Discovery of the Higgs Boson

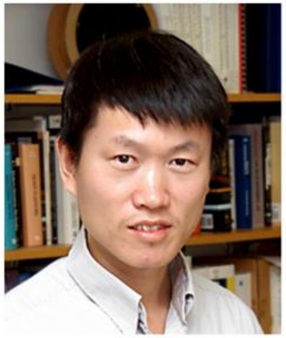
Special Panel Discussion

December 5, 2012 4:00-5:30 PM
Rackham Amphitheater (4th Floor)

Gordy Kane
Theorist

Homer Neal
Experimentalist

Jay Chapman
Experimentalist



Jianming Qian
Experimentalist

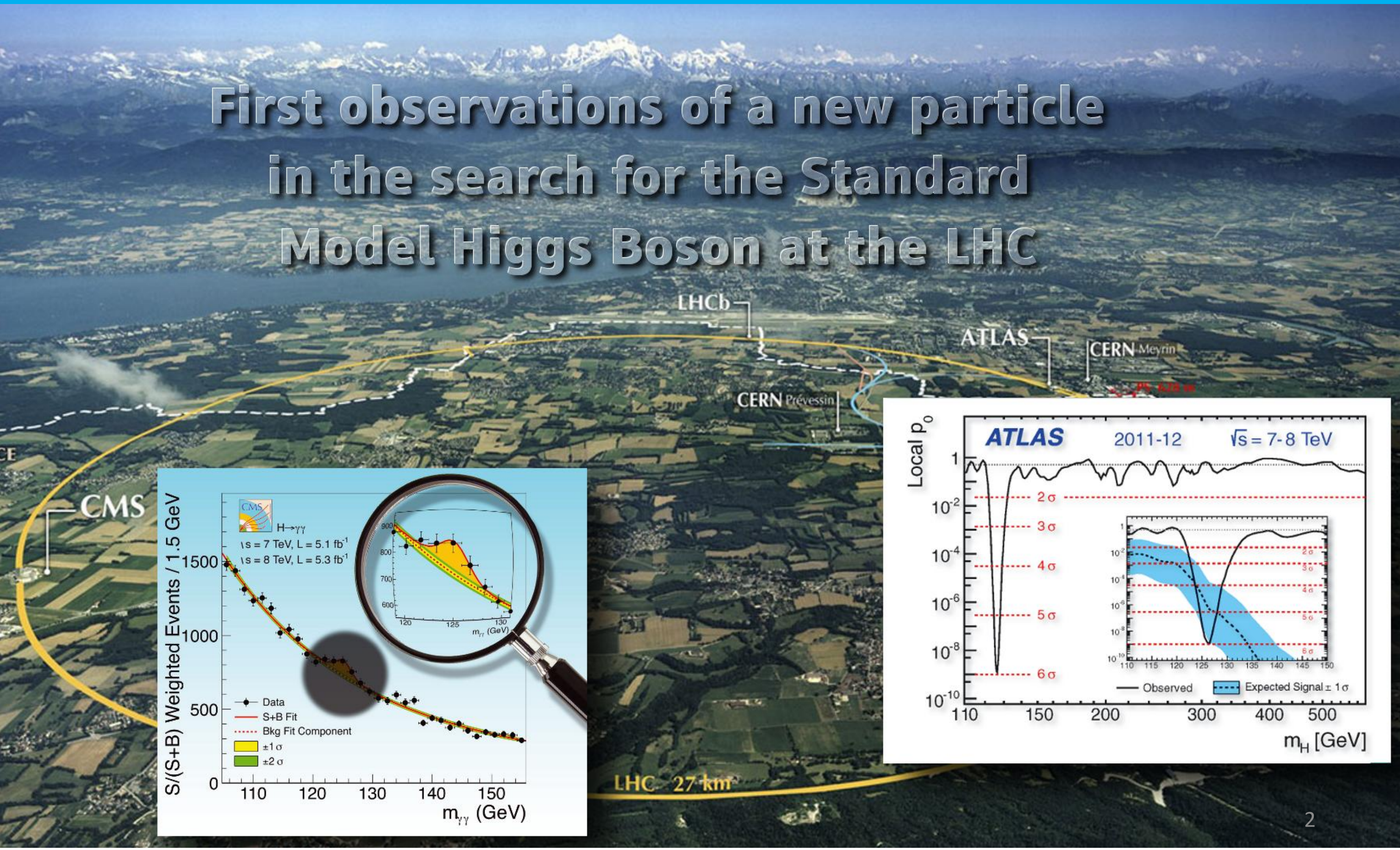
Aaron Pierce
Theorist

Experimental and Theoretical Discussions on:

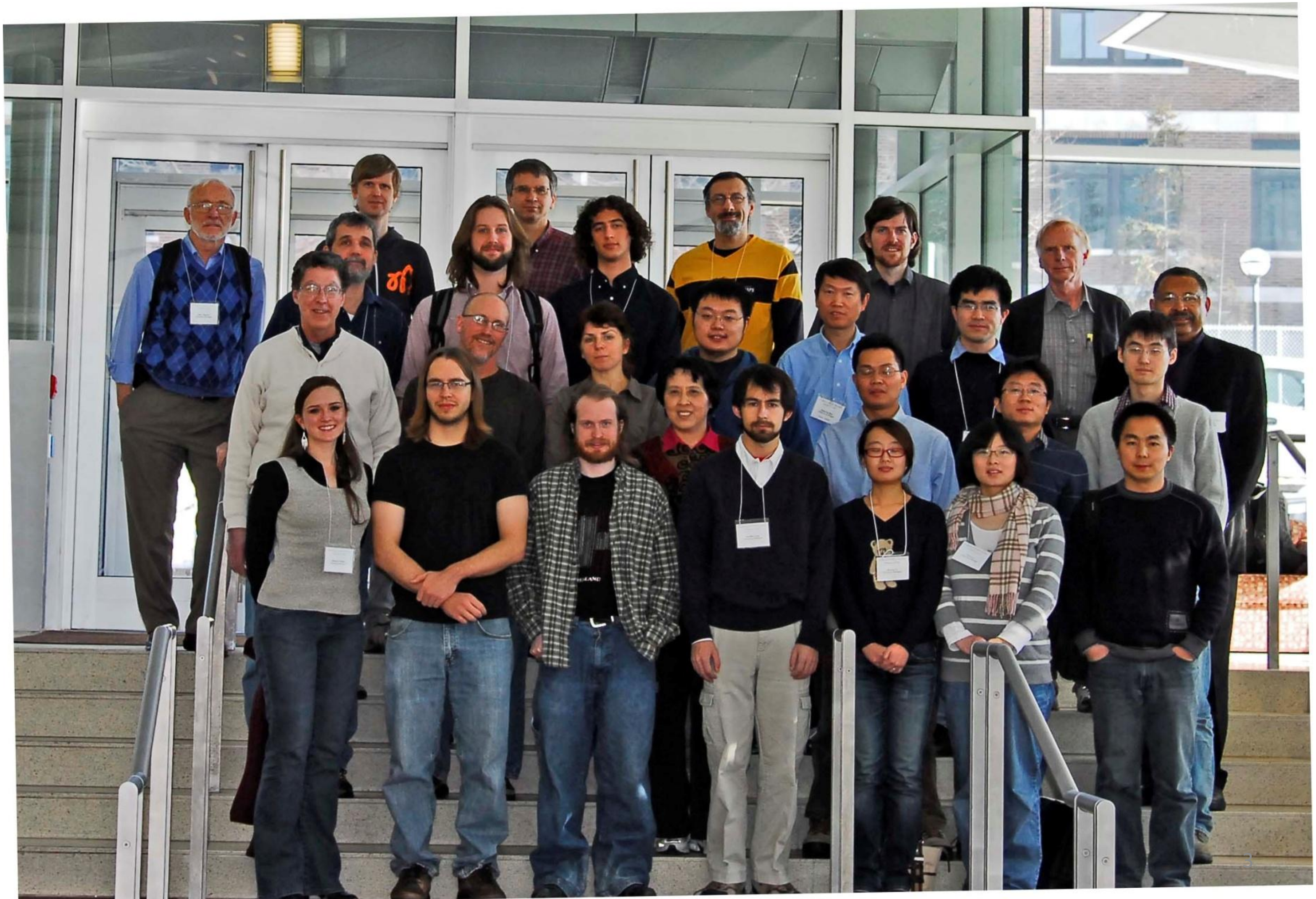
- ❑ **Particle physics history of the past half century, and how it relates to the Higgs boson.**
- ❑ **The role of UM in experiments to unlock the mystery of electroweak symmetry breaking**
- ❑ **Particle physics detector design and construction at UM**
- ❑ **The Higgs boson discovery with the ATLAS detector at the CERN Large Hadron Collider**
- ❑ **The significance and impact of the Higgs discovery in future particle physics**

The physicists will field questions at the panel's conclusion.

Discovery of Long Sought Higgs Boson



Huge Efforts at U of M Over Past Decade



HIGGS PHYSICS before the DISCOVERY

Gordy Kane

December 2012

- **Pre-LHC Higgs physics**
- **Pre-LHC history**
- **Mention pre-LHC Higgs physics theory at University of Michigan**

Not simple…

Goal of particle physics is to understand our world as well as we can – find and understand origin of the underlying laws of nature

“Standard Model” synthesis of □ 400 years, since Galileo and Kepler --

Discovery of Higgs boson last step to complete the Standard Model

And Higgs boson properties point to how to go Beyond-the-Standard Model, find a deeper underlying theory that incorporates the SM

"STANDARD MODEL" OF PARTICLE PHYSICS

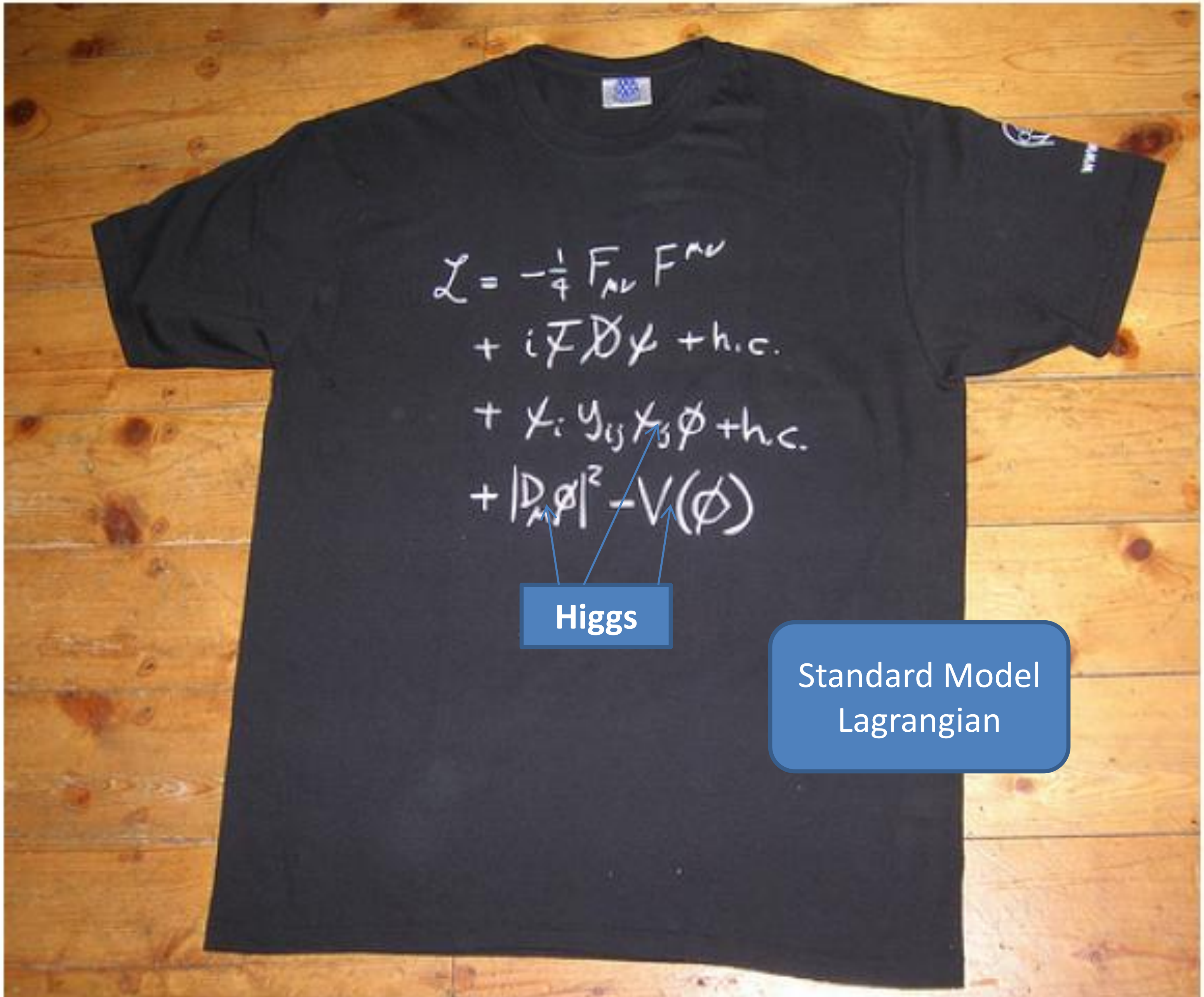
- **All forces (electromagnetic, strong, weak, gravity classical) – describes all we see – many tests**

- **What we see is built of electrons plus two quarks (up, down), bound by photons, gluons – Weak interactions mediated by W, Z bosons**

- **Quarks → protons, neutrons → nuclei, + electrons → atoms →molecules etc -- quantitative, not metaphors**

- **Predictions of SM correct, except electrons, quarks, W, Z must be massless or theory inconsistent – adding Higgs field can allow mass**

- **So Higgs field predicted – Higgs bosons are quanta of Higgs field**


$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi + h.c.$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$
Higgs
Standard Model Lagrangian

HIGGS PHYSICS -- OLDER

- **In SM electrons, quarks, W, Z (and Higgs boson) have “weak charge”**

- What gets mass? – Anything with weak charge -- quarks, electrons, W, Z bosons, and Higgs boson – gets mass from interacting with Higgs field → mass term in Lagrangian

- Protons, neutrons do not get mass from Higgs interactions (about 1%)

- Size of atoms proportional to $1/m_{electron}$

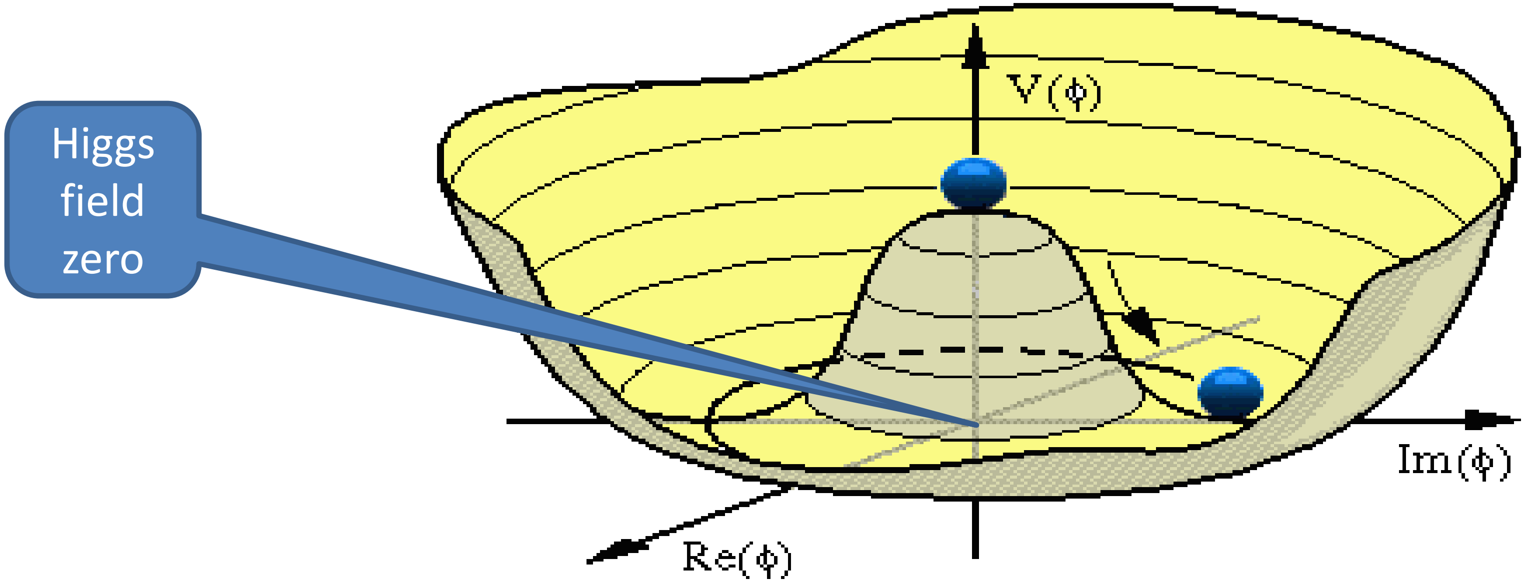
- **Not molasses etc – analogy not good, not technically ok**

  -- No good analogy, this one better than none…

- Vacuum = state of lowest energy of universe -- (Quantum fluctuations all the time, but average zero)

- **With EM field, state of lowest energy has zero field, Energy=$E^2 + B^2$**

- **For the Higgs field, state of lowest energy (vacuum) has non-zero field!**



- Higgs field with weak charge pervades vacuum of universe, Lorentz-invariant

  [in SM assume this potential – in supersymmetry derive it (1982)]

- **Higgs bosons are Higgs field quanta**

HIGGS HISTORY

- In late 1940s quantum electrodynamics was shown to be "renormalizable" – i.e. , apparent infinities could be absorbed so theory could make finite predictions – then great progress in explanations and predictions

- In early 1960s writing renormalizable theories of particles with non-zero mass wasn't working for electrons and W, Z bosons

- 1964 – Peter Higgs argued could do it (in relativistic quantum field theory) for vector bosons that could mediate the weak interactions

[photon has two polarization states, massive vector boson of weak interactions has three – need complex scalar added, one part becomes longitudinal polarization state of W,Z and the other a real scalar particle → Higgs boson]

- Also other theorists

- **Weinberg, Salam 1967 →with Higgs field it can also work for electrons, quarks**

- 1971 – ‘t Hooft (based on work with Veltman) showed could have full renormalizable theory of (electro)weak interactions with mass if Higgs field existed, AND IF neutral Higgs got non-zero vacuum value

- 1970 through 1985, many tests of electroweak theory – W, Z bosons observed at CERN, 1985 (Glashow, Weinberg , Salam Nobel Prize 1979)

- **But Higgs boson mass not calculable in SM – worse, Higgs boson mass quadratically sensitive to heavy scales, so pure SM Higgs boson not OK**

SM THEORY FULLY IN PLACE IN 1972 –

Then action shifted to how to produce and detect Higgs boson, and how to make sense of pure SM Higgs boson not making sense

1982 – large international "Snowmass" study, 3 weeks – I co-led working group on beyond-the-SM-theory – much Higgs physics not known then, e.g. how to calculate Higgs boson production rates at hadron collider – **led to SSC proposal for a U.S. facility (~ 1985)** – Reagan: "throw deep" – cancelled in 1993

SSC, LHC proton-proton (hadron) colliders since could accelerate more protons to higher energies and steer them to collide – had to have high energies since didn't know what Higgs mass to aim for – a collider is a device that converts energy into particles, $E=Mc^2$

LHC (Large Hadron Collider) design also started 1984, to replace LEP $e^+ e^-$ collider then being constructed – not cancelled

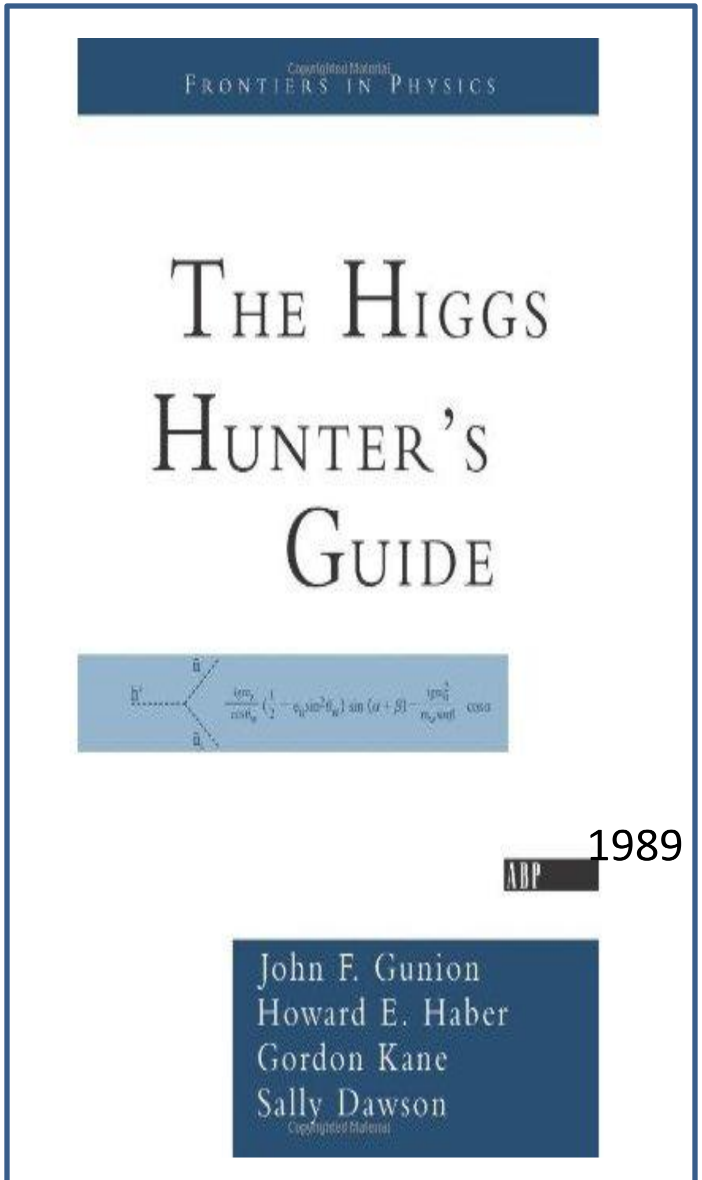
- GK – averaged a paper a year on Higgs physics since 1977, two in past year

- Showed (with Gunion, Wudka 1984) that h→□□ was best way to observe h at high intensity hadron collider, even though only one Higgs boson in about 500 decayed this way

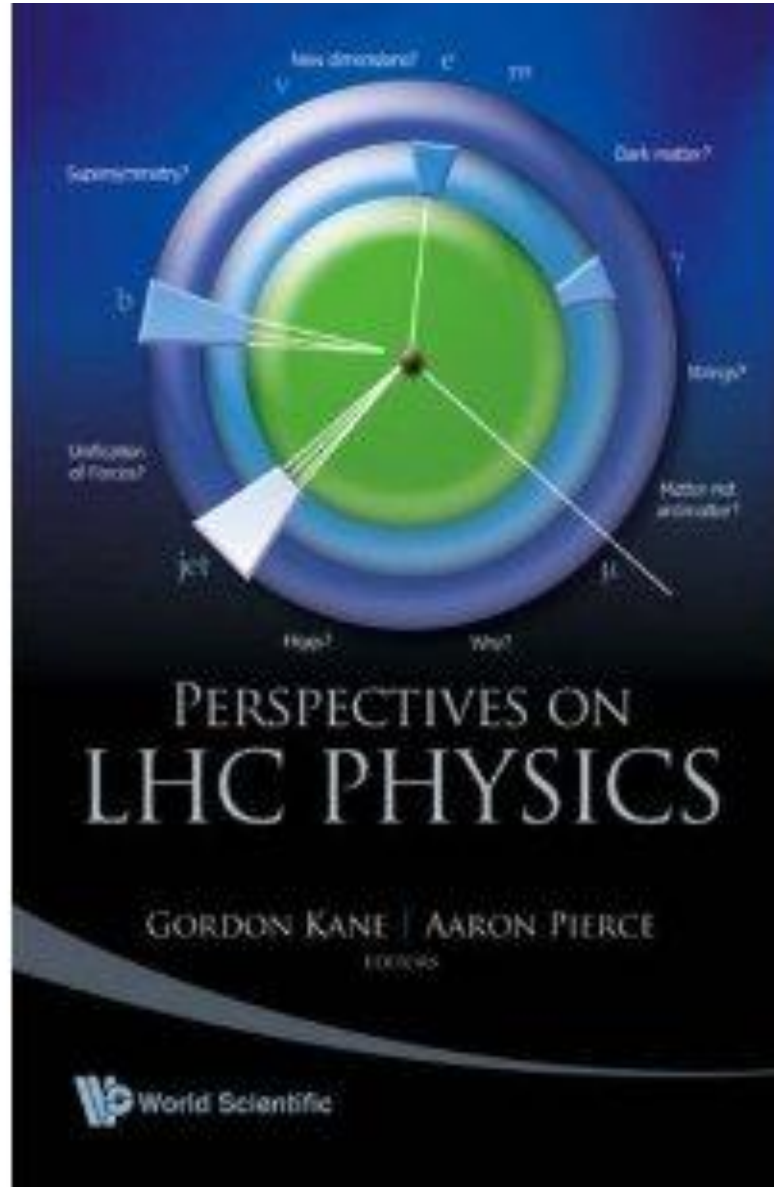
  -- also h → Z Z*

- In 1993 derived general upper limit on h mass in general supersymmetric theory (with Kolda, Wells)

- Aaron Pierce, James Wells – considerable work on observing Higgs bosons, extensions of SM Higgs physics – also Kathryn Zurek

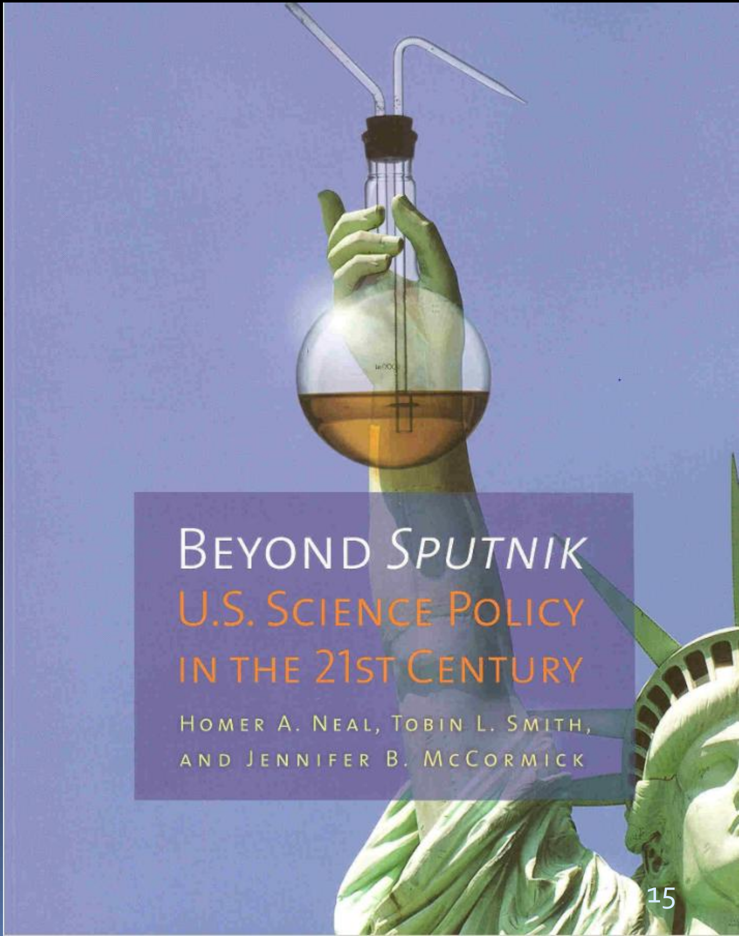

FRONTIERS IN PHYSICS
THE HIGGS HUNTER'S GUIDE
ABP
John F. Gunion
Howard E. Haber
Gordon Kane
Sally Dawson

1989


Supersymmetry?
Dark matter?
Unification of Forces?
Higgs?
PERSPECTIVES ON LHC PHYSICS
GORDON KANE | AARON PIERCE
World Scientific

THE MICHIGAN PATH TO THE HIGGS

Homer A. Neal
December 5, 2012



Presentation Targets

- Factors leading to the SSC demise (while Michigan was focusing on SSC physics preparations)
- The Michigan quest for the SSC
- Period of Mourning when SSC was cancelled -- and Ultimate Revival
- Choice of focus on Muon Spectrometer in ATLAS
- Focus on design, prototyping, construction, installation ,monitoring of muon chambers
- Massive LHC disruption by machine accident/ Resumption of data-taking and analysis
- Higgs analysis leadership
- Attempts to bring undergraduate students along
- Leadership in designing, prototyping collaborative tools for large-scale collaborations
- Discovery Elation!
- Looking backward /forward at SSC failure (national science policy)

The Human Quest

- From ancient times humans have wondered about the big questions of our Universe .. such as:
  - Where did we come from
  - How was the Earth formed
  - What are those things in the Sky and why do they move in almost regular patterns
  - **What are the ultimate building blocks of matter**
  - ....

A Big Microscope

- To look at small distances one needs probes at high energy
- We needed a large or super collider to tackle the next set of problems in fundamental particle physics
- We needed a machine of the order of 10 TeV in energy to look below the quark level and to search for the Higgs, SUSY, compositeness, etc.

Circa 1988; A Bold Initiative to explore our understanding of matter – the SSC in Texas

For the reasons mentioned by Gordy Kane, the Higgs was the key object to be searched for at the SSC

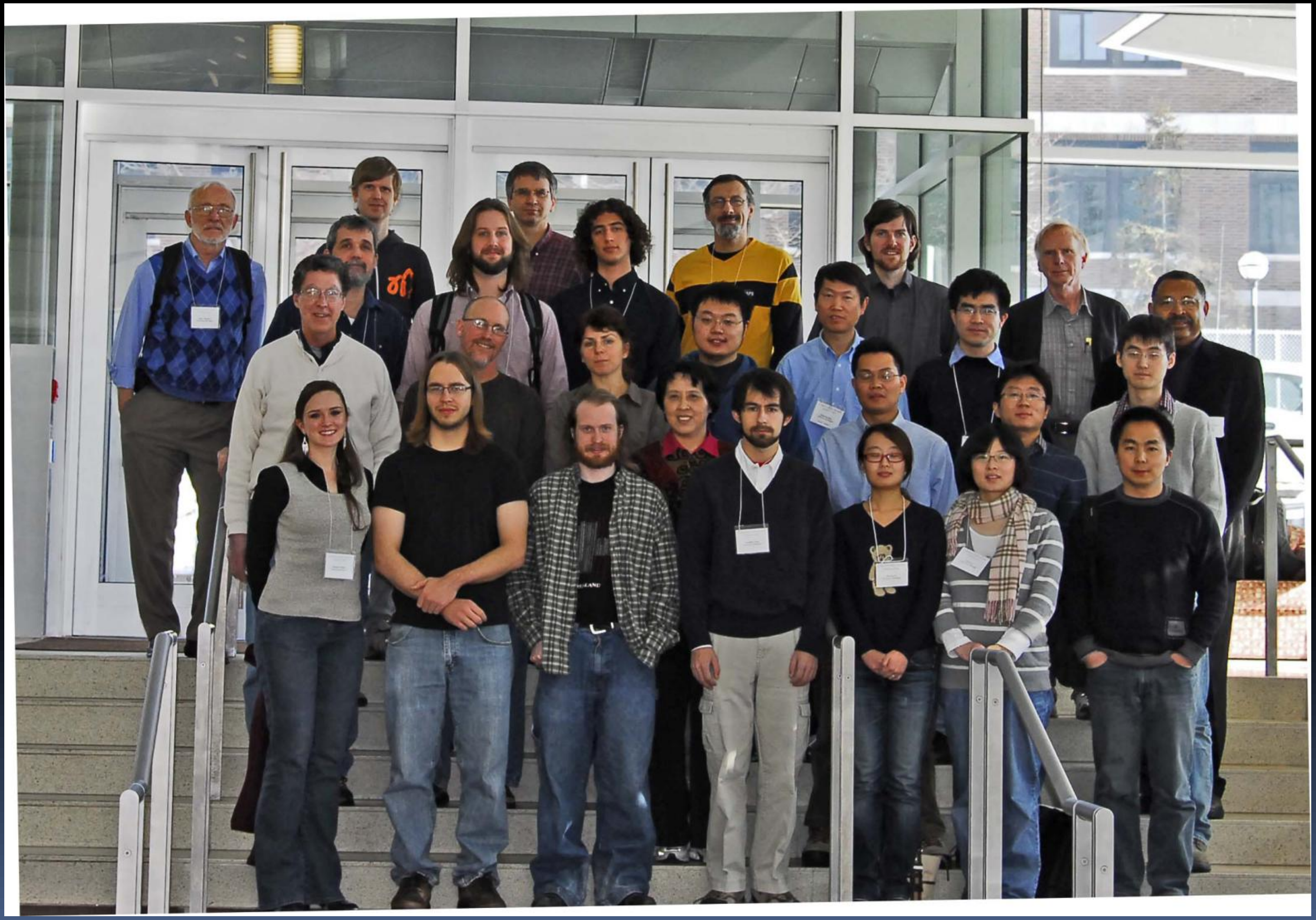
Some Reasons the SSC Failed

- The SSC suffered for having failed from the outset to incorporate international funding and participation.
- The Reagan and Bush administrations made critical early decisions about the technical design and site location as if the SSC were purely a national project.
- Only later did they proclaim it to be an international collaboration—with a goal of nearly $2 billion in foreign funding.
- Substantial foreign funding never materialized
- This shortfall eroded congressional support, which made foreign involvement even less likely, accelerating the project’s downward spiral

Michigan Pathway to the Higgs

- Strong UM physics preparation for the SSC
- Representation on SSC Board of Overseers
- Devastation on cancellation of project
- A period of rejection in Ann Arbor to joining large projects, even those being discussed in Europe
- An evolving interest to join a LHC experiment
- Decision to play a dominant role in ATLAS, the largest LHC experiment, and a commitment to become one of its most powerful groups;
- LHC → here comes the Wolverines

And we Grew and Grew … as the Collaboration Learned of our Strengths

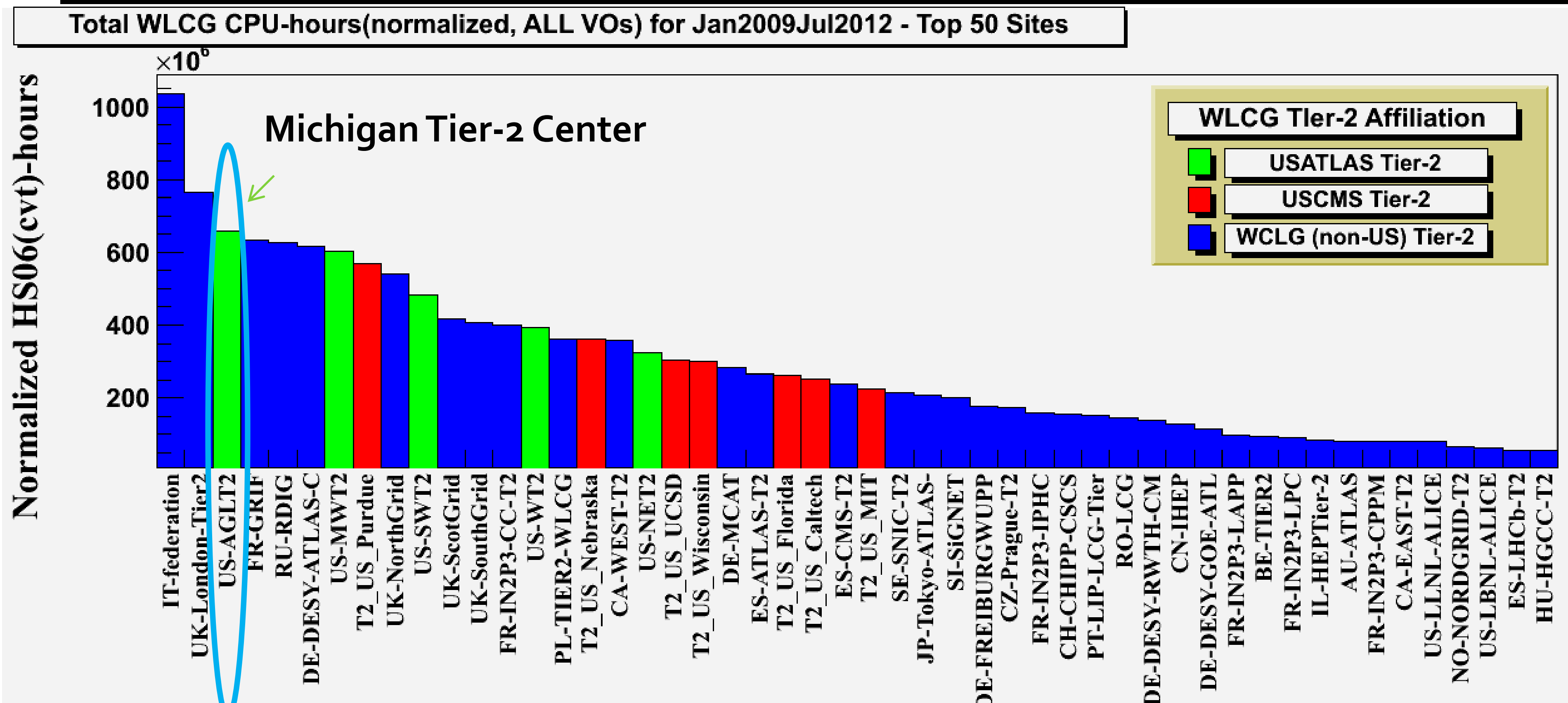


We Contributed in a Large Variety of Areas to the LHC

- Designing , Prototyping, Building, Commissioning and monitoring key elements of the ATLAS detector
- Designing basic elements of the current computing infrastructure, and operating one of the key data analysis centers
- Designing and operating one of the key muon calibration centers
- Playing a seminal role in the physics analysis
- Adapting collaborative tools so the multi-thousand person collaboration could communicate effectively with itself and with colleagues back home
- Providing the only official portal for U.S. undergraduates and teachers to participate in and observe LHC research first-hand
- --
- I will just take a few minutes to explain the topics in yellow – the core topics in white will be covered by other colleagues)

ATLAS Great Lakes Tier-2

Computing centers for High-Energy Physics providing resources for simulation and analysis



Worldwide Tier-2 delivered CPU-hours. AGLT2 was third globally because of significant support from the University of Michigan and Michigan State University (#1 and #2 are consortiums of 12 and 7 sites respectively)

ATLAS Muon Spectrometer Calibration

- The ATLA muon spectrometer measures muon momentum by measuring the deflection of muons in a magnetic field.
- The muon spectrometer uses 350,000 drift tubes (31,000 made at Michigan) to track the muons with 80 micron accuracy.
- Drift tubes require precision calibrations which are performed daily at calibration centers at Michigan, Rome, and Munich.
- Calibrations include timing offsets and drift speed.
- Data is streamed daily to the calibration centers and calibrations are performed and updated within 48 hours.

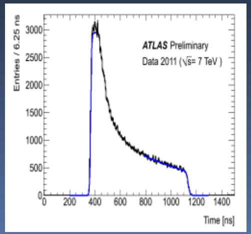
Calibration stream

100M Muons/day

Rome

Munich

Drift Tube Time spectrum



ATLAS

~20 TB storage per site

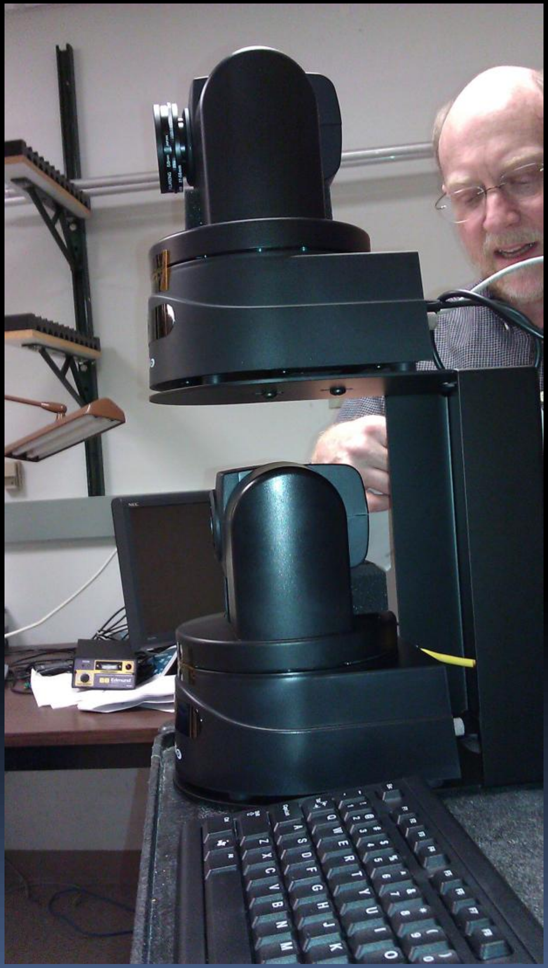
To the UM Administration and to our Department

- For your help with our special needs for computing, space, staffing, collaborative tools, travel accommodations, and moral support -- we thank you.

We contributed directly to collaborative tool developments→ Invented, Patented, Licensed a Next-Generation Camera for Tracking Speakers without a Camera Operator, and pioneered the use of QoS in videoconferencing, use of 3D VRML in detector design, convening of international conference, etc.

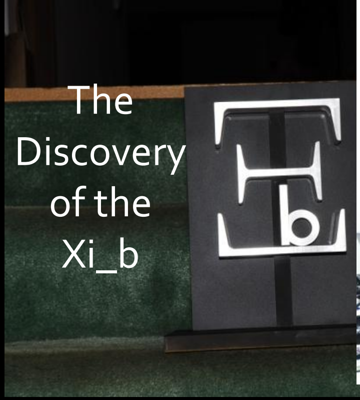
We drove the organization of the CERN/UM video conference facilities to help coordinate group activities – for ourselves and all groups

CERN-UM Conference Room -- Geneva



Established the only NSF REU CERN Site Program in Geneva to provide CERN Access to U.S. Students
Also involved UM Students locally via UROP Program

Provided LHC Access for US High School Teachers (via NSF RET Program)



A PERSONAL MONTAGE

The Wait Was Worth It

Physics in the Extreme

ATLAS, the Largest Scientific Experiment

at the Large Hadron Collider

J. Chapman = umjwc@umich.edu

Extremes in LHC Physics

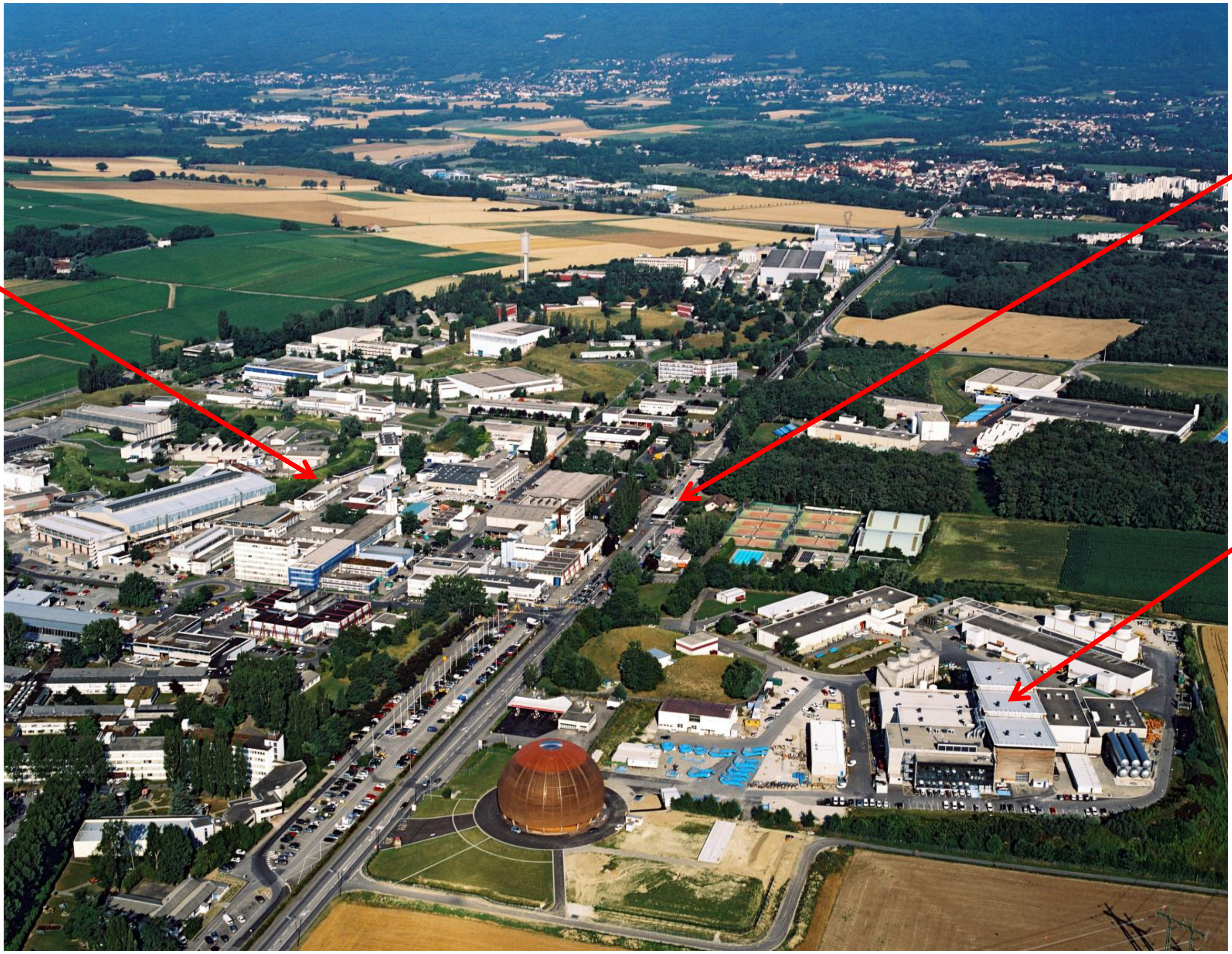
- Very small size of the fundamental objects
- Large size of the accelerator & detectors
- Extreme precision for large devices (40μm)
- Large size of the collaborations (ATLAS)
- Data a billionth of a second after Big Bang
- Very large data volume & huge computing requirement ~100K processors in huge grid
- Geographically spread global community

Culturally Diverse (ATLAS)

- 40+ Countries involved in ATLAS alone.
- 28 Languages (meetings in English)
- 173+ Institutes & Universities
- 8 Detector Subsystems plus Utilities
- ~100 Million Channels of Electronics
- Hundreds of Committees & Teams
- A lot of Very Big Egos! Immense Talent!

CERN Site & ATLAS

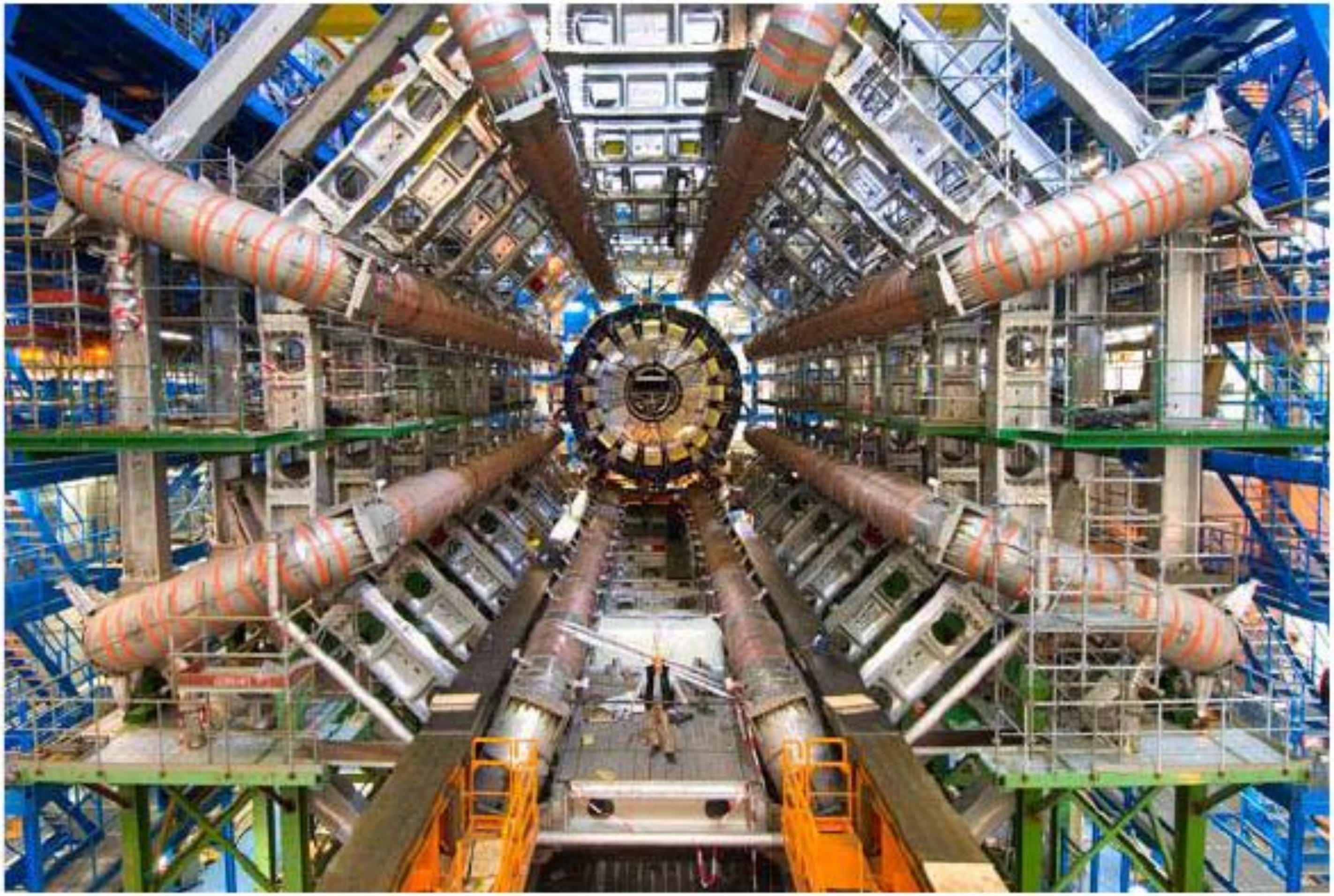
Original CERN Site



Swiss French Border

ATLAS Site

NATIONAL GEOGRAPHIC & TIME Back to the Beginning at CERN



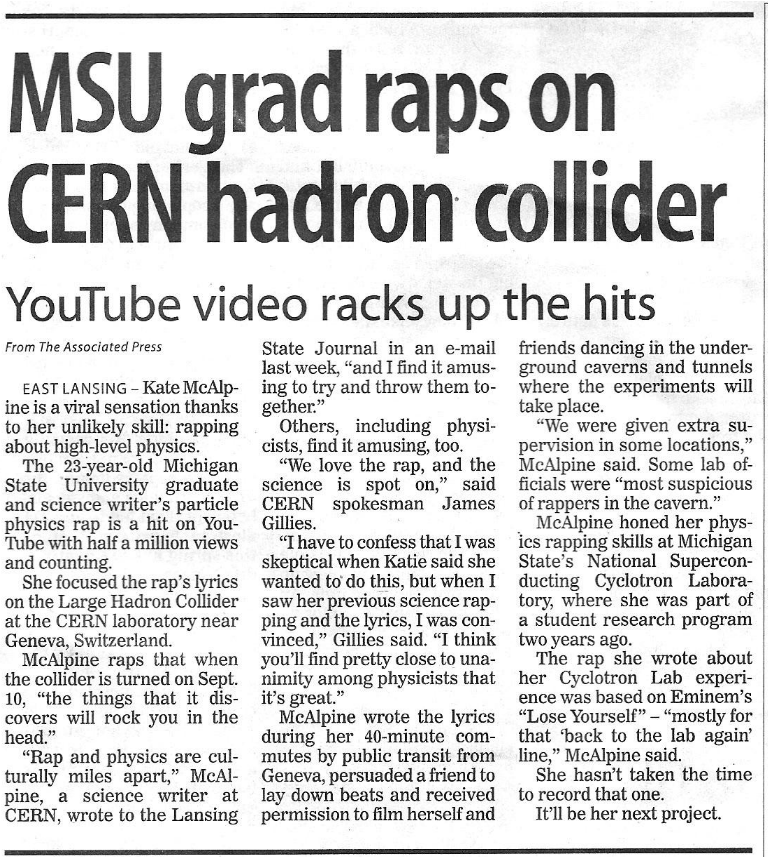
At the Heart of All Matter

Newspaper Articles & TV Shows

A Giant takes on Big Physics Questions – New York Times

Science Journal – Collider may reveal origin of mass

There's even a Rap Song



MSU grad raps on CERN hadron collider

YouTube video racks up the hits

From The Associated Press

EAST LANSING – Kate McAlpine is a viral sensation thanks to her unlikely skill: rapping about high-level physics.

The 23-year-old Michigan State University graduate and science writer's particle physics rap is a hit on YouTube with half a million views and counting.

She focused the rap's lyrics on the Large Hadron Collider at the CERN laboratory near Geneva, Switzerland.

McAlpine raps that when the collider is turned on Sept. 10, "the things that it discovers will rock you in the head."

"Rap and physics are culturally miles apart," McAlpine, a science writer at CERN, wrote to the Lansing State Journal in an e-mail last week, "and I find it amusing to try and throw them together."

Others, including physicists, find it amusing, too.

"We love the rap, and the science is spot on," said CERN spokesman James Gillies.

"I have to confess that I was skeptical when Katie said she wanted to do this, but when I saw her previous science rapping and the lyrics, I was convinced," Gillies said. "I think you'll find pretty close to unanimity among physicists that it's great."

McAlpine wrote the lyrics during her 40-minute commutes by public transit from Geneva, persuaded a friend to lay down beats and received permission to film herself and friends dancing in the underground caverns and tunnels where the experiments will take place.

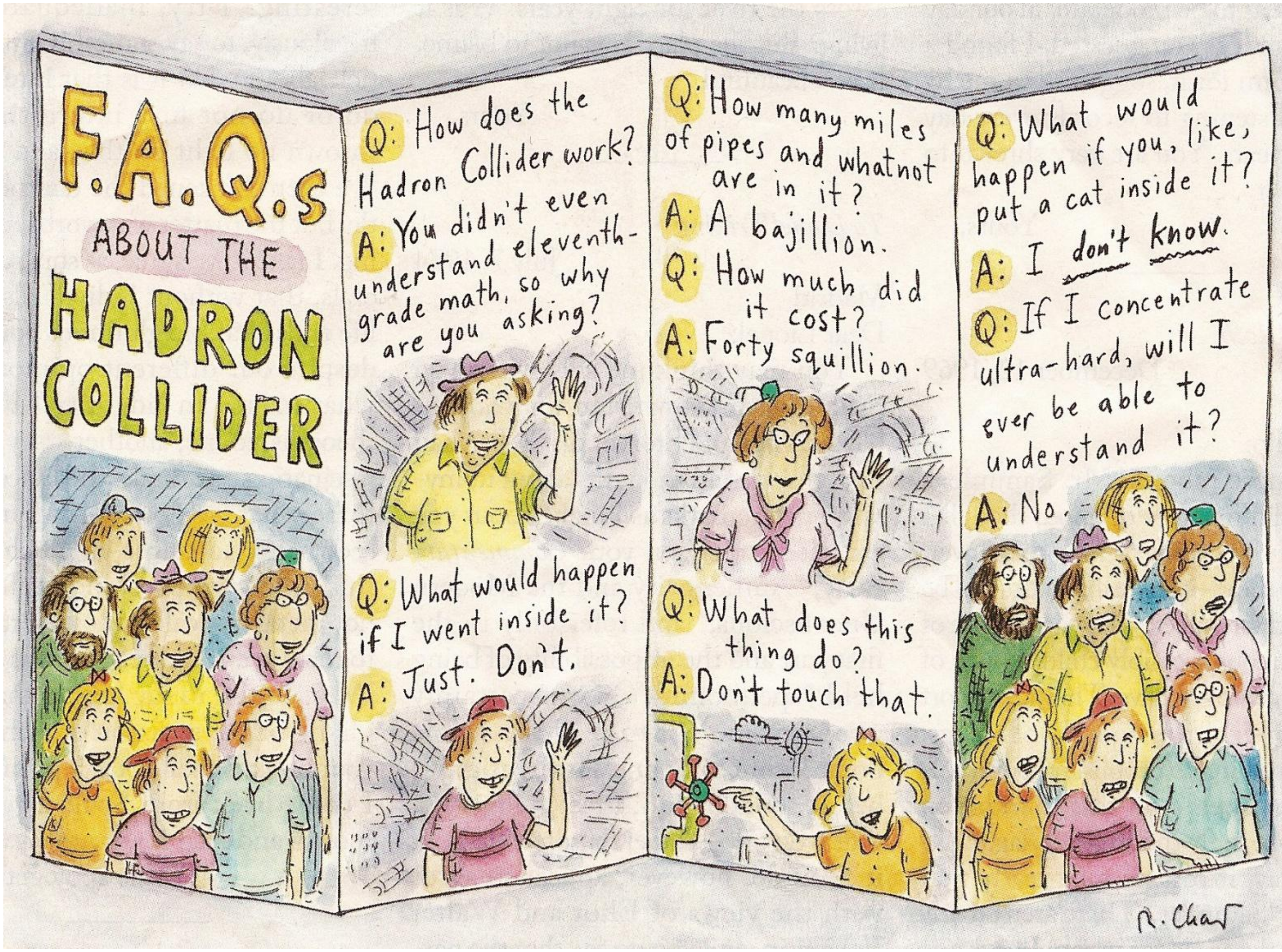
"We were given extra supervision in some locations," McAlpine said. Some lab officials were "most suspicious of rappers in the cavern."

McAlpine honed her physics rapping skills at Michigan State's National Superconducting Cyclotron Laboratory, where she was part of a student research program two years ago.

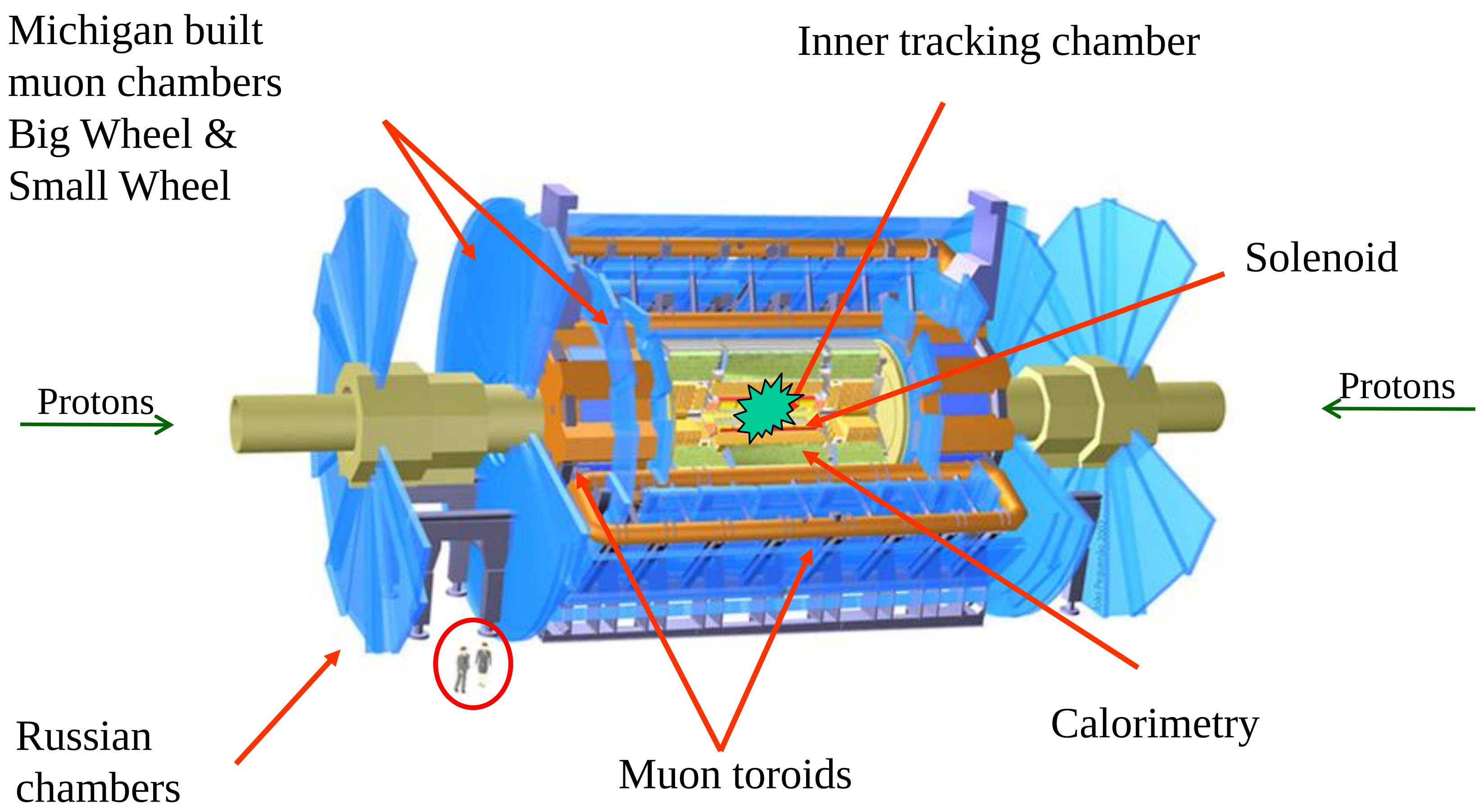
The rap she wrote about her Cyclotron Lab experience was based on Eminem's "Lose Yourself" – "mostly for that 'back to the lab again' line," McAlpine said.

She hasn't taken the time to record that one. It'll be her next project.

And a New Yorker Cartoon

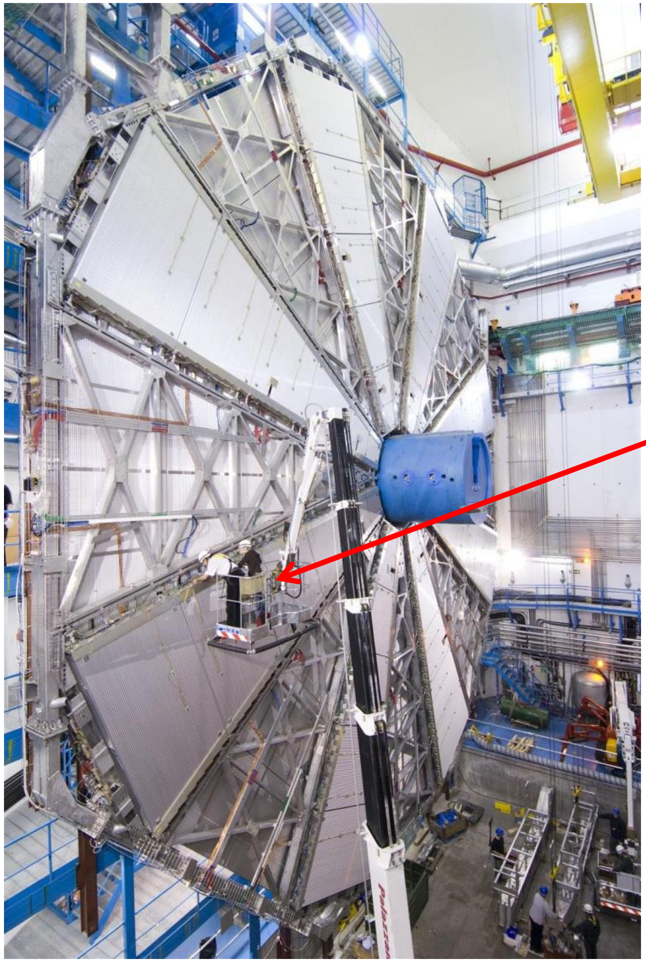


The Components of the Detector



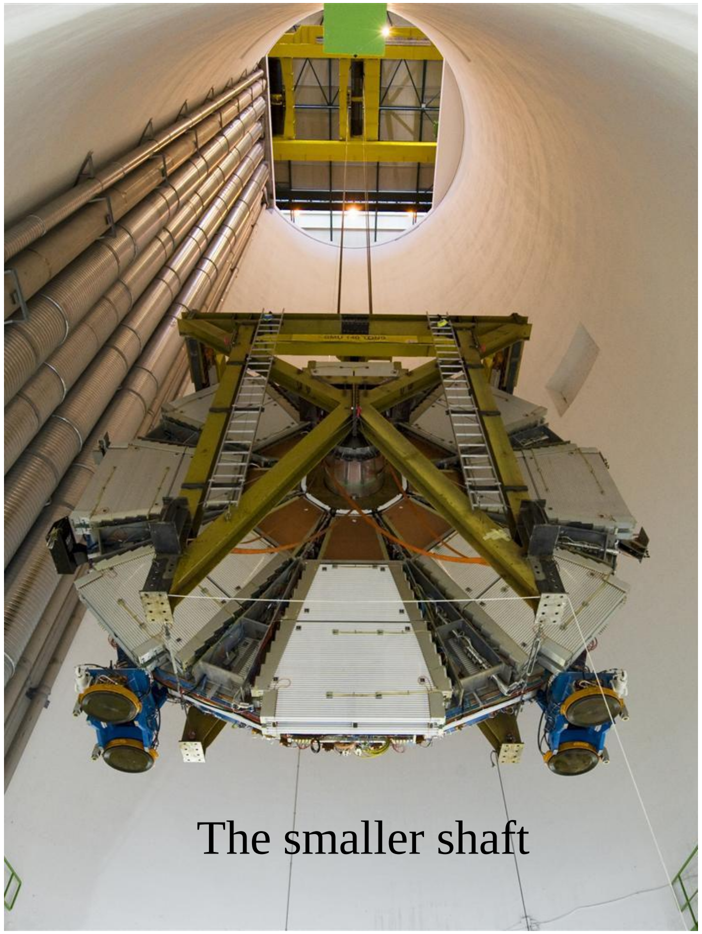
Big Wheel Assembled in Cavern

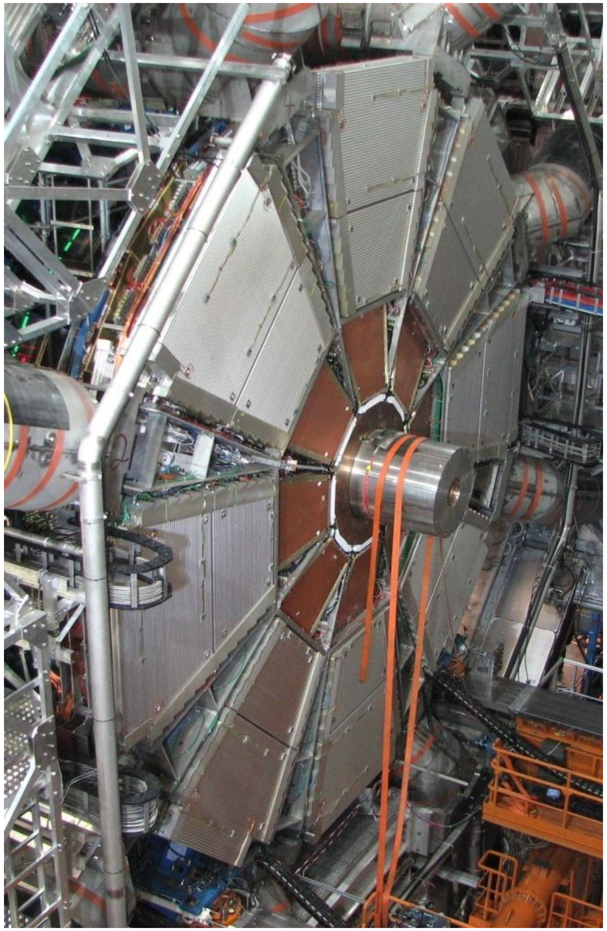
~ 100 feet



Michigan Physicist Connecting Electronics On the Big Wheel.

Lower & Position Small Wheel





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On a Familiar Site

The People in the Hunt

All these people are searching for the particle proposed by Peter Higgs and others.

Peter Higgs during a visit to Ann Arbor for an MCTP meeting shown with CDF & ATLAS experimentalist.

ATLAS collaboration

Peter Higgs

Members of the Michigan Team in the ATLAS Pit (2007)

Detection of Higgs Boson in lepton and photon decay channels

$$H \to \gamma\gamma$$

$$H \to ZZ^{*} \to 4\ell \ \ (\ell = e, \mu)$$

$$H \to WW^{*} \to \ell\nu\ell\nu$$

Thus, ATLAS needs to measure

γ, e - gamma rays & electrons with good precision

μ – muons with good precision

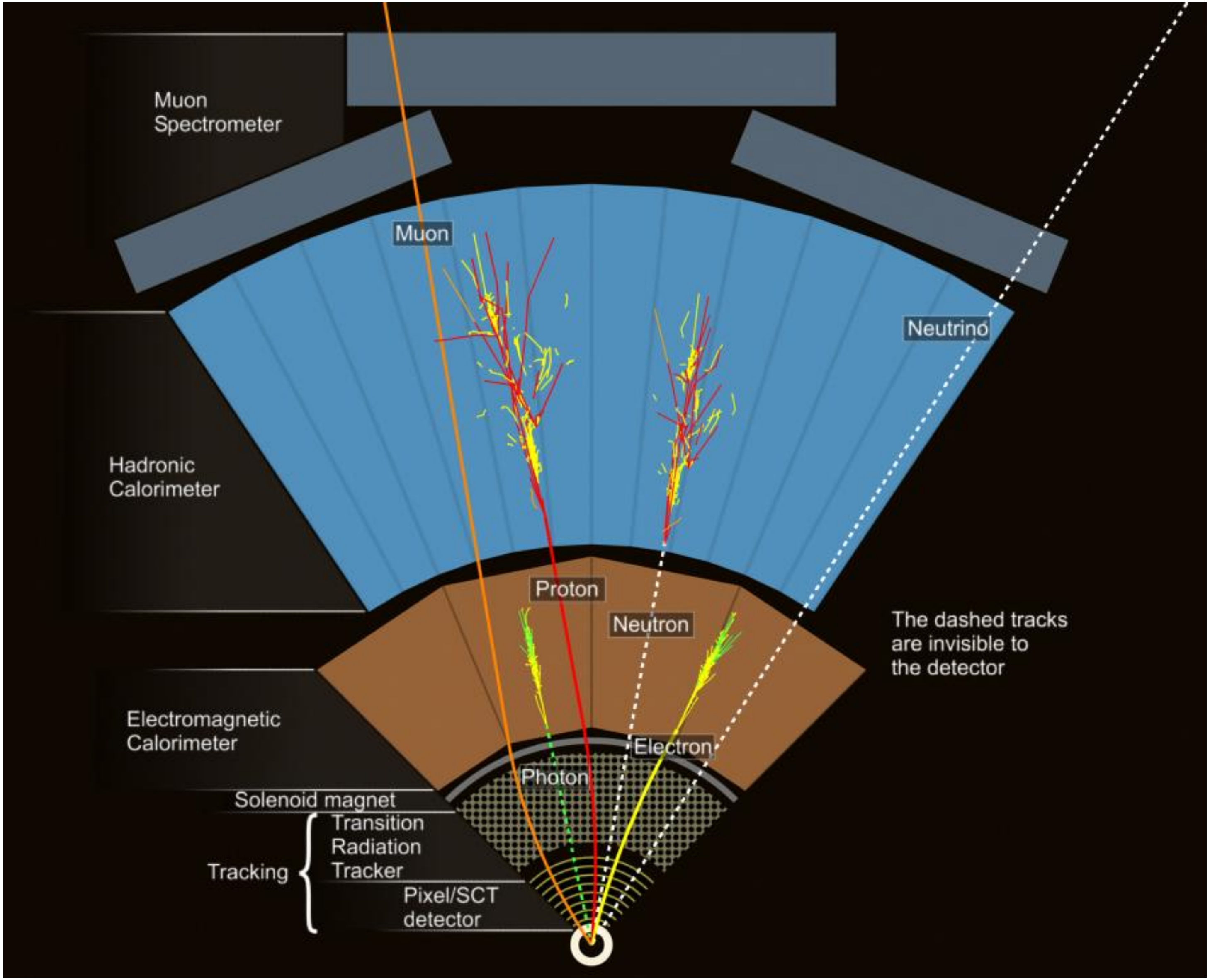
Particle Identification in ATLAS

Muon

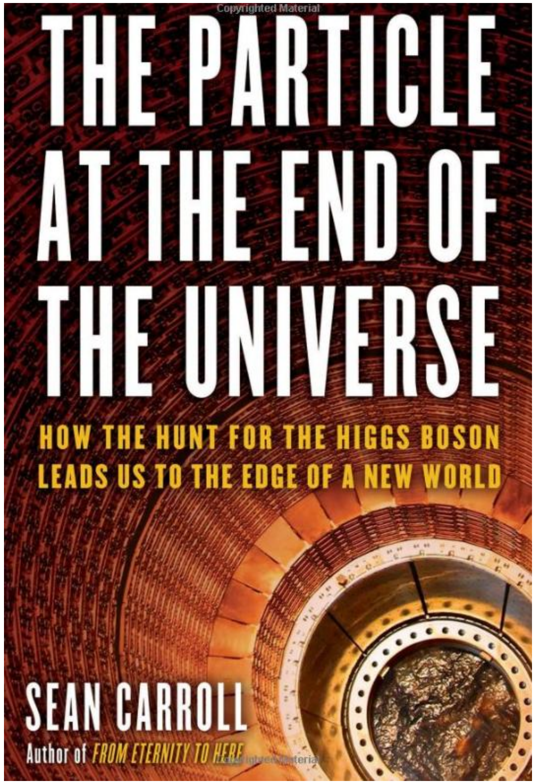
Jets

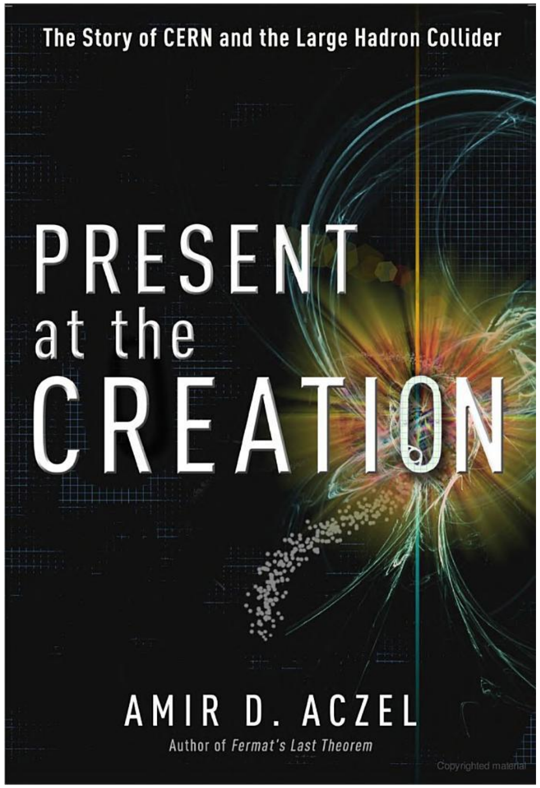
electron, γ

Charged tracks
Interaction
vertices



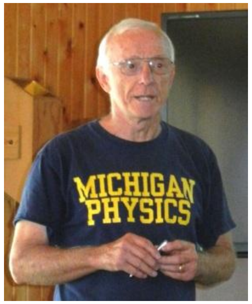
Books for Extended Reading





The Announcement

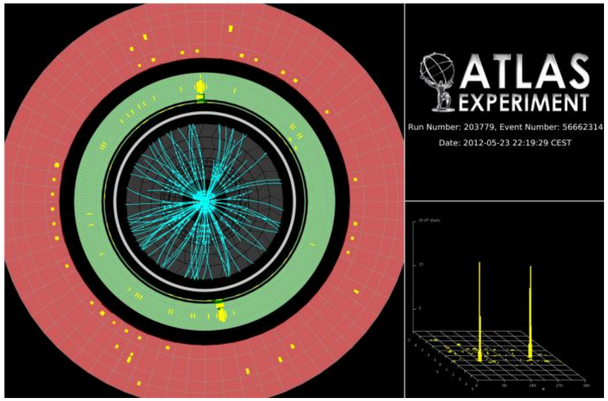
- The Announcement was July 4th from CERN & Australia (4AM EST)
- I was at Camp Michigania listening with a full moon above Lake Walloon.
- Having it all!



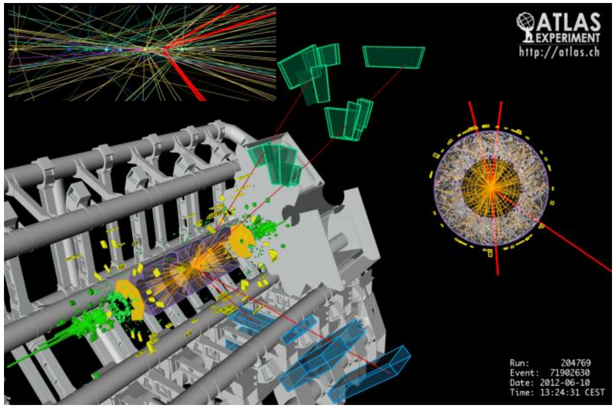
Later that day!

Observation of a Higgs-like Particle at ATLAS

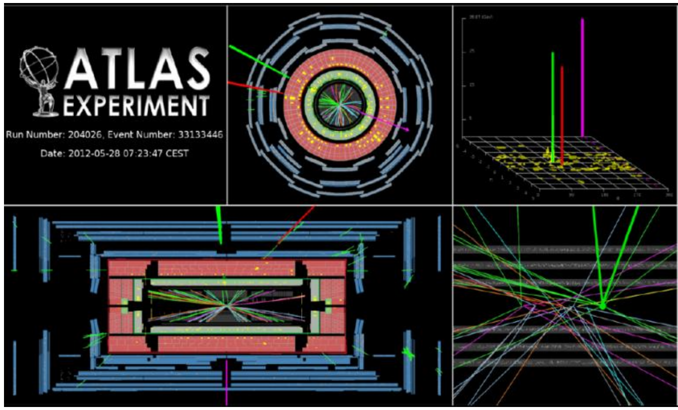
$H \rightarrow \gamma\gamma$



$H \rightarrow ZZ^* \rightarrow \mu\mu\mu\mu$



$H \rightarrow WW^* \rightarrow e\nu\mu\nu$



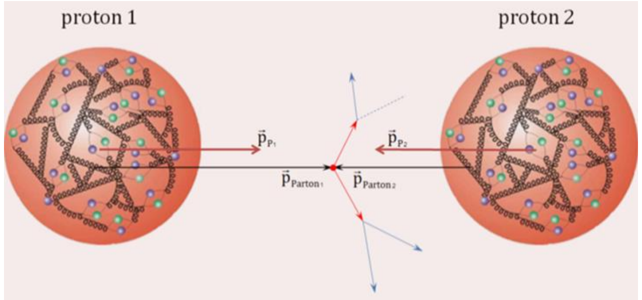
Jianming Qian

Department of Physics, University of Michigan

Proton-proton Collision Data

The Large Hadron Collider is a circular proton-proton collider with a design energy of 14 TeV. It has been in operation since 2010 running at lower energies.

When two protons collide, the actual collision occurs between quarks and gluons.



ATLAS detector selects and records “interesting” collisions for offline reconstruction and analysis.

The results presented today are based on the data taken in 2011 at 7 TeV and in 2012 (first 6 months) at 8 TeV.

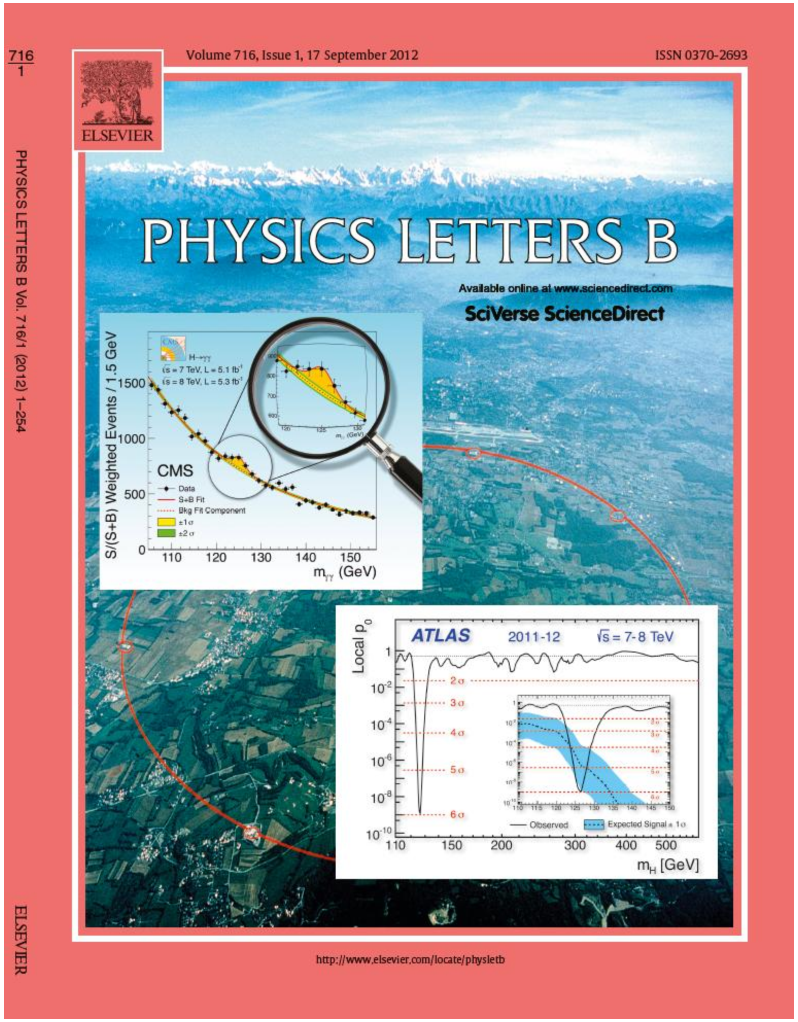
A Discovery !

CERN seminar (July 4, 2012):

Planned as an update of the search… going out with a bang!

Rolf Heuer (CERN Director General)

"We have a discovery. We have observed a new particle that is consistent with a Higgs boson."

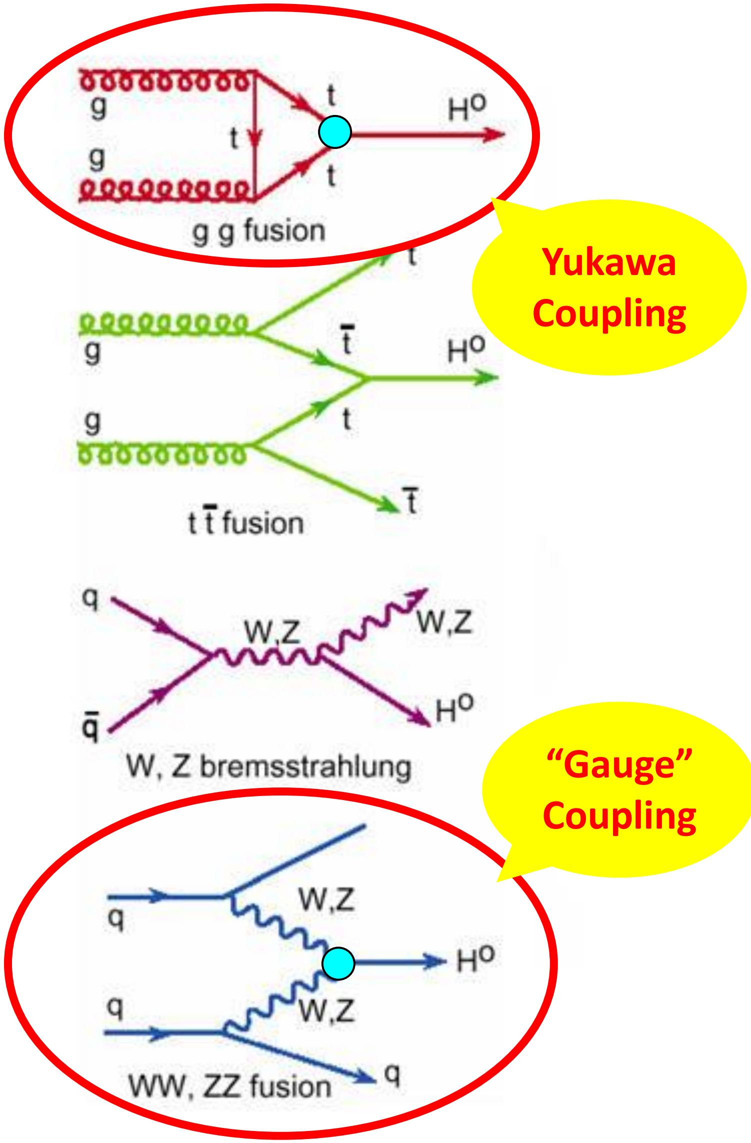


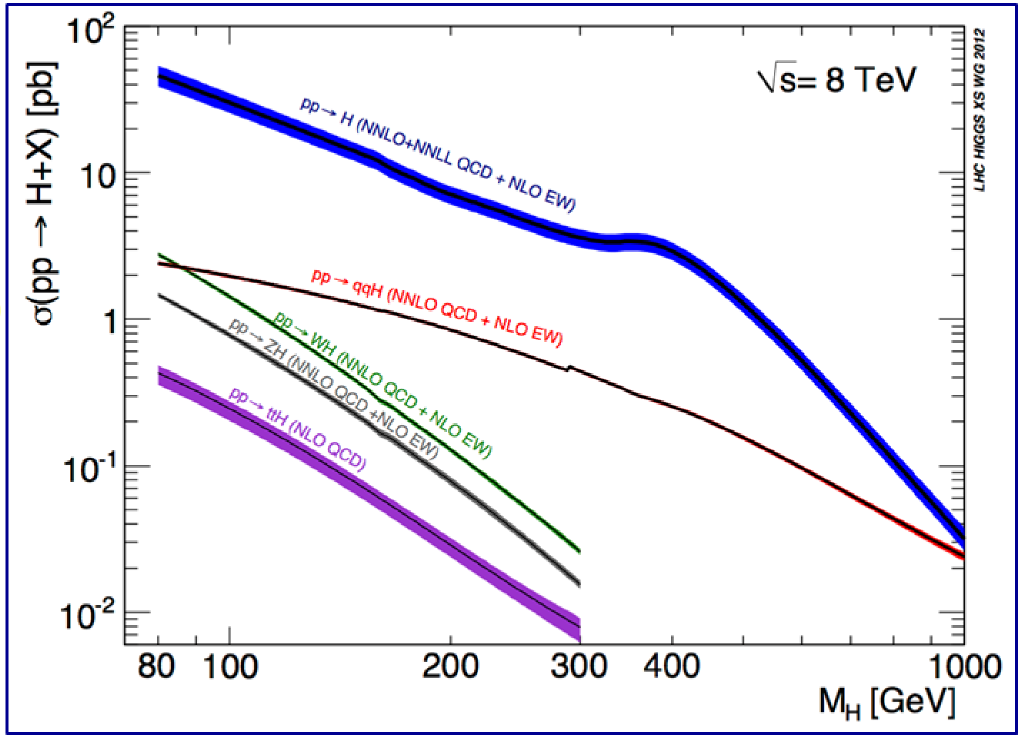
Submitted on July 31, 2012

Published: Phys. Lett. B716, 1 (2012)

http://arxiv.org/abs/1207.7214

Higgs Boson Production at LHC





$@\, m_H = 125$ GeV: cross section $(\sigma_H) \cong 22$ pb

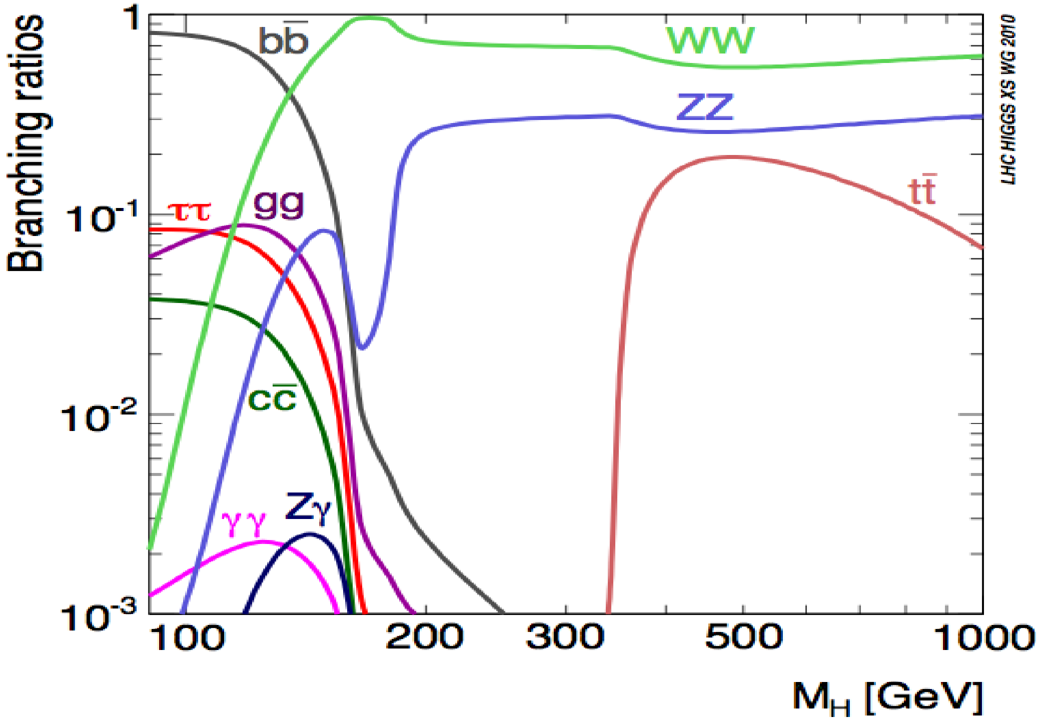
Number of signal events produced
= Luminosity × Cross Section
= 230,000

Total number of background events
$\sim 5\times10^{14} \Rightarrow$ Signal/Background$\sim10^{-10}$

Higgs Boson Decay

Higgs boson is expected to have a lifetime of ~10^{-22} sec and decays immediately to (m_H=125 GeV)

$b\bar{b}$: 57.7%
WW: 21.5%
$\tau\tau$: 6.3%
ZZ: 2.6%
$\gamma\gamma$: 0.23%



$b\bar{b}$ and $\tau\tau$ final states are overwhelmed by backgrounds, clean final states generally involve leptons (e and μ). Most sensitive channels:

$H \to \gamma\gamma$ ~ 500 events produced

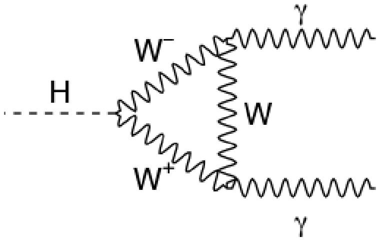
$H \to ZZ^* \to 4\ell \ (\ell = e, \mu)$ ~ 25 events produced

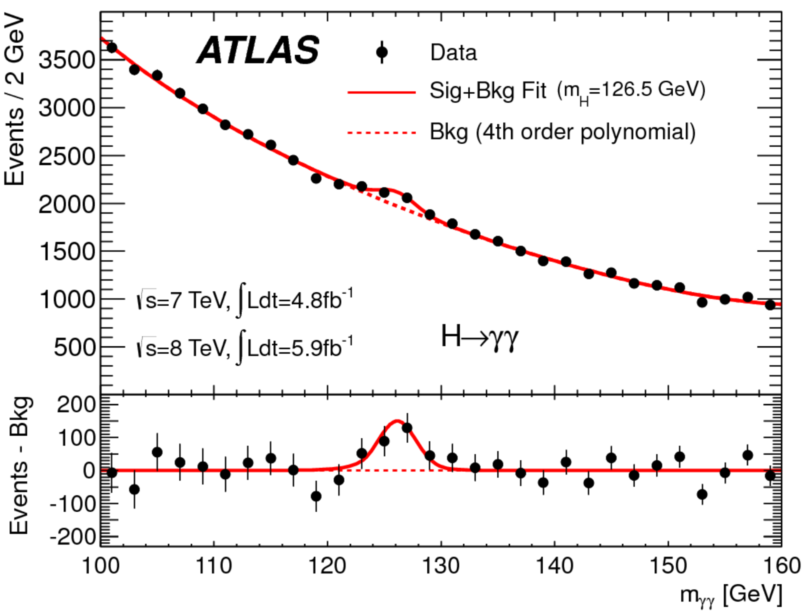
$H \to WW^* \to \ell\nu\ell\nu$ ~ 2300 events produced

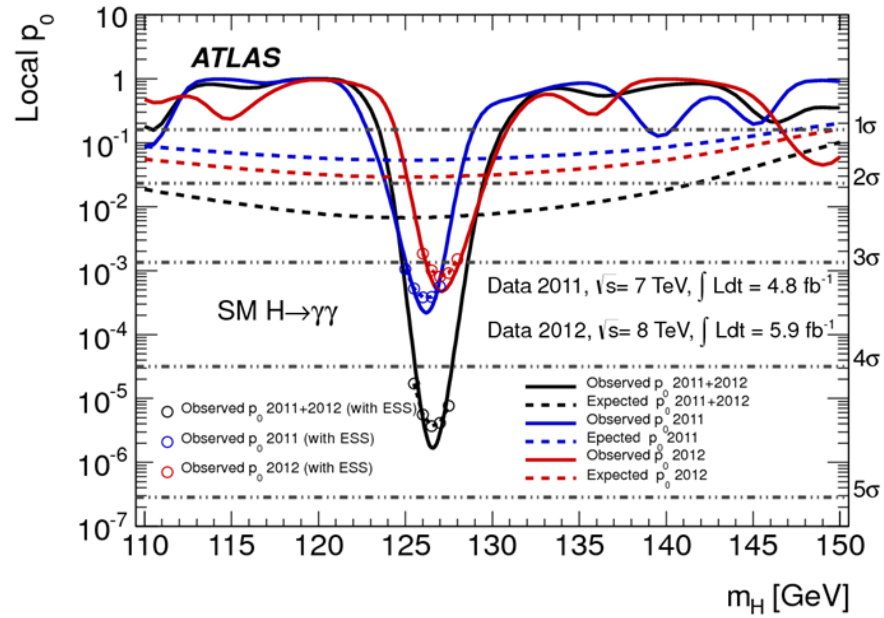
$H \rightarrow \gamma\gamma$ Search

Photons are stable particles that can be identified and measured relative easily ⇒ full reconstruction of the Higgs boson decay.

Select candidate events with two high momentum photons and reconstruct the mass of the diphoton system. Categorizing samples to improve sensitivity.





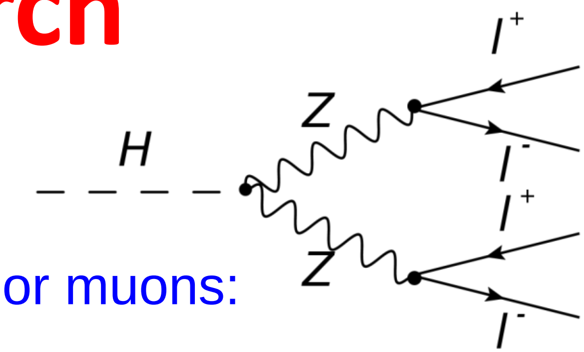


Observe an excess of ~300 events (170 expected at 126 GeV)

⇒ probability of background fluctuation: 2×10^{-6} (4.5σ)

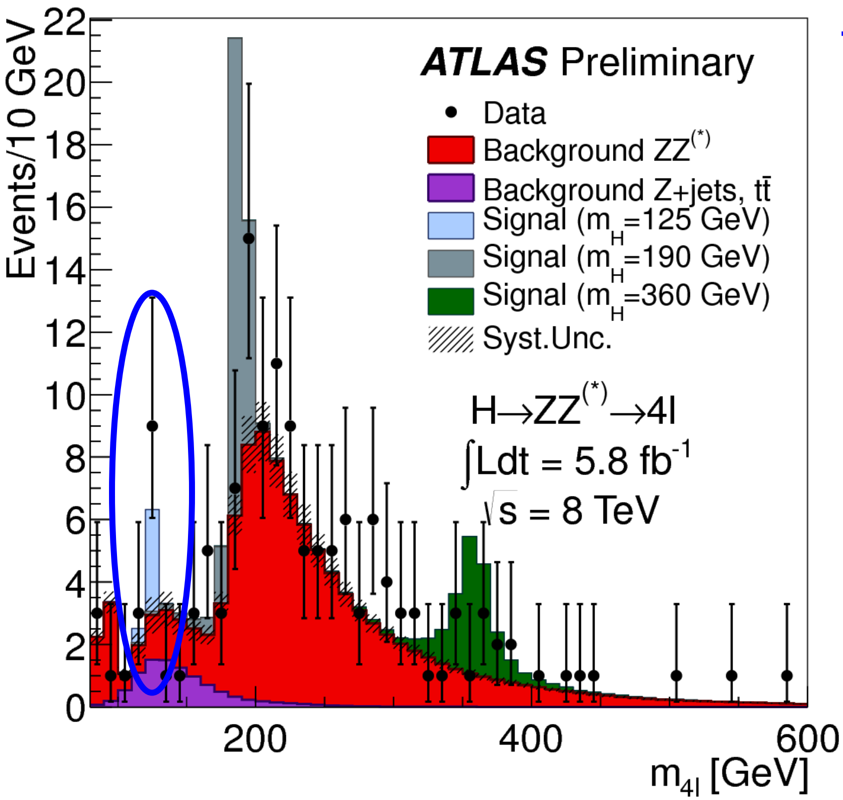
H→ZZ*→4l Search

Z bosons have a lifetime of 10^{-25} sec, only their decay products can be directly detected.



When both Z bosons decay to pairs of electrons or muons:

- very small backgrounds
- full reconstruction of the Higgs boson decay



The Analysis:

select events with two pairs of electrons or muons, reconstruct the mass of the 4-lepton system.

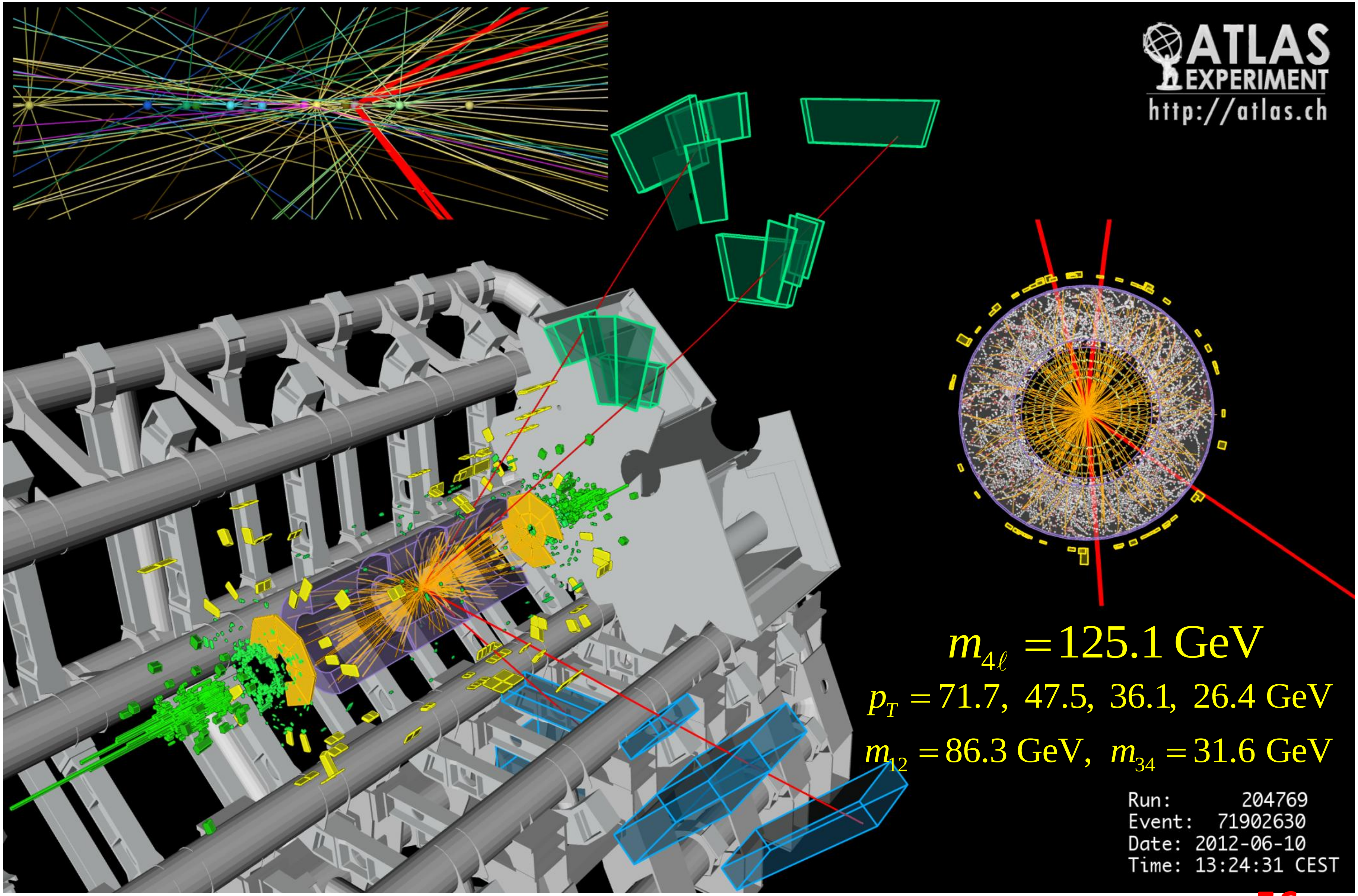
The result:

Between m_{4l}=120-130 GeV:

Backgrounds:	5.1±0.8 events
Expected signal:	5.3±0.8 events
Observed in data:	13 events

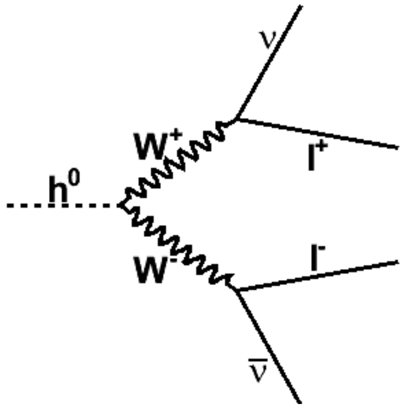
Probability of background fluctuation: 3×10^{-4} (3.4σ)

A H→ZZ*→4l Candidate



H→WW*→eν μν Search

W bosons are unstable and decay immediately. The cleanest decay is to a charged lepton and a neutrino.

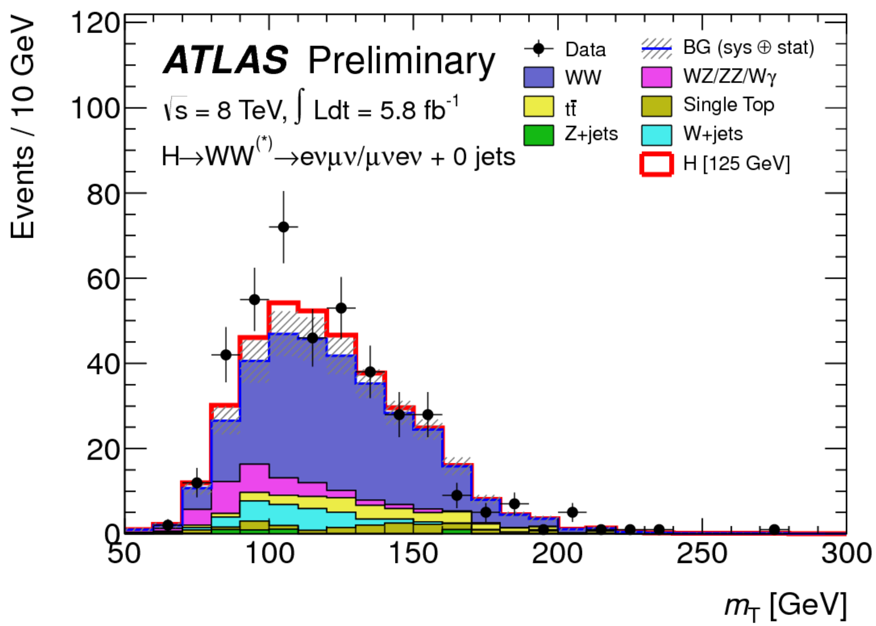


Neutrinos are weakly interacting particles and generally escape undetected

- ⇒ no full reconstruction of the Higgs decay
- ⇒ large backgrounds

Use "transverse" mass as the signal-background discriminant:

$$m_T = \sqrt{\left(E_T^{\ell\ell} + E_T^{\text{miss}}\right)^2 - \left(\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{\text{miss}}\right)^2}$$



Categorization of the samples to improve sensitivity.

Events after all selections:

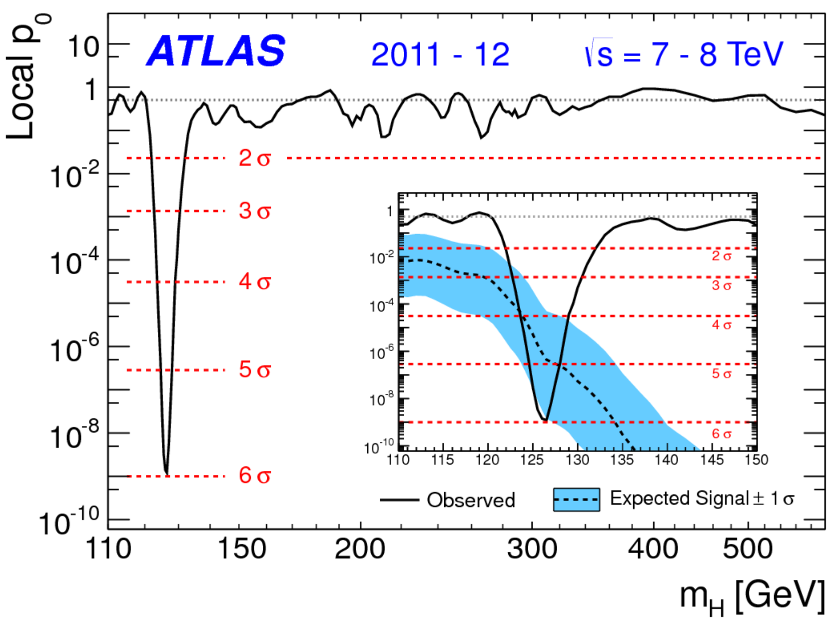
- Backgrounds: 383±28
- Expected signal: 58±9
- Observed in data: 453

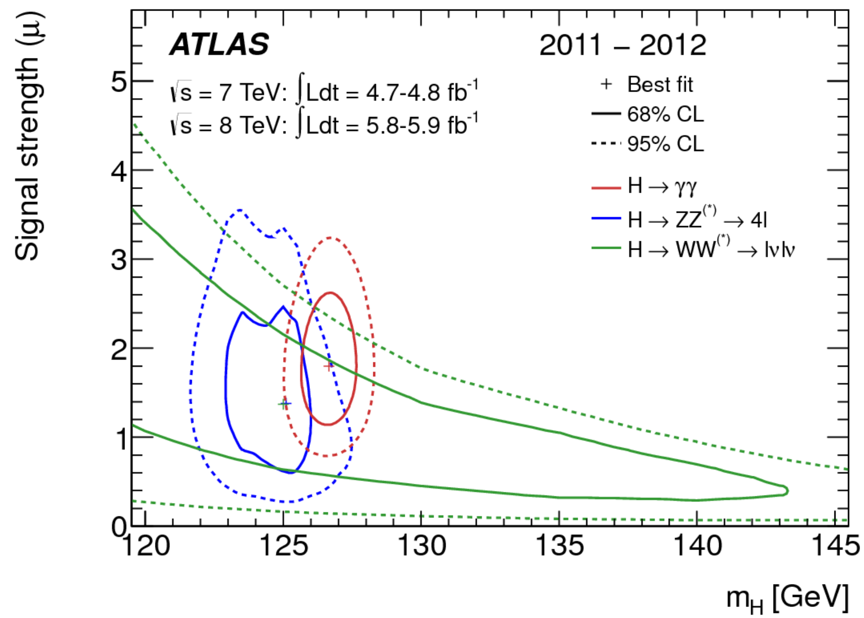
Significant excess, probability of background fluctuation: 3×10^{-3} (2.8σ)

Combination

All three individual search channels show significant excesses above background expectations.

When combined, the overall excess has a statistical significance of 5.9σ (or equivalently a probability of background fluctuation of 1.7×10^{-9})
$\Rightarrow$ exceeding the traditional 5σ threshold for a discovery!





Next Steps

We have observed a new particle in the search of the Higgs boson

Mass: 126.0±0.4(stat)±0.4(syst) GeV

Rate: 1.4±0.3 times of the rate predicted by the Standard Model

The new particle is consistent with the expectation of the long-sought Higgs Boson. However more data are needed to ascertain its identity:

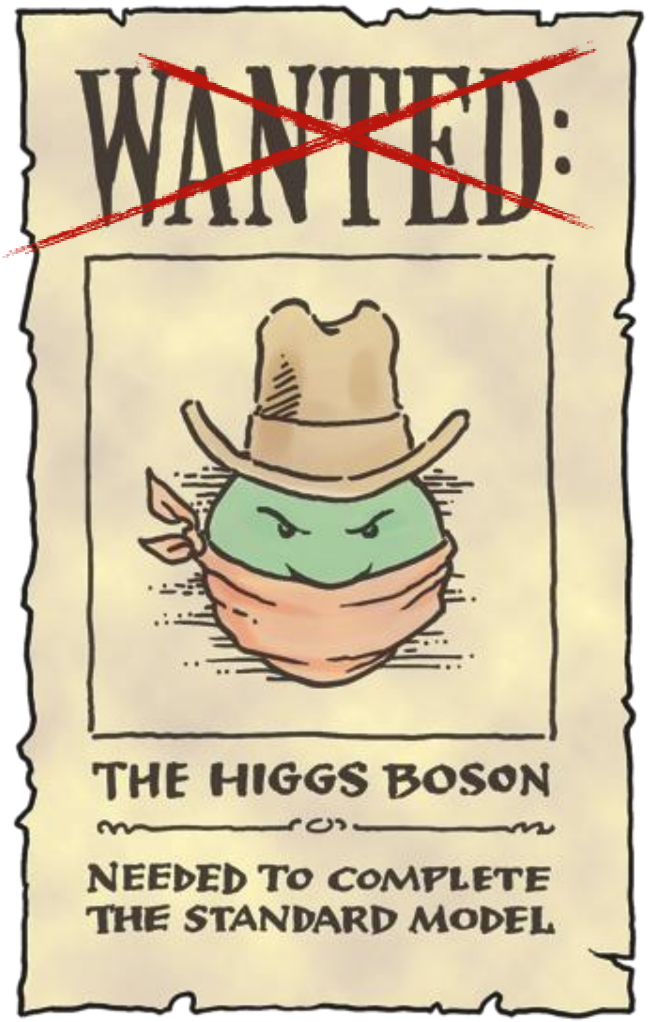
- Observed so far in boson final states ($\gamma\gamma$, WW, ZZ), it's decay to fermion final states ($b\bar{b}$, $\tau\tau$, …) needs to be established;
- Its overall production rate appears to be consistent with the expectation, but $H \rightarrow \gamma\gamma$ rate is considerably higher than expected: statistical fluctuation or indication of new physics?
- Measurement of its spin and CP properties; …

We are at a new dawn of particle physics:

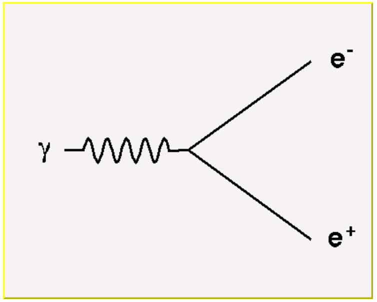
- The LHC program is at its infancy. The LHC energy will increase to 14 TeV in 2015 and the dataset increases by a factor >100;
- New facilities dedicated to study Higgs physics are being proposed…

Aaron Pierce
Theorist

FOUND?

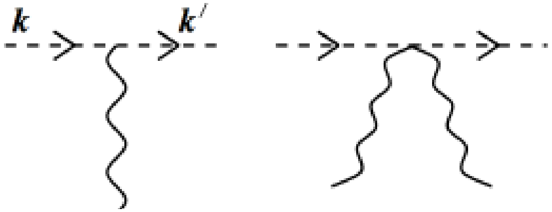


Importance of the WW/ZZ Decays

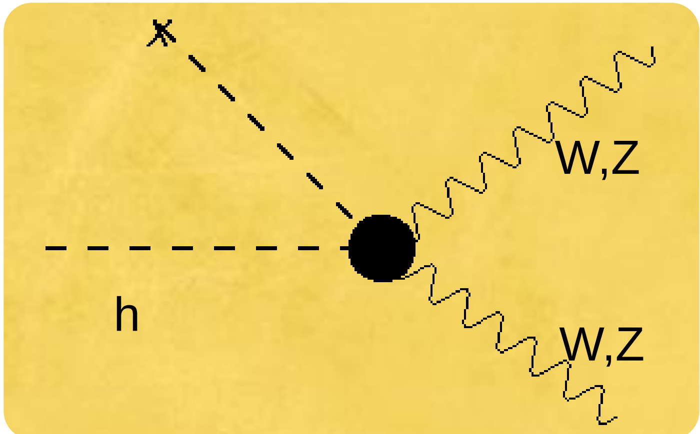


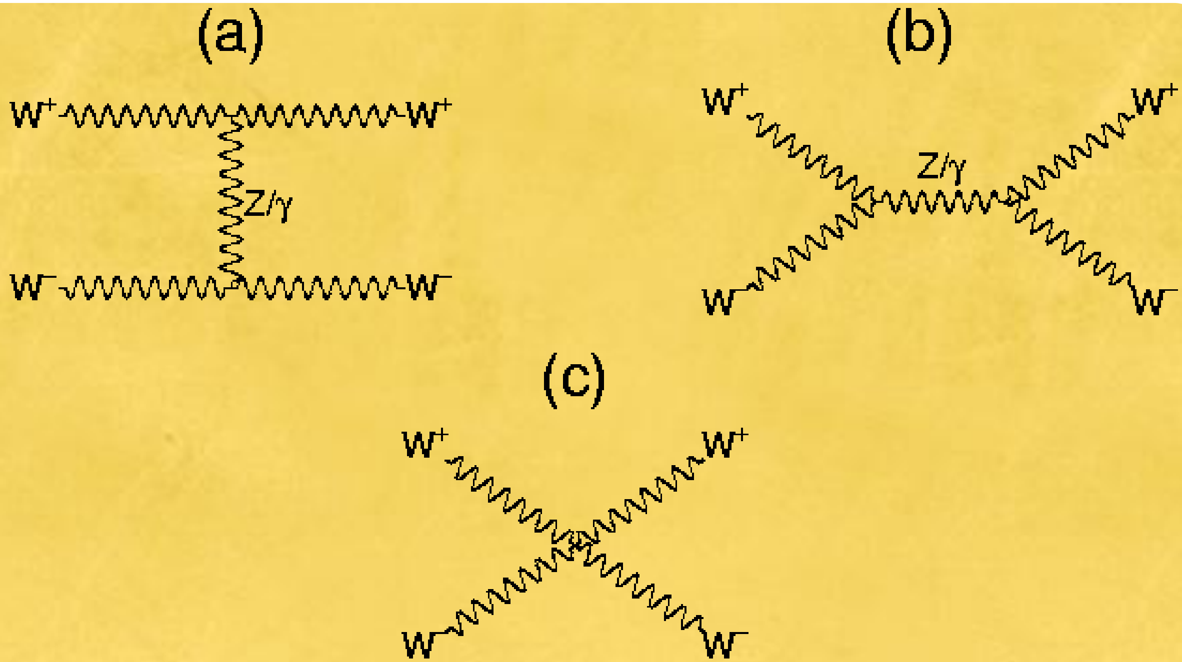
QED

$$\mathcal{L}_1 = ieA^\mu[(\partial_\mu\varphi^\dagger)\varphi - \varphi^\dagger\partial_\mu\varphi] - e^2A^\mu A_\mu\varphi^\dagger\varphi$$



"Scalar QED"





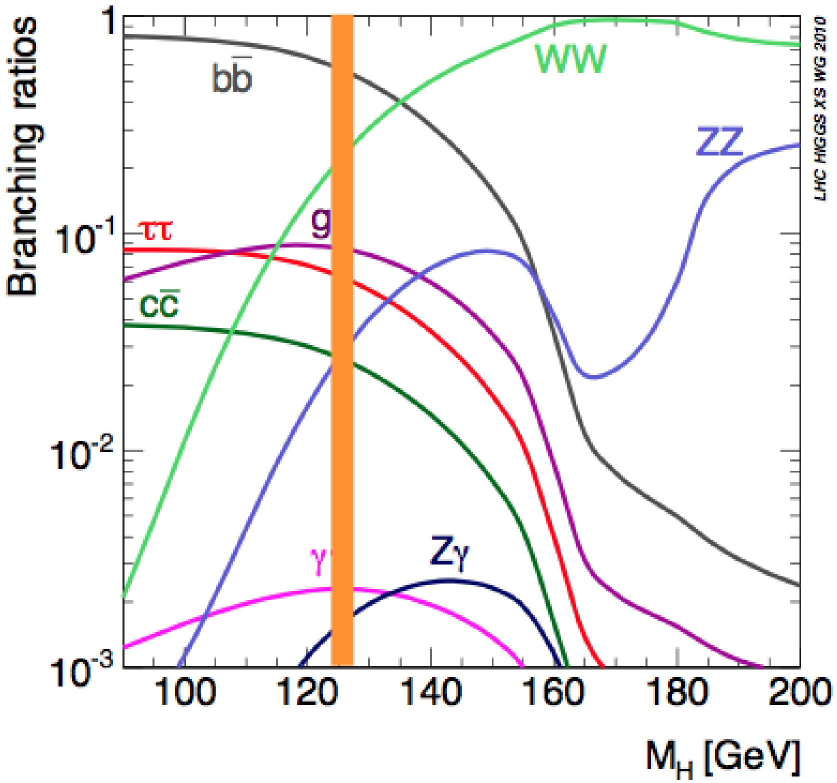
(a)
W+
W+
Z/γ
W−
W−
(b)
W+
W+
Z/γ
W−
W−
(c)
W+
W+
W−
W−

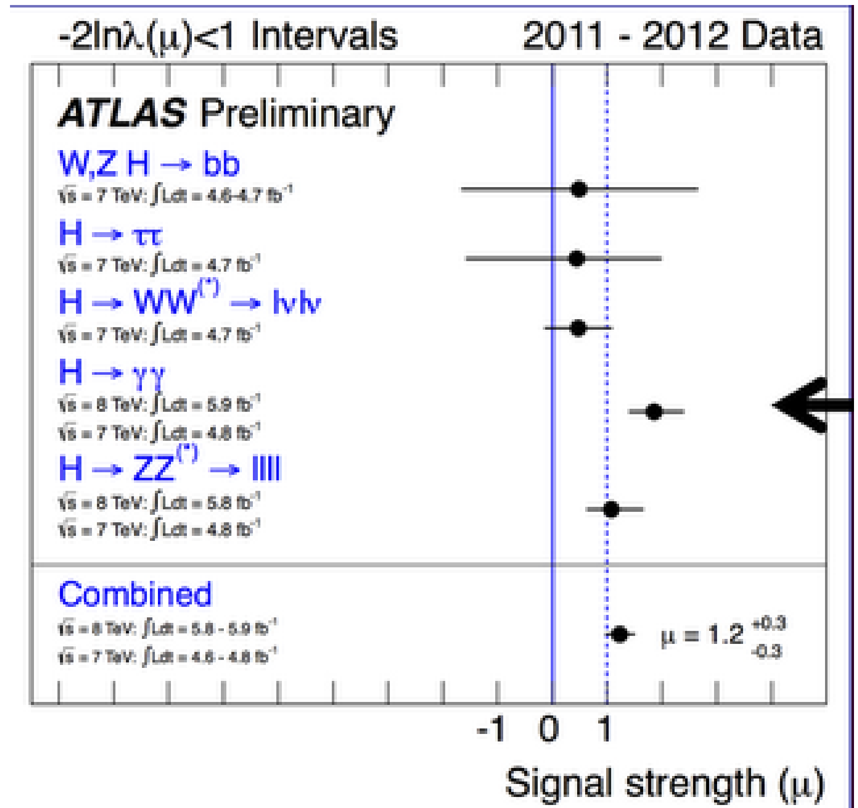
Gravity is VERY weak

$\Longleftrightarrow$ Weak Scale $<<$ $M_{\rm Pl}$

100 GeV $\quad 10^{18}$ GeV

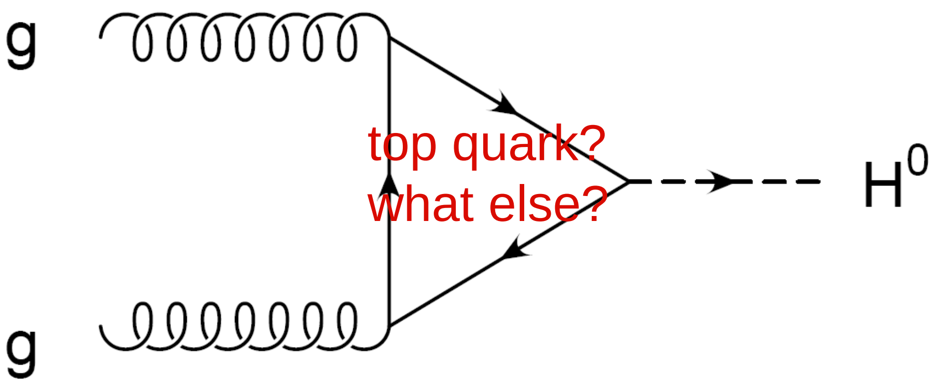
Higgs Production and Decays



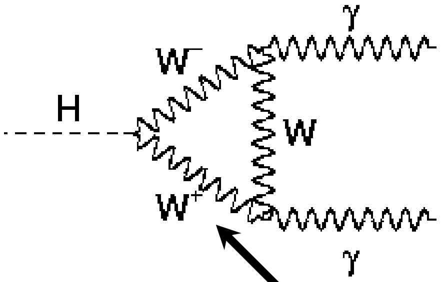


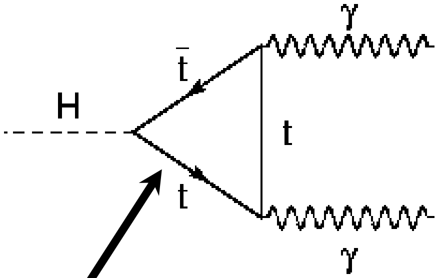
Related question: Is it THE Higgs?

Production



Decay





Anything else?

Superpartners

Standard Model

Super Partners

Identical, but

different "spin"

heavier

Supersymmetry Prediction

$$m_h \approx M_Z \quad (\text{large}\, \tan\beta)$$

SUSY Broken

$$m_h = M_Z + \Delta$$

What is Δ ?

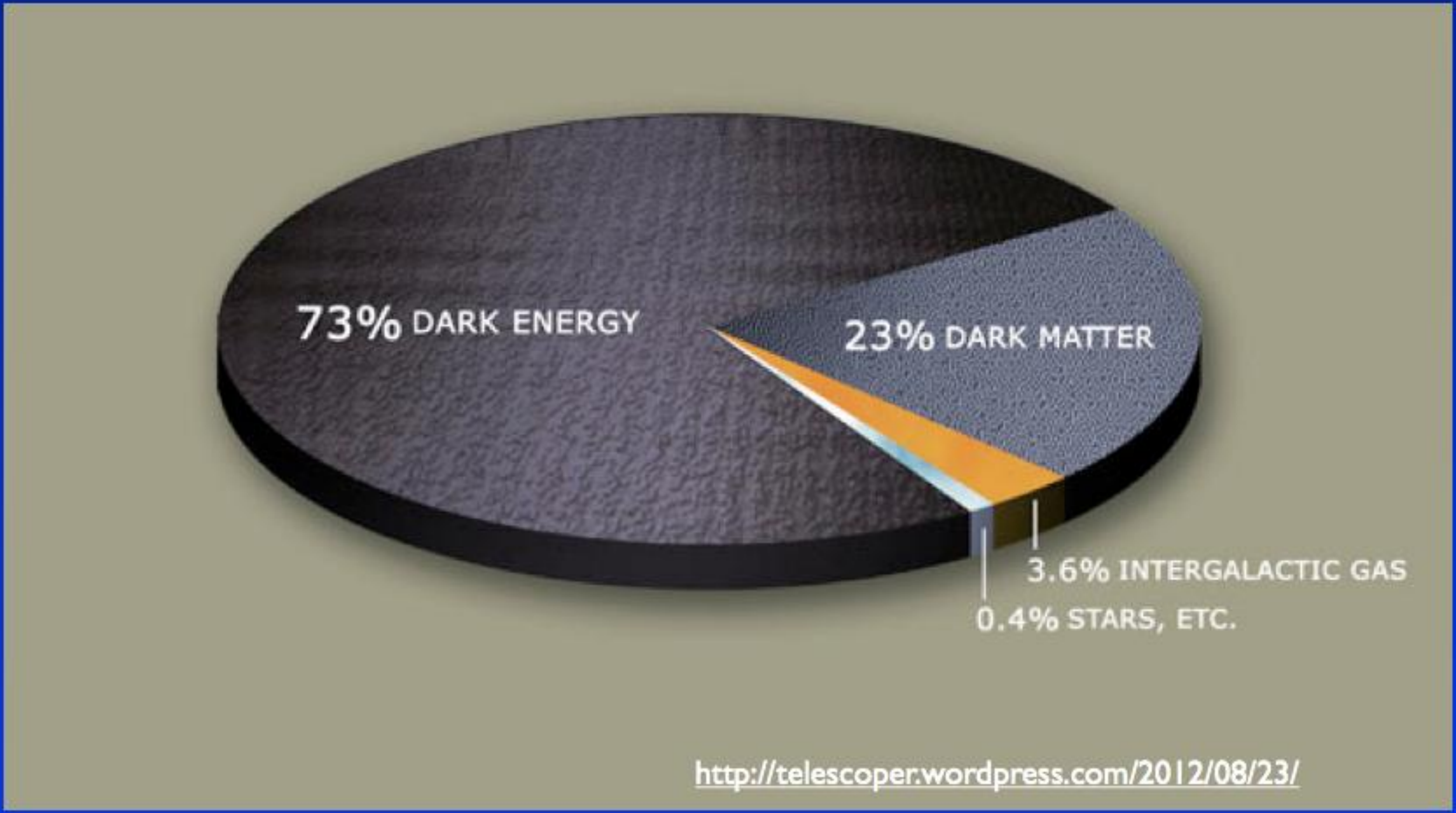
Higgs Mass Prediction for Realistic String/M Theory Vacua

Gordon Kane[†], Piyush Kumar[⋆], Ran Lu[†], and Bob Zheng[†]
[†]*Michigan Center for Theoretical Physics, University of Michigan, Ann Arbor, MI 48109 USA*

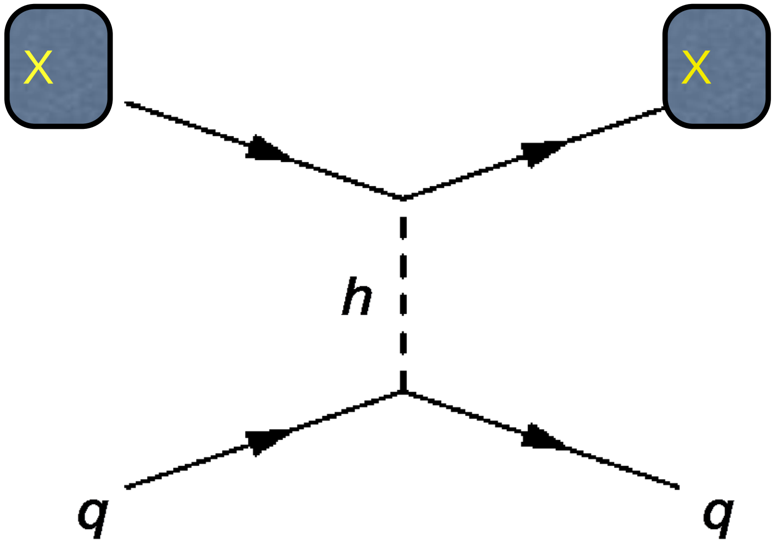
[⋆]*Department of Physics & ISCAP, Columbia University, New York, NY 10027 USA*

(Dated: December 6, 2011)

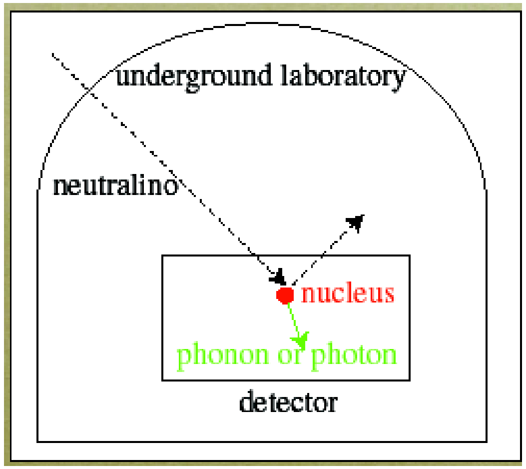
Recently it has been recognized that in compactified string/M theories that satisfy cosmological constraints, it is possible to derive some robust and generic predictions for particle physics and cosmology with very mild assumptions. When the matter and gauge content below the compactification scale is that of the MSSM, it is possible to make precise predictions. In this case, we predict that there will be a single Standard Model-like Higgs boson with a calculable mass 105 GeV $\lesssim M_h \lesssim$ 129 GeV depending on $\tan\beta$ (the ratio of the Higgs vevs in the MSSM). For $\tan\beta > 7$, the prediction is : 122 GeV $\lesssim M_h \lesssim$ 129 GeV.


73% DARK ENERGY
23% DARK MATTER
3.6% INTERGALACTIC GAS
0.4% STARS, ETC.
http://telescoper.wordpress.com/2012/08/23/

Knowing about the Higgs Sharpens Other Predictions



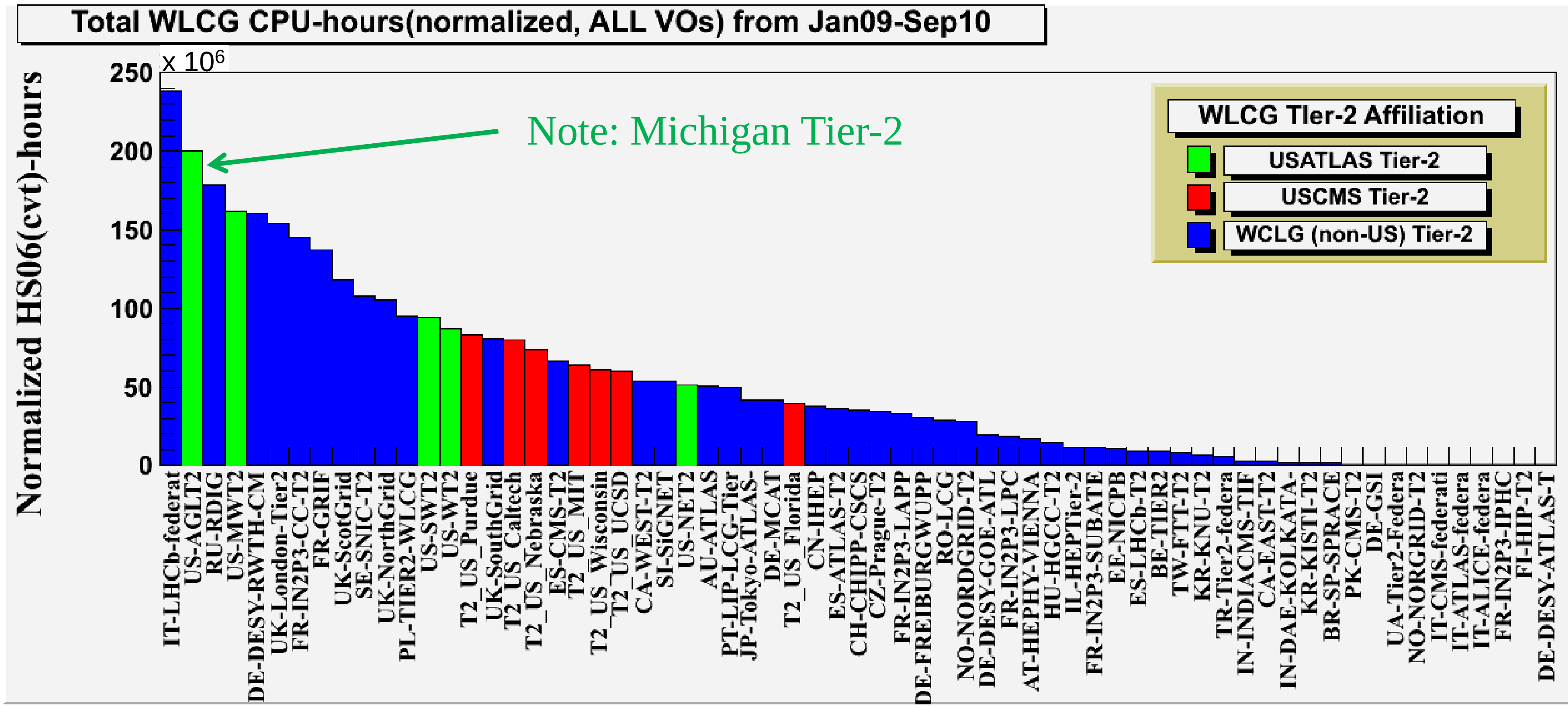
$$\sim \frac{1}{m_h^4}$$



Conclusions

- We’ve found a Higgs boson.
- Is it *the* Higgs boson?
- Why is gravity so weak?
- Dark Matter?
- Surprises? Energy nearly doubling!

Worldwide LHC CPU-hours



~ 8 billion CPU hours per year