PHYS 3313 – Section 001
Lecture # 21

From the Discovery of the Higgs to Search for Dark Matter

Monday, April 20, 2015
Dr. Jaehoon Yu

Outline

- Introduction
- What is the Higgs Particle?
- Did we discover the Higgs? What's next?
- Search for the Dark Matter at an Accelerator!
- Conclusions

Announcements

- Research paper deadline is Monday, May 4
- Research presentation deadline is Sunday, May 3
- Reminder: Homework #5
  - CH6 end of chapter problems: 34, 39, 46, 62 and 65
  - Due Wednesday, Apr. 22
- Homework #6
  - CH7 end of chapter problems: 7, 8, 9, 12, 17 and 29
  - Due on Wednesday, Apr. 29, in class
- Reading assignments
  - CH7.6 and the entire CH8
- Quiz number 5
  - At the beginning of the class Wednesday, Apr. 29
  - Covers up to what we finish Monday, Apr. 27
- Quiz 4 results
  - Class average: 25.6/50
    - Equivalent to: 51.2/100
    - Previous records: 26.5, 46.5 and 47.5
  - Top score: 50/50

We always wonder…

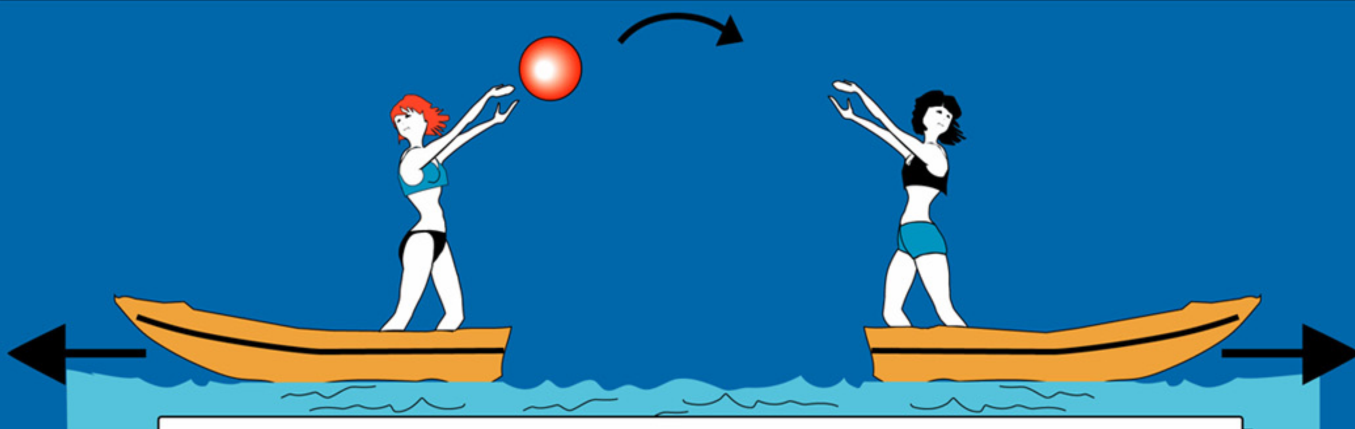
- What makes up the universe?
- How does the universe work?
- What holds the universe together?
- How can we live in the universe well?
- Where do we all come from?

High Energy Physics

- Definition: A field of physics that pursues understanding the fundamental constituents of matter and basic principles of interactions between them.
- Known interactions (forces):
  - Gravitational Force
  - Electromagnetic Force
  - Weak Nuclear Force
  - Strong Nuclear Force
- Current theory: The Standard Model of Particle Physics (SU3xSU2XU1)

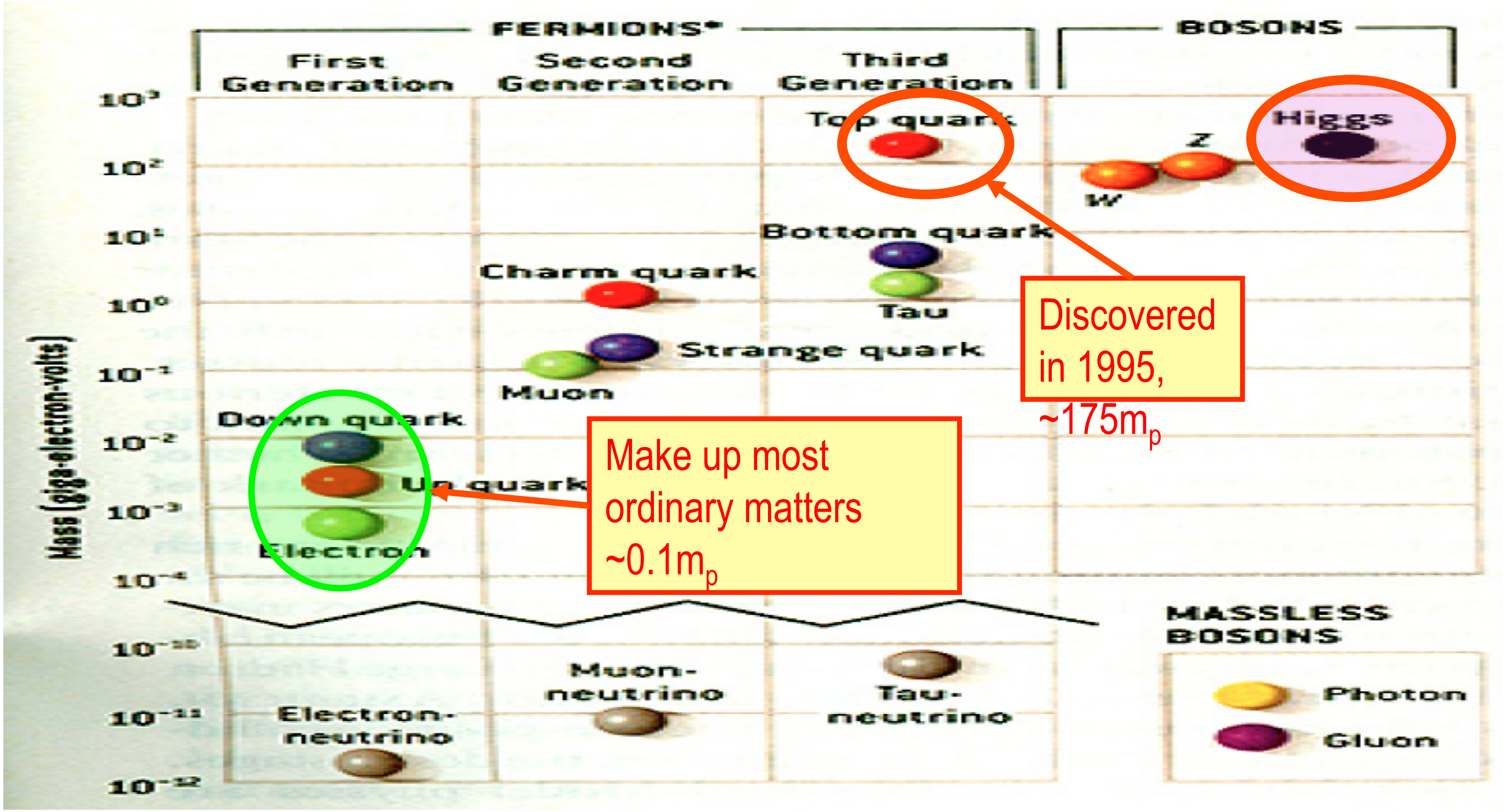
The forces in Nature

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^0, $W+$, $W-$ (HEAVY)	RADIOACTIVE BETA DESINTEGRATION
GRAVITATION	$\sim 10^{-38}$	GRAVITONS (?)	HEAVENLY BODIES



THE EXCHANGE OF PARTICLES IS RESPONSIBLE FOR THE FORCE

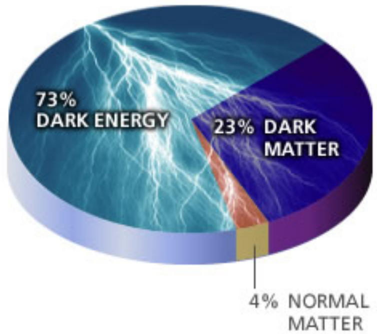
HEP and the Standard Model



- 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!

So what's the problem?

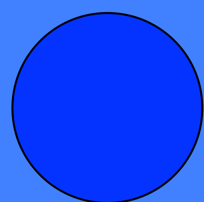
- Why is the mass range so large ($0.1m_p$ – $175\ m_p$)?
- How do matters acquire mass?
    - Higgs mechanism, did we find the Higgs?
- Why is the matter in the universe made only of particles?
- Neutrinos have mass!! What are the mixing parameters, particle-anti particle asymmetry and mass ordering?



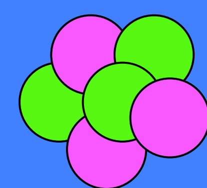
- Why are there only three apparent forces?
- Is the picture we present the real thing?
    - What makes up the ~95% of the universe?
- Are there any other theories that describe the universe better?
    - Does the super-symmetry exist?
- Where do we all come from?
- How can we live well in the universe as an integral partner?

Accelerators are **Powerful Microscopes.**

They make high energy particle beams
that allow us to see small things.



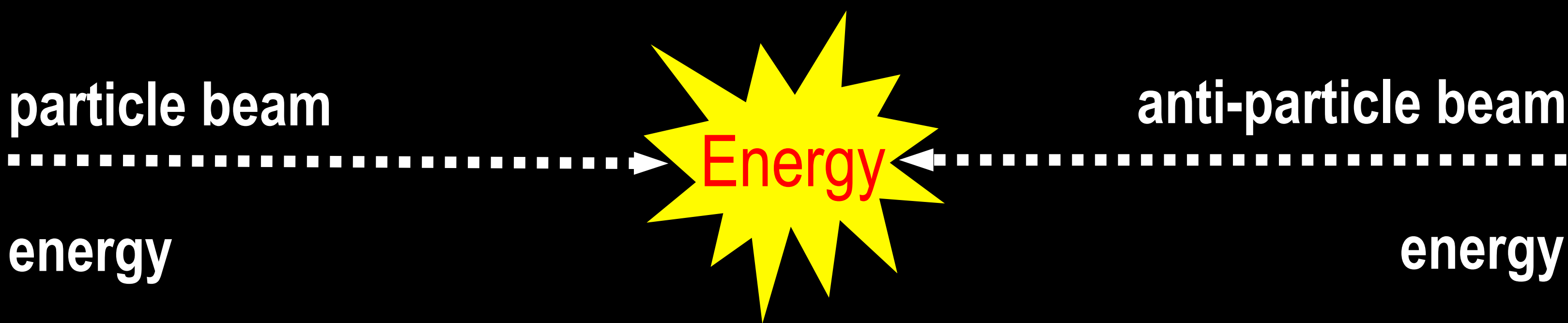
seen by
low energy beam
(poorer resolution)



seen by
high energy beam
(better resolution)

Accelerators are also Time Machines.

They make particles last seen
in the earliest moments of the universe.

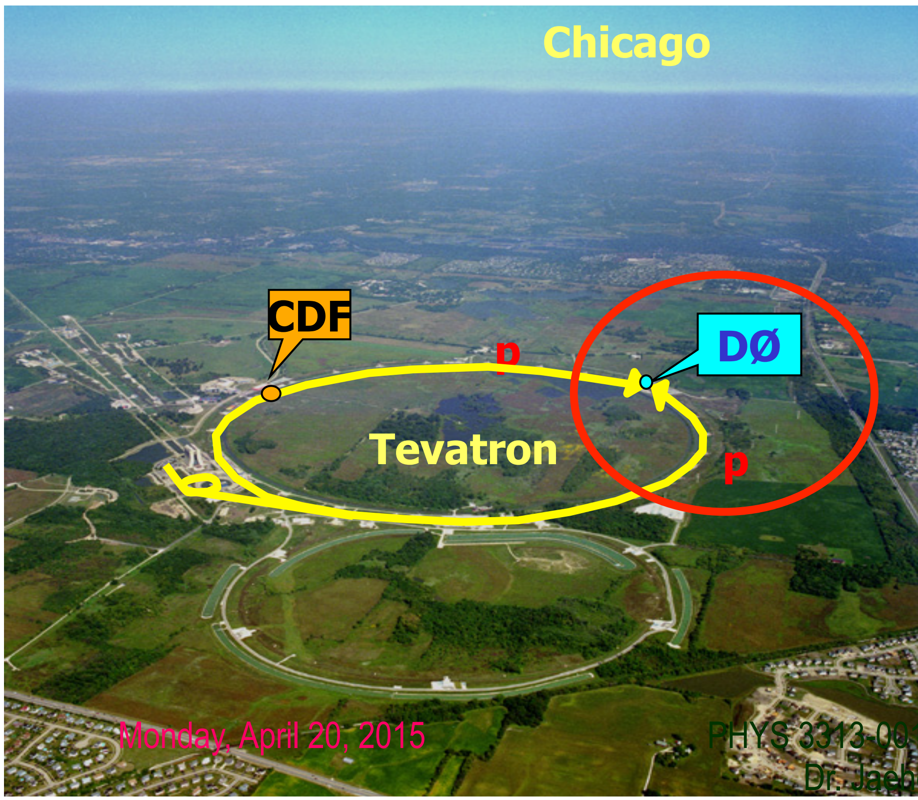


Particle and anti-particle annihilate.

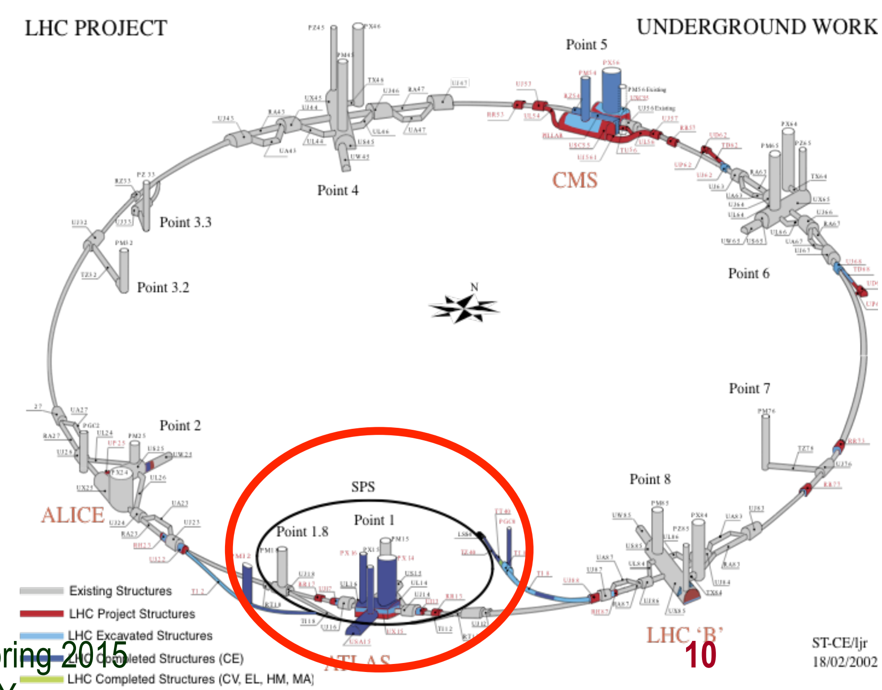
$$E = mc^2$$

Fermilab Tevatron and LHC at CERN

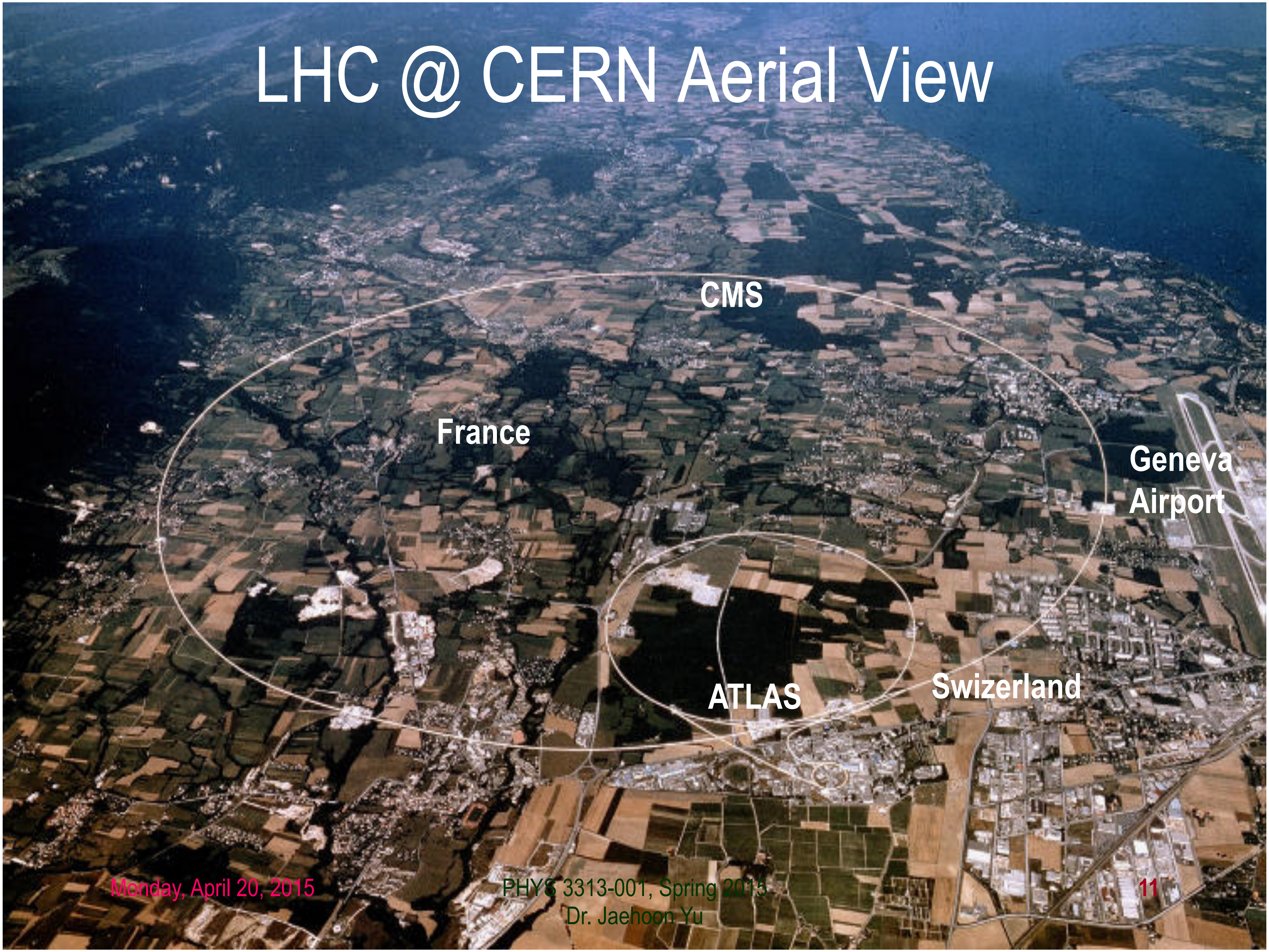
- World's Highest Energy proton-anti-proton collider
  - 4km (2.5mi) circumference
  - E_{cm}=1.96 TeV (=6.3x10^{-7}J/p➔ 13M Joules on the area smaller than $10^{-4}m^2$)
  - Equivalent to the kinetic energy of a 20t truck at the speed 81mi/hr
    - ~100,000 times the energy density at the ground 0 of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



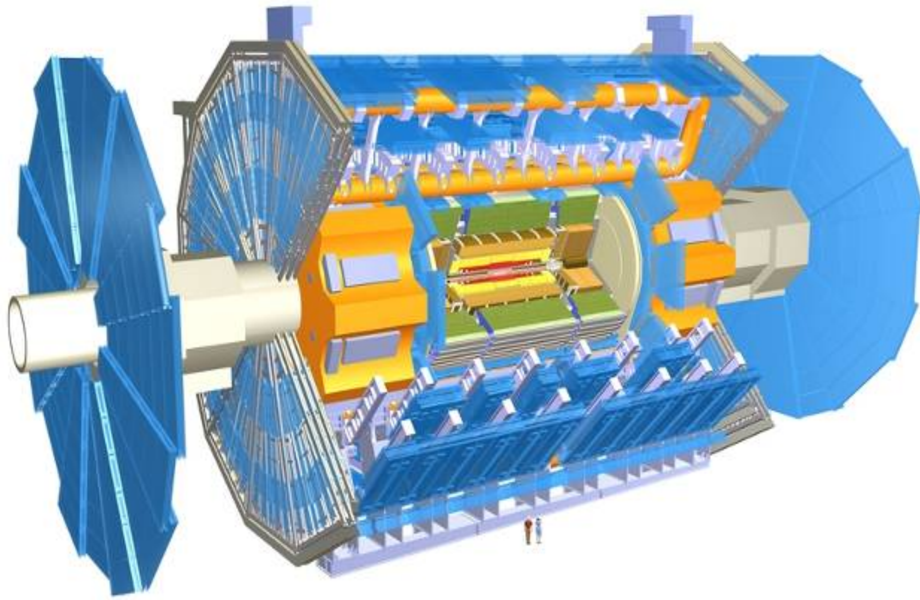
- World's Highest Energy p-p collider
  - 27km (17mi) circumference, 100m (300ft) underground
  - Design E_{cm}=14 TeV (=44x10^{-7}J/p➔ 362M Joules on the area smaller than $10^{-4}m^2$)
  - ➢ Equivalent to the kinetic energy of a B727 (80tons) at the speed 193mi/hr
    - ➢ ~3M times the energy density at the ground 0 of the Hiroshima atom bomb
- **Large amount of data accumulated in 2010 – 2013**
- **Bream circulating at 7.5TeV each at present**

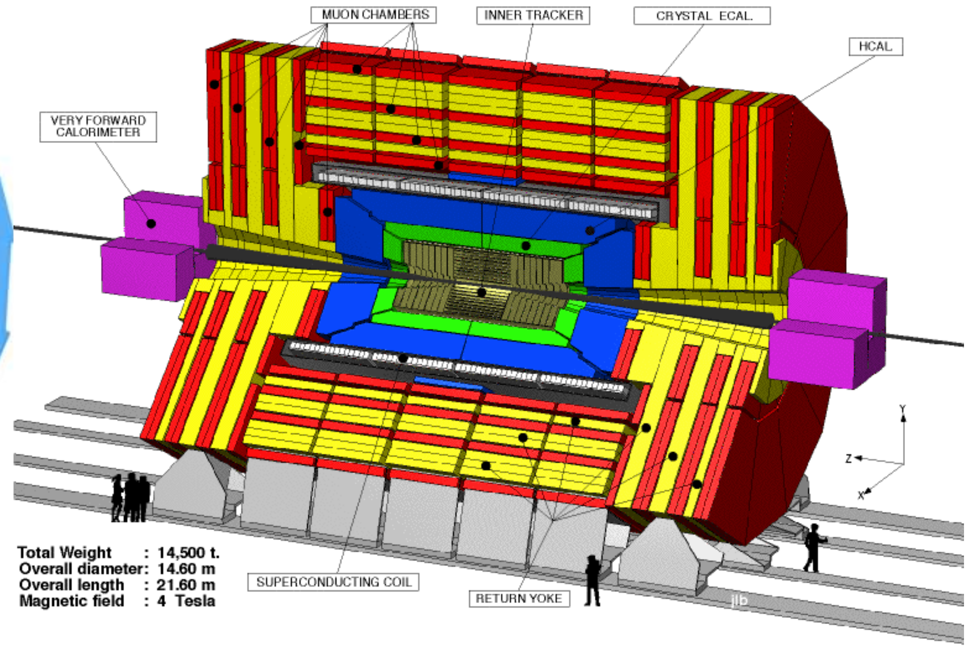


LHC @ CERN Aerial View



The ATLAS and CMS Detectors





- **Weighs 7000 tons and ~10 story tall**
- Records **200 – 400 collisions/second (out of 50million)**
- Records approximately **350** MB/second
- Records ~2 PB per year ➔ **200*Printed material of the US Lib. of Congress**

200x

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

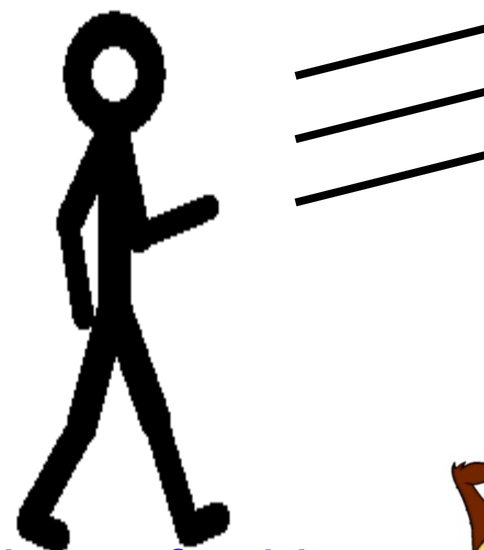
What is the Higgs and What does it do?

- 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?

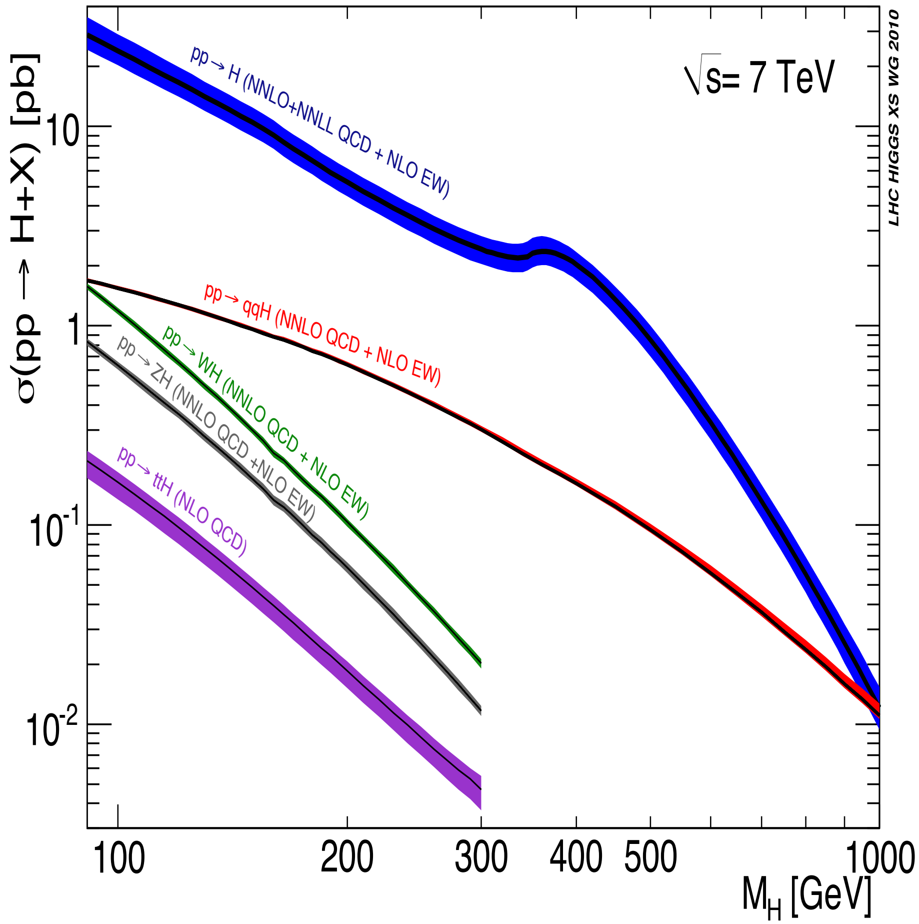
- Person in space → no symmetry breaking

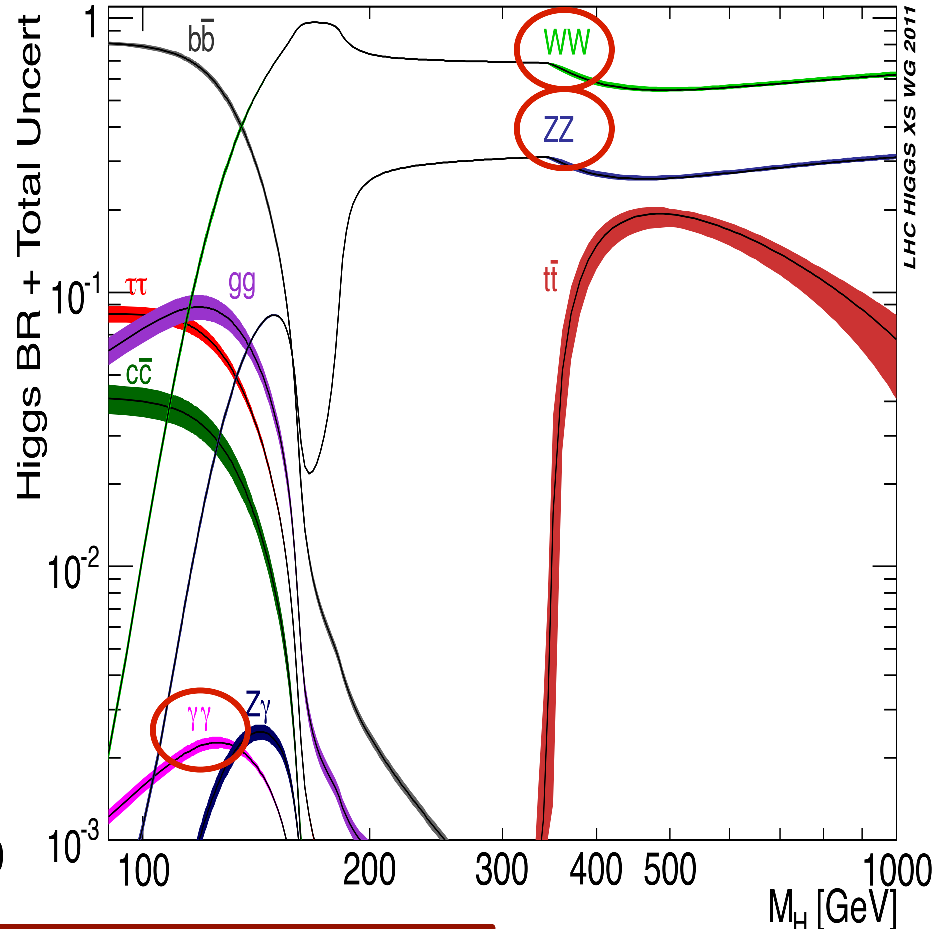
- Person in air → symmetry can be broken
- Sometimes, you get



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

Higgs Production X-sec and BR





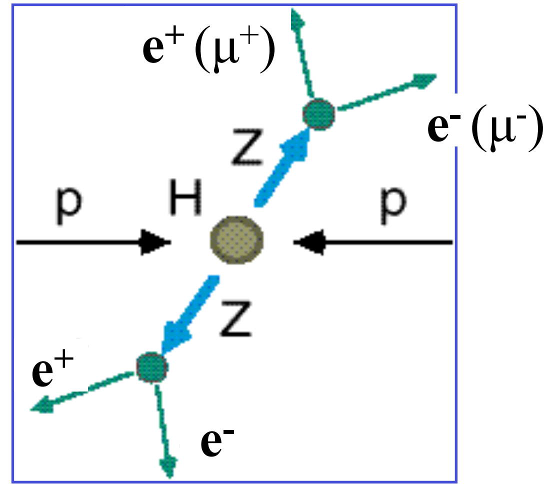
Higgs mass is not given in the theory!!

How do we look for the Higgs?

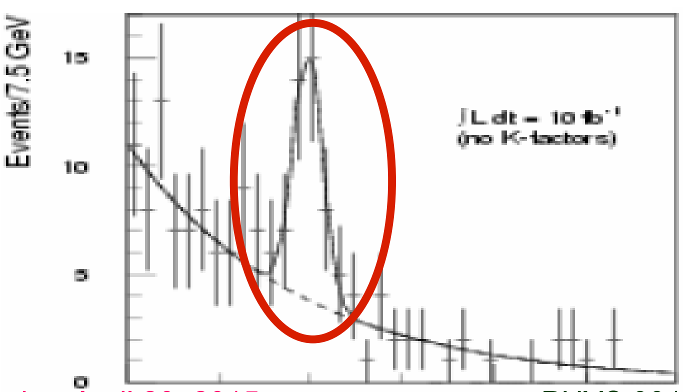
- Higgs particle is so heavy they decay into other lighter particles instantaneously
- When one searches for new particles, one looks for the easiest way to get at them
- Of many signatures of the Higgs, some are much easier to find, if it were the Standard Model Higgs
  - $H \rightarrow \gamma\gamma$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

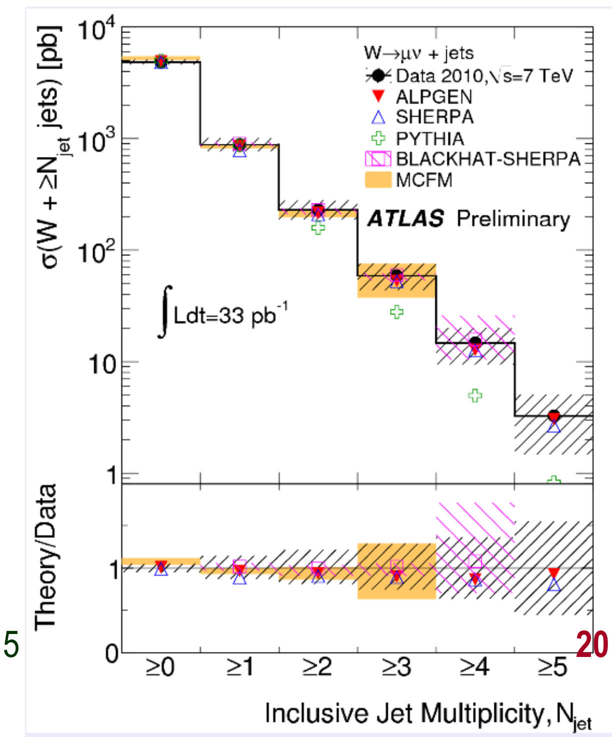
How do we look for the Higgs?

- Identify Higgs candidate events

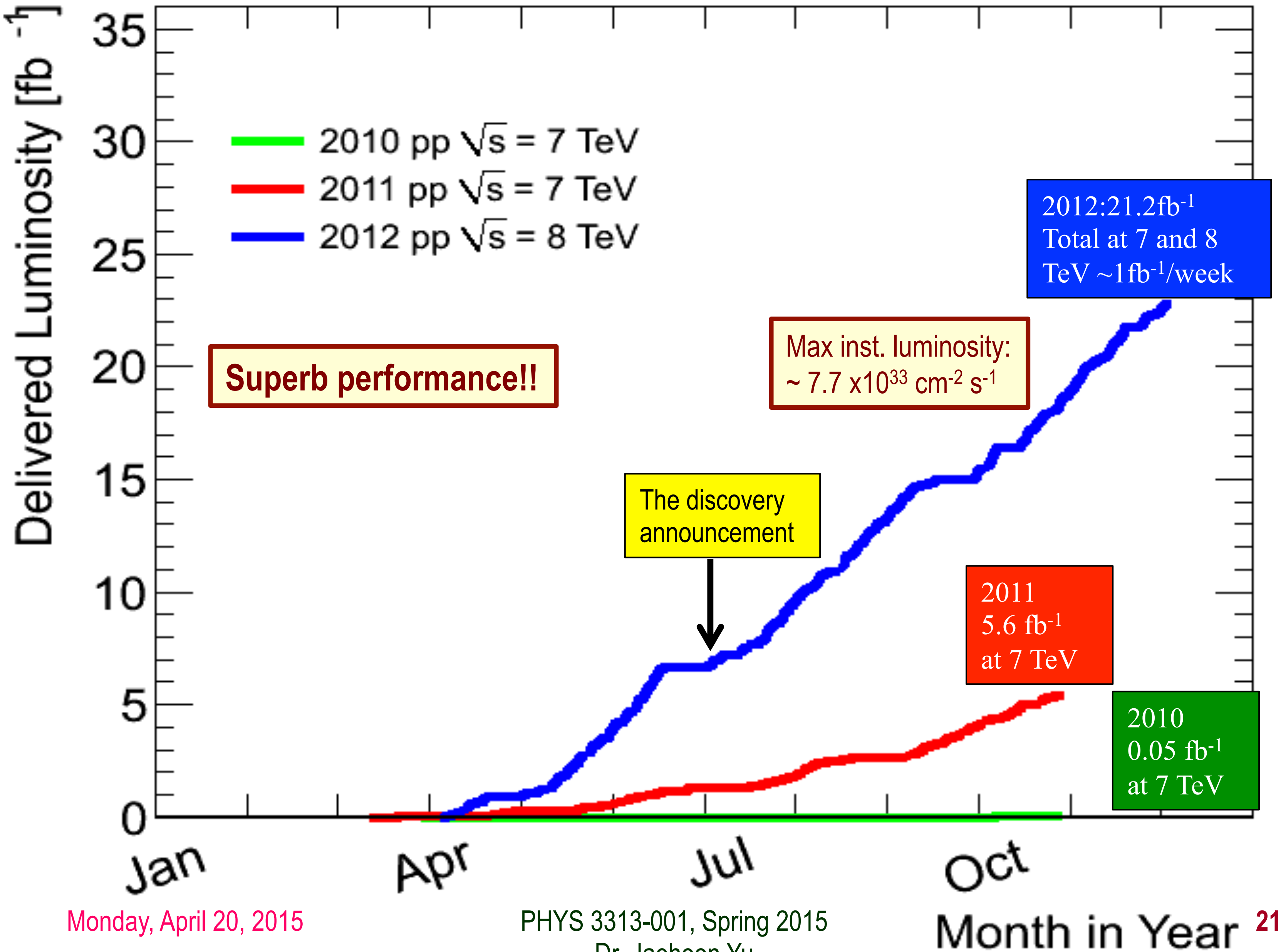


- Understand fakes (backgrounds)
- Look for a bump!!
  - Large amount of data absolutely critical

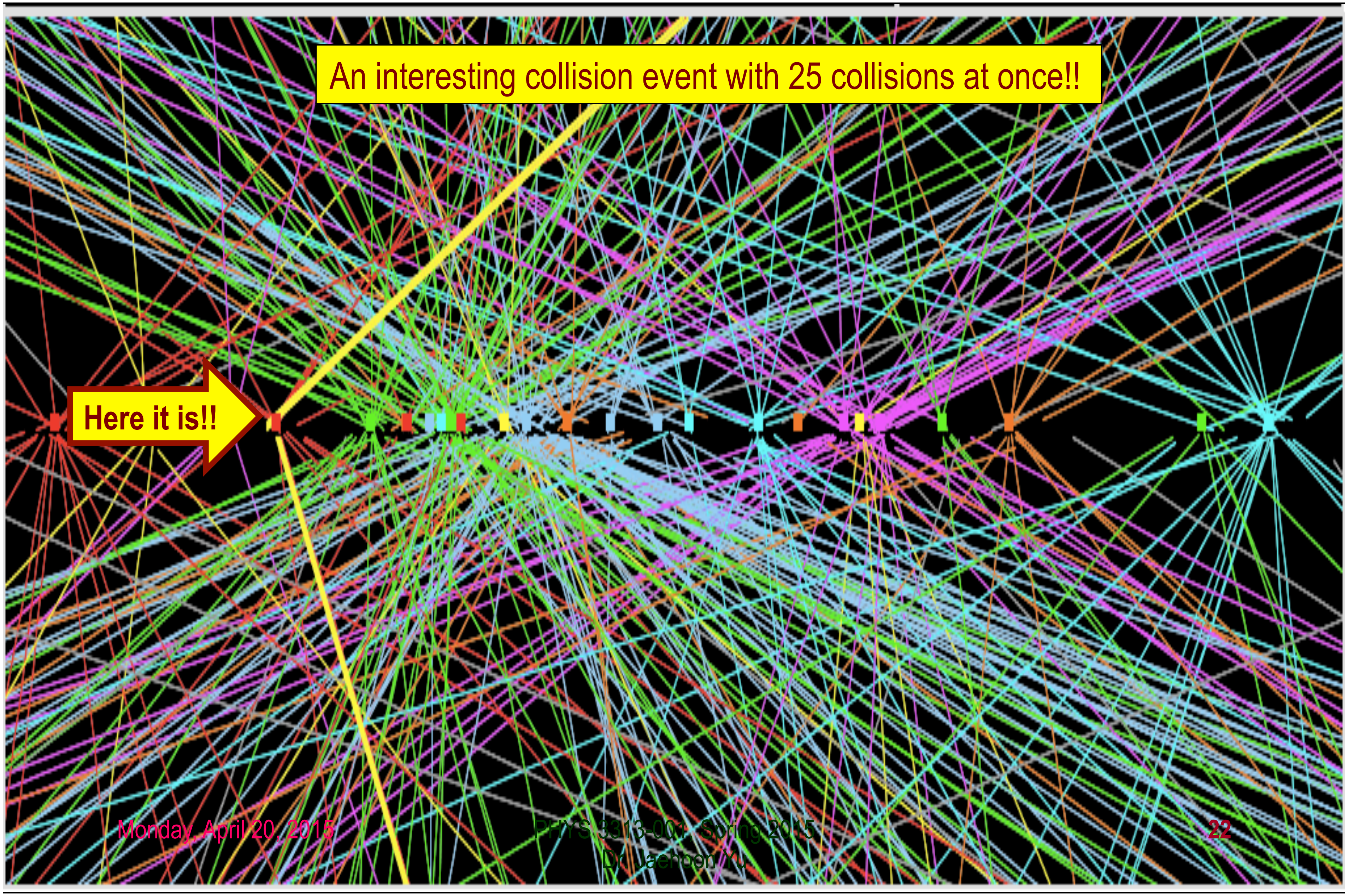




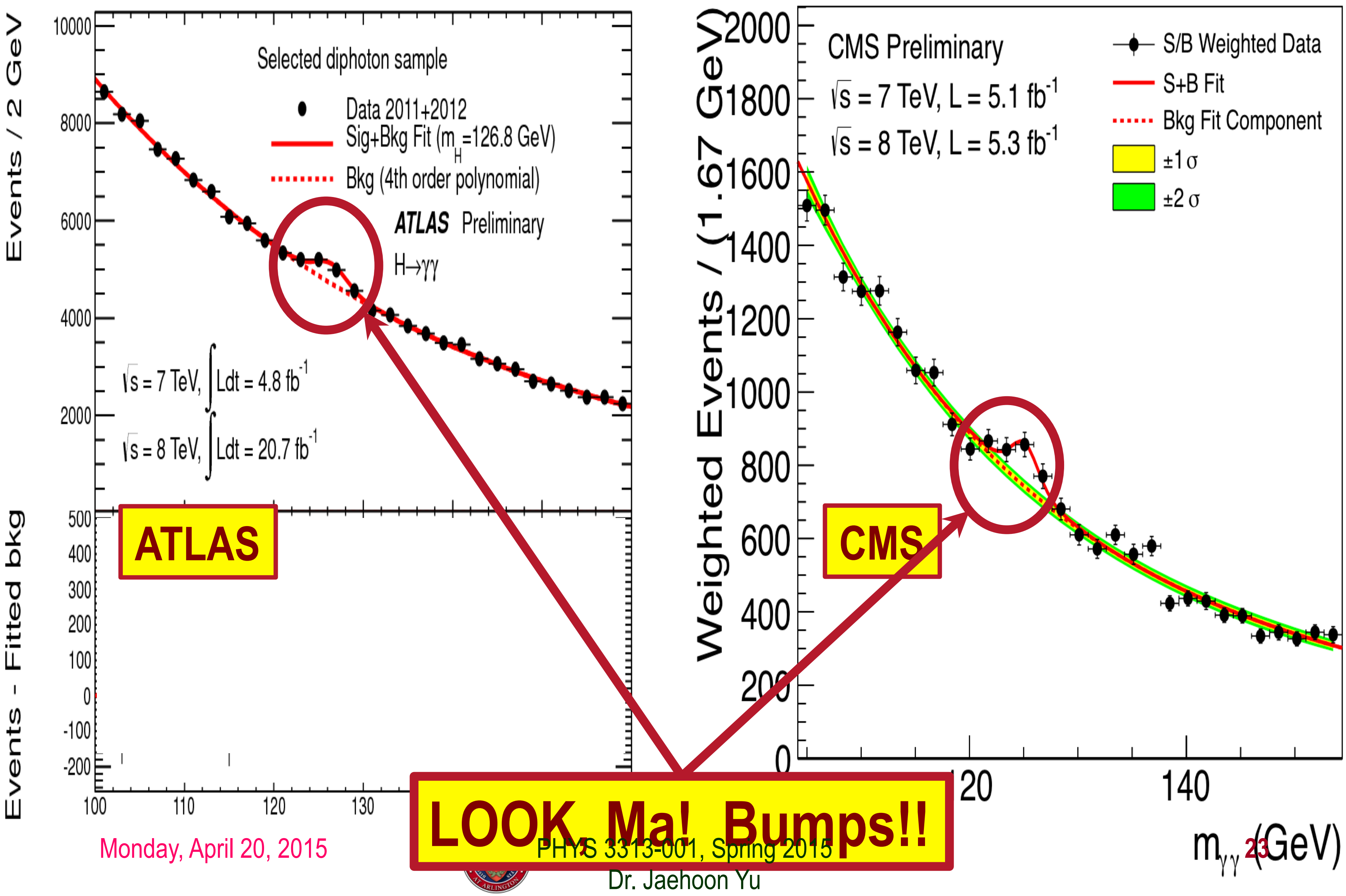
Amount of LHC Data



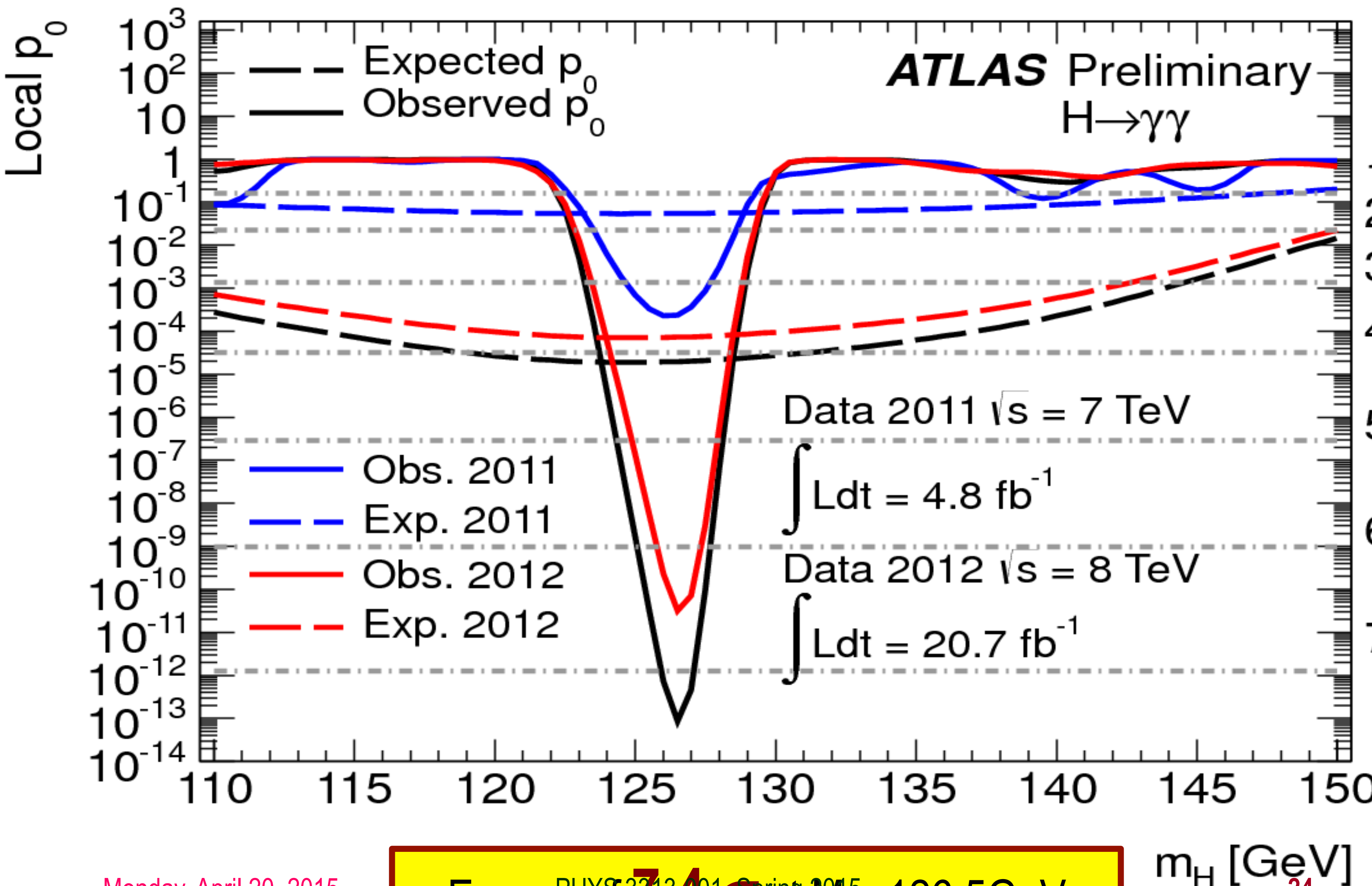
Challenges? No problem!



ATLAS and CMS Mass Bump Plots (**H→γγ**)

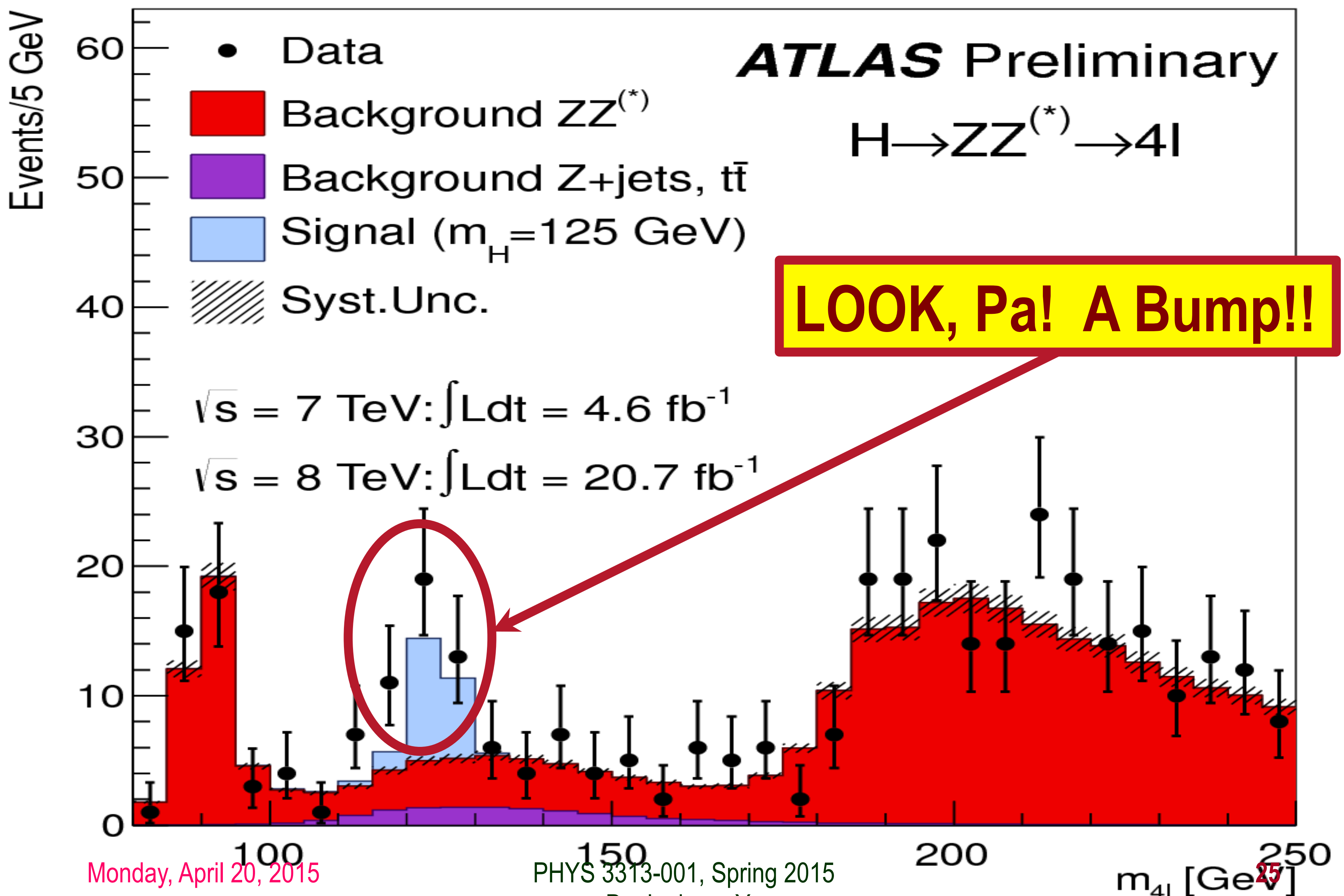


H→γγ Significance

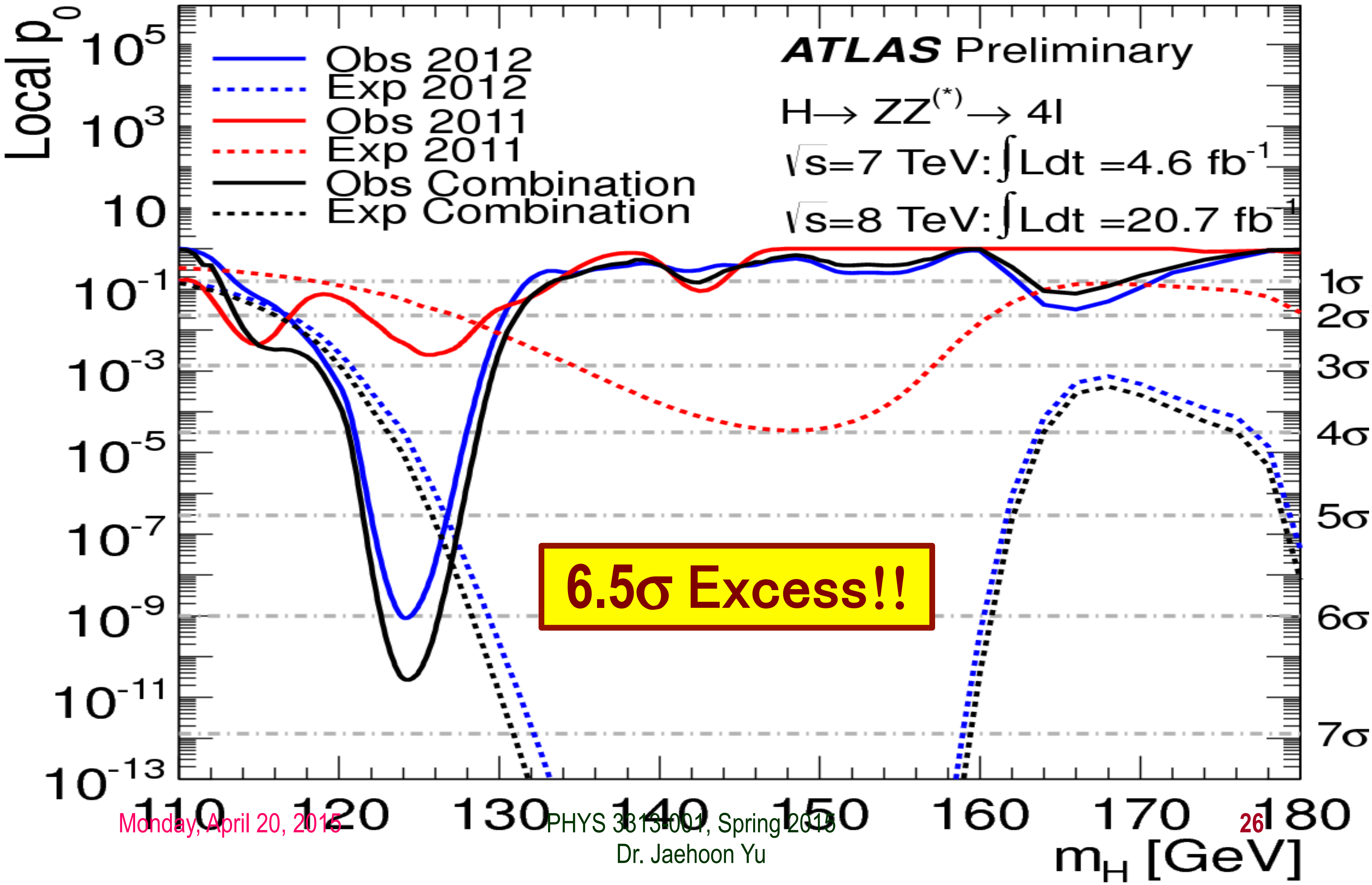


Excess of **7.4 σ** at M_H=126.5GeV

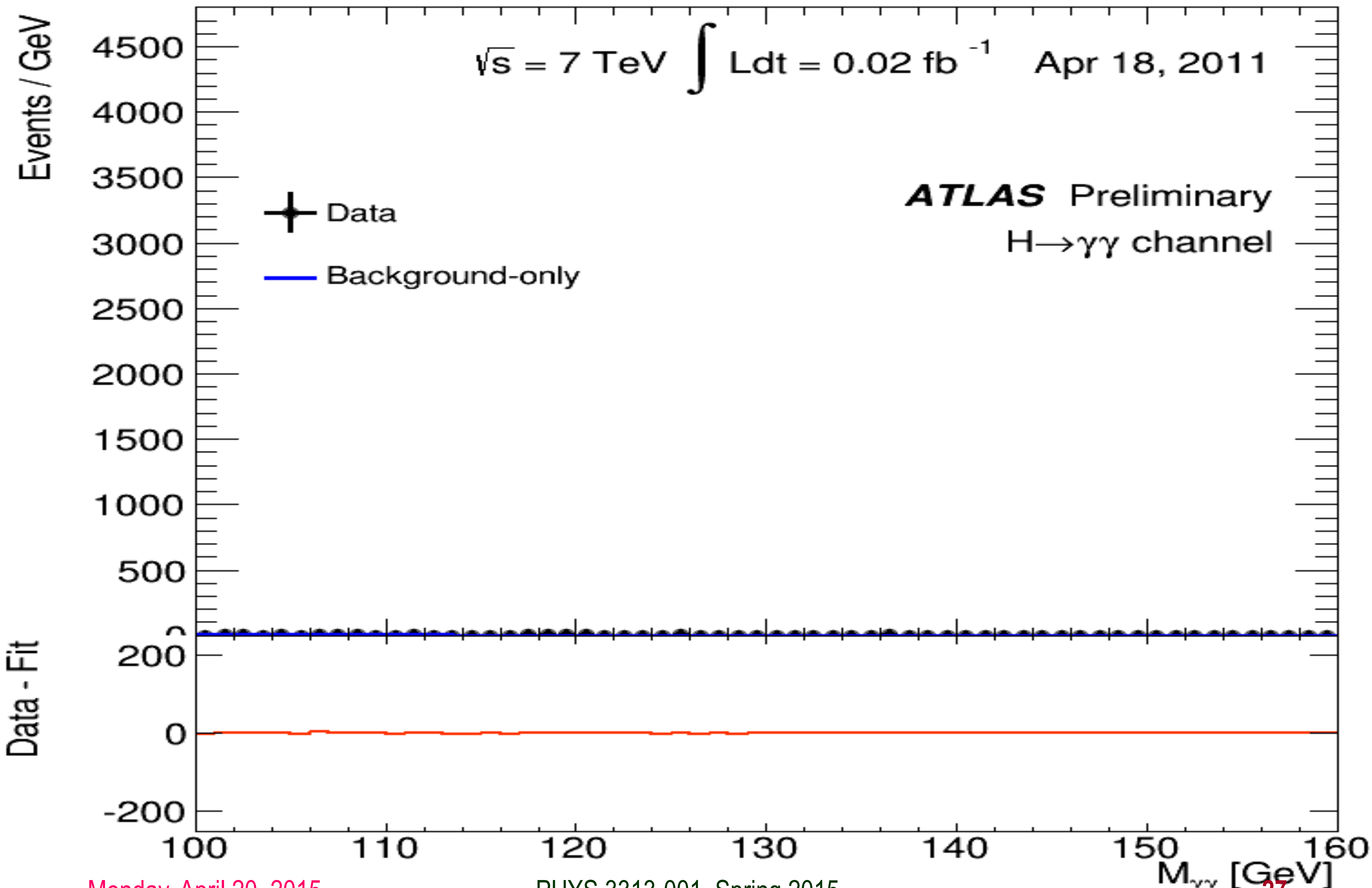
ATLAS Mass Bump Plot (H→4l)?



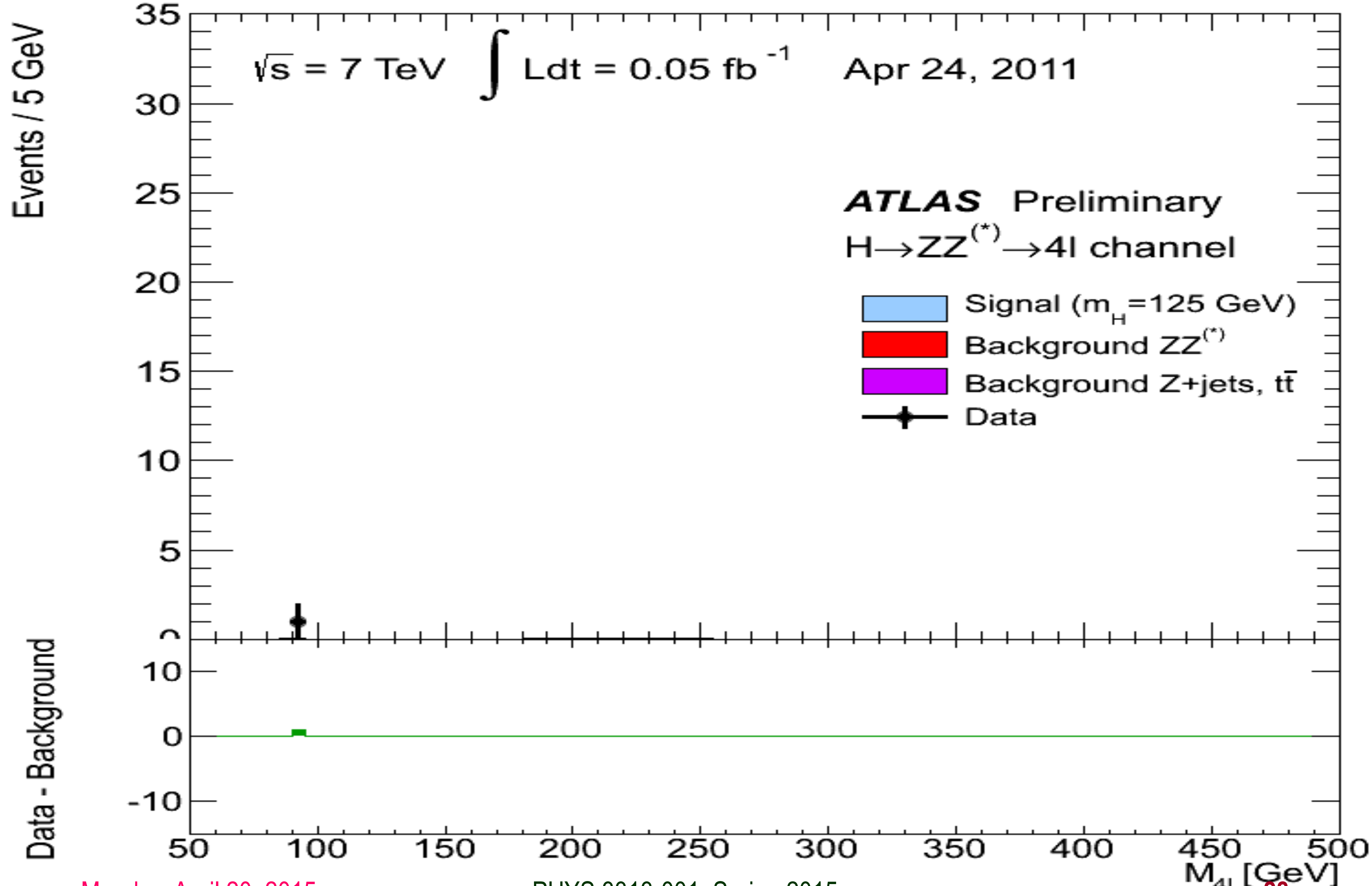
H→ZZ→4l Channel Significance



What did statistics do for Higgs?



How about this?



So have we seen the Higgs particle?

- The statistical significance of the finding is over 7 standard deviations

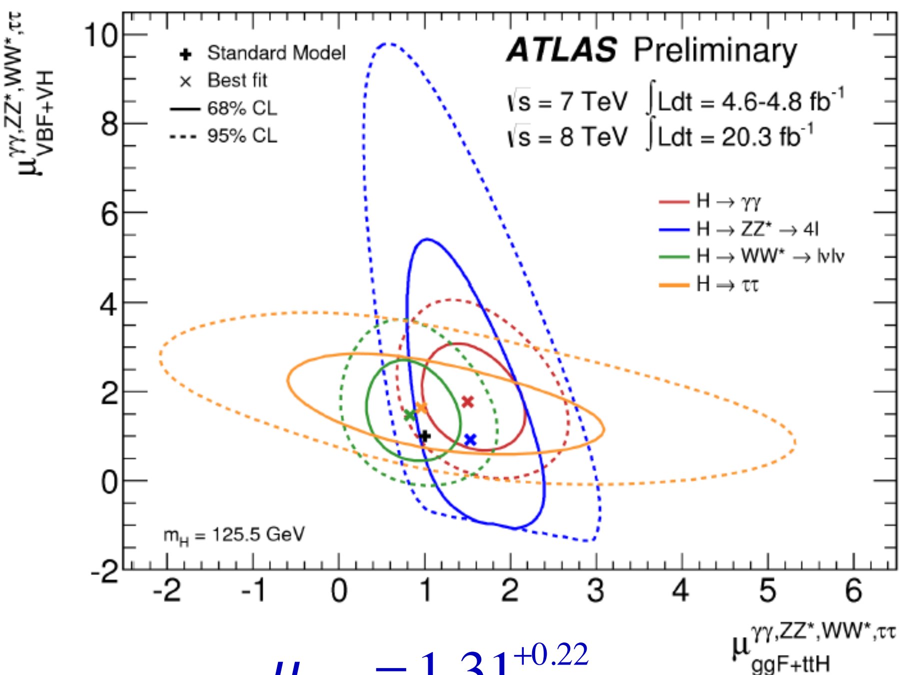
Statistical Significance Table

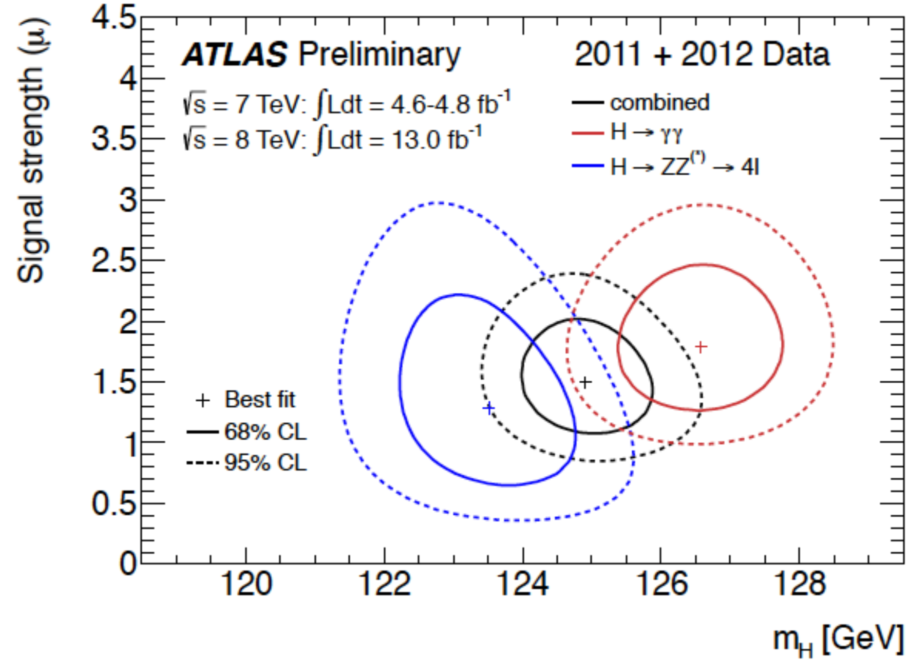
zσ	Percentage within CI	Percentage outside CI	Fraction outside CI
0.674 490σ	50%	50%	1 / 2
0.994 458σ	68%	32%	1 / 3.125
1σ	68.268 9492%	31.731 0508%	1 / 3.151 4872
1.281 552σ	80%	20%	1 / 5
1.644 854σ	90%	10%	1 / 10
1.959 964σ	95%	5%	1 / 20
2σ	95.449 9736%	4.550 0264%	1 / 21.977 895
2.575 829σ	99%	1%	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]999 999%	[illegible]%	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!!)
- 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

Precision Measurements of Higgs





$$\mu_{ggF} = 1.31^{+0.22}_{-0.20}$$

$$\mu_{VBF} = 1.62^{+0.47}_{-0.43}$$

$$\mu_{VH} = 0.50^{+0.58}_{-0.56}$$

$$M_{H\to\gamma\gamma} = 126.3 \pm 0.35(stat.) \pm 0.30(syst.)$$

$$M_{H\to ZZ\to 4l} = 124.5^{+0.5}_{-0.6}$$

$$M_{H-combined} = 125.2 \pm 0.3(stat.) \pm 0.6(syst.)$$

- Higgs coupling to various final states show close to SM predictions
- ATLAS H→γγ and H→ZZ→4l mass difference still persists at 2.3σ.

Long Term LHC Plans

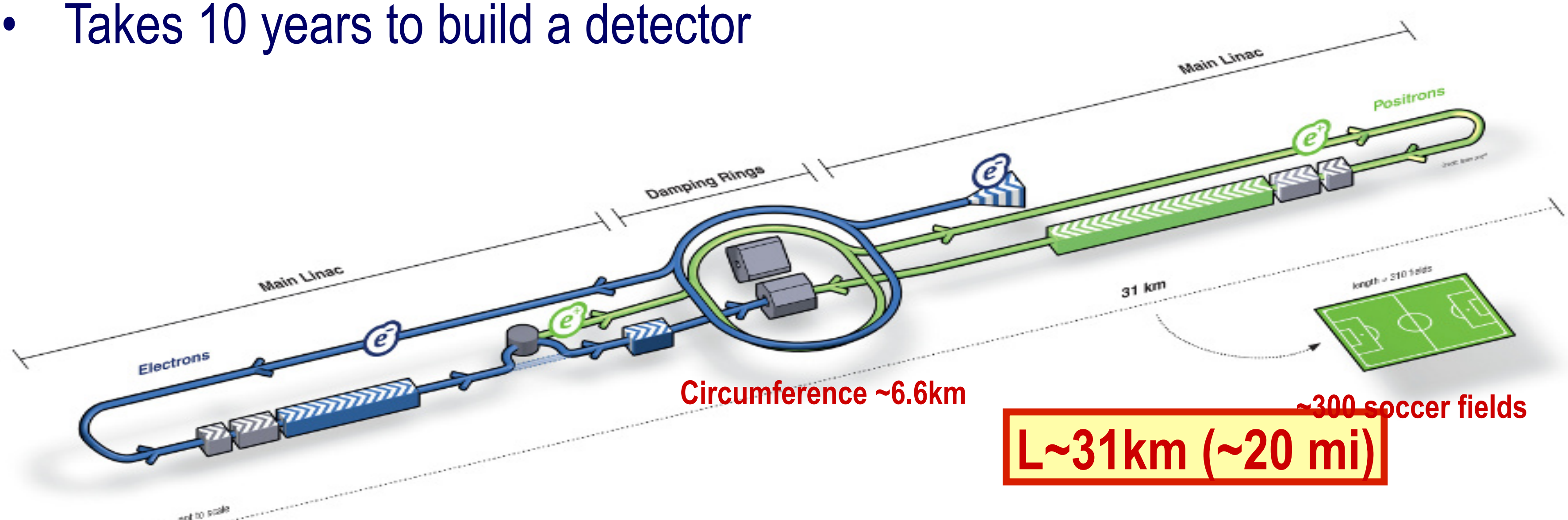
- 2015 – 2017: $\sqrt{s}$= 13TeV→ 14TeV, L~10^{34}, 2 times the energy and 4 times the data we have now
- 2018: Shut-down (LS2) for detector upgrades
- 2019 – 2021: $\sqrt{s}$~=13 – 14TeV, L~2x10^{34}, 3 times the data in 2015 – 2017
- 2022 – 2023: Shut-down (LS3)
- 2023 – 2030(?): $\sqrt{s}$=13 – 14TeV, L~5x10^{34} (HL-LHC), 10 times the data in 2019 – 2021

What does this discovery mean?

- 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!!

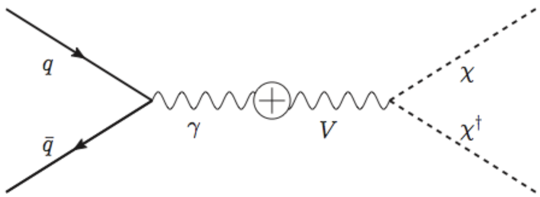
What's next? Future Linear Collider

- 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 announced the selection of the site for the ILC in Aug. 2013!!
- Takes 10 years to build a detector

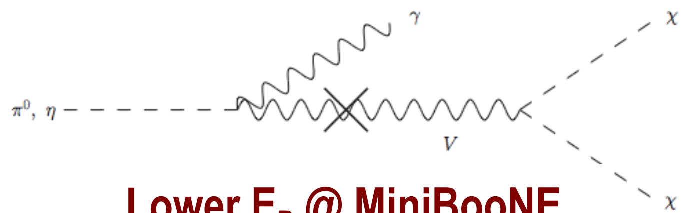


Light DM Production at High Intensity Accelerator

- 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!!

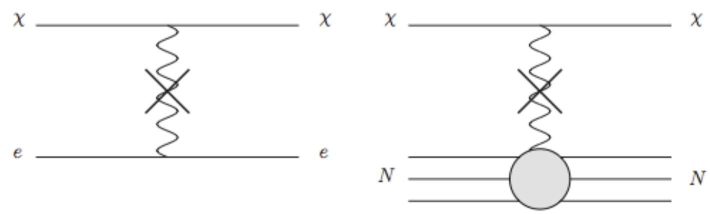


Higher E_P @ DUNE

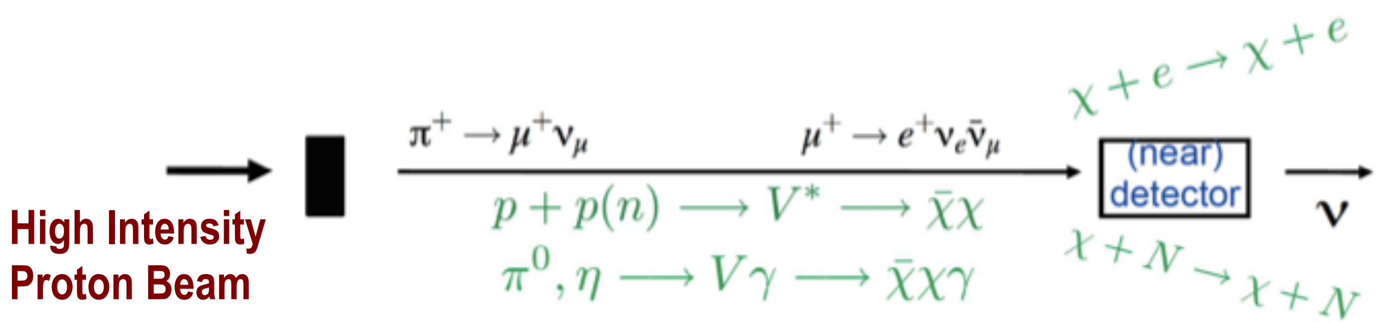


Lower E_P @ MiniBooNE

- Detection of DM:



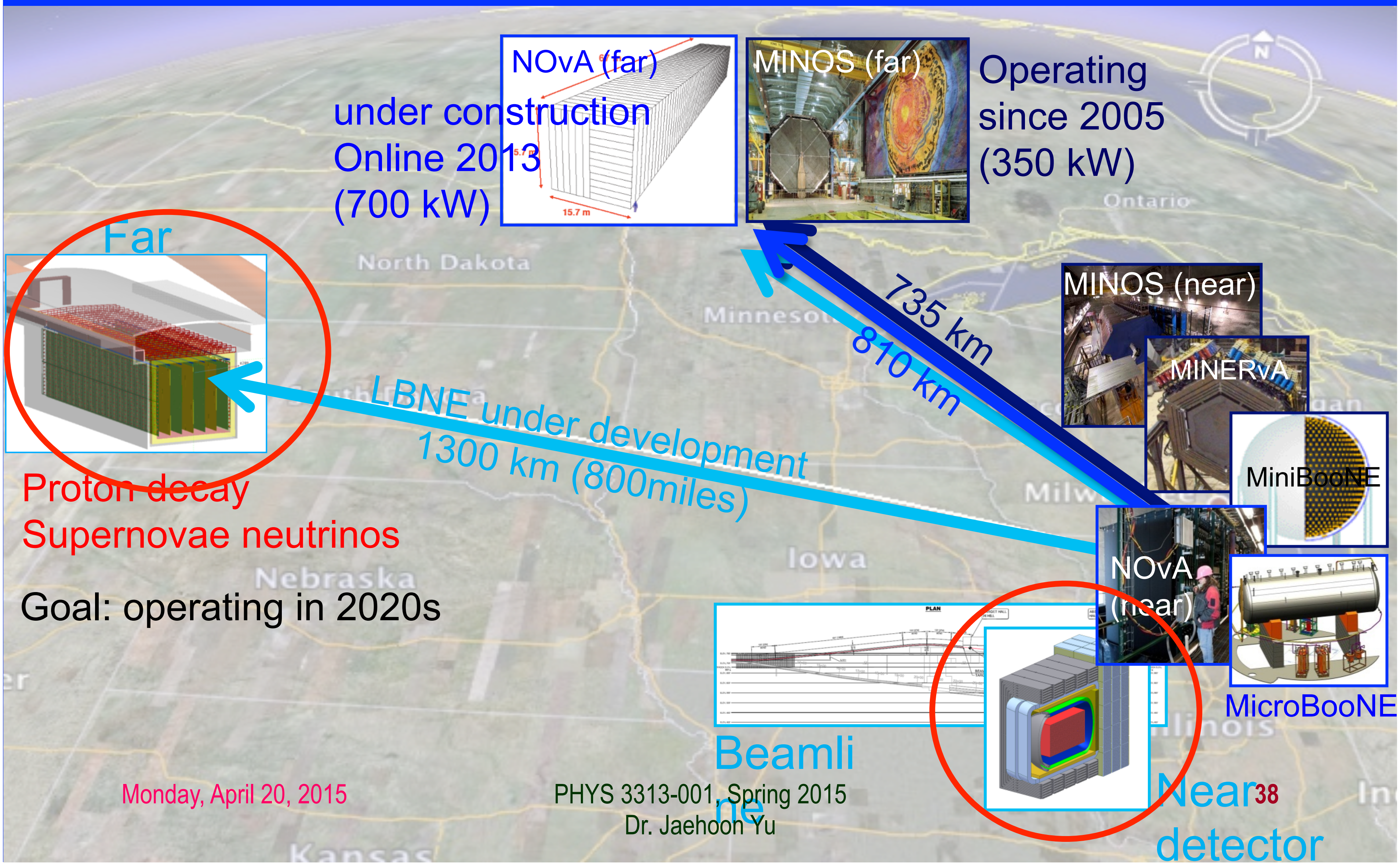
- How does a DM event look in an experiment?:



Search for Dark Matter at an Accelerator

- Fermi National Accelerator Laboratory is turning into a lab with very high intensity accelerator program

Intensity Frontier at Fermilab

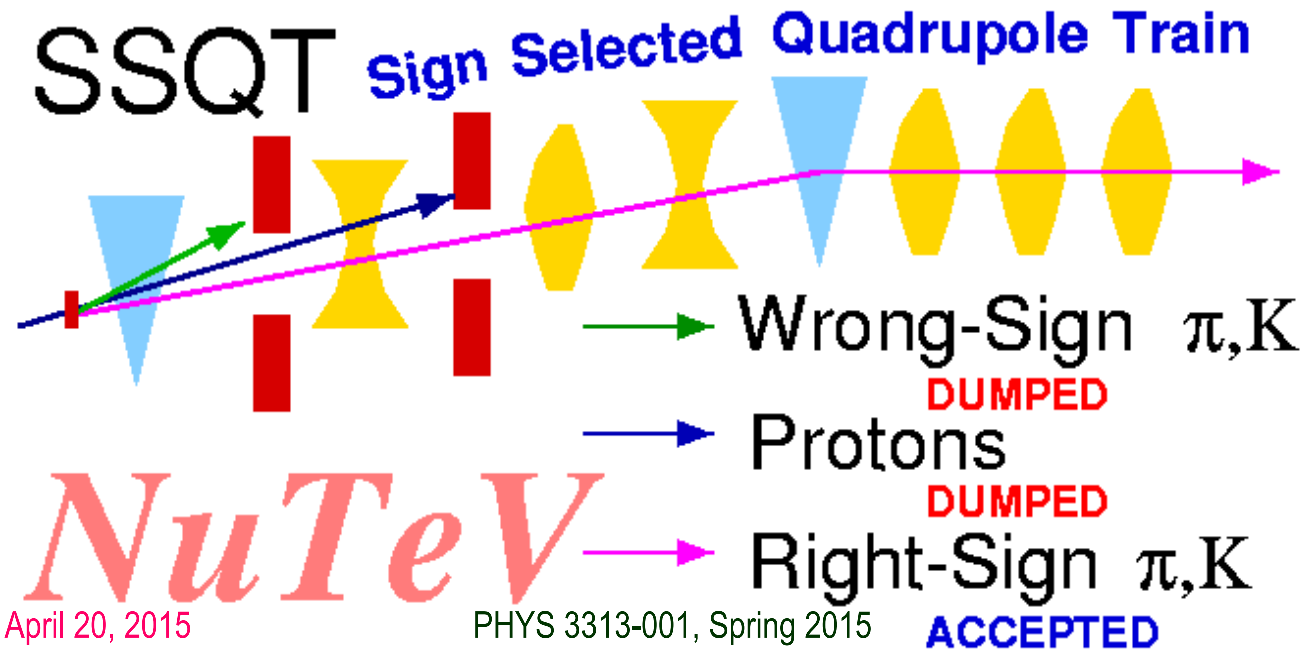


Some thoughts on DM searches in ν experiments at IF

- High flux P beams ideal for DM stats
- High Energy P beams good for distinguishing sub-GeV DM from ν for boosted DM
  - Can take advantage of kinematic quantities
  - Need high precision – position, angular, time and energy resolutions – near detector
- But we've still got significant background from neutrinos due to sheer numbers
  - How do we eliminate them and still co-exist with neutrino experiments?

Sign Selected Beam Idea for DM Searches

- The biggest background is neutrinos in the beam
  - Neutrinos are primarily produced from charged meson decays
  - WIMPS have no electrical charges and are produced in the primary target
- We can have a beamline that separates neutrinos and anti-neutrinos from DM's



Dark Matter Searches at Fermilab

- Fermi National Accelerator Laboratory is turning into a lab with very high intensity accelerator program
- UTA group is part of three experiments at Fermilab
  - Deep Underground Neutrino Experiment (DUNE), a $2B flagship experiment, with data expected in 2025
    - High flux secondary beam and a near detector enables searches for DM
    - In addition to precision measurements of key neutrino param..
    - UTA playing very significant role in this experiment
- A rich physics program for the next 20 – 30 years!!
- If we see DM, we could use this to make DM Beam??

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!

DUNE Neutrino Beam Assembly

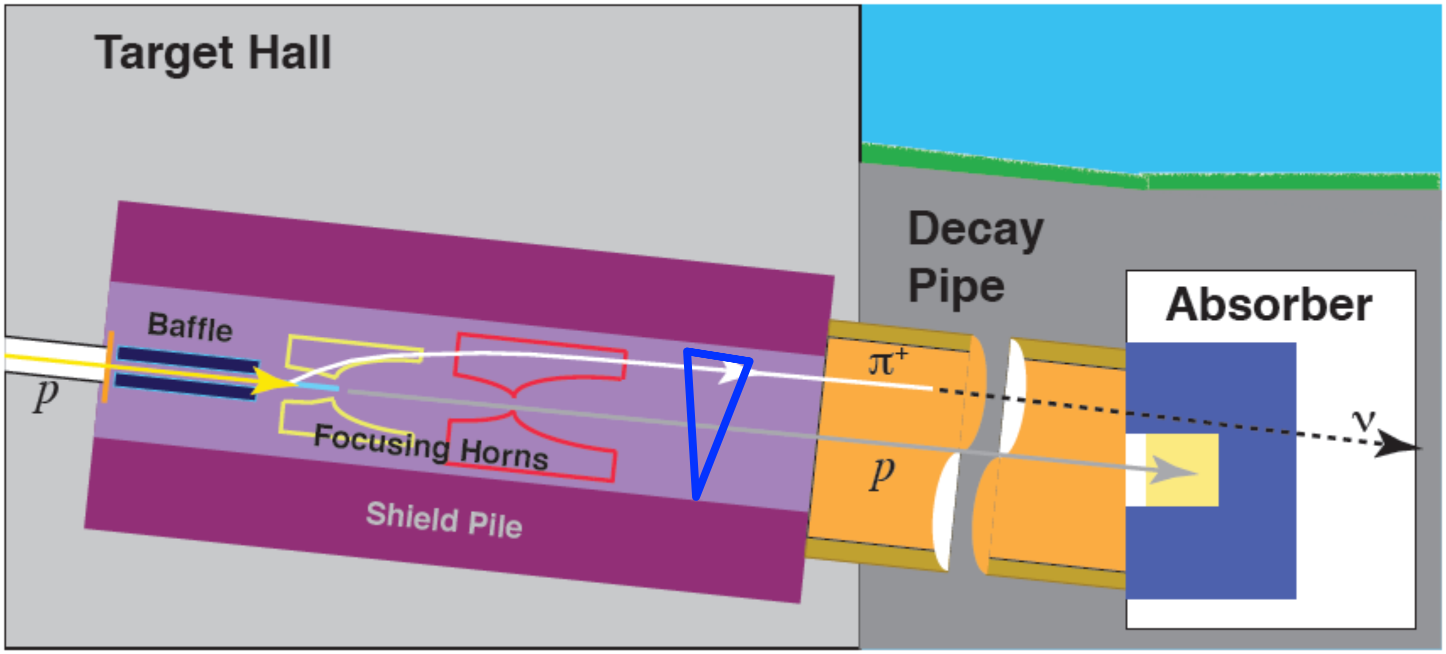


Figure 3–1: A cartoon of the neutrino beamline showing the major components of the neutrino beam. From left to right, the beam window, horn-protection baffle, target, the two toroidal focusing horns, decay pipe and absorber. The air volume surrounding the components between the window and the decay pipe is called the target "chase". The target chase and rooms for ancillary equipment (power supplies, cooling, air recirculation and so on) is included in the area called the target complex (not pictured).

Doubly Sign-selected Horn System (DSHS)

- Add a dipole after the mesons are fully focused with the 2nd horn