PY 482: Computation for Particle Physics

Professor Kevin Black

Goals of the course

- Main goal is to introduce the skill sets you will need for your research projects
  - Computing, C++, the root analysis program, data analysis (statistics and probability)
  - Introduction to ideas of particle physics, background material

WHAT WILL WE COVER

- Very brief review of Standard Model and elementary particles
- Overview of how we do experiments (how do we produce, detect, and record interactions of particles?)
- Tools of the trade (CORE of class)
    - C++, unix, root package
    - representing data (histograms), parameter estimation, likelihoods, simulations, event displays, confidence intervals and limits

Specifics

- Root analysis package
  - How to manage files
  - Object oriented computing (C++ and all that jazz)
  - How data is stored and accessed
  - How to represent data (4 vectors, histograms, graphs)
  - Event Displays
  - Parameter estimation in root
  - Fitting in root
  - Likelihoods
  - Confidence Intervals

What is expected of you

- Assigned readings
- Weekly homework assignments (5 of them in total)
- Presentation in class , ~15-20 min, researching a classic particle physics experiment from paper
- Final data analysis project

GRADING

- 50% from homework
- 20% from presentation
- 30% from final project

Details of Course

- 6 week course, meeting twice a week for 2 hours at CERN
- Homework will be due Tuesday by the beginning of class
- More detailed breakdown in course syllabus
- Blackboard site - post everything there

Tools you will need

- Access to a machine with the ROOT analysis program
  - all should have accounts on buphy and CERN, also standalone versions available on mac or windows
  - note - it is useful to have it locally installed at least for things that don't require a large amount of storage (graphics are slow with low bandwidth internet connections)

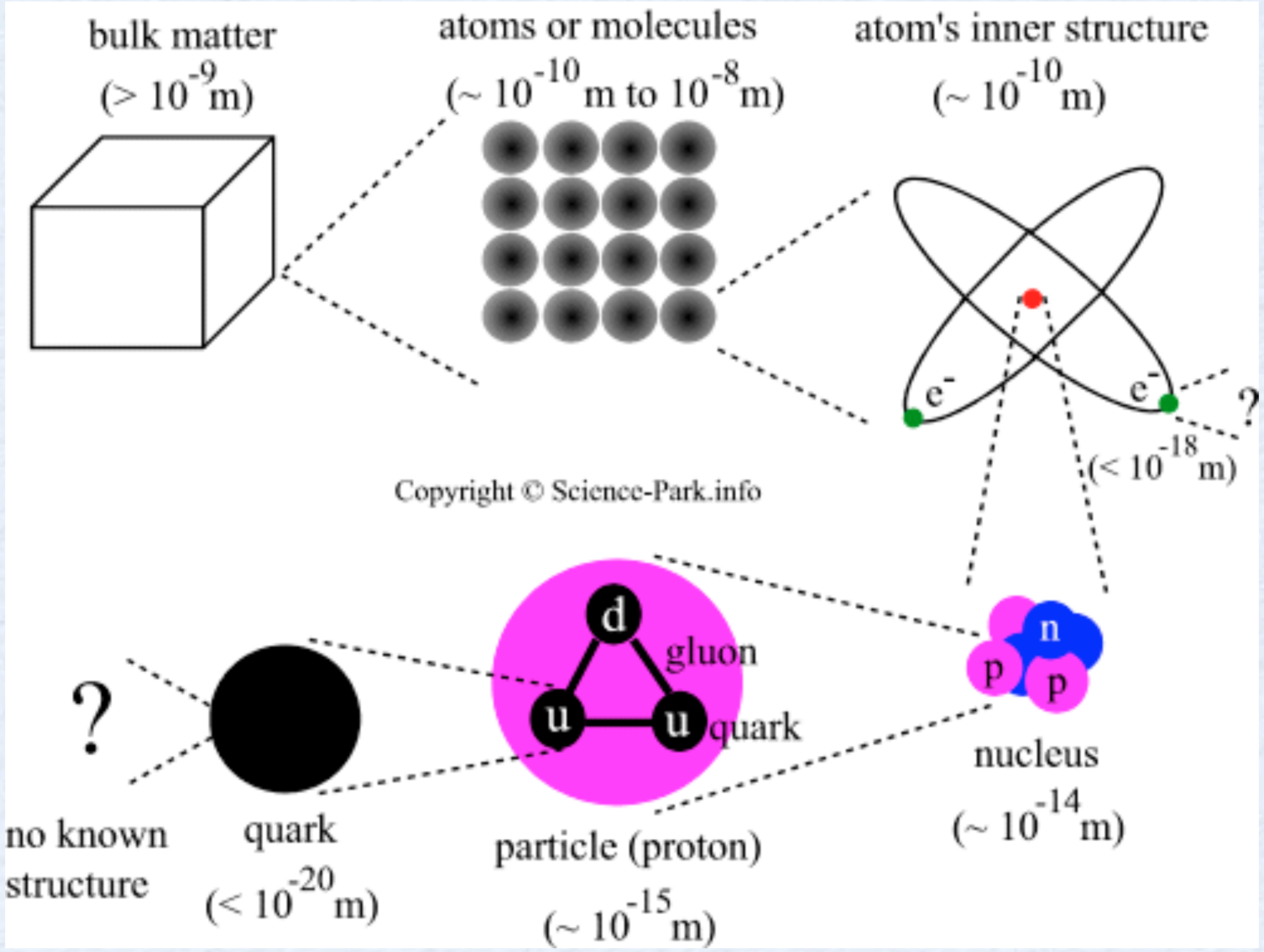
Today's Lecture!

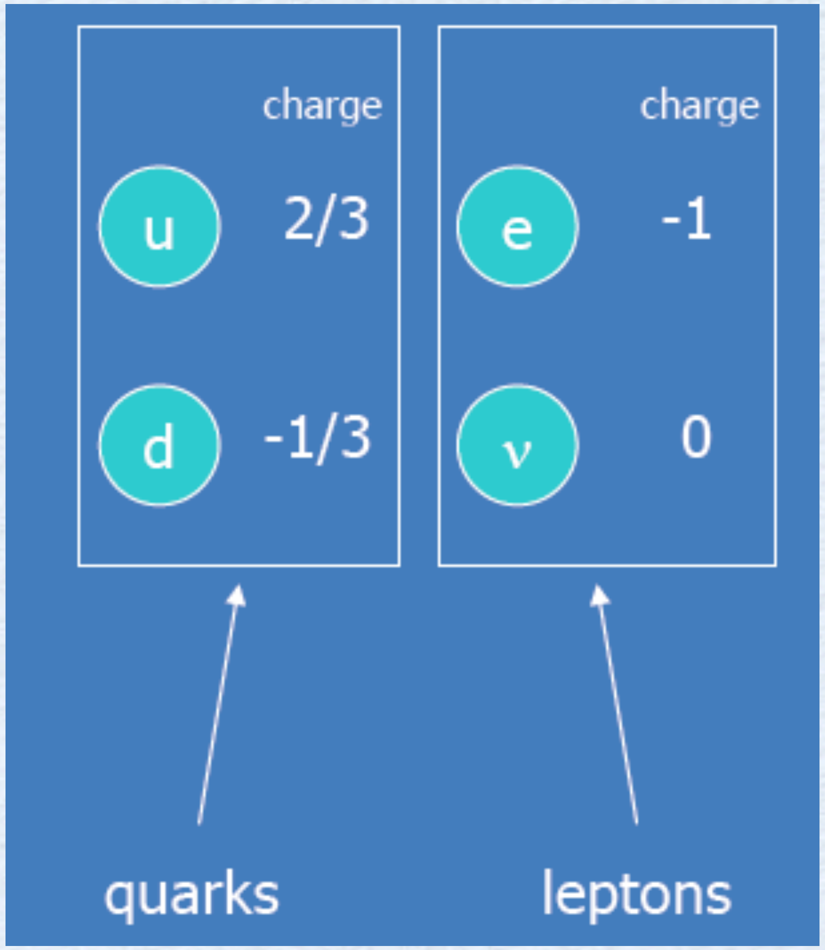
Review

- Today we will give a brief overview of many topics to put in to context all the technical stuff you will learn during this course
- I will show you why you need to learn computation and analysis to do physics

Overview and Background ...

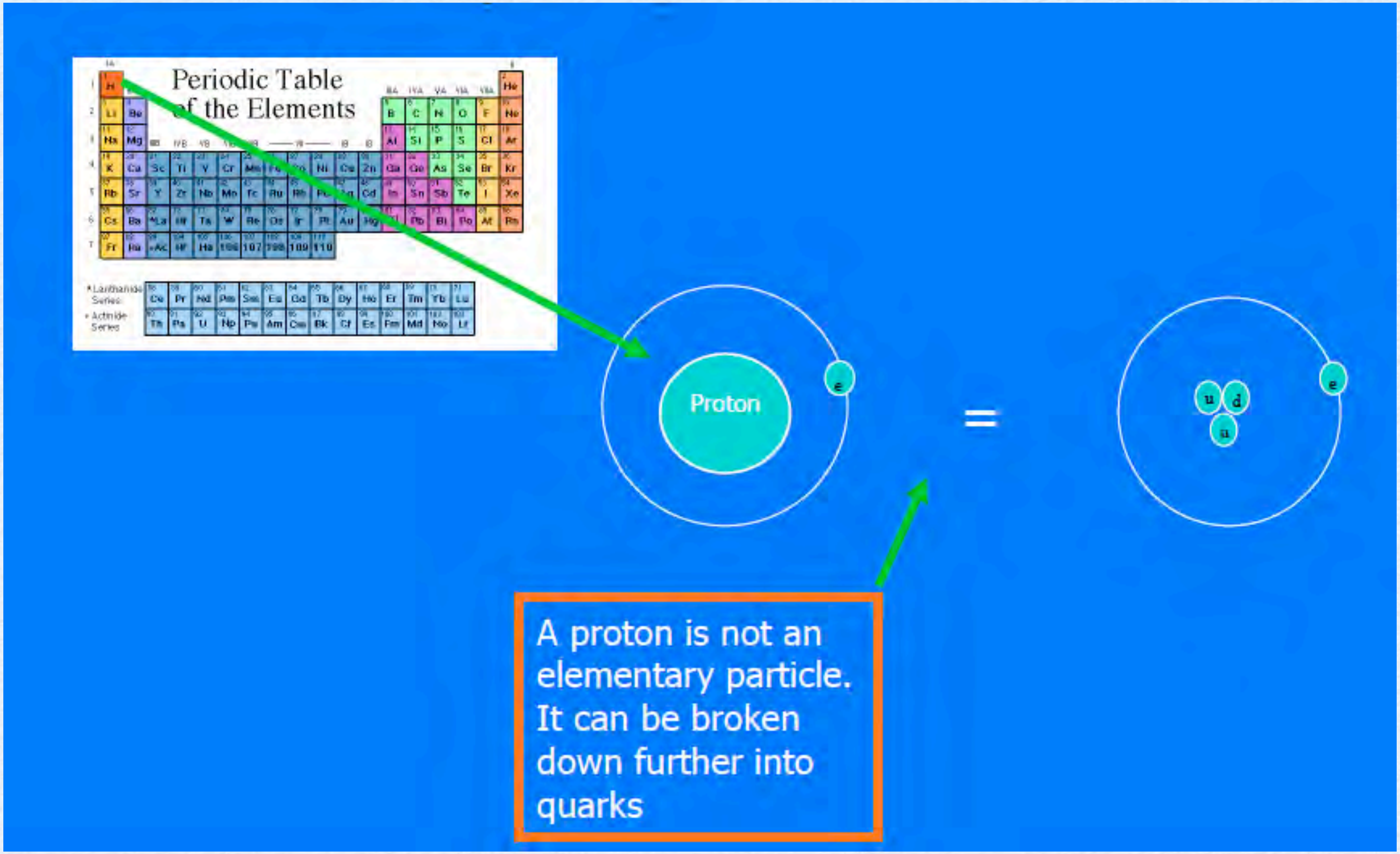
- What is the world made of?
- How can we describe it?
- For all the complexity we see , can we explain it in a simple way?





Rough history of particle physics, the deeper you probe smaller and more basic the pieces become

Basic Building Blocks



Three Quarks to Muster Mark

- So far we have introduced only 2 quarks (u) and (d)
- This works to describe **almost** everything we see around us
- In 1963, Gell-Mann introduced a third quark (s) the strange quark to explain the existence of a new particle the ϕ
- He took the name from James Joyce ...

Murray Gell-Mann

But wait, there's more!

	1st generation	2nd generation	3rd generation	charge
Quarks	u ~0.003 GeV	c ~1.2 GeV	t ~175 GeV	+2/3
	d ~0.006 GeV	s ~0.1 GeV	b ~4.5 GeV	-1/3
Leptons	e ~ 0.0005 GeV	μ ~ 0.105 GeV	τ ~ 1.8 GeV	-1
	ν_e ~ 0.0 GeV	ν_μ ~ 0.0 GeV	ν_τ ~ 0.0 GeV	0

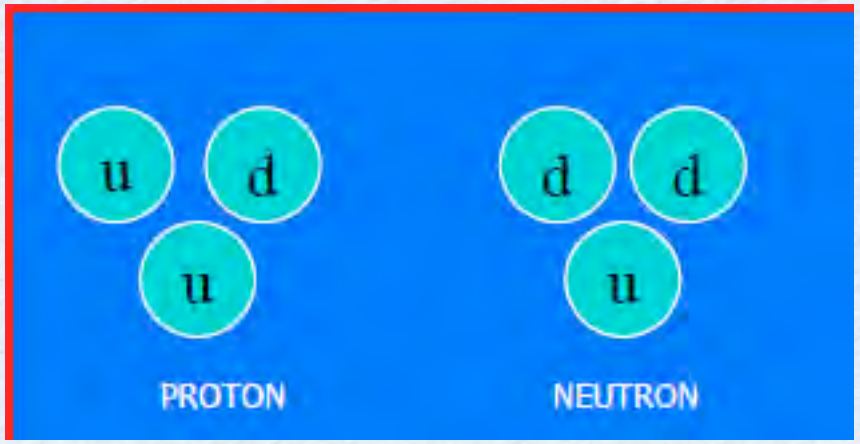
(Each generation box lists "mass" above the masses.)

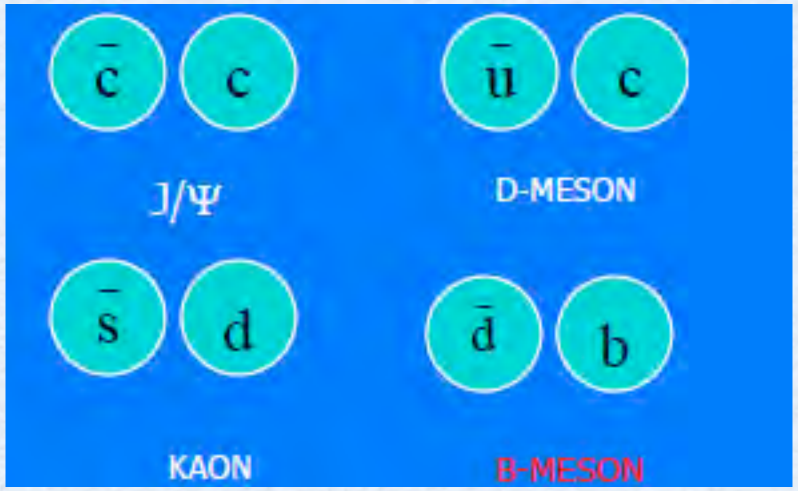
- In 1928 Paul Dirac proposed that you could create particles from energy based on negative energy solutions to his attempt to unify quantum mechanics and special relativity
- But how can you create a single electron? Won't that violate conservation of charge and angular momentum?

- In 1928 Paul Dirac proposed that you could create particles from energy based on negative energy solutions to his attempt to unify quantum mechanics and special relativity
- But how can you create a single electron? Won't that violate conservation of charge and angular momentum?
- Yes - but you can produce an electron and anti-electron (positron) pair and conserve quantum numbers

BUILDING BLOCKS

- Stable particles - almost all of the world around us is composed of the 1st generation of elementary particles





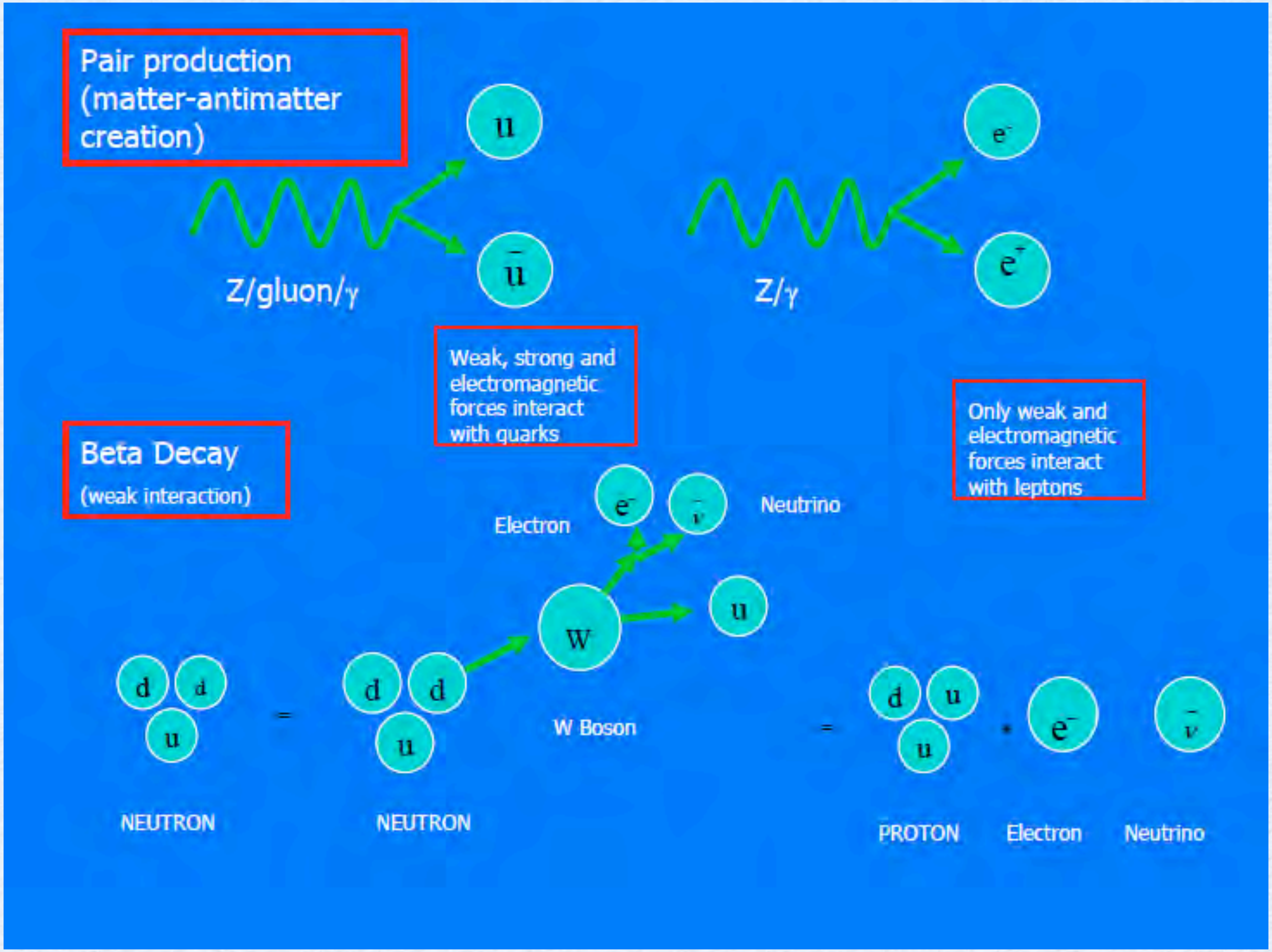
- Unstable particles
- Need to be created by high energy interactions
- 'Heavy' and do not live long decay into lighter particles

Interactions

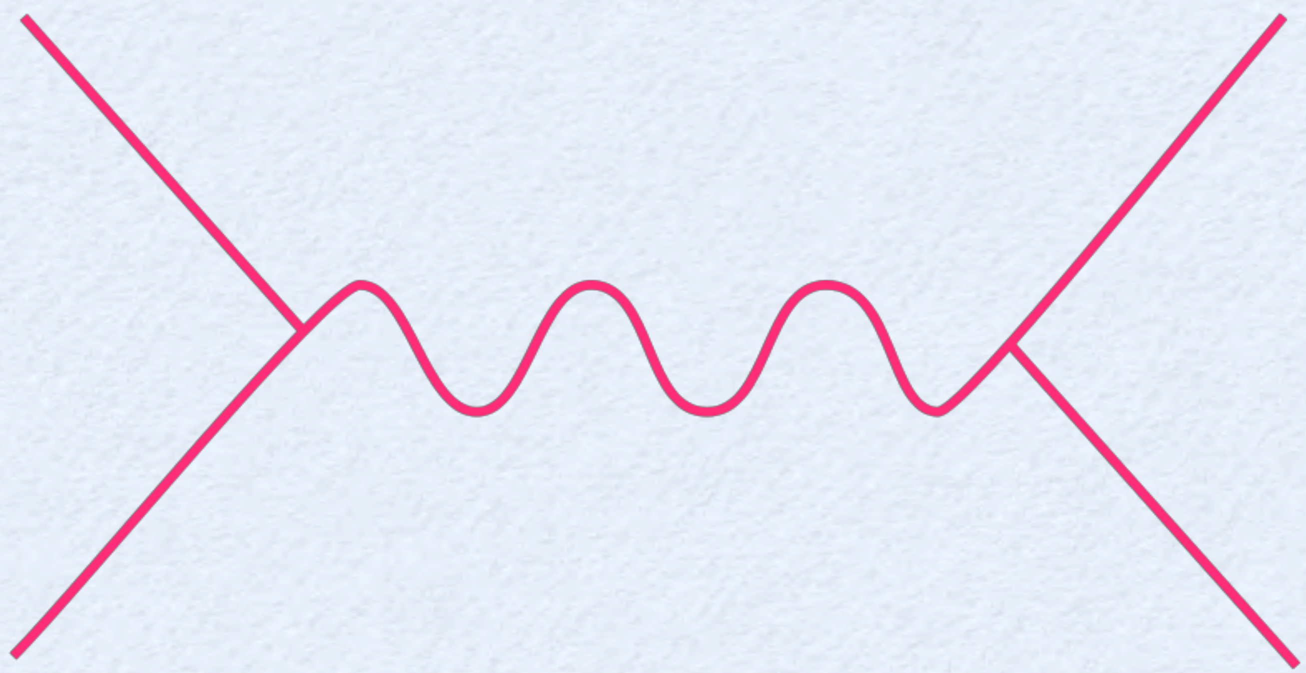
Force	Particle	Where found?
Electromagnetic	γ	magnets
Strong	gluon	Sun, nuclei
Weak	W^+, W^-, Z^0	Beta-decay
Gravity	Graviton (still to be discovered)	Earth

- What causes particle interactions?
- 4 fundamental forces
  - E&M
  - Strong Nuclear Force
  - Weak Nuclear Force
  - Gravity

Interactions



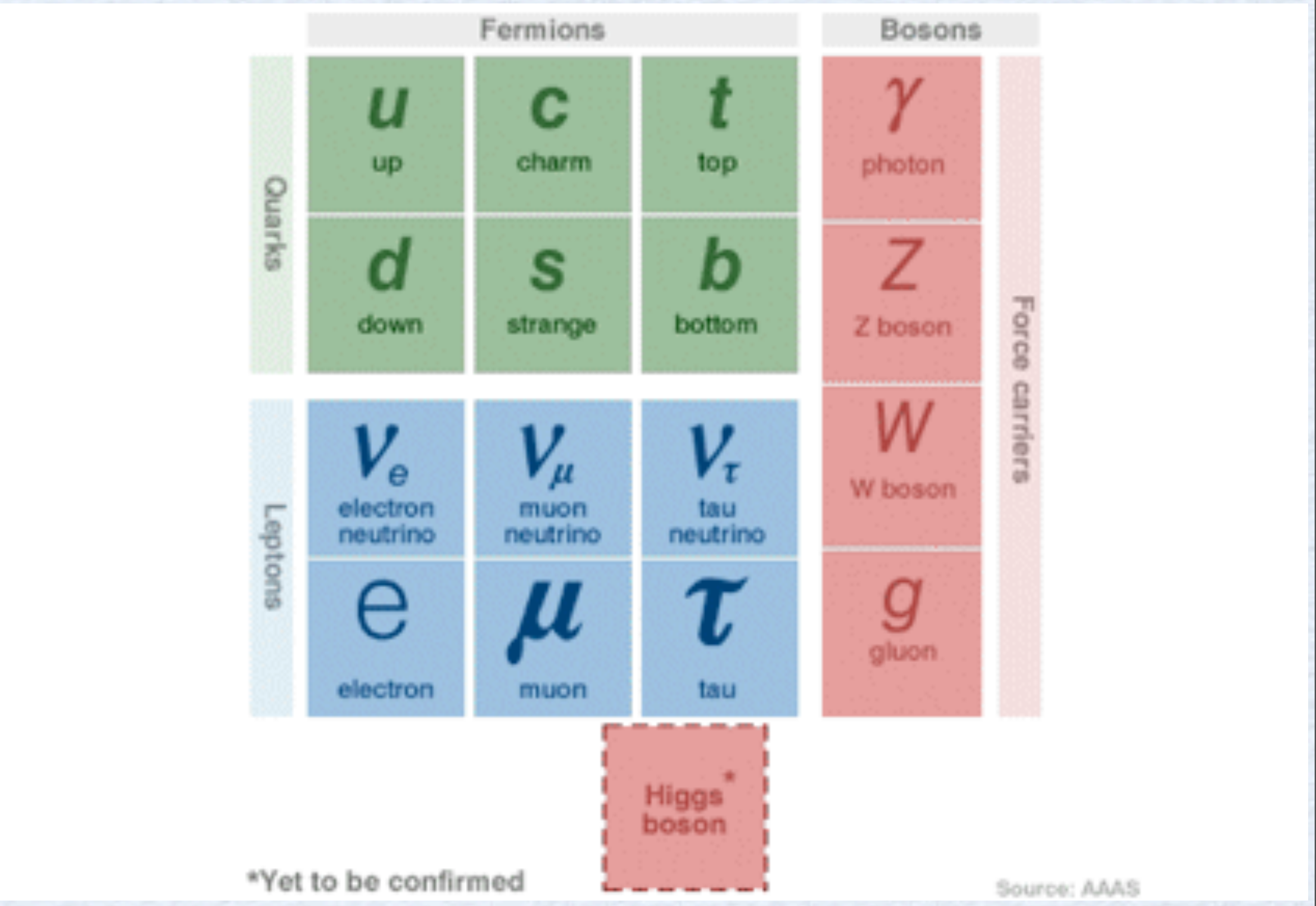
Interactions



- Forces can be explained in terms of exchange of particles (bosons)
- The calculation of different processes is done in Quantum Field Theory which describes elementary particles and their interactions

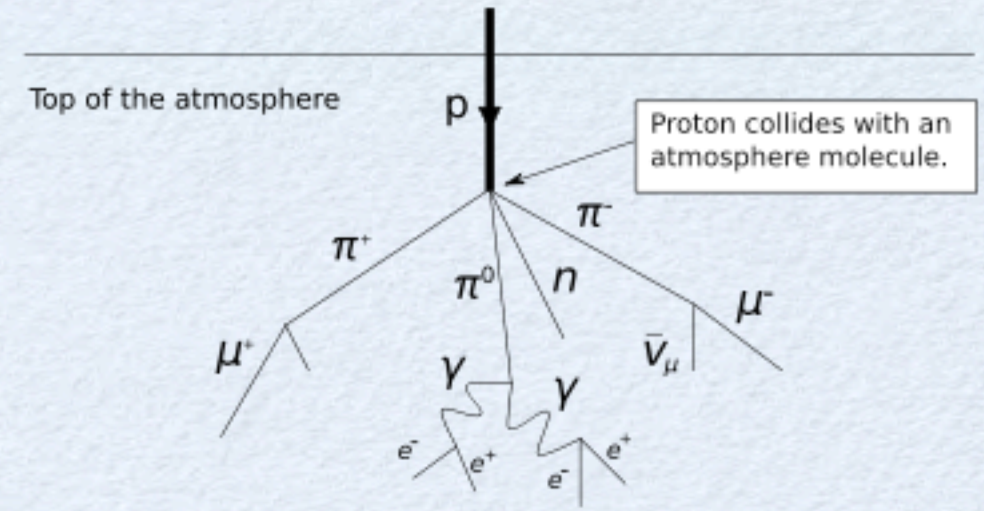
The Standard Model

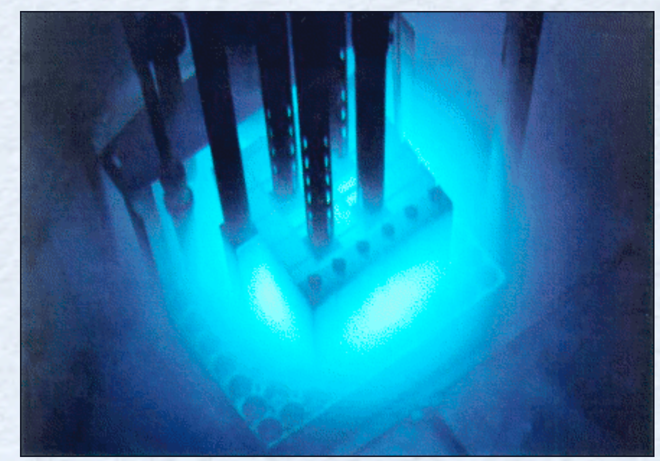
- We can describe matter and their interactions using 6 quarks, 6 leptons, and 4 force carrying bosons
- The particle content and their interactions is called the 'Standard Model'
- What about Gravity?
- Experimentally we have not detected a graviton so we cannot verify any quantum field theory



How do we study particles?

- Need to have the particles around to study
  - electrons and protons are no problem - they are everywhere!
  - more exotic particles are more difficult
- Essentially three ways:
  - Cosmic Rays
  - Nuclear Reactors
  - Particle Accelerators





Review of Special Relativity

- In HEP, you need to be acquainted with special relativity because particles are generally moving at relativistic speeds! (i.e HIGH energy)
- Going to assume basic familiarity with relativity and notation
- If this is completely unfamiliar to you please look it up and review (PDG, online, a variety of text books)
- For the exercises and in this class and the research progress you need a working knowledge of how to manipulate 4-vectors, compute invariant masses, angles, etc...

Four-vectors

- To describe interactions of elementary particles we need to describe how they interact eg:
    - how they collide or scatter
    - how they decay
- Regardless of the interactions we need to conserve energy and momentum during these processes
    - For particles moving at speeds close to the speed of light we need to use relativistic kinematics
    - interestingly - as an experimentalist this turns out to be a much more important skill set then quantum mechanics...

4-VECTORS

The components of a 4-vector can be written

$$a^{\mu} = (a^0, \vec{a}) = (a^0, a^1, a^2, a^3)$$

c = 1

$$\gamma = \sqrt{\frac{1}{1-\beta^2}}$$

Transformed into a moving frame

$$(a^0)' = \gamma(a^0 - \beta \cdot a^3)$$
$$(a^1)' = a^1$$
$$(a^2)' = a^2$$
$$(a^3)' = \gamma(a^3 - \beta \cdot a^0)$$

Lorentz Transformation

Covariant notation

$$a_\mu = (a_0, a_1, a_2, a_3) = (a^0, -a^1, -a^2, -a^3)$$

- Since the metric has -1 along the diagonal for the spatial components

$$a \cdot b = \sum_\mu a_\mu \cdot b^\mu = a_\mu b^\mu = (a^0)^2 - (\vec{a})^2$$

- Adopt this notation for easy computation
- By explicit calculation one can show that the dot product of two four-vectors is a Lorentz invariant (do this at home!)

$$a \cdot b = a' \cdot b'$$

4-MOMENTUM

The 4-momentum of a particle can be written

$$p^{\mu} = (E, p_x, p_y, p_z) = (E, \vec{p})$$

The mass is invariant w.r.t Lorenz transformations , and in particular in the rest frame of the particle

$$p_{\mu} p^{\mu} = E^2 - \vec{p}^2 = E^2_{rest} = m^2$$

Classically p = mv so a massless particle would also have zero momentum. Relativistically this is no longer the case and with v = c a massless particle can have any momentum

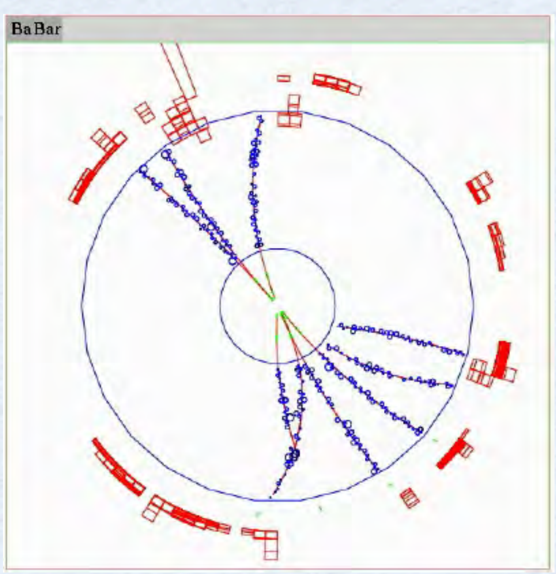
How does this come up?

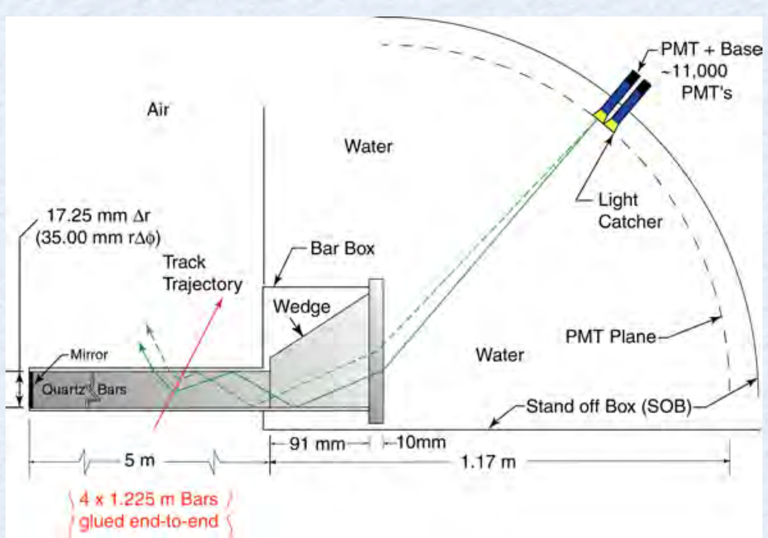
We don't have detectors which measure elementary particle mass directly! But...

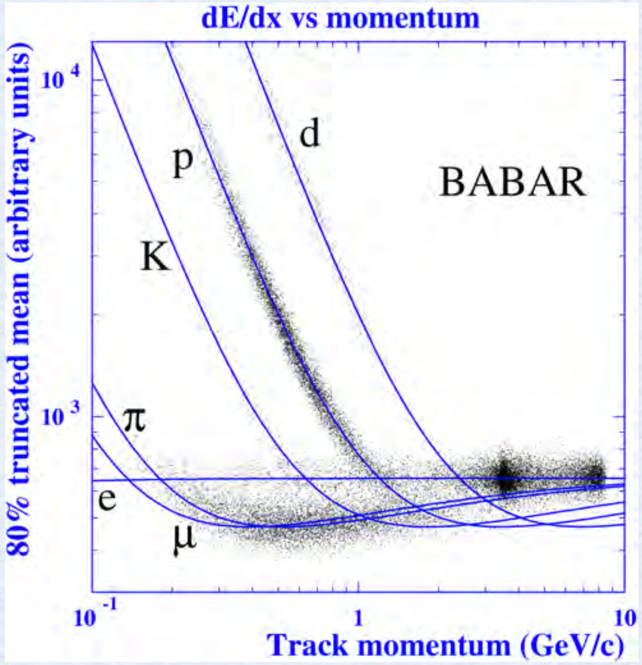
We measure momenta of charged tracks from their radii of curvature in a magnetic field:

$$p = m\beta\gamma = 1/r$$

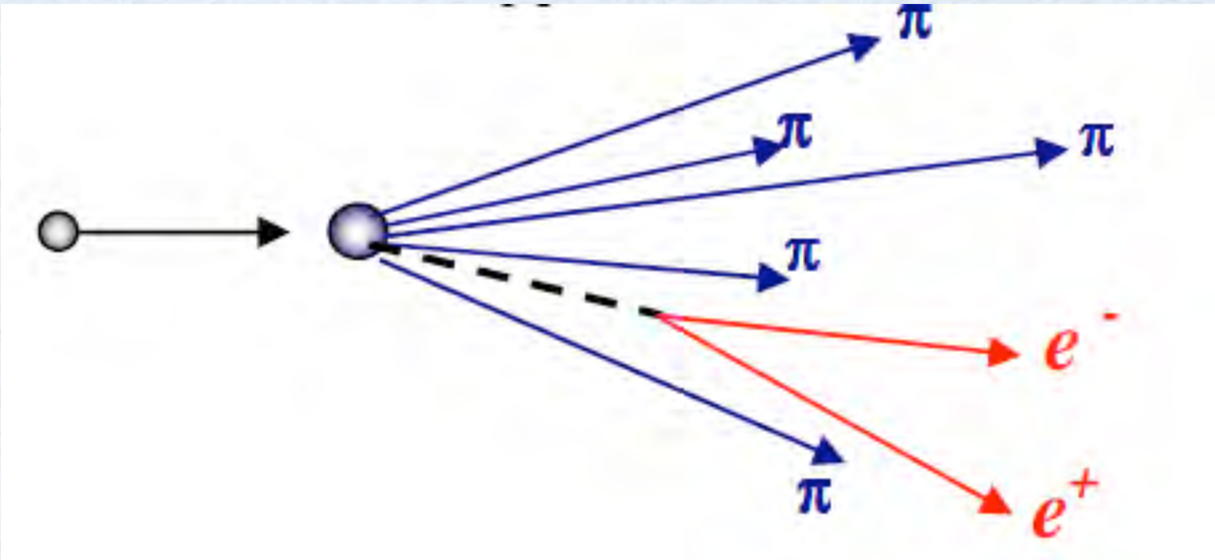
Cerenkov light and specific ionization depend directly on the speed of a particle, β .



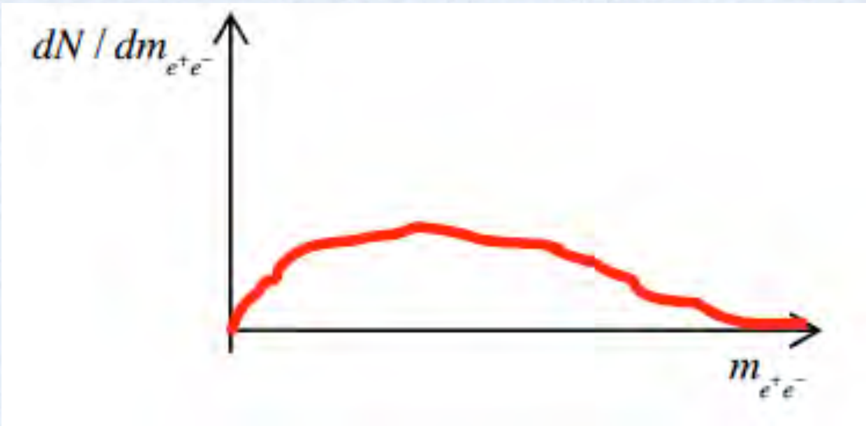




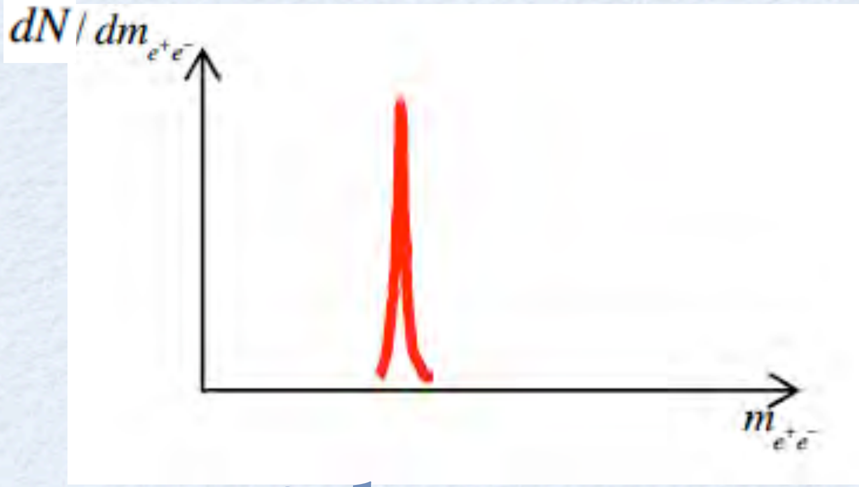
Simple but typical example



- Say we collide a proton with a nucleus of a target
- Many new particles created



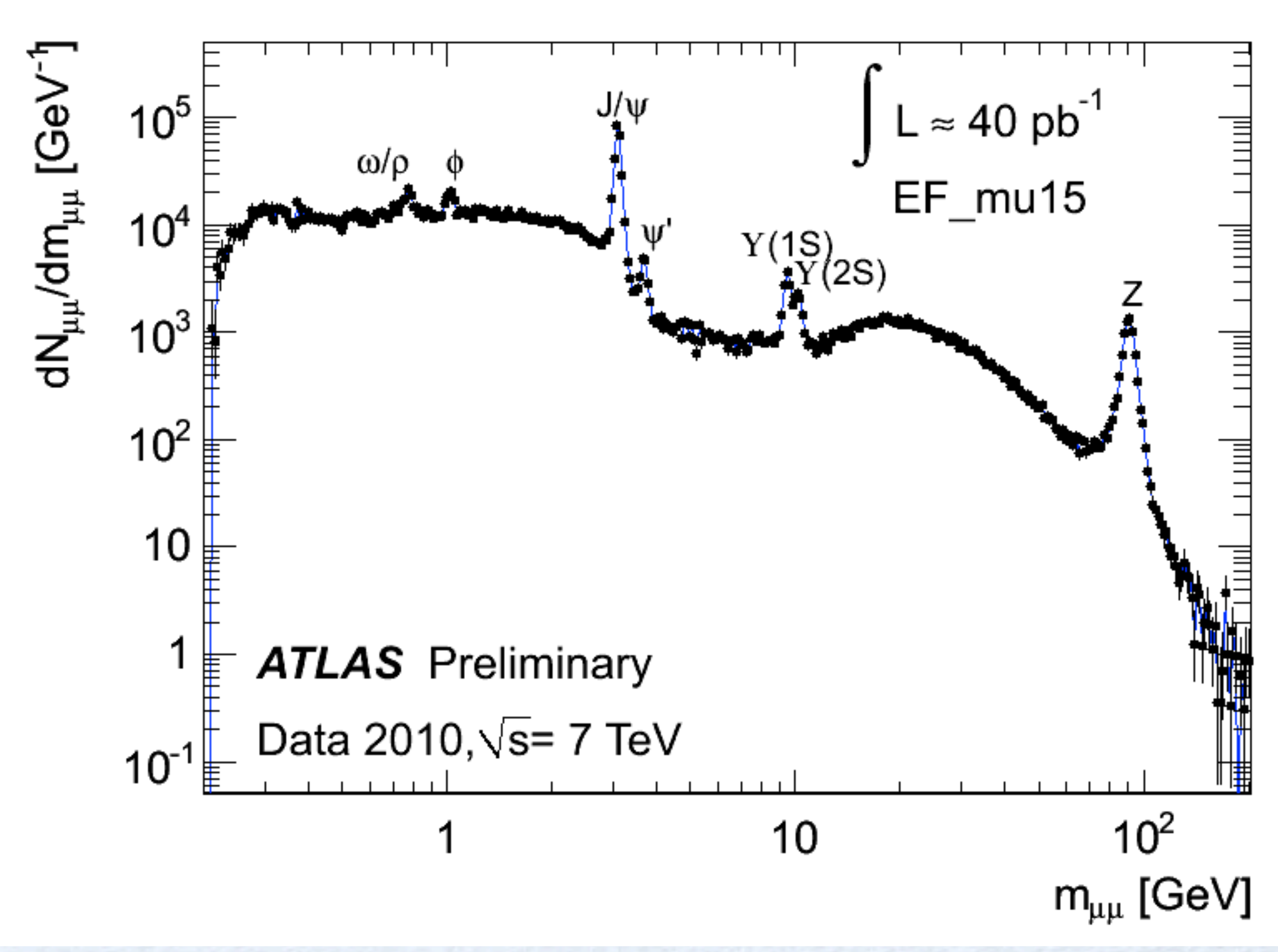
if the electrons were created independently



If they came from the decay of a particle

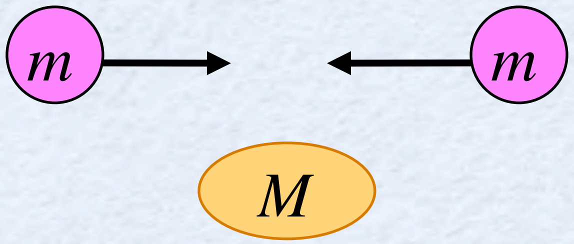
A Real Example

- Invariant mass of dimuon pairs from the ATLAS experiment
- Particles appear as resonances in the spectrum



EXAMPLE

- Two lumps of clay, each with mass m, collide head on at 3/5 c producing one larger mass of clay. What is the mass of the mass of the final lump of clay.



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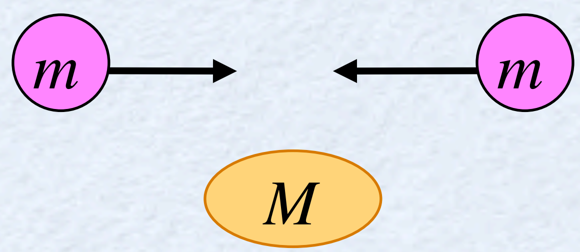

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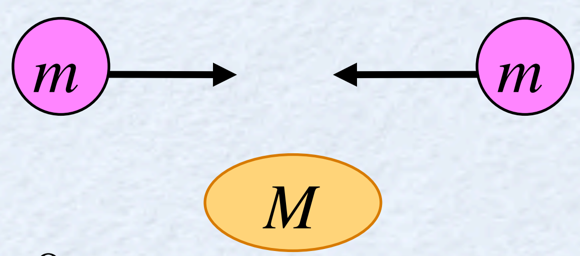

$$\vec{p} = \vec{p_1} + \vec{p_2} = 0$$

$$\begin{aligned} E = E_1 + E_2 = 2m\gamma &= \frac{2m}{1-\beta} \\ &= \frac{2m}{1-0.6^2} \\ &= \frac{2m}{0.8} \\ &= \frac{5}{2}m \end{aligned}$$

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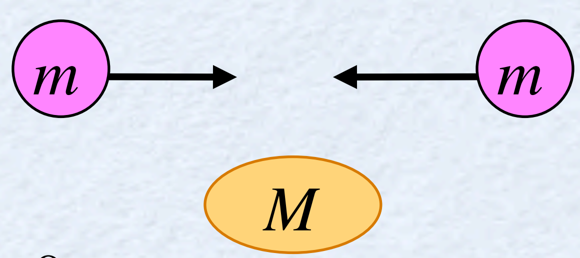

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$$M^2 = E^2 - p^2 = E^2$$

$$m = E = \frac{5}{2}m > 2m$$

For Homework

- A pion at rest decays into a muon and a neutrino (take as massless). What is the speed of the muon?

Particle Colliders

- Why do we collide particles?
- If you wanted to know how your wrist watch worked would you through two of them together really hard?

Particle Colliders

- while you can take apart a watch and look at all the pieces with a screwdriver - you can't do this with an elementary particle?
- The probe needs to be smaller or on the same size as the thing you are trying to investigate!
- For an elementary particle the only thing you have are other elementary particles!

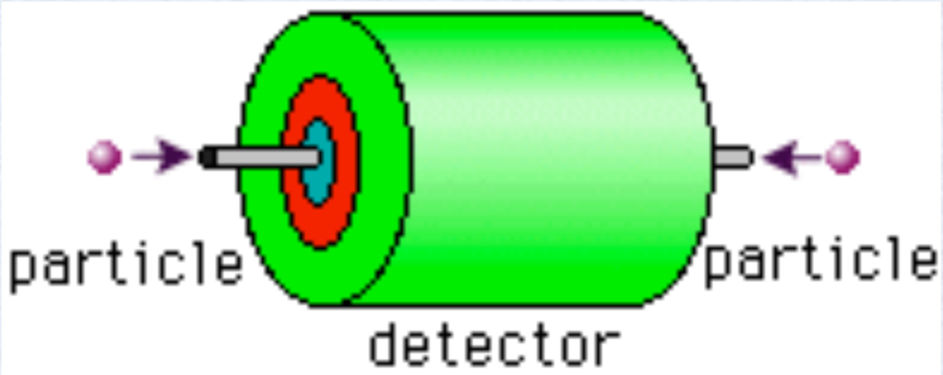
What type of collider

- Fixed Target:
  - collide particles into a macroscopic sized fixed target of dense material
  - ADVANTAGE: (relatively) large probability for the probe particles to hit the target

why is the detector in a small wedge?

What type of collider

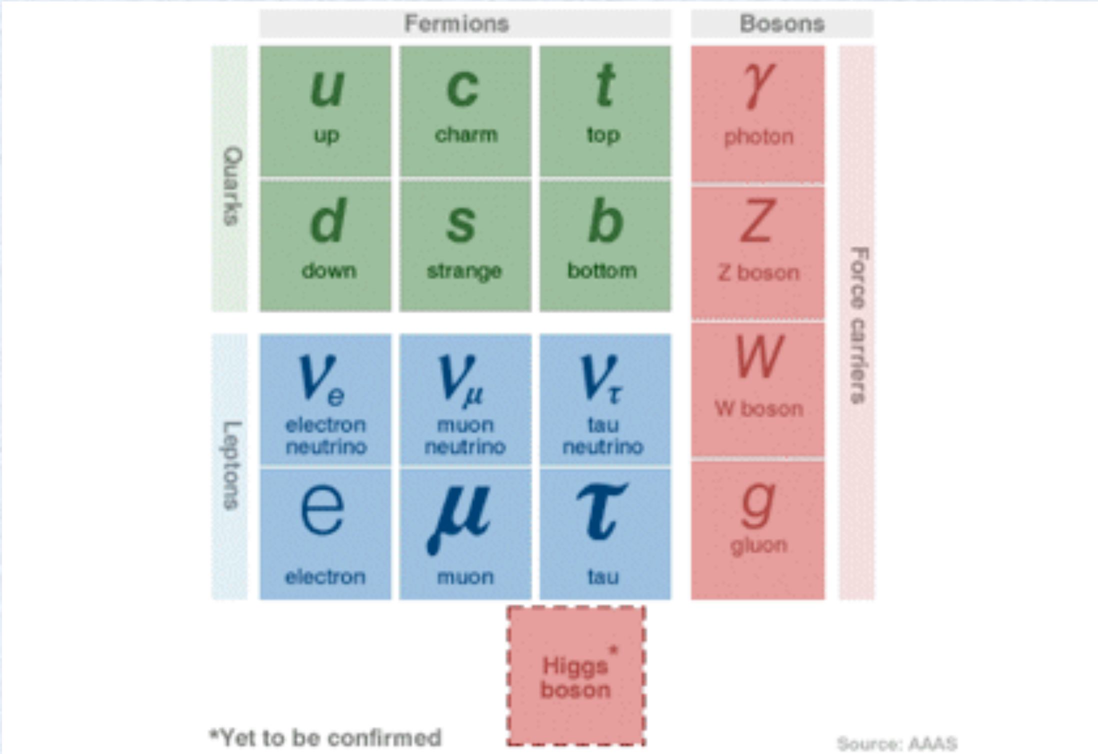
- Colliding beams
  - smash two high energy particles into each other
  - ADVANTAGE: more of the energy in the center of mass frame for heavy particle production



why is the detector surrounding the interaction point?

The LHC: Why did we build it?

The Standard Model is a beautiful theory
- explains a wide variety of phenomena and interactions
-withstood 3 decades of assault with experiment



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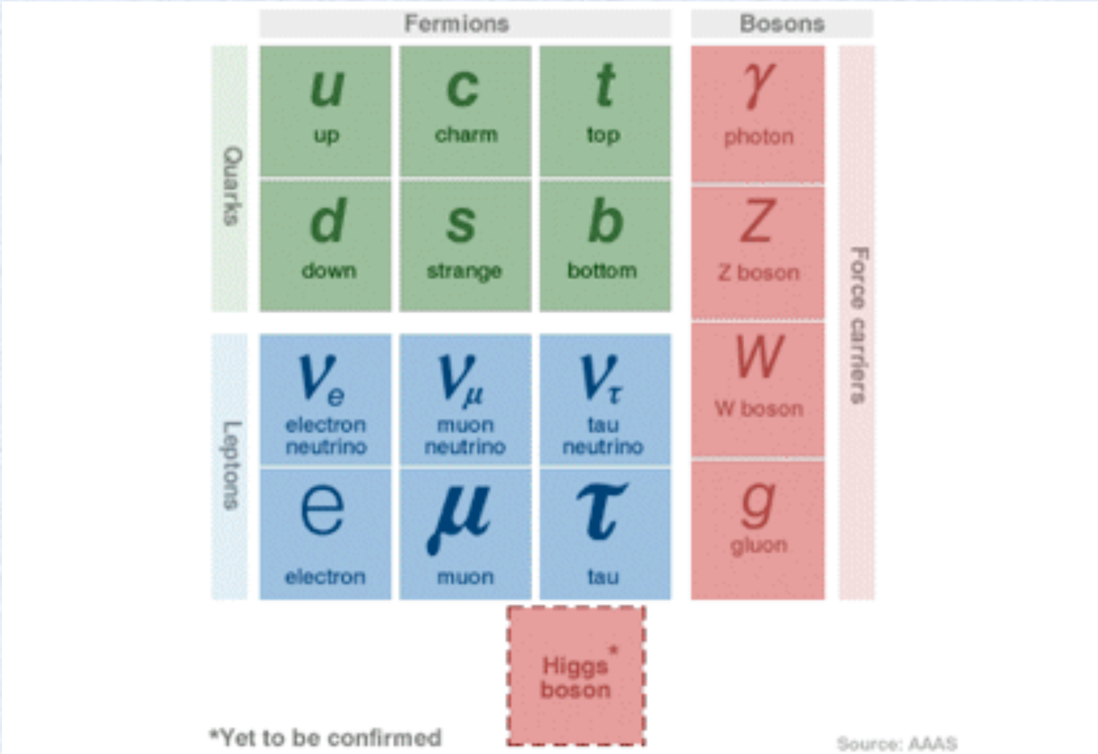
    - does not explain gravity
    - does not explain dark matter
    - mechanism of mass generation not yet verified



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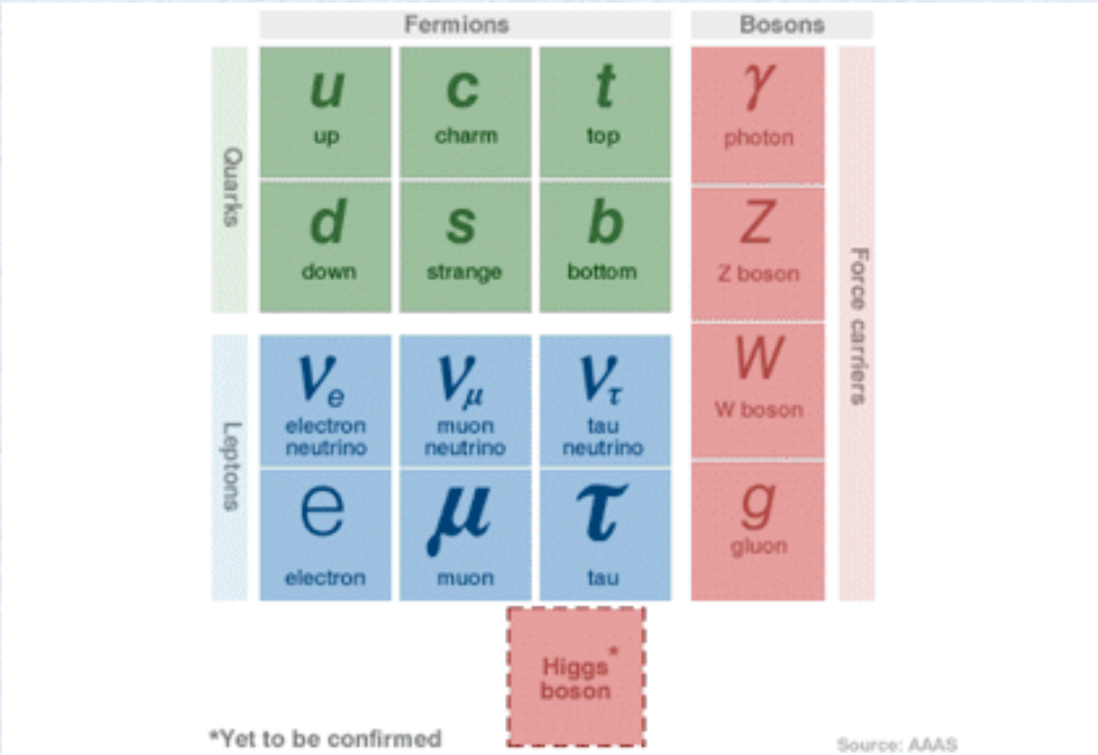
    - mathematical inconsistencies at high energy - must be an effective theory
    - many seemingly arbitrary but crucial parameters



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Build a high energy collider that can produce new heavy particles and test the consistency at high energy!

TABLE TOP

J.J. Thomson with apparatus used to identify electron as elementary particles (Cambridge, 1897)

Table top = too small

J.J. Thomson with apparatus used to identify electrons as elementary particles (Cambridge, 1897)

University/Lab Scale

Bevatron 6.5 GeV proton accelerator, Berkeley, USA.
discovery of the antiproton (1955) and antineutron (1956)

Still too small

Bevatron 6.5 GeV proton accelerator, Berkeley, USA:
discovery of the antiproton (1955) and antineutron (1956)

The largest machine ever built!

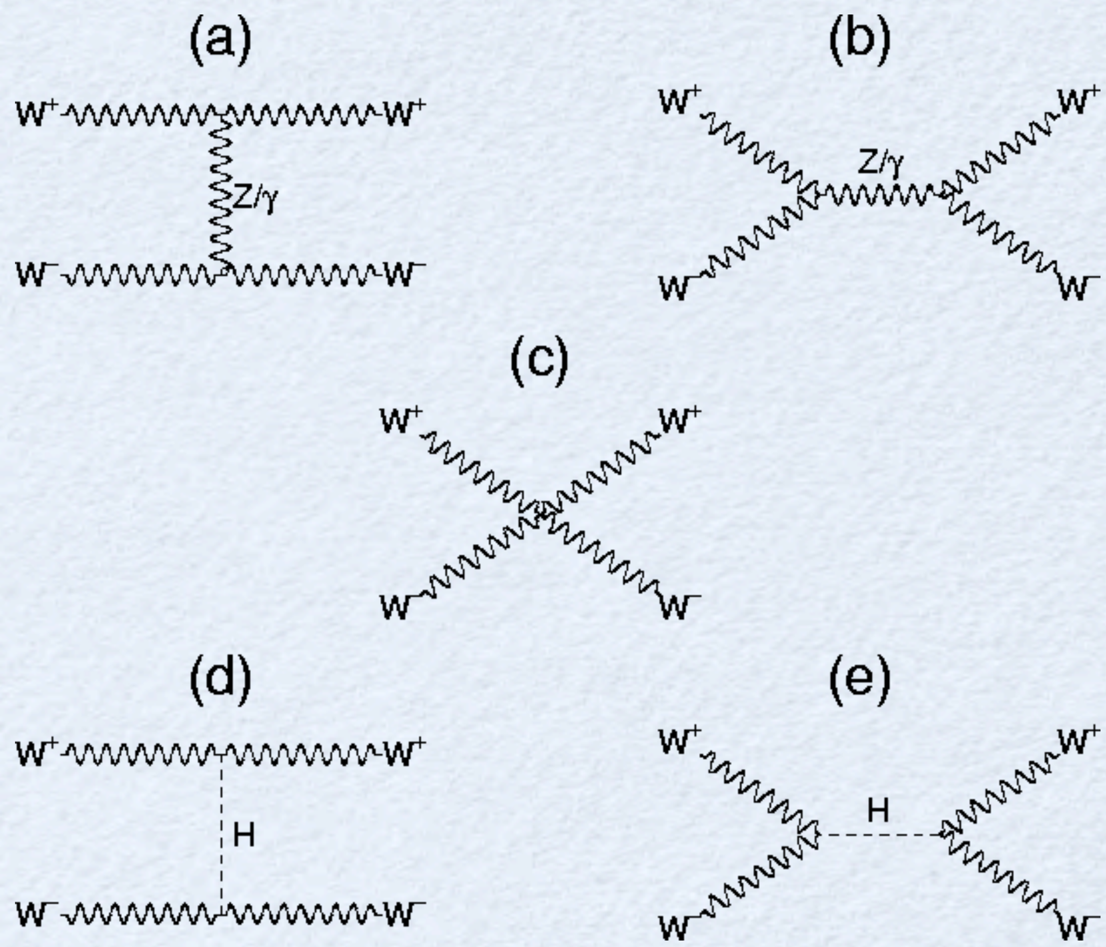
You are here •

HOW TO BUILD IT

- First choice - fixed target or collider?

What energy do we need?

- As it turns out - the Standard Model breaks down at ~1 TeV without something to regulate WW amplitudes



Fixed target or colliding beams?

Assume we want to reach $\sqrt{s} \approx 1$ TeV $>> m_p$

pp Collider

$s = (p_1 + p_2)^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$

For a symmetric collider with beam energy $E_b = E_1 = E_2$:

$\sqrt{s} = 2E_b \Rightarrow E_b = 500$ GeV for $\sqrt{s} = 1$ TeV

Proton beam on proton target

$s = (p_1 + p_2)^2 = (E_b + m_p)^2 - (\vec{p}_b + 0)^2$

$s = E_b^2 + 2m_pE_b + m_p^2 - p_b^2 \approx 2m_pE_b$

$\sqrt{s} = \sqrt{2m_pE_b} \Rightarrow E_b = 500$ TeV for $\sqrt{s} = 1$ TeV

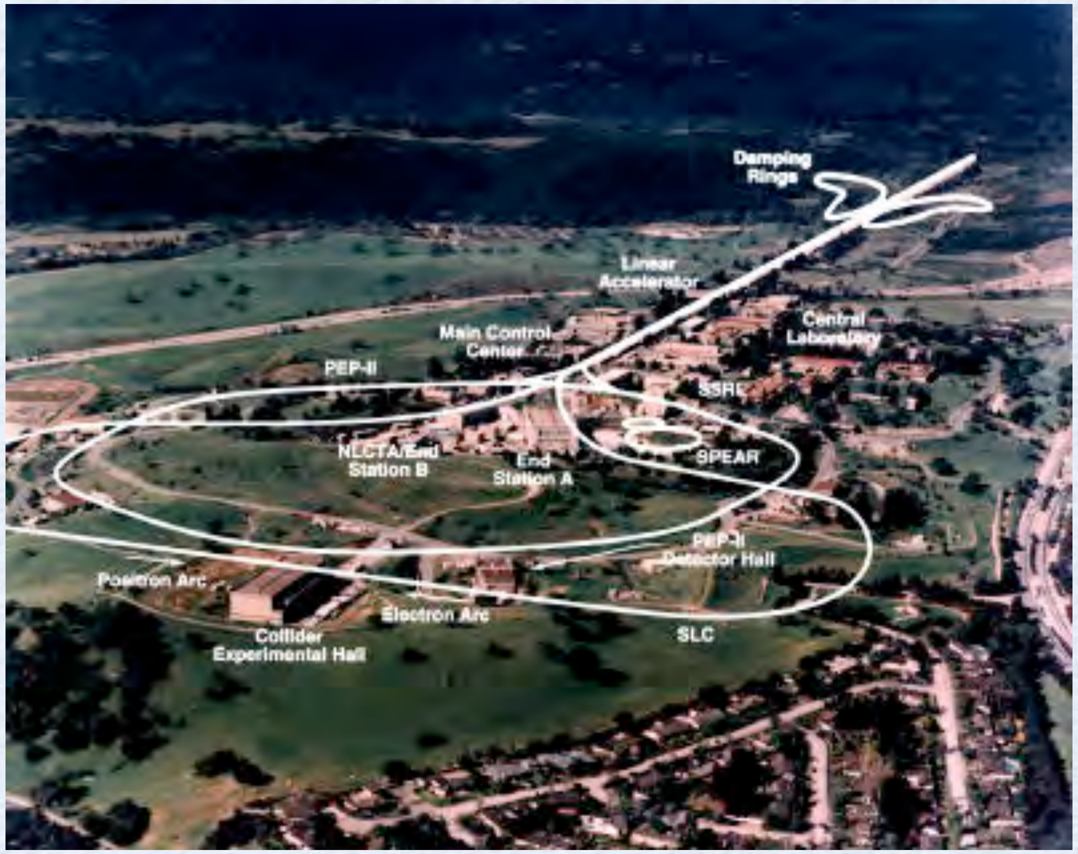
Unfortunately, we don't know how to make 500 TeV beams

What particles to collide

- So far we have collided
  - electrons, positrons, protons, antiprotons
- Everything else decays!

What about e+e-?

- Colliding fundamental particles , e+e-, means that essentially every interaction is a fundamental one.
- e+e- completely annihilate and and all energy can go into particle production
- long history of e+e- success



Recall Basic E&M

- Charged particles radiate when they are accelerated
- When going in circles this is called 'synchrotron radiation'

Circular machines limited by synchrotron radiation.
For a circular machine of radius R, particles radiate at a rate:

$$P = \frac{1}{6\pi\epsilon_0}\frac{e^2a^2}{c^3}\gamma^4$$

where $a = v^2/R$ and $\gamma = E/m$ is the Lorentz factor.

The energy loss per turn W is P multiplied by the time spent in the bending magnets $2\pi R/v$

Limitations on Design

Strong dependence on mass of particle being accelerated!

Electrons
For $v \approx c$, E in GeV and R in kilometers:
$W = 8.85 \times 10^{-5} E^4/R$ MeV/turn

$W = 14$ MeV/turn for $E = M_Z/2$ at LEP,
$W \approx 200$ GeV/turn for $E = 500$ GeV at LEP
$\Rightarrow$ a 1 TeV e^+e^- machine must be a linear collider

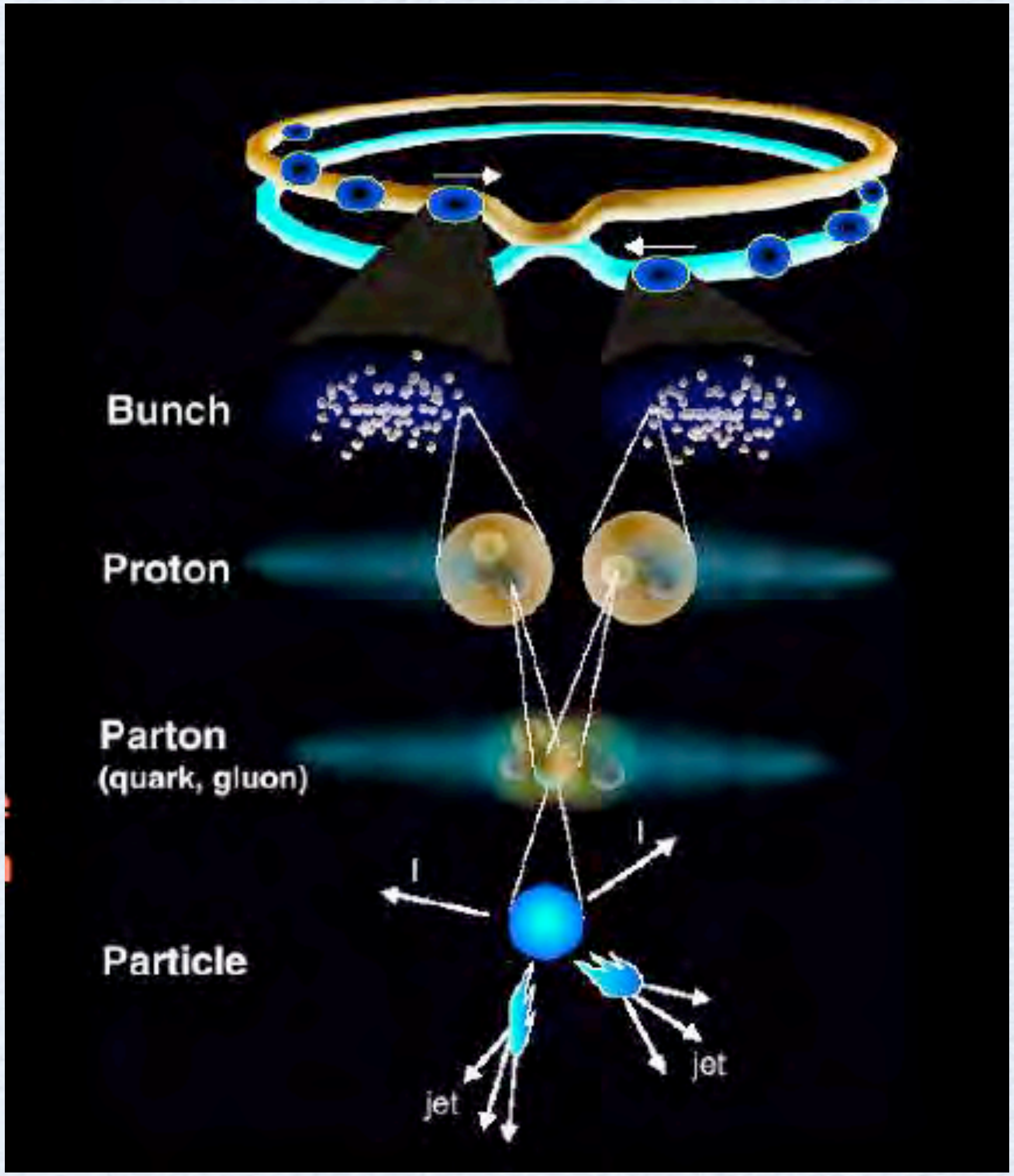
Protons
W down by a factor of $(m_e/m_p)^4$.
For $v \approx c$, E in TeV and R in kilometers:
$W = 7.8 \times 10^{-3} E^4/R$ keV/turn

BUT...

- Keep in mind when a theorist tells you 1 TeV, they mean it could be 1 or 2 or maybe 3 TeV or you know for sure less than 10 TeV!"
- Exploring this energy range faster means going with a proton collider as we have not yet built a 1 TeV electron/positron machine!

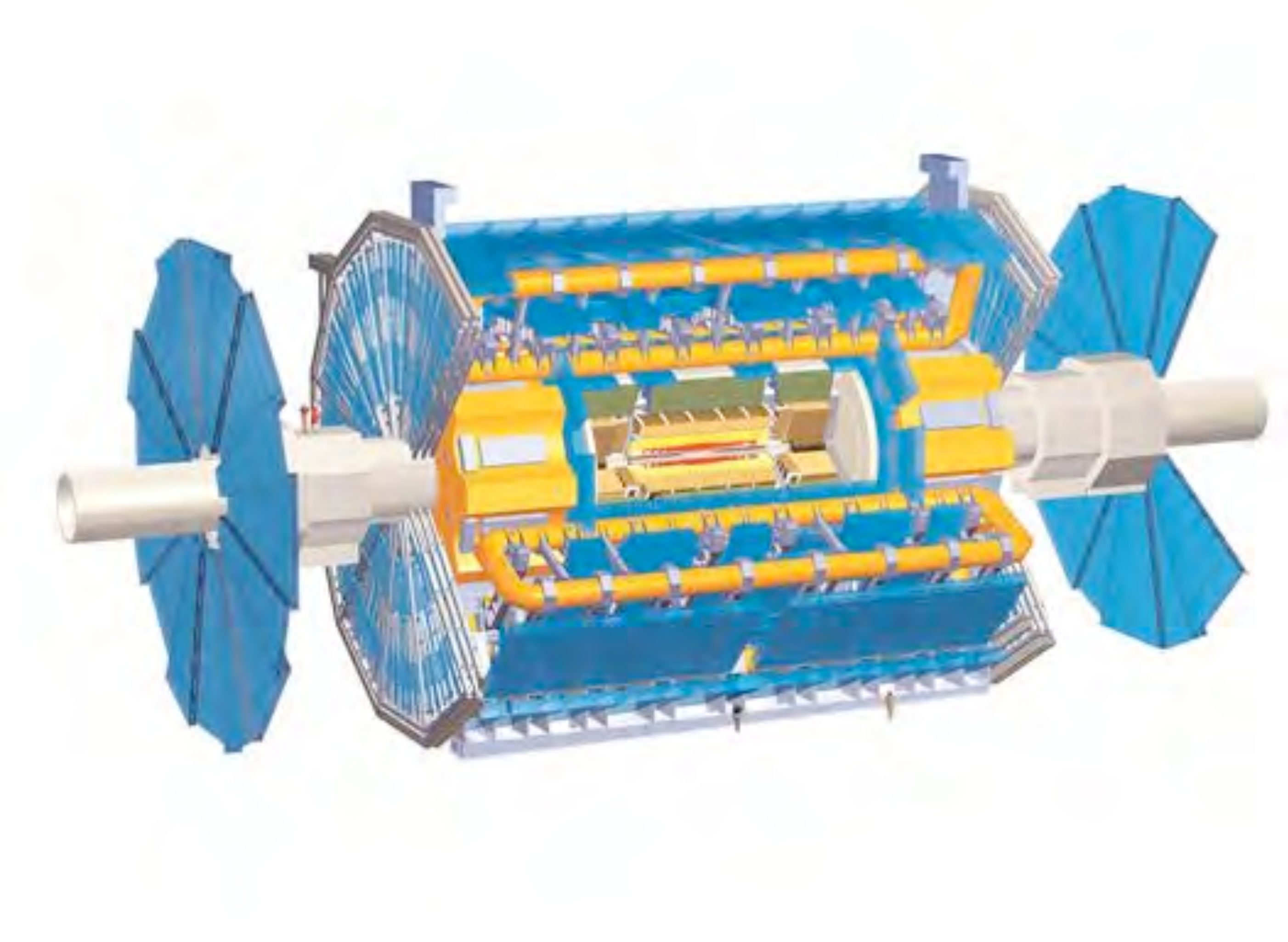
LHC Basics

- Two beams circulating in opposite directions with ~3000 bunches of 10^11 protons
- usually in separate pipes, but crossing each other in 4 places
- ~20 collisions every 25 ns
- need gazillions of collisions because the ones that we are really interested in may only happen one in a billion or one in a trillion collisions!

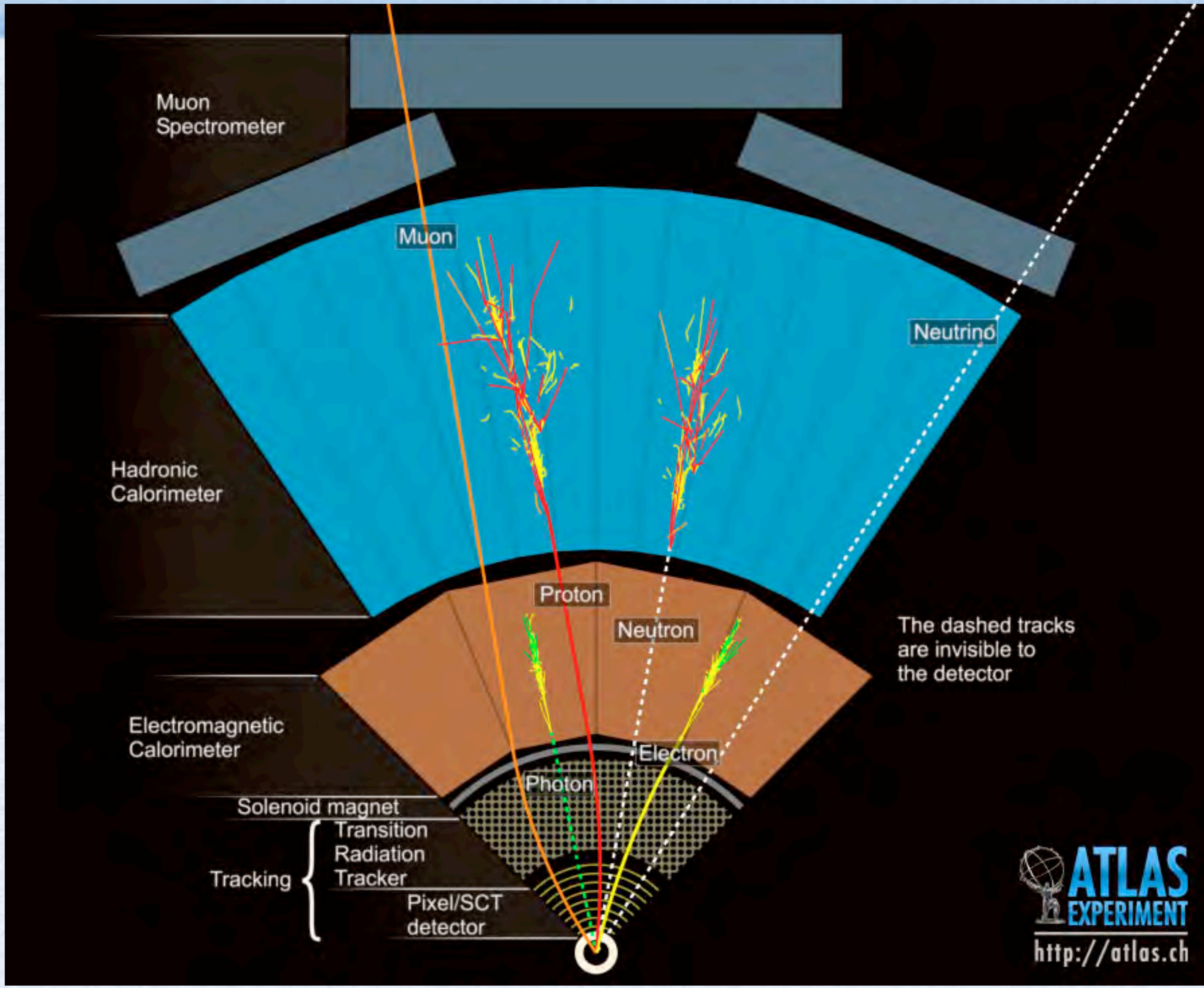


Detectors

- So far we have produced, accelerated, and collided particles
- But we cannot yet know what happened during each collision exactly.
- But we can identify and measure the particles that come out of the collision and `reconstruct'

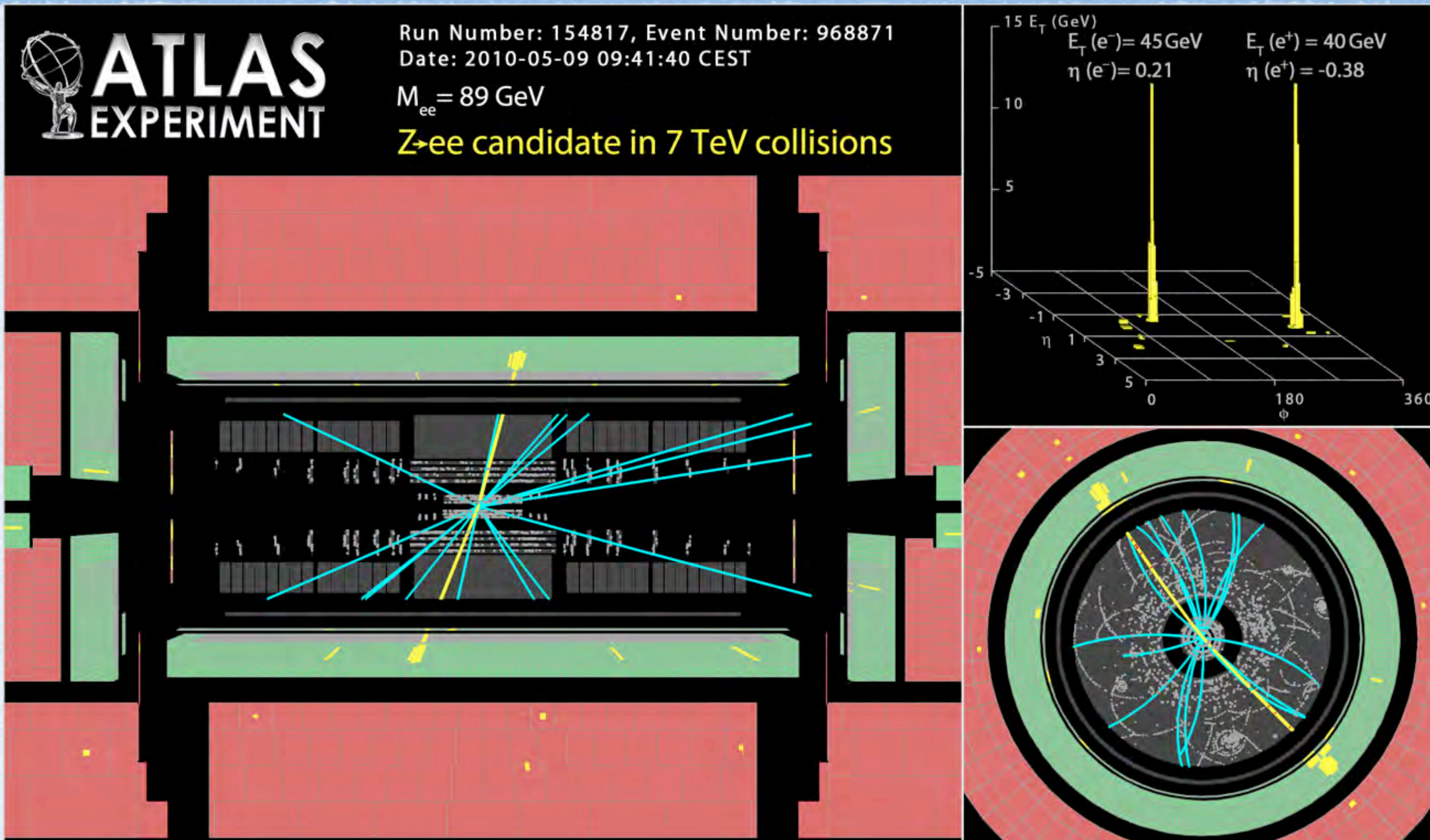


ONE EXAMPLE..



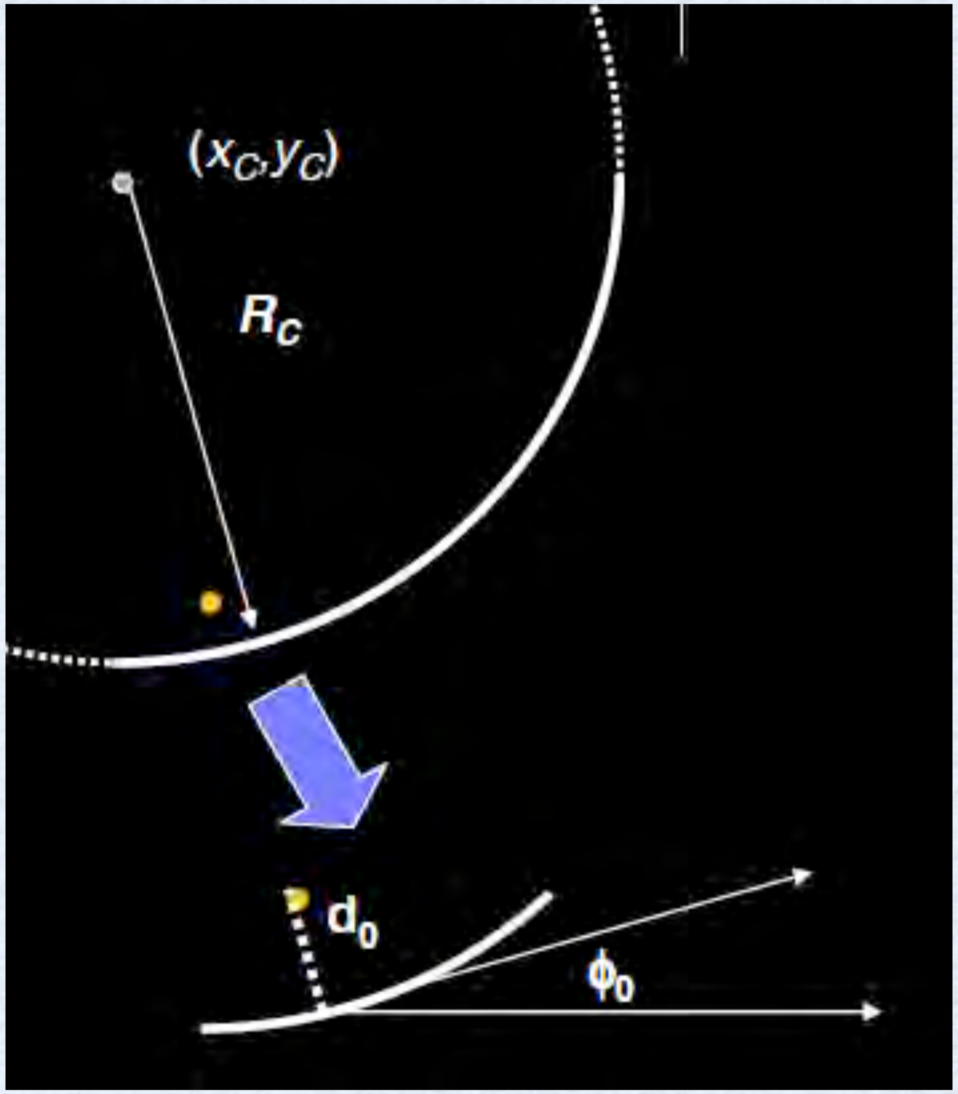
Muon
Spectrometer
Muon
Neutrino
Hadronic
Calorimeter
Proton
Neutron
The dashed tracks
are invisible to
the detector
Electromagnetic
Calorimeter
Electron
Photon
Solenoid magnet
Transition
Radiation
Tracker
Tracking
Pixel/SCT
detector
ATLAS
EXPERIMENT
http://atlas.ch

Reconstructed Event



Track Reconstruction

- Tracks curl in a magnetic field (you remember how from EM)
- Describe geometric helix
  - simplest geometry B-field from a solenoid
- 5 parameters
  - d0 - distance of closest approach in transverse plane
  - phi0 - phi at distance of closest approach
  - curvature - 1 /R
  - z0 - distance of closest approach in longitudinal direction
  - cot(theta) - other angle

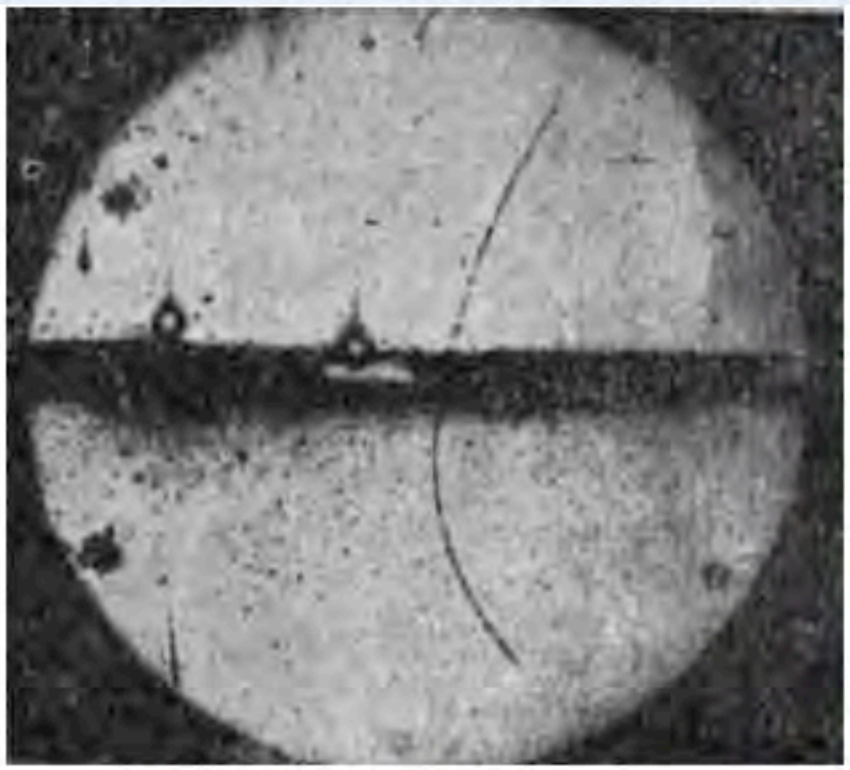


TRACKING

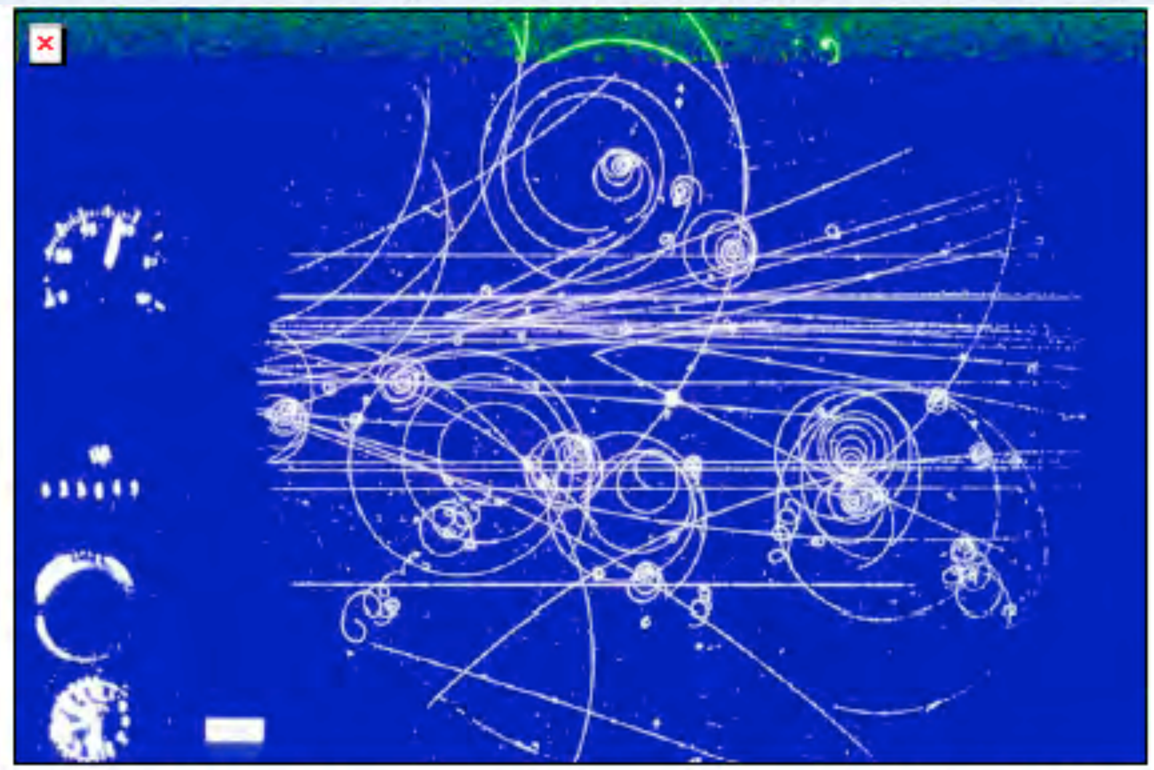
- Moving object disturbs the material through which it passes
- Keen observers can learn:
  - identity - what made the track
  - position - where did it go through
  - direction - which way did it go
  - velocity - how fast was it moving

Charged particle tracking

Charged particles leave tracks as they penetrate material



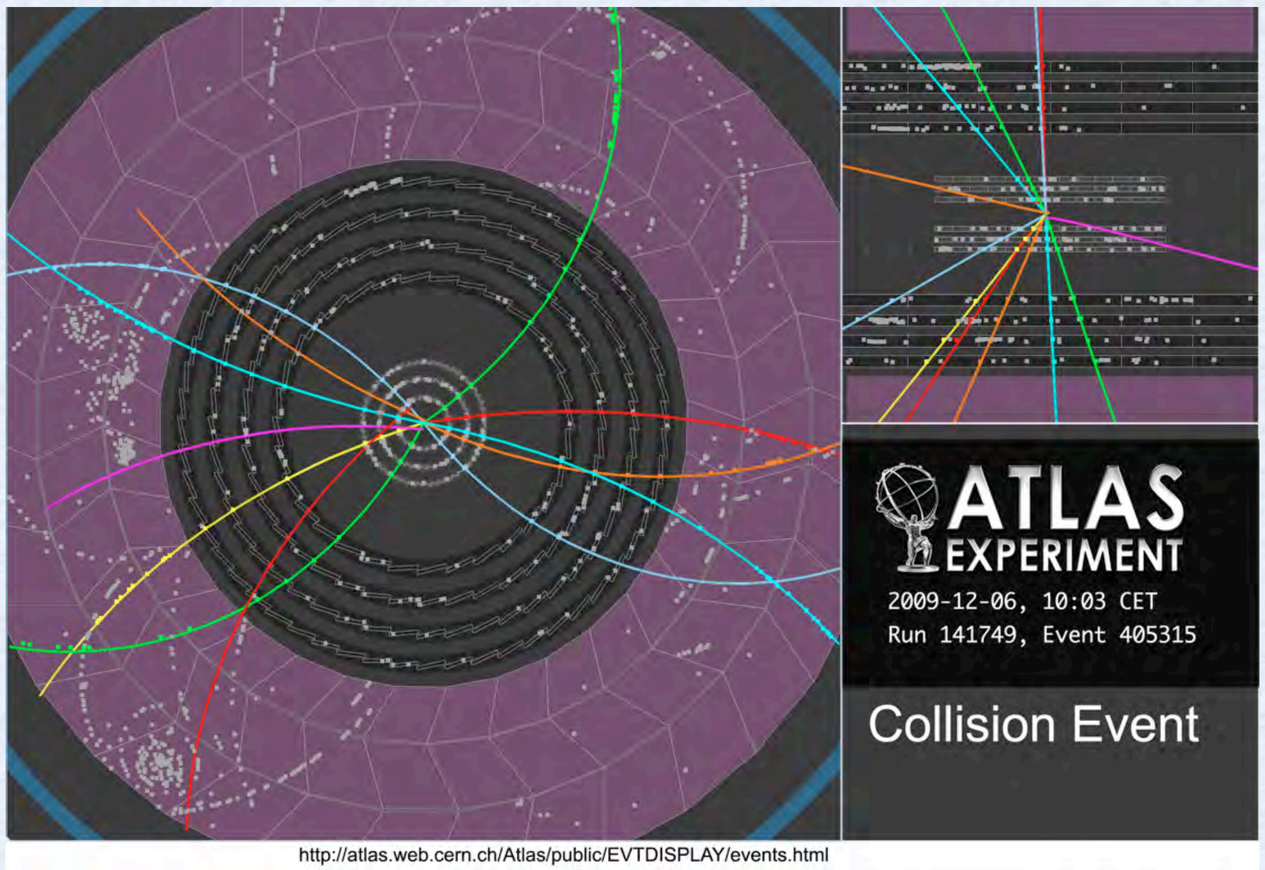
Discovery of the positron
Anderson, 1932



16 GeV π^- beam entering a liquid-H_2 bubble chamber at CERN, circa 1970

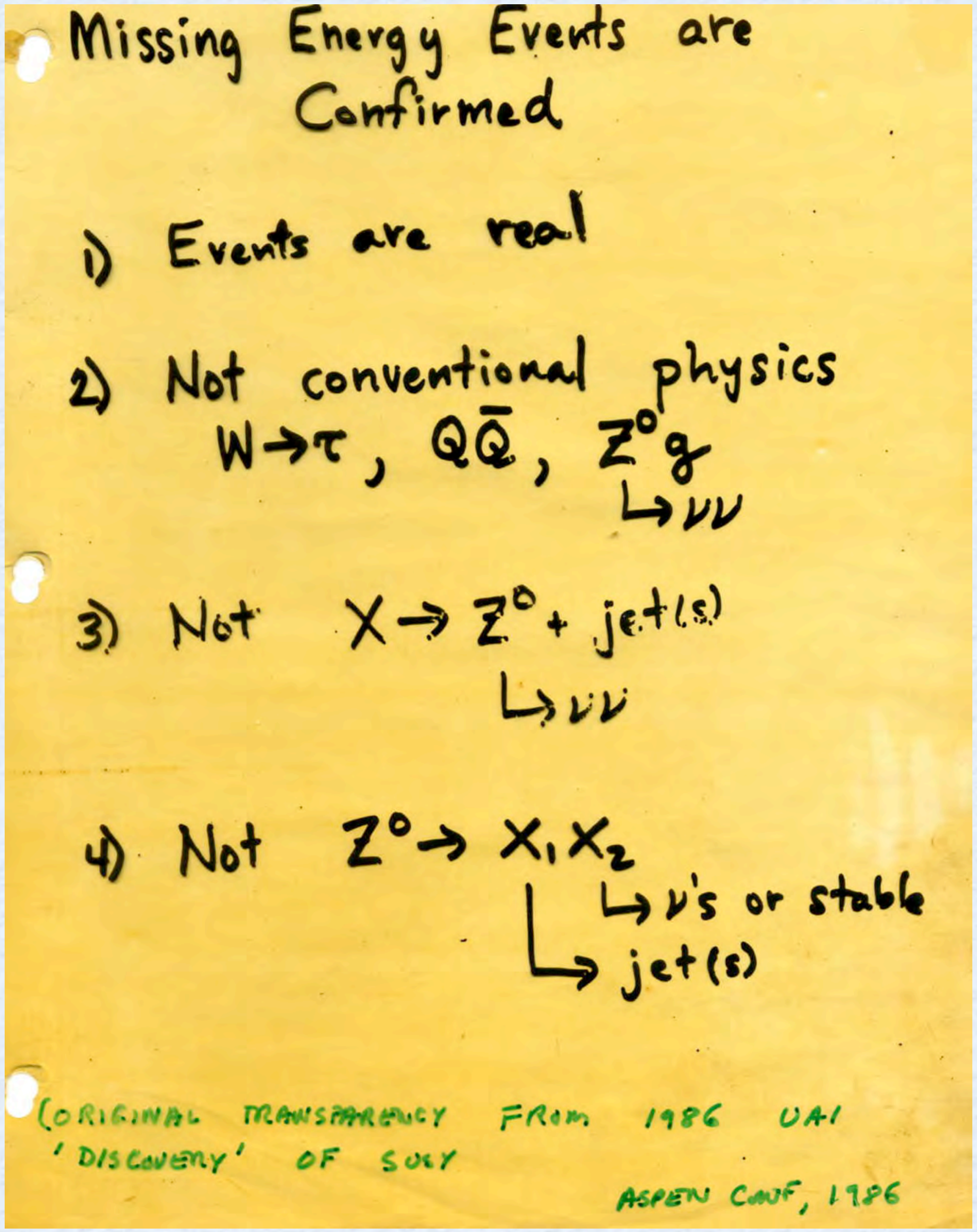
"Footprint" in this case is excitation/ionization of the detector material by the incoming particle's electric charge

From Ionization to 4-vectors



- Would like to know particle type and 4-vectors of these particles that came out of the interaction
- what you actually measure is some basic physical quantity (voltage , current)
- many steps in between
  - alignment (have to know where the detector is)
  - calibration (what does the signal mean)
  - pattern recognition - how do you do pattern recognition with a computer program?
  - parameter estimation - how do i extract this?

LESSONS FROM PAST



Missing Energy Events are Confirmed

1) Events are real

2) Not conventional physics
$W \to \tau$, $Q\bar{Q}$, $Z^0 g$
$\hookrightarrow \nu\nu$

3) Not $X \to Z^0 +$ jet(s)
$\hookrightarrow \nu\nu$

4) Not $Z^0 \to X_1 X_2$
$\hookrightarrow$ ν's or stable
$\hookrightarrow$ jet(s)

(ORIGINAL TRANSPARENCY FROM 1986 UA1 'DISCOVERY' OF SUSY
ASPEN CONF, 1986

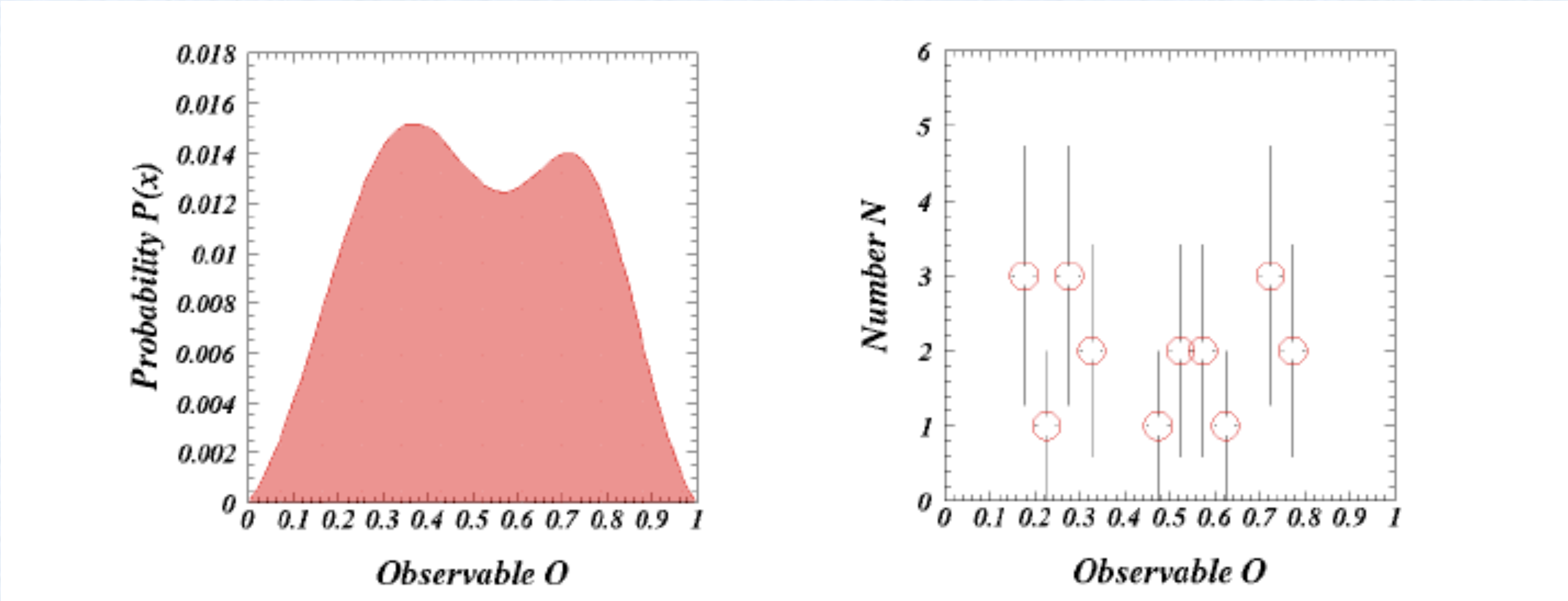
- UA1 reported an excess of jet mono jet + missing et events
- From hand scanning events determined that these were not compatible with background event
- Possible discovery of supersymmetry?

UNFORTUNATELY

- A combination of a lot of 'negligible' backgrounds
    - None alone could account for the observed number of data events
    - All mimicked the signature with some low probability
- Lesson : it is important to understand the details!

Process	Events (total)	Events with $L_\tau < 0$	Events with $L_\tau < 0$ and $E_T^{jet} < 40$ GeV
$W \to e\nu$ $W \to \mu\nu$ $W \to \tau\nu \to$ leptons	3.6	2.0	1.4
$W \to \tau\nu$ $\to \nu\bar{\nu}$ + hadrons	36.7	8.0	7.1
$W \to c\bar{s}$	<0.1	<0.1	<0.1
$Z^0 \to \tau^+\tau^-$	0.5	0.1	0.1
$Z^0 \to \nu\bar{\nu}$ (3 neutrino species)	7.4	7.1	5.6
$Z^0 \to c\bar{c}$ and $b\bar{b}$	<0.1	<0.1	<0.1
$c\bar{c}$ and $b\bar{b}$ (direct production)	0.2	0.2	0.2
Jet fluctuations (fake missing energy)	3.8	3.4	3.4
TOTAL	56 52.2	24 **20.8** $\pm$ 5.1 $\pm$ 1.0	**17.8** $\pm$ 3.7 $\pm$ 1.0

Monte Carlo



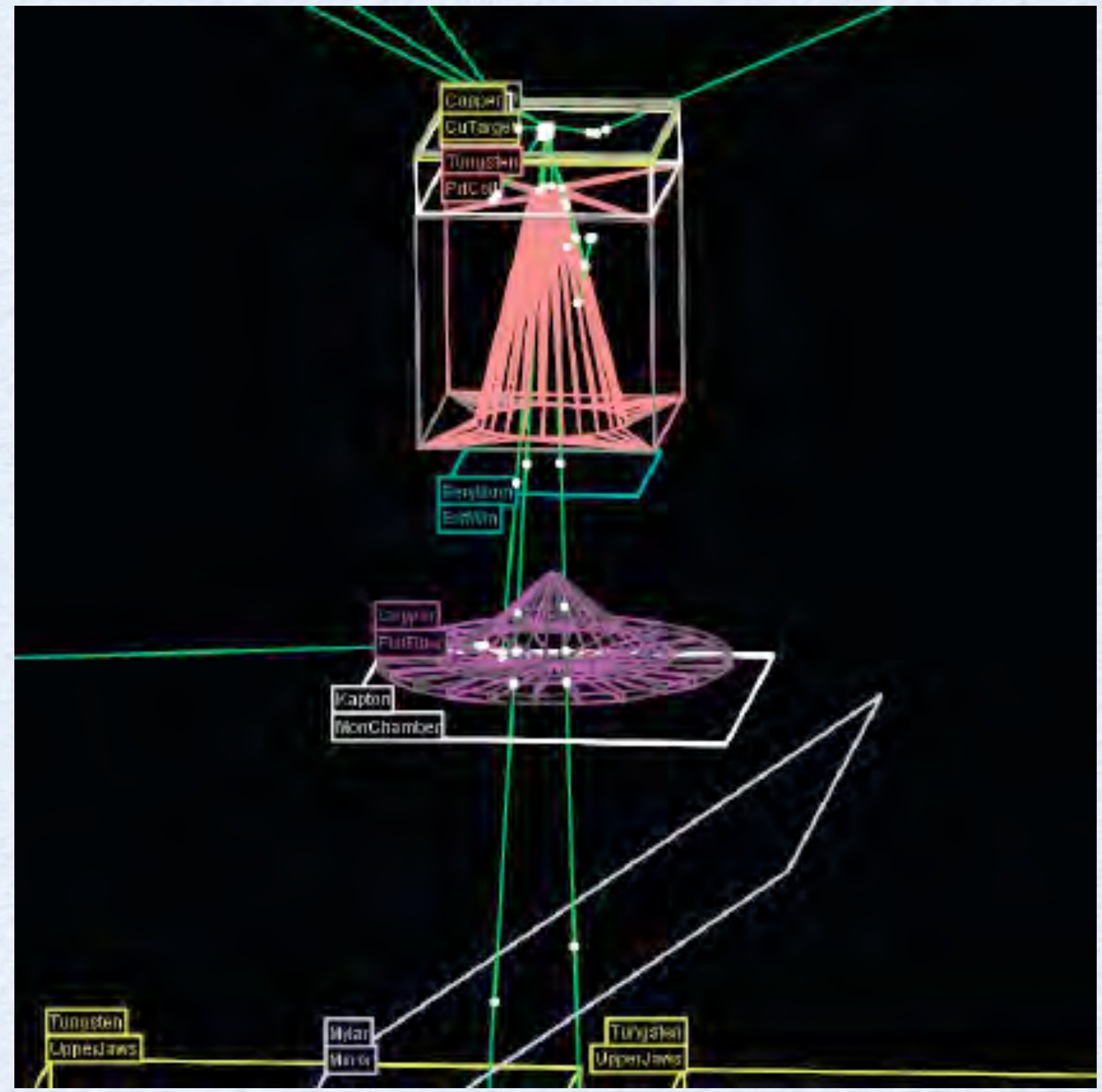
- P(x) -> N performed using the Monte Carlo method
  - estimate physical quantities (cross-sections, angular distributions, etc)
  - sample quantities (generate events) one at a time
- Relies on ability to generate (pseudo) random numbers with a computer
  - why are they pseudo random ?!

Simulation

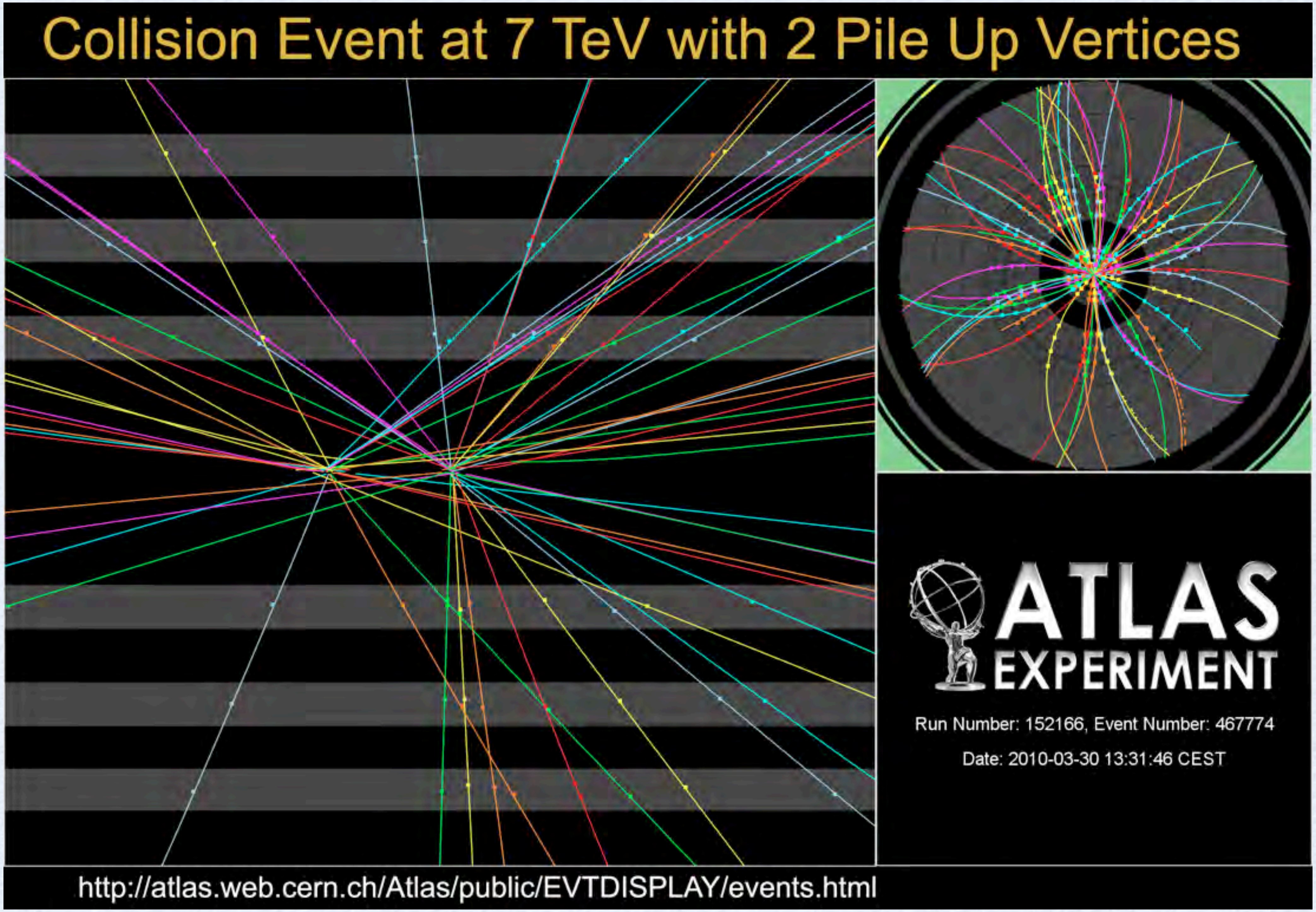
- In modern particle physics experiments the detectors are so large in complicated it is often difficult to know precisely what a particular event should look like

- Rely on detailed simulations to model active and passive material

- Propagate particles through detector



Event Displays



Event Displays

- Being able to see events is very important
  - human brain is amazing at seeing patterns, recognizing characteristics
  - human brain is not so great at complicated numeric calculations
  - i bet you had an easier time finding the tracks than you did at calculating their momentum
- Interestingly - computer programs are the exact opposite.
  - Great at doing numeric computation!
  - Much more difficult to write a program to find a track in a noisy environment than it is to estimate its momentum once you have found it with a program!

Notes

- Assigned reading on blackboard (i have also placed the entire root manual there for a reference - please don't read all 500 pages tonight) Please look through the first two chapters
- Homework assignment #1 due next week
- On Thursday we start with root!