Experimental Techniques in High Energy Physics

Pushpa Bhat

General Course Information

- Web Page: http://home.fnal.gov/~pushpa/phy690.htm
- Class Schedule:
  Saturdays 10:00 am - 12:30 pm, FW227
- Contact Email: pushpa@fnal.gov
- Recommended Books:
  - The Physics of Particle Detectors, Dan Green, Cambridge University Press, 2000
  - Introduction to Particle Physics, Richard Fernow, Cambridge University Press, 1986
  - Data Analysis Techniques for High Energy Physics, R. Fruhwirth *et al,* (Cambridge U Press , 2000, II Edition)
- There are plenty of web resources:
  - PDG: http://pdg.lbl.gov/

Syllabus

- Overview
- Physics of Particle Detection
  - Interaction of Particles with matter
  - Detection Mechanisms
- Detector Technologies
  - Charged Particle Tracking
    - **Gaseous Detectors**
    - **Semiconductor Detectors**
  - Calorimetry
  - Other
- Particle Identification
- Case Studies of HEP Detectors
- Triggers and Data Acquisition
- Event Reconstruction
- Data Analysis and Statistics

Overview

Particle Physics

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In search of the fundamentals ..

- Particle Accelerators and detectors have been the tools for exploration and discovery
- Ambitious Explorations →Seek answers to
  - What are the most basic forms of matter that everything in the universe is made up of?
    - **We thought we have learnt so much, now we think we only know about 4% of the stuff the universe is made up of.**
  - How do they interact?
  - What are their properties and do we understand them?
    - **For example, what is the origin of mass?**
  - Can we understand everything in the universe and about it from understanding the basic structure of matter and energy?
  - …

The Periodic Table of Elements

Mid-1800's **Mendeleyev**

A summary of hundreds of years of alchemy and Chemistry

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Ha	106 Sg	107 Ns	108 Hs	109 Mt	110 Uun								

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

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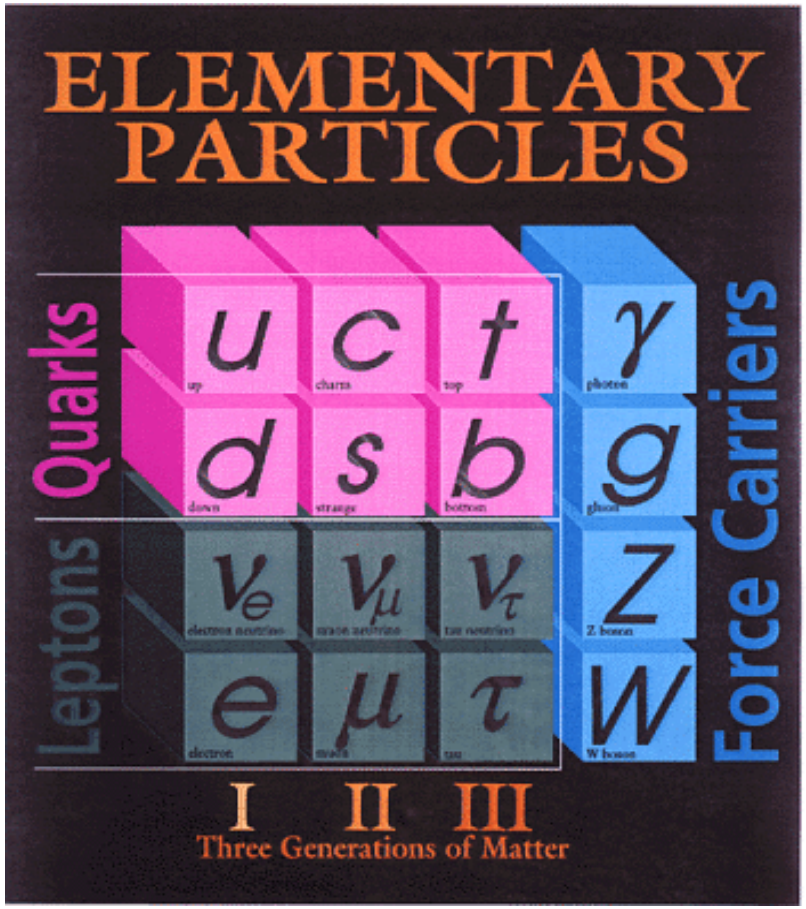
The Atom

- Detailed understanding of the atom began about 50 years after Mendeleyev
  - Discovery of the electron, Thompson 1892
  - Discovery of the nucleus, Rutherford 1911
  - Rudimentary atomic model, Bohr
    - **The atom with a central nucleus and electrons in orbits**
  - …

Mid – 20th Century

- Colliding protons with nuclei of atoms, using the new particle accelerators, led to the discovery of a large number of new and unanticipated particles
- The complexity hints that the situation is similar to what we had with molecules
- Gellmann explains a plethora of particles using sophisticated mathematical symmetry groups and predicts unseen particle the "Omega"
- Gellmann and Zweig hypothesize the next layer of matter → "Quarks" (Experimentally demonstrated in early 1970's)

Our New Periodic Table



The Standard Model includes

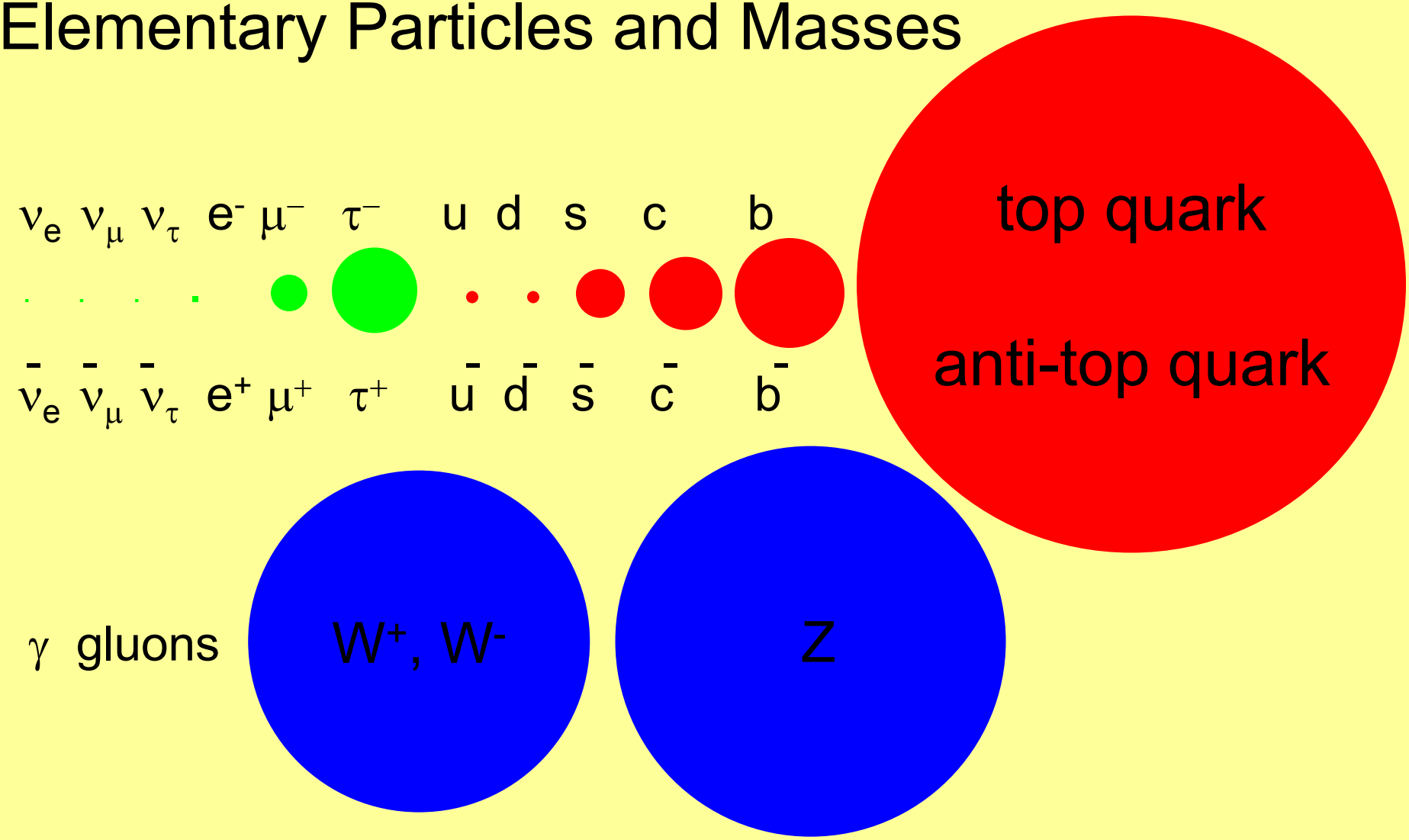
- 3 generations of quarks and leptons
- Quantum field theories for 3 forces: strong, electromagnetic and weak
- And the "Higgs Boson" that is not discovered yet

- Gravity difficult to integrate
- An effective model that breaks down at higher energy
  - New physics around 1 TeV?

Top Quark discovered at Fermilab in 1995

Tau Neutrino discovered at Fermilab in 2000

Elementary Particles and Masses



(Mass proportional to area shown: proton mass = ●)

Are they the smallest things?

Why are there so many?

Where does mass come from?

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The Advent of Particle Accelerators

Starting in 1930's

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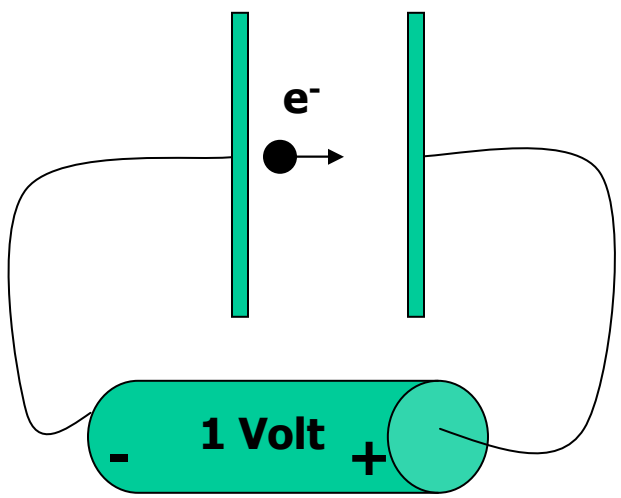
Particle Acceleration and Energy Units

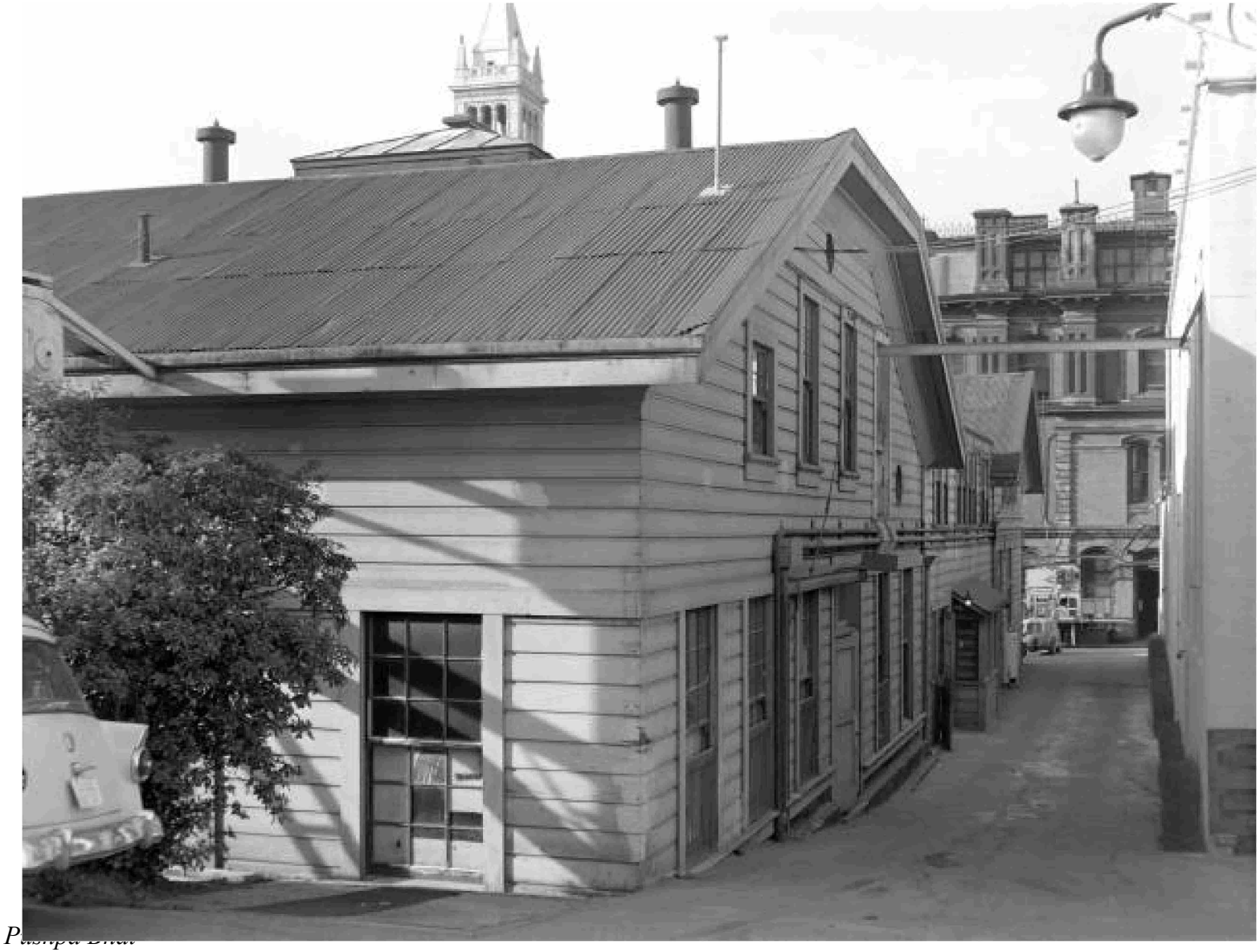
- 1 electron Volt (eV) is the amount of energy gained by a particle with unit charge when it is accelerated across a 1 Volt potential difference

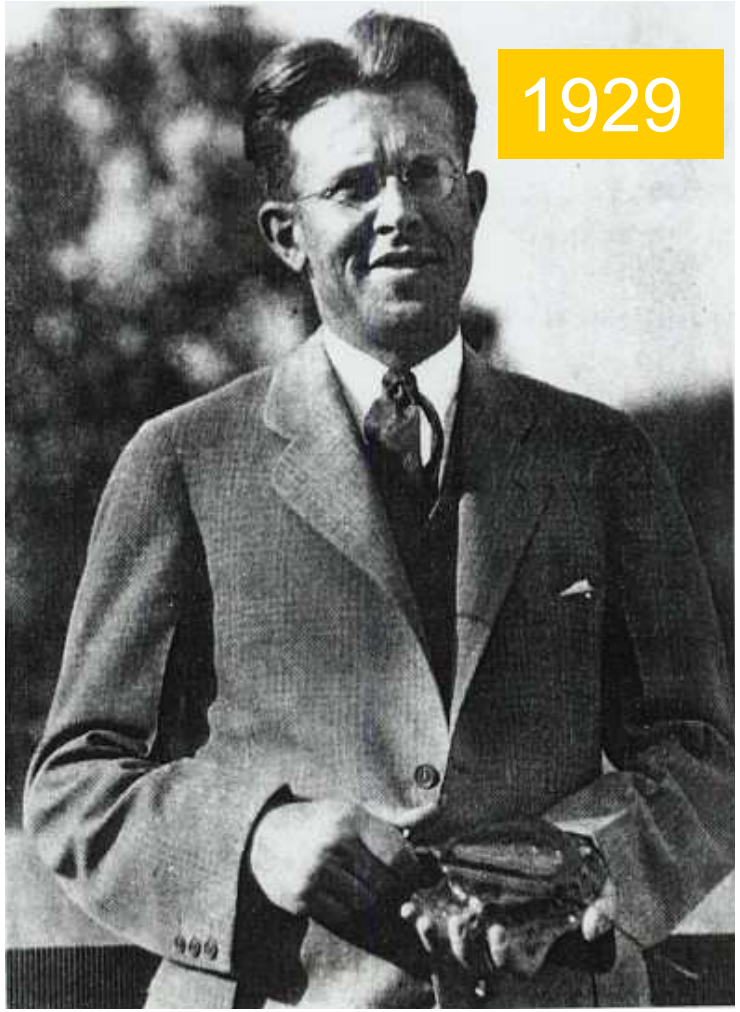


Energy E = 1 eV
= 1.6 x 10^{-19} J

1 keV = 10^3 eV
1 MeV = 10^6 eV ~ 2 x mass of the electron
1 GeV = 10^9 eV ~ mass of the proton, neutron
1 TeV = 10^{12} eV ~ energy of protons and pbars in the Fermilab Tevatron
Energy density in the Universe at < 10^{-9} sec after the Big Bang

Berkeley Radiation Laboratory



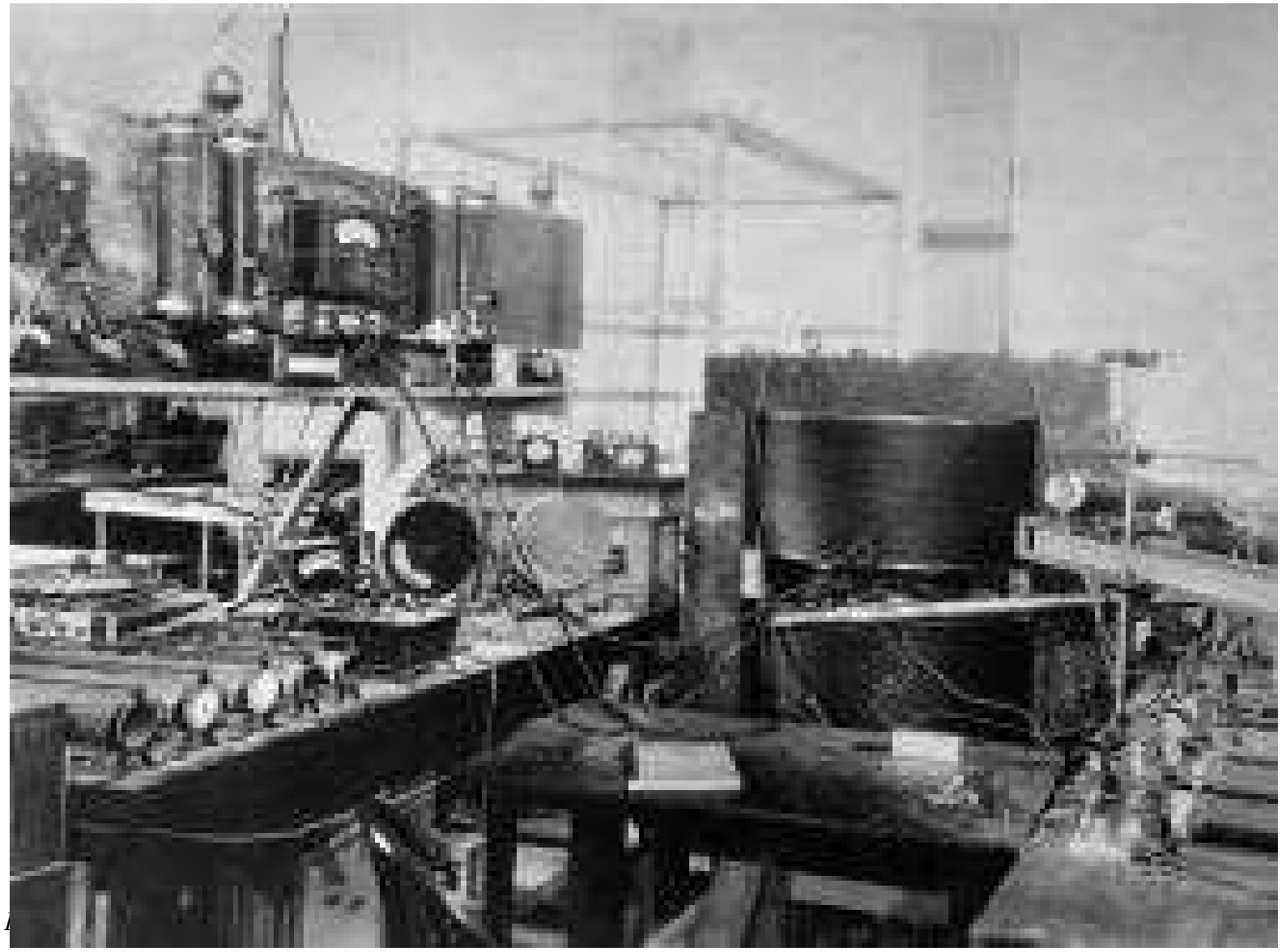


Ernest Lawrence
(1901 - 1958)

The First Cyclotron
Lawrence, Berkeley -- 1929

11-inch Cyclotron, Berkeley -- 1930's

The first Million electron Volt (MeV) accelerator



60-inch Cyclotron, Berkeley -- 1930's

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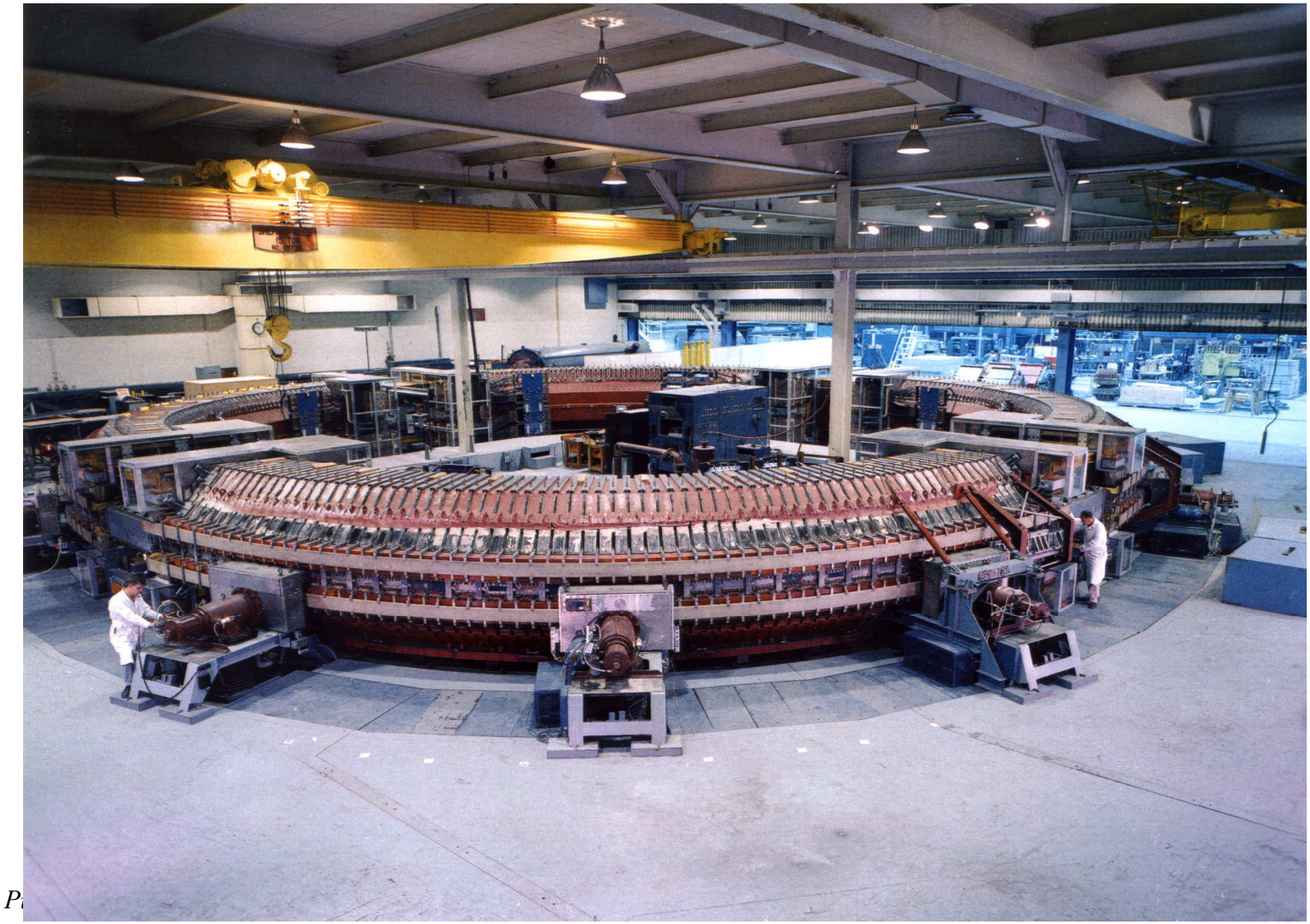
184-inch Cyclotron, Berkeley -- 1940's

Cosmotron, Brookhaven -- 1950's

Design: 3.3 GeV



Synchrophasotron, Dubna -- 1950's

Design: 10 GeV

AGS, Brookhaven -- 1960's

Design: 33 GeV

Fermilab Tevatron, Batavia, IL
1.96 TeV, Highest energy to date

Accelerators at Fermilab

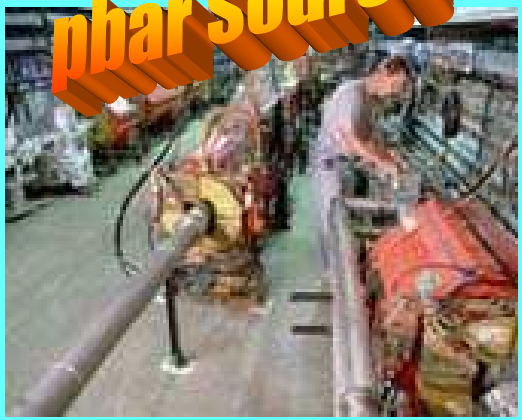
Cockroft-Walton
750 keV

Linac
400 MeV

Booster Synchrotron
8 GeV

Main Injector
150 GeV

pbar Source



Tevatron
980 GeV

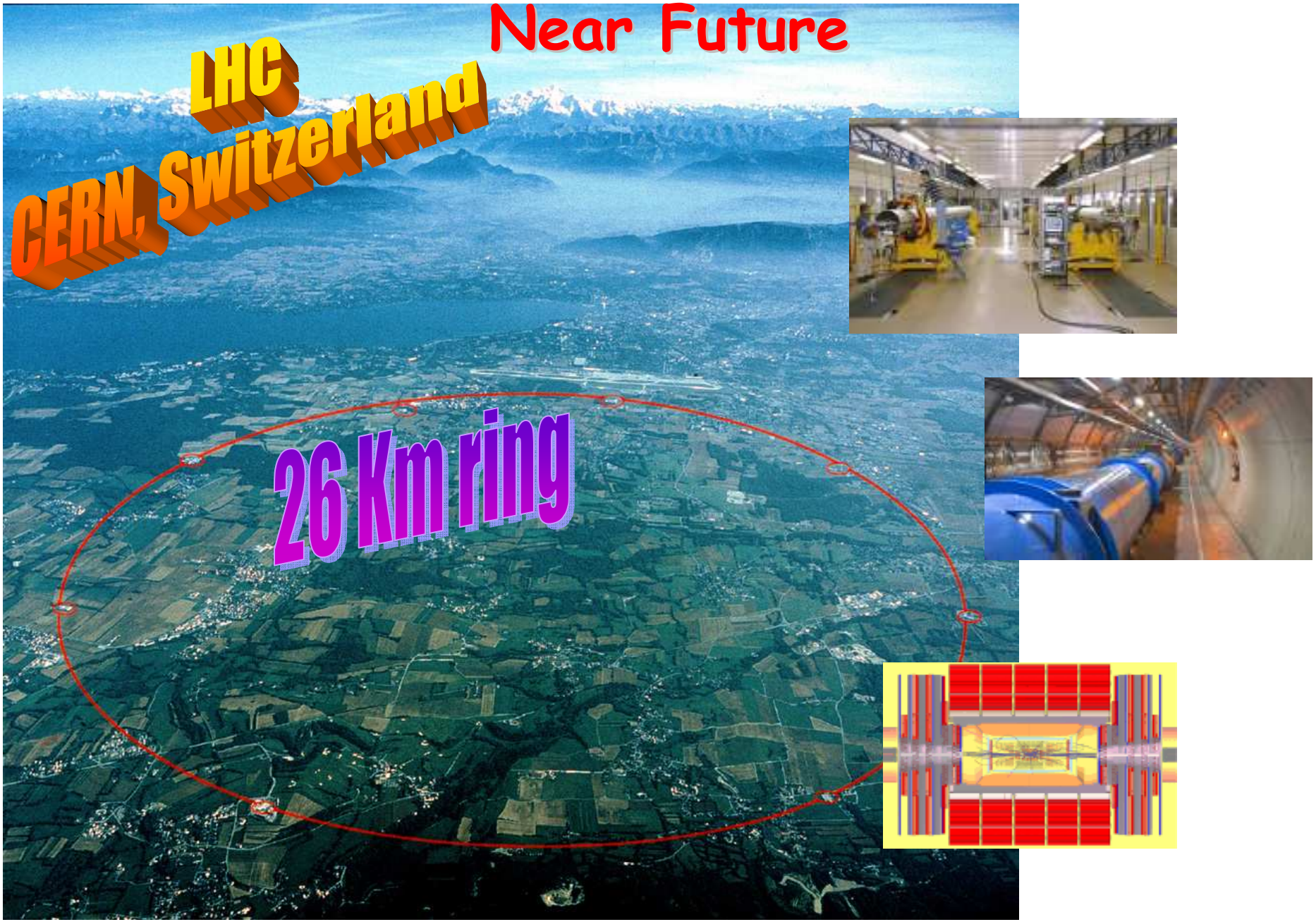
World's first superconducting accelerator

Fermilab Accelerators

Accelerator	Maximum Energy (eV)	Velocity (Fraction of the speed of light)	Length (m)
Cockcroft-Walton	750,000	0.012643094	10
Linac	400,000,000	0.713054226	130
Booster	8,000,000,000	0.994475049	477
Main Injector	120,000,000,000	0.999969904	3319
Tevatron	980,000,000,000	0.999999543	6218

Tevatron energy ~ 1 TeV = 10^{12} eV

LEP, e+e- Geneva -- 1990's



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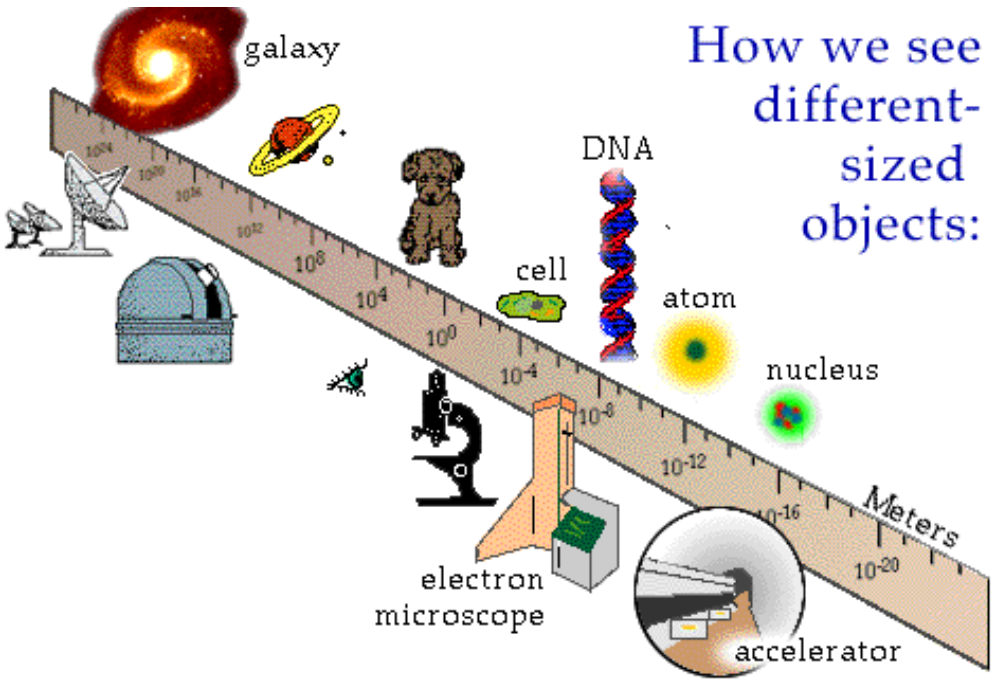
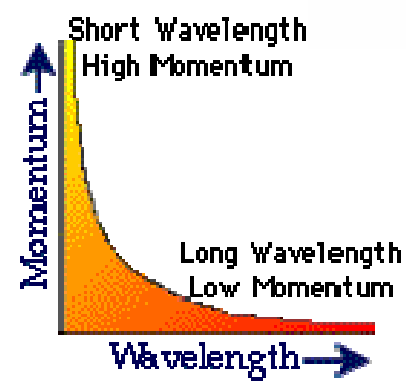
Large Hadron Collider, CERN
14 TeV C.M. energy

Why High Energy Particle Beams?



De Broglie said moving particles have an equivalent wavelength,

$$\lambda \propto \frac{1}{p}$$

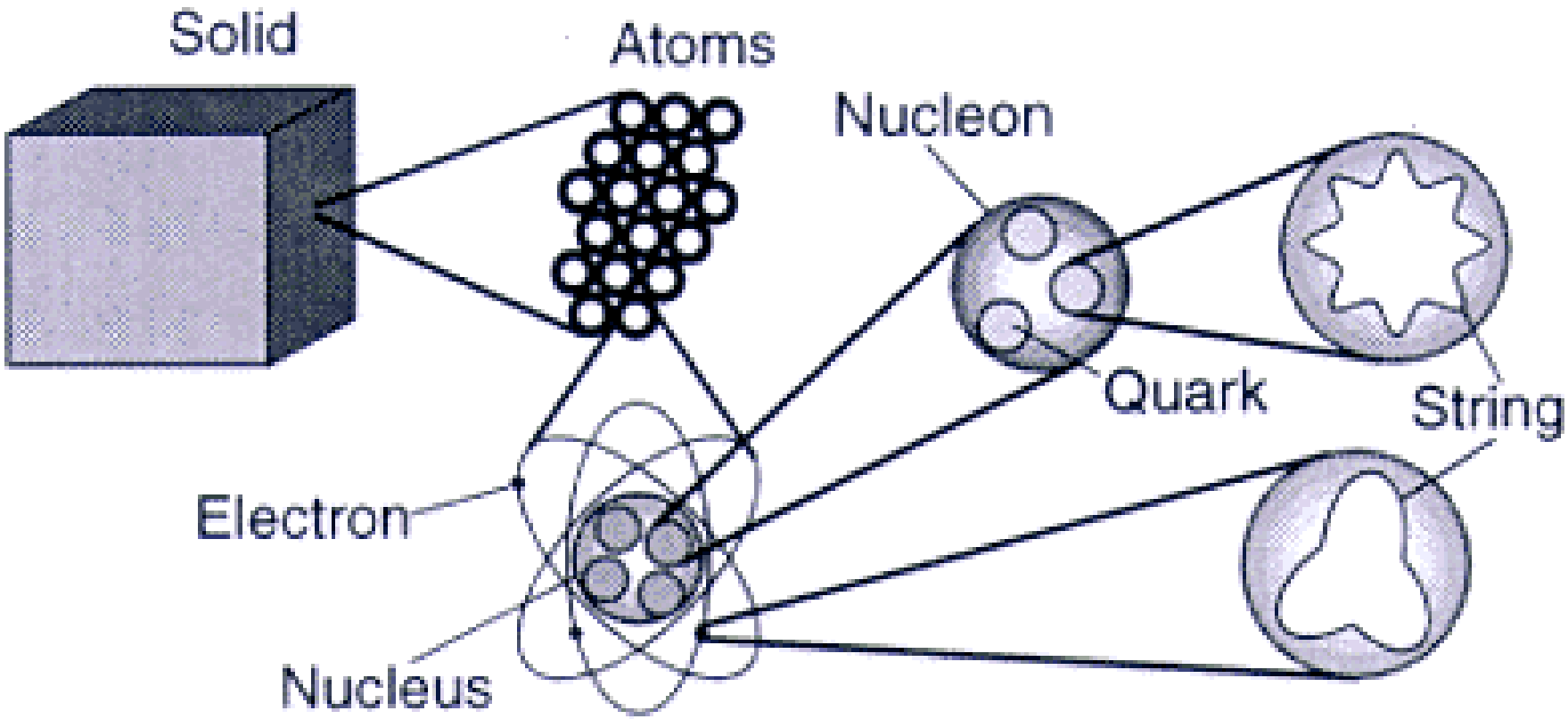


Add a little bit of relativity:

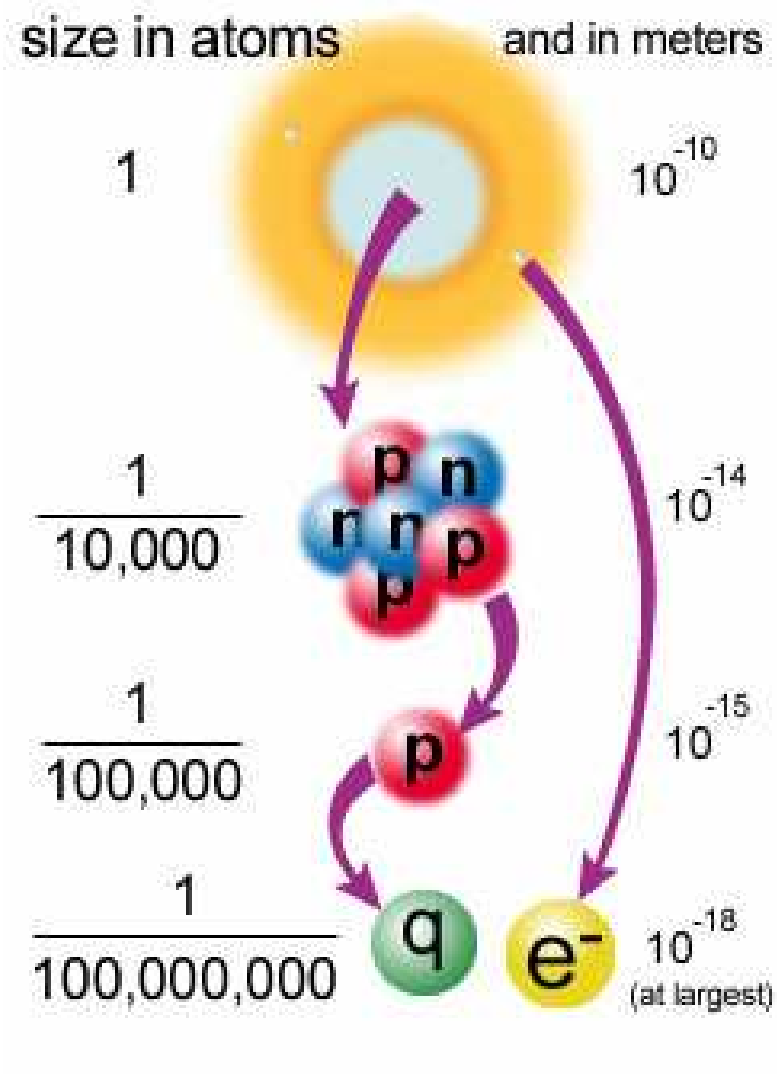
$$E^2 = (mc^2)^2 + (pc)^2$$

High energy gives us high momentum meaning short wavelengths so that we can resolve small distance scales

Looking deeper and deeper



Small Objects need Large Machines



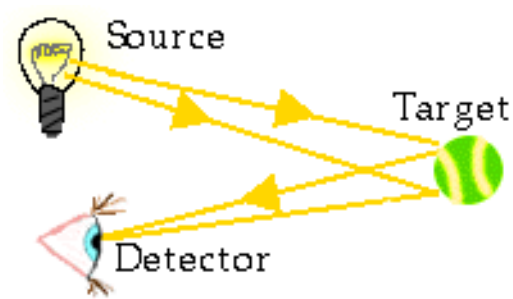
To resolve very small objects, we need to use very high energy.

↓

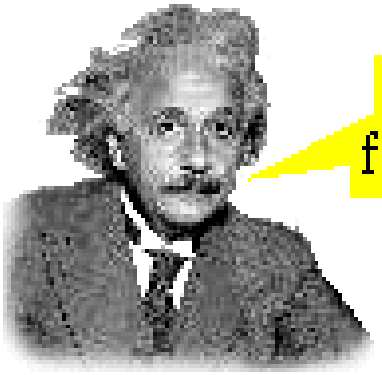
We need powerful particle accelerators.

↓

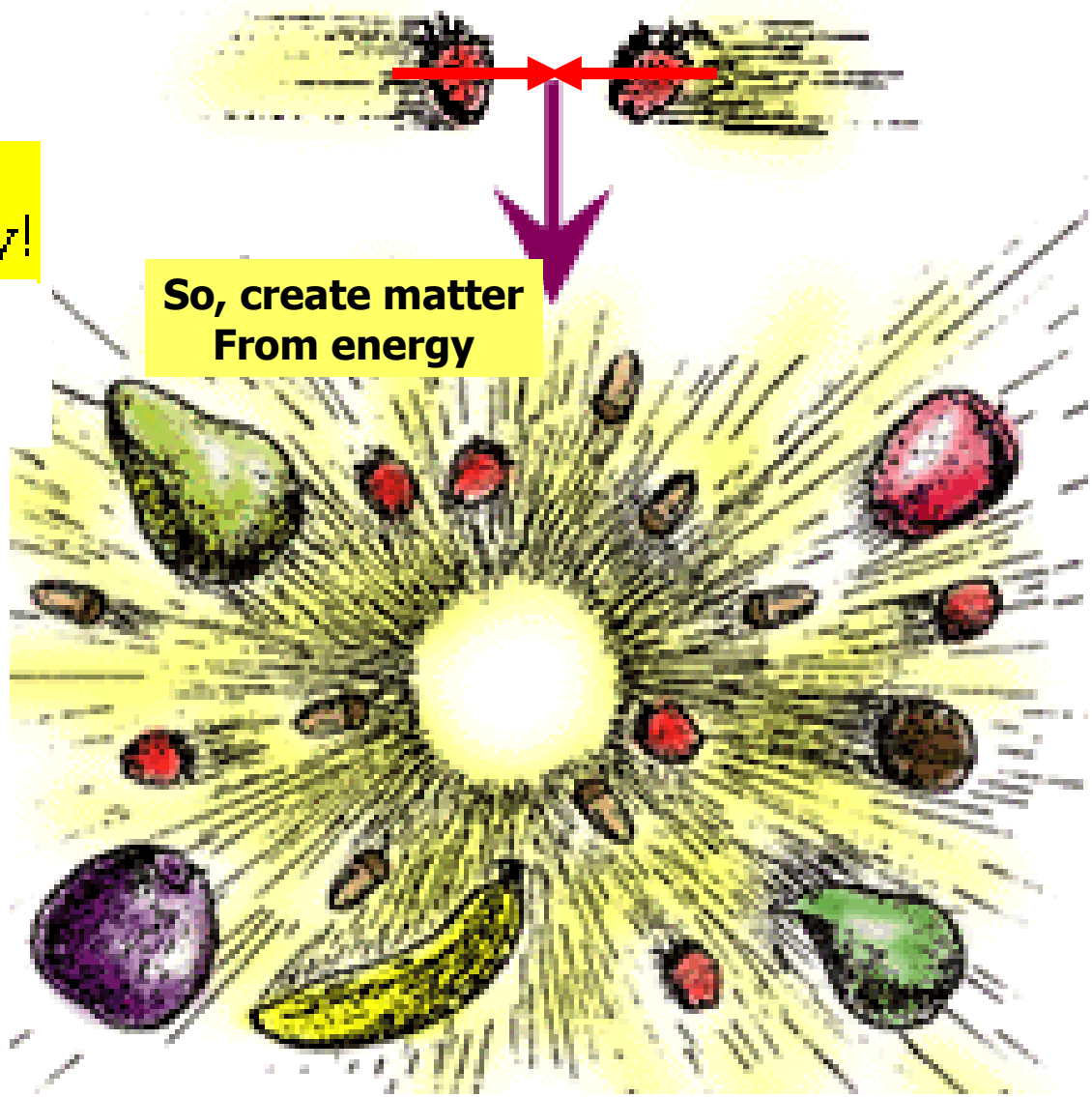
High energy collisions also create new particles. ($E=mc^2$)



Mass and Energy



Mass is just a form of energy!



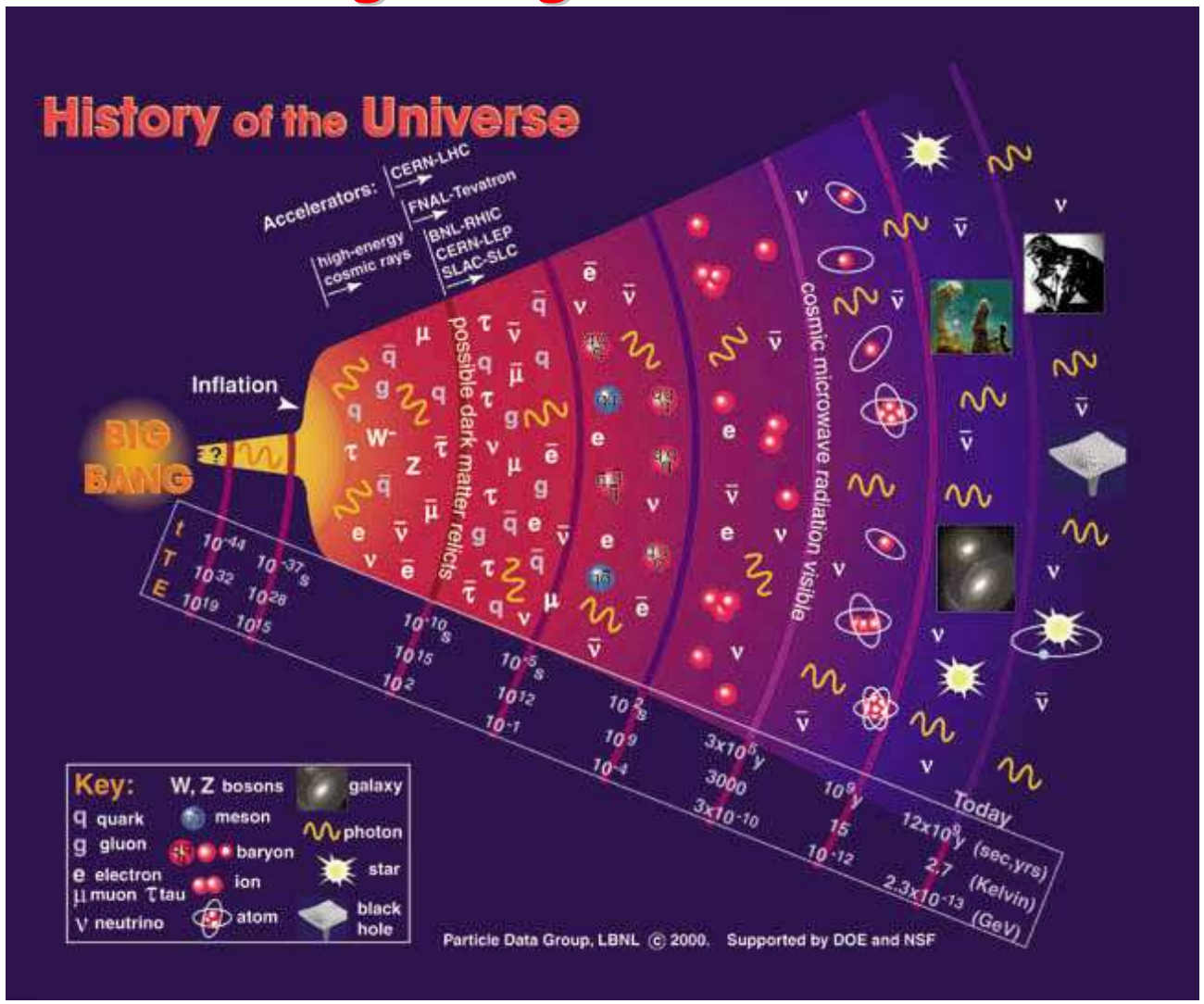
Beam energy at Fermilab =980 GeV
Speed = c-495 km/h

The First Particle Physics Experiment: The Big Bang

10 microseconds
Quarks form protons.

300,000 years
Nuclei capture electrons and form atoms. The universe becomes transparent.

13,700,000,000 years
Today



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The Era of Fermilab

10^{-8} seconds

- Temperature
  1000 trillion K

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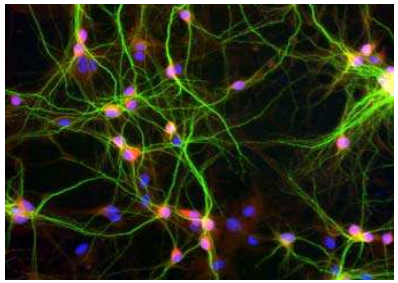
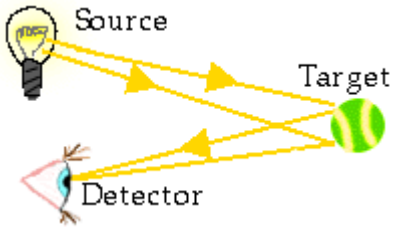
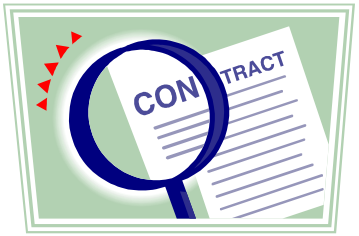
Experiments

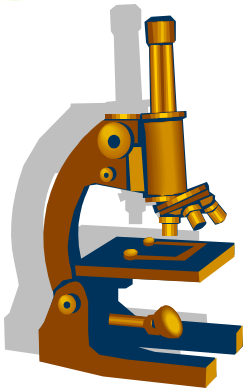
The Process of Observation

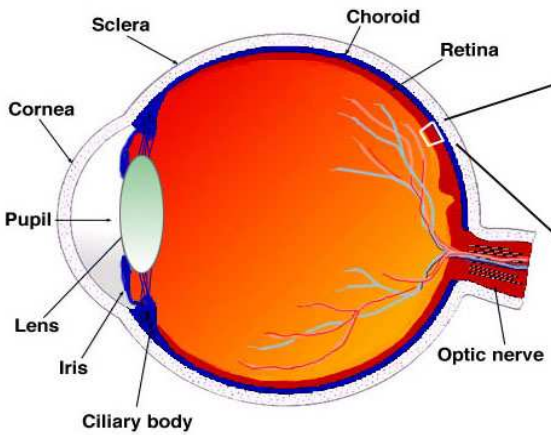
- Eye is an ingenious design of a photon detector, even though it senses only a tiny part of the electromagnetic spectrum! Along with the brain and the connectors forms a complete system for experimental observation and analysis

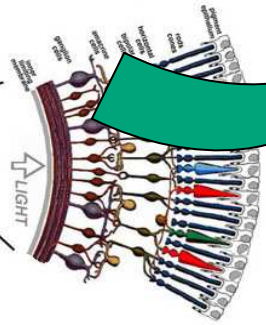












We need to see more, learn and understand! Augment our eyes and brains!

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Global/Composite Detector Systems for HEP

Need to find

–Number of particles

–Event topology

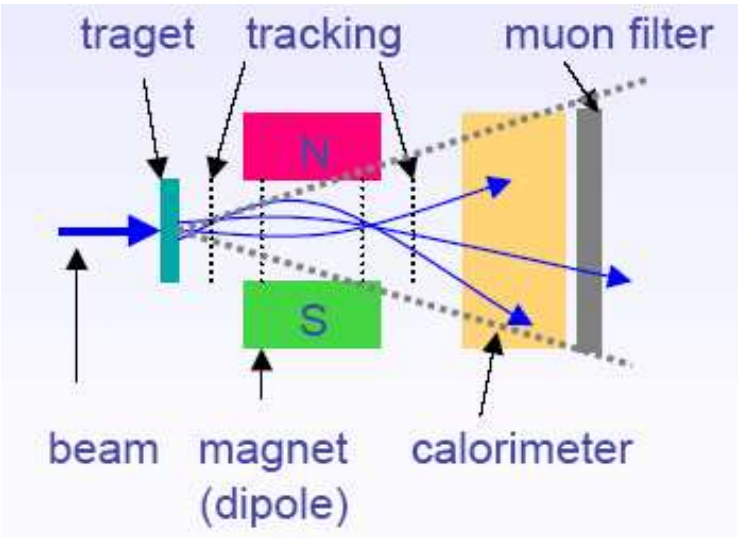
–Momentum/energy

–Particle identity

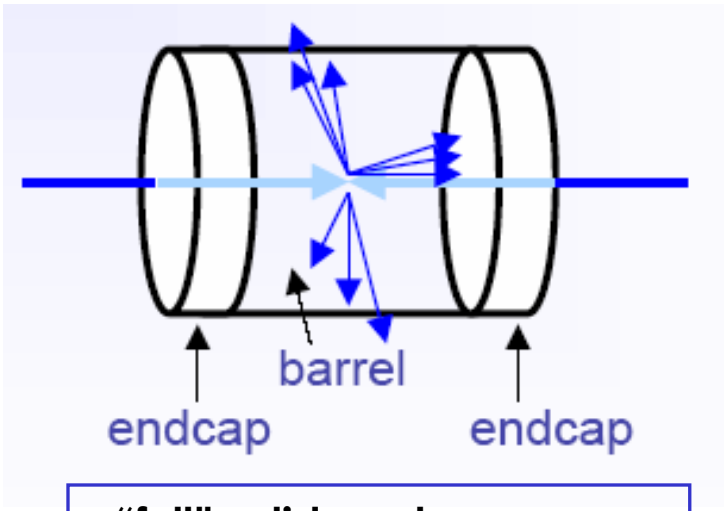
No single detector does it all…

→ **Create detector systems**

Fixed Target Geometry



Collider Geometry



• "full" solid angle coverage

Fermilab E831 FOCUS

Charm Photoproduction Precision study of charm decays

Silicon, Scintillation, cerenkov detectors, drift chambers, etc.

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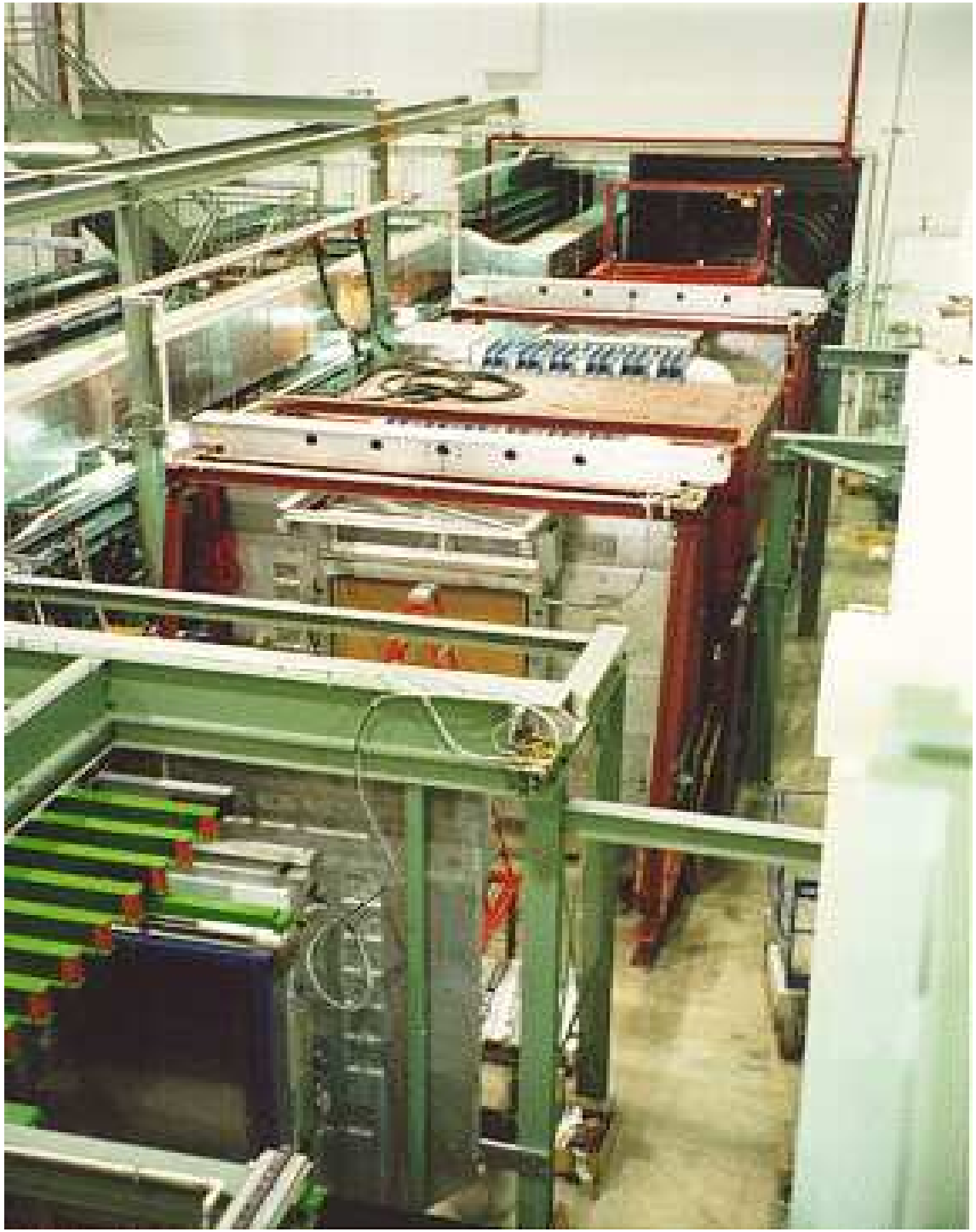
KTEV Experiment

Kaons at the Tevatron

Studies of rare K decays
Study CP violation



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Miniboone, Fermilab

Spherical Tank (12 m dia) filled with mineral oil and equipped with photomultiplier tubes

Looking for neutrino oscillations

Fixed Target Neutrino Experiment, Fermilab

CDMS in Soudan Mine: Search for Dark Matter

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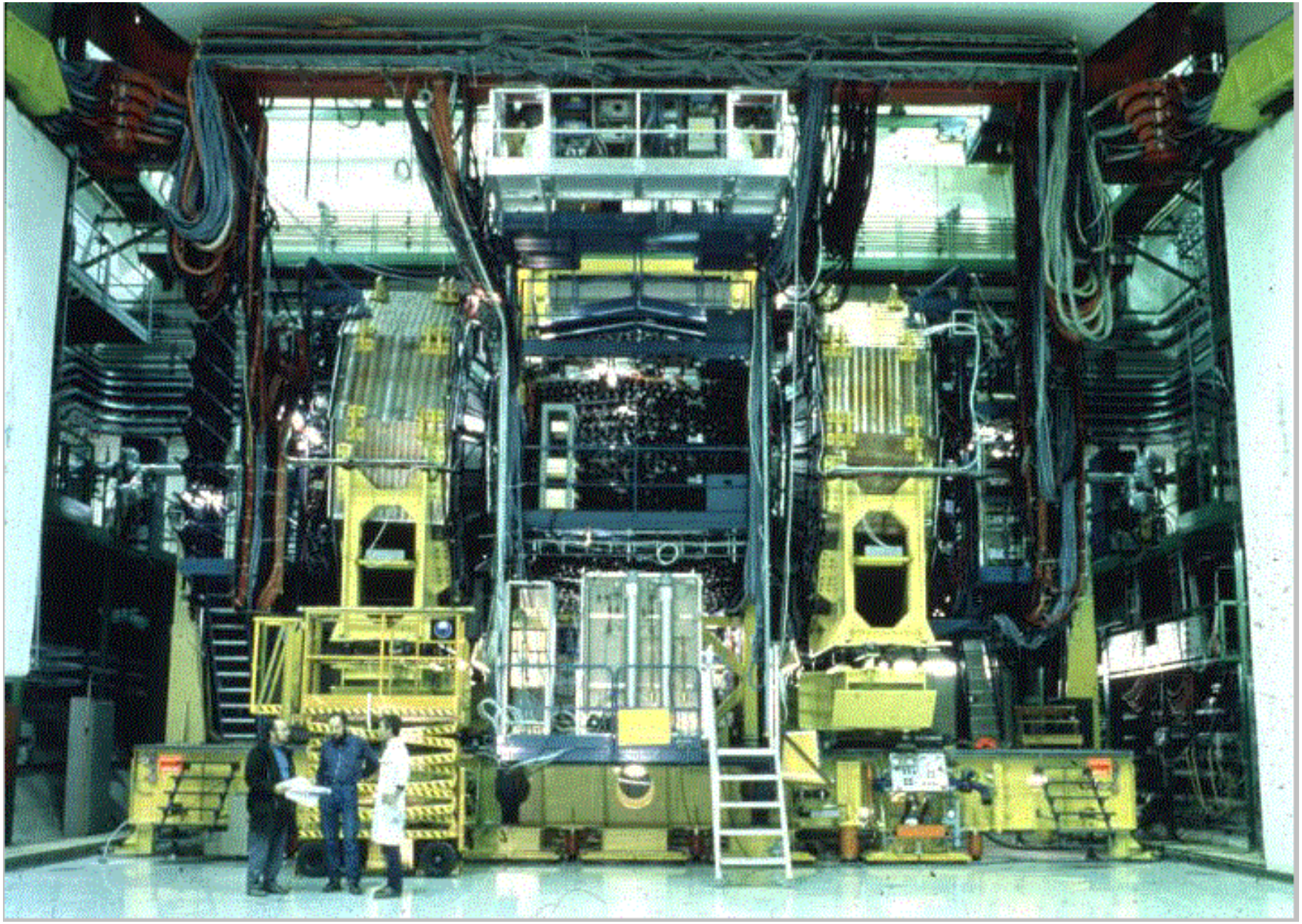

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UA2, CERN

Aleph at LEP (CERN)

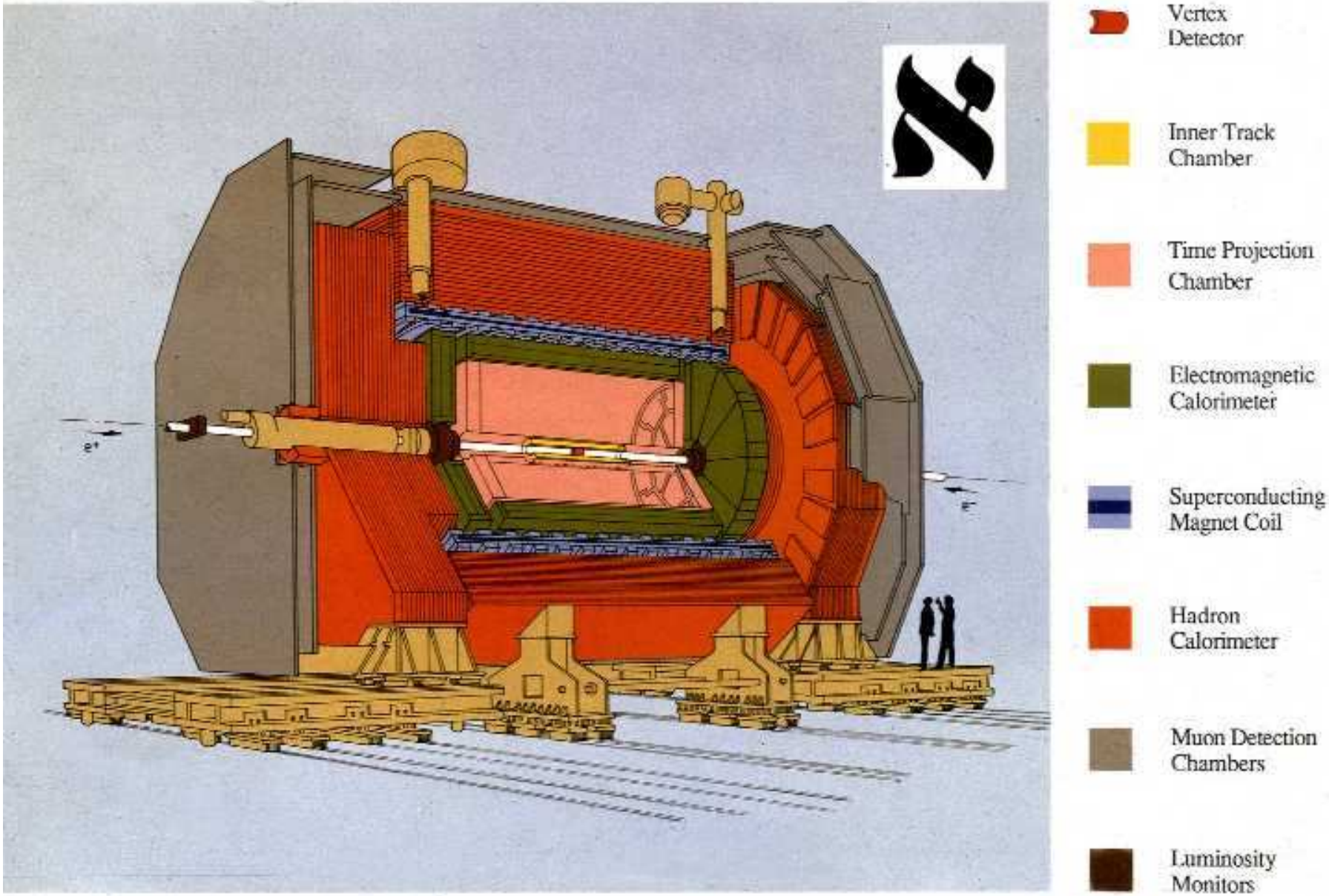
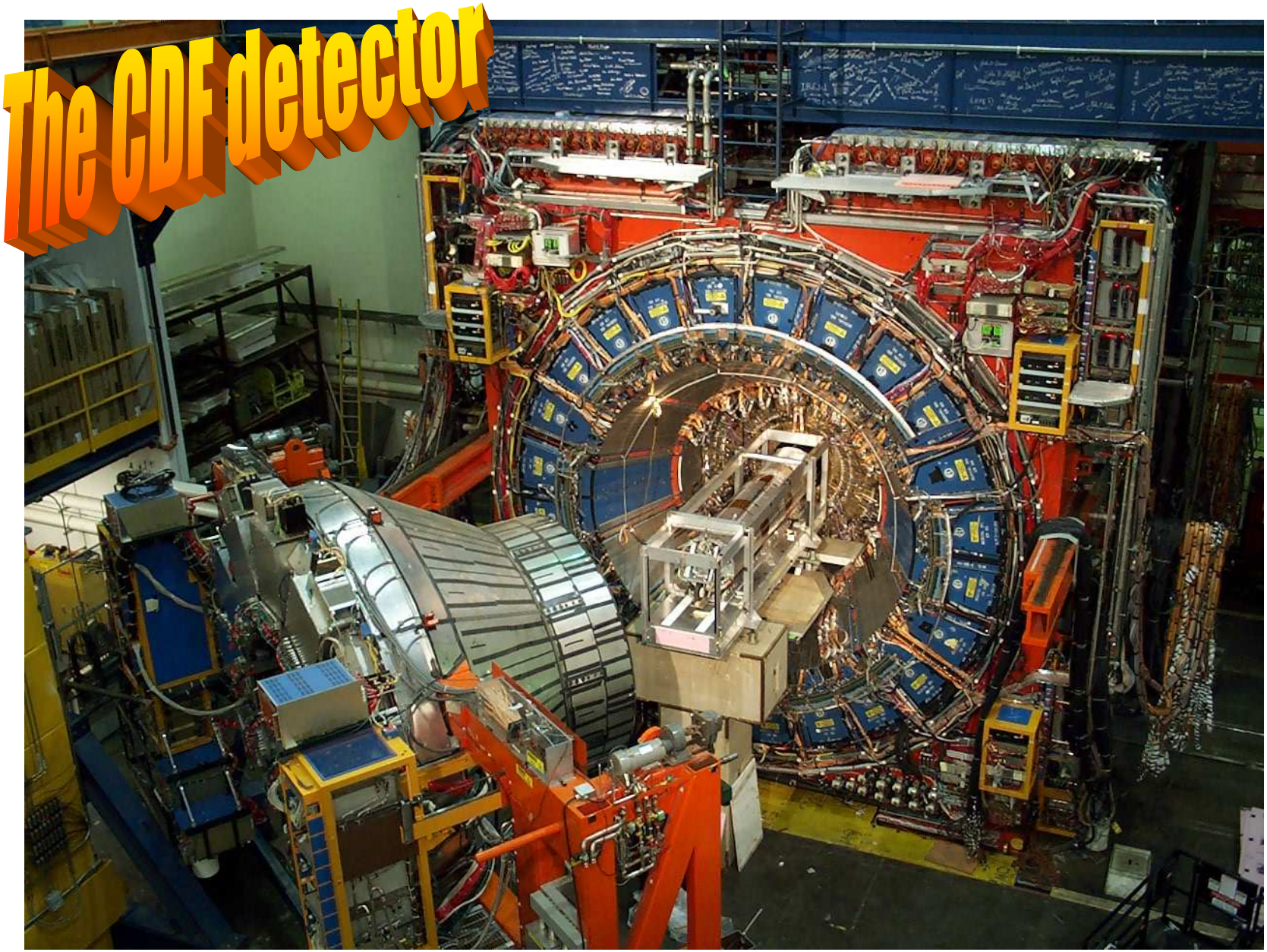


Fig. 1 - The ALEPH Detector

The CDF detector



Installing silicon tracker, prior to CDF detector roll-in

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The DZero Detector

DØ detector installed in the Collision Hall, January 2001

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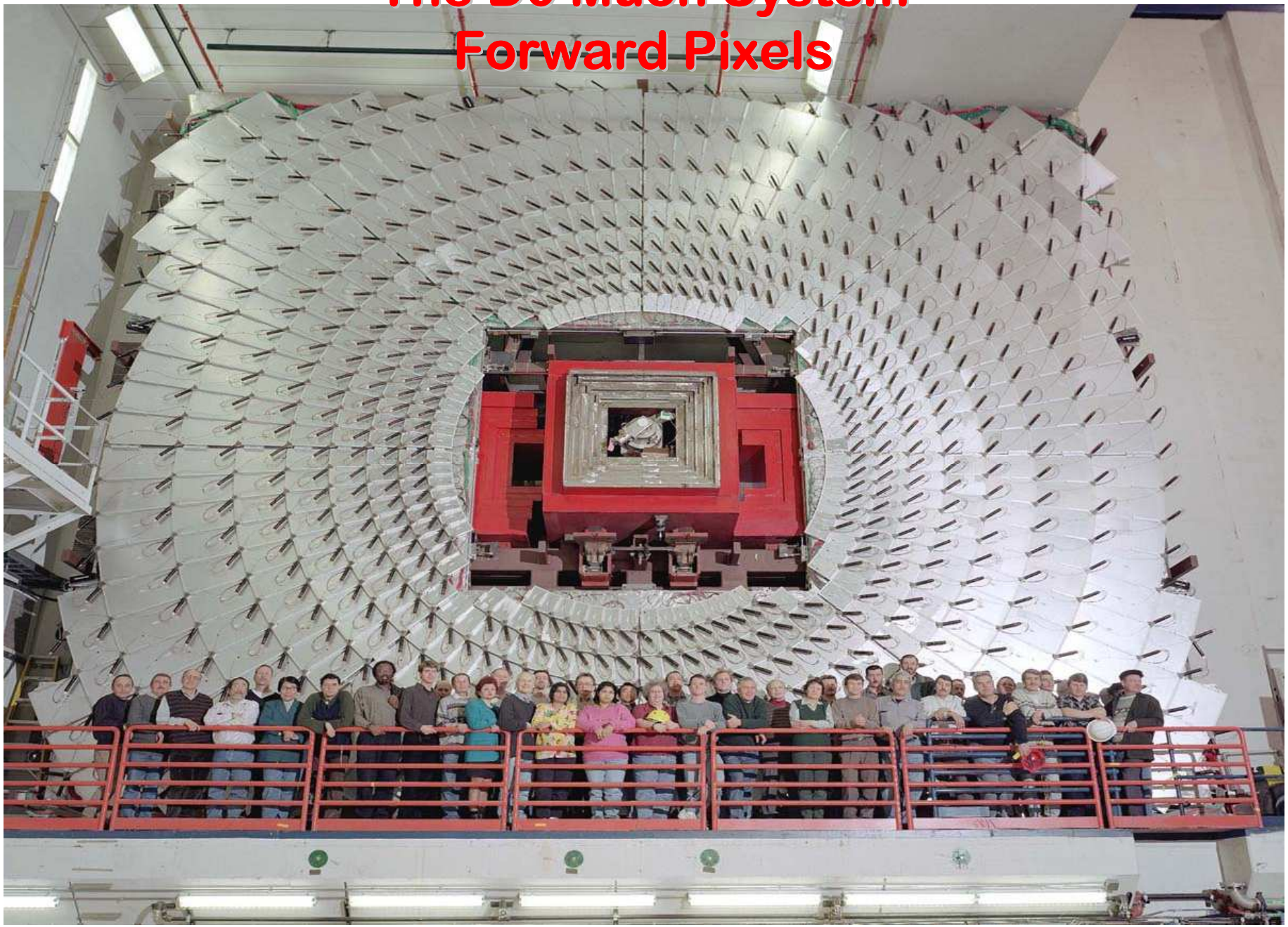
The D0 Muon System
Forward Pixels



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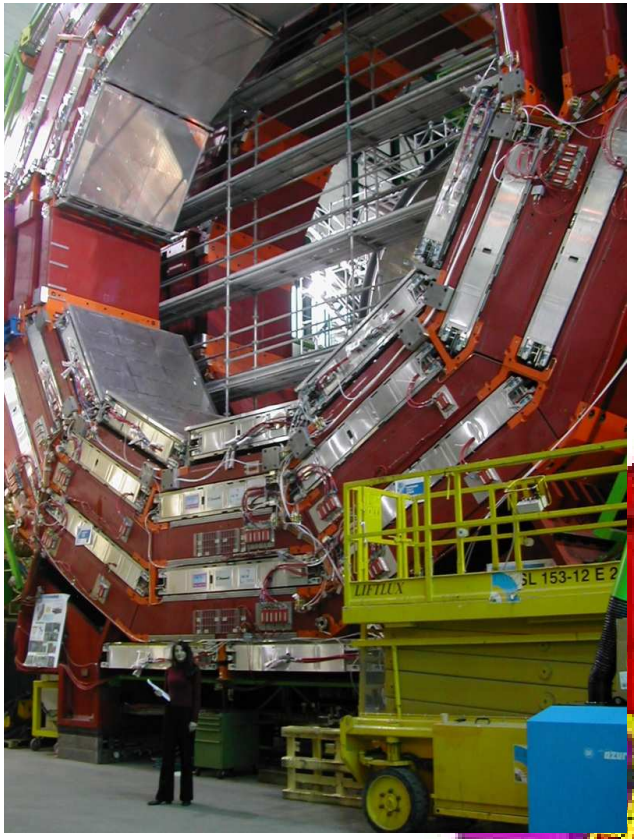
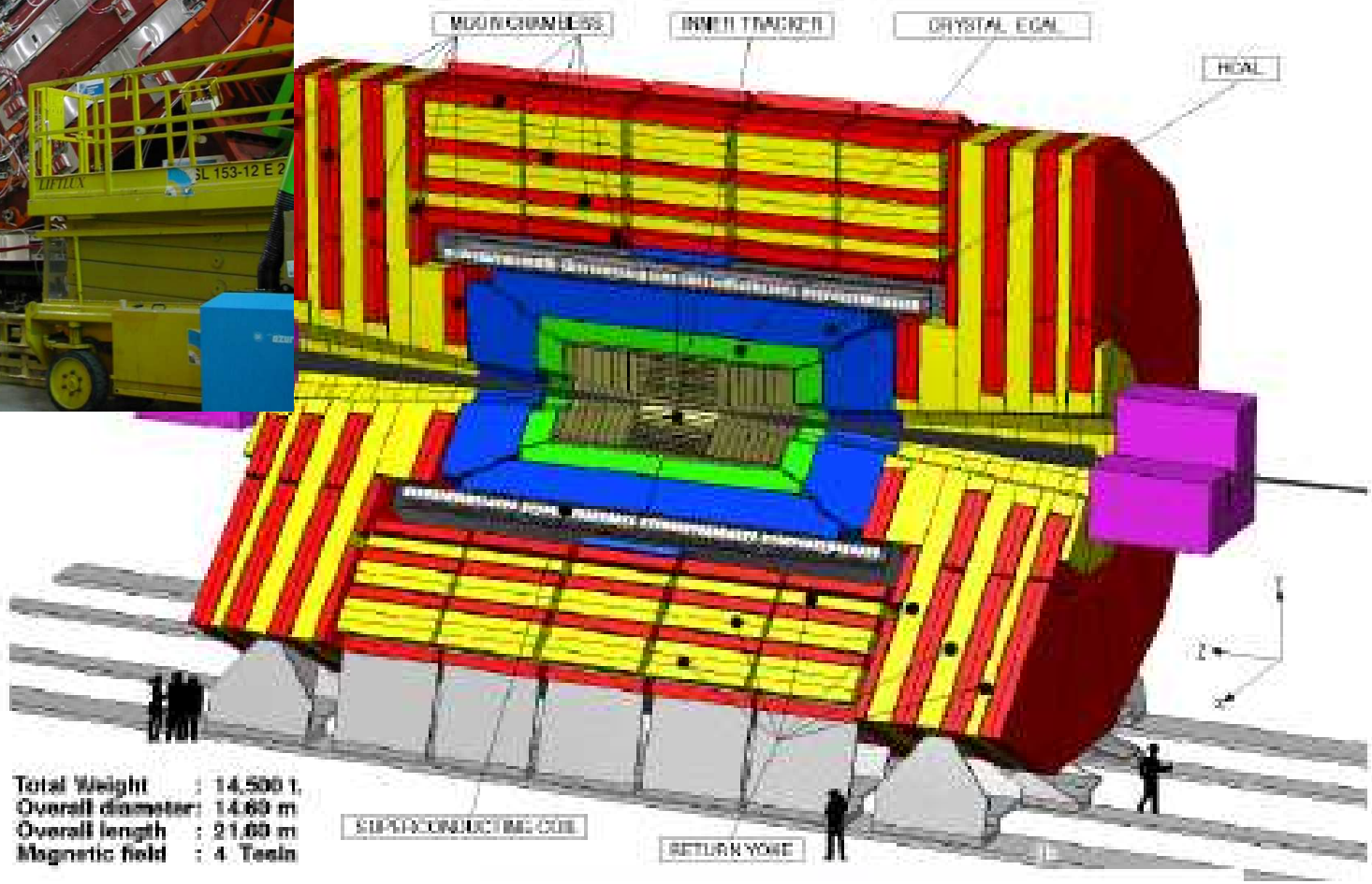
CMS





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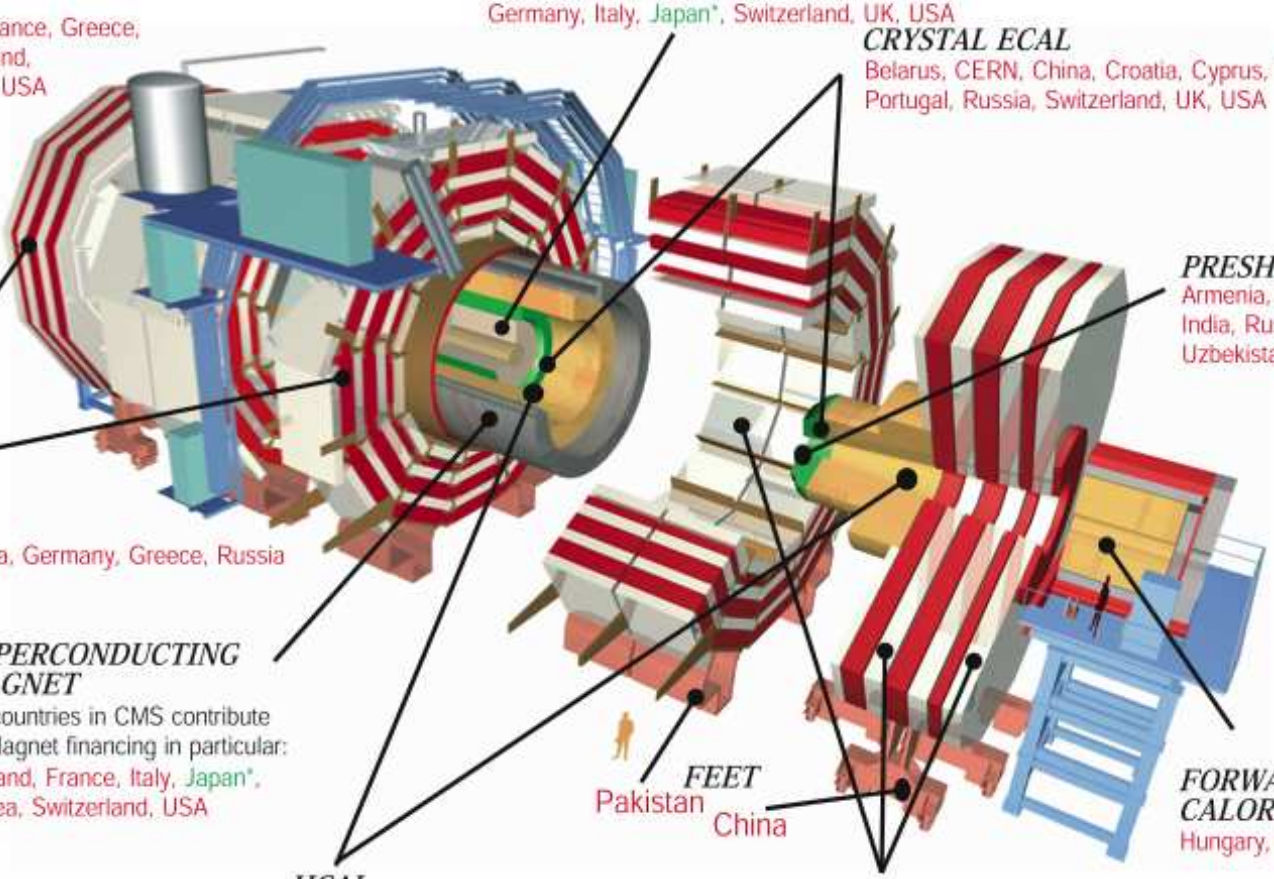
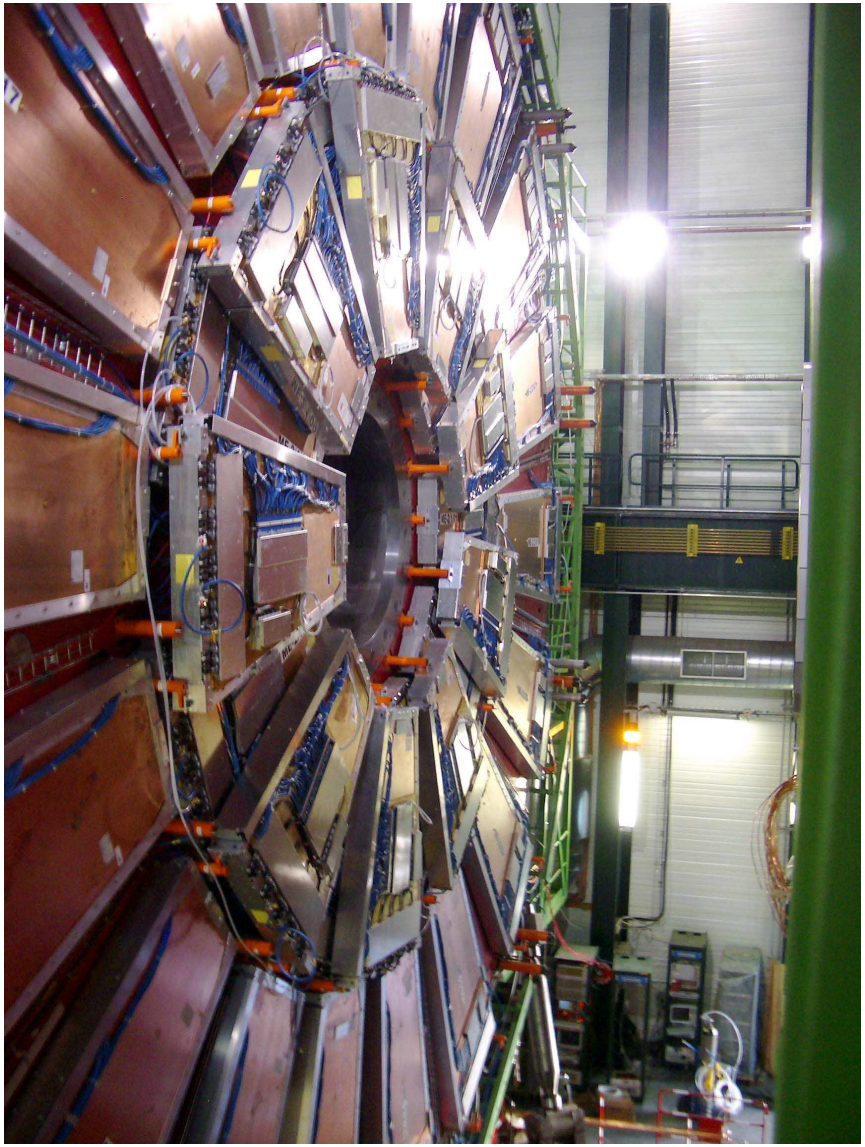
CMS at CERN



Total weight	**:**	**12500 T**
Overall diameter	**:**	**15.0 m**
Overall length	**:**	**21.5 m**
Magnetic field	**:**	**4 Tesla**

Solenoid

CMS



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CMS (SX5)

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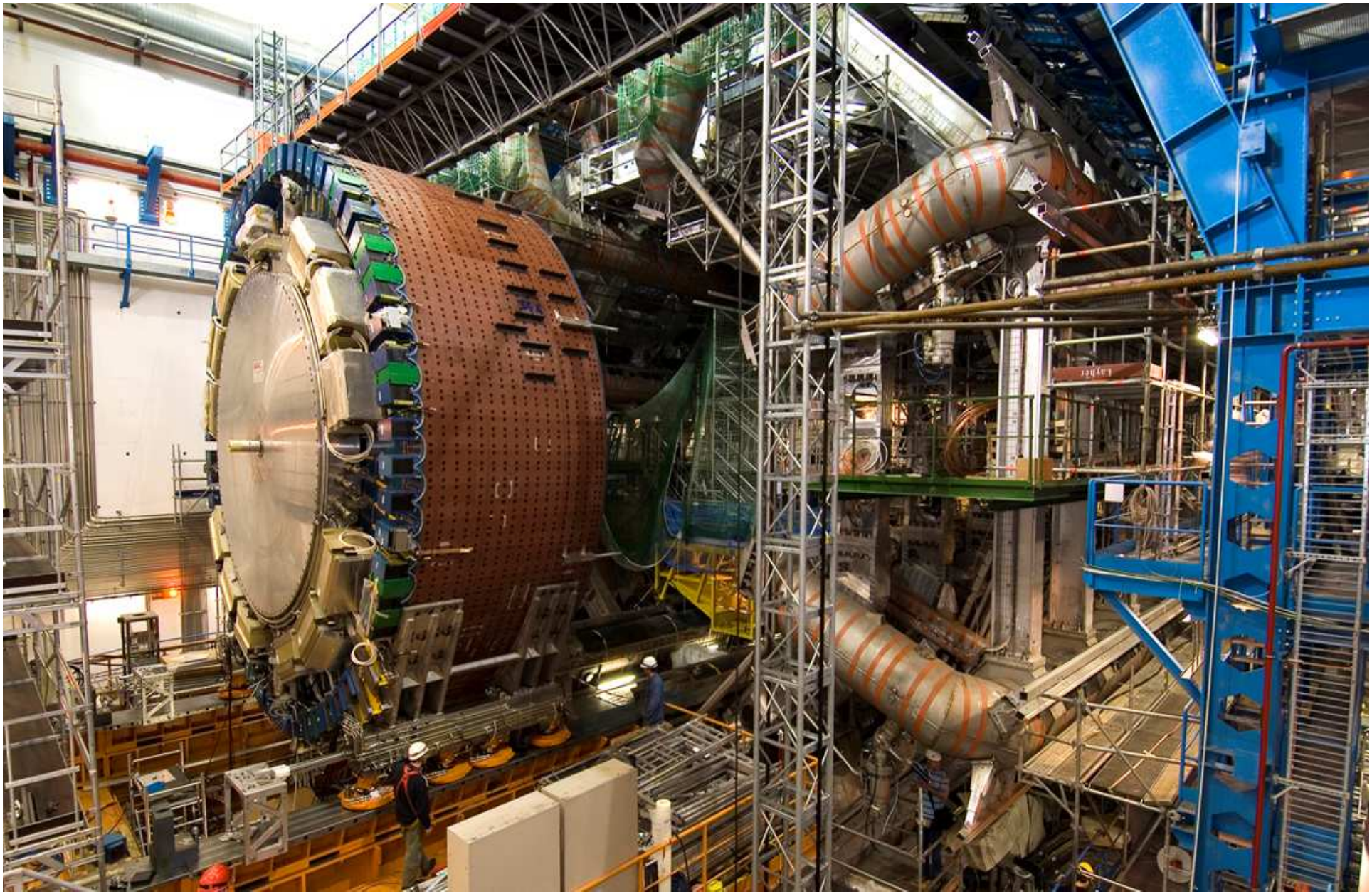
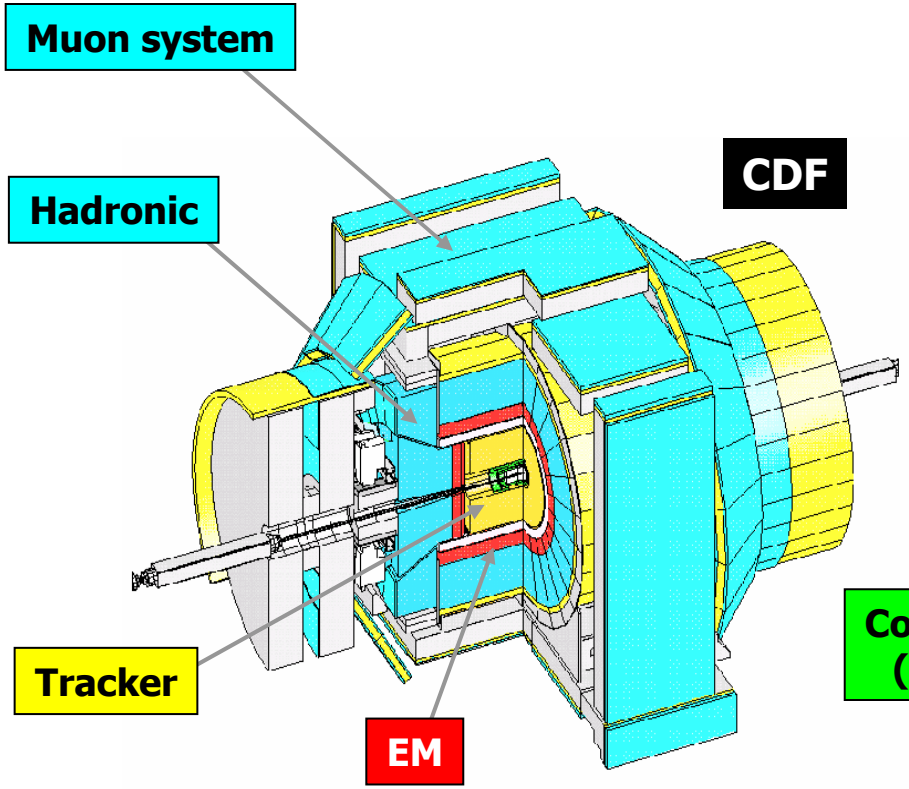
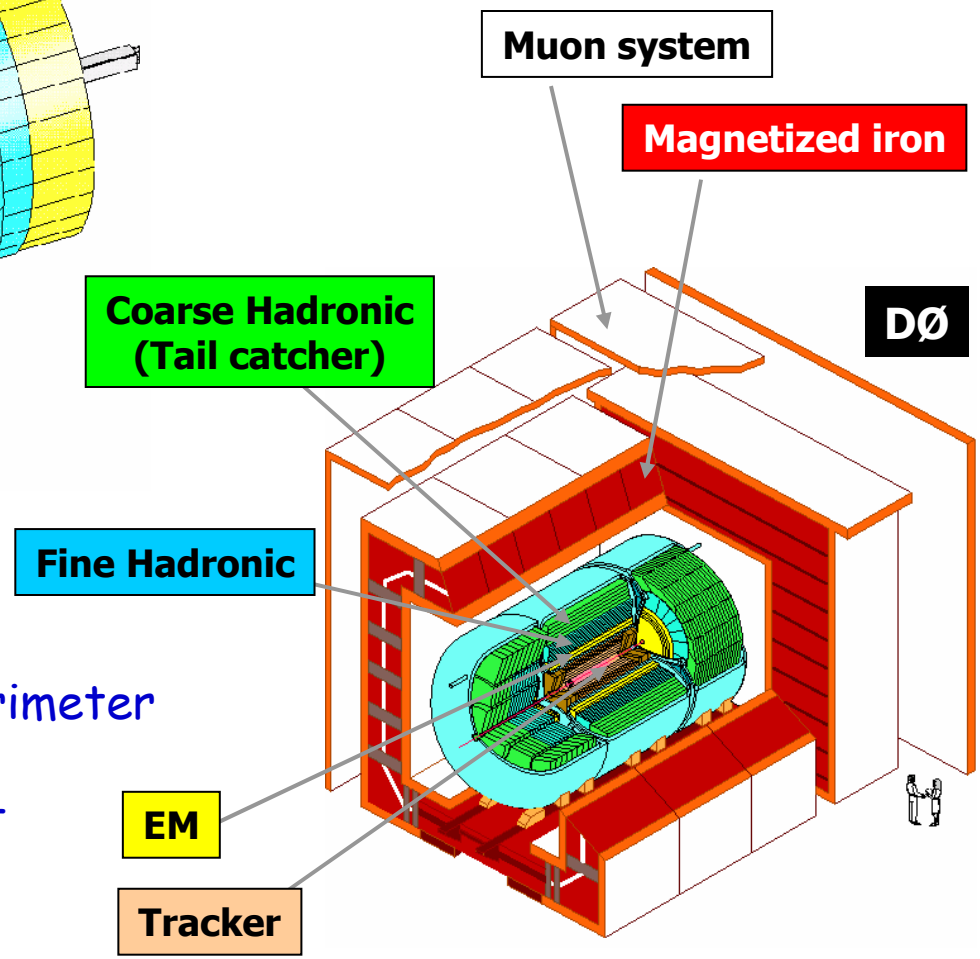
ATLAS





Arrays of sensitive instrumentation
> Million electronic channels each



- "Transparent" central tracking in a magnetic field
- Energy measurement of photons, electrons and hadrons in the calorimeter (most particles absorbed)
- Muons measured in the outermost magnetic spectrometer
- Missing energy (neutrinos) from measuring everything else

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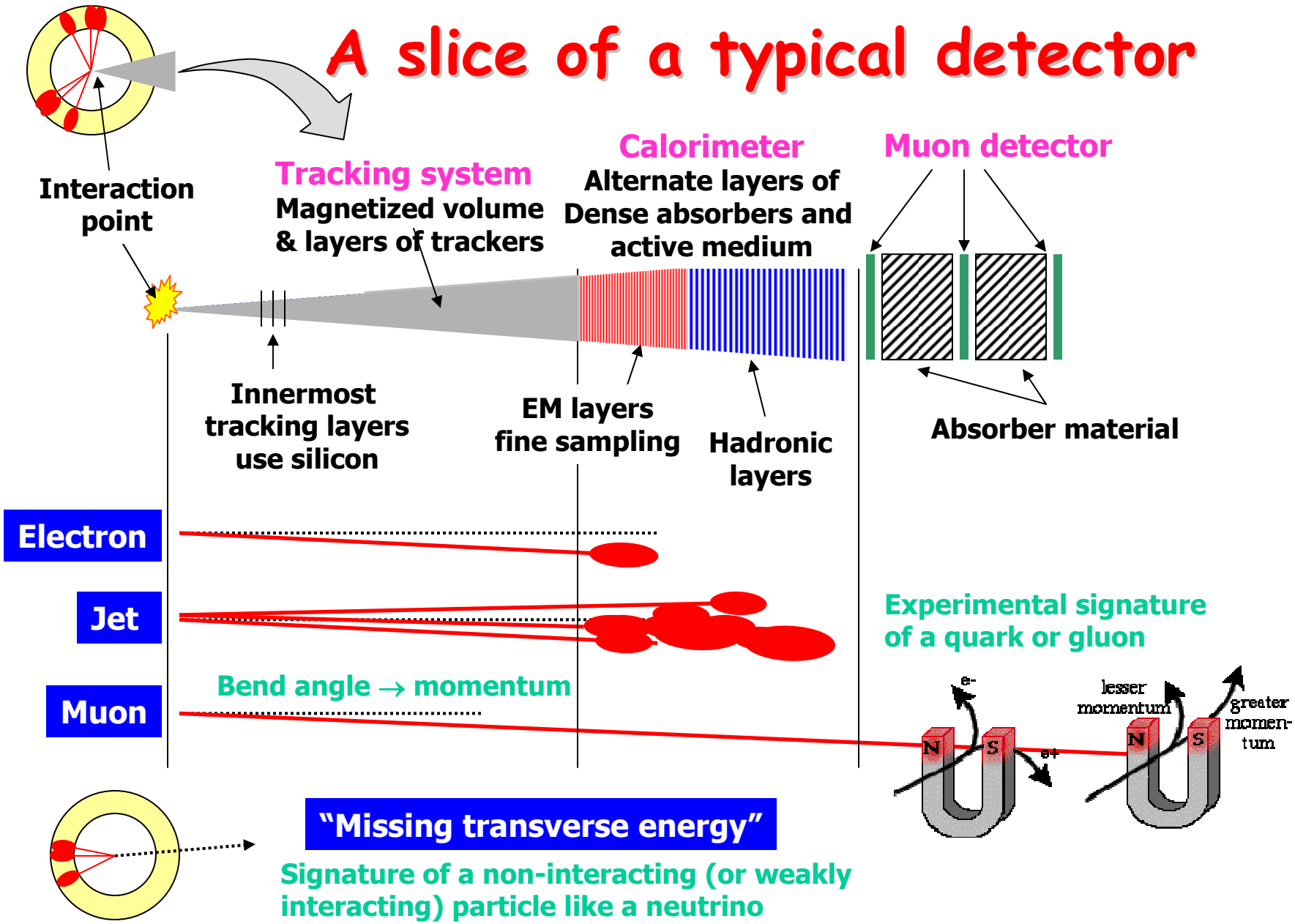
A slice of a typical detector



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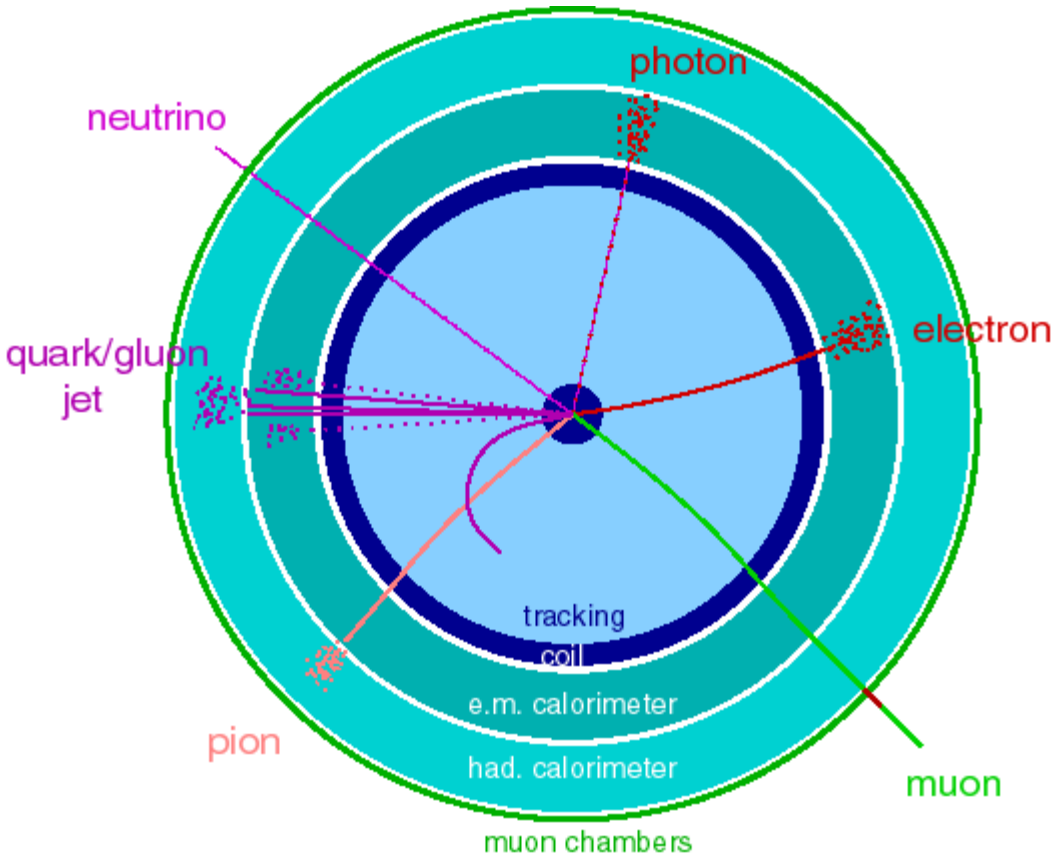
TYPICAL Collider Detector

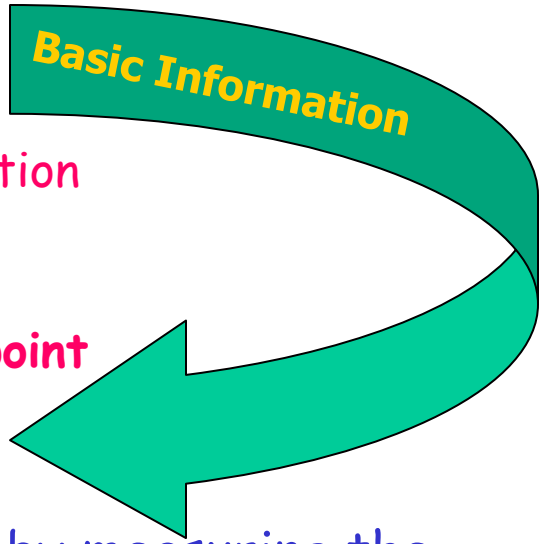
Cross sectional View



Identify and Measure Particles

- Detectors should
  - Track, match and count particles
  - Measure energy/momentum
  - Find particle identity
  - Measure charge
  - Measure missing energy
  - Provide full solid angle coverage, fine segmentation
  - Have fast response, ideally zero deadtime

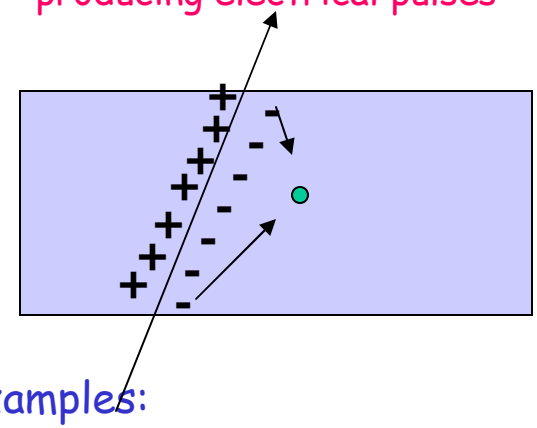
  ⇒ **Many kinds of detectors → sub-systems with several layers surrounding the collision point**



- Find Collision vertex
- Find and measure short-lived parent particles by measuring the children
- Perform analysis to understand the process that produced the event

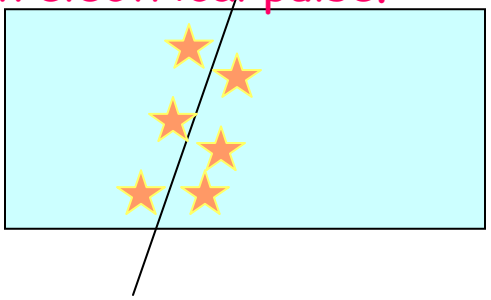
Tracking the Particles

- Ionization detectors
  - Energetic charged particles ionize the medium. Charges are collected at an electrode producing electrical pulses



- Examples:
  - CDF/D0 Silicon detectors, Hit Res: 10-15 um
  - CDF Central Outer Tracker, Hit Res: 180 um
  - CDF/D0 muon chambers
    Hit Res: 500 um

- Scintillation detectors
  - High energy particles excite molecules which scintillate producing light. Light is collected and converted into an electrical pulse.



- Examples:
  - D0 Central Fiber Tracker
  - D0 Muon pixel detectors

Particle Detectors as Active Cameras

- To learn about what happens in high energy collisions, we need to track, identify and measure particles produced
  - Very large, Multi-layered, multi-system detectors surrounding the interaction region
    - **Fermilab detectors -- many stories high, ~5000 tons each**
  - Fine granularity → millions of readout channels
  - Fast readout electronics
  - Complex, multi-tier data-acquisition systems
  - Huge computing needs for data processing

The Top Quark

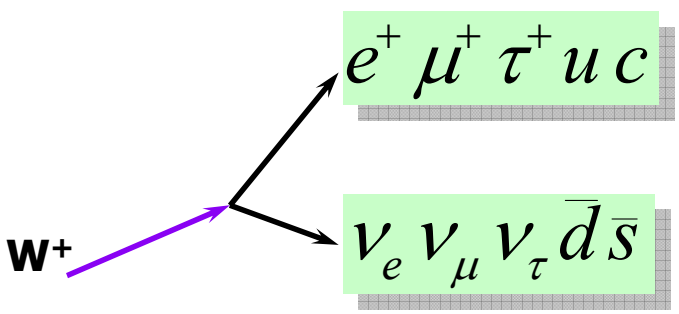
Discovered at Fermilab, 1995

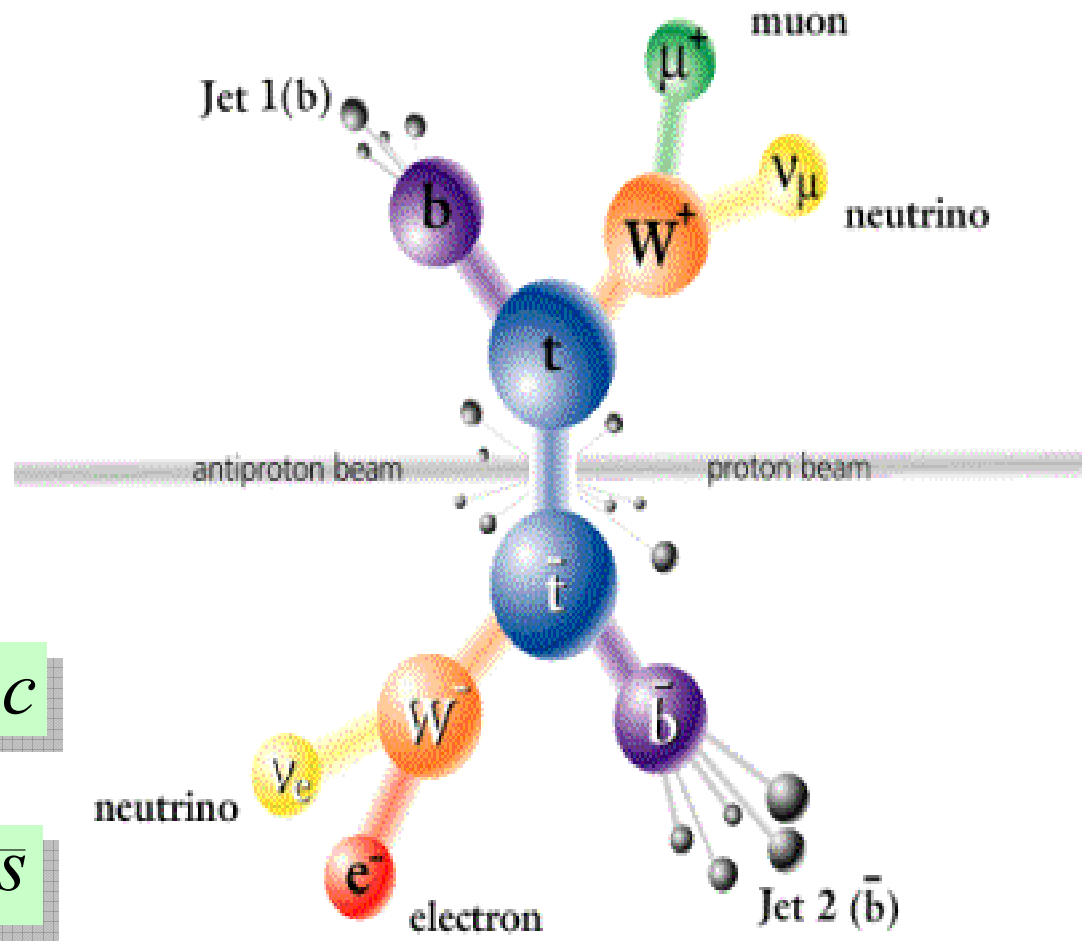
Presently, Tevatron is the only source of top quarks!

Top decays to a W boson and a b-quark

Extremely heavy (~175 GeV)

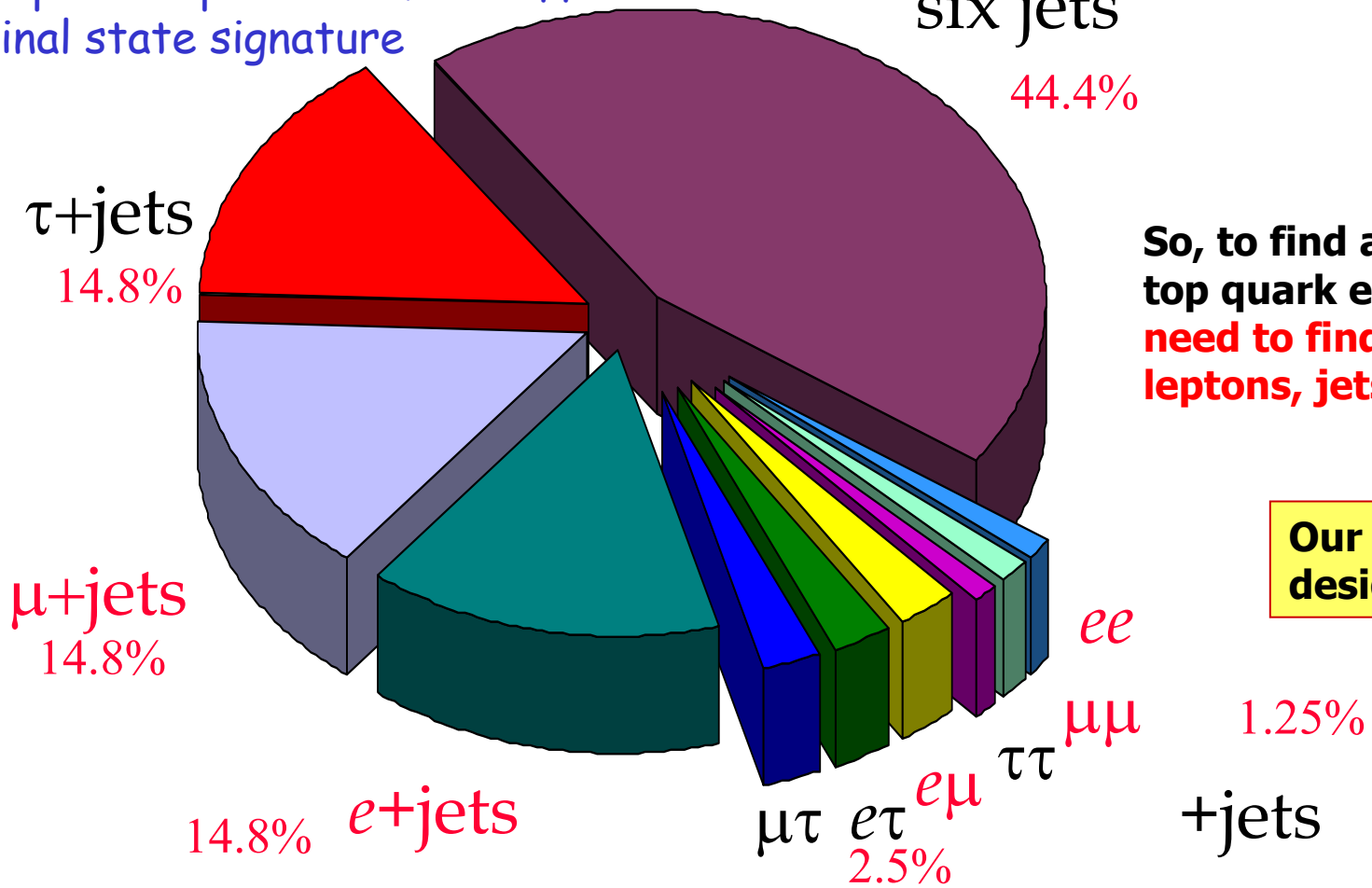
Extremely short-lived! Lifetime ~ 10^{-25} sec!!!!





Top Quark Decay Modes

Depending on how the W's decay, Top-antitop events have different final state signature



So, to find and study top quark events, we need to find and measure leptons, jets and neutrinos.

Our detectors are designed to do this

+ neutrinos in all cases except six jets mode

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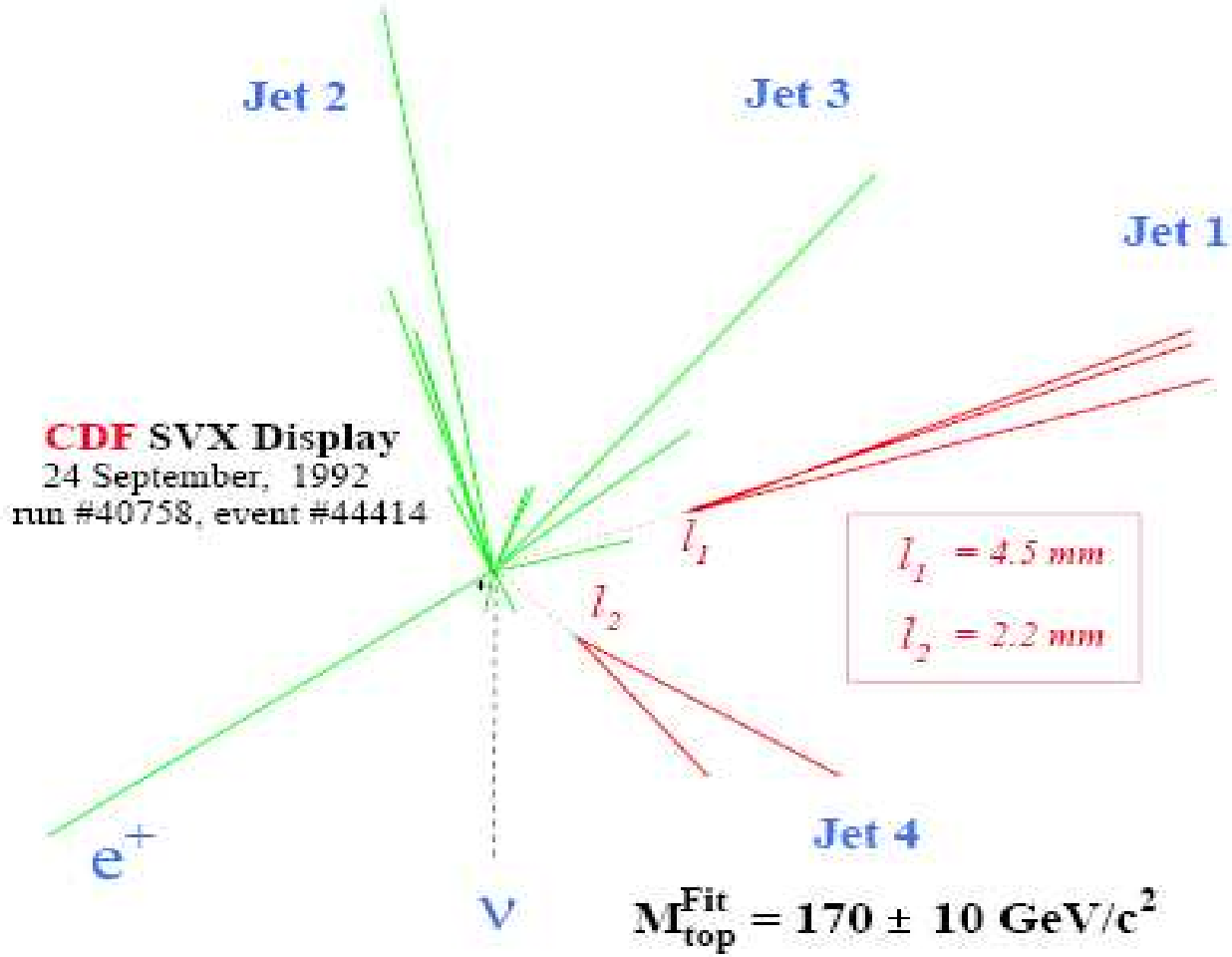
CDF's 1st Top Event… (run 1)



Complicated Collisions

A simulated event in ATLAS (CMS) $H \rightarrow ZZ \rightarrow 4\mu$

pp collision at $\sqrt{s}$ = 14 TeV, $\sigma_{inel.} \approx 70$ mb

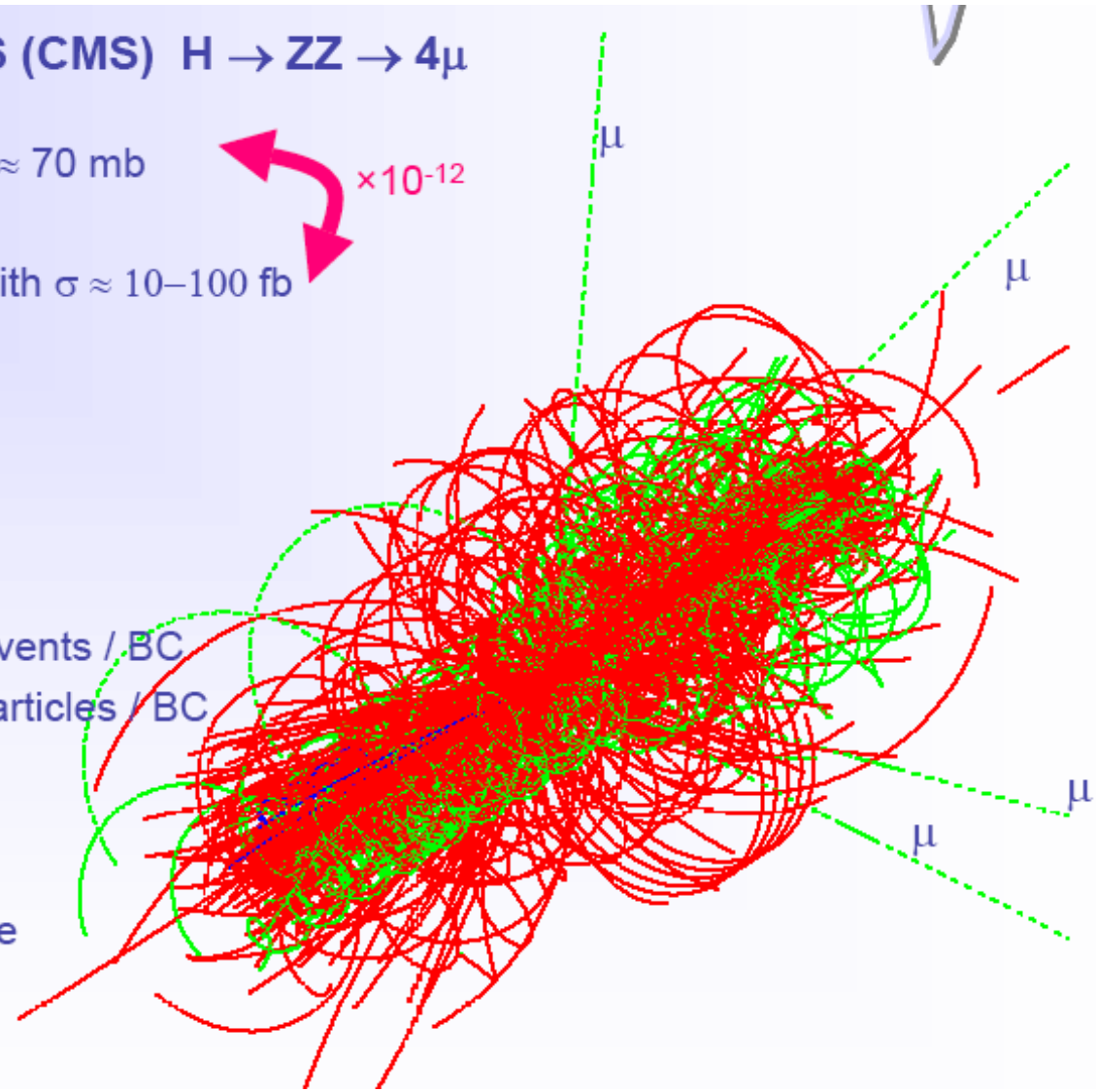
$\times 10^{-12}$

We are interested in processes with $\sigma \approx 10$–100 fb

$L = 10^{34}$ cm^{-2} s^{-1},
bunch spacing 25 ns

≈ 23 overlapping minimum bias events / BC
≈ 1900 charged + 1600 neutral particles / BC

Brave people have started to think about a Super LHC upgrade to $L = 10^{35}$ cm^{-2} s^{-1} !!!



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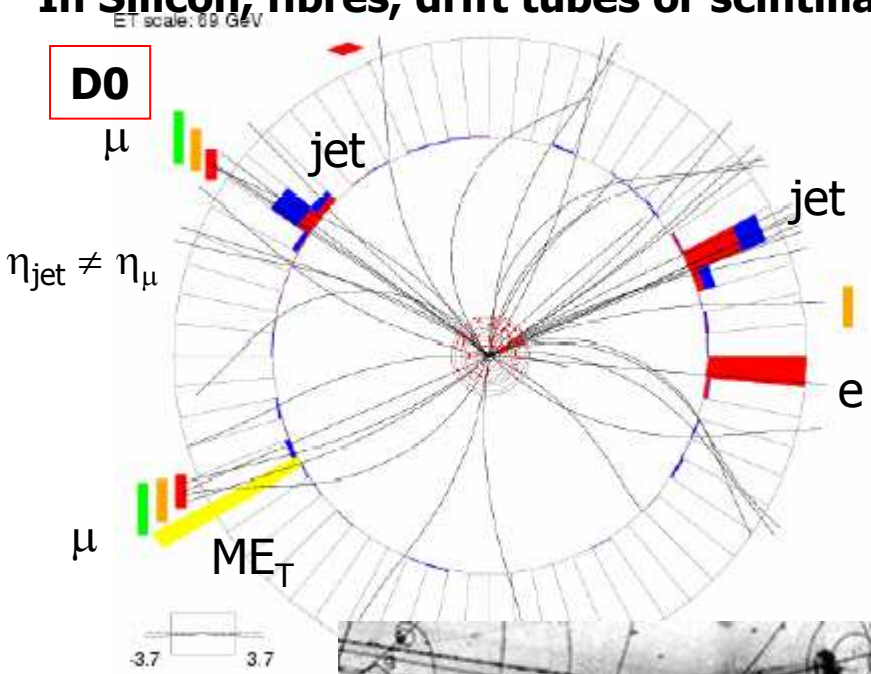
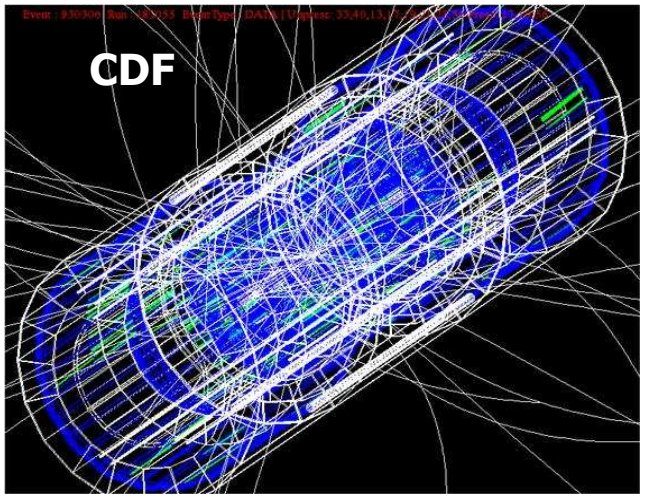
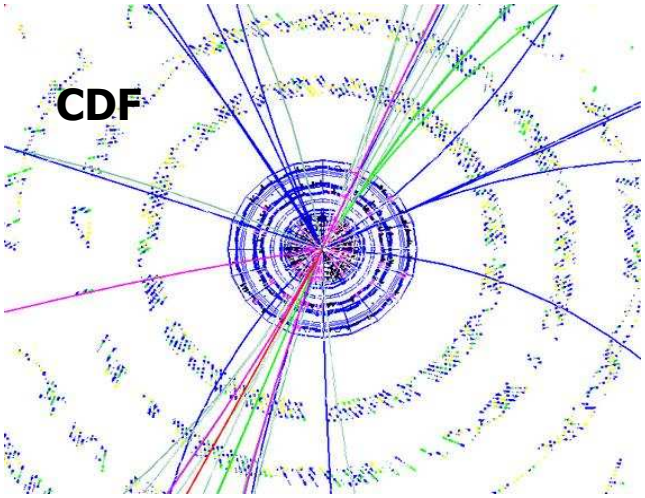
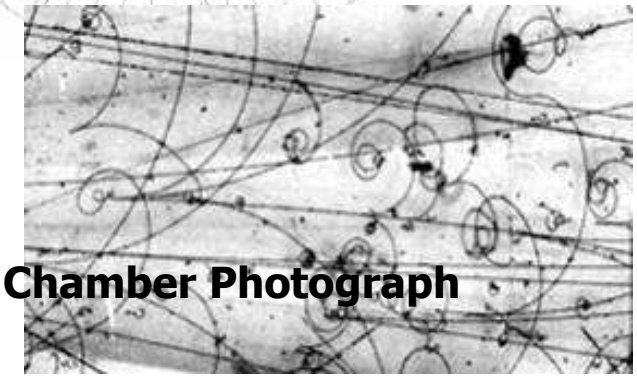
Tracks Reconstructed

Modern trackers:
Tracks reconstructed from electronic signals (hits) from the readout cells
In Silicon, fibres, drift tubes or scintillators









Old Bubble Chamber Photograph

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Trigger on Interesting Events

CDF/DØ

proton → Bang! ← antiproton

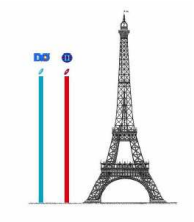
2.5 Million collisions per second

Is this collision interesting?
3-Level trigger framework

NO → Reset electronics

YES → Digitize all signals → Write event to tape

50x250 Kbytes/sec



CDF and D0 each record about 500 Gb of data per day + 1100 Gb come from processing this data

200 meters of CDs per year

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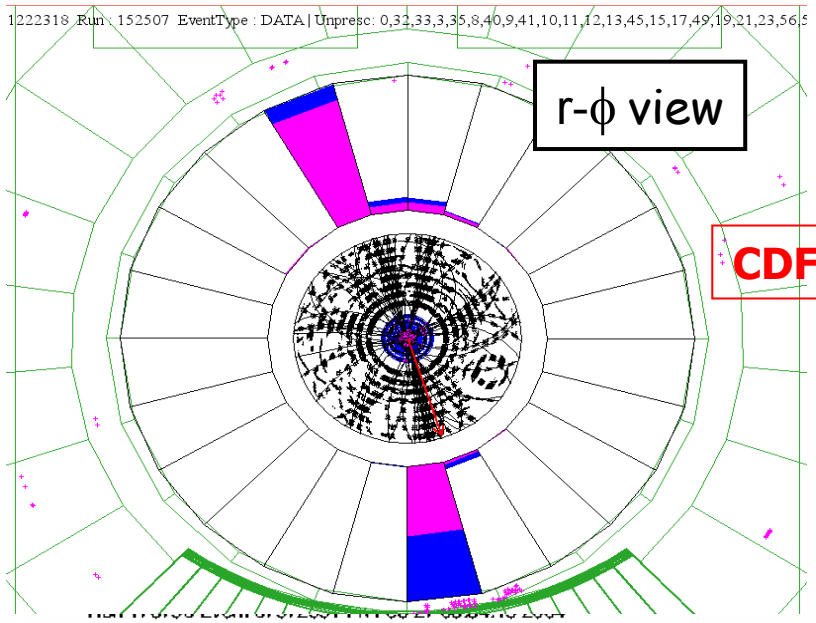
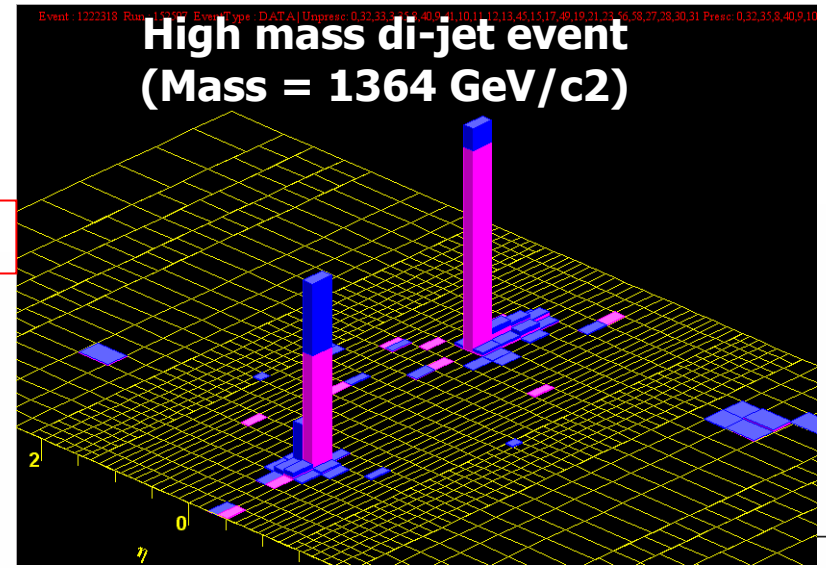
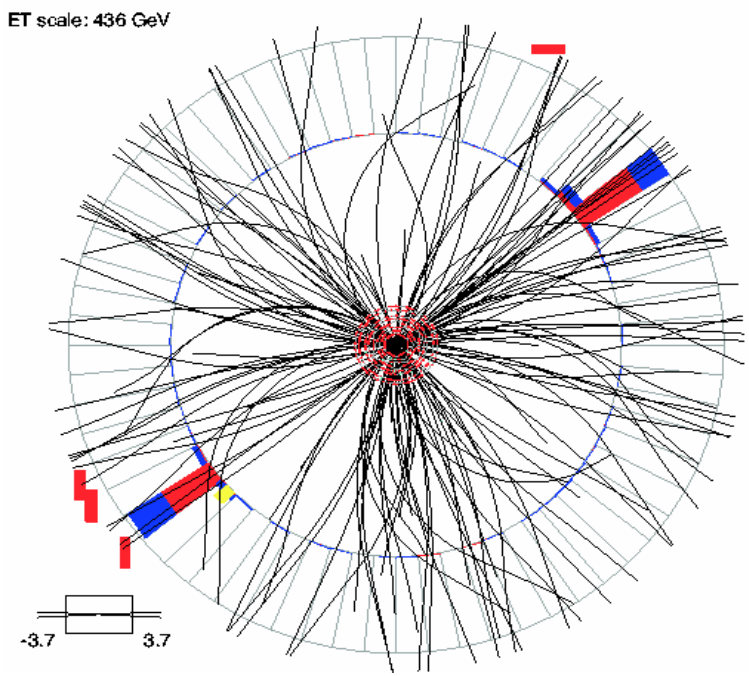
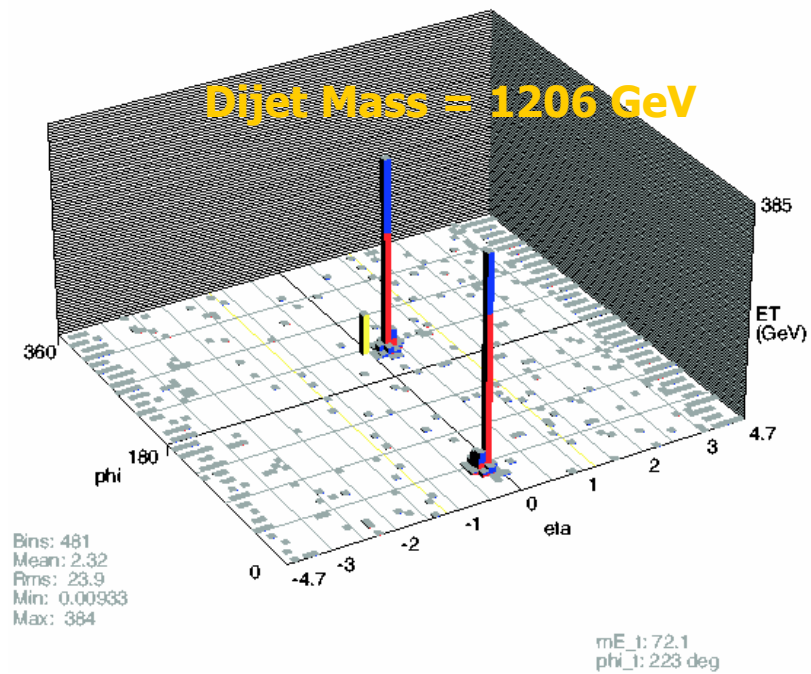


CDF





D0



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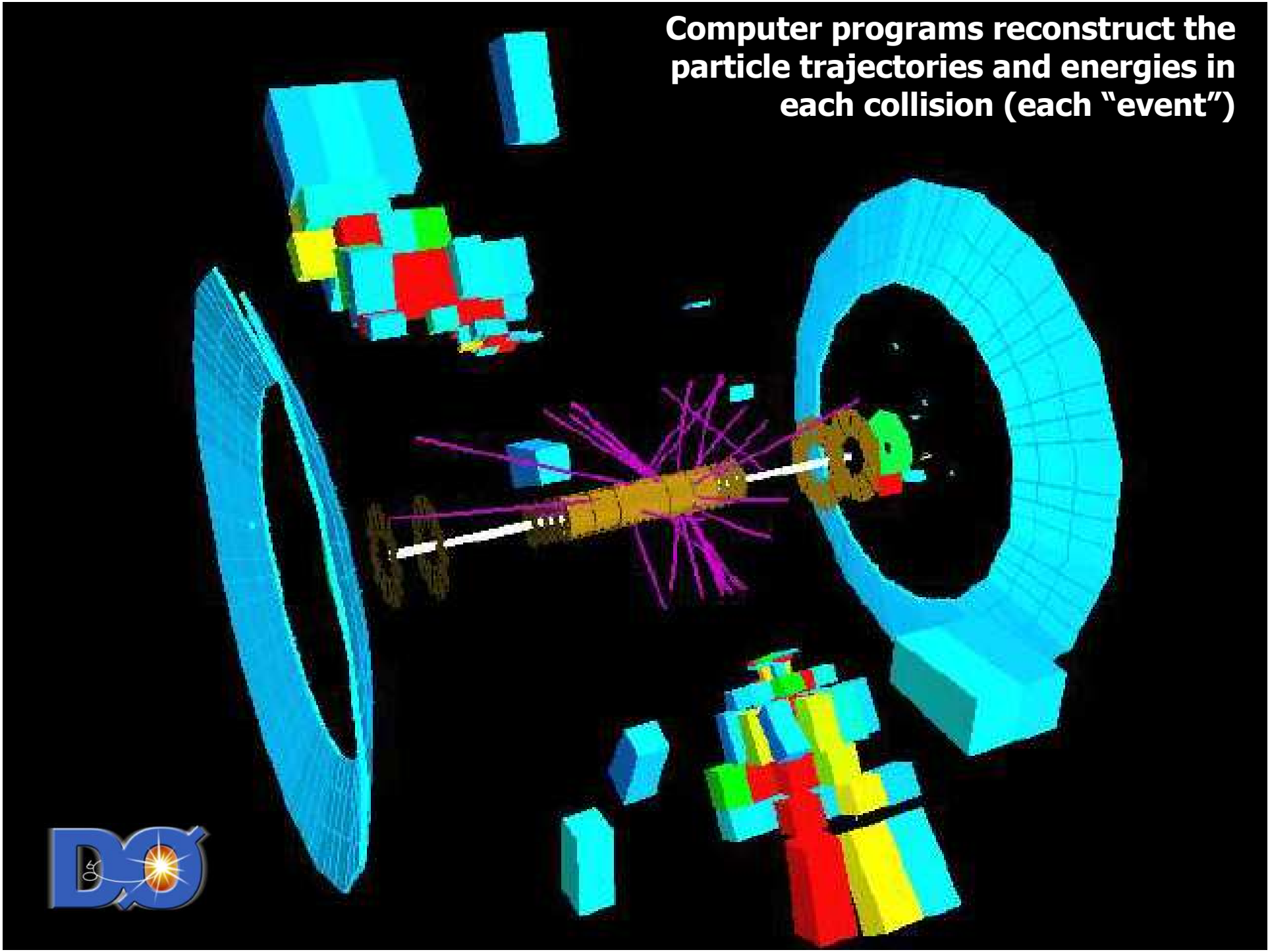
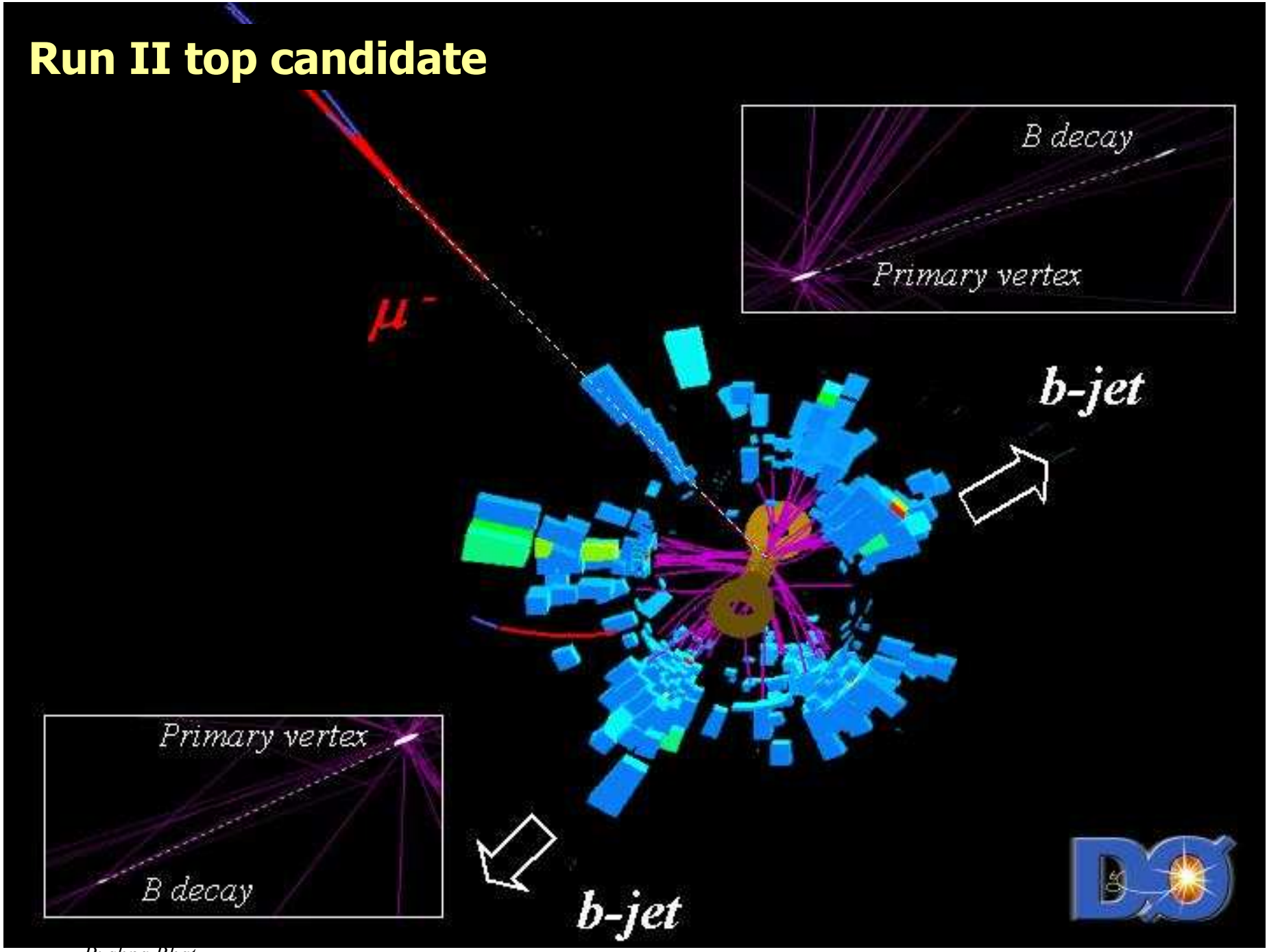

Computer programs reconstruct the particle trajectories and energies in each collision (each "event")

Run II top candidate



What are we up against?

Let us take top quark production to see how it all works

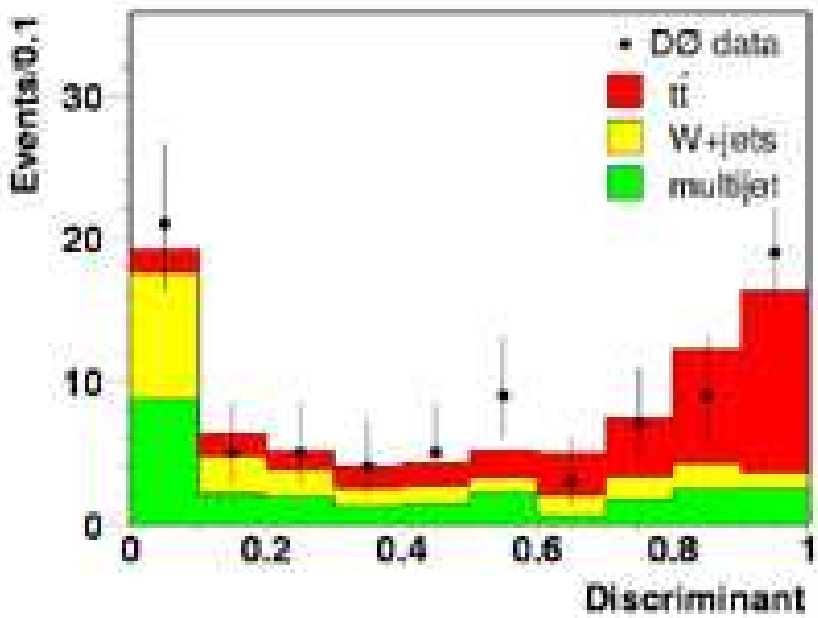
- 2.5 Million p-pbar crossings/sec most of which are "uninteresting"!
- Total inelastic cross section ~ 60 mb = 6×10^{-2} barn
  - **1 barn $= 10^{-24}$ cm^2**
  - At $L = 10^{32}$ cm^{-2} sec^{-1}, N = 6 Million interactions /sec
- Top-antitop pair production cross section $\sigma(t\bar{t})$ ~ 6.7 pb = 6.7×10^{-12} barn
  - 10 orders of magnitude lower!
  - 1 top pair event for every 10 billion "uninteresting" events!

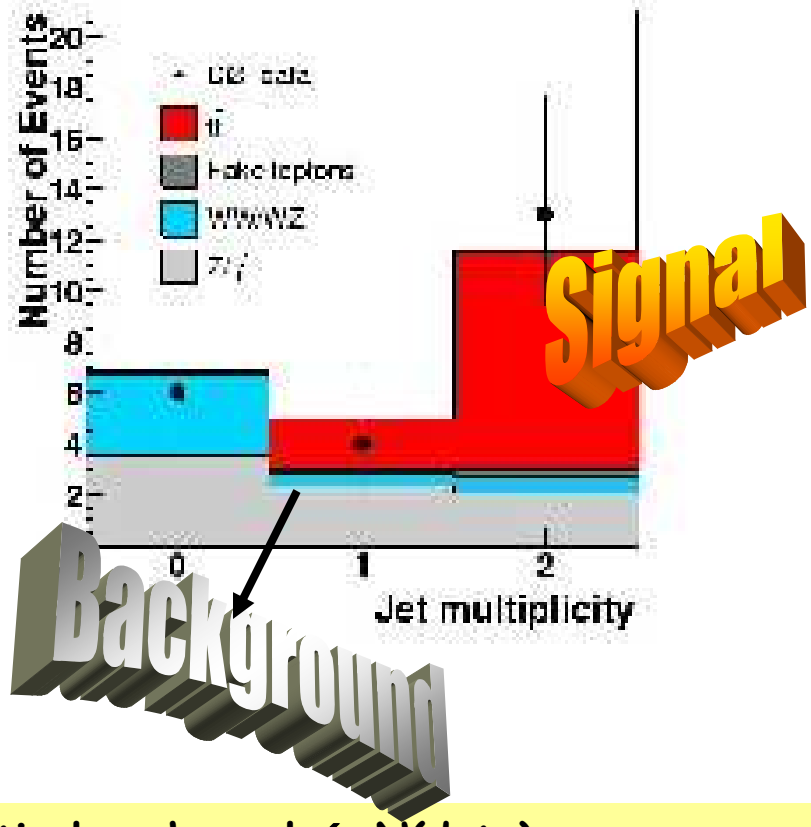
➔Finding a needle in a huge haystack!

Data Analysis

- How do we discriminate signal from background?
- How do we make precision measurements?

Finding the Signal

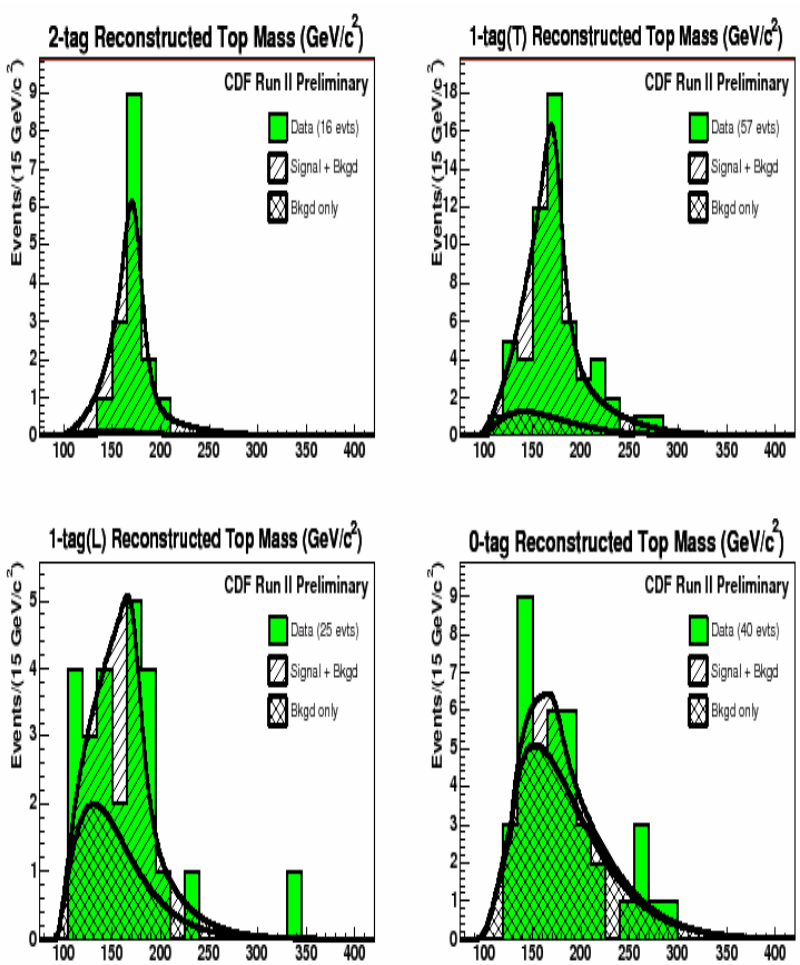


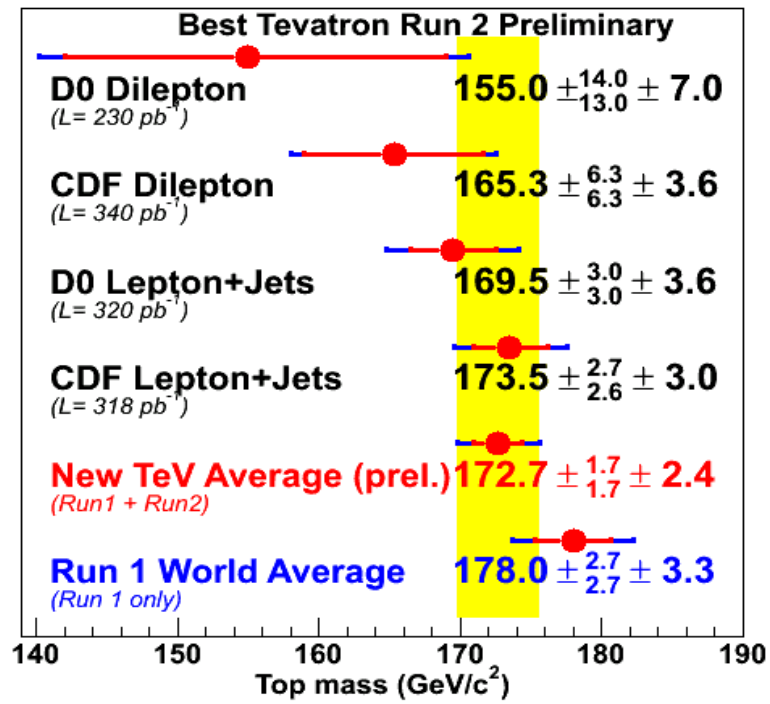


- Count the number of events seen in a particular channel ← N(data)
- Estimate the number of events from known, expected phenomena ← N(Bkg)
- Signal is the excess over the known, predicted background
- N(signal) = N(data) –N(Bkg)

Top Mass Measurement

CDF





Top mass ~ 175 GeV

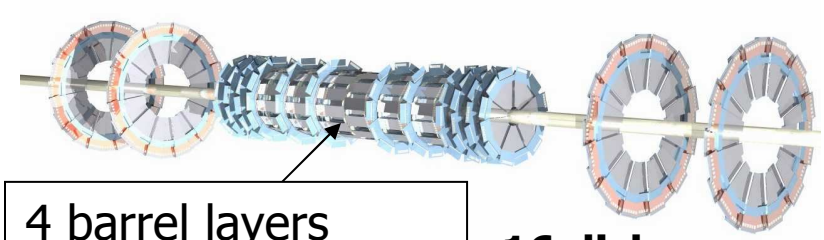
Summary

- So, by the end of the course, you should be prepared to embark on HEP research on one of the existing or future experiments!

Miscellaneous Slides

DØ Trackers

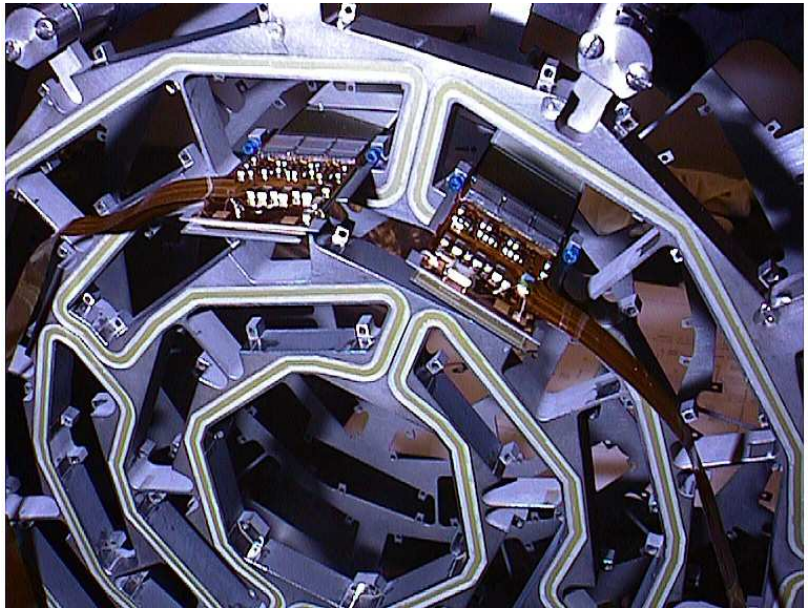
Silicon Microstrip Detector



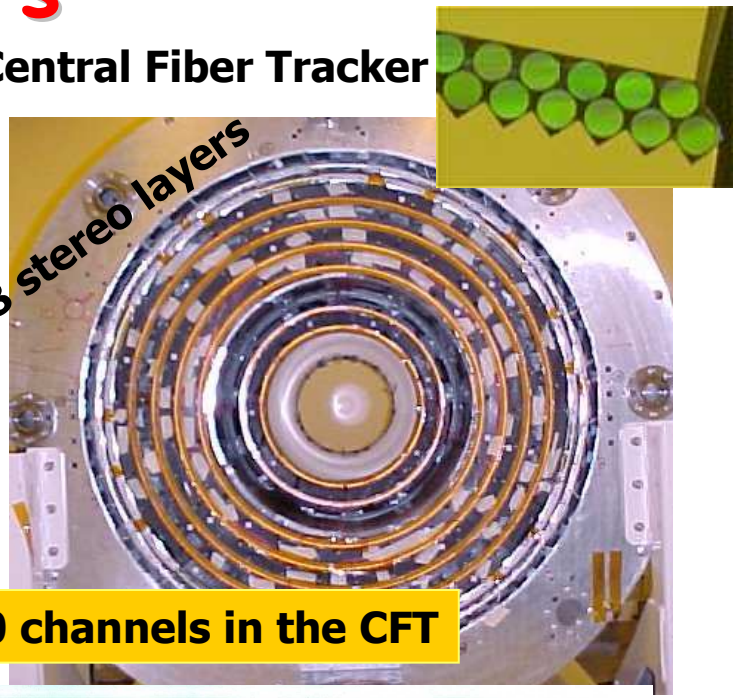
4 barrel layers
axial + stereo strips

16 disks

Total of 800,000 Si channels

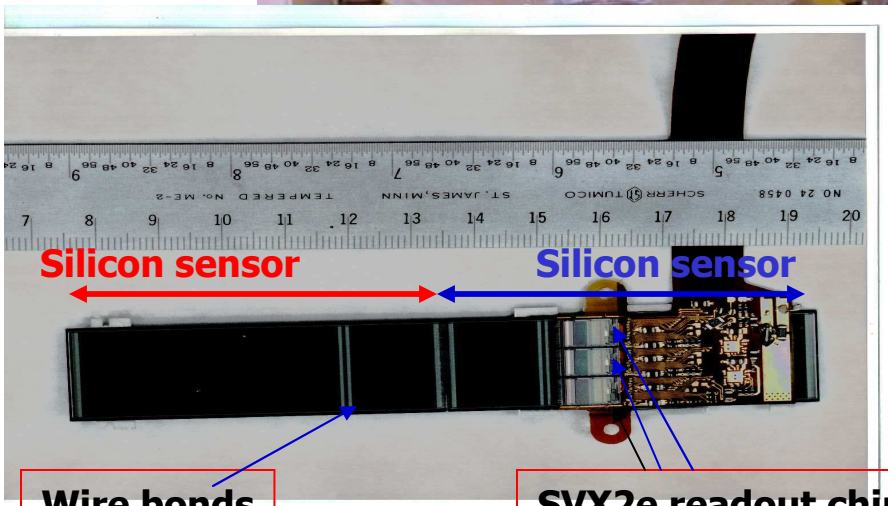


Central Fiber Tracker



8 axial, 8 stereo layers

80,000 channels in the CFT



Wire bonds

SVX2e readout chips

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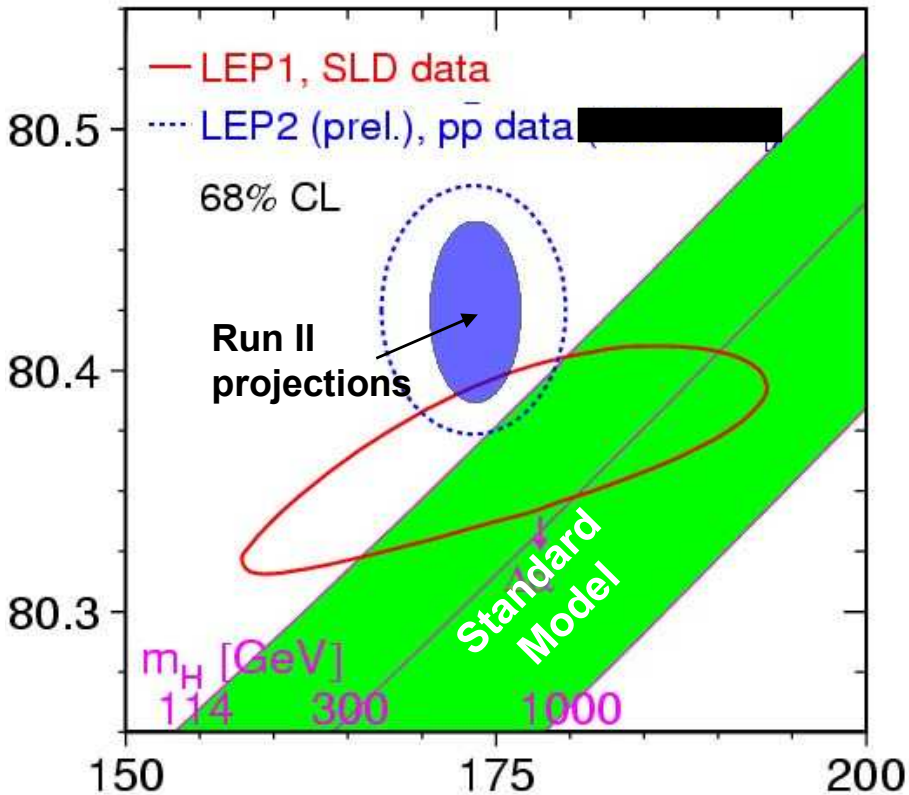
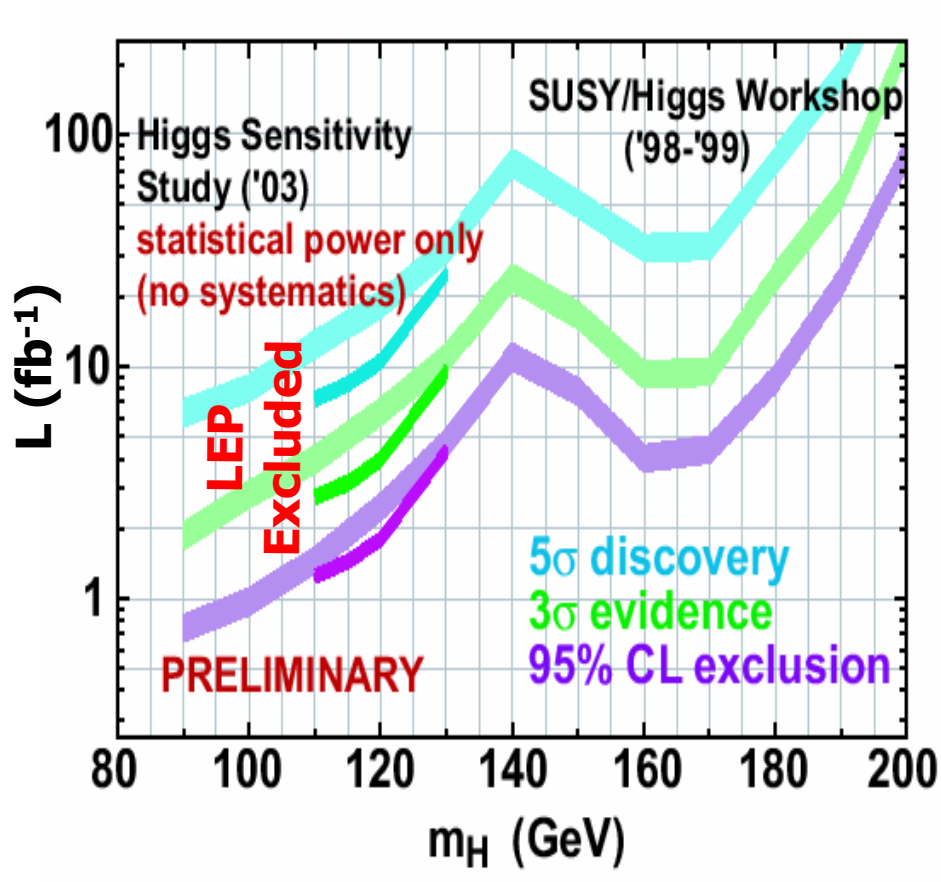
Prospects

- Major accelerator upgrades that are underway continue to push the luminosity higher
- Fermilab Tevatron will run through 2009
- Integrated luminosity of 8 fb-1 expected by 2009, by which time the energy Frontier will have moved to CERN
- Opportunity to find Higgs, new physics signals – SUSY? Technicolor? Extra dimensions? …

The Higgs Boson





Is Nature SuperSymmetric?

- A postulated symmetry between bosons and fermions:
  - all the presently observed particles would have new, more massive superpartners (SUSY is a broken symmetry)

"Discovery of supersymmetry would begin a reworking of Einstein's ideas in the light of quantum mechanics."

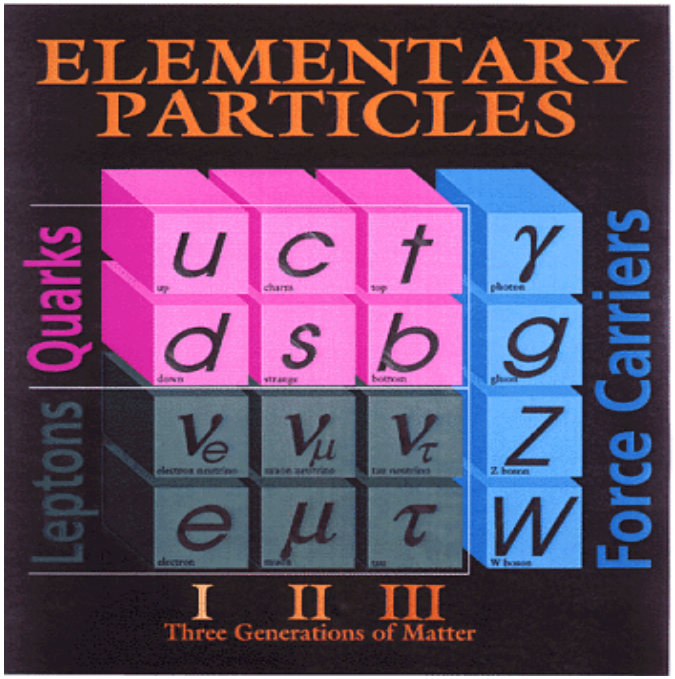
- It is a firm prediction of string theory (the "ultimate" theory?)

- Solves many deficiencies of the Standard Model

- Does this elegant theory describe nature?

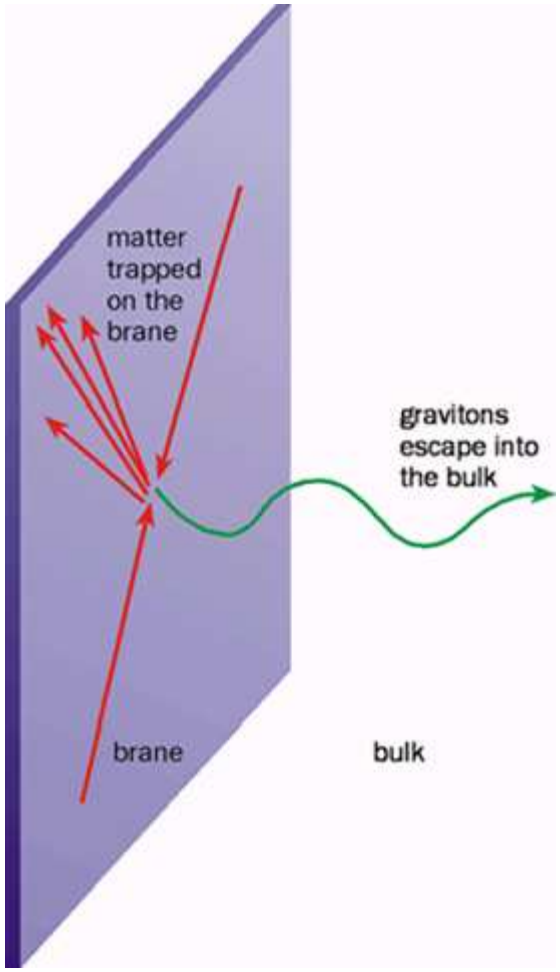
  Only experiment can tell us.

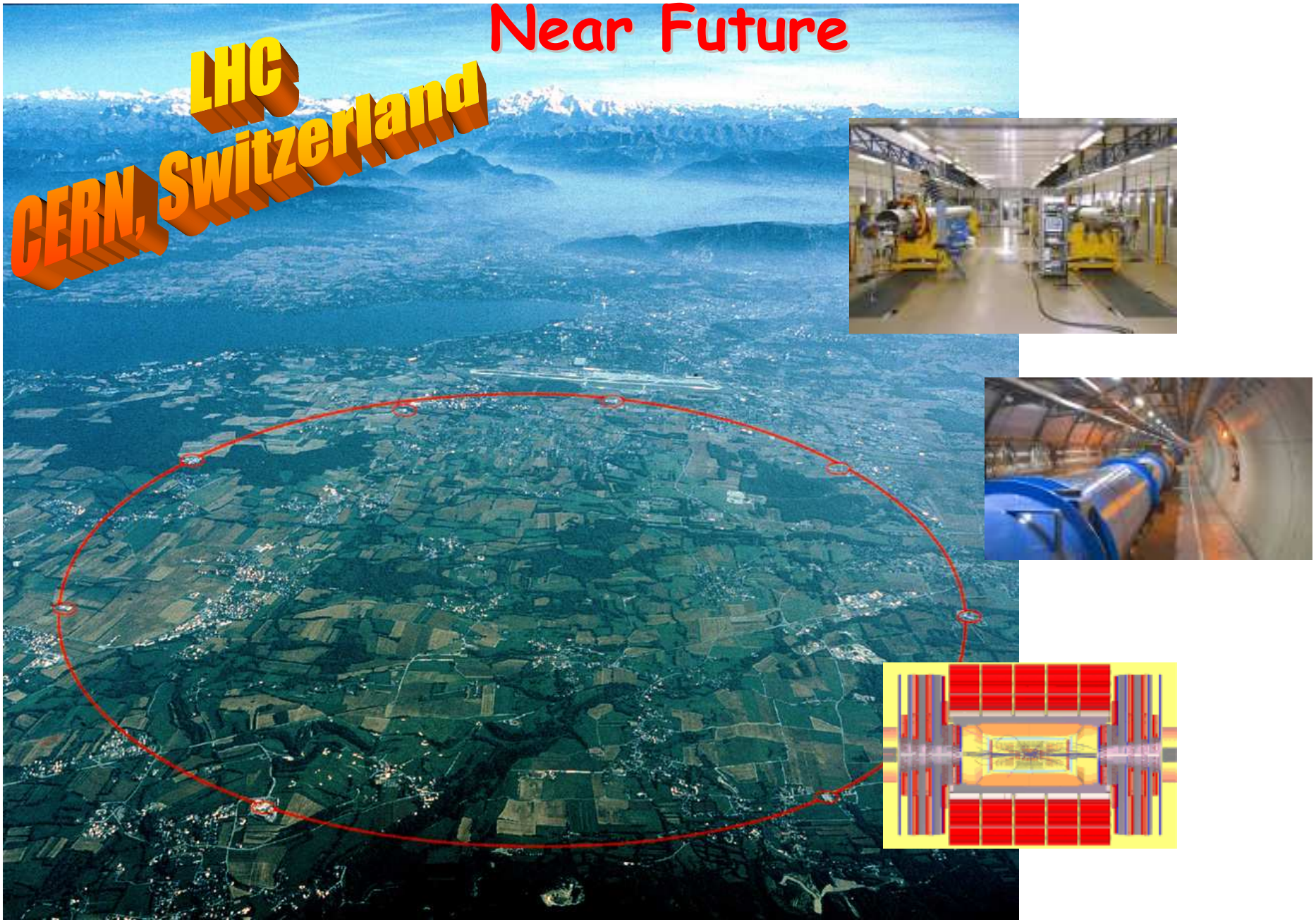
particle	superpartner
quark	squark
gluon	gluino
photon	photino



Are there Extra Space-time Dimensions?

- Why do we think there might be extra dimensions?
  - String theory needs them
  - They can be used to explain why gravity seems weak to us
  - They would also solve other mysteries of particle physics.
- The extra dimensions are hard to see, for some reason. They might be compact and small. If an extra spatial dimension is compact, coiled up with size R, we would see new massive "Kaluza-Klein" particles m=1/R, 2/R, ...
  - We can produce these at colliders if there is enough energy.
- The extra dimensions could be large, but we are trapped on a 3-dimensional membrane in a higher-dimensional space-time.
  - Only gravity acts in the extra dimensions, which can be of macroscopic size.





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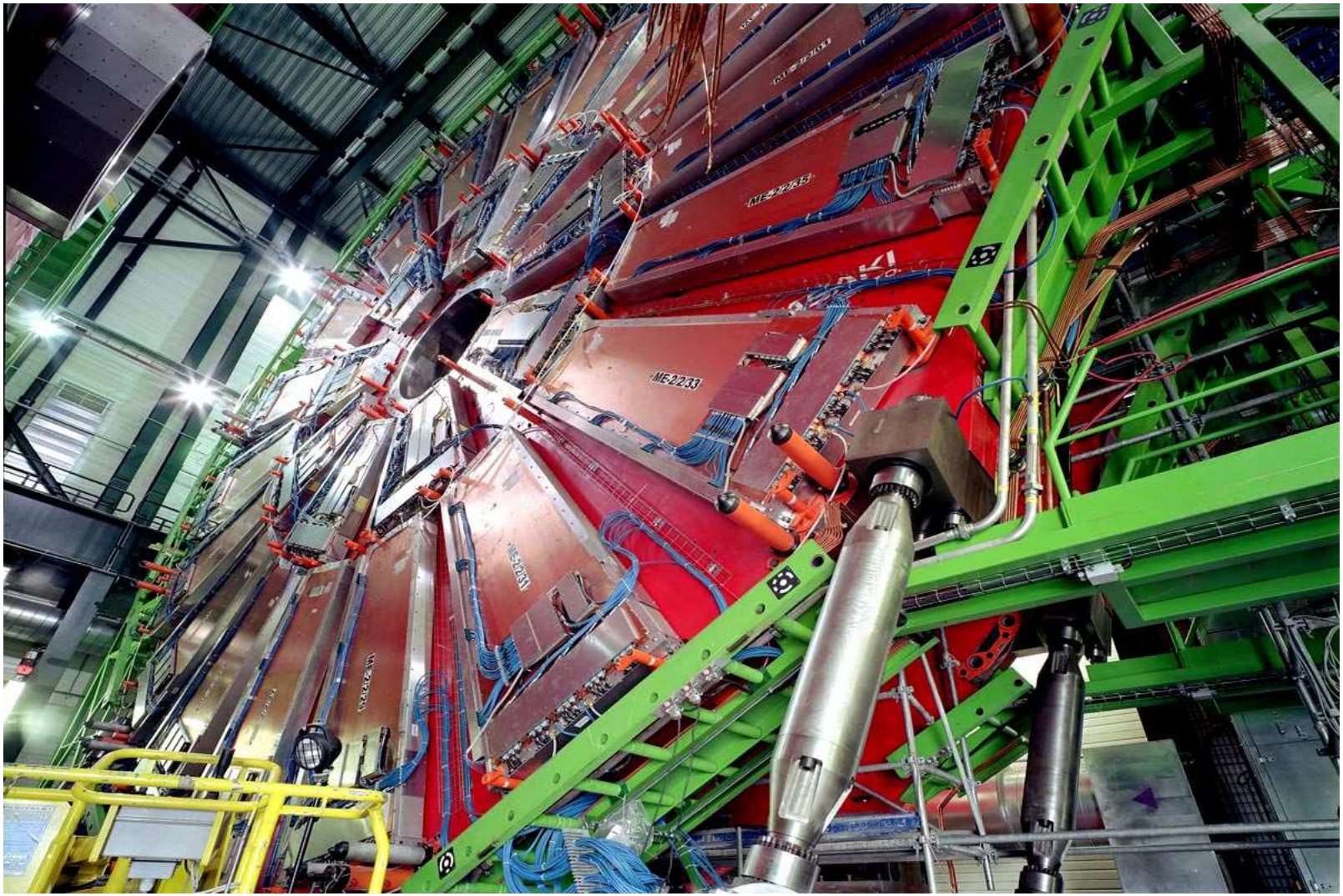
LHC Experiment: CMS



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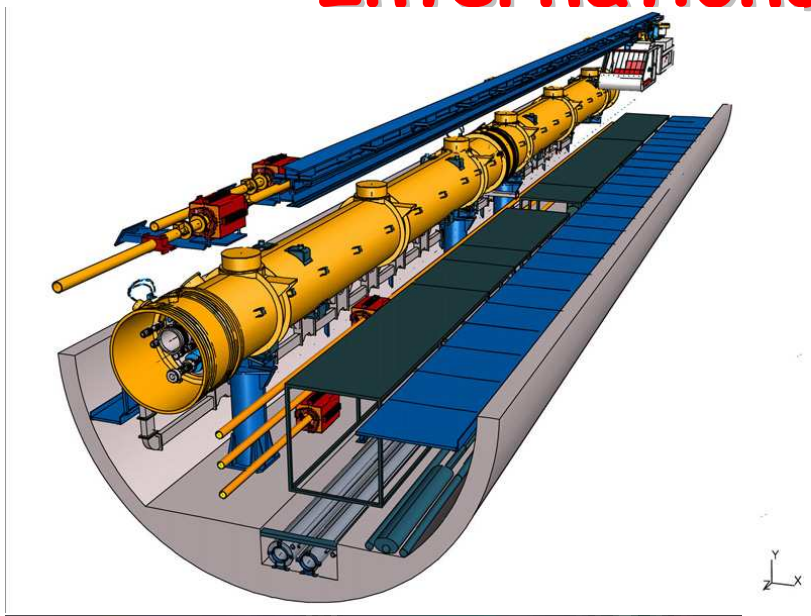
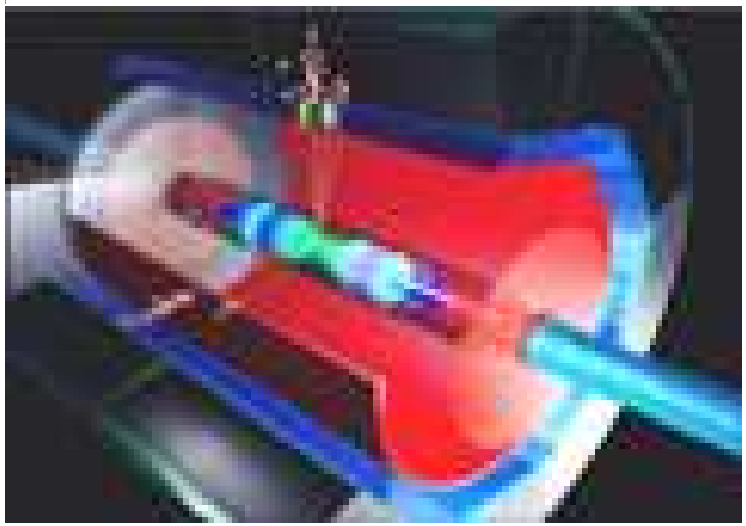
International Linear Collider





Linear electron, positron accelerators
Each about 20 km long

(Near) Fermilab is the favorite site

Luminosity

- Collider Luminosity

Instantaneous Luminosity $L \approx \dfrac{\text{Rev. Freq.} \times Nbunches \times \text{Np} \times \text{N}\overline{\text{p}}}{\text{Trans. Beam Area}}$

Tevatron luminosity > 1x 10^{32} cm^{-2} sec^{-1}

Integrated Luminosity $= \int L dt$ **expressed as inverse picobarns or inverse femtobarns**

1 barn =10^{-24} cm^2 **measure of cross section**

Run 1 Int. Lum ~ 125 pb^{-1}
Run 2, already delivered ~1200 pb^{-1}

- Event Rate

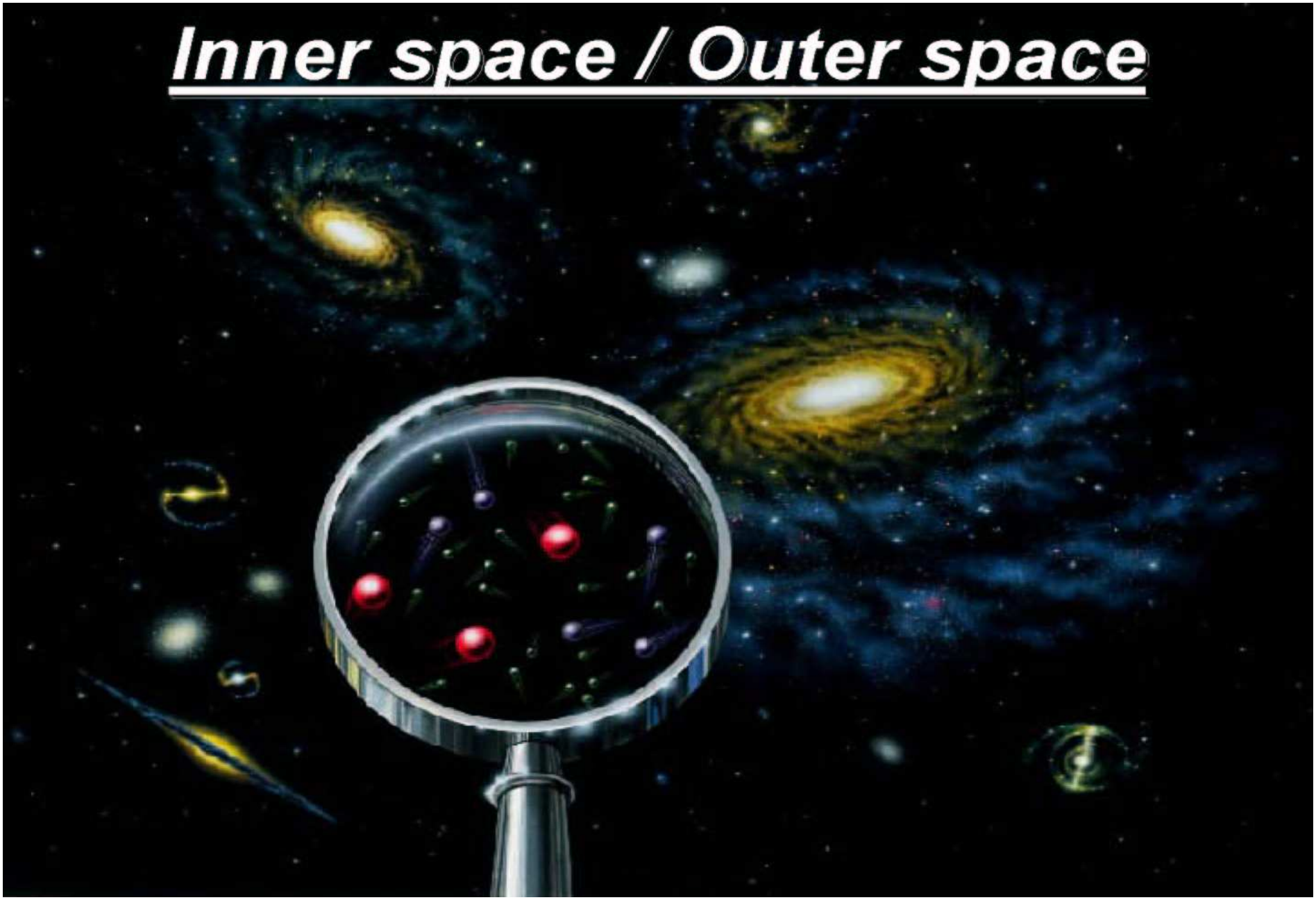
$$N = L \times \sigma$$

Cross-section σ ← effective area of interaction, cm^2
← probability for a process to occur

There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy.

-- Shakespeare

Experiments may reveal something unexpected and exciting!



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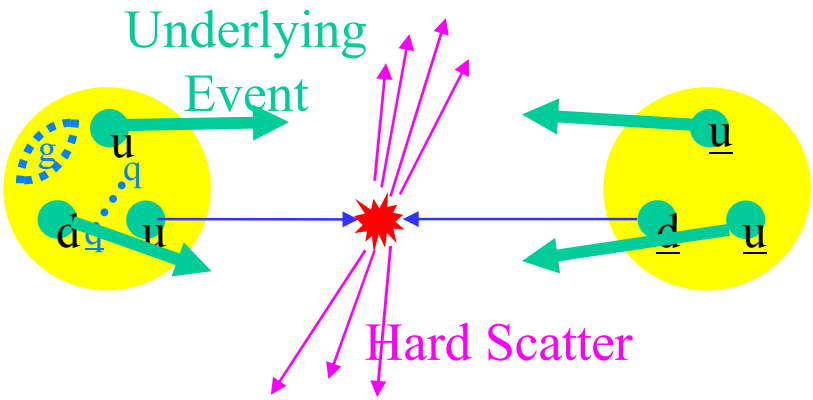
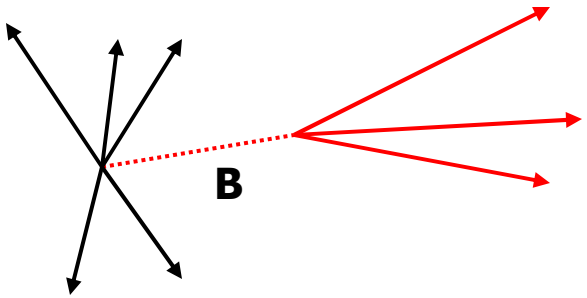
Collider Physics

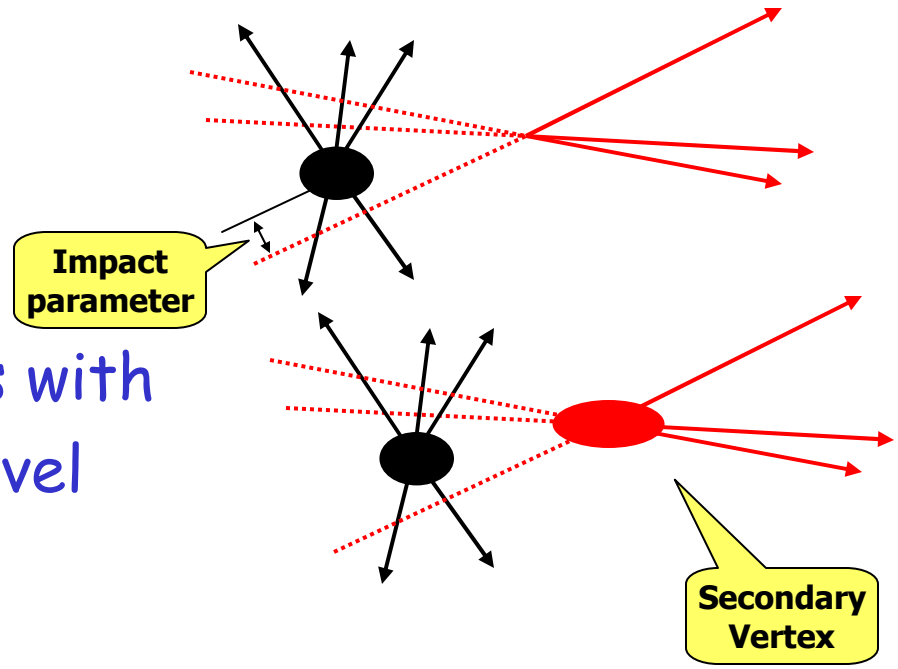
- A very broad program and a rich harvest of physics
  - Quantum chromo dynamics
    - Study of quarks and gluons
  - Electroweak physics
    - W, Z bosons
  - C- and B- physics
  - Top physics
    - Strong and electroweak production of top, top properties
  - Higgs
    - Search for the SM and Supersymmetric (SUSY) Higgs
  - Searches for new phenomena and particles beyond SM
    - Supersymmetry (symmetry between fermions and bosons)
    - Technicolor (New strong interactions)
    - Leptoquarks (motivated by symmetry between quarks and leptons)
    - …
  - More Exotic possibilities → Extra dimensions, dark matter, tiny black holes



Finding b-quark jets

- The ability to identify b-quarks is very important
  - signatures for the top quark, supersymmetry, Higgs boson
- b quark forms a B-meson, travels a few mm before decaying

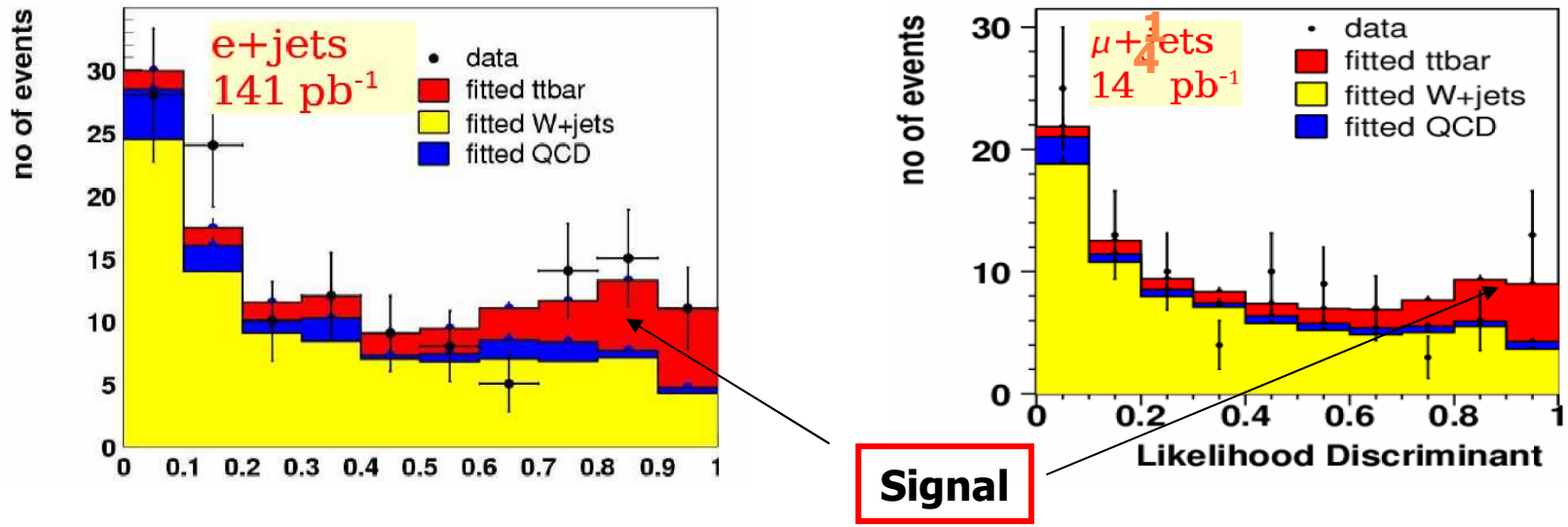




- need to measure tracks with a precision at the 10μm level

Top Cross Section (D0, Run II)

Lepton + jets Channel

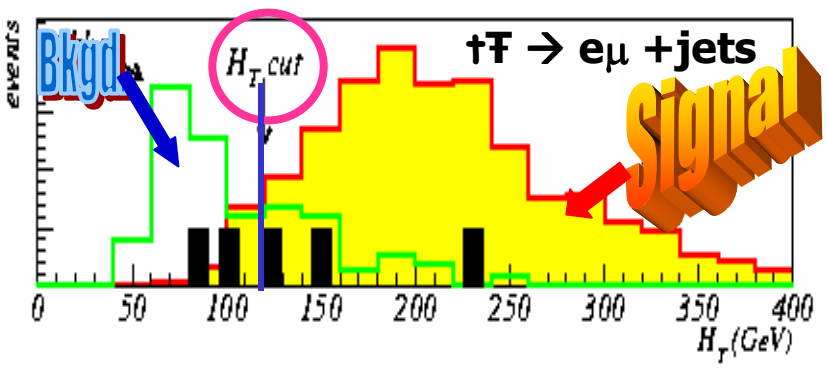


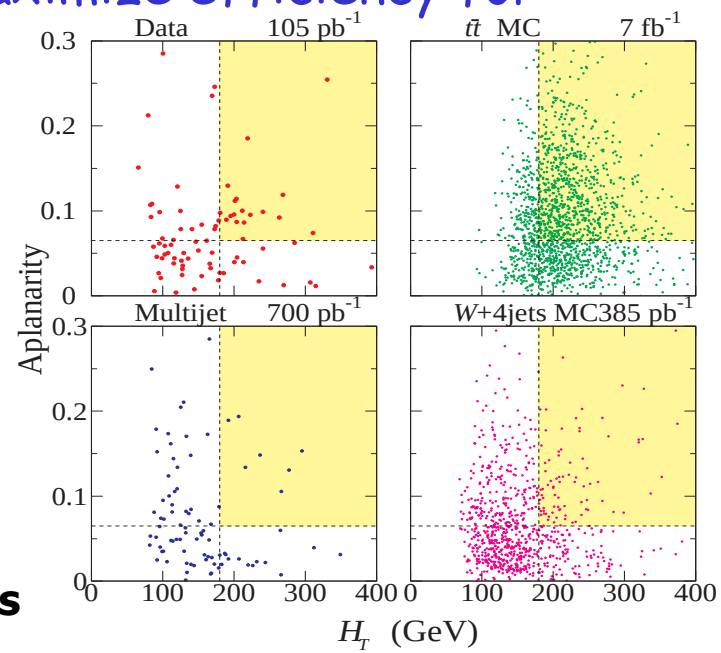
	muons	electrons
Nev	100	136
fitted N^{W}	74.7 + 12.7 – 12.0	94.6 + 15.8 - 15.0
fitted N^{QCD}	7.1 + 0.9 – 0.9	14.1 + 1.2 - 1.2
fitted N^{tt}	17.8 + 9.9 – 8.7	27.5 + 12.7 - 11.7

$$\sigma(t\bar{t}) = 7.2^{+2.6}_{-2.4}(stat)^{+1.7}_{-2.2}(sys)\ pb$$

Signal/Background Discrimination

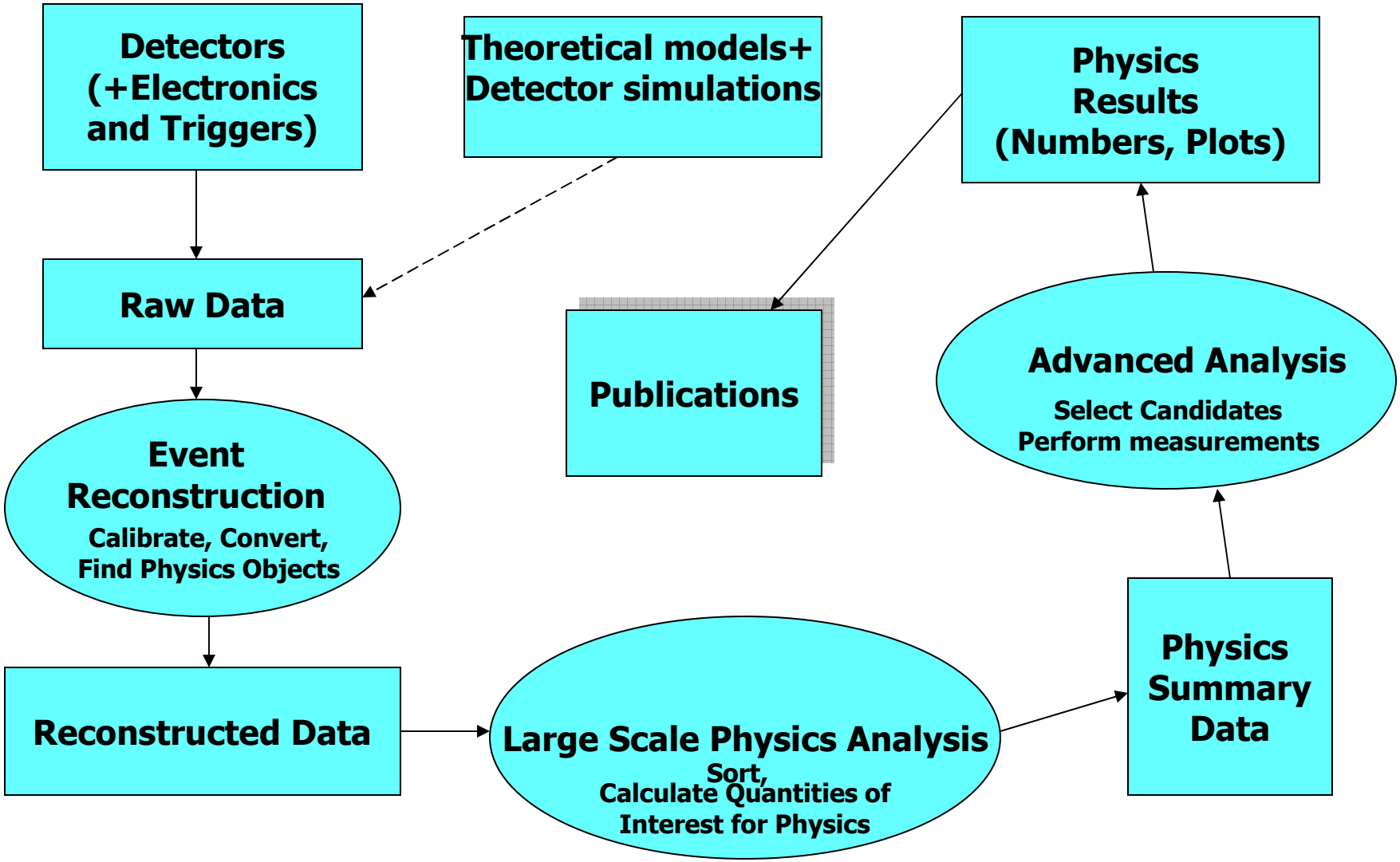
- Select events with final state signature
- Compare kinematics (energy/momenta/angles) of objects in the signal events and background events from models/simulations
- Develop selection strategies to maximize efficiency for signal selection





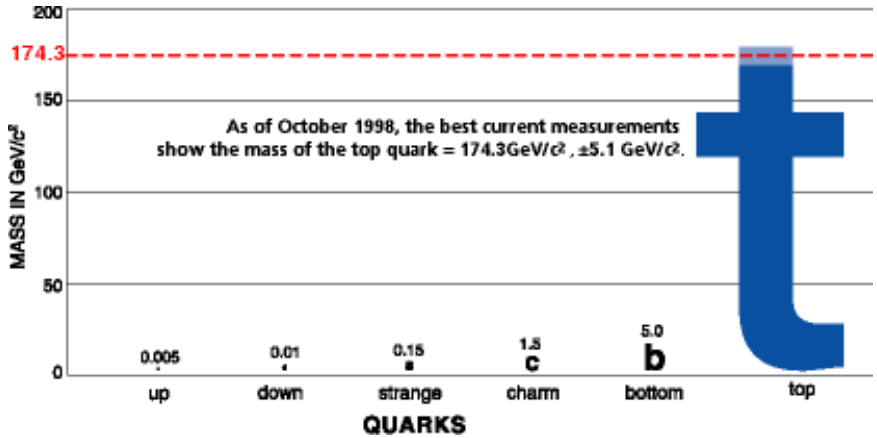
H_T = Sum Transverse energy of all objects

Data Processing in an HEP Experiment



Top as a window on New Physics?

- Why is the top so heavy? ~ 40x that of b-quark
  - It is a mystery!
- The large mass is allowed in the SM but *not required*
  - May have profound implications
  - Constrains the mass of the Higgs boson! Very important!



- In SUSY theories, a heavy top can induce spontaneous electroweak symmetry breaking
- $t\bar{t}$ condensate can act "Higgs-like"
- It is extremely important to measure top production rates, its decays and mass as precisely as possible.

What might CDF and D0 discover?

- Higgs is the most-wanted particle!
  - Study e.g.,WH $\rightarrow e\nu/\mu\nu$ + 2 b-jets, ZH $\rightarrow ee/\mu\mu/\nu\nu$ + 2 b-jets
  - So, final state particles are similar to top events
  - We will need about 15-20 times more data than we now have to find the Higgs if its mass is below 130 GeV
    - **Maybe much lighter than the top quark but its production rate is 10 times smaller!**
- SUSY?
  - Each particle will have a sparticle (or a super-partner)
  - If SUSY exists at the TeV scale, we should see some of those particles soon!
- Other exotics – Leptoquarks, technicolor, evidence for extra-dimensions
- Something completely unexpected!

Luminosity

- Collider Luminosity

Instantaneous Luminosity $L \approx \dfrac{\text{Rev. Freq.} \times Nbunches \times \text{Np} \times \text{N}\overline{\text{p}}}{\text{Trans. Beam Area}}$

Tevatron luminosity > 1x 10^{32} cm^{-2} sec^{-1}

Integrated Luminosity $= \int L dt$ **expressed as inverse picobarns or inverse femtobarns**

1 barn =10^{-24} cm^2 **measure of cross section**

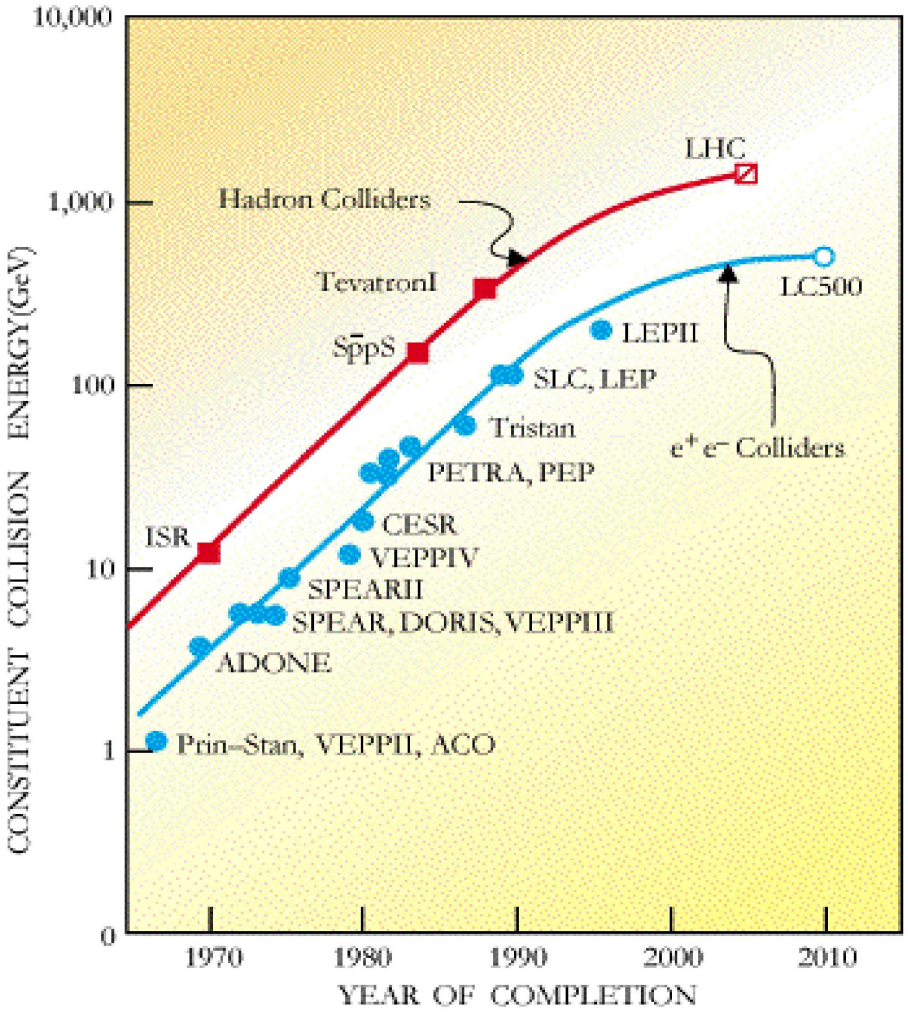
Run 1 Int. Lum ~ 125 pb^{-1}
Run 2, already delivered ~1200 pb^{-1}

- Event Rate

$$N = L \times \sigma$$

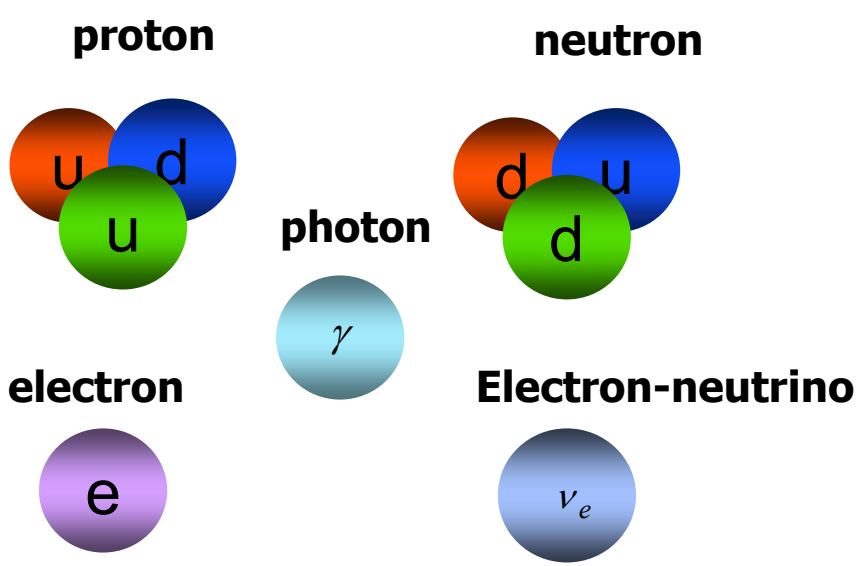
Cross-section σ ← effective area of interaction, cm^2
← probability for a process to occur

Livingston Plot



Pushpa Bhat

- Everything in our world is made up of protons, neutrons and electrons
- Protons and neutrons are made of "up" and "down" quarks
- Ordinary Matter



Matter

Anti-Matter

For every type of particle there exists an antiparticle type

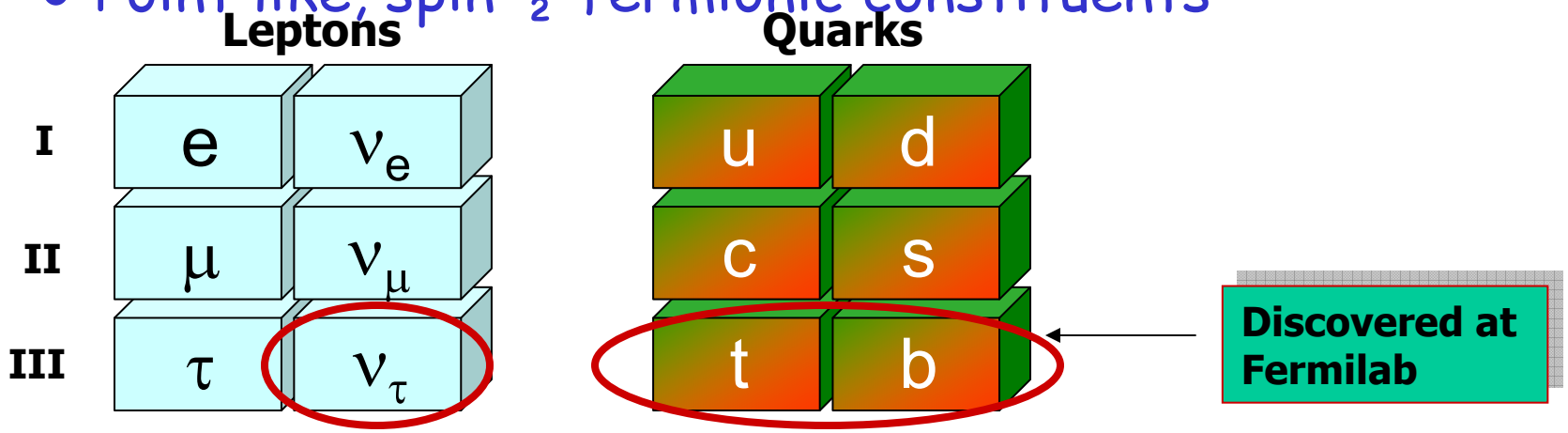
More than necessary

- Even though up and down quarks, the electron and its neutrino were sufficient, we kept finding others
- Muons in cosmic rays, 1937
- "Strange" particles containing "strange" quarks
- The November Revolution, 1974:
  - Charmonium (containing Charm quarks) discovered at Brookhaven and at Stanford Linear Accelerator Center
- The "tau" lepton, 1975
- The "beauty" or "bottom" quark, Fermilab, 1977
- Then, after a long break and heroic efforts worldwide ---
- The "top" quark, 1995, Fermilab
- The "tau neutrino", 2000, Fermilab

The "Standard Model"

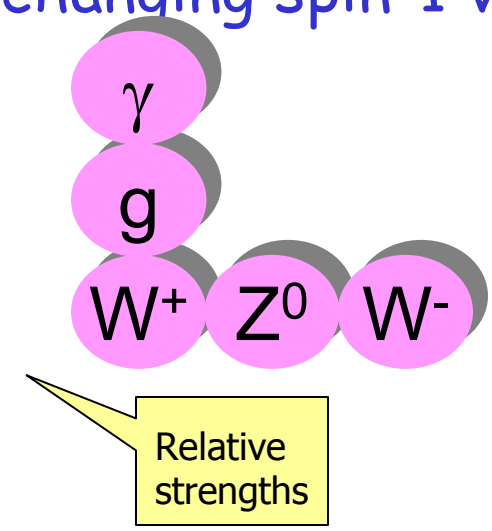
The Prevailing Theory of Matter and Forces

- Point like, spin-$\frac{1}{2}$ fermionic constituents



which interact by exchanging spin-1 vector bosons

Electromagnetic	**10^{-2}**
Strong	**1**
Weak	**10^{-6}**
For Comparison, Gravity	**10^{-40}**



Higgs

Pushpa Bhat

Some Numbers…

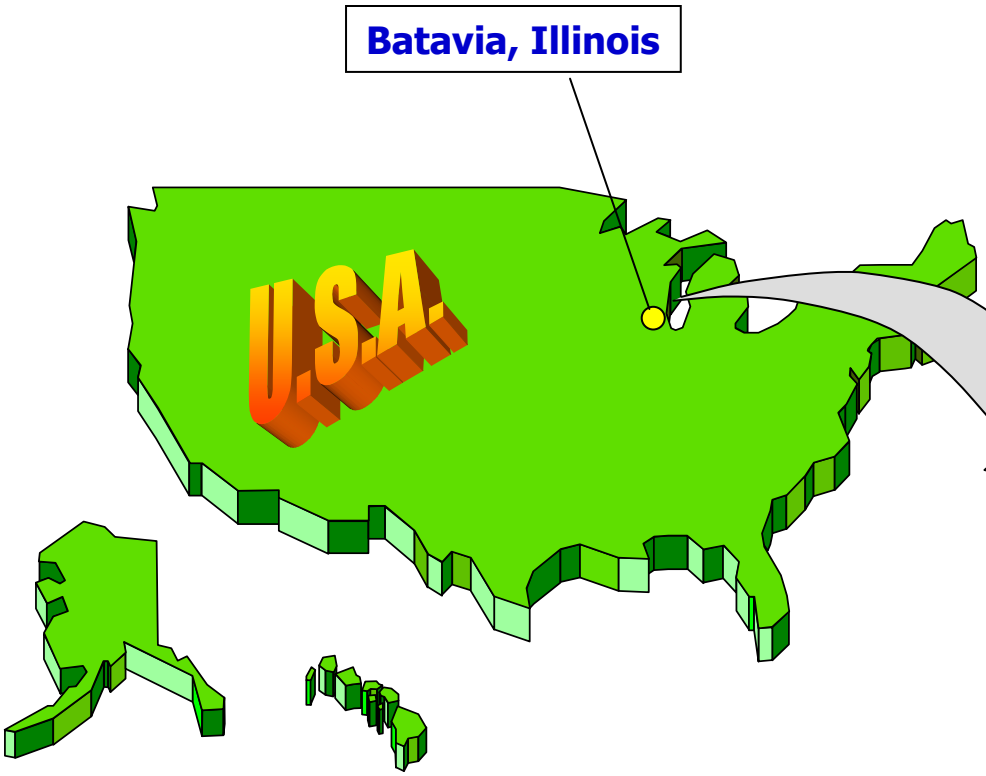
- In the Tevatron we inject 36 bunches each of protons and antiprotons (pbars)
  - $N_{protons} = 2\times10^{11}$, $N_{pbars} = 4\times10^{10}$, in each bunch
  - *Revolution frequency* = $(3\times10^5$ km/sec)/6 km,
  - *Transverse area of beams A* = π (60 μm)^2 = π (0.0060 cm)^2
  - *Luminosity = 36 . f. Nprotons. Npbars /A* → $L = 1 \times 10^{32}$ cm^{-2} sec^{-1}
- Cross section of a proton/antiproton collision

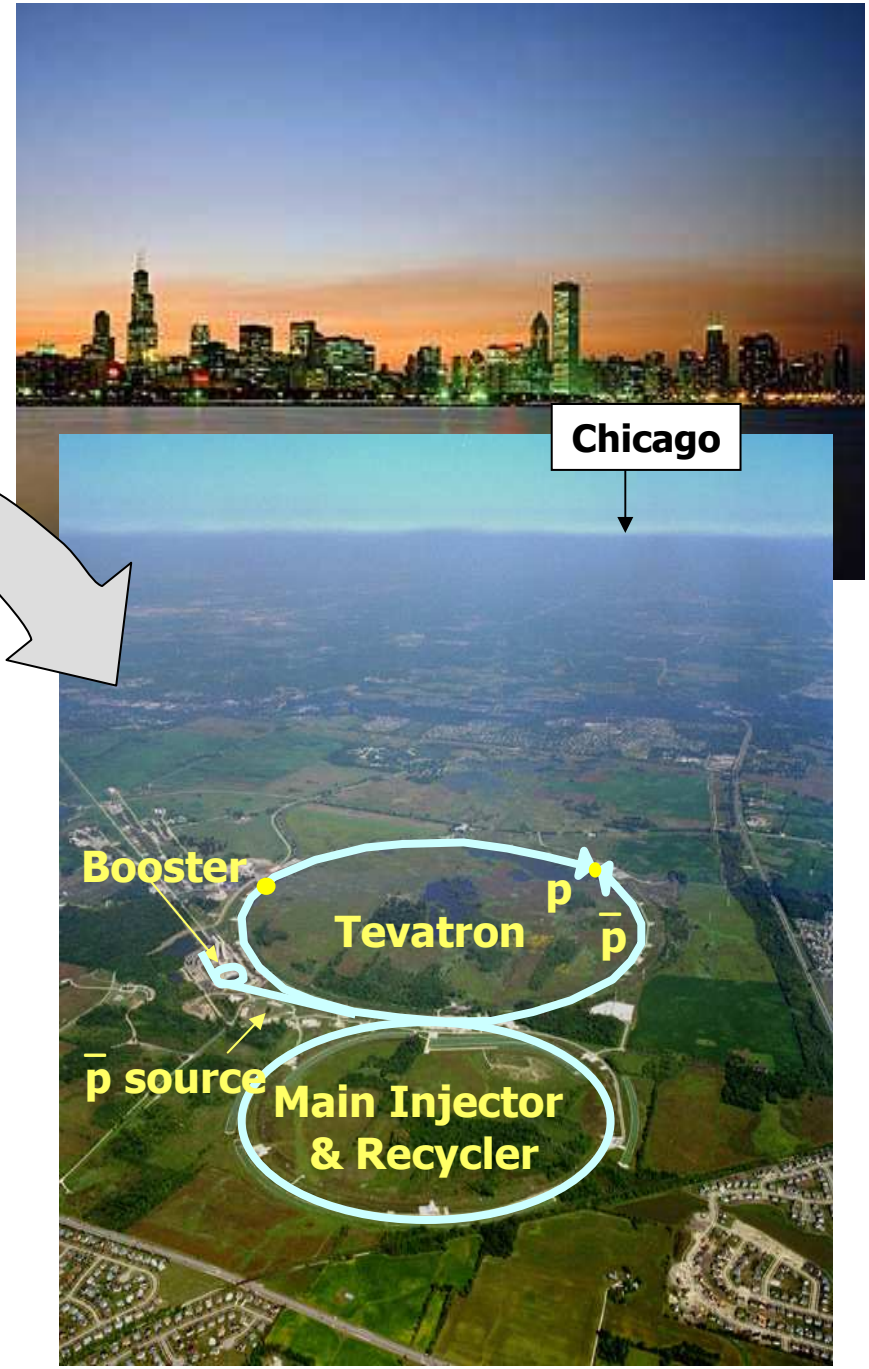
  $\sigma \sim 6 \times 10^{-26}$ cm^2
- Event rate = L. σ
- So, we get about 6×10^6 collisions per second!
  - The Collider detectors must be able to gather, examine, sort, store data at this rate
- Each proton/antiroton has energy of

  980 GeV = $980 \times 10^9 \times (1.6 \times 10^{-19}$ J) = 1.6×10^{-7} J
- So, *power* delivered in the collision region is only about

  $2 \times 1.6 \times 10^{-7}$ J $\times$ 6×10^6 /sec ~ 2 watt!

Where is Fermilab?

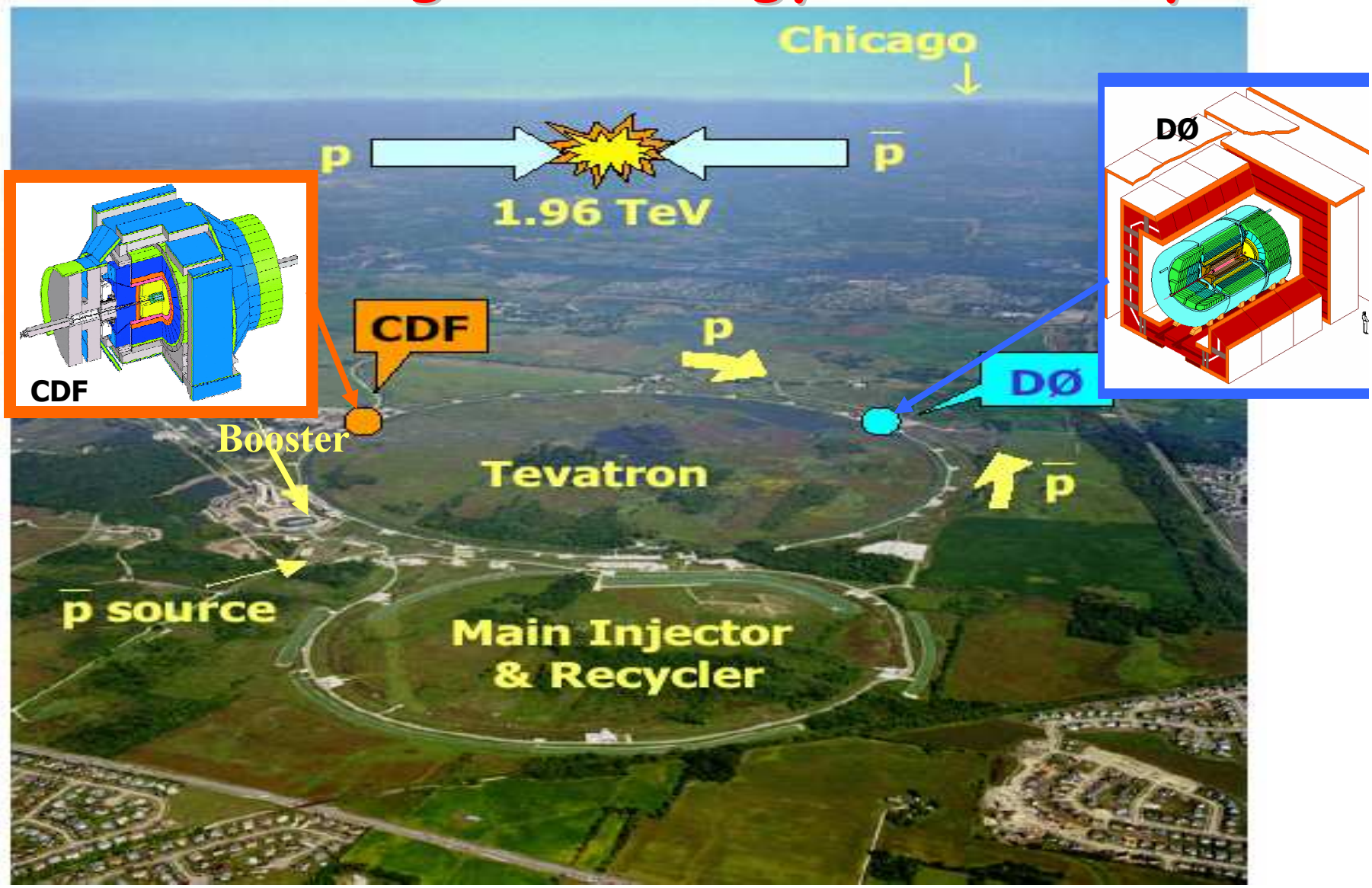
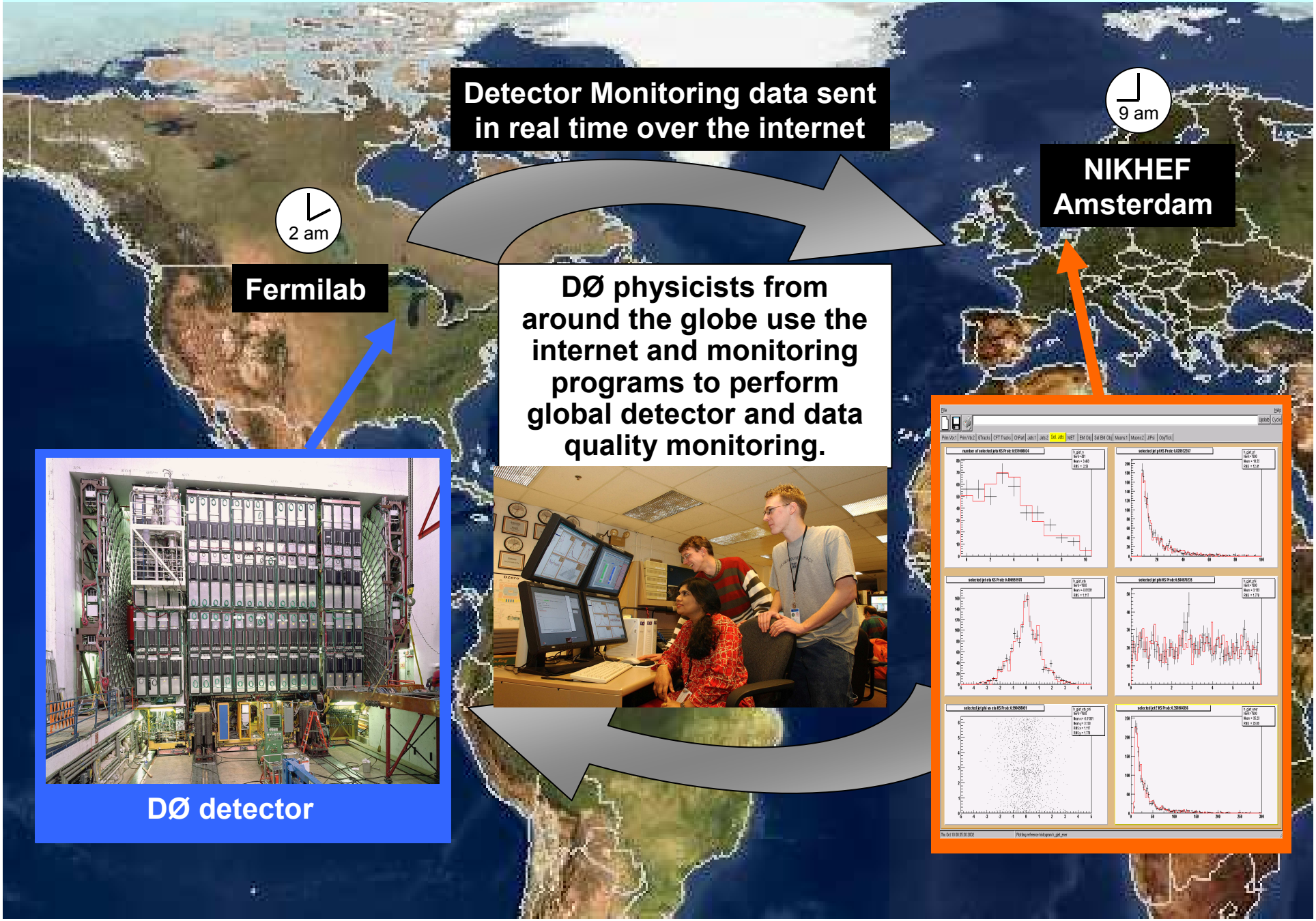




45 miles west of Chicago

Fermilab
BATAVIA, IL

World's Highest Energy Laboratory



Remote International Monitoring for the DØ Experiment