

Large-Scale Scientific C++ For Casual Coders: Why You (Should) Care

Axel Naumann, CERN
ACCU 2015



CERN, People, Code

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Content

- CERN
- People
- Code



Content



- Curiosity
- Sharing
- Pragmatism

CERN

typeid(CERN)



- European Organization for Nuclear (read: Particle!) Research, est. 1954, near Geneva
- Fundamental research (WWW: inventions happen)
knowledge CERN(money, curious_brains)
- What is mass? What's in the universe? Probing smallest scale particles: Higgs particle, super symmetry,...

Fact Sheet

- CERN facilities used
 - by 11,000 physicists
 - from 760 universities
 - from 113 nations
- CERN itself has approximately 2000 employees

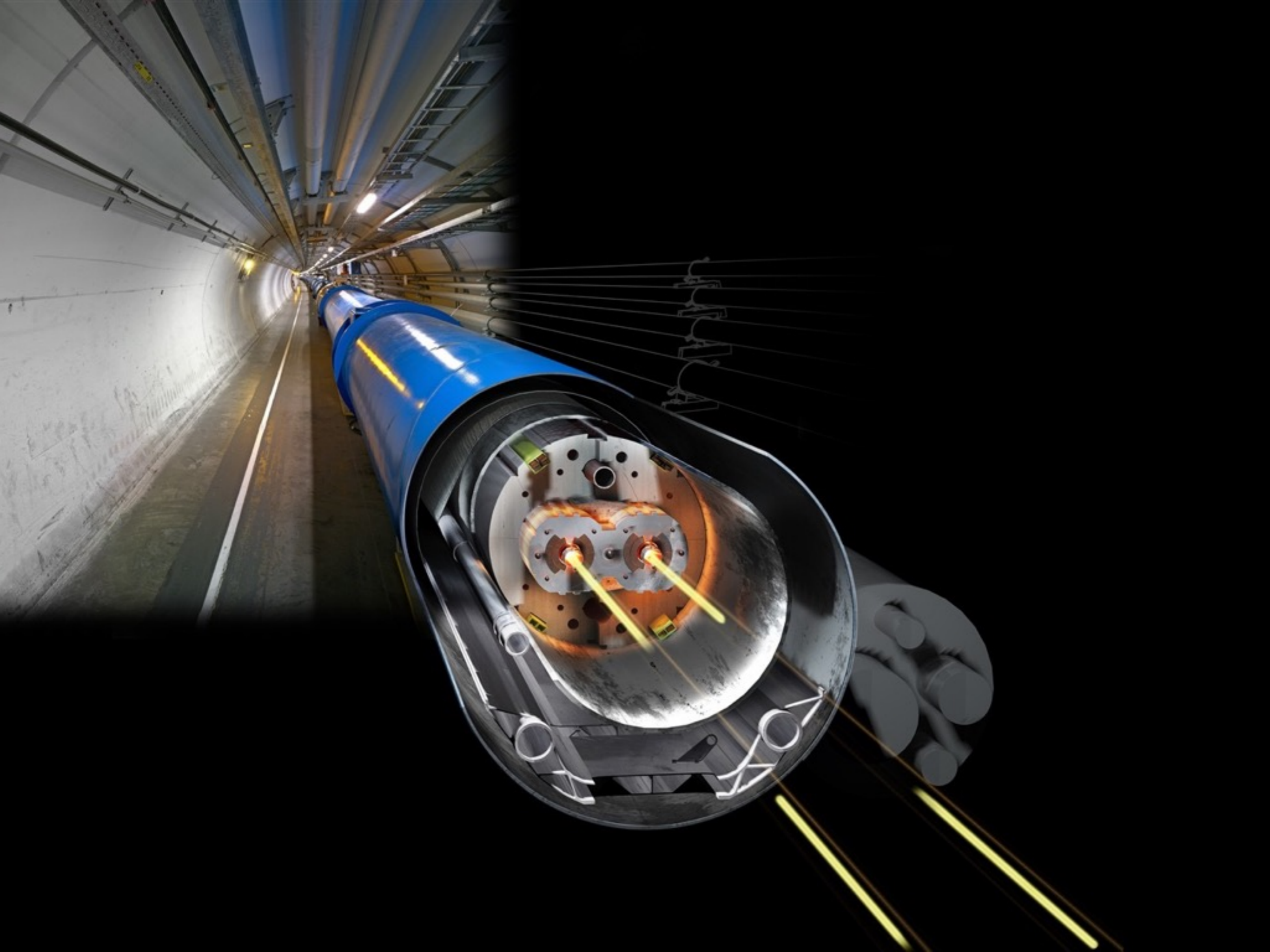


Large Hadron Collider

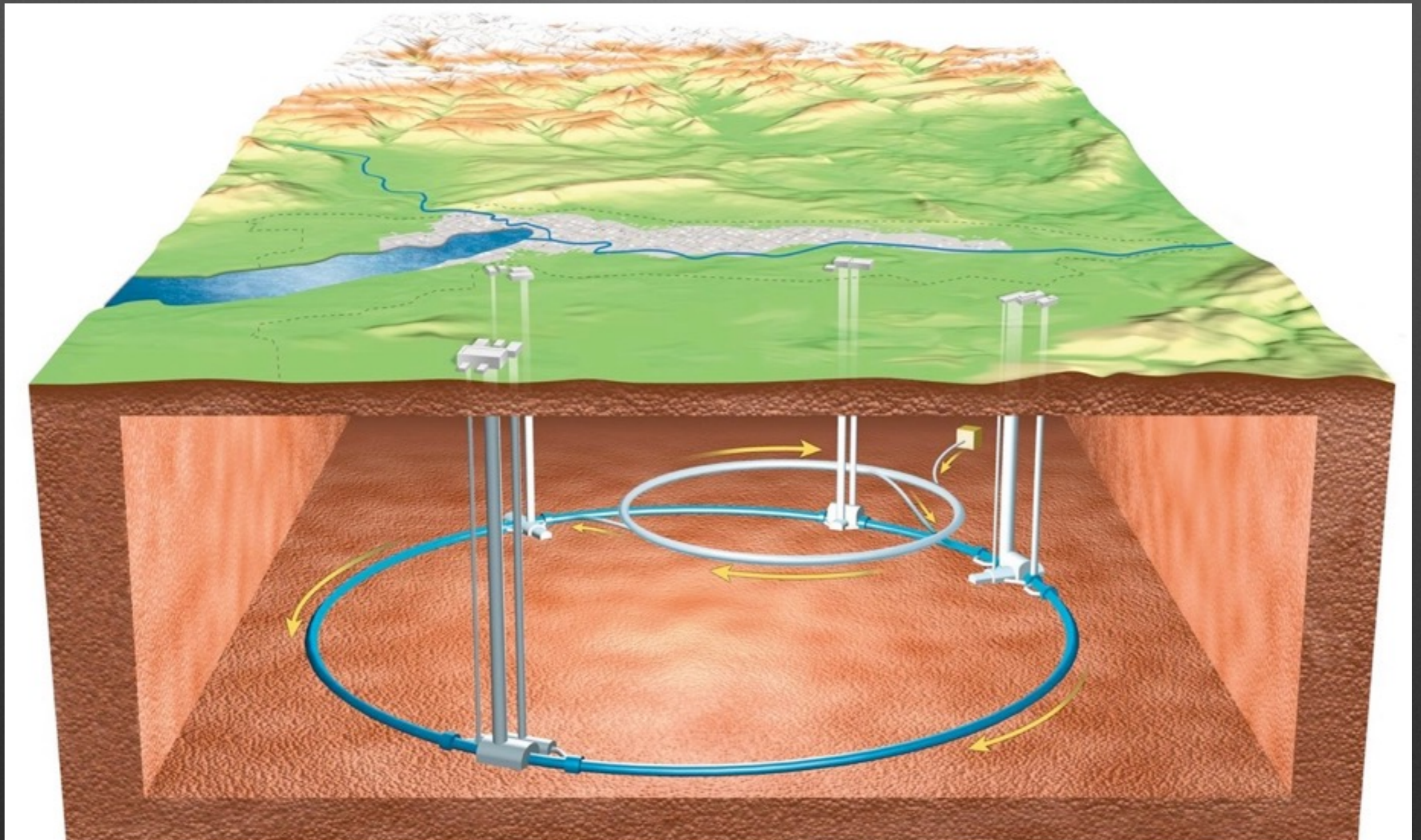


Large Hadron Collider

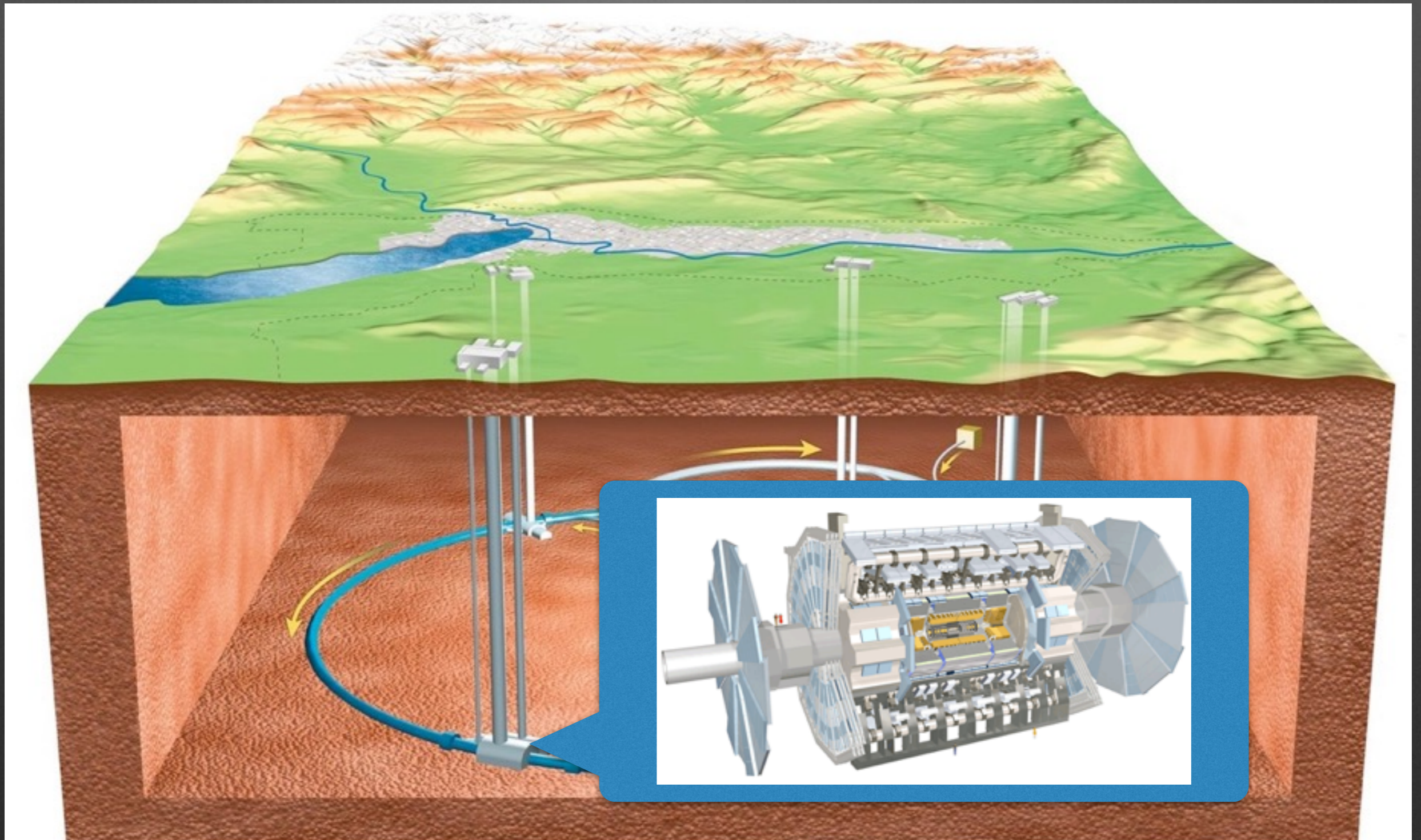




Large Hadron Collider



Large Hadron Collider

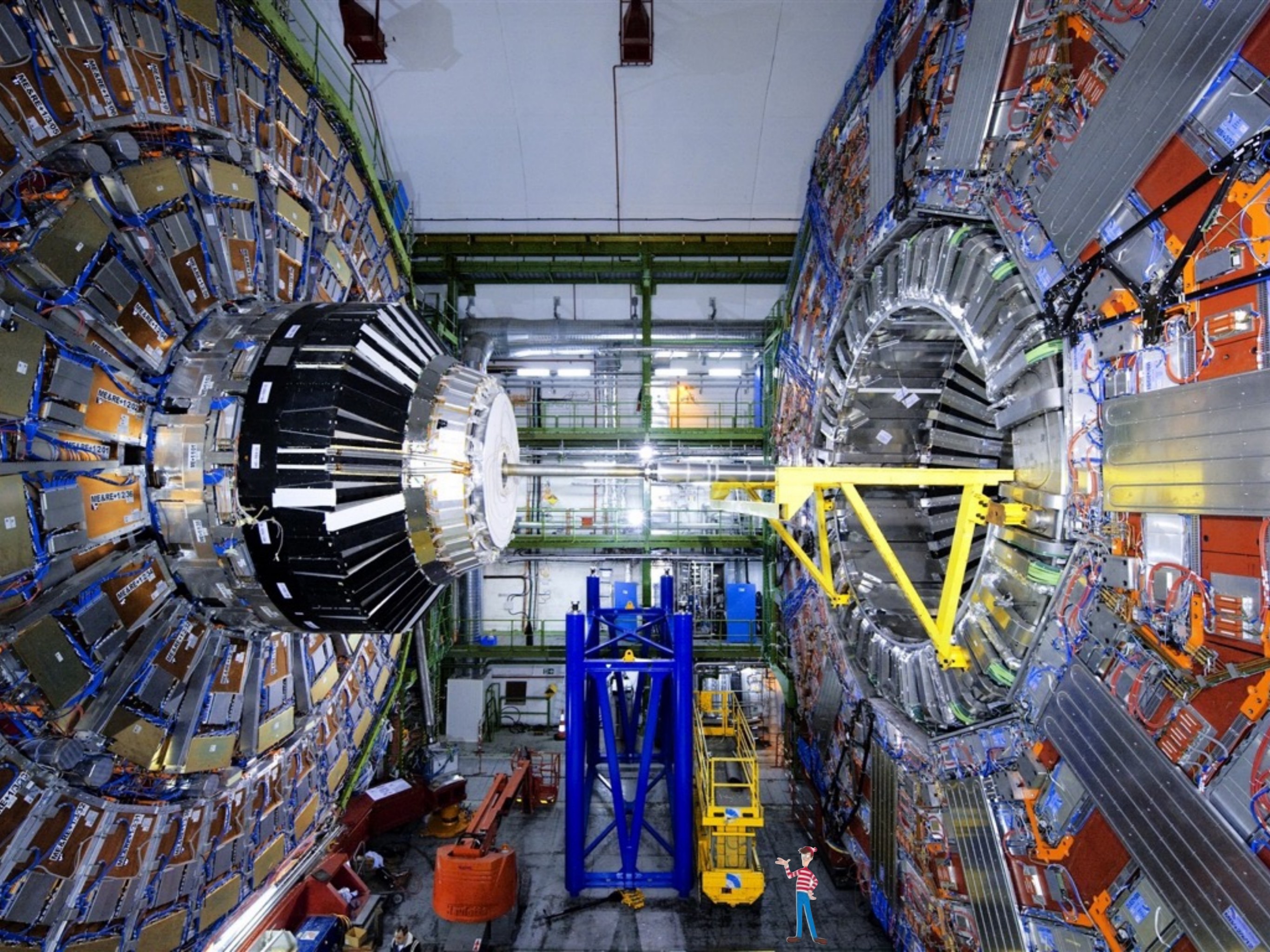


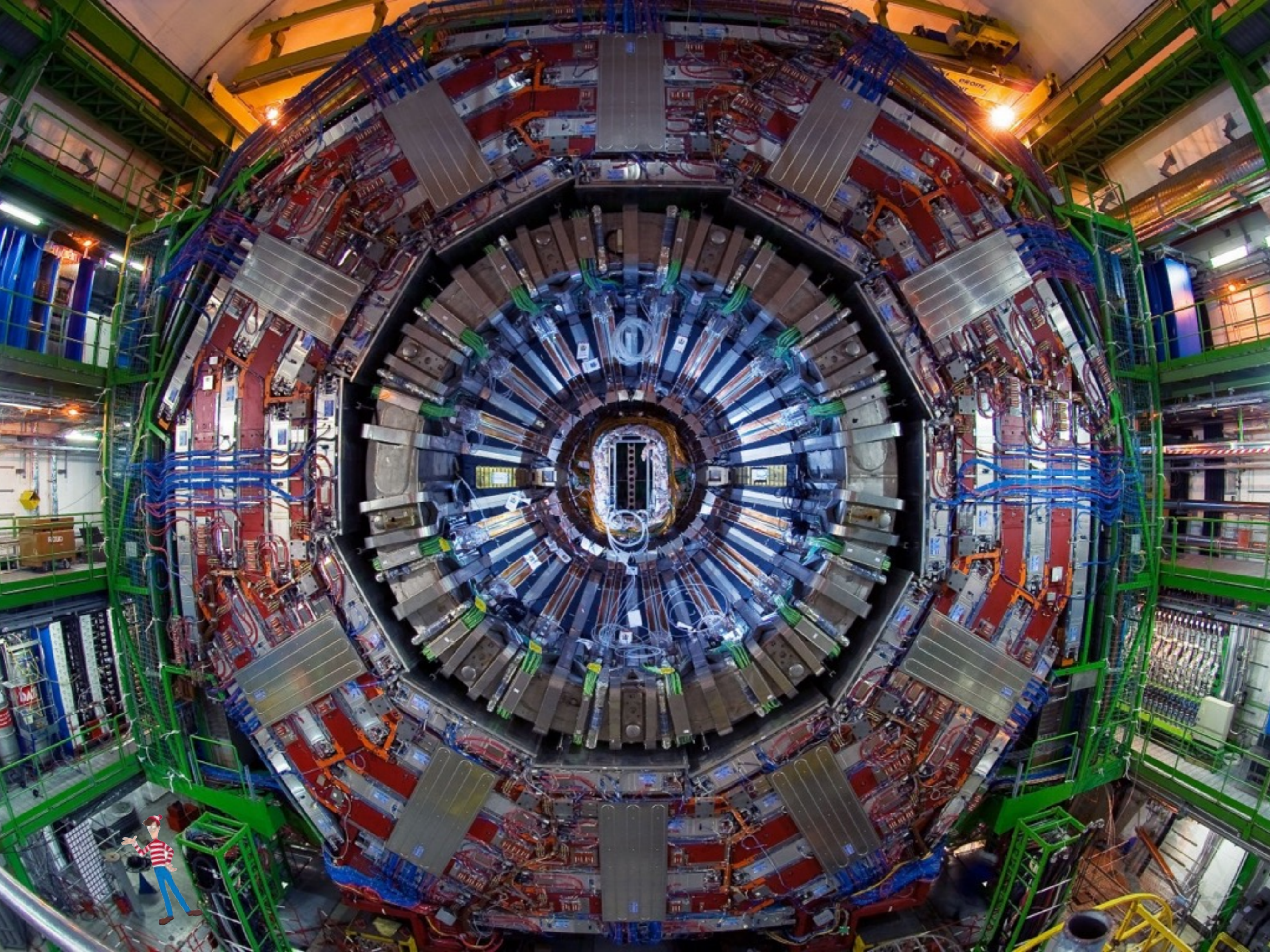
Large Hadron Collider

- World's “biggest” particle accelerator
- Ring with 27km in circumference, 100m below Switzerland and France
- Four large experiments ALICE, ATLAS, CMS, LHCb
- Expected to run until approximately 2030
- Run 2 about to start - first beam has already circulated









Detectors

- Like a massive camera
 - $O(100M)$ “pixels”
 - $O(100M)$ pictures per second
- Identify particles
- Measure their properties

Life at CERN



Work At CERN

Data Taking



Studying the Forces



Scientific Discourse

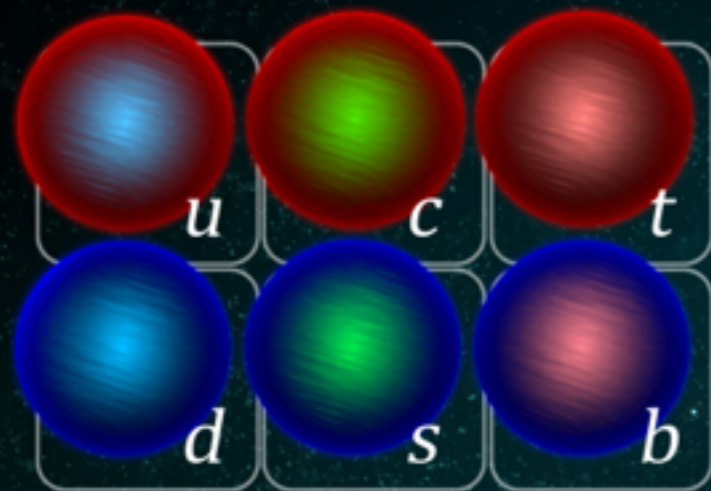


Lecturing and Being Lectured

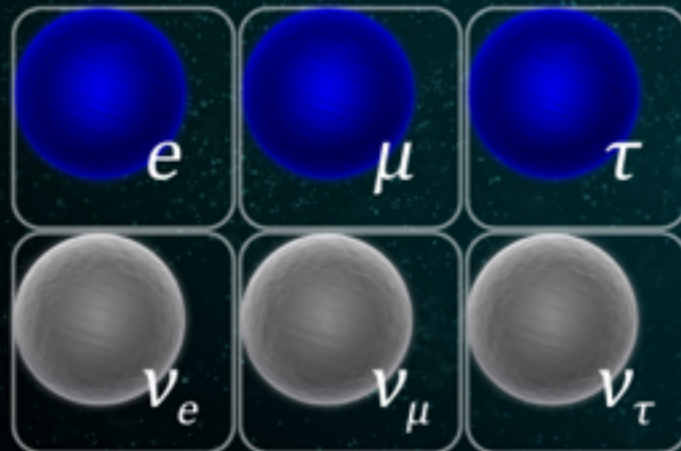


**We Do Physics.
Here's Yours.**

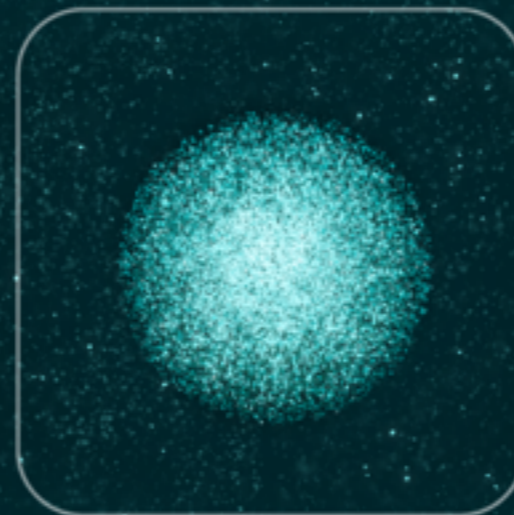
Our Bits



Quarks



Leptons

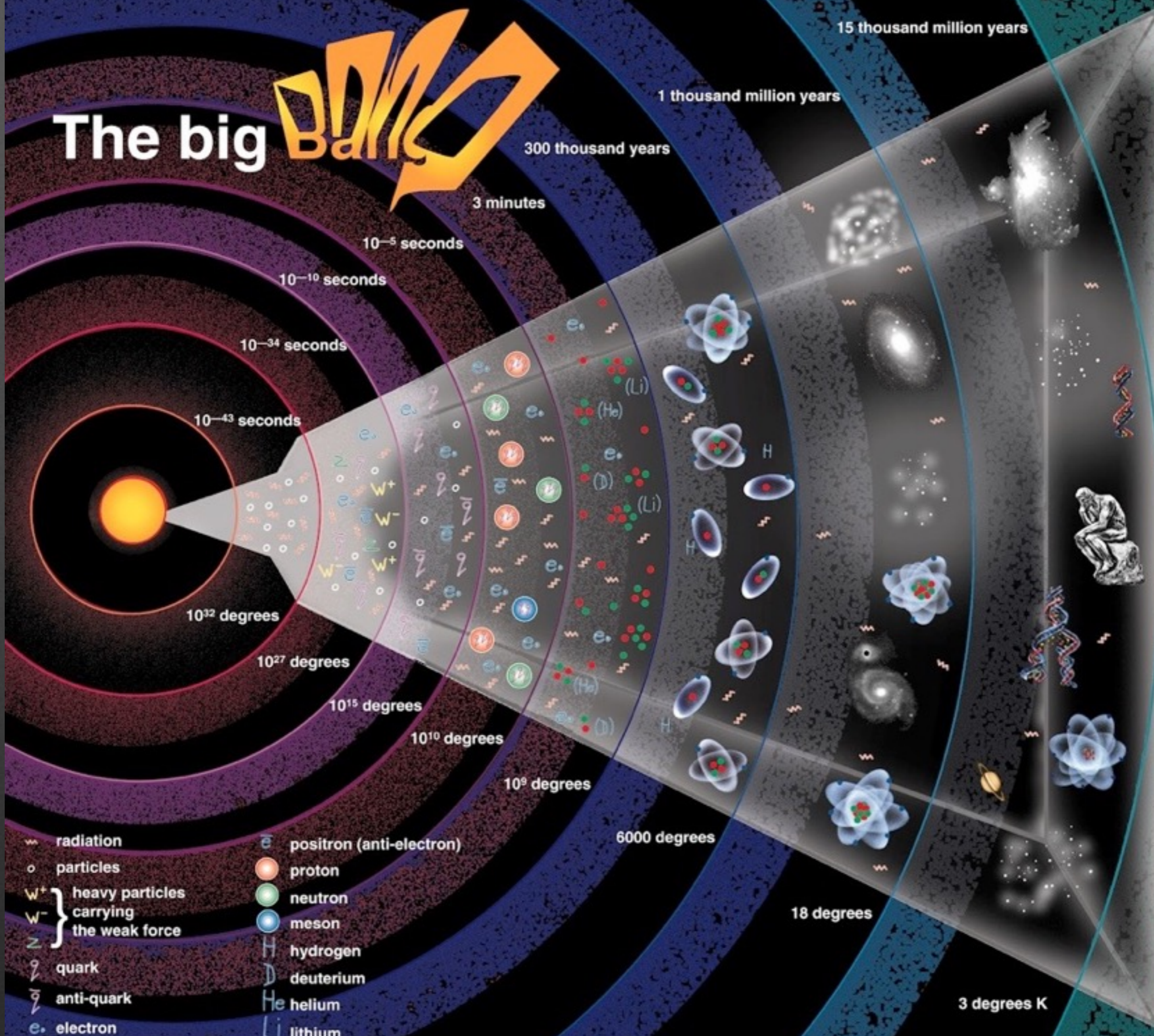


Higgs boson



Forces

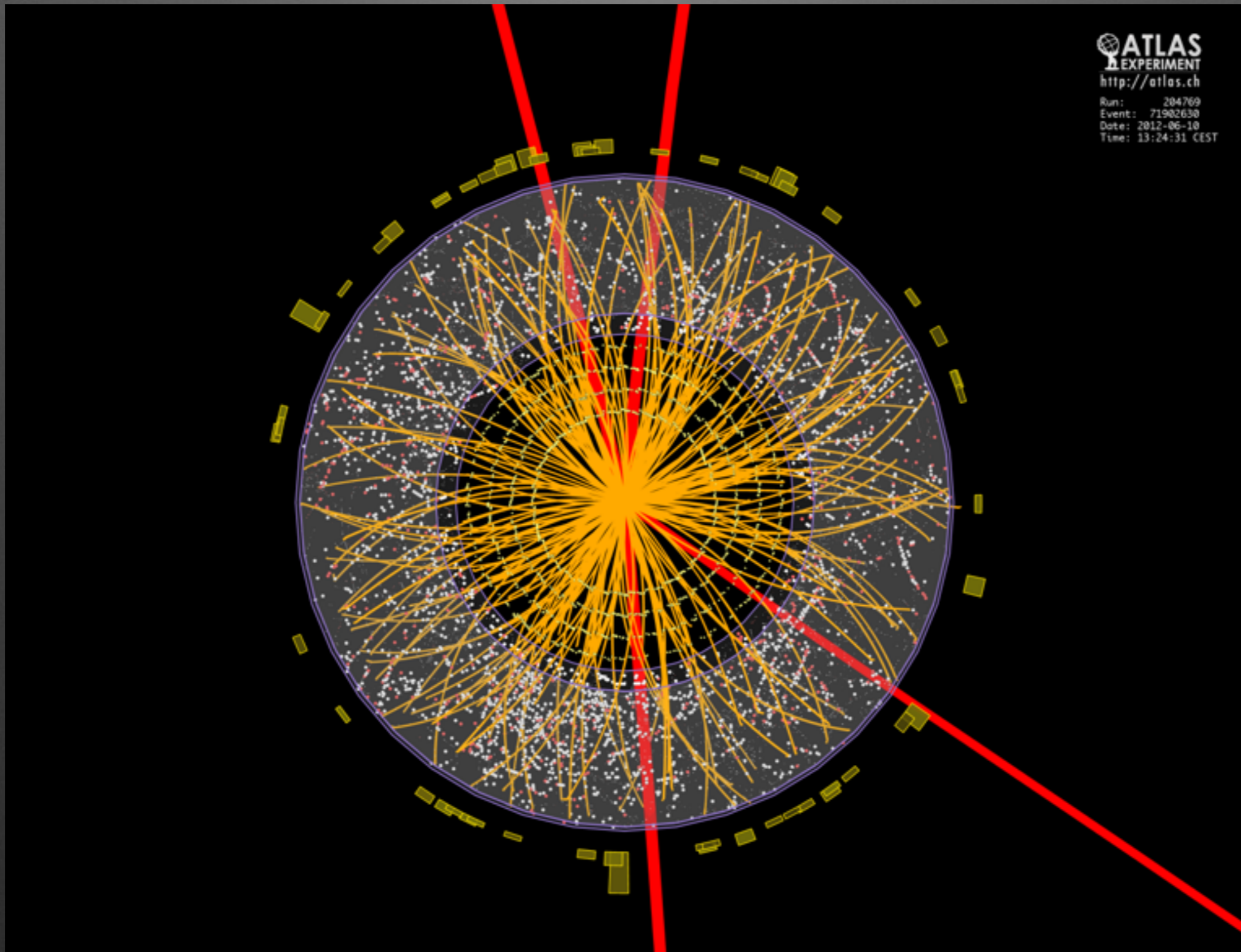
The big Bang

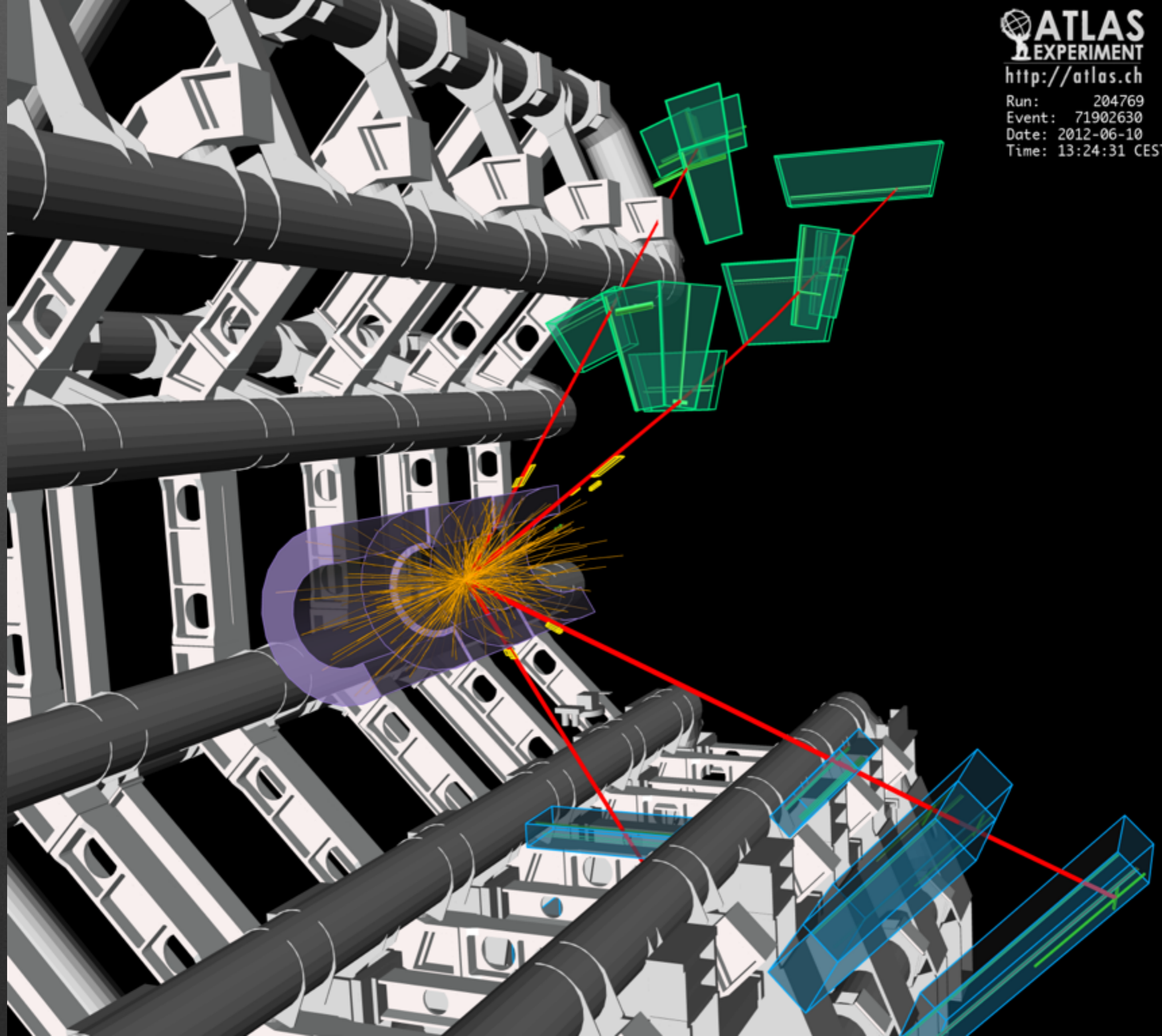


- ☞ radiation
- particles
- W⁺ } heavy particles carrying the weak force
- W⁻ }
- Z }
- q quark
- q̄ anti-quark
- e⁻ electron

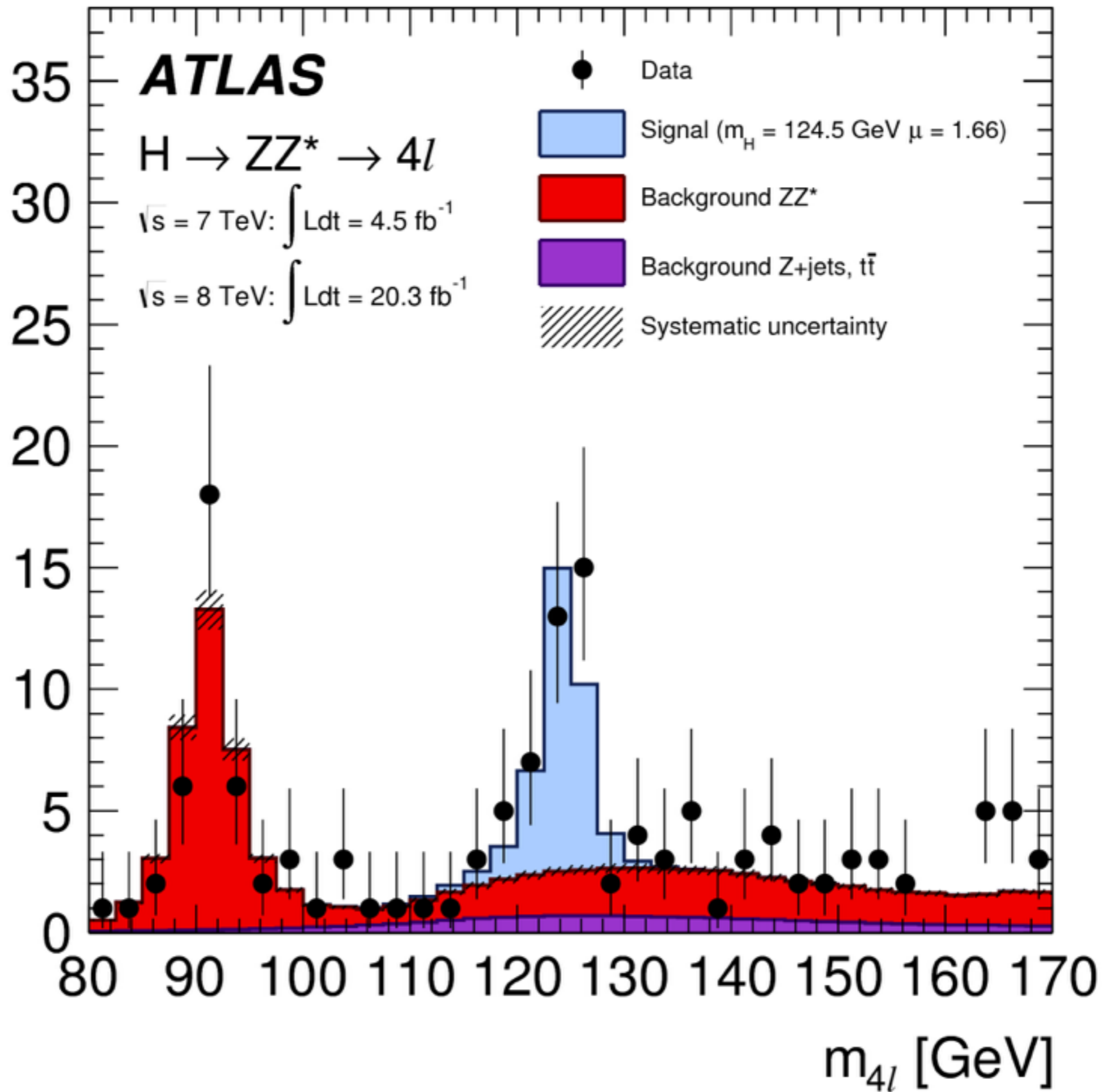
- e⁺ positron (anti-electron)
- proton
- neutron
- meson
- H hydrogen
- D deuterium
- He helium
- Li lithium

Particles + Detectors = Data





Events / 2.5 GeV



ATLAS $H \rightarrow \gamma\gamma$

CMS $H \rightarrow \gamma\gamma$

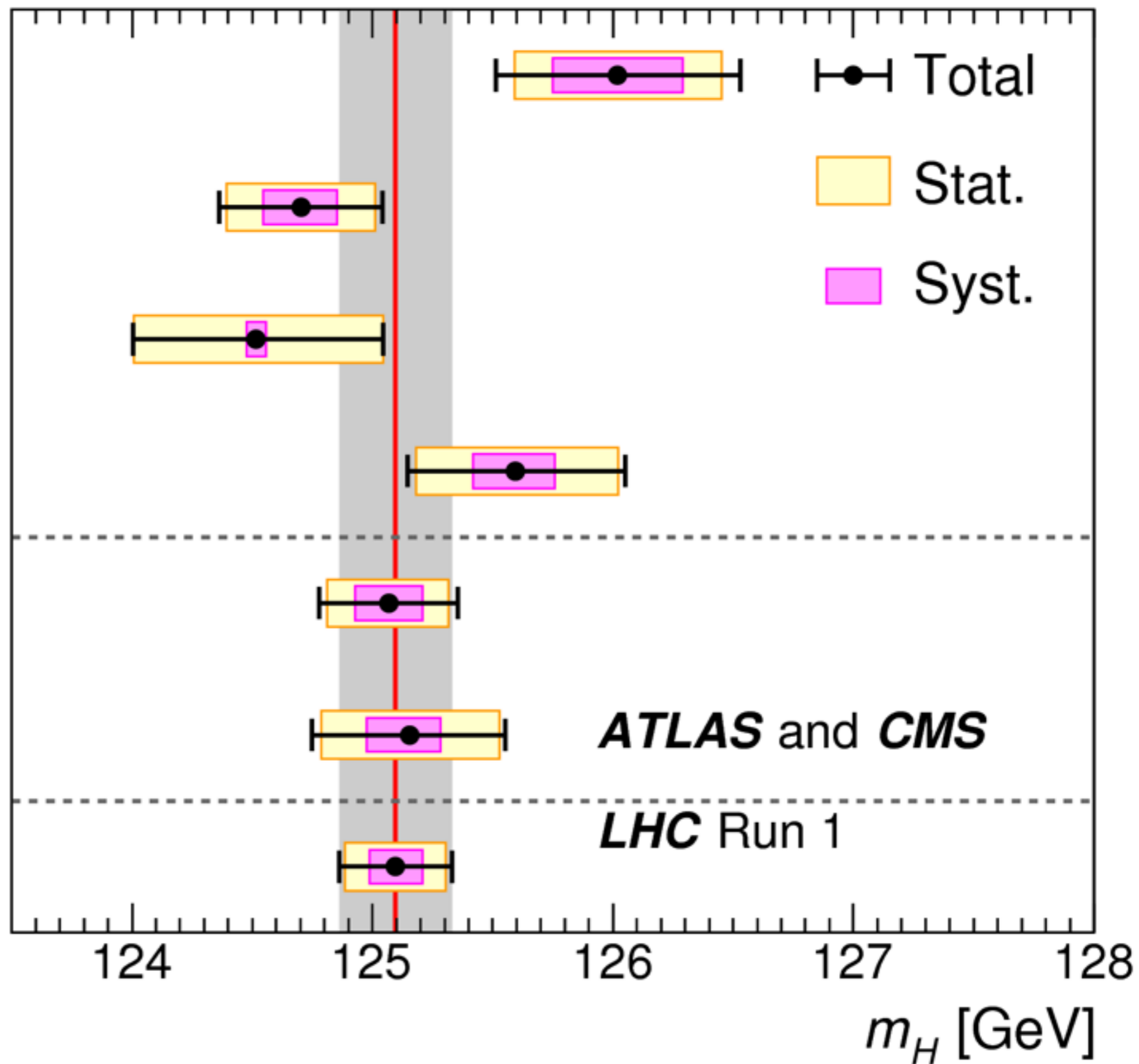
ATLAS $H \rightarrow ZZ \rightarrow 4l$

CMS $H \rightarrow ZZ \rightarrow 4l$

ATLAS+CMS $\gamma\gamma$

ATLAS+CMS $4l$

ATLAS+CMS $\gamma\gamma+4l$



ATLAS

$H \rightarrow \gamma\gamma$

$\sqrt{s} = 8 \text{ TeV } \int \mathcal{L} dt = 20.7 \text{ fb}^{-1}$

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

$\sqrt{s} = 7 \text{ TeV } \int \mathcal{L} dt = 4.6 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV } \int \mathcal{L} dt = 20.7 \text{ fb}^{-1}$

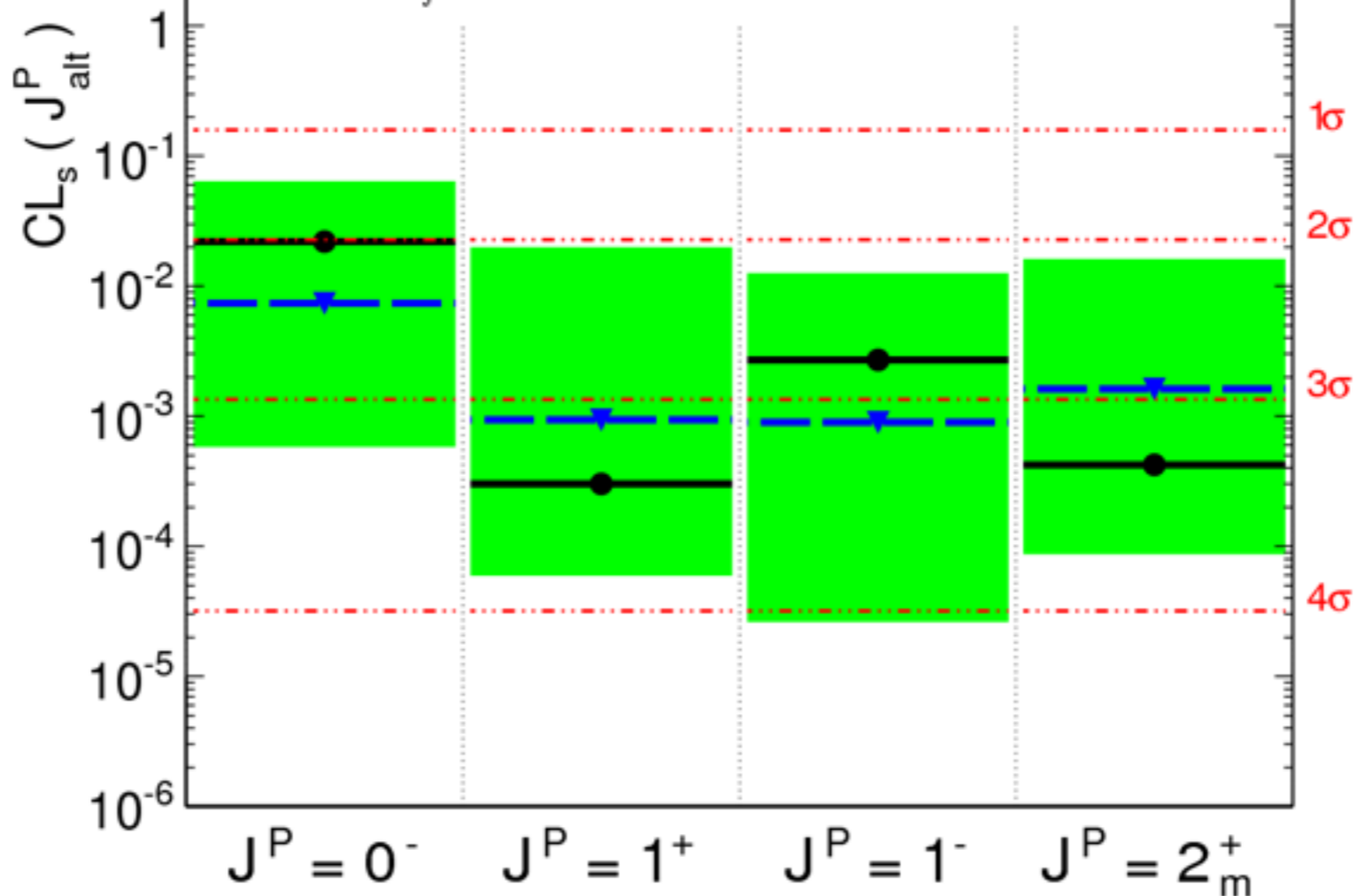
$H \rightarrow WW^* \rightarrow e\nu\mu\nu/\mu\nu e\nu$

$\sqrt{s} = 8 \text{ TeV } \int \mathcal{L} dt = 20.7 \text{ fb}^{-1}$

● Data

▼ CL_s expected
assuming $J^P = 0^+$

■ $\pm 1\sigma$

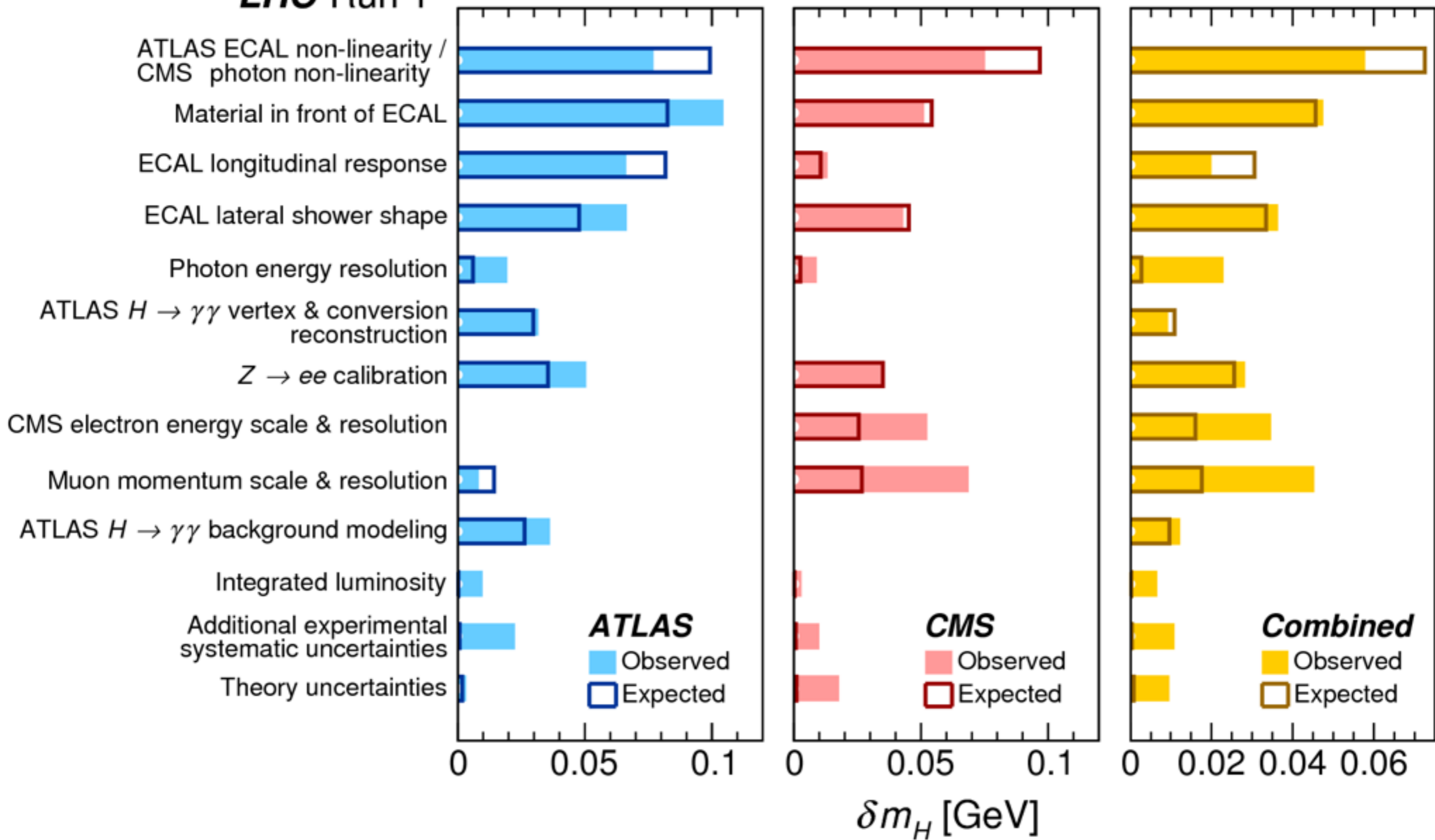


**ATLAS and CMS
LHC Run 1**

Uncertainty in ATLAS
combined result

Uncertainty in CMS
combined result

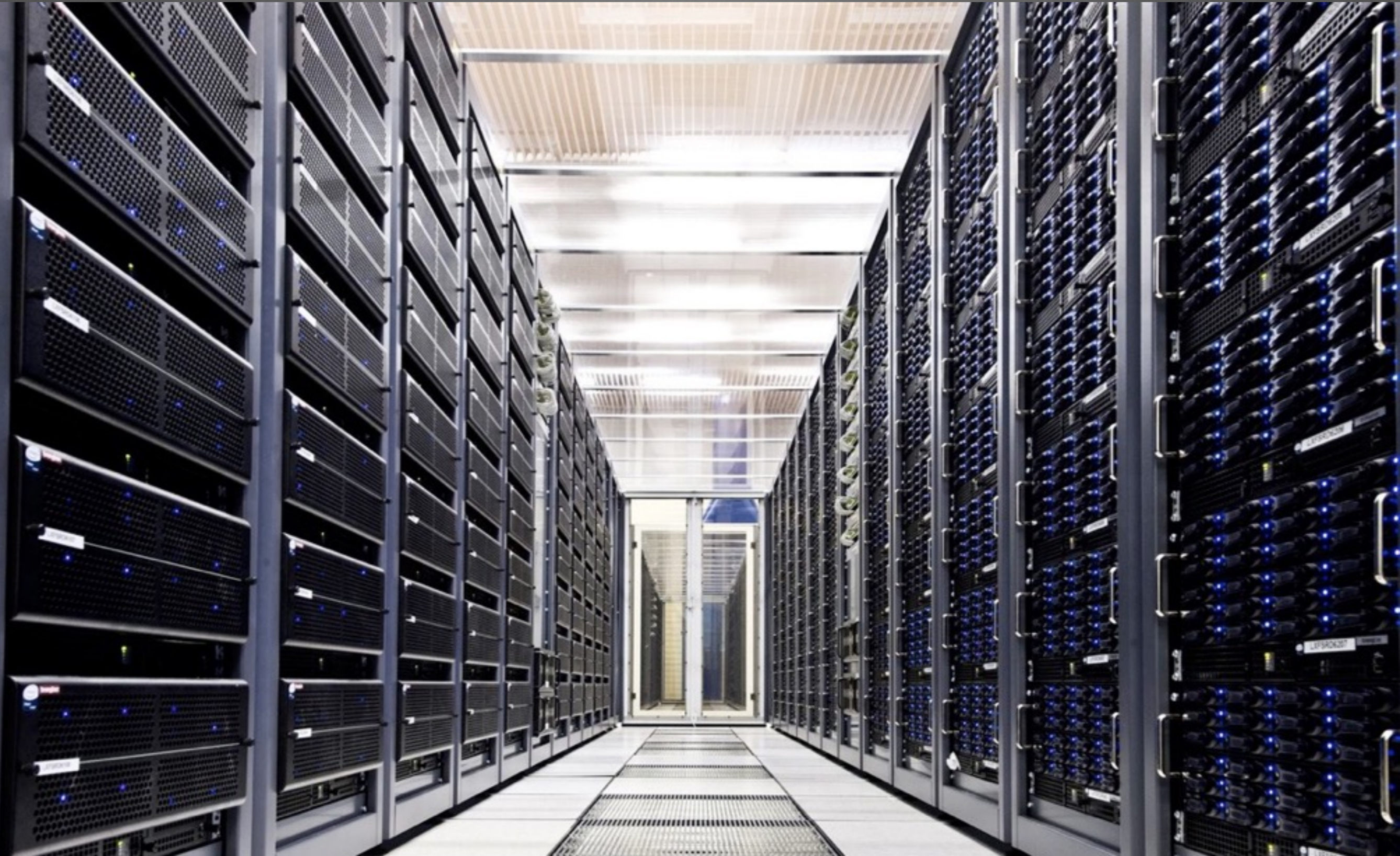
Uncertainty in LHC
combined result



You survived.

Computing

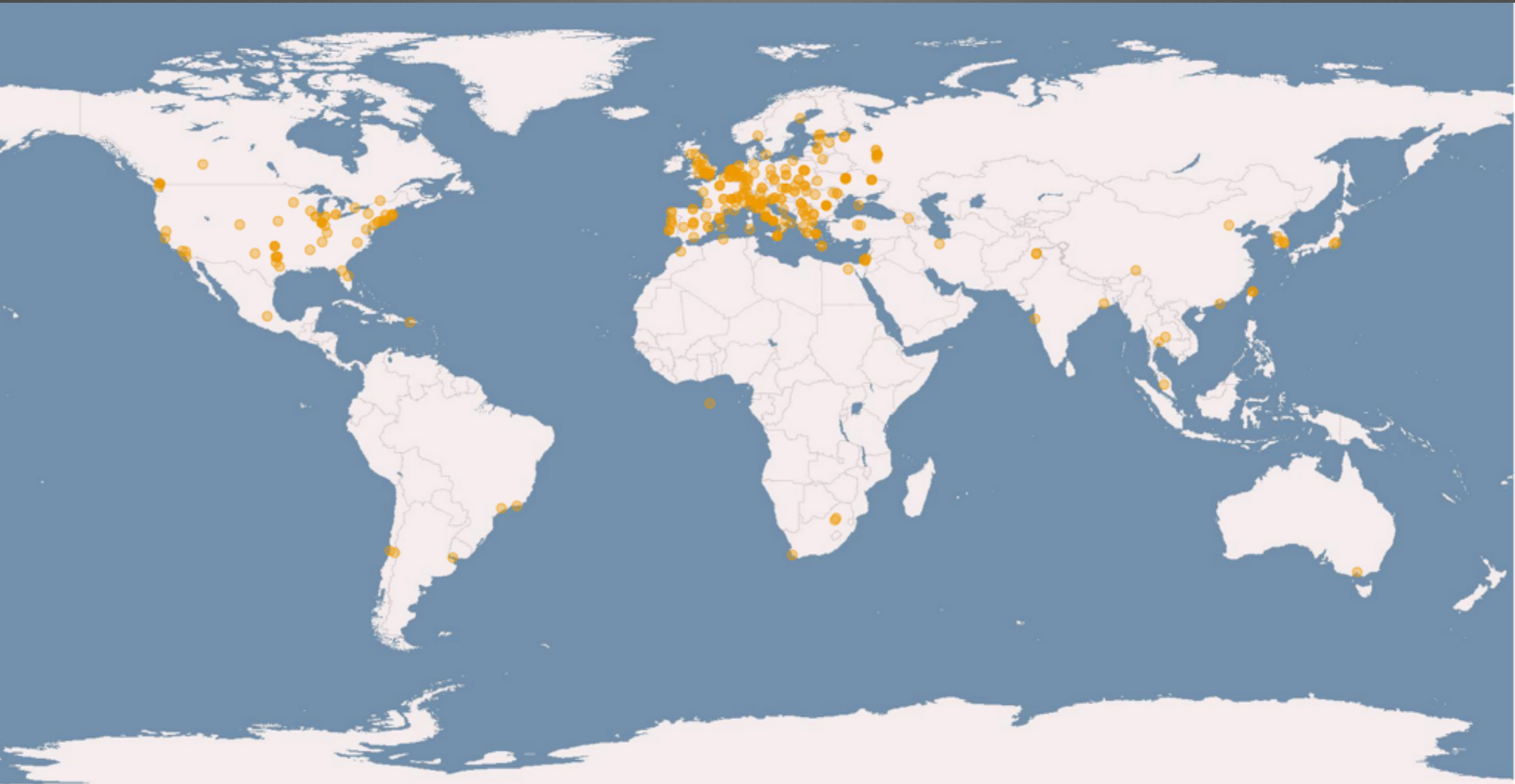
Computers



Computers



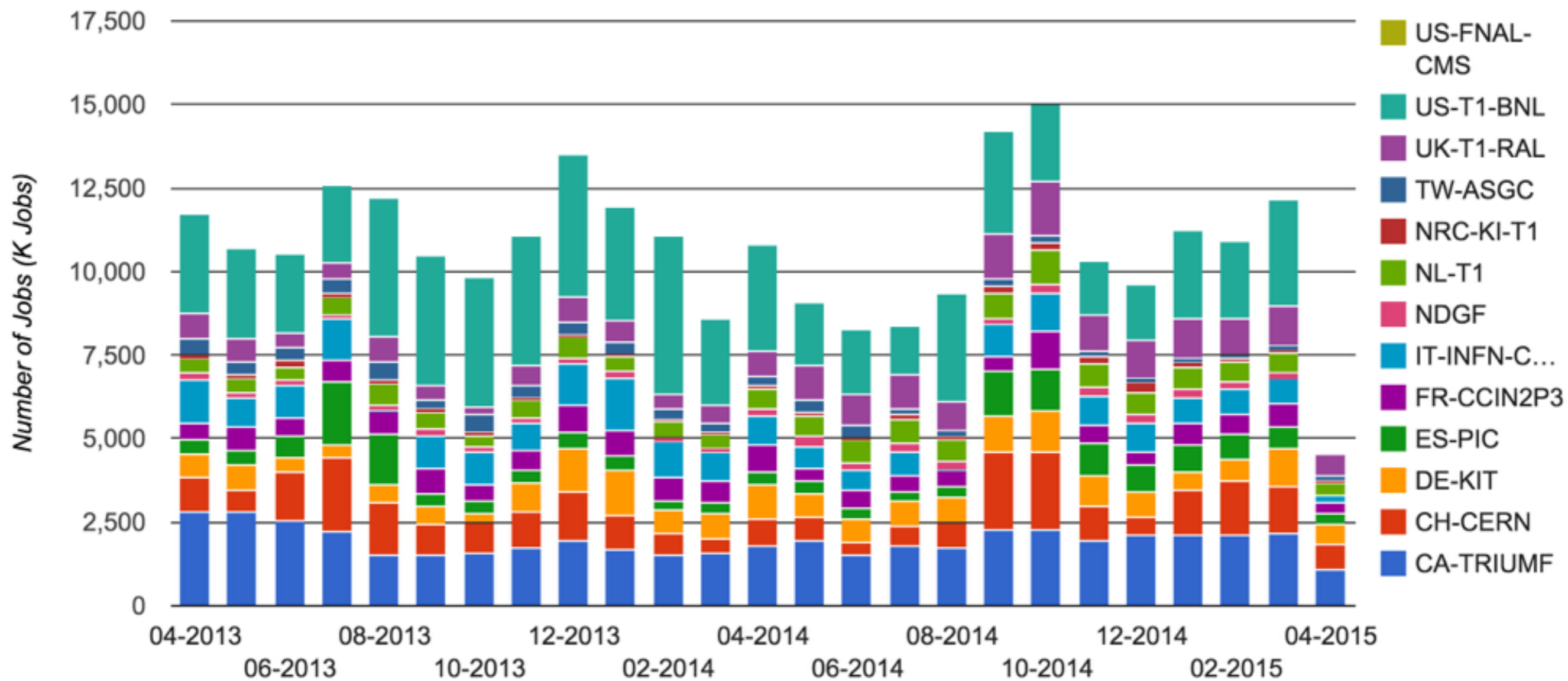
162 Compute Centers = The Grid



The Grid

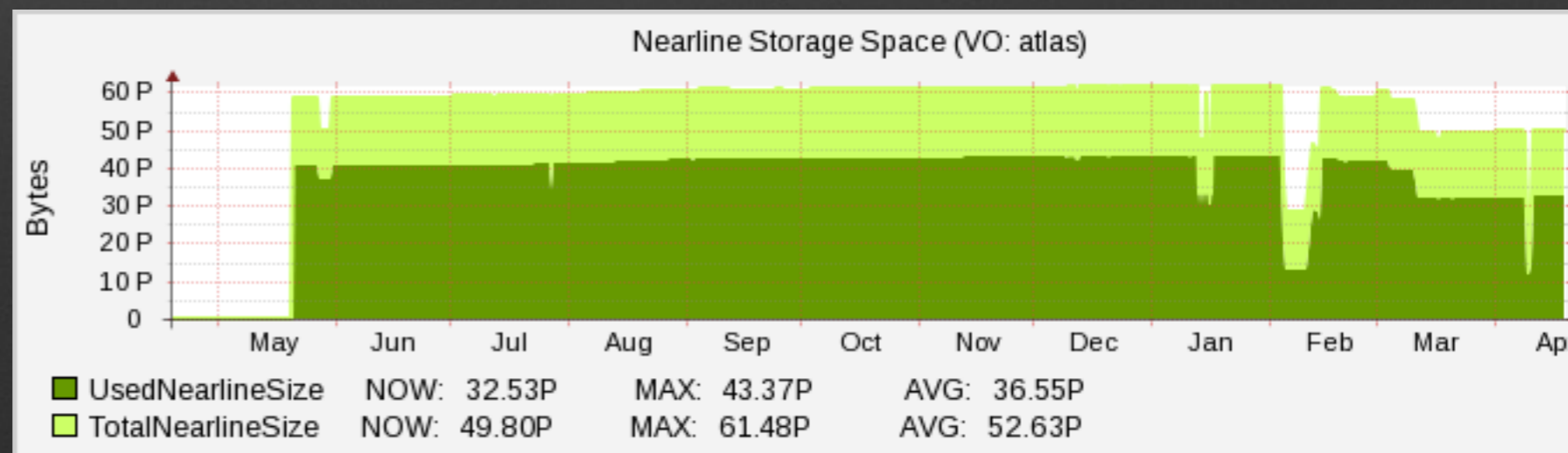
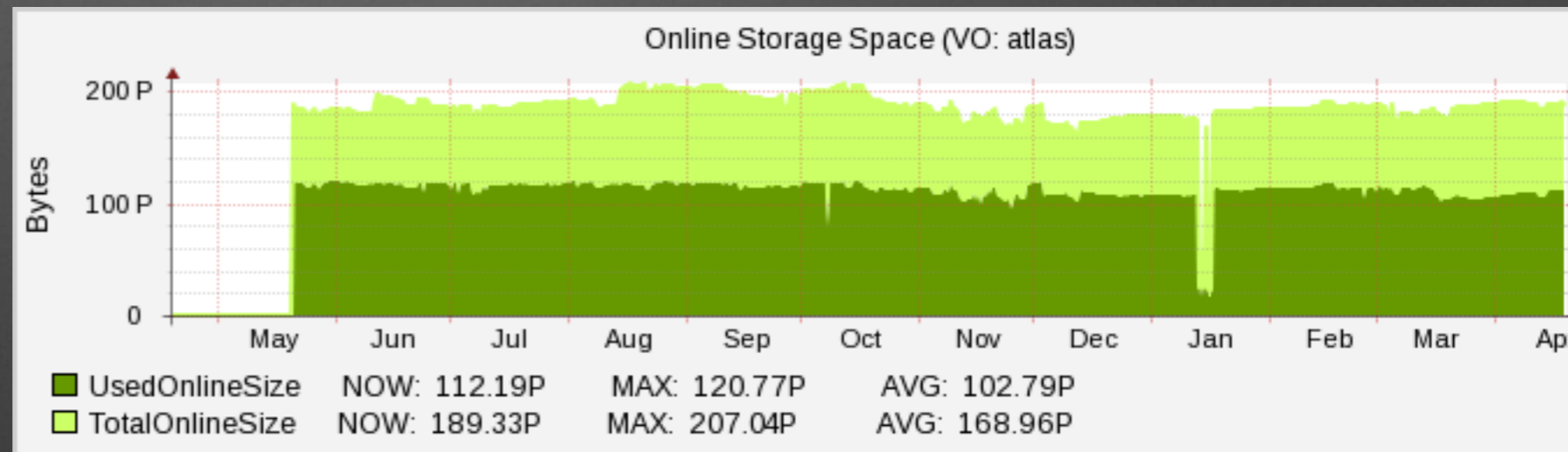
- “WLCG”: world-wide LHC computing grid
- About 500,000 cores
- Used for large-scale data operations

Number of Jobs (ATLAS): All Tier-0 and Tier-1 Sites



Storage

- Tera, Peta, Exa: 1EB = 1,000,000 TB
- Capacity: 0.4 EB
- Usage: 0.3 EB



The Life Of a Byte

- Detector collects (“raw”) data
 - CERN stores a copy; another copy is distributed
- The Grid finds particle traces / collision properties: reconstruction
 - reconstructed data kept at “main sites”
- Physicists analyze some form of reconstructed data

Some Form Of Reconstructed Data

- Repeated filtering - custom data sets



Workbook1

Search in Sheet

Home Layout Tables Charts

Edit Font Alignment Number

Paste Calibri (Body) 12 B I U %

AVA8946 Higgs:

	AUZ	AVA	AVB	AVC	AVD
8942					
8943					
8944		GRAND TOTAL			
8945		Coffee:	1028		
8946		Higgs:	1027		
8947					
8948					

Sheet1

Normal View Ready

C++!

- Approx 50 million lines of C++ at CERN
- Very few devs have formal education in computer science / engineering
- C++ instead of Excel
 - Physicists write their analysis in C++! Themselves!

Analysis Ingredients

- Detector simulation: how much do I expect?
- Reconstruction software: how much did I get?
- Statistics: is that expected?

Analysis Software

- Experiment specific “framework”
>1GB of binaries / shared libraries; >10k classes
- Generic tools, developed and maintained by the community
- Hand-written (e.g. ctrl-C ctrl-V) code by physicists

Data Characteristics

- Collisions are stochastically independent
 - embarrassingly parallel! :-)
 - but whatever happened to Moore?! :-)
- Roughly 1MB chunks of structured floating point and integers
- Reconstruction of a chunk needs about 1GB of RAM

Sharing

Budget

- 1.1B CHF = 1.1B EUR = 0.8B GPB = 1.2B USD
 - contribution by status, gross national product
 - Wikipedia: 2.2CHF / citizen
- THANK YOU.
- And: CONGRATULATIONS!

Society and CERN

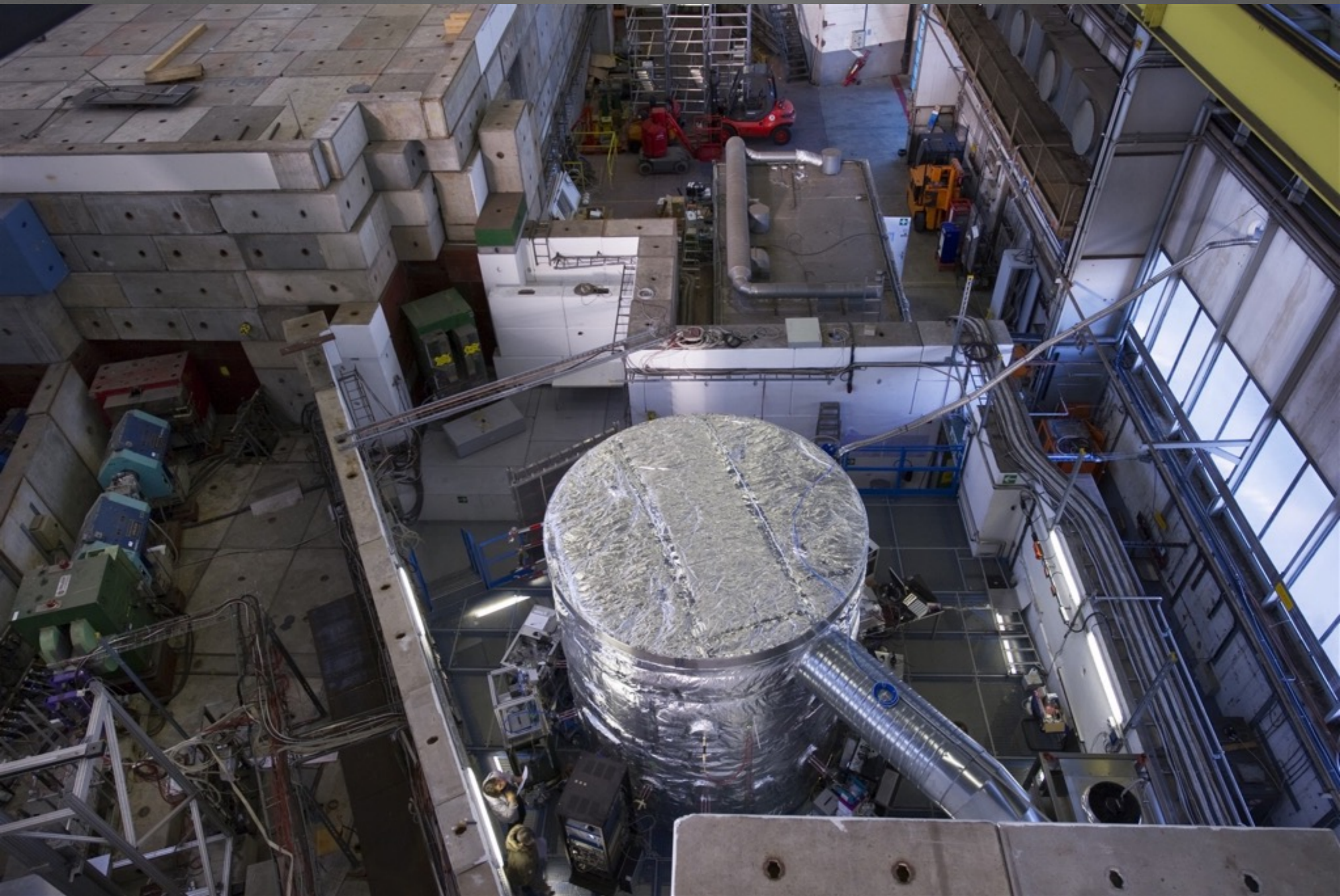
- We can do what we do because of YOU
- We try to make EVERYTHING accessible to YOU
 - research results, in lots of forms
 - hardware
 - data
 - software

Sharing Research

- All publications Open Access, e.g. scoap3.org
 - a revolution!
- Immense effort goes into communication and “popularization”
 - we love to talk about what we do, we owe it to you to share, explain and answer what we can
- home.web.cern.ch/about - and come visit us!

Applying Research

- Influence of cosmic rays in cloud formation
 - cern.ch/cloud



Applying Research

- Energy from nuclear waste, reprocessing to non-weapon nuclear material (“energy amplifier”)
- cern.ch/go/N7PL

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/AT/95-44 (ET)

CONCEPTUAL DESIGN OF A FAST NEUTRON OPERATED HIGH POWER ENERGY AMPLIFIER

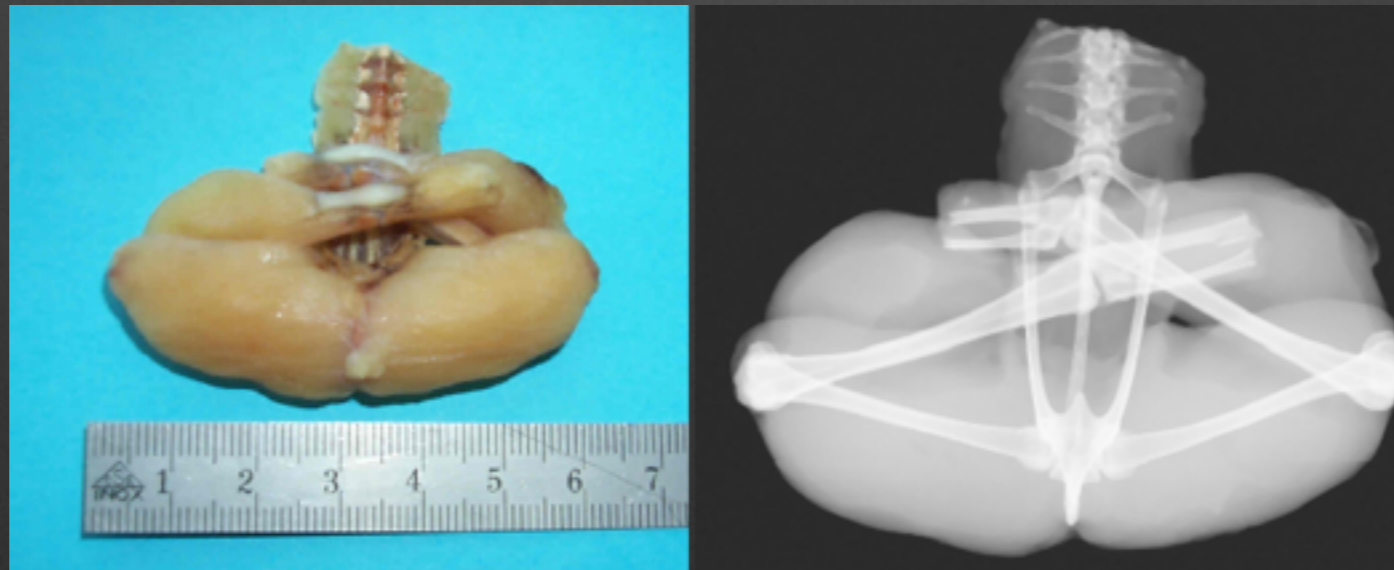
C. Rubbia, J.A. Rubio, S. Buono¹⁾, F. Carminati, N. Fiétier²⁾, J. Galvez, C. Gelès,
Y. Kadi, R. Klapisch, P. Mandrillon²⁾, J.P. Revol and Ch. Roche

Abstract

The basic concept and the main practical considerations of an Energy Amplifier (EA) have been exhaustively described in Ref. [1]. Here the realisation of the EA is further explored and schemes are described which offer a high gain, a large maximum power density and an extended burn-up, well in excess of 100 GW × day/t corresponding to about five years at full power operation with no intervention on the fuel core. Most of these benefits stem from the use of fast neutrons, as already

Applying Research

- Re-purposing detectors
- e.g. cern.ch/MEDIPIX



Hardware, Data,...

- Open Hardware www.ohwr.org/
 - e.g. White Rabbit: deterministic Ethernet
- Open Data opendata.cern.ch/
- LHC@home lhathome.web.cern.ch/
 - and the new & excellent Virtual Atom Smasher test4theory.cern.ch/vas/ (coming soon to the Internet near you)



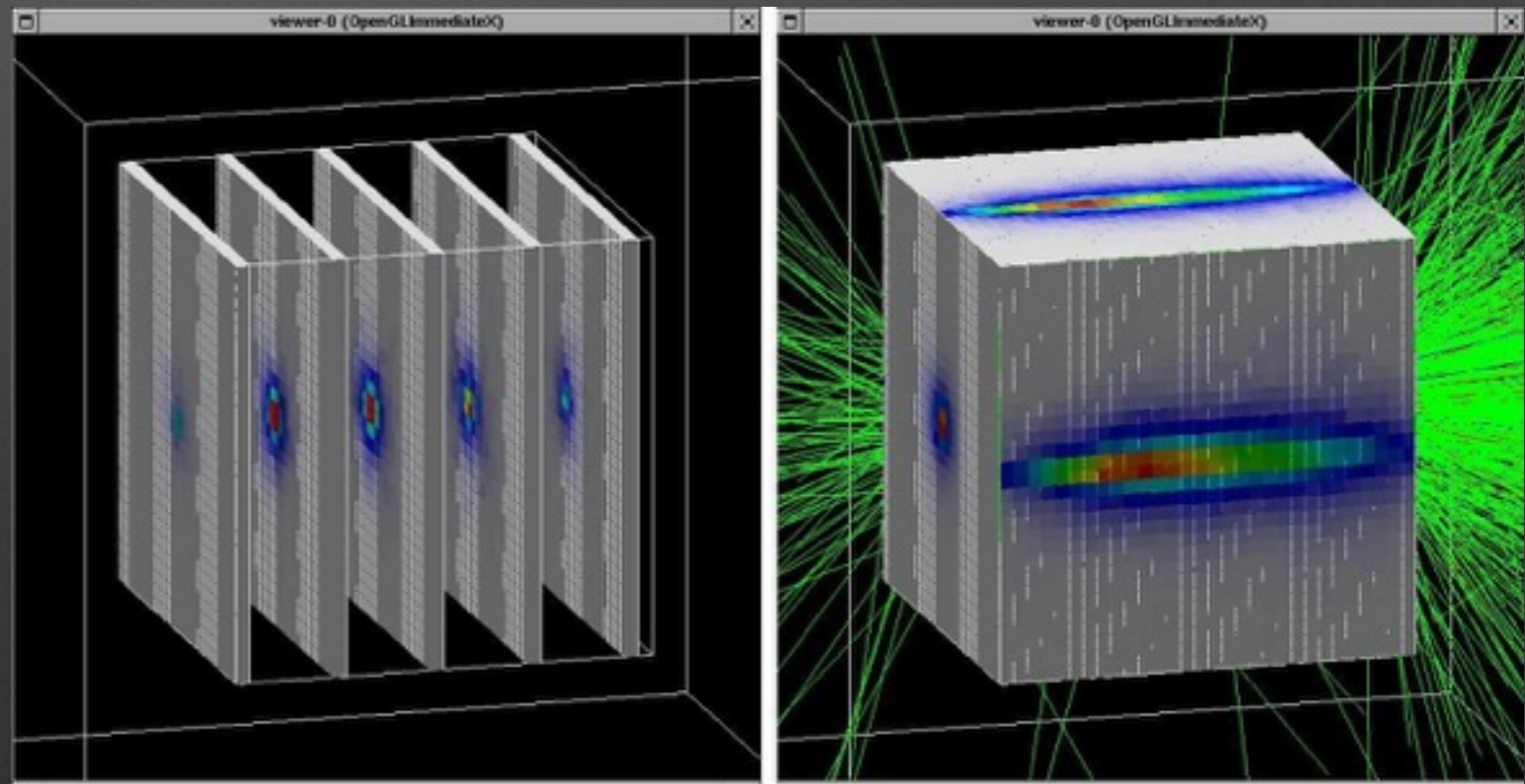
Using Open Source

- Almost everything at CERN is Open Source
- Use and contribute
 - GCC, clang, Puppet, OpenStack, Xen, Ceph, Jenkins, Andrew File System, LaTeX, Drupal,...

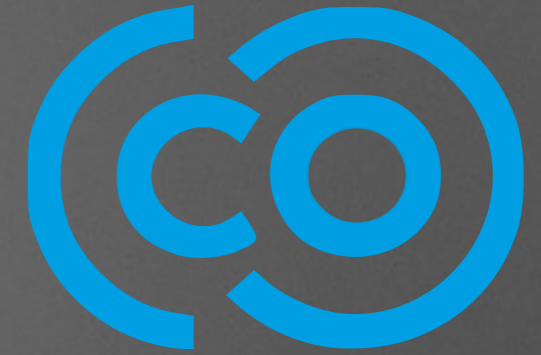
Creating Open Source

Geant

- Simulates interaction of particles with matter
 - used by people like us
 - NASA
 - medical radiation facilities
- geant4.cern.ch/



Indico



- Used to organize meetings and conferences
 - meeting room registration / search
 - manages time table, material, even paper reviewing
- Scales, production grade
 - > 20,000 users; protection / access schemes etc
- indico.github.io

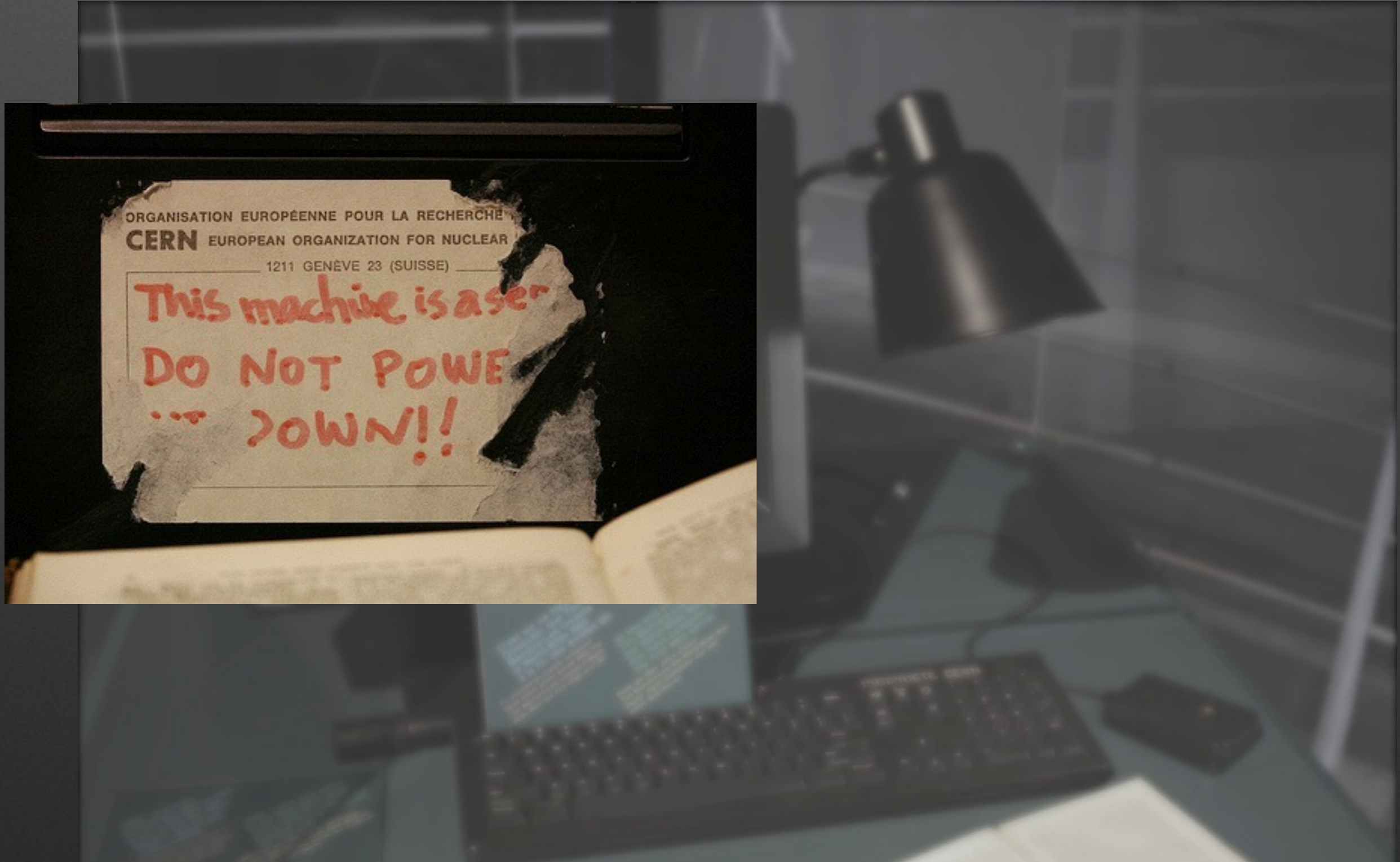
DaviX

- We love http!

WWW @ CERN



WWW @ CERN



ORGANISATION EUROPÉENNE POUR LA RECHERCHE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR
1211 GENEVE 23 (SUISSE)

This machine is a ser
DO NOT POWE
... DOWN!!

DaviX

- We love http!
- Library for transparent http, WebDAV, S3 data transfer
- High throughput!
- Handles large collections of files
- cern.ch/davix

CernVM-FS

- Distribute huge releases onto 100,000 boxes: scp?
- No: cern.ch/cvmfs
 - http-based (!) network file system; write-few-read-many; robust, scalable
 - aggressive caching (even content-delivery systems)
 - can even boot a Virtual Machine out of thin air (but not vacuum)

ROOT

- root.cern.ch
- Data analysis workhorse for all High Energy Physics
- Since 1995, now 2.5MLOC C++
- Physicists' interface to huge, complex frameworks



David And Good Goliath

- You start your PhD, now write analysis against >10k classes
 1. Copy & paste from older PhD candidates
 2. Explore data and existing interfaces

Exploring Code

- Plan A: documentation is the key
- Sometimes keys get lost:

```
/// Retrieves the answer. WARNING: CPU intense.  
TheAnswerToTheUltimateQuestionOfLifeTheUniverseAn  
dEverything::getReply();
```

Exploring Code with Realistic Doc

- Plan B: look at source code
- With millions of LOC, virtuality, templates: good luck!
(and now try as a computing novice)
- Works for local cases, not for complex frameworks /
algorithms

Exploring Complex Code With Realistic Doc

- Plan C:

Exploring Complex Code With Realistic Doc

- Plan C:

erm...

Interpreting C++ (still ROOT)

Exploring Code Through Experiments!

- We LOVE experiments.
- Did you ever probe functions using gdb?
- We use a C++ Interpreter: load complex parts, pick interfaces you need (or might need), test drive them!
- No linking, re-linking, and linking again
- Just keep trying (and keep saving - it *is* C++)

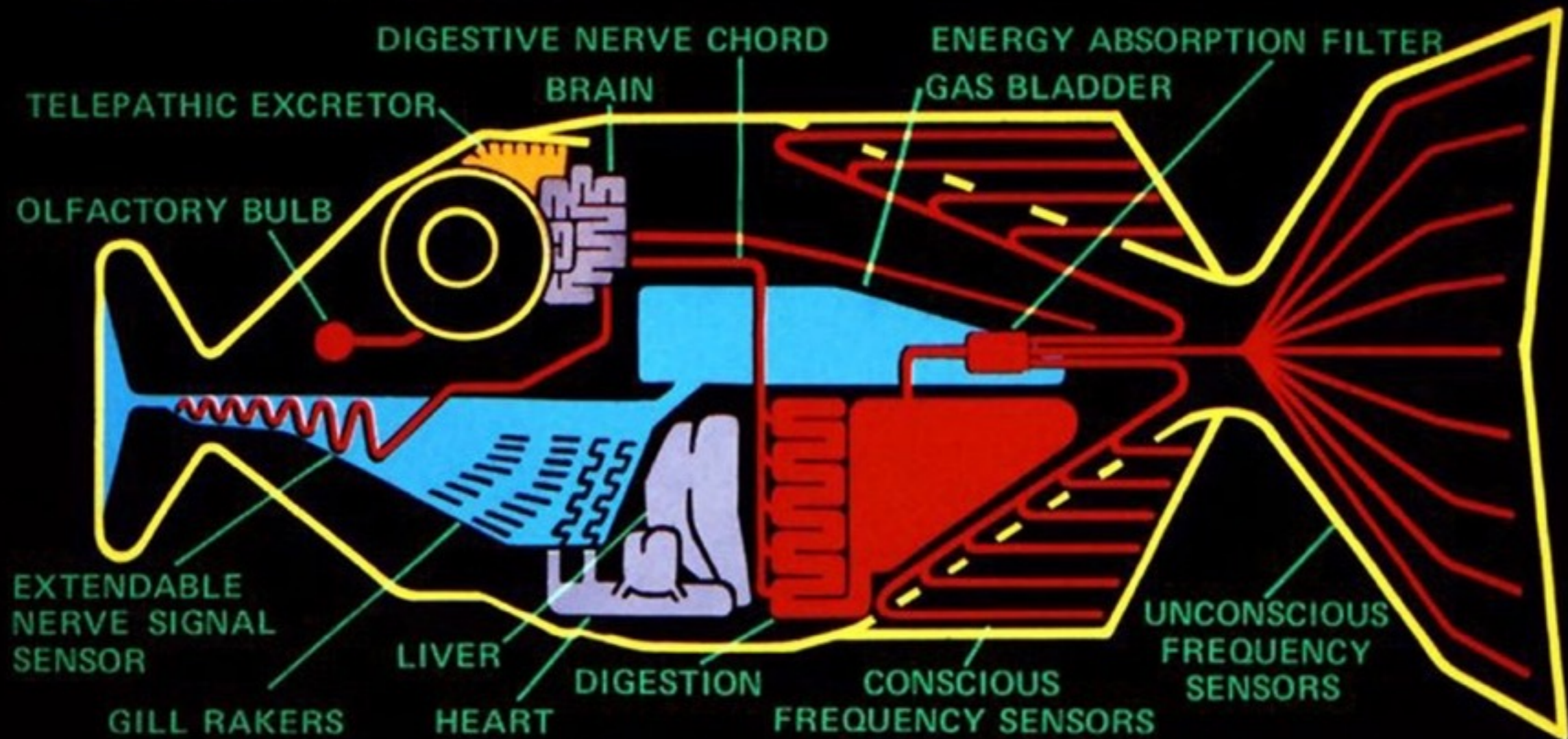
Explorative Coding

- Completely changed the way we develop C++ code
 - organized framework used by creative, spontaneous, vivid bubble of all kinds of code
 - can shift from the bubble into the framework as code becomes stable and useful
- All collaborative coding techniques now apply to physics analyses!

Interpreting C++

- CINT from 1993-2013, based on the amazing brain of Masaharu Goto
- Now cling cern.ch/cling based on clang + llvm
 - complete C++ support!
 - great just-in-time-compiler (love OrcJIT!)
 - going into production as the LHC starts up...!

BABEL FISH



THE BABEL FISH IS SMALL, YELLOW, LEECHLIKE, AND PROBABLY THE ODDEST THING IN THE UNIVERSE. IT FEEDS ON BRAIN WAVE ENERGY, ABSORBING ALL

And Python, Too

- Do. Not. Use. SWIG. At least not on this scale.
- cling and Python share knowledge:
 - dynamic binding to Python, back and forth
 - C++ types in Python, C++ objects in Python!
 - Pythonization of C++ types: `begin()` + `end()`? iterable!
- Dynamic! At runtime! (Remember the vivid bubble?)

Interpreter + A Few = Serialization

- Interpreter governs AST
 - authoritative source of runtime reflection
- Build serialization on top
- Nicely scales to 0.x Exabytes of data, so far.

High Energy Physics Data

- Maps types to data structure:
 - A house has
 - windows: with size, opening direction; has
 - frames: with color and material
 - doors: ...
 - A city has many houses (embarrassingly parallel)

Data Structures

- Nested collections
- The same layout again, and again, and again, billion times, for each collision
- But layout is specific for experiment, physics analysis, physicist etc
- Define the “city” type and ROOT will serialize

Efficient Serialization

- Binary, compressed, file-based (databases don't scale)
- Column-wise storage
 - partial read: skip columns / rows. Nobody needs to know *everything* of a subset of houses. Plumbers don't care about colors of window frames.
 - co-locality of similar data: increased compression
- Parallel prefetching (remote files!)

Production Grade Serialization

- I shall not lose our data.
- I shall not lose our data.
- I shall not lose our data.
- I shall not lose our data.
- I shall not lose our data.
- I shall not lose our data.
- I shall not lose our data.



Production Grade Serialization

- **Robustness:**
 - data description stored with data
 - schema evolution
 - recovery: read-what-we-can
- **Backward and forward compatibility**
- **Huge success in high energy physics**

ROOT

- ...and that was only a *part* of ROOT.
- ...which is all open source.

ROOT

- ...and that was only *a part* of ROOT.
- ...which is all open source.
- (... and guess who else is using it.)



Conclusion

Why Should You Care?

CERN and Society

- You enable great stuff - thank you!
- We want to share, and we do
 - we have good outreach people for science
 - not so much for software
 - but we do have good software! :-)



Scientific Computing

- Many building blocks existed outside our field
- Some crucial ones did not
 - C++ data serialization and distribution
 - scale, scale, scale
 - computing for non-computer scientists
- More natural sciences arrive at the petabyte data range; they meet the same challenges

Complexity and Novices

- Had to solve novice-versus-MLOCs
 - interactive, explorative development approach (with lots of copy&paste) works well for us
- C++ still a hurdle for novices
 - but field agreed to pay the price for efficiency
 - and Python integration helps

Contact

- Still here for lunch
- axel@cern.ch
- Here, now!