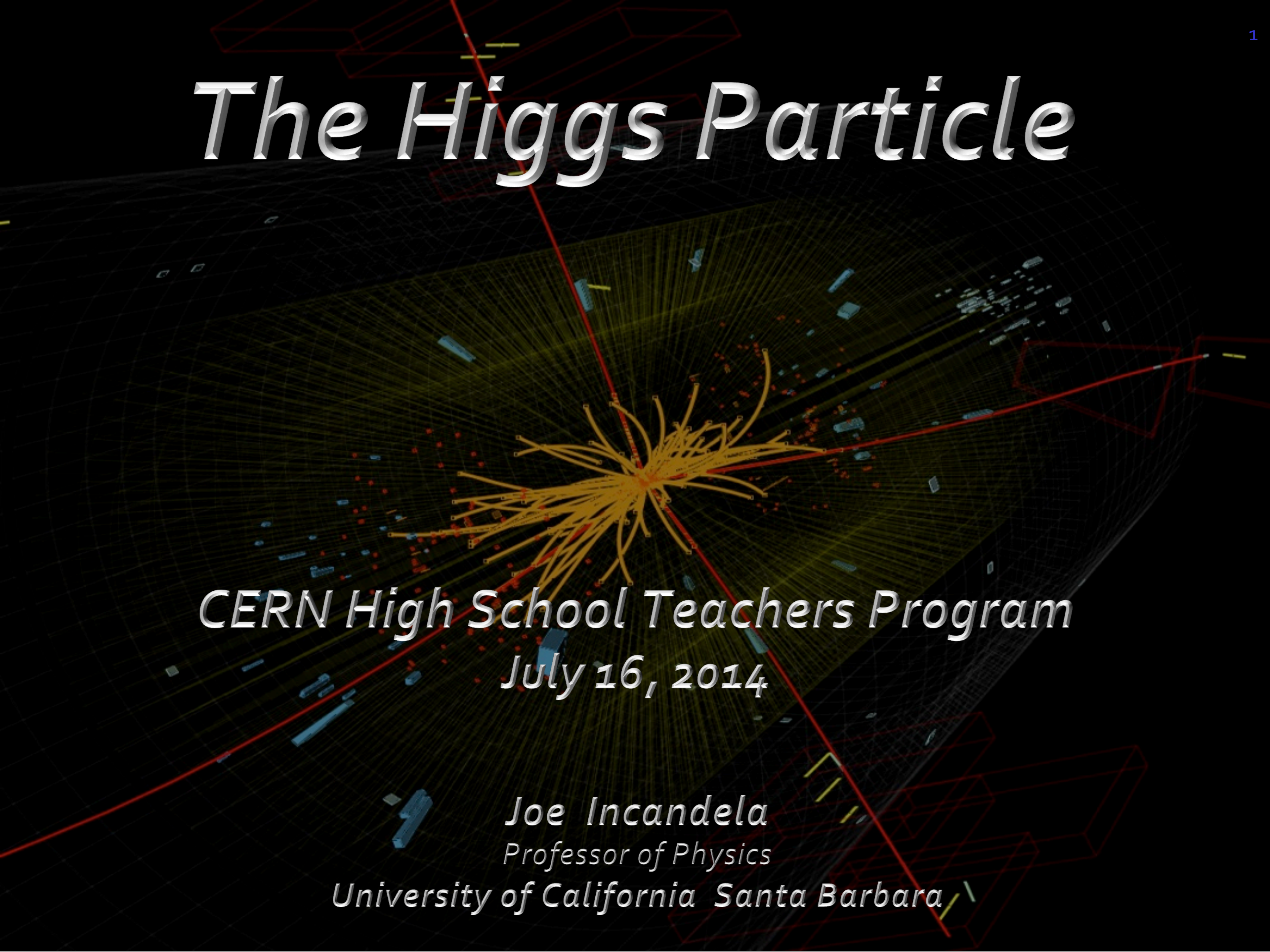


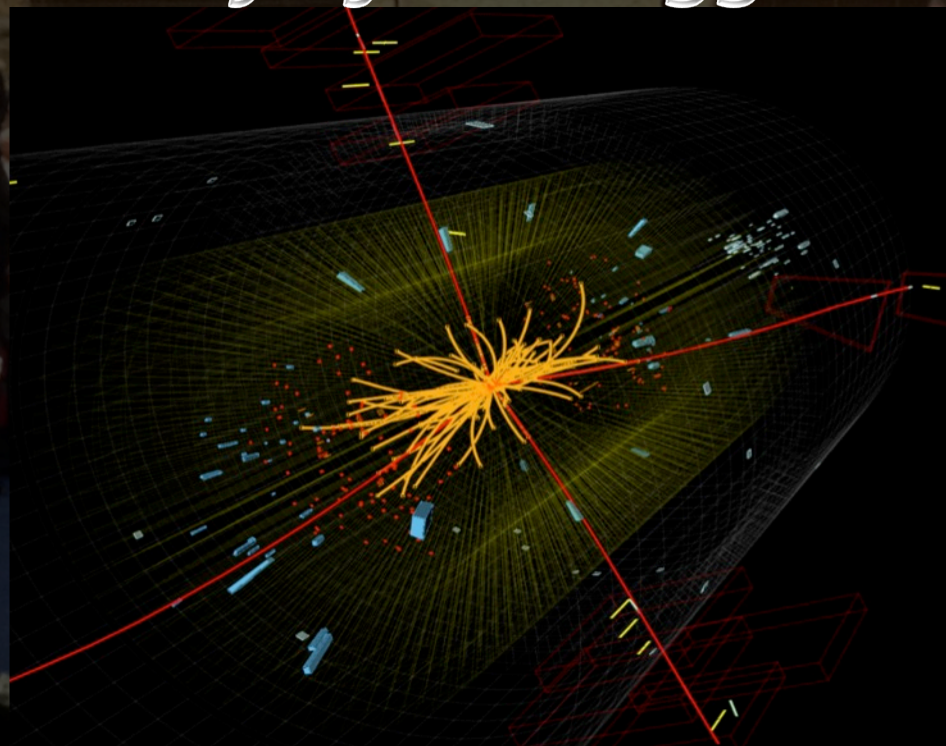
The Higgs Particle

CERN High School Teachers Program

July 16, 2014

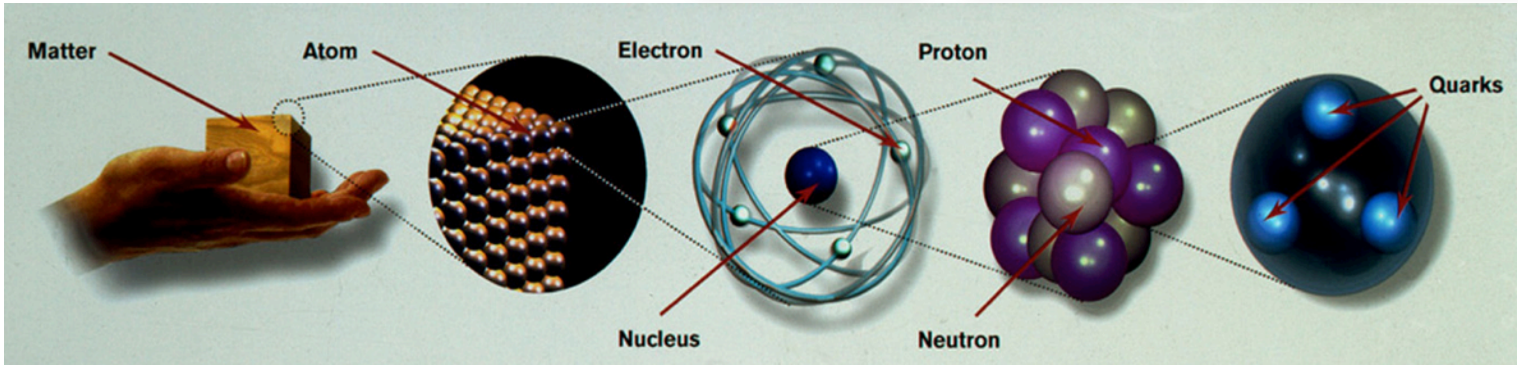
Joe Incandela
Professor of Physics
University of California Santa Barbara

And Then There Was Mass: The Origin of Mass and the Discovery of the Higgs Boson



Particle Physics: Going to ever deeper levels and higher energies (eV – electron Volts)

10^{-10} m | 10^{-14} m | 10^{-15} - 10^{-18} m



Motion of air atom **E = 0.04 eV**	Chemical reactions/atom **E = 1 to a few eV**	Nuclear reactions/atom **E = Millions of eV (MeV)**	Energy $E=mc^2$ of proton **E ~ 1 Billion eV(GeV)**

LHC probes distances down to **~10^{-20} meters**

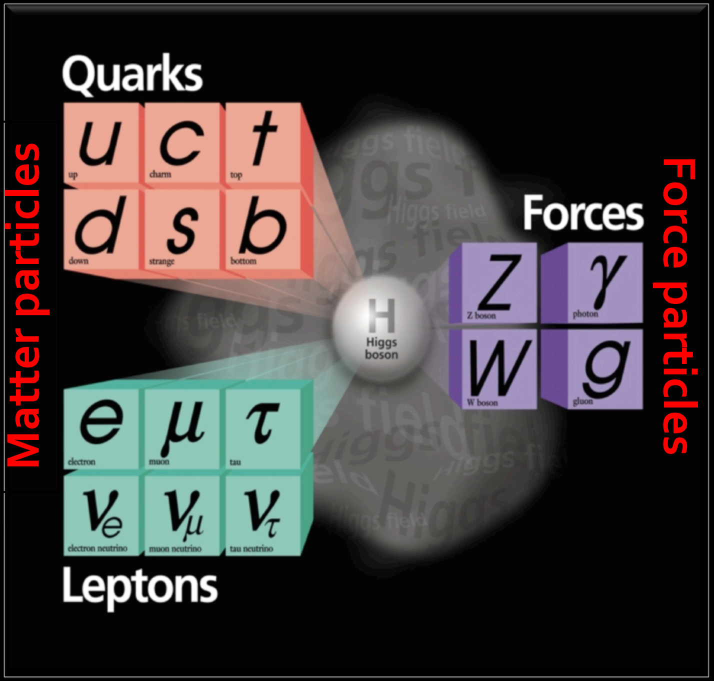
Each proton in LHC beams has energy **E = 4 TeV** (4×10^{12} eV)

Corresponding to temperatures at ~10^{-11} to 10^{-12}sec after the big bang:

10^{-12} = a thousandth of a billionth

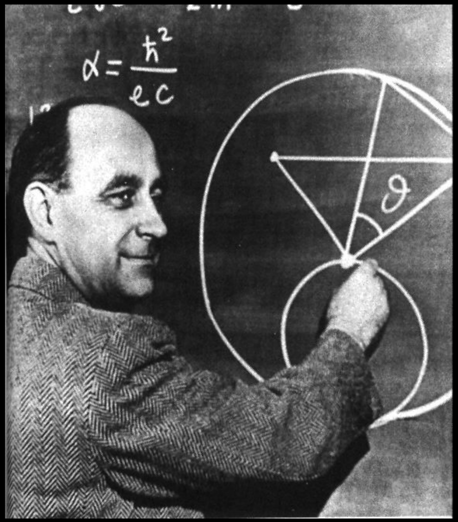
The Standard Model

- 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



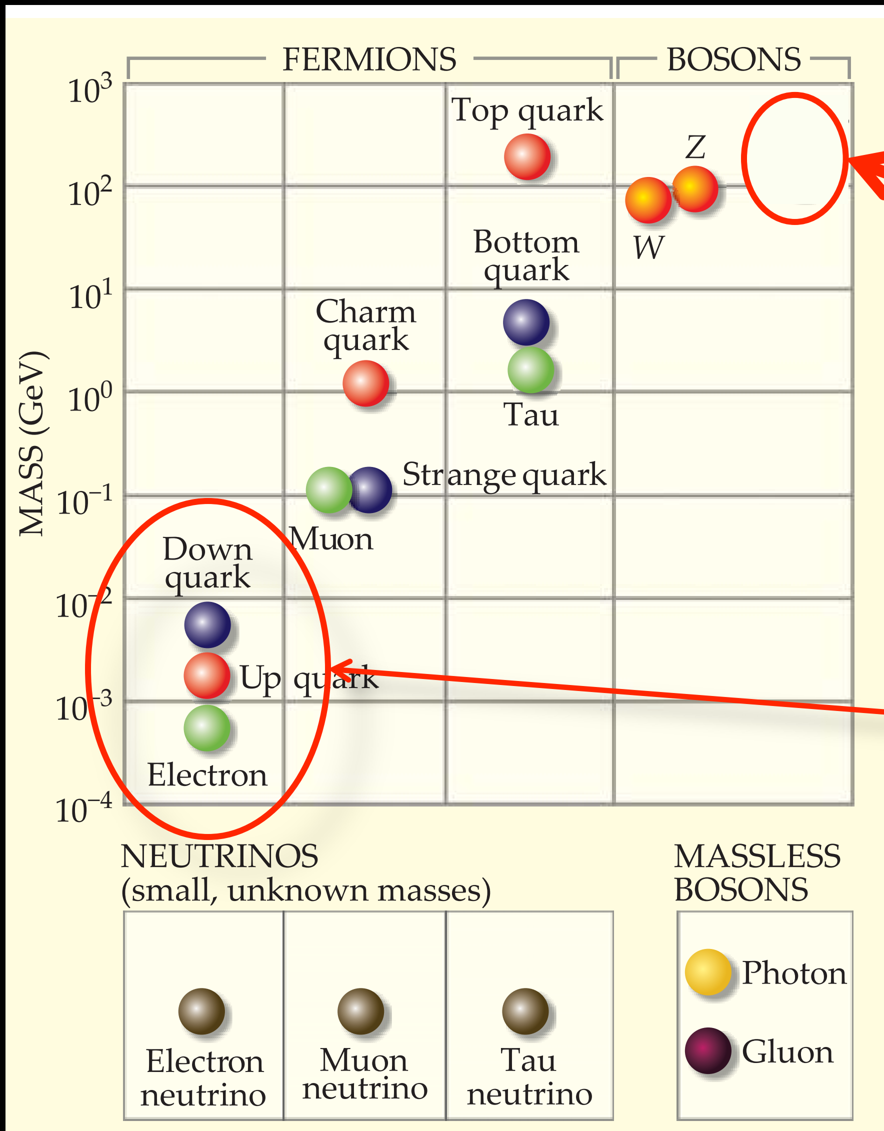
Fermions

Bosons



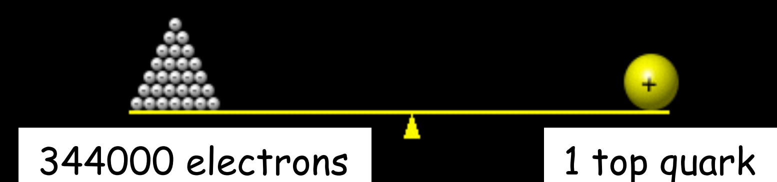
$$
\begin{aligned}
\mathcal{L}_{SM} =\; & -\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a\partial^2 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 - \frac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H\partial_\mu H - \frac{1}{2}m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- \\
& -M^2\phi^+\phi^- - \frac{1}{2}\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 + \frac{1}{2}(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] \\
& -\frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_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] \\
& -\frac{1}{8}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 - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H \\
& -\frac{1}{2}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] + \frac{1}{2}g\left[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right] \\
& +\frac{1}{2}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^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu\left[H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right] - \frac{1}{4}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^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) \\
& +\frac{1}{2}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) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\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(\frac{4}{3}s_w^2 - 1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)\right] \\
& +\frac{ig}{2\sqrt{2}}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\sqrt{2}}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\sqrt{2}}\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{g}{2}\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\sqrt{2}}\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\sqrt{2}}\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{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\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^5 u^\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{Y}X^- - \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{Y}X^+) + 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^-) - \frac{1}{2}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^-] \\
& +\frac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]
\end{aligned}
$$

The Standard Model (SM)



Last piece of the puzzle

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



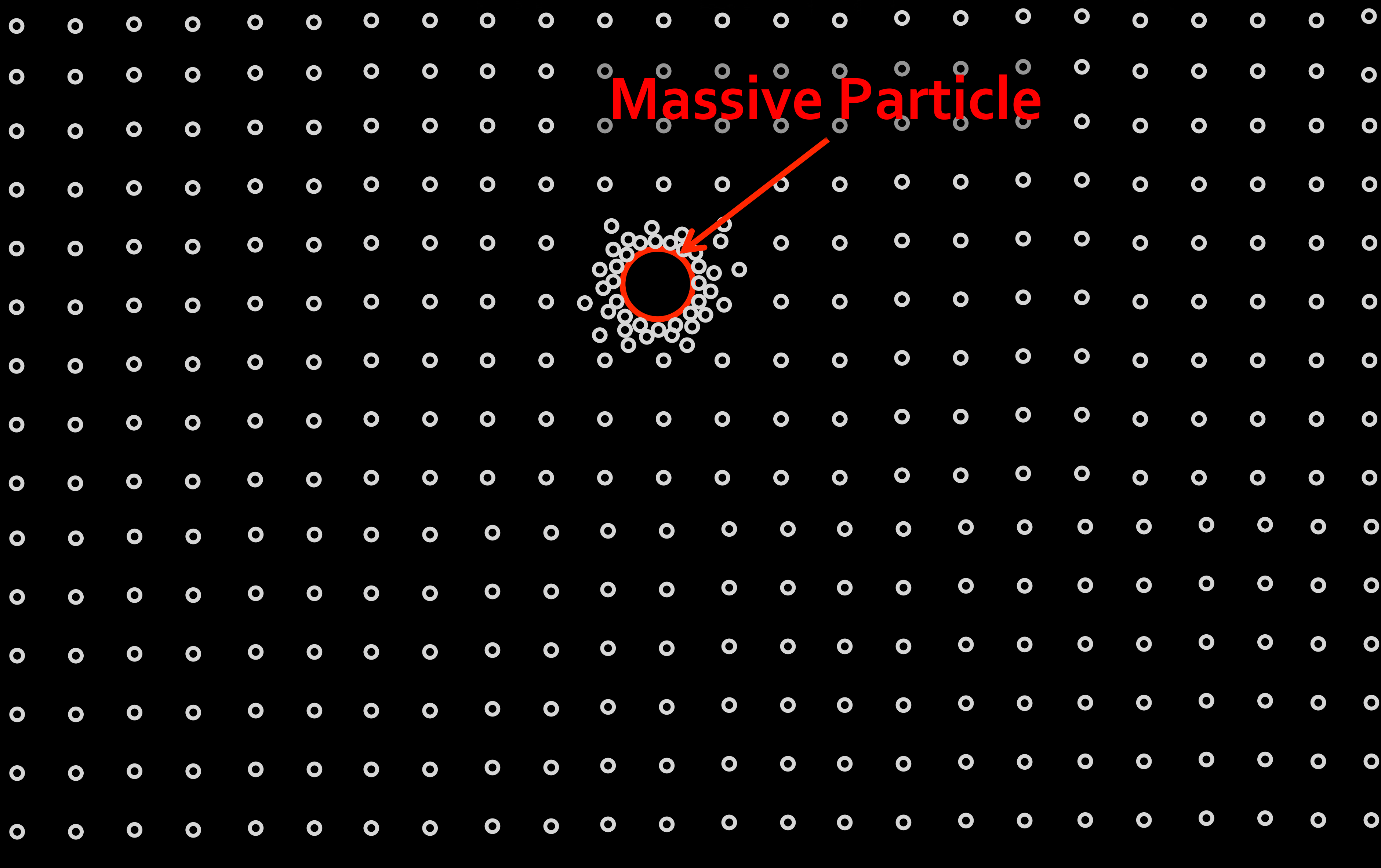
Why???

What is a Higgs boson?

- Discovery of nuclear forces created a problem
  - Particles that carry forces should be massless
  - Nuclear forces are short range => Massive carriers:

    Range $\lambda \sim h/M$ *(Yukawa)*
- What *is* mass, anyway?
- An ingenious idea:
  - Suppose there's a field filling the universe that interacts with particles, shielding them to concentrate their energy in space – impeding their speed to less than that of light?
    - *This means they have mass*
- *The basic rules do not change, it is the playing field that is changed!!*

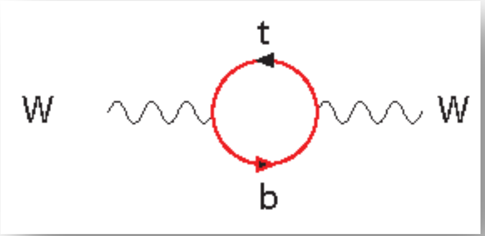
Higgs Field Interaction



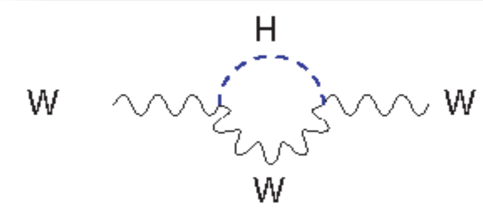
Courtesy of Stefan Spanier (UT)

Fundamental connections

- Fundamental particles have deep connections
  - The mass of the W particle depends on the masses of the top quark and the Higgs…



This "Feynman diagram" shows a W particle transforming into a top and a bottom quark and back again to a W



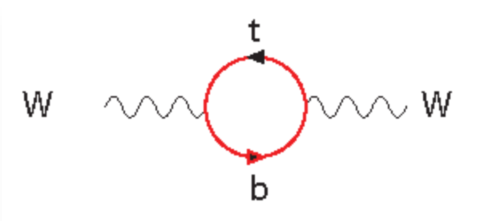
Here we see a W particle transforming itself into a W + H and back again to a W

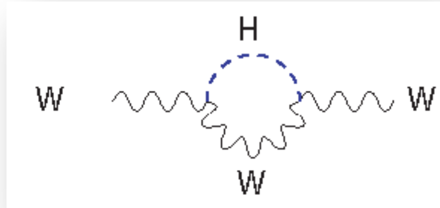
- The identity of a particle is not separable from what it can become (or decay into)

Upshot

- If you were to measure the top quark and W masses very precisely, you could predict the mass of the Higgs in the Standard Model (SM)

Summer 2011





$m_t = 173.2 \pm 0.9$

$m_W = 80.399 \pm 0.023$

- 95% chance the Higgs is in the range

  $114 < M_H < 185$ GeV

Cracking the code

- Particles we don’t see have a big impact
- Determining the structure & evolution of the universe
  - Masses of elementary particles come from the Higgs field but also depend on each other!
- We want to make these particles
  - By recreating the conditions of the early hot universe
- And study them

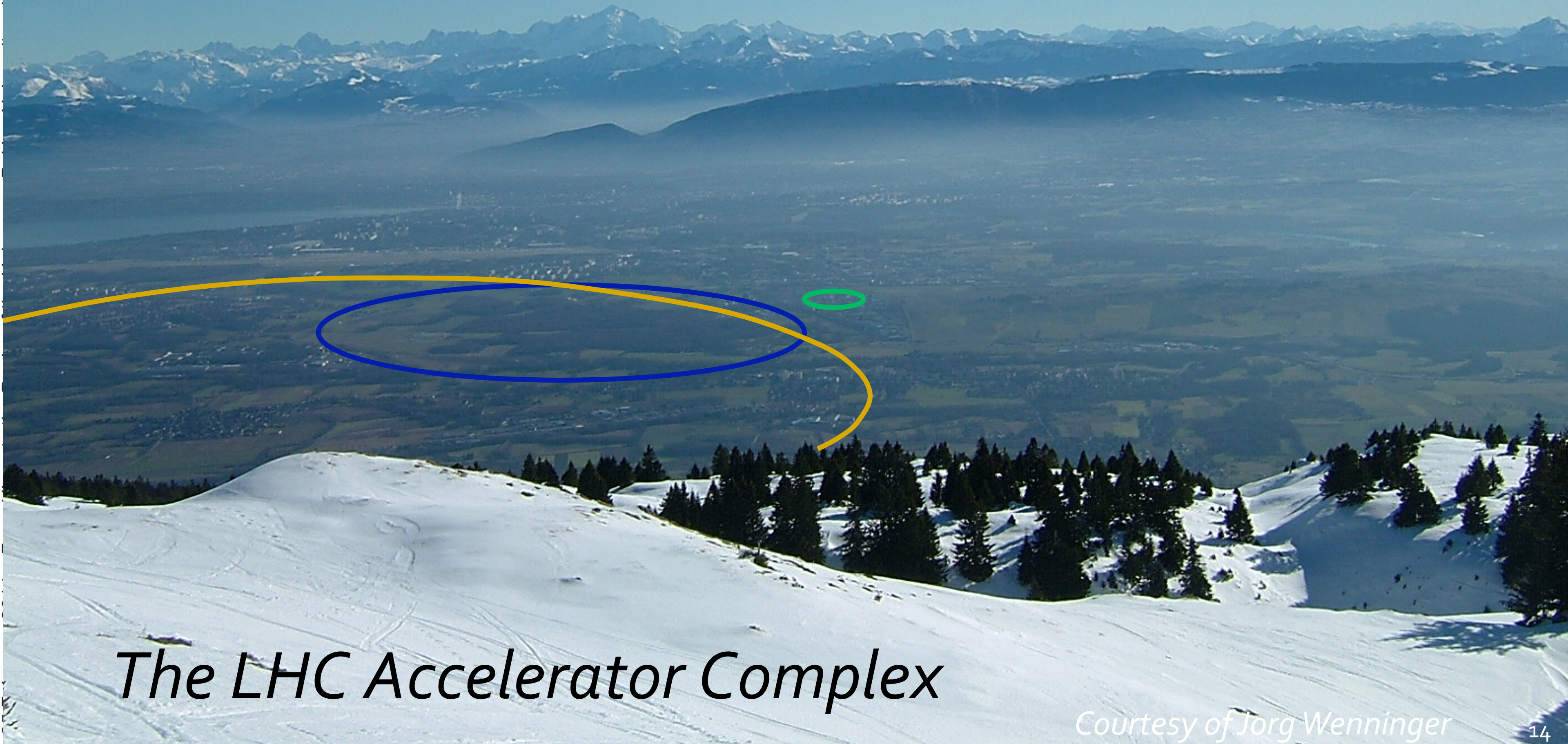
Creating and studying new particles

- If we concentrate enough energy in one small spot…
  - We can make heavy particles that we have not seen before.
  - They can tell us about the underlying code of our universe

- **What do we use?**

A Large Hadron Collider

- LHC Design Goals
  - Cover all Higgs Mass values (0.1-1.0 TeV)
  - Search for strongly produced new physics into the multi-TeV region



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

  ($\sqrt{s}$ = 900 GeV)

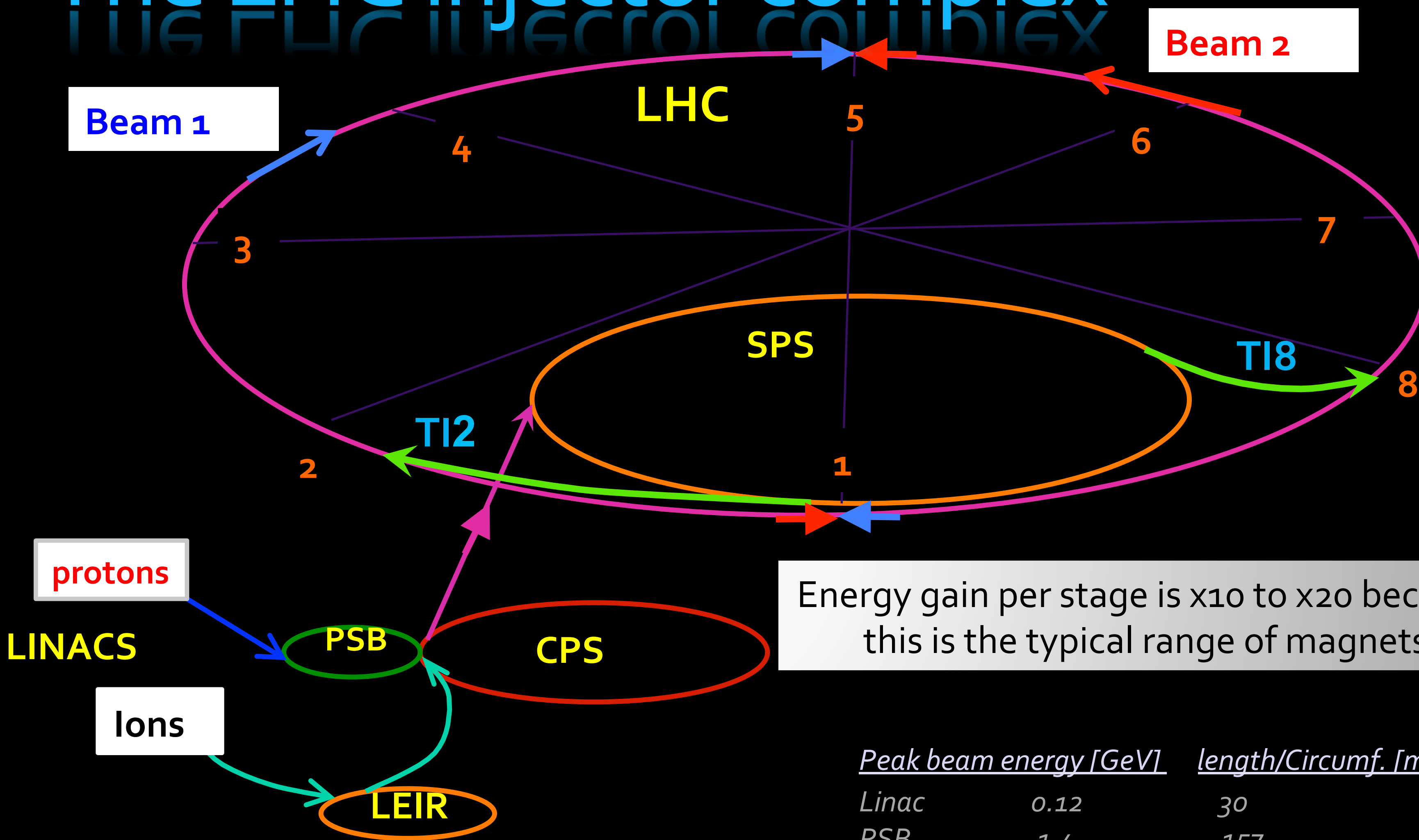
It has required a lot!

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

The LHC Accelerator Complex

Courtesy of Jorg Wenninger

The LHC injector complex



Energy gain per stage is x10 to x20 because this is the typical range of magnets

Peak beam energy [GeV]		*length/Circumf. [m]*
Linac	*0.12*	*30*
PSB	*1.4*	*157*
CPS	*26*	*628 = 4 PSB*
SPS	*450*	*6'911 = 11 x PS*
LHC	*7000*	*26'657 = 27/7 x SPS*

Limit stored energy ⇒ 8 power sectors.

~1 GJ/sector

Sector = 2.9 km, 154 dipoles + 50 quads

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

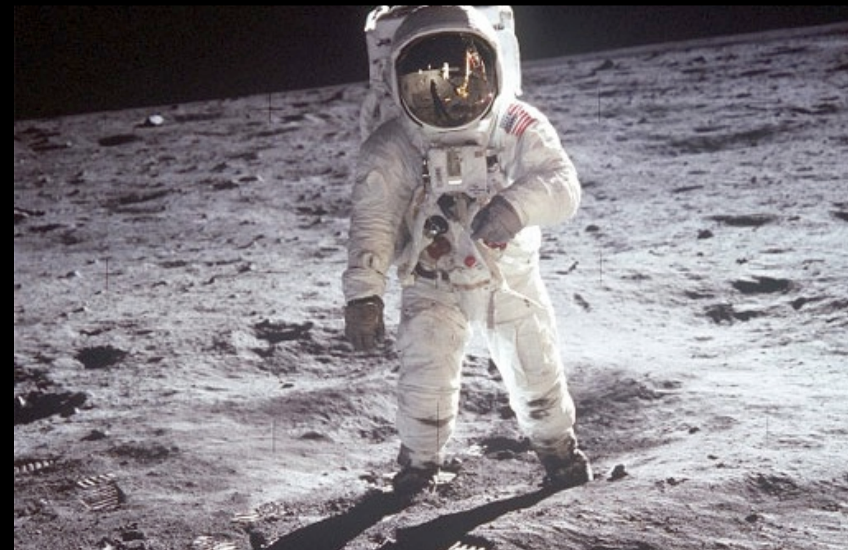
- 23 kg of TNT
- 15 kg of chocolate

- 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

ATLAS

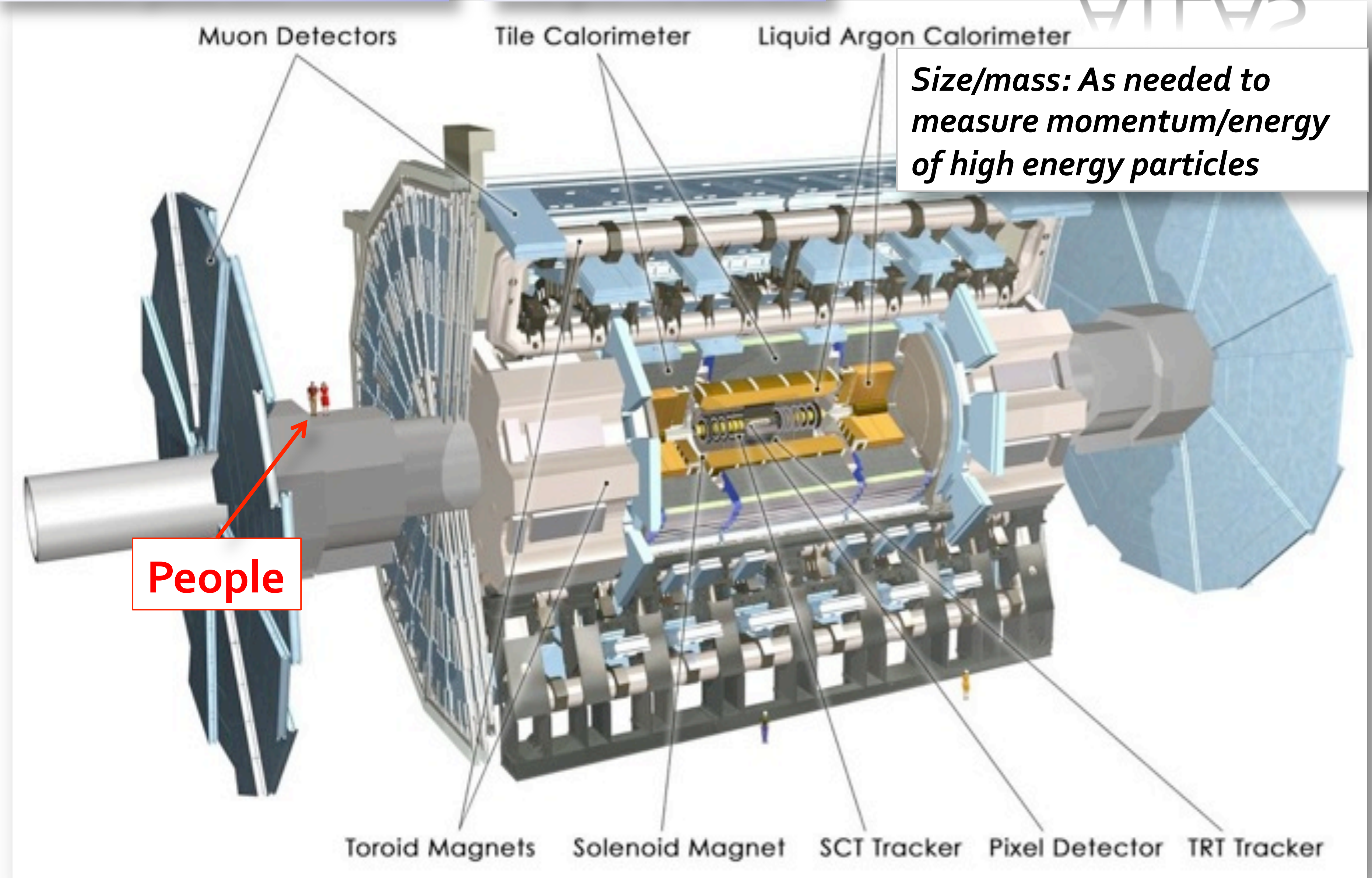
http://atlas.web.cern.ch/

- Weight : 7000 tons
- Cables: 3000 km

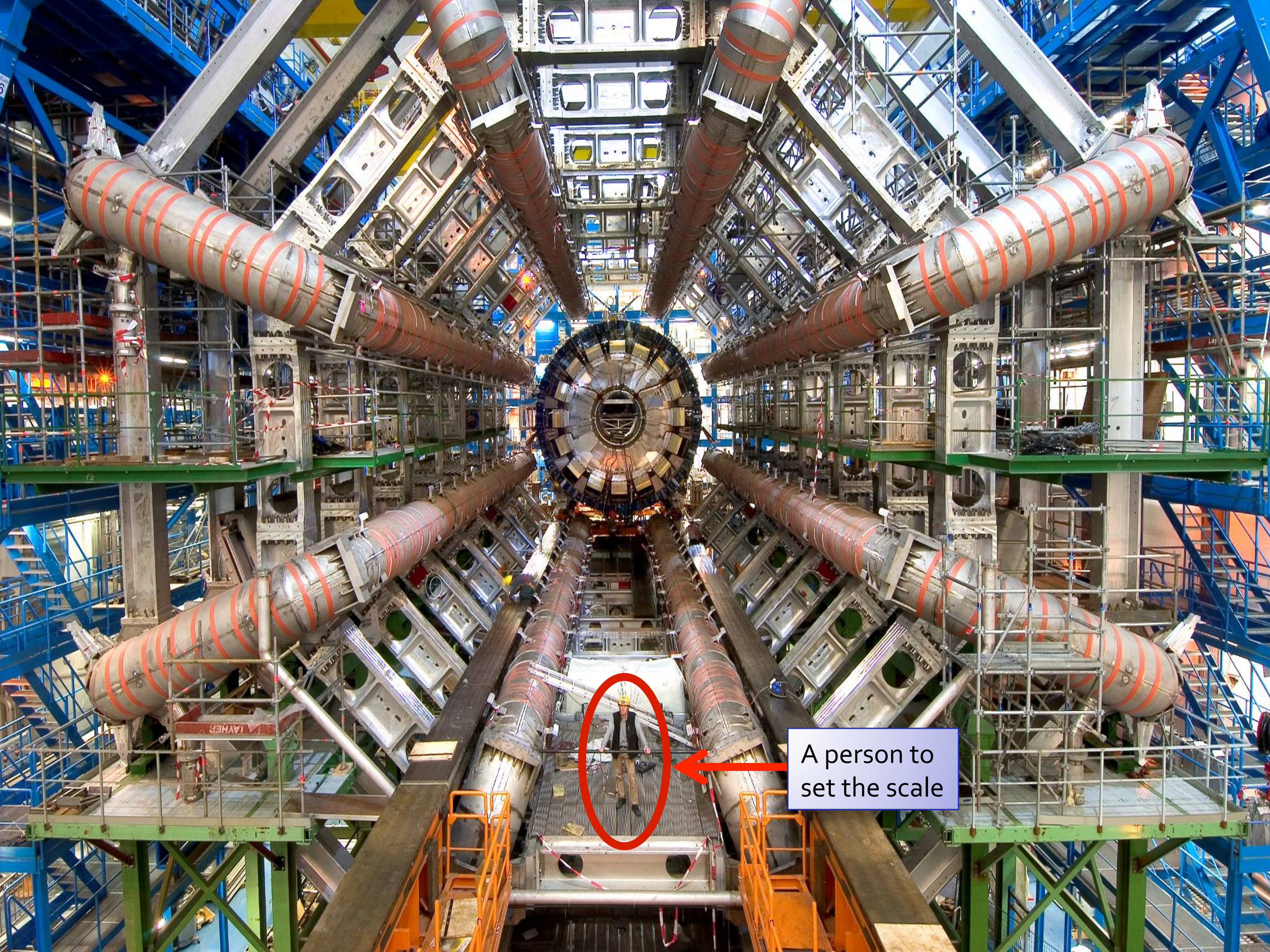
- Length : 46 m
- Height : >6 stories

ATLAS

Size/mass: As needed to measure momentum/energy of high energy particles

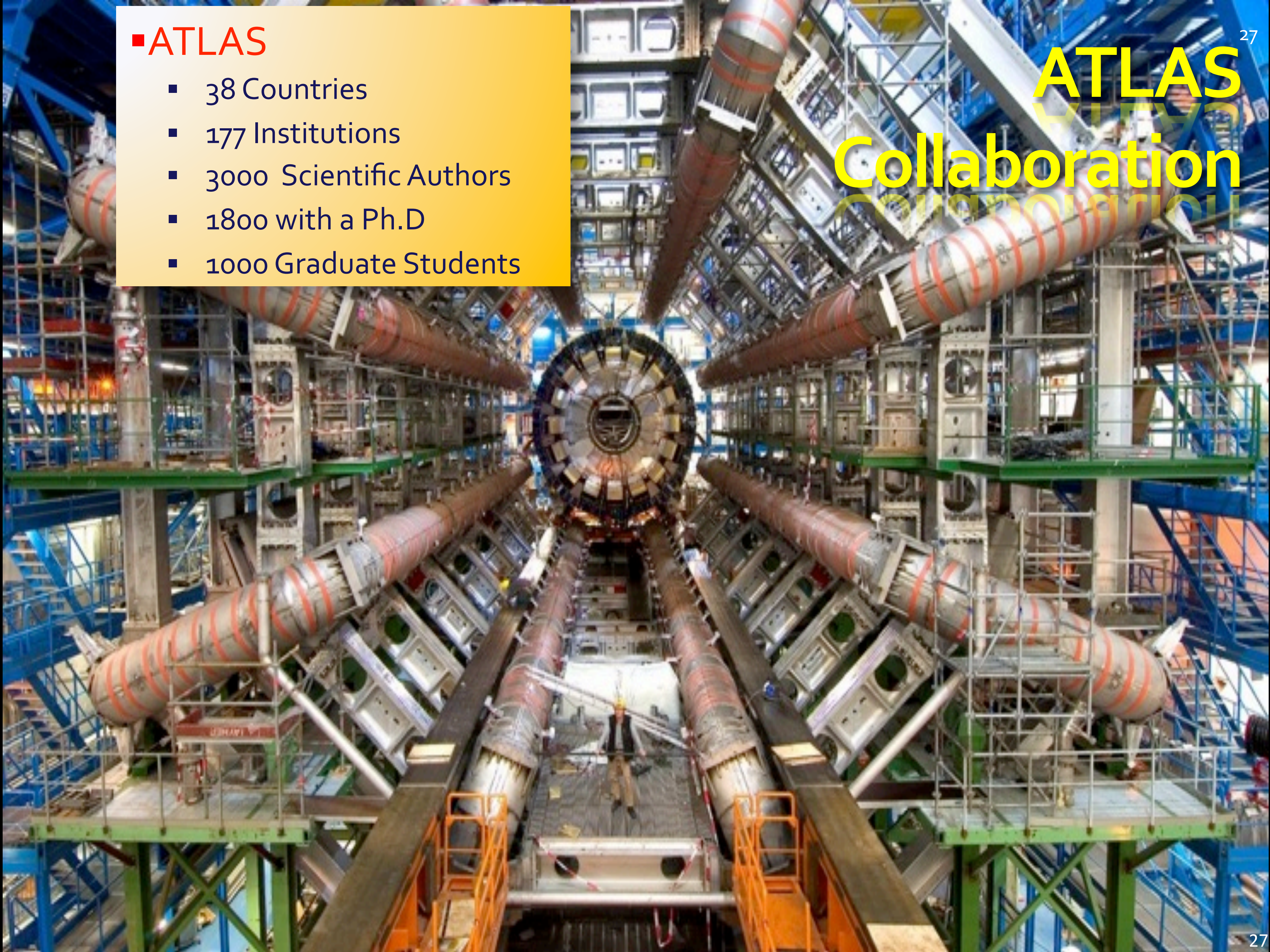


ATLAS cavern (-100 m) in June 2003


A person to
set the scale

ATLAS Collaboration

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

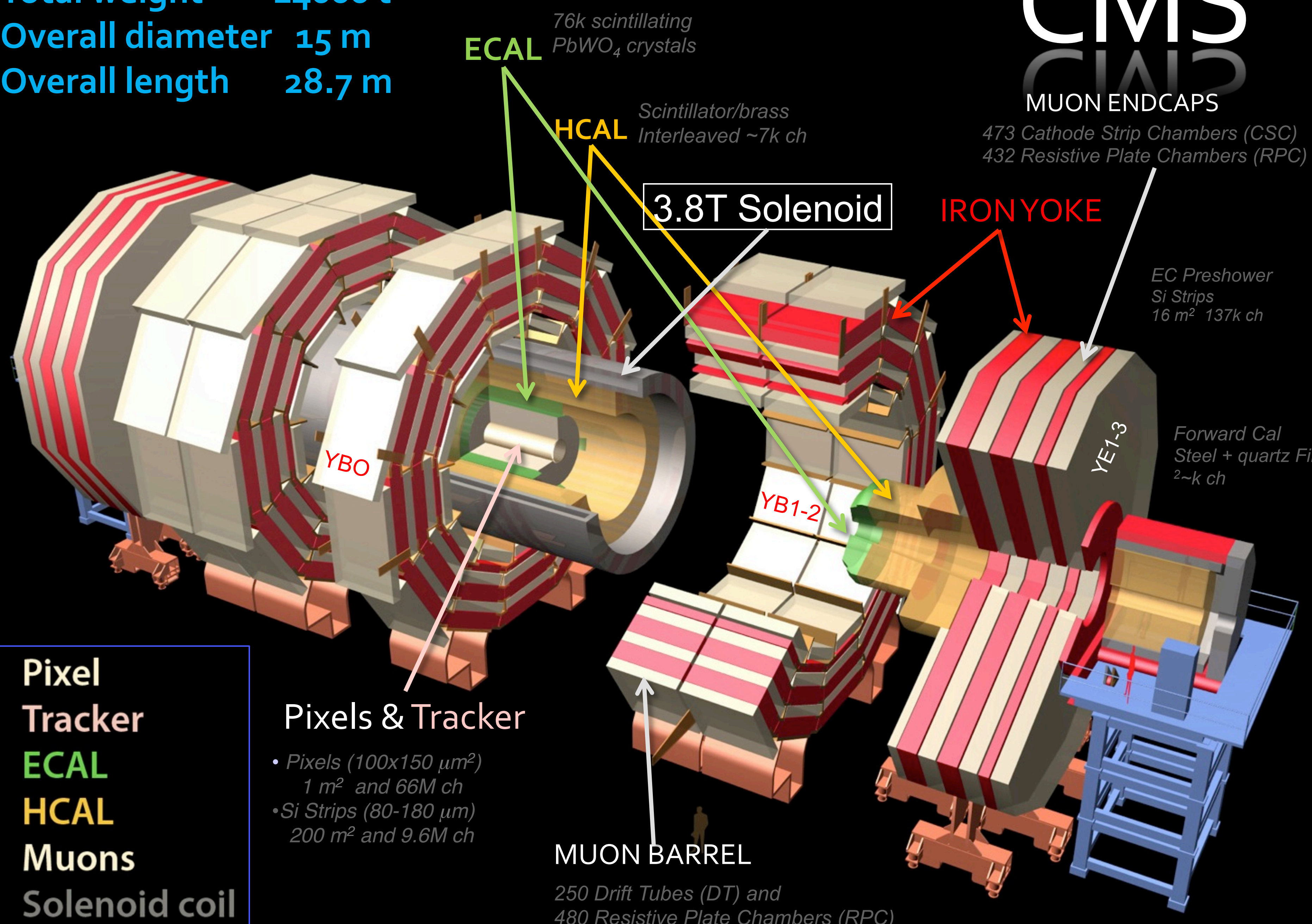


CMS

http://cms.web.cern.ch

CMS

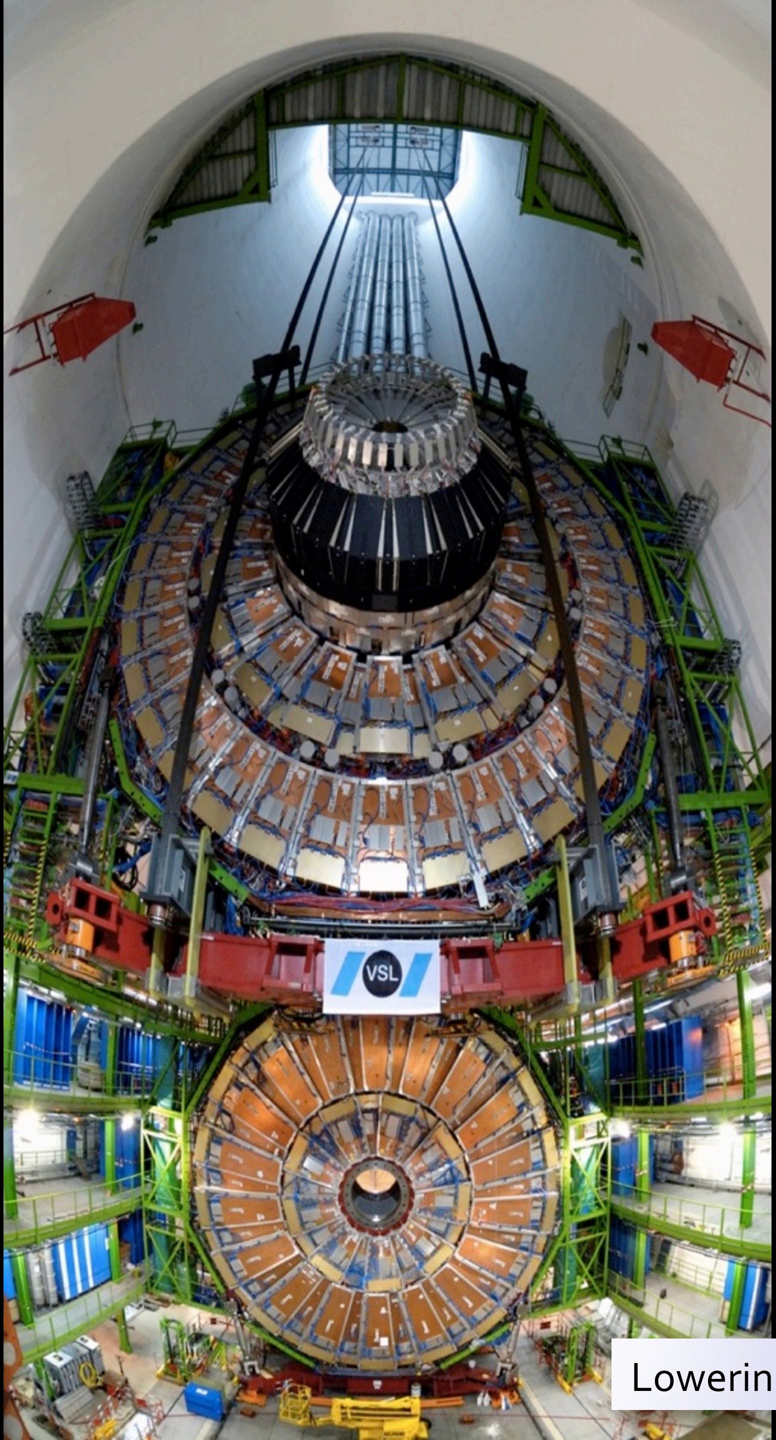
Total weight	14000 t
Overall diameter	15 m
Overall length	28.7 m



Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil

CMS

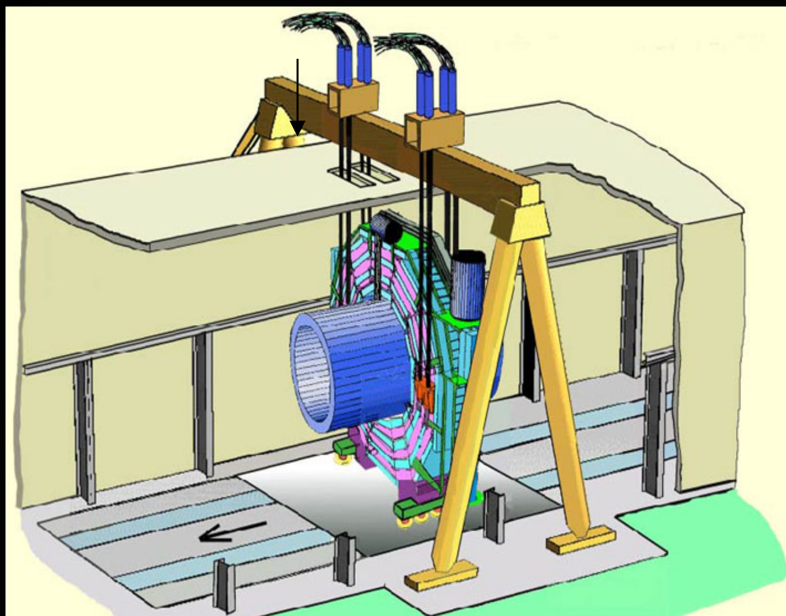
- Construction/installation
  - CMS was built in large sections on the surface
  - Sections were lowered 100 m underground

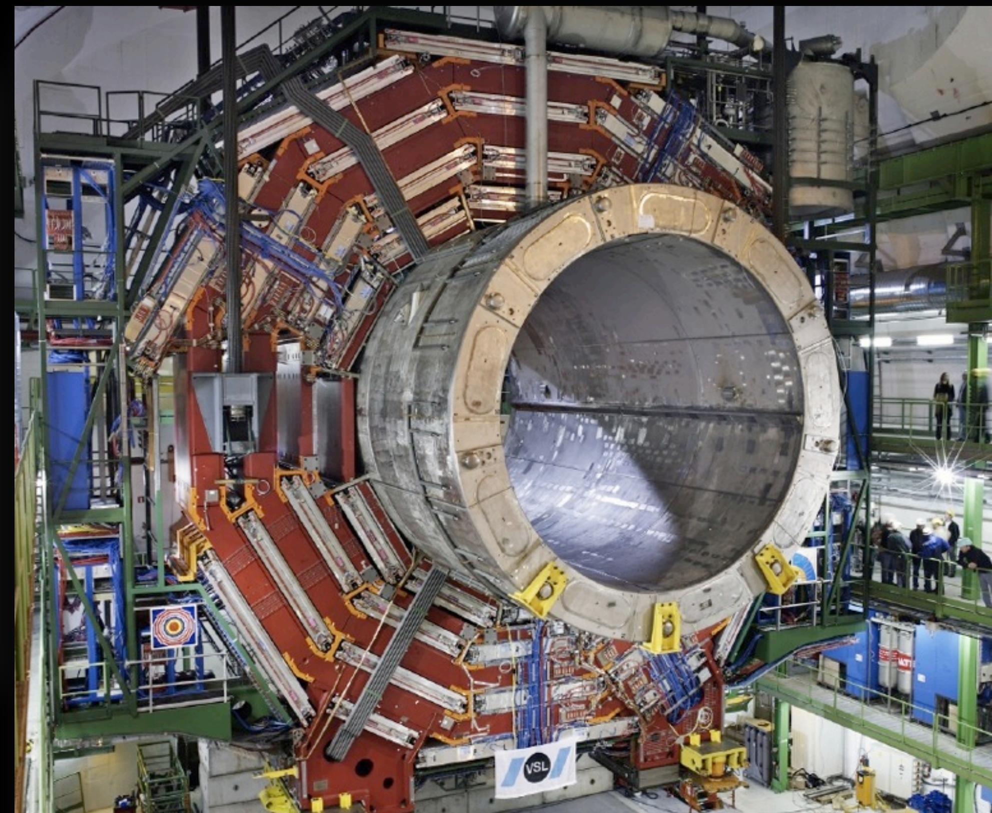


Lowering YE+1 (Jan'07)

Lowering of the heaviest slice (2000 tons) of the CMS detector in the underground cavern Feb. 2007

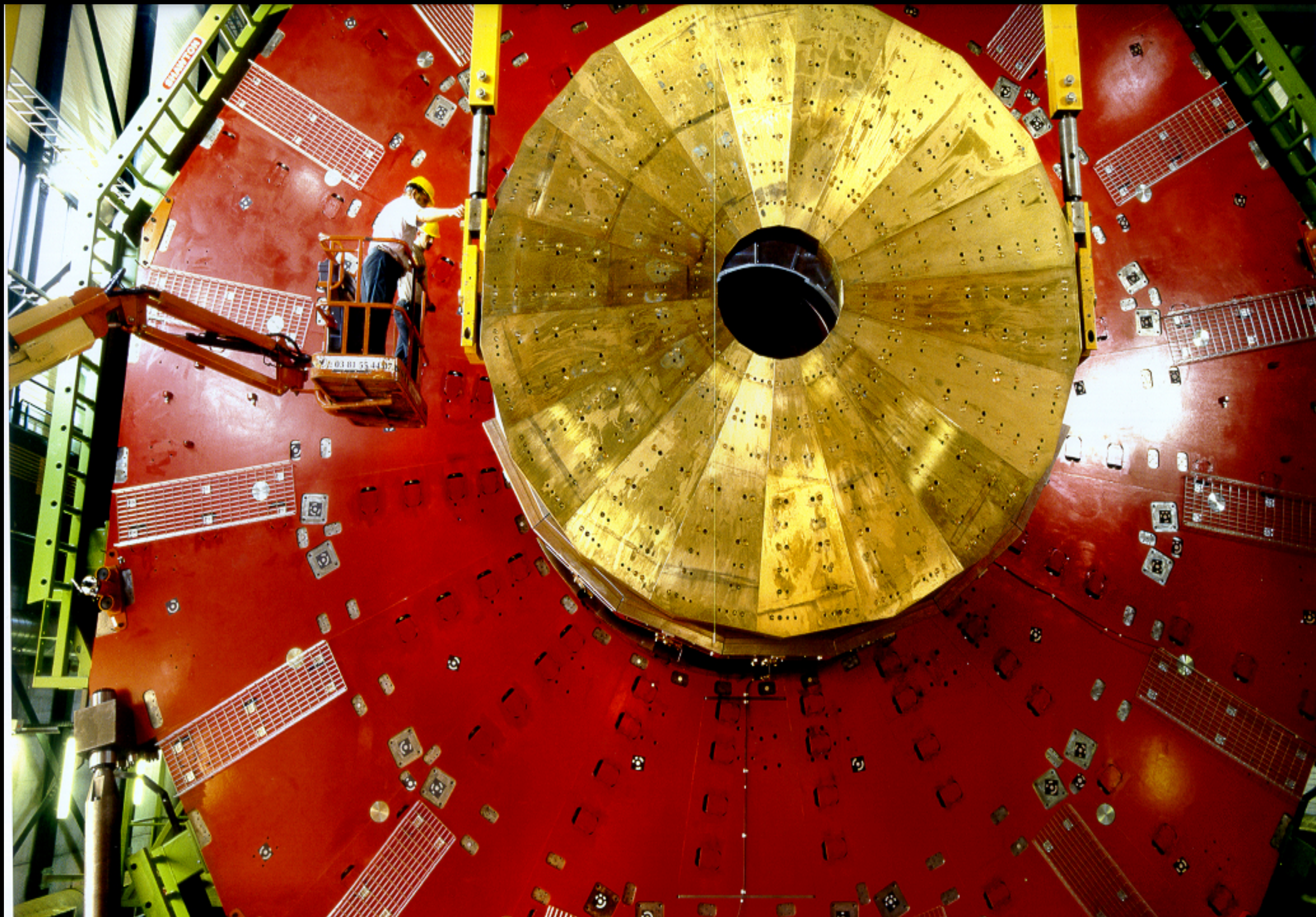
CMS



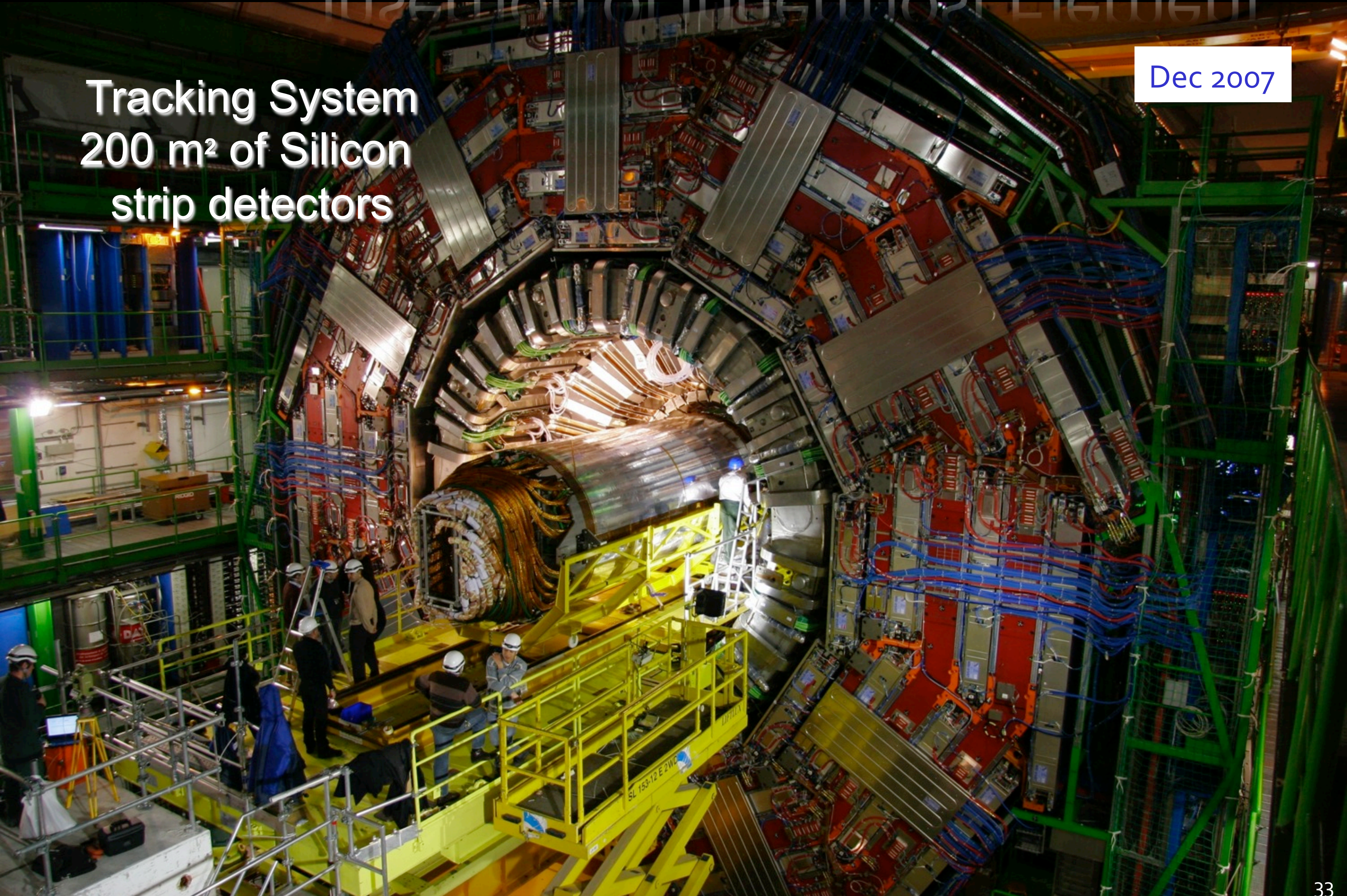


Largest, most powerful superconducting magnet ever built

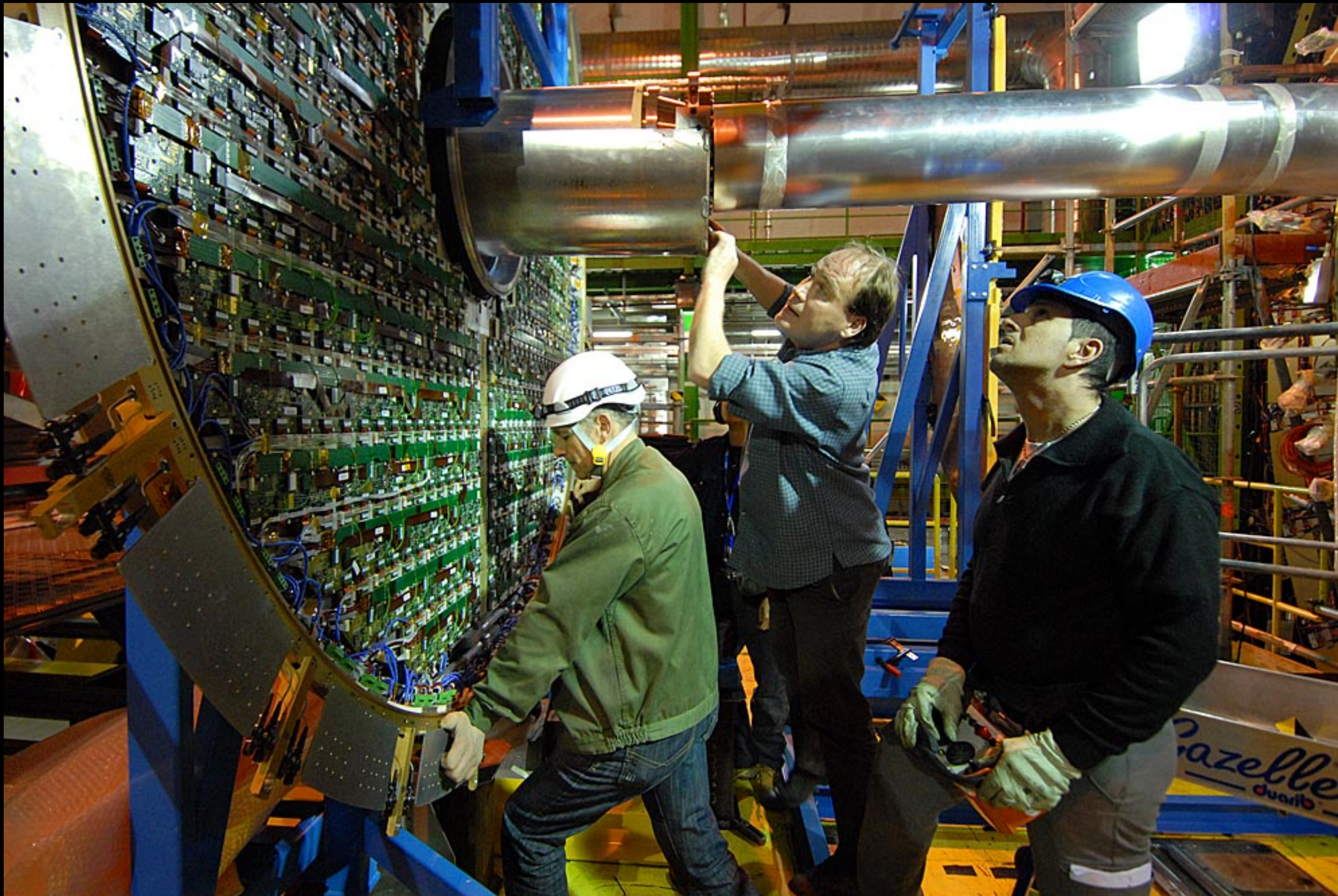
Recycling brass shell casings for hadron calorimetry



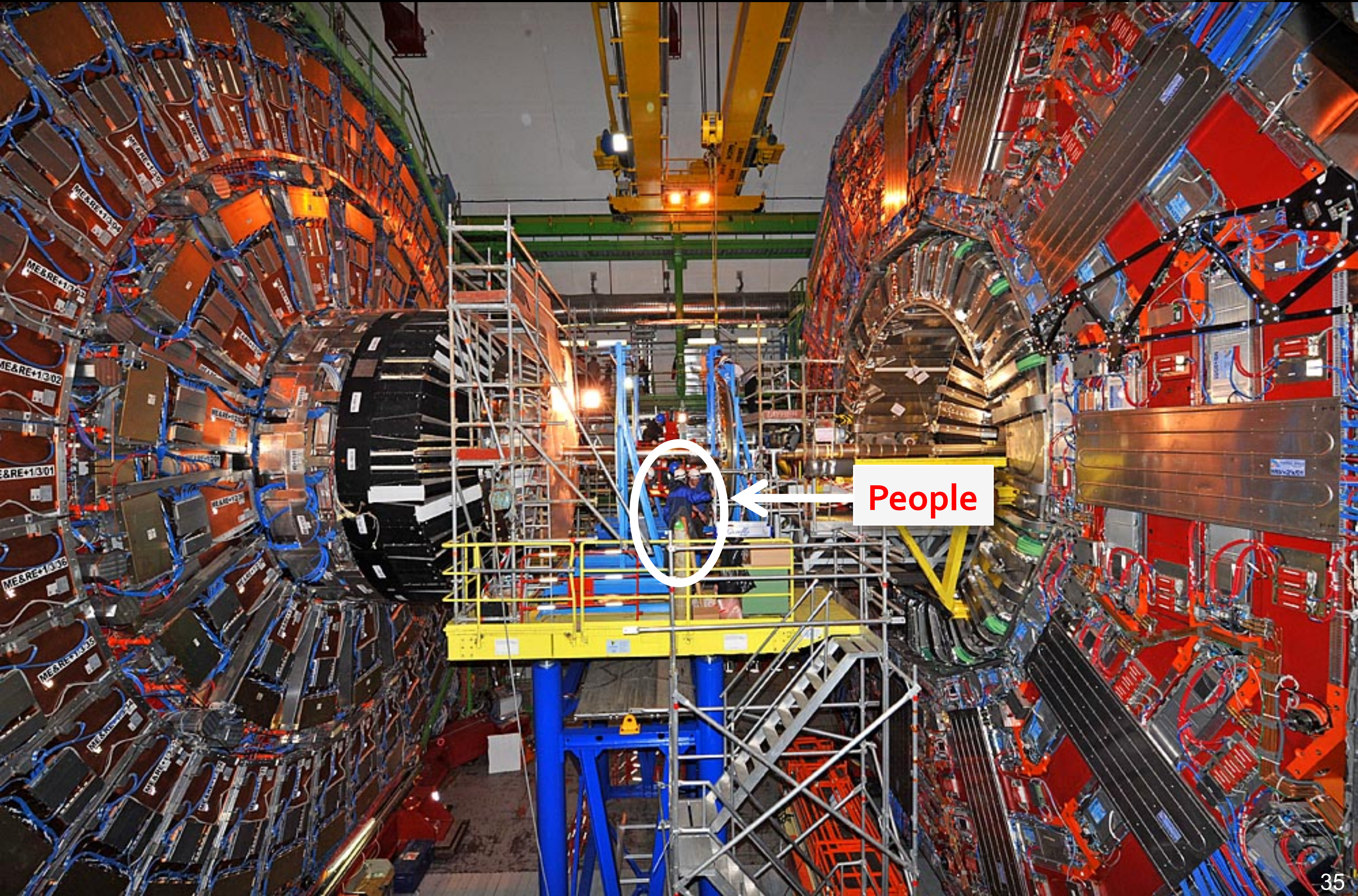
Insertion of Innermost Element



The last piece

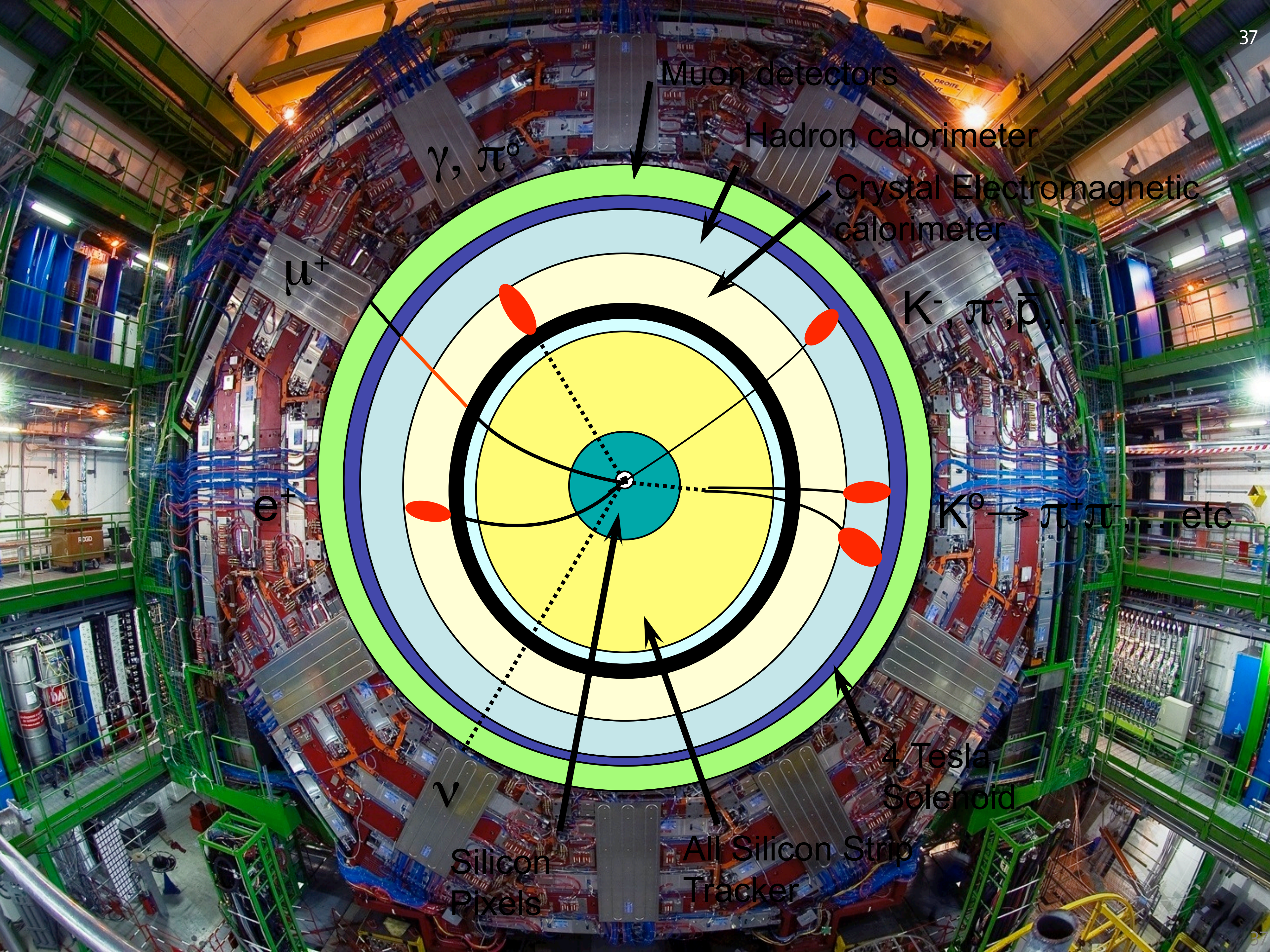


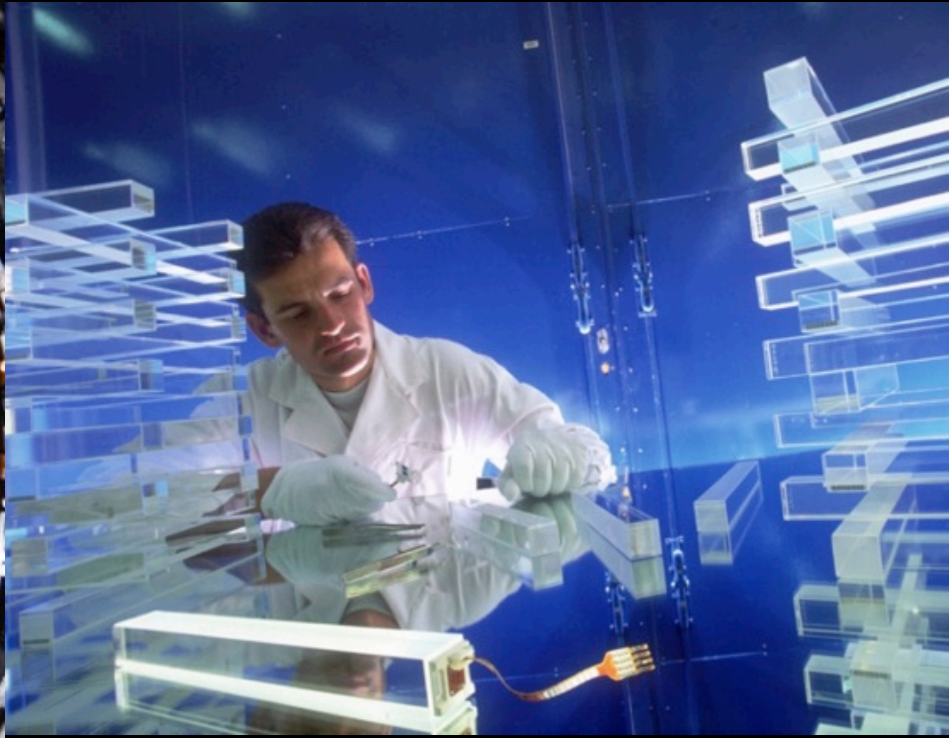
The last piece



CMS Collaboration

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

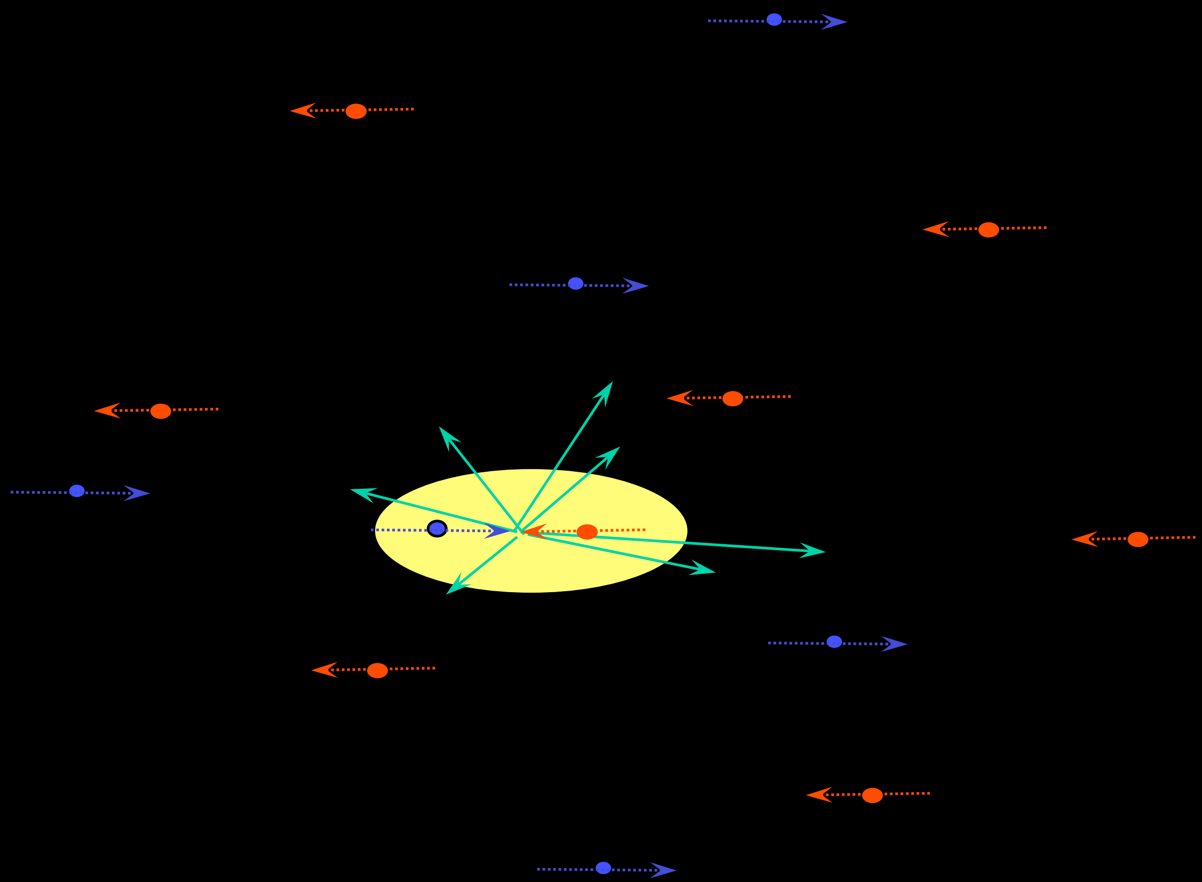

Muon detectors
Hadron calorimeter
Crystal Electromagnetic calorimeter
γ, π°
μ+
K-, π-, p̄, . . .
e+
K° → π+π-, . . . etc
ν
4 Tesla Solenoid
Silicon Pixels
All Silicon Strip Tracker

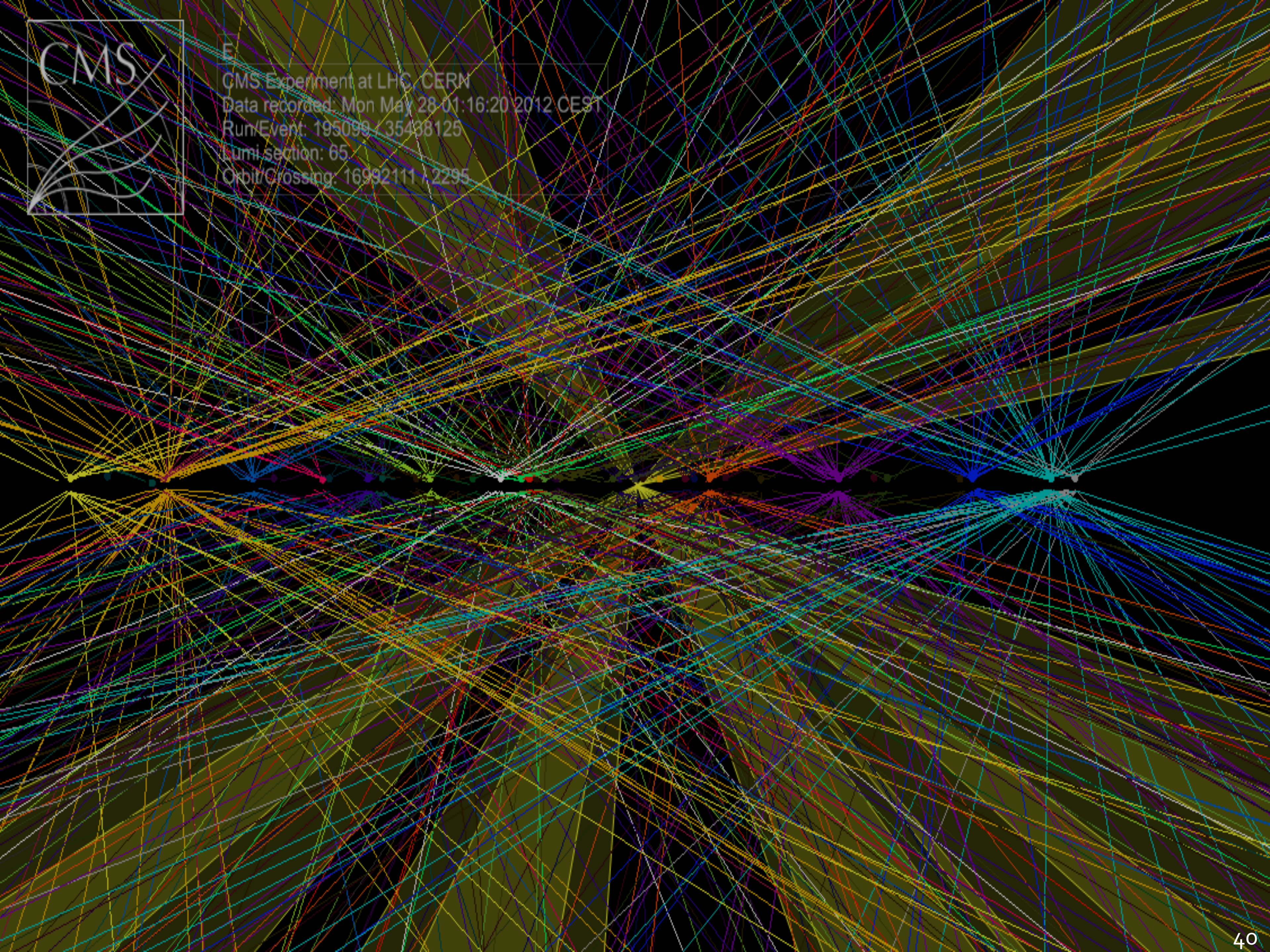


Colliding Beams

2 beams of ~1380 bunches go around the LHC in opposite directions. Each bunch has 100 billion protons.

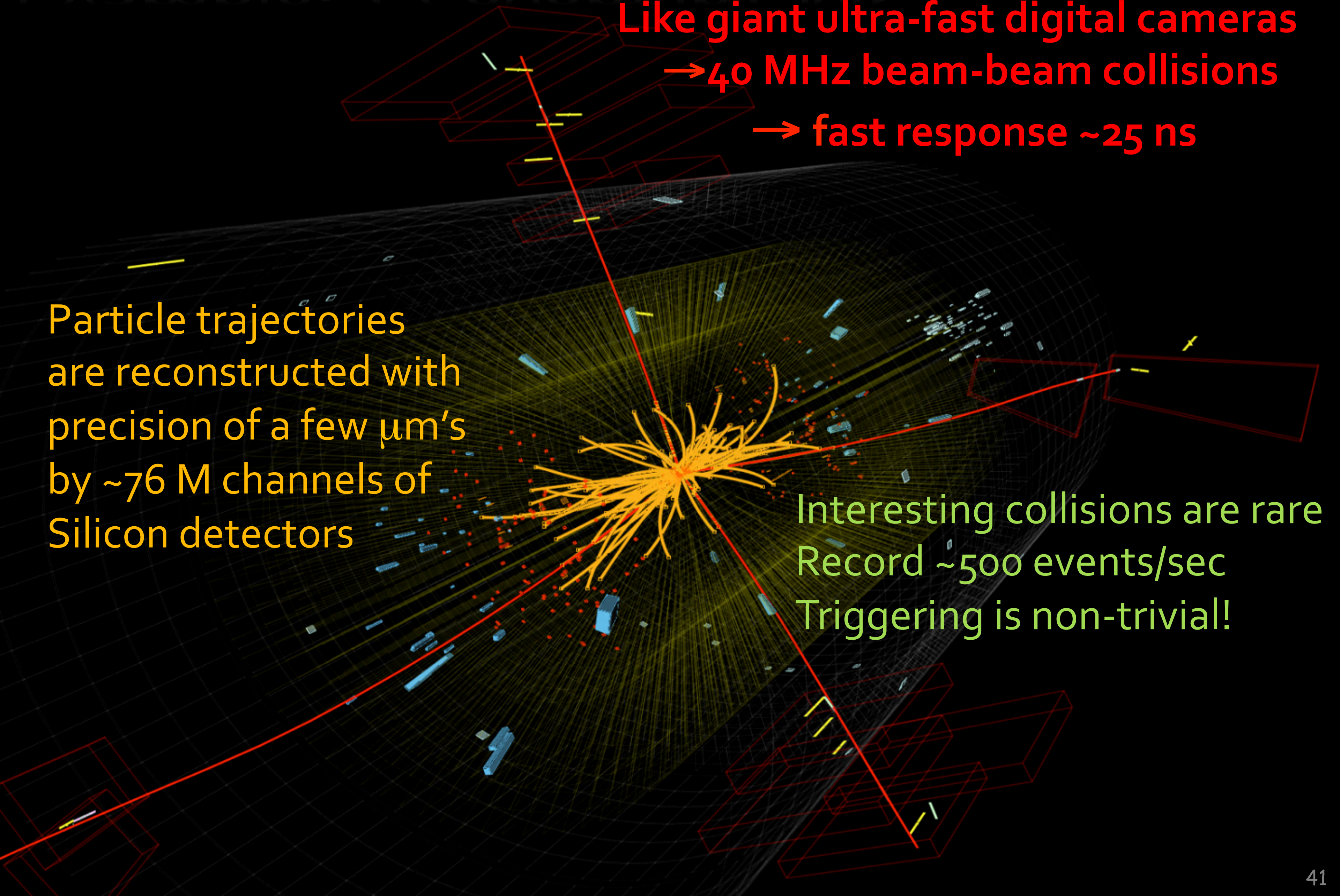
~20-30 protons collide when bunches cross in CMS/ATLAS




CMS
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

Example: ZZ event in CMS

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!

LHC Data Recorded

22 Petabytes in 2011

30 Petabytes in 2012

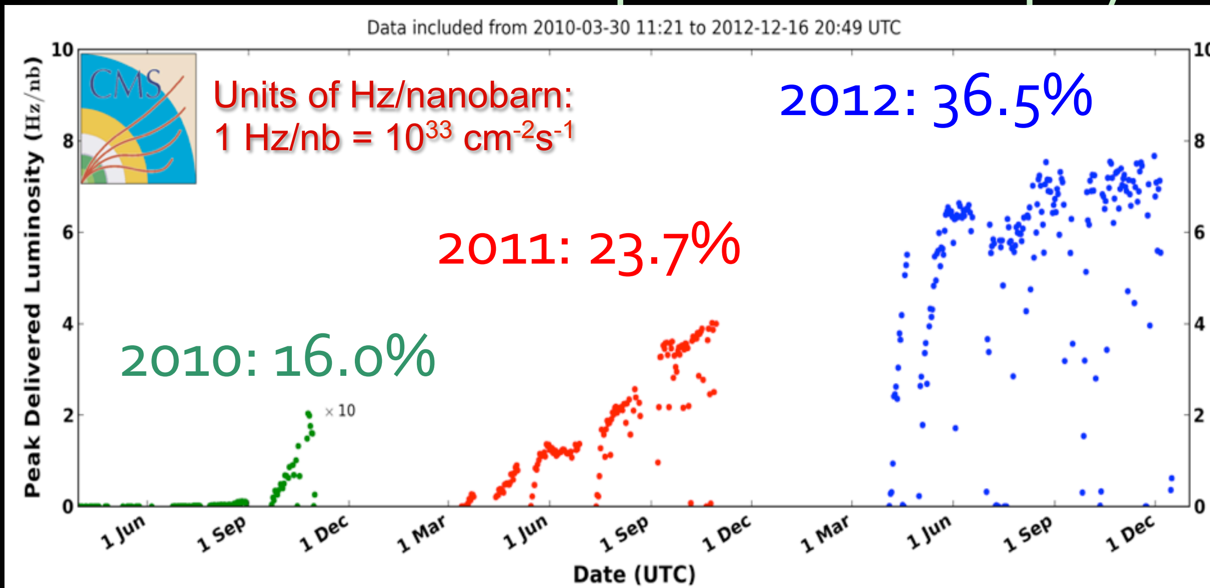
- *Computing grid:*

~250,000 processors in ~150 computing centers in ~35 countries

How well does it work?

Accelerator & Detectors

- Fraction of LHC operations for physics:



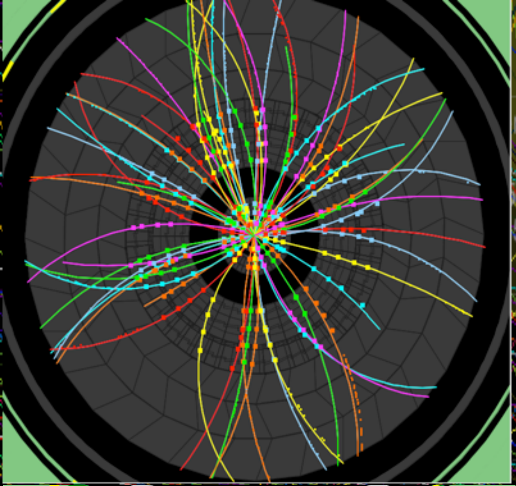
Many luminosity records, especially in 2010 and 2011.

Luminosity stabilized at ~7×10^{33} $cm^{-2}\,s^{-1}$ later in 2012

- The detectors worked spectacularly well!
  - With almost no change after 3 years of operation
  - All sub-systems at 95-100% operational

- This means high data quality:
  Results are based upon ~90% of all beam crossings

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

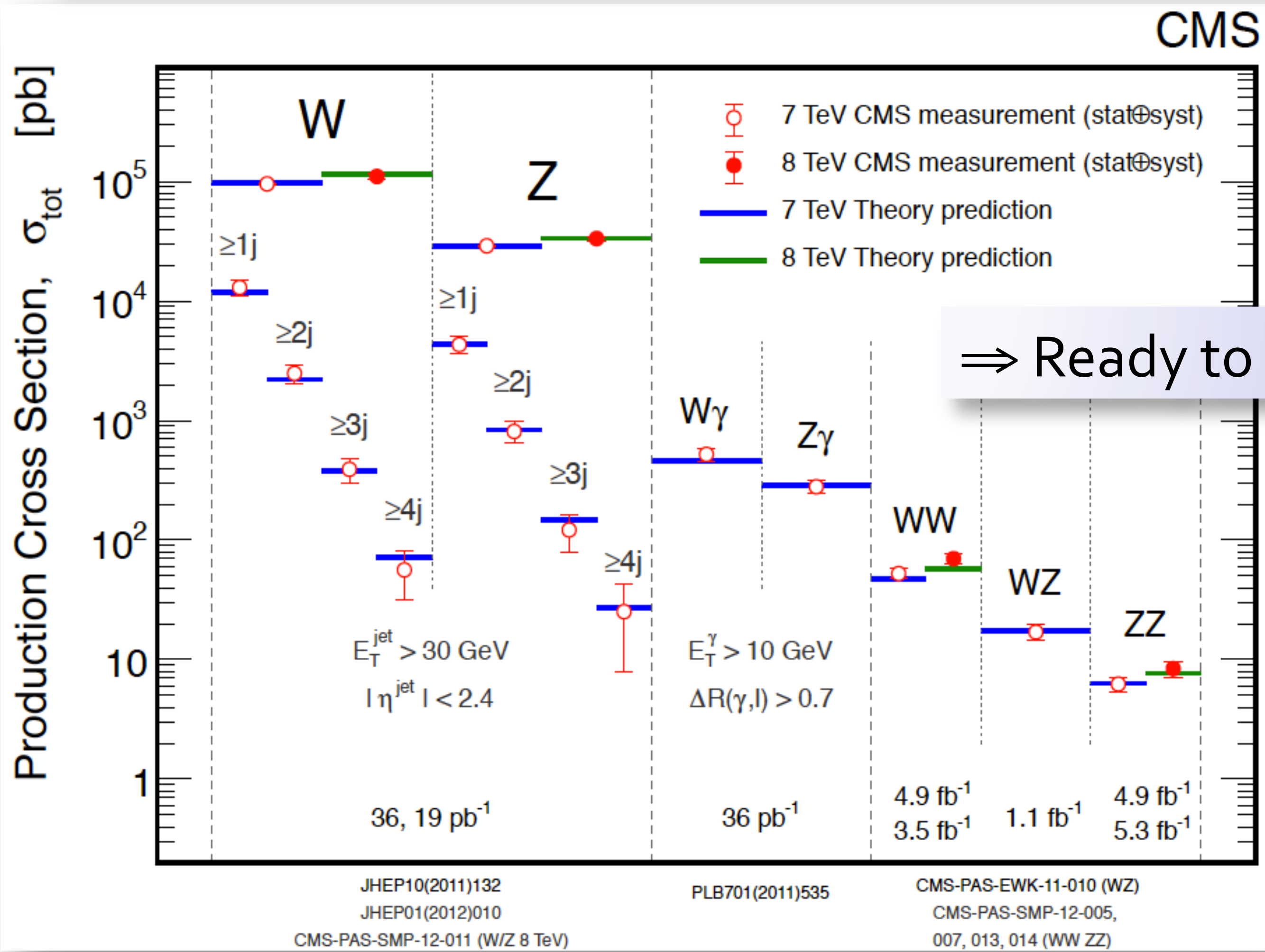
O(20-30) Pile-up events

50 ns inter-bunch spacing

Design value exceeded!

In 2012: measurements spanning >4 orders

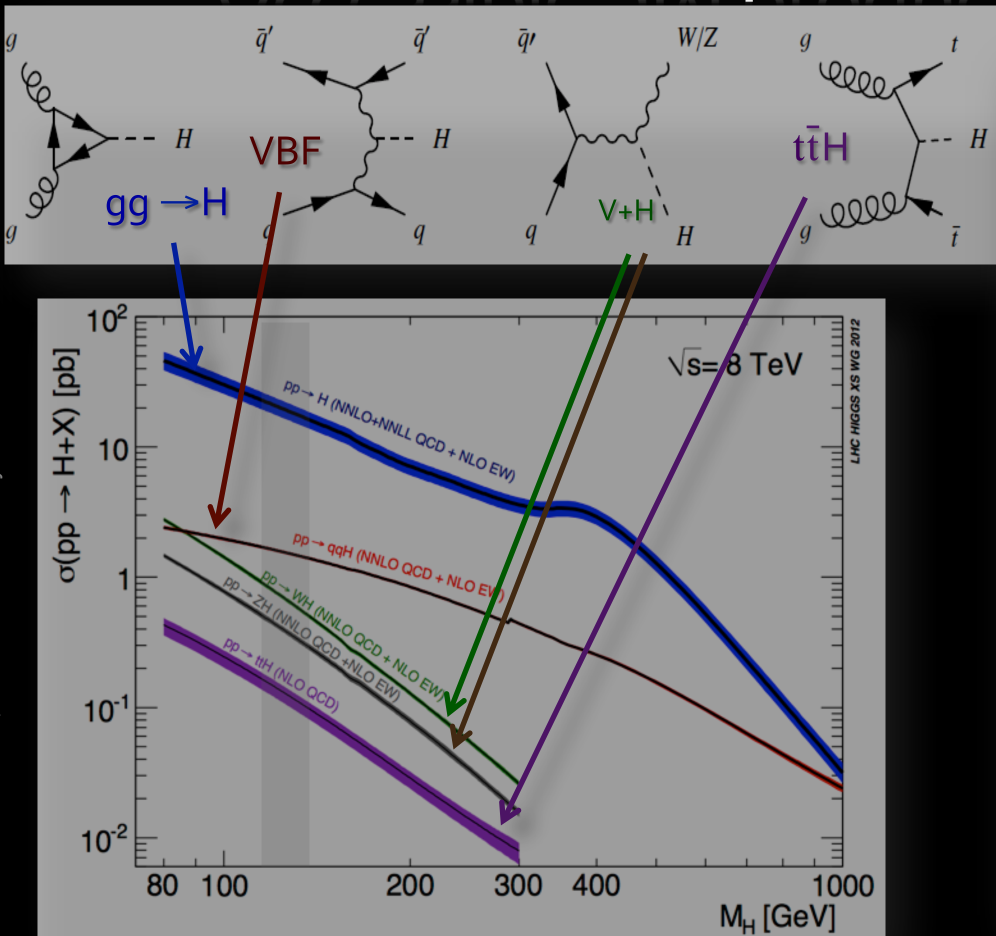
Good understanding of the detector + accurate theory predictions
→Precision measurements of known process

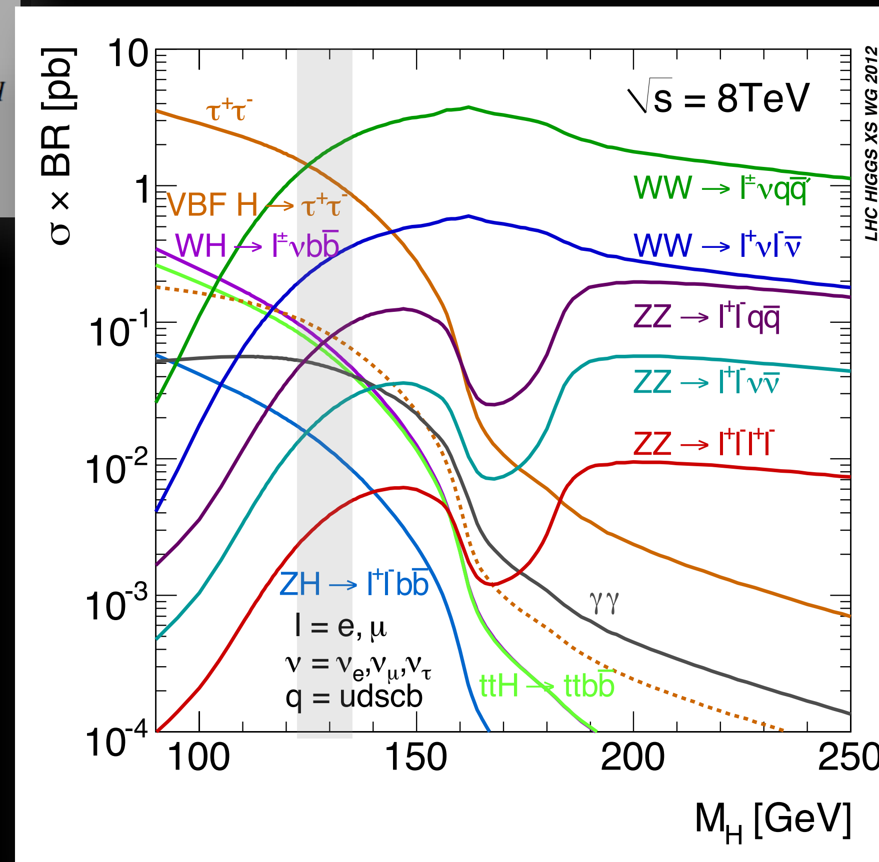


⇒ Ready to hunt for the Higgs

Discovery

Accessible SM production and decay modes





Most sensitive (in order) for 120 < m < 130 GeV:

$H \to ZZ^* \to$ 4leptons, $H \to \gamma\gamma$, $H \to WW^* \to l\nu l\nu$

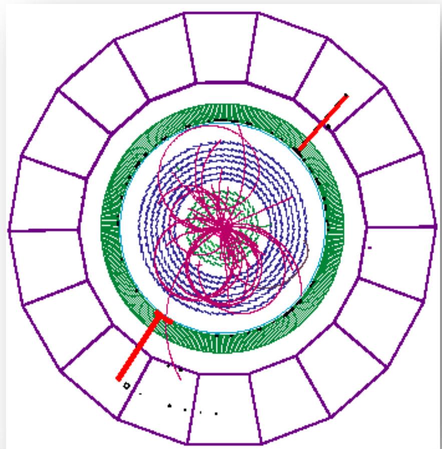
$H \to \tau\tau$ and V+H with $H \to b\bar{b}$

Tiny rates, low S/B, complex final states

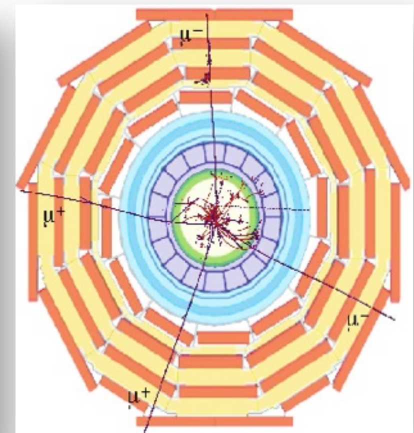
Narrow Peaks

LHC produces ~1/hour
- 500 per experiment after final selection in full dataset
- 18k background events
- Signal/Background ~3%
  up to 20-90% in VH, VBF production modes

$H \rightarrow \gamma\gamma$

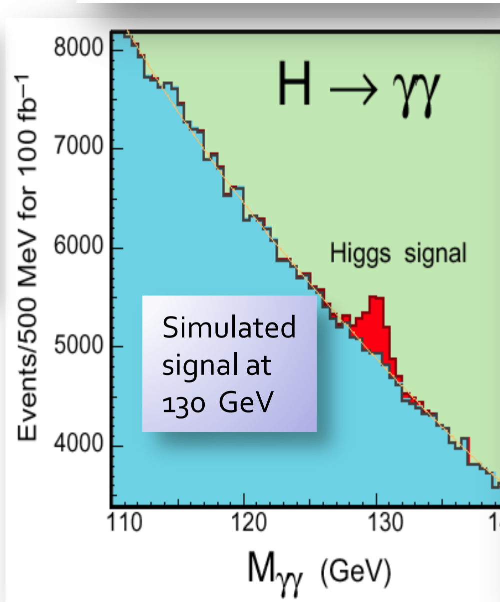


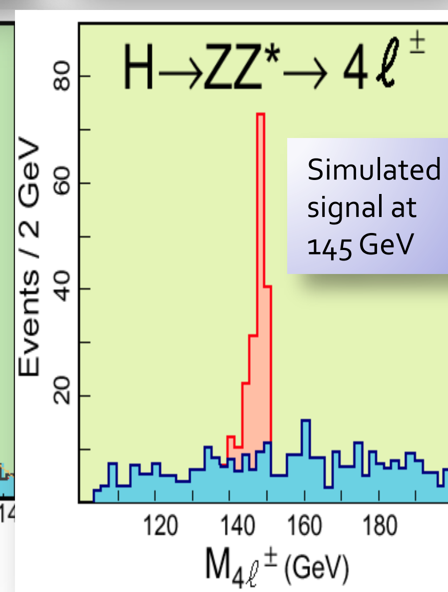
$H \rightarrow ZZ^* \rightarrow 4l$



Tiny Signal but:
- Low background:
  - S/B ~ 1
- 4 leptons with minimum p_T in the 5-20 GeV range
- Main background:
  - $ZZ^* \rightarrow 4l$

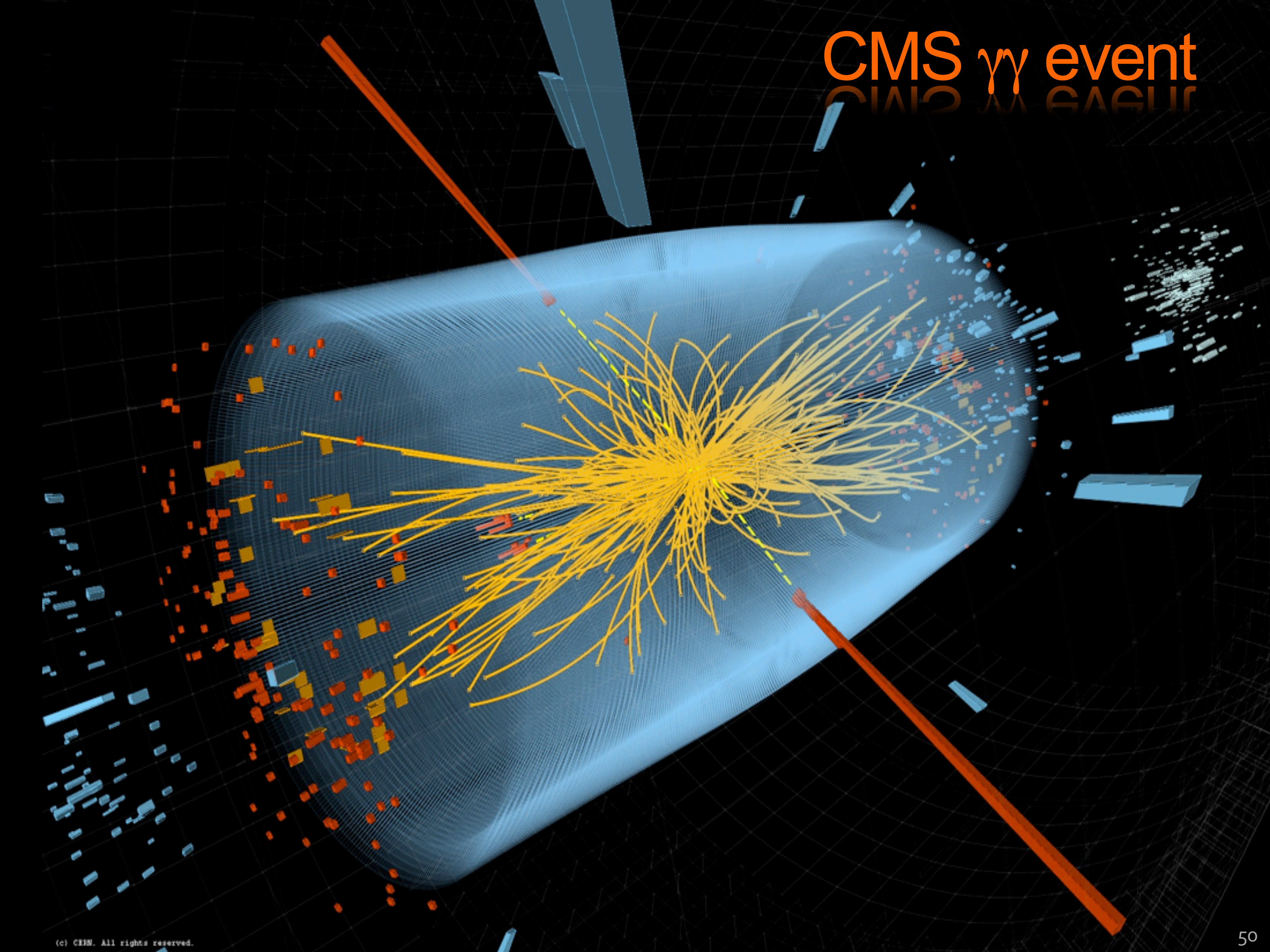
Crucial issue:
$\gamma\gamma$ mass resolution to form a narrow signal peak on top of a HUGE background



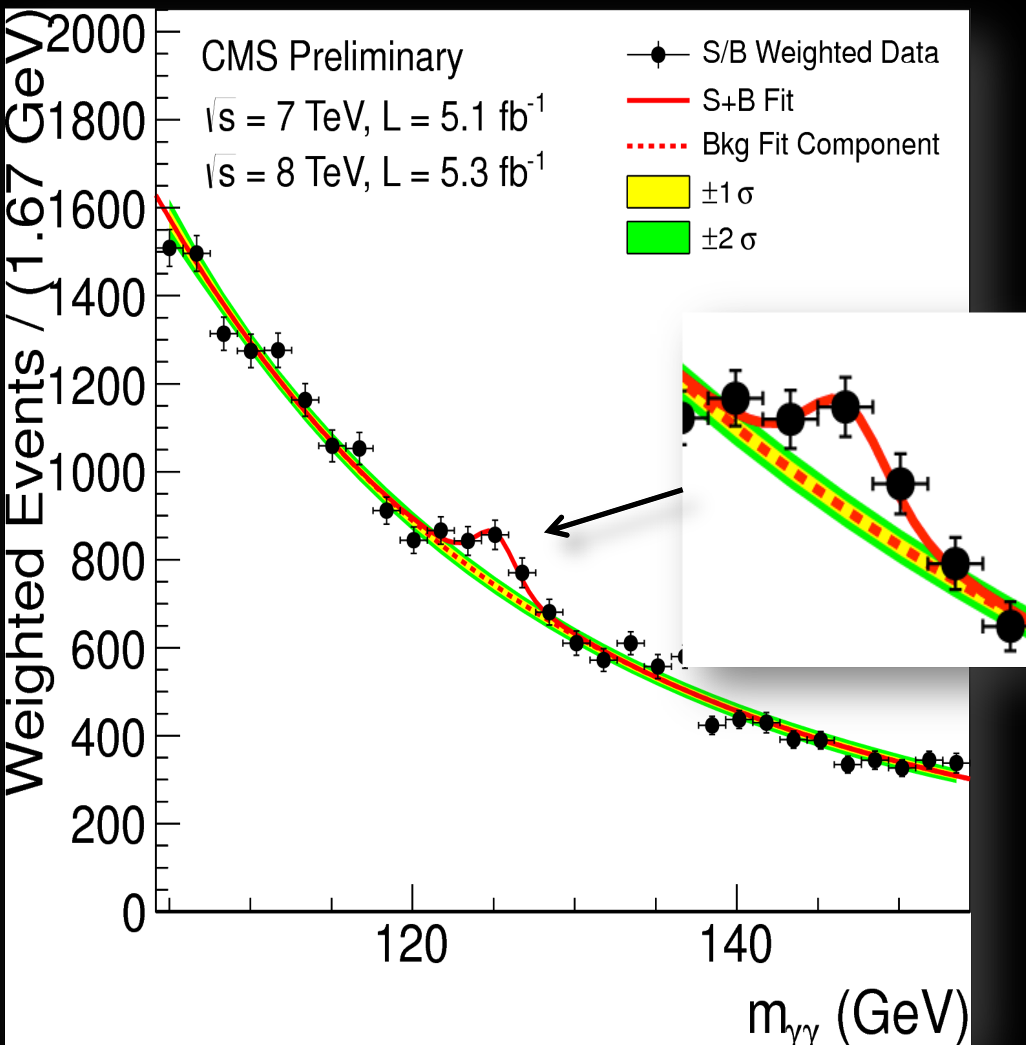


Crucial issue:
Identifying leptons with high efficiency down to low p_T to capture as much (tiny) signal as possible

CMS $\gamma\gamma$ event

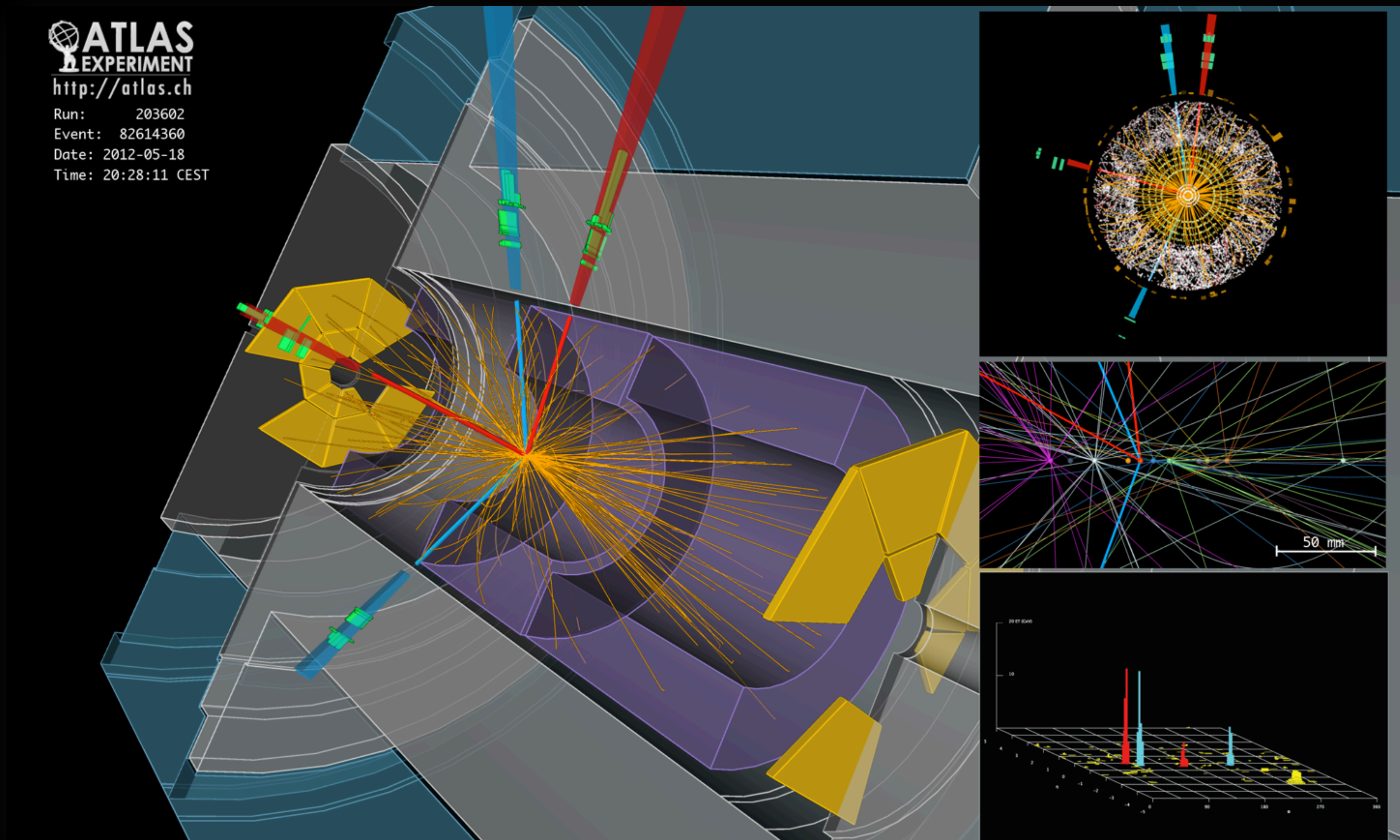


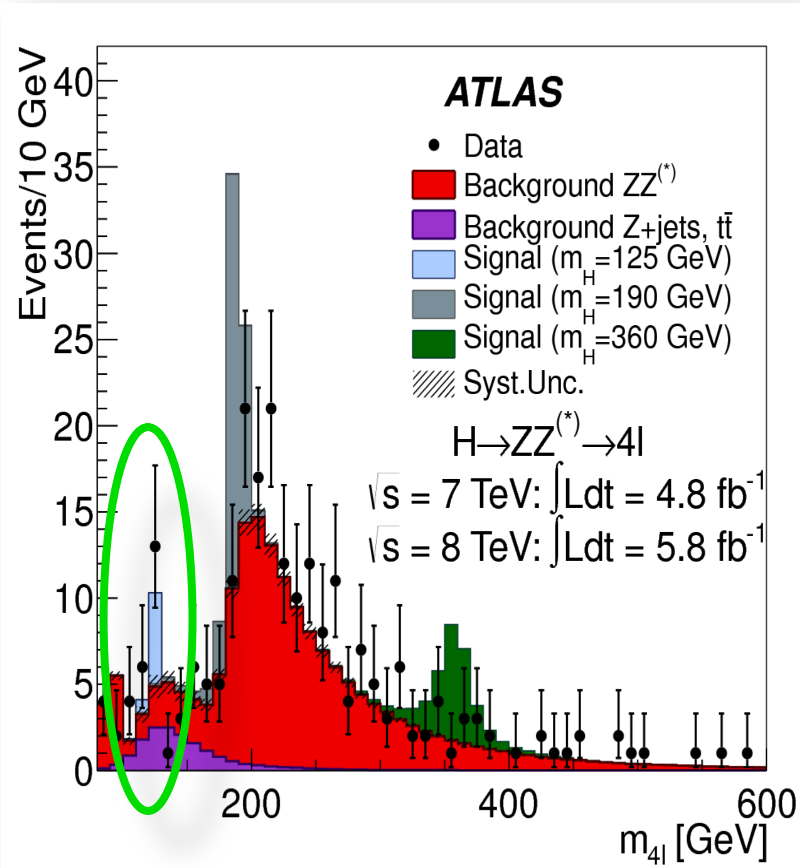
γγ Mass Distribution

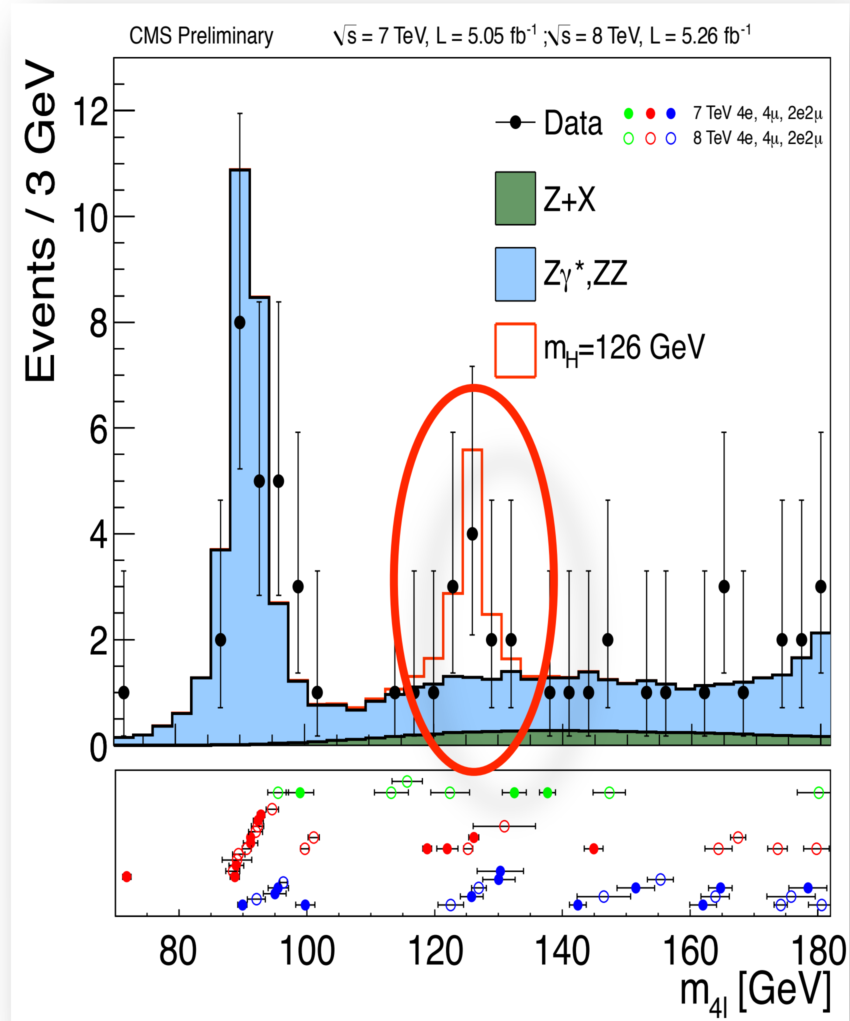


- What's in the bump?
  - A few hundred extra events with two photons that reconstruct to a mass near 125 GeV
- It took how many collisions?
  - 10^{15} = 1,000,000,000,000,000

ATLAS $H \rightarrow ZZ \rightarrow eeee$ candidate




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]
0
5
10
15
20
25
30
35
40
200
400
600


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]
0
2
4
6
8
10
12
80
100
120
140
160
180

A major discovery of a "Higgs-like" particle

- Both experiments see excesses of events at a mass of ~125 GeV in several different channels
- After very extensive analysis of the data, we know they are not from previously known processes
- Results are consistent with what is expected for a Higgs
- The significance of the results (sizes of the bumps, coincidence of all the channels showing excess at the same mass) is at the level required for discovery

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

CERN

Melbourne

> 1 billion

people saw TV footage

1,034

TV stations

5,016

Broadcasts

17,000

news articles in

108

Countries

HOW THE HIGGS COULD BECOME ANNOYING

Yes, the discovery of the Higgs boson is thrilling and game-changing. But it could also introduce some aggravating situations.

3 Ways the Higgs Boson Discovery Will Impact Financial Services

Summary of the July 4th Updates at √s=7 and 8 TeV

- **ATLAS :**
  - $H \to \gamma\gamma$ 4.5 σ (2.4 σ)*
  - $H \to ZZ^* \to 4l$ 3.4 σ (2.6 σ)
- **Combined:**
  - **5.0 σ (4.6 σ)**
    - 7 TeV only for WW, ττ, bb

- **CMS: unblinded**
  - $H \to \gamma\gamma$ 4.1 σ (3.2 σ)
  - $H \to ZZ^* \to 4l$ 3.2 σ (3.8 σ)
  - $H \to WW^* \to l\nu l\nu$ ~1.5 σ (~2 σ)
- **Bosons 5.1 σ (5.0 σ)**
- **Fermions**
  - $H \to bb$ slight excess
  - $H \to \tau\tau$ deficit
- **Combined:**
  - **4.9 σ (5.9 σ)**

*Observed and (Expected)

$l = e, \mu$

Is it 'Higgs-like'
Or is it a Higgs we like?

- Rolf Heuer (CERN DG) ca. winter 2012

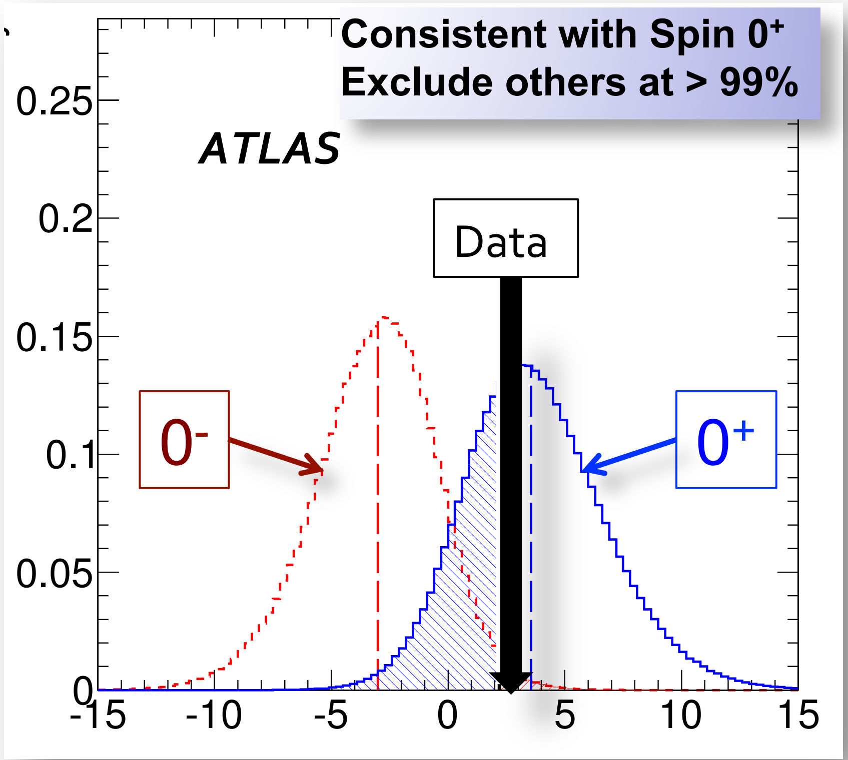
Emphasis on its properties

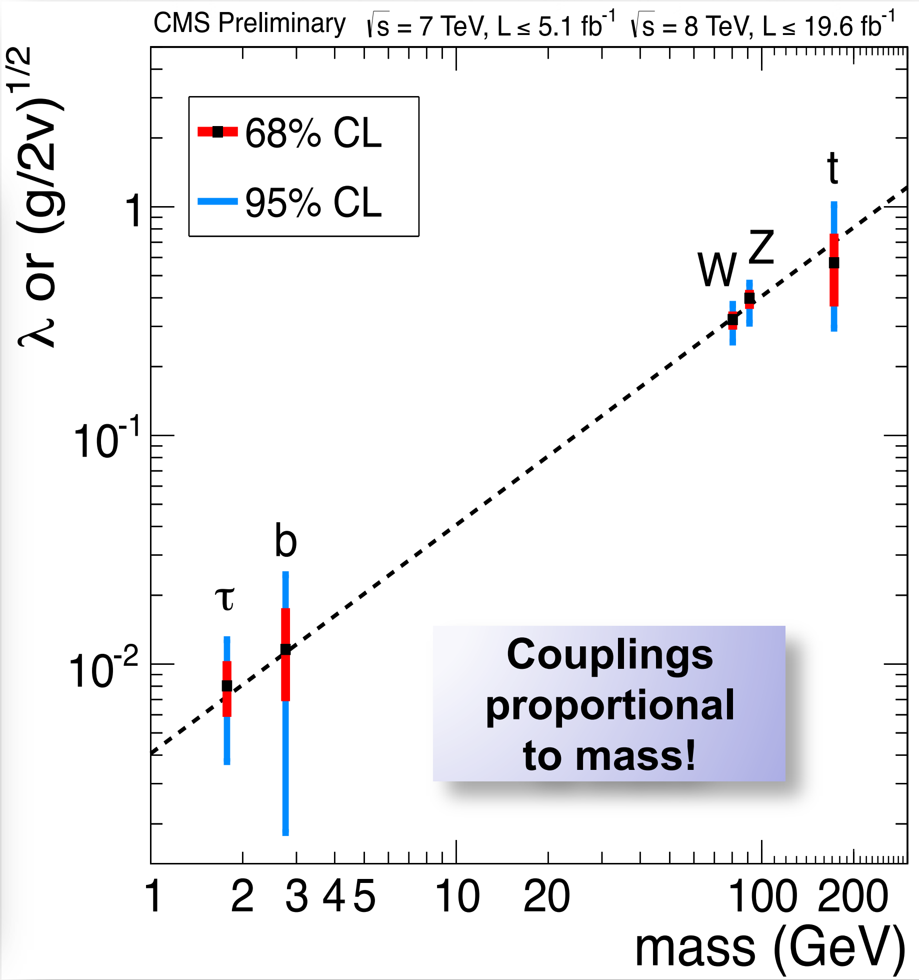
- Two important ‘fingerprints’:
  - Does it couple to particles proportional to their masses
    - w/different proportionality factors for Fermions vs. Bosons?
  - Does it have spin zero and positive parity ?

Studies were carried out with ~ 2.5 times the data used for the discovery

- *And mostly for future studies:*
  - *Is it elementary ?*
    - *The first elementary scalar ever*
    - *Or is it composite ? Does it have (any degree of) negative parity ?*
  - *Do its couplings deviate from SM expectations ?*
    - *Are there New Physics contributions to $gg \to H$ or $H \to \gamma\gamma$ loops ?*
    - *Does it decay to invisible particles ? Is it alone ?*

Spin, Couplings to other particles?

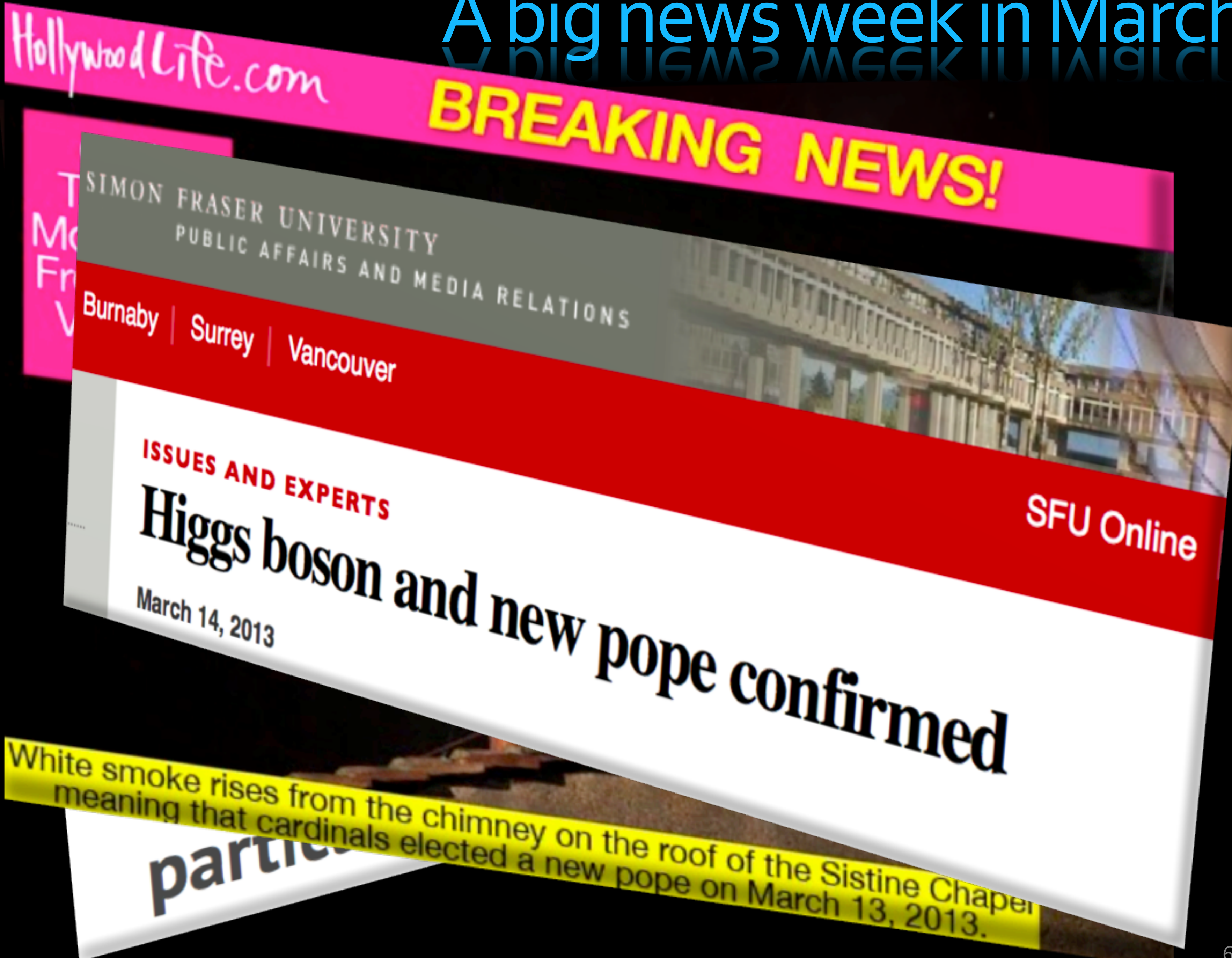


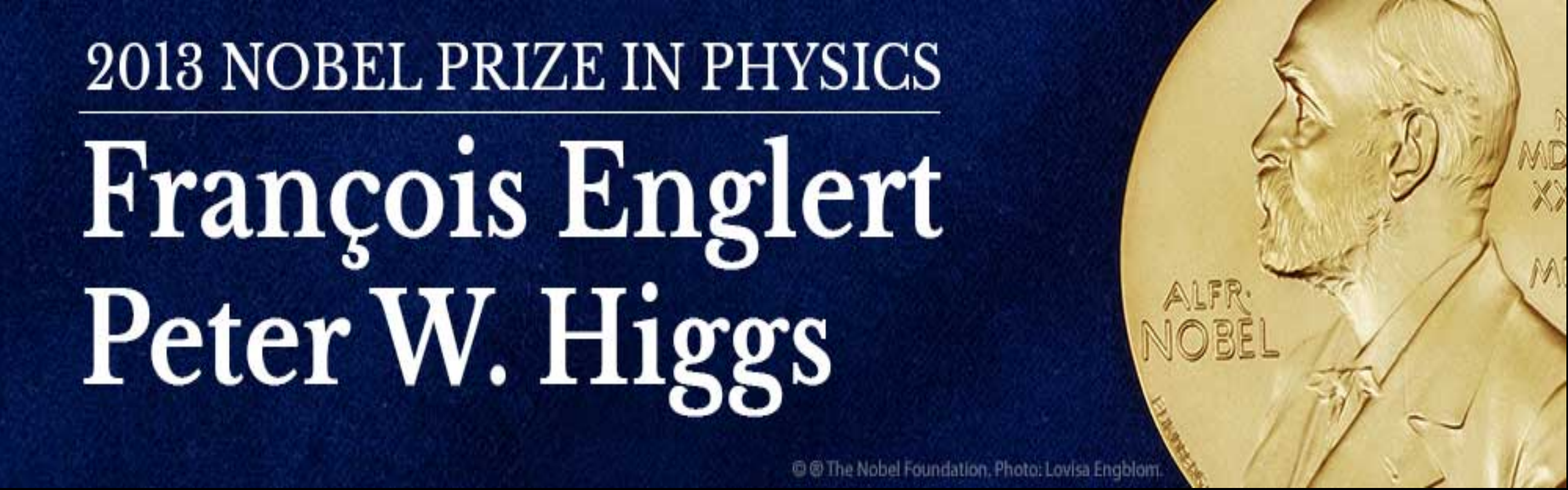


- Gathered more than twice as much data and signal is much stronger!

Meets expectations for a Higgs!

A big news week in March





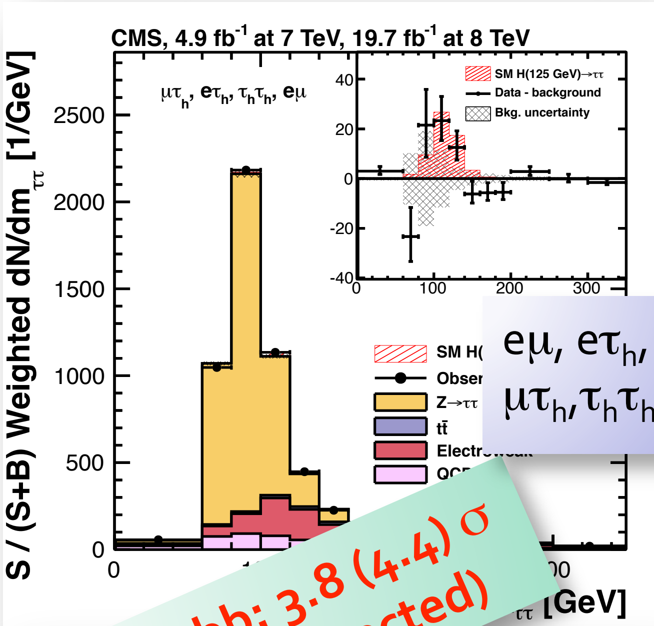
8 October 2013

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to François Englert and Peter 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"

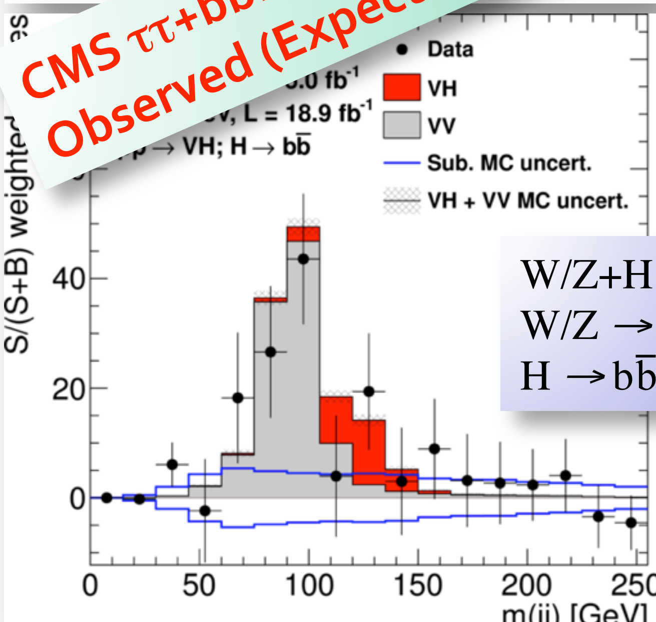
Highlights of other results and some recent results

December 2013: Direct decay to Fermions

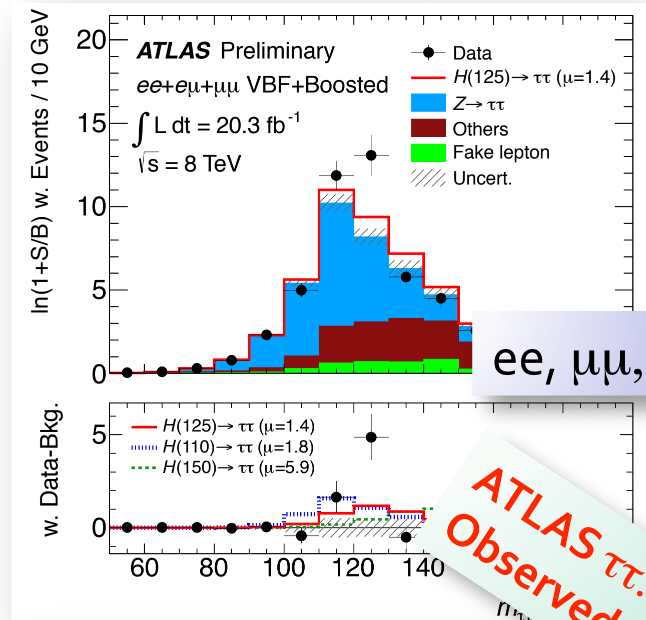


eμ, eτ$_h$, μτ$_h$, τ$_h$τ$_h$

CMS ττ+bb: 3.8 (4.4) σ Observed (Expected)

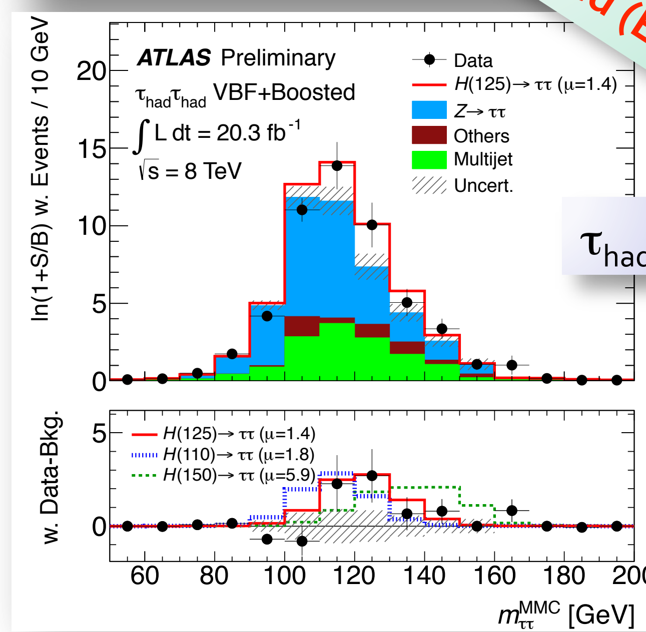


W/Z+H with
W/Z → lν/ll
H → b$\bar{b}$



ee, μμ, μe

ATLAS ττ: 4.1 (3.2) σ Observed (Expected)



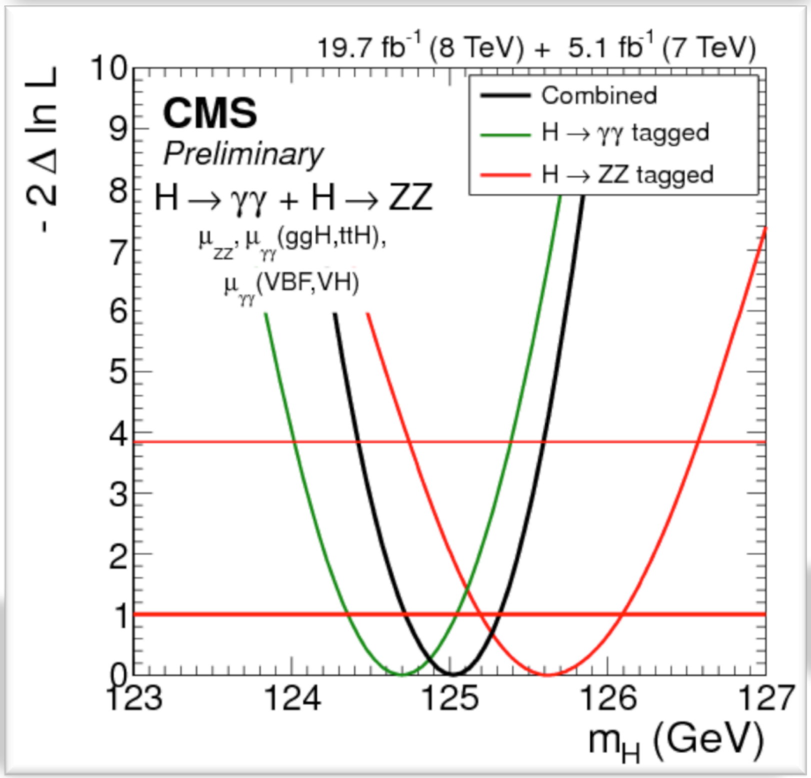
τ$_{had}$, τ$_{had}$

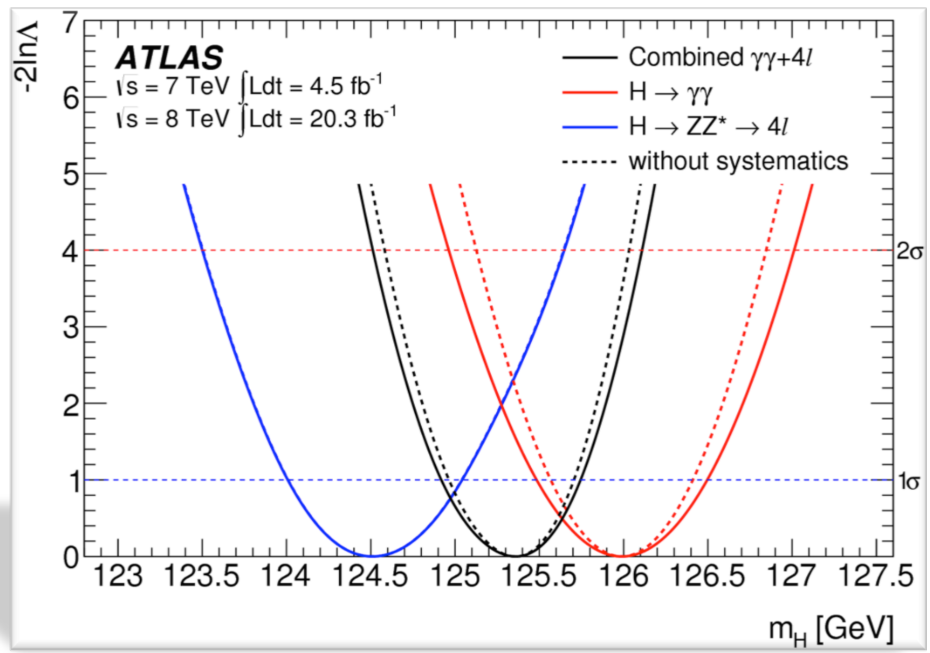
Mass Measurements – Very recent

Both experiments combine measured masses in the two most precise channels: **H → γγ** and **H → ZZ* → 4leptons**

m = 125.03 ± 0.30 GeV

m = 125.36 ± .41 GeV





$$m_H = 125.03 \pm 0.30 \left[{}^{+0.26}_{-0.27}(\text{stat.})\,{}^{+0.13}_{-0.15}(\text{syst.})\right] \text{ GeV}$$

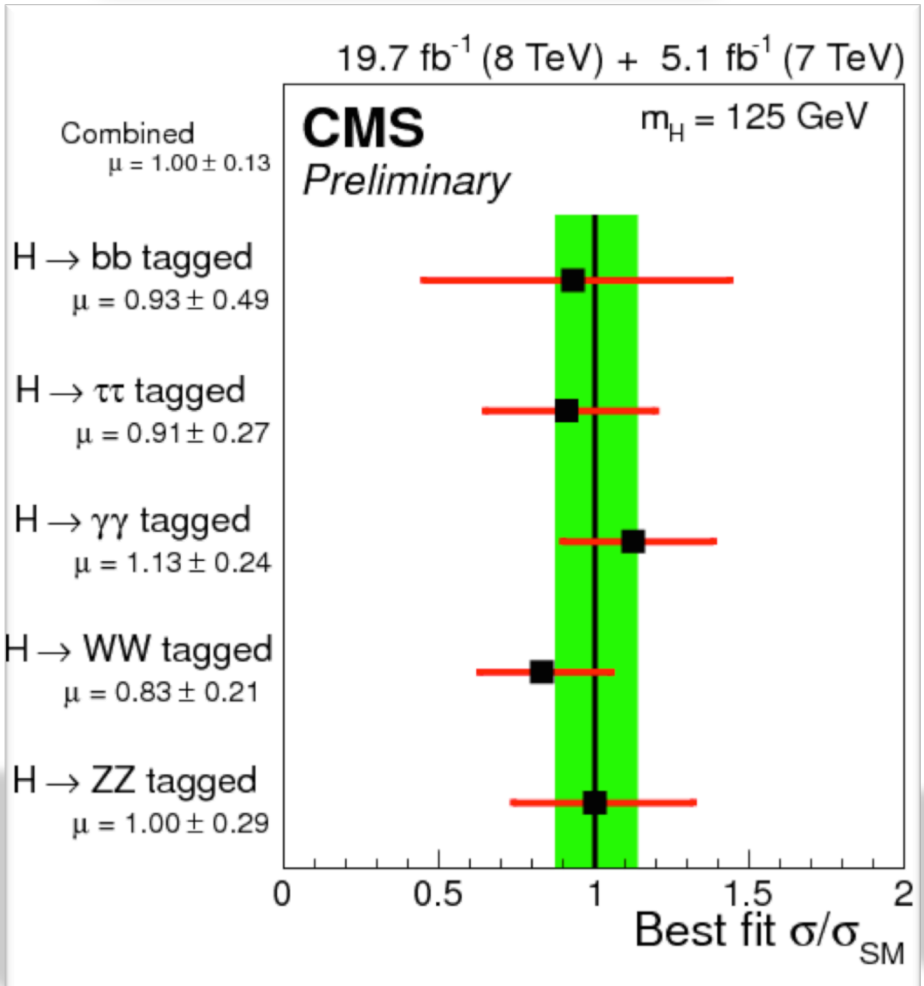
$$m_H = 125.36 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{syst})\ \text{GeV}$$

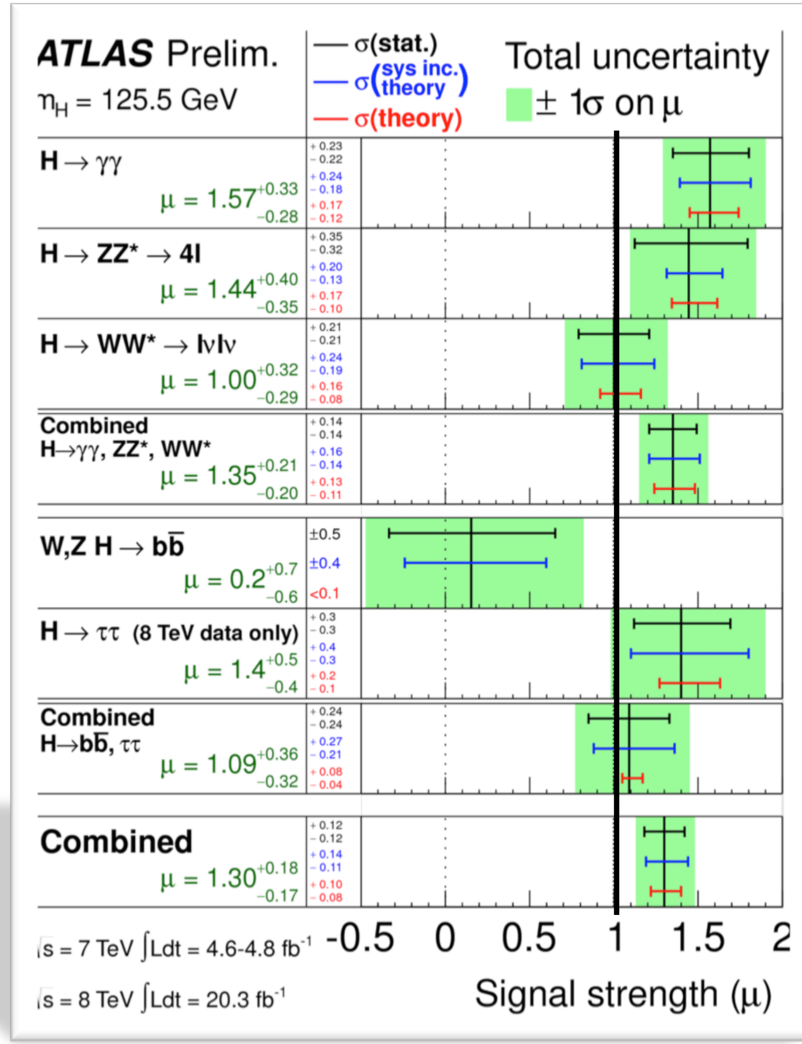
Weighted mean: m = 125.15 ± 0.24

Couplings of Higgs to SM particles: μ =Observed/ Expected

NEW from CMS: 1.00 ± 0.13

$\mu = 1.30 \pm 0.12\ (\text{stat})\ \pm 0.10\ (\text{th})\ \pm 0.09\ (\text{syst})$



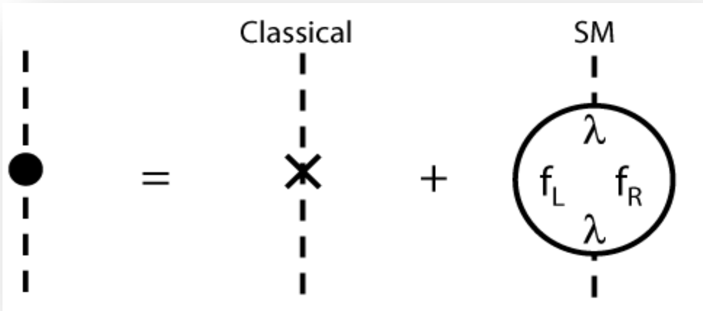


$[\pm 0.09(\text{stat})^{+0.08}_{-0.07}(\text{theo}) \pm 0.07(\text{syst})]$

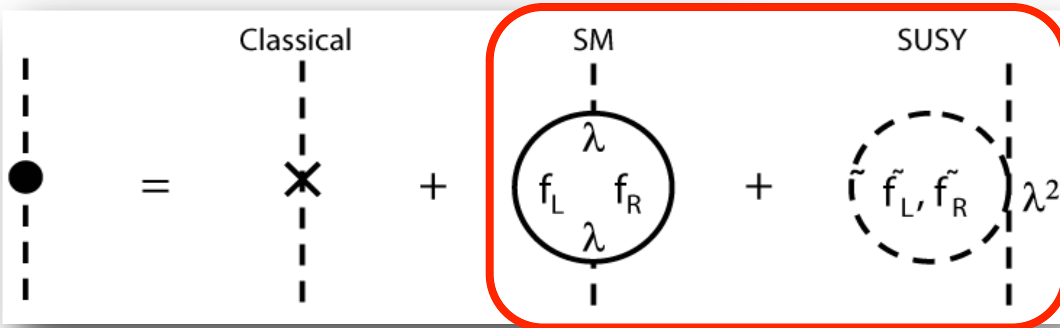
Looking ahead

CMS

June 2013 - photo by
Michael.Hoch@CERN.ch



- The Higgs mass:
  - Standard Model particles contribute to the Higgs mass like the top quark does to the W mass but the effects should be huge!
    - Could be 10^{19} times the mass of the proton (Planck scale)
  - This is a theoretical and/or philosophical problem
    - Something is needed to cancel out these effects!
    - Or is the universe 'impossibly' fine-tuned?



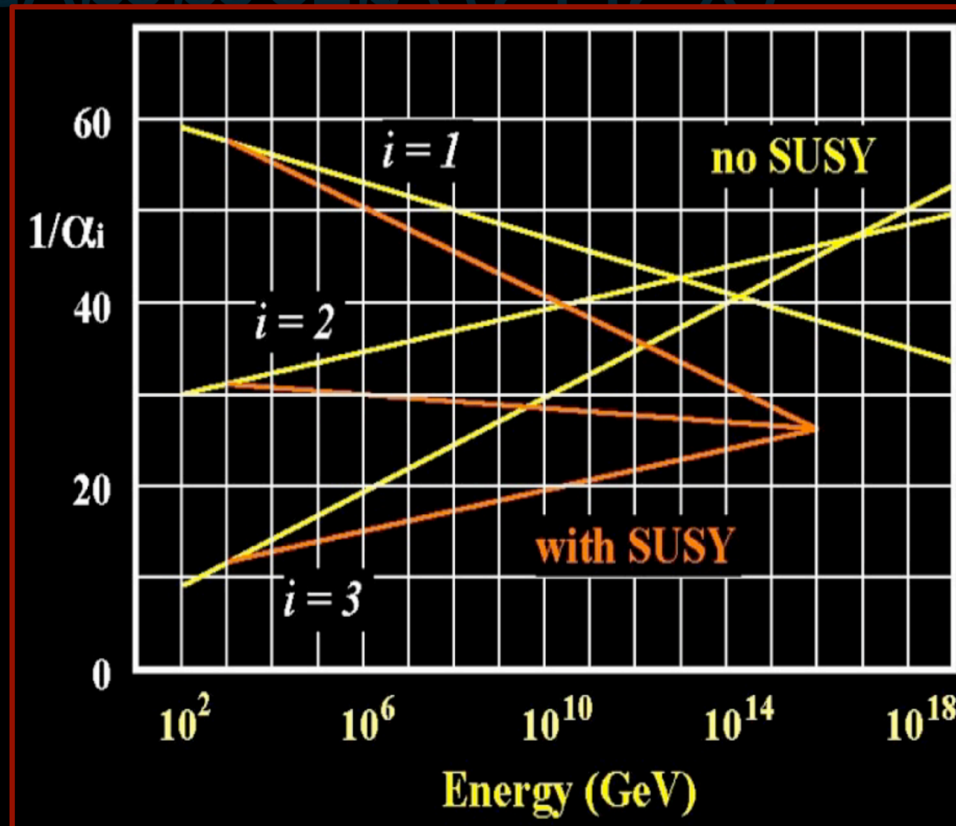
- New 'partner particles' :
  - Cancel the effects of Standard Model particles
    - A much smaller term is all that's left.

How do you get partners to all of the particles in the Standard Model ?

Supersymmetry (SUSY)

A basic symmetry

For each known Fermion there is a new Boson partner particle and for each known Boson, a new Fermion partner



- Unifies the strengths of all forces at ~10^{16} GeV
- Predicts Higgs boson with mass < 130 (we found 126!)
- Provides clues to the dark side of the universe

Cosmological Connection - Dark Matter

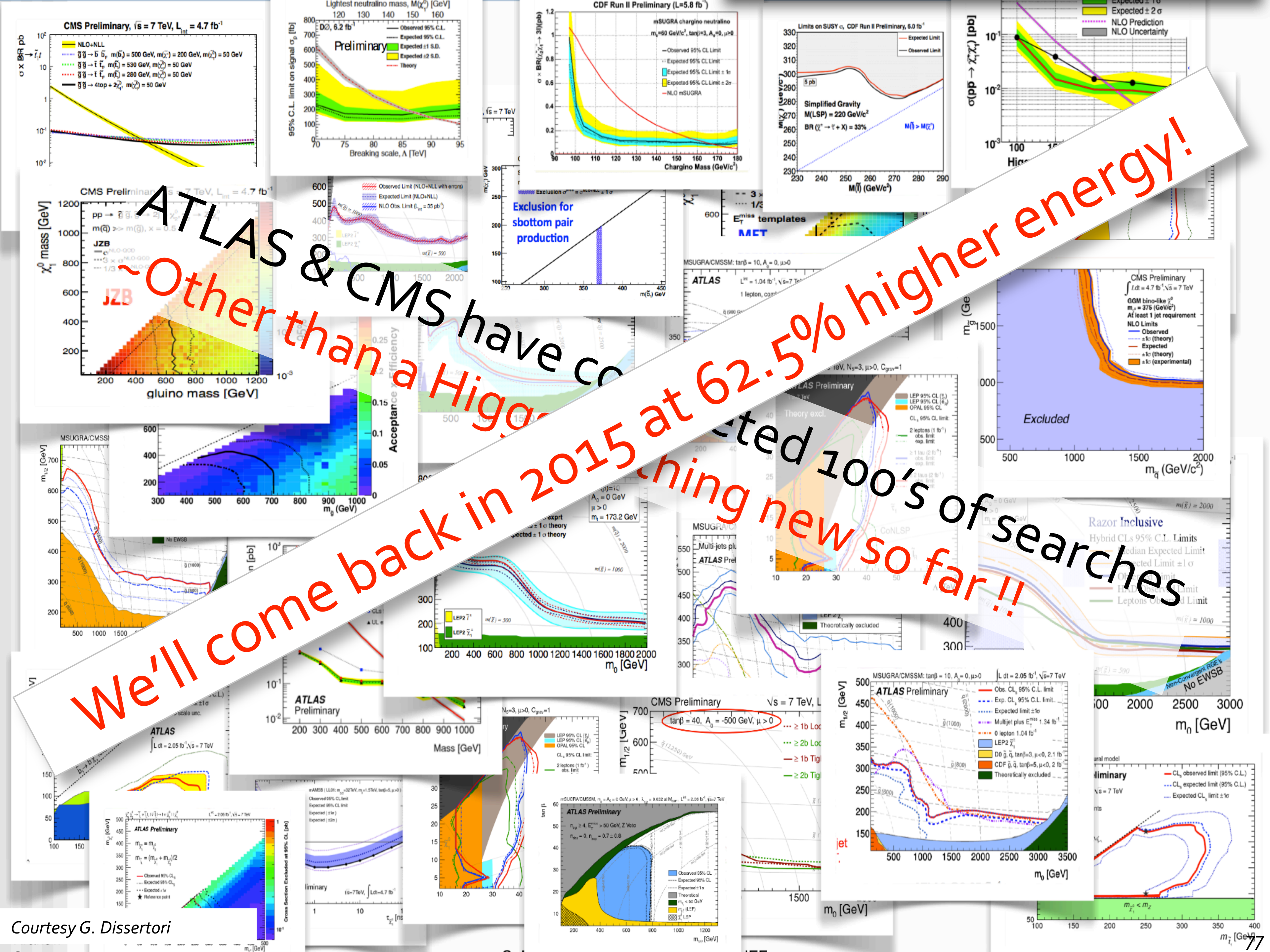
The Dark Side

- We now know
  - ~5% of the universe is ordinary matter
  - 28% is "Dark Matter"
    - SUSY has "Dark Matter" candidates
    - And even predicts the right amount !
  - The remainder is "Dark Energy"
    - We're not sure what this is!
      - It will probably be taxed someday
        - Ministry 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) or new 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 Large Hadron Collider (LHC) is the right tool to be using.



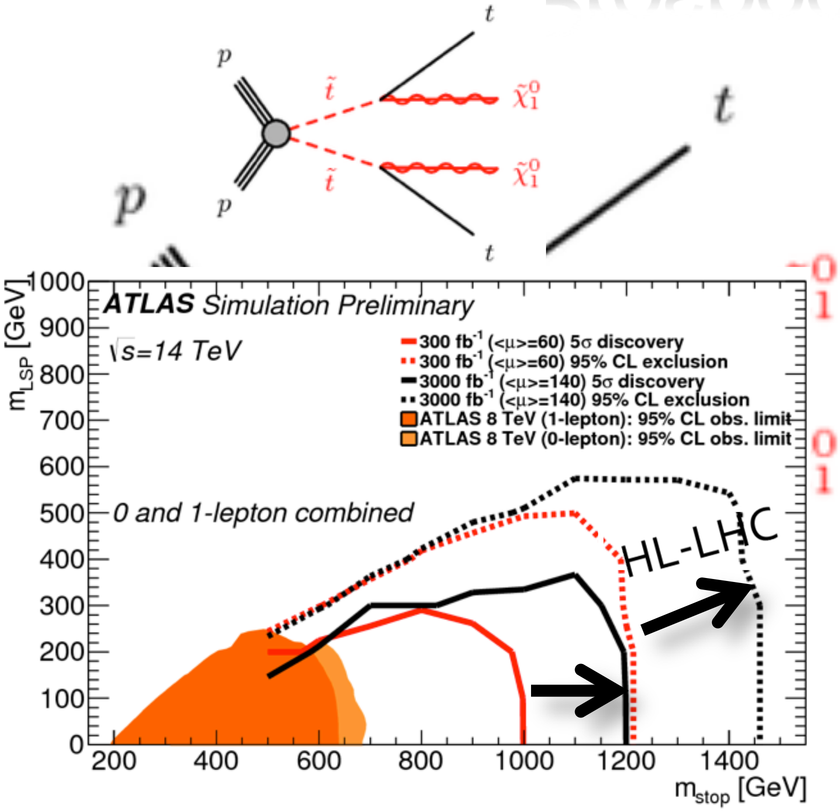
ATLAS & CMS have conducted 100's of searches

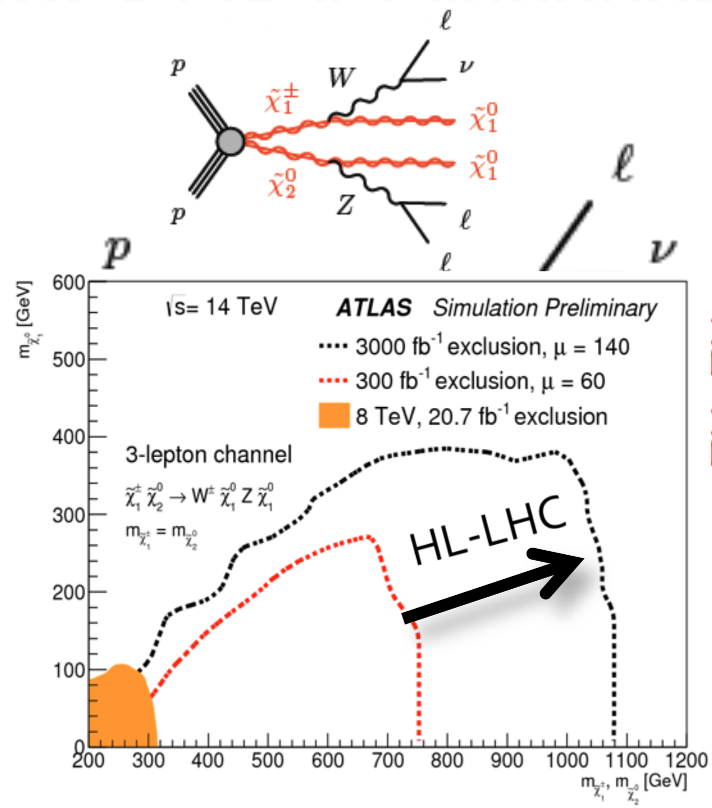
~Other than a Higgs, nothing new so far !!

We'll come back in 2015 at 62.5% higher energy!

Courtesy G. Dissertori

Future Prospects for SUSY Discovery





- **In coming decade we will get >10x more date: roughly 300 fb^{-1}**
  - **Reach in mass for SUSY top partner and LSP (Lightest SUSY Partner) will double**
  - **Reach in mass for SUSY gauge boson partners may more than double**
- **High Luminosity-LHC (2024-2035) extends discovery reach even further with 3000 fb^{-1}**
  - Probe stop masses up to ~1.5 TeV
  - Probe chargino/neutralino masses up to ~1 TeV
  - Probe gluino masses well beyond 2 TeV

CMS-PAS-FTR-13-014
ATLAS-PHYS-PUB-2013-011

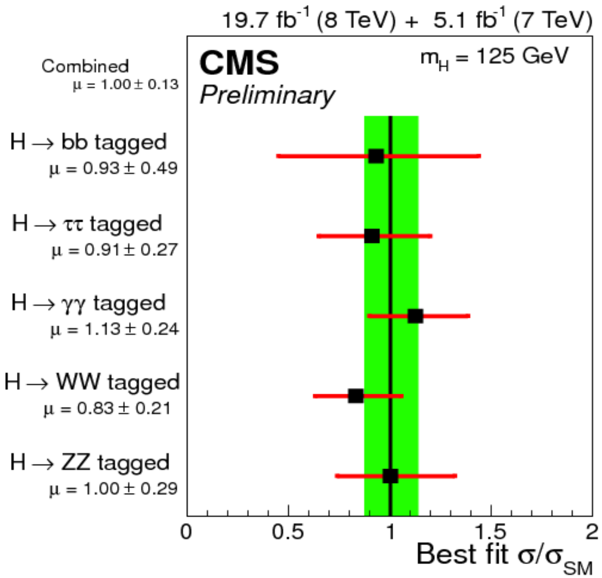
Future LHC Higgs Measurements

Observable number of Higgs events per LHC experiment	Run-1 25 fb^{-1}	2009-2024 300 fb^{-1}	HL-LHC 2025-2035? 3000 fb^{-1}
$H \rightarrow$ 4leptons	20	400	4,000
$H \rightarrow \gamma\gamma$	350	1300	130,000
VBF $H \rightarrow \tau\tau$	50	2000	20,000

Future LHC Higgs Measurements

Higgs Snowmass report (arXiv:1310.8361)

Current Results on signal strength compared to SM



±50%

- Run 1 precision on σ/σ_{SM} about 20-50% (10-25% on couplings)
- Need coupling precision of ~3% to probe TeV particles in loops

Deviation of Higgs couplings from SM due to particles with M=1 TeV

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

CMS projections for coupling precision (*arXiv:1307.7135*)

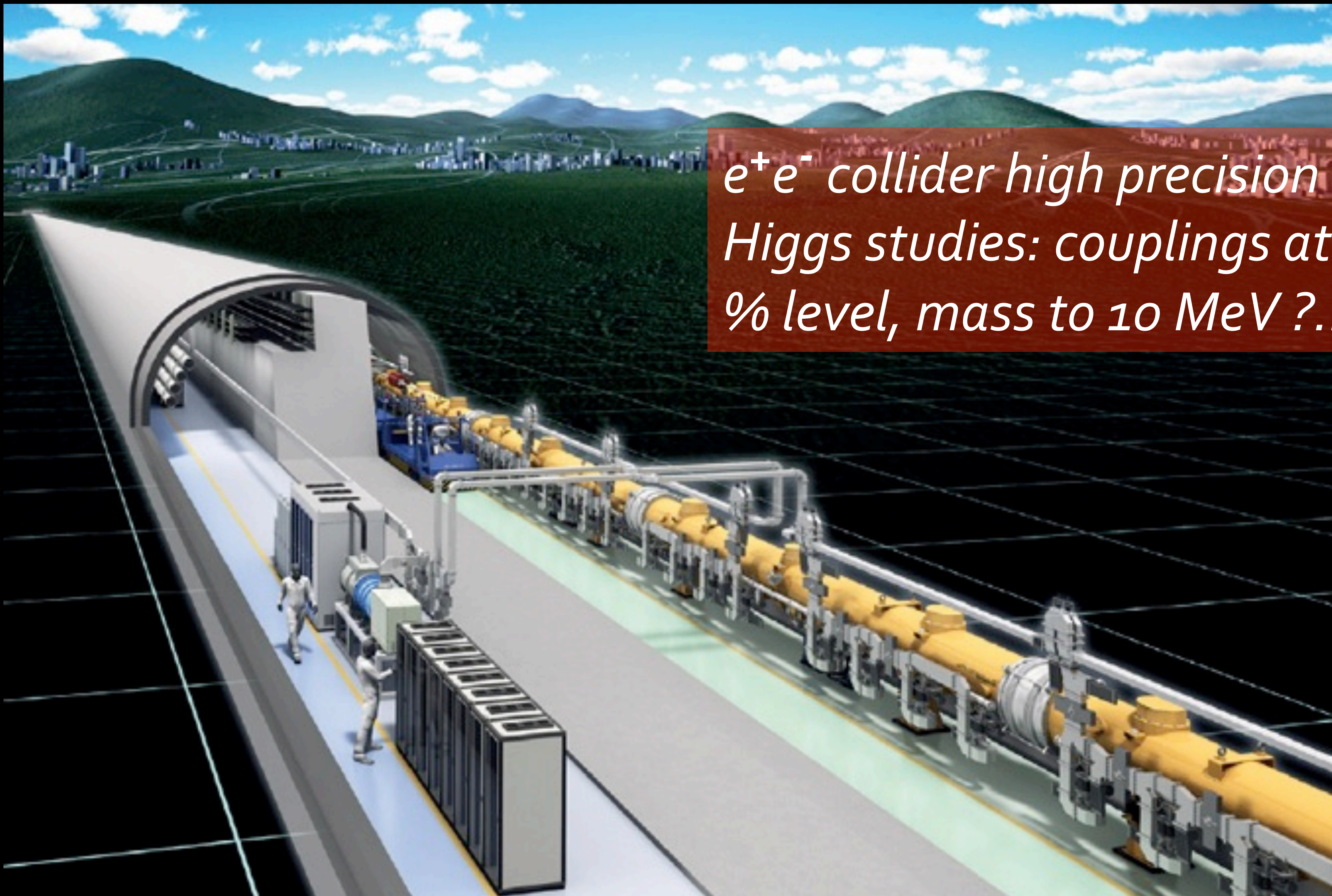
L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$	BR_{SM}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]	[7, 11]

HL-LHC 3000 fb^{-1} **will enable precision Higgs physics:**

- Most couplings with 2-8% ⇒ x3 improvement from 300 fb^{-1} LHC results
- Access to important rare decays

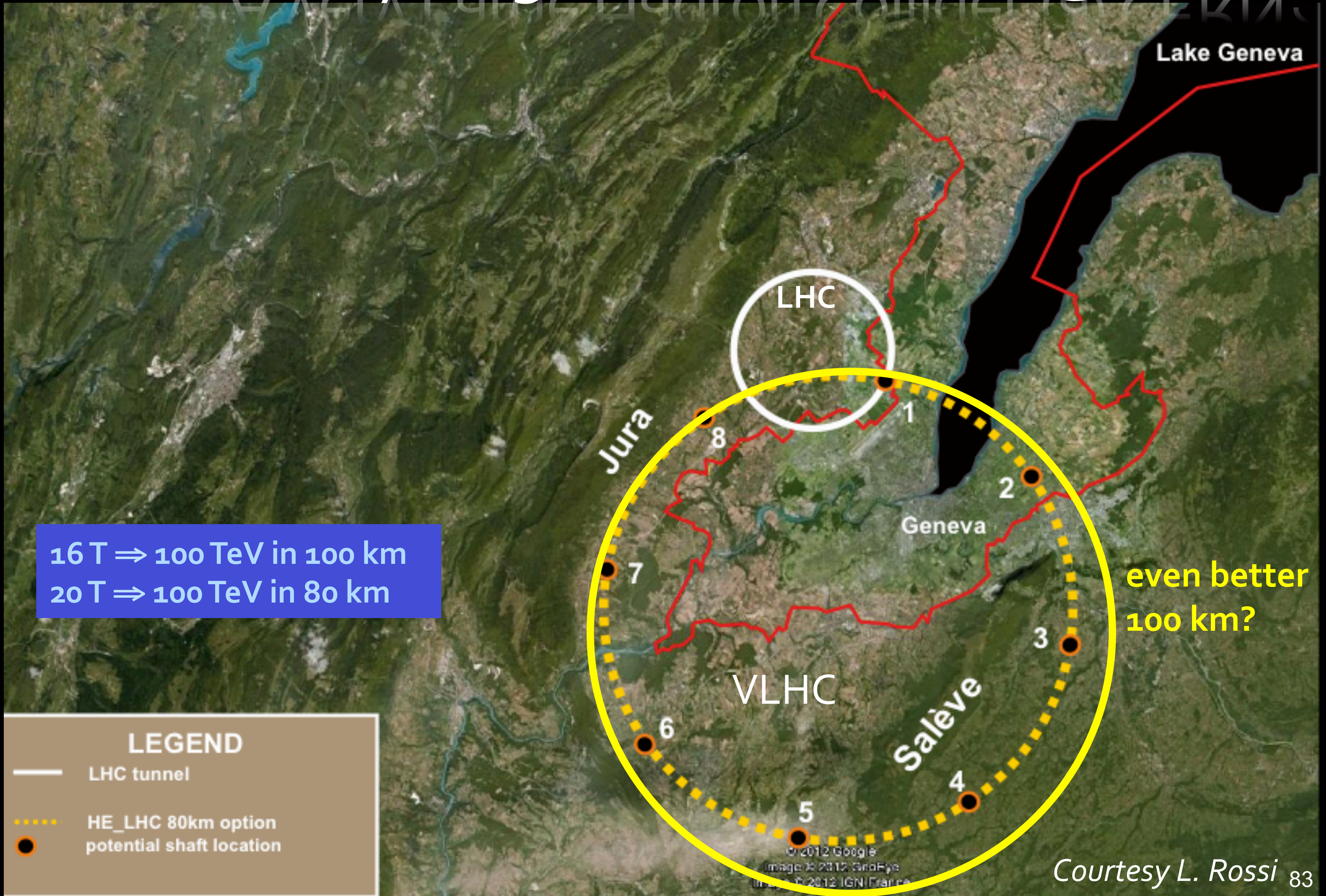
What else is under consideration?

International Linear Collider (Japan)

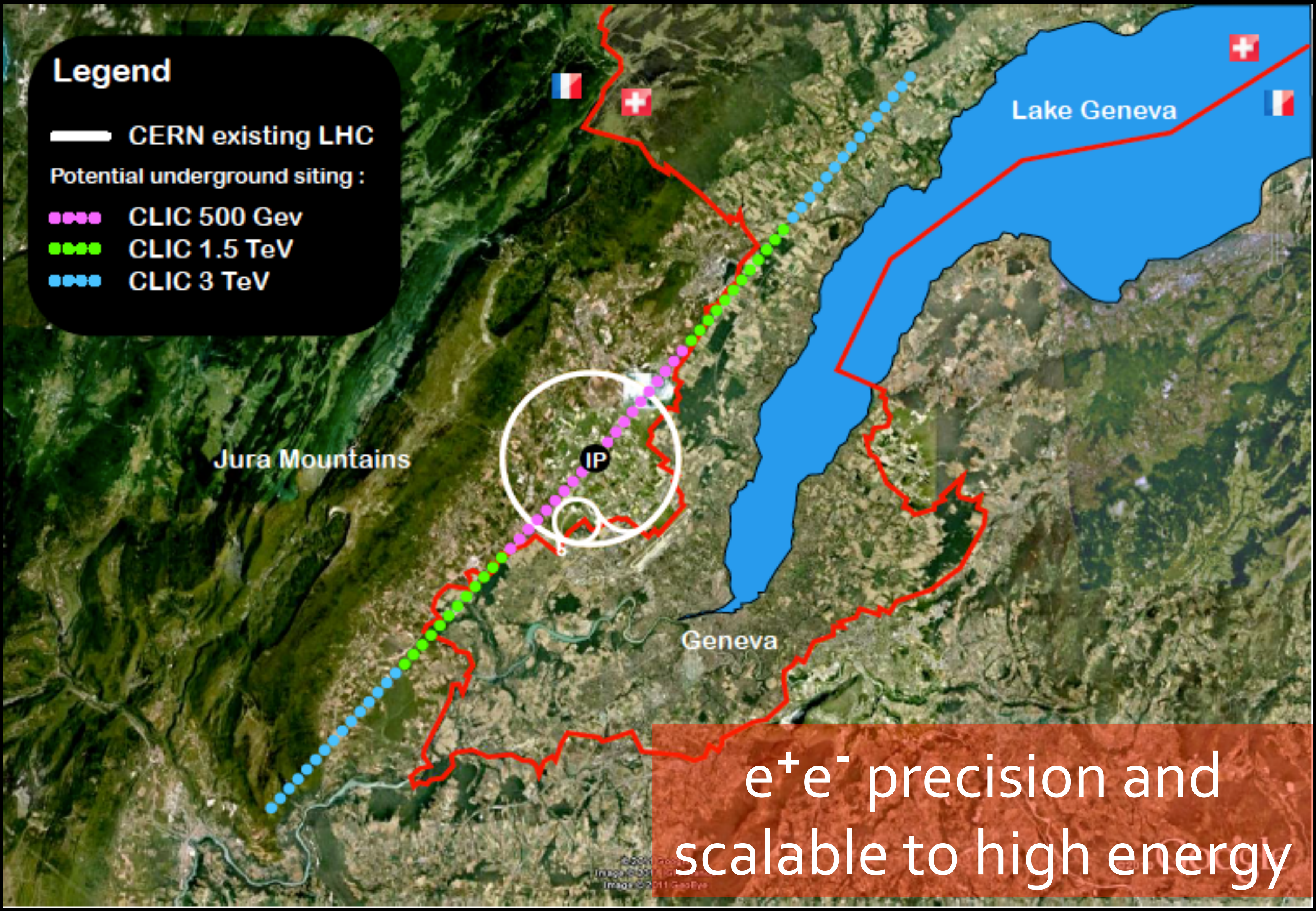


e^+e^- collider high precision Higgs studies: couplings at % level, mass to 10 MeV ?...

A Very Large Hadron Collider @ CERN?



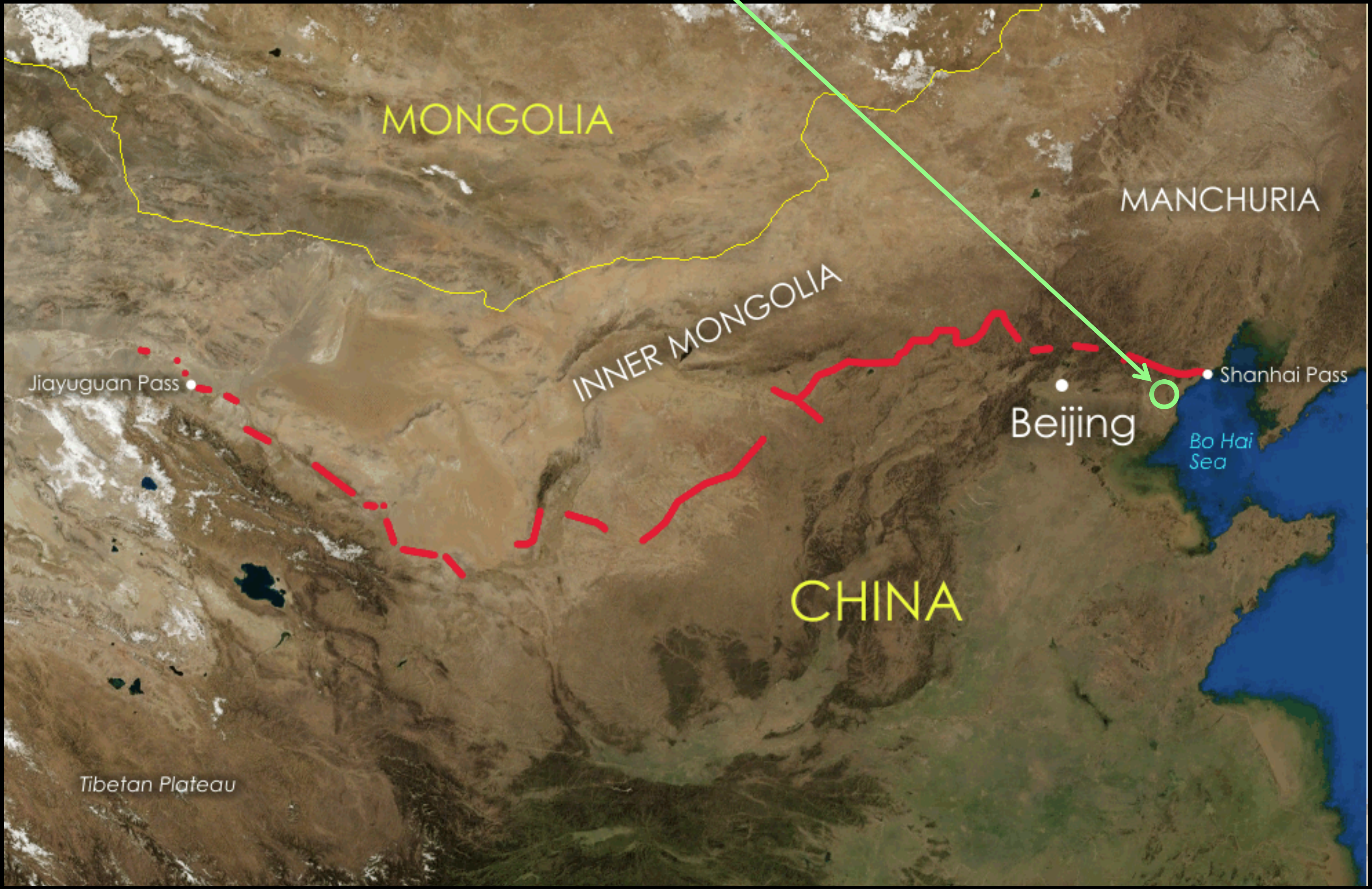
Linear e+e- collider at CERN (CLIC)



e^+e^- precision and scalable to high energy

The Great Ring of China ?

Qinhuangdao (秦皇岛)



Summary: A new boson has been found!

The End

Or possibly just the beginning …