And Then There Was Mass: From the Higgs to the Unknown

KITP teacher's conference

Prof. Joe Incandela
University of California Santa Barbara

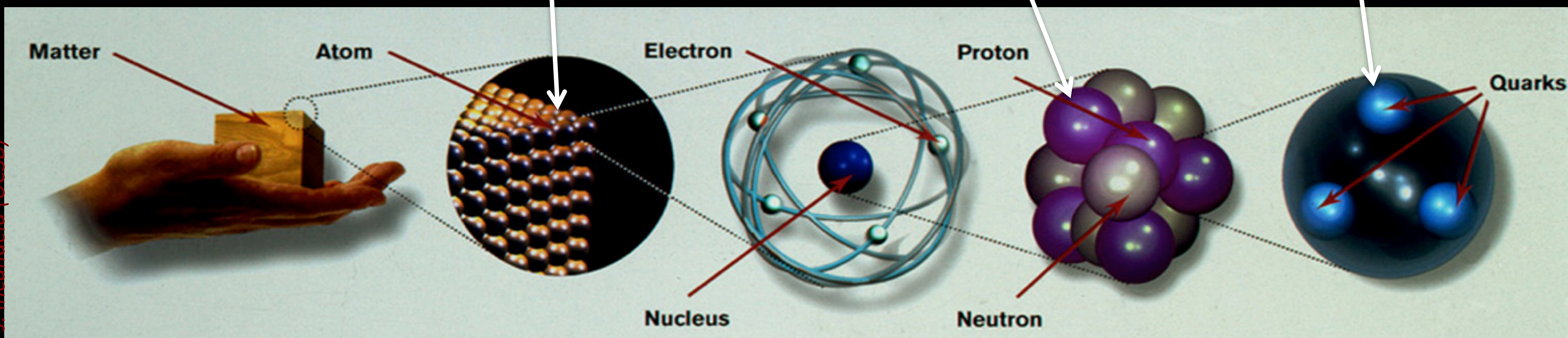
21 May 2016

Use high energies to probe deep into matter, space-time

Atom is a few billionths of an inch

Proton= Atom/10,000

Quark= Proton/100



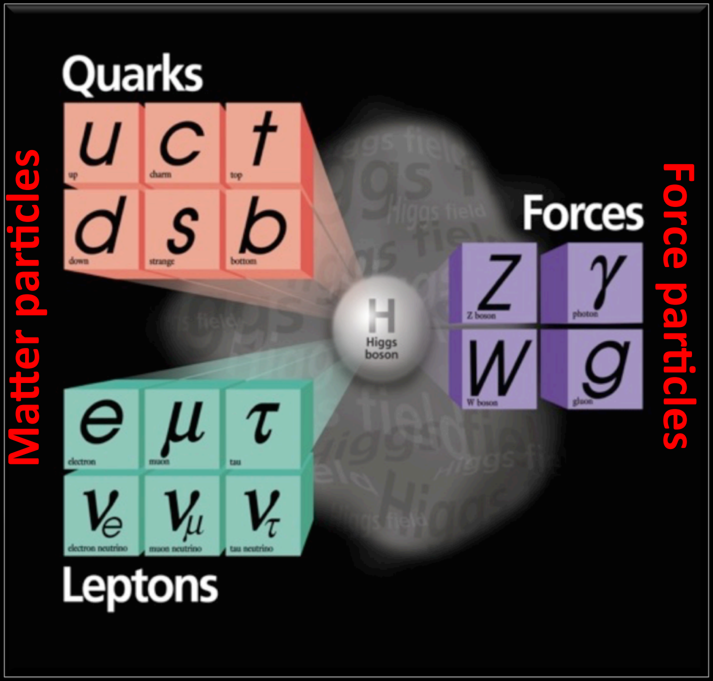
The LHC is now probing down to **~10^{-20} m** = 10 *Zeptometers*

To an atom, this is what an atom is to a human

nano-nano science…

The Standard Model

- Over the last ~100 years: The discovery of many sub-atomic particles and advances in theoretical physics has led to **The Standard Model of Particle Physics**
- A "Periodic Table" of fundamental particles



Described by one simple equation!

$$\mathcal{L}_{SM} =$$

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4} g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2} i g_s^2 (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu$$

$$-\partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \frac12 \partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \frac12 \partial_\mu A_\nu \partial_\mu A_\nu - \frac12 \partial_\mu H \partial_\mu H - \frac12 m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^-$$

$$-M^2\phi^+\phi^- - \frac12 \partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2} M\phi^0\phi^0 - \beta_h\left[\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac12(H^2+\phi^0\phi^0+2\phi^+\phi^-)\right] + \frac{2M^4}{g^2}\alpha_h$$

$$-igc_w\left[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)\right]$$

$$-igs_w\left[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)\right]$$

$$-\frac12 g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac12 g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 \left(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu\right) + g^2 s_w^2 \left(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu\right)$$

$$+g^2 s_w c_w \left[A_\mu Z^0_\nu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu\right] - g\alpha\left[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right]$$

$$-\frac18 g^2\alpha_h\left[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right] - gMW^+_\mu W^-_\mu H - \frac12 g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H$$

$$-\frac12 ig\left[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right] + \frac12 g\left[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right]$$

$$+\frac12 g\frac{1}{c_w}Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^-$$

$$-\phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac14 g^2 W^+_\mu W^-_\mu\left[H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right] - \frac14 g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2$$

$$+2(2s_w^2-1)^2\phi^+\phi^-] - \frac12 g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \frac12 ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac12 g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+)$$

$$+\frac12 ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar\nu^\lambda\gamma\partial\nu^\lambda$$

$$-\bar u^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \bar d^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_wA_\mu[-(\bar e^\lambda\gamma^\mu e^\lambda) + \frac23(\bar u^\lambda_j\gamma^\mu u^\lambda_j) - \frac13(\bar d^\lambda_j\gamma^\mu d^\lambda_j)]$$

$$+\frac{ig}{4c_w}Z^0_\mu\left[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar e^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar u^\lambda_j\gamma^\mu(\frac43 s_w^2 - 1 - \gamma^5)u^\lambda_j) + (\bar d^\lambda_j\gamma^\mu(1-\frac83 s_w^2 - \gamma^5)d^\lambda_j)\right]$$

$$+\frac{ig}{2\sqrt2}W^+_\mu\left[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar u^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right] + \frac{ig}{2\sqrt2}W^-_\mu\left[(\bar e^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar d^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right]$$

$$+\frac{ig}{2\sqrt2}\frac{m_e^\lambda}{M}\left[-\phi^+(\bar\nu^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar e^\lambda(1+\gamma^5)\nu^\lambda)\right] - \frac g2\frac{m_e^\lambda}{M}\left[H(\bar e^\lambda e^\lambda) + i\phi^0(\bar e^\lambda\gamma^5 e^\lambda)\right]$$

$$+\frac{ig}{2M\sqrt2}\phi^+\left[-m_d^\kappa(\bar u^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m_u^\lambda(\bar u^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j)\right] + \frac{ig}{2M\sqrt2}\phi^-\left[m_d^\lambda(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j)\right]$$

$$-\frac g2\frac{m_u^\lambda}{M}H(\bar u^\lambda_j u^\lambda_j) - \frac g2\frac{m_d^\lambda}{M}H(\bar d^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar u^\lambda_j\gamma^5u^\lambda_j) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar d^\lambda_j\gamma^5 d^\lambda_j) + \bar X^+(\partial^2 - M^2)X^+ + \bar X^-(\partial^2-M^2)X^-$$

$$+\bar X^0\left(\partial^2 - \frac{M^2}{c_w^2}\right)X^0 + \bar Y\partial^2 Y + igc_wW^+_\mu(\partial_\mu\bar X^0X^- - \partial_\mu\bar X^+X^0) + igs_wW^+_\mu(\partial_\mu\bar YX^- - \partial_\mu\bar X^+Y) + igc_wW^-_\mu(\partial_\mu\bar X^-X^0 - \partial_\mu\bar X^0X^+)$$

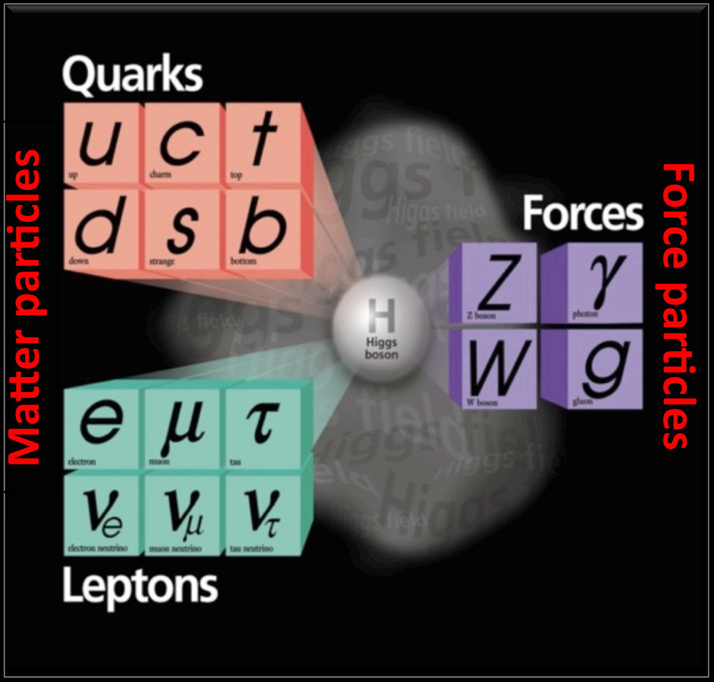
$$+igs_wW^-_\mu(\partial_\mu\bar X^-Y - \partial_\mu\bar YX^+) + igc_wZ^0_\mu(\partial_\mu\bar X^+X^+ - \partial_\mu\bar X^-X^-) + igs_wA_\mu(\partial_\mu\bar X^+X^+ - \partial_\mu\bar X^-X^-) - \frac12 gM[\bar X^+X^+H + \bar X^-X^-H$$

$$+\frac{1}{c_w^2}\bar X^0X^0H] + \frac{1-2c_w^2}{2c_w}igM[\bar X^+X^0\phi^+ - \bar X^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-] + igMs_w[\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-]$$

$$+\frac12 igM[\bar X^+X^+\phi^0 - \bar X^-X^-\phi^0]$$

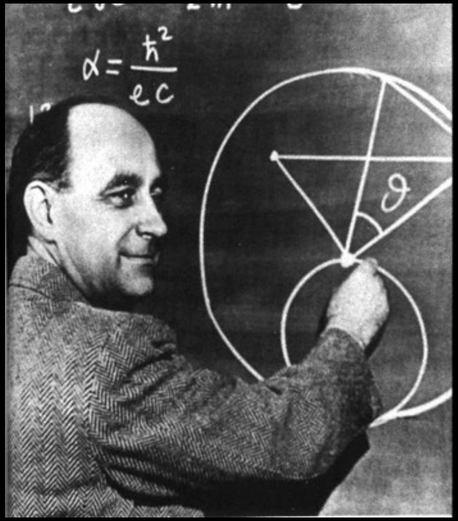
The Standard Model

- Over the last ~100 years: The discovery of many sub-atomic particles and advances in theoretical physics has led to **The Standard Model of Particle Physics**
- A new "Periodic Table" of fundamental elements

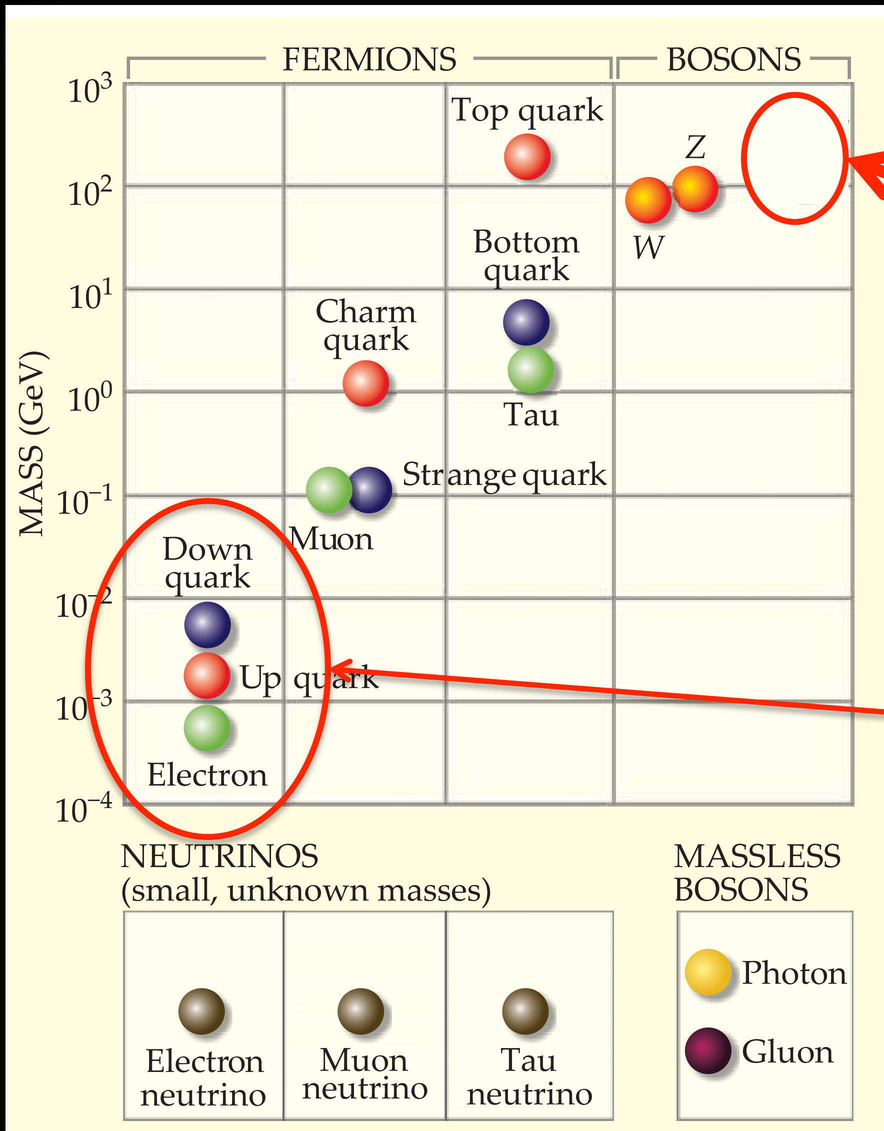


Fermions

Bosons

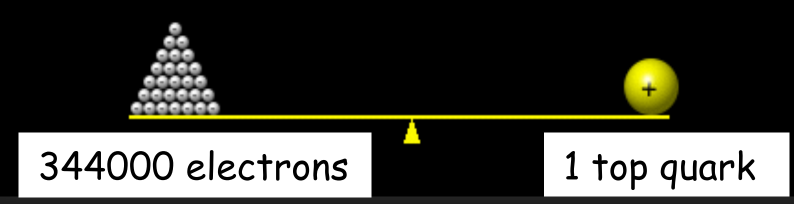


The Standard Model (SM)



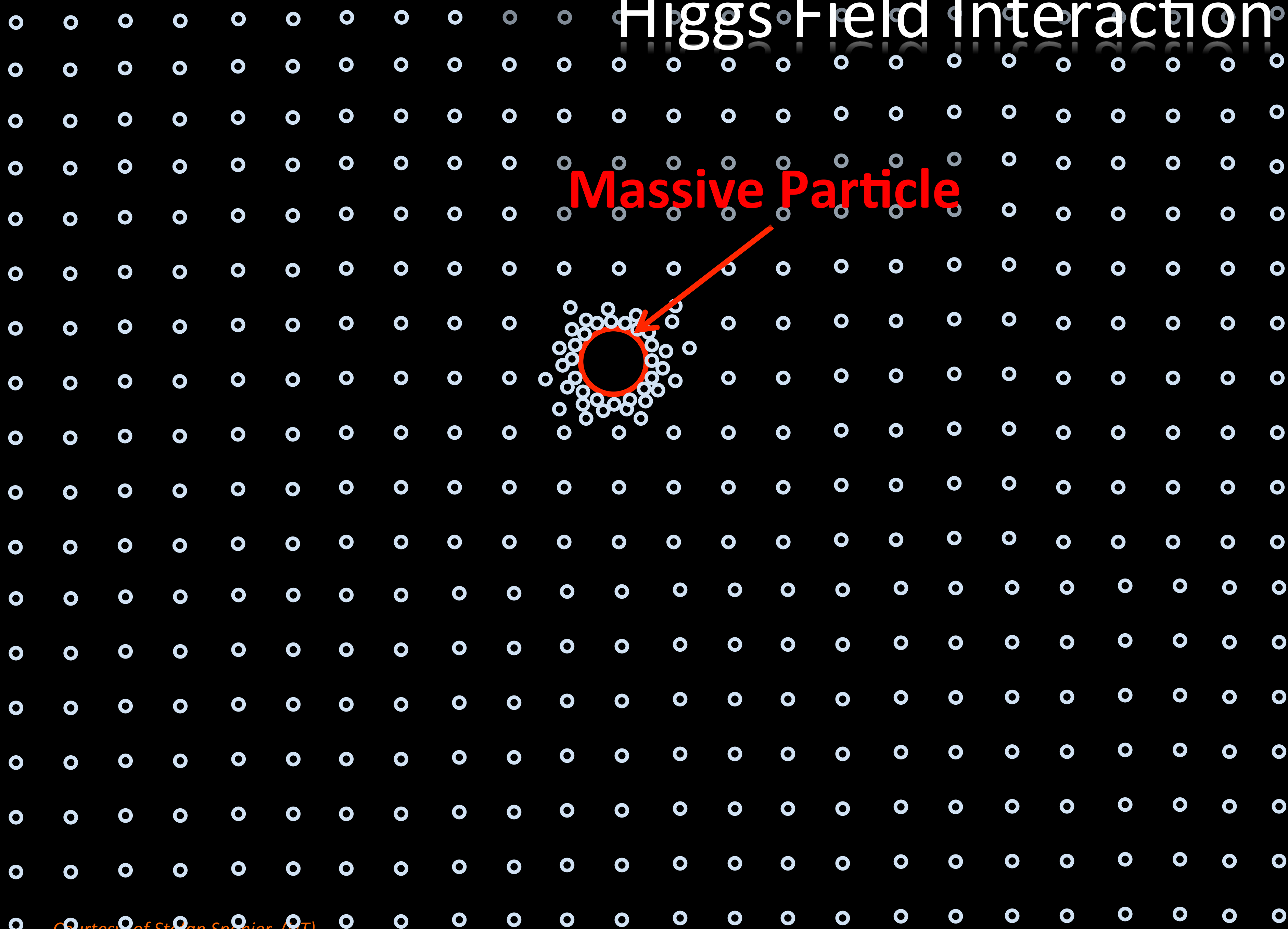
Last piece of this puzzle

These make everything we "see" but the others are crucial to who we are and how the universe works.



Why???

Higgs Field Interaction

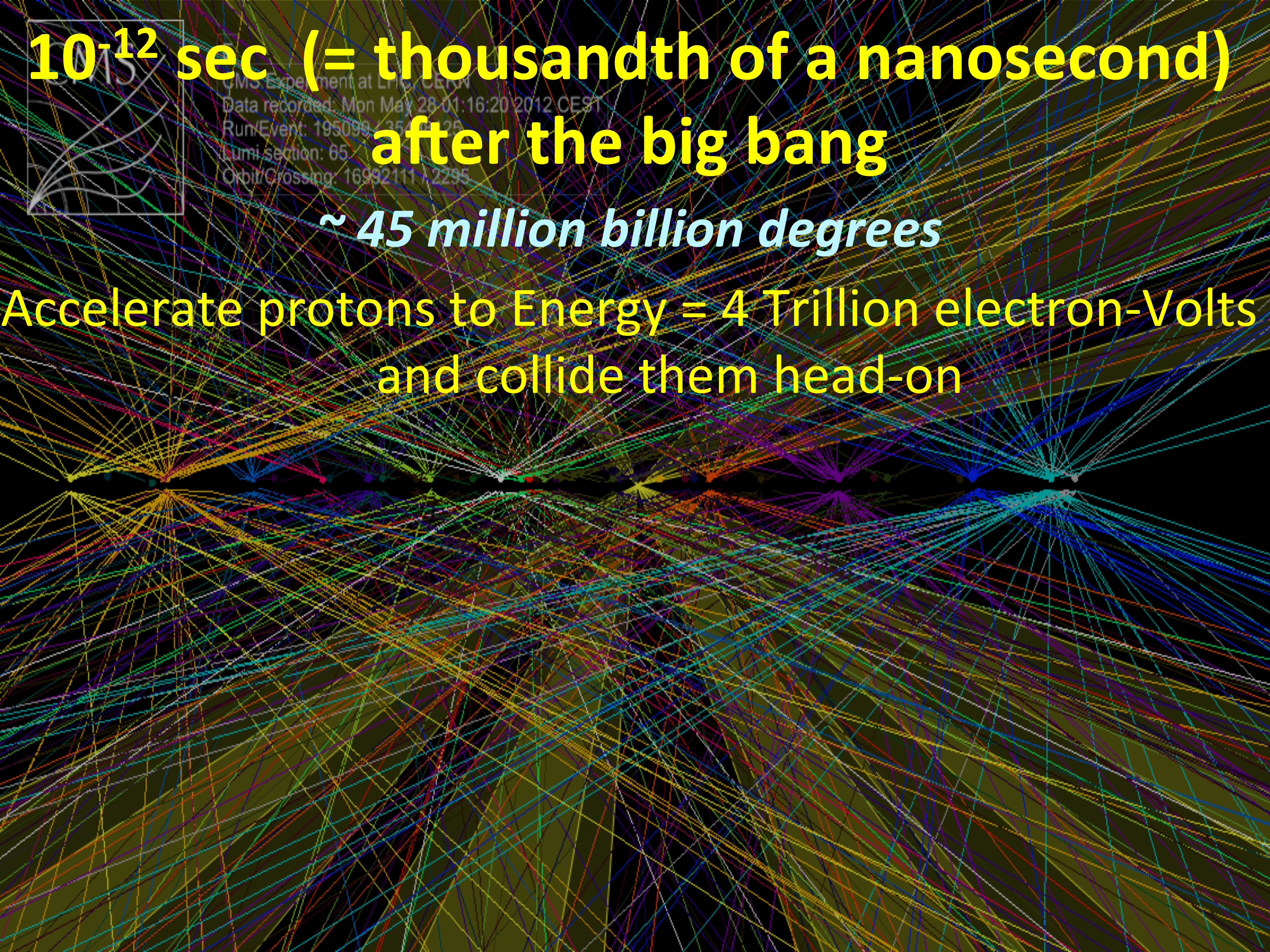


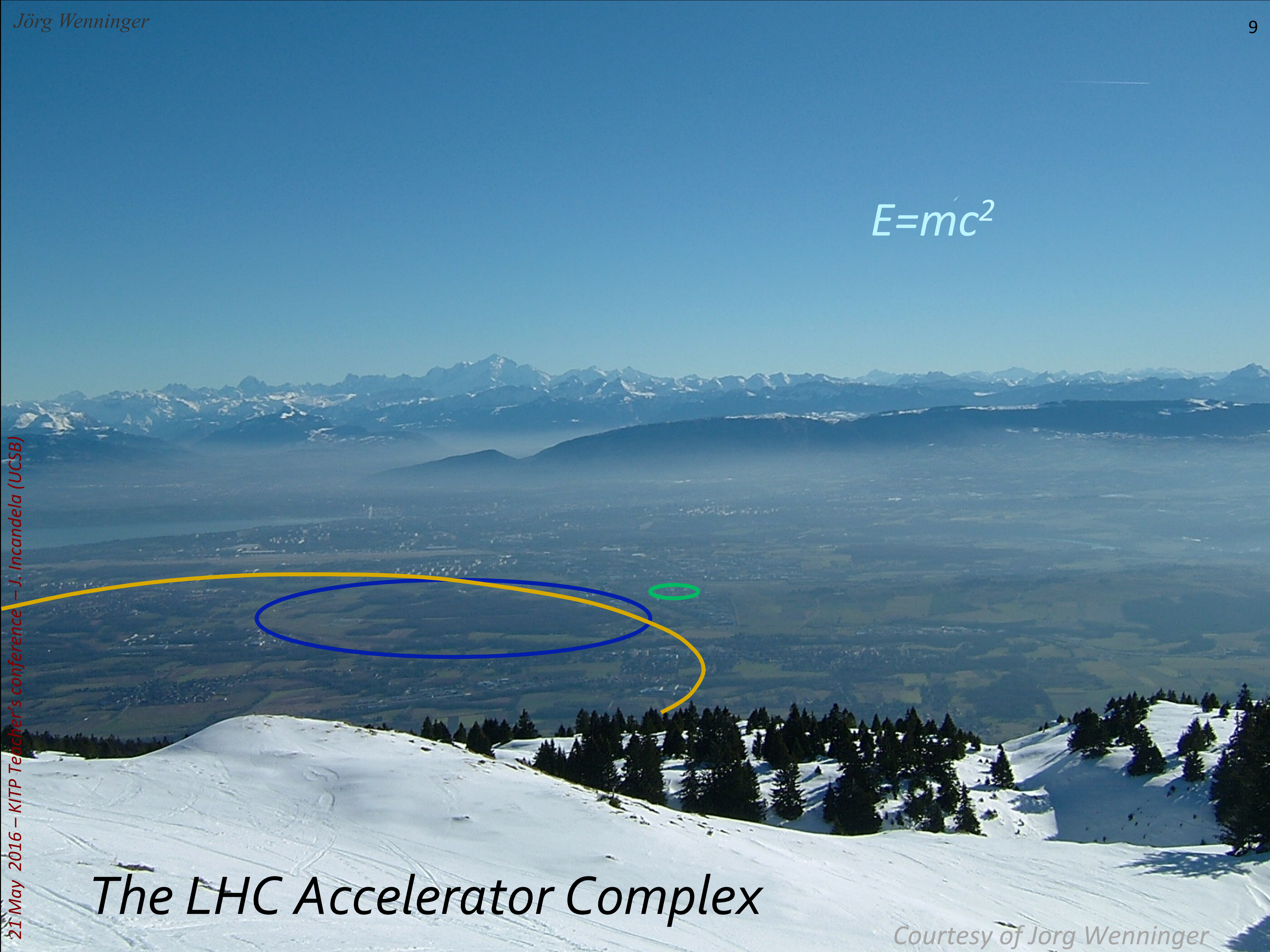
Courtesy of Stefan Spanier (UT)

10^{-12} sec (= thousandth of a nanosecond) after the big bang

~ 45 million billion degrees

Accelerate protons to Energy = 4 Trillion electron-Volts and collide them head-on

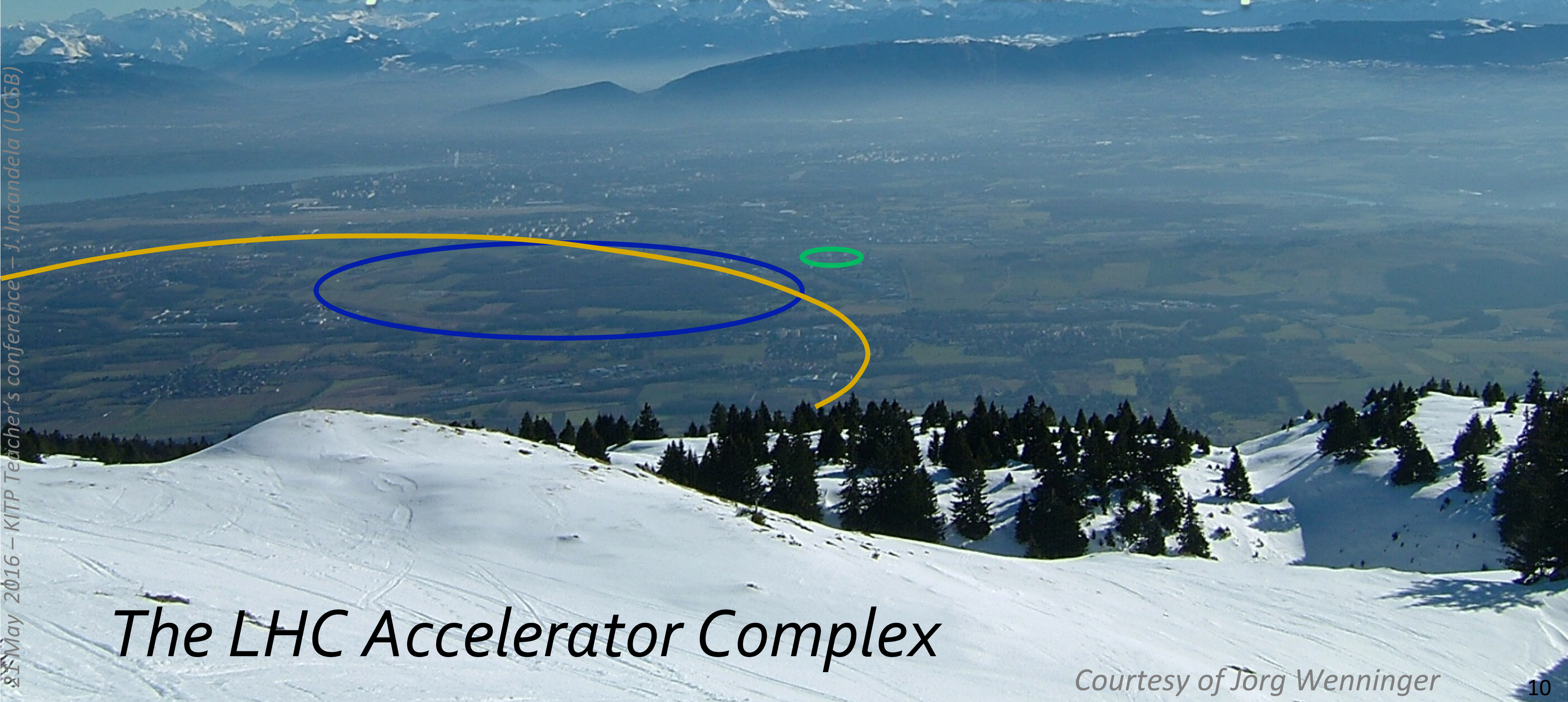




The LHC Accelerator Complex

Courtesy of Jorg Wenninger

- **LHC Design Goals**
  - **Cover all possible Higgs Mass values - roughly 100 to 1000 times the mass of the proton**
  - **Search for new particles with masses as high as many thousands times the mass of the proton**



The LHC Accelerator Complex

Courtesy of Jörg Wenninger

- **1984 : First studies**
- **1994 : LHC approved**
- **1996 : Construction starts**
- **2003 : Start installation**
- **2009 : First collisions**

It has required a lot!

- ***New concepts and Innovation:***
  Magnets, cryogenics, electronics, …
- ***Huge worldwide effort:***
  Patience, perseverance, optimism …

The LHC Accelerator Complex

Courtesy of Jörg Wenninger

Like Swiss chocolate

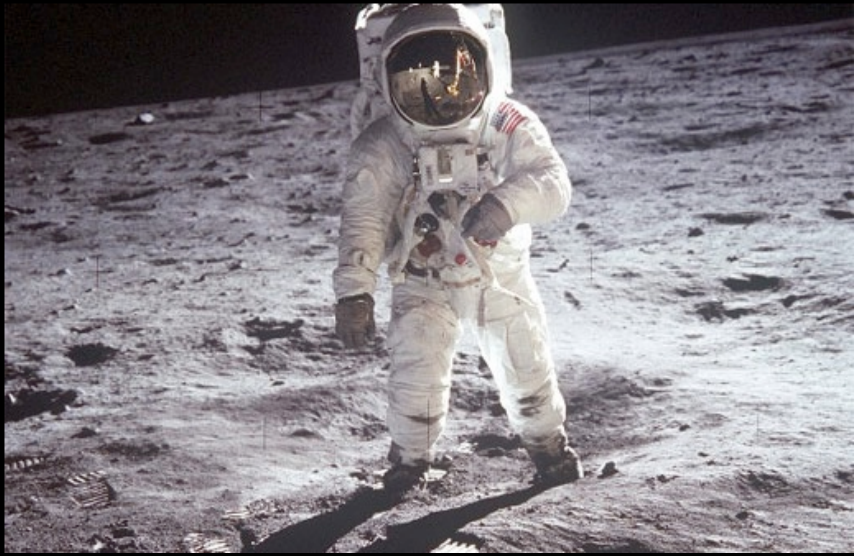
- LHC magnets have 11 GJ stored energy
  - Enough to melt 12 tons of Copper!
  - The kinetic energy of an A380 at 700 km per hour

- 23 kg of TNT
- 15 kg of chocolate

- How much energy is stored in the LHC beams? **350 MJ**

Courtesy of Jorg Wenninger

Inside the LHC

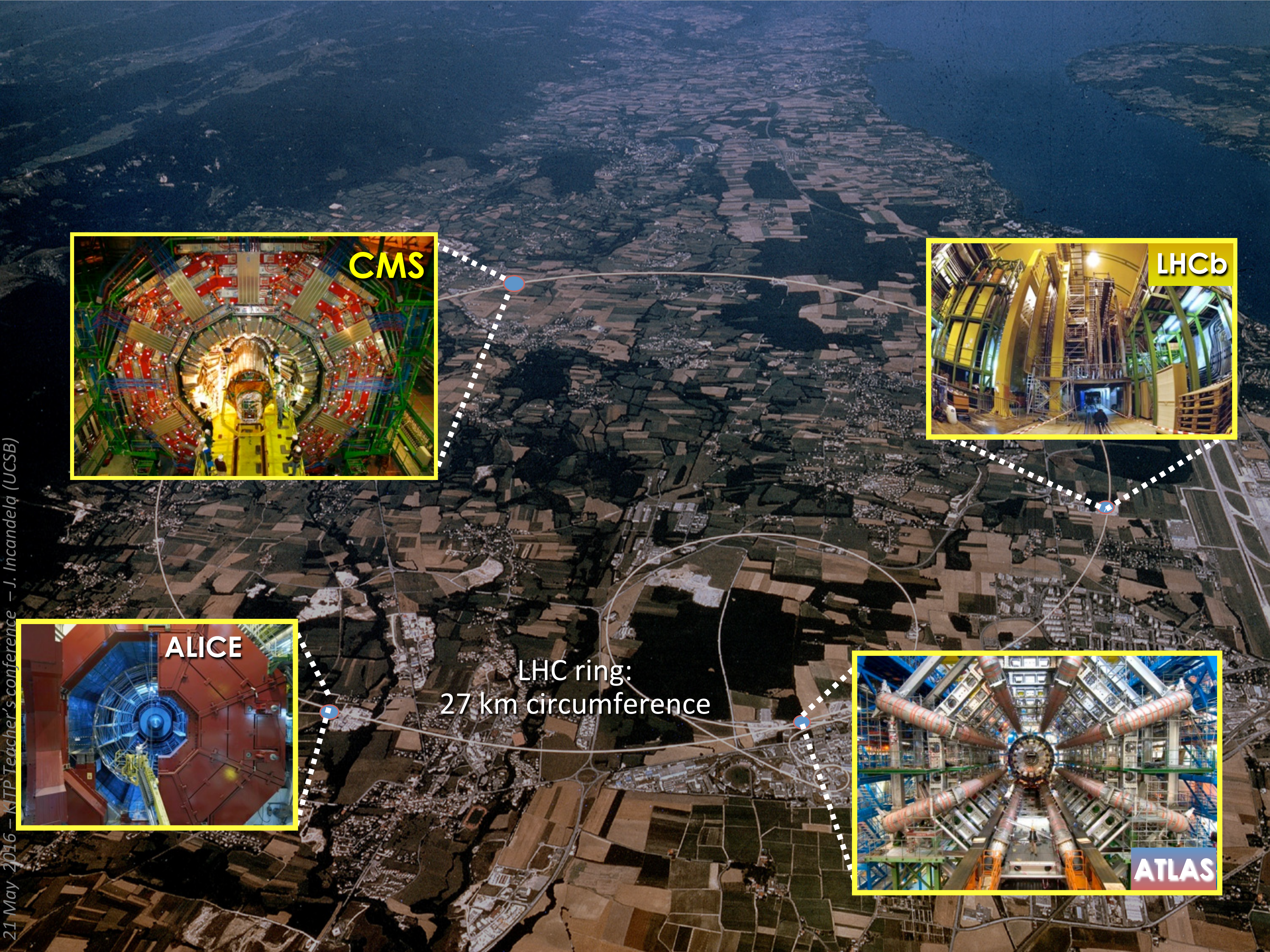


Largest cryogenic system in the world

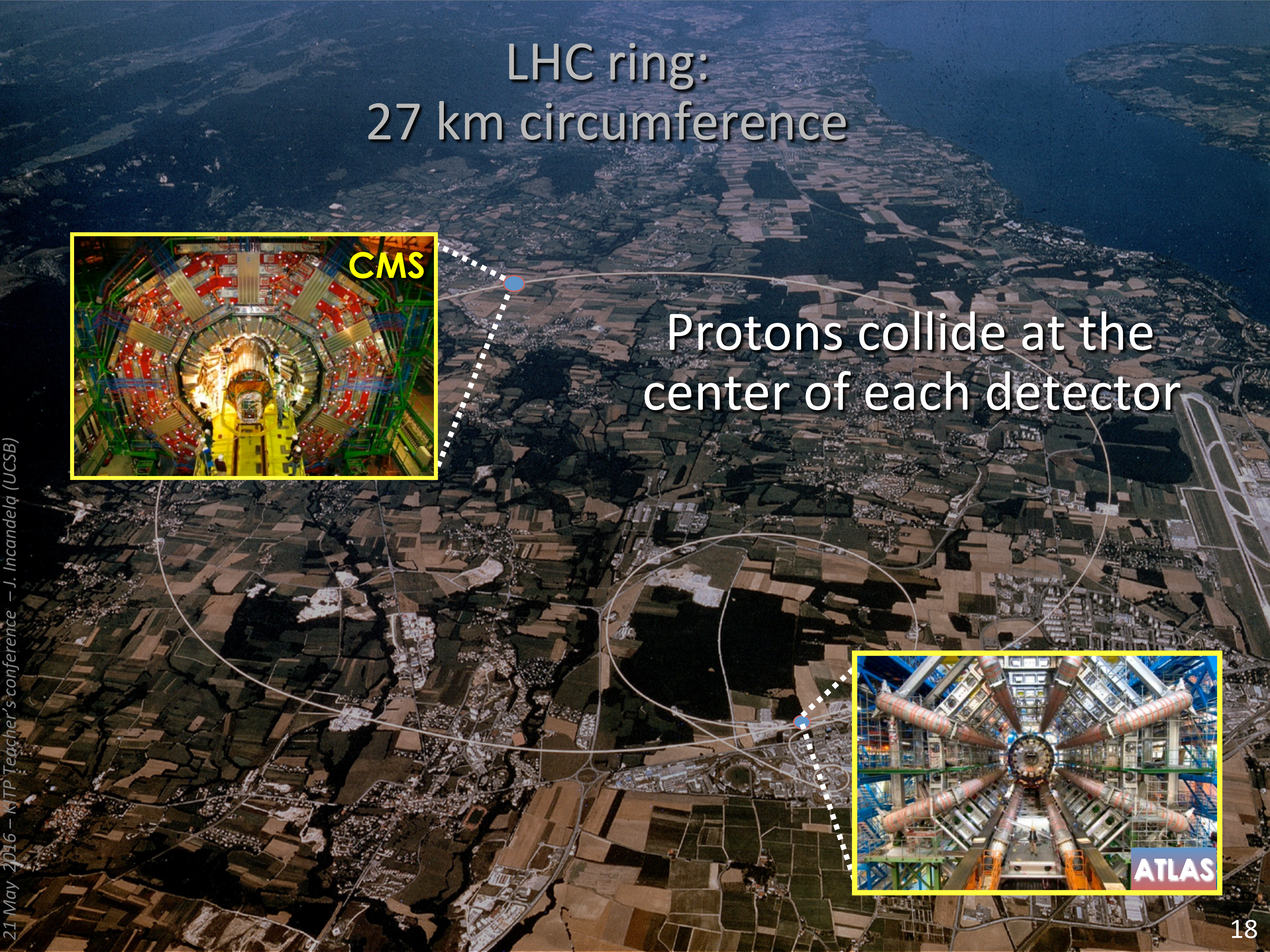
- Air pressure (inside two 16 mile-long vacuum pipes)
  - Lower than on the moon!
- Magnets cooled by 100 metric tons of superfluid helium
  - Colder than outer space!

LHC Experiments


LHC ring:
27 km circumference


CMS
LHCb
ALICE
LHC ring:
27 km circumference
ATLAS

LHC ring: 27 km circumference



Protons collide at the center of each detector

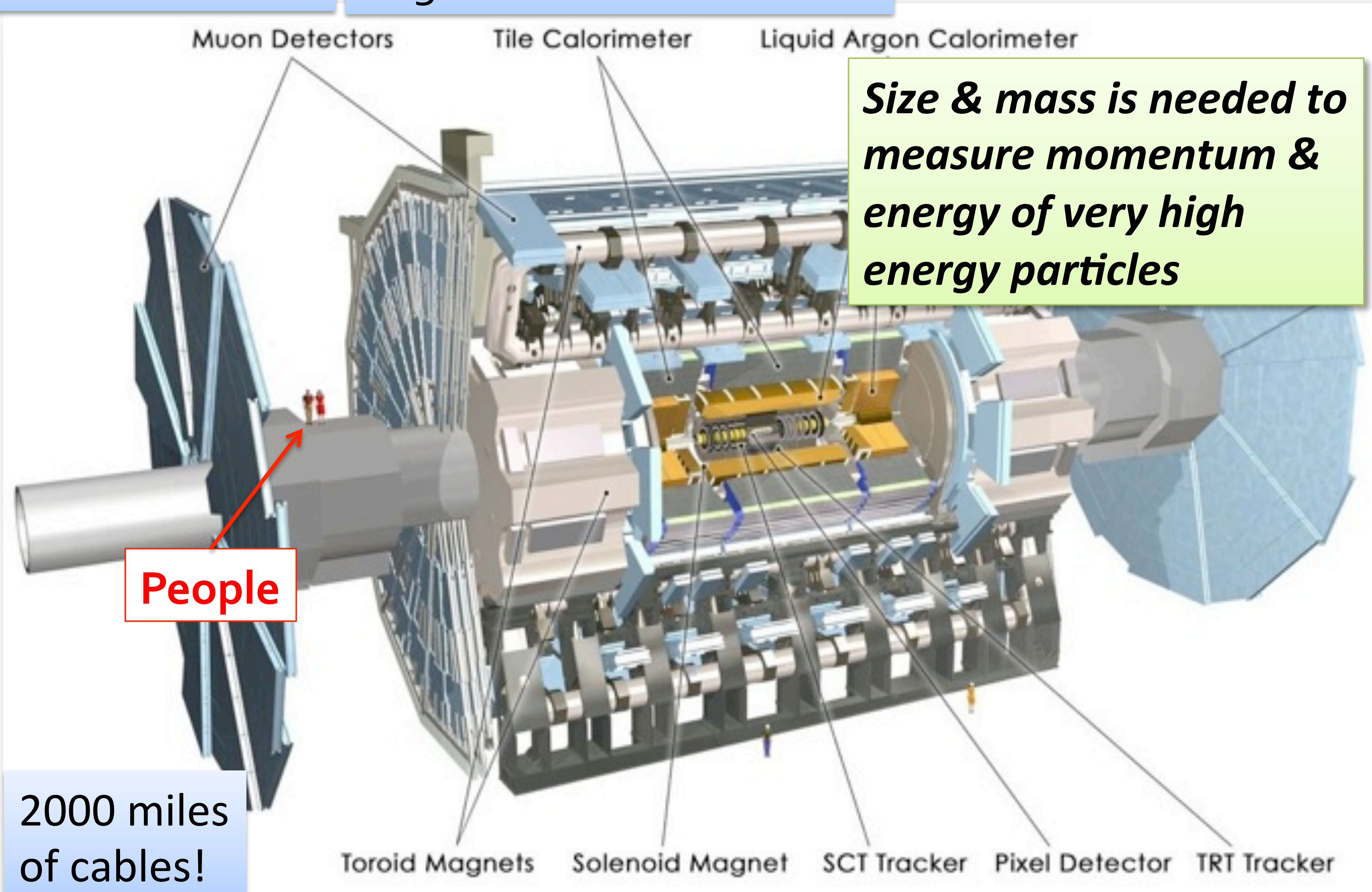
ATLAS

http://atlas.web.cern.ch/

7000 metric tons
≈ 1 Eiffel Tower

Length > ½ a football field
Height ~ 6 stories

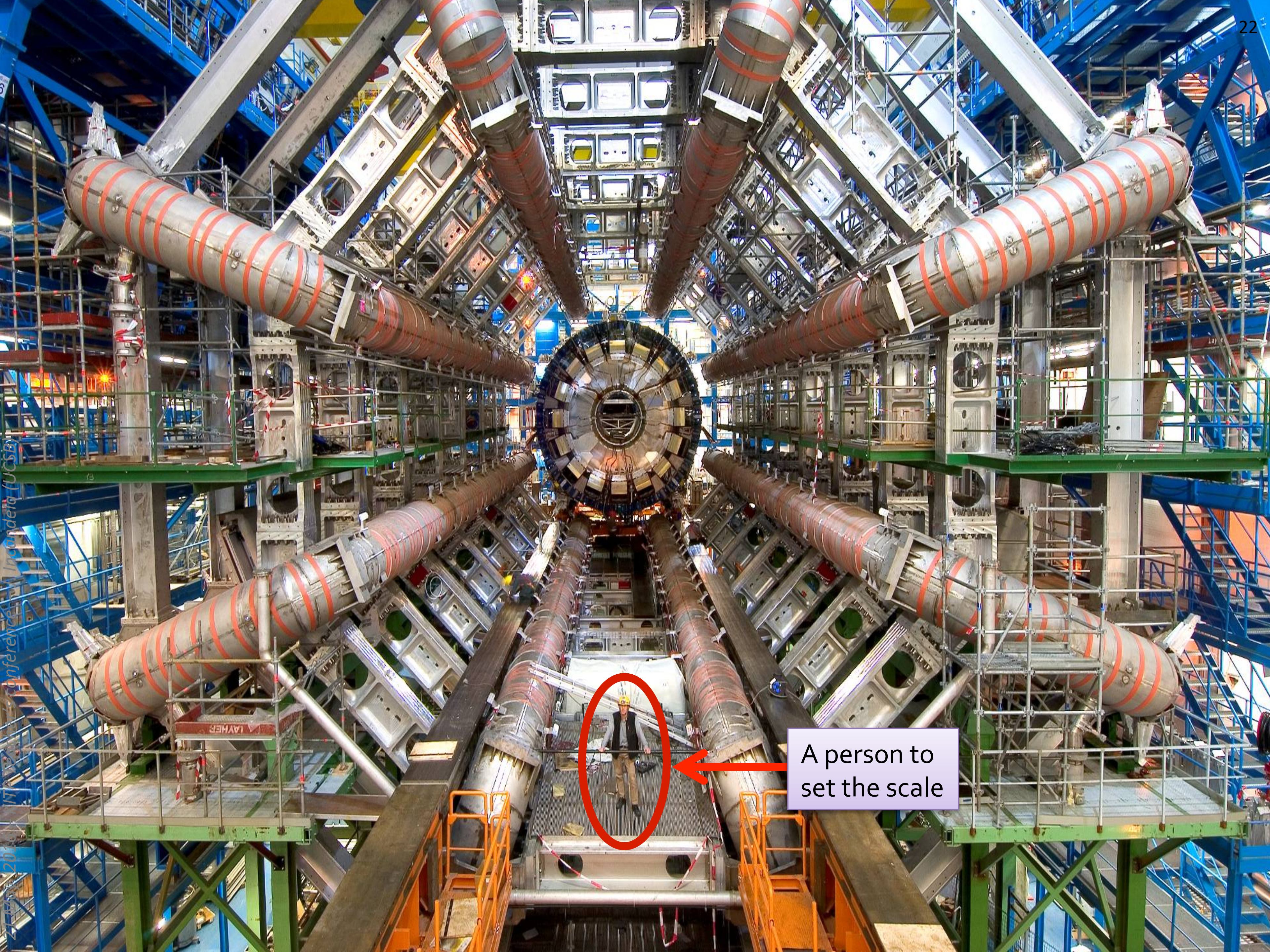
ATLAS



Size & mass is needed to measure momentum & energy of very high energy particles

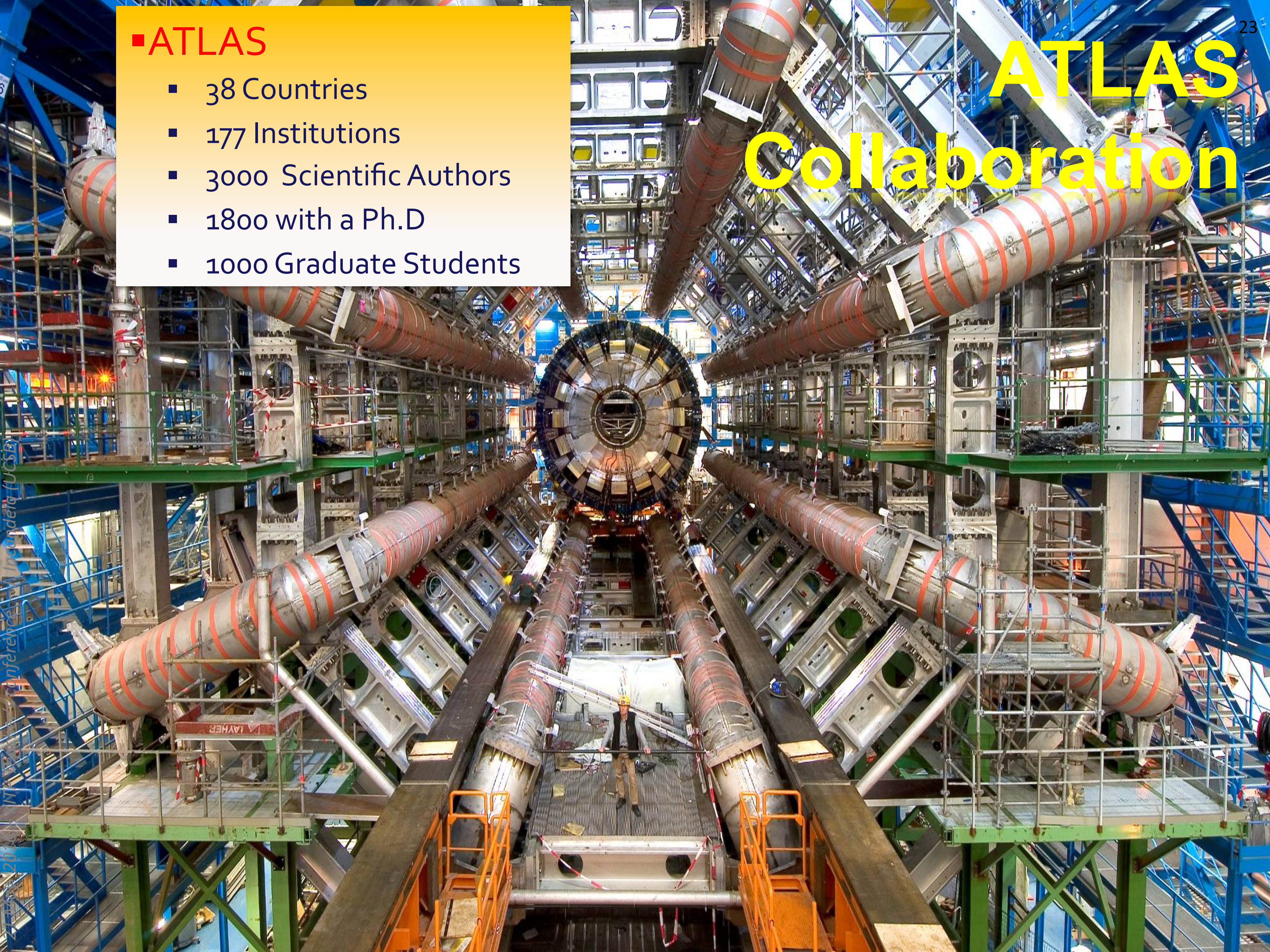
2000 miles of cables!

ATLAS cavern (-330 feet) in June 2003

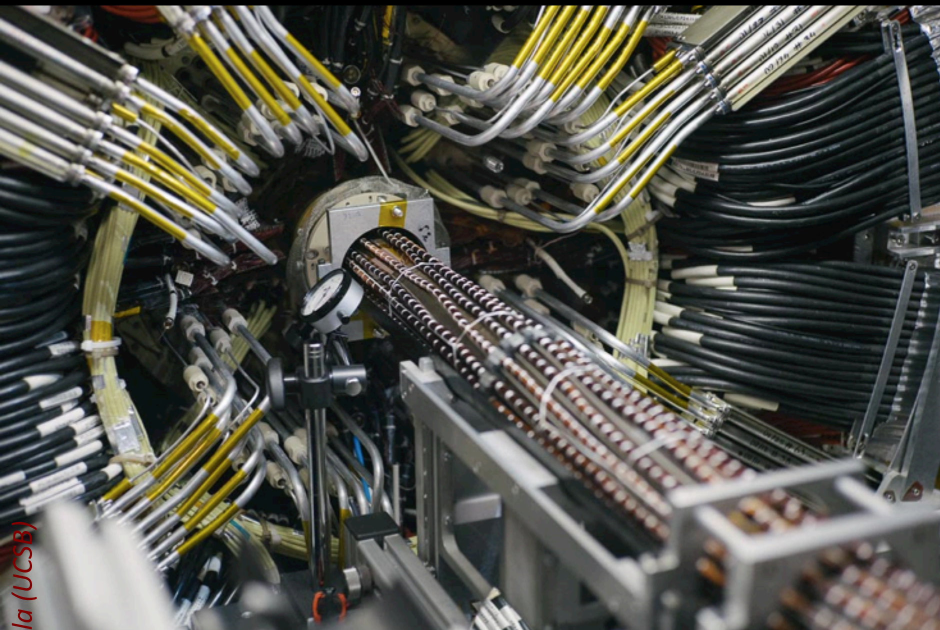

A person to
set the scale

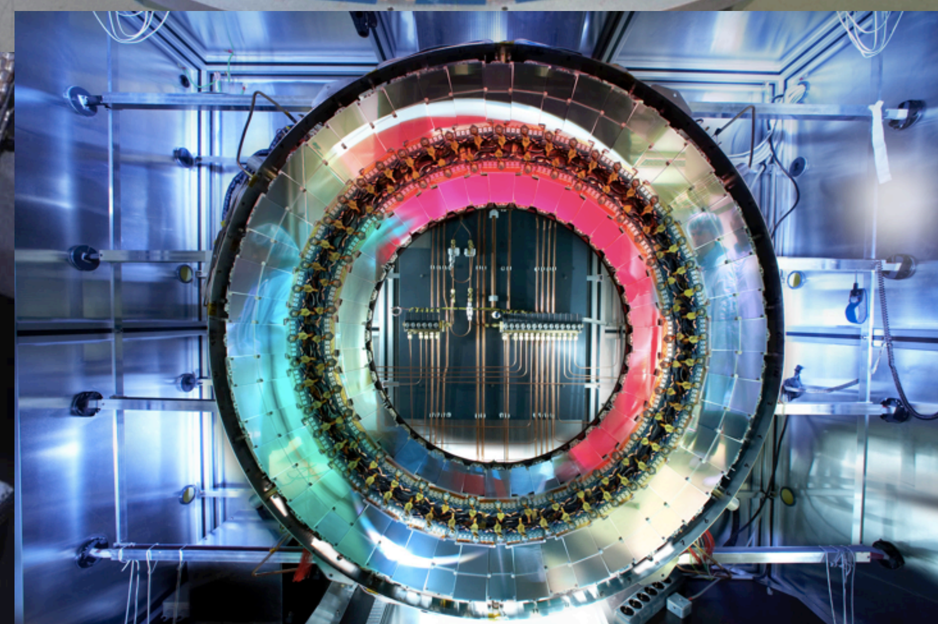
ATLAS Collaboration

- **ATLAS**
  - 38 Countries
  - 177 Institutions
  - 3000 Scientific Authors
  - 1800 with a Ph.D
  - 1000 Graduate Students



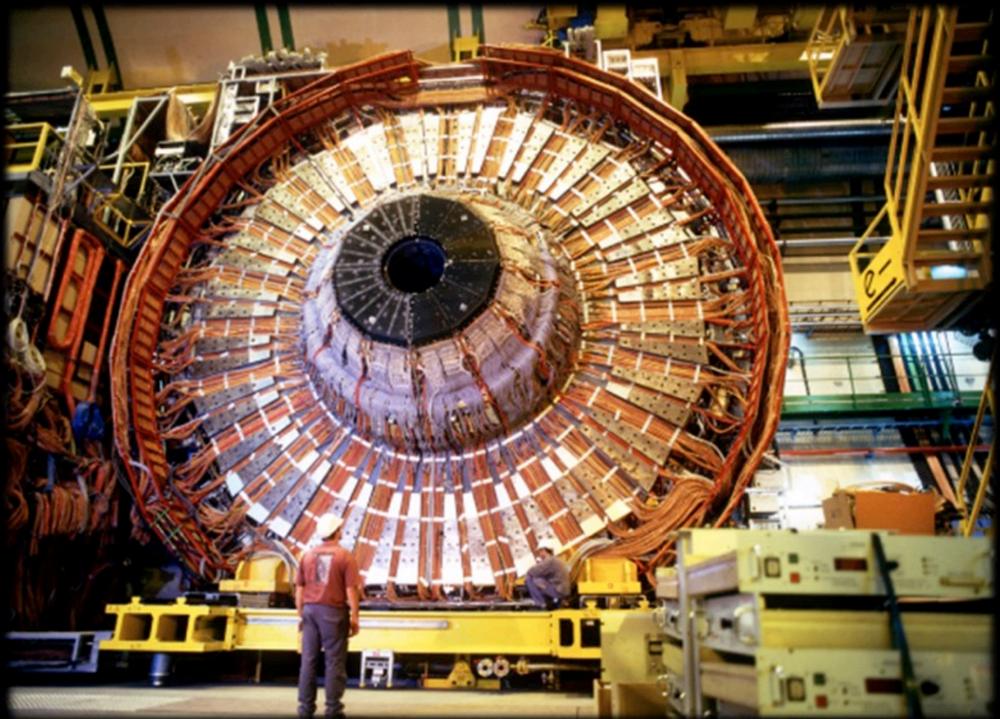
Inside ATLAS



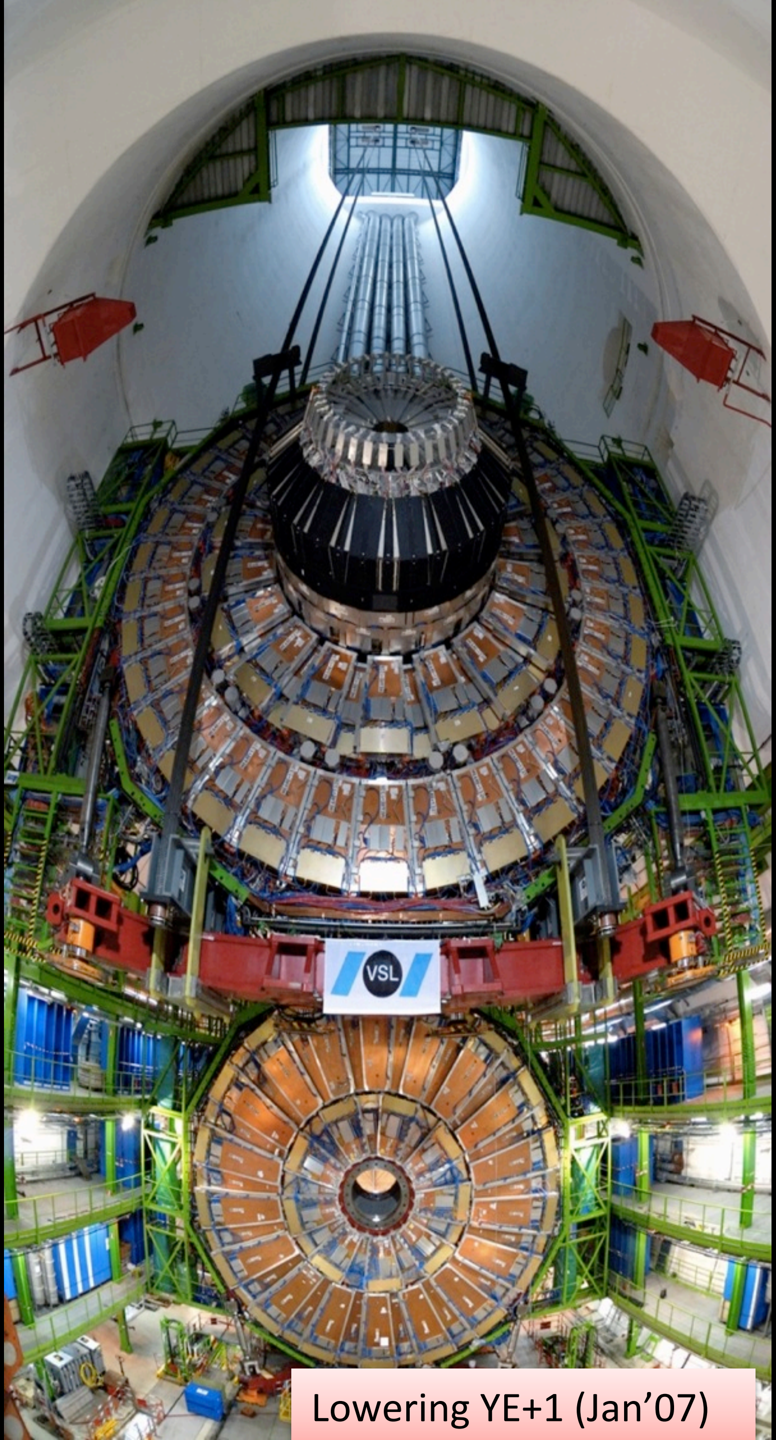


CMS

http://cms.web.cern.ch



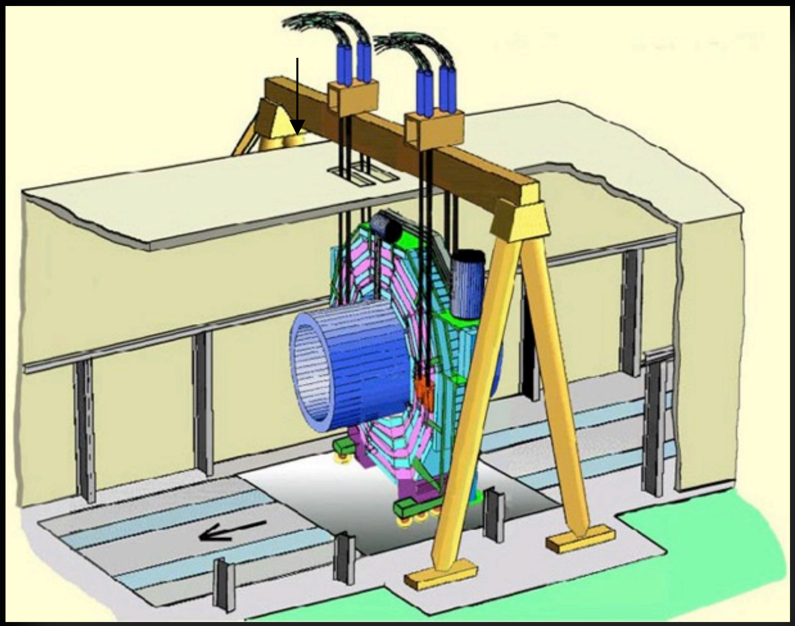
- Sections (several million pounds each) were built on the surface and then lowered ~300 feet (~25 stories) underground

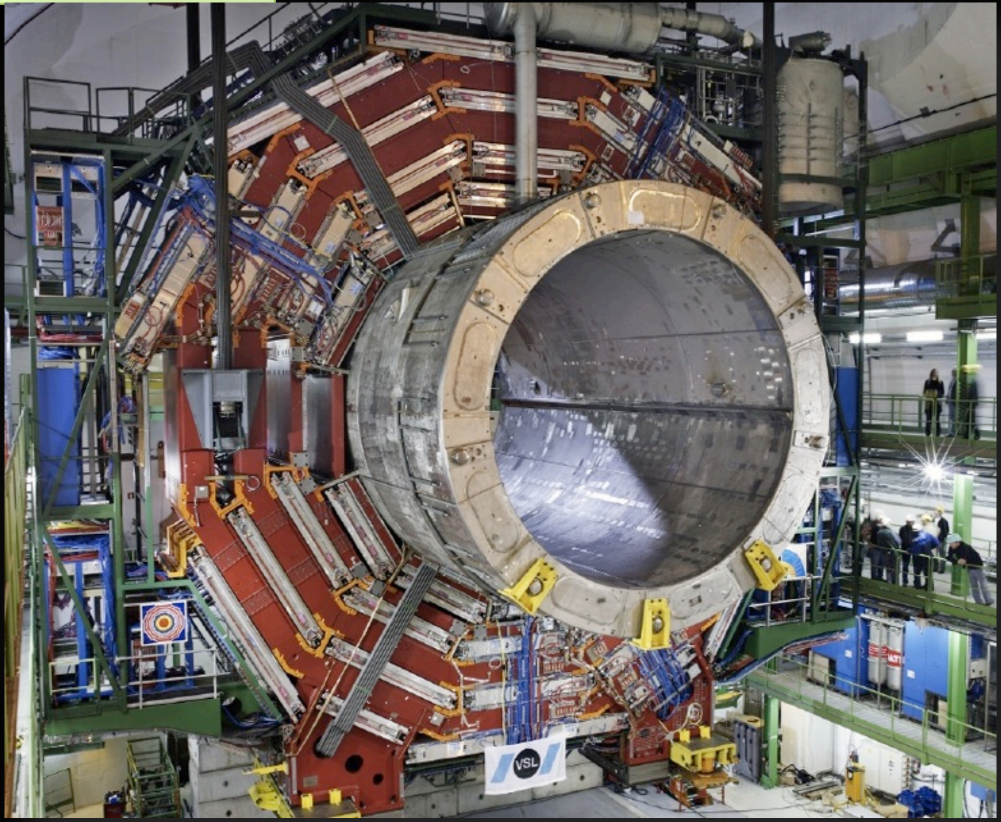


Lowering YE+1 (Jan'07)

Lowering of the heaviest slice
(4.4 million pounds) of the CMS detector
In the underground cavern Feb. 2007

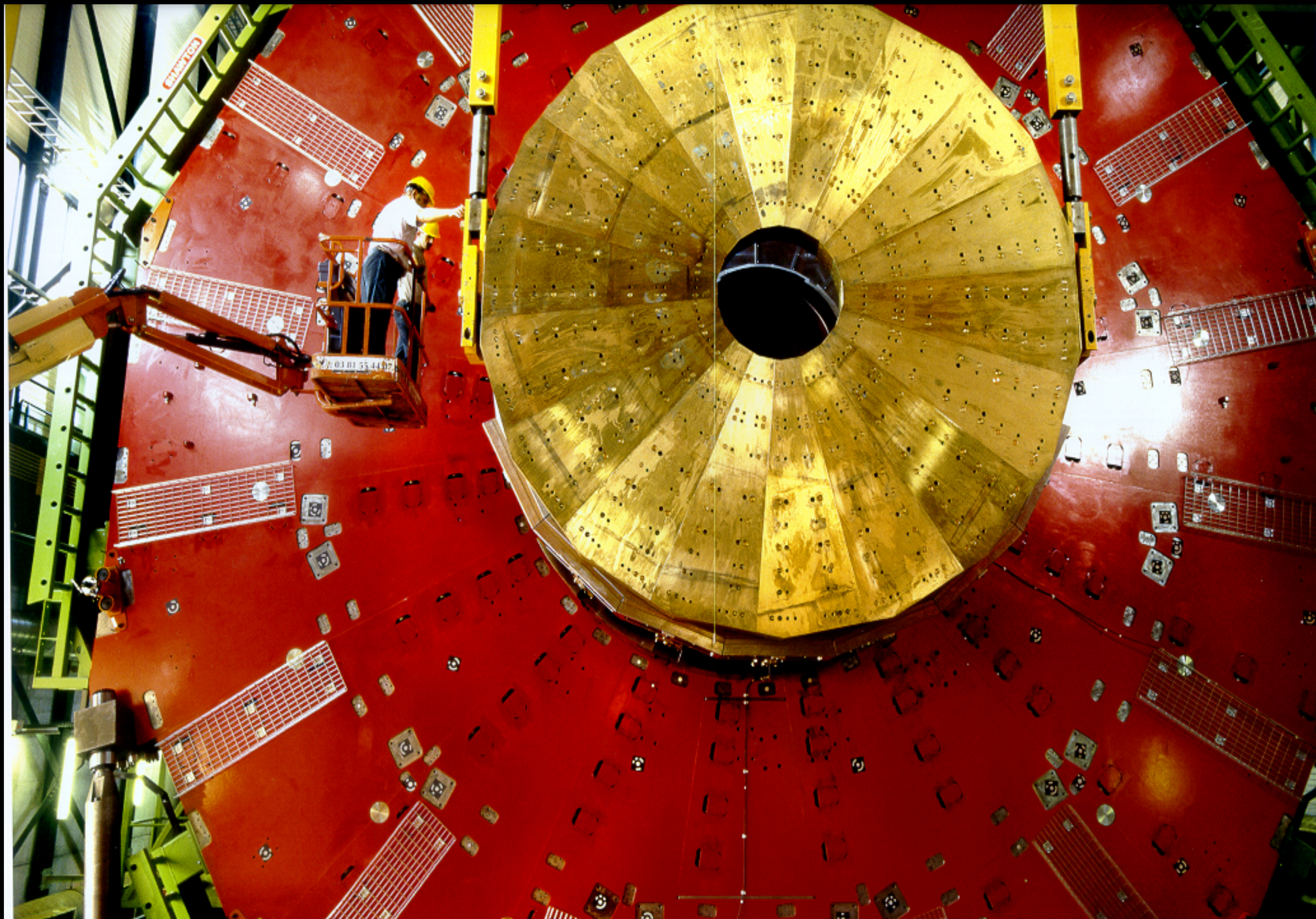
CMS



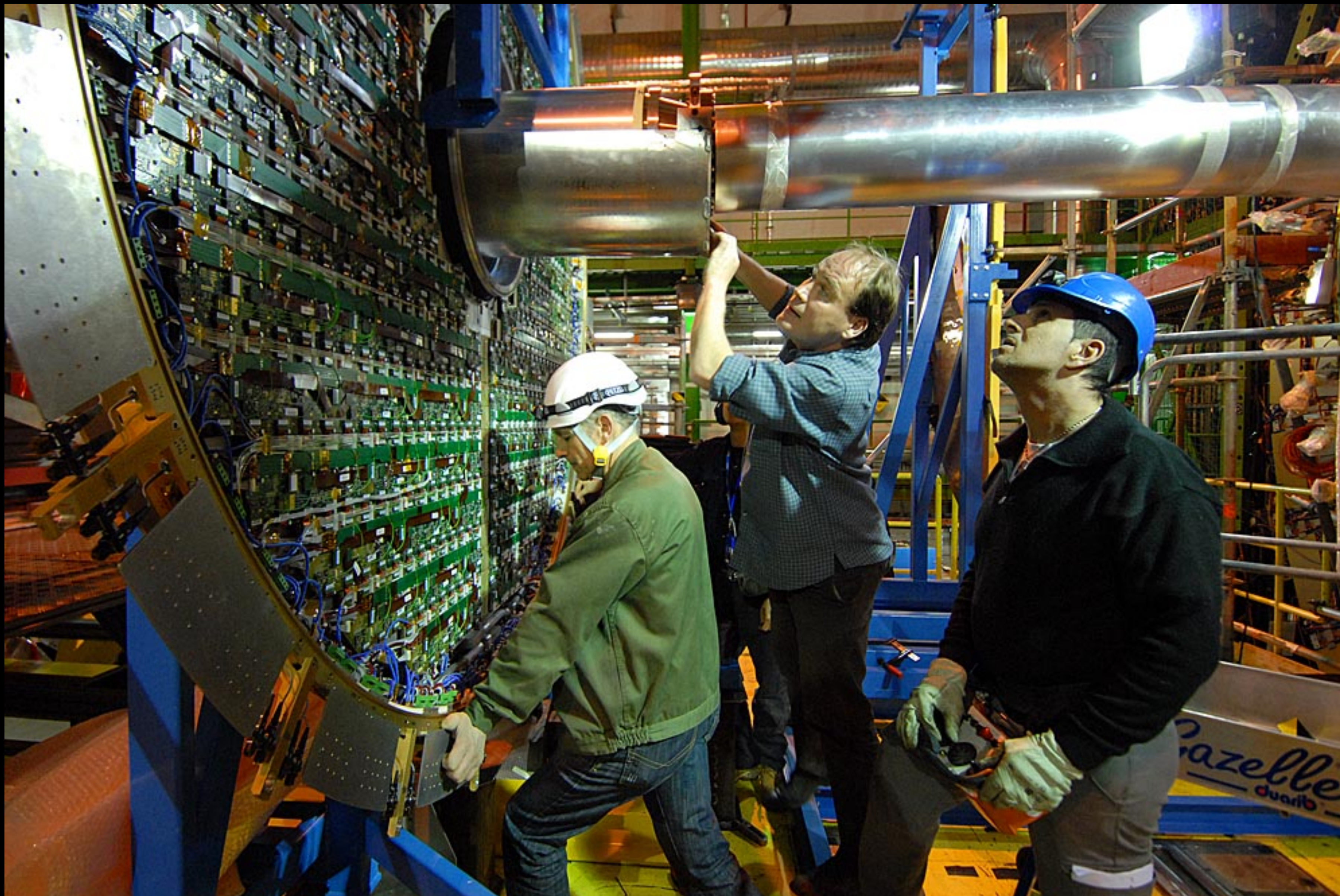


Largest, most powerful
superconducting magnet

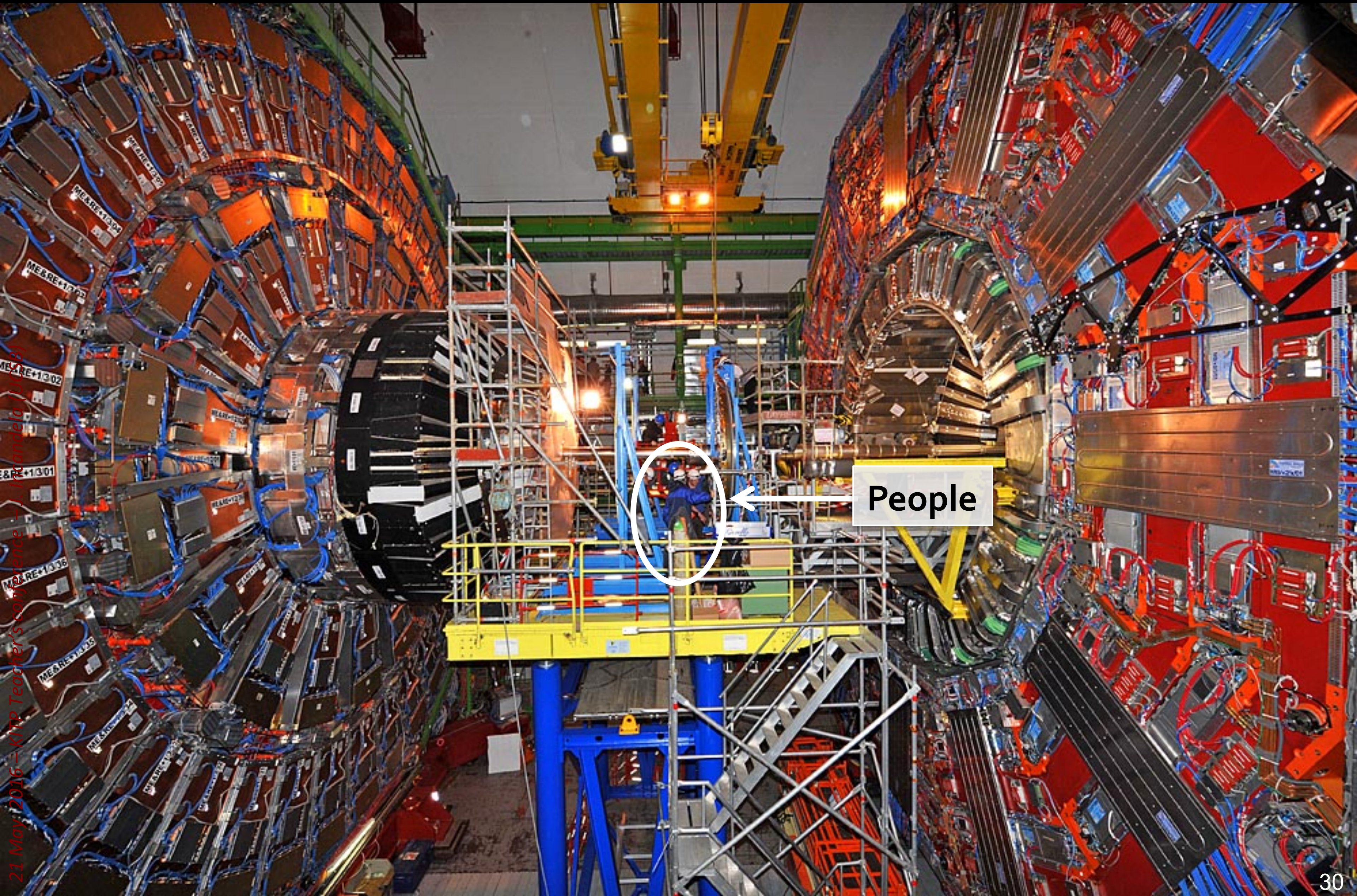
We Recycle



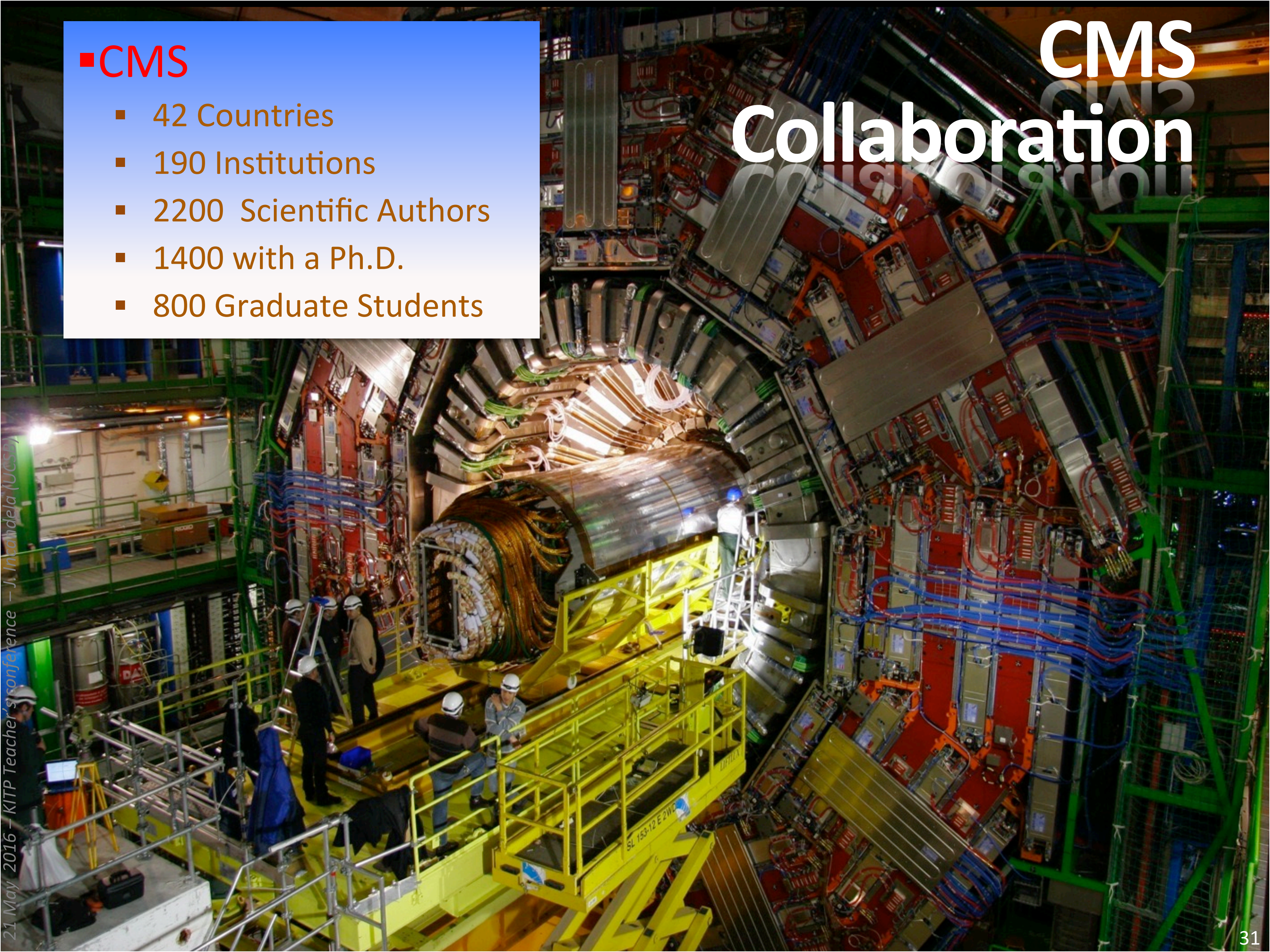
The last piece (2009)



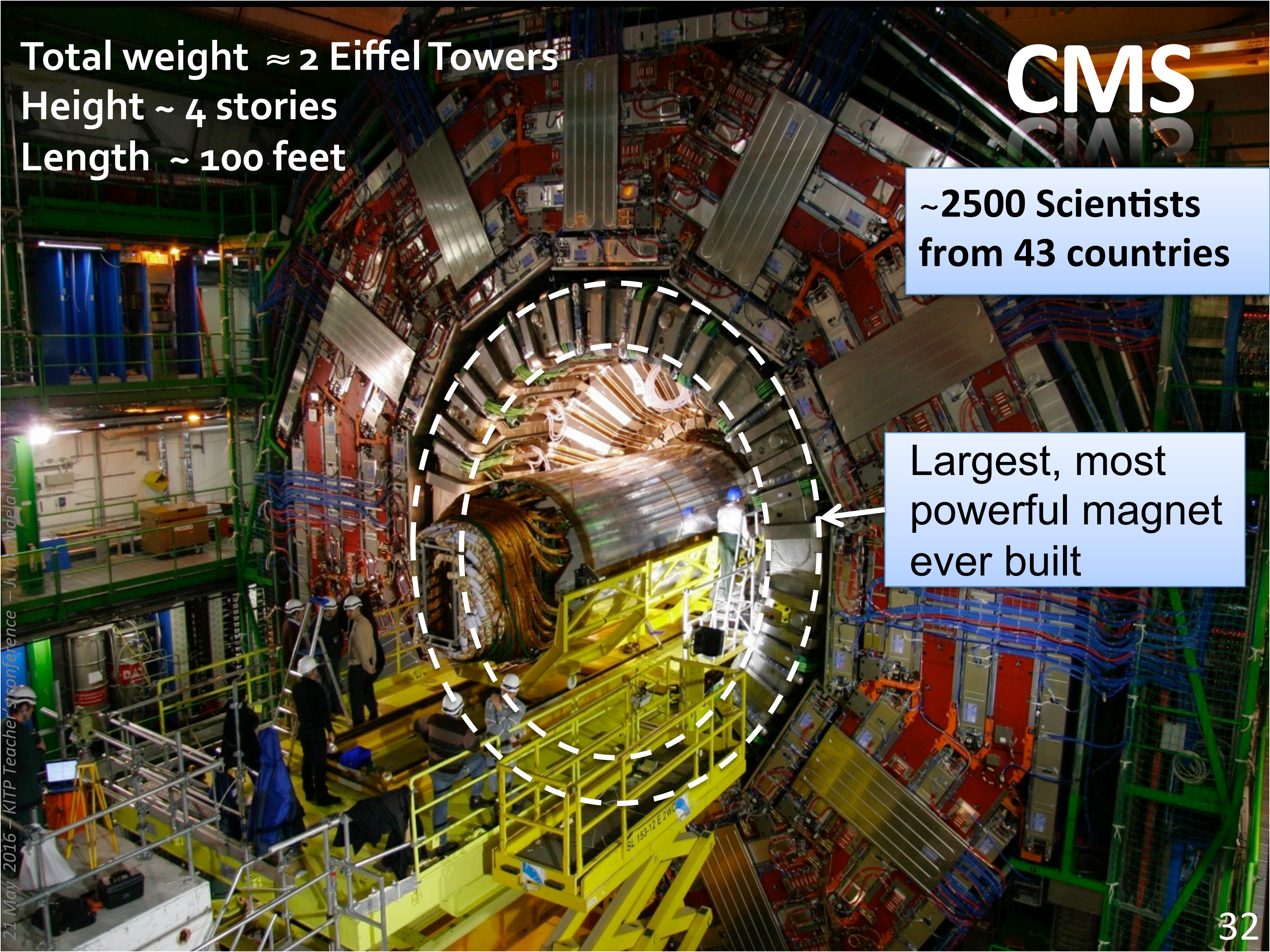
The last piece (2009)



CMS Collaboration

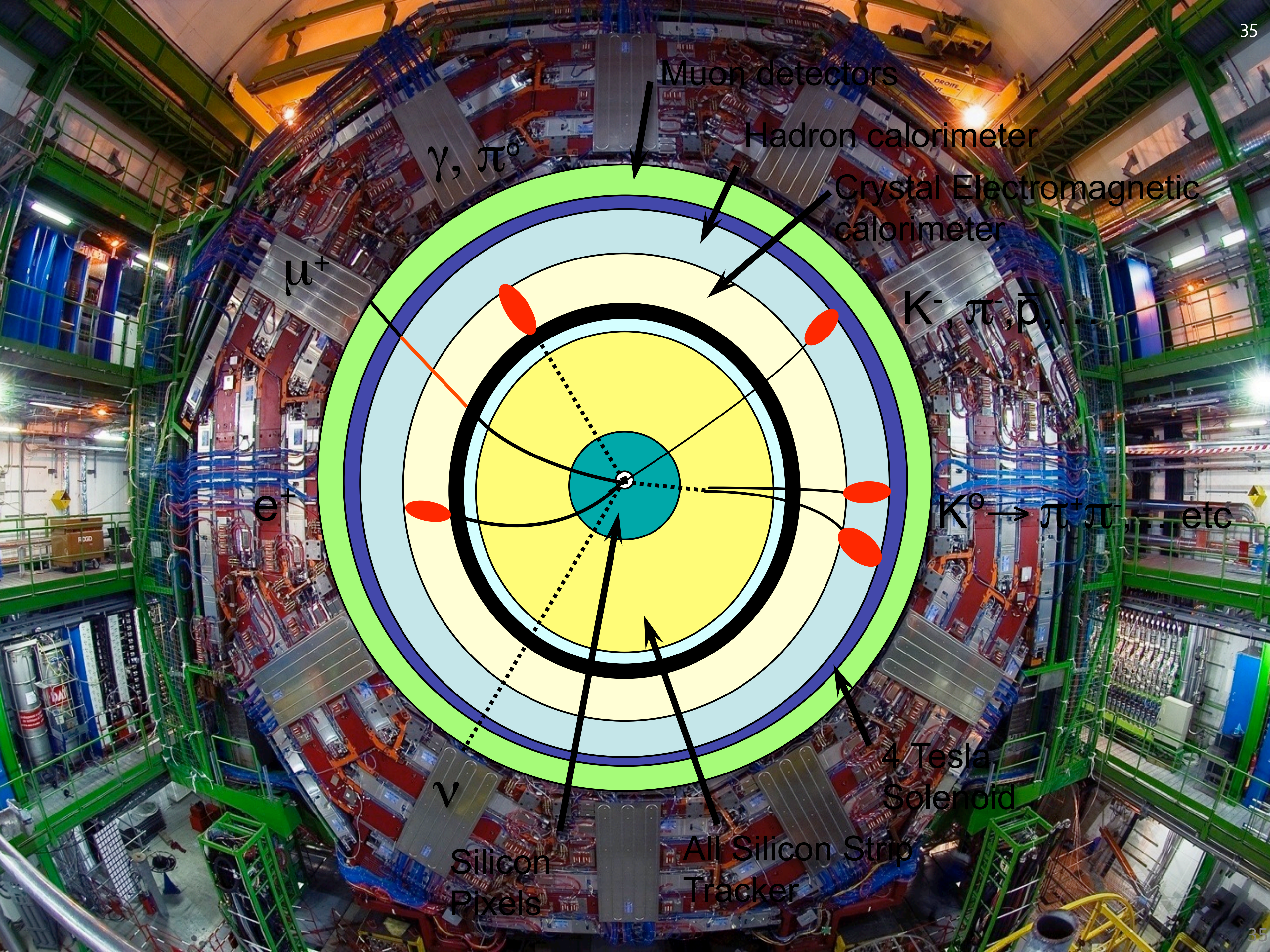


- CMS
  - 42 Countries
  - 190 Institutions
  - 2200 Scientific Authors
  - 1400 with a Ph.D.
  - 800 Graduate Students


Total weight ≈ 2 Eiffel Towers
Height ~ 4 stories
Length ~ 100 feet
CMS
~2500 Scientists from 43 countries
Largest, most powerful magnet ever built
SL 153-12 E 2WD

Inside CMS

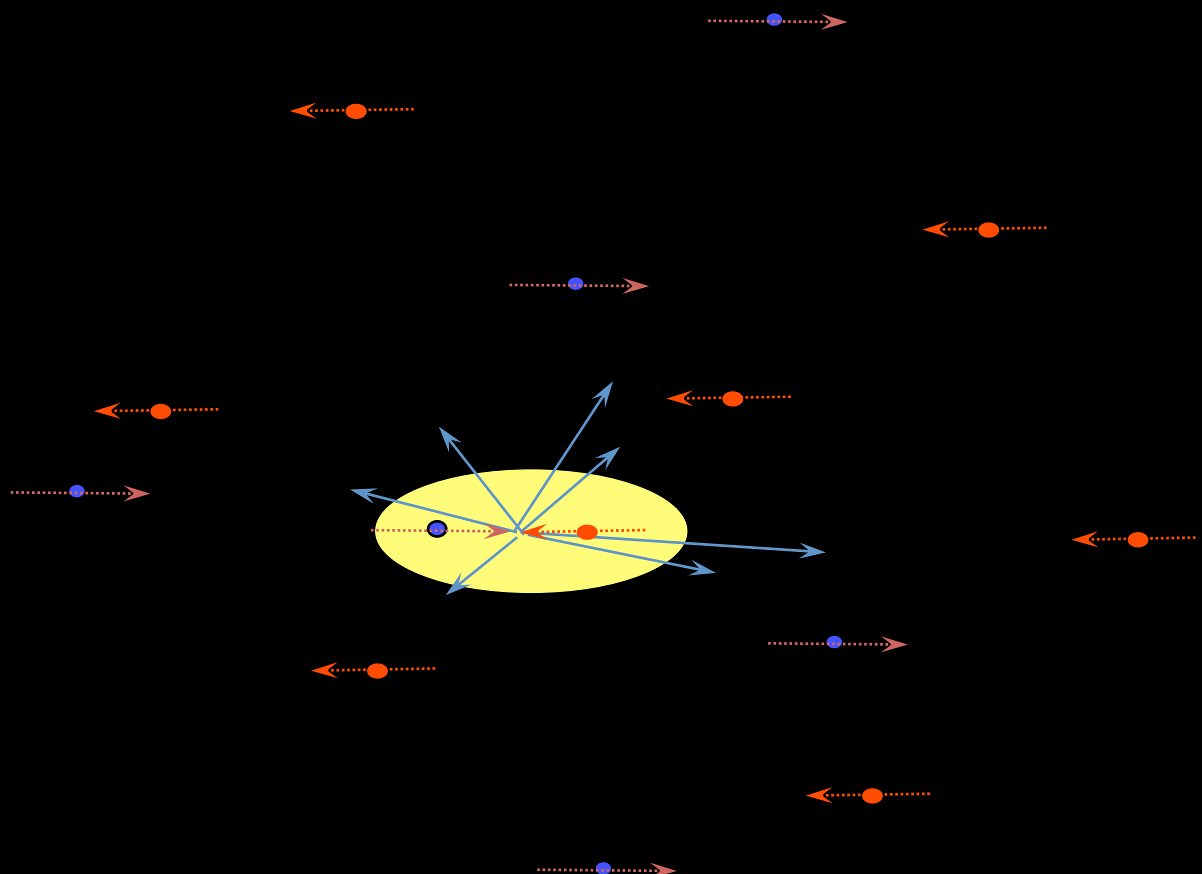

Newsweek
The Biggest Experiment Ever
(And It's European)
The new CERN collider in Geneva

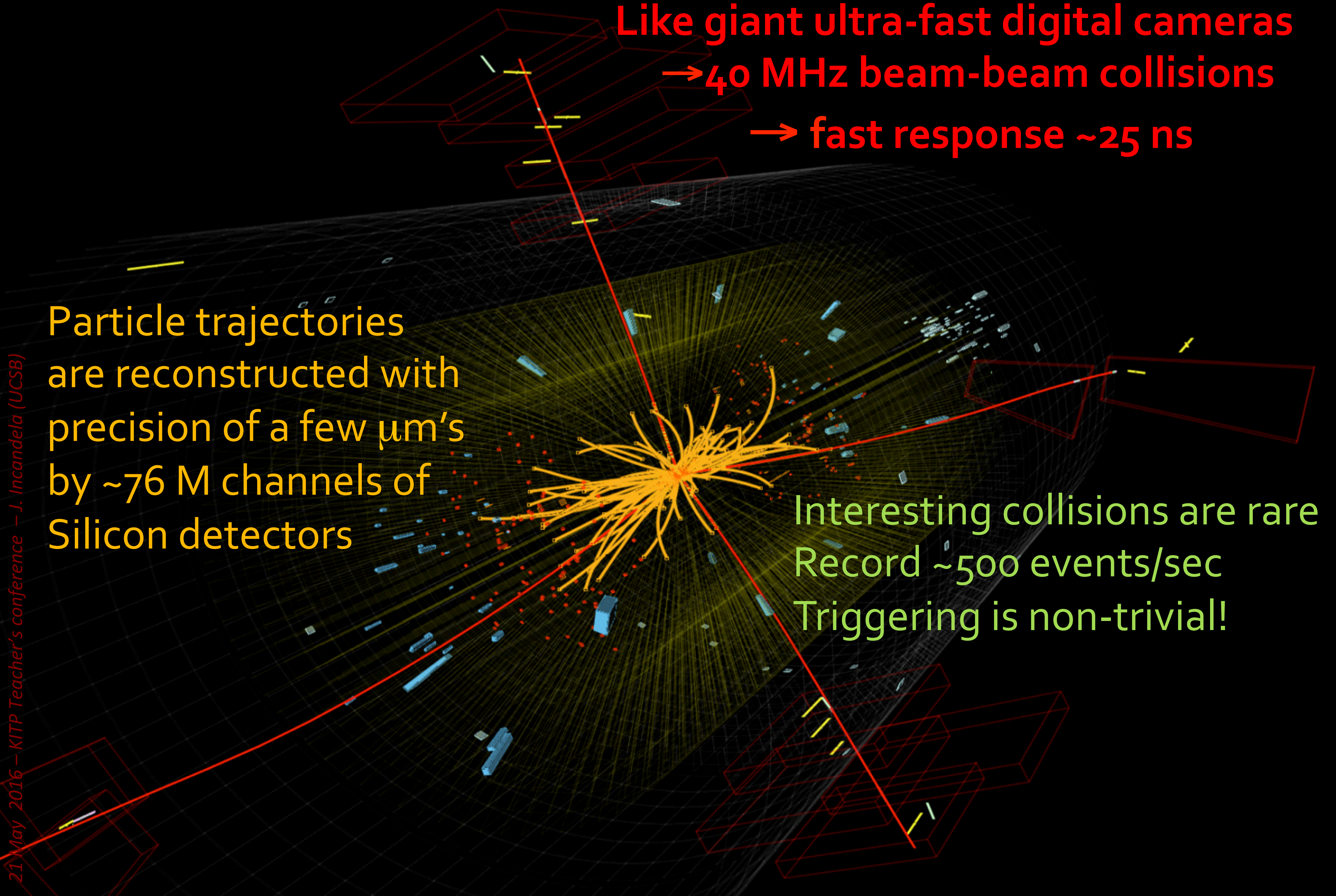

Muon detectors
Hadron calorimeter
Crystal Electromagnetic calorimeter
γ, π^o
μ^+
$K^-, \pi^-, \bar{p}, \ldots$
e^+
$K^o \rightarrow \pi^+\pi^-, \ldots$ etc
ν
4 Tesla Solenoid
Silicon Pixels
All Silicon Strip Tracker

Colliding Beams

2 beams of ~2000 bunches go around the LHC in opposite directions. A bunch has 100 billion protons.

~20-30 pp collisions each time bunches cross in CMS/ATLAS





Like giant ultra-fast digital cameras
→40 MHz beam-beam collisions
→ fast response ~25 ns

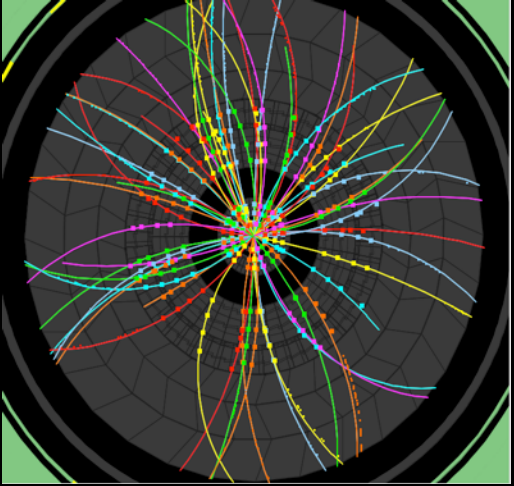
Particle trajectories are reconstructed with precision of a few μm's by ~76 M channels of Silicon detectors

Interesting collisions are rare
Record ~500 events/sec
Triggering is non-trivial!

More challenges

The pileup challenge for Physics

Events taken at random (filled) bunch crossings



2010

O(2) Pile-up events

150 ns inter-bunch spacing

2011

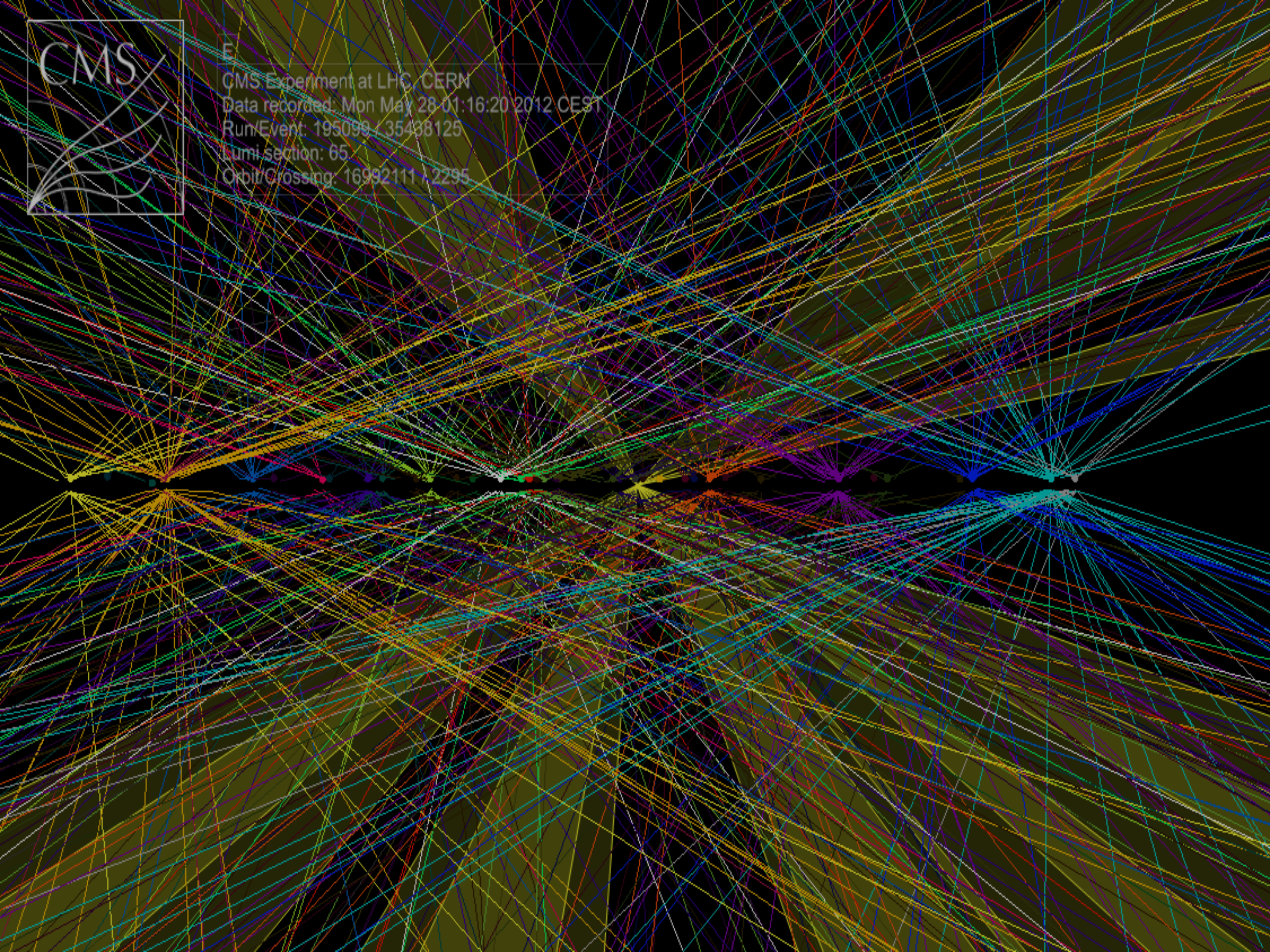
O(5-10) Pile-up events

50-75 ns inter-bunch spacing

2012

O(20-30) Pile-up events

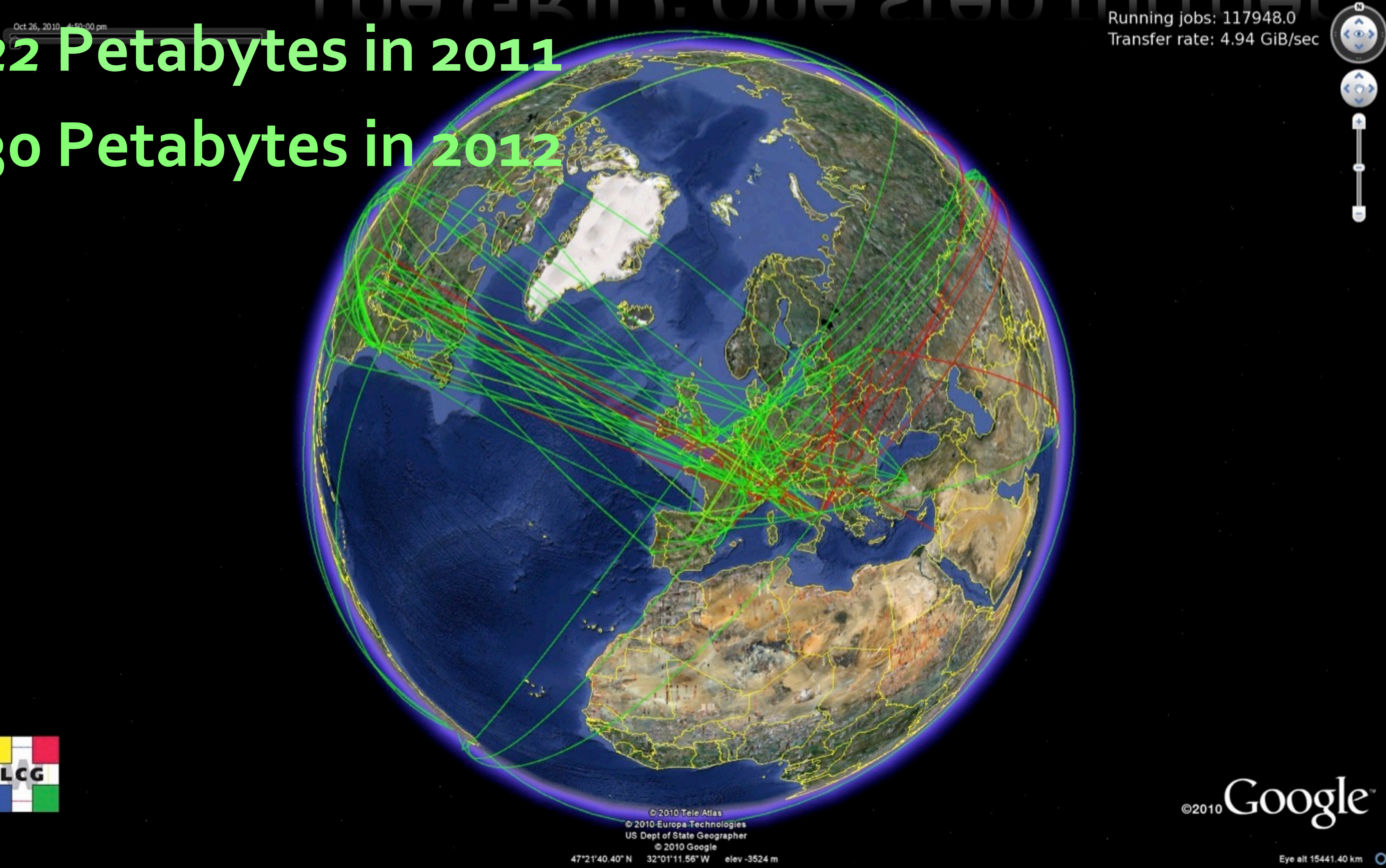
50 ns inter-bunch spacing


CMS
E
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CEST
Run/Event: 195099 / 35438125
Lumi section: 65
Orbit/Crossing: 16992111 / 2295

The GRID: one step further

22 Petabytes in 2011

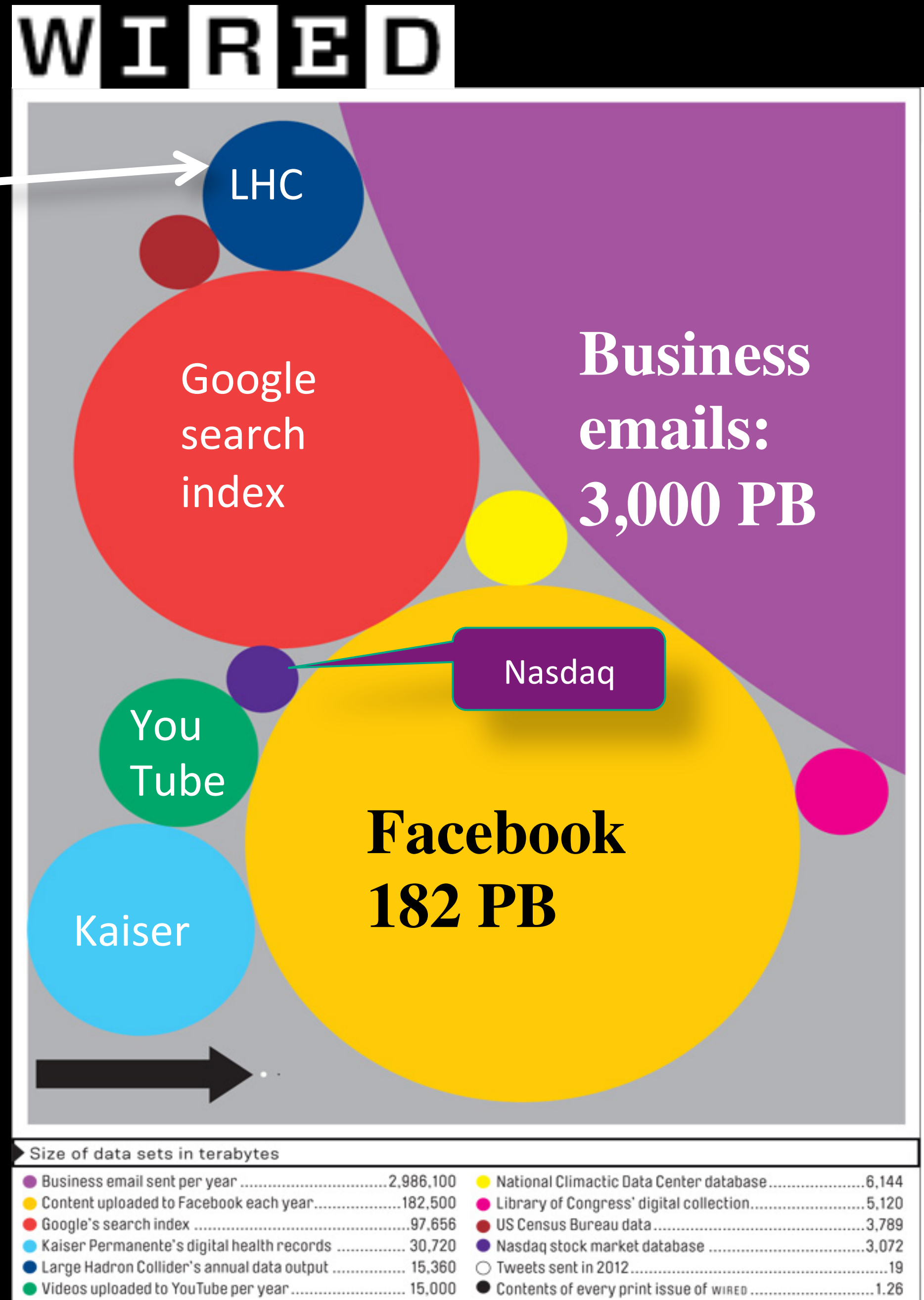
30 Petabytes in 2012



- *Computing grid ~400,000 processors in ~50 countries*

LHC so far

Estimate 1,000 times larger dataset before we are through



Discovery

Most sensitive decays

- For a mass of around 100 times the proton mass:

$H \rightarrow ZZ^* \rightarrow$ 4leptons

$H \rightarrow \gamma\gamma$

Most important channels initially because Can look for a peak or bump in the Mass spectrum

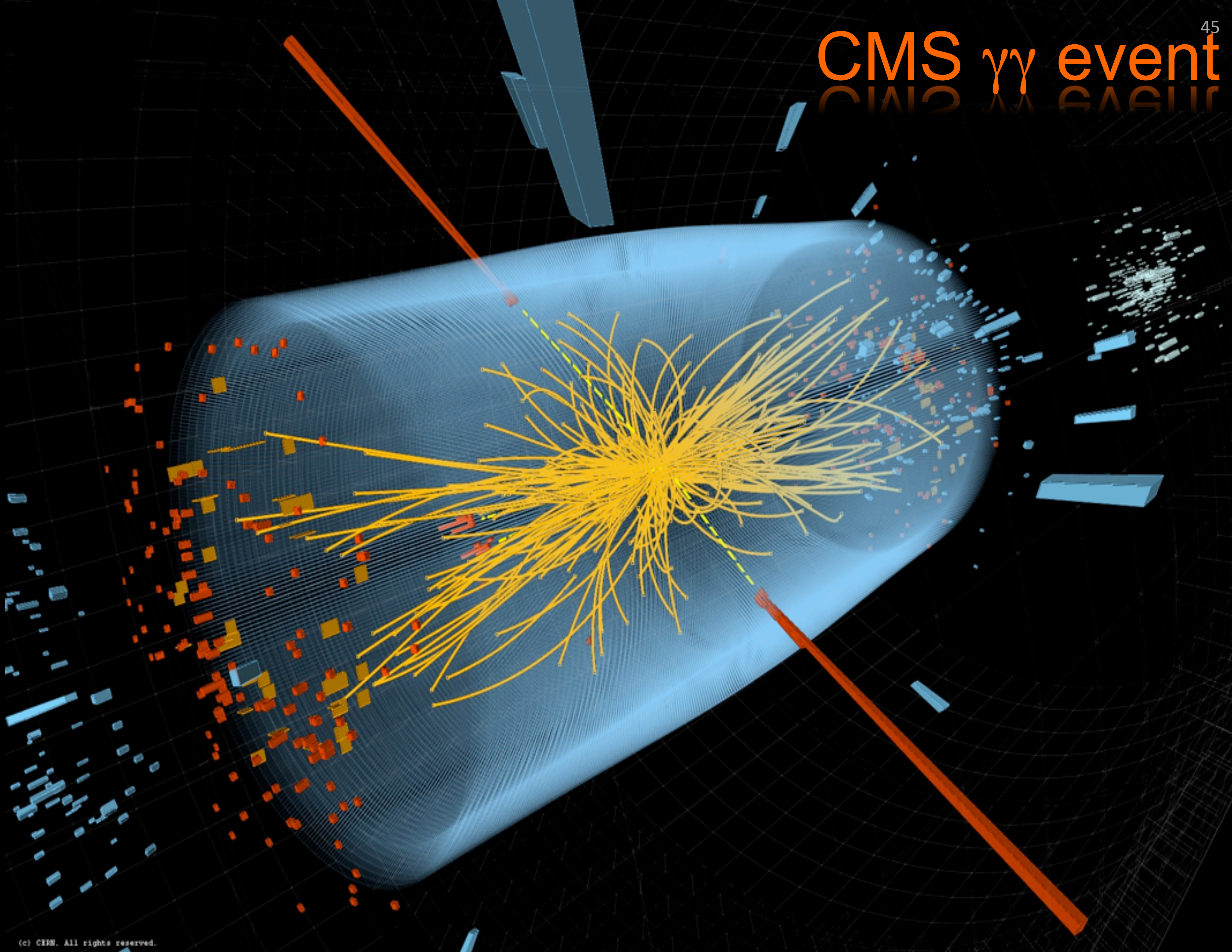
$H \rightarrow WW^* \rightarrow l\nu l\nu$

$H \rightarrow \tau\tau$

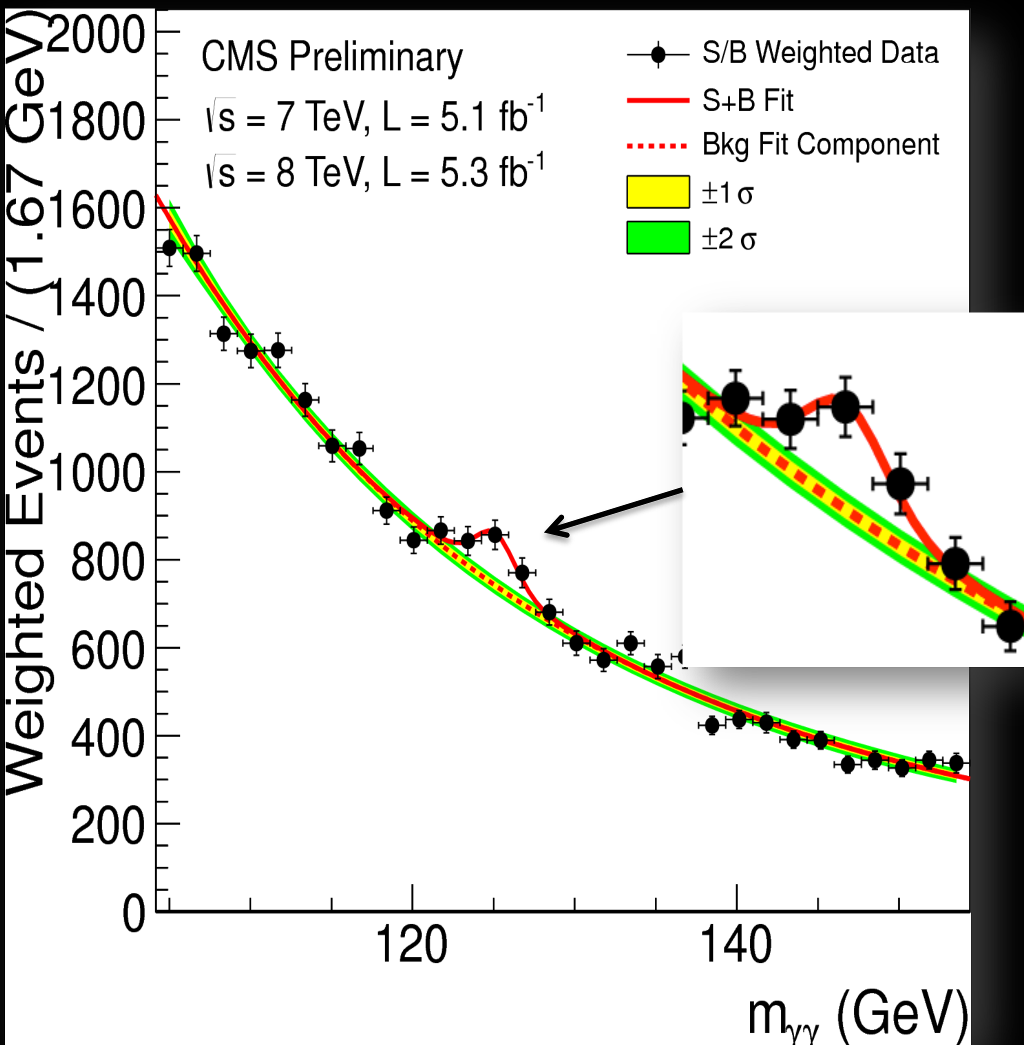
$H \rightarrow bb$

- Tiny rates, low S/B, complex final state

CMS γγ event

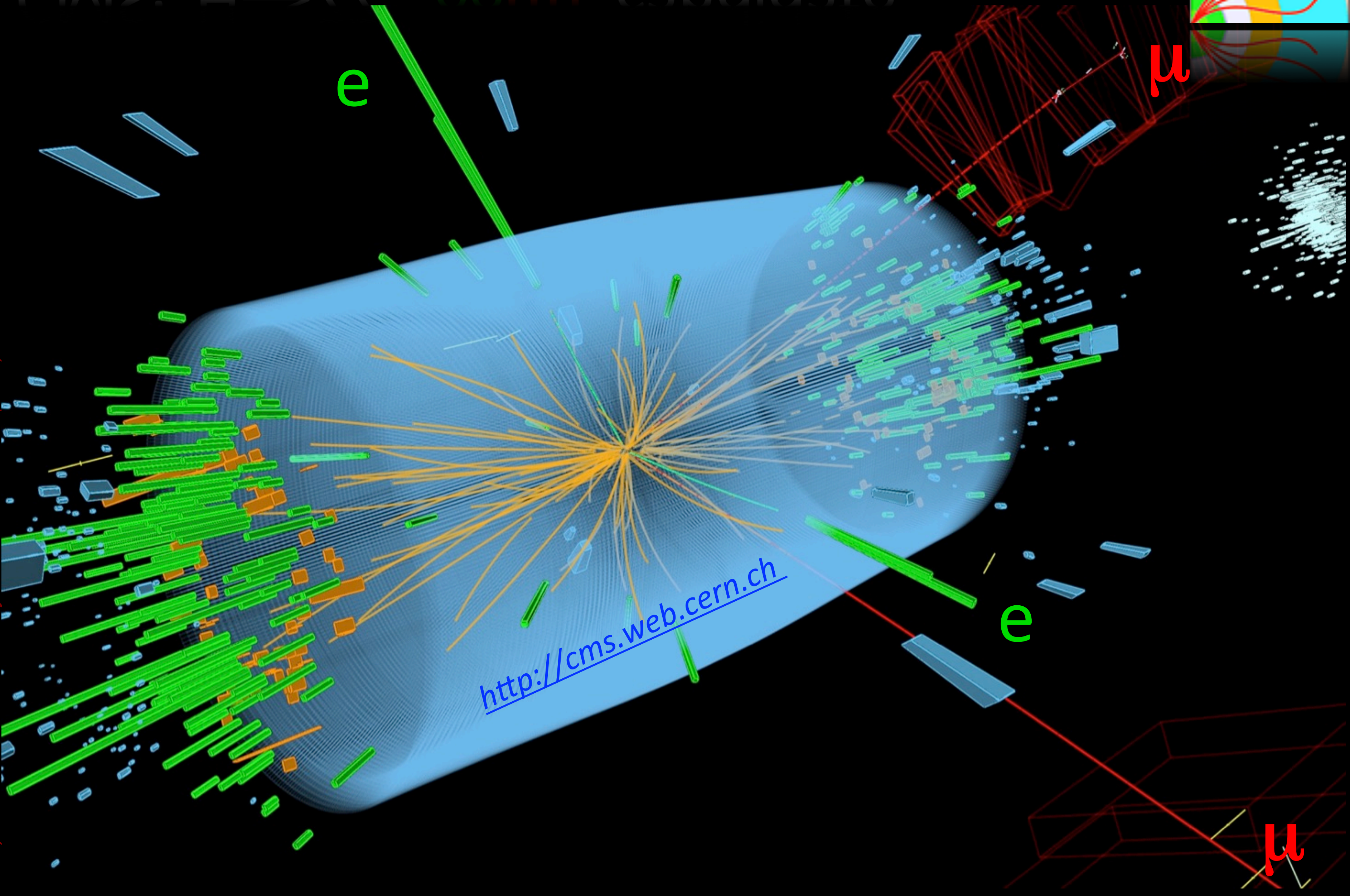


$\gamma\gamma$ Mass Distribution

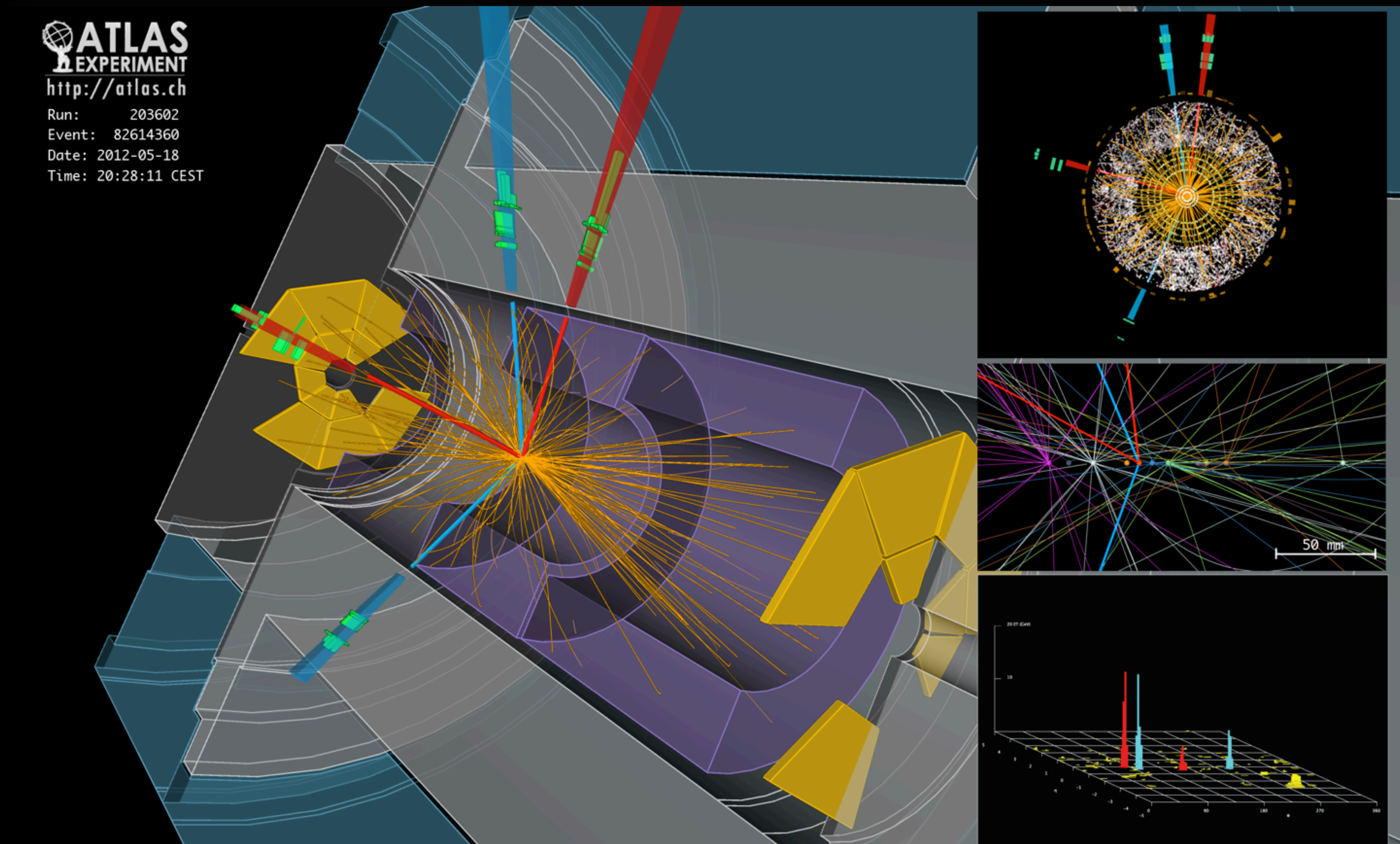


- What's in the bump?
  - A few hundred extra events with two photons that reconstruct to a mass near 125 GeV
- It took how many collisions?
  - 10^{15} 1,000,000,000,000,000

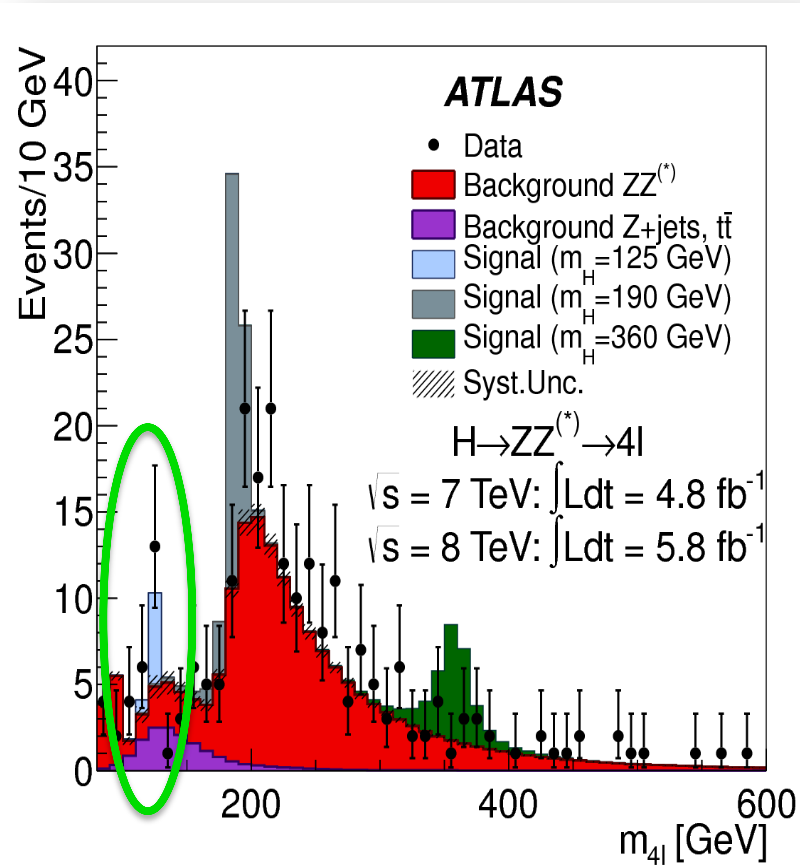
CMS: H→ZZ→eeμμ candidate

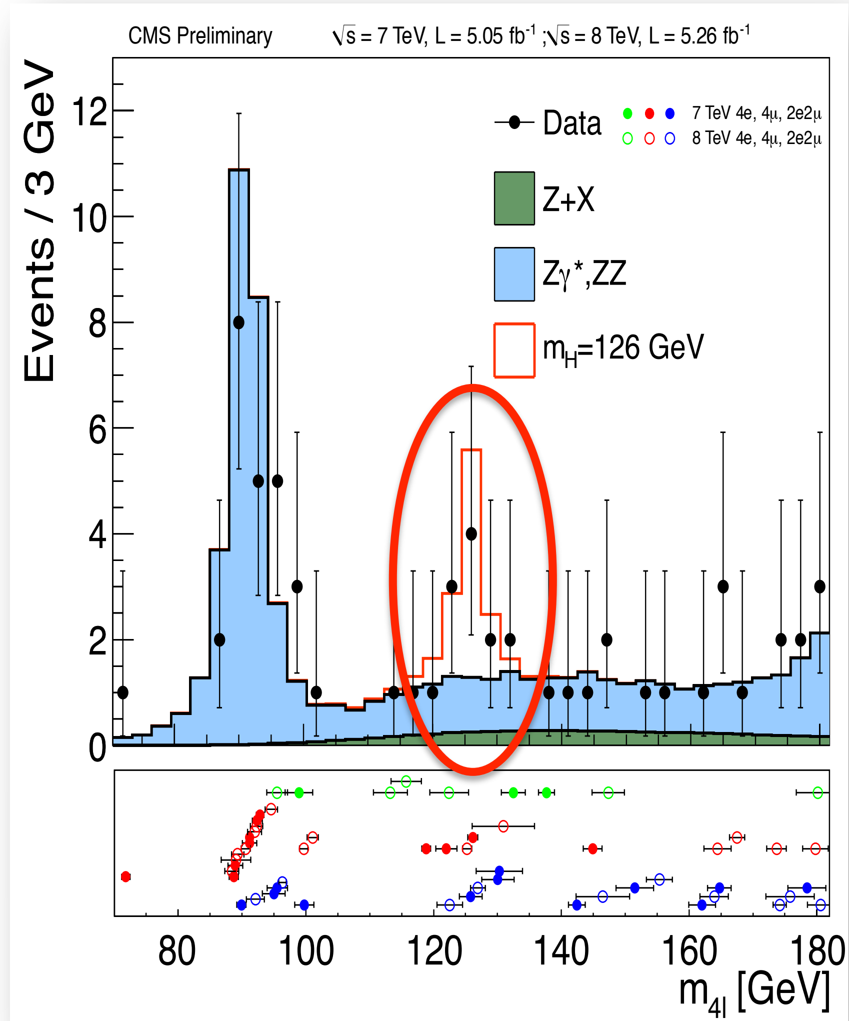


ATLAS: H→ ZZ→ eeee candidate



H→ ZZ


ATLAS
Data
Background ZZ(*)
Background Z+jets, tt̄
Signal (mH=125 GeV)
Signal (mH=190 GeV)
Signal (mH=360 GeV)
Syst.Unc.
H→ZZ(*)→4l
√s = 7 TeV: ∫Ldt = 4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8 fb-1
Events/10 GeV
m4l [GeV]


CMS Preliminary
√s = 7 TeV, L = 5.05 fb-1 ;√s = 8 TeV, L = 5.26 fb-1
Data
7 TeV 4e, 4μ, 2e2μ
8 TeV 4e, 4μ, 2e2μ
Z+X
Zγ*,ZZ
mH=126 GeV
Events / 3 GeV
m4l [GeV]

July 4th 2012

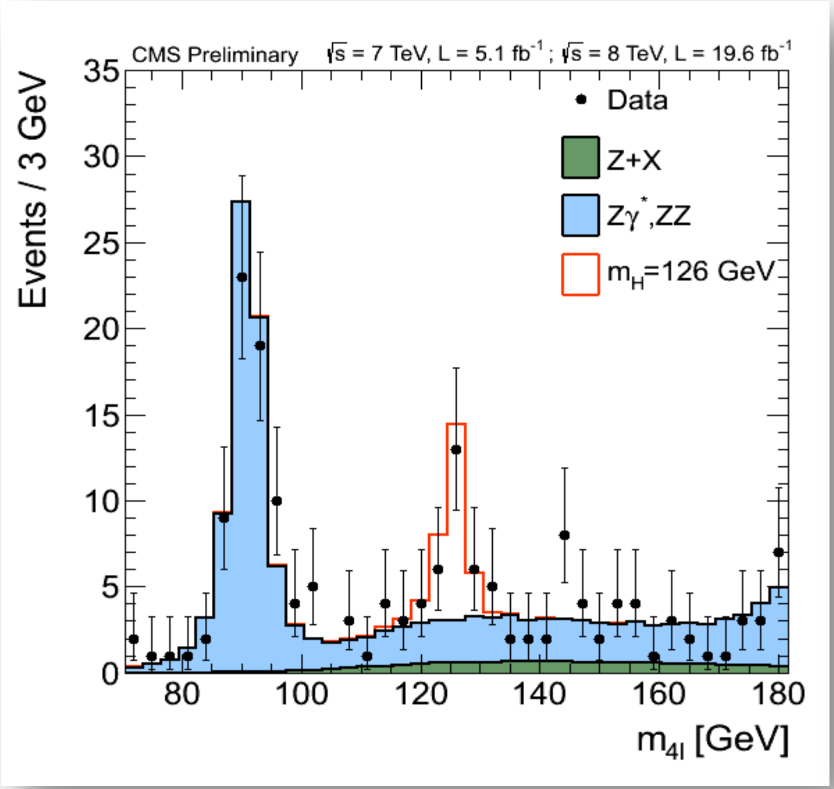
- Official announcement of the discovery of a 'Higgs-like' particle at a mass of ~125 GeV by CMS and ATLAS.
  - Historic seminar at CERN with live link to the largest particle physics conference of 2012 in Melbourne, Australia

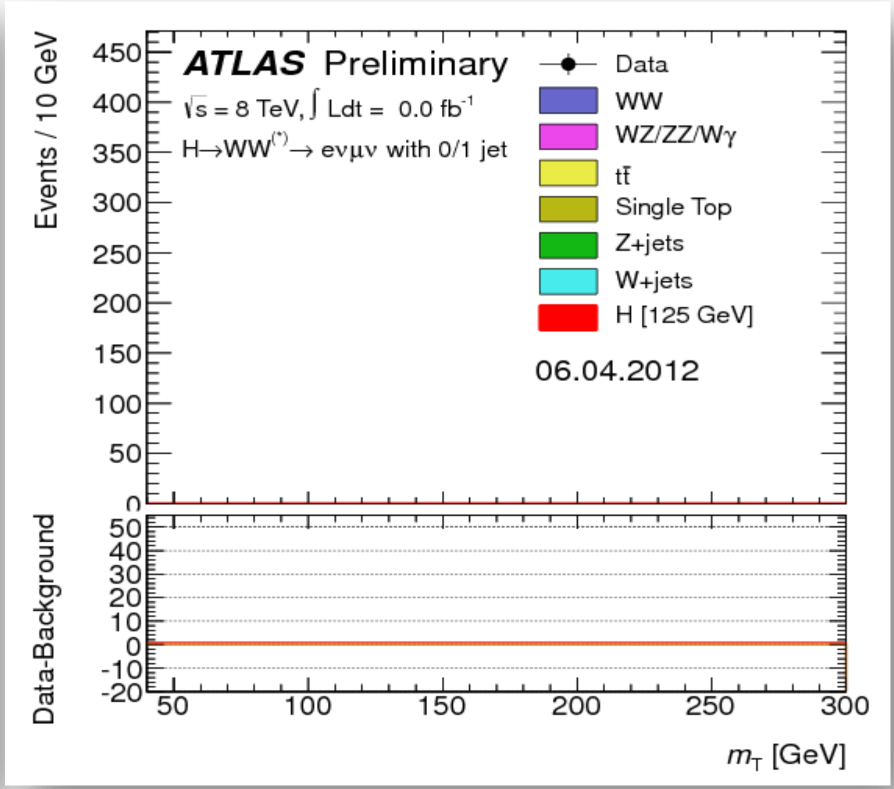
Melbourne

CERN

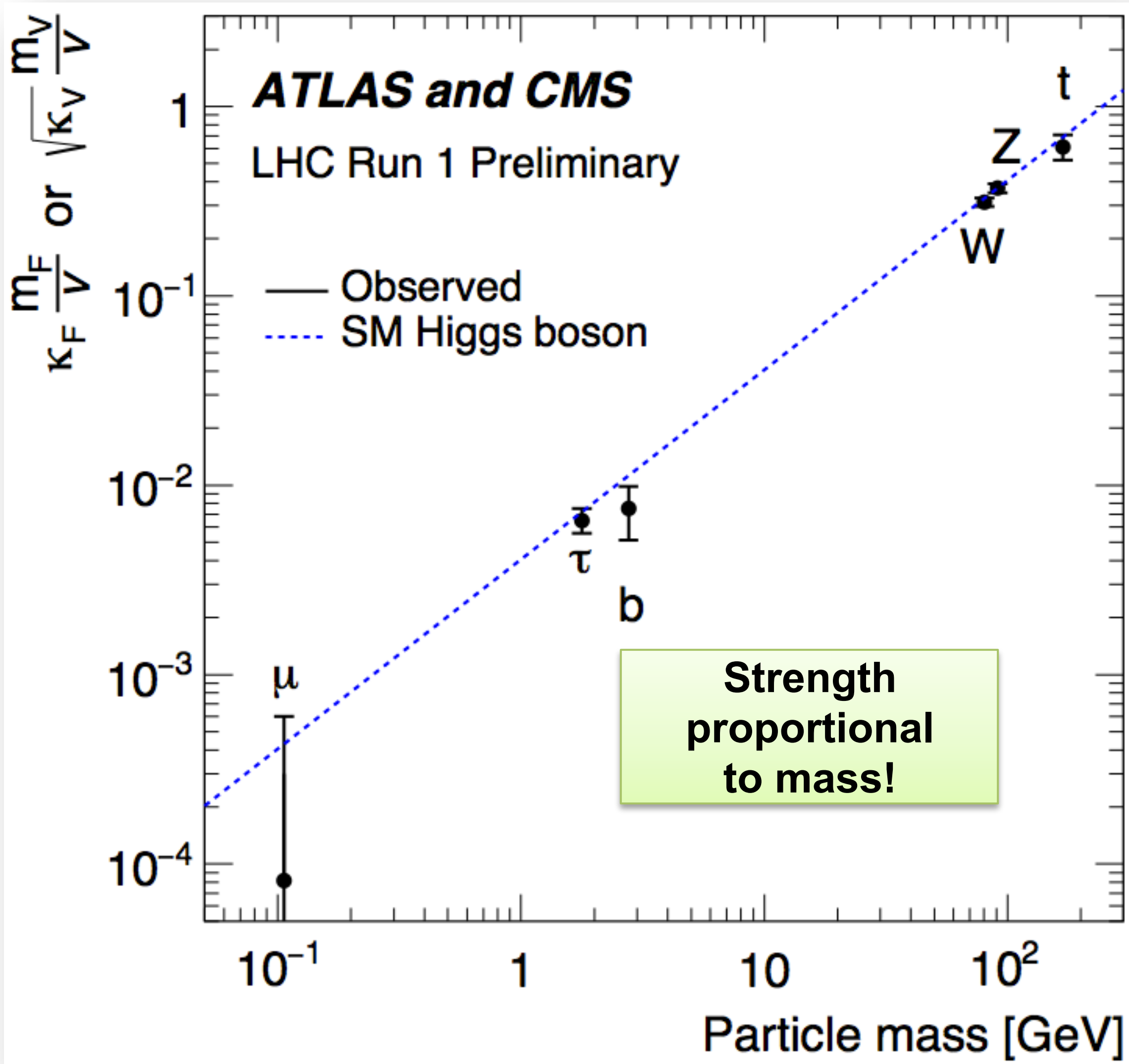
$H \rightarrow ZZ^* \rightarrow 4$ *leptons*

$H \rightarrow WW^* \rightarrow l\nu l\nu$





Connections to other particles?



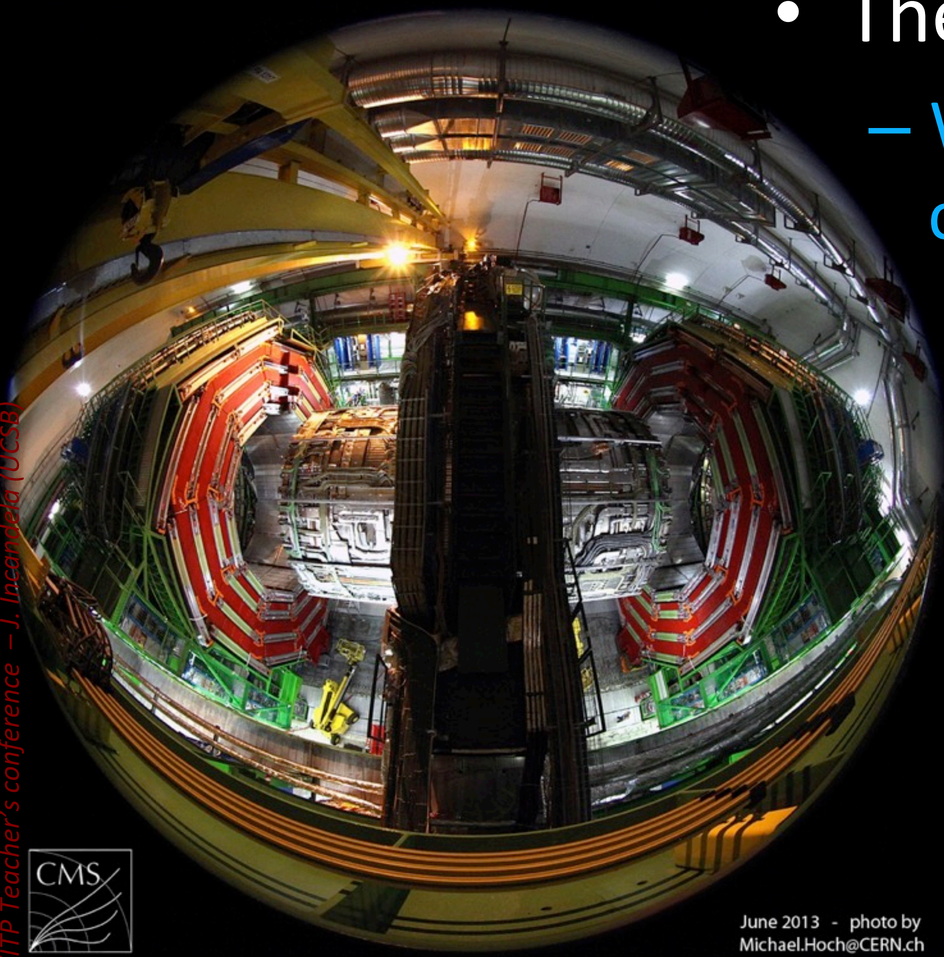
Meets expectations!

A big news week in March

Nobel Prize in Physics 2013

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".*

Looking to the future



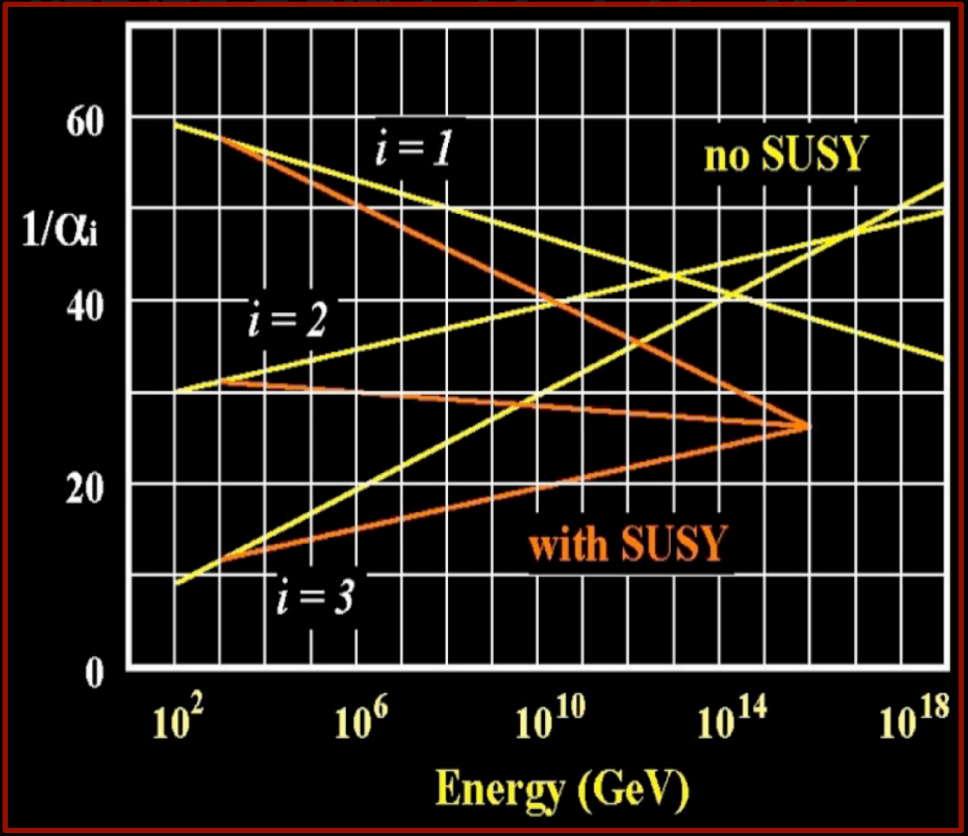
- There must be New Physics
  - We know the Standard Model cannot be the whole story
    - There are things in the universe it simply cannot explain

So, what comes next?

- Maybe Supersymmetry (SUSY)
  - `SUSY' provides a mirror image of the Standard Model ... with a twist
    - A new partner particle for every known particle ... but the partners of fermions are bosons and those of bosons are fermions!

Supersymmetry (SUSY)

Some benefits of SUSY



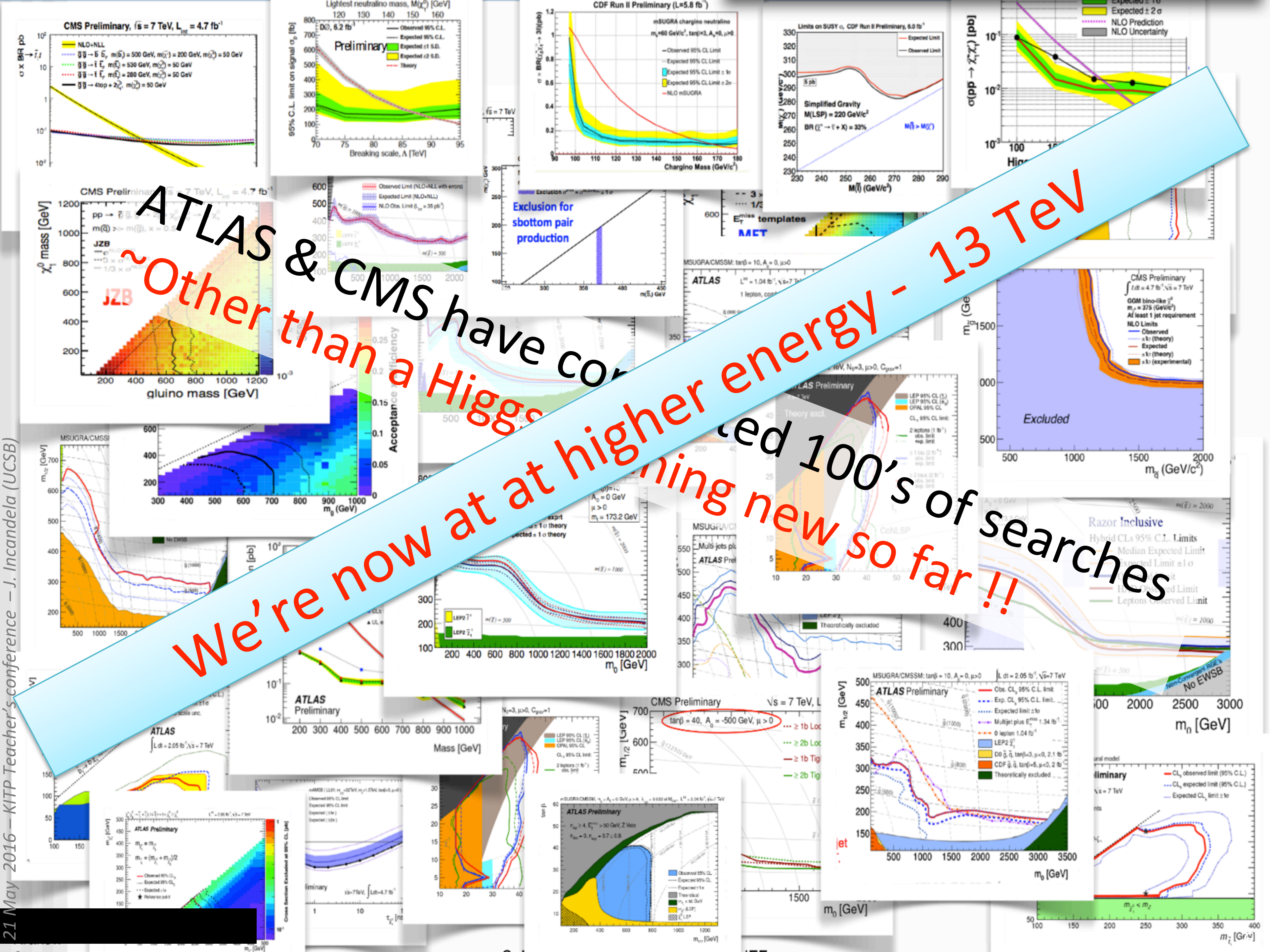
- Unifies the strengths of all forces at high energy
- Predicts Higgs boson with mass < 130 (we found one at 125)
- Provides clues to the dark side of the universe

The Dark Side

- We now know
  - Only ~5% of the universe is ordinary matter
  - ~28% is "Dark Matter"
    - SUSY has "Dark Matter" candidates
    - And even predicts the right amount !
  - The remaining ~67% is "Dark Energy"
    - We're not sure what this is!
      - It will probably be taxed someday
        - » Department of Dark Energy?

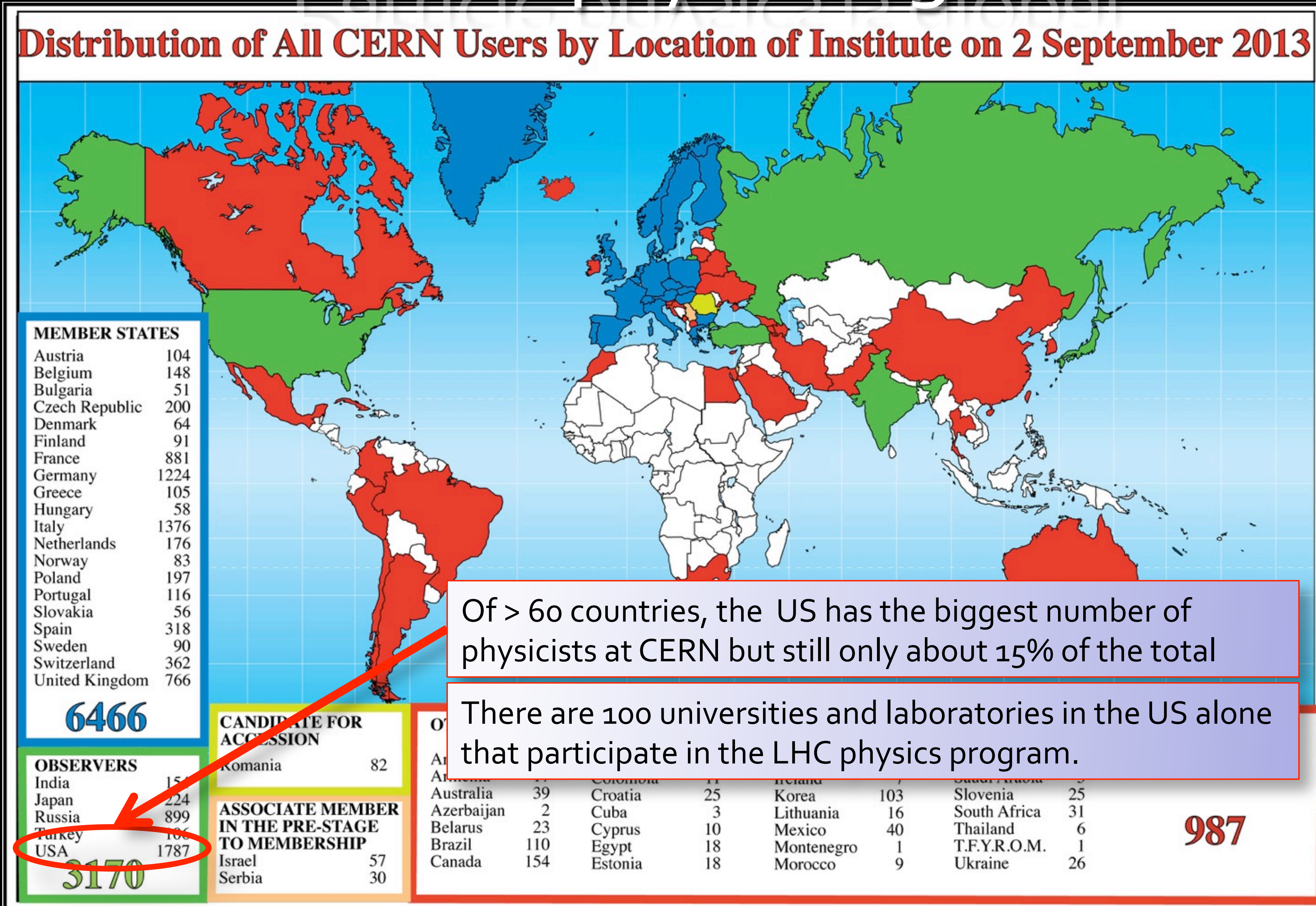
Or maybe not …

- The absence of any appearance of SUSY so far has motivated alternative models.
- These are characterized by new particles (like SUSY), more (or less) spatial dimensions…
  - Little Higgs (with T Parity)
  - Universal extra dimensions (with KK parity)
  - Strong dynamics
  - Extra dimensions (large or warped)
  - Hidden Valleys
  - Split SUSY
  - …
- If you don't exactly know what you're looking for, a **L**arge **H**adron **C**ollider (**LHC**) is the right tool to be using.


ATLAS & CMS have conducted 100's of searches
~Other than a Higgs, nothing new so far !!
We're now at at higher energy - 13 TeV

[redacted]

Particle physics is global



Of > 60 countries, the US has the biggest number of physicists at CERN but still only about 15% of the total

There are 100 universities and laboratories in the US alone that participate in the LHC physics program.

But is it useful ... ?

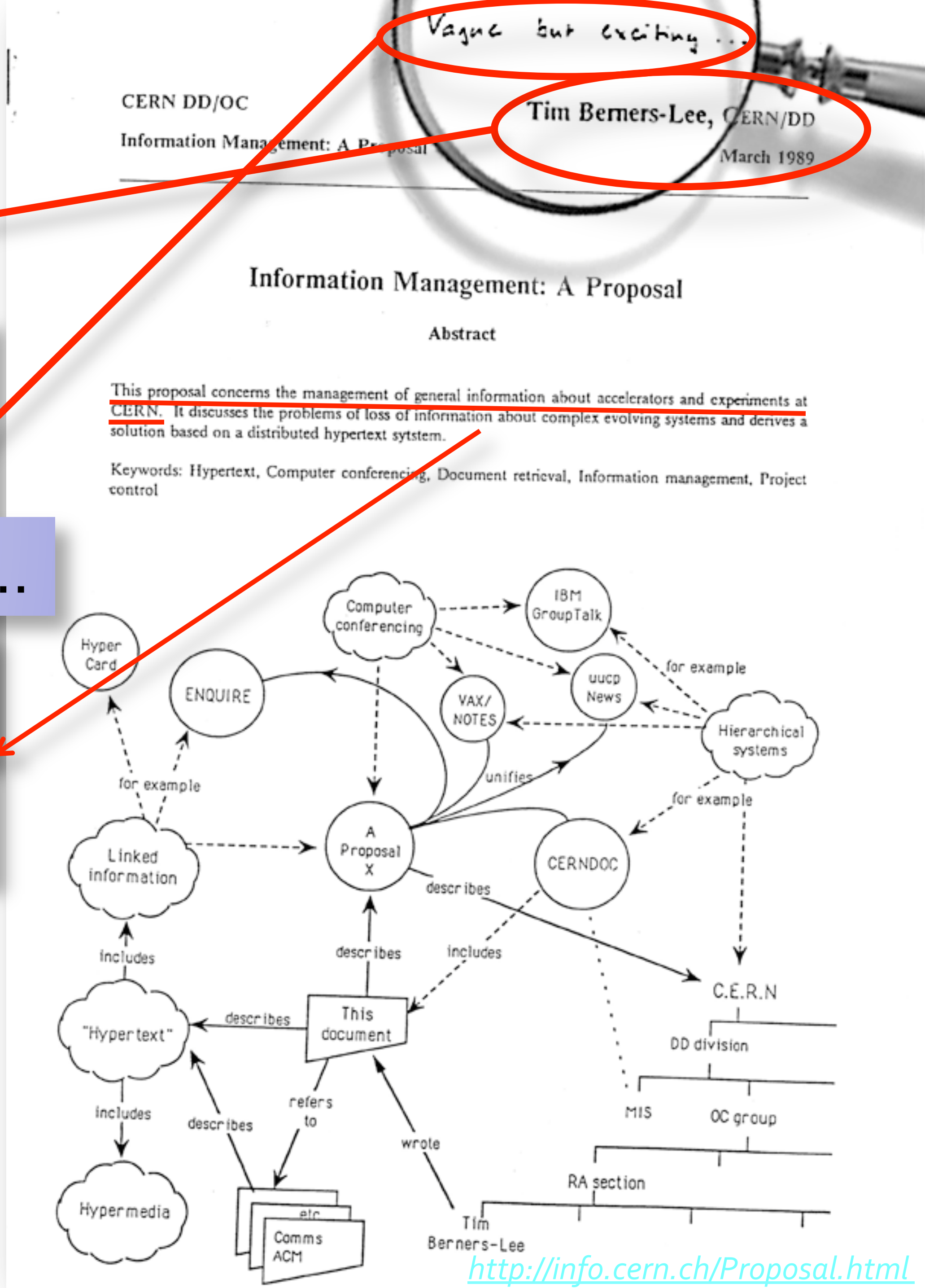
Tim Berners-Lee, CERN DD
March 1989

- Example: The coordination of

“Vague but exciting…”

– A slight understatement…

“This proposal concerns the management of general information about accelerators and experiments at CERN….”


Vague but exciting ...

CERN DD/OC

Information Management: A Proposal

Tim Berners-Lee, CERN/DD

March 1989

Information Management: A Proposal

Abstract

This proposal concerns the management of general information about accelerators and experiments at CERN. It discusses the problems of loss of information about complex evolving systems and derives a solution based on a distributed hypertext sytstem.

Keywords: Hypertext, Computer conferencing, Document retrieval, Information management, Project control

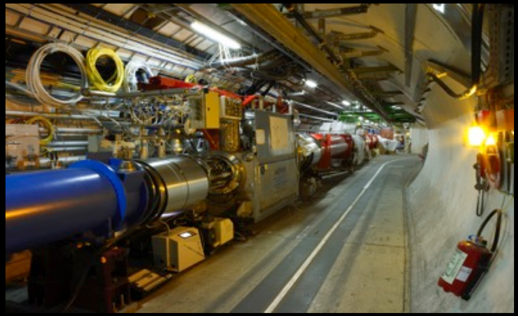
http://info.cern.ch/Proposal.html

Innovation in fundamental research

- Accelerators for medicine, material studies, …
- Superconducting wire
  - *Invented at Fermilab (Chicago) – cut power cost ~90%*
- World Wide Web
  - *Invented at CERN by Tim Berners-Lee*
- Grid technology (for unprecedented LHC datasets)
  - Now used by many sciences and industry - digital libraries, medical applications, bio-informatics, drug discovery, etc.
- Positron Emission Tomography (PET)
  - High performance crystals for the CMS experiment now used in medical imaging
- New MRI being developed using LHC magnet technology
- Many other examples …

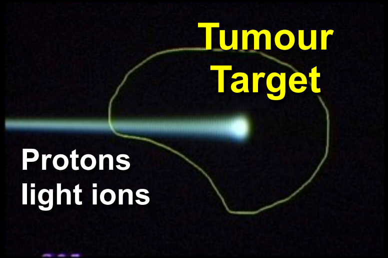
Spin-off Example: Medical Applications

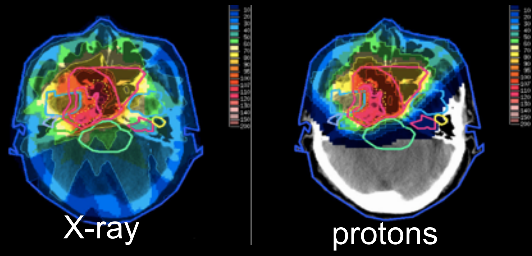
Combining Physics, Biology and Medicine to fight cancer



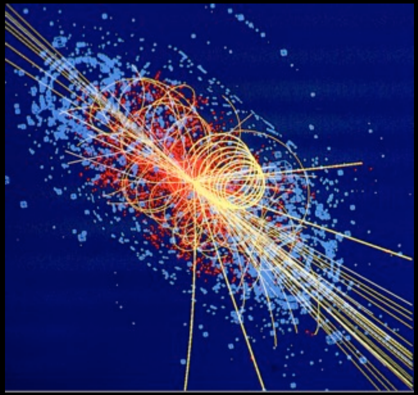
Accelerating particle beams
~30,000 accelerators worldwide
~17,000 used for medicine

Hadron Therapy





>70,000 patients worldwide (30 facilities)

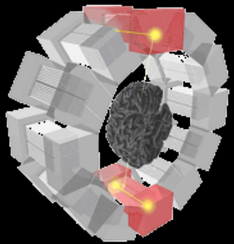


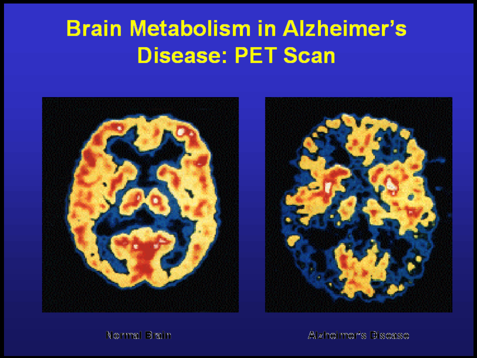
Detecting particles

Imaging

Clinical trial for new breast imaging system (ClearPEM)

PET Scanner

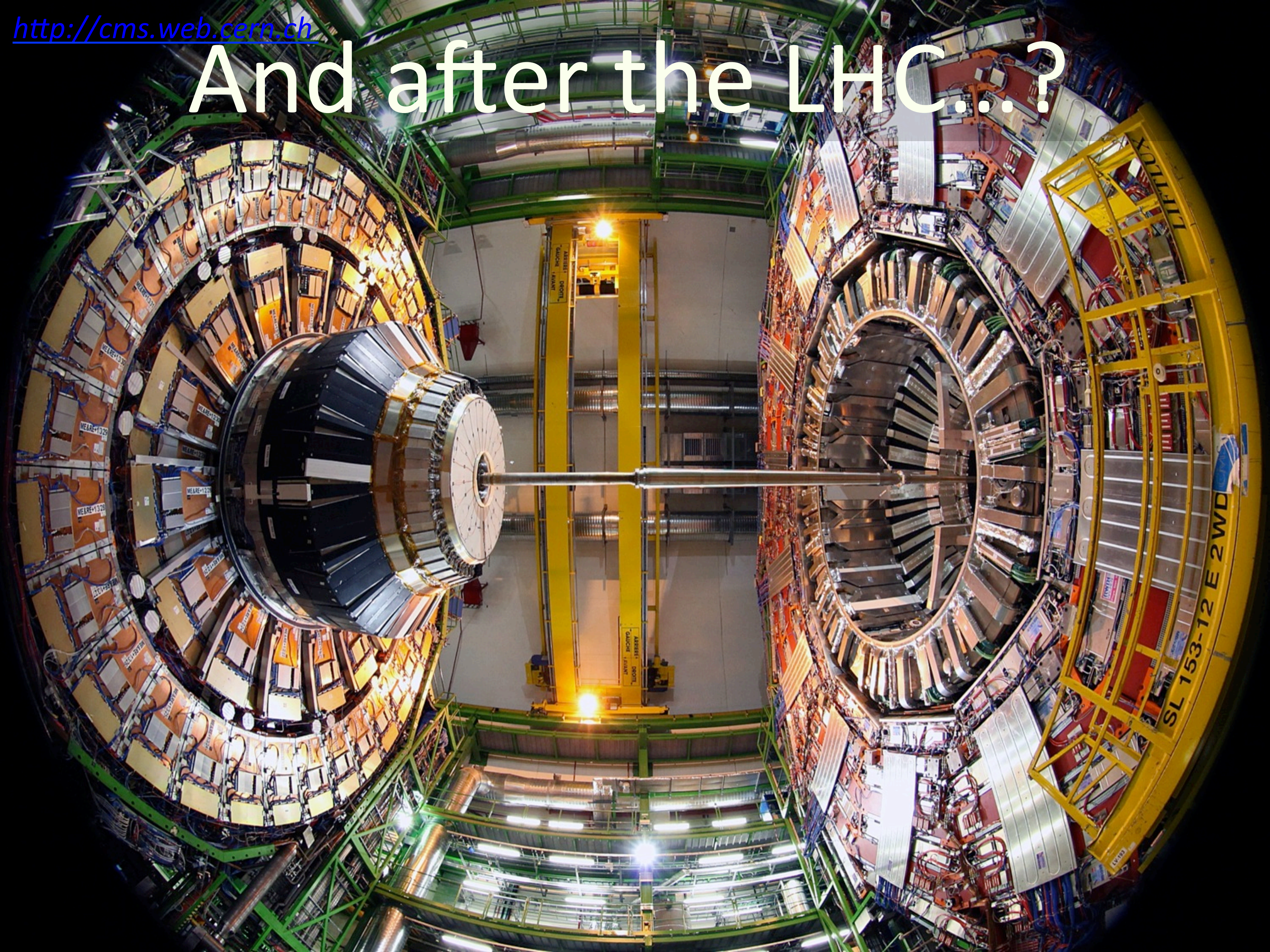




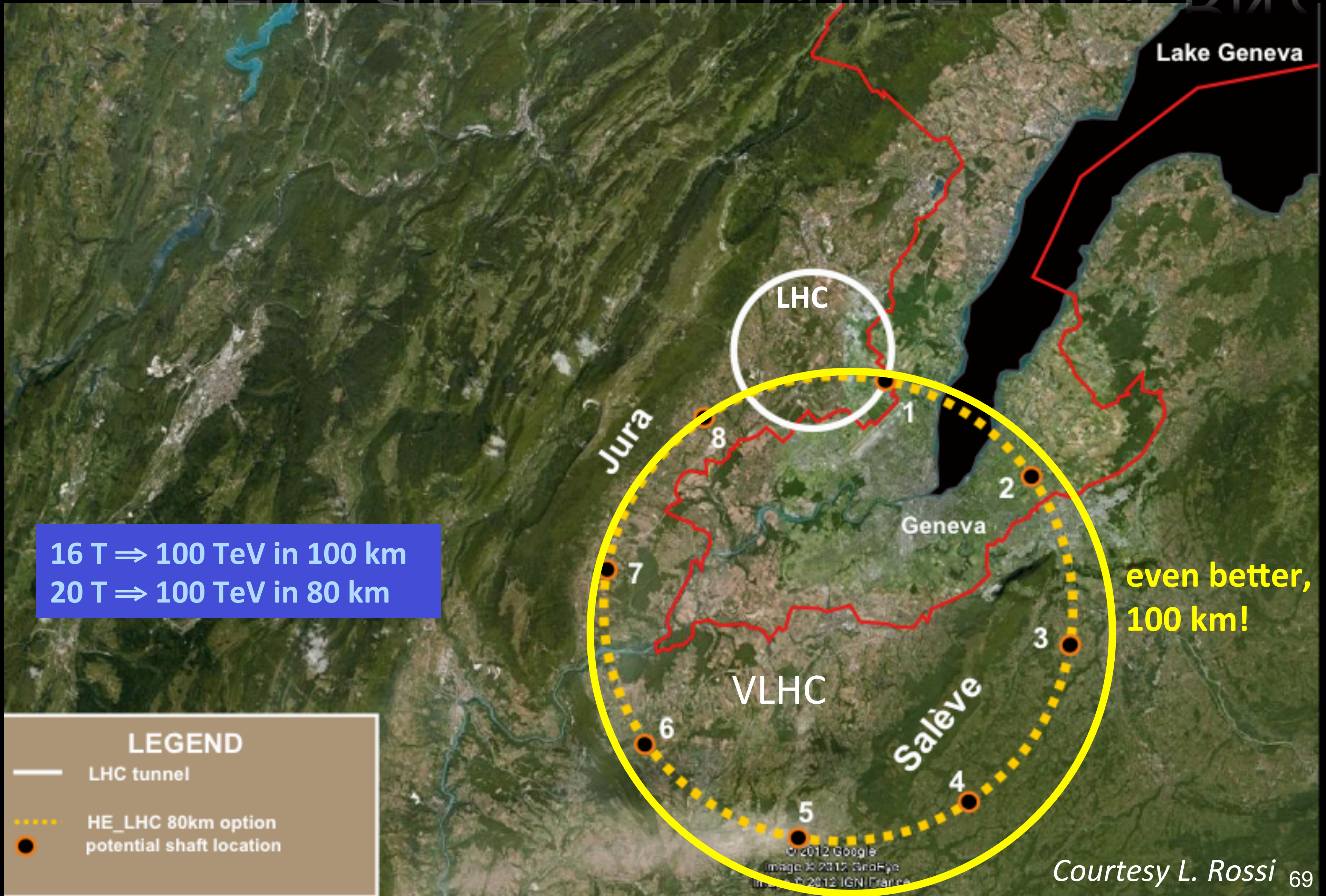
Summary: A new boson has been found!

http://cms.web.cern.ch

And after the LHC...?



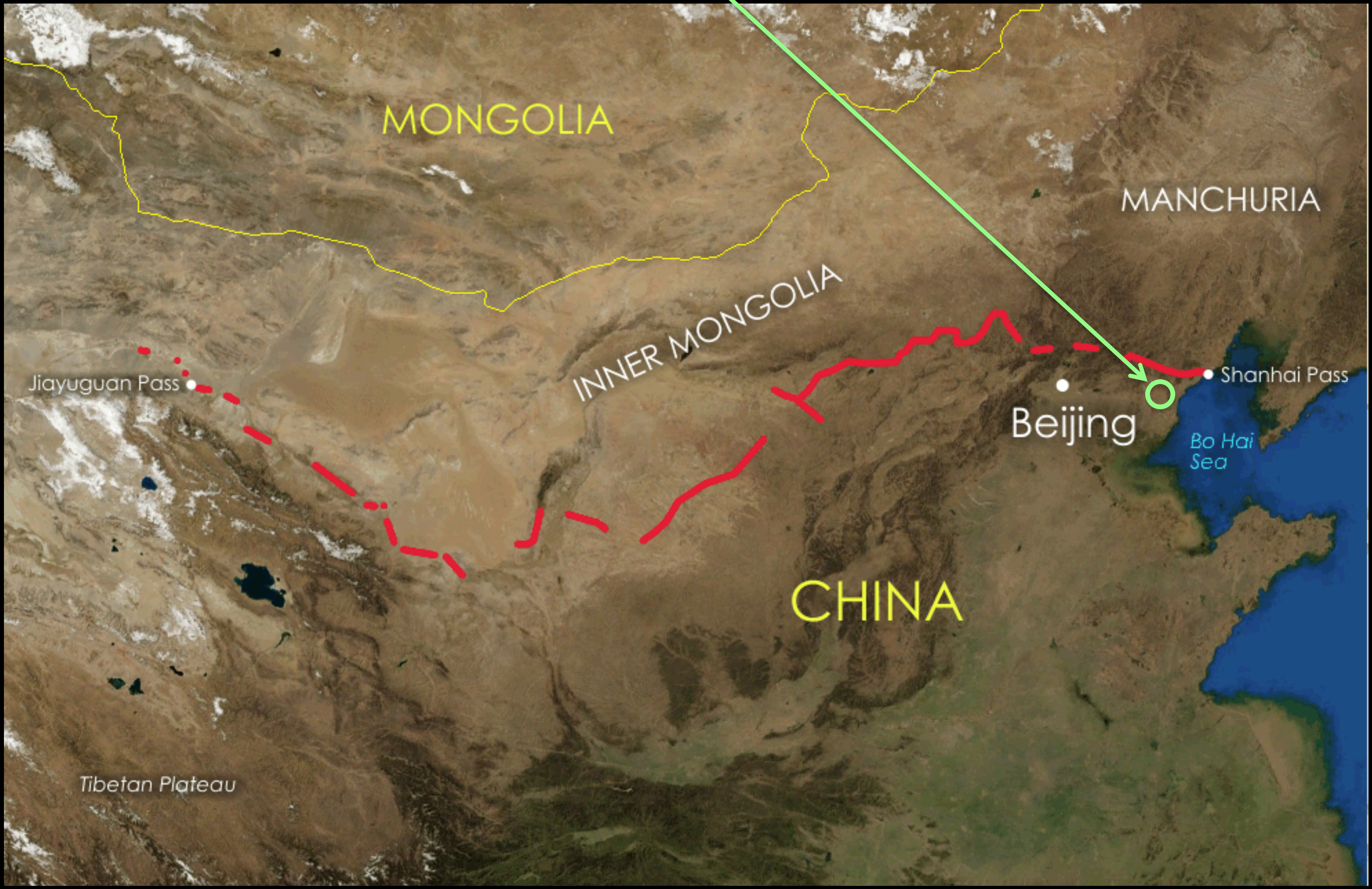
A Very Large Hadron Collider @ CERN?



Courtesy L. Rossi

The Great Ring of China ?

Qinhuangdao (秦皇岛）




There's much more to learn…
Support basic science!