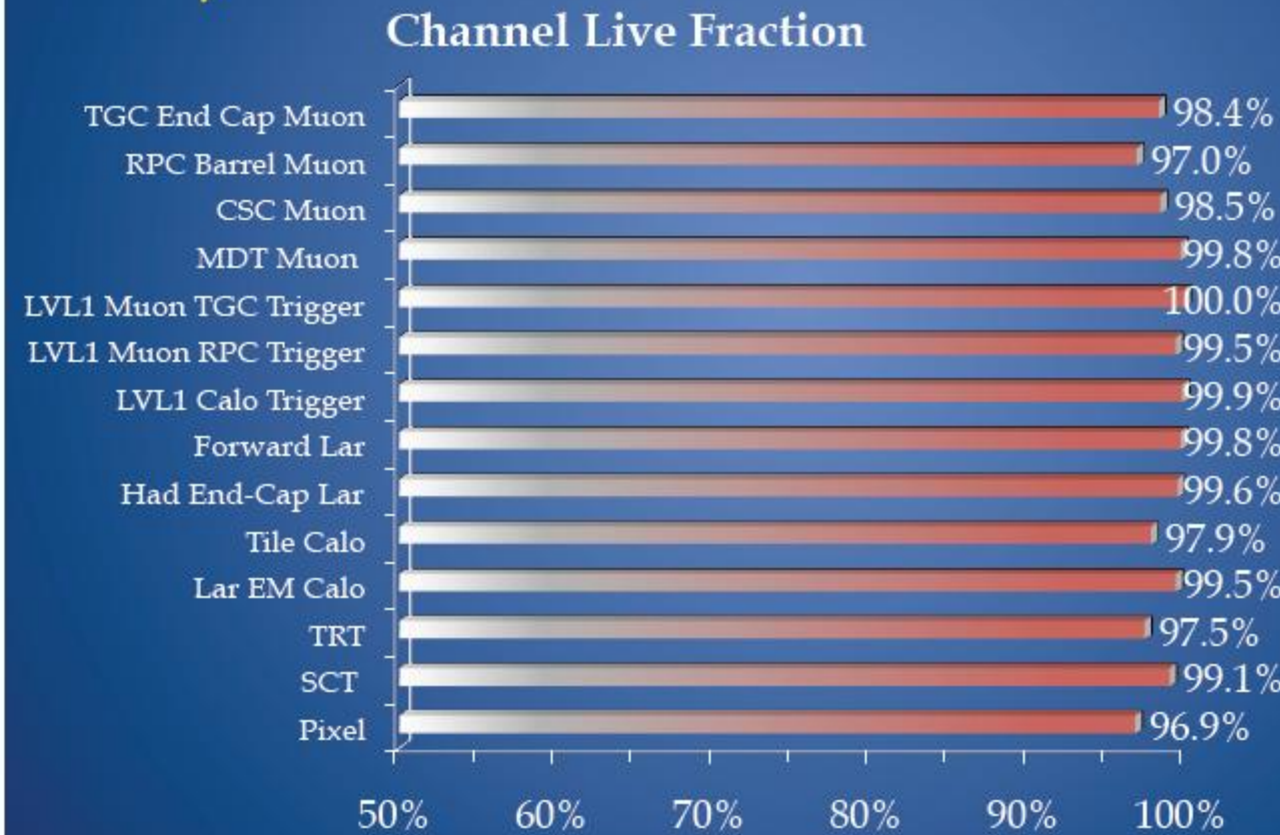
Hadronic Calorimeters:
- 3 layers of scintillating tile/steel to $|\eta|<1.7$
- 4 layers copper/LAr for $1.5<|\eta|<3.2$

Small Wheel Muon Chambers – my contribution



Detector Operations

- Fraction of operational channels close to 100 % for all systems



Number of Channels
320 K
370 K
31 K
350 K
320 K
370 K
7 K
3.5 K
5.6 K
9.8 K
170 K
350 K
6.3 M
80 M

Data from the LHC

- About 6000 (2000 now) bunches of 7 TeV (3.5 TeV now) protons fill two 27 km rings, ½ moving clockwise, ½ moving counterclockwise.
- Bunches cross every 25 ns (50 ns now).
- About 20 collisions (5-10 now) per bunch crossing. Most of these are grazing and send particles down beam pipe. Interesting events send particles into detectors. These produce fast hardware triggers.
- There are about 100,000,000 individual detectors.
- Each detector has local electronics which records local activities and prepares 32 bit words to send in response to triggers (the data contain trigger numbers and BCIDs). These are sent to the main DAQ computers asynchronously.
- Events are *built* from all these words flowing in by using massive computing power.
- Data are analyzed around the world using multiple computing centers.

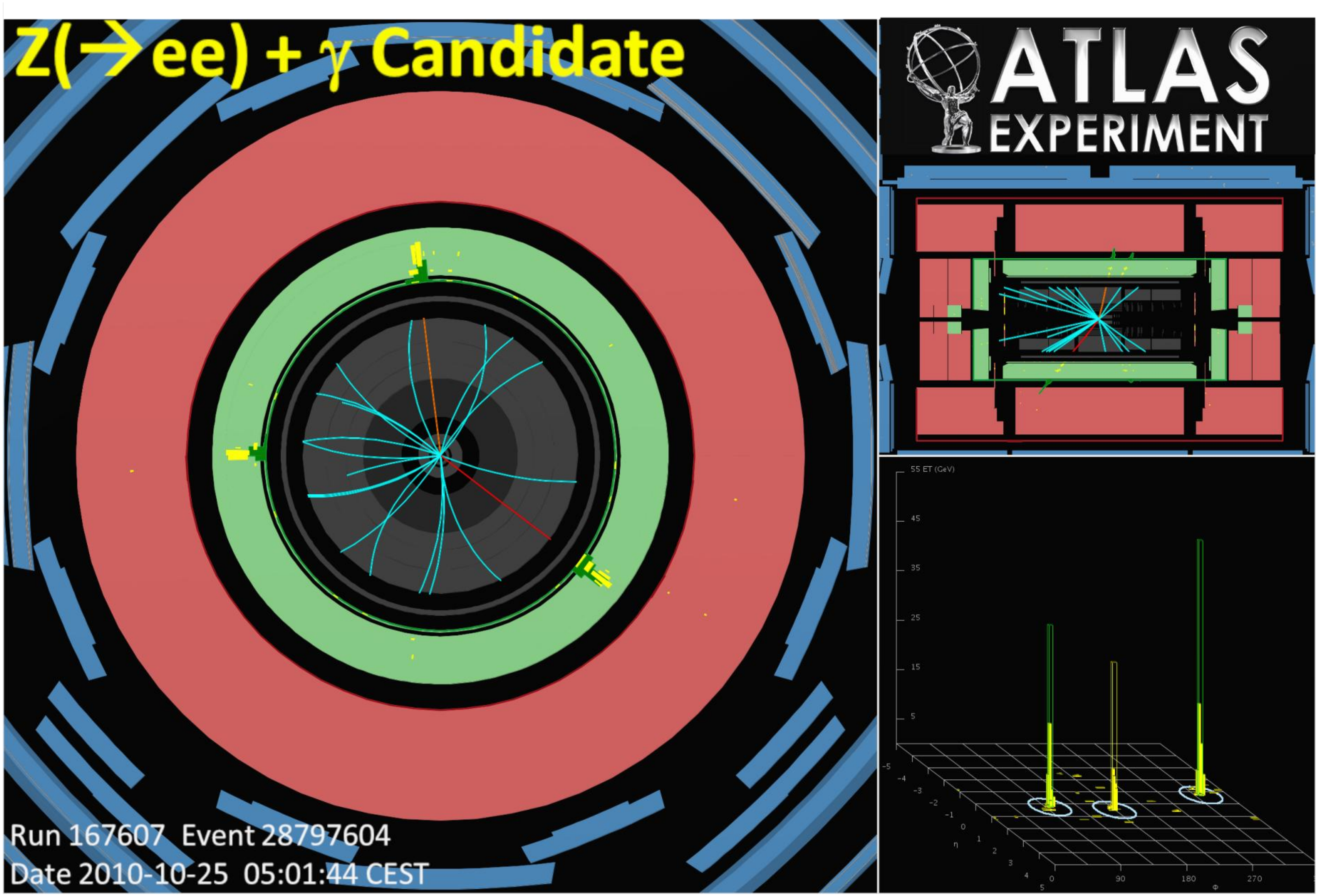
Invariant mass

$$(p_1 + p_2)\cdot(p_1 + p_2) = p_1 \cdot p_1 + p_2 \cdot p_2 + 2p_1 \cdot p_2$$

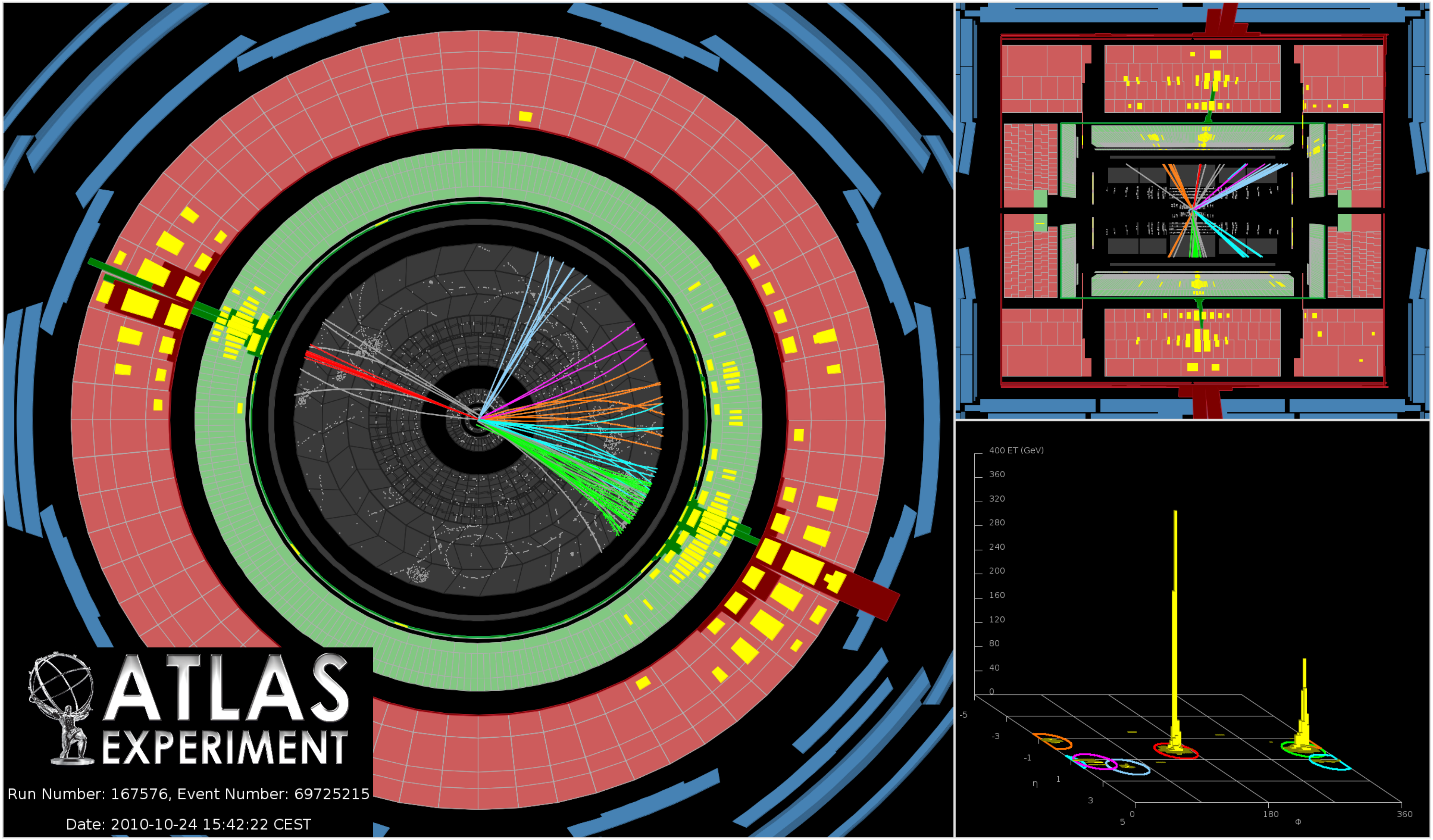
$$(p_1 + p_2)\cdot(p_1 + p_2) = m_1^2 + m_2^2 + 2E_1E_2 - 2\vec{p}_1 \cdot \vec{p}_2 = M^2$$

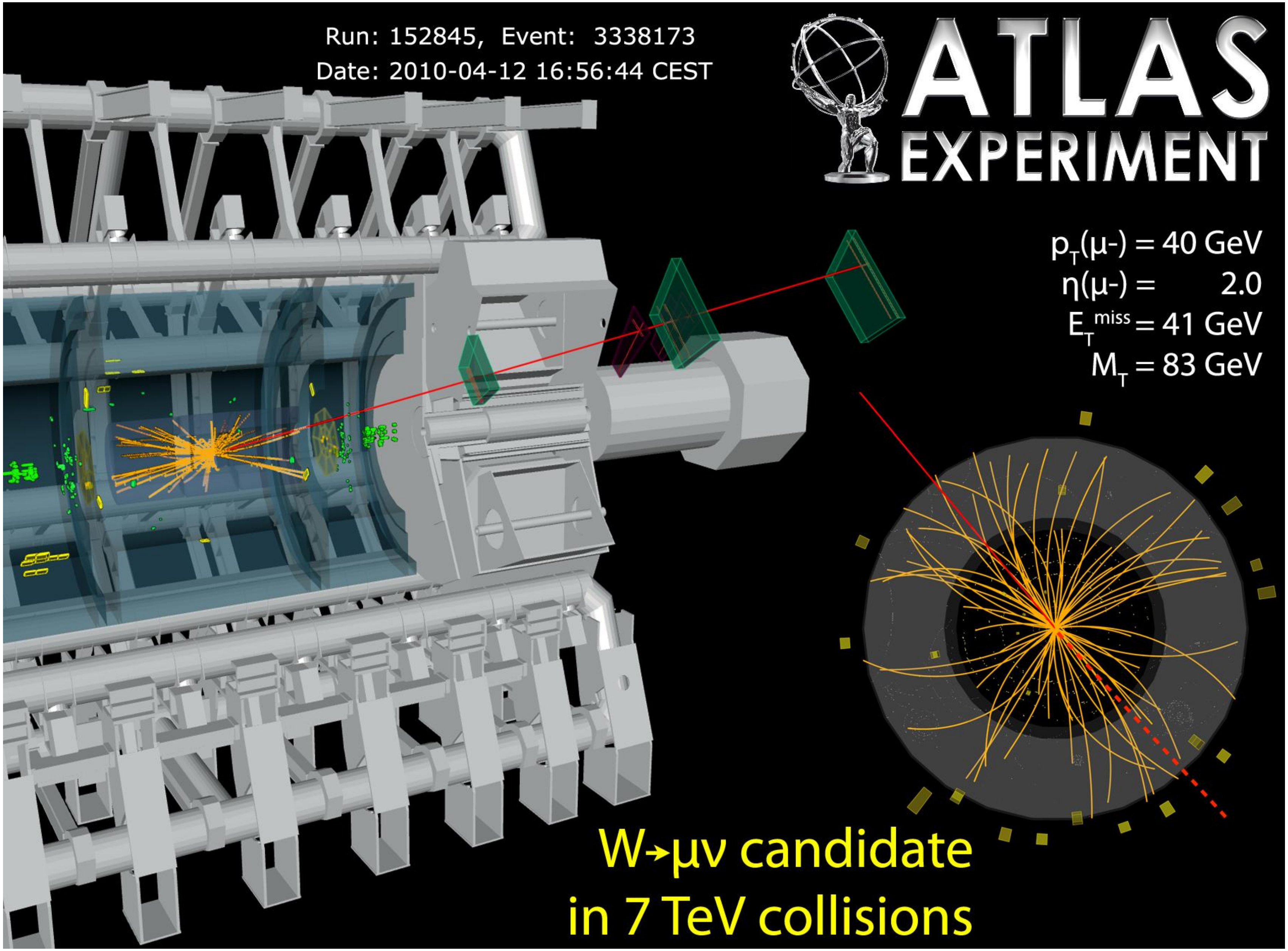
- Suppose a particle of mass M decays to 2 particles (mass m_1 and m_2 – these might be an electron and positron, a quark and antiquark, or a muon and antimuon).
- The invariant mass equation (above) from special relativity can be used to calculate the mass M.
- Many new particles have been discovered by observing bumps at mass M in the invariant mass distribution.
- The distribution has no bumps if the particle pairs do not come from decaying particles.
- We need to measure momentum and energy for particles coming out of collisions, and we need to do this with good resolution.

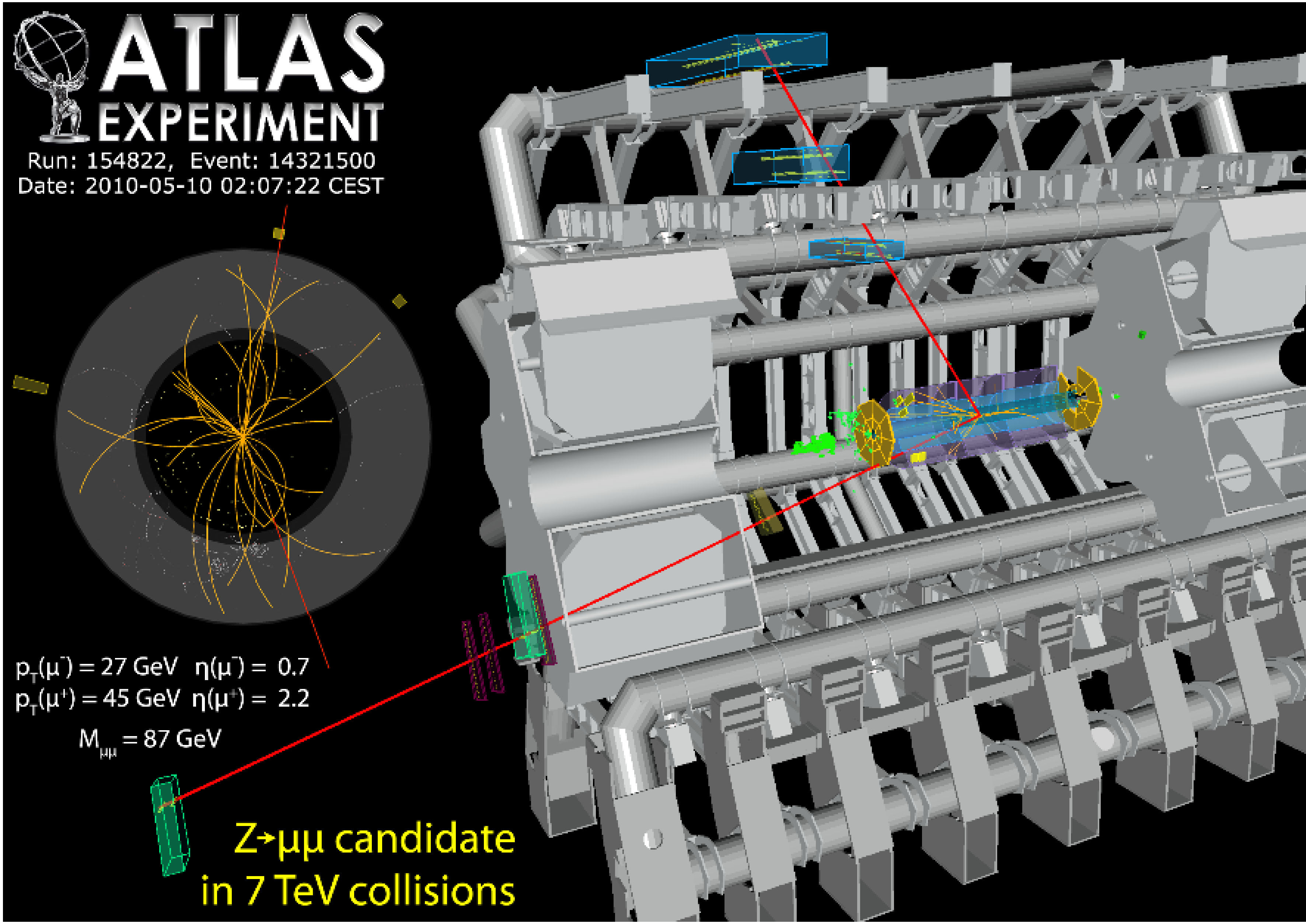
Candidate for a Z->ee decay, with the Z boson produced in association with a photon, collected on 28 October 2010. The Z boson invariant mass is 91 GeV. The two electrons and the photon are well isolated. Further event properties: $P_T(e^+)$ = 51 GeV, $P_T(e^-)$ = 37 GeV, P_T(gamma) = 30 GeV

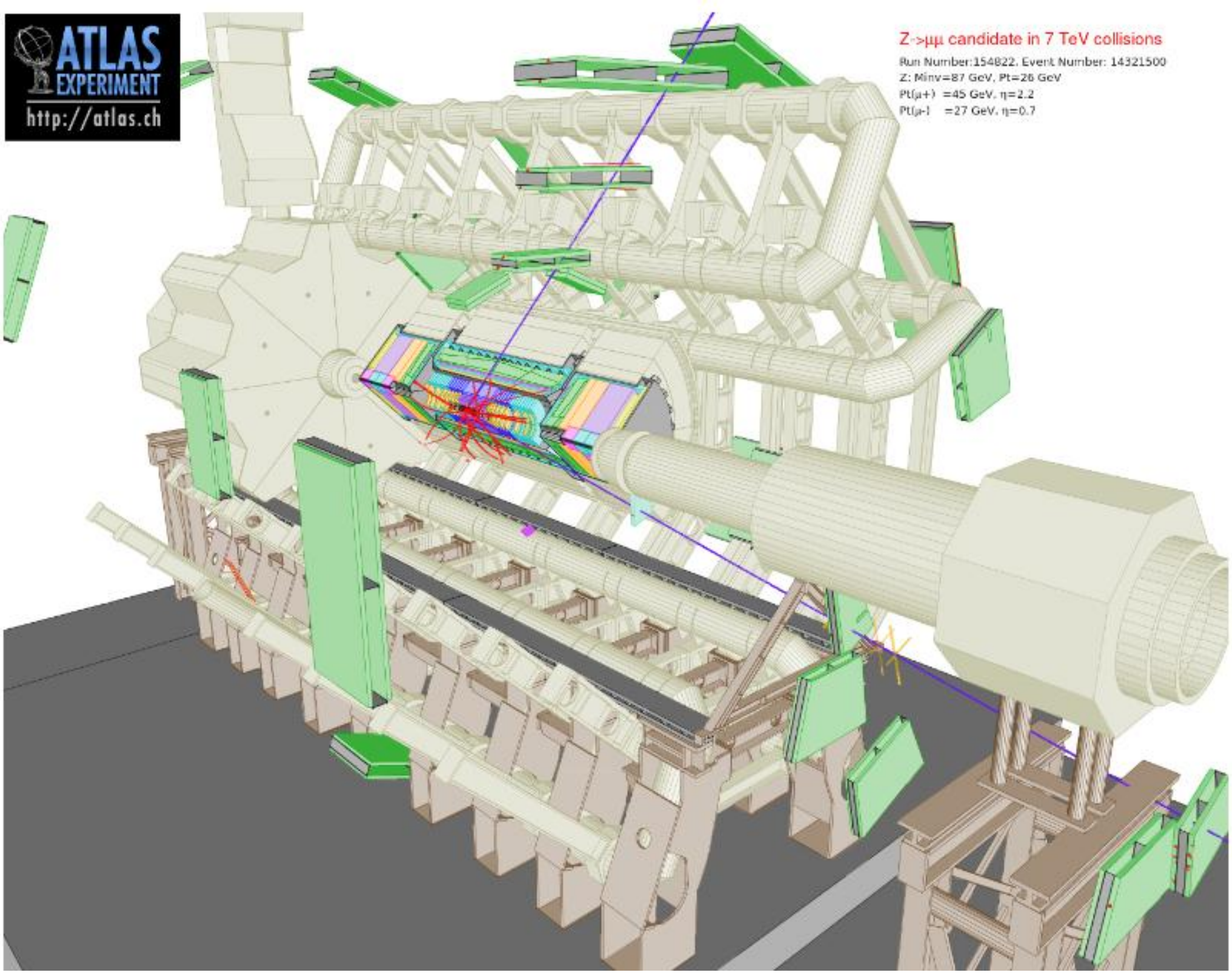


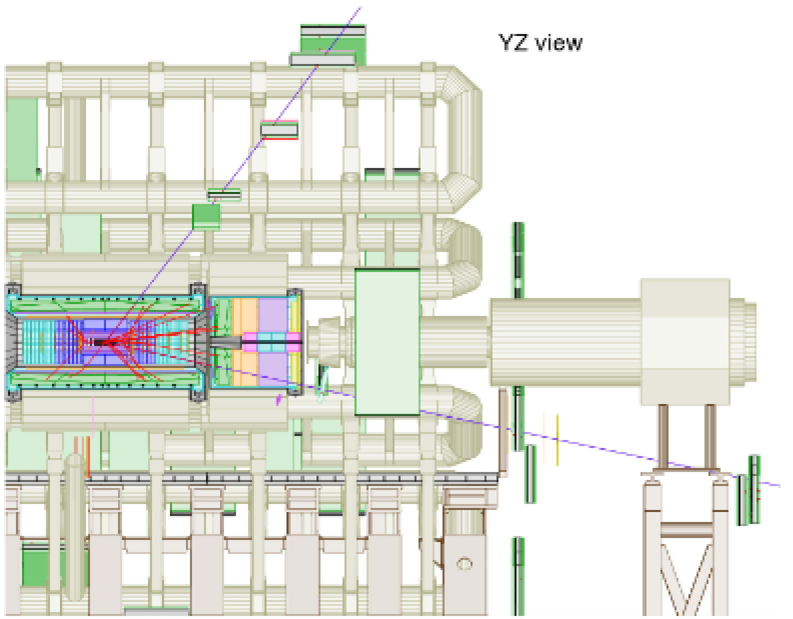
The highest mass central dijet event and the highest-p_T jet collected by the end of October 2010: two central high-p_T jets have an invariant mass of 2.6 TeV and the highest p_T jet has p_T of 1.3 TeV. 1st jet (ordered by p_T): p_T = 1.3 TeV, η = 0.2, ϕ = 2.8; 2nd jet: p_T = 1.2 TeV, η = 0.0, ϕ = -0.5; Missing E_T = 42 GeV, ϕ = 1.5; Sum E_T = 2.2 TeV

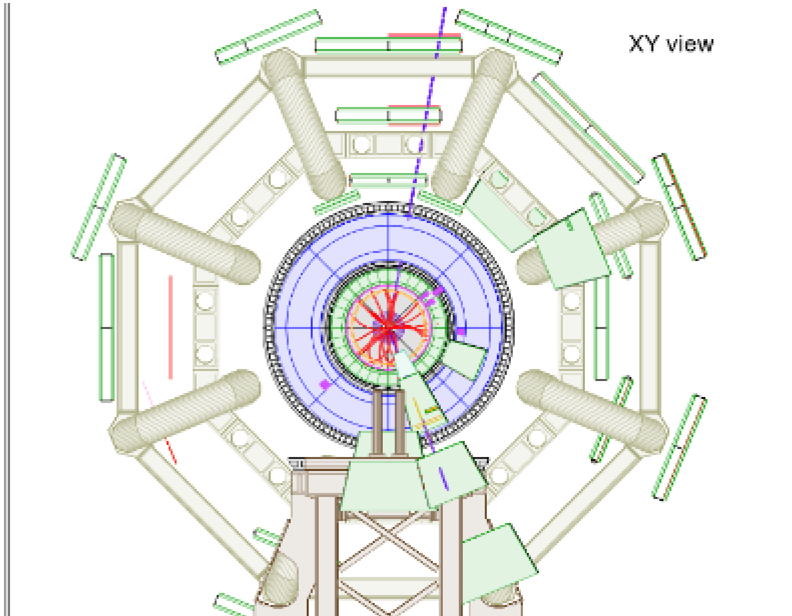


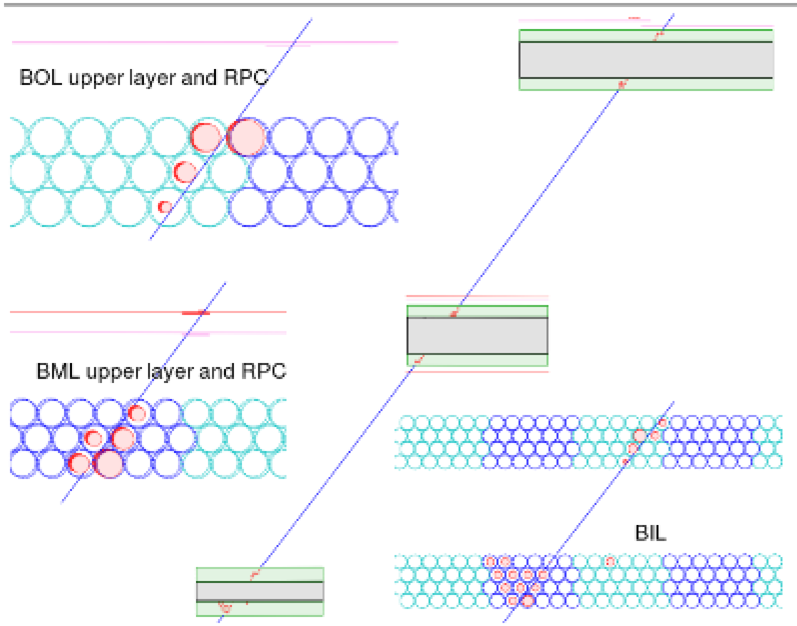

Run: 152845, Event: 3338173
Date: 2010-04-12 16:56:44 CEST
ATLAS
EXPERIMENT
$p_T(\mu-) = 40$ GeV
$\eta(\mu-) = 2.0$
$E_T^{miss} = 41$ GeV
$M_T = 83$ GeV
W→μν candidate
in 7 TeV collisions

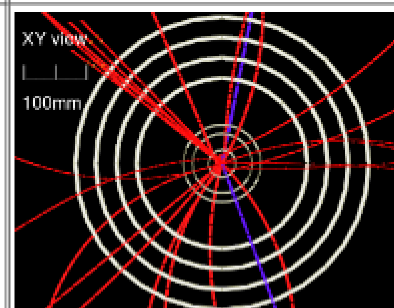

ATLAS EXPERIMENT
Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST
$p_T(\mu^-) = 27$ GeV $\eta(\mu^-) = 0.7$
$p_T(\mu^+) = 45$ GeV $\eta(\mu^+) = 2.2$
$M_{\mu\mu} = 87$ GeV
Z→μμ candidate
in 7 TeV collisions


ATLAS
EXPERIMENT
http://atlas.ch
Z->μμ candidate in 7 TeV collisions
Run Number:154822, Event Number: 14321500
Z: Minv=87 GeV, Pt=26 GeV
Pt(μ+) =45 GeV, η=2.2
Pt(μ-) =27 GeV, η=0.7









Z->μμ candidate in 7 TeV collisions

Run Number:154822, Event Number: 14321500

Z: Minv=87 GeV, Pt=26 GeV

Pt(μ+) =45 GeV, η=2.2

Pt(μ-) =27 GeV, η=0.7

ATLAS EXPERIMENT http://atlas.ch

Muon momentum resolution requirements for ATLAS are σ_{p_T}/p_T = 10% at p_T = 1 TeV, requiring location of the muon track to 50 microns over 15 meters. Current Z' limit is about 1.8 TeV.