PHYS 3313 – Section 001
Lecture #26

Monday, April 29, 2019
Dr. Jaehoon Yu

- Introduction to Particle Physics
- Elementary Particles and Their Interactions
- The Standard Model of Particle Physics
- Particle Accelerators
- Particle Detectors
- Hot Issues in Physics Frontier
- Where Does the Future Lie?

Announcements

- Final exam is **11am – 1:30pm**, Friday, May 10
  - Location: CRB114
  - Comprehensive exam covering from CH1 – CH8 + what we've learned today (some in CH14) + appendices 3 – 7
  - Bring your calculator but DO NOT input formula into it!
  - BYOF: You can prepare a one 8.5x11.5 sheet (front and back) of **handwritten** formulae and values of constants for the exam
    - No additional formulae or values of constants will be provided!
    - No Maxwell's equations allowed!
- Planetarium extra credit
  - Tape one side of your ticket stubs on a sheet of paper with your name on it
  - Submit the sheet in the morning of May 10

Introduction to Particle Physics

- What are the 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

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

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 energy scale, 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 the 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$/c^2$
Hadrons	Mesons	$\pi^+, \pi^-, \pi^0, K^+, K^-, K^0,$ $\rho^+, \rho^-, \rho^0, \ldots$	135 MeV$/c^2$ – few GeV$/c^2$
Hadrons	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 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 have the 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 (or empirical)
- 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 observations 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

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

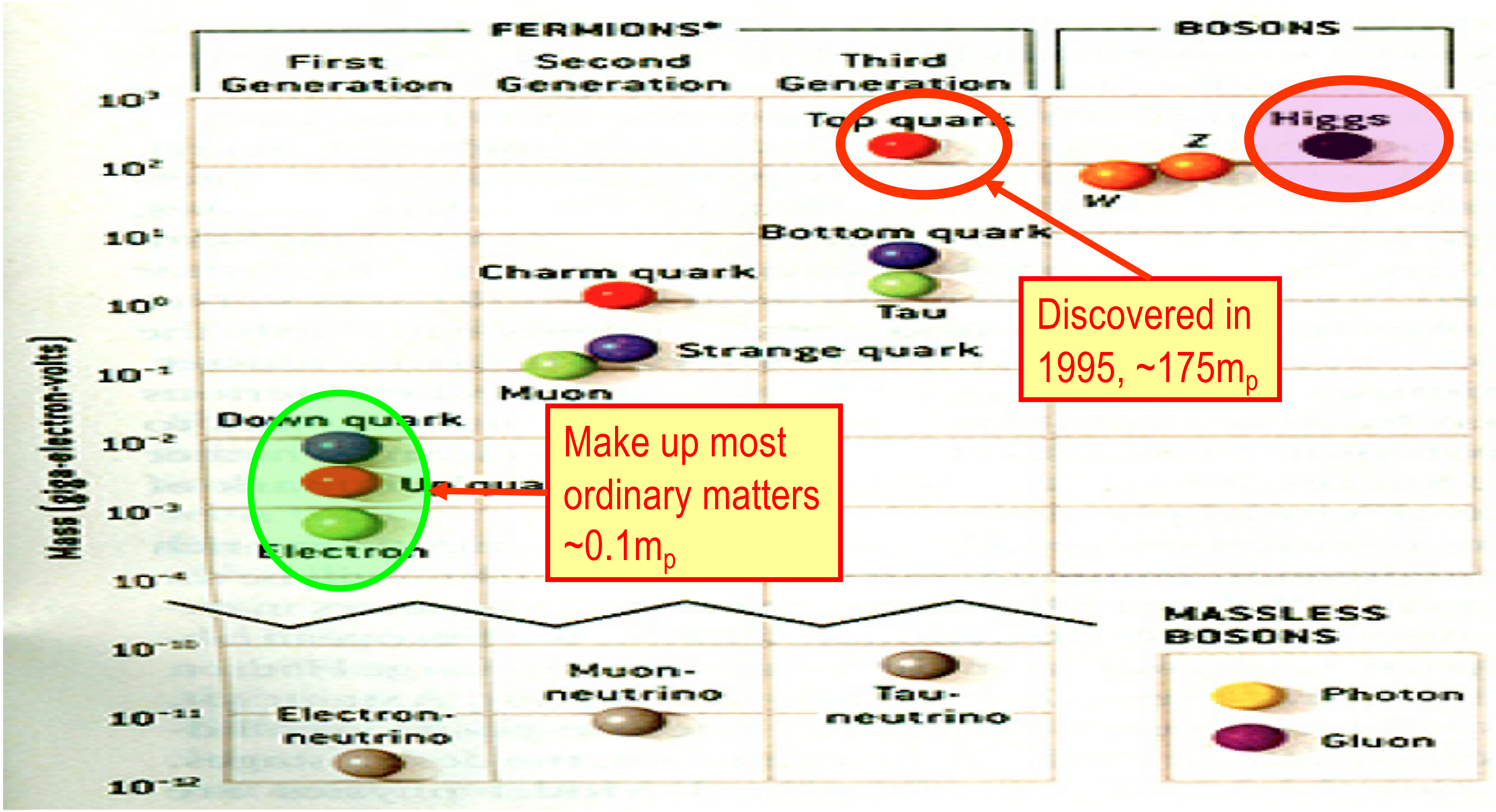
  – ➔ Increasing order of lepton masses

- 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 $\frac{1}{2}\hbar$

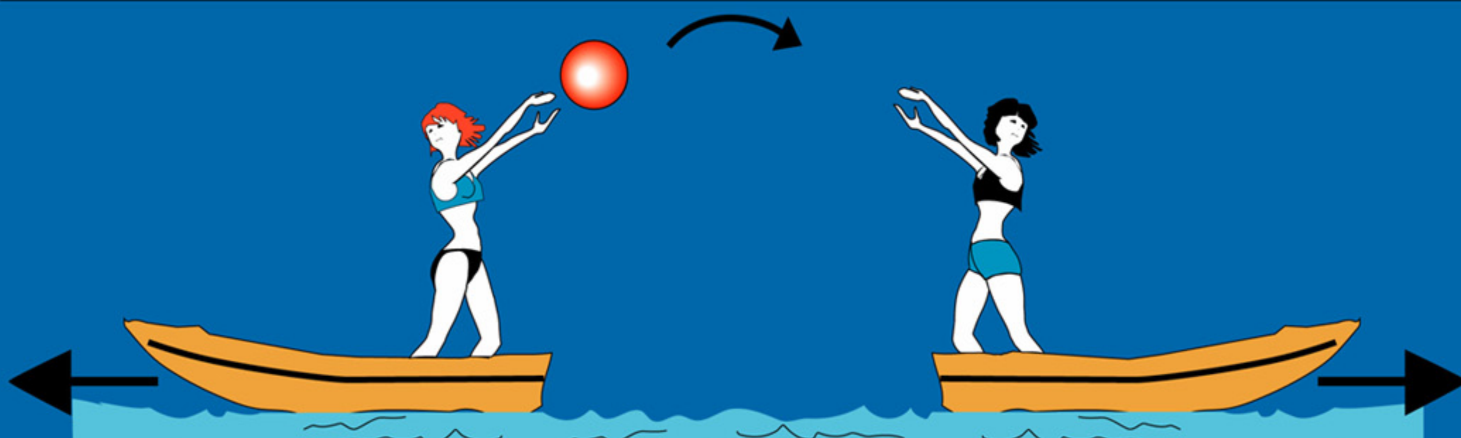
HEP and the Standard Model



- 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	~ 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

Particle Accelerators

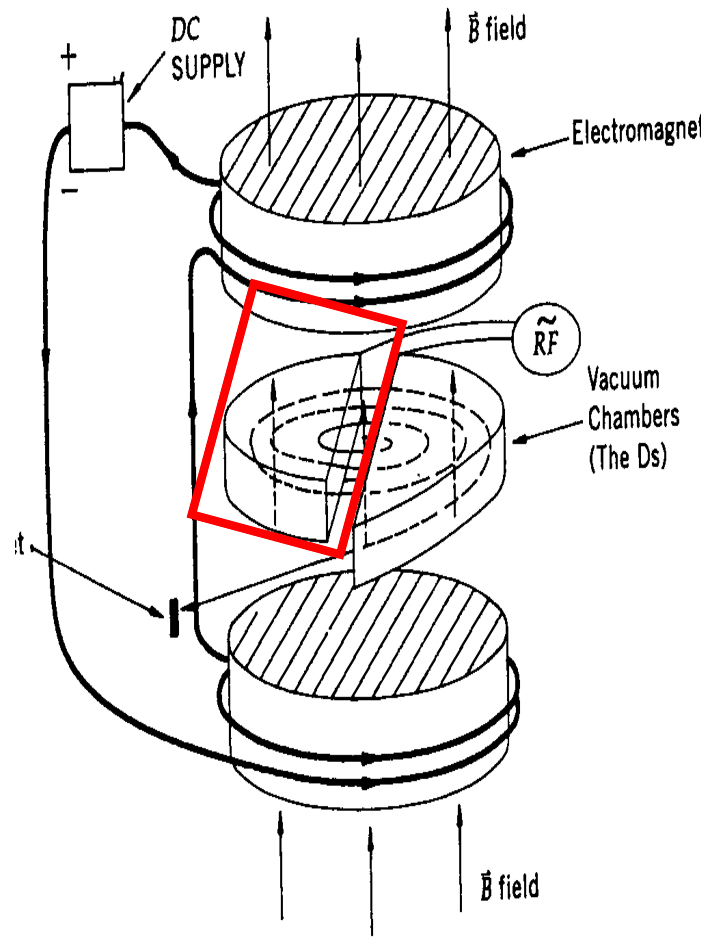
- How can one obtain high energy particles?
  - Cosmic ray ➔ Sometimes we observe 1000TeV cosmic rays
    - Low flux and cannot control energies well
- Need to look into small distances to probe the fundamental constituents with full control of particle energies and fluxes
  - Particle accelerators
- 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 precisely 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 ➔ Nucleon 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 and focused 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 mid-range future
    - Muon-anti-muon: Conceptual accelerator in the far future
  - Lepton-hadron colliders: HERA at DESY

Resonance Accelerators: Cyclotron

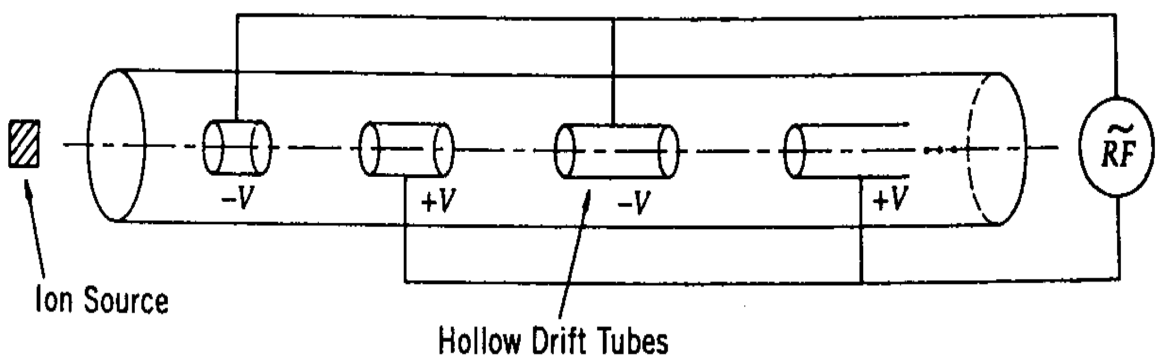
- Invented by E. Lawrence at Berkeley in 1930's
- While the two D shaped vacuum chambers are connected to HV sources, there is no electric field inside them due to Faraday effect
- Strong electric field exists only in the gap between the two D's
- An ion source is placed in the gap
- The path is circular due to the perpendicular magnetic field
- The ions do not feel any acceleration inside the D but gets bent due to magnetic field
- When the particle exits one 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



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

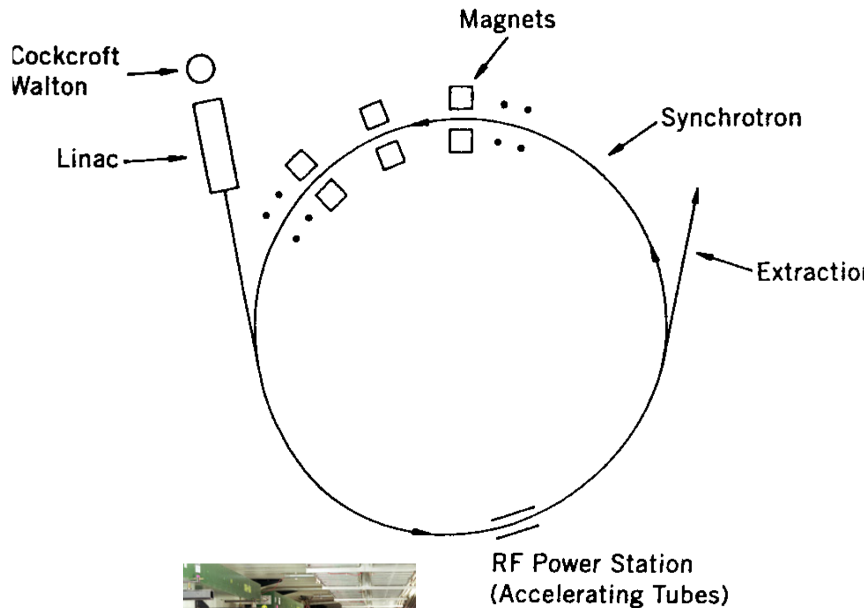
Resonance Accelerators: Linear Accelerator

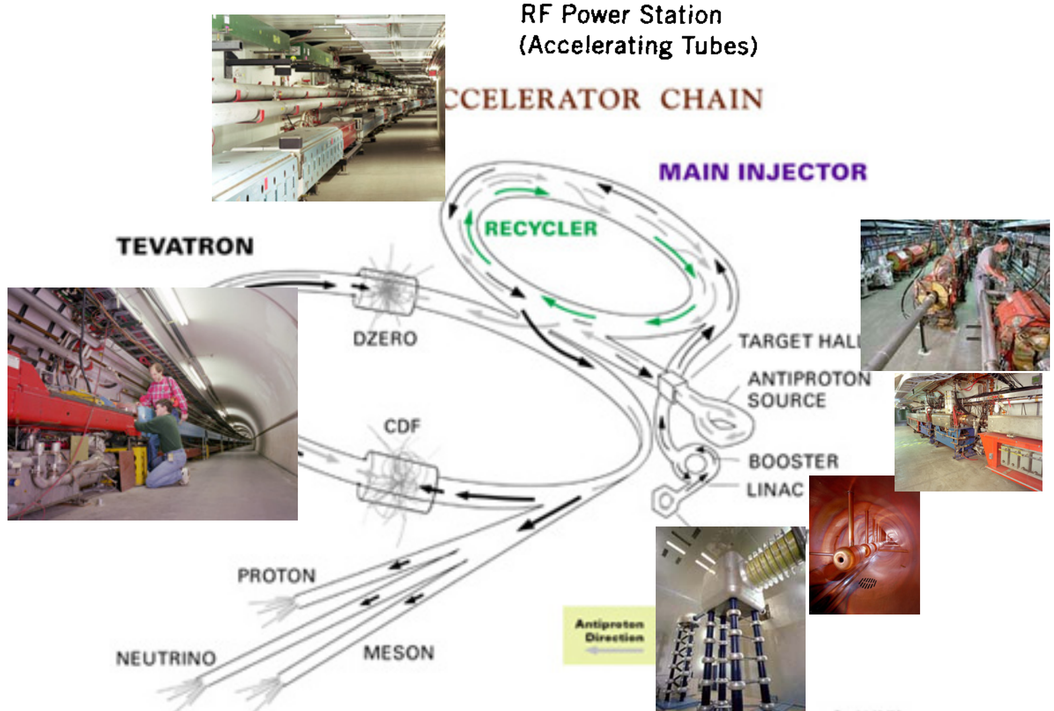
- Accelerates particles along the linear path using the resonance principle
- A series of metal tubes are located in a vacuum vessel and connected successively to alternating terminals of radio frequency oscillator
- The direction of the electric field changes before the particles exit the given tube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



Synchroton Accelerators

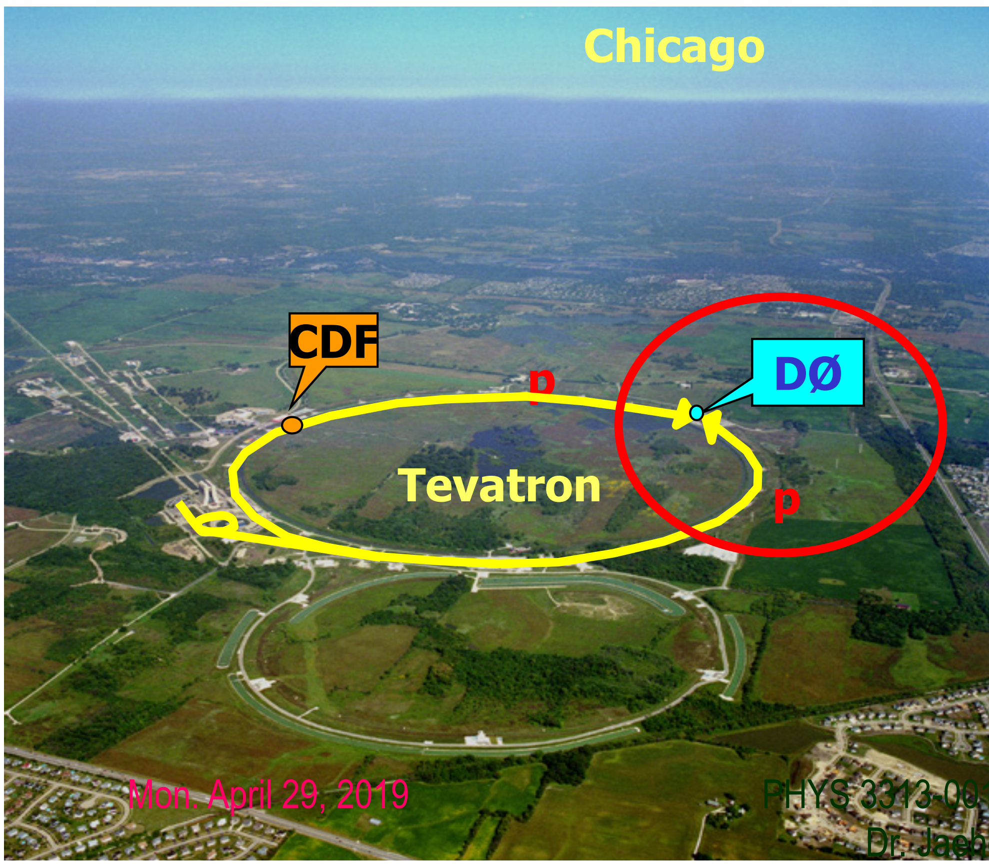
- Synchrotons use magnets arranged in a ring-like fashion with varying magnetic field and frequency
- Multiple stages of accelerations are needed before reaching over GeV ranges of energies
- RF power stations are located throughout the ring to pump electric energies into the particles



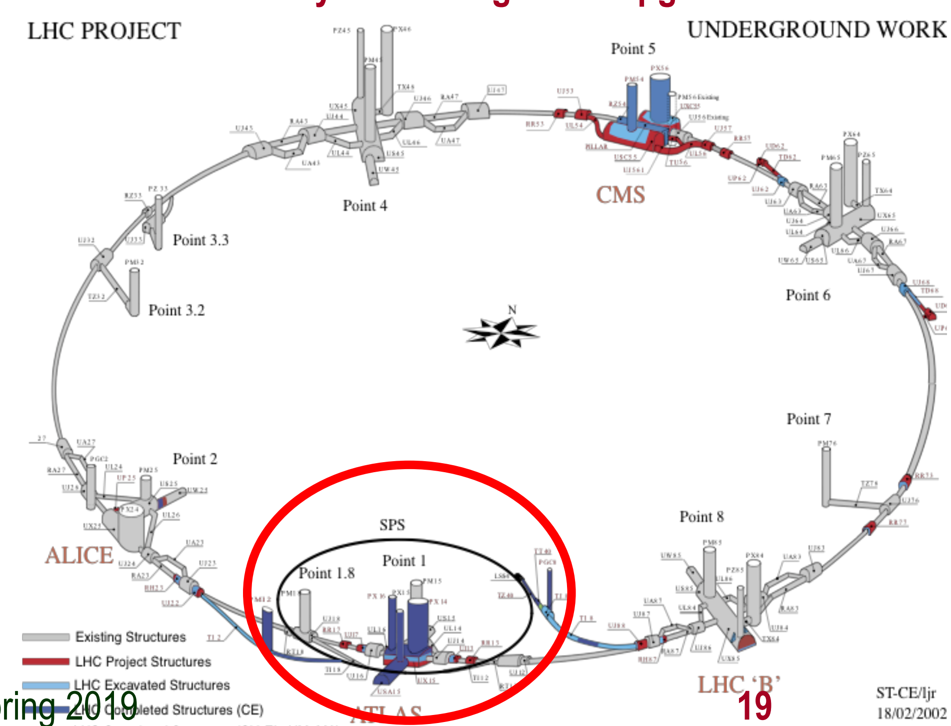


Fermilab Tevatron and LHC at CERN

- 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 130km/hr
    - ~100,000 times the energy density at the ground 0 of the Hiroshima atom bomb
  - **Tevatron was shut down in 2011**
  - **New frontiers with high intensity proton beams including the search for dark matter with beams!!**



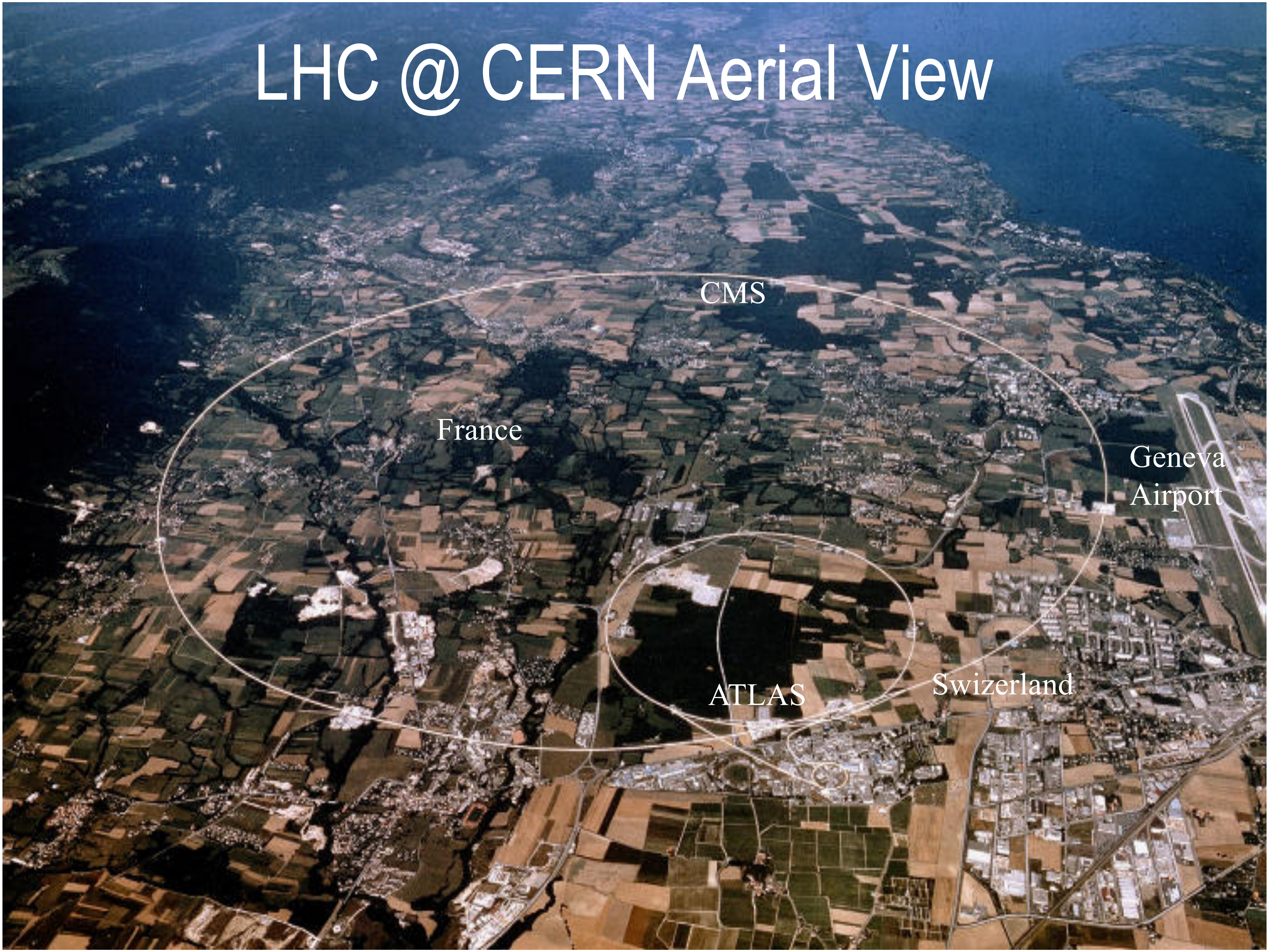
- World's Highest Energy p-p collider
  - 27km (17mi) circumference, 100m (300ft) underground
  - Design E_{cm}=14 TeV (=44x10^{-7}J/p➔ 362M Joules on the area smaller than $10^{-4}m^2$)
  - ➢ Equivalent to the kinetic energy of a B727 (80tons) at the speed 310km/hr
    - ➢ ~3M times the energy density at the ground 0 of the Hiroshima atom bomb
- **Discovered a new heavy particle that looks Higgs in 2012**
- **Search for new particles had been ongoing!!**
- **Shut down for two years for high stat. upgrade!**



Comparisons between Tevatron and the LHC

- Tevatron: A proton-anti proton collider at 2TeV
  - Need to produce anti-protons using accelerated protons at 120GeV
  - Takes time to store a sufficient number of anti-protons
    - Need a storage accelerator for anti-protons
  - Can use the same magnet and acceleration ring to circulate and accelerate the 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

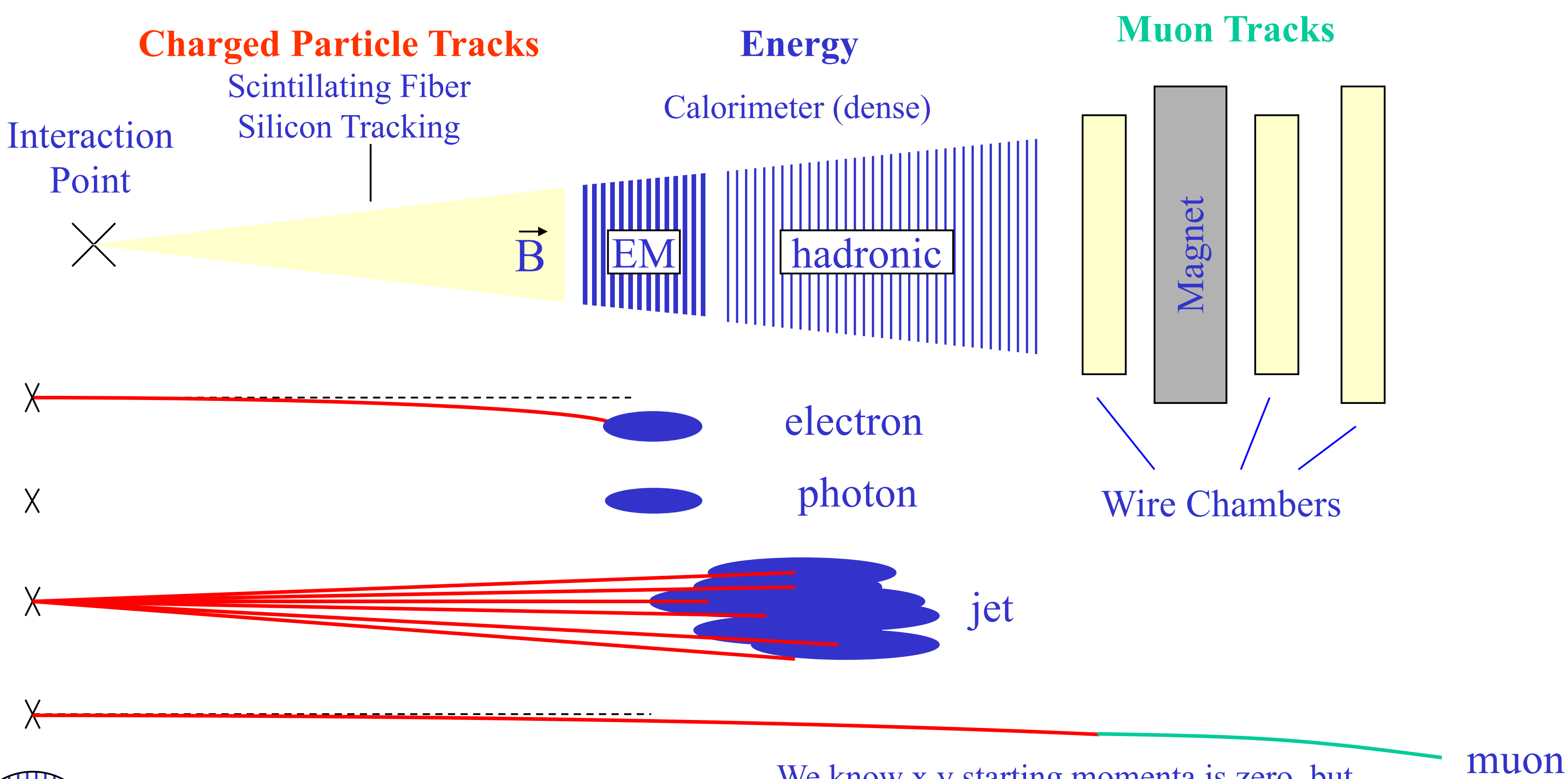
LHC @ CERN Aerial View

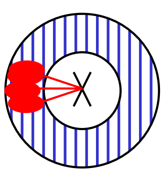


Particle Detectors

- 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 for the given physics?
    - 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 (like the cloud chamber)
    - 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

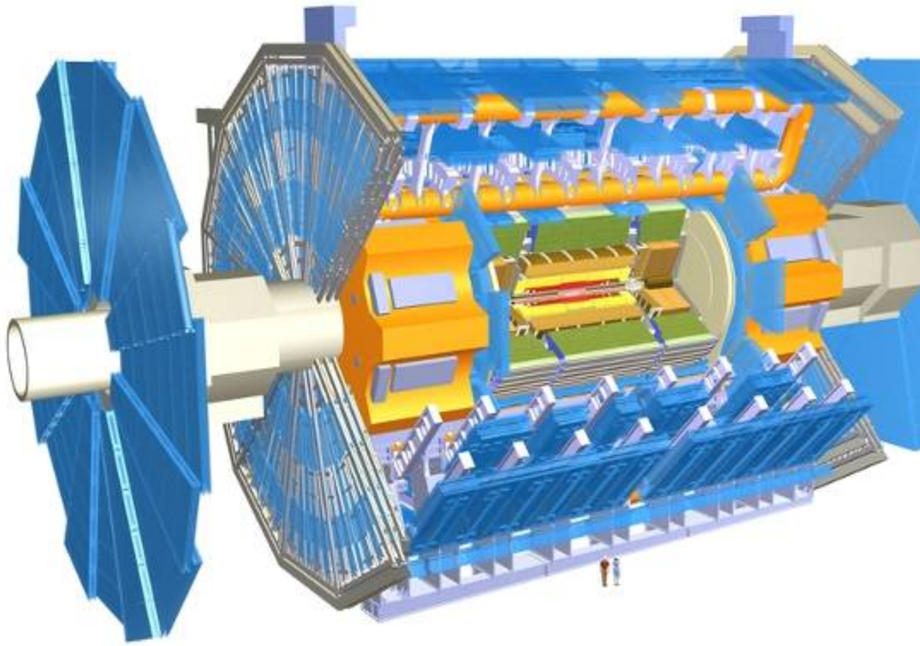


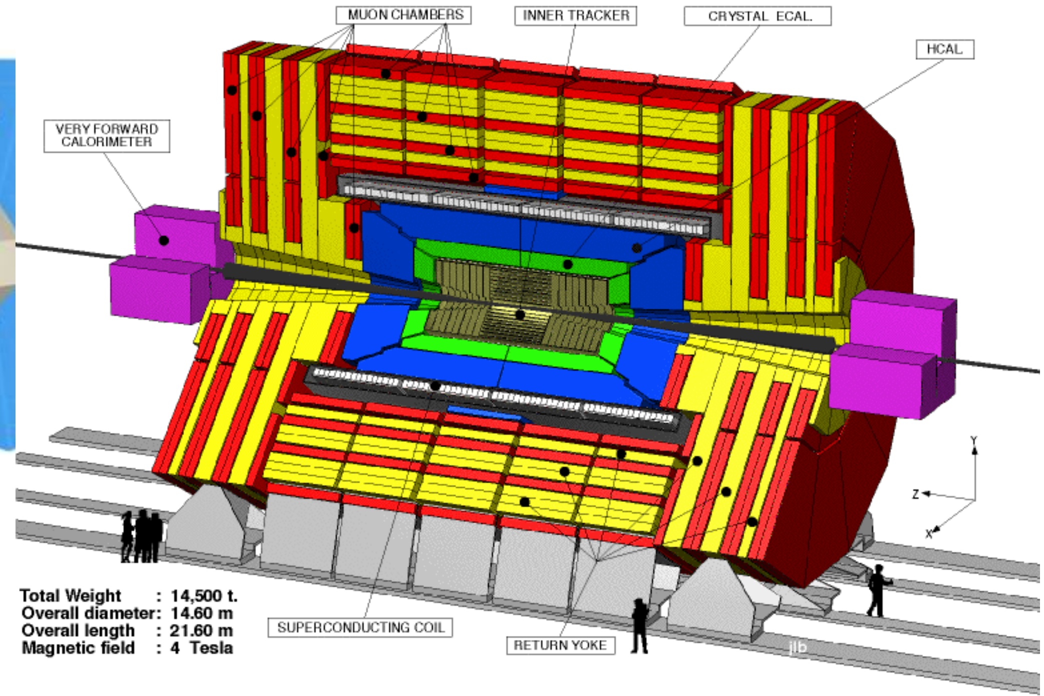


neutrino -- or any non-interacting particle missing transverse momentum

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

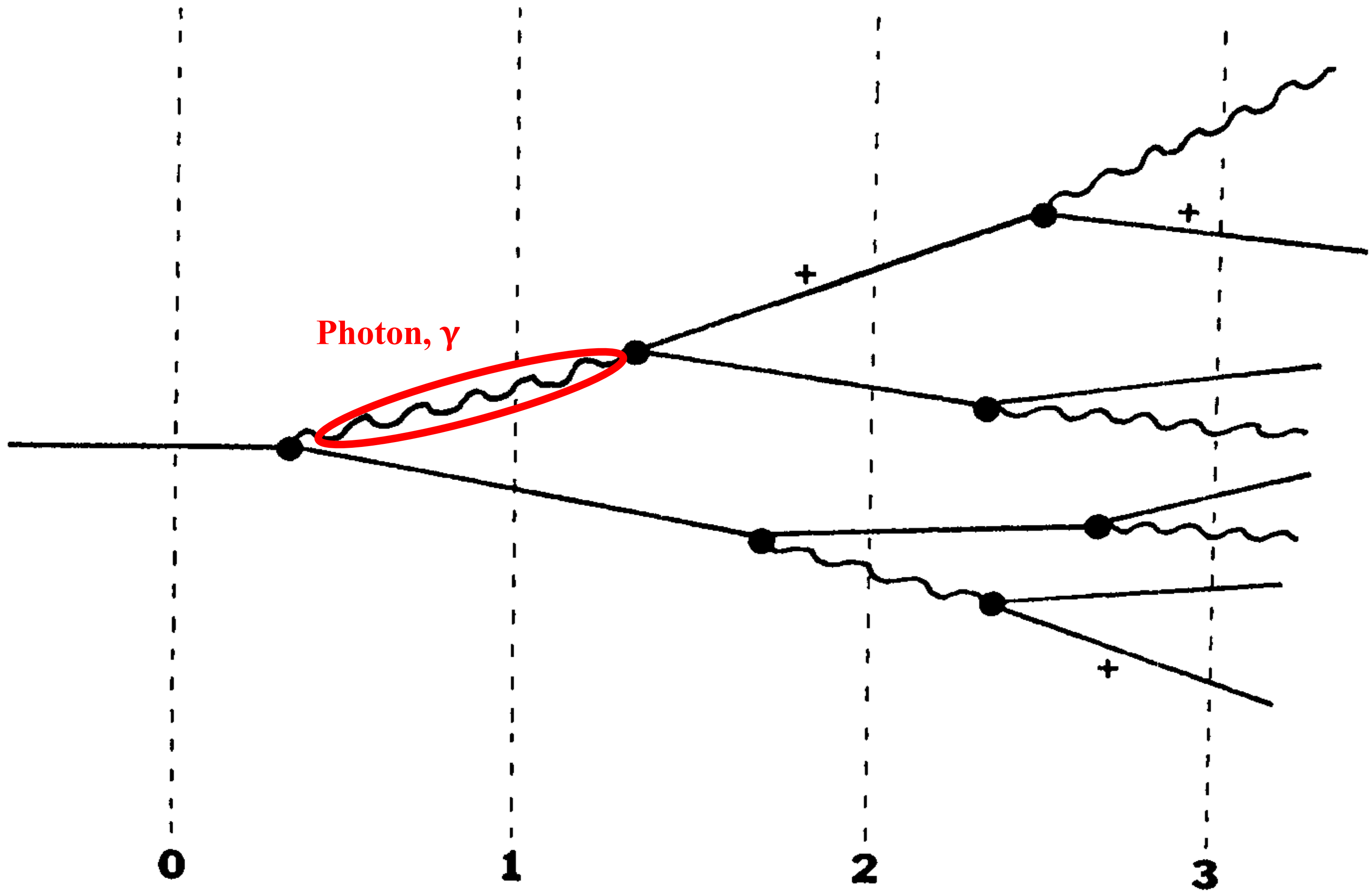
The ATLAS and CMS Detectors





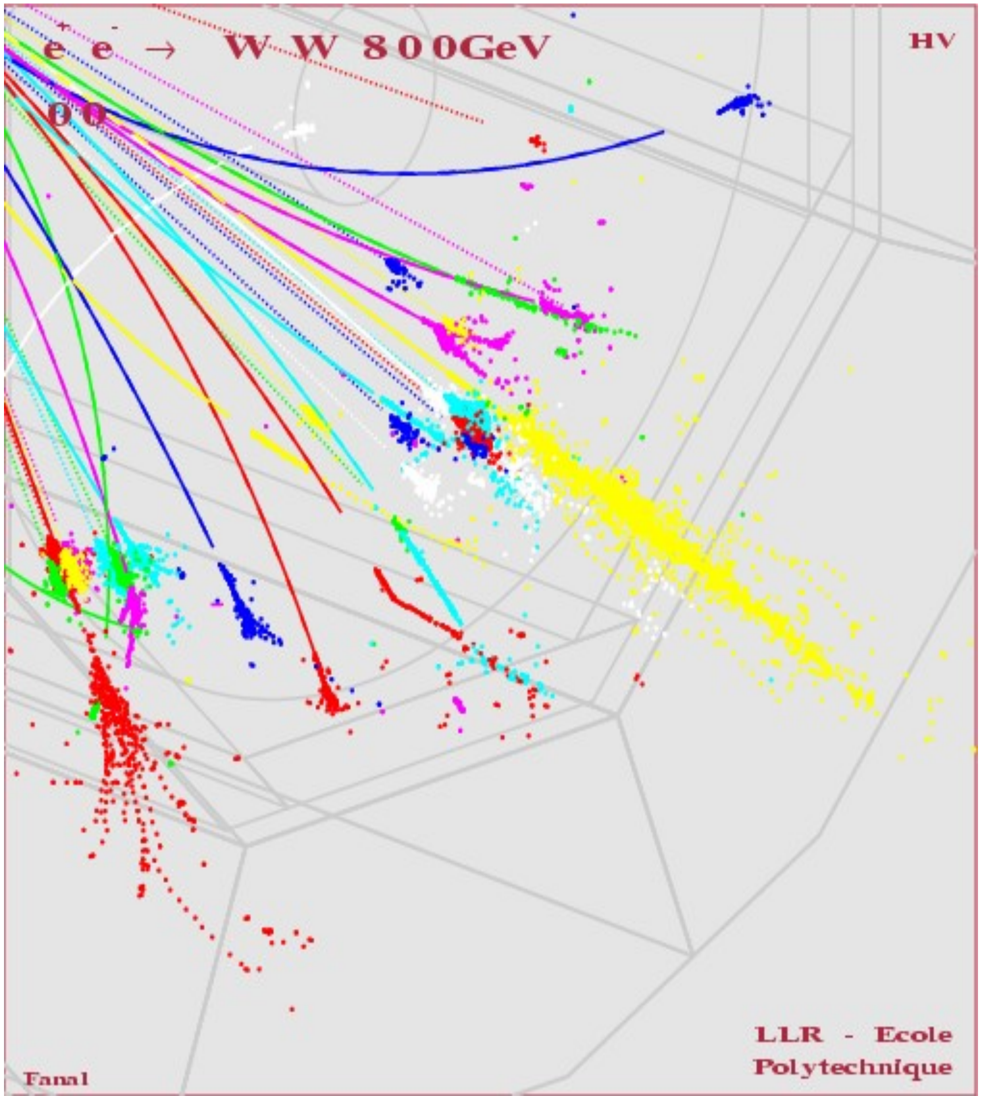
- **Fully multi-purpose detectors with emphasis on lepton ID & precision E & P**
- **Weighs 7000 tons and 10 story tall**
- Records **200 – 400 collisions/second**
- Records approximately **350** MB/second
- Record over 2 PB per year ➔ **200*Printed material of the US Lib. of Congress**

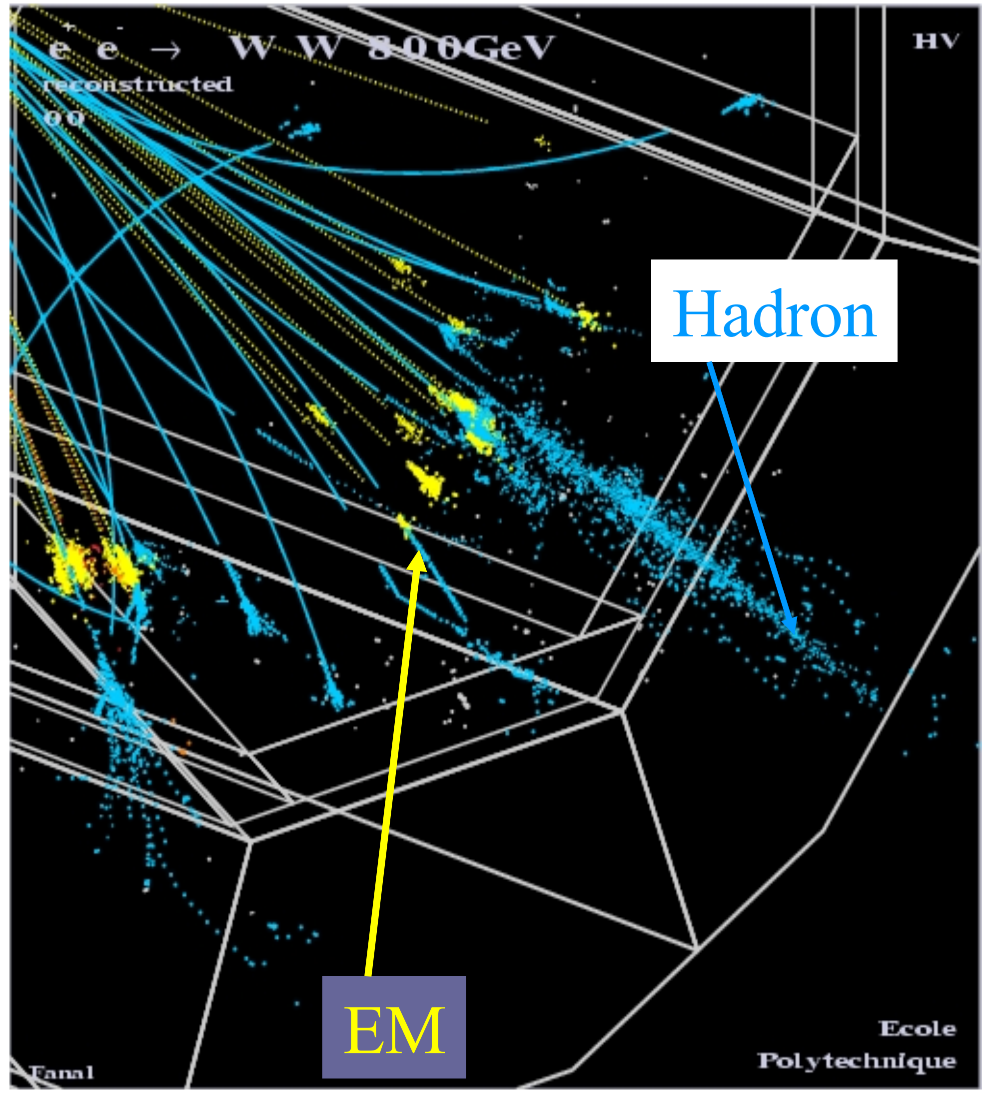
Electron Interactions in material (showering)



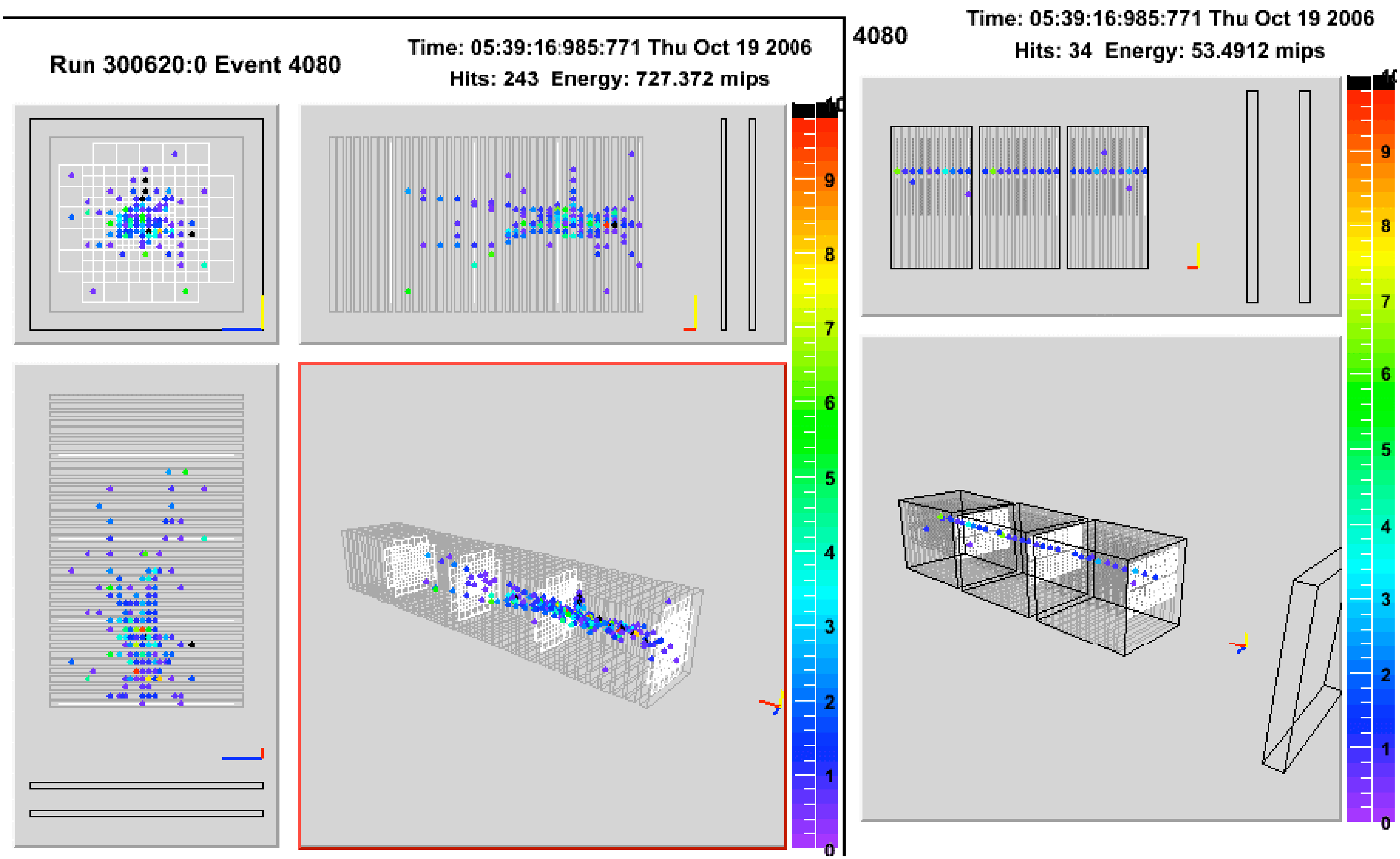
Method of measuring the particle energy in a calorimeter!!

How particle showers look in detectors

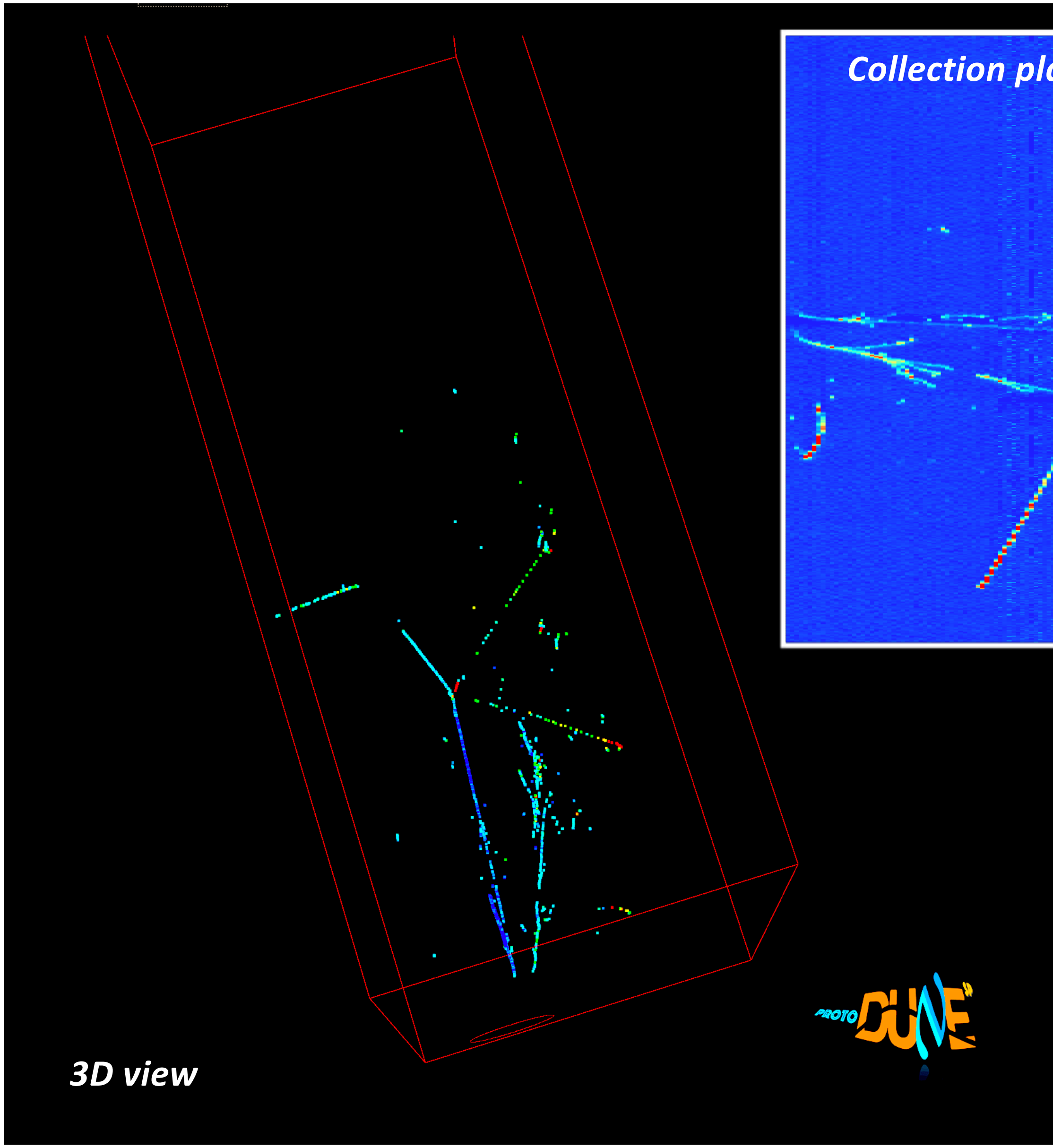


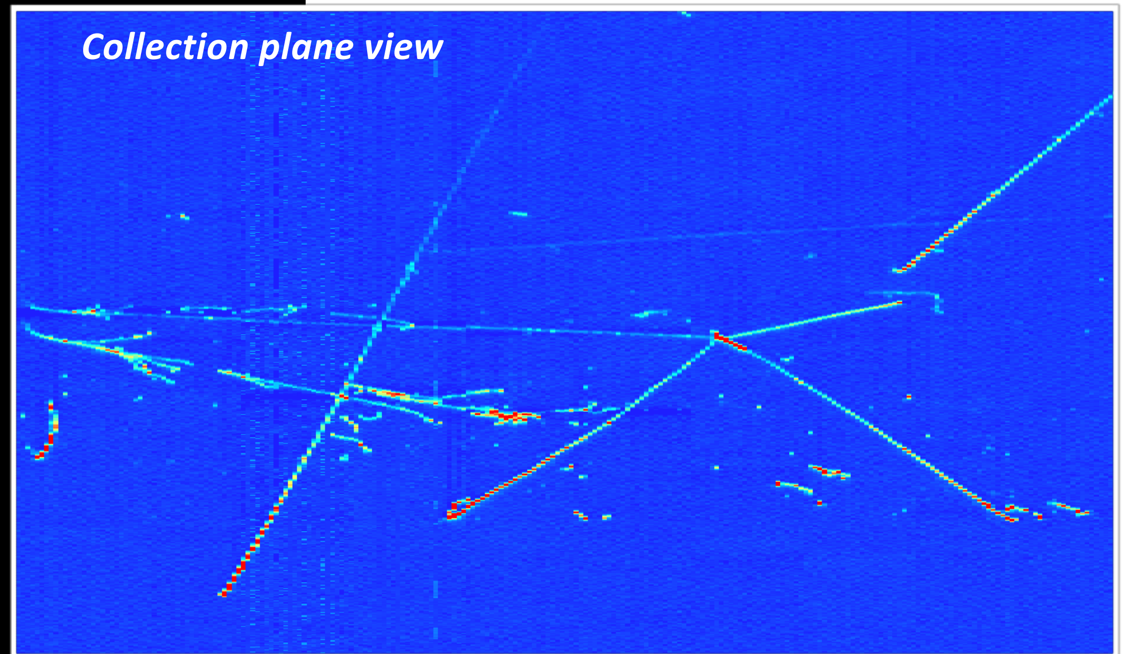


Example Hadronic Shower (20GeV)



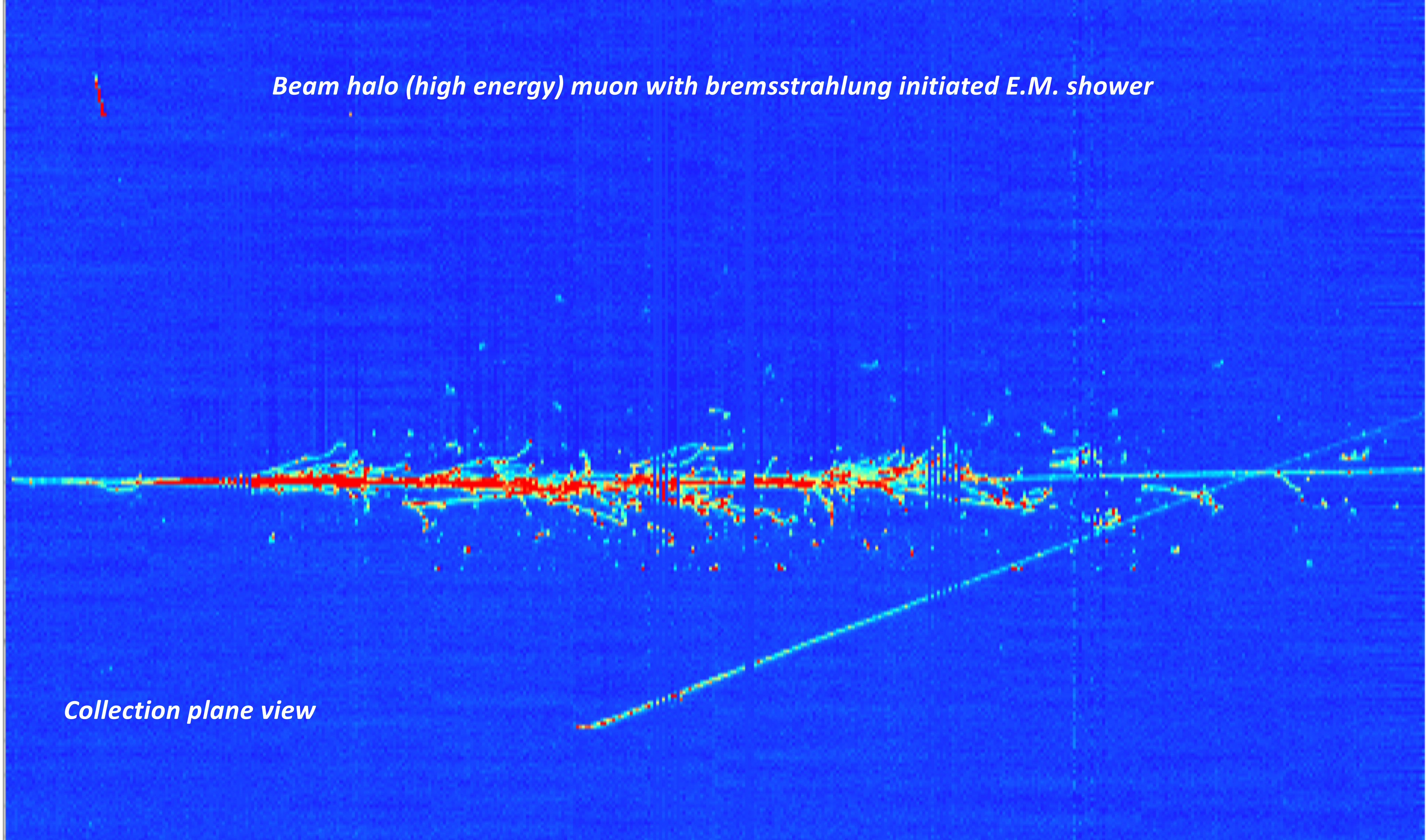
ProtoDUNE SP Beam Pile-up





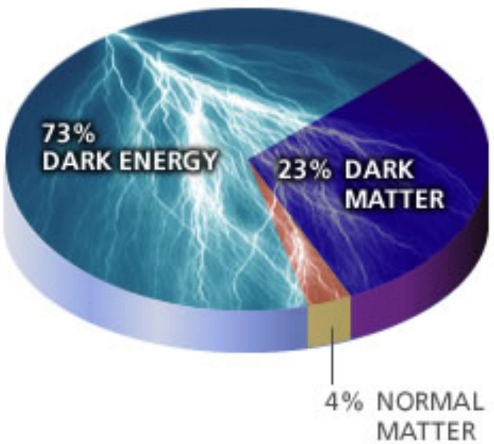
Run 4696, Ev 103:
2 EM showers and a pion interaction with 4 outcoming particles

ProtoDUNE SP First Event



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?
- 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

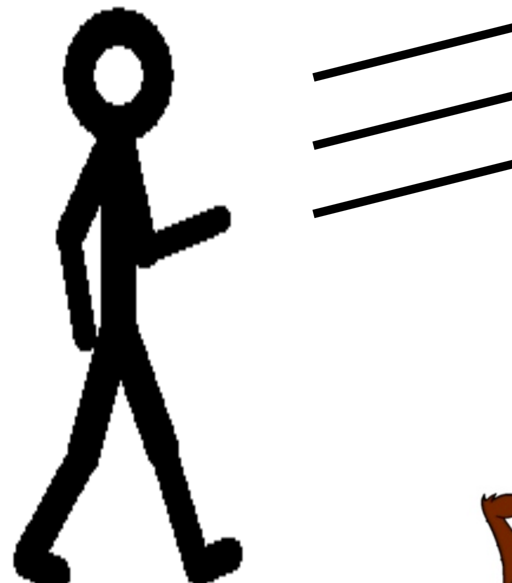
What is the Higgs and What does it do?

- 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



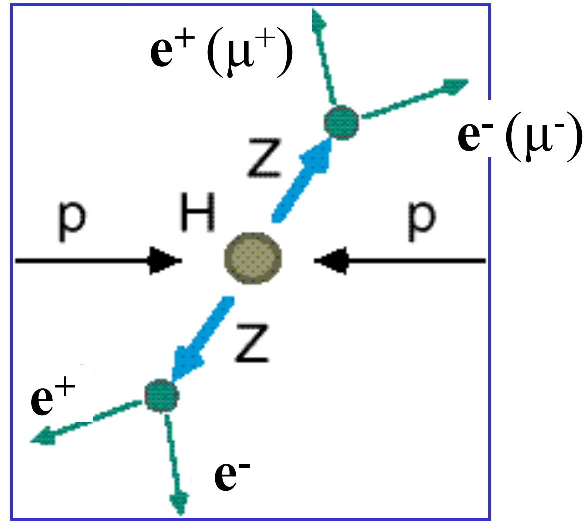
Just like a tornado is a piece of evidence of the existence of air, Higgs particle is a piece of evidence of Higgs mechanism

How do we look for the Higgs?

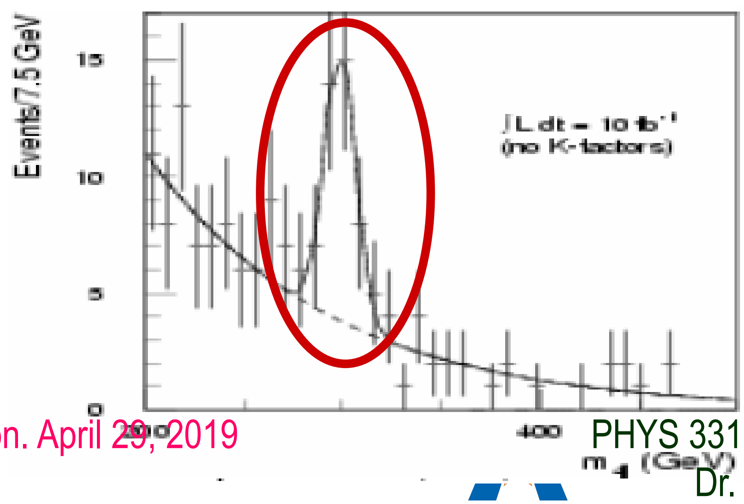
- Higgs particle is so heavy they decay into other lighter particles instantaneously
- When one searches for new particles, one looks for the easiest way to get at them
- Of many signatures of the Higgs, some are much easier to find, if it were the Standard Model Higgs
  - $H \rightarrow \gamma\gamma$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

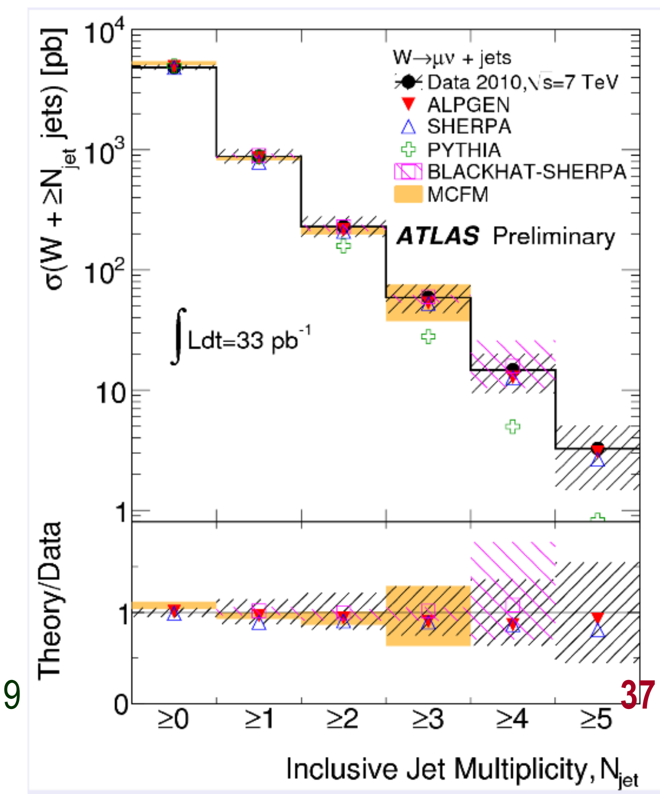
How do we look for the Higgs?

- Identify Higgs candidate events

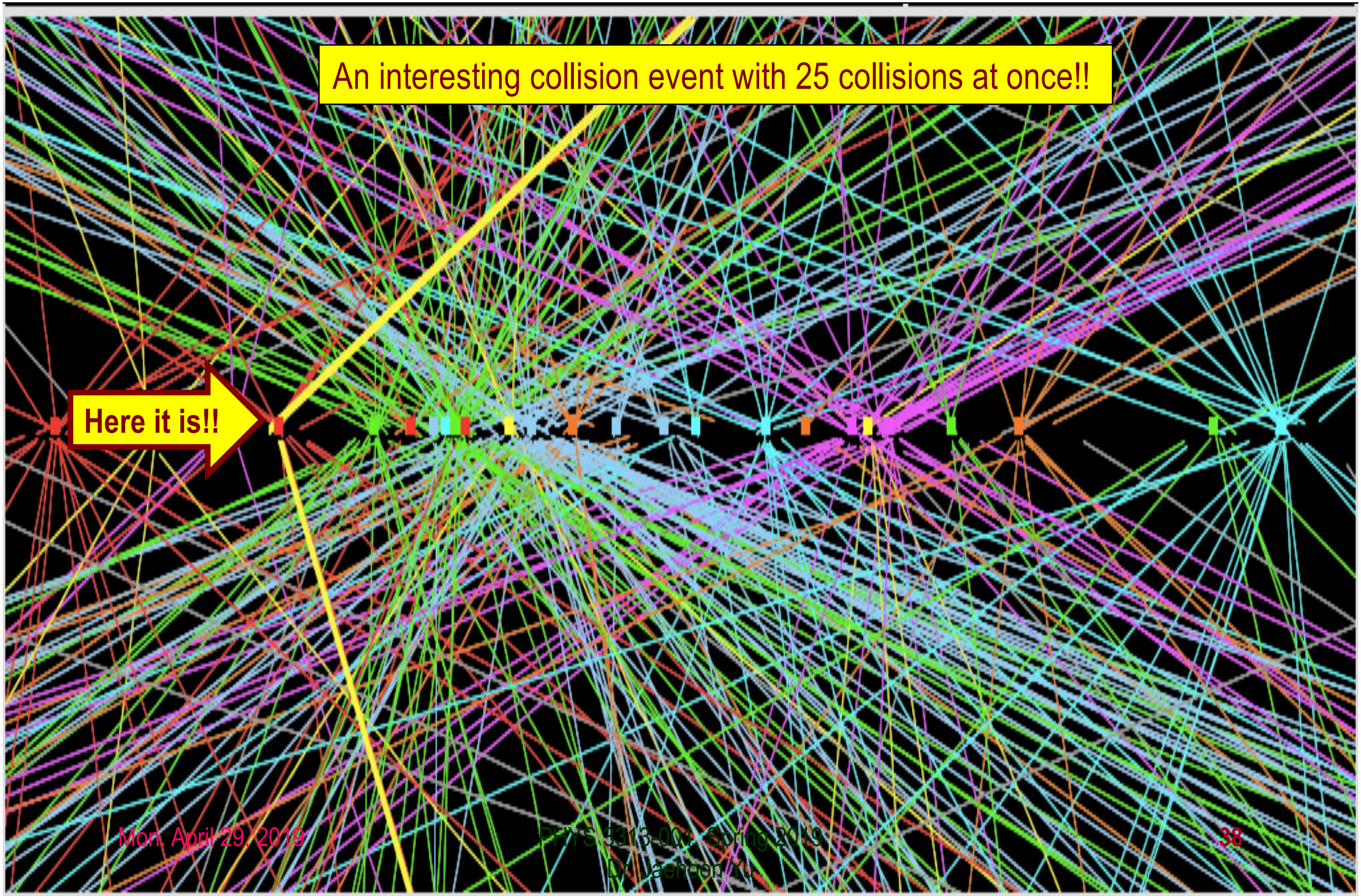


- Understand fakes (backgrounds)
- Look for a bump!!
  - Large amount of data absolutely critical

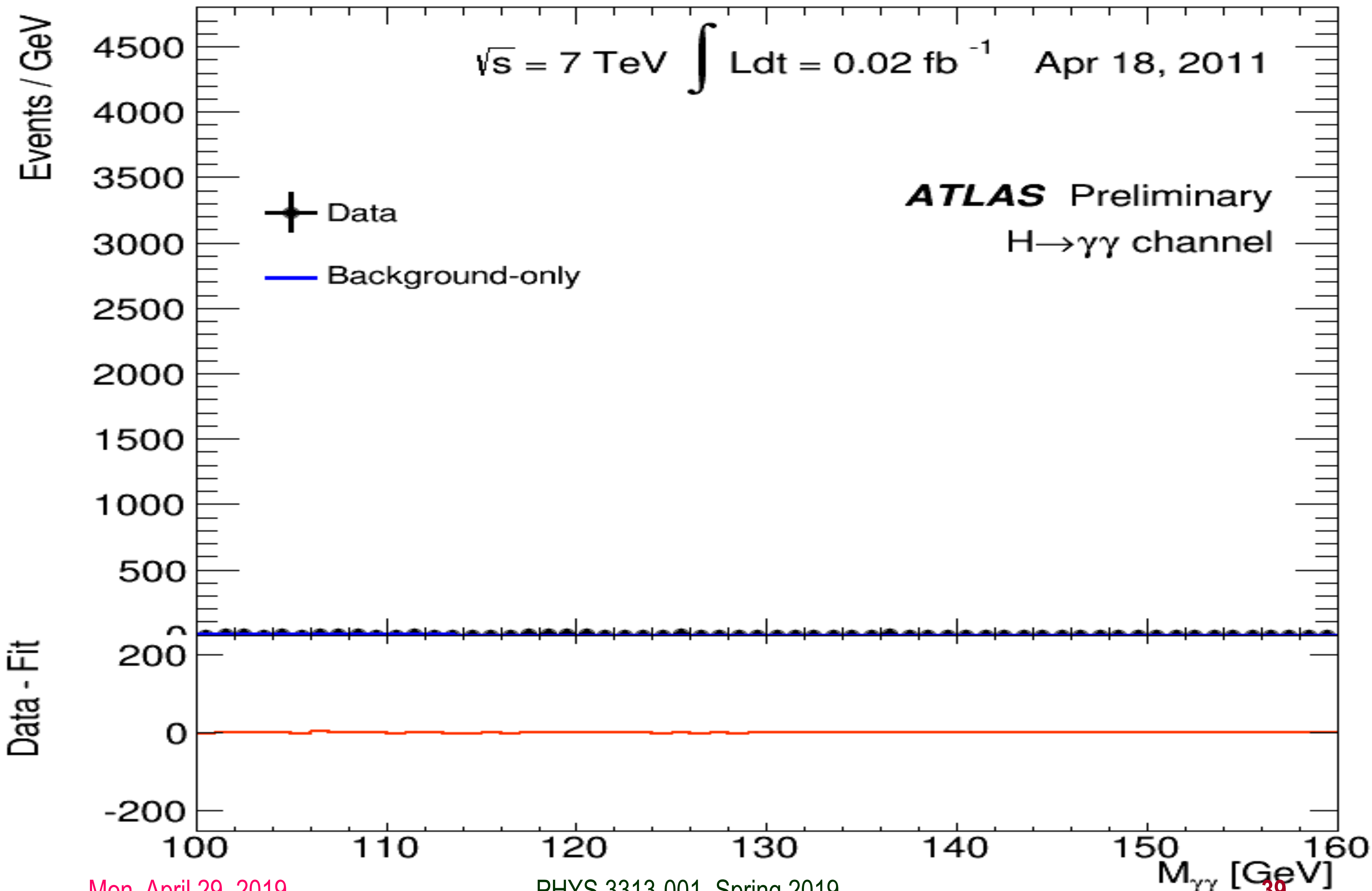




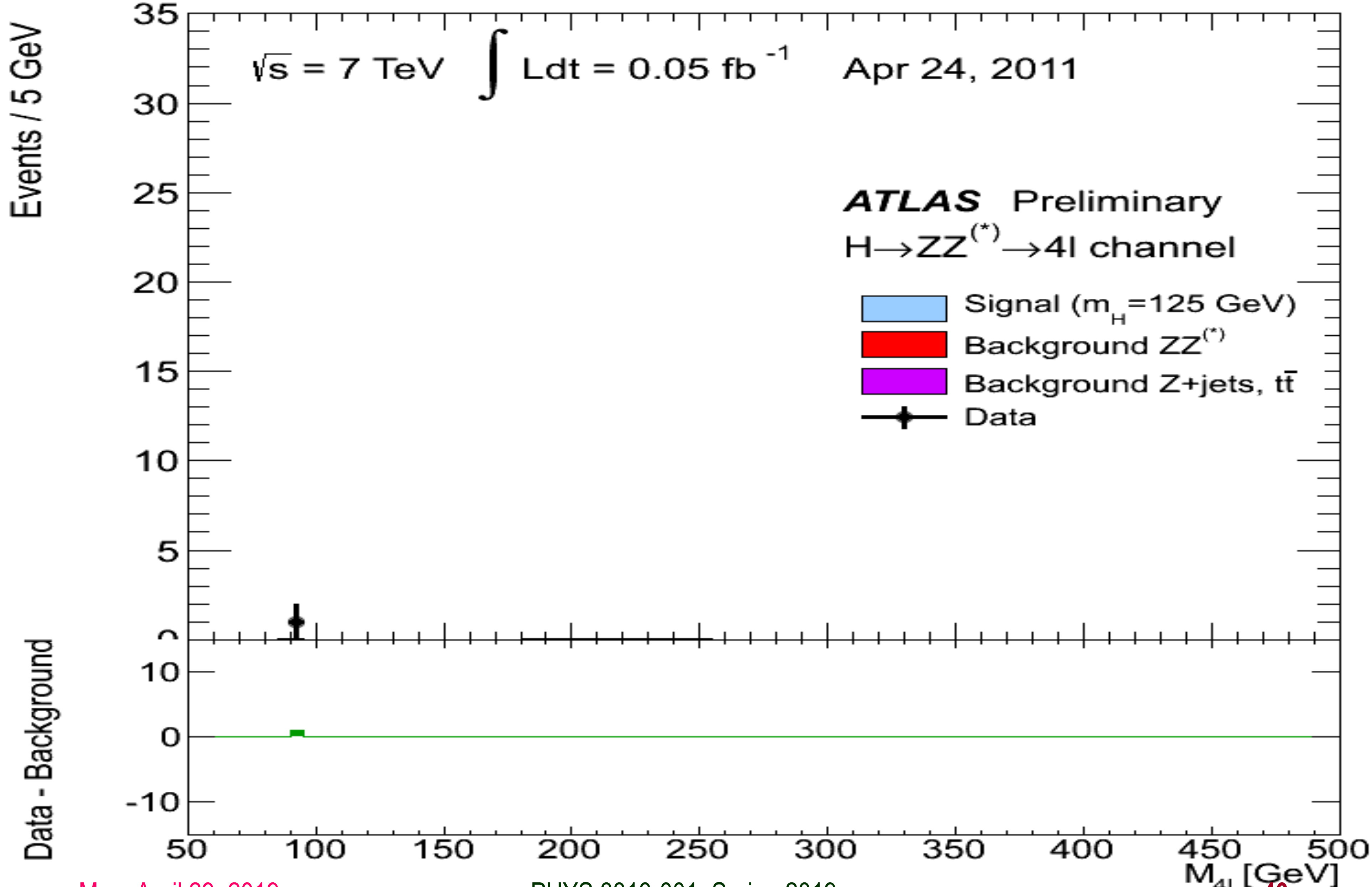
Challenges? No problem!



What did statistics do for Higgs?



How about this?



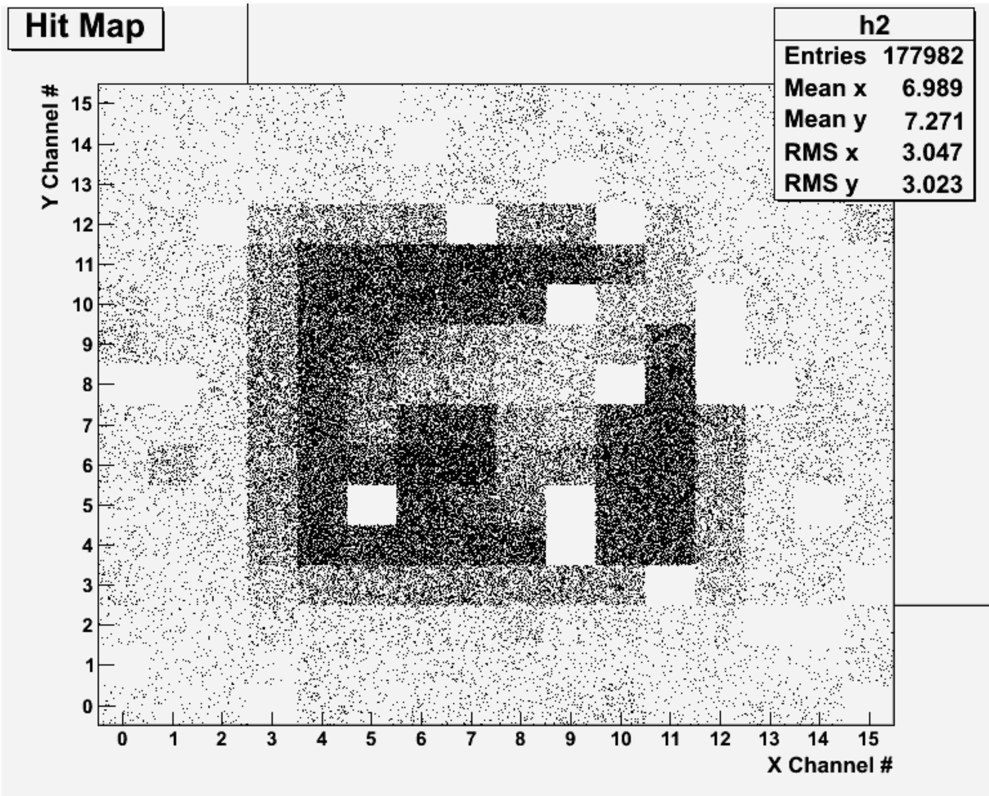
Statistical Significance Table

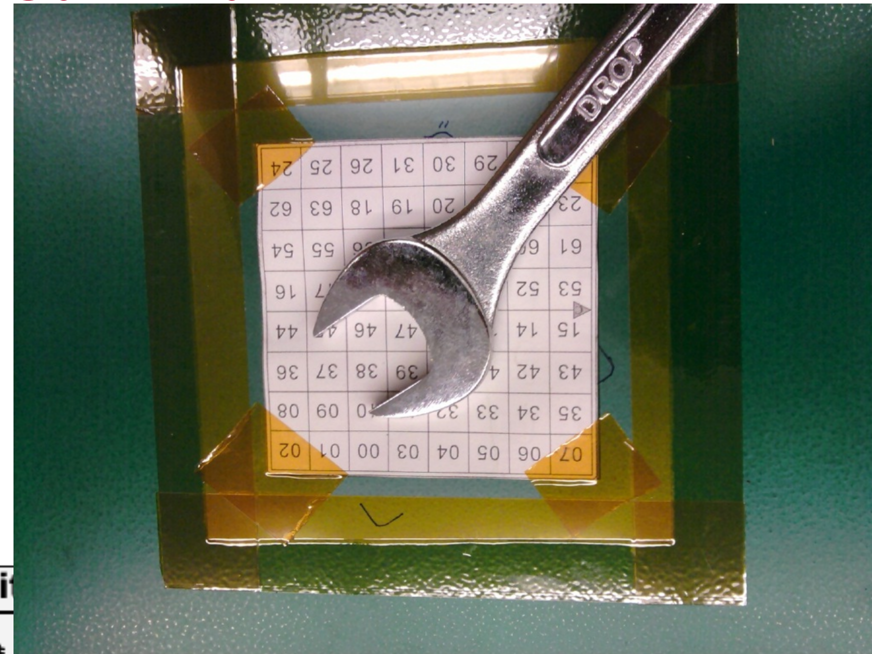
zσ	Percentage within CI	Percentage outside CI	Fraction outside CI
0.674 490σ	50%	50%	1 / 2
0.994 458σ	68%	32%	1 / 3.125
1σ	68.268 9492%	31.731 0508%	1 / 3.151 4872
1.281 552σ	80%	20%	1 / 5
1.644 854σ	90%	10%	1 / 10
1.959 964σ	95%	5%	1 / 20
2σ	95.449 9736%	4.550 0264%	1 / 21.977 895
2.575 829σ	99%	1%	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	[illegible]9 999 999%	[illegible]%	1 / 100,000,0[illegible]0,000
7σ	99.999 999 999 7440%	0.[illegible] 000 256%	1 / 390,682,215,445

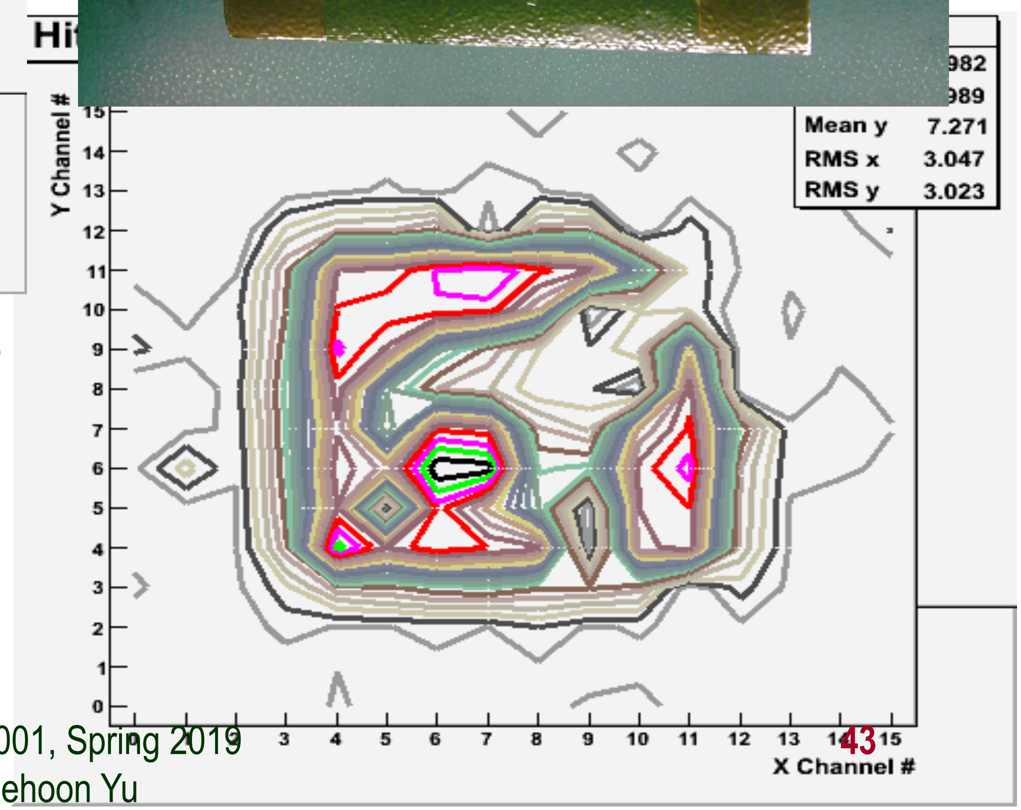
So have we seen the Higgs particle?

- 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 ~12,500 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

Bi-product of High Energy Physics Research





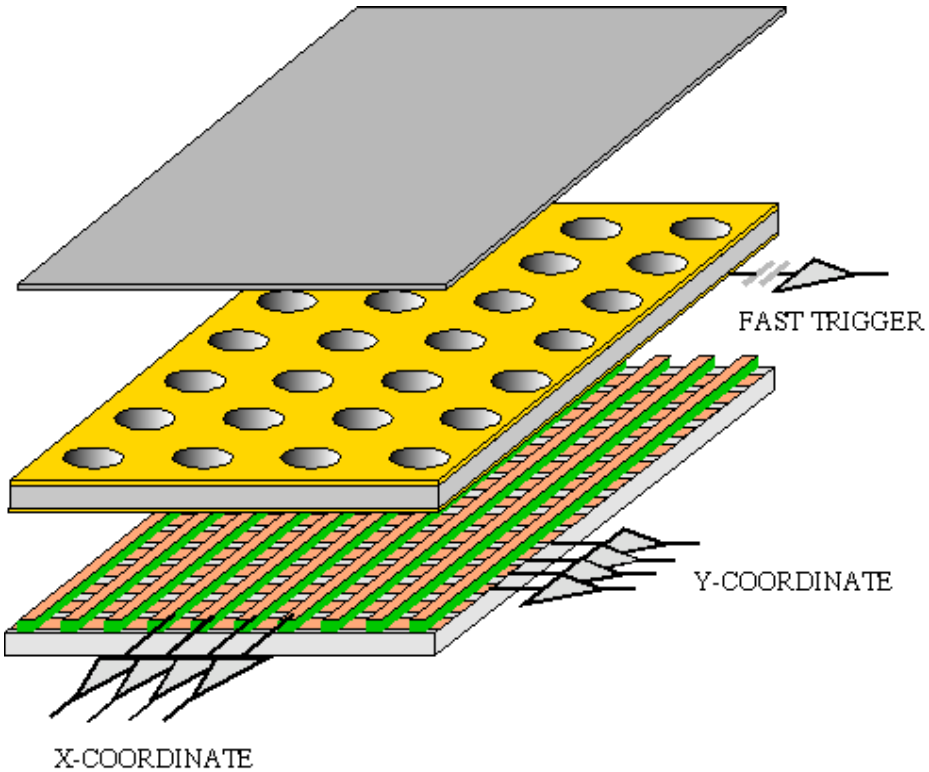


Can you see what the object is?
(GEM Detector X-ray Image)

And in not too distant future, we could do …

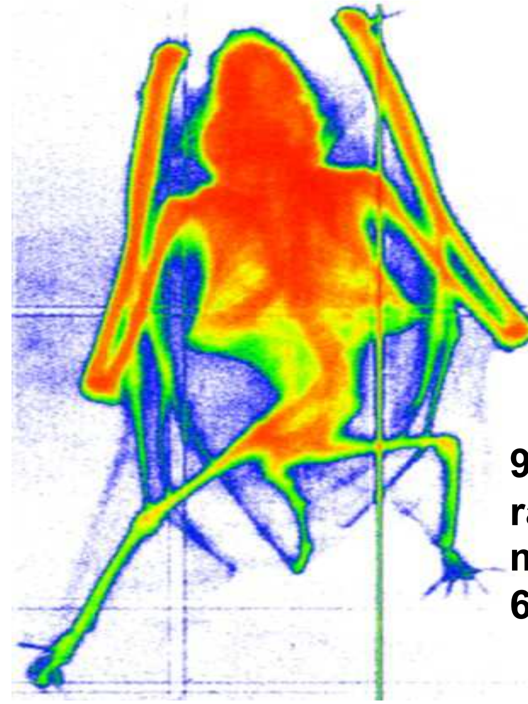
GEM Application Potential

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



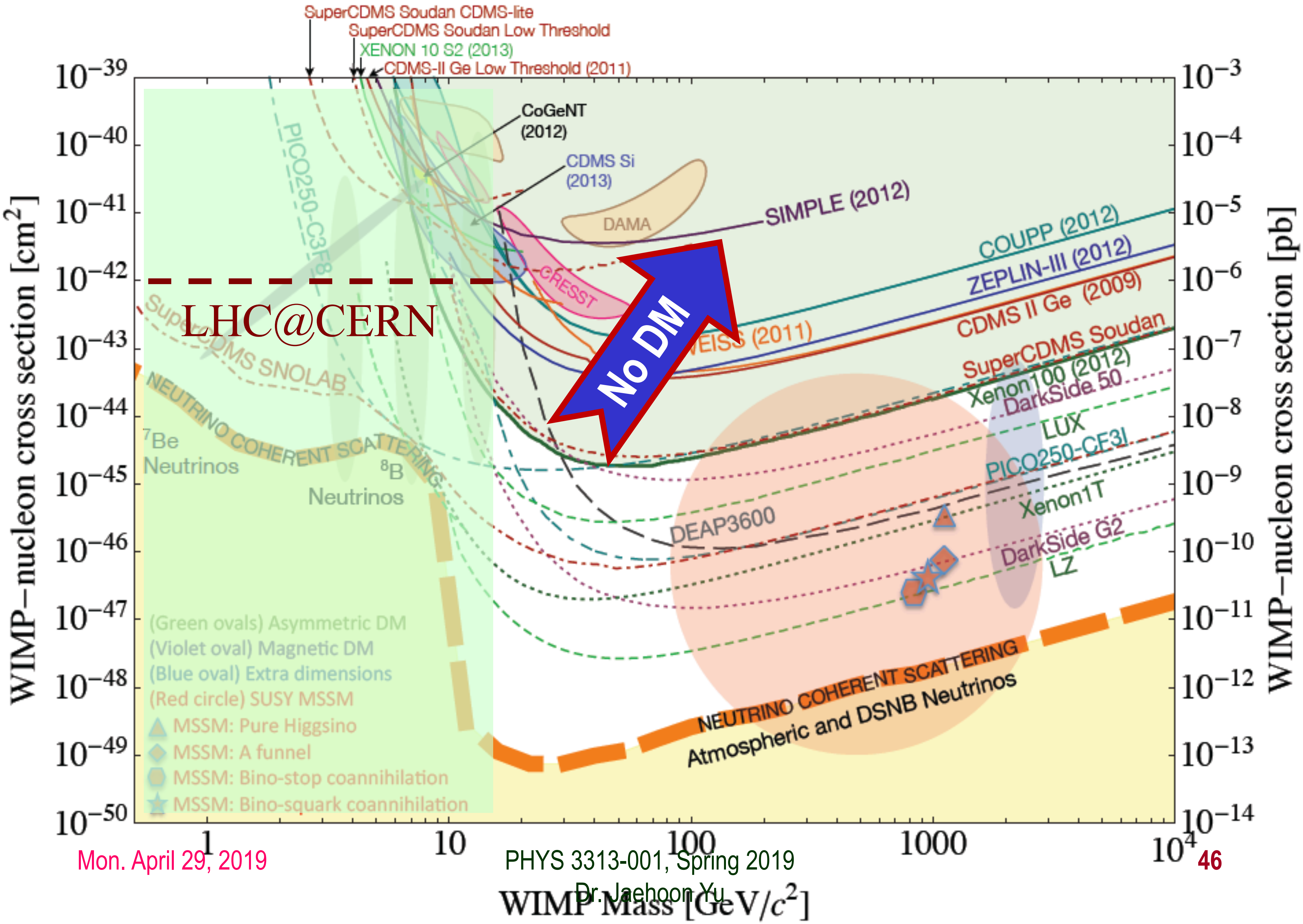
A. Bressan et al,
Nucl. Instr. and Meth. A 425(1999)254
F. Sauli, Nucl. Instr. and Meth.A 461(2001)47

FAST X-RAY IMAGING



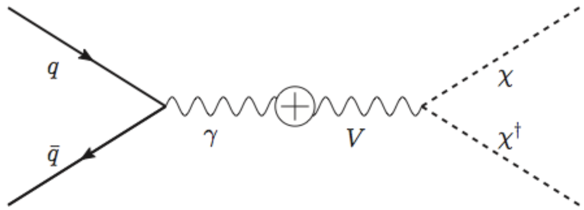
9 keV absorption radiography of a small mammal (image size ~ 60 x 30 mm^2)

Dark Matter Search Motivation

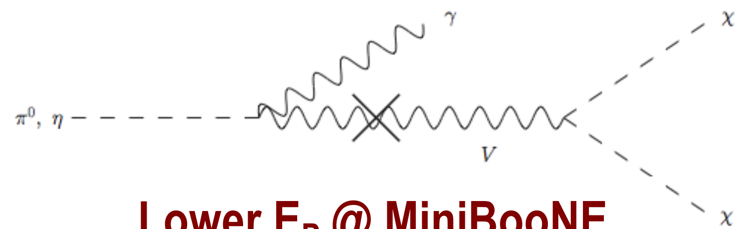


Light DM Production at High Intensity Accelerator

- 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!!

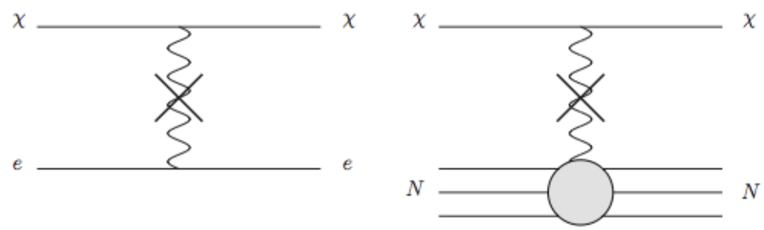


Higher E_P @ LBNE

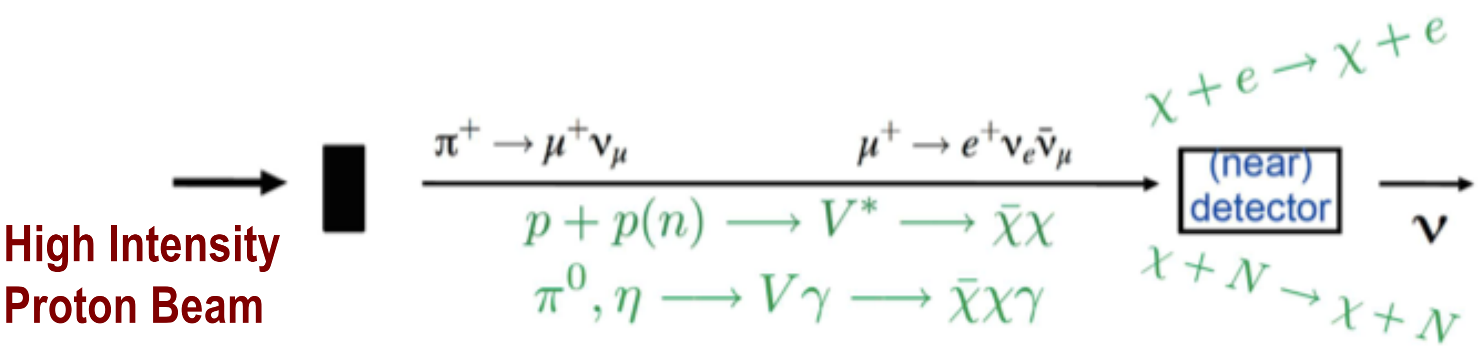


Lower E_P @ MiniBooNE

- Detection of DM:



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



So What?

- 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

So What?

- 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!

Congratulations!!!!

You all are impressive and have done very well!!!

I certainly had a lot of fun with ya'll and am truly proud of you!

Good luck with your exam!!!

Have a safe summer!!