Tevatron Collider Physics

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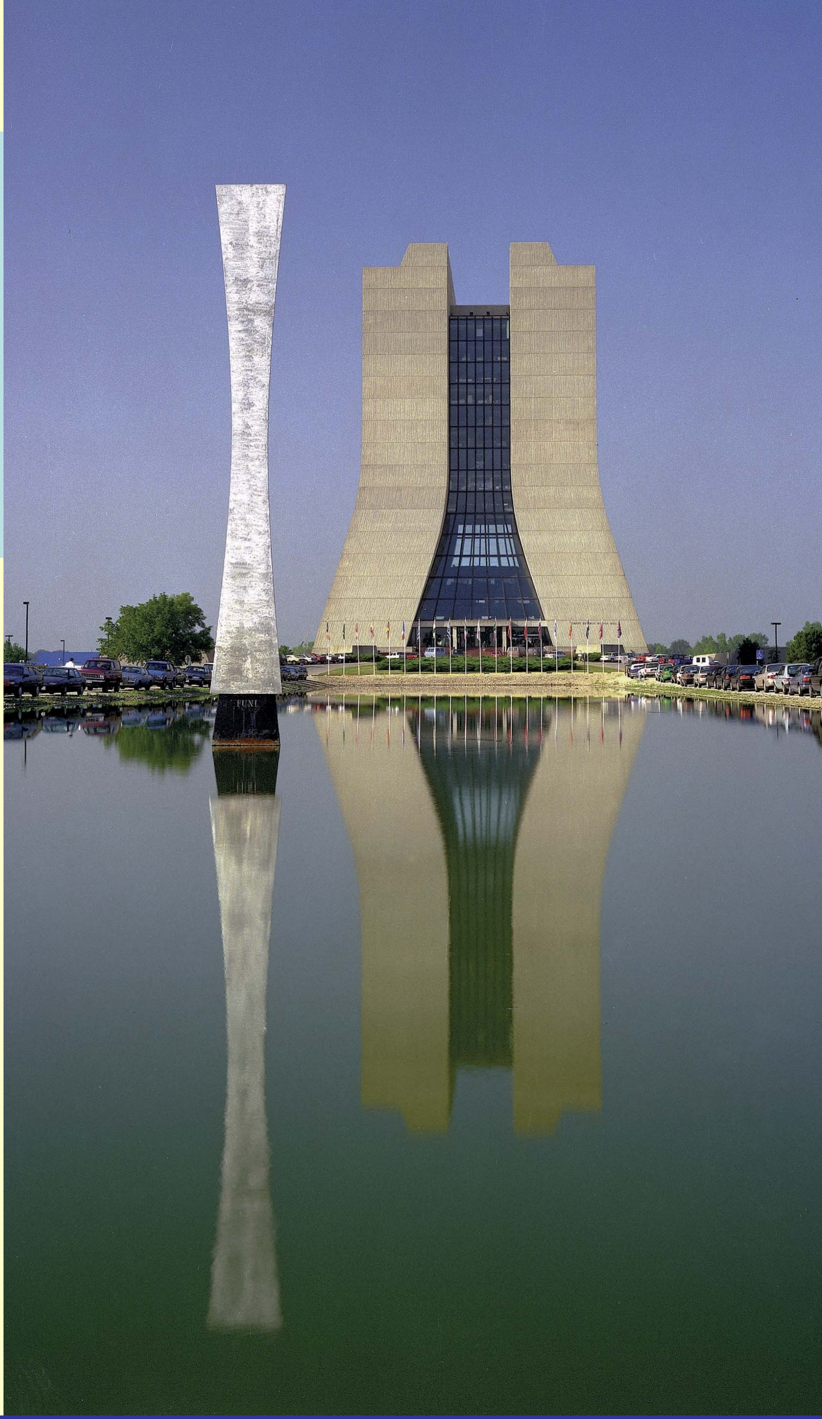
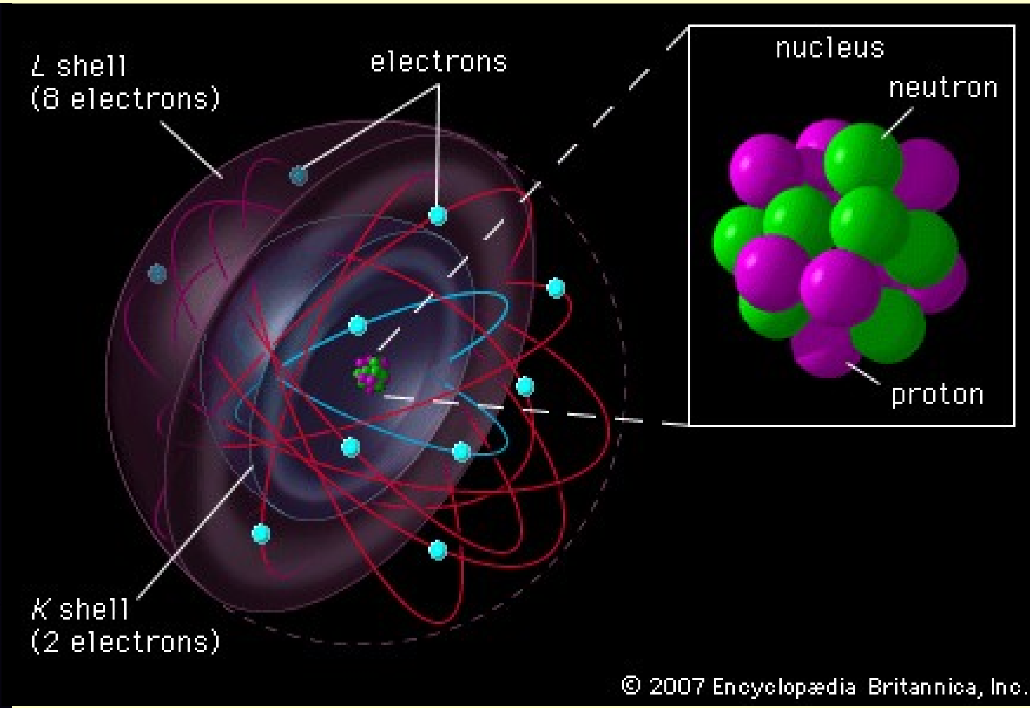
Particle Physics Division



Fundamental Questions

- ✗ Regardless of field, knowledge is driven by asking questions.
  - Curiosity and imagination provide a powerful force for advancement.
- ✗ For a complex problem, there are no simple answers.
  - Each answer introduces new questions.
  - Our goal: identify the important questions and find paths to answers.
  - Inspiration can come from many areas…



Today's Outline

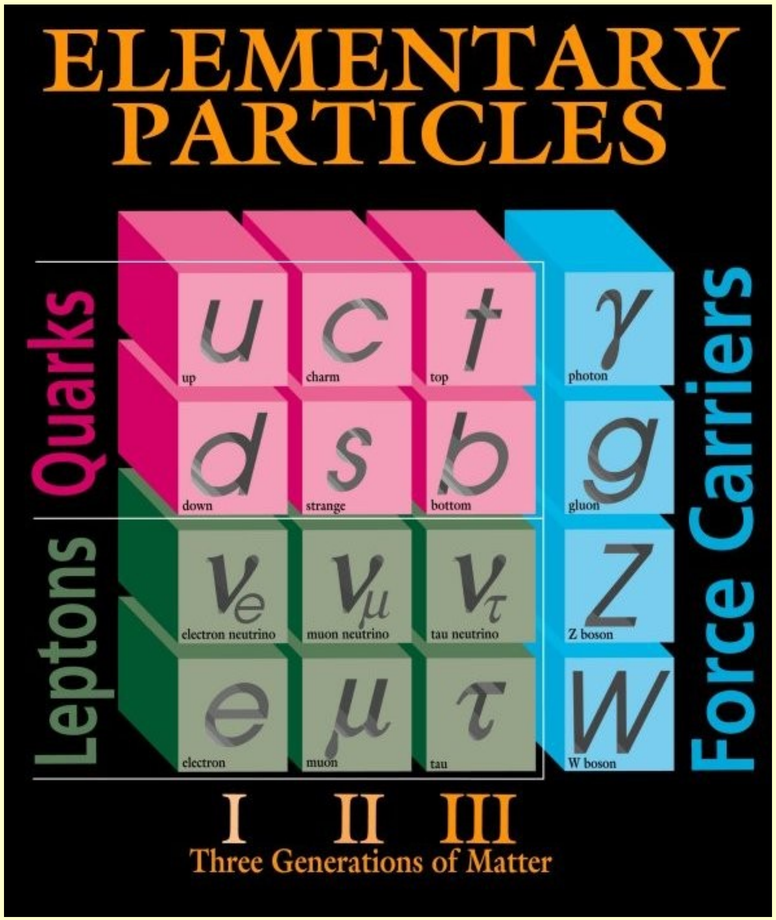
Tevatron Collider Experiments

- The physics motivation for Fermilab's collider experiments
- Creating particles in Tevatron collisions
- Particle masses and decays
- Detecting particles and particle signatures
- From detector to analysis

Physics Analysis Techniques

- Analysis design by example: Z bosons
- Event simulation and measurements
- Searches for new physics
- Multi-variable classification technology

- The two Tevatron collider experiments are designed to study physics in the field of elementary particles
  - Particle physics involves the study of matter, forces carriers, and the interactions amongst these particles



Cast of characters includes

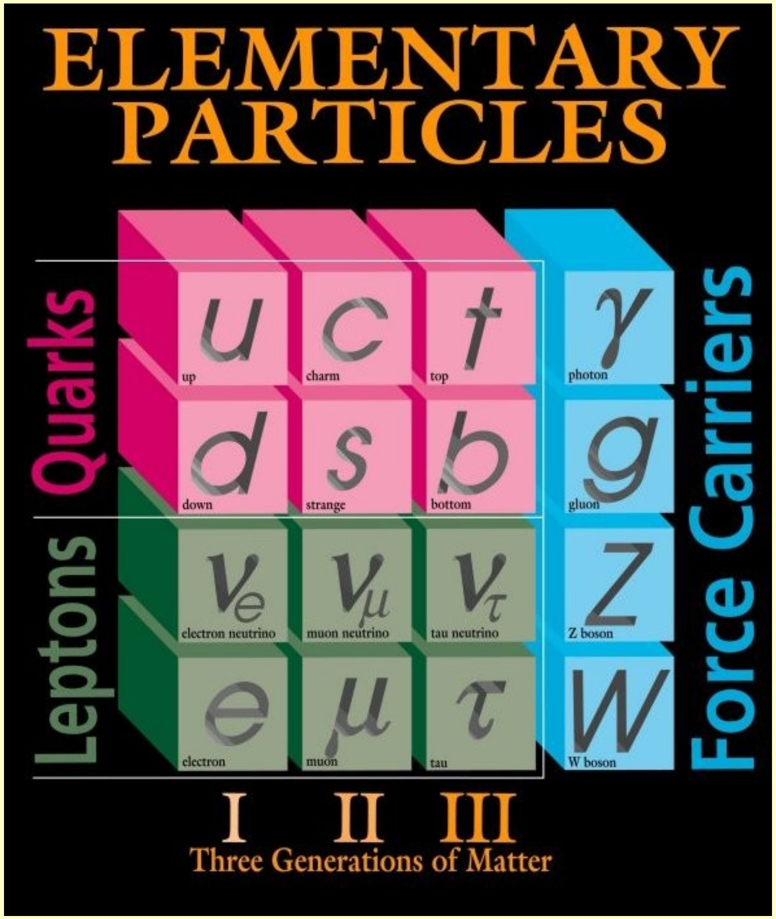
- Matter particles (fermions): quarks and leptons
- Force carriers (bosons): photon, gluon, $W^{\pm}/Z^{0}$

Highly successful predictive model

- *But this is just the tip of the iceberg!! The picture is far from complete.*

Asking Questions

- ✗ Everyone has questions about this field (not just the audience!)
  Consider this simple picture for inspiration



Why only three generations of matter?

Could there be more? How many?

Why only four force carriers?

Are there more forces?

Why are the particles in each generation heavier than the last?

What does mass mean anyway?

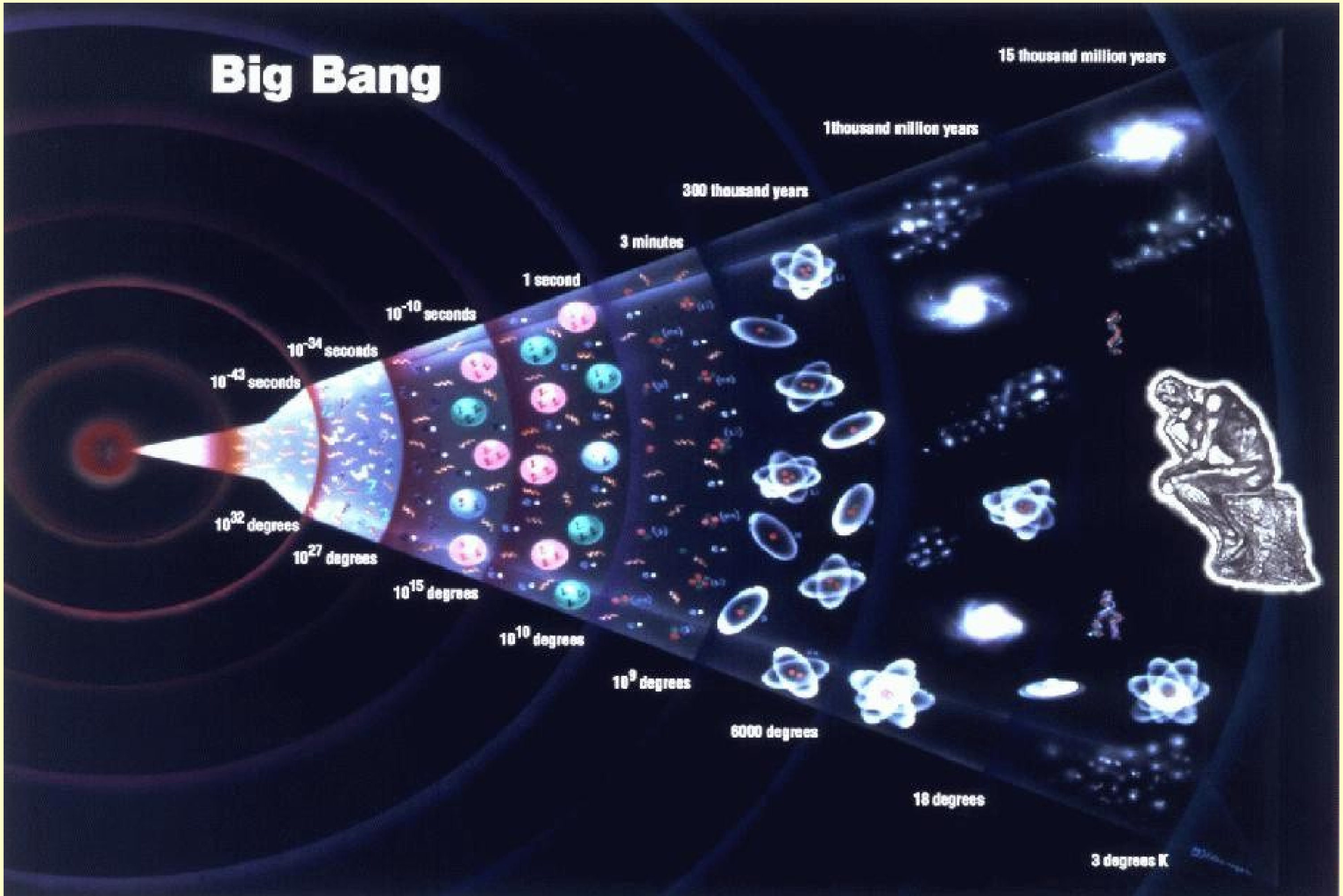
What else could be missing from this tidy picture?

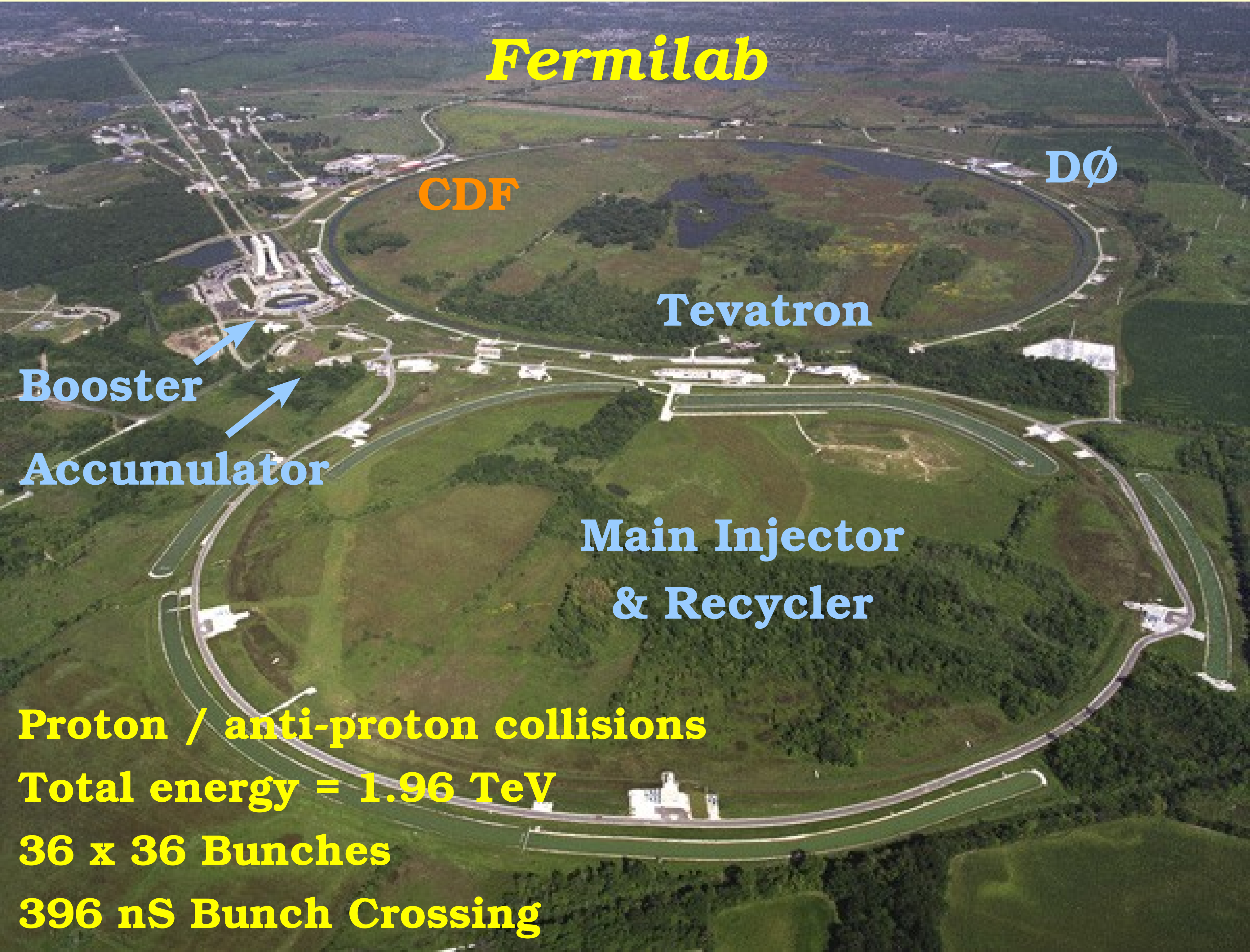
Gravity?

Connecting Some Dots

- After the big bang, the universe expanded and cooled. This allowed fundamental particles to slowly condense to form the structures of our universe.

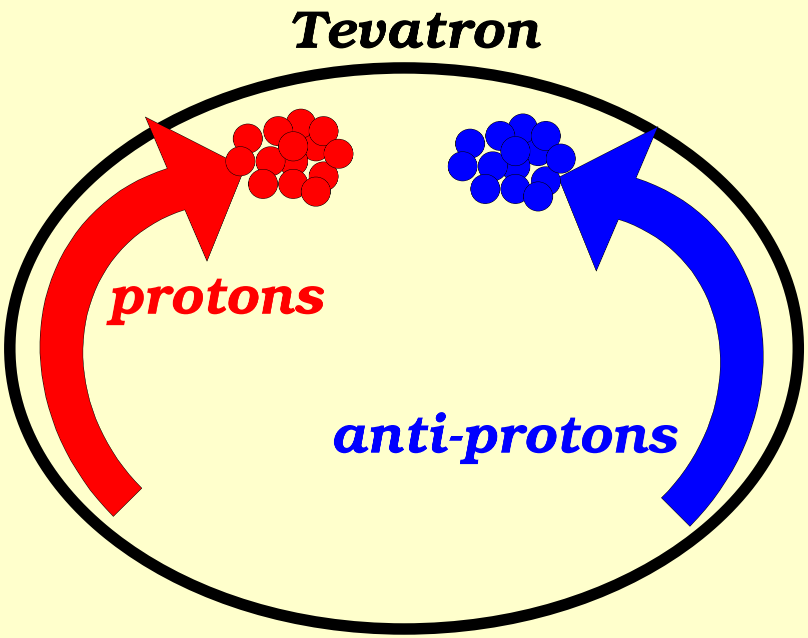
Studying these elementary particles allows us to turn back the clock

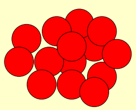


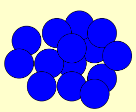

Fermilab
CDF
DØ
Tevatron
Booster
Accumulator
Main Injector
& Recycler
Proton / anti-proton collisions
Total energy = 1.96 TeV
36 x 36 Bunches
396 nS Bunch Crossing

Colliding Particles

- ✗ The Tevatron collides bunches of protons and anti-protons

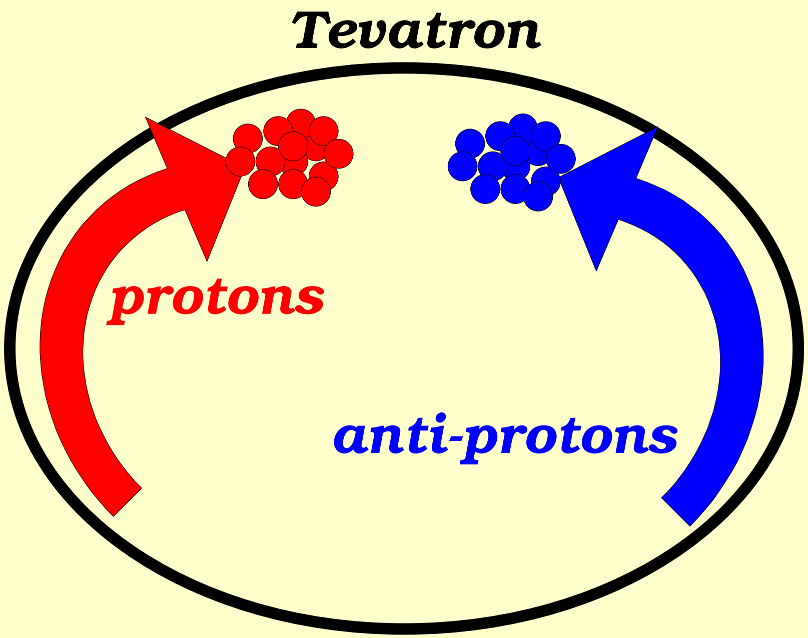


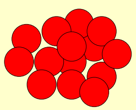
 ~3×10^{11} protons per bunch

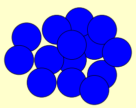
 ~3×10^{10} anti-protons per bunch

Colliding Particles

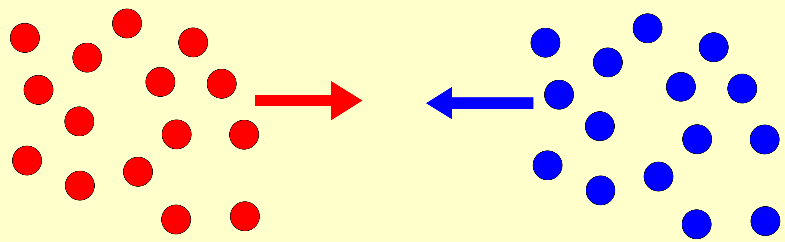
- The Tevatron collides bunches of protons and anti-protons
  - Bunch density is arranged to have one hadron collision per crossing



 ~3×10^{11} protons per bunch

 ~3×10^{10} anti-protons per bunch

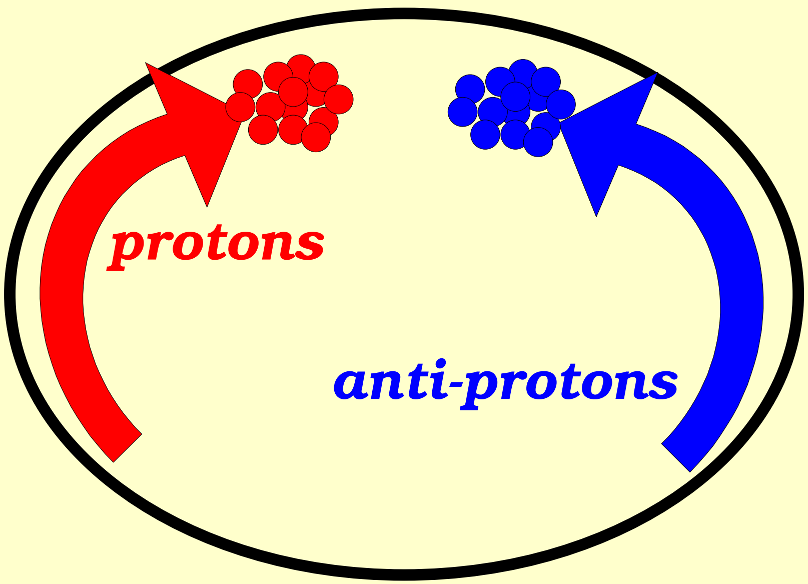
Zoom in a bit…

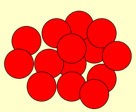


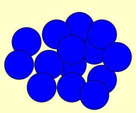
Colliding Particles

- ✗ The Tevatron collides bunches of protons and anti-protons
  - Bunch density is arranged to have one hadron collision per crossing
  - Non-colliding particles continue around the ring for more collisions

Tevatron



 ~3×10^{11} protons per bunch

 ~3×10^{10} anti-protons per bunch

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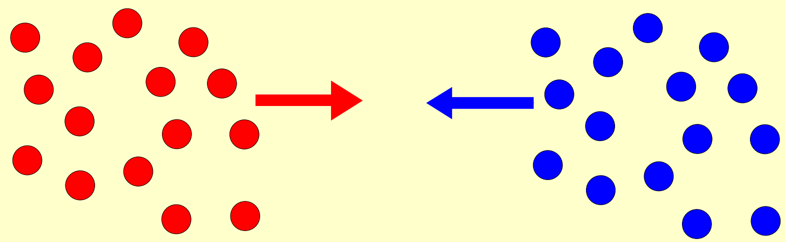
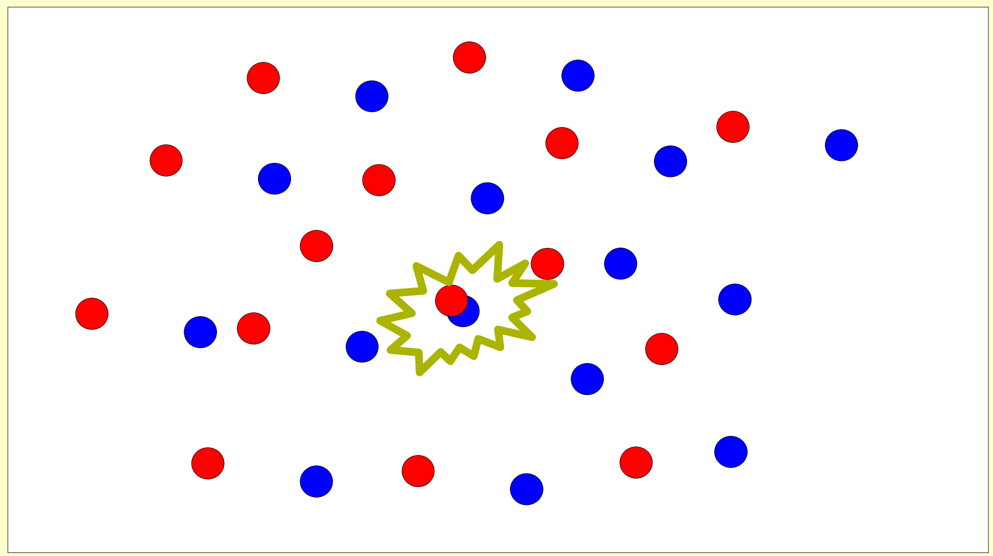
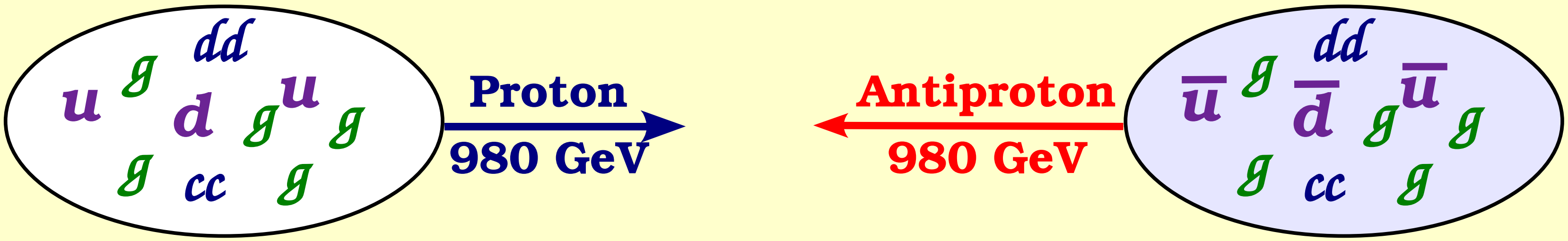


Colliding bunches

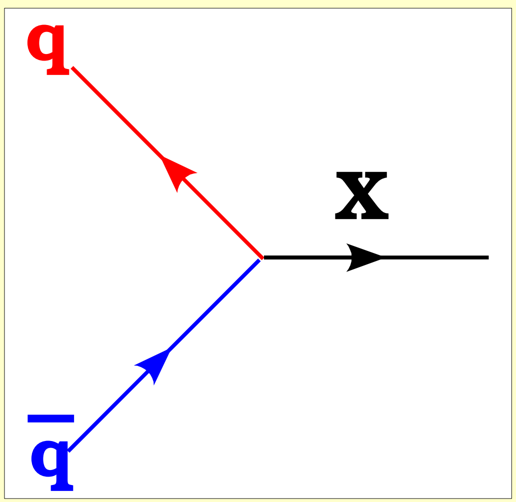


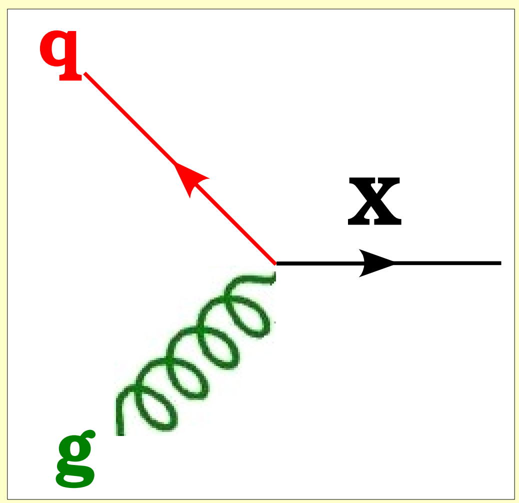
Creating Particles

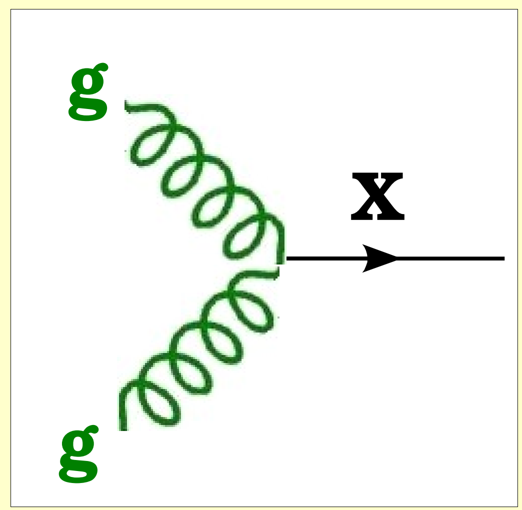
- ✗ Hadrons (protons & anti-protons) don't collide like billiard balls!
  - Quark and gluon sub-structure provides combination of quark-quark, gluon-gluon, quark-gluon collisions



- ✗ We use Feynman diagrams to illustrate particle interactions
  - The resulting particle(s) depends on details of interaction







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- **Particle masses and decays**
- **Detecting particles and particle signatures**
- **From detector to analysis**

Conservation Laws

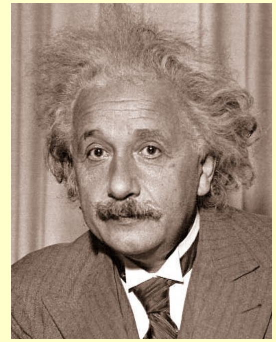
✗ OK, so we've collided *something*, what's next?

Quantum mechanics describes many potential outcomes of each collision, but each interaction must follow simple conservation laws.

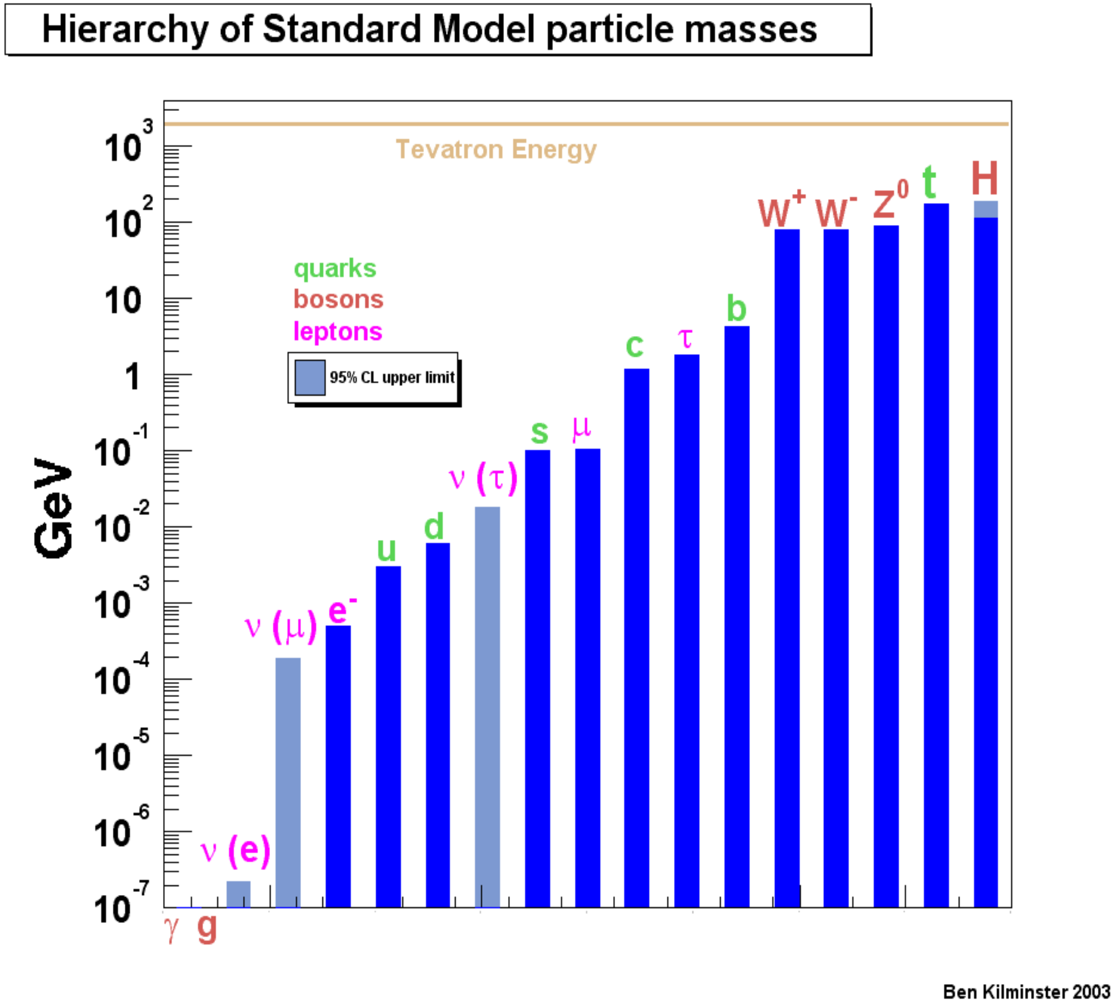
"Top Six" Conservation Laws

1) Conservation of energy: energy in = energy out
2) Conservation of momentum
3) Conservation of angular momentum
4) Conservation of electric charge: must balance total charge
5) Conservation of lepton number: each electron must be accompanied by a positron or electron-neutrino (same goes for muons, taus). The total number is conserved.
6) Conservation of baryon number: baryons are particles made of quarks and their number is conserved.

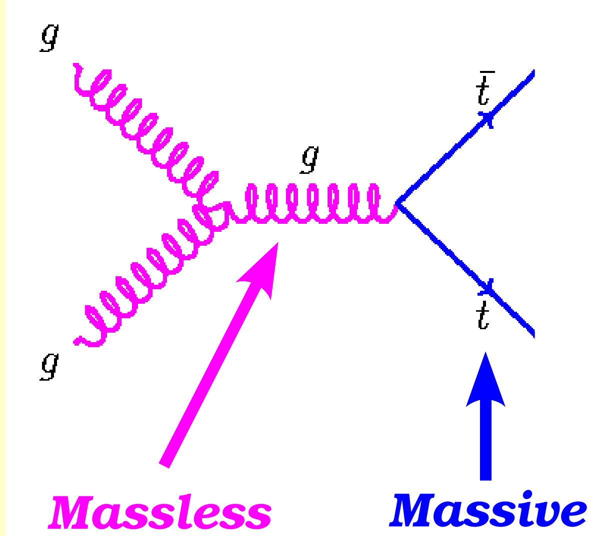
Mass Hierarchy



- ✗ According to Einstein's special theory of relativity, mass and energy are different forms of the same thing.
  - If our particles collide with enough energy, we can produce massive particles!

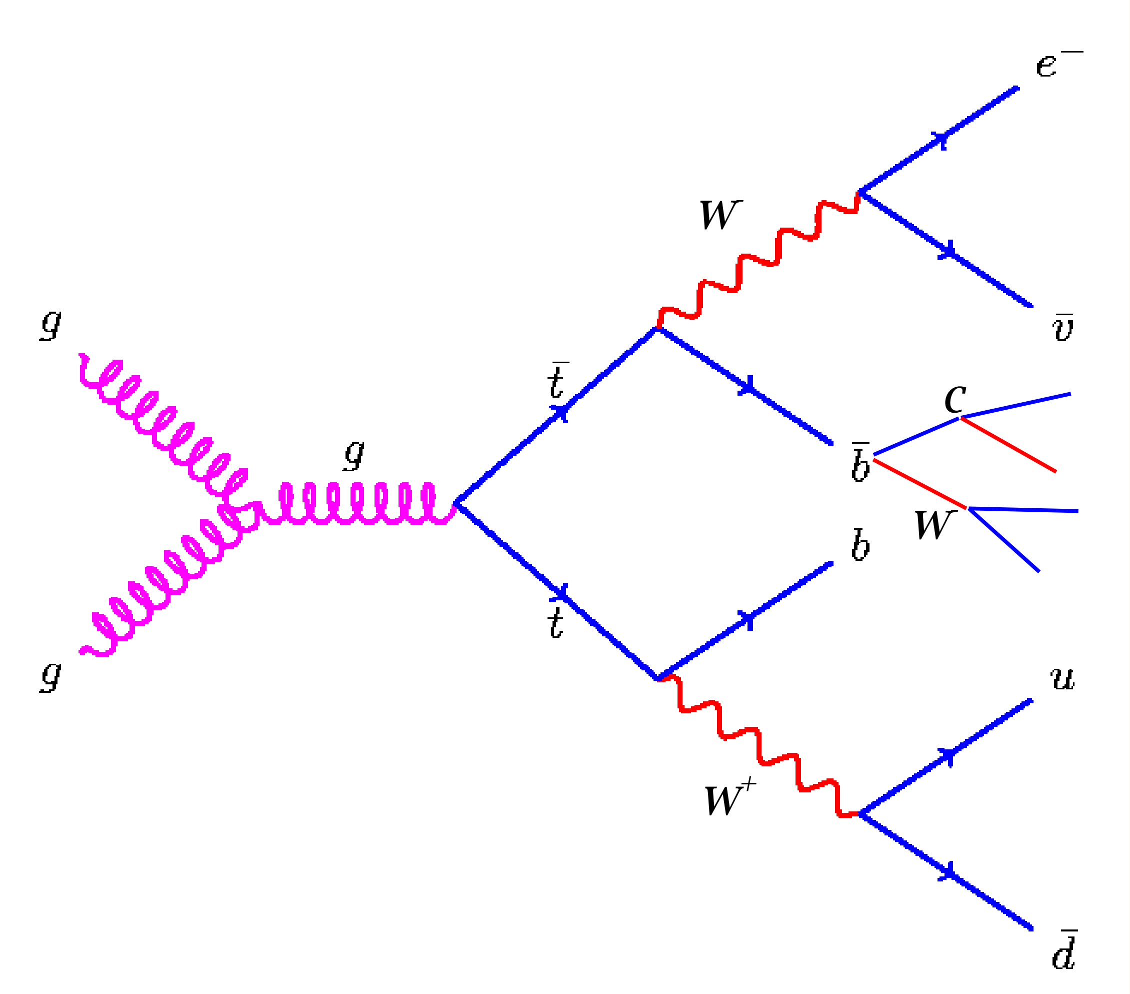


Top Quark Pair Production



Particle Decays

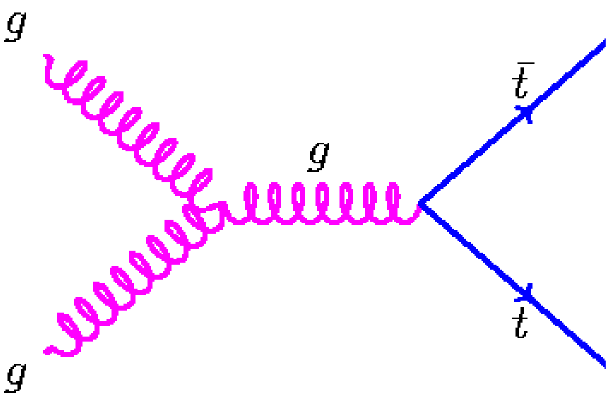
- ✗ Heavy particles can decay to lighter particles
  - Process can continue until it reaches the lightest particles possible while satisfying conservation laws. Example, top quark decay cascades.
  - Particles decay on very short timescales: 10^{-6} s (muon) ⇒ 10^{-25} s (W/Z/top)



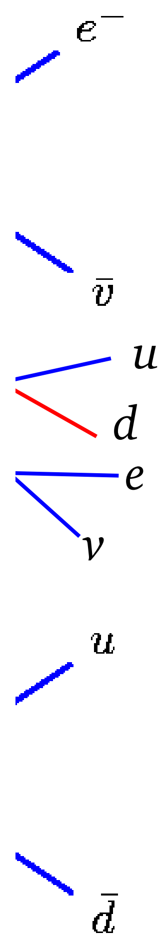
Particle Decay Consequences

- ✗ Particle decays dictate what can be observed
  - Production signature can be very clean and obvious…
  - …but the detector signature can be very complicated!!

Produced by the Tevatron



Observed by the Detectors



Detecting Particles

- ✗ To reconstruct events, we would like to know (amongst other things):
  1) Particle momenta (ie, paths & velocities)
  2) Particle energies (momentum + energy tells us about mass)
  3) Particle charge
  4) An indication of particle type

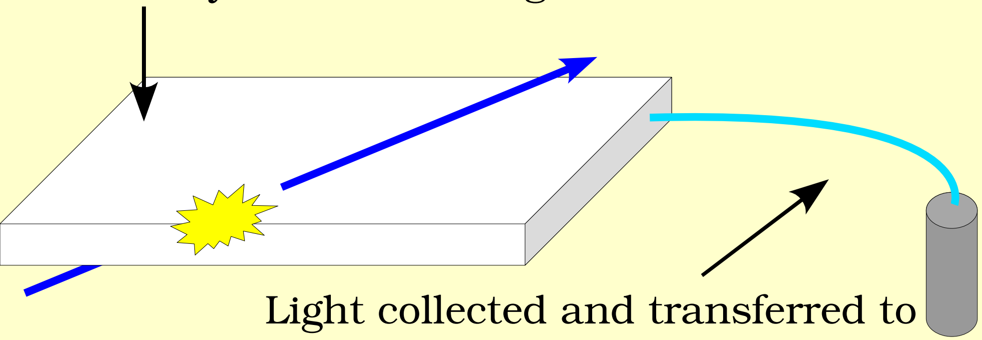
- ✗ To learn these things, we must exploit particle properties to achieve these measurements:
  1) Elementary particles have known electric charges
  2) Only quarks can interact via the strong nuclear force
  3) Neutrinos interact so rarely, we assume they leave no signature

Particle Detection

SIST Lecture
July 1st, 2008

Scintillation light generated by excitation from particle charge

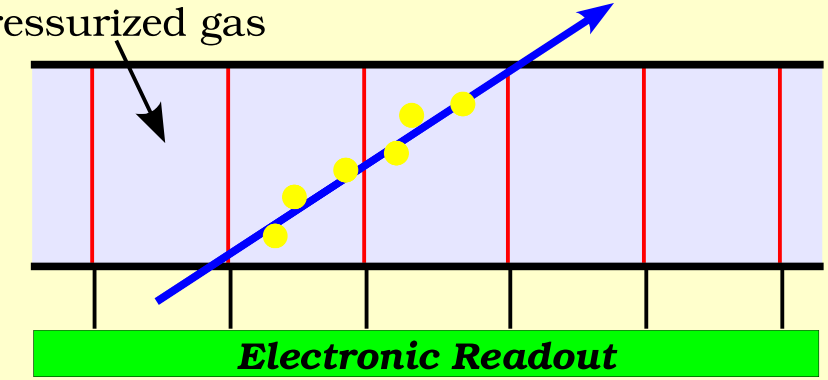
Plastic doped with scintillating molecules
or crystal scintillating material



Light collected and transferred to
photo-detector via fiber optics.

Gas ionization created by passing particle charge

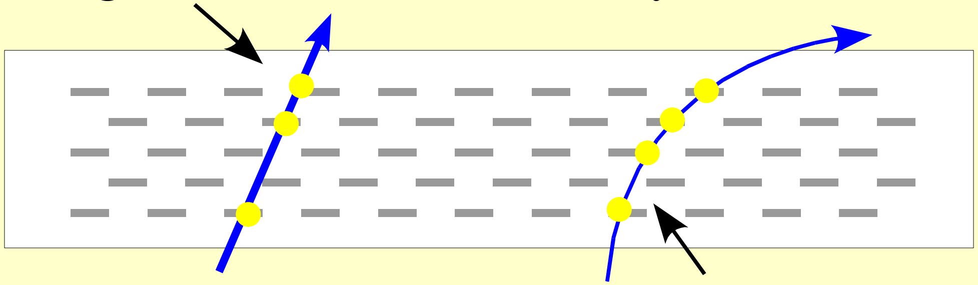
Pressurized gas



Ions are collected on anode wires **(red)**
and signal recorded via electronic readout

Semiconductor ionization created by passing particle charge

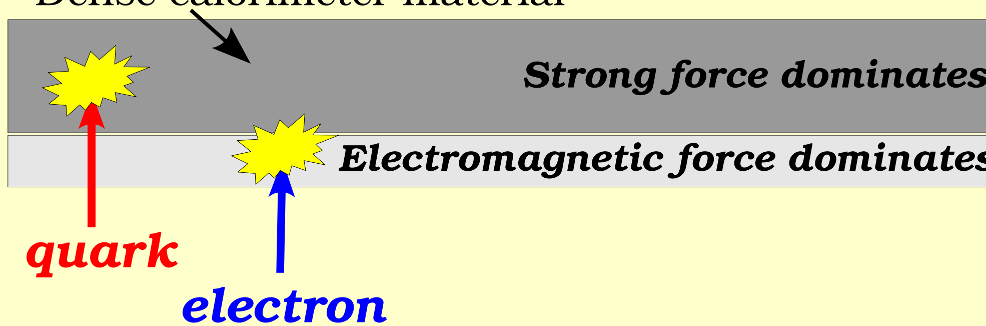
Particles ionize thin silicon layers and this
charge can be collected to identify a “track”



By placing in a solenoidal magnetic field, Lorentz
force on particle measures momentum

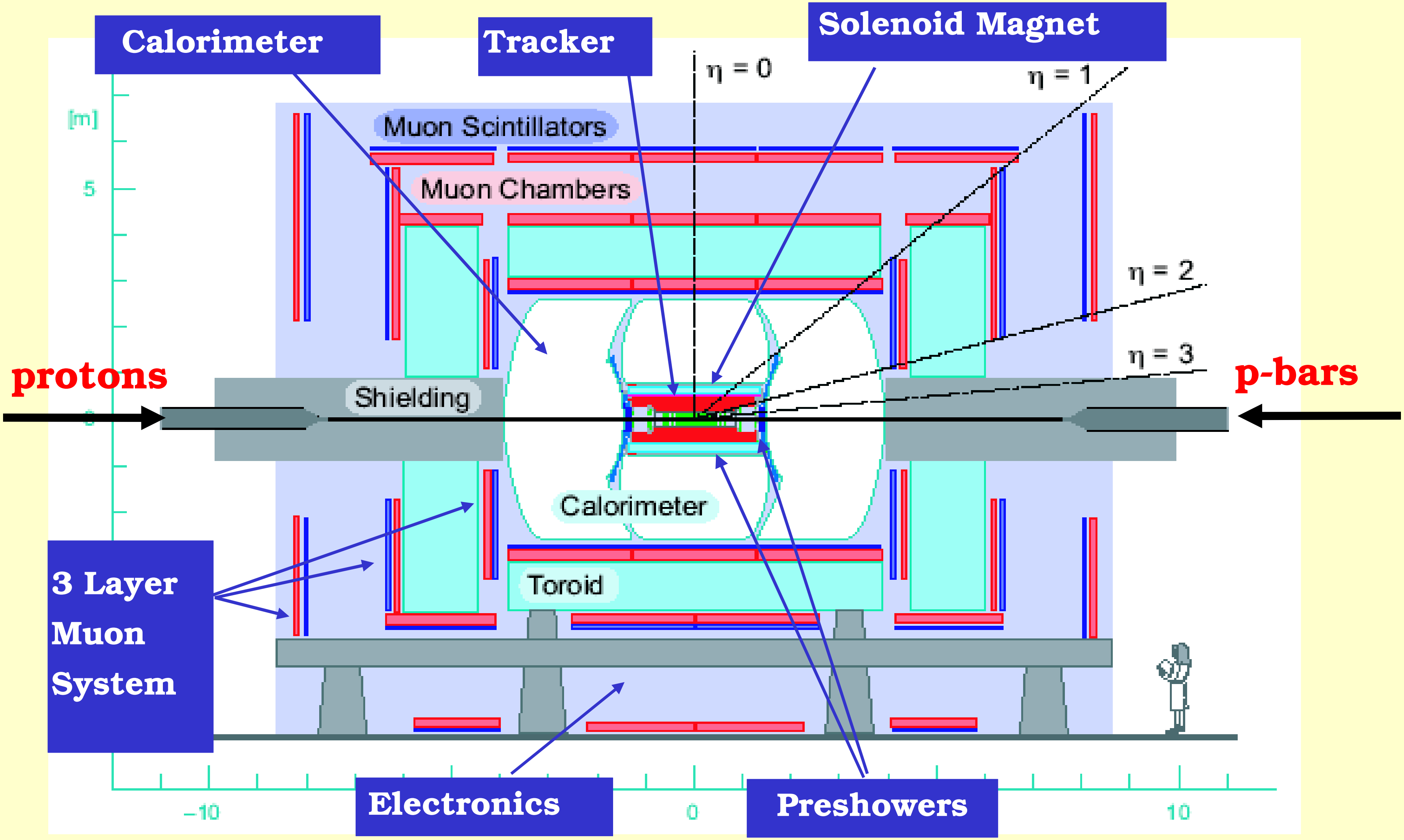
Energy measurement via calorimetry

Dense calorimeter material



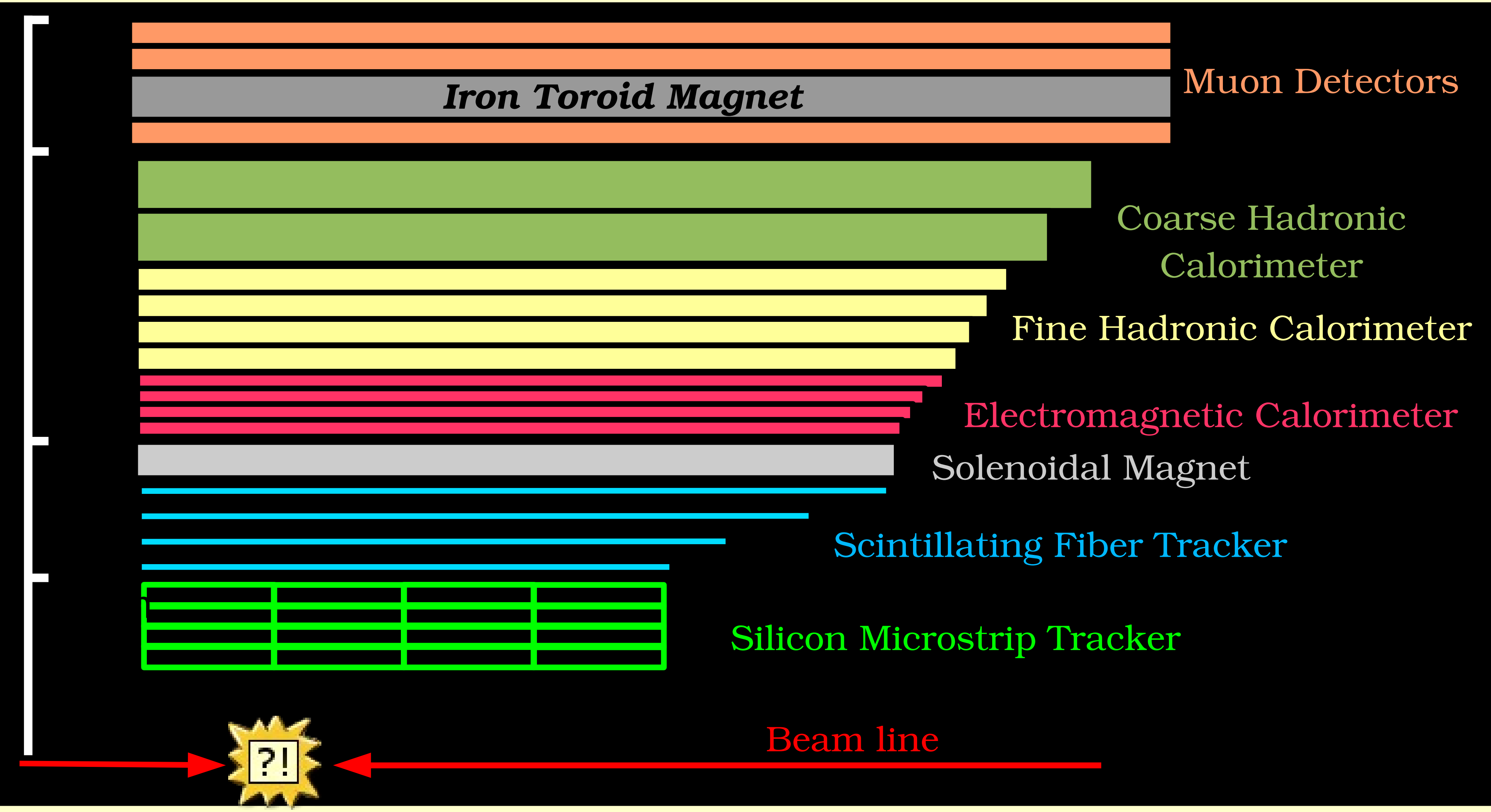
Using dense materials sensitive to
different interactions, stop particles
and measure energy.

The DØ Detector

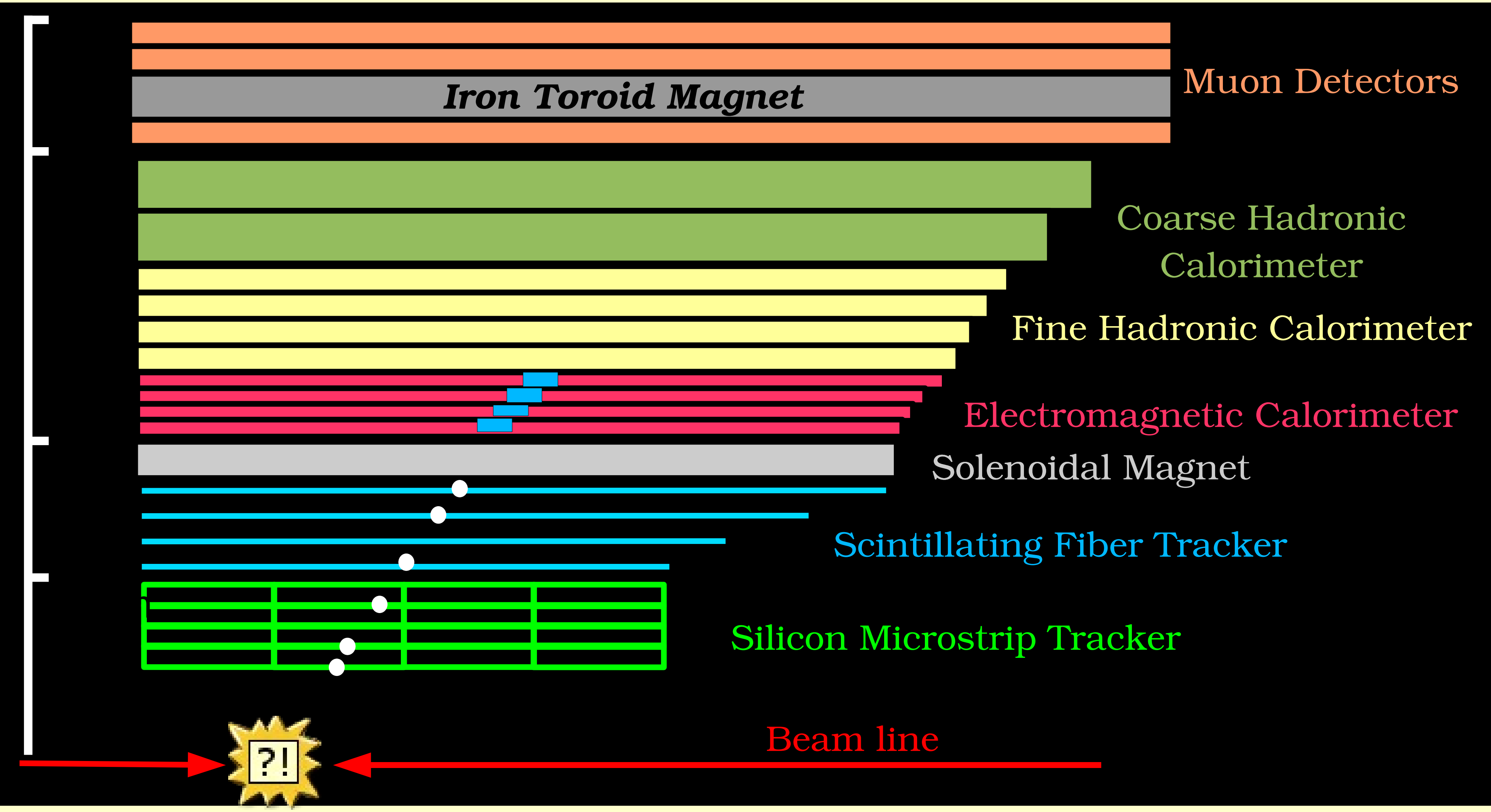


The CDF detector has similar features of detector design

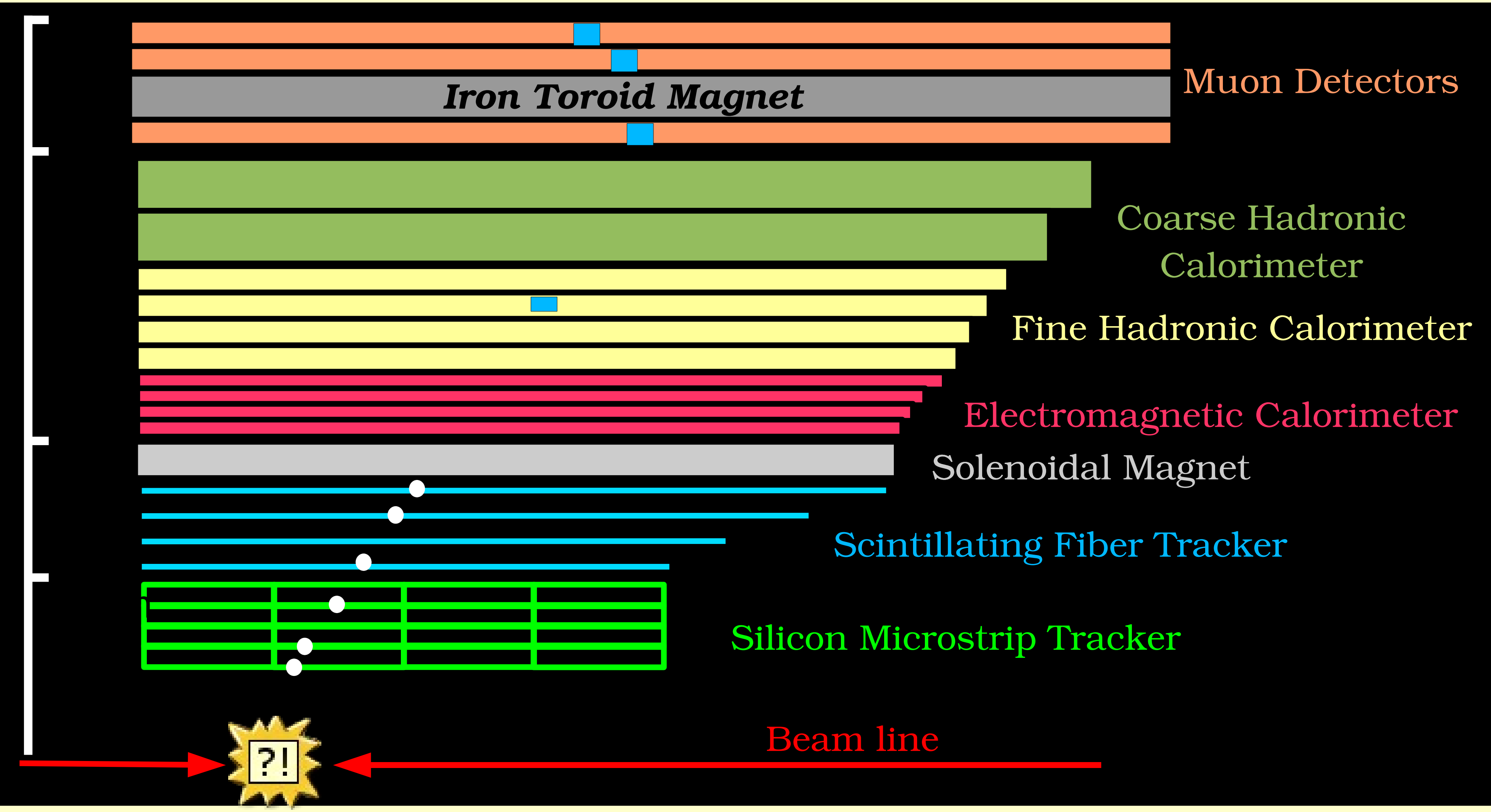
Particle Detection



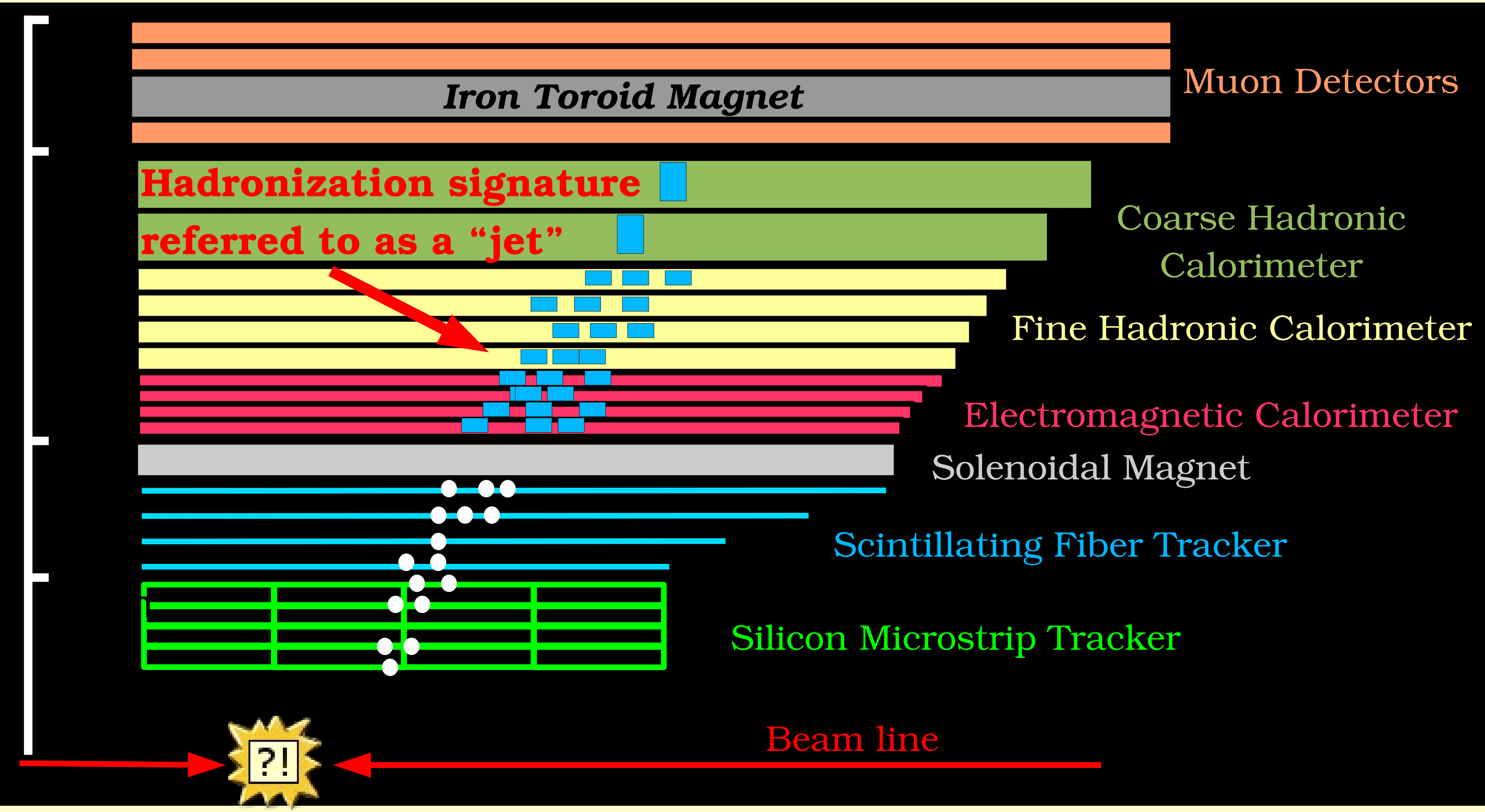
Particle Detection: Electrons



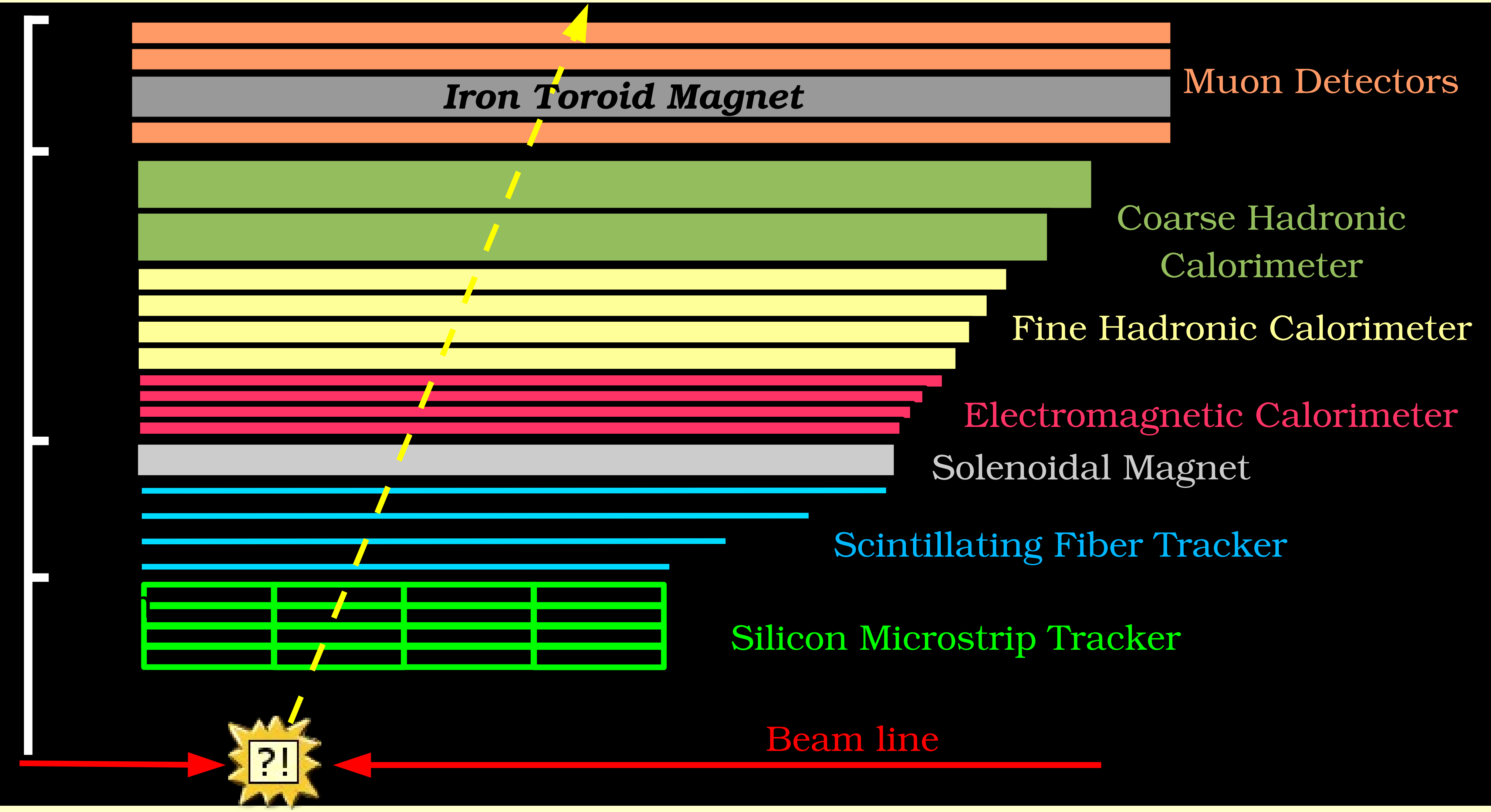
Particle Detection: Muons



Particle Detection: Quarks & Gluons

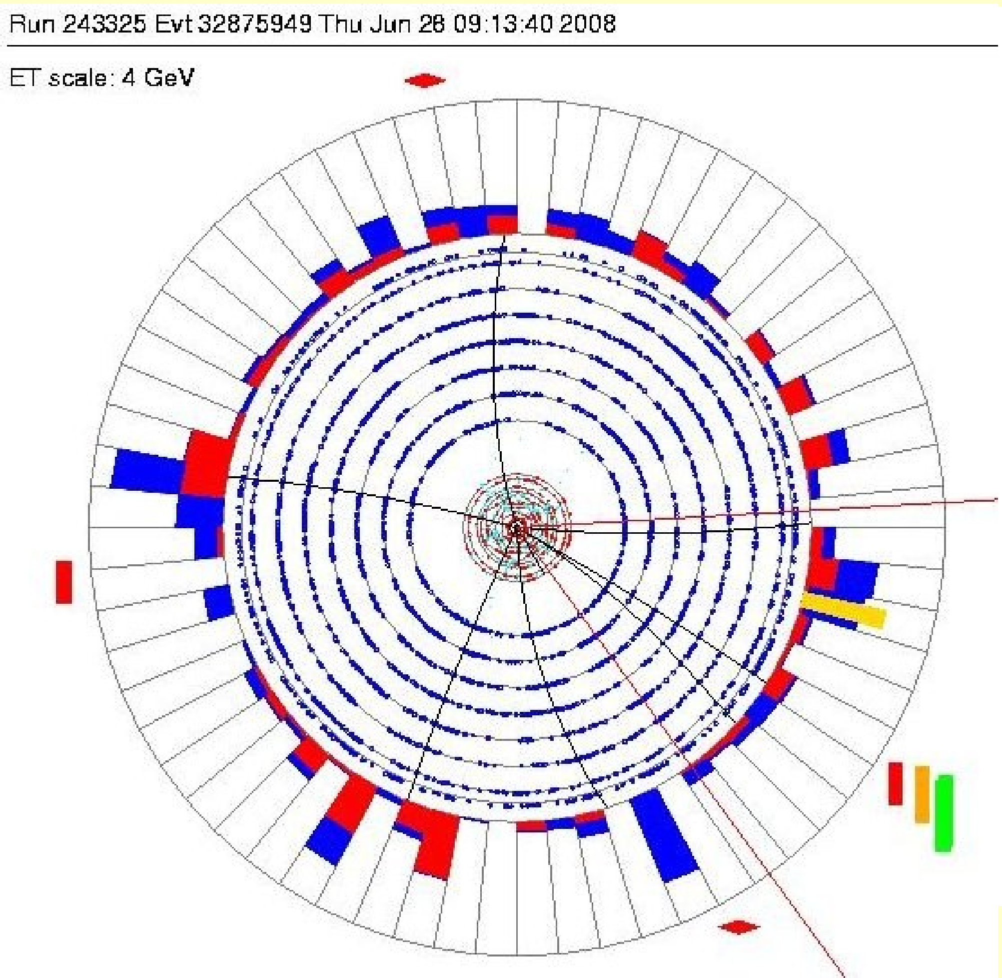


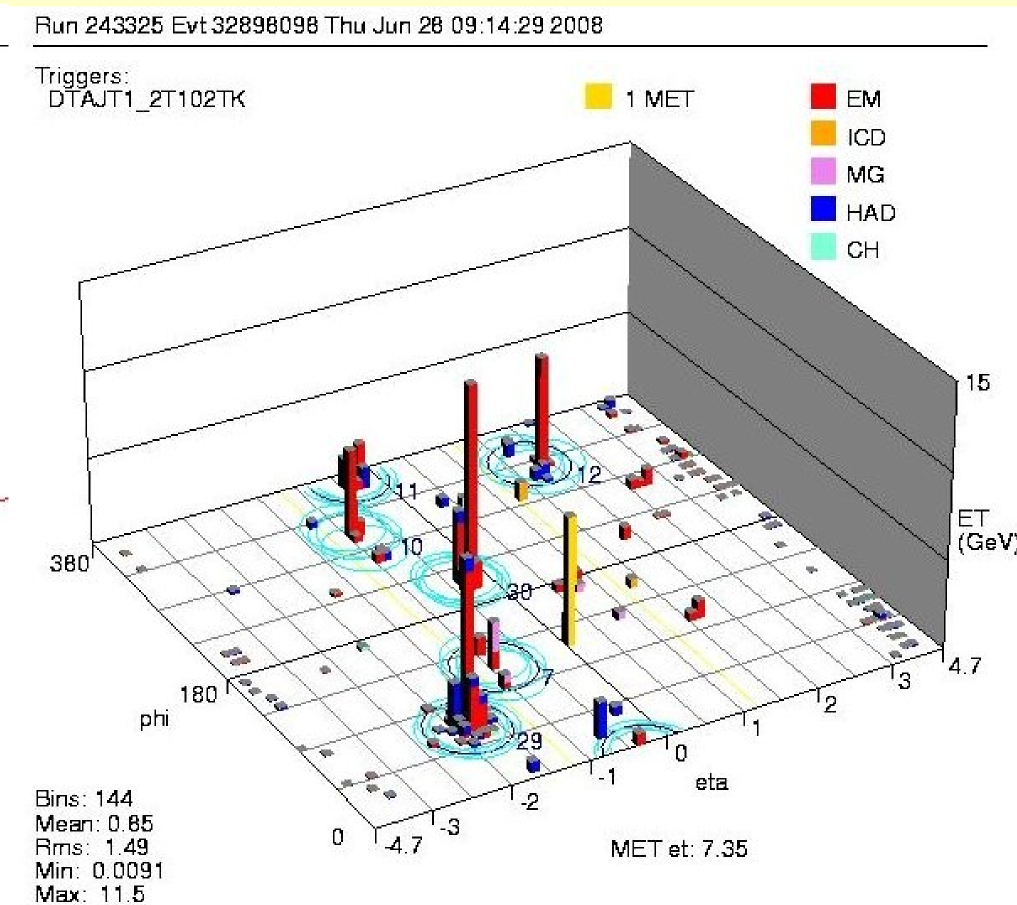
Particle Detection: Neutrinos



Reconstructing Events

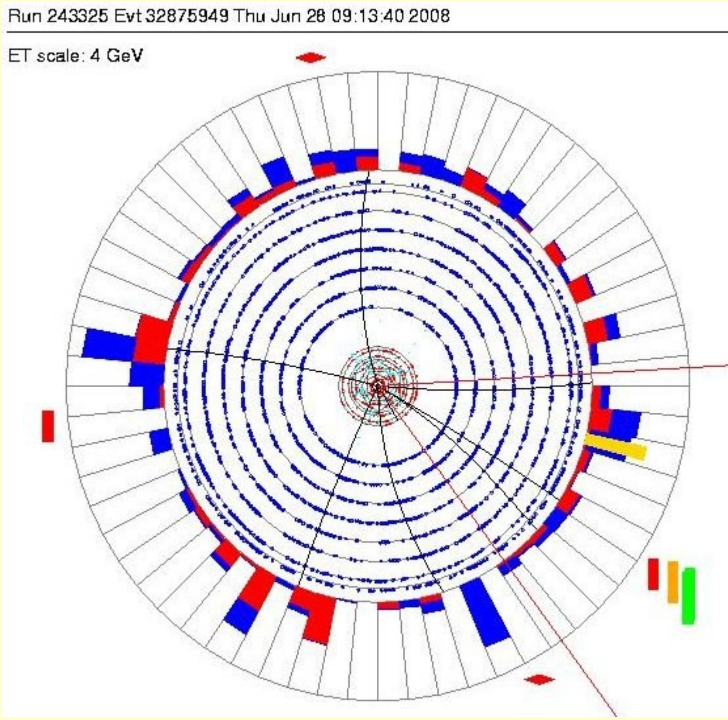
- ✗ Given a single event recorded by the detector, now we must reconstruct what happened! Example from DZero below.
  - Event deciphered by grouping tracks, calorimeter energy, & muon signatures into individual particles.





Reconstructing Events (II)

- Once you've identified your particles, you can start reconstructing your events. The logic returns to our conservation rules.
  1) Total momentum and energy in the event is conserved. Due to the nature of hadron collisions, momentum along the beamline is not zero. But transverse to the beamline it is to a good approximation. ***"Missing" energy and momentum is a common signature of neutrinos!***
  2) Particle charges and momenta are determined by track curvature in the solenoid magnet. ***Conservation of charge helps determine which particles belong with others.***
  3) Massive particles have an energy-momentum relationship indicative of the particle mass. ***Particle mass is an essential identifier.***



Collecting Data

- ✗ The Tevatron delivers one bunch crossing every 396 ns
  - That gives ~2M possible interesting interactions every second ☺
  - ...but there's no possible way to record all that data ☹
- ✗ The solution is known as a readout triggering system
  - Events that satisfy a pre-determined threshold of "interestingness" trigger the detector readout system to keep that event.
- ✗ An example from the DZero experiment:
  - **Level 1 trigger:** Look for large calorimeter energy depositions and muons. Resulting output rate ~2kHz.
  - **Level 2 trigger:** Combine info from trackers, calorimeter, muon system to find roughly ID'd physics objects. Ouput rate ~1kHz.
  - **Level 3 trigger:** Using all possible information, fully reconstruct events and find interesting signatures. Output rate ~100Hz
- ✗ The output of DZero's L3 trigger is written to tape for later analysis.
  - Each event is ~200 kilobytes ⇒ rate to tape ~20 gigabytes / second

Collected Data

- We measure the particles delivered by the Tevatron in units of ***Luminosity***, a measure of the total flux of particles

  The ***instantaneous*** luminosity (ie, what's colliding right NOW) is measured in particles per unit area per unit time, eg. 10^{30} cm^{-2} s^{-1}

<u>*Classically:*</u>

Rate = beam density × beam velocity × beam size

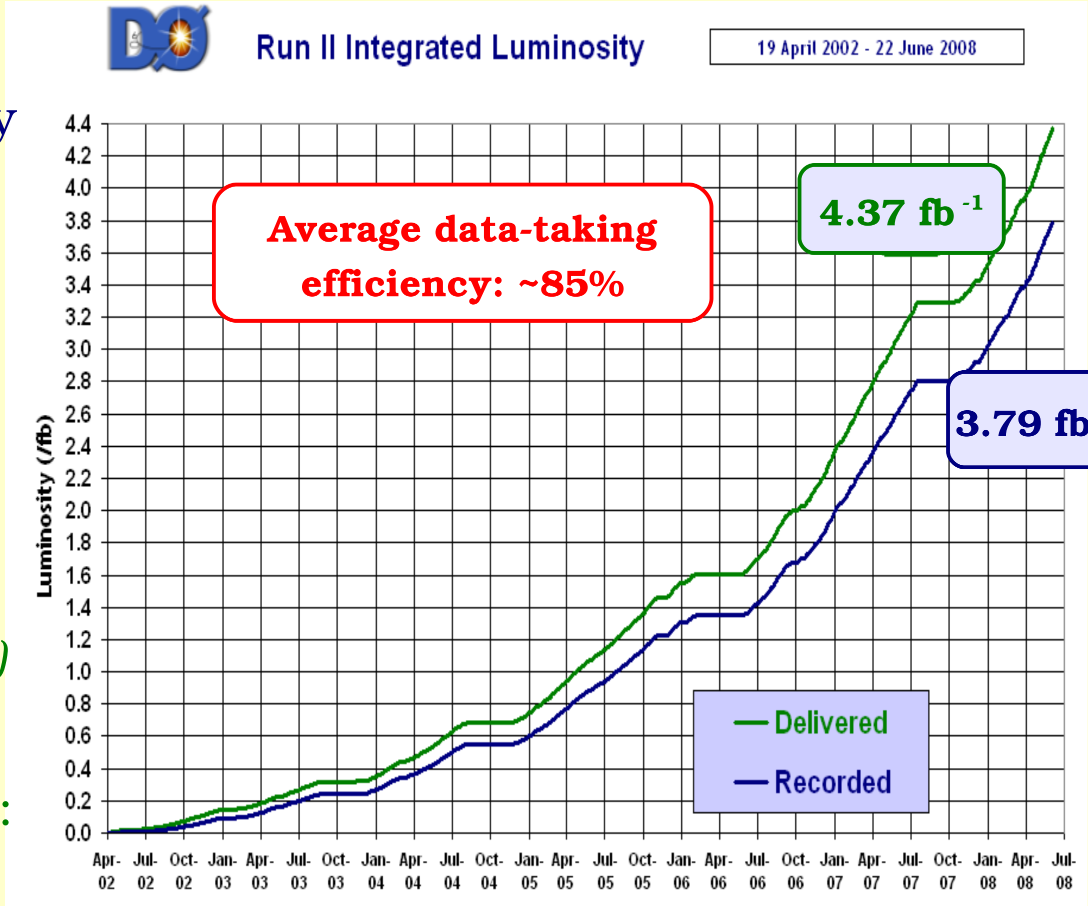
($s^{-1} = m^{-3} \times m/s \times m^2$)

<u>*Particle Colliders:*</u>

Rate = inst lumi × cross section

Cross sections reported in units of barns (!?): 1 barn = 10^{-28} m^2
(roughly the size of a gold nucleus)

Luminosity integrated over time reported in units of inverse barns:
1 fb^{-1} = 10^3 pb^{-1} = 10^{15} b^{-1}



Some Units

Integrated luminosity is given in units of **inverse barns**: 1 $fb^{-1} = 10^3\ pb^{-1} = 10^{15}\ b^{-1}$

The quantum mechanical probability (*cross section*) for a proton/anti-proton collision to produce a particular final state is measured in **barns**

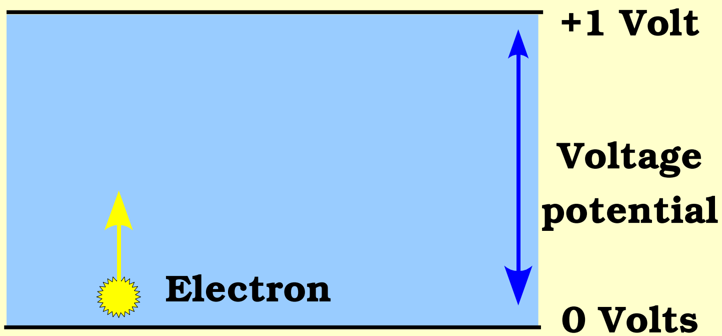
Thus, the total number of events for a given process is determined by how much data you've collected: **# events = integrated luminosity × cross section**

Einstein's special theory of relativity equates energy and mass

$$E^2 = (mc^2)^2 + (\vec{p}c)^2$$

E=energy, **m** = mass, **c** = speed of light, **p** = momentum vector

We adopt units in which **c = 1.0** and energies are measured in electron volts (eV)



An electron accelerated through one volt of electric potential will gain an energy of 1 eV.

At Tevatron scales, we interact with particles on the GeV scale: 1 GeV = 10^{12} eV

Example: *Z* boson mass = 91.2 GeV/c^2

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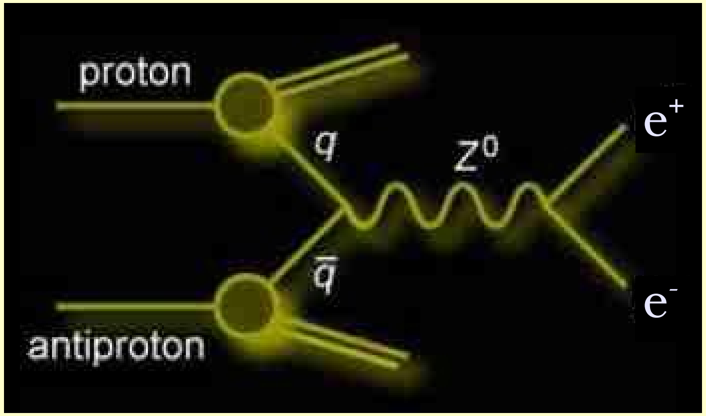
Physics Analysis Techniques

- **Analysis design by example: Z bosons**
- **Event simulation and measurements**
- Searches for new physics
- Multi-variable classification techniques

Example Analysis: Z bosons

- ✗ As an example, let's design an analysis to find the cross section for producing Z bosons at the Tevatron. This analysis is referred to as a ***measurement*** because we're testing something we know is there.
  1) We know Z bosons decay, so let's focus on $Z \rightarrow e^+e^-$ decays as a detector signature.



  2) We need to think carefully and predict the other processes that could also generate this final state. These non-primary sources are called ***backgrounds***.

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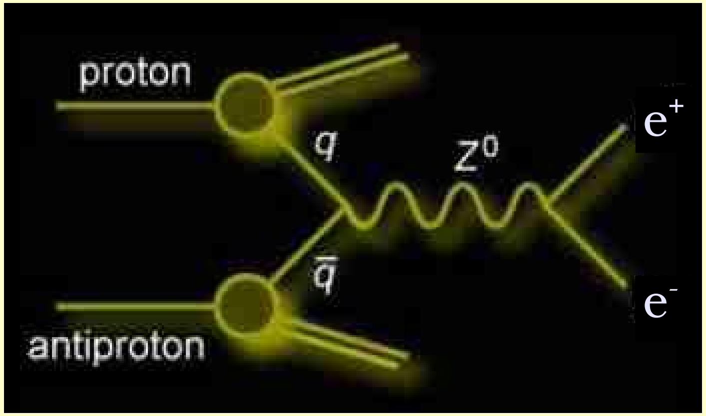

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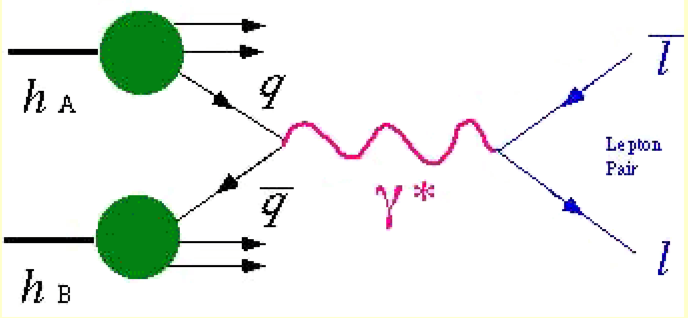

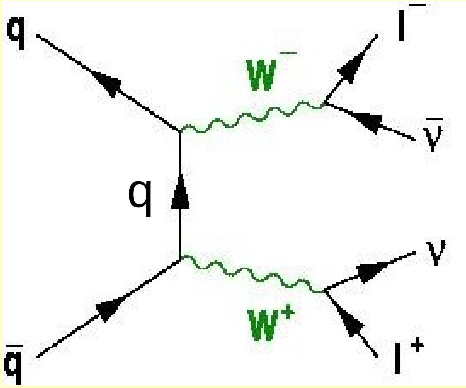

Z boson Analysis

- ✗ Next, we browse through 2.5 fb^{-1} of data and select events with two calorimeter electron-type objects: we count **30.2 million events!**

  Theories predict the **$Z/\gamma \rightarrow e^+e^-$** production cross sections at **~110/480 pb**.

  Theories predict the **$W^+W^- \rightarrow e^+\nu e^-\nu$** cross section to be **~0.25 pb**. We expect **# events = Lumi × cross section = 2500 pb^{-1} × 600 pb = ~1.5 million events**. Thus, 30.2M is way too many! What did we miss??

Z boson Analysis

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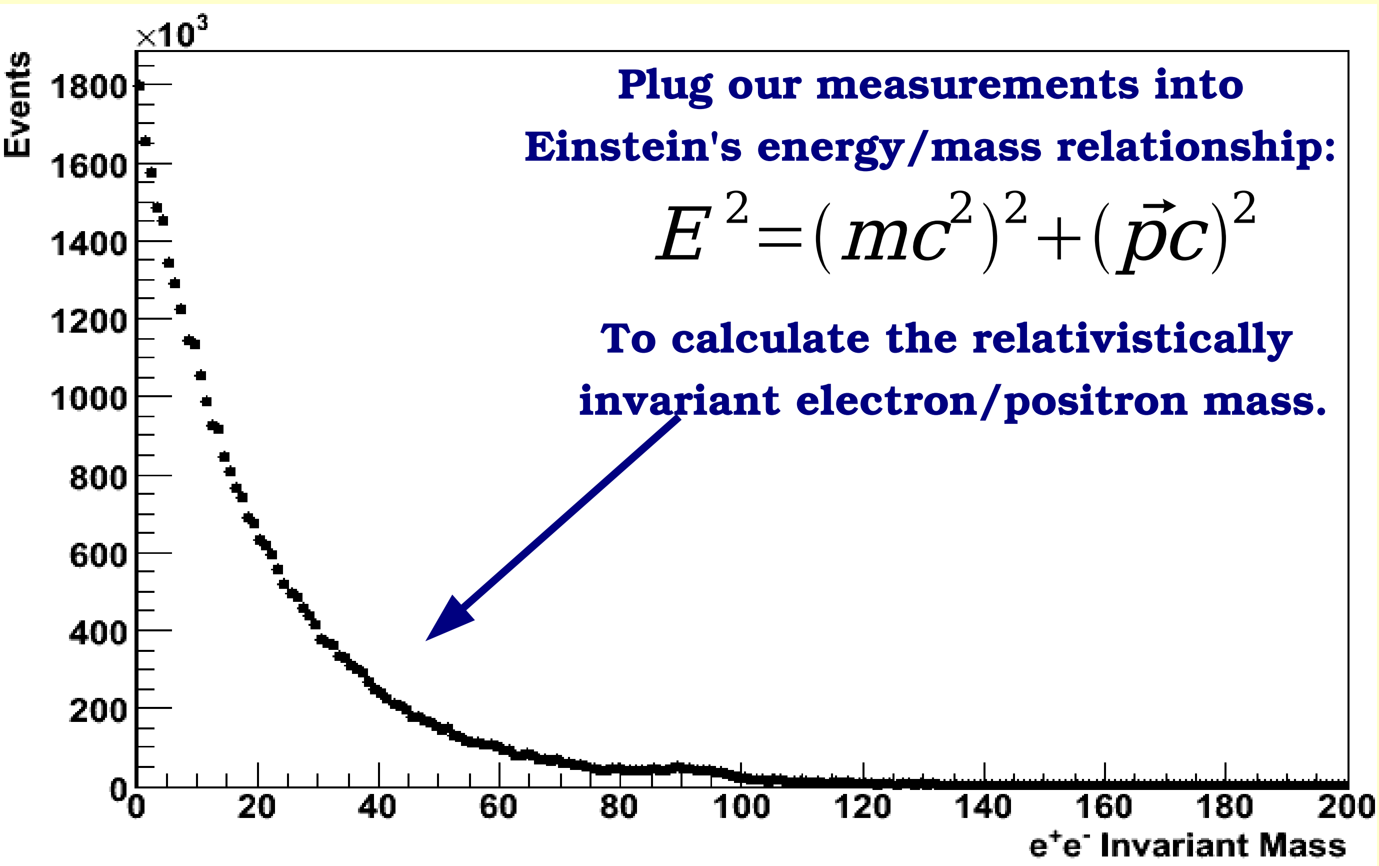
Theories predict the **$W^+W^- \rightarrow e^+ve^-v$** cross section to be **~0.25 pb**. We expect **# events = Lumi × cross section = 2500 pb^{-1} × 600 pb = ~1.5 million events**. Thus, 30.2M is way too many! What did we miss??



Histograms:

A common visualization technique.

Categorize events into “bins” of fixed width in mass to see the shape of the distribution.

Summing over all bins gives the total number of events

Z boson Analysis

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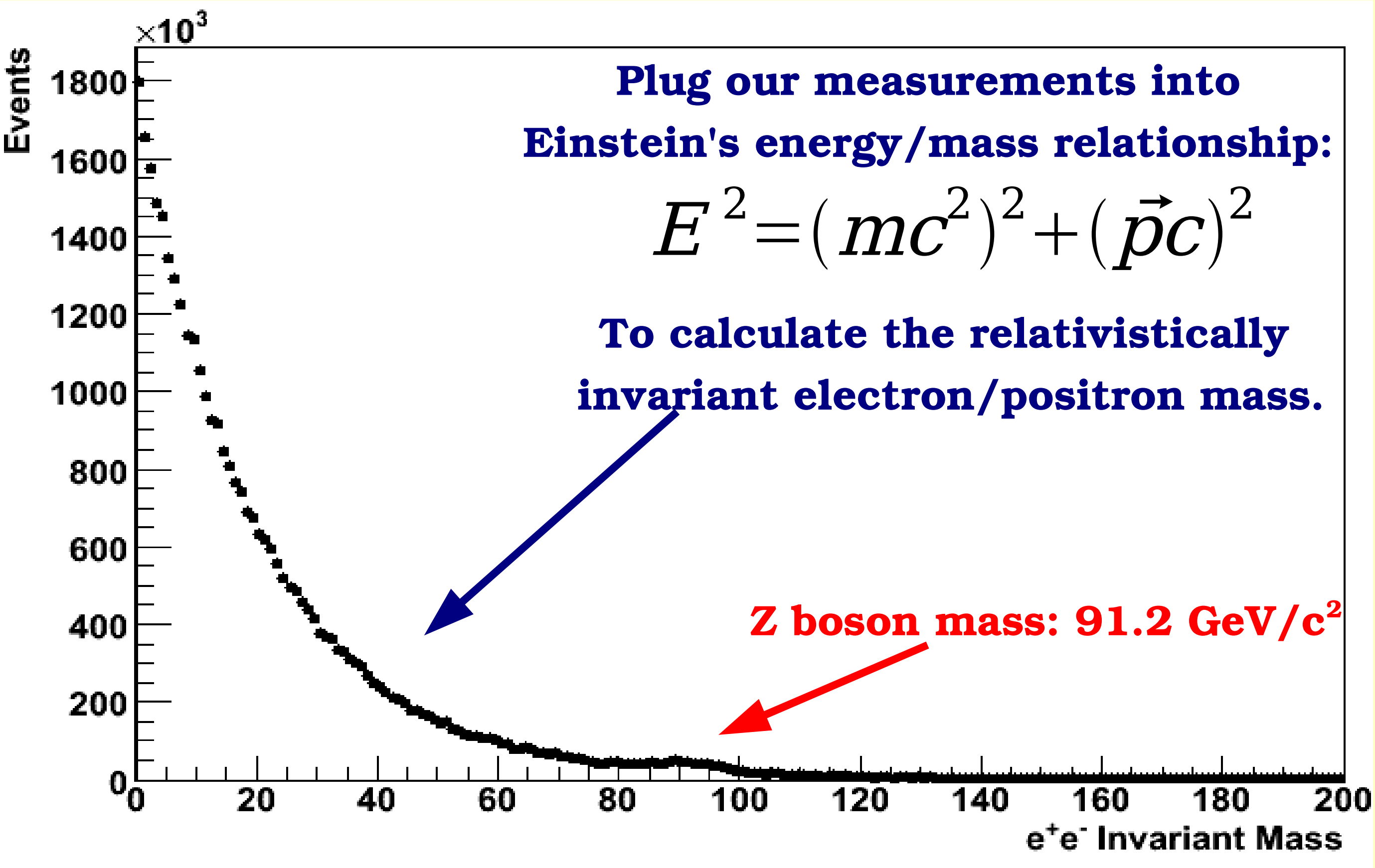

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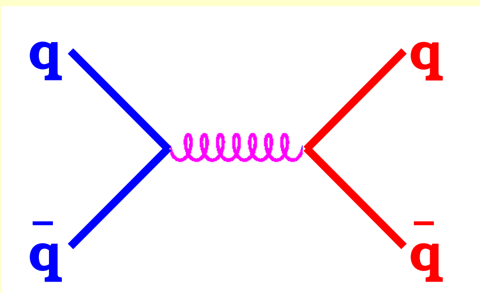

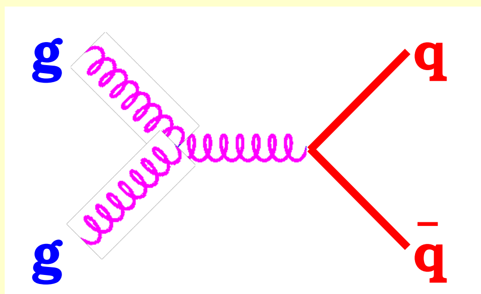

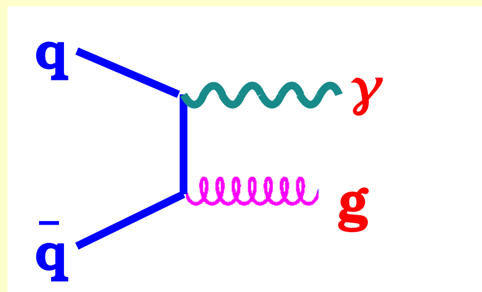

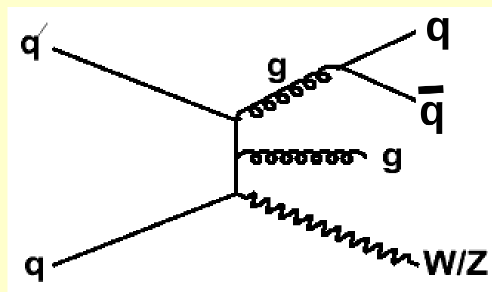

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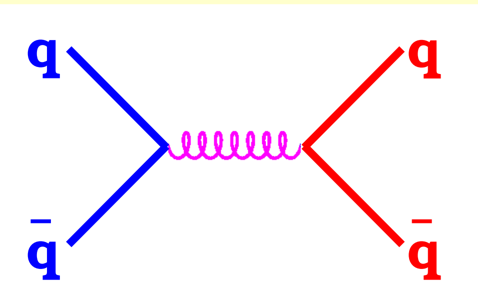
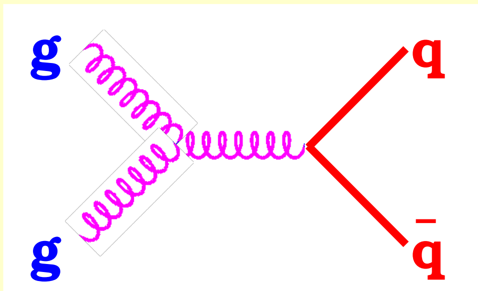
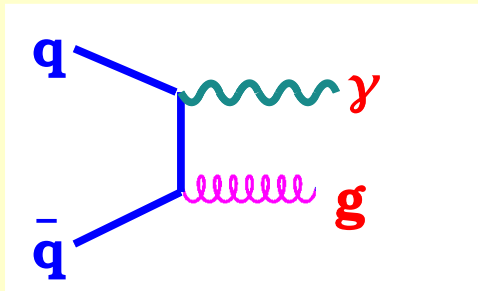
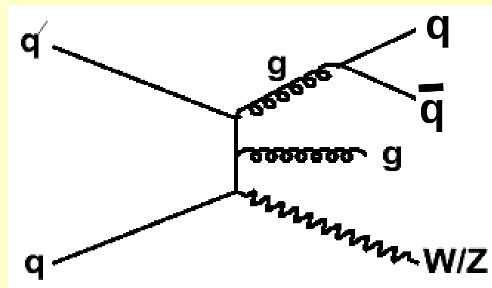


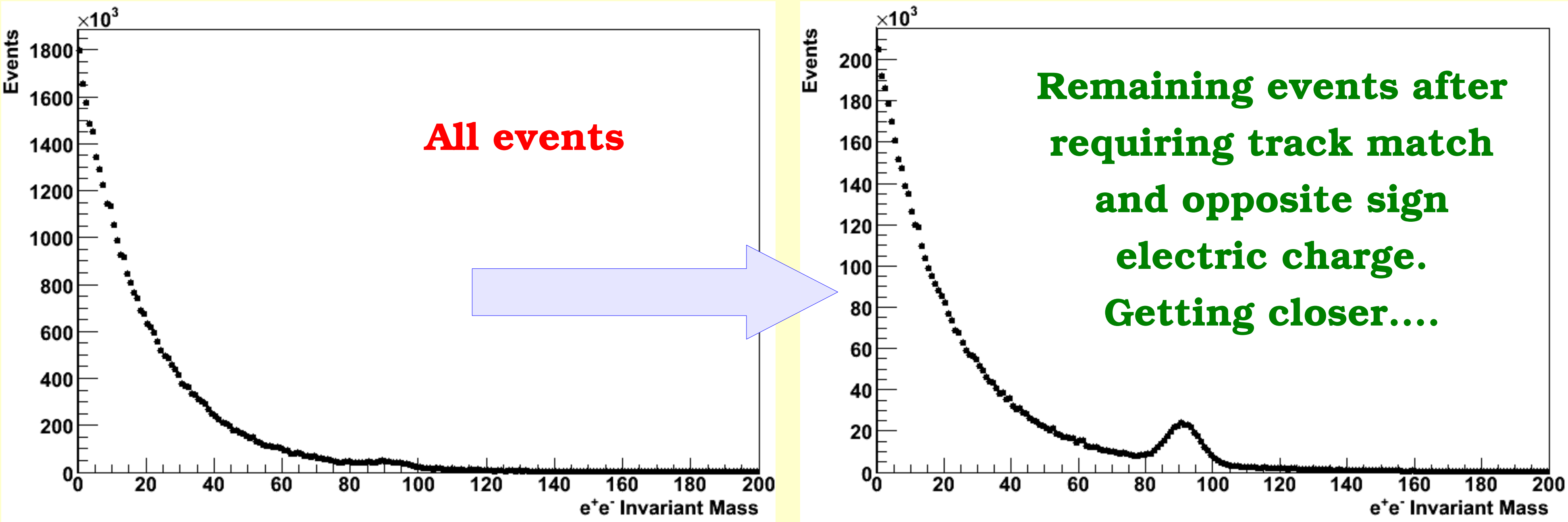






Solution: Require that each EM object be ***matched to a track*** in the tracking detectors (kill photons & fakes!) and that the two tracks have ***opposite charge signs*** (kill fakes!). New event count: **4.9 million events**

Z boson Analysis (II)



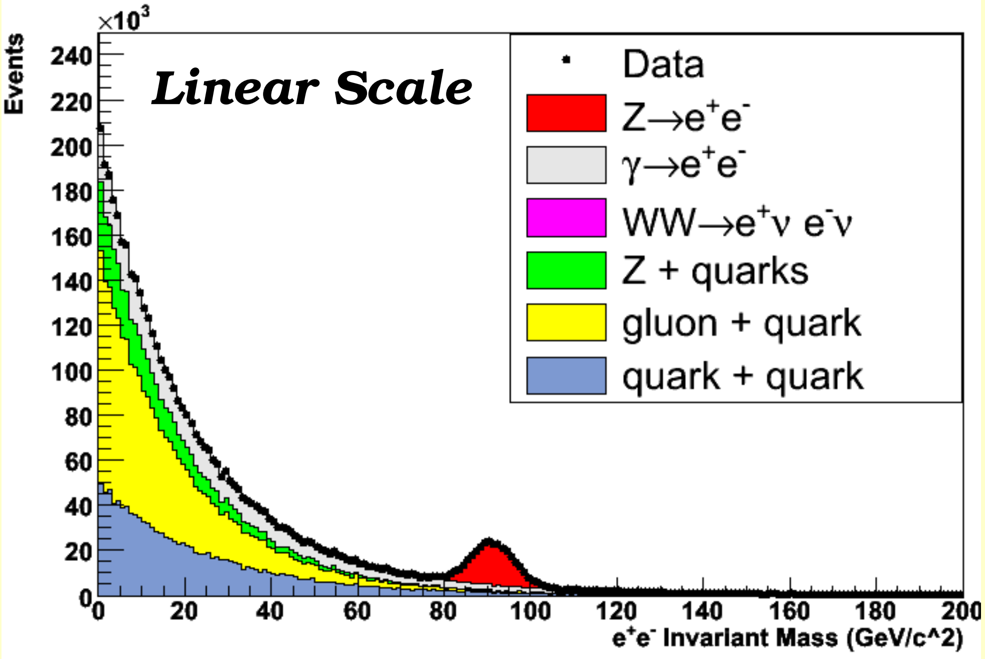
- ✗ A common problem: we expect ~1.5M events in our $\mathbf{Z/\gamma \rightarrow e^+e^-}$ sample, but we find ~4.9M. *We need some way to visualize the problem.*

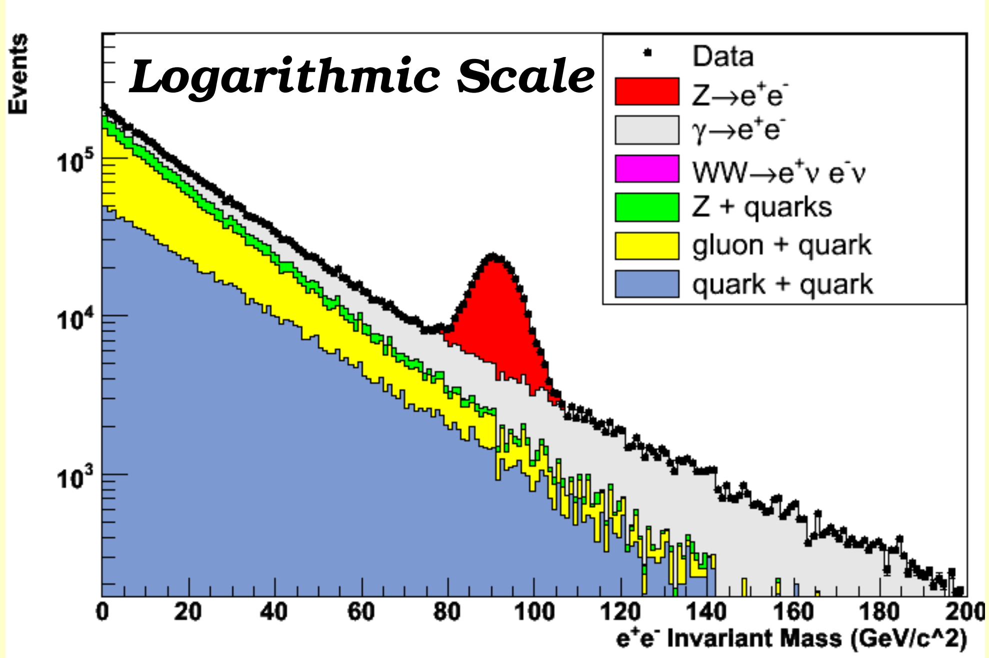
  Ideally we predict the behavior of any extra contributions to see what's missing

- ✗ <u>Solution:</u> Simulation of expected contributing processes

  1) Start with a theoretical model for each process.
  2) Calculate cross sections & kinematic behavior, then generate "raw" events.
  3) Simulate detector response to raw events to predict real event signatures.

Z boson Analysis (III)





- ✗ With simulated predictions for expected sources of events, we can see what is contributing to our selection.
  - Each background is unique and can be reduced with careful selection criteria
- ✗ These predictions must be carefully tuned at the theoretical level and the detector simulation level to provide accurate predictions
  - Precision of energy measurements, tracking resolution, etc. all impact the quality of our simulated events.

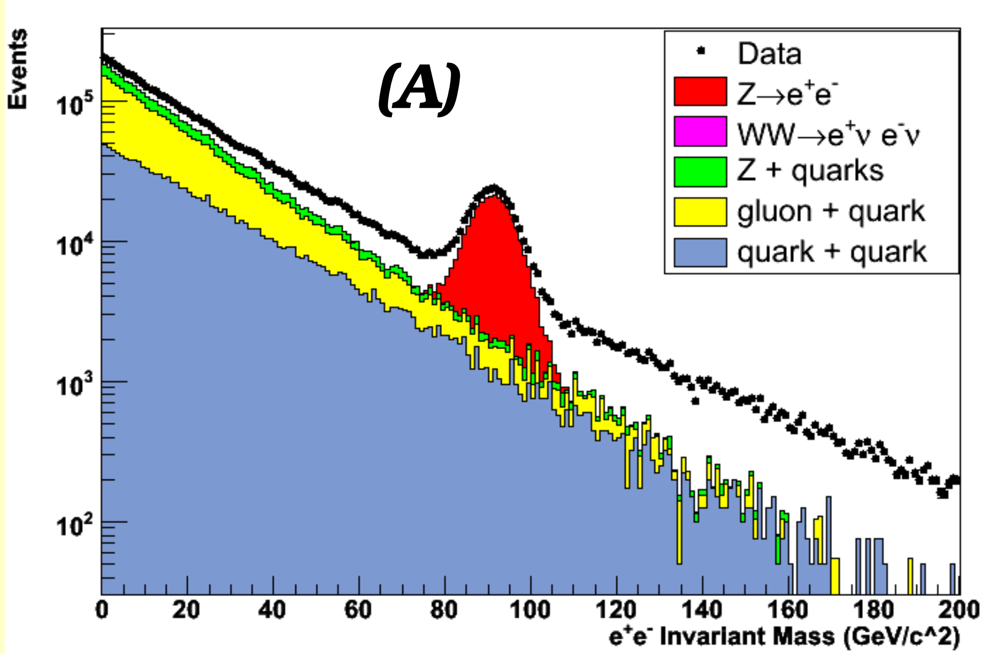
Z boson Analysis (IV)

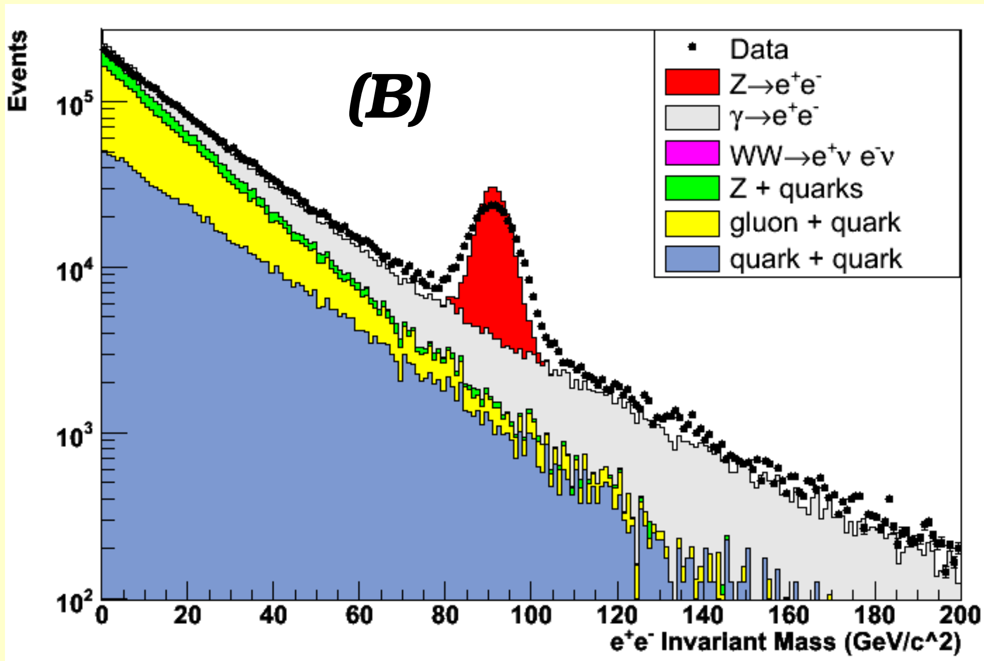
SIST Lecture
July 1st, 2008

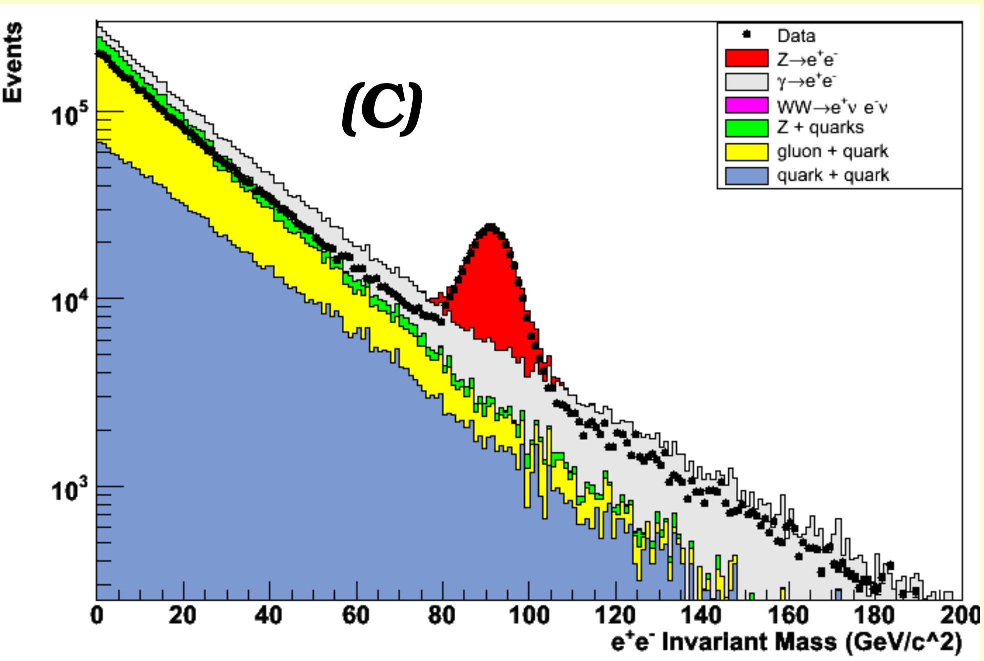
✗ Simulated events tell us what may be wrong with our physics or detector modeling.

<u>Clockwise:</u> **(A)** Missing background prediction, **(B)** Incorrect electron energy measurement, **(C)** Incorrect background cross sections (*rates*)

These effects are referred to as systematic uncertainties

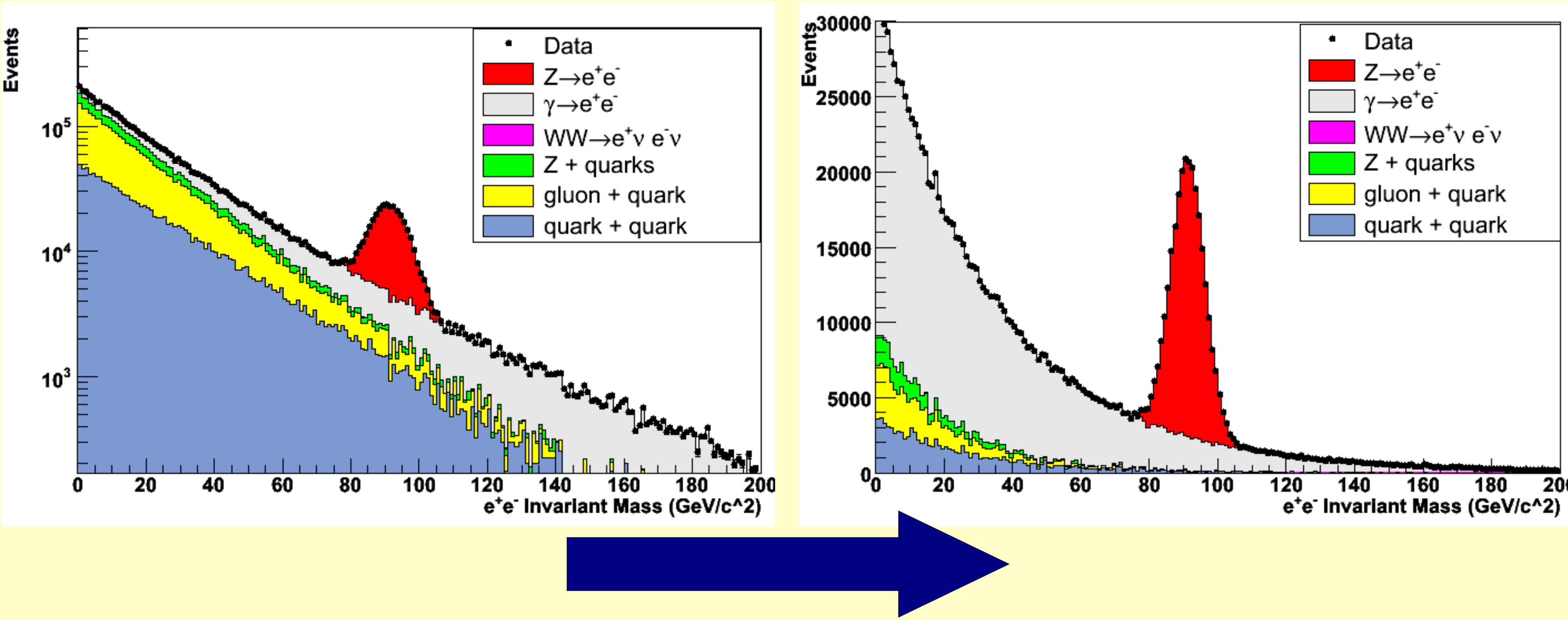






Z boson Analysis (V)

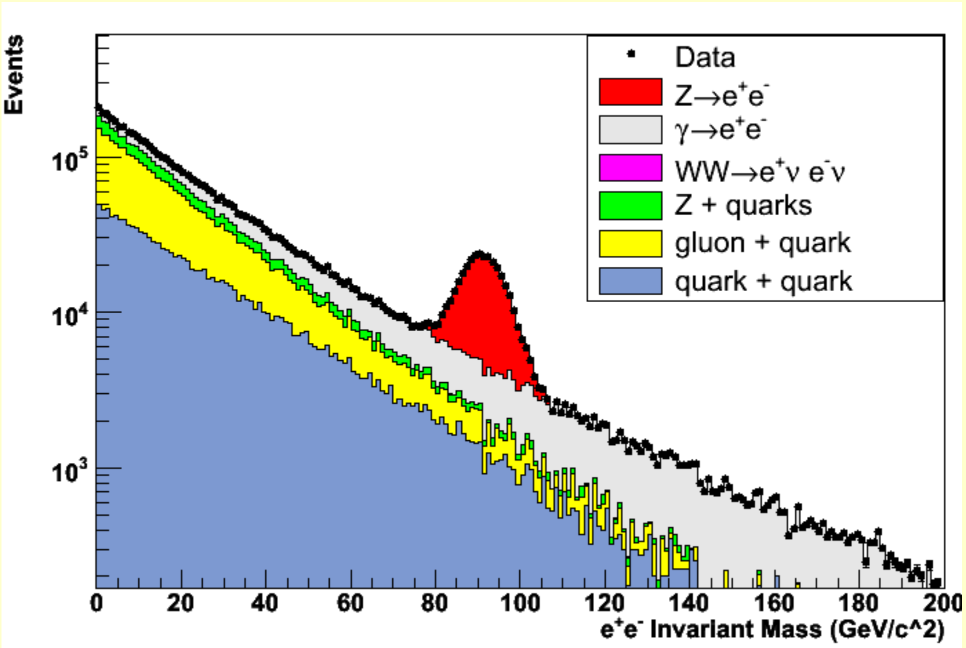
- Final steps: tighten electron identification requirements to remove "fake" electron backgrounds and prepare for measurement of the Z boson cross section.

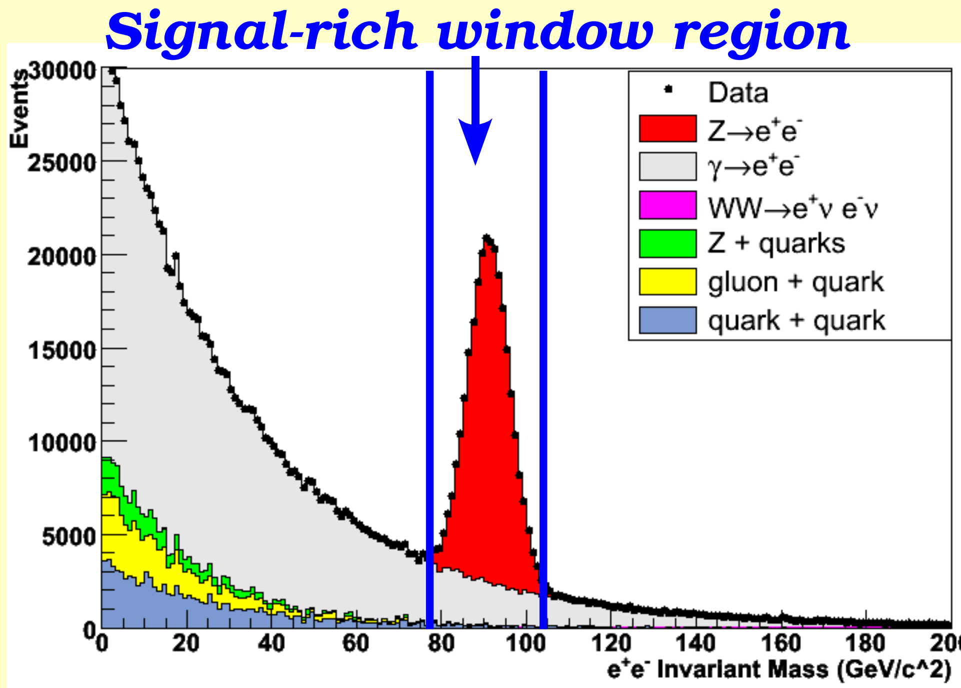


Increase rejection of "fake" electrons from quarks and gluons

Z boson Analysis (V)

- Final steps: tighten electron identification requirements to remove "fake" electron backgrounds and prepare for measurement of the Z boson cross section.



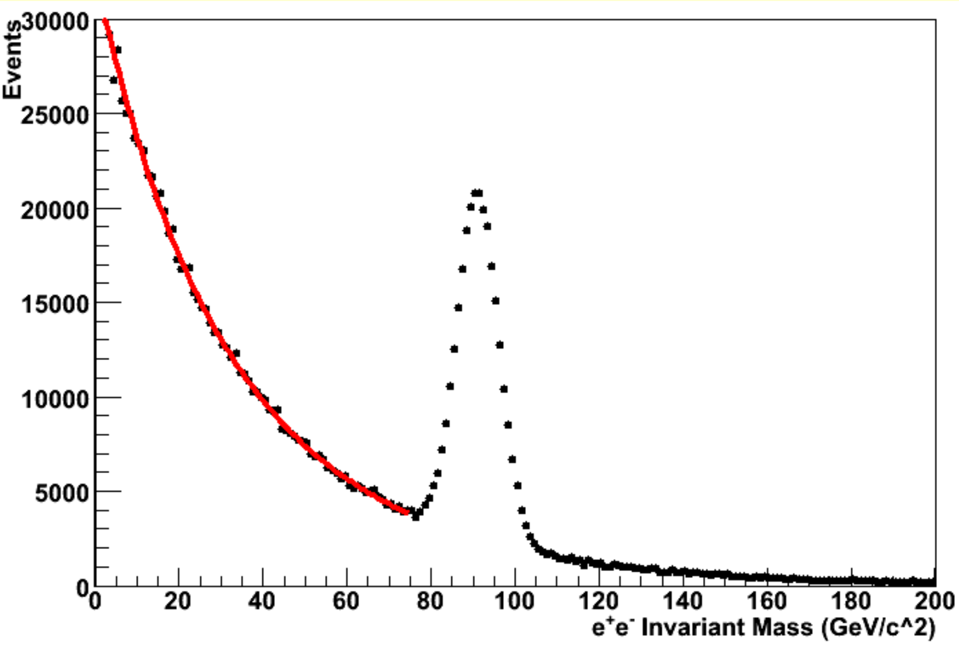


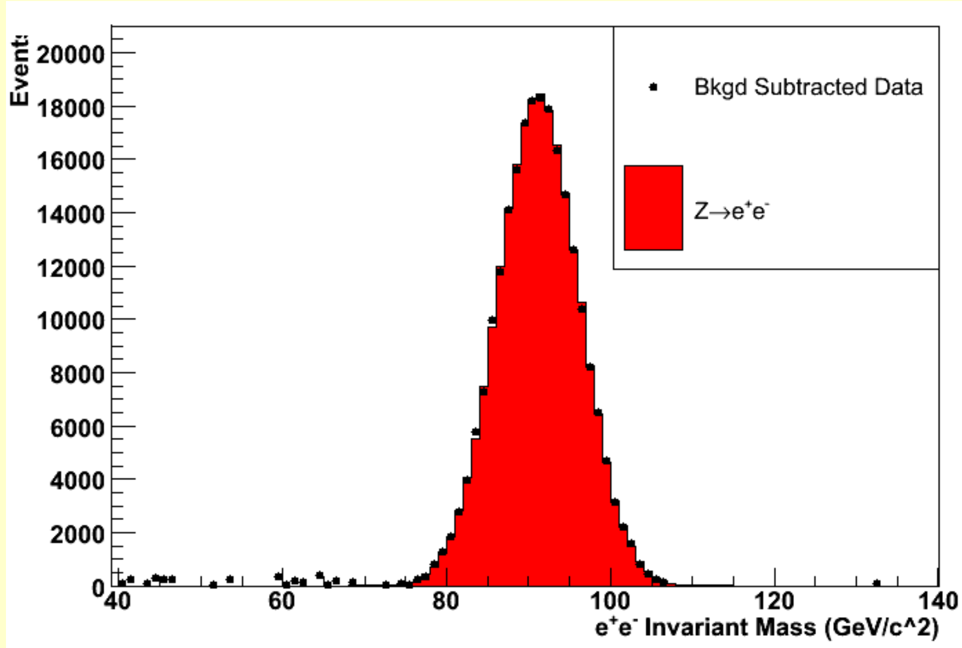
 # events = Luminosity × cross section × selection efficiency

- We still have background events in our signal window

  Solution: perform a background subtraction to create a signal-only prediction.

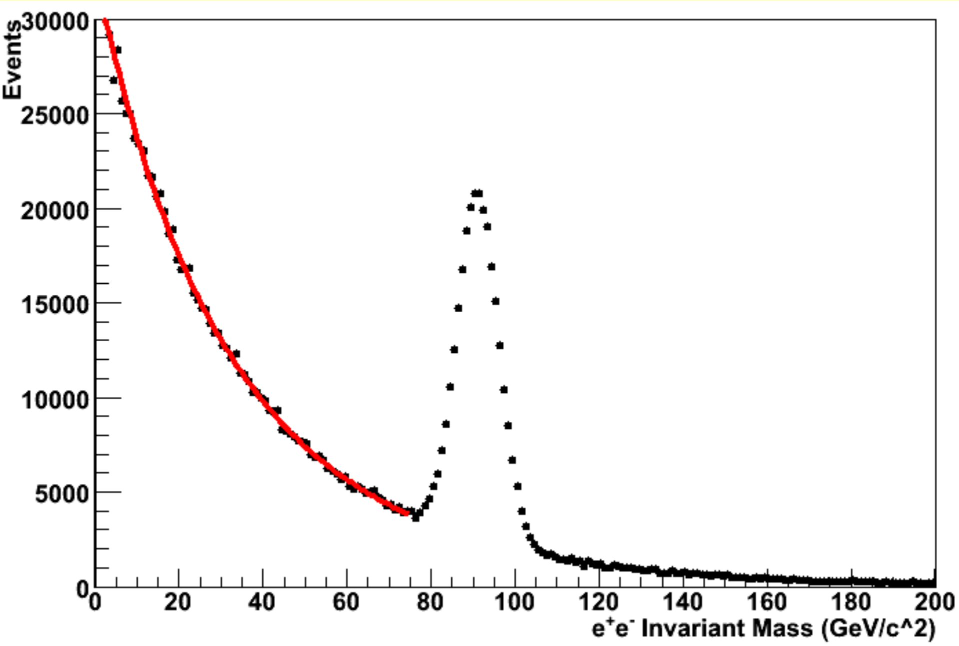
Z boson Analysis (VI)

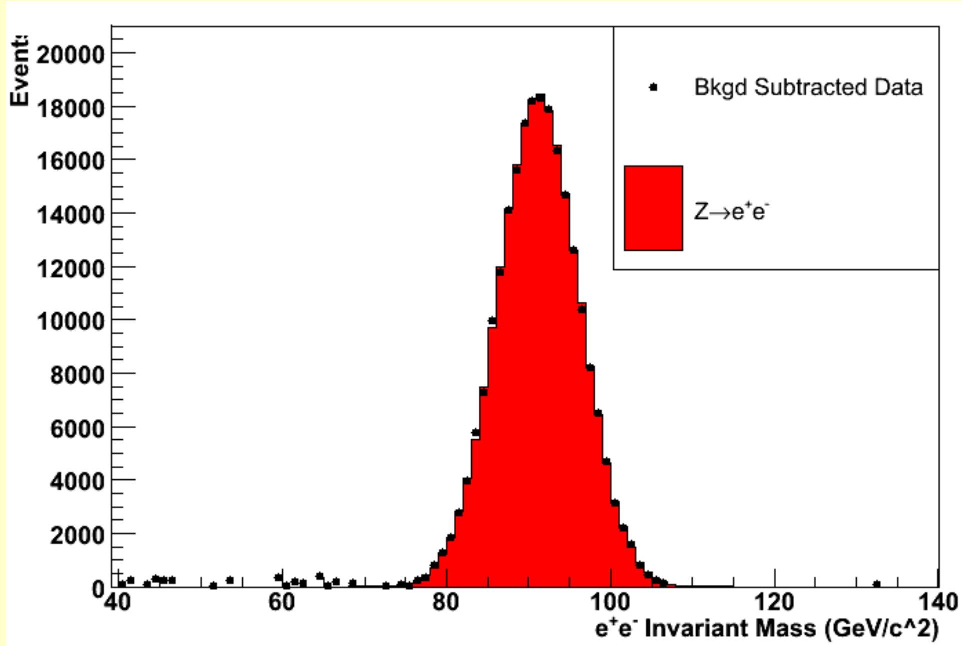




Subtract fitted background prediction

Z boson Analysis (VI)





- ✗ Using our background free model, we can now measure our **$Z \rightarrow e^+e^-$** production cross section

 # events = Luminosity × cross section × selection efficiency

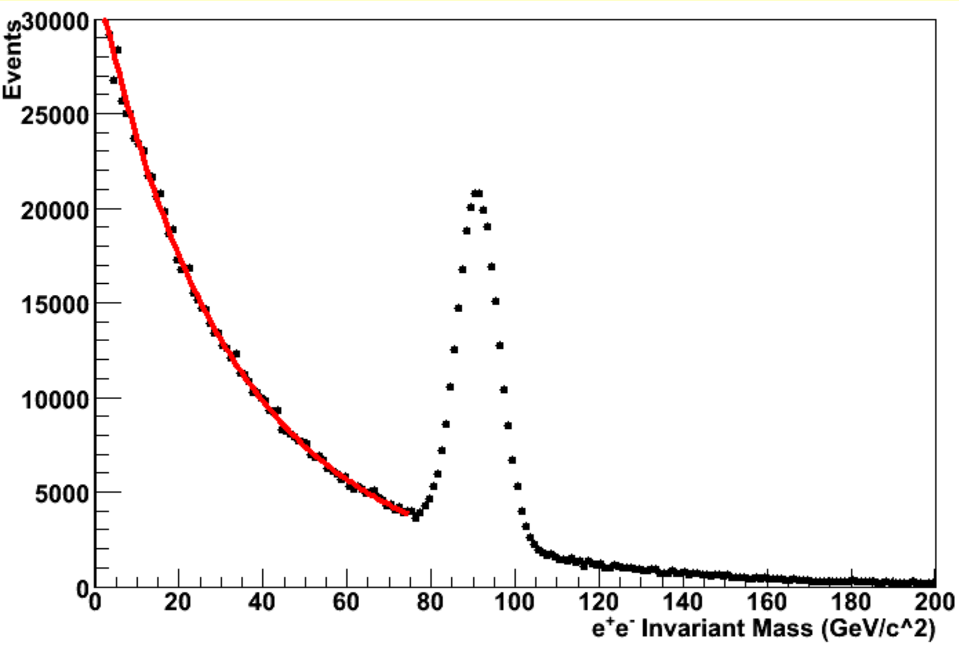
cross section = (# events) / (Luminosity × selection efficiency)

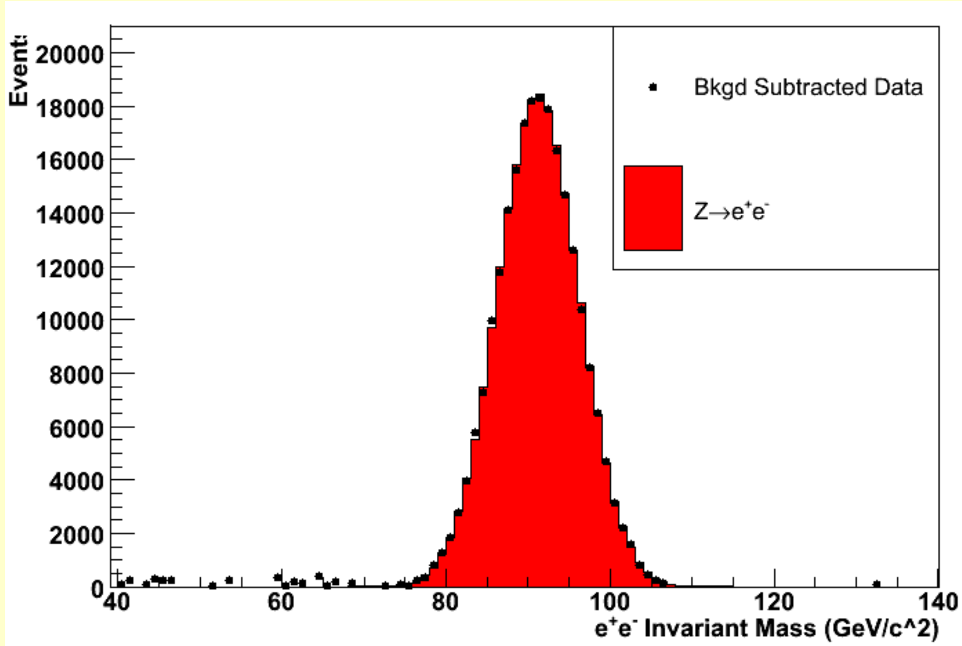
Determined from final event sample

Measured as Tevatron produces collisions

Found from simulation: ε = # passing cuts / # total

Z boson Analysis (VI)





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 # events = Luminosity × cross section × selection efficiency

cross section = (# events) / (Luminosity × selection efficiency)

= (216,684) / (2500 pb-1 × 83%)

= 104.4 pb ← ***Theory predicted 110 pb!***

Today's Outline

Tevatron Collider Experiments

- The physics motivation for Fermilab's collider experiments
- Creating particles in Tevatron collisions
- Particle masses and decays
- Detecting particles and particle signatures
- From detector to analysis

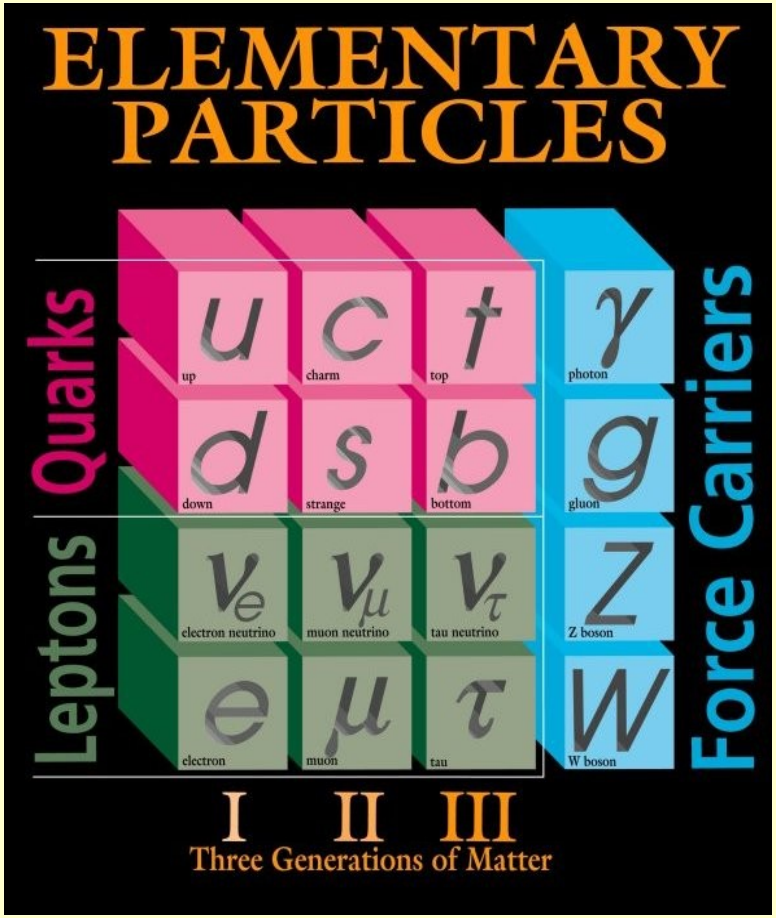
Physics Analysis Techniques

- Analysis design by example: Z bosons
- Event simulation and measurements
- **Searches for new physics**
- **Multi-variable classification techniques**

Searching for New Physics

✗ Measurements tell us precise details about things we know exist

At Fermilab, we measure properties of all the particles in the table below



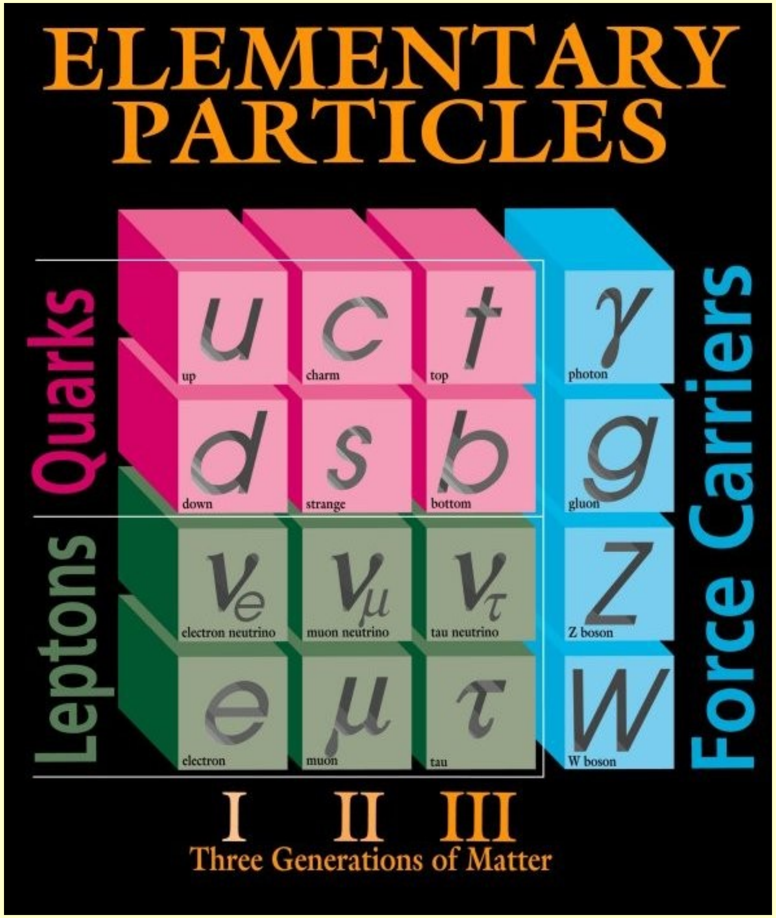
1977: Leon Lederman & colleagues (*E288*) discover the bottom quark.

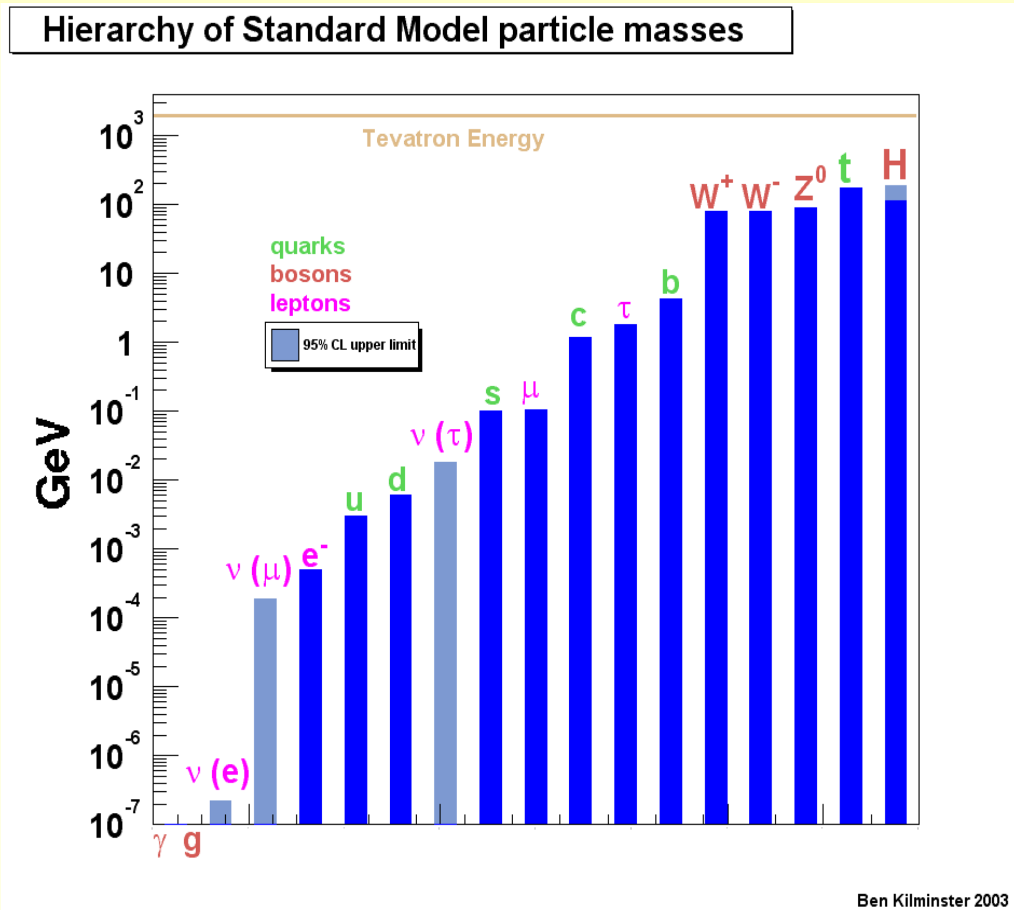
1995: The CDF and DZero collaborations announce discovery of the top quark.

2008: Fermilab community is active in searches for extra dimensions, evidence for the theory of Super-Symmetry, **the Higgs boson**, and many more.

Searching for the Higgs Boson

- ✗ The Higgs boson is hot topic and we believe needs to exist in order for matter to have the property of mass
  - Theories without a Higgs-like mechanism predict zero mass for particles
  - We **know** particles have mass, but we do not know **why** or **what** it means

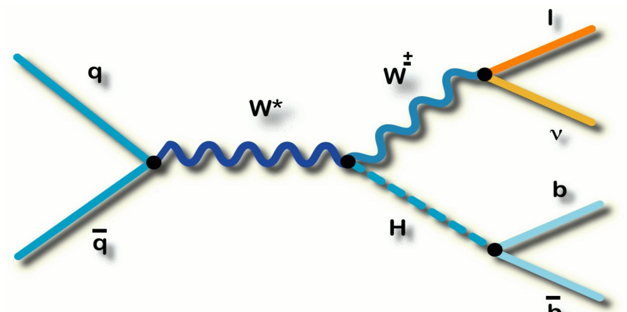




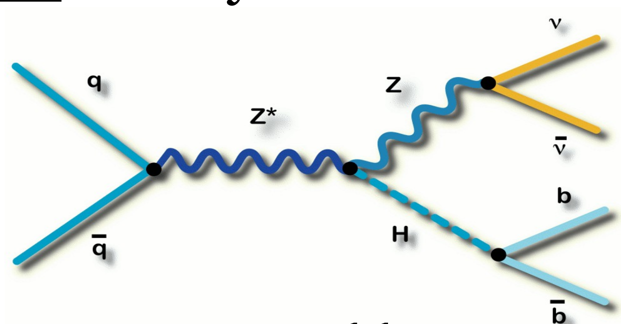
Searching for the Higgs Boson

- ✗ Higgs boson cross sections are very small at the Tevatron (~75 fb).
  - In 2500 pb^{-1}, we expect only ~200 Higgs boson events total.
  - Our measurement example had 220k events!
- ✗ *And theories don't predict the mass of the Higgs boson itself! We don't know for sure where to search!*

<u>Associated Production:</u> Heavy weak bosons couple to the Higgs.



WH→lνbb



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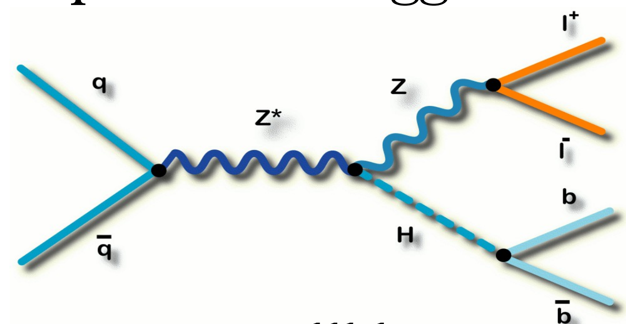
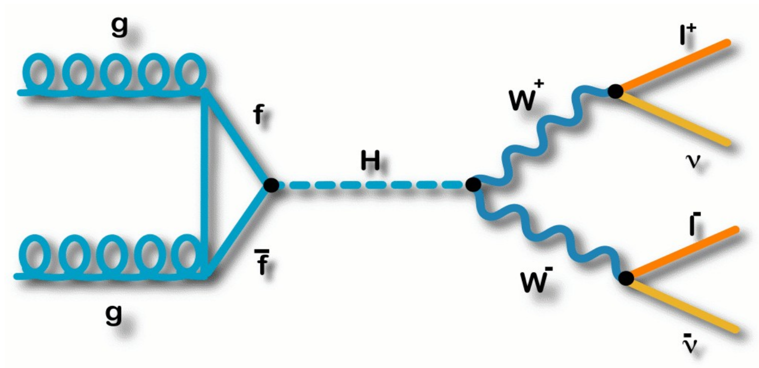


ZH→llbb

<u>Gluon Fusion Production:</u>

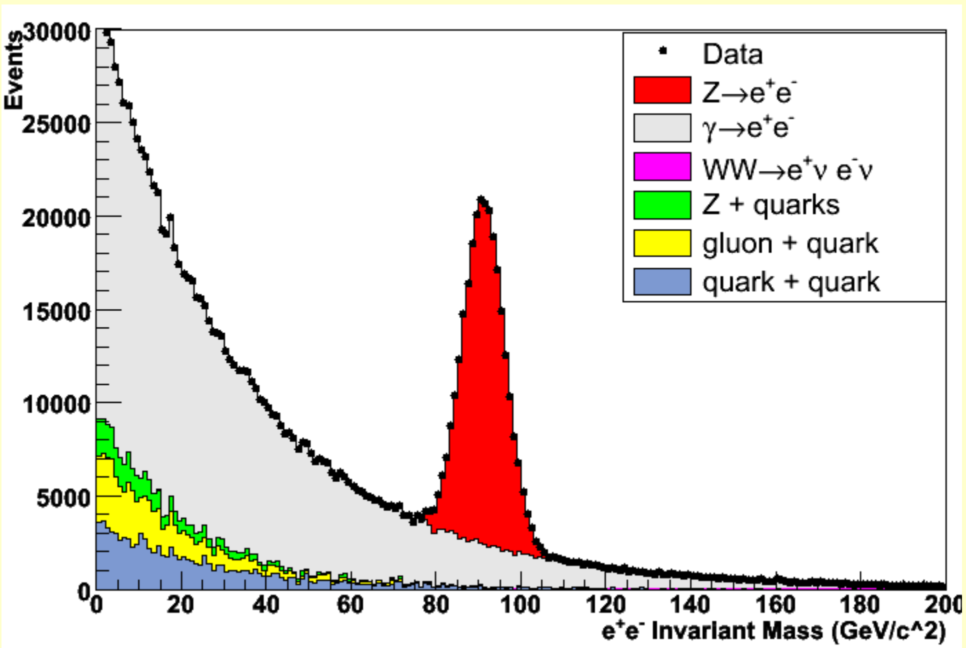
Gluons are massless, so the Higgs couples to a top quark. Leptons and neutrinos define this final state.



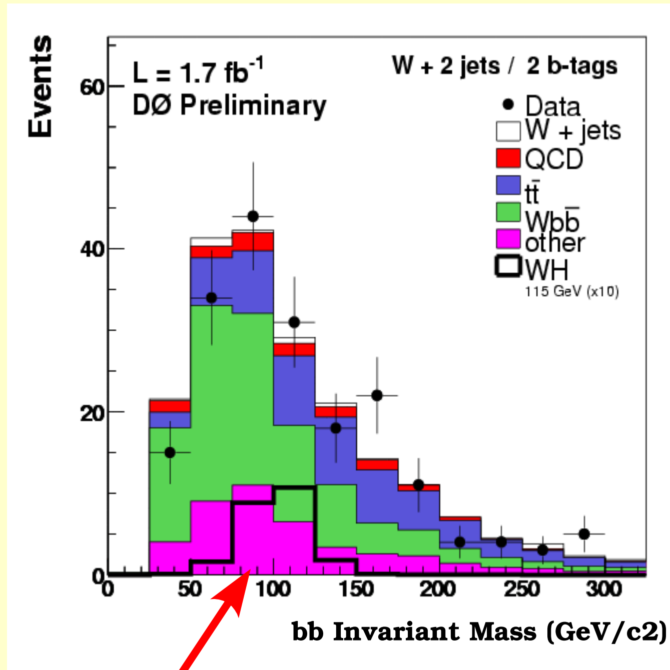
Searching for the Higgs Boson

- ✗ Searches proceed in a similar fashion to measurements
  - Simulate expected backgrounds and signal
  - Select data events consistent with signal signature
  - Reject backgrounds by restricting features incompatible with signal

Our Z→e⁺e⁻ example analysis



Real Higgs boson search



A predicted Higgs signal multiplied by 10!

Cornering a Signal

Choose your analogy: we're looking for a tiny signal in a HUGE background

To claim that we found something new, it must be *unambiguous*

This poses a large challenge for experimental physicists

Multi-varible Classifiers

- ✗ We need tools to efficiently distinguish the two event classes
  - By using more than one event feature (*variable*) we can better classify events
  - Basic principle: Classify events into two categories, **signal (1)** or **background (0)**

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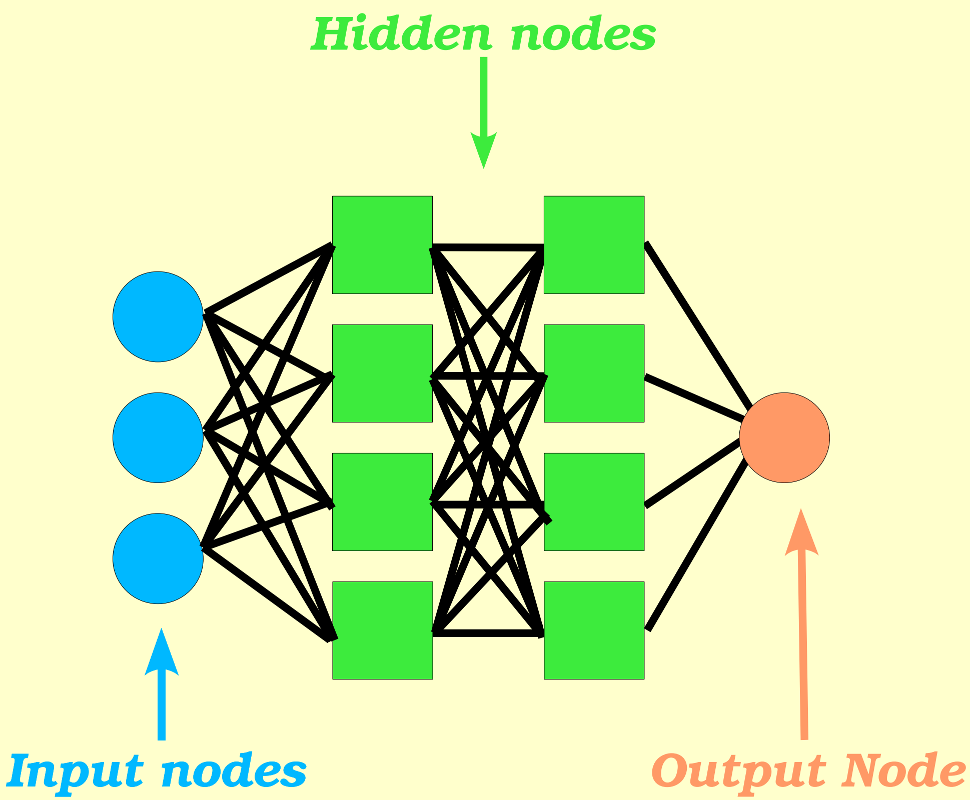
The Neural Network

Based on the model of inter-connected neurons in a brain

Neural networks are trained to recognize signal events via characteristic features

Data is entered via “input nodes”, processed in “hidden nodes”, and a classification is returned via the output node(s).



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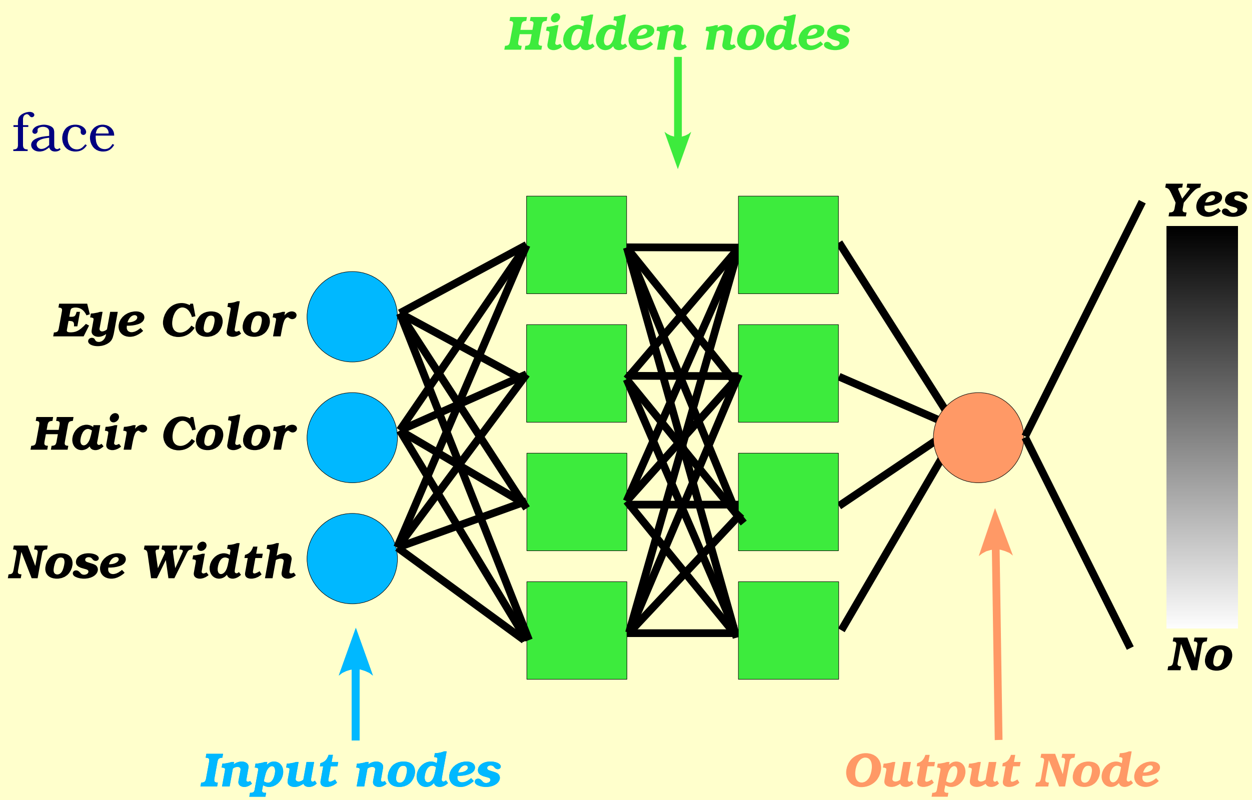
The Neural Network

Imagine a neural network trained to identify your face

Input facial features

Output a decision



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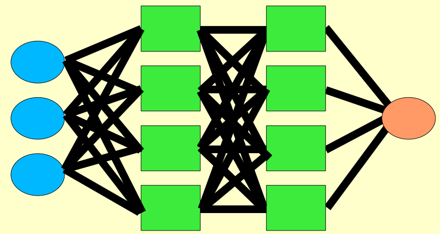
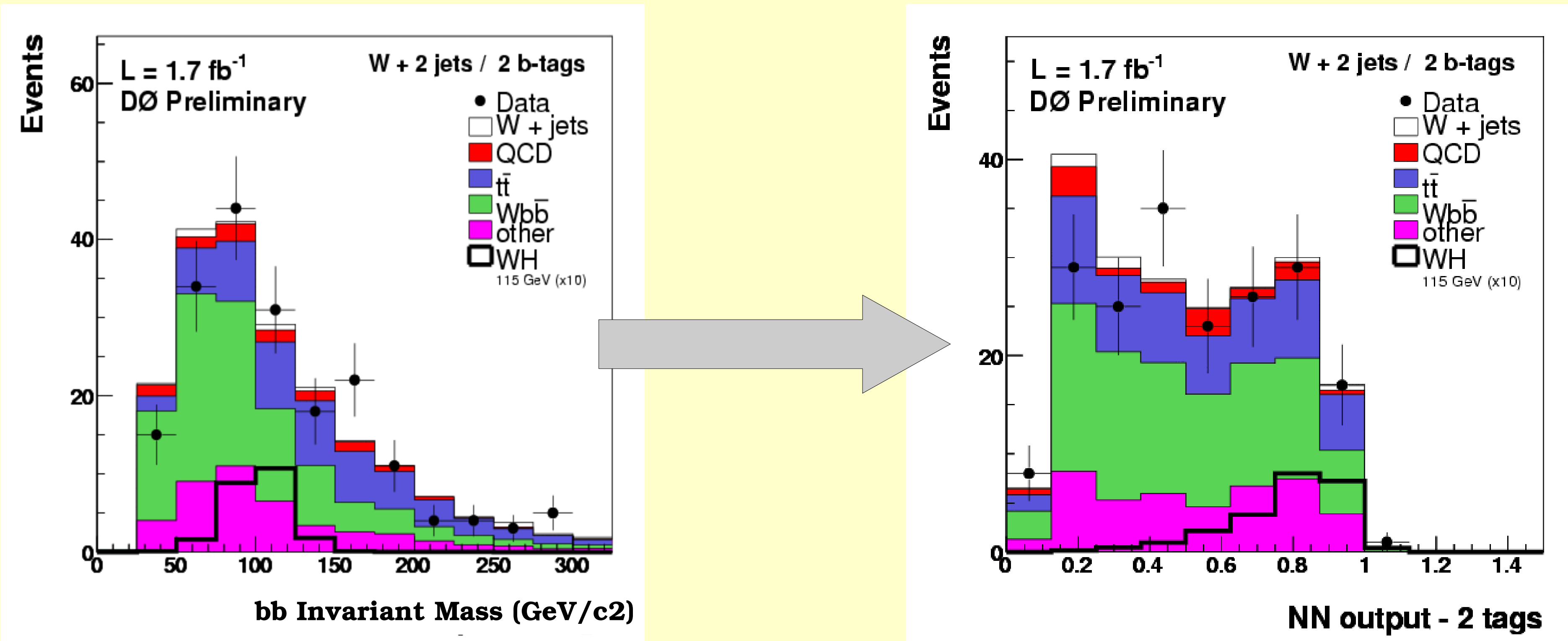
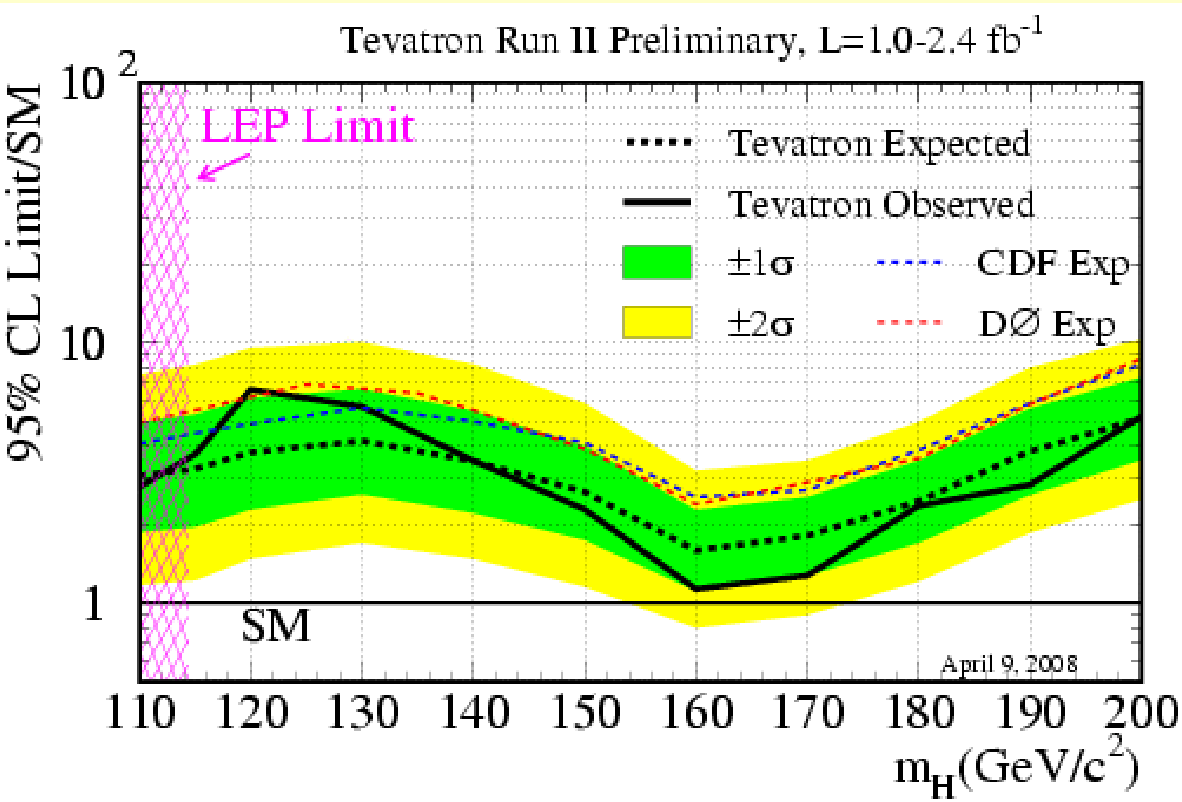




Limits

- ✗ A search can return three semi-distinct answers:
  1) We unambiguously found something new!
  2) We found something incompatible with the zero-signal model.
  3) We found no significant departure from the background-only model.



95% Confidence Level Limits

Definition: If we repeated our search many times, this is the maximum size of signal cross section that would not be lost in the background in more than 5% of searches.

We're 95% sure it's smaller than this!

Limits provide a mathematical statement about how certain we are about our null result.

Summary

✗ Today we've covered a lot of ground!

Production of particles in Tevatron collisions

Proton/Anti-proton consituent partons, particle decays

Particle detection, identification, and data collection

Ionization and excitation signatures of particle passage

Conservation laws: energy, momentum, charge, etc.

Triggering (or filtering) of interesting events

Analysis logic and design

Example of Z boson cross section measurement

Techniques of histogramming, event selection, and simulation

Searching for the undiscovered

The search for the Higgs boson

Neural networks and limits

Our Driving Principle

- ✗ The first thing we talked about was **asking questions**
  - You've heard it before: there are no dumb questions!
  - We don't learn anything without asking "Why?", "How?", or "What?"

We live in a universe filled with inspiration, don't be afraid to find yours!