PHYS 3313 – Section 001
Lecture #22

Wednesday, Nov. 28, 2012
Dr. Jaehoon Yu

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

Announcements

- Your presentations are in classes on Dec. 3 and Dec. 5
  - All presentation ppt files must be sent to me by 8pm this Sunday, Dec. 2
- Final exam is 11am – 1:30pm, Monday, Dec. 10
  - You can prepare a one 8.5x11.5 sheet (front and back) of handwritten formulae and values of constants for the exam
  - No formulae or values of constants will be provided!
- Planetarium extra credit
  - Tape one side of your ticket stubs on a sheet of paper with your name on it
  - Submit the sheet on Wednesday, Dec. 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 these 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

Prohibited Proton Decay

- Can the decay $p \rightarrow e^{+} + \pi^{0}$ occur?
  - Kinematically??
    - Yes, proton mass is a lot larger than the sum of the two masses
  - Electrical charge?
    - Yes, it is conserved
- But this decay does not occur ($<10^{-40}$/sec)
  - Why?
    - Must be a conservation law that prohibits this decay
  - What could it be?
    - An additive and conserved quantum number, Baryon number (B)
    - All baryons have B=1
    - Anti-baryons? (B=-1)
    - Photons, leptons and mesons have B=0
- Since proton is the lightest baryon, it does not decay.

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

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

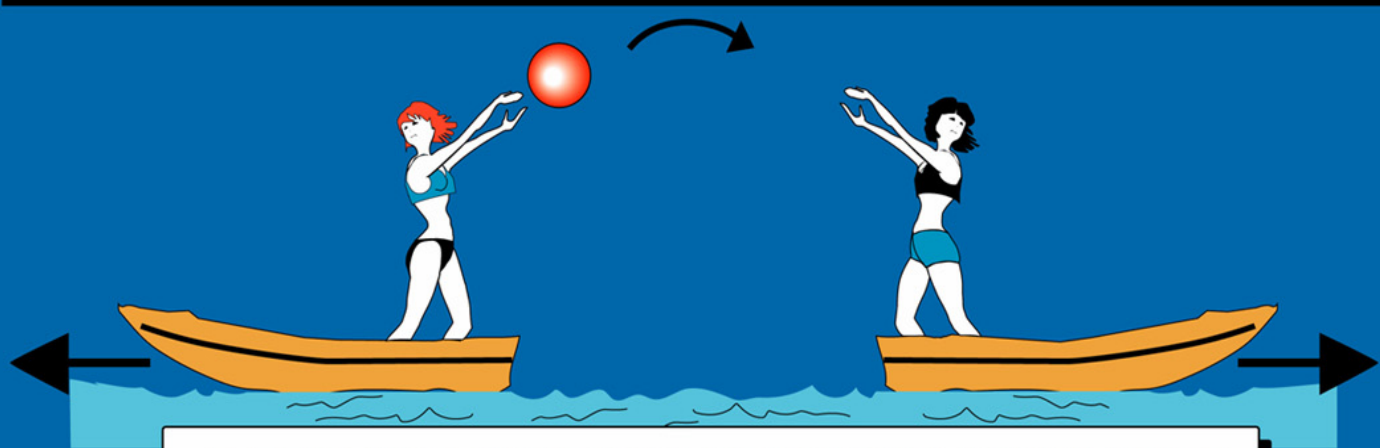
  - ➔ Increasing order of lepton masses
  - Convention used in strong isospin symmetry, higher member of multiplet carries higher electrical charge
- And three families of quark constituents

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

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

The forces in Nature

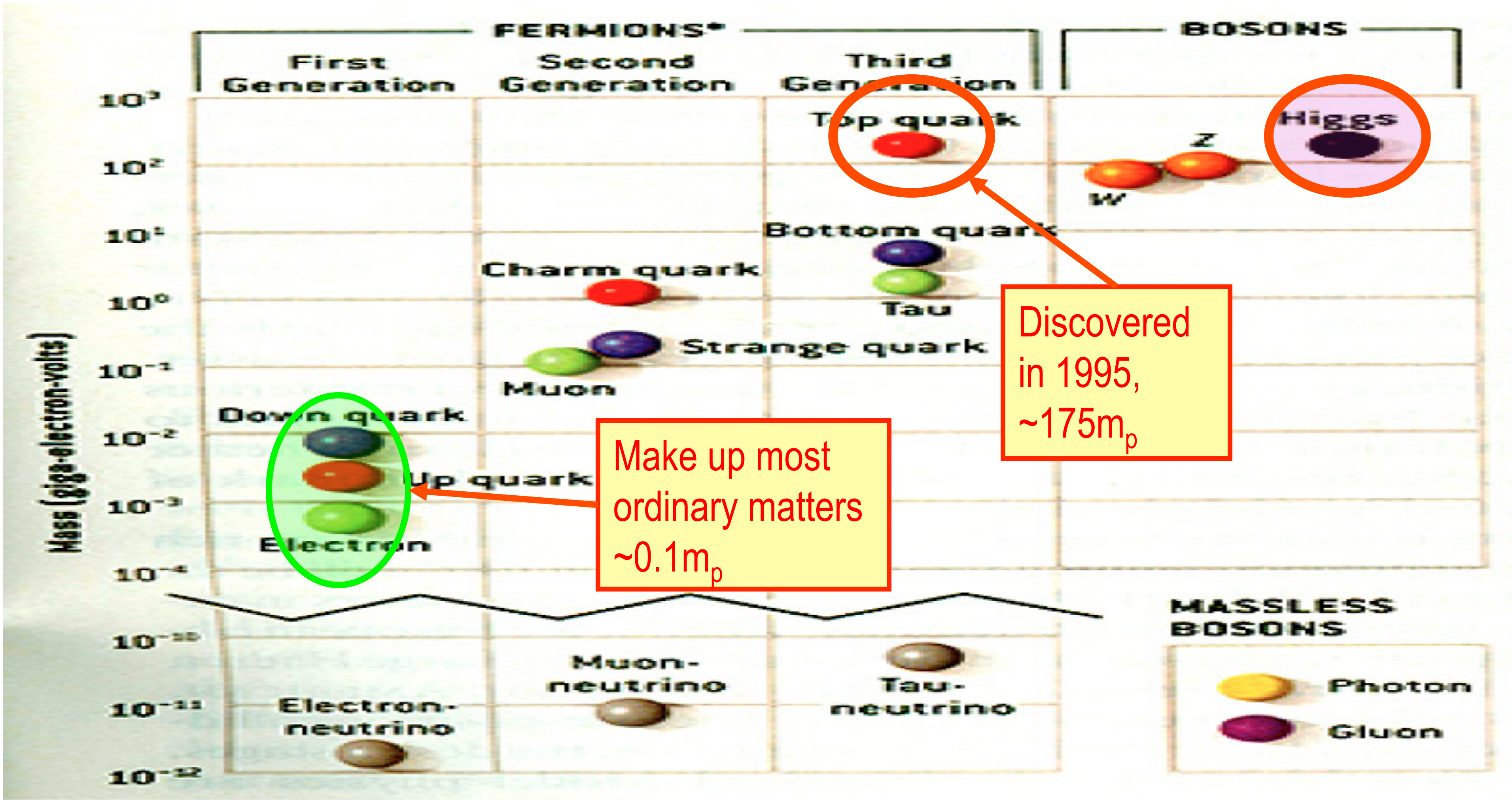
TYPE	INTENSITY OF FORCES (DECREASING ORDER)	BINDING PARTICLE (FIELD QUANTUM)	OCCURS IN :
STRONG NUCLEAR FORCE	~ 1	GLUONS (NO MASS)	ATOMIC NUCLEUS
ELECTRO -MAGNETIC FORCE	~ 10^{-3}	PHOTONS (NO MASS)	ATOMIC SHELL ELECTROTECHNIQUE
WEAK NUCLEAR FORCE	~ 10^{-5}	BOSONS Z^o, W+ , W- (HEAVY)	RADIOACTIVE BETA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



THE EXCHANGE OF PARTICLES IS RESPONSIBLE FOR THE FORCE

CERN AC _Z04_ V25/8/1992

The Standard Model



- Total of 16 particles make up the matter in the universe! ➔ Simple and elegant!!!
- Tested to a precision of 1 part per million!

Particle Accelerators

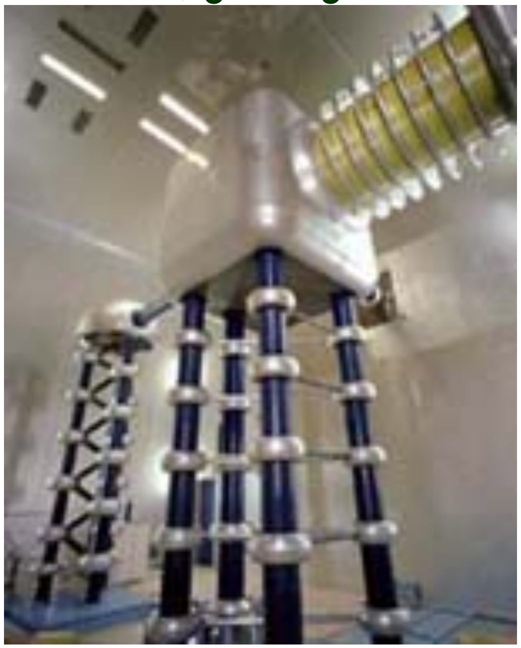
- How can one obtain high energy particles?
  - Cosmic ray ➔ Sometimes we observe 1000TeV cosmic rays
    - Low flux and cannot control energies too well
- Need to look into small distances to probe the fundamental constituents with full control of particle energies and fluxes
  - Particle accelerators
- 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

Electrostatic Accelerators: Cockcroft-Walton

- Cockcroft-Walton Accelerator
  - Pass ions through sets of aligned DC electrodes at successively increasing fixed potentials
  - Consists of ion source (hydrogen gas) and a target with the electrodes arranged in between
  - Acceleration Procedure
    - Electrons are either added or striped off of an atom
    - Ions of charge q then get accelerated through series of electrodes, gaining kinetic energy of T=qV through every set of electrodes
- Limited to about 1MeV acceleration due to voltage breakdown and discharge beyond voltage of 1MV.
- Available commercially and also used as the first step high current injector (to ~1mA).

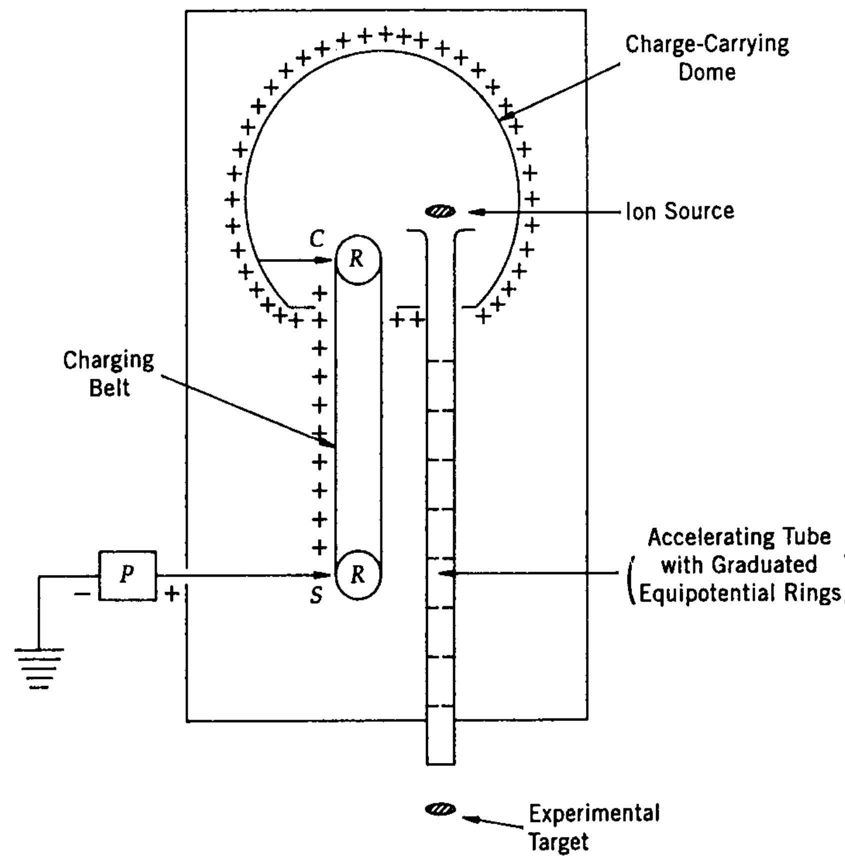


Electrostatic Accelerators: Van de Graaff

- Energies of particles through DC accelerators are proportional to the applied voltage
- Robert Van de Graaff developed a clever mechanism to increase HV
  - The charge on any conductor resides on its outermost surface
  - If a conductor carrying additional charge touches another conductor that surrounds it, all of its charges will transfer to the outer conductor increasing the charge on the outer conductor, thereby increasing voltage higher

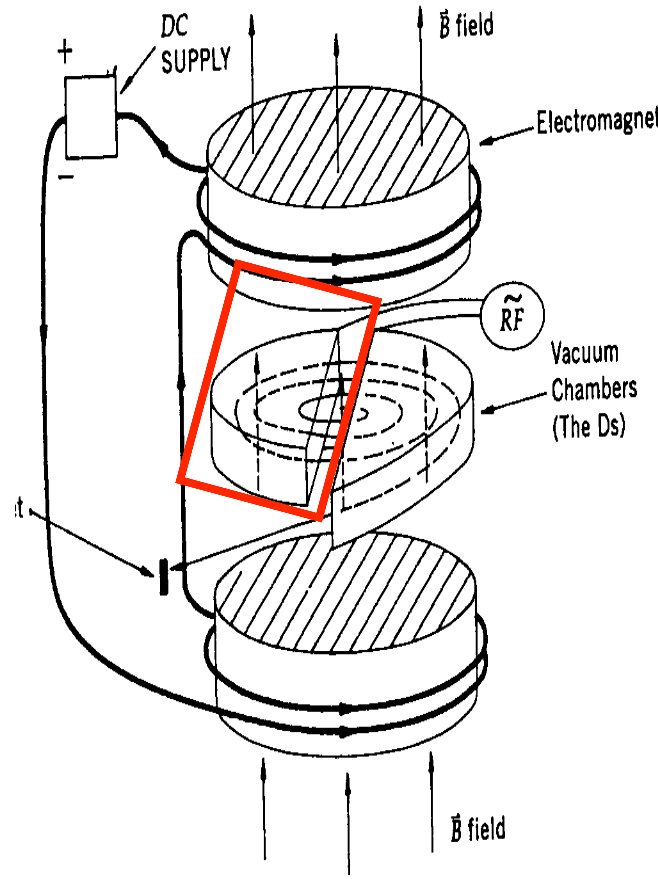
Electrostatic Accelerators: Van de Graaff

- Sprayer adds positive charge to the conveyor belt at corona points
- Charge is carried on an insulating conveyor belt
- The charges get transferred to the dome via the collector
- The ions in the source then gets accelerated to about 12MeV
- Tandem Van de Graff can accelerate particles up to 25 MeV
- This acceleration normally occurs in high pressure gas that has very high breakdown voltage



Resonance Accelerators: Cyclotron

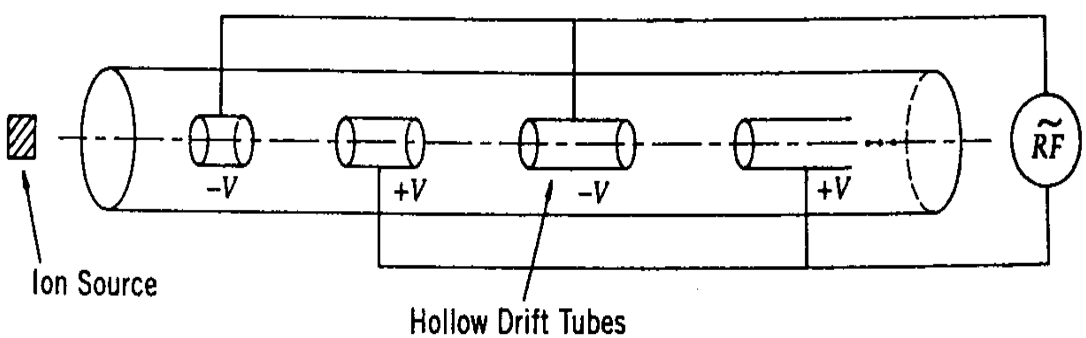
- Invented by E. Lawrence at Berkeley in 1930's
- While the D's are connected to HV sources, there is no electric field inside the chamber due to Faraday effect
- Strong electric field exists only in the gap between the D's
- An ion source is placed in the gap
- The path is circular due to the perpendicular 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



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

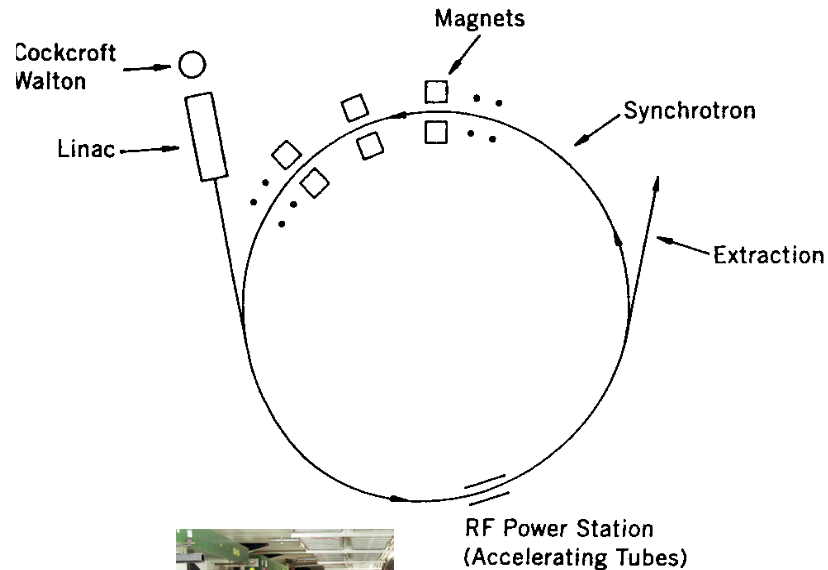
Resonance Accelerators: Linear Accelerator

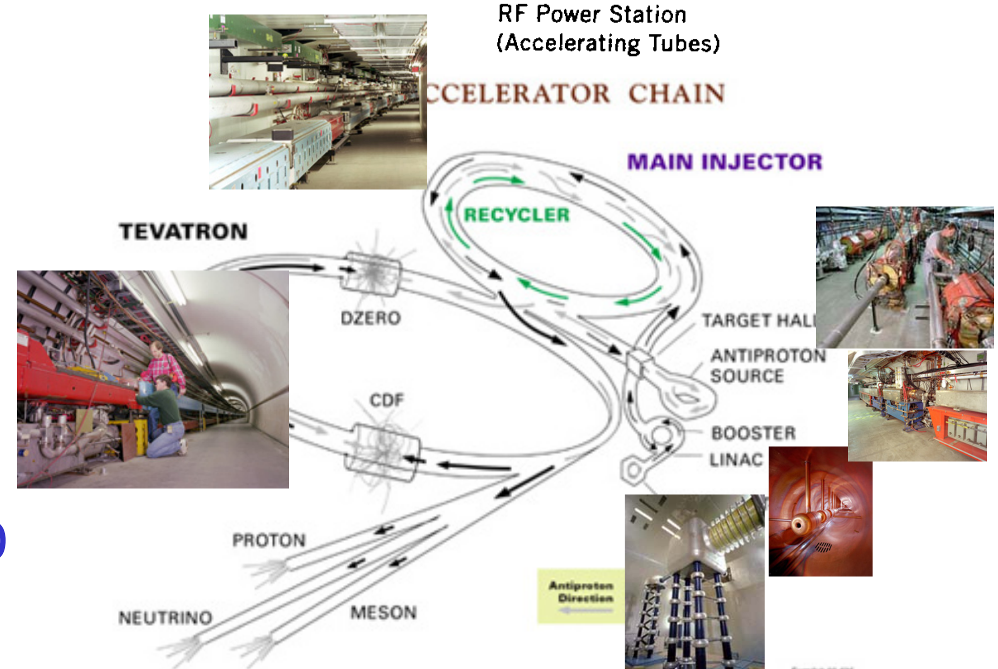
- Accelerates particles along a linear path using resonance principle
- A series of metal tubes are located in a vacuum vessel and connected successively to alternating terminals of radio frequency oscillator
- The directions of the electric fields changes before the particles exits the given tube
- 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

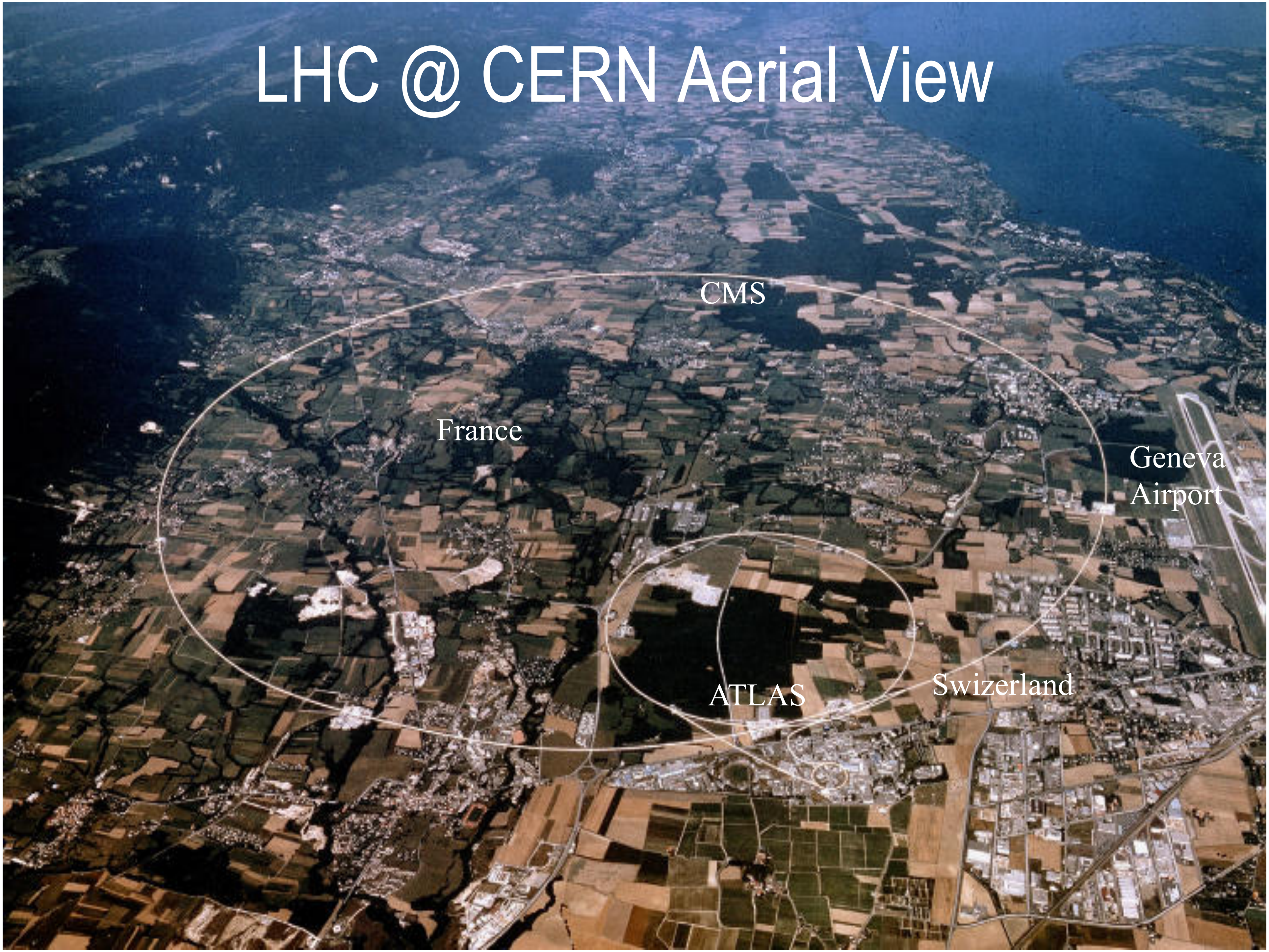




Comparisons between Tevatron and LHC

- 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

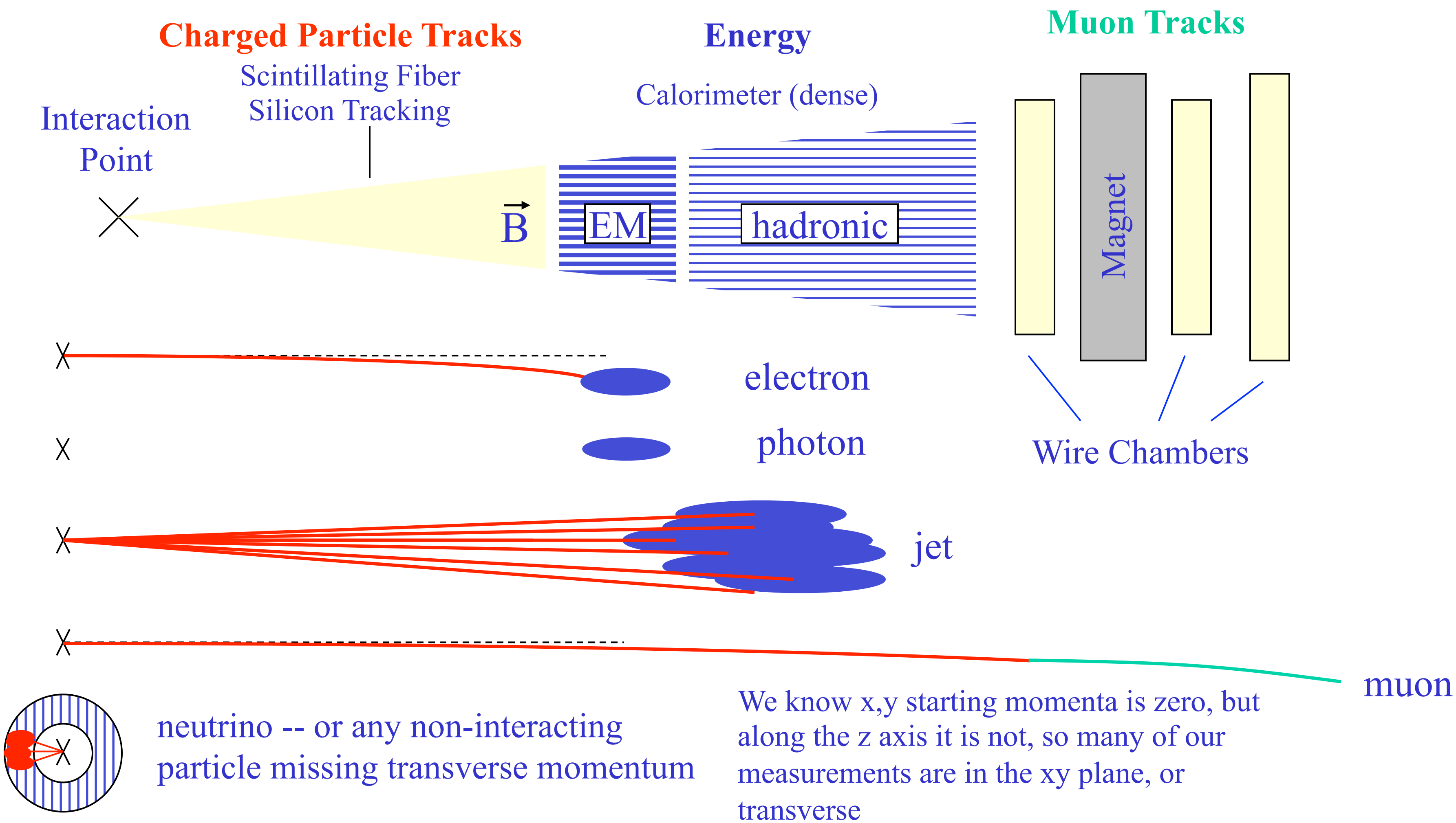
LHC @ CERN Aerial View



Particle Detectors

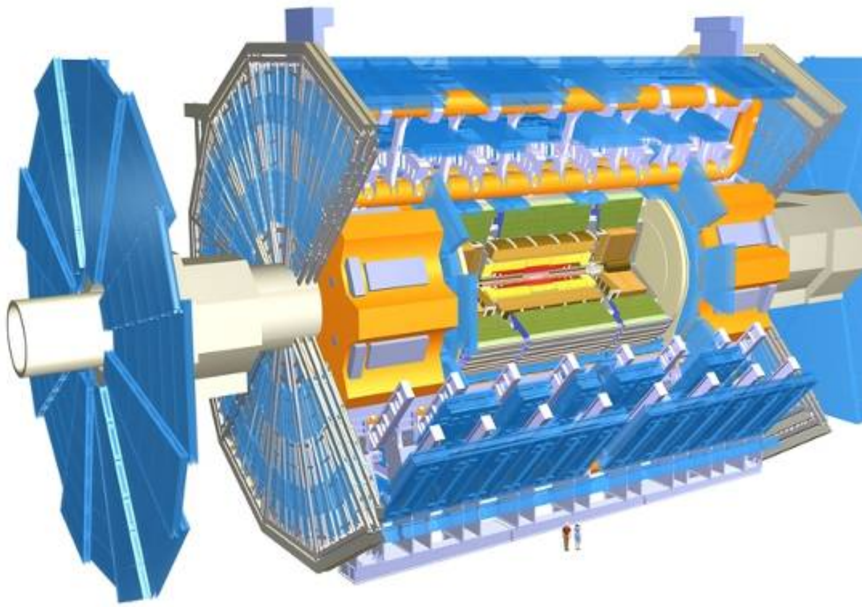
- Subatomic particles cannot be seen by naked eyes but can be detected through their interactions within matter
- What do you think we need to know first to construct a detector?
  - What kind of particles do we want to detect?
    - Charged particles and neutral particles
  - What do we want to measure?
    - 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

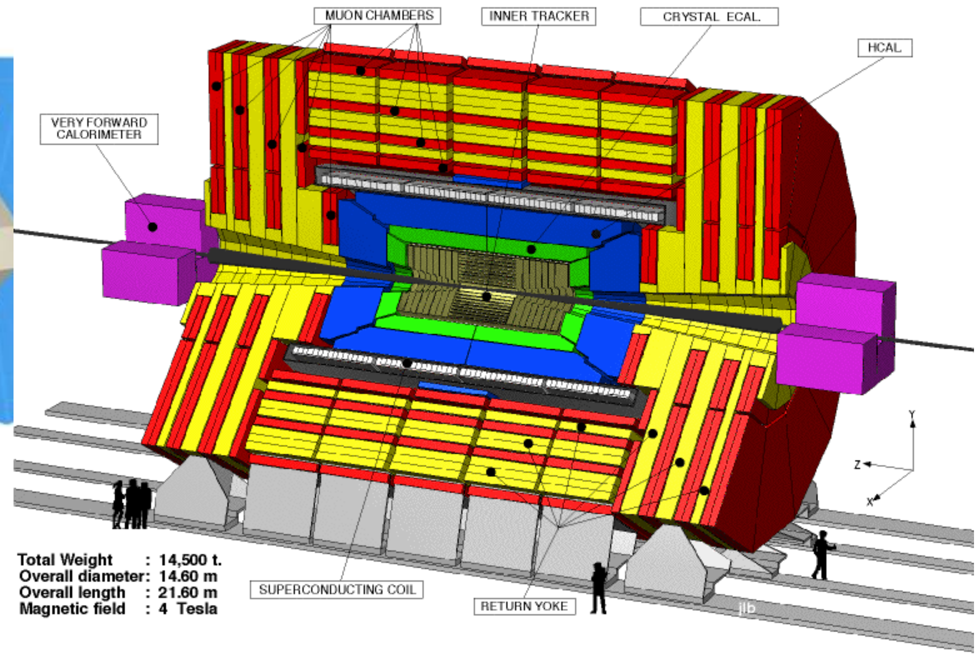
Particle Detection Techniques



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

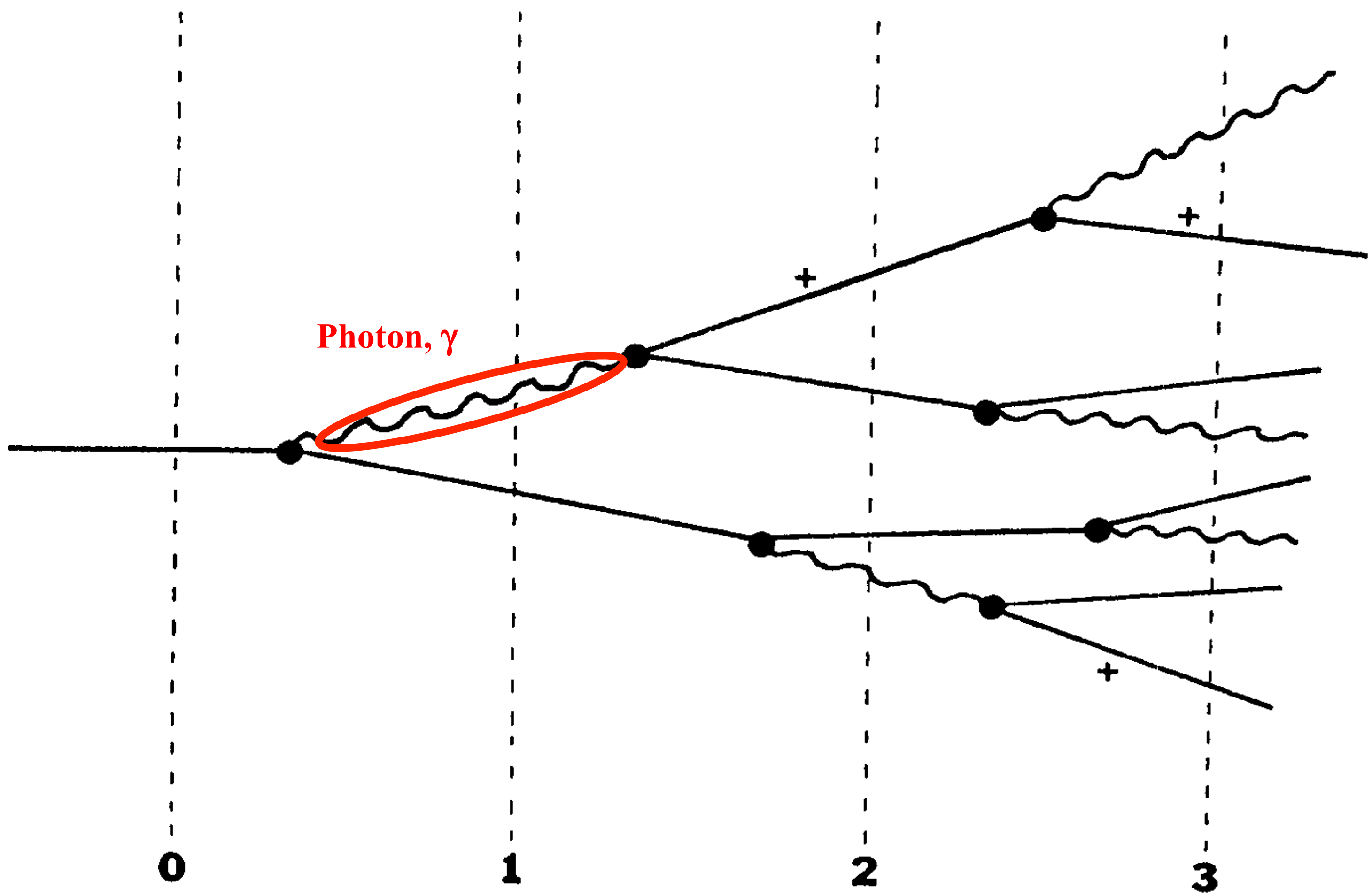
The ATLAS and CMS Detectors





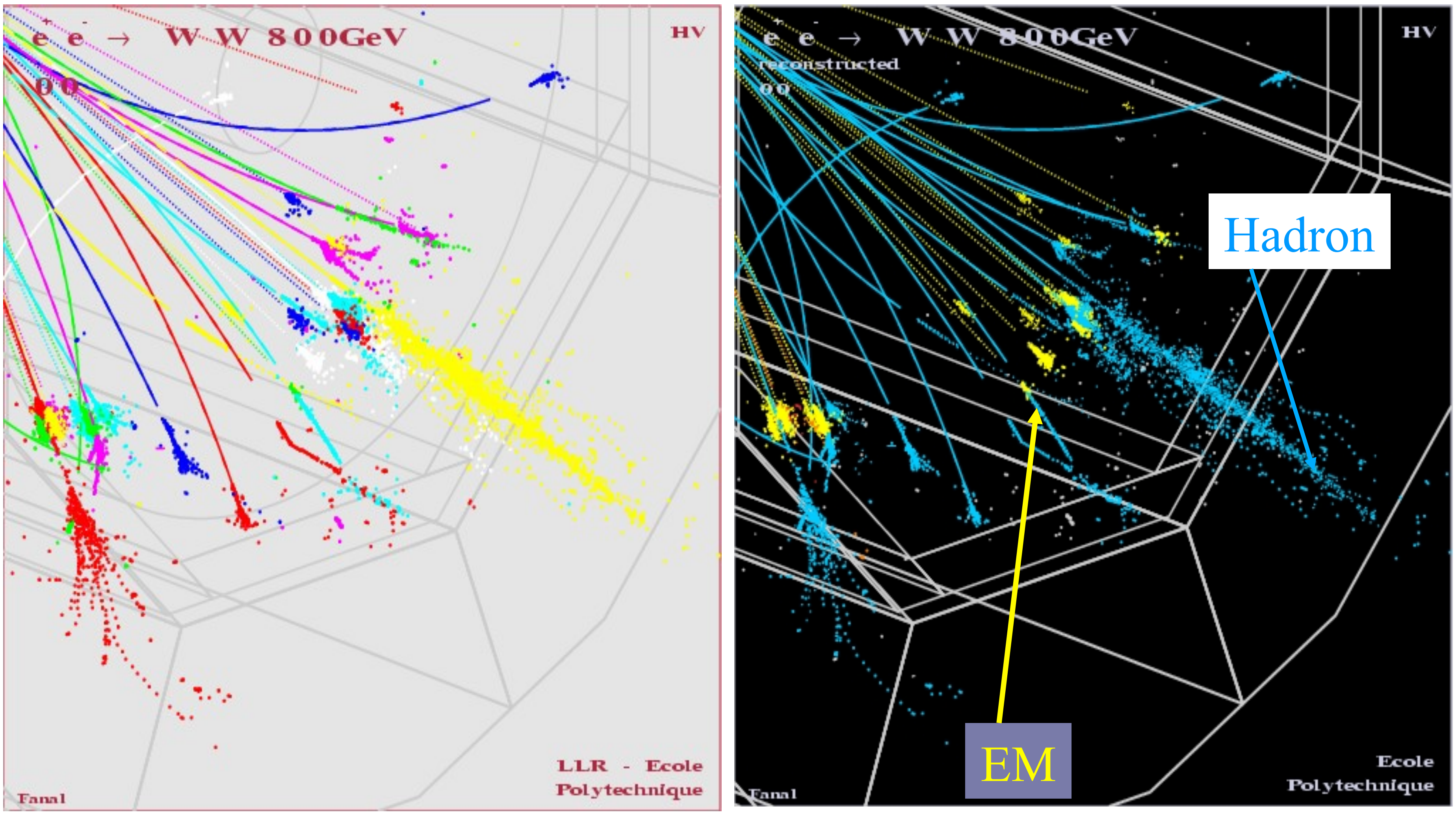
- **Fully multi-purpose detectors with emphasis on lepton ID & precision E & P**
- **Weighs 7000 tons and 10 story tall**
- Records **200 – 400 collisions/second**
- Records approximately **350** MB/second
- Record over 2 PB per year ➔ **200*Printed material of the US Lib. of Congress**

Electron Interactions in material (showering)

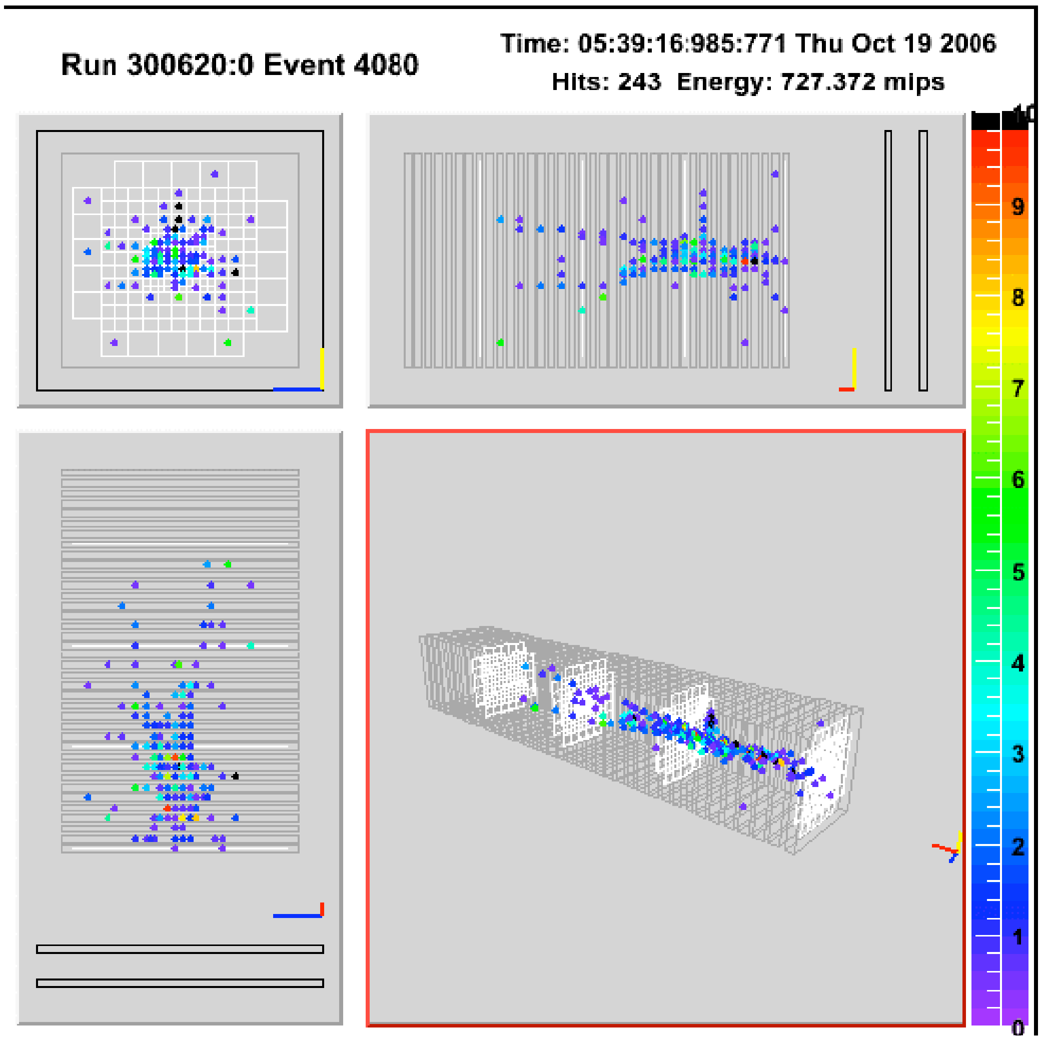


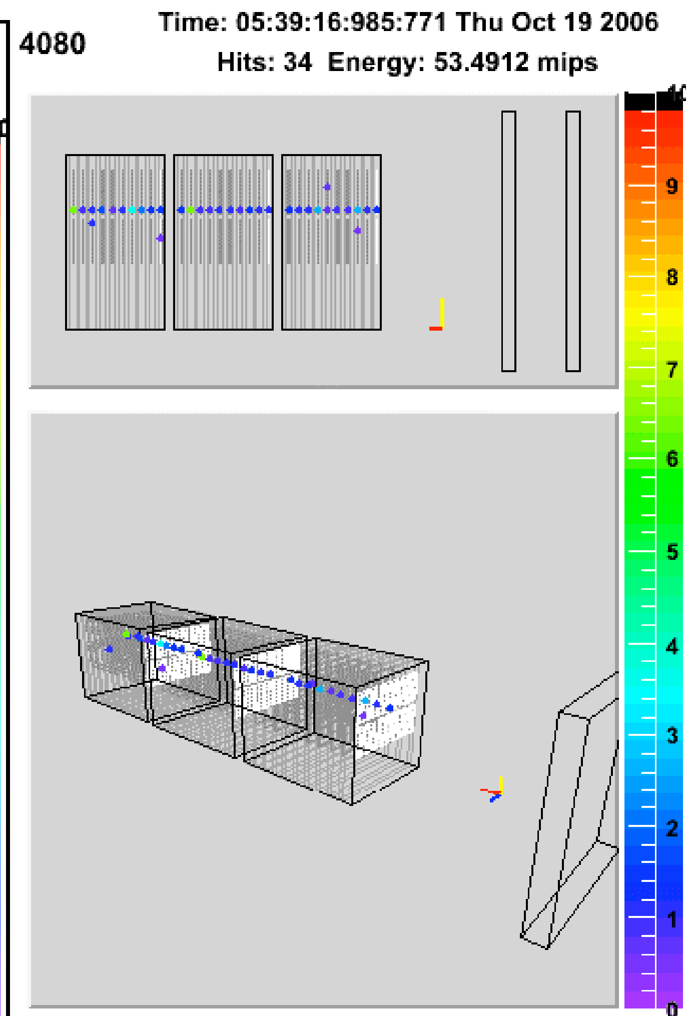
Method of measuring the particle energy in a calorimeter!!

How particle showers look in detectors



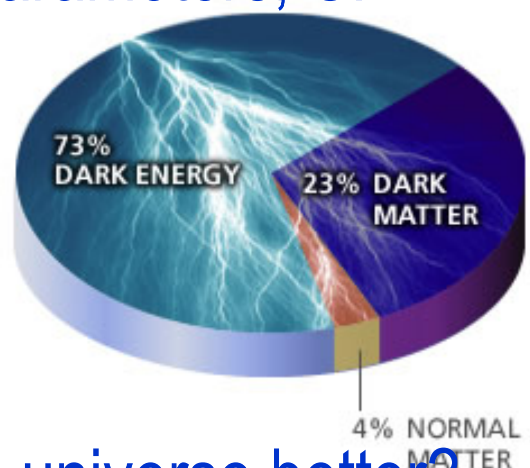
Example Hadronic Shower (20GeV)





What's the current hot issues?

- Why is the mass range so large ($0.1 m_p$ – $175\ m_p$)?
- 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, CP violations and mass ordering?
- Why are there only three apparent forces?
- Is the picture we present the real thing?
  - What makes up the 96% 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?

What is the Higgs and What does it do?

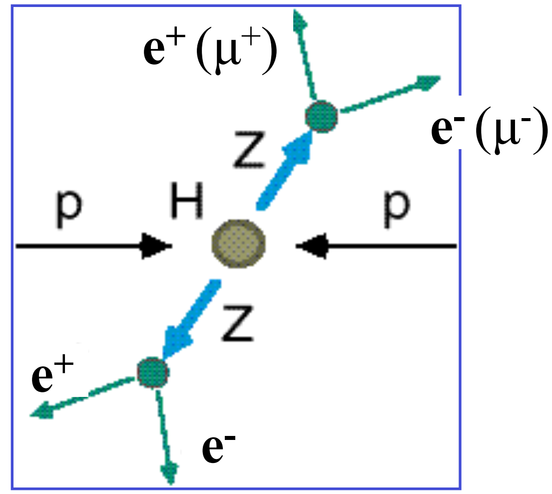
- When there is perfect symmetry, one cannot tell directions!
- Only when symmetry is broken, can one tell directions
- Higgs field works to break the perfect symmetry and give mass
  - This field exists right now amongst us so that we have mass
- Sometimes, this field spontaneously generates a particle, the Higgs particle
- So the Higgs particle is the evidence of the existence of the Higgs field!

How do we look for the Higgs?

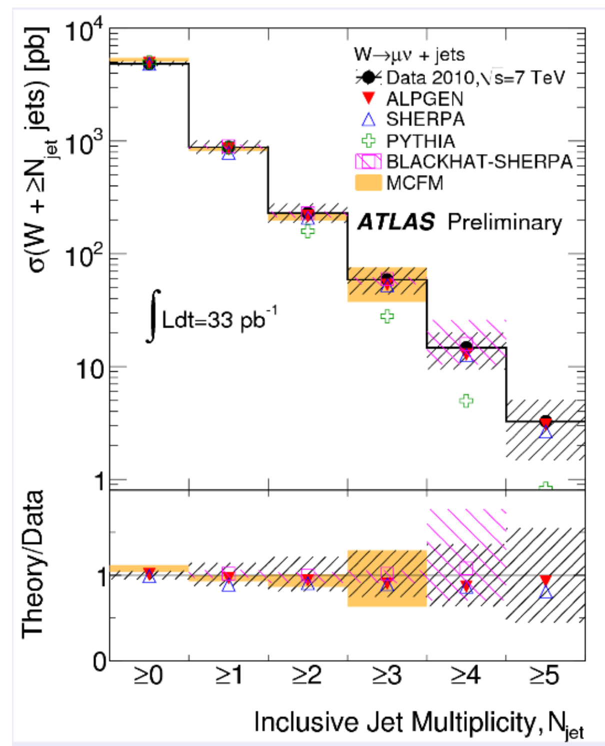
- Higgs particle is so heavy they decays into some other particles very quickly
- When one searches for a new particle, you look for the easiest way to get at them
- Of these the many signatures of the Higgs, some states are much easier to find, if it were the Standard Model one
  - $H \rightarrow \gamma\gamma$
  - $H \rightarrow ZZ^* \rightarrow 4e, 4\mu, 2e2\mu, 2e2\nu$ 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?

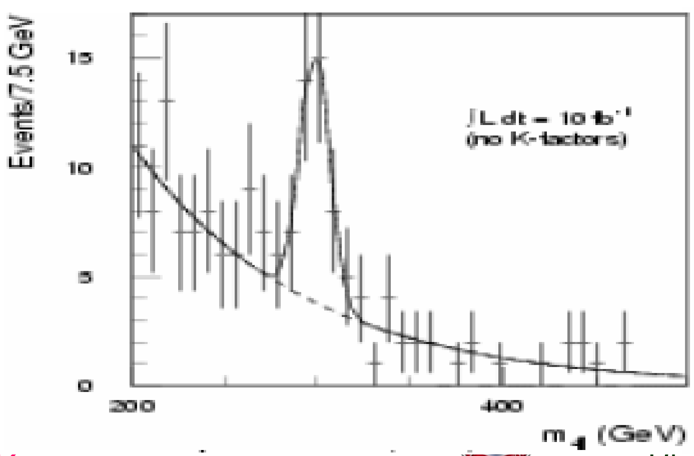
- Identify the Higgs candidate events



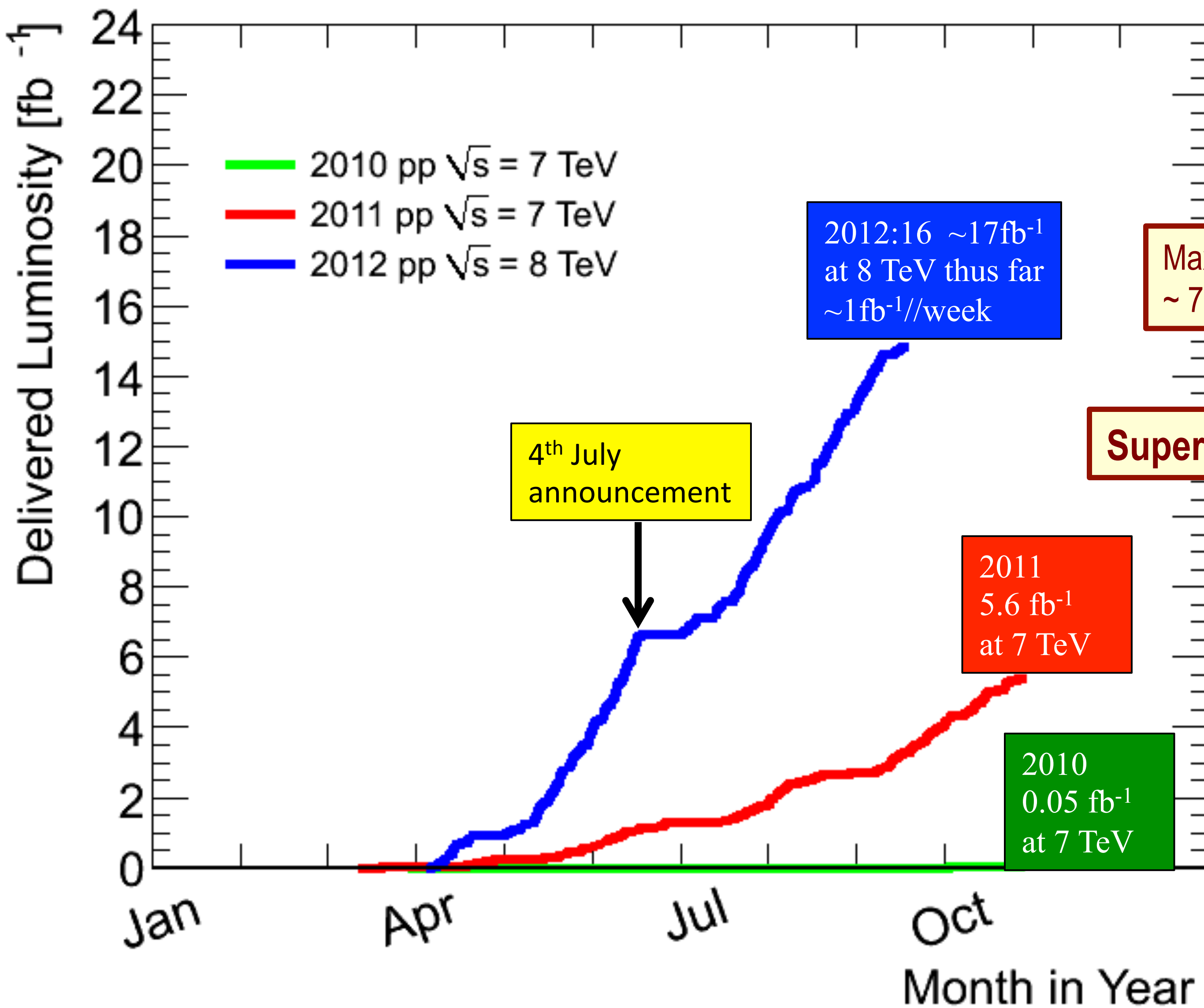
- Understand fakes (backgrounds)



- Look for a bump!!



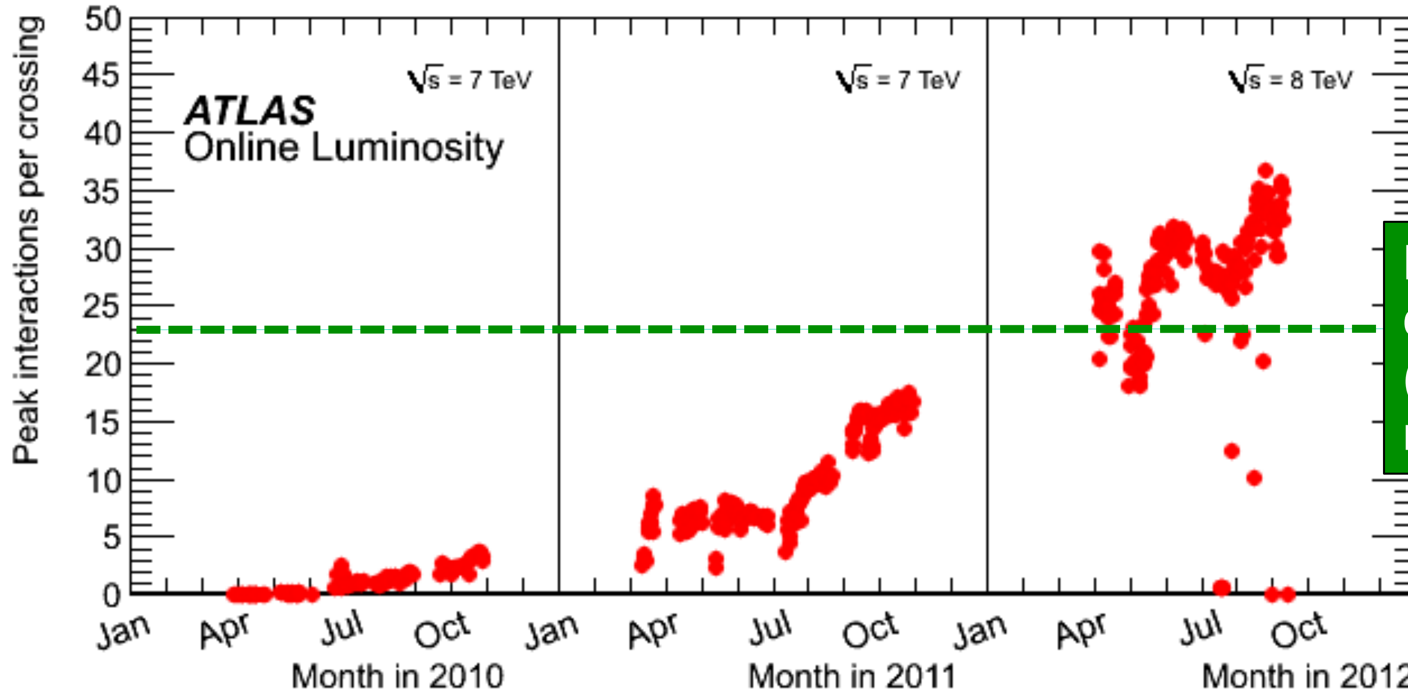
Amount of LHC Data



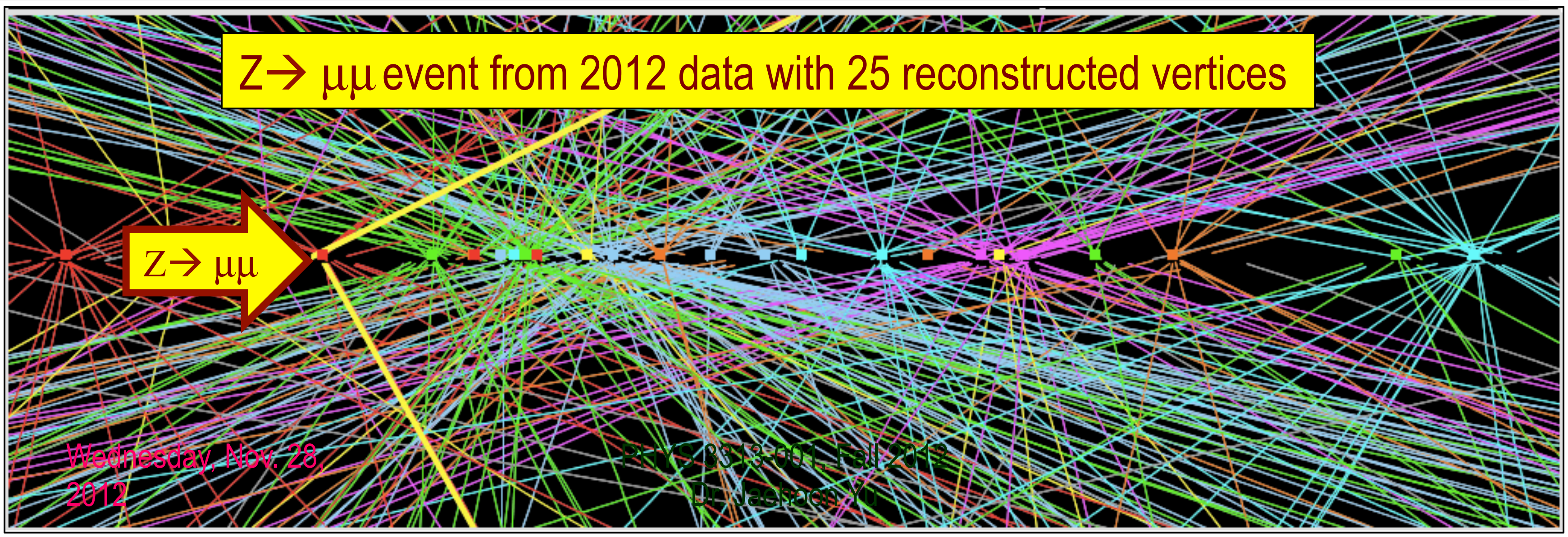
Max inst. luminosity: ~ 7.7 x10^{33} cm^{-2} s^{-1}

Superb performance!!

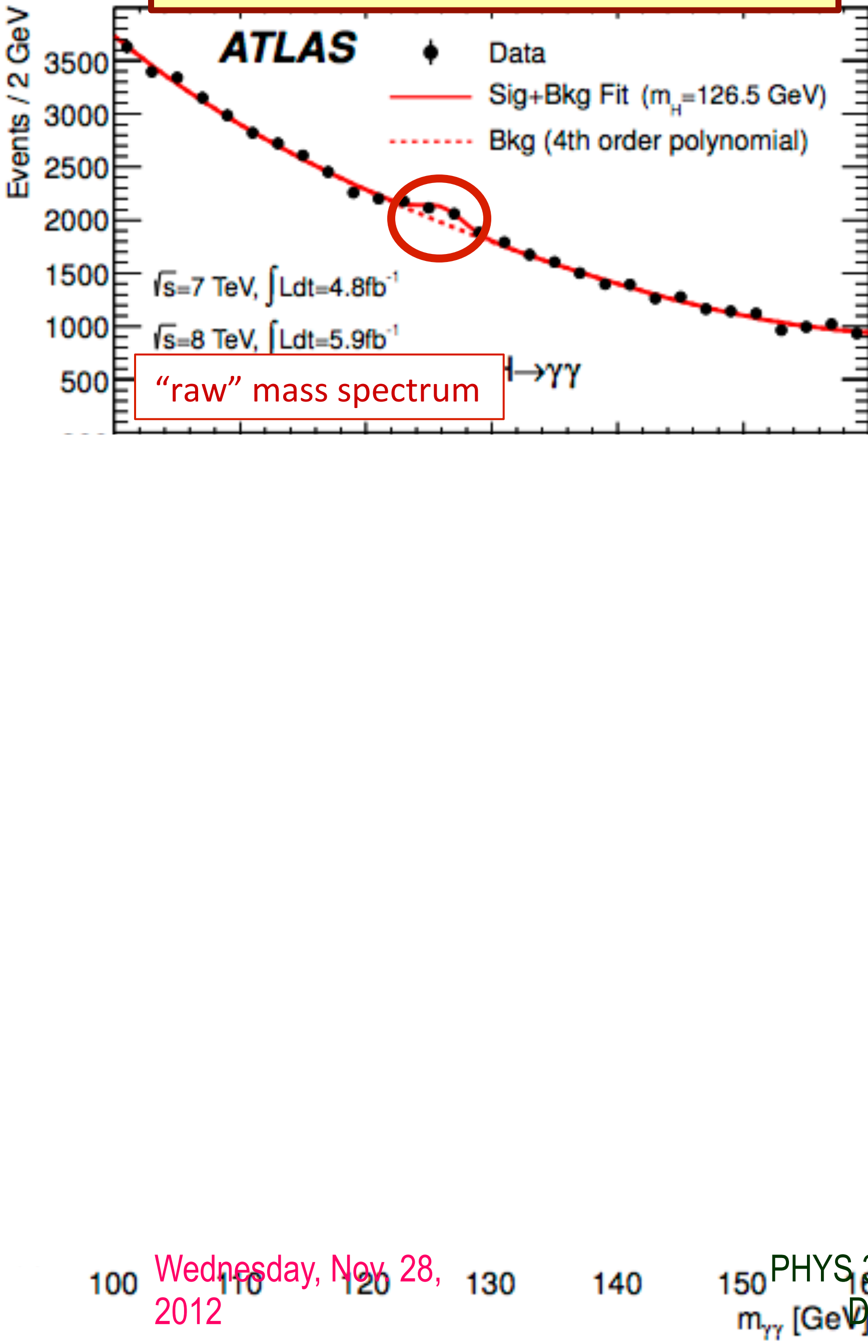
The BIG challenge in 2012: PILE-UP



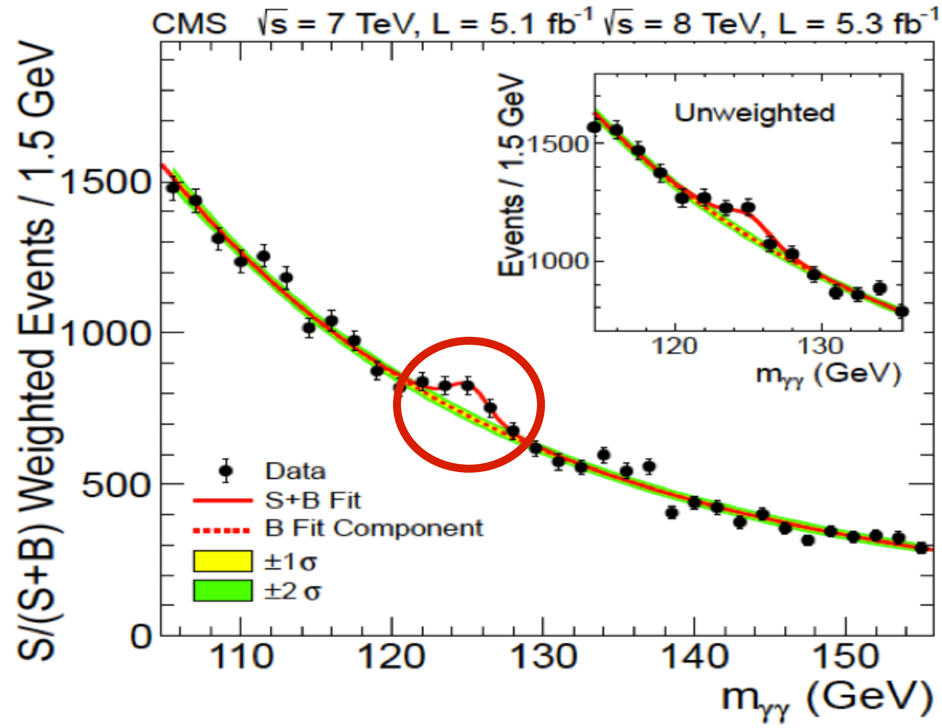
Experiment's design value (expected to be reached at $L=10^{34}$!)



After all selections: 59059 events



"raw" mass spectrum

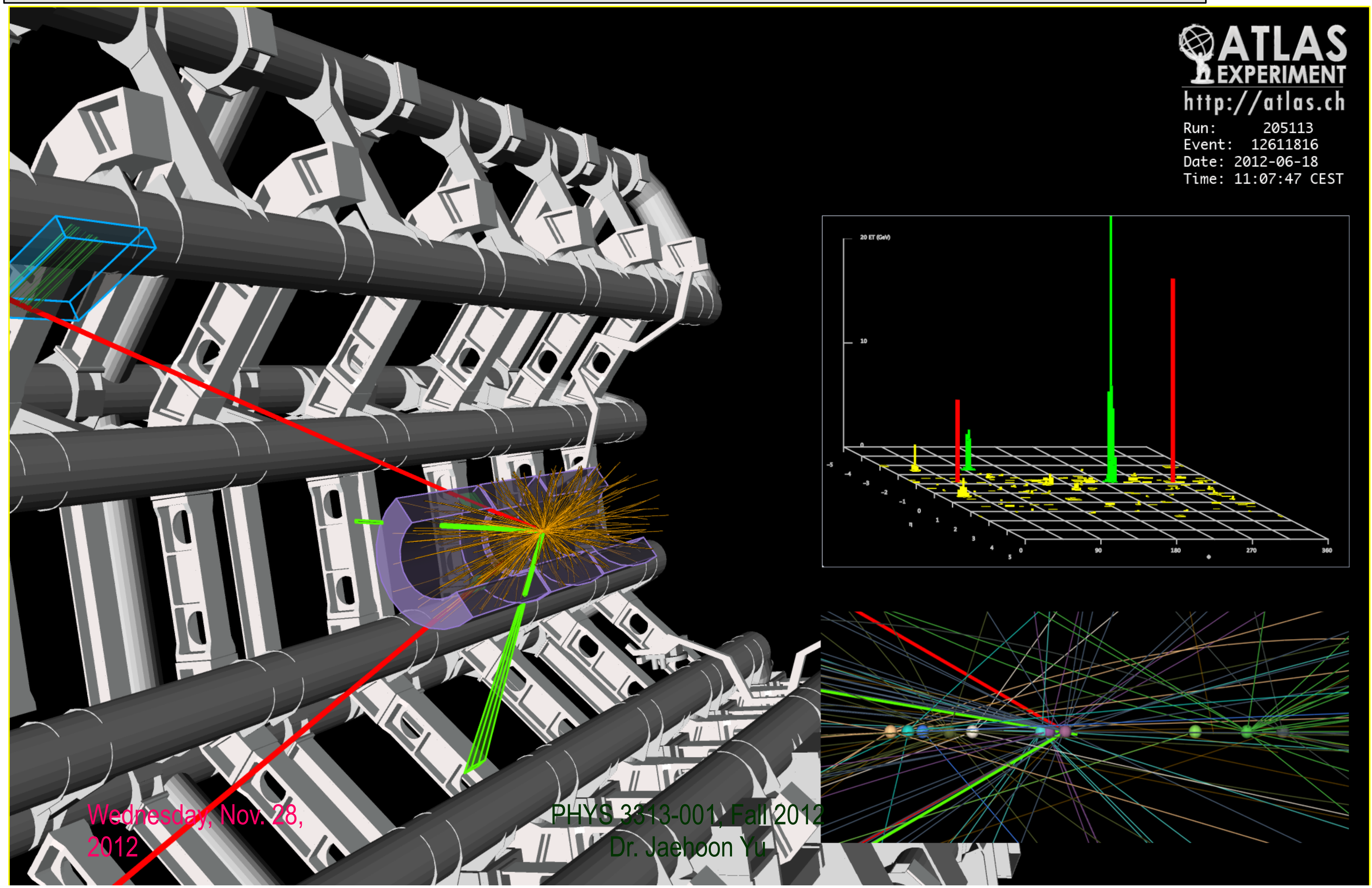


Data sample	m_H of max significance	local significance **obs.** (exp. SM H)
2011	126 GeV	**3.4 σ** (1.6)
2012	127 GeV	**3.2 σ** (1.9)
2011+2012	126.5 GeV	**4.5 σ**(2.5) ATLAS
2011+2012	125.5GeV	**4.1 σ**(2.8) CMS

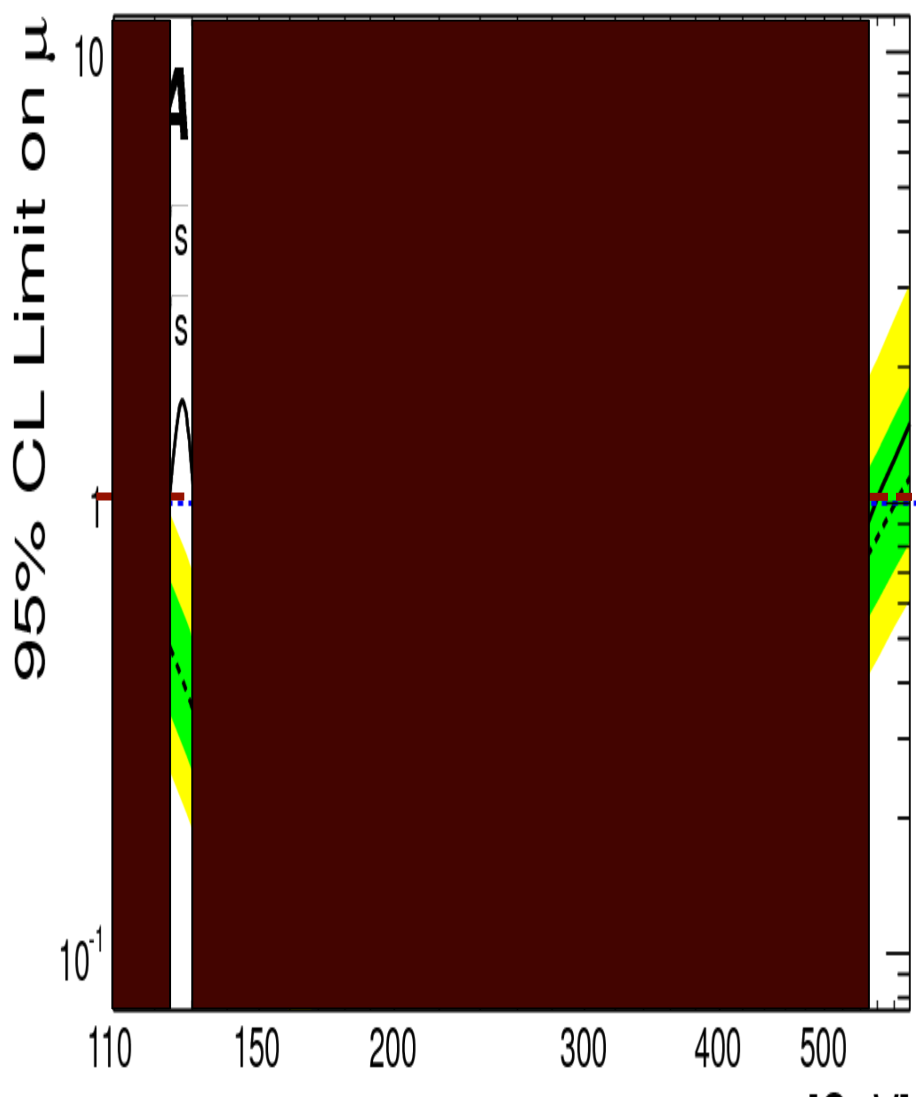
peak above a large smooth background, relies upon excellent mass resolution

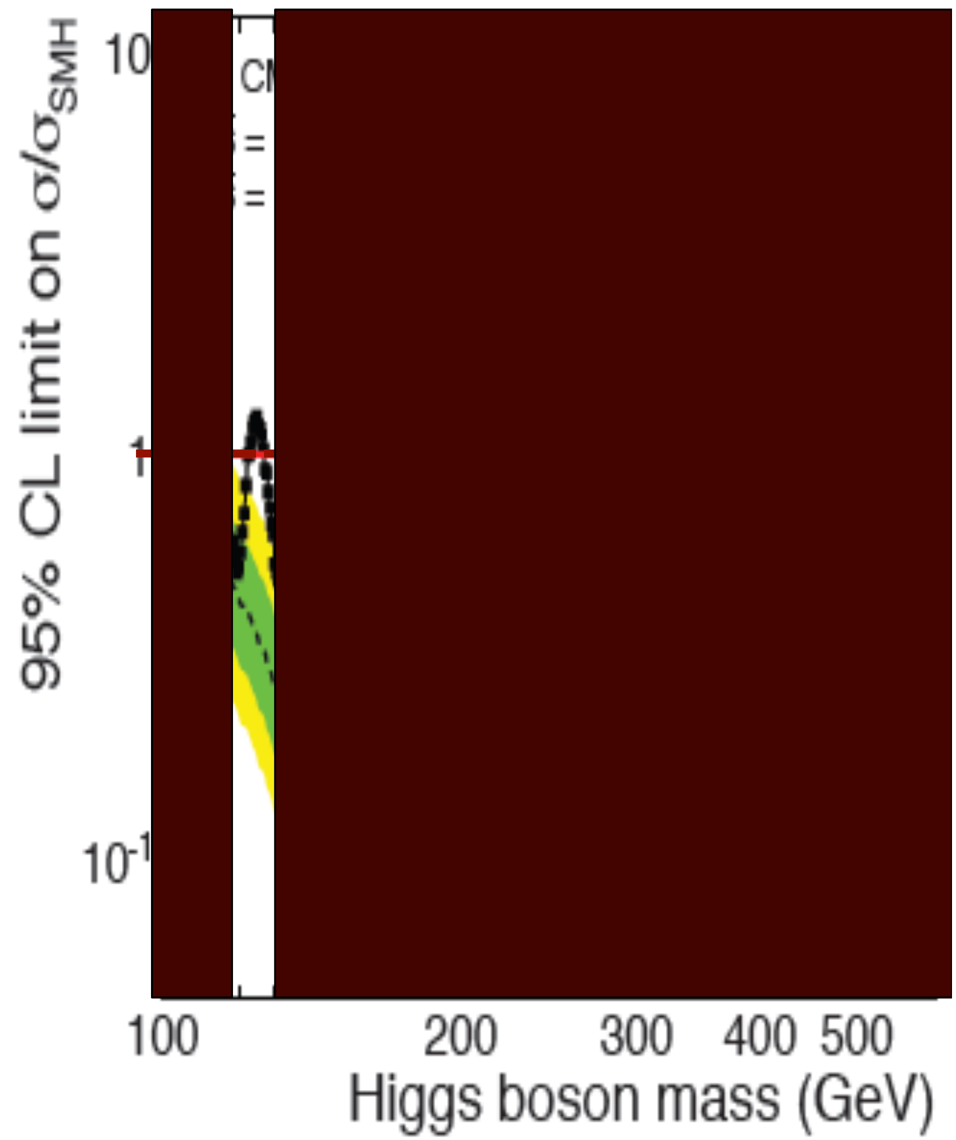
2e2μ candidate event w/ M2e2μ=123.9GeV

p_T (e,e,μ,μ)= 18.7, 76, 19.6, 7.9 GeV, $m(e^+e^-)$= 87.9 GeV, $m(\mu^+\mu^-)$ =19.6 GeV
12 reconstructed vertices



All Channel Combined Exclusion

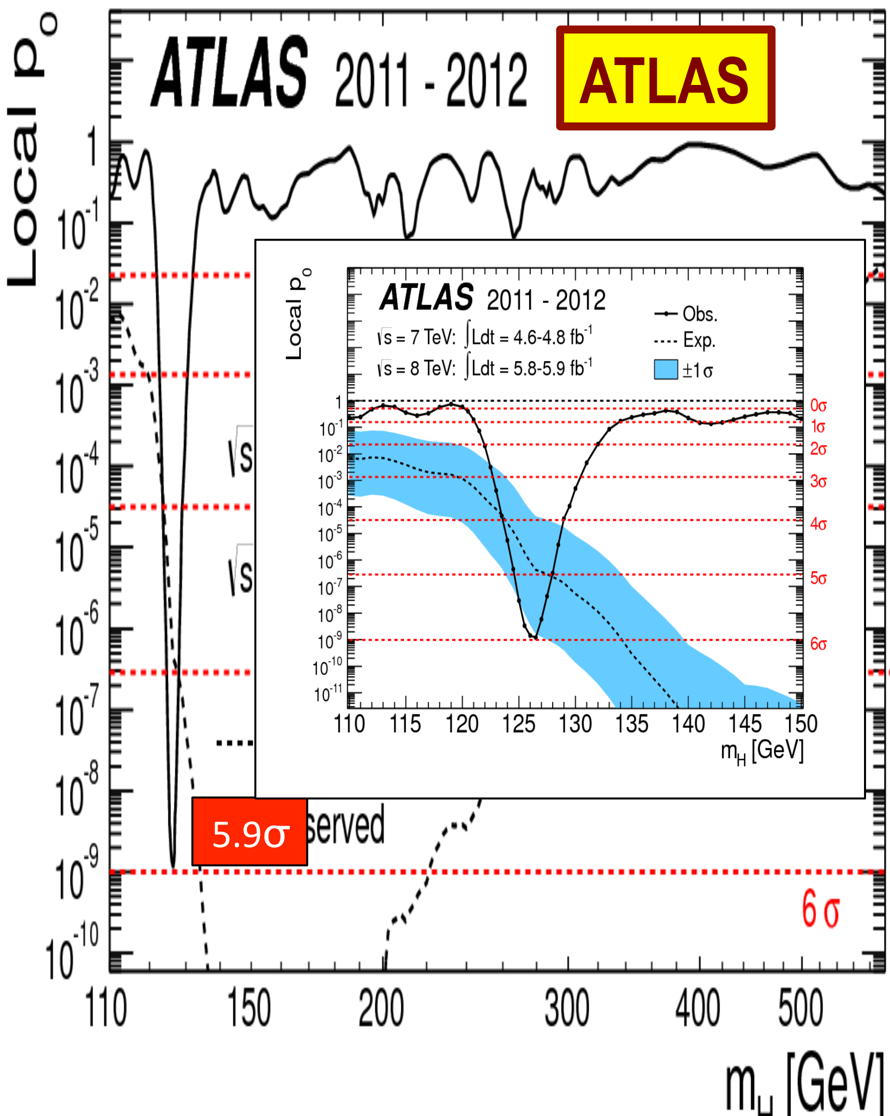


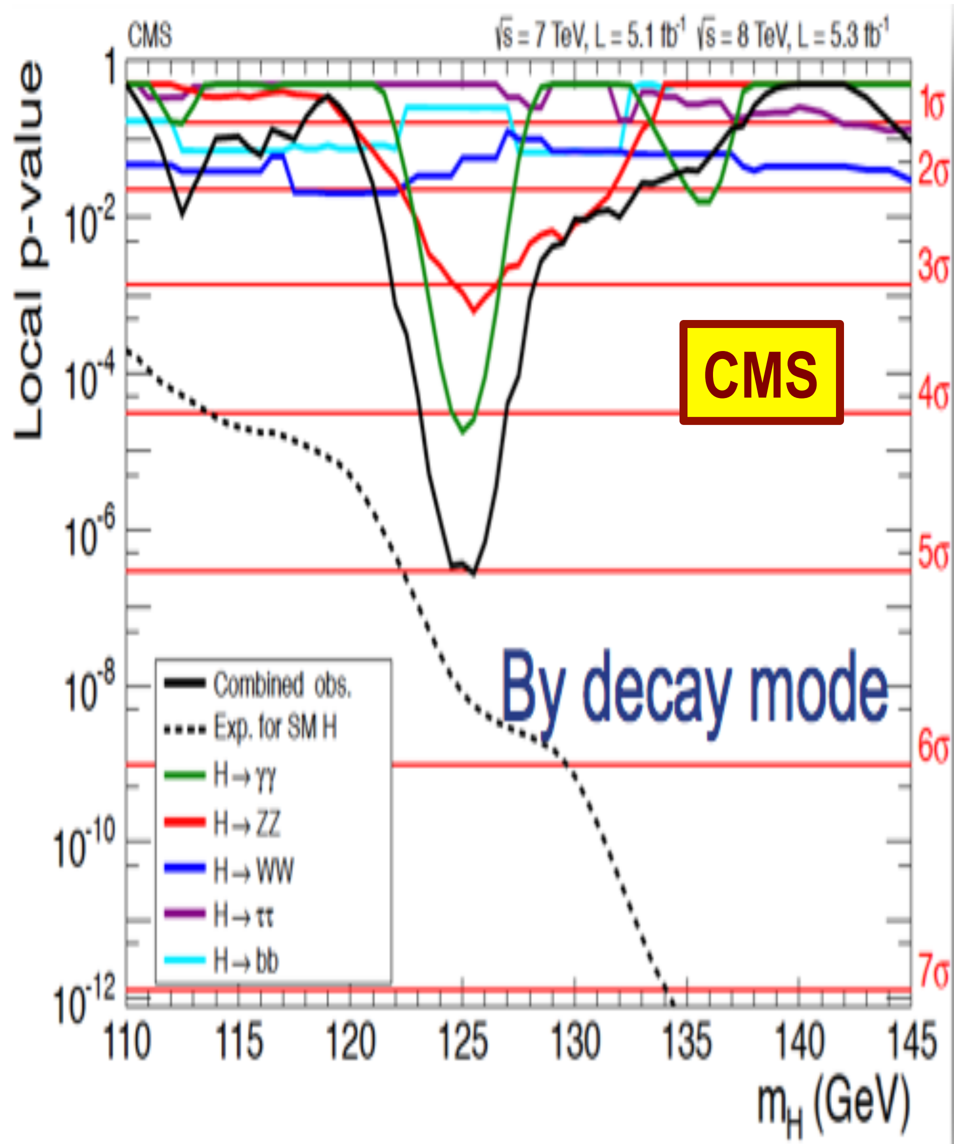


Excluded at 95% CL:
112-122, 131-559 GeV

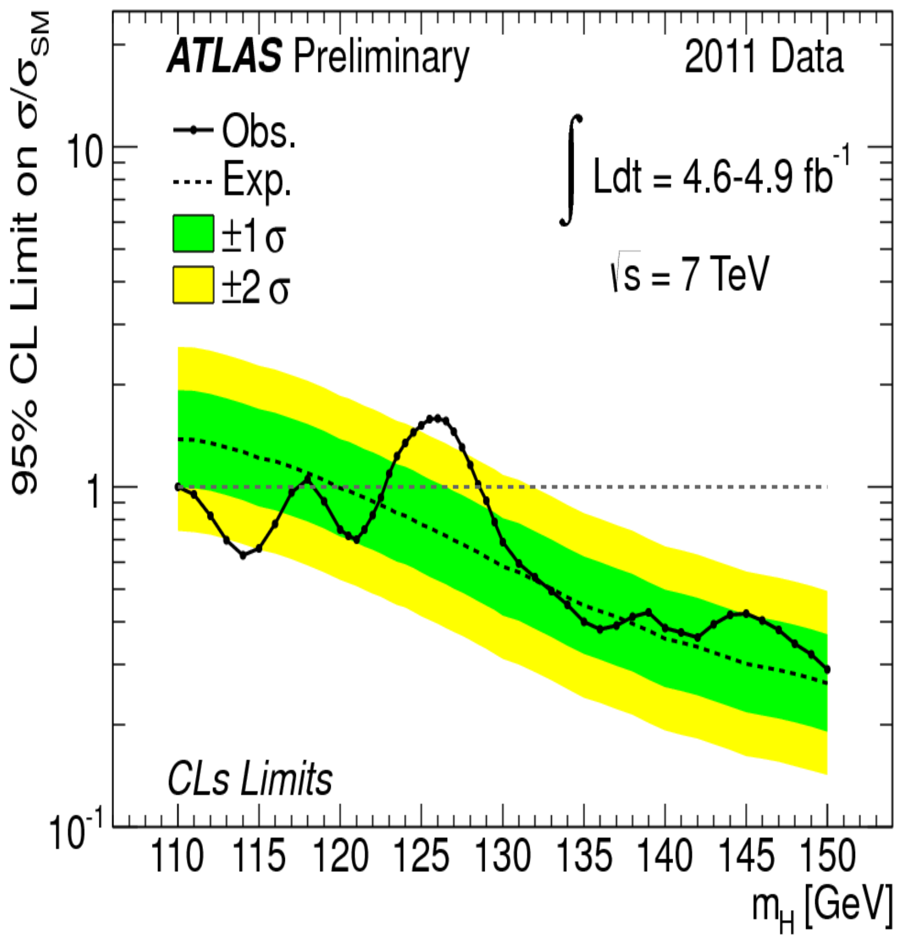
Only little sliver in 122 – 135 GeV and high mass left

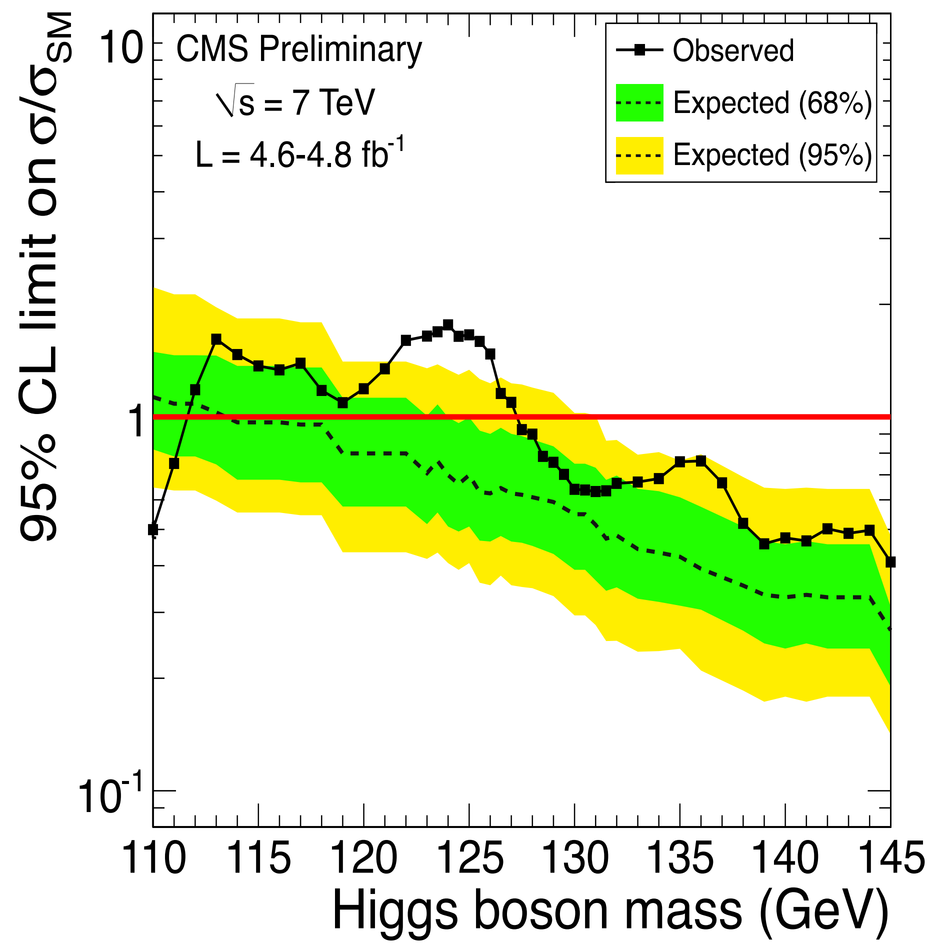
All Channel Combined Significance





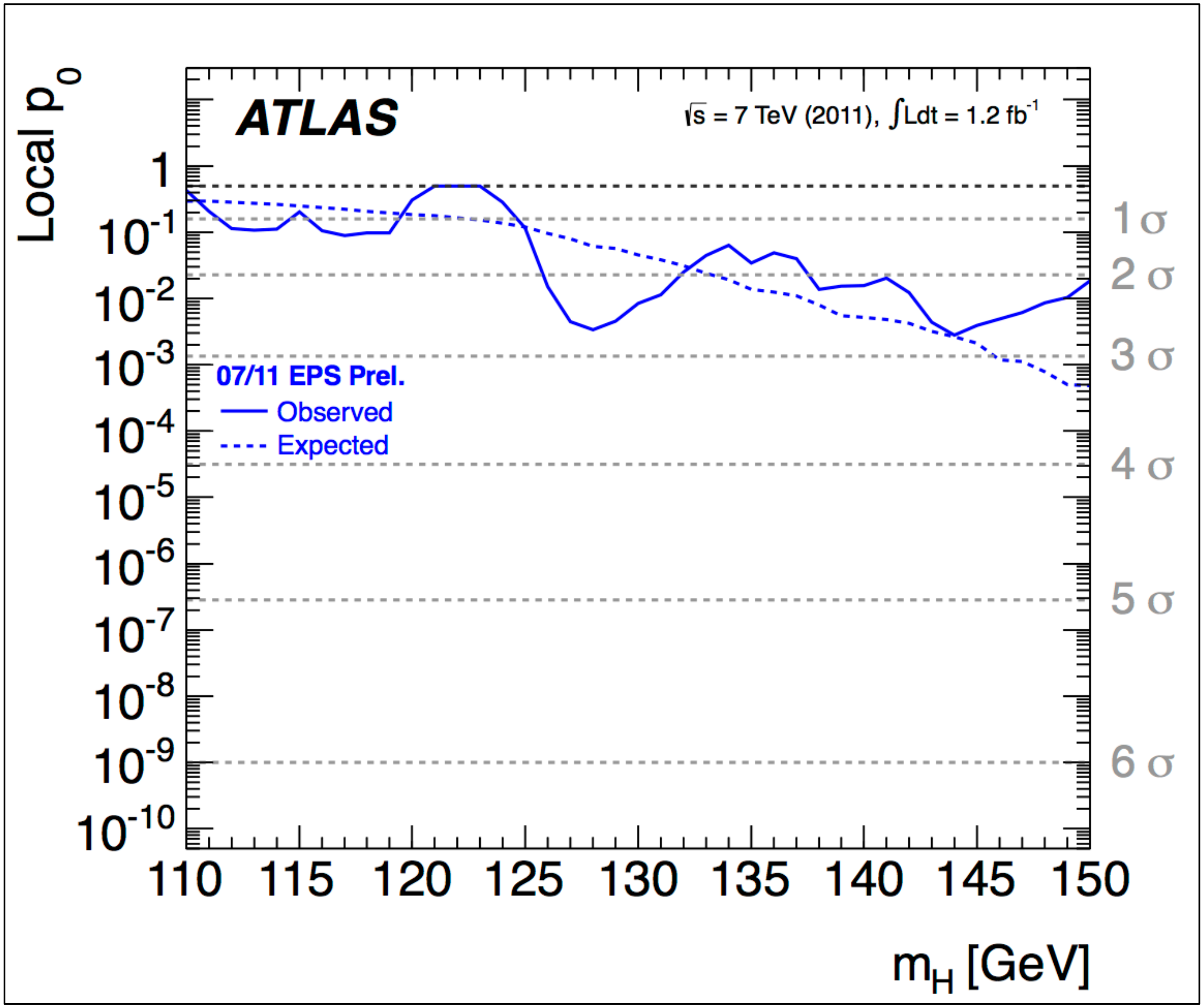
ATLAS and CMS Combined Higgs – end of 2011



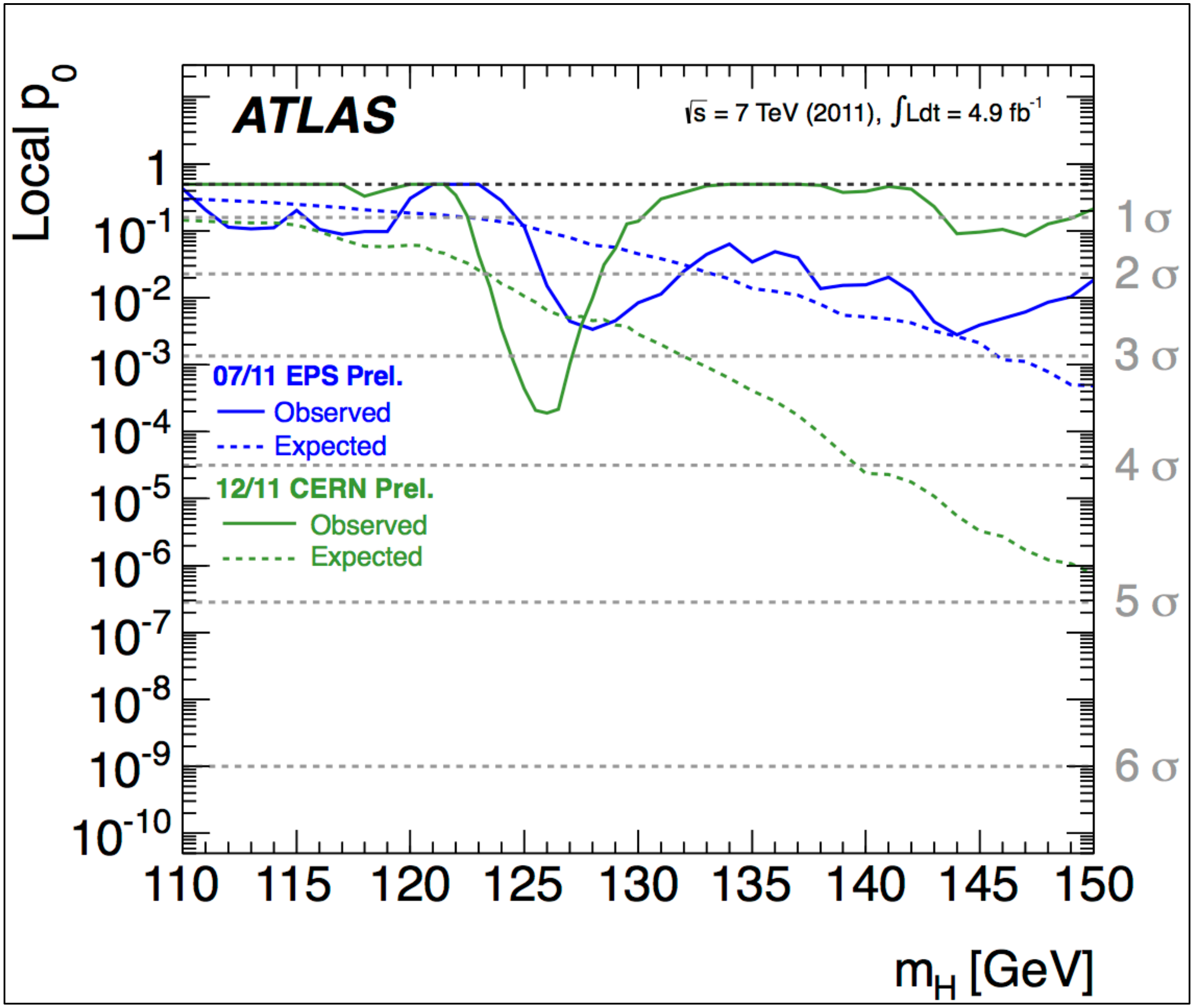


Standard Model Higgs excluded in 110.0 <M_H<117.5 GeV, 118.5 <M_H< 122.5 GeV, and 129<M_H<539 GeV & 127.5<M_H<543GeV

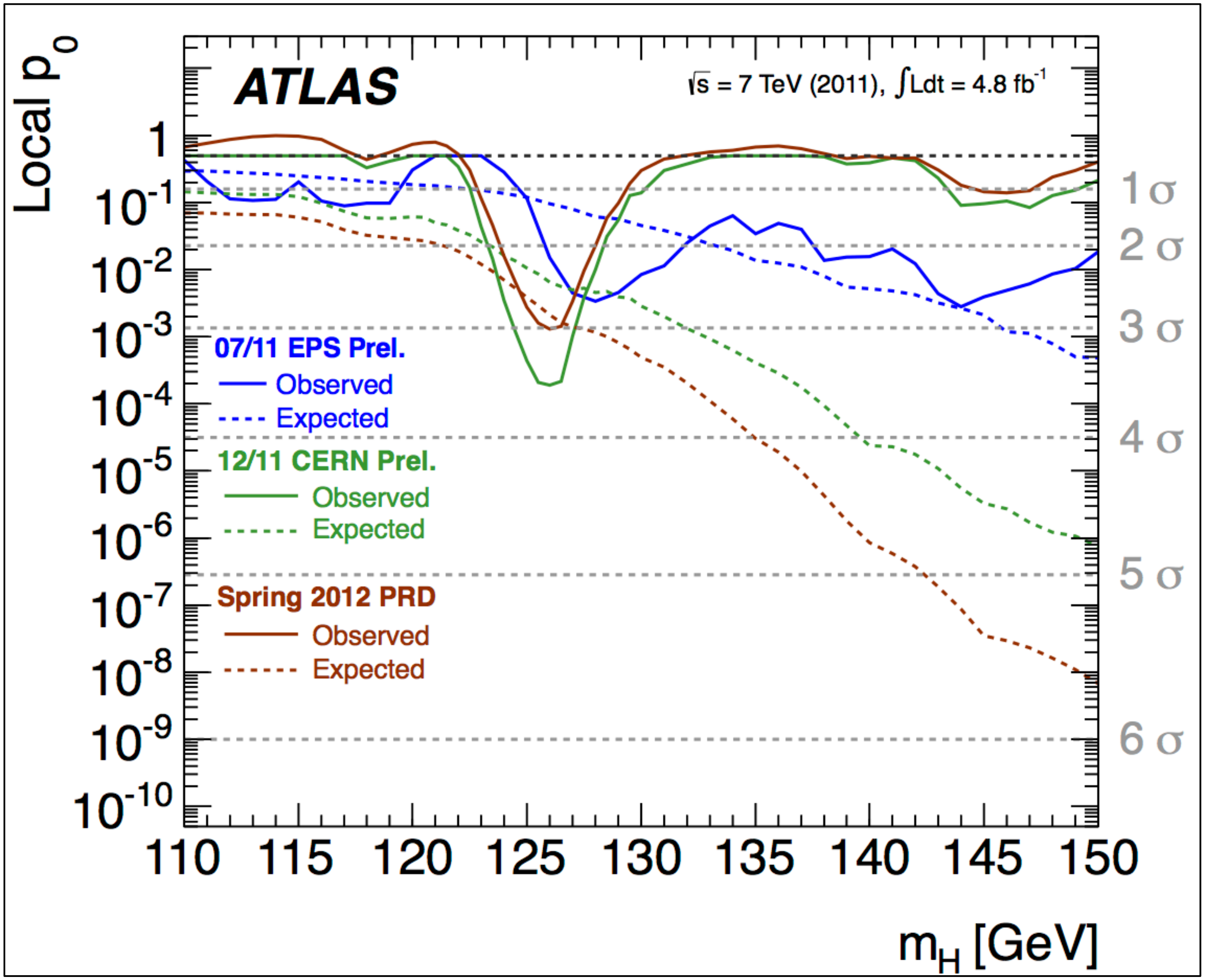
Evolution of the excess with time – Importance of a Large Data Set



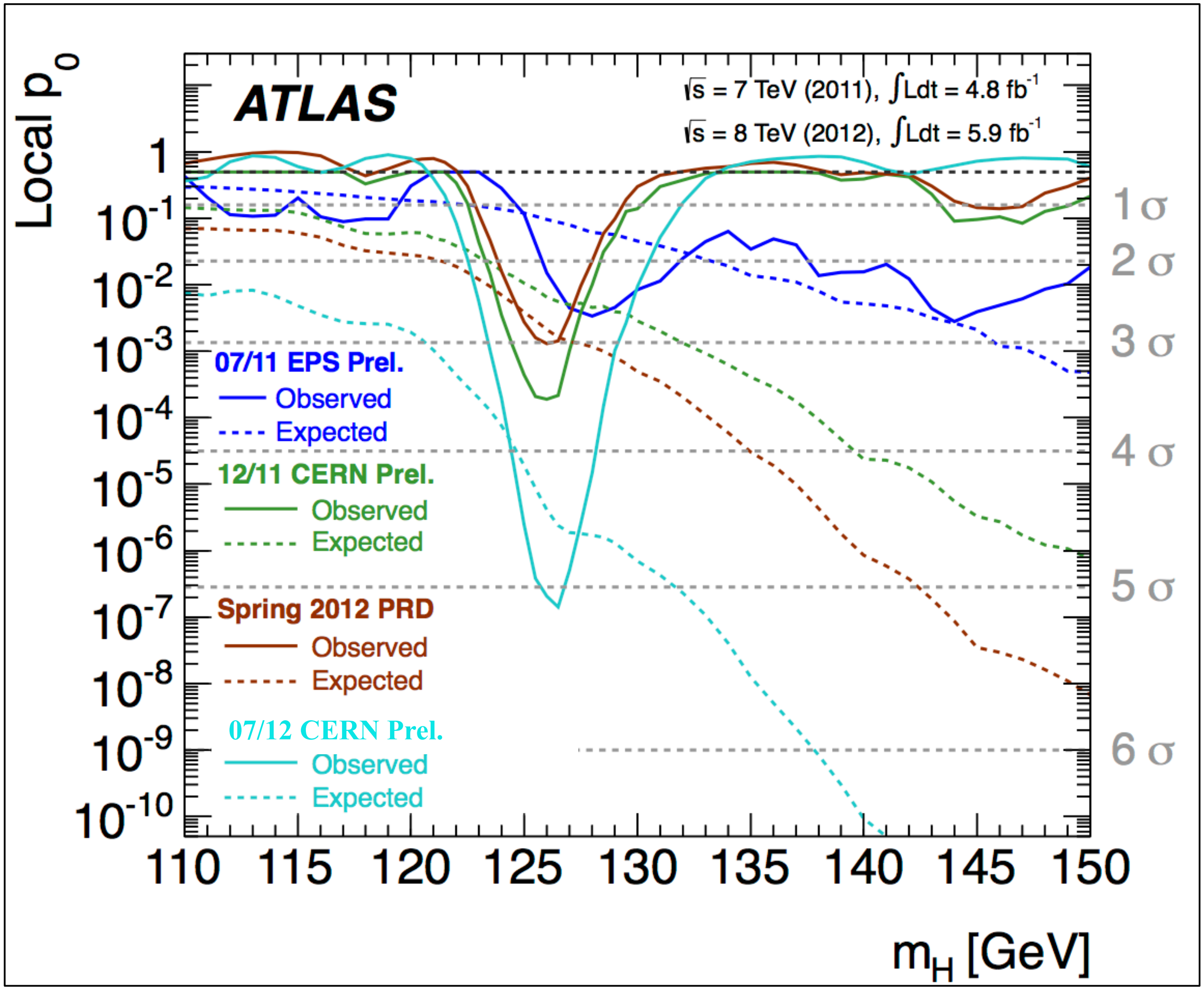
Evolution of the excess with time – Importance of a Large Data Set



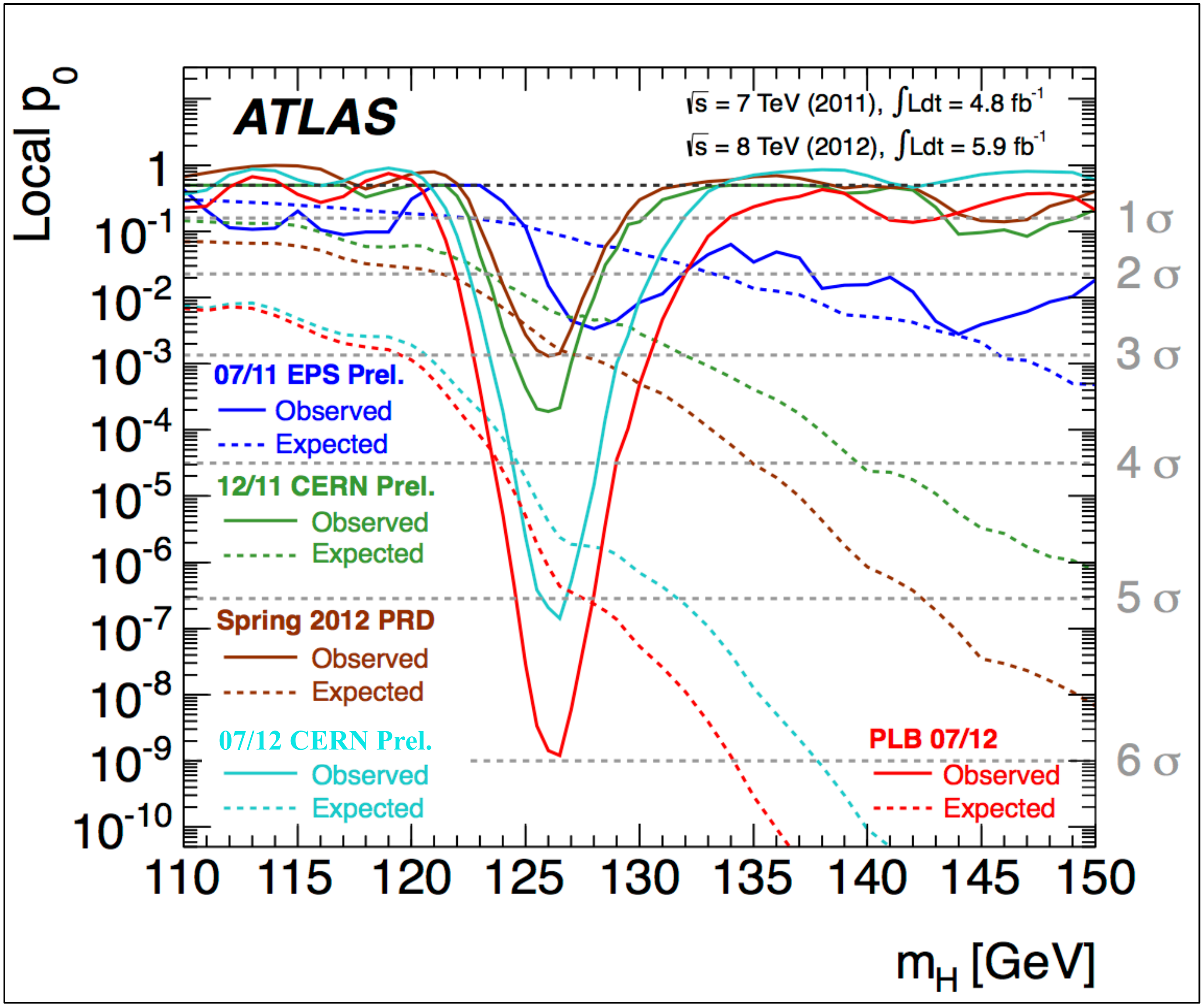
Evolution of the excess with time – Importance of a Large Data Set



Evolution of the excess with time – Importance of a Large Data Set



Evolution of the excess with time – Importance of a Large Data Set



So have we seen the Higgs particle?

- The statistical significance of the finding is over 5 standard deviation
  - Level of significance: 99.99994%
  - We can be wrong once if we do the same experiment 1,740,000 times
- So did we find the Higgs particle?
  - We have discovered a new particle, the heaviest boson we've seen thus far
    - Since this particle decays to two spin 1 particles, the possible spin states of this new boson is either 0 or 2!
  - It has some properties consistent with the Standard Model Higgs particle
  - We, however, do not have enough data to precisely measure all the properties – mass, life time, the rate at which this particle decays to certain other particles, etc – to definitively determine

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

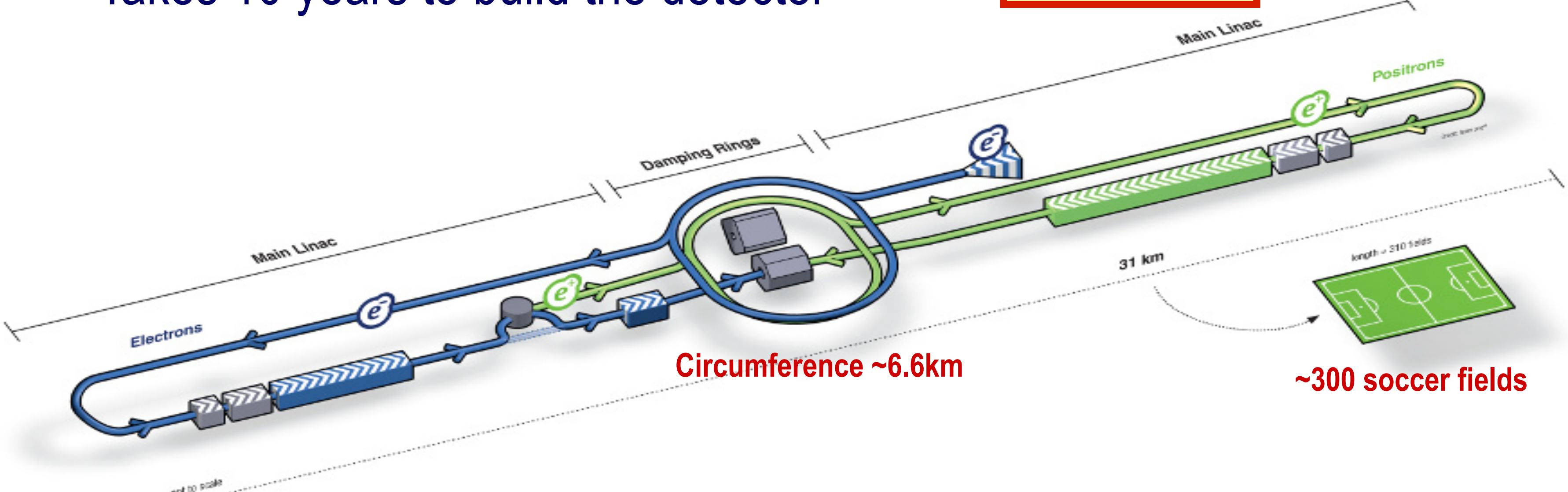
Long Term LHC Plans

- 2012 run will end with ~23fb^{-1}
  - Combined with 2011 run (5.6fb^{-1}), a total of ~29fb^{-1}
- 2013 – 2014: shutdown (LS1) to go to design energy (13 – 14TeV) at high inst. Luminosity
- 2015 – 2017: $\sqrt{s}$=13 – 14TeV, L~10^{34}, ~100fb^{-1}
- 2018: Shut-down (LS2)
- 2019 – 2021: $\sqrt{s}$~=13 – 14TeV, L~2x10^{34}, ~300fb^{-1}
- 2022 – 2023: Shut-down (LS3)
- 2023 – 2030(?): $\sqrt{s}$=13 – 14TeV, L~5x10^{34} (HL-LHC), ~3000fb^{-1}

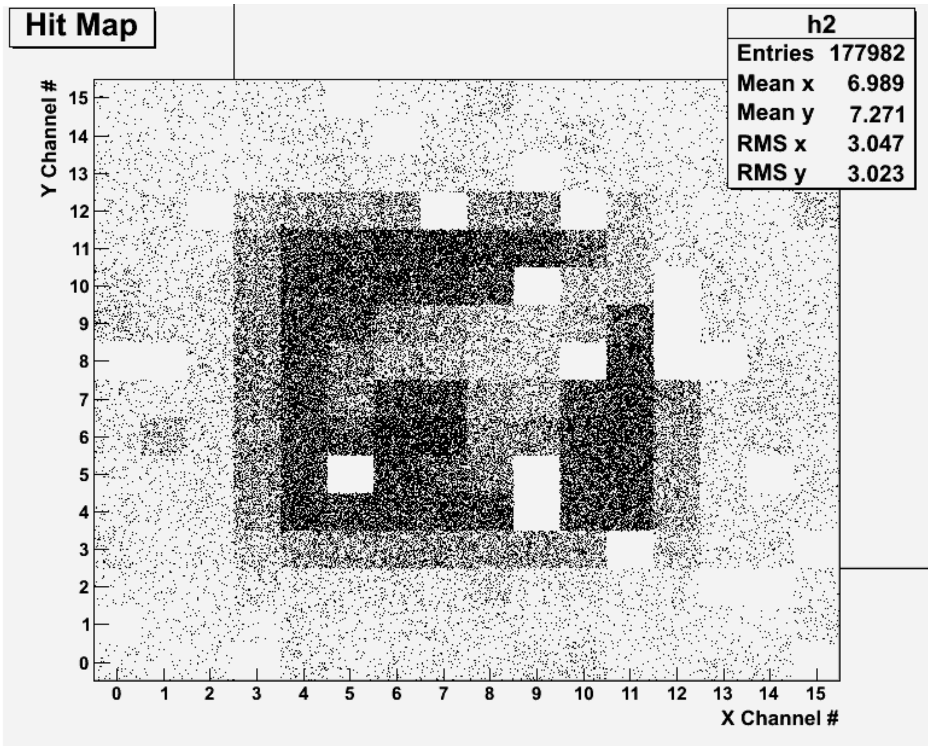
What next? Future Linear Collider

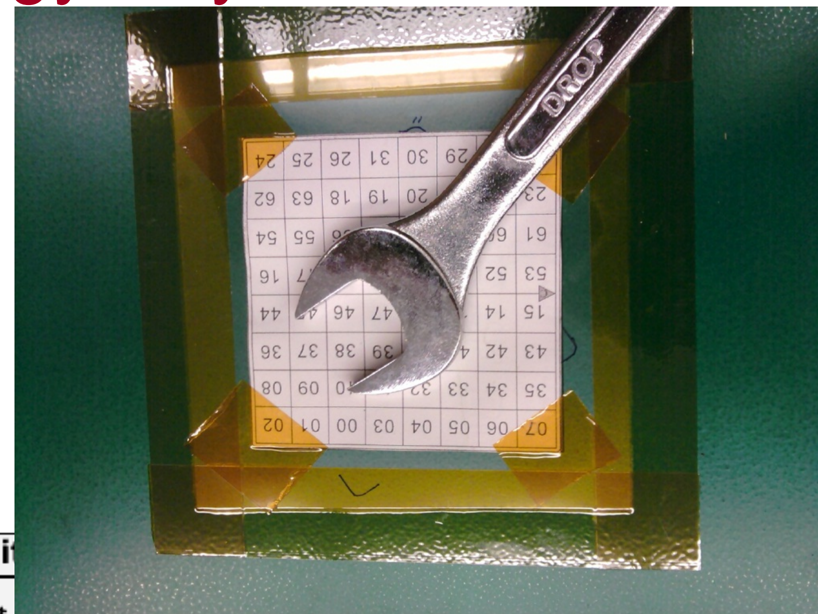
- Now that we have found a new boson, precision measurement of the particle's properties becomes important
- An electron-positron collider on a straight line for precision measurements
- 10~15 years from now (In Dec. 2011, Japanese PM announced that they would bid for a LC in Japan)
  - our Japanese colleagues have declared that they will bid for building a 250GeV machine in Japan!!
- Takes 10 years to build the detector

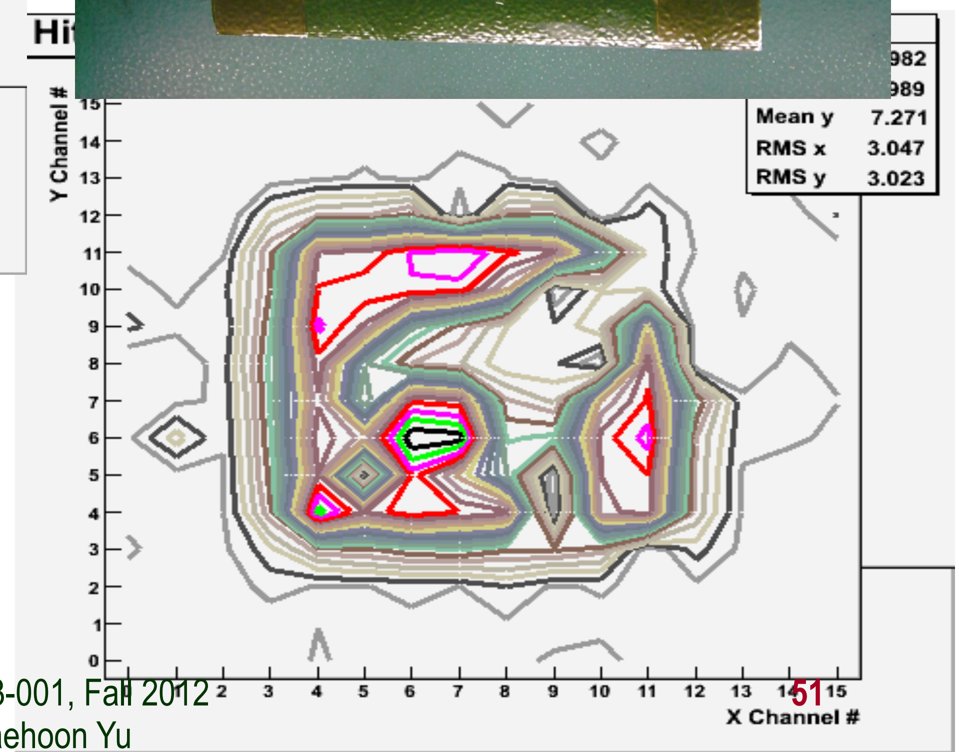
L~31km



Bi-product of High Energy Physics Research







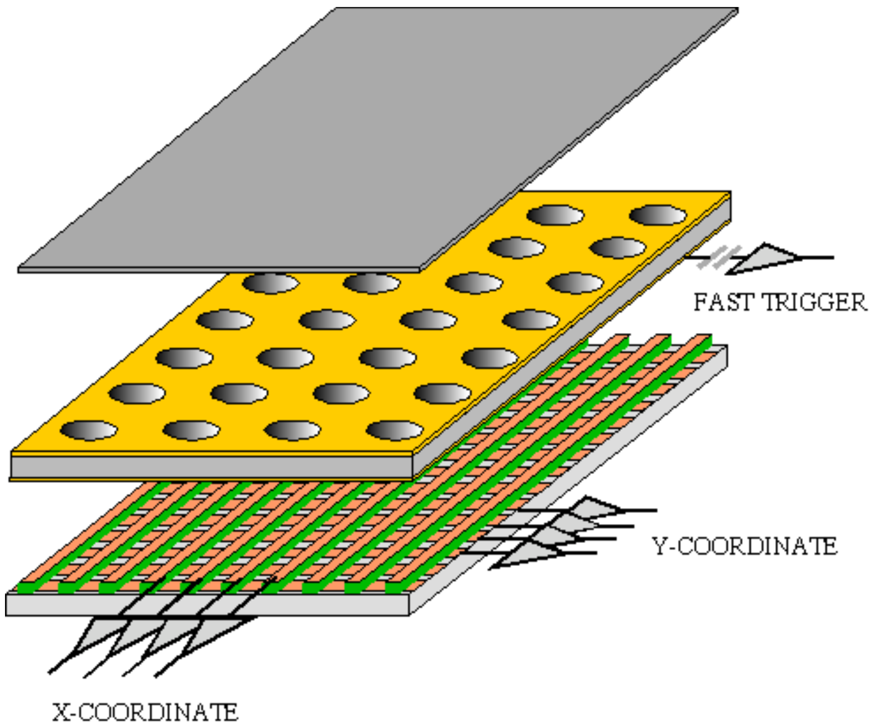
Can you see what the object is?

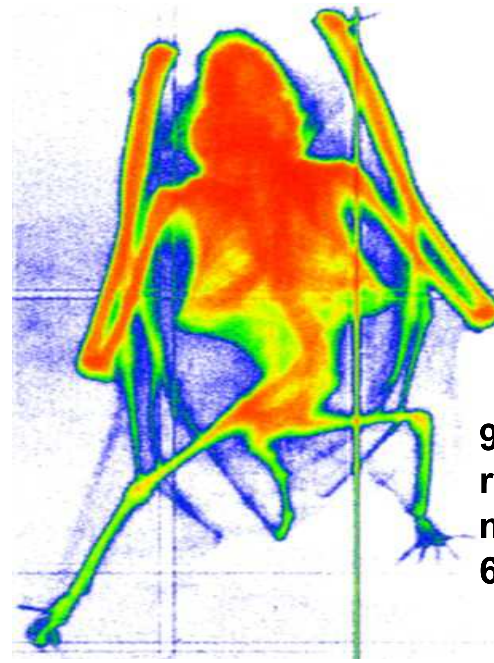
WWW Came from HEP!!!

GEM Application Potential

FAST X-RAY IMAGING

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





9 keV absorption radiography of a small mammal (image size ~ 60 x 30 mm²)

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

So what?

- The LHC opened up a whole new kinematic regime
  - The LHC performed extremely well in 2011 and 2012!
    - Accumulated 23fb^{-1} thus far, and still have a weeks to go – additional ~1fb^{-1} expected!
- Searches conducted with 4.8fb^{-1} at 7TeV and 5.8fb^{-1} at 8TeV of data
- Observed a neutral boson couple to vector bosons and whose measured mass is

$$M_{ATLAS} = 126.0 \pm 0.4(\text{stat.}) \pm 0.4(\text{syst.}) \qquad M_{CMS} = 125.6 \pm 0.4(\text{stat.})^{+0.4}_{-0.3}(\text{syst.})$$

  - At 5.9σ/5.0σ significance, corresponds to 1.7x10^{-9} bck fluctuation probability!
  - Compatible with production and decay of SM Higgs boson
- Excluded M_H=112 – 122 and 131 – 559GeV (ATLAS) @95% CL
- Linear collider and advanced detectors are being developed for future precision measurements of Higgs and other newly discovered particles
- Outcome and the bi-product of HEP research impacts our daily lives
  - 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 & coming 100 yrs
- Continued and sufficient investment to forefront scientific endeavors are absolutely necessary for the future!