PHYS 3446 – Lecture #23

Monday, Nov. 28, 2016

Dr. Jaehoon Yu

The Standard Model

- Quarks and Leptons
- Gauge Bosons
- Symmetry Breaking and the Higgs particle
- Issues in the Standard Model

Announcements

- Reading Assignments: CH11 and 12
- Term Exam #2
  - Next Monday, Dec. 5
  - Comprehensive: CH1.1 through what we cover today
  - BYOF
- Please fill out class feedback surveys
  - Only 1 has done as of last Saturday!
- Remember to submit your report by Wed. Dec. 7!
- Reminder the double extra credit opportunities
  - Colloquium this Wednesday
    - Dr. Steven Sands
  - Colloquium next Wednesday
    - Dr. K.C.Kong

The Standard Model of Particle Physics

- Prior to 70's, low mass hadrons are thought to be the fundamental constituents of matter, despite some new particles that seemed to have new flavors
  - Even the lightest hadrons, protons and neutrons, show some indication of substructure
    - Such as magnetic moment of the neutron
  - Raised questions whether they really are fundamental particles
- In 1964 Gell-Mann and Zweig suggested independently that hadrons can be understood as composite of quark constituents
  - Recall that the quantum number assignments, such as strangeness, were only theoretical tools rather than real particle properties

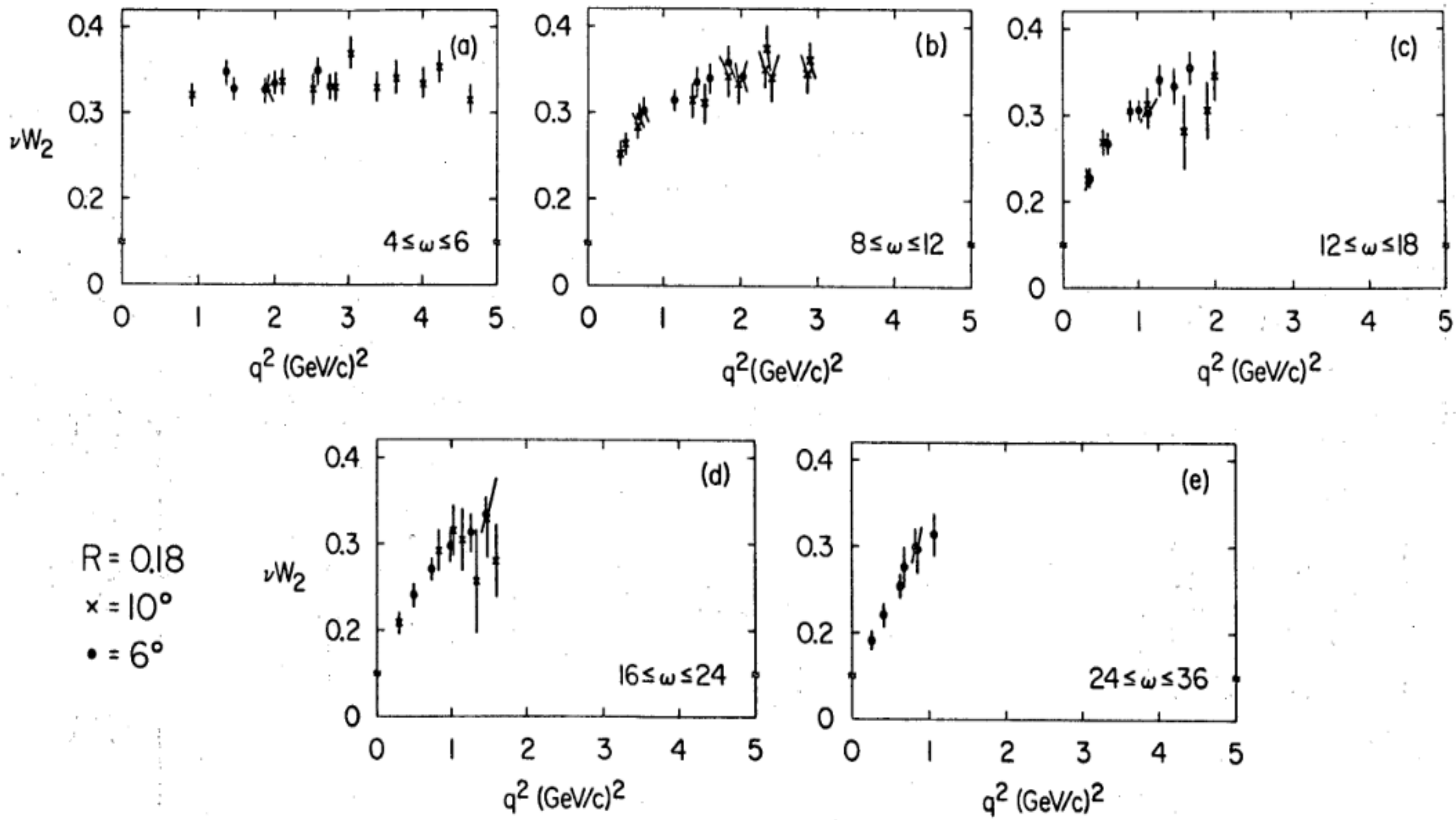
The Standard Model of Particle Physics

- In late 60's, Jerome Friedman, Henry Kendall and Rich Taylor designed an experiment with electron beam scattering off of hadrons and deuterium at SLAC (then Stanford Linear Accelerator Center – now SLAC National Laboratory) (Shared a Nobel in 1990)
  - Data could be easily understood if protons and neutrons are composed of point-like objects with charges -1/3e and +2/3e.
  - A point-like electrons scattering off of point-like quark partons inside the nucleons and hadrons
    - Corresponds to modern day Rutherford scattering
    - Higher energies of the incident electrons could break apart the target particles, revealing the internal structure

The Standard Model of Particle Physics

- Elastic scatterings at high energies can be described well with the elastic form factors measured at low energies
  - Since the interaction is elastic, particles behave as if they are point-like objects
- Inelastic scatterings cannot be described well with the elastic form factors since the target is broken apart
  - Inelastic scatterings of electrons with large momentum transfer (q^2) provide opportunities to probe shorter distances, breaking apart nucleons
  - The fact that the form factor for inelastic scattering at large q^2 is independent of q^2 shows that there are point-like object in a nucleon

Friedman Experimental Results



The Standard Model of Particle Physics

- Elastic scatterings at high energies can be described well with the elastic form factors measured at low energies, why?
  - Since the interaction is elastic, particles behave as if they are point-like objects
- Inelastic scatterings cannot be described well with the elastic form factors since the target is broken apart
  - Inelastic scatterings of electrons with large momentum transfer (q^2) provide opportunities to probe shorter distances, breaking apart nucleons
  - The fact that the form factor for inelastic scattering at large q^2 is independent of q^2 shows that there are point-like object in a nucleon
    - Bjorken scaling
- Nucleons contain both quarks and glue particles (gluons) both described by individual characteristic momentum distributions (Parton Distribution Functions)

The Standard Model of Particle Physics

- By early 70's, it was clear that hadrons (baryons and mesons) are not fundamental point-like objects
- But leptons did not show any evidence of internal structure
  - Even at high energies they still do not show any structure
  - Can be regarded as elementary particles
- The phenomenological understanding along with observation from electron scattering (Deep Inelastic Scattering, DIS) and the quark model
- Resulted in the Standard Model that can describe three of the four known forces along with quarks, leptons and gauge bosons as the fundamental particles

Quarks and Leptons

- In SM, there are three families of leptons   Q

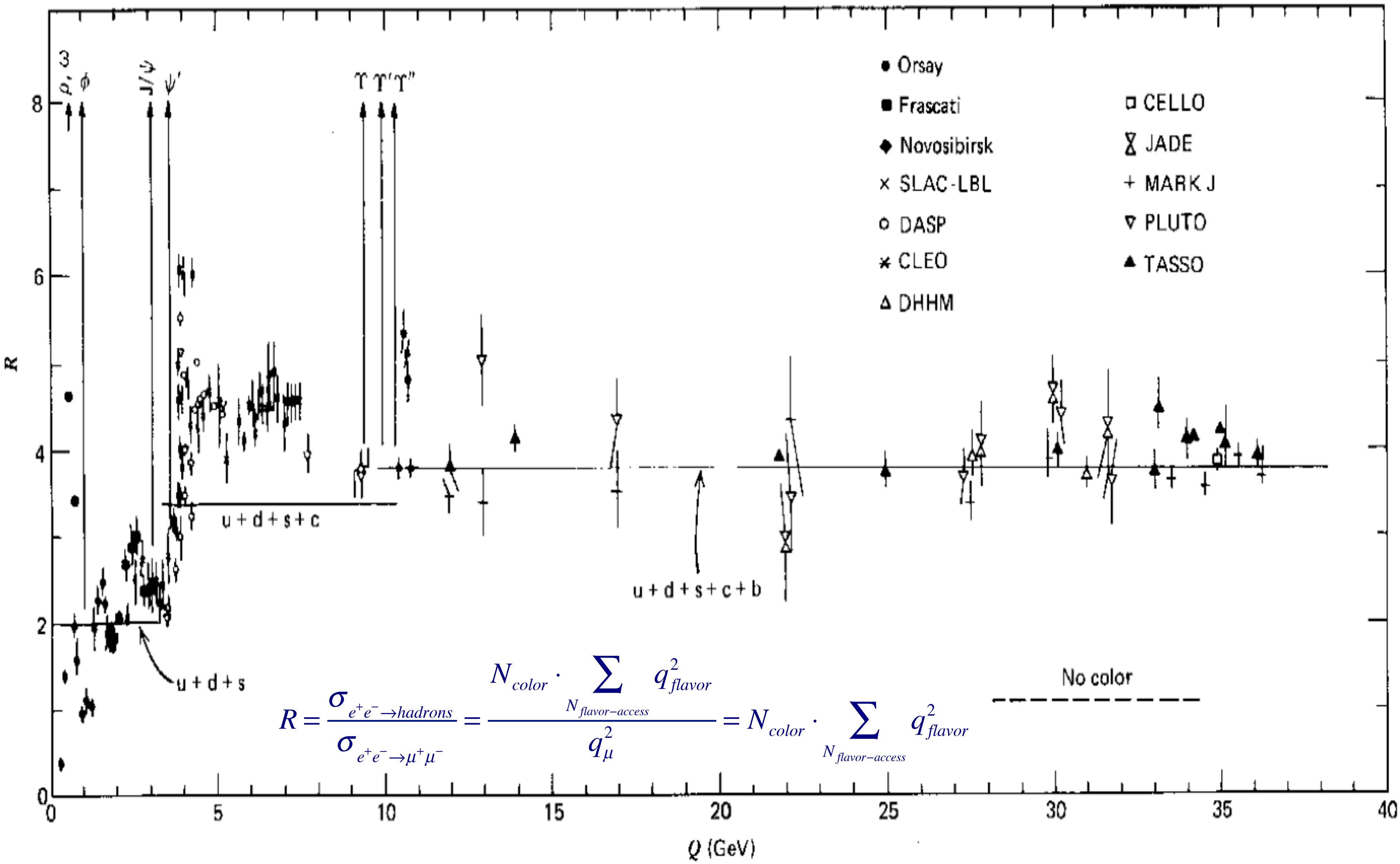
$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix} \quad \begin{matrix} 0 \\ -1 \end{matrix}$$

  - ➔ Increasing order of charged lepton mass
  - The same convention used in strong isospin symmetry, higher member of multiplet carries higher electrical charge
- And three families of quark constituents   Q

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix} \quad \begin{matrix} +2/3 \\ -1/3 \end{matrix}$$

- All these fundamental particles are fermions w/ spin $\frac{1}{2}\hbar$

Further Experiments on Quarks



$$R=\frac{\sigma_{e^+e^-\to hadrons}}{\sigma_{e^+e^-\to\mu^+\mu^-}}=\frac{N_{color}\cdot\sum_{N_{flavor-access}} q_{flavor}^2}{q_\mu^2}=N_{color}\cdot\sum_{N_{flavor-access}} q_{flavor}^2$$

Fig. 11.3 Ratio R of (11.6) as a function of the total $e^- e^+$ center-of-mass energy. (The sharp peaks correspond to the production of narrow 1^- resonances just below or near the flavor thresholds.)

Standard Model Elementary Particle Table

- Assumes the following fundamental structure:

- Total of 6 quarks, 6 leptons and 12 force mediators form the entire universe

Quark Content of Mesons

- Meson spins are measured to be integer.
  - They must consist of an even number of quarks
  - They can be described as bound states of quarks
- Quark compositions of some mesons
  - Pions

$$\pi^+ = u\bar{d}$$

$$\pi^- = \bar{u}d$$

$$\pi^0 = \frac{1}{\sqrt{2}}\left(u\bar{u} - d\bar{d}\right)$$

Strange mesons

$$K^+ = u\bar{s}$$

$$K^- = \bar{u}s$$

$$K^0 = d\bar{s}$$

$$\bar{K}^0 = \bar{d}s$$

Quark Content of Baryons

- Baryon spins are measured to be ½ integer.
  - They must consist of an odd number of quarks
  - They can be described as a bound states of three quarks based on the studies of their properties
- Quark compositions of some baryons
  - Nucleons | Strange baryons | Other Baryons
  - s=1 | s=2

Nucleons	Strange baryons s=1	Strange baryons s=2	Other Baryons
$p = uud$	$\Lambda^0 = uds$	$\Xi^0 = uss$	$\Delta^{++} = uuu$
$n = udd$	$\Sigma^+ = uus$	$\Xi^- = dss$	
	$\Sigma^0 = uds$		
	$\Sigma^- = dds$		

- Since baryons have B=1, the quarks must have baryon number 1/3

Need for Color Quantum Number

- The baryon Δ^{++} has an interesting characteristics
  - Its charge is +2, and spin is 3/2
  - Can consists of three u quarks ➔ These quarks in the ground state can have parallel spins to give Δ^{++} 3/2 spin
  - A trouble!! What is the trouble?
    - The three u-quarks are identical fermions and would be symmetric under exchange of any two of them
    - This is incompatible to Pauli's exclusion principle
  - What does this mean?
    - Quark-parton model cannot describe the Δ^{++} state
    - So should we give up?

Need for Color Quantum Number

- Since the quark-parton model works so well with other baryons and mesons it is imprudent to give the model up
- Give an additional internal quantum number that will allow the identical fermions in different states
- A color quantum number can be assigned to the quark
  - Red, Green or Blue
  - Baryons and Mesons (the observed particles) are color charge neutral
- It turns out that the color quantum number works to the strong forces as the electrical charge to EM force
- The dynamics is described by the theoretical framework, Quantum Chromodynamics (QCD)
  - Wilcek and Gross ➔ The winners of 2004 physics Nobel prize
- Gluons are very different from photons since they have non-zero color charges

Formation of the Standard Model

- Presence of the global symmetry can be used to classify particle states according to some quantum numbers
- Presence of local gauge symmetry requires an introduction of new vector particles as the force mediators
- The work of Glashow, Weinberg and Salam through the 1960's provided the theory of unification of electromagnetic and weak forces (GSW model), incorporating Quantum Electro-Dynamics (QED)
  - References:
    - L. Glashow, Nucl. Phys. **22**, 579 (1961).
    - S. Weinberg, Phys. Rev. Lett. **19**, 1264 (1967).
    - A. Salam, Proceedings of the 8th Nobel Symposium, Editor: N. Svartholm, Almqvist and Wiksells, Stockholm, 367 (1968)
- The addition of Quantum Chromodynamics (QCD) for strong forces (Wilcek & Gross) to GSW theory formed the Standard Model in late 70's
- Current SM is **U(1)xSU(2)xSU(3) gauge** theory

Introduction of Gauge Fields

- To maintain a local symmetry, additional fields had to be introduced
  - This is in general true even for more complicated symmetries
  - A crucial information for modern physics theories
- A distinct fundamental force in nature arises from the local invariance of physical theories
- The associated gauge fields generate these forces
  - These gauge fields are the mediators of the given force
- This is referred as the gauge principle, and such theories are gauge theories
  - Fundamental interactions are understood through this theoretical framework

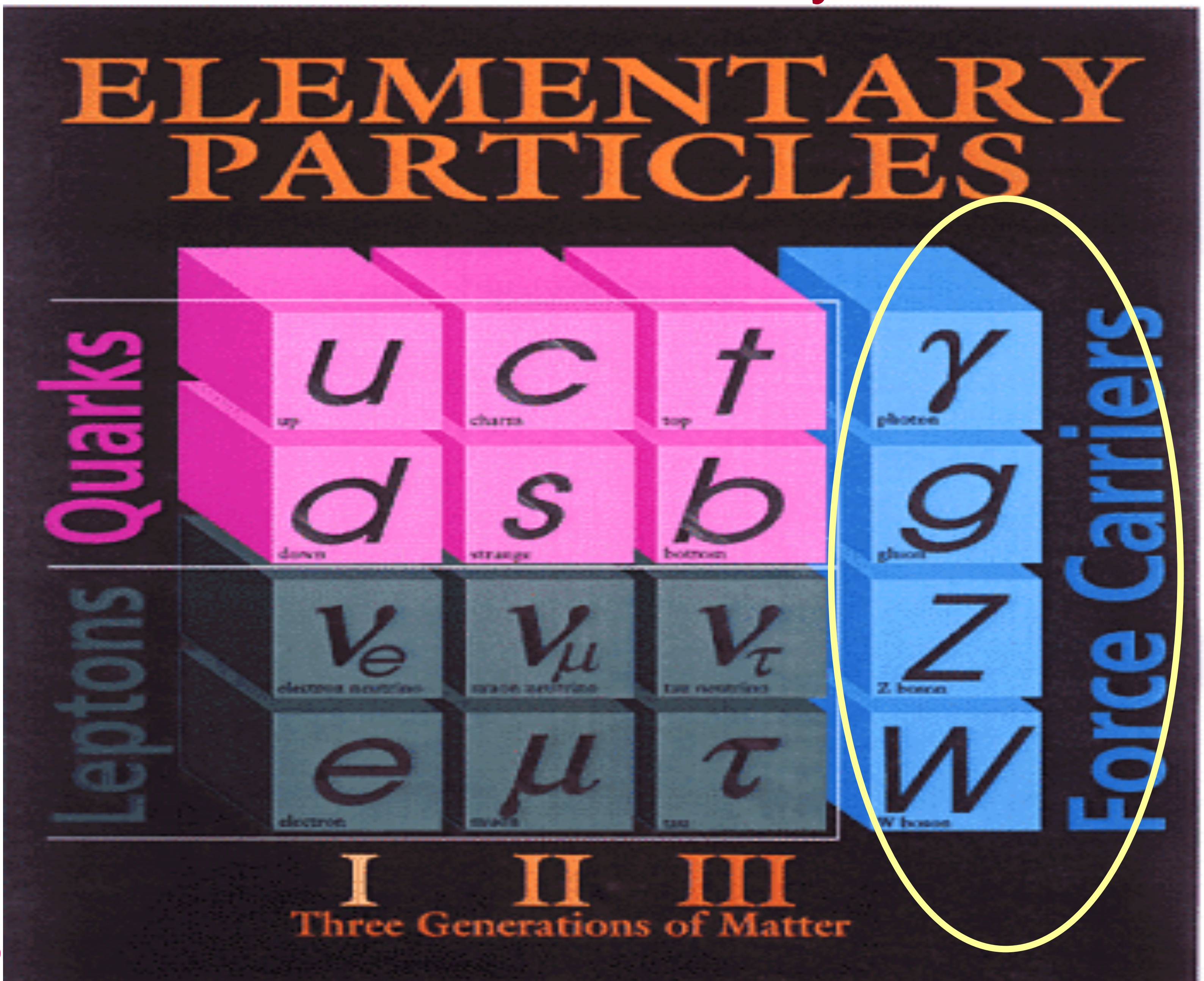
Gauge Fields and Mediators

- To keep local gauge invariance, new particles had to be introduced in gauge theories
  - **U(1) gauge** introduced a new field (particle) that mediates the electromagnetic force: **Photon**
  - **SU(2) gauge** introduces three new fields that mediates weak force
    - Charged current mediator: **W^+** and **W^-**
    - Neutral current: **Z^0**
  - **SU(3) gauge** introduces **8 mediators (gluons)** for the strong force
- Unification of electromagnetic and weak force SU(2)xU(1) gauge introduces a total of four mediators
  - Neutral current: Photon, Z^0
  - Charged current: W^+ and W^-

Gauge Bosons

- Through the local gauge symmetry, the Standard Model employs the following vector bosons as force mediators
  - Electro-weak: photon, Z^0, W^+ and W^- bosons
  - Strong force: 8 colored gluons
- If the theory were to be validated, these additional force carriers must be observed
- The electro-weak vector bosons were found at the CERN proton-anti proton collider in 1983 independently by C. Rubbia & collaborators and P. Darriulat & collaborators

Standard Model Elementary Particle Table



Z and W Boson Decays

- The weak vector bosons couples quarks and leptons
  - Thus they decay to a pair of leptons or a pair of quarks
- Since they are heavy, they decay instantly to the following channels and their branching ratios
  - Z bosons: M_Z=91GeV/c^2
  - $Z^0 \to q\bar{q} \quad (69.9\%)$
  - $Z^0 \to l^+ l^-$ (3.37% for each charged lepton species)
  - $Z^0 \to \nu_l \bar{\nu}_l$ (20%)
  - W bosons: M_W=80GeV/c^2
  - $W^\pm \to q\bar{q}' \quad (68\%)$
  - $W^\pm \to l^\pm \nu_l$ (~10.6% for each charged lepton species)

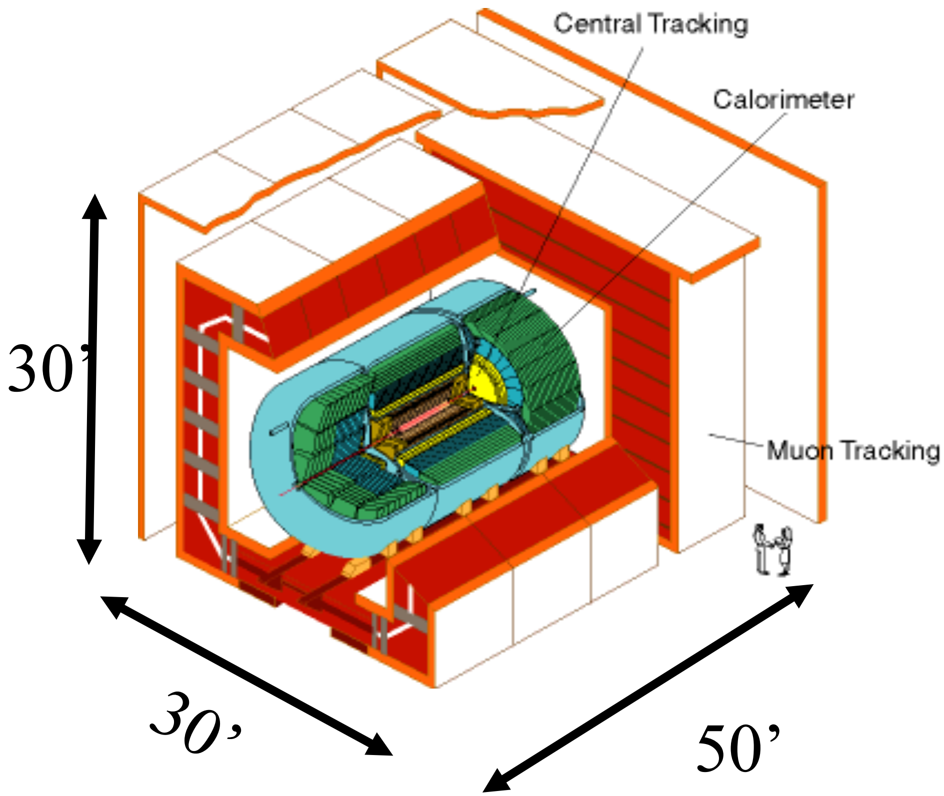
Z and W Boson Search Strategy

- The weak vector bosons have masses of 91 GeV/c^2 for Z and 80 GeV/c^2 for W
- While the most abundant decay final state is qqbar (2 jets of particles), the multi-jet final states are also the most abundant in collisions
  - Background is too large to be able to carry out a meaningful search
- The best channels are using leptonic decay channels of the bosons
  - Especially the final states containing electrons and muons are the cleanest
- So what do we look for as signature of the bosons?
  - For Z-bosons: Two isolated electrons or muons with large transverse momenta (P_T)
  - For W bosons: One isolated electron or muon with a large transverse momentum along with a signature of high P_T neutrino (Large missing ET).

What do we need for the experiment to search for vector bosons?

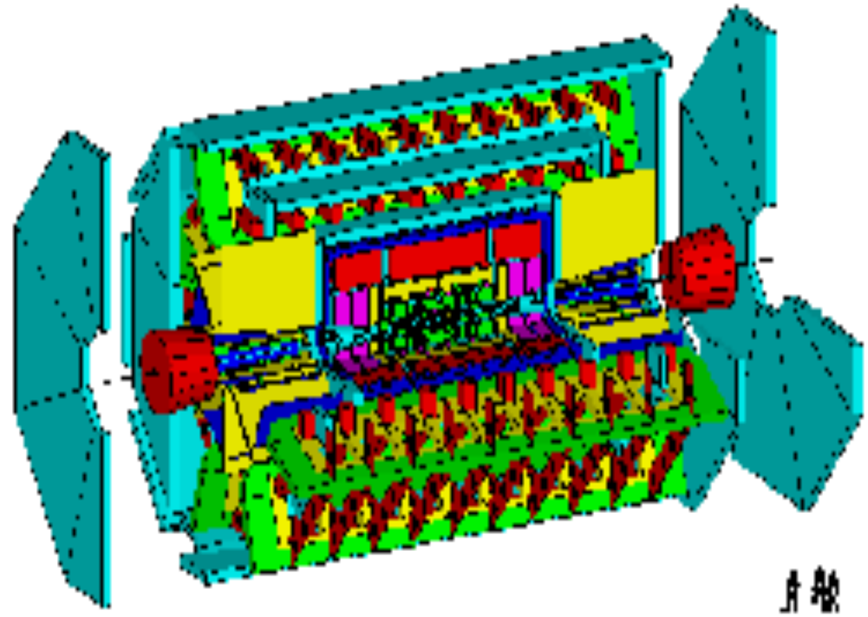
- We need to be able to identify isolated leptons
  - Good electron and muon identification
  - Charged particle tracking
- We need to be able to measure transverse momentum well
  - Good momentum and energy measurement
- We need to be able to measure missing transverse energy well
  - Good coverage of the energy measurement (hermeticity) to measure transverse momentum imbalance well

DØ Detector



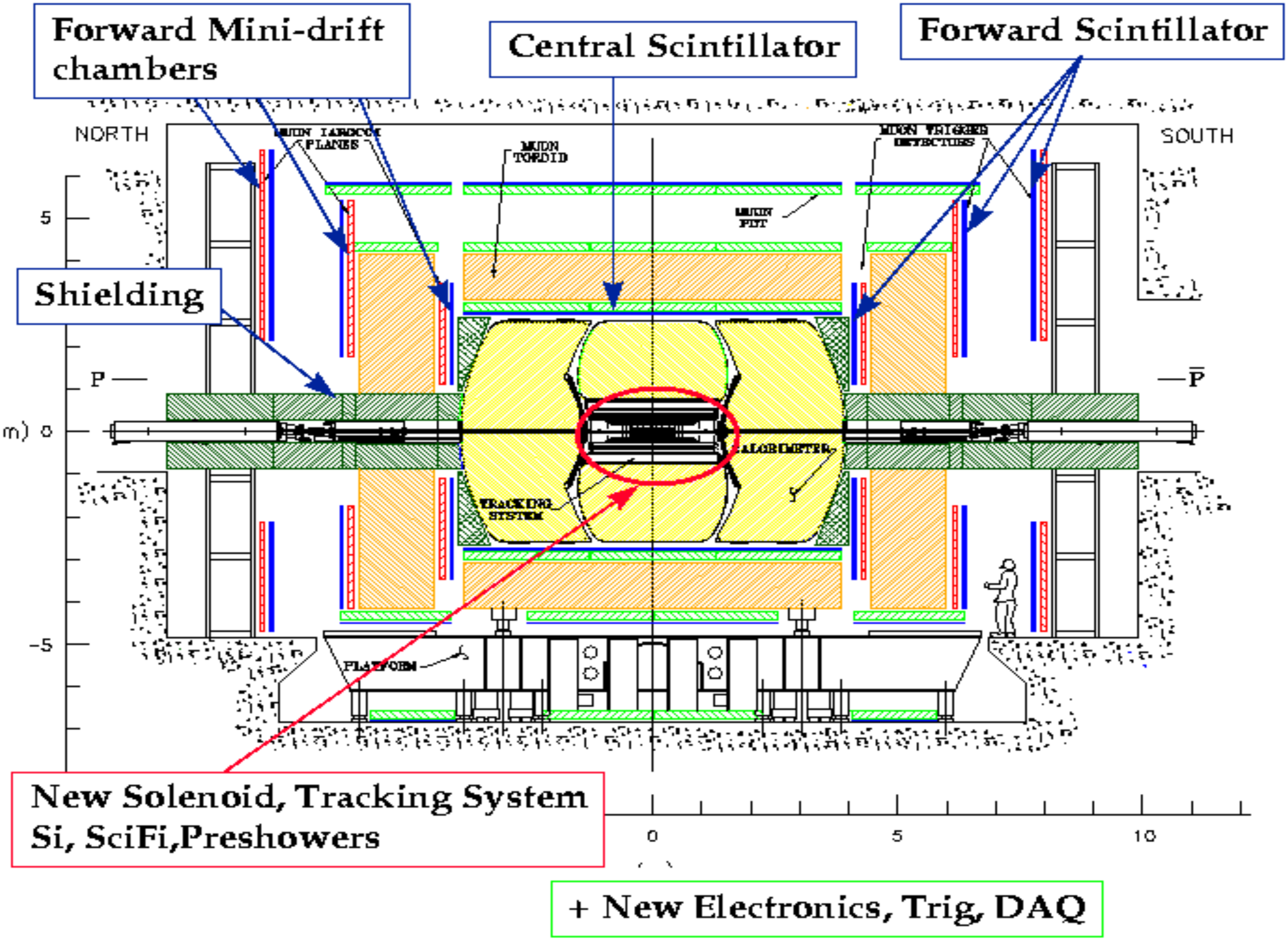
- Weighs 5000 tons
- Can inspect 3,000,000 collisions/second
- Recordd 50 - 75 collisions/second
- Records approximately 10,000,000 bytes/second
- Records 0.5×10^{15} (500,000,000,000,000) bytes per year (0.5 PetaBytes).

ATLAS Detector



- Weighs 10,000 tons
- Can inspect 1,000,000,000 collisions/second
- Will record 100 collisions/second
- Records approximately 300,000,000 bytes/second
- Will record 1.5×10^{15} (1,500,000,000,000,000) bytes each year (1.5 PetaByte).

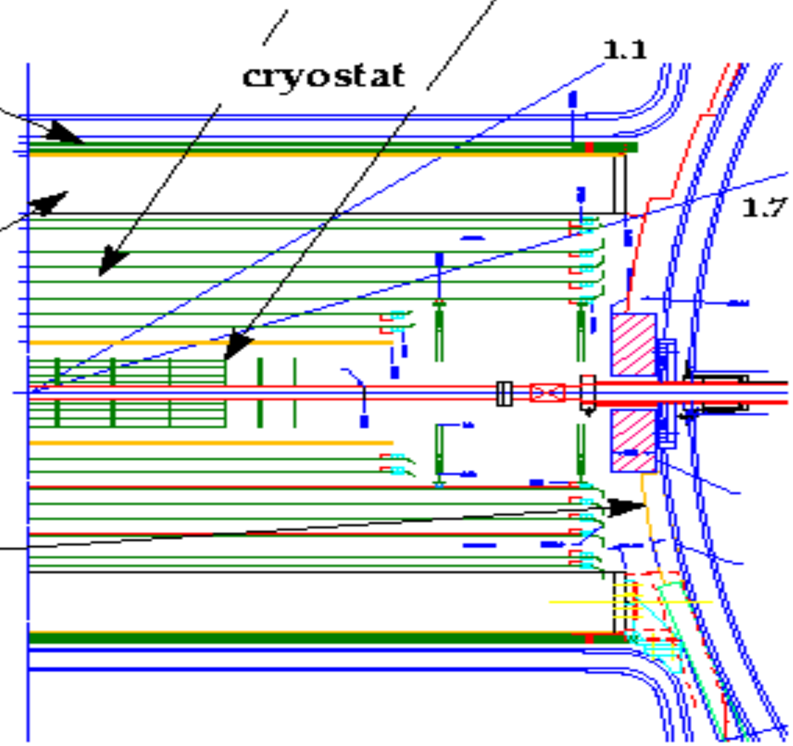
Run II DØ Detector



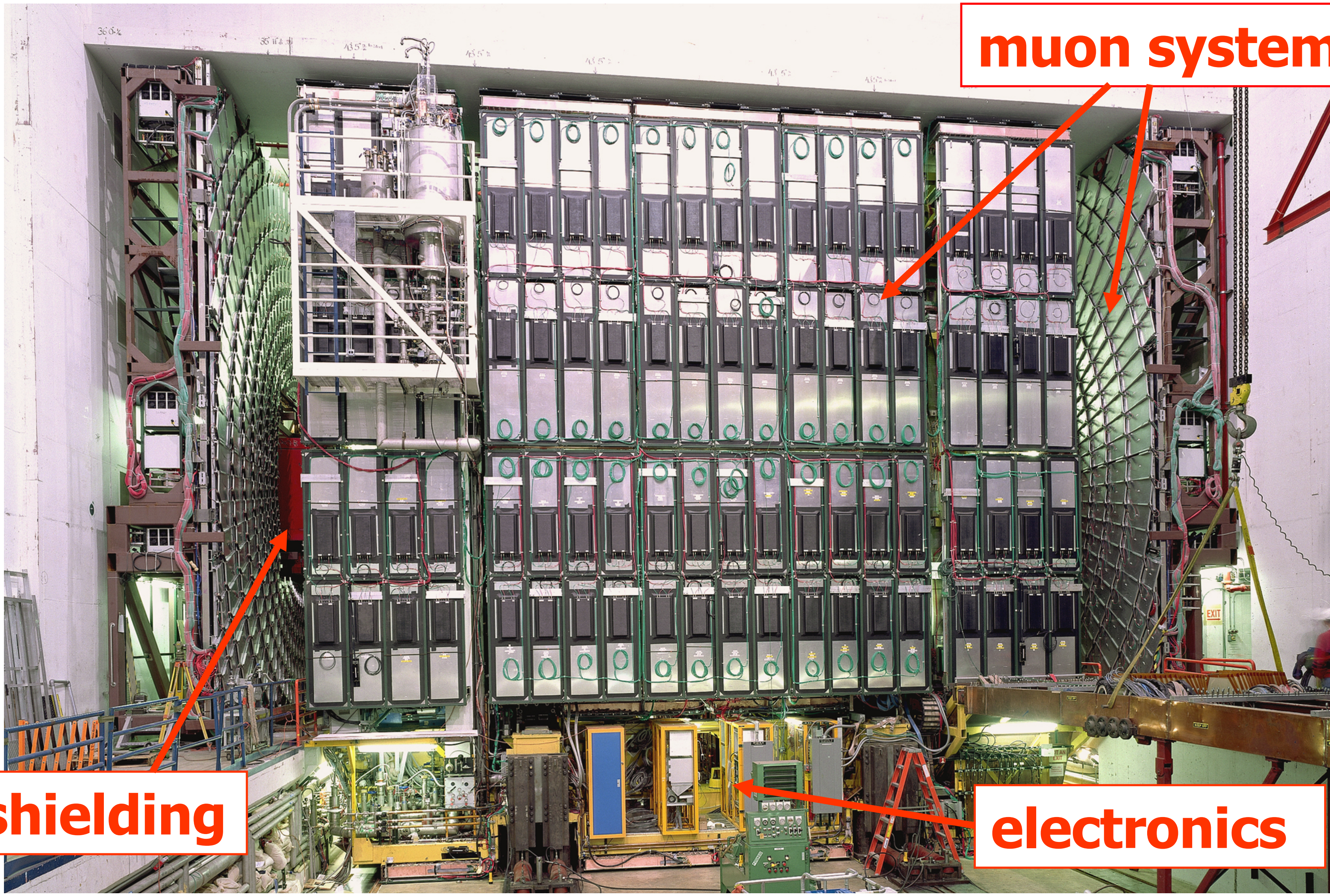
The DØ Upgrade Tracking System

- **Silicon Tracker**
  - Four layer barrels (double/single sided)
  - Interspersed double sided disks
  - 840,00 channels
- **Fiber Tracker**
  - Eight layers sci-fi ribbon doublets (z-u-v, or z
  - 74,000 830um fibers w/ VLPC readout
- **Central Preshower**
  - Scintillator strips, WLS fiber readout
  - 6,000 channels
- **Solenoid**
  - 2T superconducting
- **Forward Preshower**
  - Scintillator strips, stereo, WLS readout
  - 16,000 channels

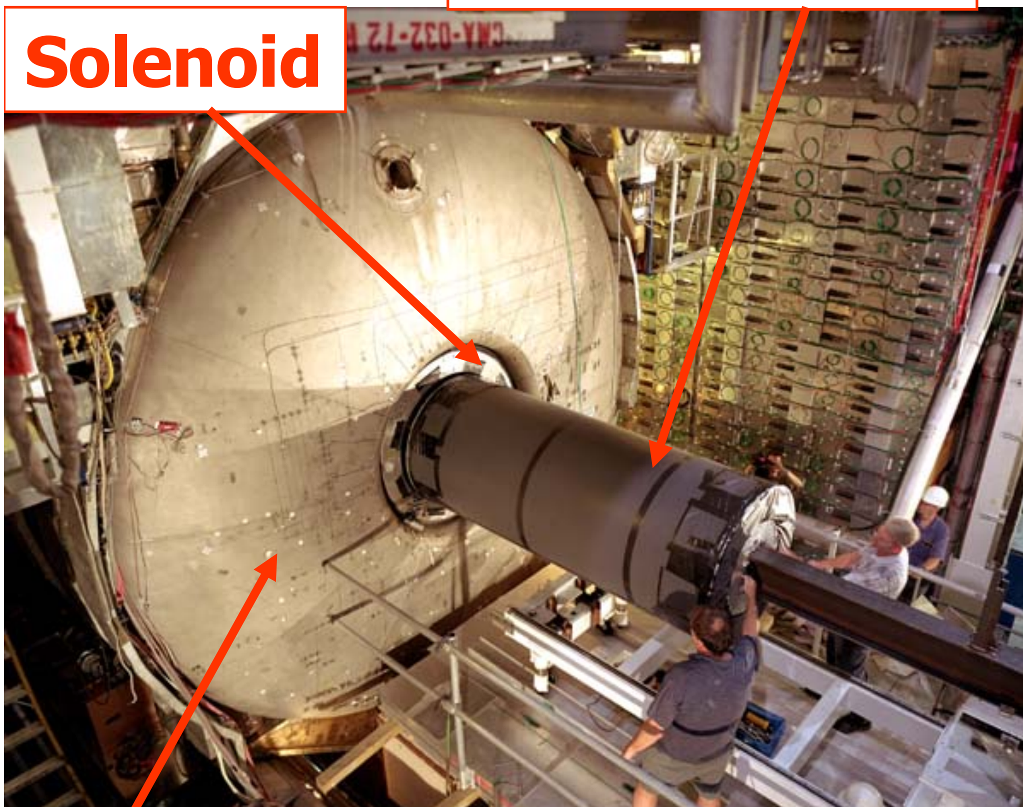
Charged Particle Momentum Resolution
$\Delta p_T/p_T \sim 5\%$ @ p_T = 10 GeV/c

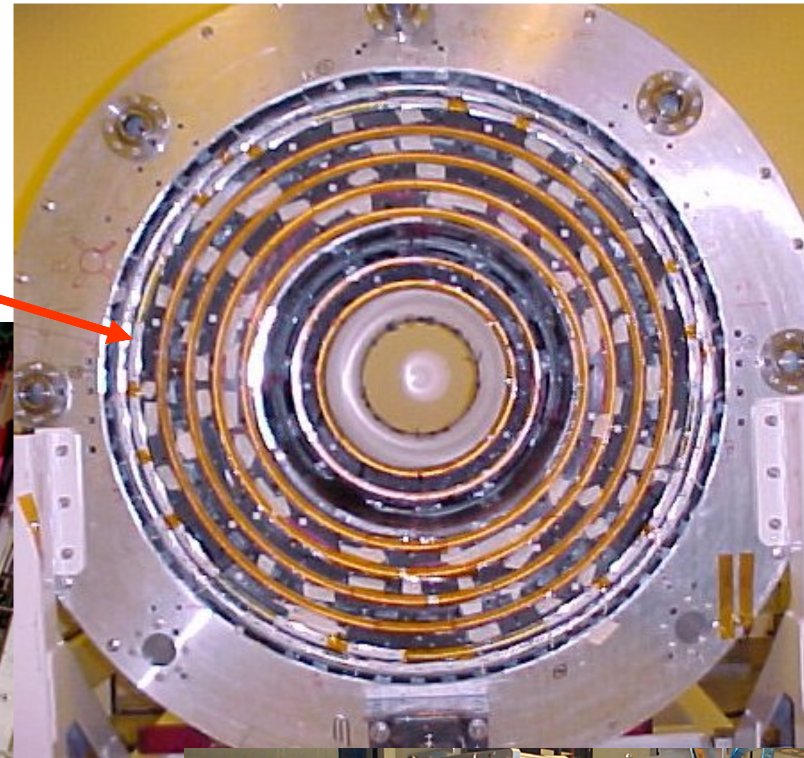


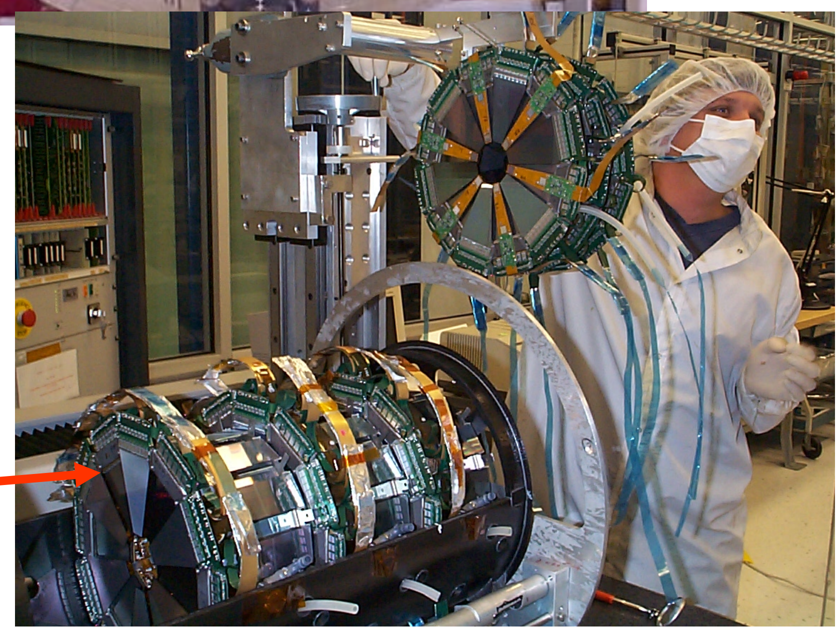
DØ Detector



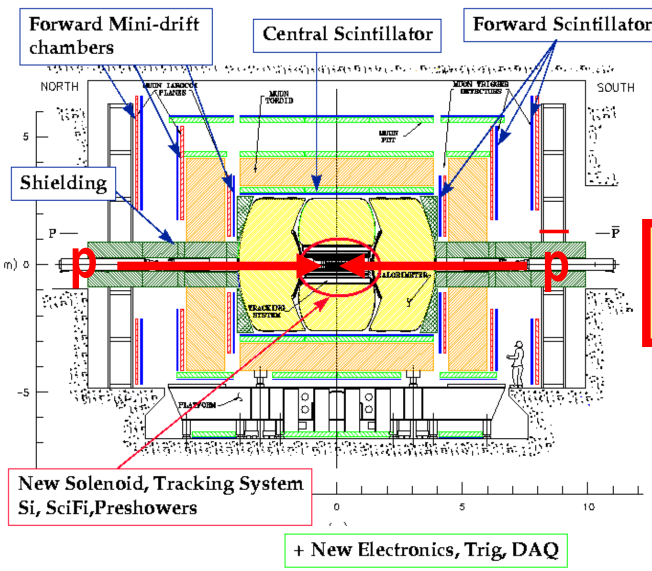
DØ Detector



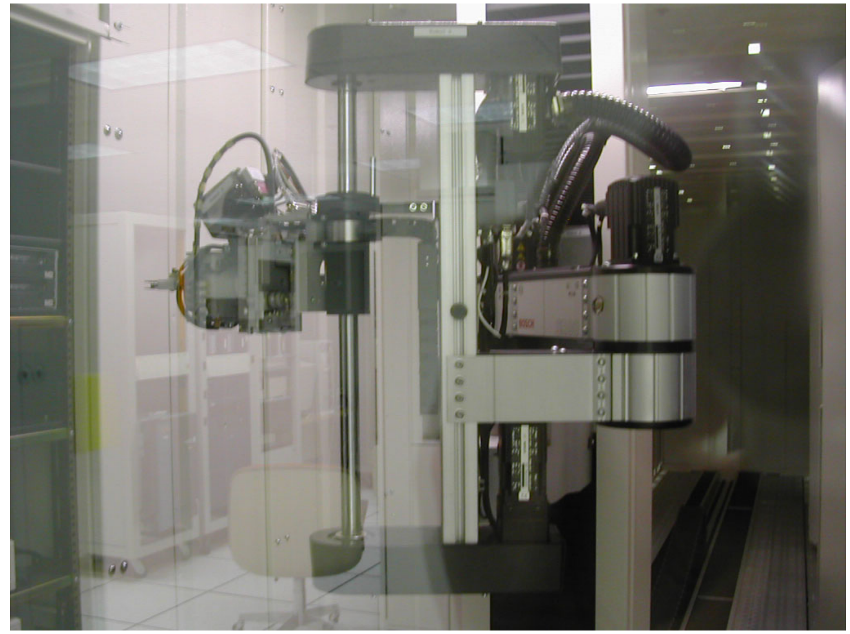




How are computers used in HEP?

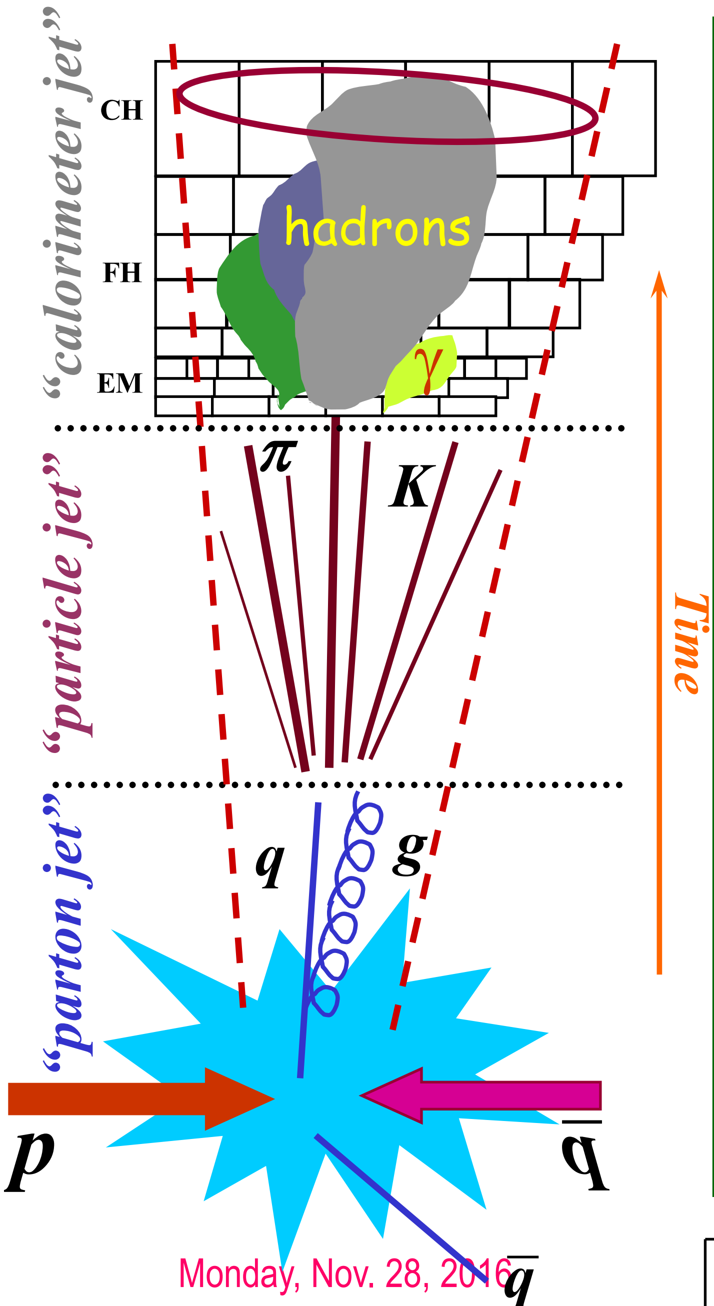


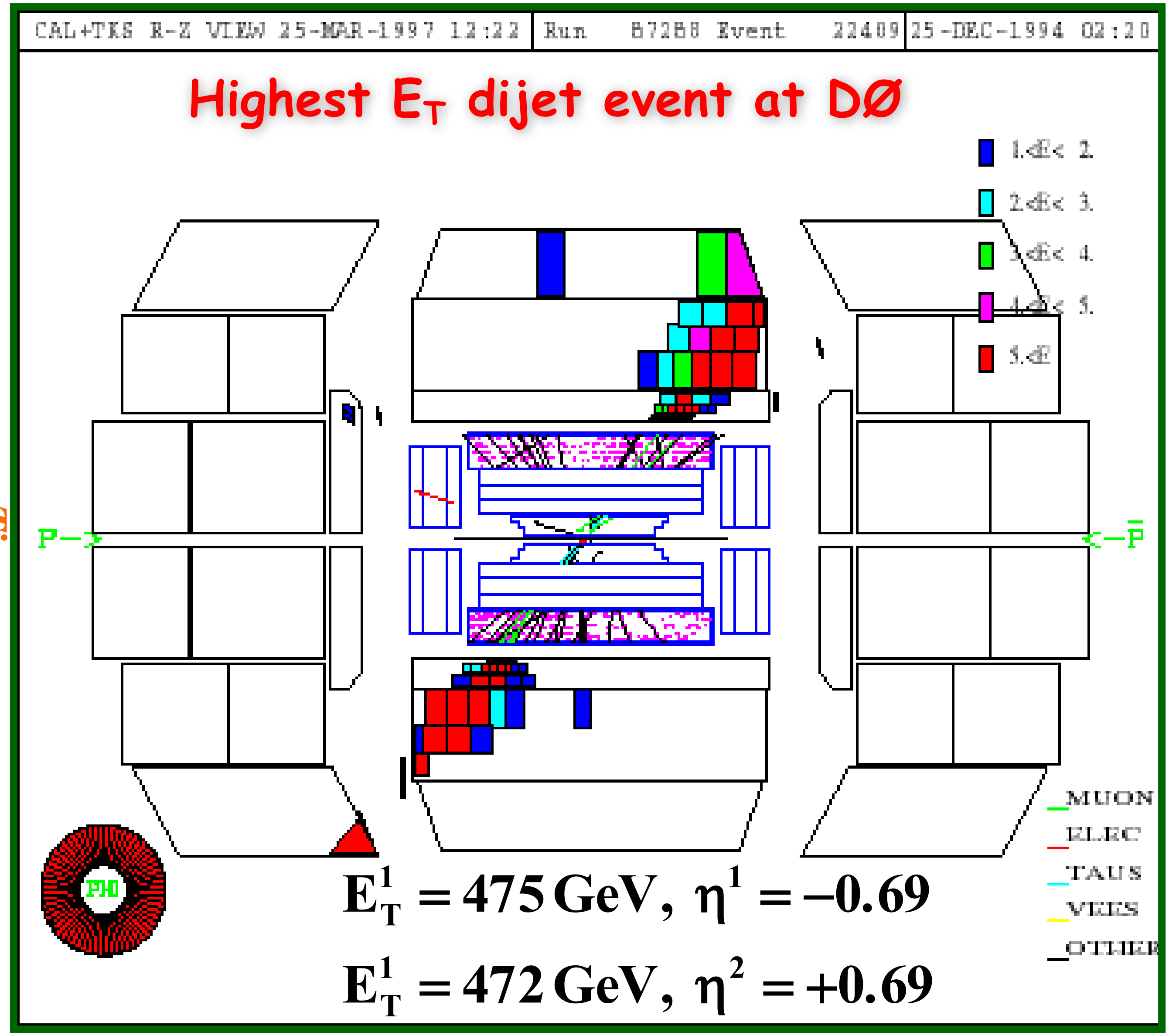
Digital Data



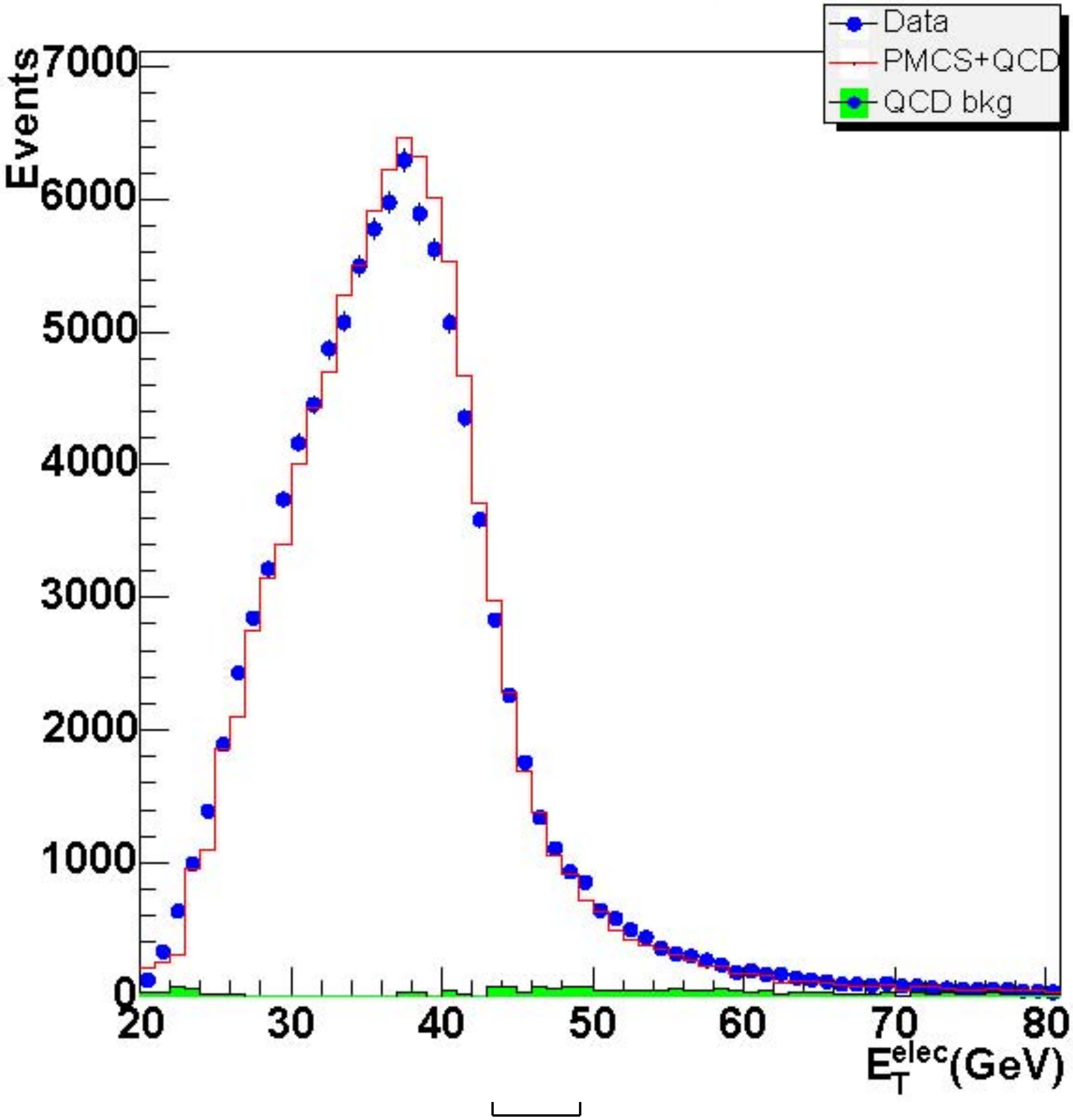
Data Reconstruction

How does an Event Look in a HEP Detector?



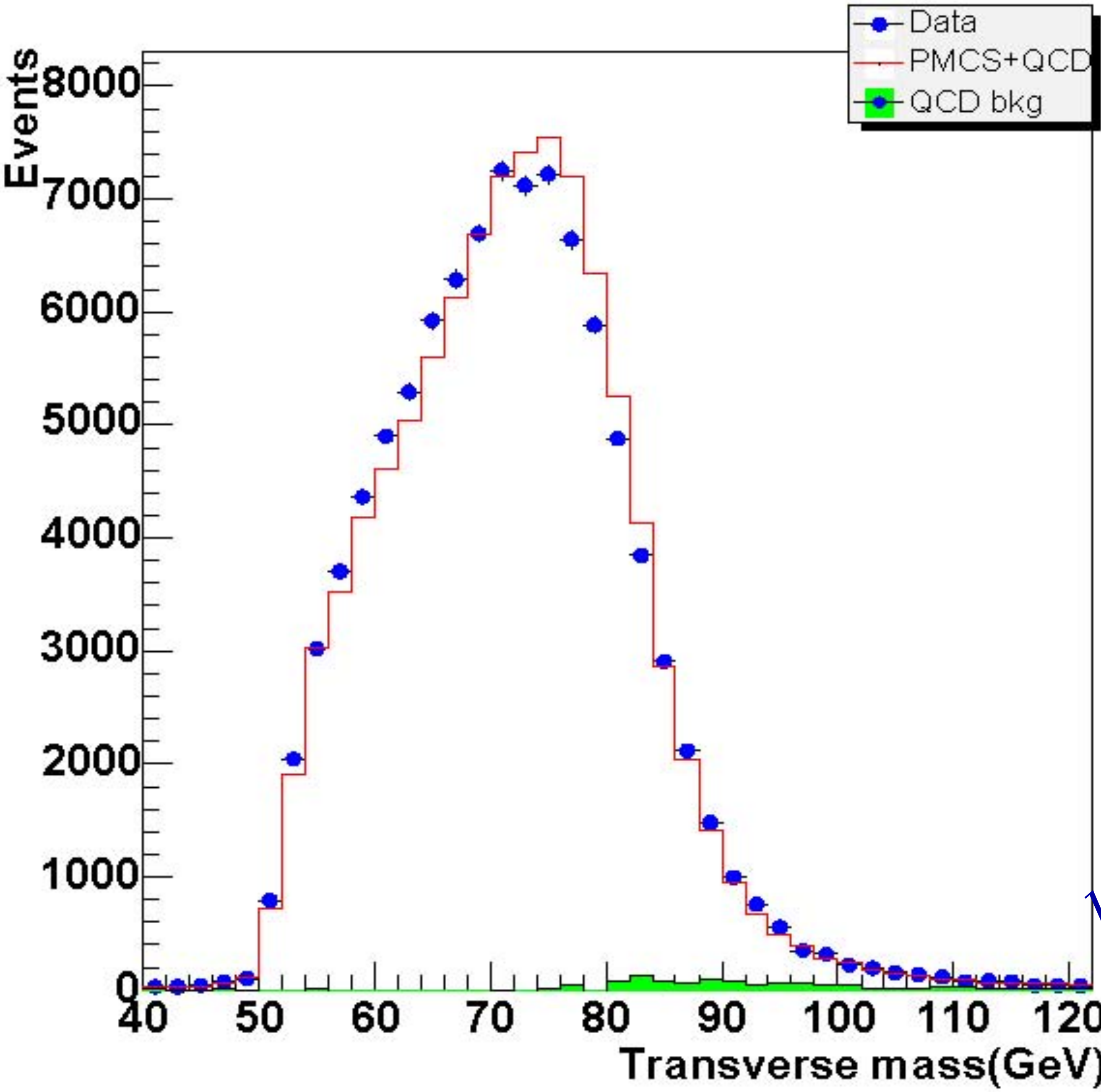


Electron Transverse Momentum W(→eν) +X



- Transverse momentum distribution of electrons in W+X events

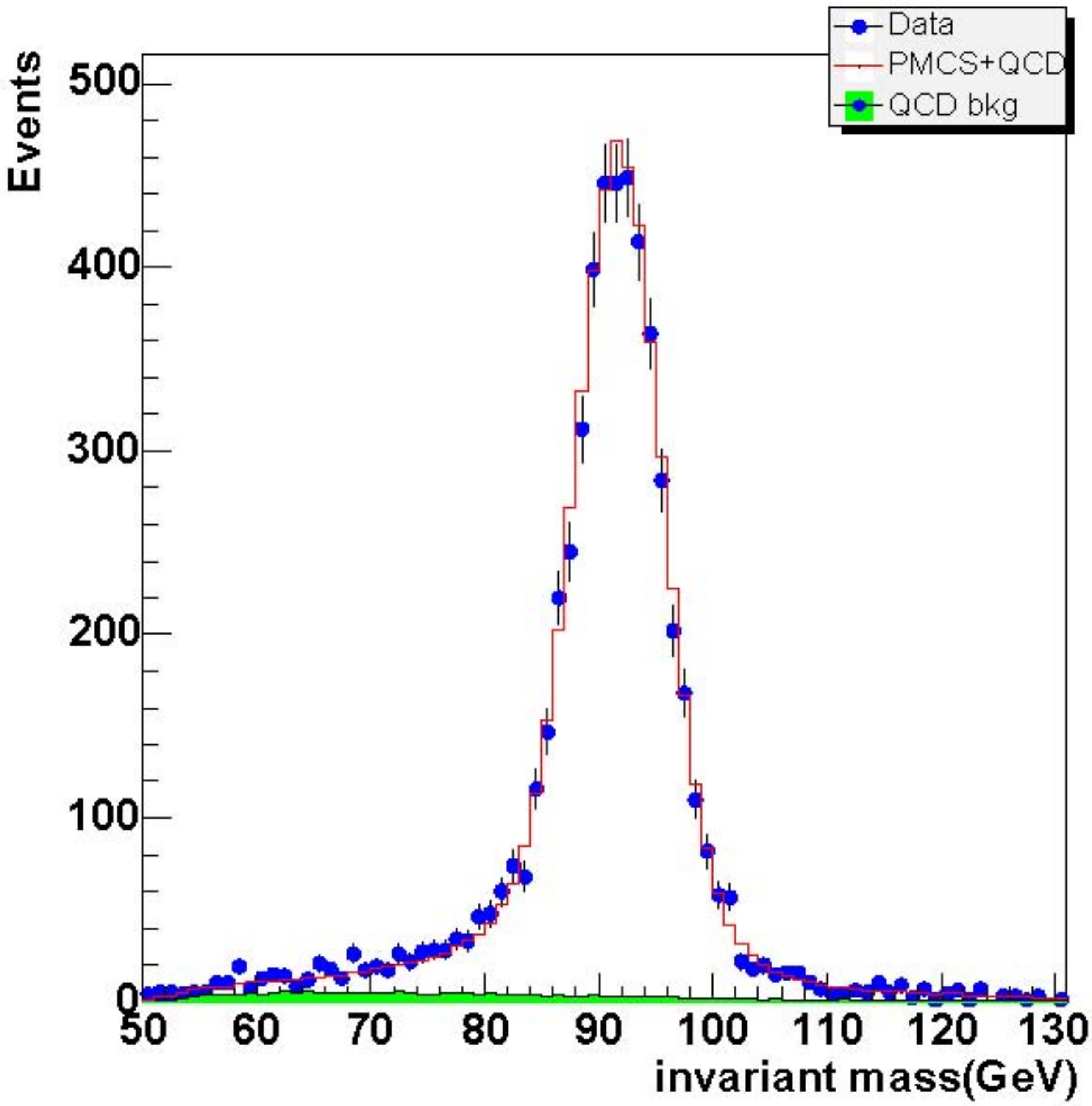
W Transverse Mass W(→eν) +X



- Transverse mass distribution of electrons in W+X events

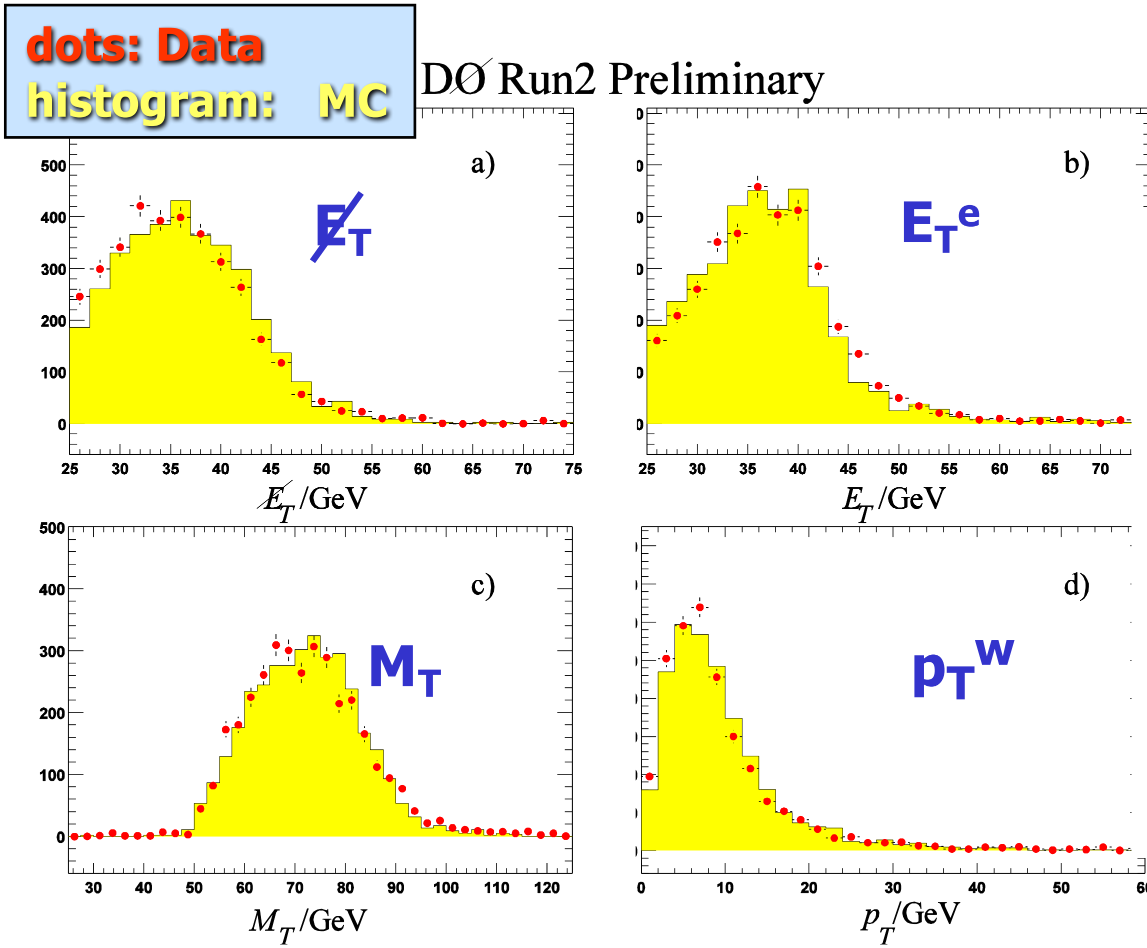
$$M_T^W \equiv \sqrt{2E_T^e \not{E}_T \left(1-\cos\Delta\varphi_{e\nu}\right)}$$

Electron Invariant Mass Z(→ee) +X

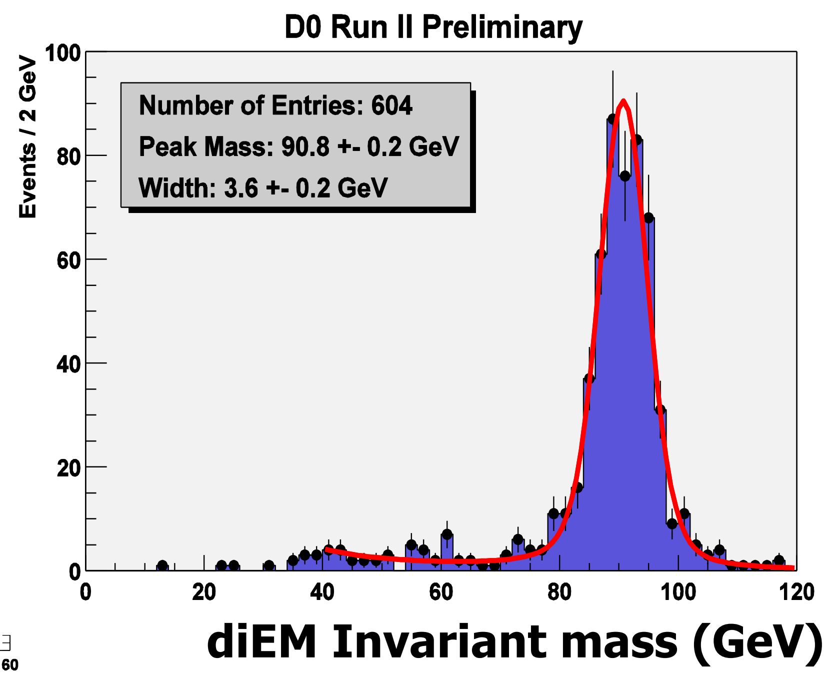


- Invariant mass distribution of electrons in Z+X events

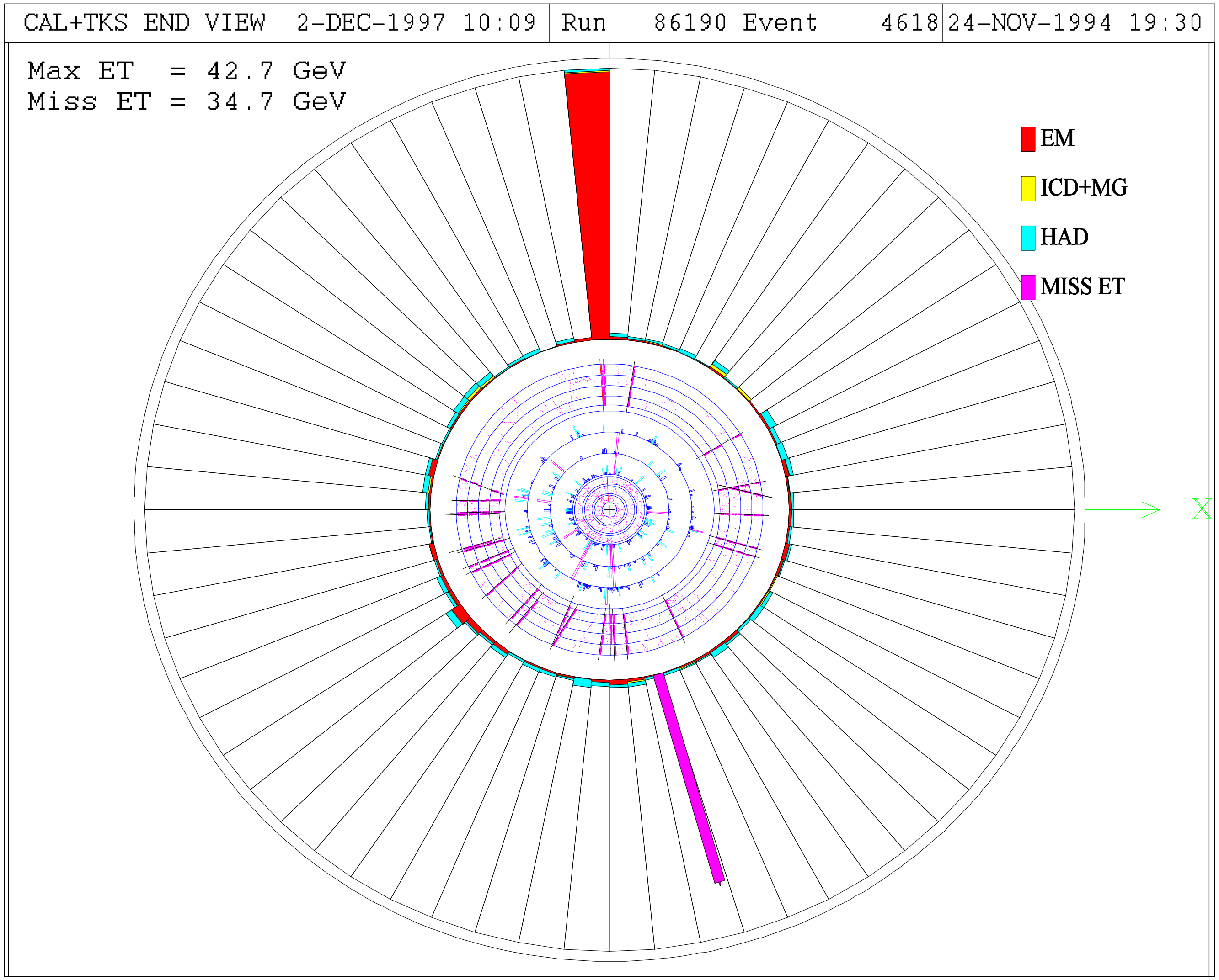
W and Z event kinematic properties



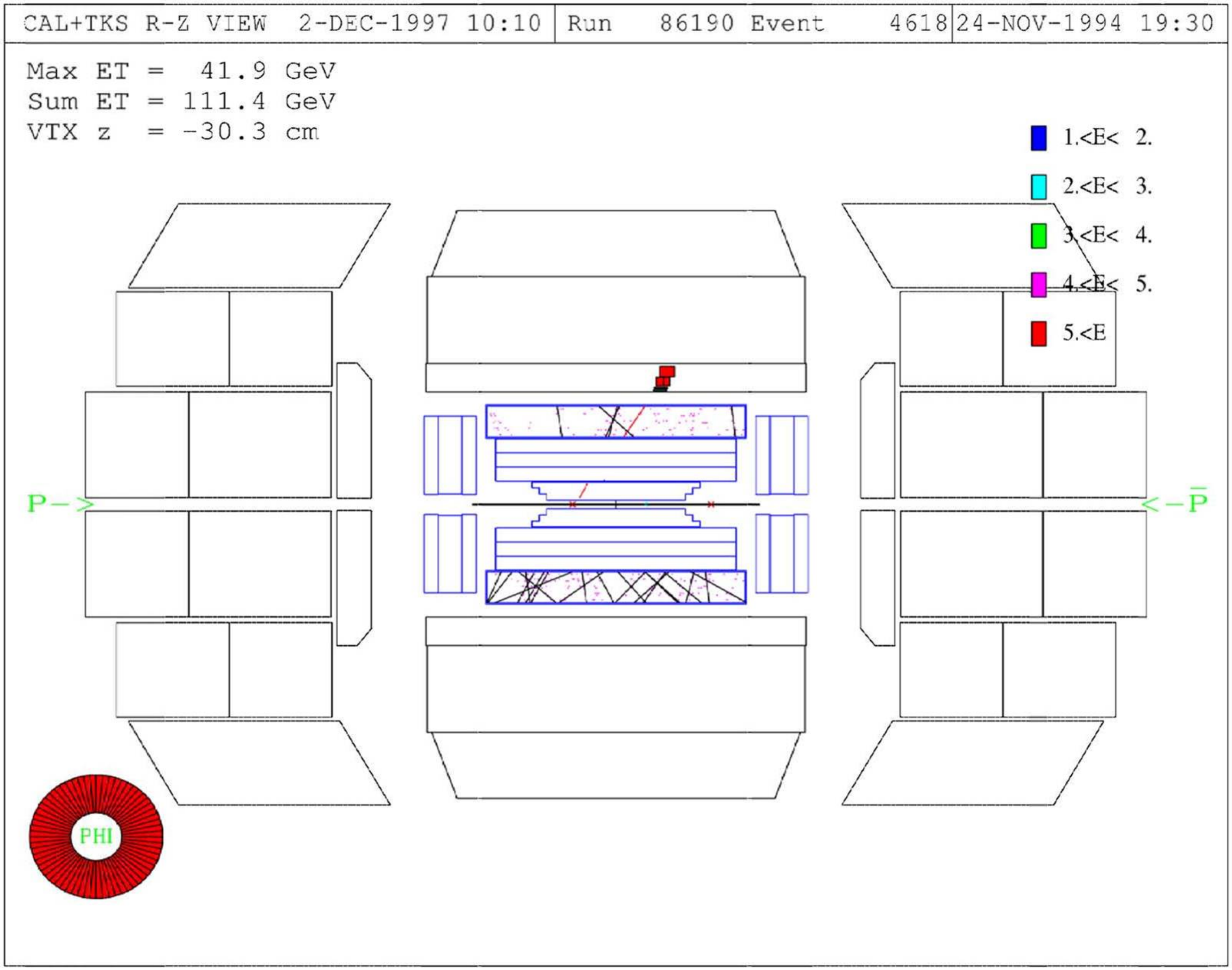
- $Z \rightarrow e^+e^-$ cross-section



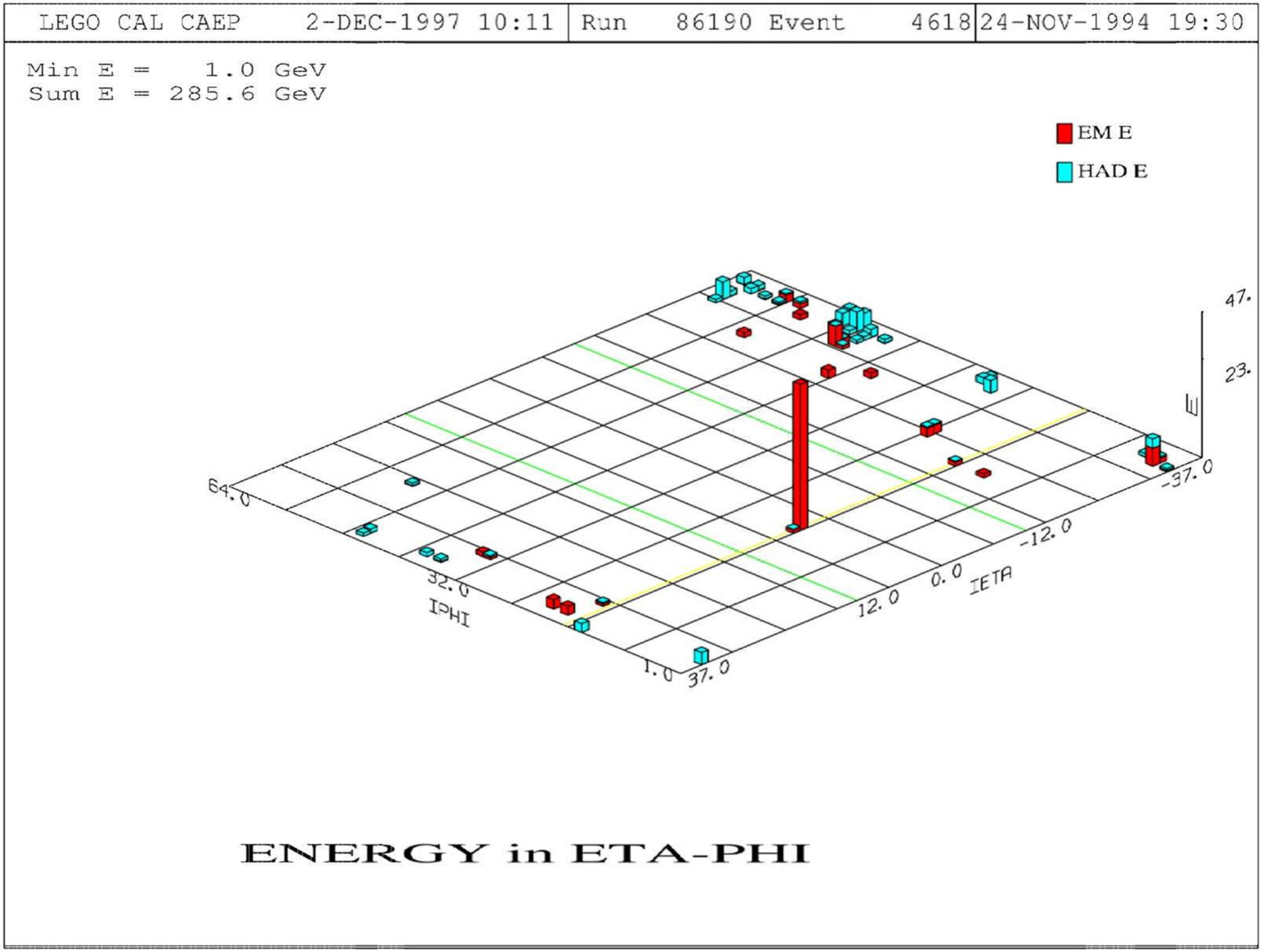
A W → e+ν Event, End view



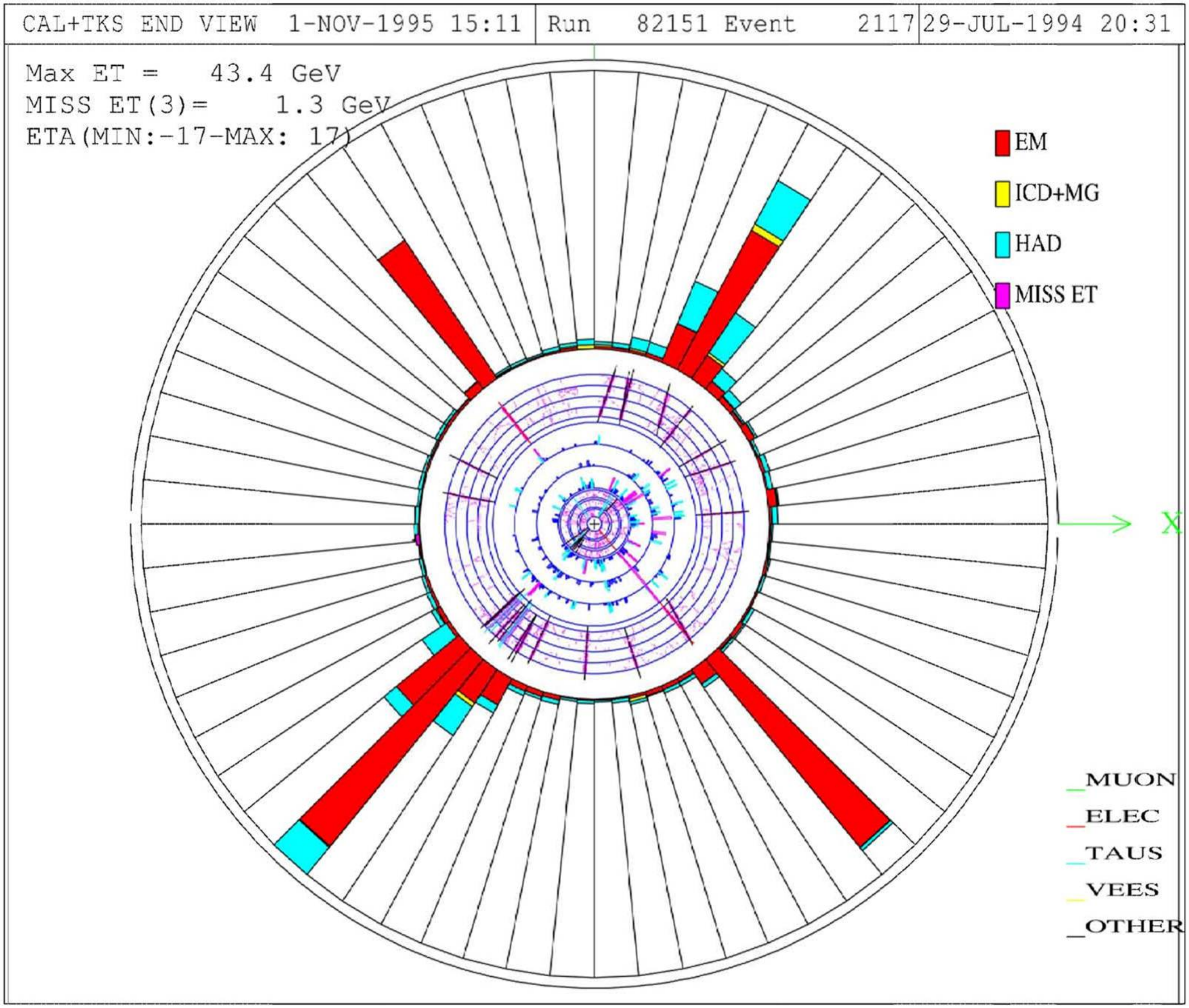
A W → e+ν Event, Side View



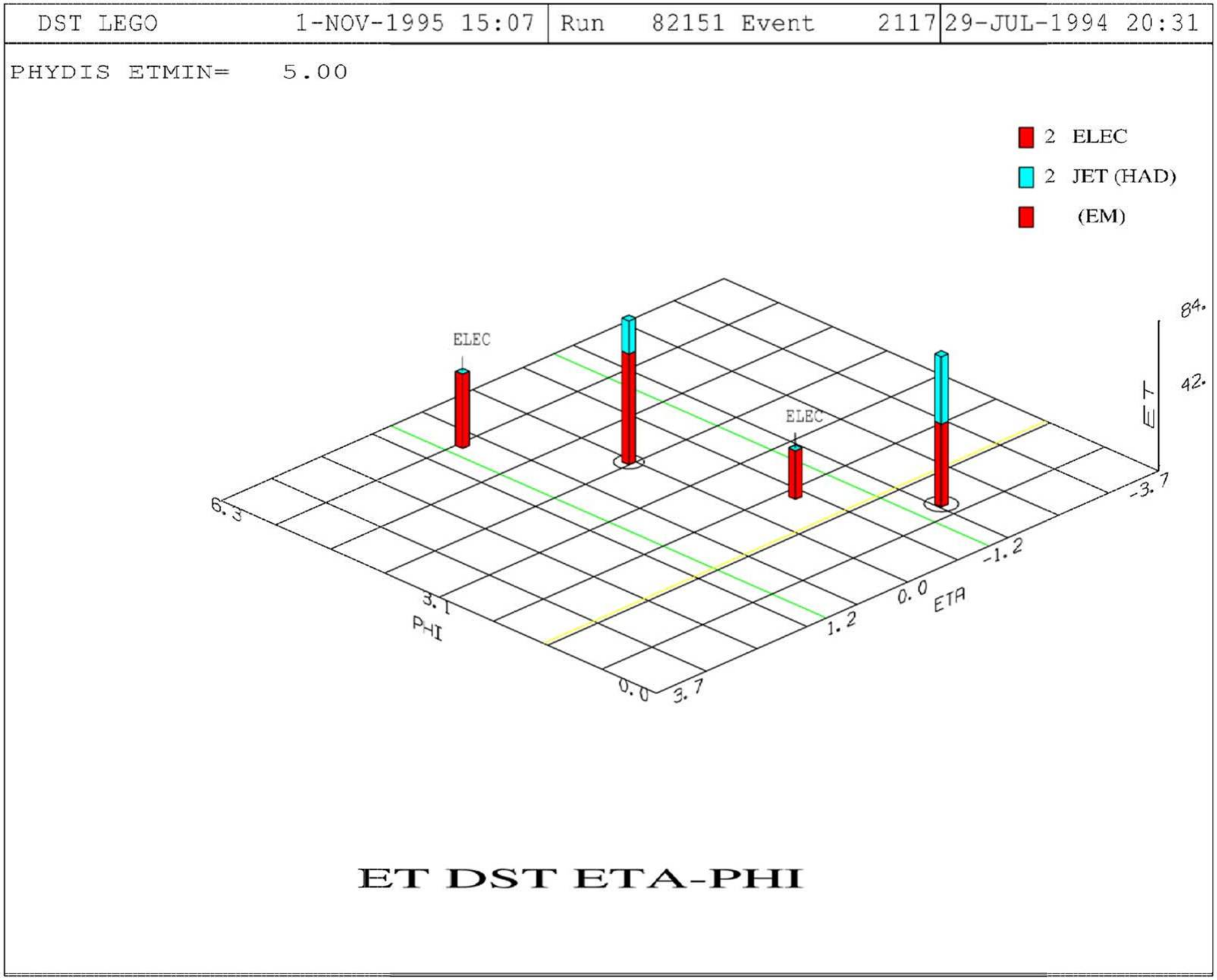
A W → e+ν Event, Lego Plot



A Z → e^+e^-+2jets Event, End view



A Z → e^+e^-+2jets Event, Lego Plot



Spontaneous Symmetry Breaking

While the collection of ground states does preserve the symmetry in $\mathcal{L}$, the Feynman formalism allows to work with only one of the ground states through the local gauge symmetry $\rightarrow$ Causes the symmetry to break.

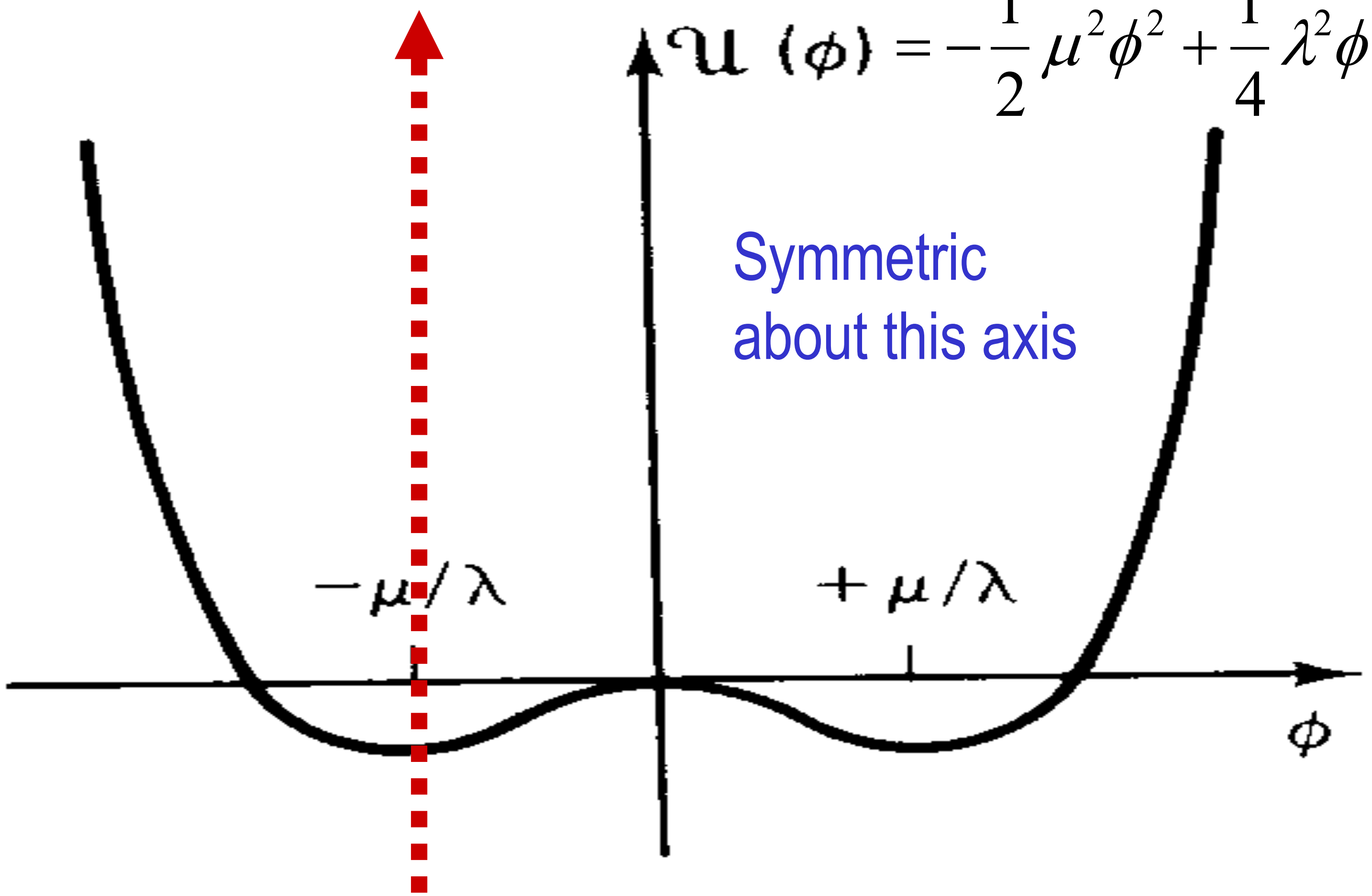
This is called "spontaneous" symmetry breaking, because symmetry breaking is not externally caused.

The true symmetry of the system is hidden by an arbitrary choice of a particular ground state. This is the case of discrete symmetry w/ 2 ground states.

EW Potential and Symmetry Breaking

Not symmetric about this axis

$$\mathcal{U}(\phi) = -\frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda^2\phi^4$$



The Higgs Mechanism

The Higgs Mechanism

- Recovery from a spontaneously broken electroweak symmetry gives masses to gauge fields (W and Z) and produce a massive scalar boson
  - The gauge vector bosons become massive (W and Z)
  - The massive scalar boson produced through this spontaneous EW symmetry breaking is the Higgs particle
- In SM, the Higgs boson is a ramification of the mechanism that gives **masses to weak vector bosons, leptons and quarks**

Issues in SM

- **We have come a long way on SM to describe how the universe works but we are not done yet! Actually a long way from done!**
- Why are the masses of quarks, leptons and vector bosons the way they are?
- Why are there three families of fundamental particles?
- What gives the particle their masses?
- Do the neutrinos have mass?
- Why is the universe dominated by particles?
  - What happened to anti-particles?
- What are the dark matter and dark energy?
- Are quarks and leptons the “real” fundamental particles?
- Other there other particles that we don’t know of?
- Why are there only four forces?
- How is the universe created?