PHYS 3313 – Section 001
Lecture #25

Wednesday, Apr. 23, 2014
Dr. Jaehoon Yu

- Introduction to Particle Physics
- Particle Accelerators
- Particle Physics Detectors
- Hot topics in Particle Physics
- What's coming in the future?

Announcements

- Due for your research materials
  - Research presentation PPT files by 8pm this Sunday, Apr. 27
  - Research papers double-sided and stapled by beginning of the class Monday, Apr. 28
- Final exam is 11am – 1:30pm, Monday, May 5, SH103
  - Comprehensive exam covering from CH1.1- CH7.6, CH9.7 (Liquid He), CH10.5 and CH14.1 – CH14.8 + appendices 3 – 7
  - BYOF: one handwritten, letter size, front and back
    - No derivations or solutions of any problems allowed!
- Submit your planetarium extra-credit sheet
  - At the beginning of the exam, Monday, May 5
- Please be sure to fill out the feedback survey.
- Colloquium today at 4pm in SH101

Introduction

- What are elementary particles?
  - Particles that make up all matters in the universe
- What are the requirements for elementary particles?
  - Cannot be broken into smaller pieces
  - Cannot have sizes
- The notion of "elementary particles" have changed from early 1900's through present
  - In the past, people thought protons, neutrons, pions, kaons, ρ-mesons, etc, as elementary particles
- Why?
  - Due to the increasing energies of accelerators that allowed us to probe smaller distance scales
- What is the energy needed to probe 0.1–fm?
  - From de Broglie Wavelength, we obtain

$$P = \frac{h}{\lambda} = \frac{hc}{\lambda c} = \frac{197\text{fm} - MeV}{0.1\text{fm}\ c} \approx 2000 MeV/c$$

Interaction Time

- The ranges of forces also affect interaction time
  - Typical time for Strong interaction ~10^{-24}sec
    - What is this time scale?
    - A time that takes light to traverse the size of a proton (~1 fm)
  - Typical time for EM force ~10^{-20} – 10^{-16} sec
  - Typical time for Weak force ~10^{-13} – 10^{-6} sec
- In GeV ranges, the four forces (now three since EM and Weak forces are unified!) are different
- These are used to classify elementary particles

Elementary Particles

- Before the quark concept in 70's, all known elementary particles were grouped in four depending on the nature of their interactions

Particle	*Symbol*	*Range of Mass Values*
Photon	γ	$\lesssim 2 \times 10^{-16}$ eV/c^2
Leptons	$e^-, \mu^-, \tau^-, \nu_e, \nu_\mu, \nu_\tau$	$\lesssim 3$ eV/c^2 – 1.777 GeV/c^2
Mesons	$\pi^+, \pi^-, \pi^0, K^+, K^-, K^0,$	
	$\rho^+, \rho^-, \rho^0, \ldots$	135 MeV/c^2 – few GeV/c^2
Baryons	$p, n, \Lambda^0, \Sigma^+, \Sigma^-, \Sigma^0, \Delta^{++},$	
	$\Delta^0, N^{*0}, Y_1^{*+}, \Omega^-, \ldots$	938 MeV/c^2 – few GeV/c^2

Elementary Particle Interactions

- How do the elementary particles interact??
  - All particles, including photons and neutrinos, participate in gravitational interactions
  - Photons can interact electromagnetically with any particles with electric charge
  - All charged leptons participate in both EM and weak interactions
  - Neutral leptons do not have EM couplings
  - All hadrons (Mesons and baryons) respond to the strong force and appears to participate in all the interactions

Bosons, Fermions, Particles and Antiparticles

- Bosons
  - All have integer spin angular momentum, follow BE statistics
  - All mesons (consists of two quarks) are bosons
- Fermions
  - All have half integer spin angular momentum follow FD statistics
  - All leptons and baryons (consist of three quarks) are fermions
- All particles have anti-particles
  - What are anti-particles?
    - Particles that has same mass as particles but with opposite quantum numbers
  - What is the anti-particle of
    - A π^0?
    - A neutron?
    - A K^0?
    - A Neutrino?

Allowed Interactions

- When can an interaction occur?
  - If it is kinematically allowed
  - If it does not violate any recognized conservation laws
    - Eg. A reaction that violates charge conservation will not occur
  - In order to deduce conservation laws, a full theoretical understanding of forces are necessary
- Since we do not have full theory for all the forces
  - Many of general conservation rules for particles are based on experiments
- One of the clearest conservation is the lepton number conservation
  - While photon and meson numbers are not conserved

The Standard Model of Particle Physics

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

The Standard Model of Particle Physics

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

Quarks and Leptons

- In SM, there are three families of leptons

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

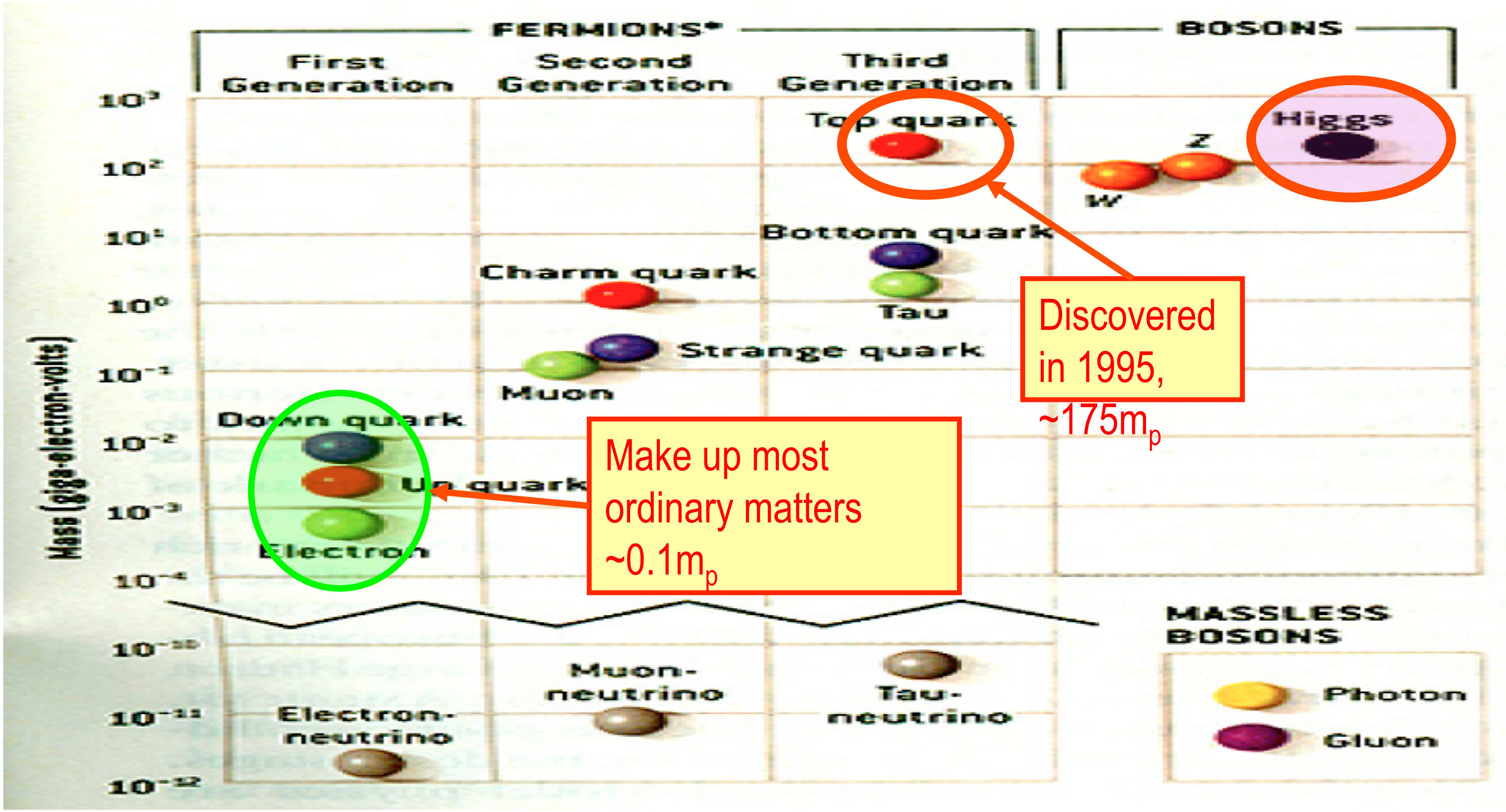
  – ➔ Increasing order of lepton masses
  – Convention used in strong isospin symmetry, higher member of multiplet carries higher electrical charge

- And three families of quark constituents

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

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

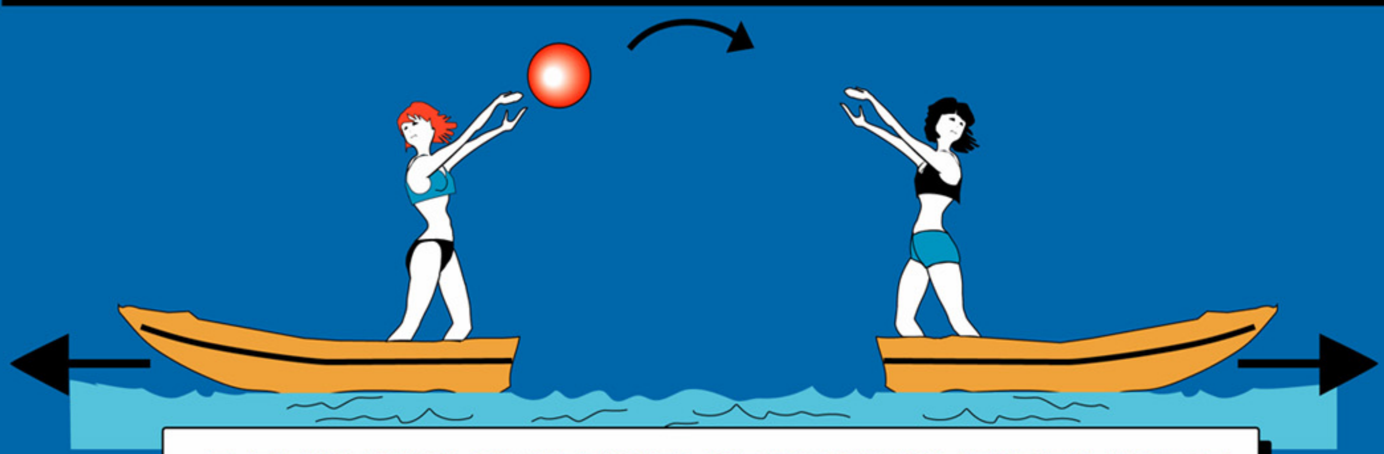
HEP and the Standard Model



- Total of 16 particles (12+4 force mediators) make up all the visible matter in the universe! ➔ Simple and elegant!!!
- Tested to a precision of 1 part per million!

The forces in Nature

TYPE	INTENSITY OF FORCES (DECREASING ORDER)	BINDING PARTICLE (FIELD QUANTUM)	OCCURS IN :
STRONG NUCLEAR FORCE	~ 1	GLUONS (NO MASS)	ATOMIC NUCLEUS
ELECTRO -MAGNETIC FORCE	$\sim 10^{-3}$	PHOTONS (NO MASS)	ATOMIC SHELL ELECTROTECHNIQUE
WEAK NUCLEAR FORCE	$\sim 10^{-5}$	BOSONS Z^{o}, $W+$, $W-$ (HEAVY)	RADIOACTIVE BETA DESINTEGRATION
GRAVITATION	$\sim 10^{-38}$	GRAVITONS (?)	HEAVENLY BODIES



THE EXCHANGE OF PARTICLES IS RESPONSIBLE FOR THE FORCE

CERN AC _Z04_ V25/8/1992

Particle Accelerators

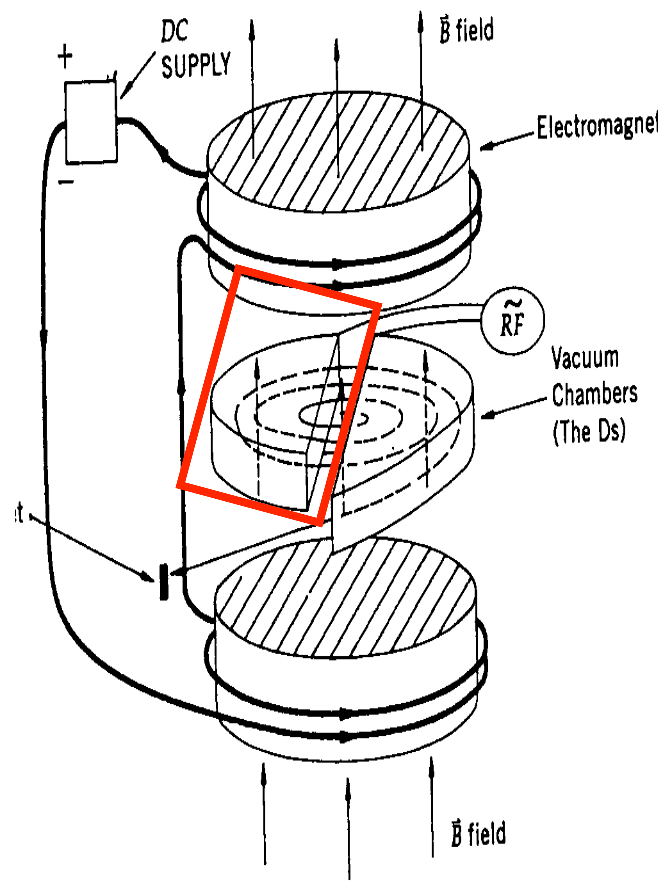
- How can one obtain high energy particles?
  - Cosmic ray ➔ Sometimes we observe 1000TeV cosmic rays
    - Low flux and cannot control energies too well
- Need to look into small distances to probe the fundamental constituents with full control of particle energies and fluxes
  - Particle accelerators
- Accelerators need not only to accelerate particles but also to
  - Track them
  - Maneuver them
  - Constrain their motions to the order of 1μm or better
- Why?
  - Must correct particle paths and momenta to increase fluxes and control momenta

Particle Accelerators

- Depending on what the main goals of physics are, one needs different kinds of accelerator experiments
- Fixed target experiments: Probe the nature of the nucleons ➔ Structure functions
  - Results also can be used for producing secondary particles for further accelerations ➔ Tevatron anti-proton production
- Colliders: Probes the interactions between fundamental constituents
  - Hadron colliders: Wide kinematic ranges and high discovery potential
    - Proton-anti-proton: TeVatron at Fermilab, $Sp\bar{p}S$ at CERN
    - Proton-Proton: Large Hadron Collider at CERN (turned on early 2010)
  - Lepton colliders: Very narrow kinematic reach, so it is used for precision measurements
    - Electron-positron: LEP at CERN, Petra at DESY, PEP at SLAC, Tristan at KEK, ILC in the med-range future
    - Muon-anti-muon: Conceptual accelerator in the far future
  - Lepton-hadron colliders: HERA at DESY

Resonance Accelerators: Cyclotron

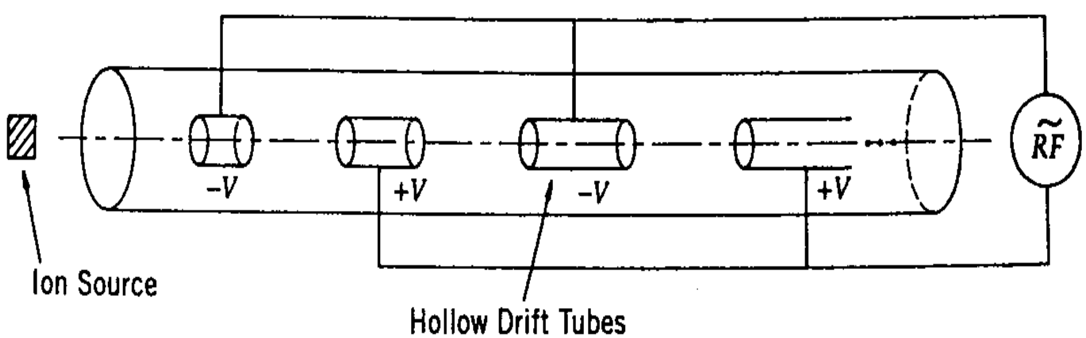
- Invented by E. Lawrence at Berkeley in 1930's
- While the D's are connected to HV sources, there is no electric field inside the chamber due to Faraday effect
- Strong electric field exists only in the gap between the D's
- An ion source is placed in the gap
- The path is circular due to the perpendicular magnetic field
- Ion does not feel any acceleration inside a D but gets bent due to magnetic field
- When the particle exits a D, the direction of voltage can be changed and the ion gets accelerated before entering into the D on the other side
- If the frequency of the alternating voltage is just right (cyclotron frequency), the charged particle gets accelerated continuously until it is extracted
- The maximum energy is determined by the accelerator radius and the magnetic field strength

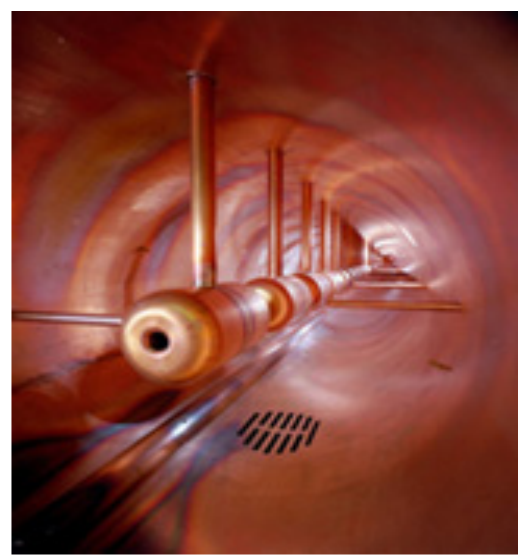


$$T_{max} = \frac{1}{2} m v_{max}^2 = \frac{1}{2} m \varpi^2 R^2 = \frac{(qBR)^2}{mc^2}$$

Resonance Accelerators: Linear Accelerator

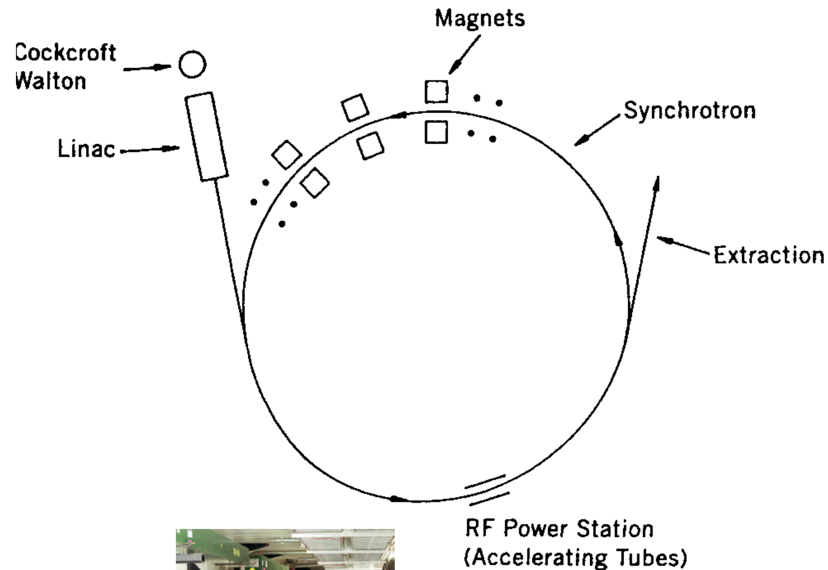
- Accelerates particles along a linear path using resonance principle
- A series of metal tubes are located in a vacuum vessel and connected successively to alternating terminals of radio frequency oscillator
- The directions of the electric fields changes before the particles exits the given tube
- The tube length needs to get longer as the particle gets accelerated to keep up with the phase
- These accelerators are used for accelerating light particles to very high energies

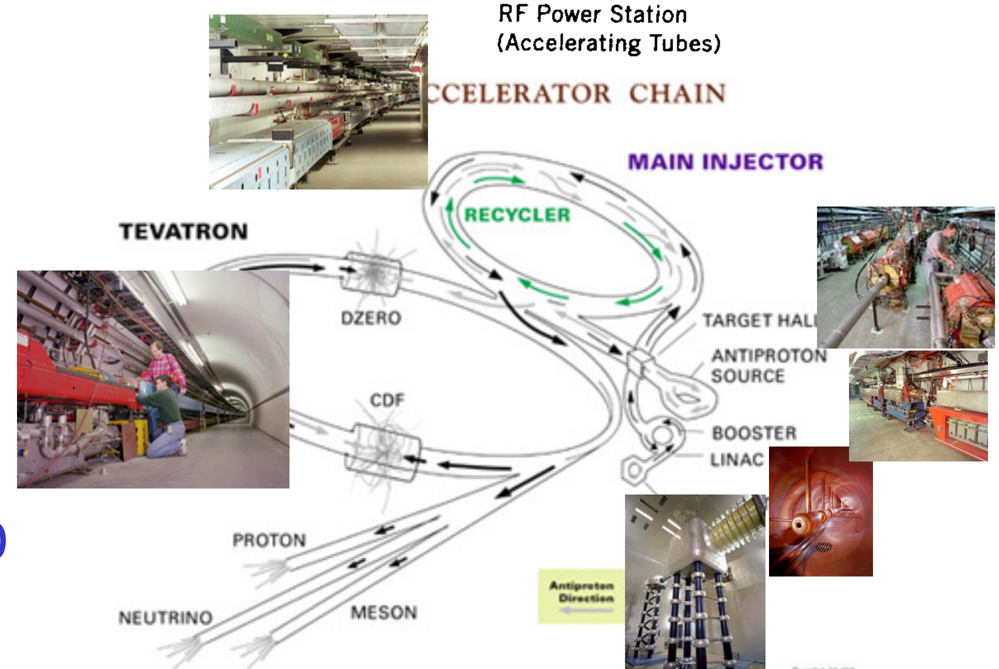




Synchroton Accelerators

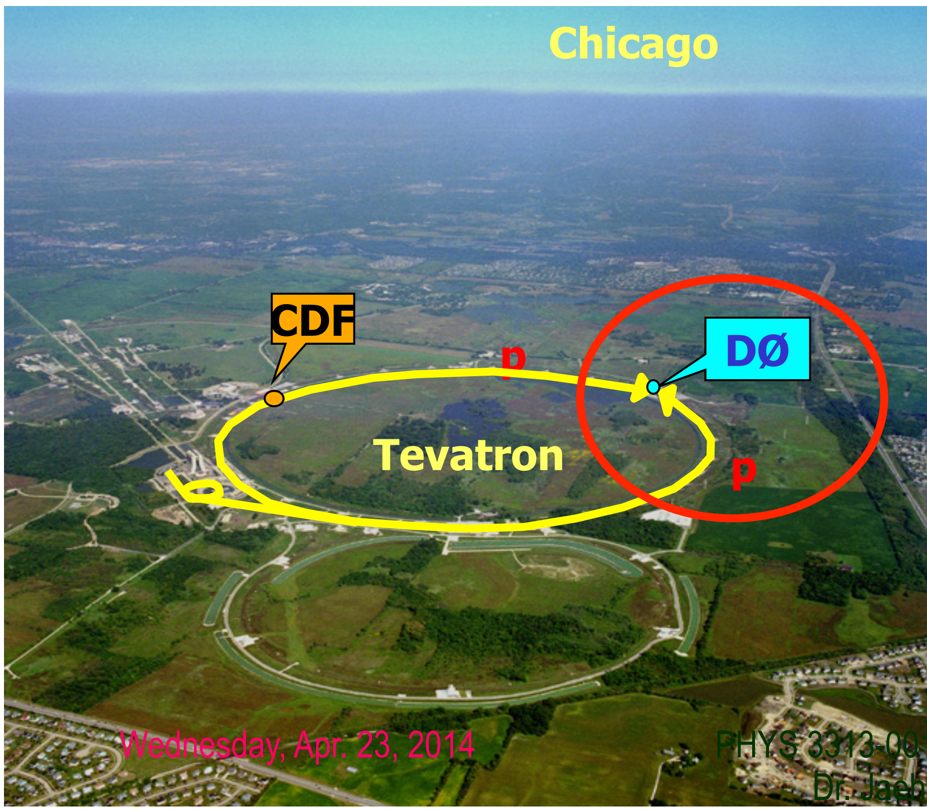
- Synchrotons use magnets arranged in a ring-like fashion with varying magnetic field and frequency
- Multiple stages of accelerations are needed before reaching over GeV ranges of energies
- RF power stations are located through the ring to pump electric energies into the particles



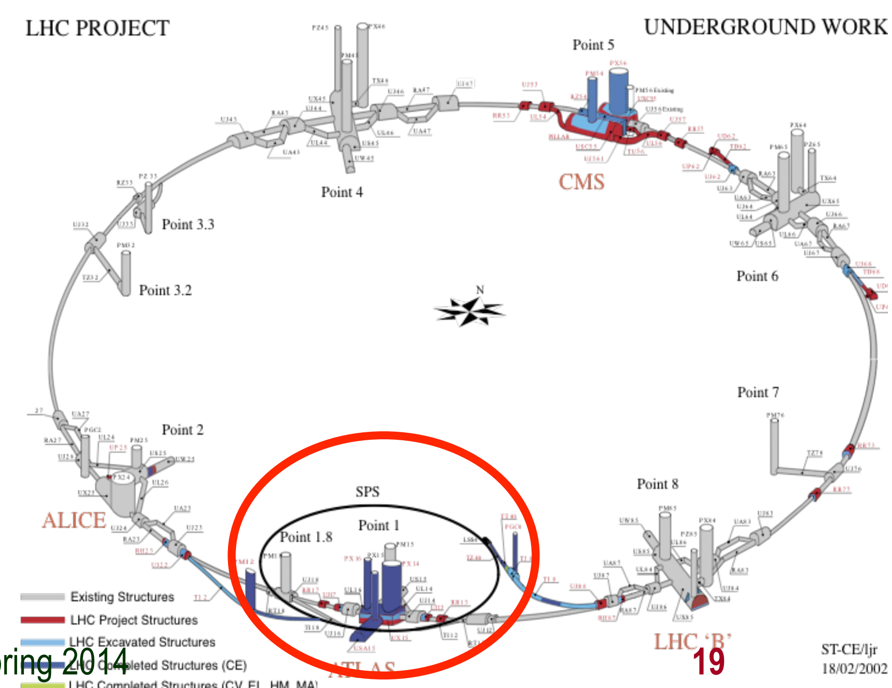


Fermilab Tevatron and LHC at CERN

- World's Highest Energy proton-anti-proton collider
  - 4km (2.5mi) circumference
  - E_{cm}=1.96 TeV (=6.3x10^{-7}J/p➔ 13M Joules on the area smaller than $10^{-4}m^2$)
  - Equivalent to the kinetic energy of a 20t truck at the speed 81mi/hr
    - ~100,000 times the energy density at the ground 0 of the Hiroshima atom bomb
  - **Tevatron was shut down in 2011**
  - **Vibrant other programs running, including the search for dark matter with beams!!**

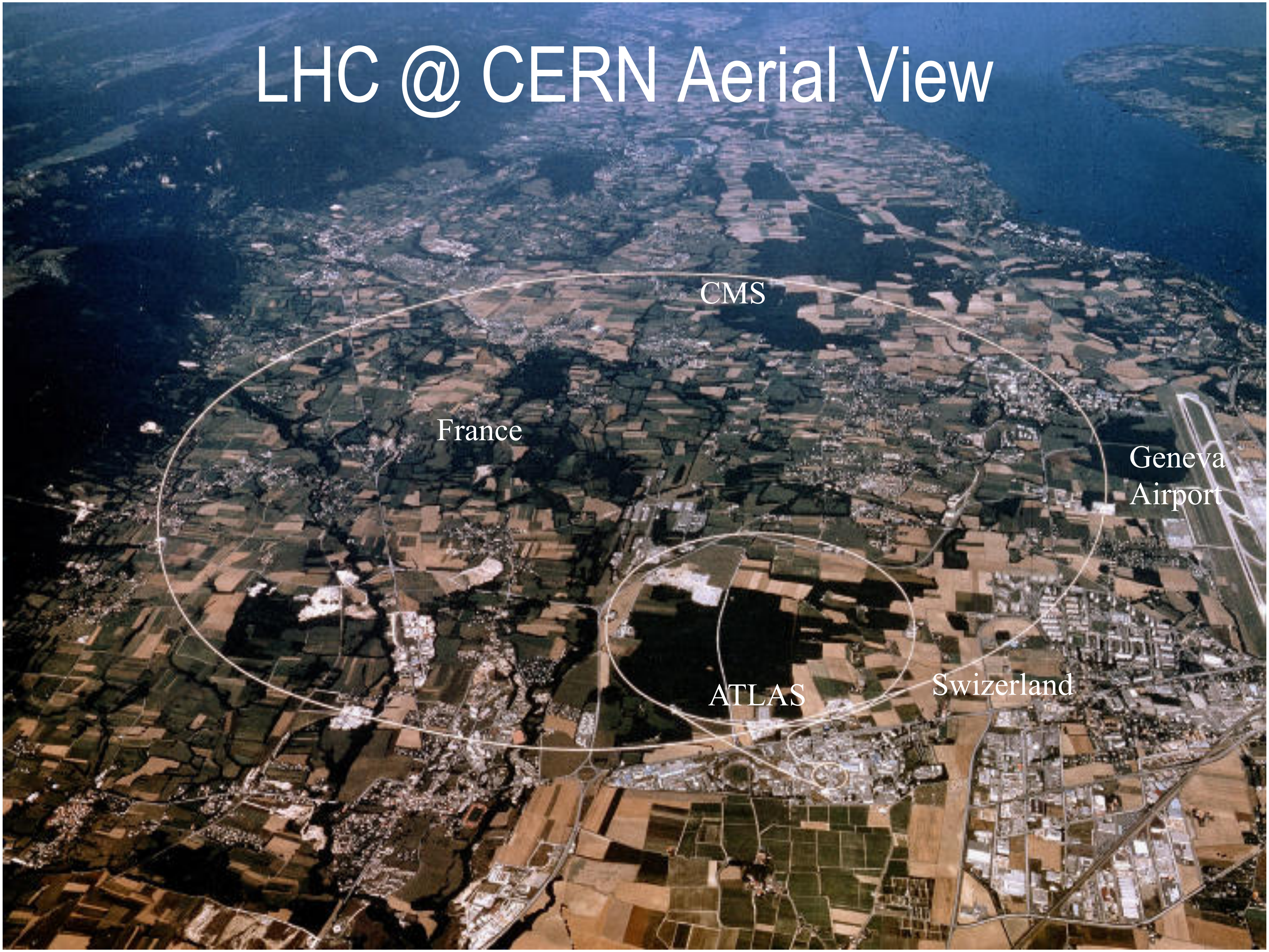


- World's Highest Energy p-p collider
  - 27km (17mi) circumference, 100m (300ft) underground
  - Design E_{cm}=14 TeV (=44x10^{-7}J/p➔ 362M Joules on the area smaller than $10^{-4}m^2$)
  - ➢ Equivalent to the kinetic energy of a B727 (80tons) at the speed 193mi/hr
    - ➢ ~3M times the energy density at the ground 0 of the Hiroshima atom bomb
- **Large amount of data accumulated in 2010 – 2013**
- **Shutdown in Feb. 2013 & on track to resume Mar. 2015**



Comparisons between Tevatron and LHC

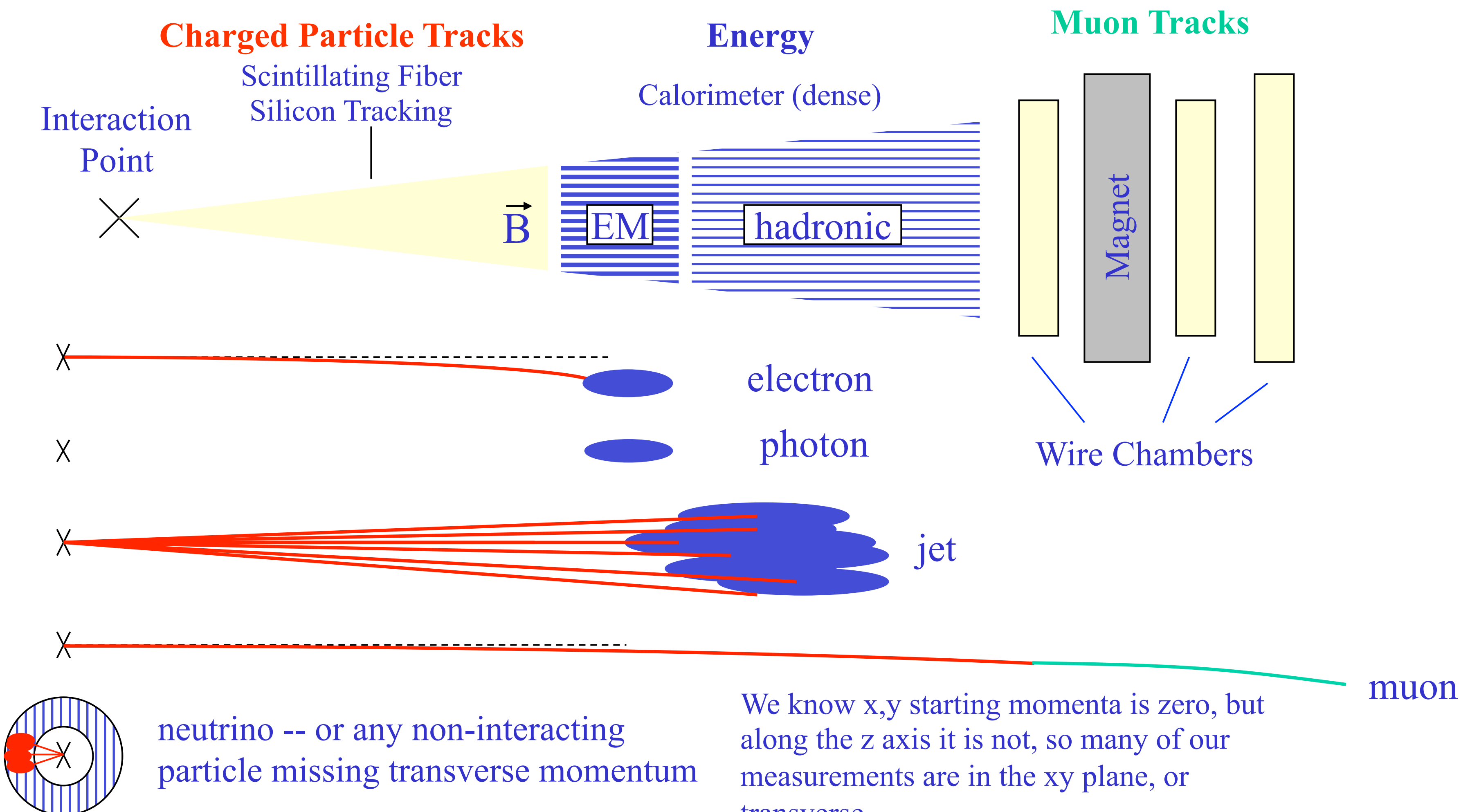
- Tevatron: A proton-anti proton collider at 2TeV
  - Need to produce anti-protons using accelerated protons at 150GeV
  - Takes time to store sufficient number of anti-protons
    - Need a storage accelerator for anti-protons
  - Can use the same magnet and acceleration ring to circulate and accelerator particles
- LHC: A proton-proton collier at 14TeV design energy
  - Protons are easy to harvest
  - Takes virtually no time to between a fresh fill of particles into the accelerator
  - Must use two separate magnet and acceleration rings


LHC @ CERN Aerial View
CMS
France
Geneva
Airport
ATLAS
Swizerland

Particle Detectors

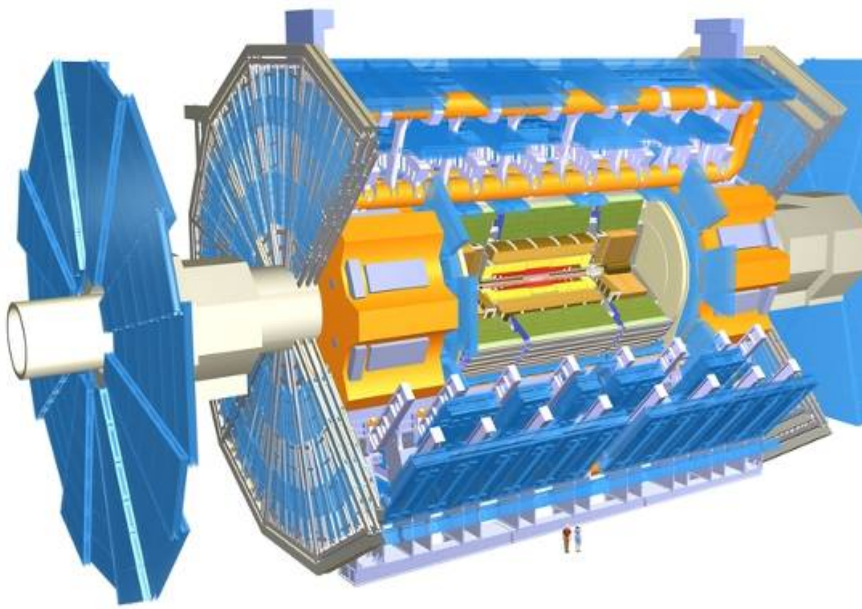
- Subatomic particles cannot be seen by naked eyes but can be detected through their interactions within matter
- What do you think we need to know first to construct a detector?
  - What kind of particles do we want to detect?
    - Charged particles and neutral particles
  - What do we want to measure?
    - Their momenta measured by tracking detectors and magnetic field
    - Trajectories measured by tracking detectors
    - Energies measured by the calorimeter
    - Origin of interaction (interaction vertex) measured by a precision tracking det.
    - Etc
  - To what precision do we want to measure?
- Depending on the answers to the above questions we use different detection techniques

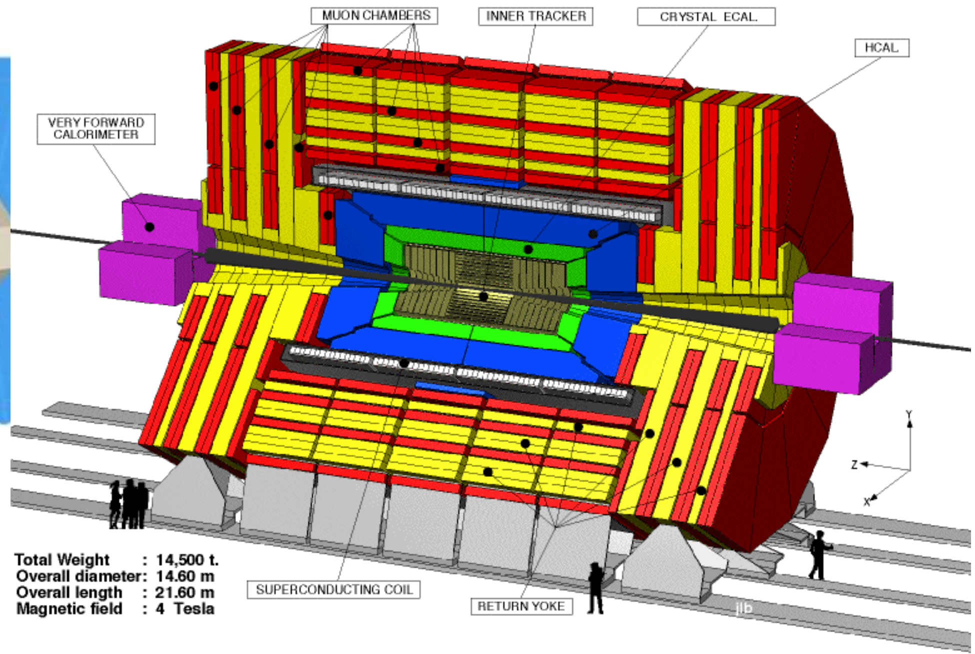
Particle Detection Techniques



We know x,y starting momenta is zero, but along the z axis it is not, so many of our measurements are in the xy plane, or transverse

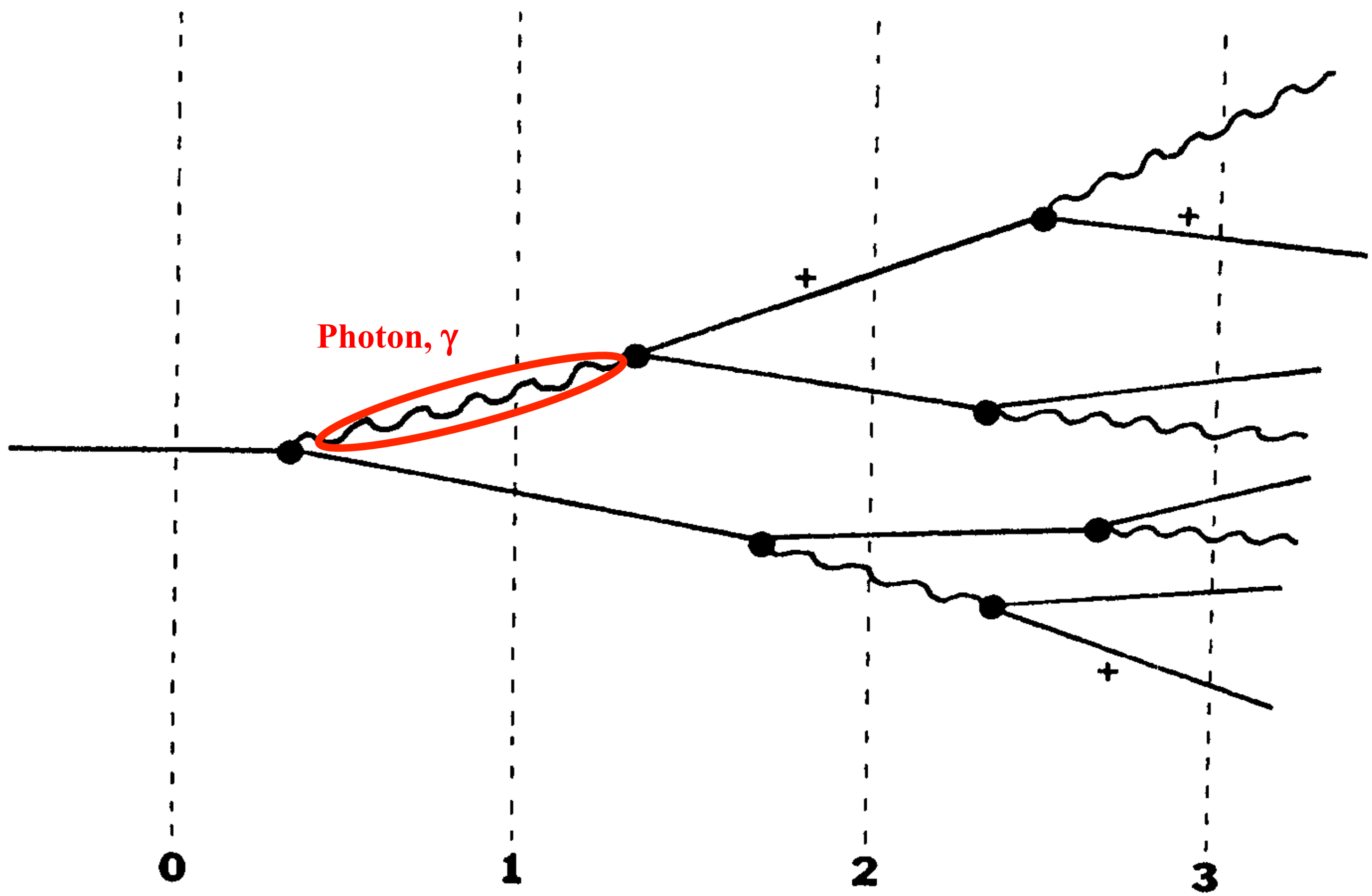
The ATLAS and CMS Detectors





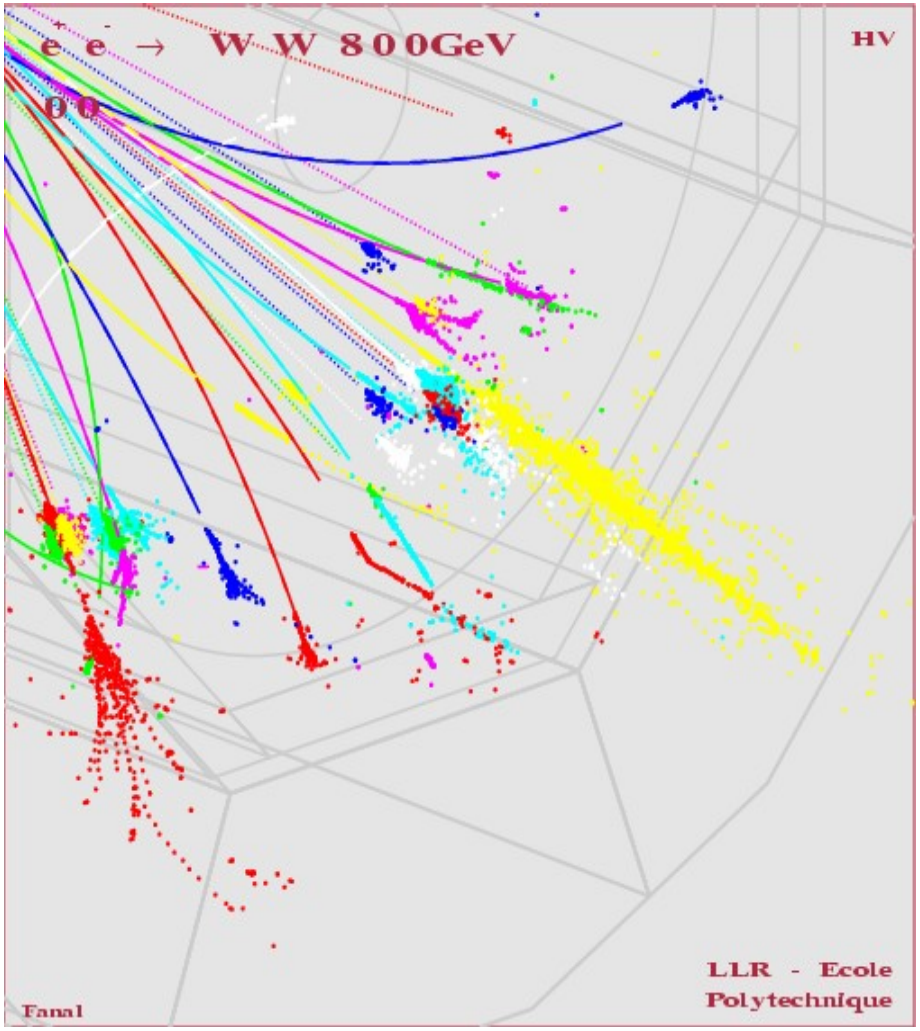
- **Fully multi-purpose detectors with emphasis on lepton ID & precision E & P**
- **Weighs 7000 tons and 10 story tall**
- Records **200 – 400 collisions/second**
- Records approximately **350** MB/second
- Record over 2 PB per year ➔ **200*Printed material of the US Lib. of Congress**

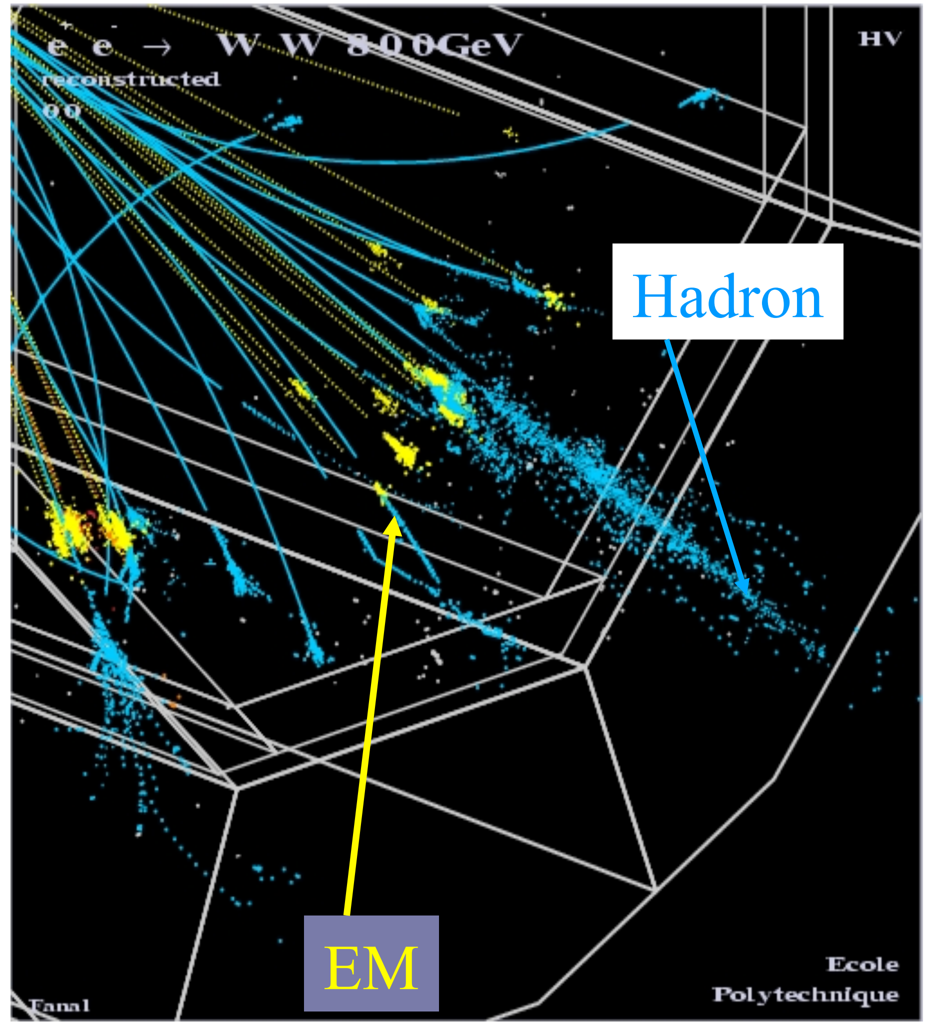
Electron Interactions in material (showering)



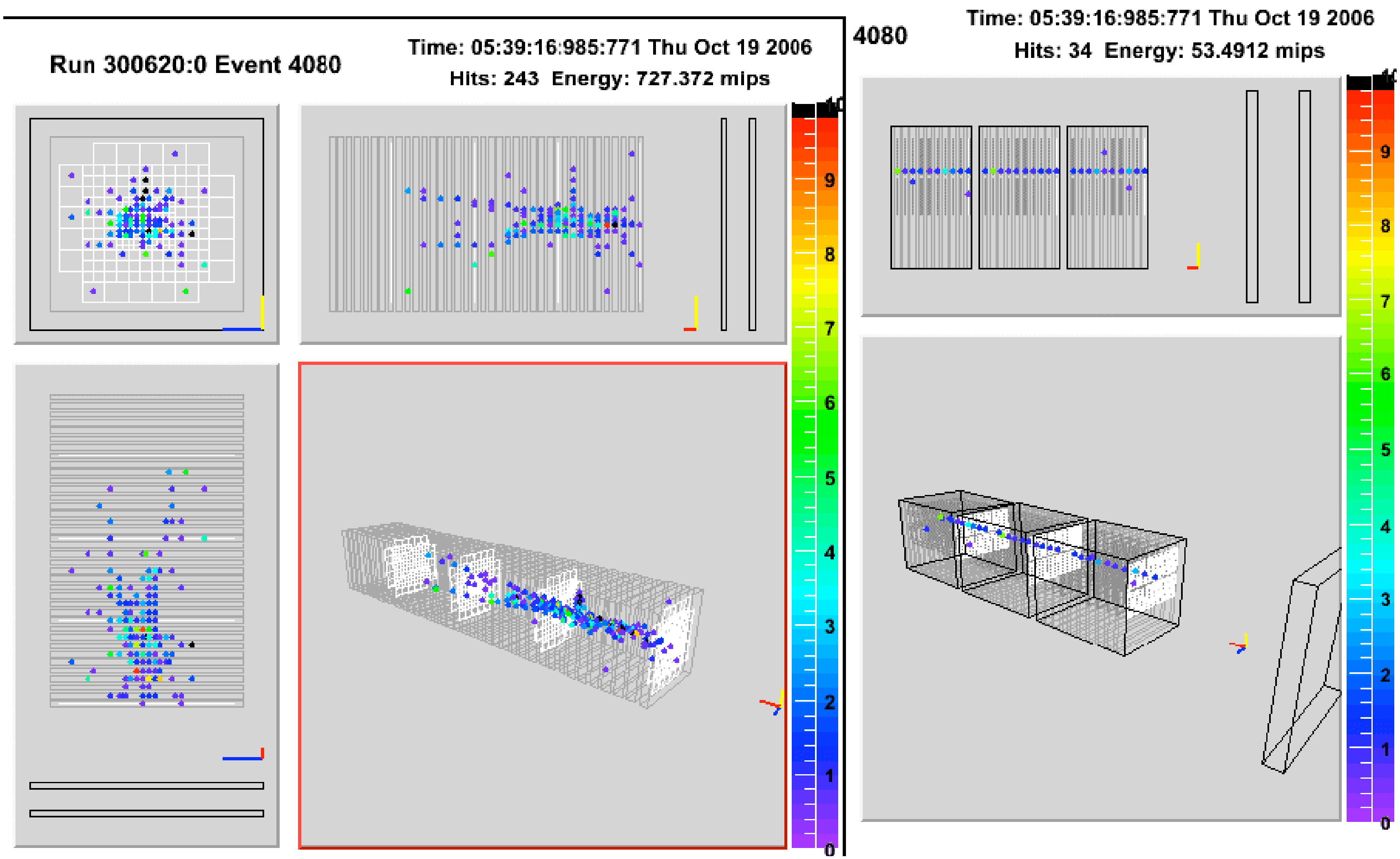
Method of measuring the particle energy in a calorimeter!!

How particle showers look in detectors



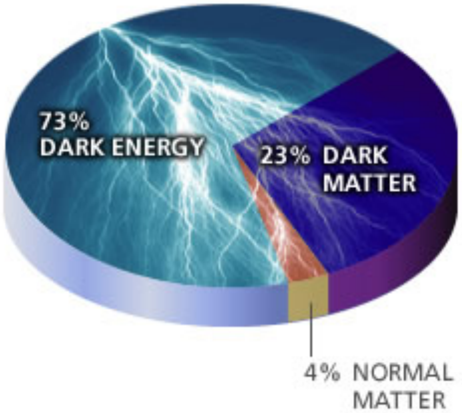


Example Hadronic Shower (20GeV)



What are the current hot issues?

- Why is the mass range so large ($0.1m_p$ – $175\ m_p$)?
- How do matters acquire mass?
  - Higgs mechanism, did we find the Higgs?
- Why is the matter in the universe made only of particles?
- Neutrinos have mass!! What are the mixing parameters, particle-anti particle asymmetry and mass ordering?
- Why are there only three apparent forces?
- Is the picture we present the real thing?
  - What makes up the ~95% of the universe?
  - How about extra-dimensions?



- Are there any other theories that describe the universe better?
  - Does the super-symmetry exist?
- Where is new physics?
- Where do we all come from?
- How can we live well in the universe as an integral partner?

What is the Higgs and What does it do?

- When there is perfect symmetry, one cannot tell directions!

What? What's the symmetry?

- Where is the head of the table?
- Without a broken symmetry, one cannot tell directional information!!

A broken symmetry

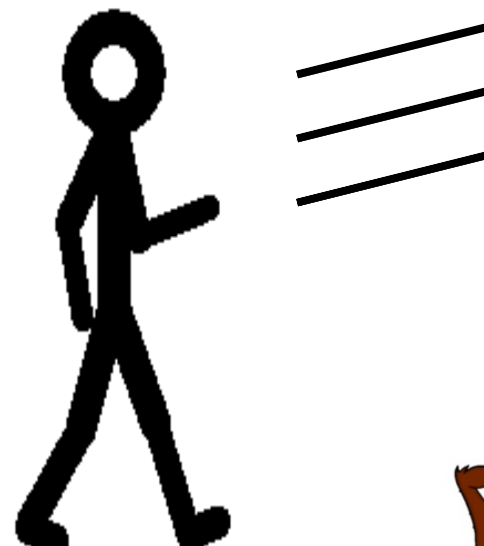
What is the Higgs and What does it do?

- When there is perfect symmetry, one cannot tell directions!
- Only when symmetry is broken, can one tell directions
- Higgs field works to break the perfect symmetry and gives mass to all fundamental particles
- Sometimes, this field spontaneously generates a particle, the Higgs particle
- So the Higgs particle is the evidence of the existence of the Higgs field!

So how does Higgs Field work again?

- Person in space ➔ no symmetry breaking

- Person in air ➔ symmetry can be broken
- Sometimes, you get



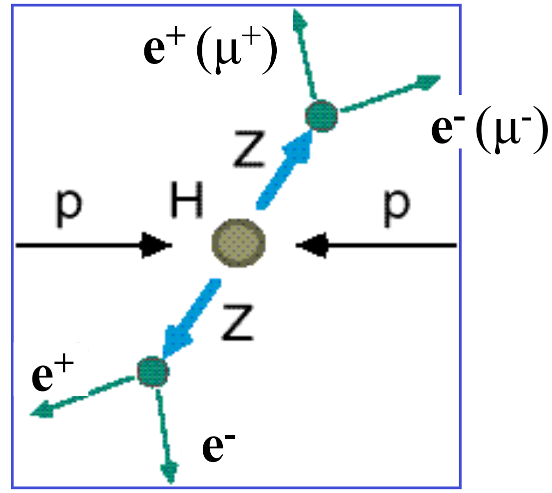
Just like a tornado is a piece of evidence of the existence of air, Higgs particle is a piece of evidence of Higgs mechanism

How do we look for the Higgs?

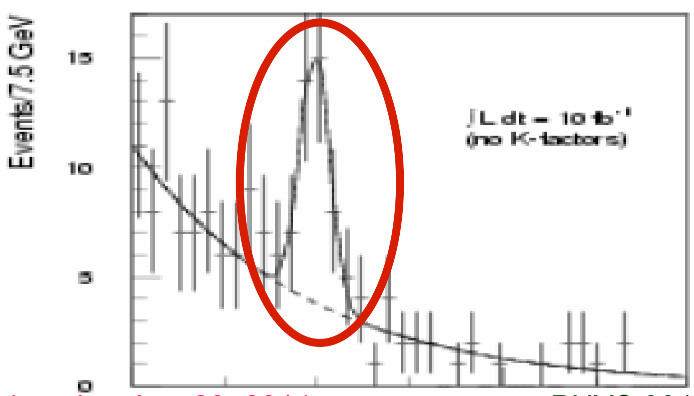
- Higgs particle is so heavy they decay into other lighter particles instantaneously
- When one searches for new particles, one looks for the easiest way to get at them
- Of many signatures of the Higgs, some are much easier to find, if it were the Standard Model Higgs
  - $H \rightarrow \gamma\gamma$
  - $H \rightarrow ZZ^* \rightarrow 4e, 4\mu, 2e2\mu, 2e2\nu$ and $2\mu2\nu$
  - $H \rightarrow WW^* \rightarrow 2e2\nu$ and $2\mu2\nu$
  - And many more complicated signatures

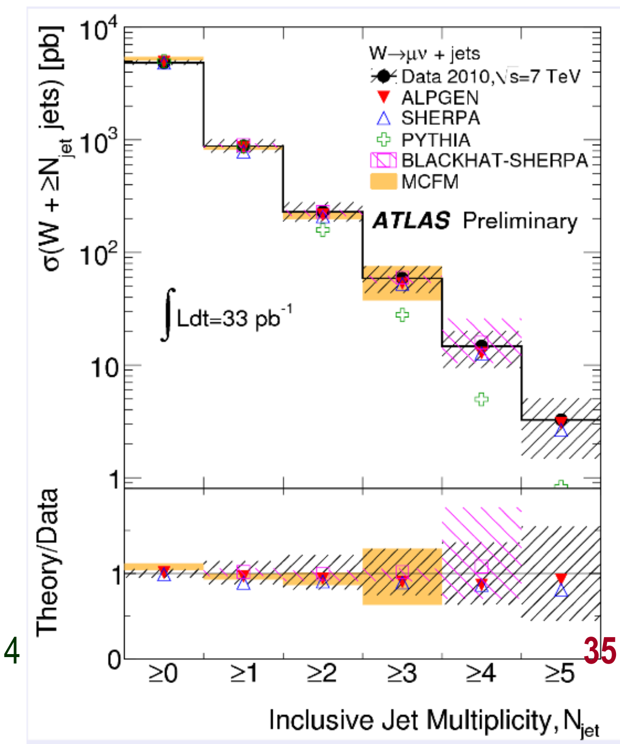
How do we look for the Higgs?

- Identify Higgs candidate events

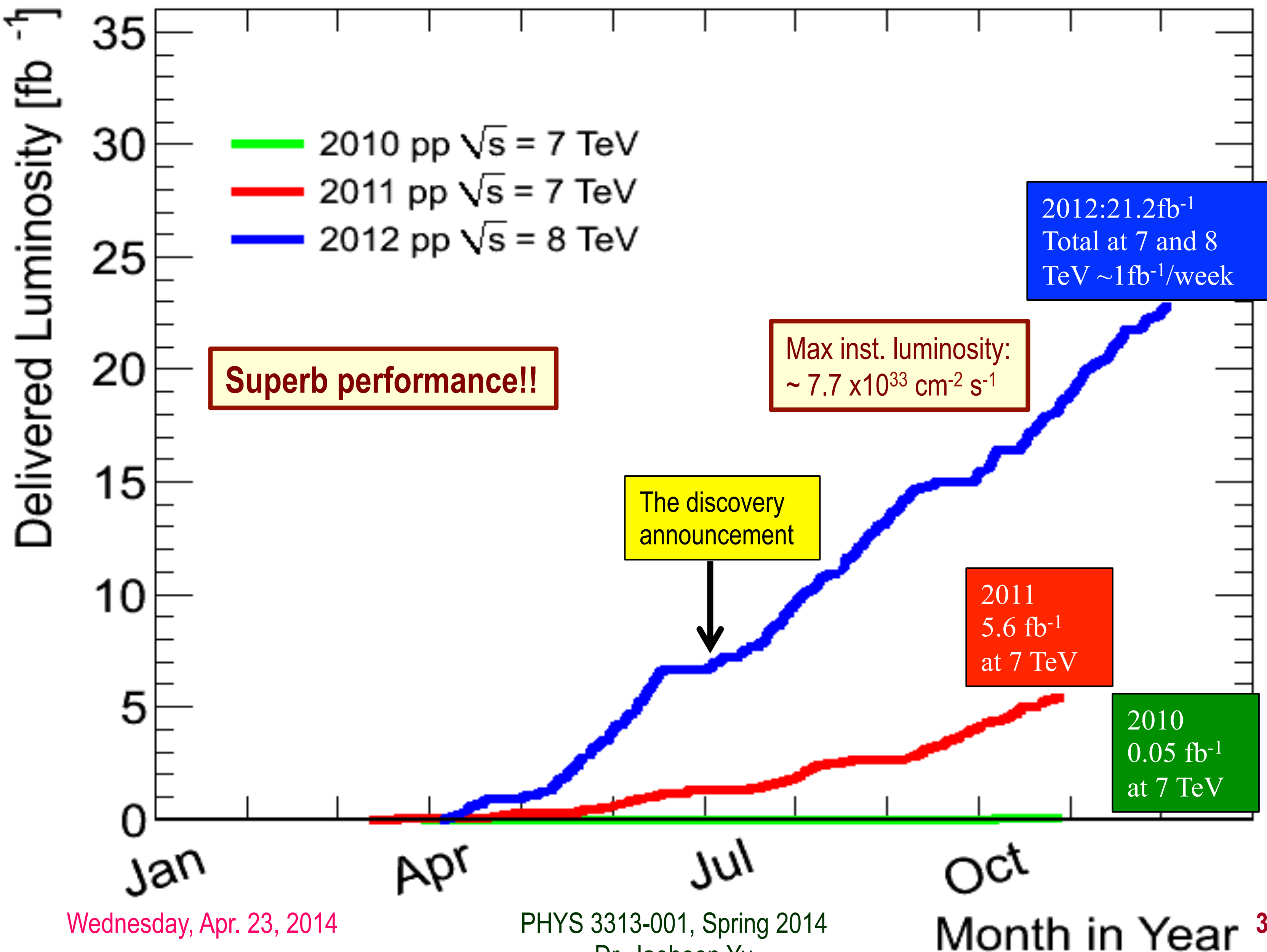


- Understand fakes (backgrounds)
- Look for a bump!!
  - Large amount of data absolutely critical

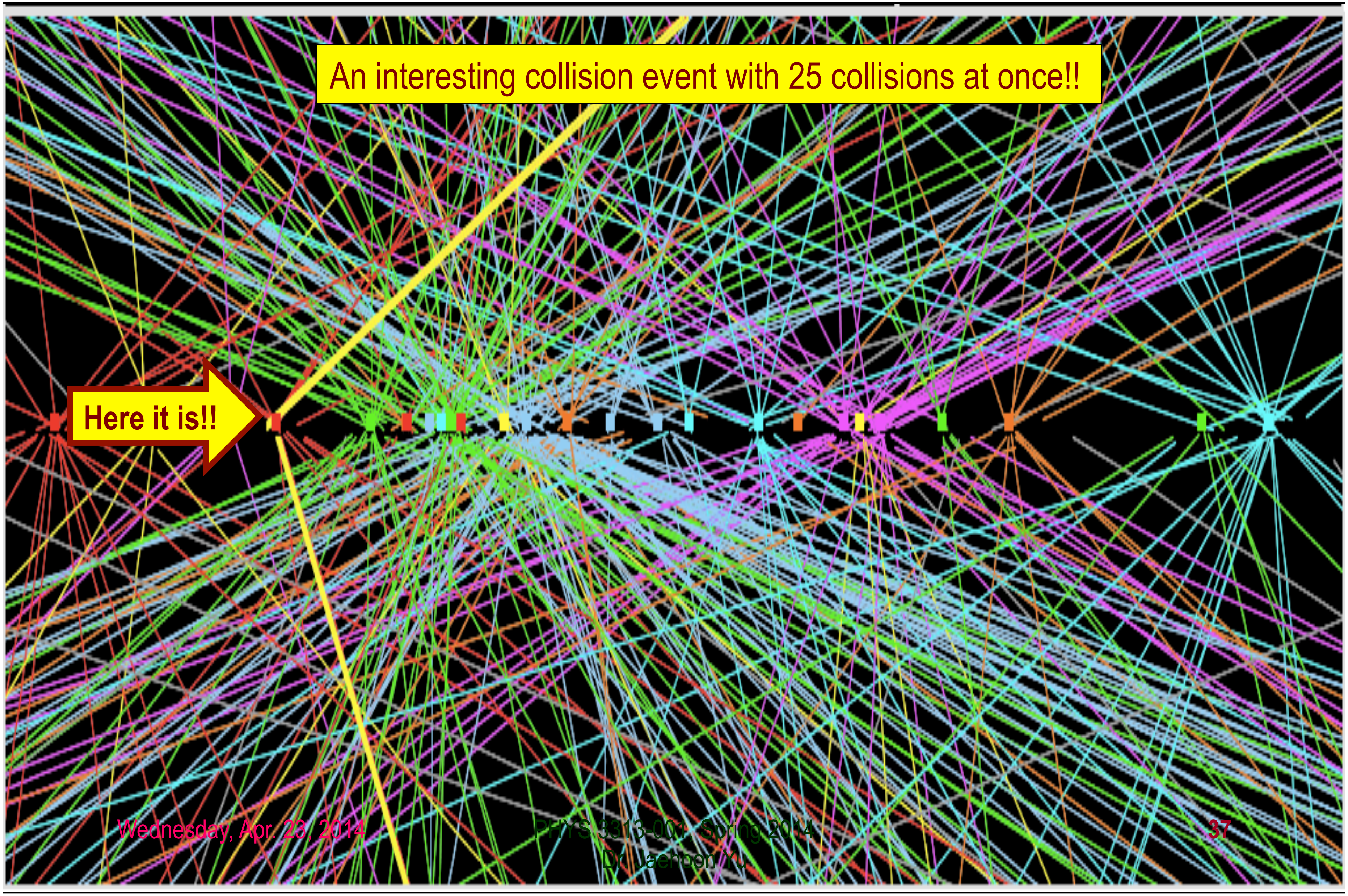




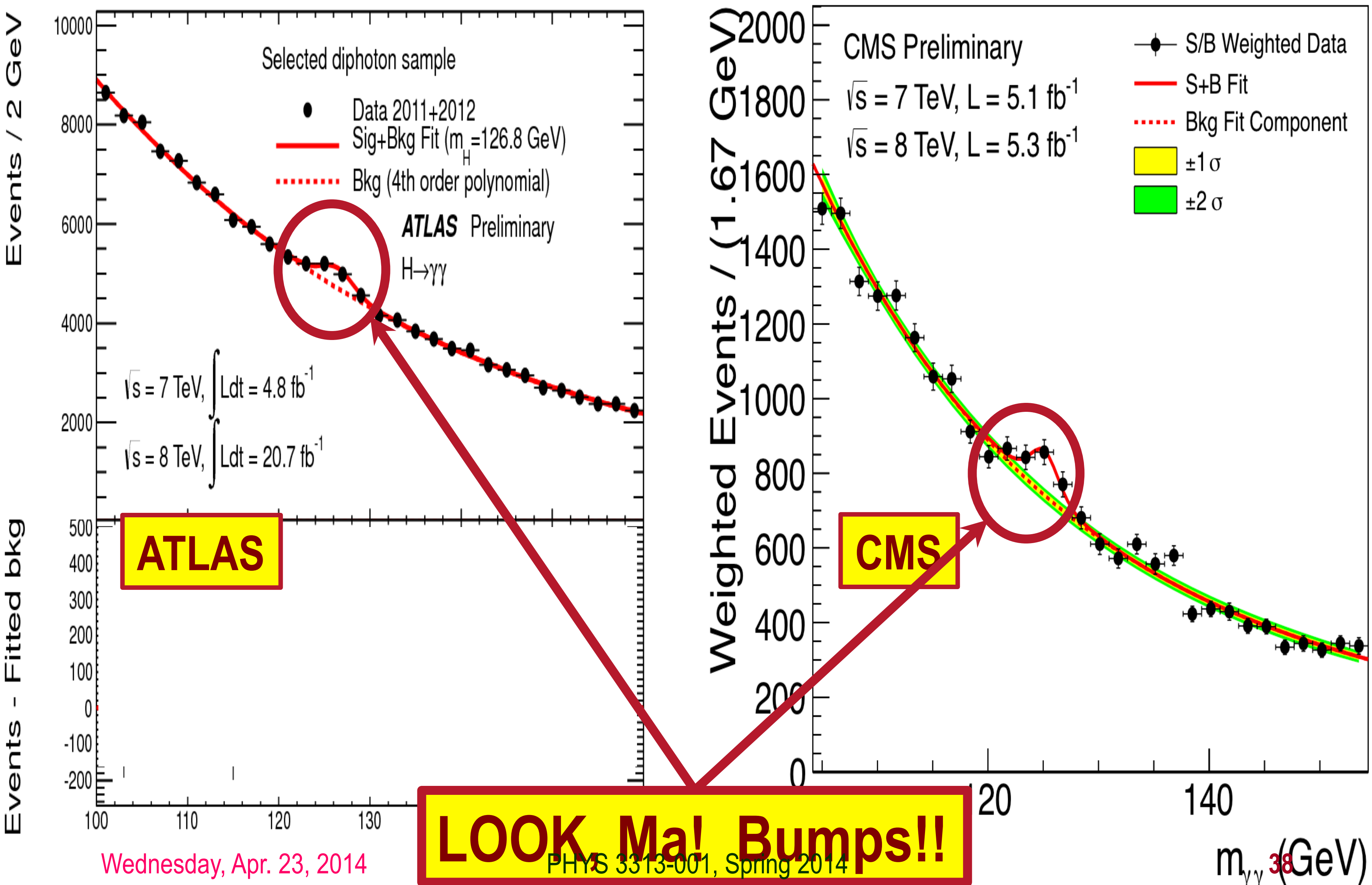
Amount of LHC Data



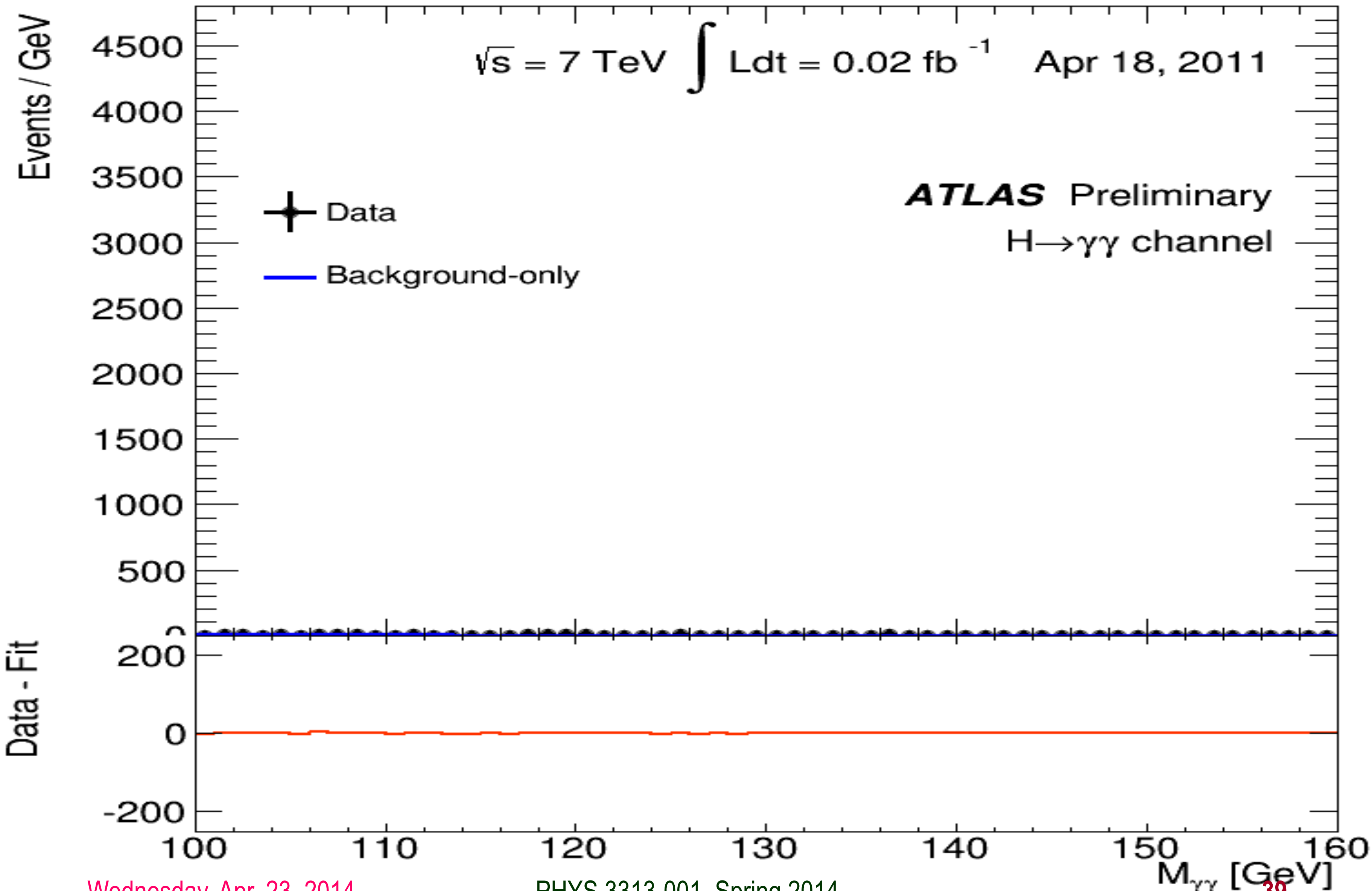
Challenges?   No problem!



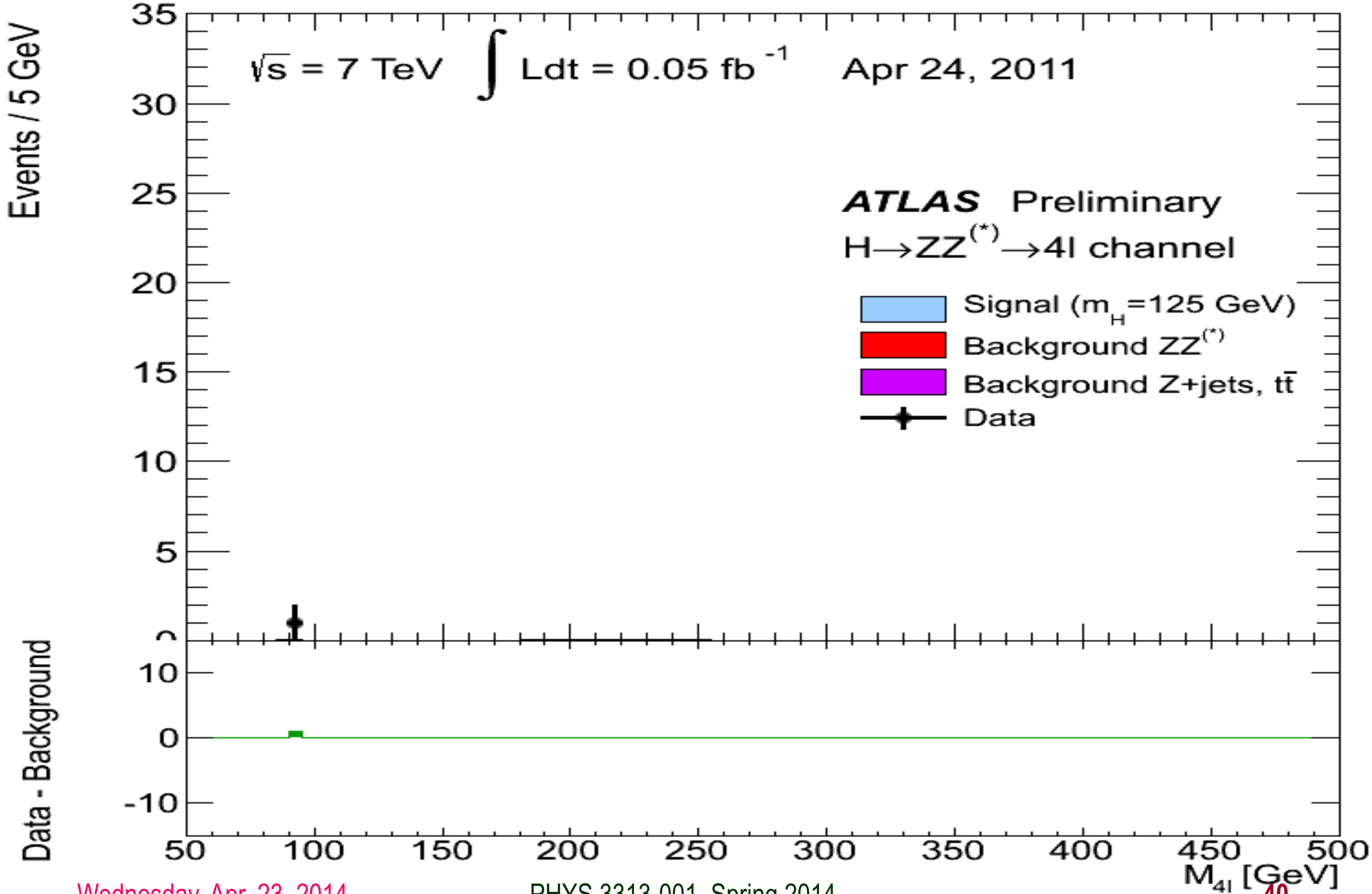
ATLAS and CMS Mass Bump Plots (H→γγ)



What did statistics do for Higgs?



How about this?



Statistical Significance Table

zσ	Percentage within CI	Percentage outside CI	Fraction outside CI
0.674 490σ	50%	50%	1 / 2
0.994 458σ	68%	32%	1 / 3.125
1σ	68.268 9492%	31.731 0508%	1 / 3.151 4872
1.281 552σ	80%	20%	1 / 5
1.644 854σ	90%	10%	1 / 10
1.959 964σ	95%	5%	1 / 20
2σ	95.449 9736%	4.550 0264%	1 / 21.977 895
2.575 829σ	99%	1%	1 / 100
3σ	99.730 0204%	0.269 9796%	1 / 370.398
3.290 527σ	99.9%	0.1%	1 / 1,000
3.890 592σ	99.99%	0.01%	1 / 10,000
4σ	99.993 666%	0.006 334%	1 / 15,787
4.417 173σ	99.999%	0.001%	1 / 100,000
4.891 638σ	99.9999%	0.0001%	1 / 1,000,000
5σ	99.999 942 6697%	0.000 057 3303%	1 / 1,744,278
5.326 724σ	99.999 99%	0.000 01%	1 / 10,000,000
5.730 729σ	99.999 999%	0.000 001%	1 / 100,000,000
6σ	99.999 999 8027%	0.000 000 1973%	1 / 506,797,346
6.109 410σ	99.999 9999%	0.000 0001%	1 / 1,000,000,000
6.466 951σ	99.999 999 99%	0.000 000 01%	1 / 10,000,000,000
6.806 [illegible]σ	99.999 [illegible]99 999%	[illegible]1 %	1 / 100,000,000,000
7σ	99.999 999 999 7440%	0.000 000 000 256%	1 / 390,682,215,445

So have we seen the Higgs particle?

- The statistical significance of the finding is much bigger than seven standard deviations
  - Level of significance: much better than 99.999 999 999 7% (eleven 9s!!)
  - We could be wrong once if we do the same experiment 391,000,000,000 times (will take ~13,000 years even if each experiment takes 1s!!)
    - Probability of winning the $0.5B Power Ball Jackpot was 175,233,510
- So did we find the Higgs particle?
  - We have discovered the heaviest new boson we've seen thus far
  - It has many properties consistent with the Standard Model Higgs particle
    - It quacks like a duck and walks like a duck but…
  - We do not have enough data to precisely measure all the properties – mass, lifetime, the rate at which this particle decays to certain other particles, etc – to definitively determine its nature
- Precision measurements and searches in new channels ongoing

Long Term LHC Plans

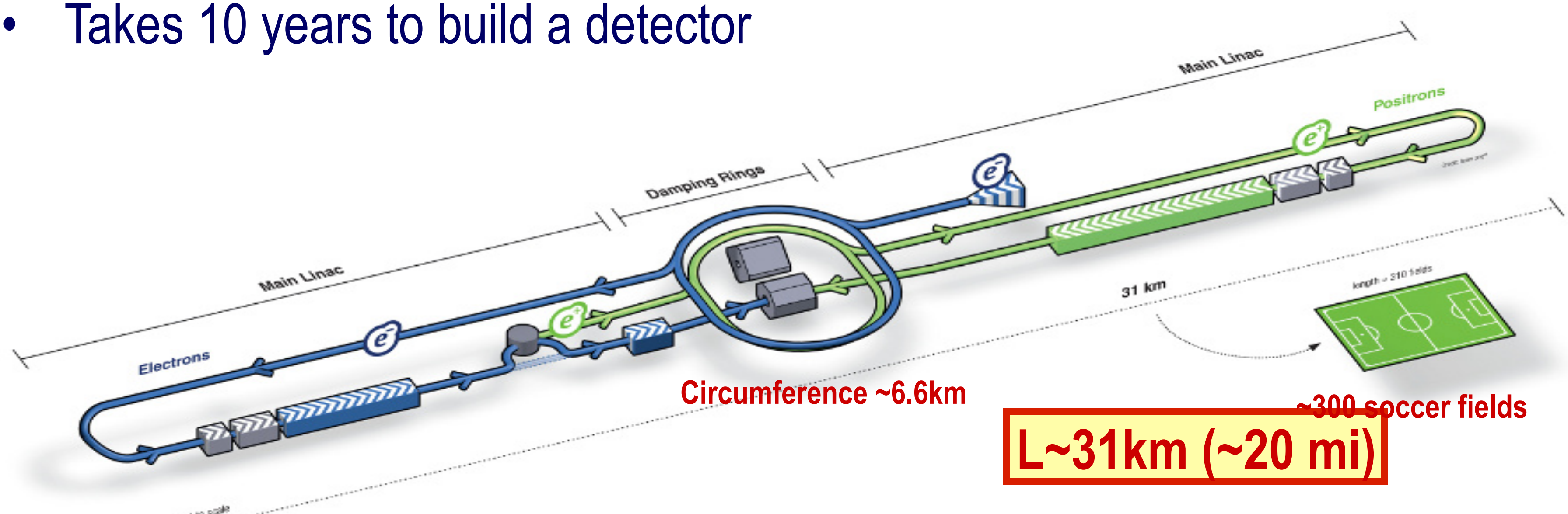
- 2013 – 2014: shutdown (LS1) ongoing to go to the design energy (13 – 14TeV) at high inst. Luminosity
- 2015 – 2017: $\sqrt{s}$=13 – 14TeV, L~10^{34}, 2 times the energy and 4 times the data we have now
- 2018: Shut-down (LS2) for detector upgrades
- 2019 – 2021: $\sqrt{s}$~=13 – 14TeV, L~2×10^{34}, 3 times the data in 2015 – 2017
- 2022 – 2023: Shut-down (LS3)
- 2023 – 2030(?): $\sqrt{s}$=13 – 14TeV, L~5×10^{34} (HL-LHC), 10 times the data in 2019 – 2021

So why is this discovery important?

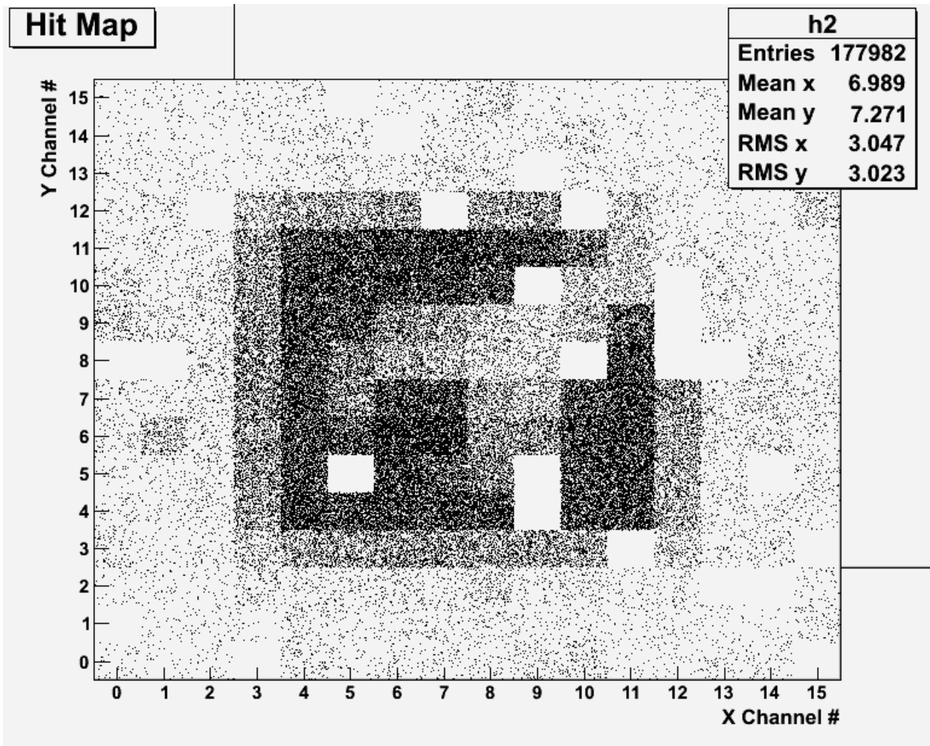
- This is the giant first in completing the Standard Model
- Will help understand the origin of mass and the mechanism at which mass is acquired
- Will help understand the origin and the structure of the universe and the inter-relations of the forces
- Will help us make our lives better
- Generate excitements and interests on science and train the next generation
  - UTA Had a Nobel laureate visit for a public lecture in 2012
    - 1200 people attended the lecture!!

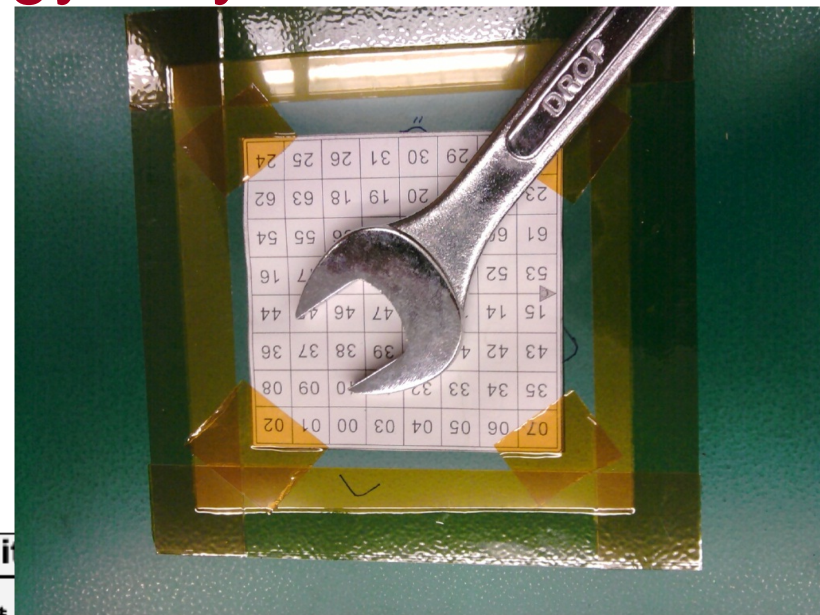
What's next? Future Linear Collider

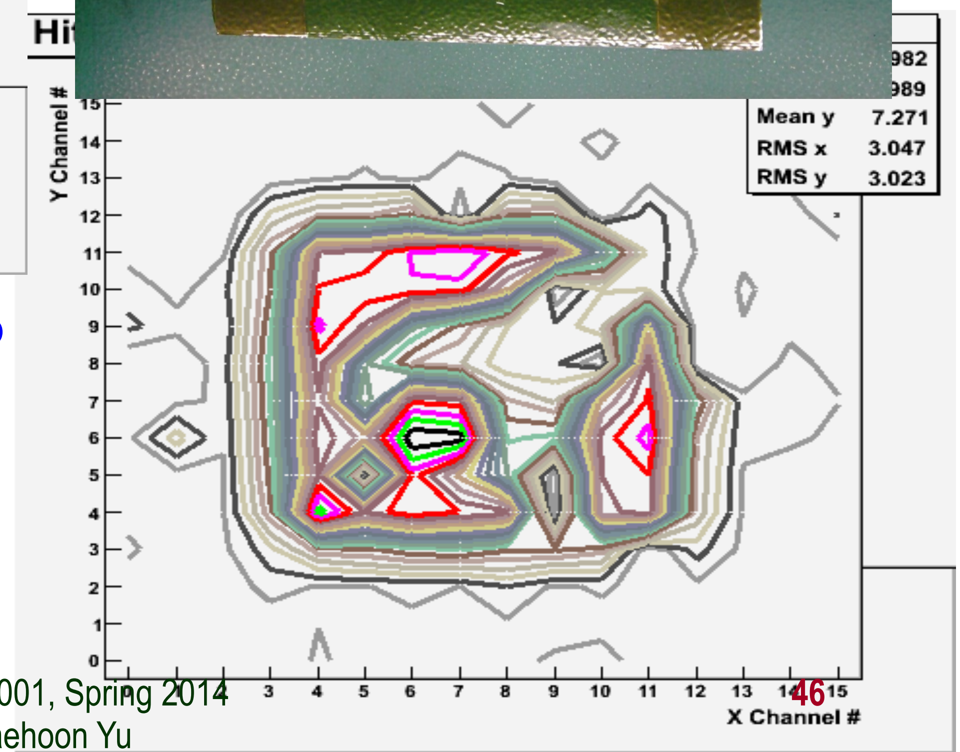
- Now that we have found a new boson, precision measurement of the particle's properties becomes important
- An electron-positron collider on a straight line for precision measurements
- 10~15 years from now (In Dec. 2011, Japanese PM announced that they would bid for a LC in Japan and reaffirmed by the new PM in 2013)
  - Our Japanese colleagues have declared that they will bid for building ILC
  - Japan just announced the selection of the site for the ILC in Aug. 2013!!
- Takes 10 years to build a detector



Bi-product of High Energy Physics Research





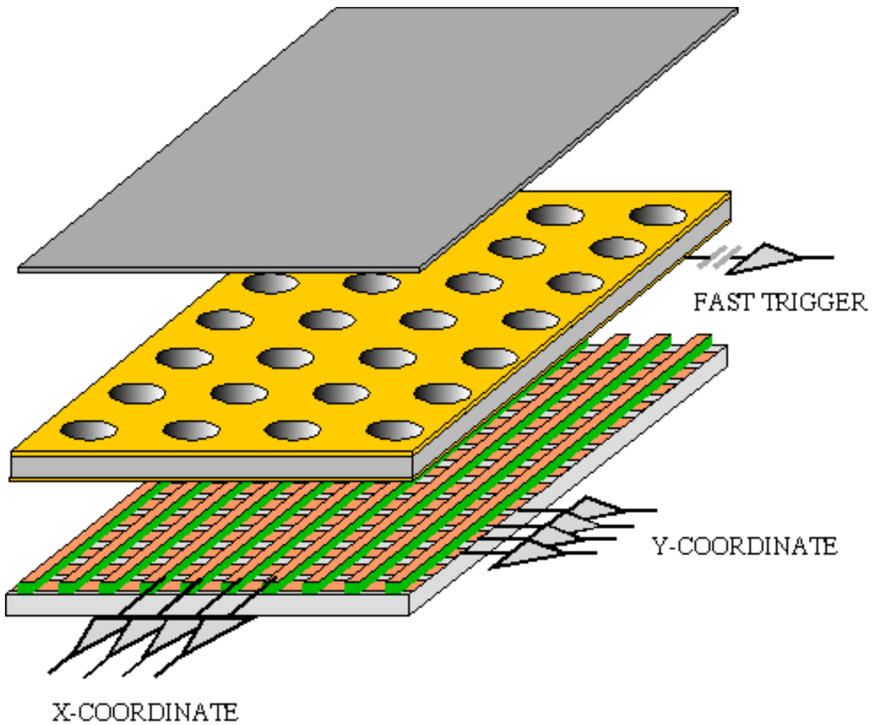


Can you see what the object is?
(GEM Detector X-ray Image)

And in not too distant future, we could do …

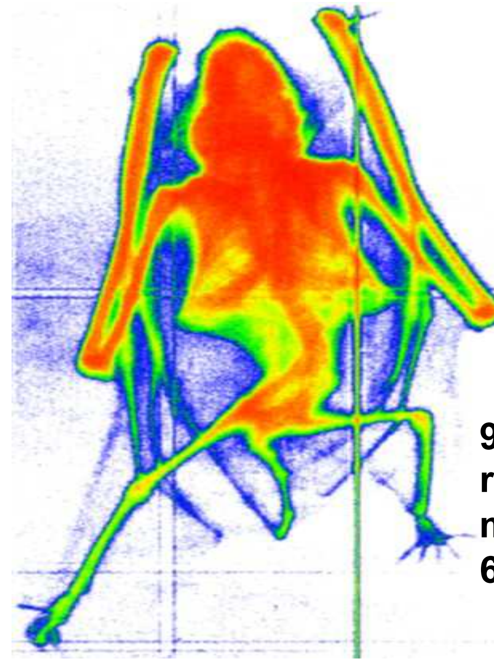
GEM Application Potential

Using the lower GEM signal, the readout can be self-triggered with energy discrimination:



A. Bressan et al,
Nucl. Instr. and Meth. A 425(1999)254
F. Sauli, Nucl. Instr. and Meth.A 461(2001)47

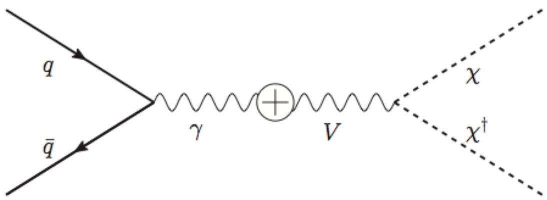
FAST X-RAY IMAGING



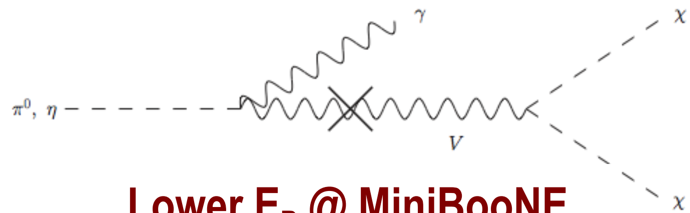
9 keV absorption radiography of a small mammal (image size ~ 60 x 30 mm^2)

Light DM Production at High Intensity Accelerator

- Now the Higgs particle, a part of only 5% of the universe, may've been seen
- It is time for us to look into the 95% of the universe!!

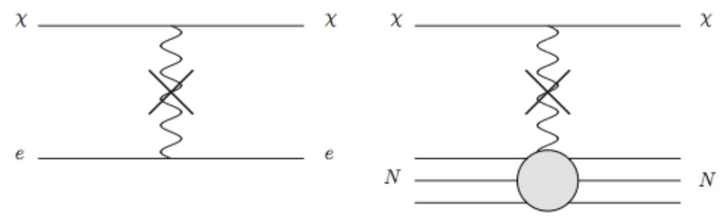


Higher E_P @ LBNE

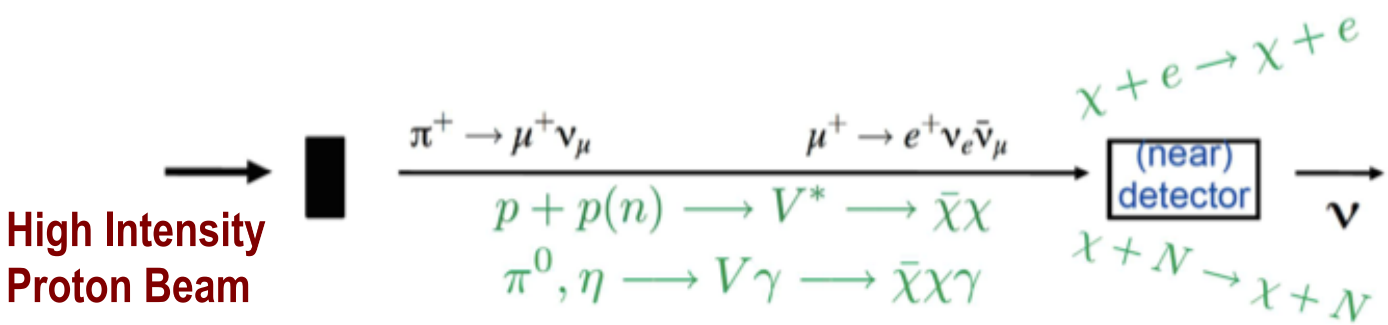


Lower E_P @ MiniBooNE

- Detection of DM:



- How does a DM event look in an experiment?:



Conclusions!

- The LHC opened up a whole new world!!
- Discovered one new charge neutral particle that couples to vector force carriers and whose measured mass is 125 times the proton mass
  - The discovery is no longer a matter of significance
- Properties of the discovered particle being intensely studied
  - Confirmed that some properties are like the Standard Model Higgs Particle ➔ Walks like the Higgs and Quacks like the Higgs
  - Still not enough though…
- Linear collider and advanced detectors are being developed for future precision measurements of Higgs and other newly discovered particles

Conclusions, cnt'd

- The new frontier at Fermilab will give us a chance to look for dark matter at an accelerator and possibly making DM beams, Yeah!!
- Outcome and the bi-product of HEP research improves our daily lives directly and indirectly
  - WWW came from HEP
  - GEM will make a large screen low dosage X-ray imaging possible
- Many technological advances happened through the last 100 years & will happen through the coming 100 yrs
- UTA is a big contributor in this endeavor!
- Continued and sufficient investments to forefront scientific endeavor is essential for the future!