The discovery of the Higgs boson

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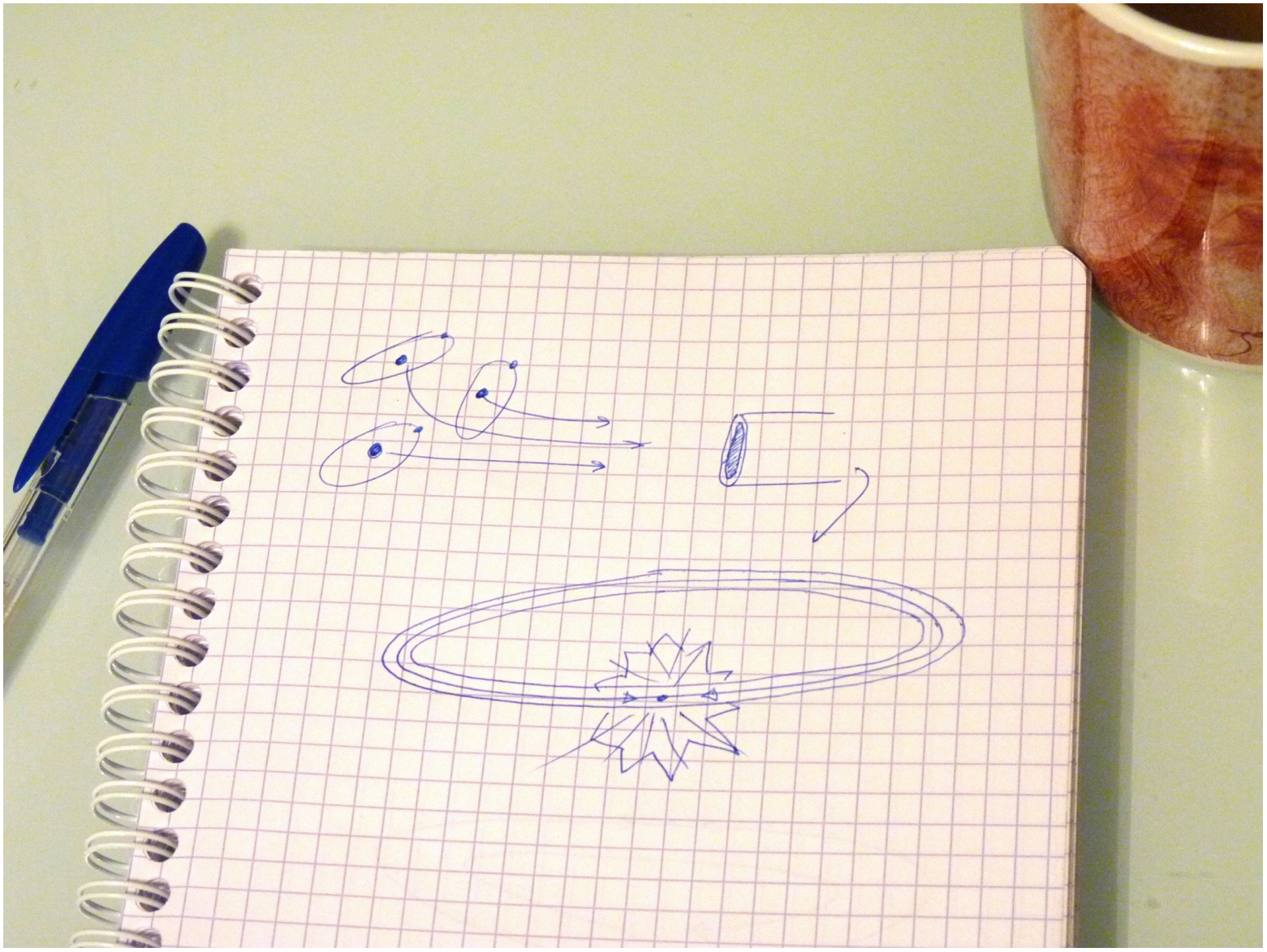
The Chinese University of Hong Kong

International High School Teachers Program 2023

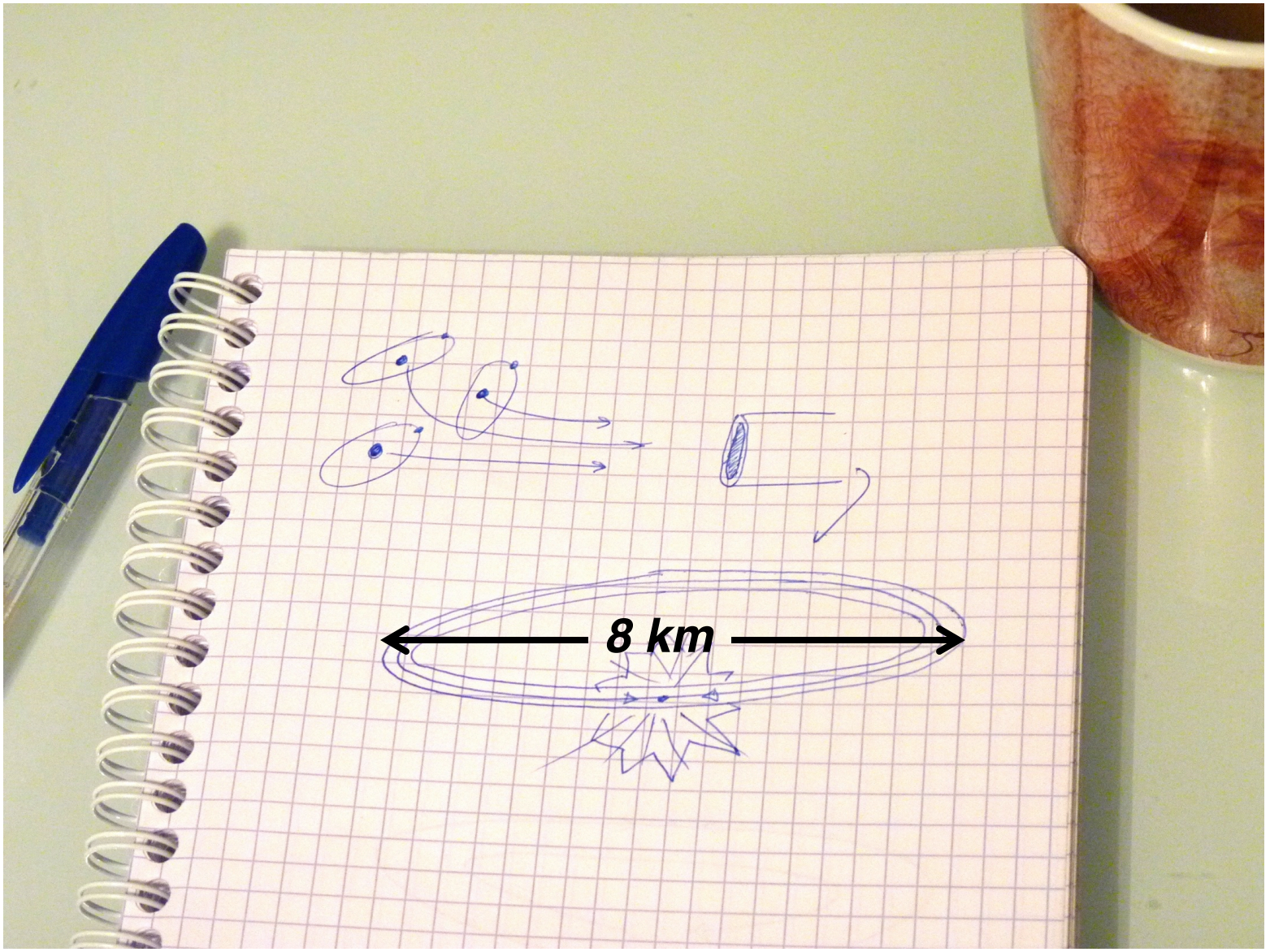
CERN, Switzerland

July 4, 2023

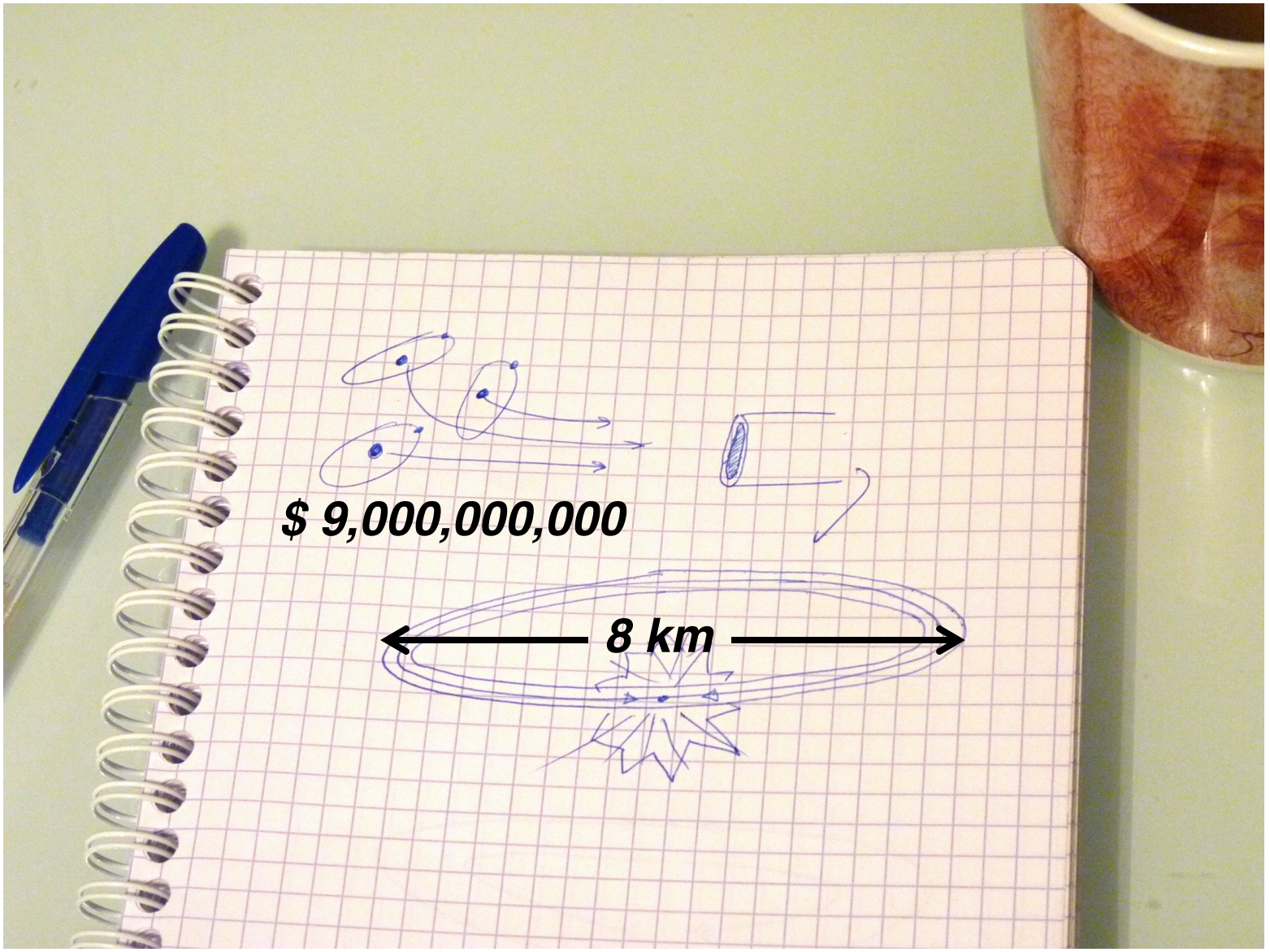
Aiming high



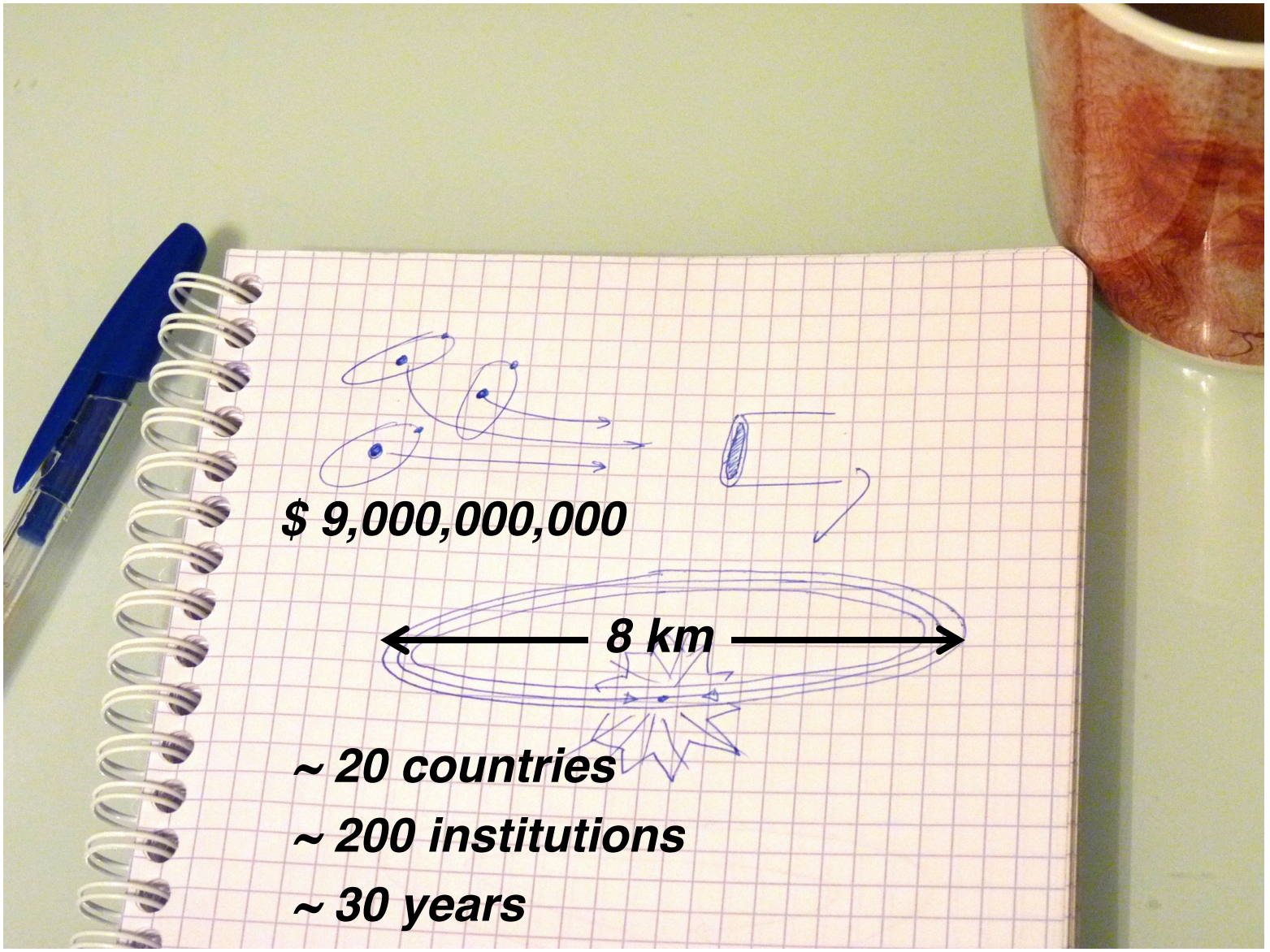
Aiming high

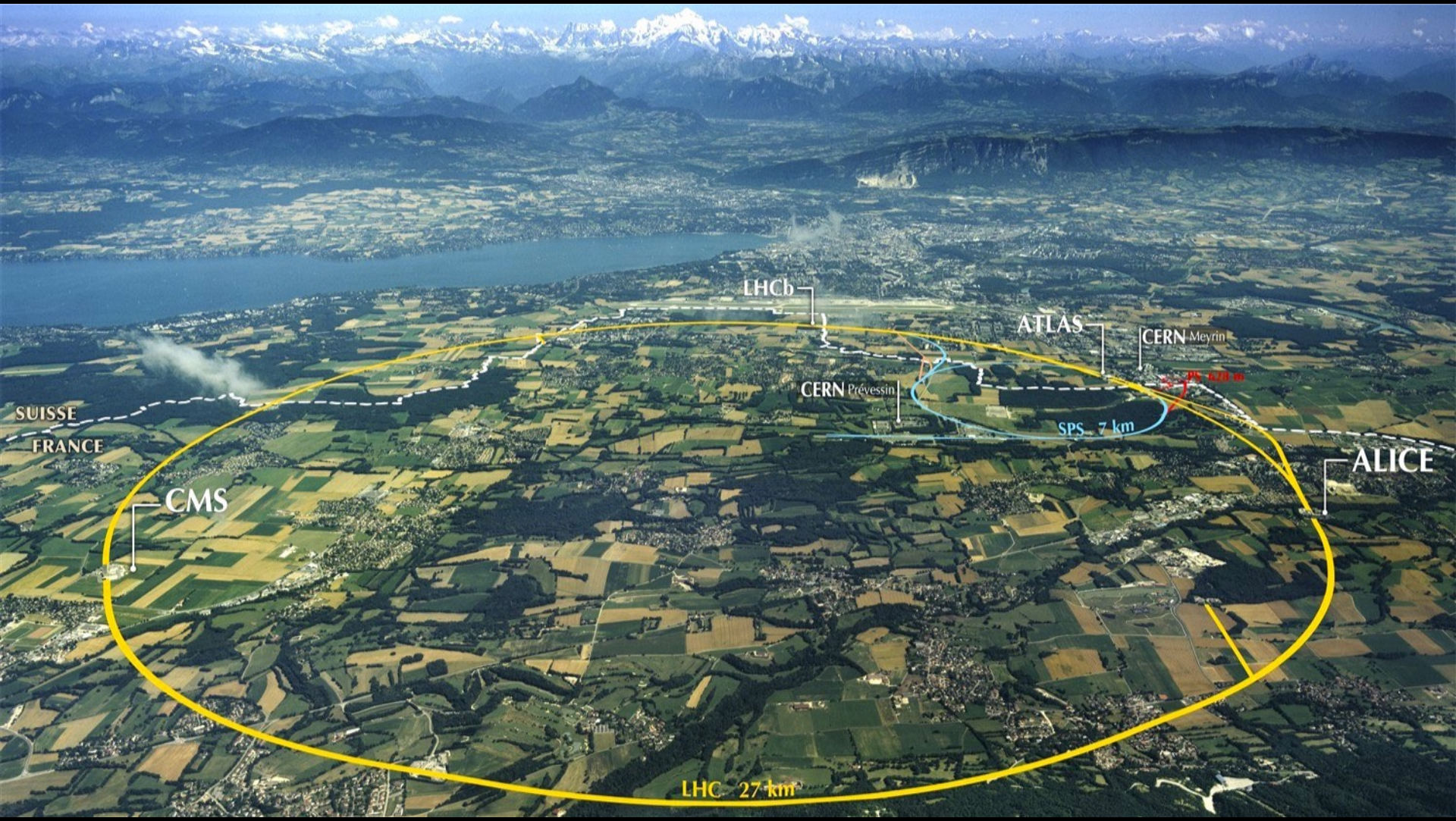


Aiming high



Aiming high




LHCb
ATLAS
CERN Meyrin
CERN Prévessin
PS 0.628 km
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km

July 4, 2012

"I think we have it" – Rolf Heuer, CERN's Director General

International Herald Tribune

Discovery upends world of physics

JULY 5, 2012

THE AGE

Origin of universe revealed

JULY 5, 2012

The New York Times

A New Particle Could Be Physics' Holy Grail

JULY 4, 2012

AUSTRALIA

After 50 years – and billions of dollars the God particle is no longer a theory

JULY 4, 2012

TIME

The elusive Higgs boson is at last found—and the universe gets a little less mysterious

BY JEFFREY KLUGER

JULY 23, 2012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A giant leap for science
Finding the Higgs boson
Worldwide excluding UK
JULY 7TH - 13TH 2012


NEWSPAPER OF THE YEAR
Wimbledon 2012
Dramatic victory takes Murray through to semi-finals
Scientists prove existence of 'God particle'
'Momentous' find after 45-year hunt for Higgs boson
Professor weeps as his life's work finally bears fruit
Physicist deserves the Nobel Prize, says Hawking

Nobelpriset 2013

The Nobel Prize 2013

The Nobel Prize in Physics 2013

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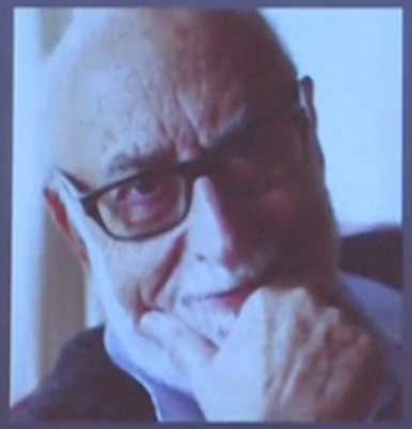
THE ROYAL SWEDISH ACADEMY OF SCIENCES



François Englert
Université Libre de Bruxelles, Belgium

Peter W. Higgs
University of Edinburgh, UK

"För den teoretiska upptäckten av en mekanism som bidrar till förståelsen av massans ursprung hos subatomära partiklar, och som nyligen, genom upptäckten av den förutsagda fundamentala partikeln, bekräftats av ATLAS- och CMS-experimenten vid CERN:s accelerator LHC."

"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."

Nobelprize.org

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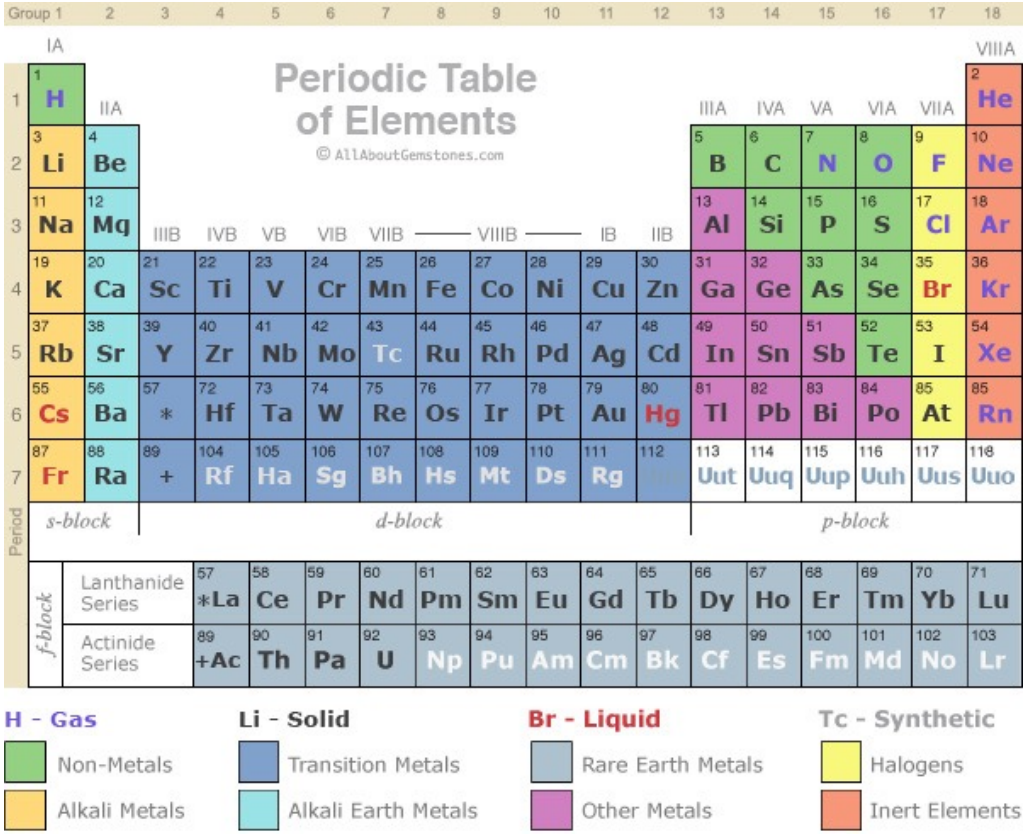
October 8, 2013

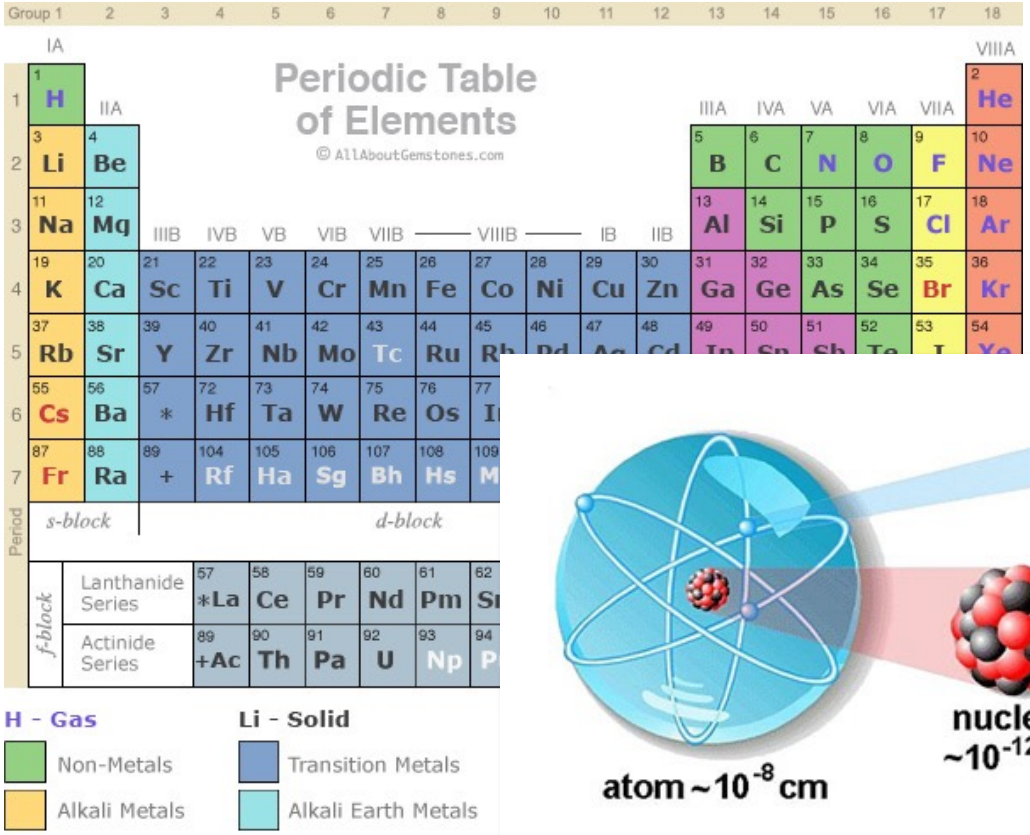
What is the Higgs boson?

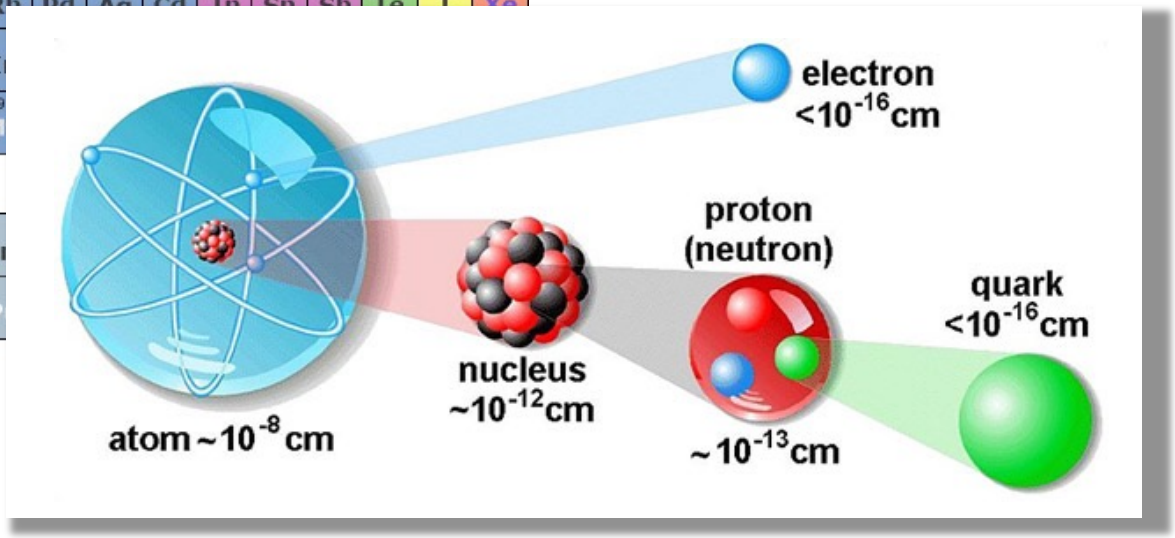
Fundamental building blocks?



- ~1869, Mendeleyev published **"Principles of Chemistry"**
- All that complexity from ~100 "elements"

Fundamental building blocks?

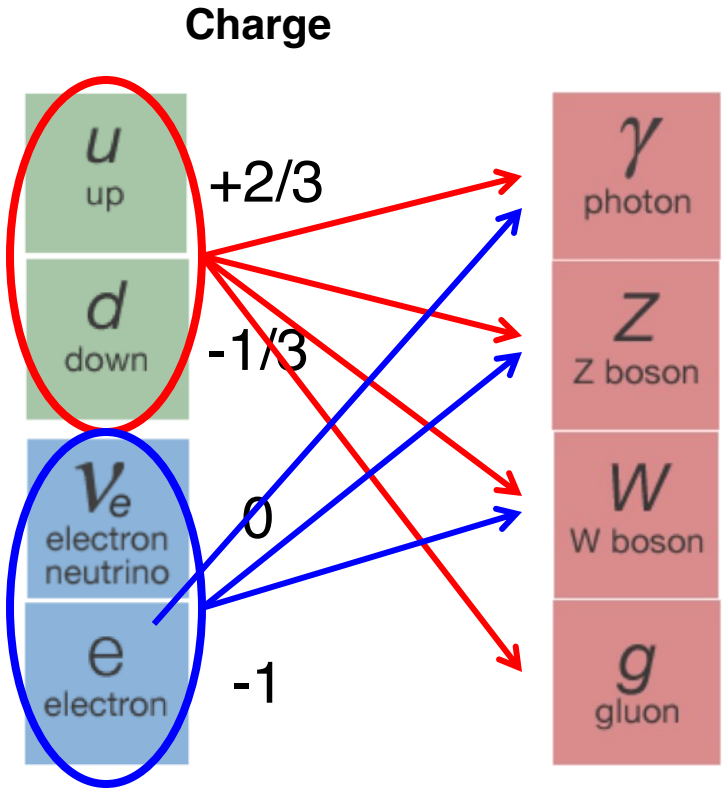




… but all of them are combinations of THREE particles.

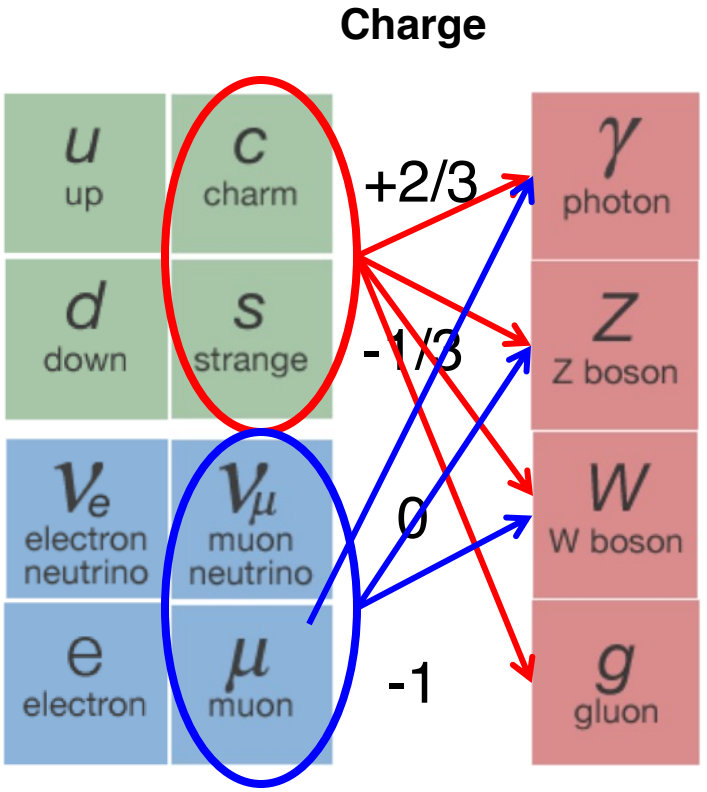
Fundamental building blocks?

- Besides those three, …



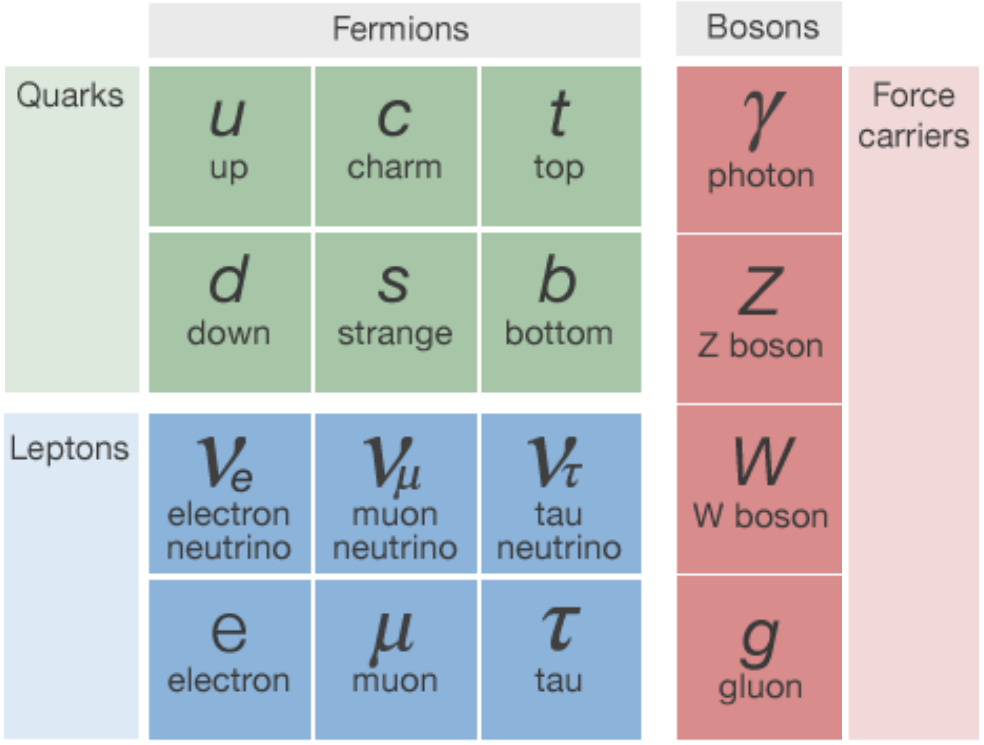
Fundamental building blocks?

- Besides those three, …



Fundamental building blocks?

- Besides those three, there are 13 more
- They describe almost all known physical phenomena



- In 1964, there was a problem: the model worked only if all elementary particles had ZERO mass

"Zero mass"?

– "Mass" is the resistance to transform energy into motion
  Black beach ball vs bowling ball:
  the lower the mass, the larger the speed acquired

– Are there any particles with mass = 0 ?
  Yes: photons and gluons travel at the speed of light

– What if **all elementary particles** traveled at light speed?
  - There would be no atoms
  - No clusters of matter (hence: no stars, no planets)
  - No life as we know it

– In 1964, Higgs, Englert+Brout, Guralnik+Hagen+Kibble found a solution by postulating a new field,
  … and a new elementary particle.

Idea: Prof. David J. Miller Image: CERN

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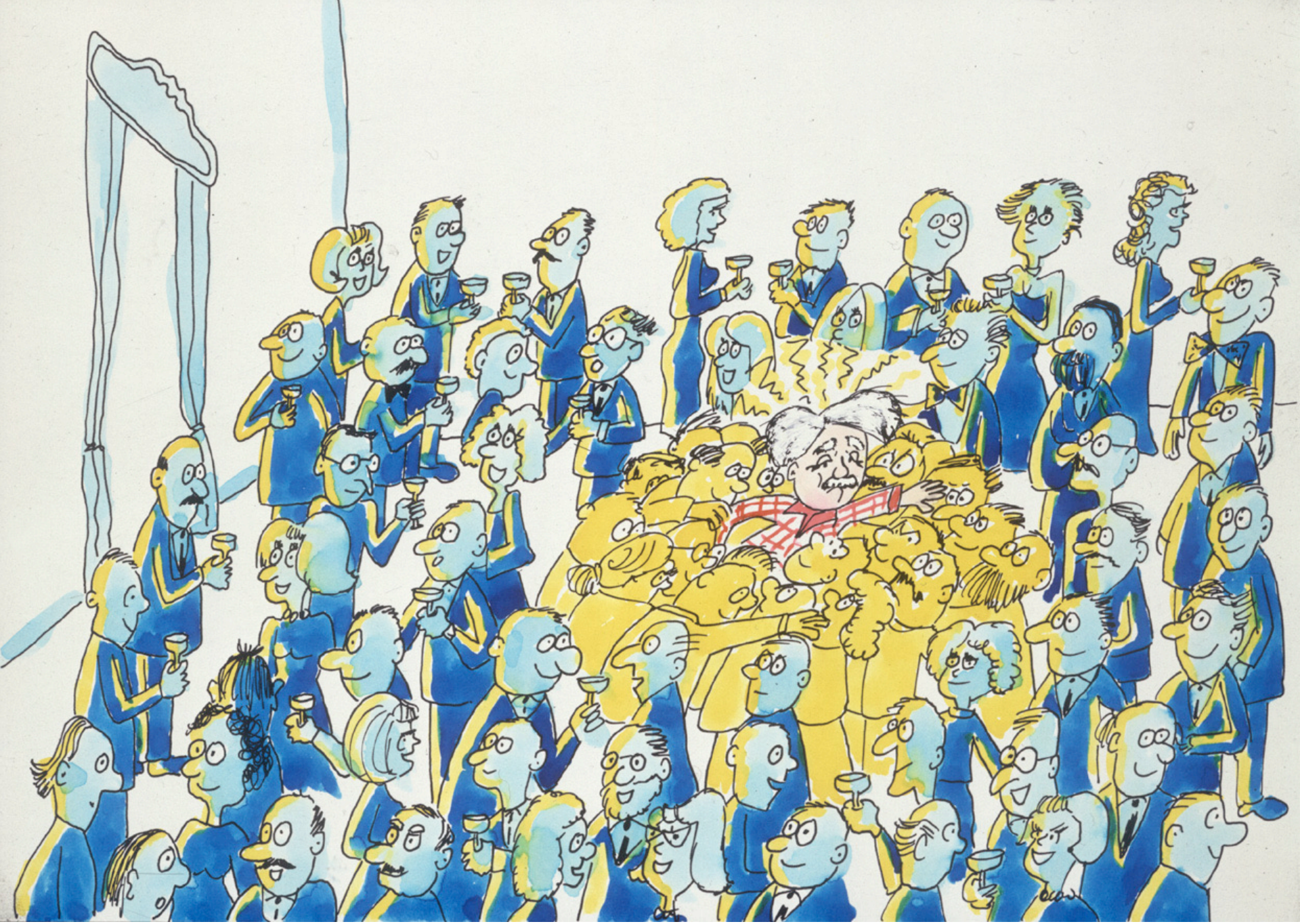
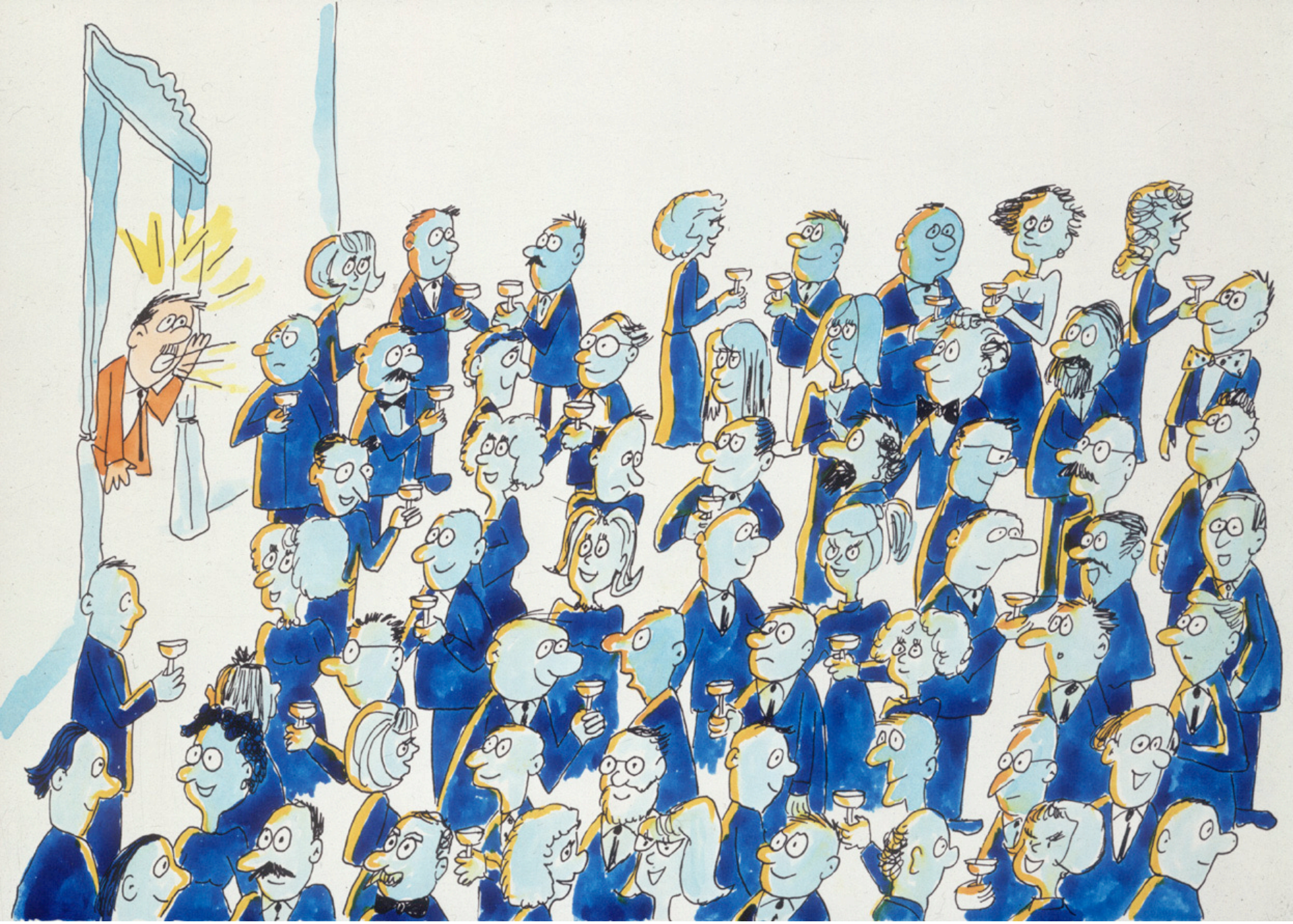


Idea: Prof. David J. Miller Image: CERN



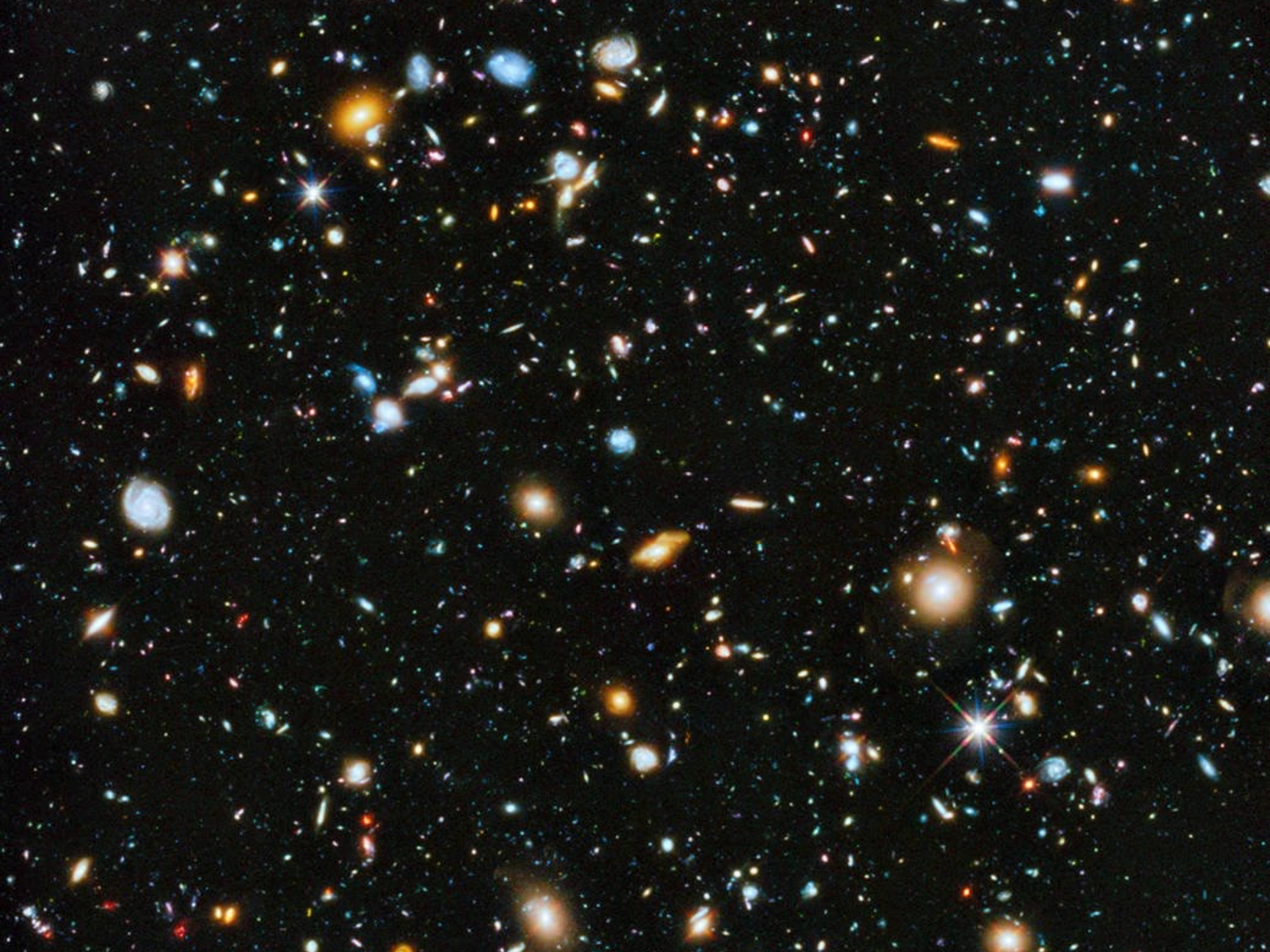
Idea: Prof. David J. Miller Image: CERN

Idea: Prof. David J. Miller Image: CERN

“For every complex problem there is an answer that is clear, simple, …

“For every complex problem there is an answer that is clear, simple, and wrong.”

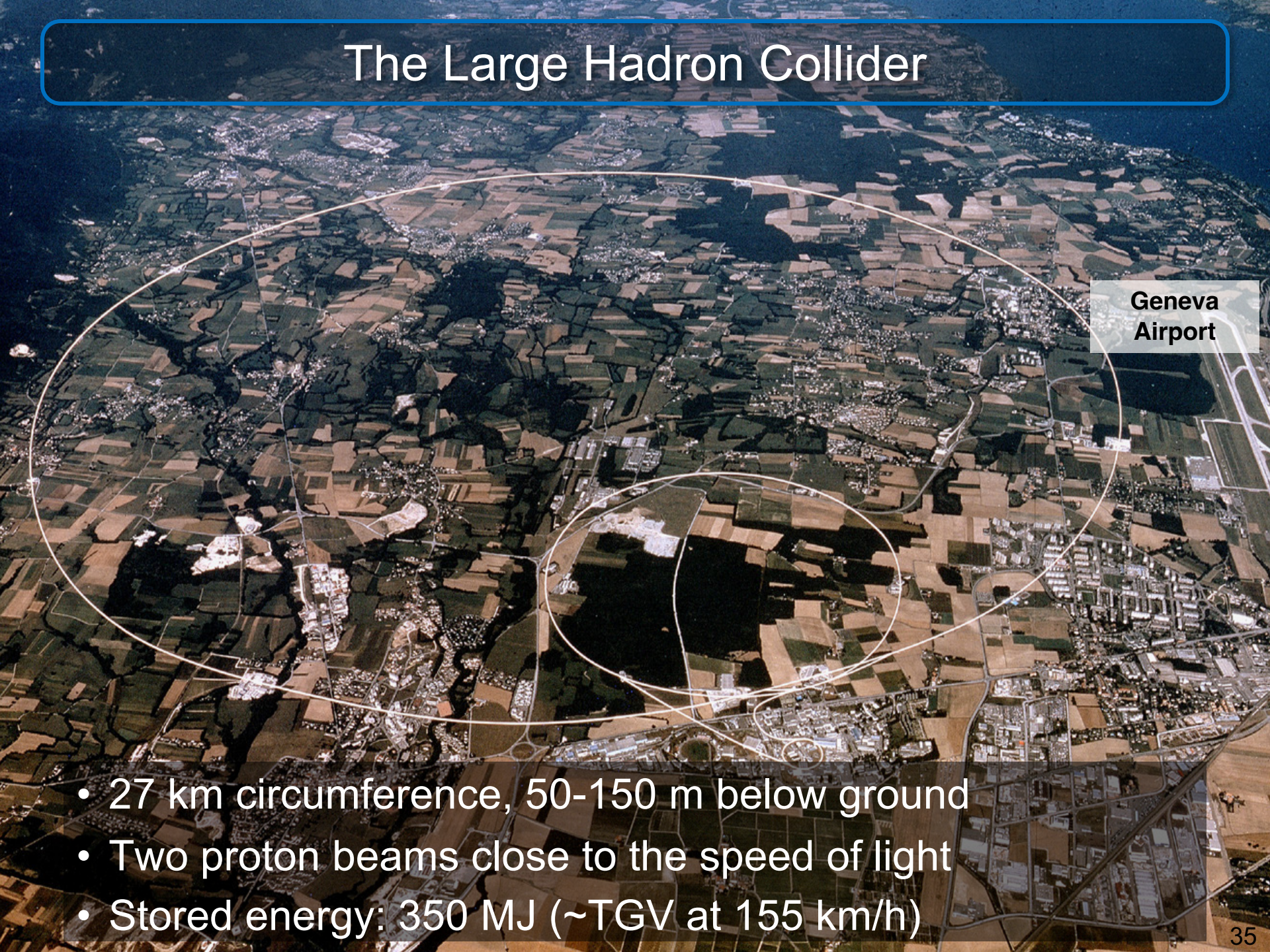
– H. L. Mencken



How was this particle discovered?

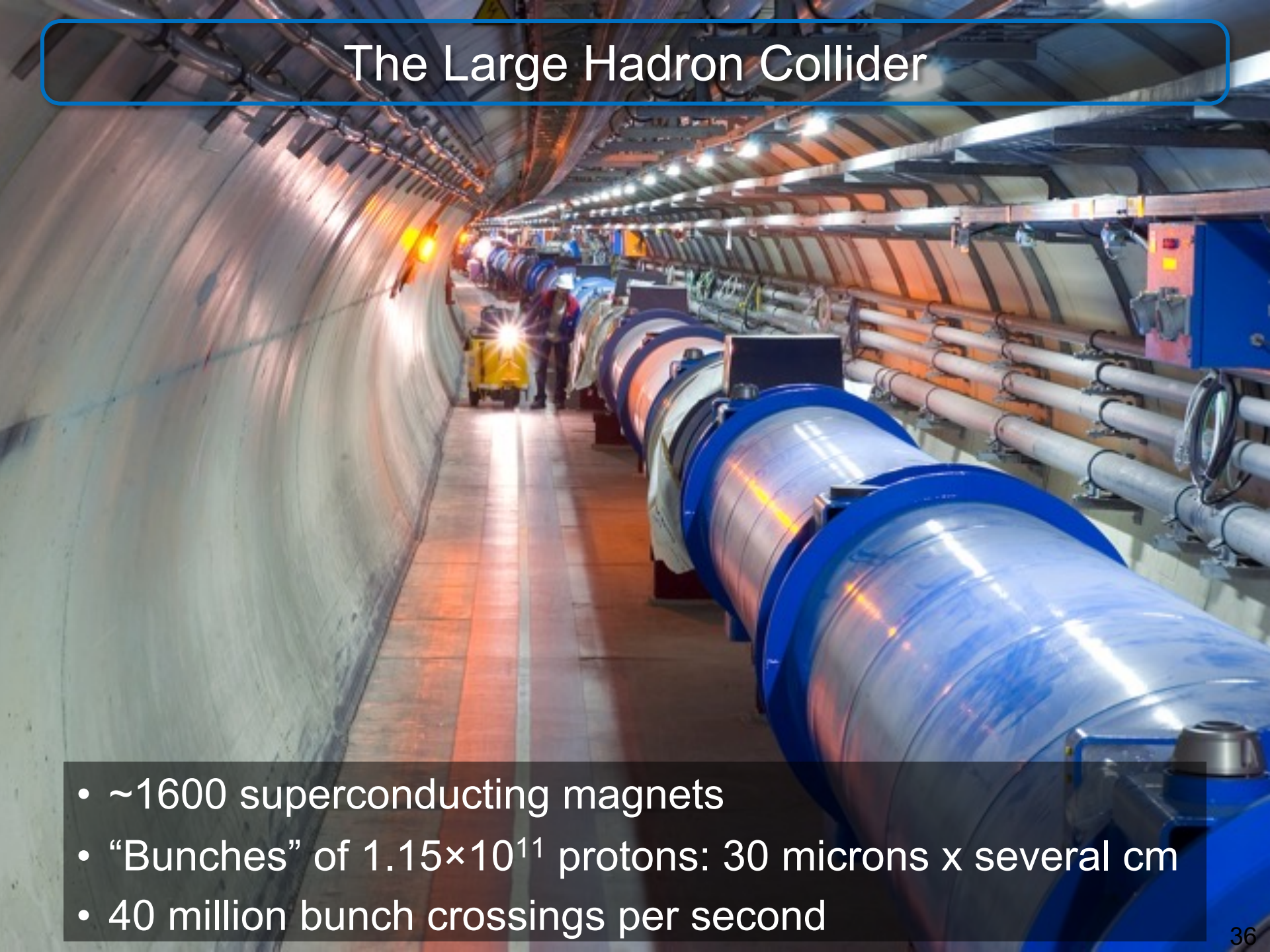
$$E = mc^2$$

The Large Hadron Collider



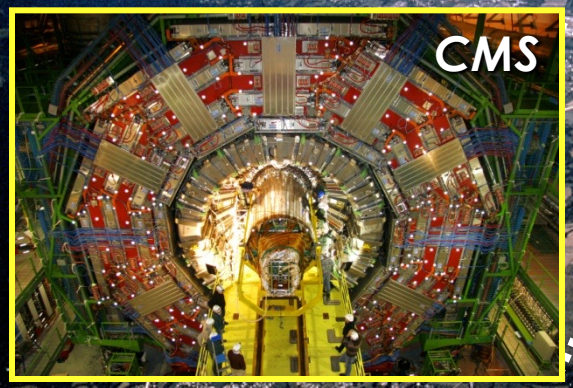
- 27 km circumference, 50-150 m below ground
- Two proton beams close to the speed of light
- Stored energy: 350 MJ (~TGV at 155 km/h)

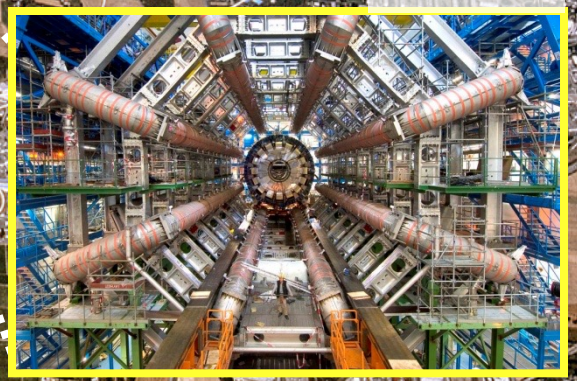
The Large Hadron Collider



- ~1600 superconducting magnets
- “Bunches” of 1.15×10^{11} protons: 30 microns x several cm
- 40 million bunch crossings per second

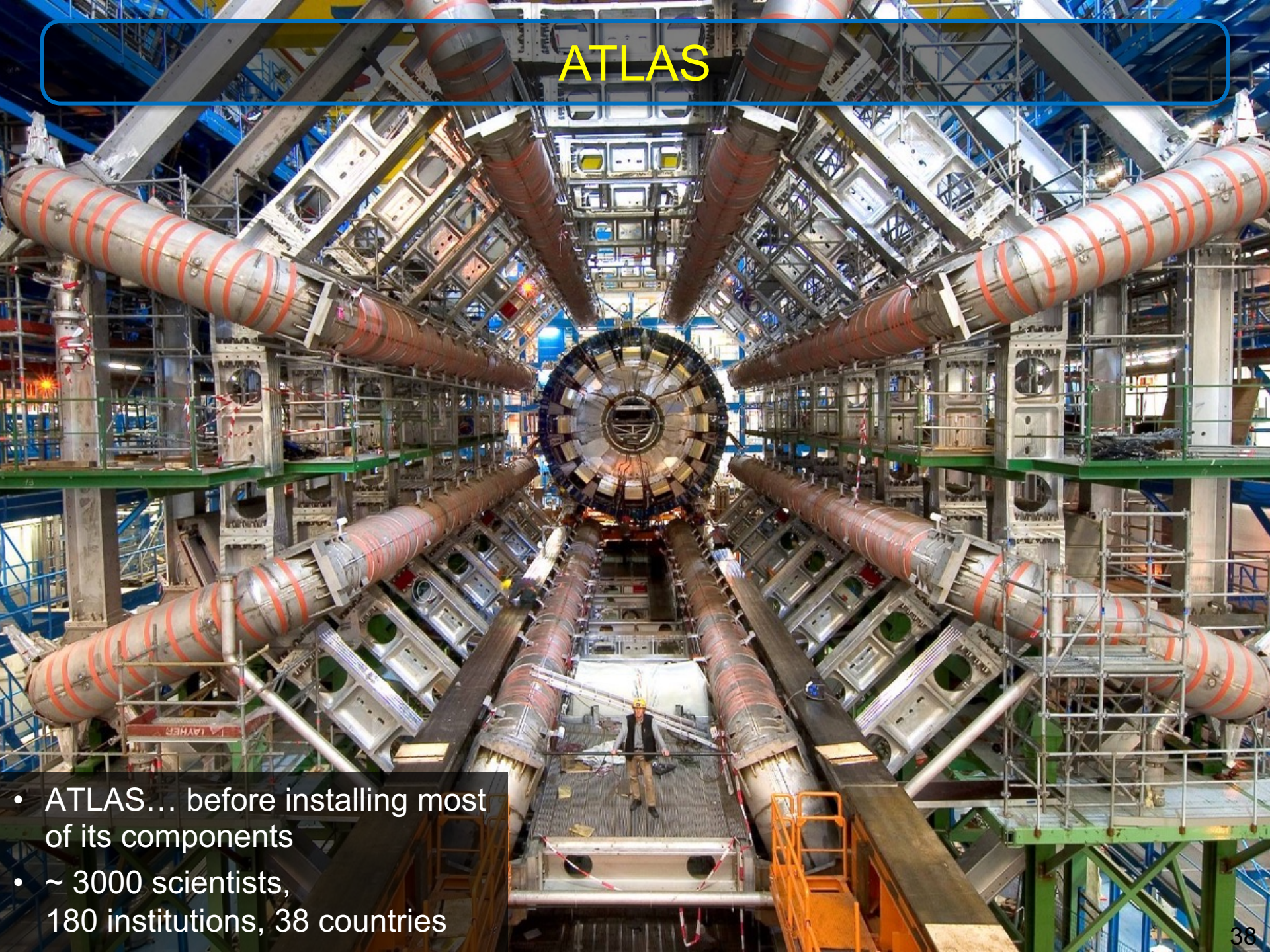
Detectors





- Four collision points
- One detector on each
- Discovery: ATLAS, CMS

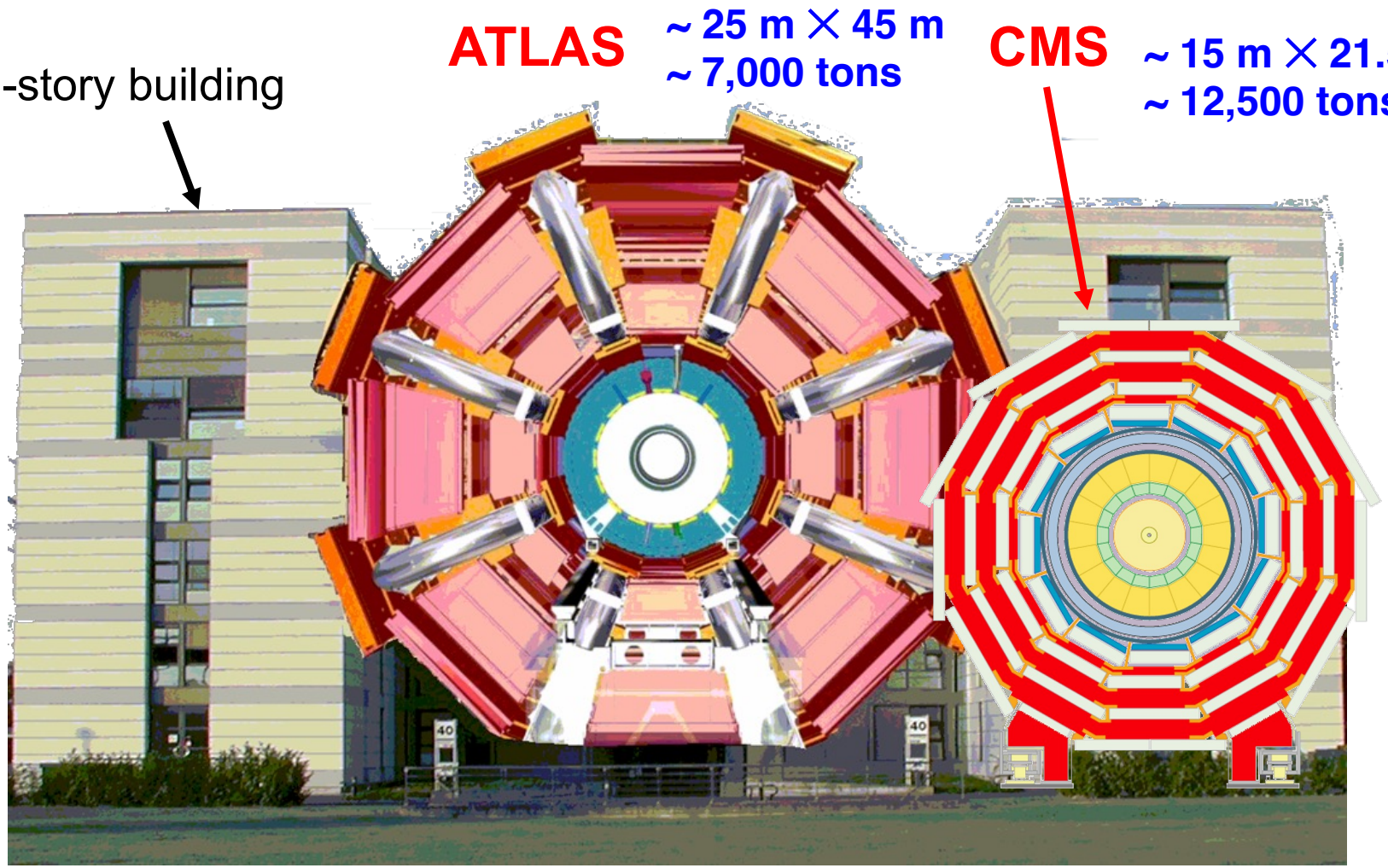
ATLAS



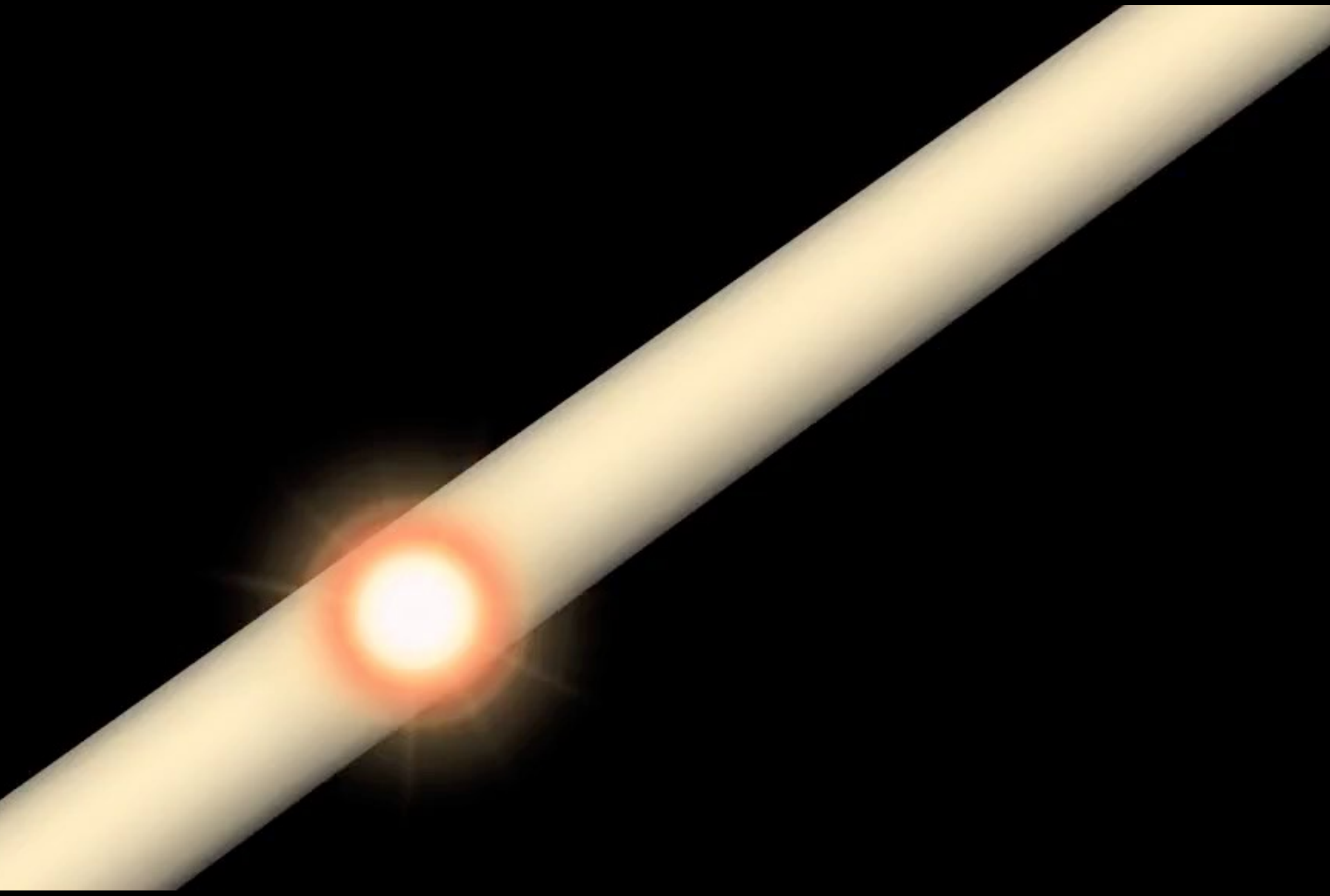
- ATLAS… before installing most of its components
- ~ 3000 scientists,
  180 institutions, 38 countries

CMS

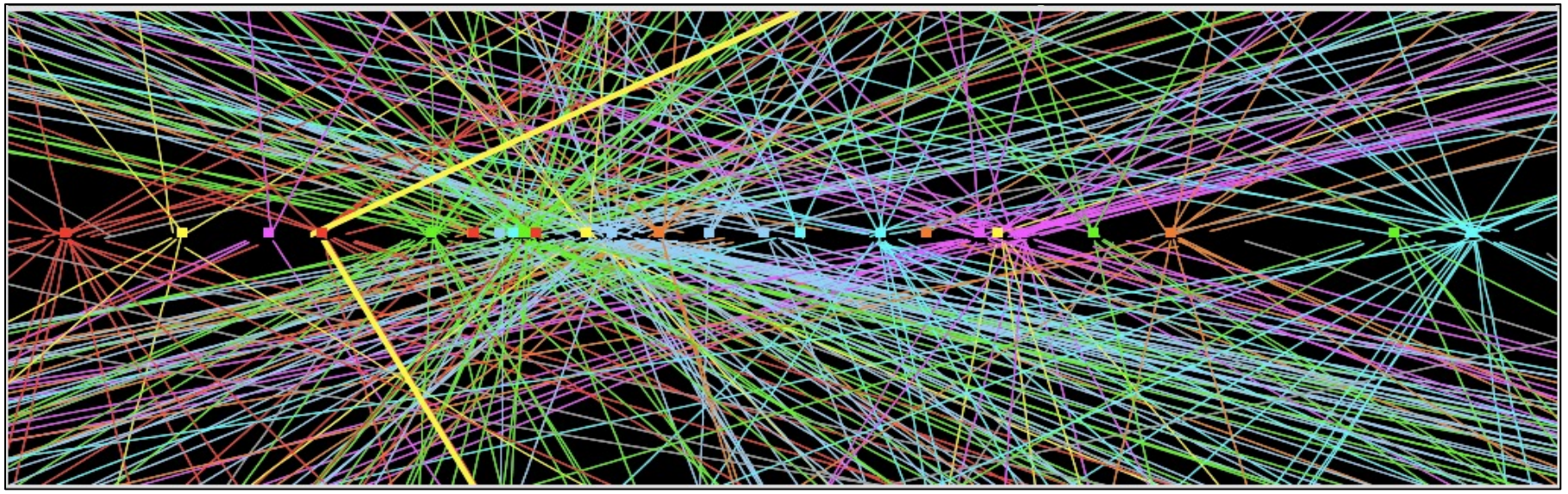
~ 3000 scientists, 182 institutions, 42 countries



- About 100 millions sensors each
- Much beyond a 12-megapixel camera: **40 million pictures/second**



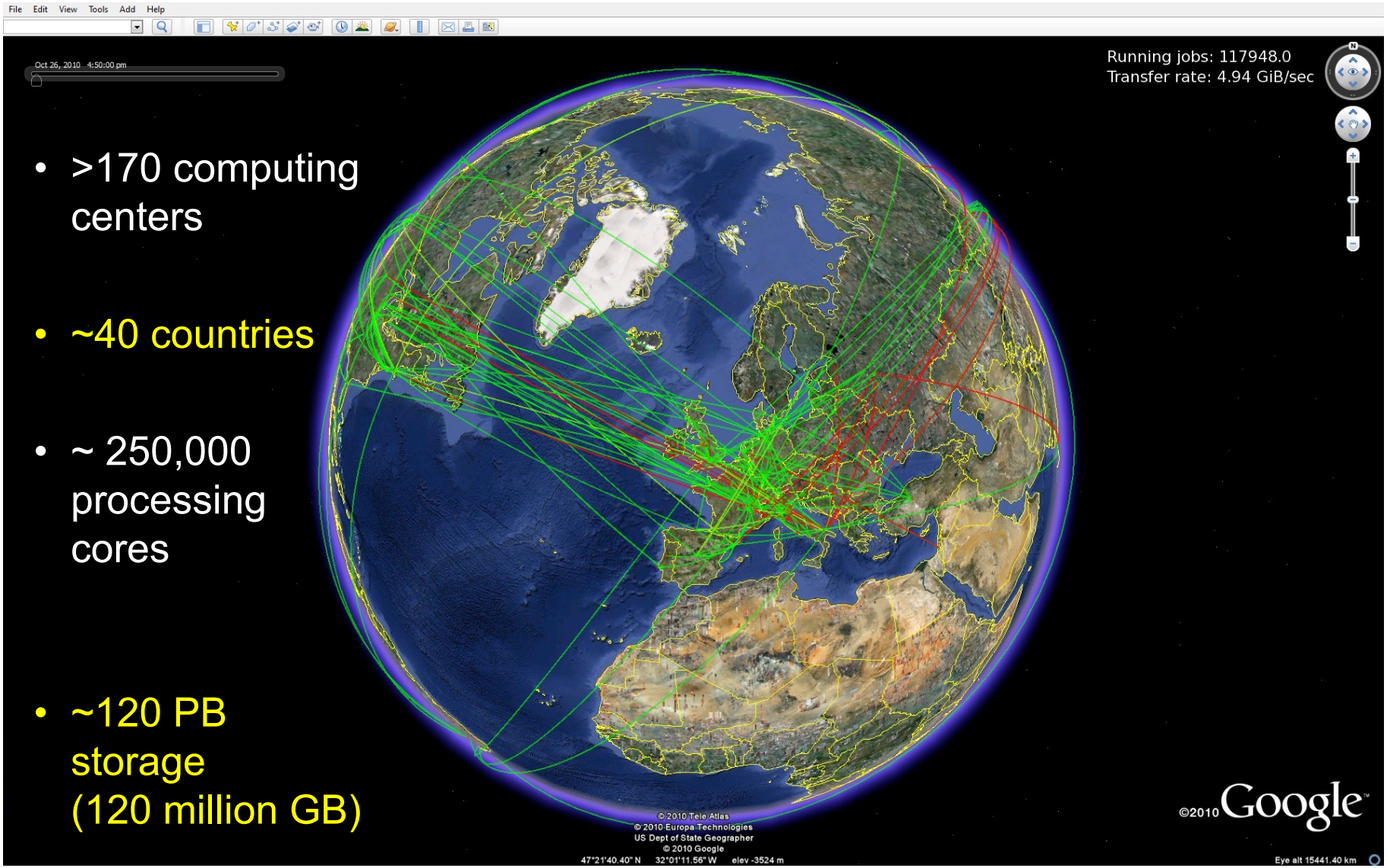
Data



Z→μμ event from 2012, with 25 reconstructed vertices

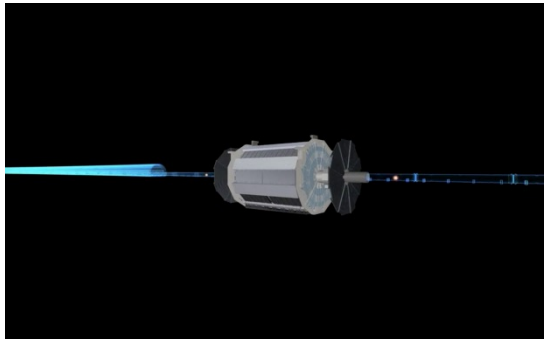
- Each bunch crossing ~20 *pp* interactions
- 40 M crossings per second × 20 pp por crossing, spacing: 600 M pp/s
- Fast selection systems (“trigger systems”) keep only 400 colisions/s
- Each pp collision produces hundreds of particles
- If stored in musing CD’s, …

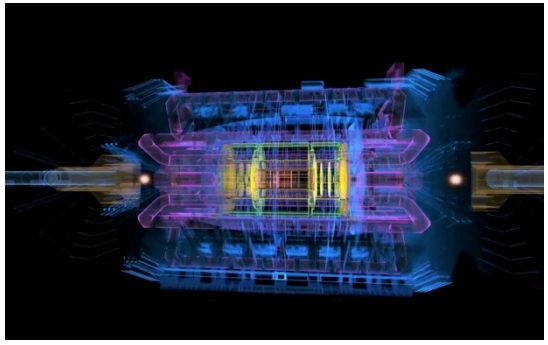
Worldwide LHC Computing Grid

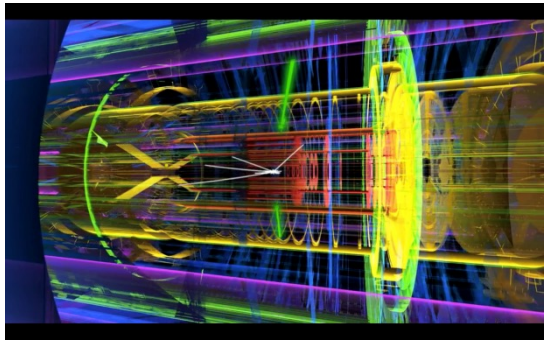


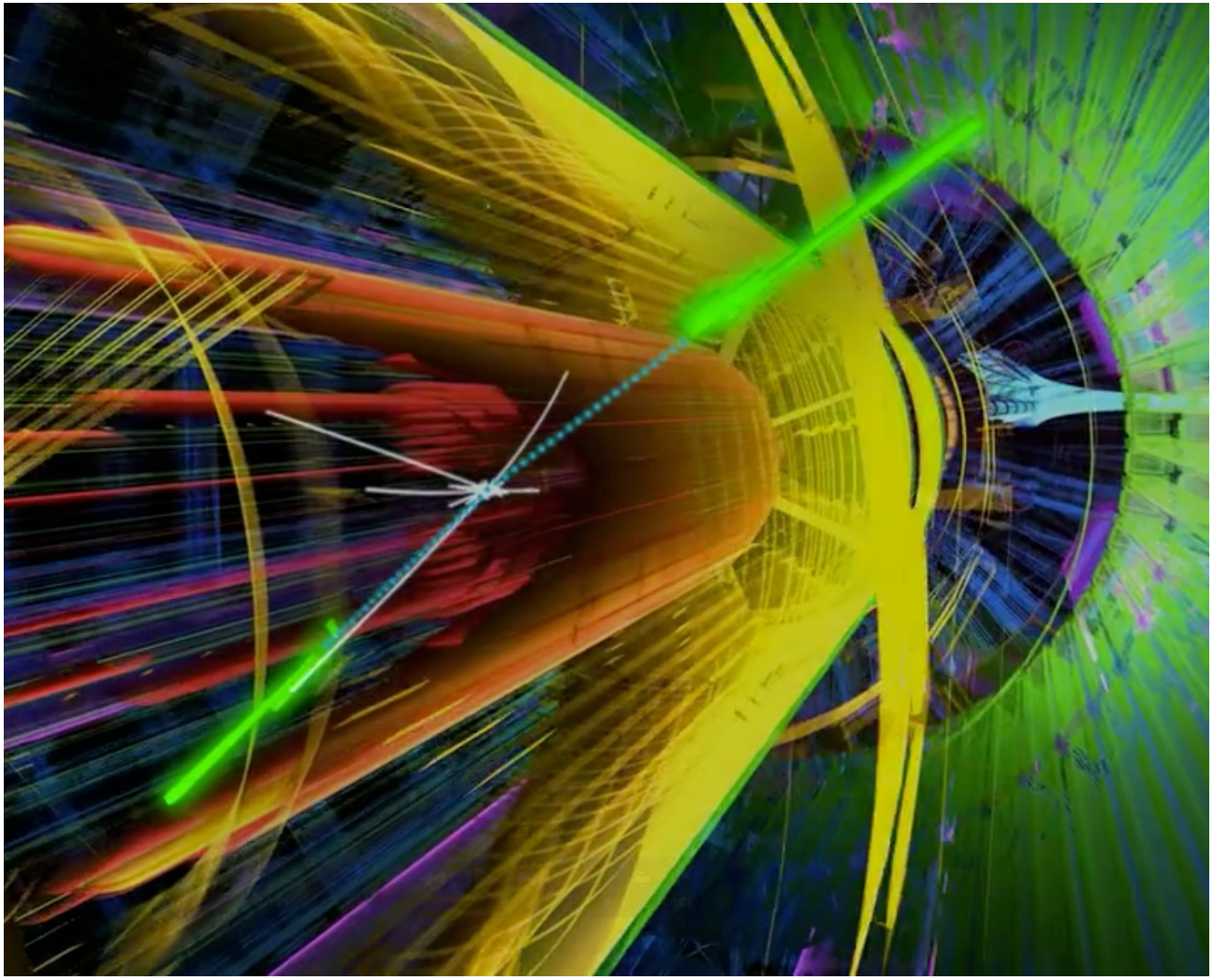
- >170 computing centers
- ~40 countries
- ~ 250,000 processing cores
- ~120 PB storage (120 million GB)

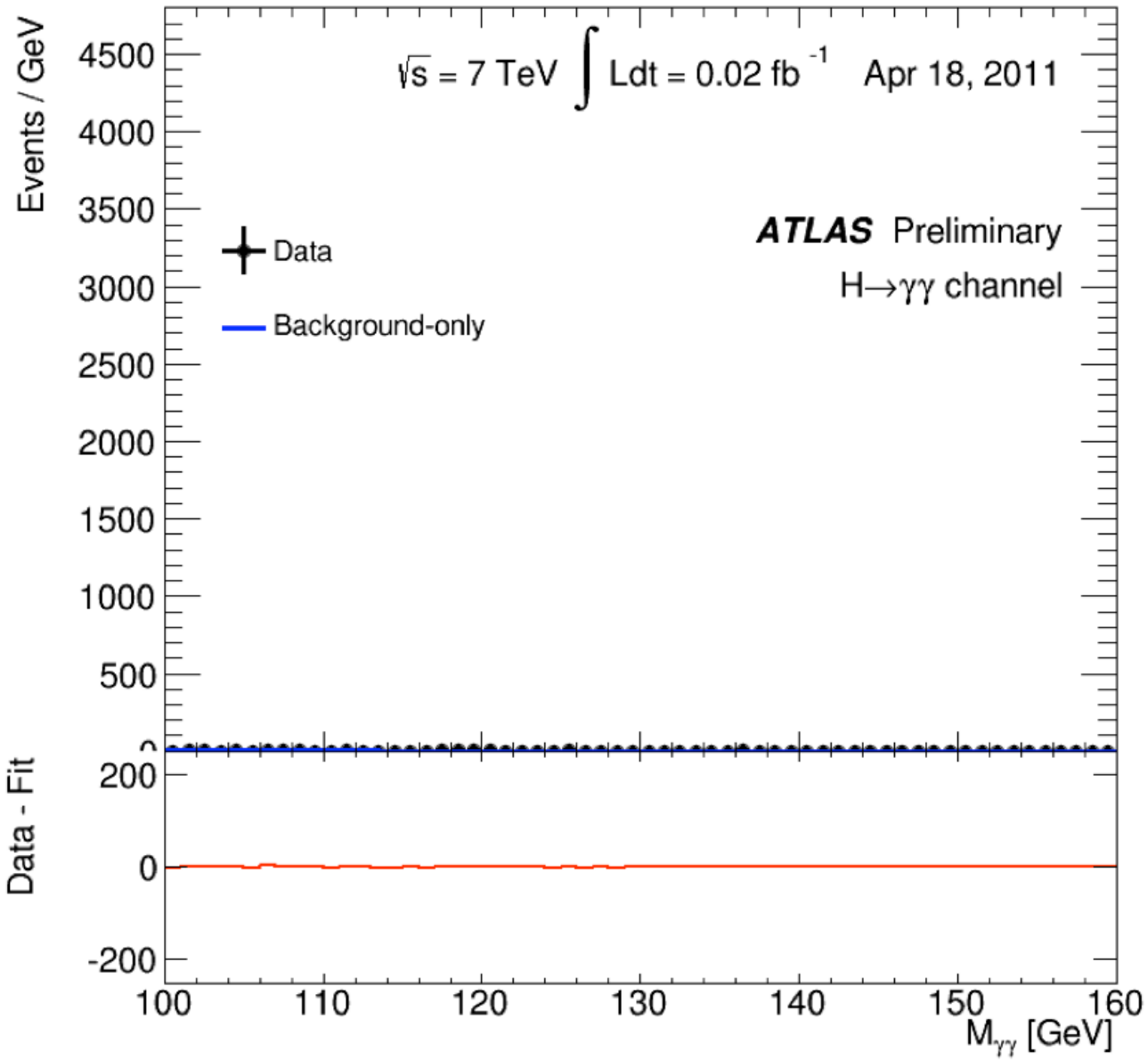
H→γγ

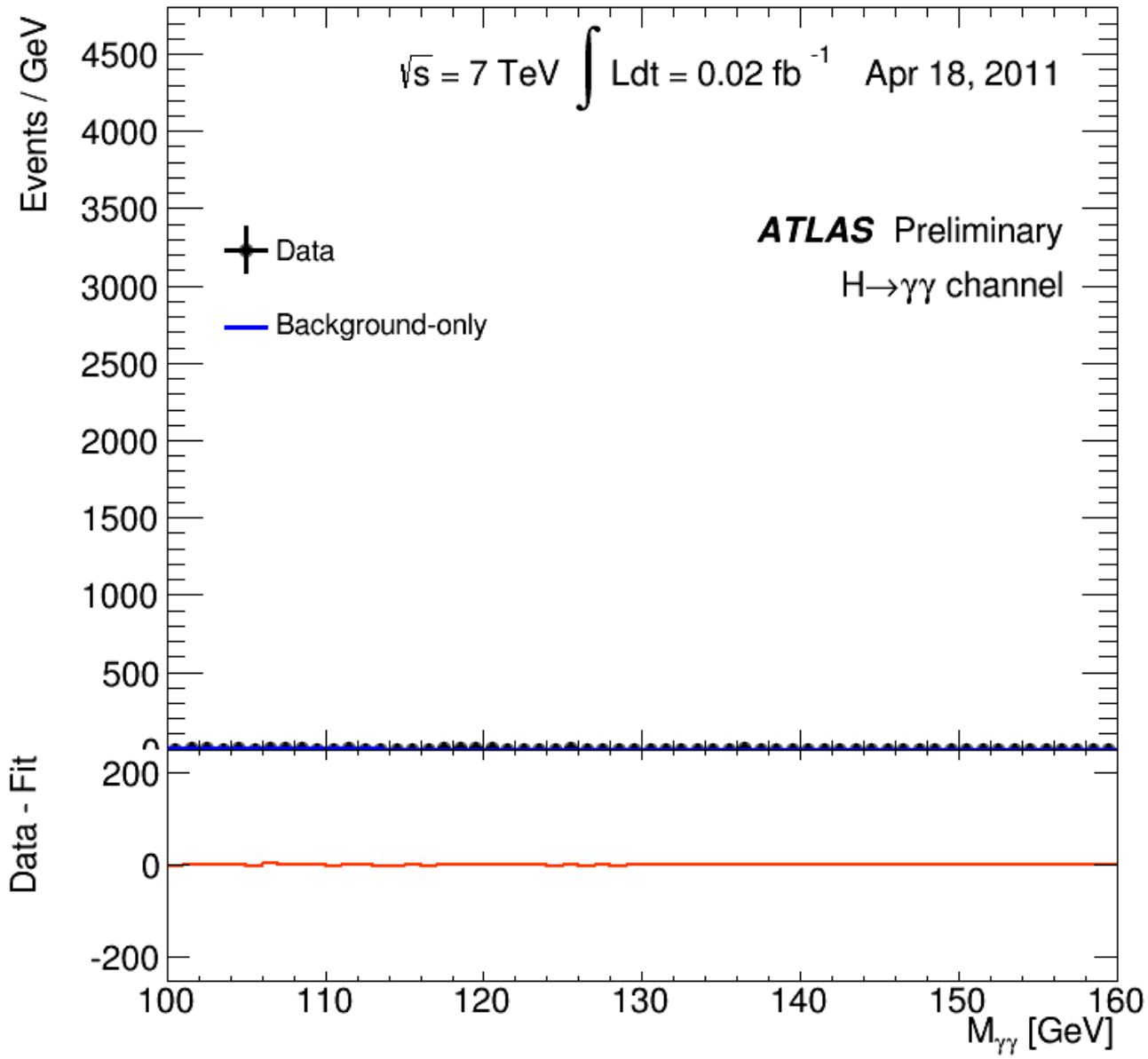




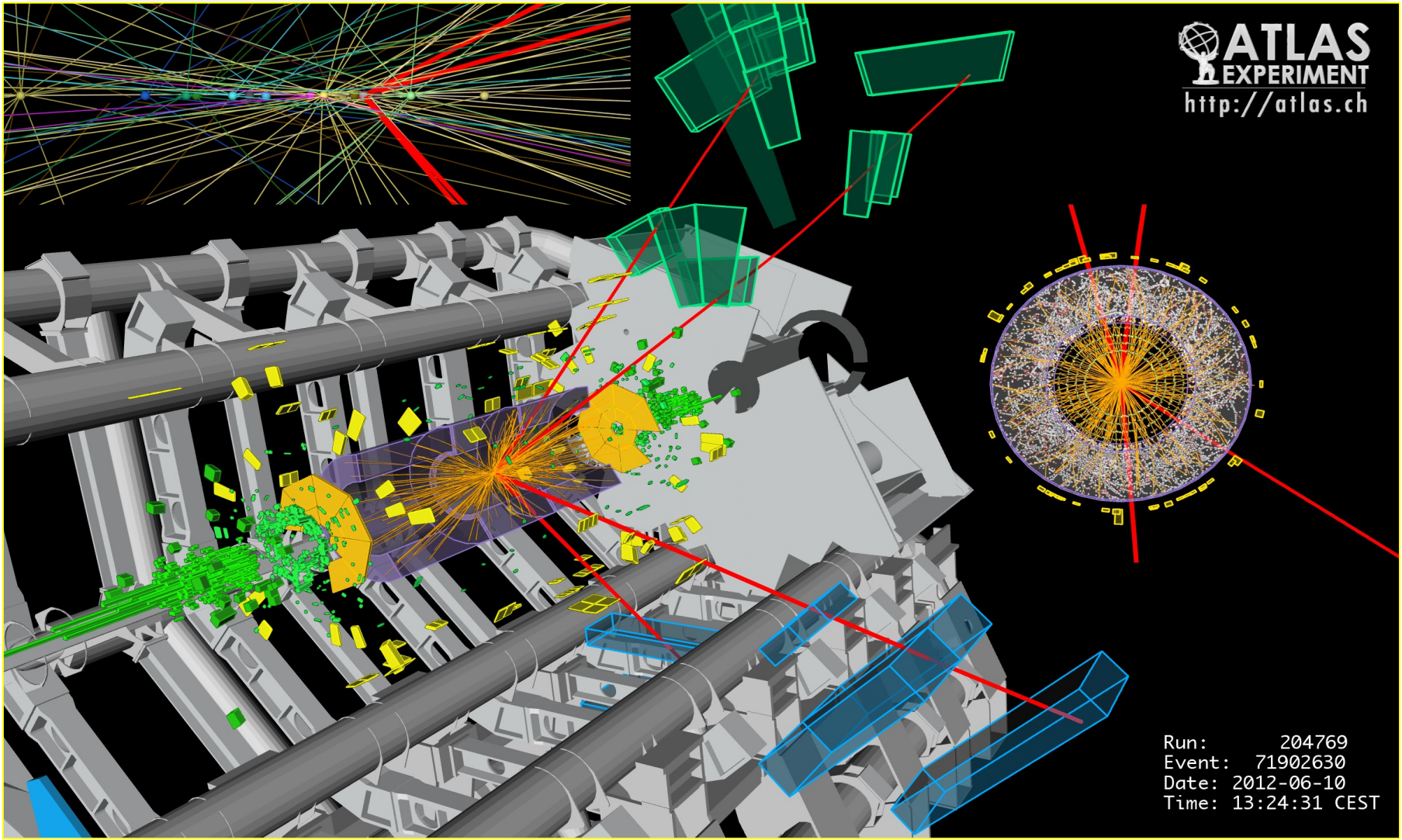





√s = 7 TeV ∫ Ldt = 0.02 fb -1 Apr 18, 2011
ATLAS Preliminary
H→γγ channel
Data
Background-only
Events / GeV
Data - Fit
M γγ [GeV]
4500
4000
3500
3000
2500
2000
1500
1000
500
200
0
-200
100
110
120
130
140
150
160

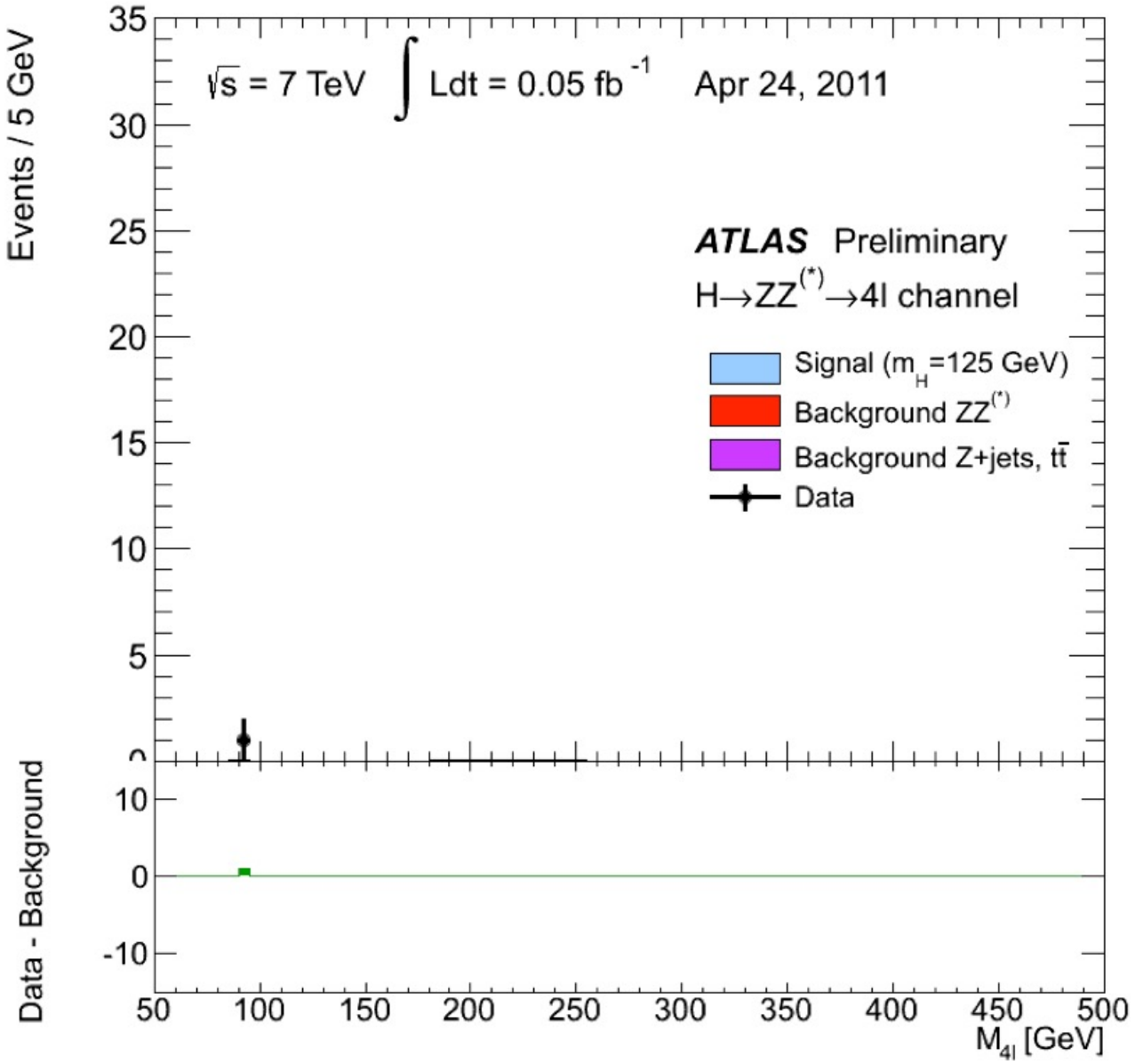

√s = 7 TeV ∫ Ldt = 0.02 fb -1 Apr 18, 2011
ATLAS Preliminary
H→γγ channel
Data
Background-only
Events / GeV
Data - Fit
M_γγ [GeV]
4500
4000
3500
3000
2500
2000
1500
1000
500
200
0
-200
100
110
120
130
140
150
160

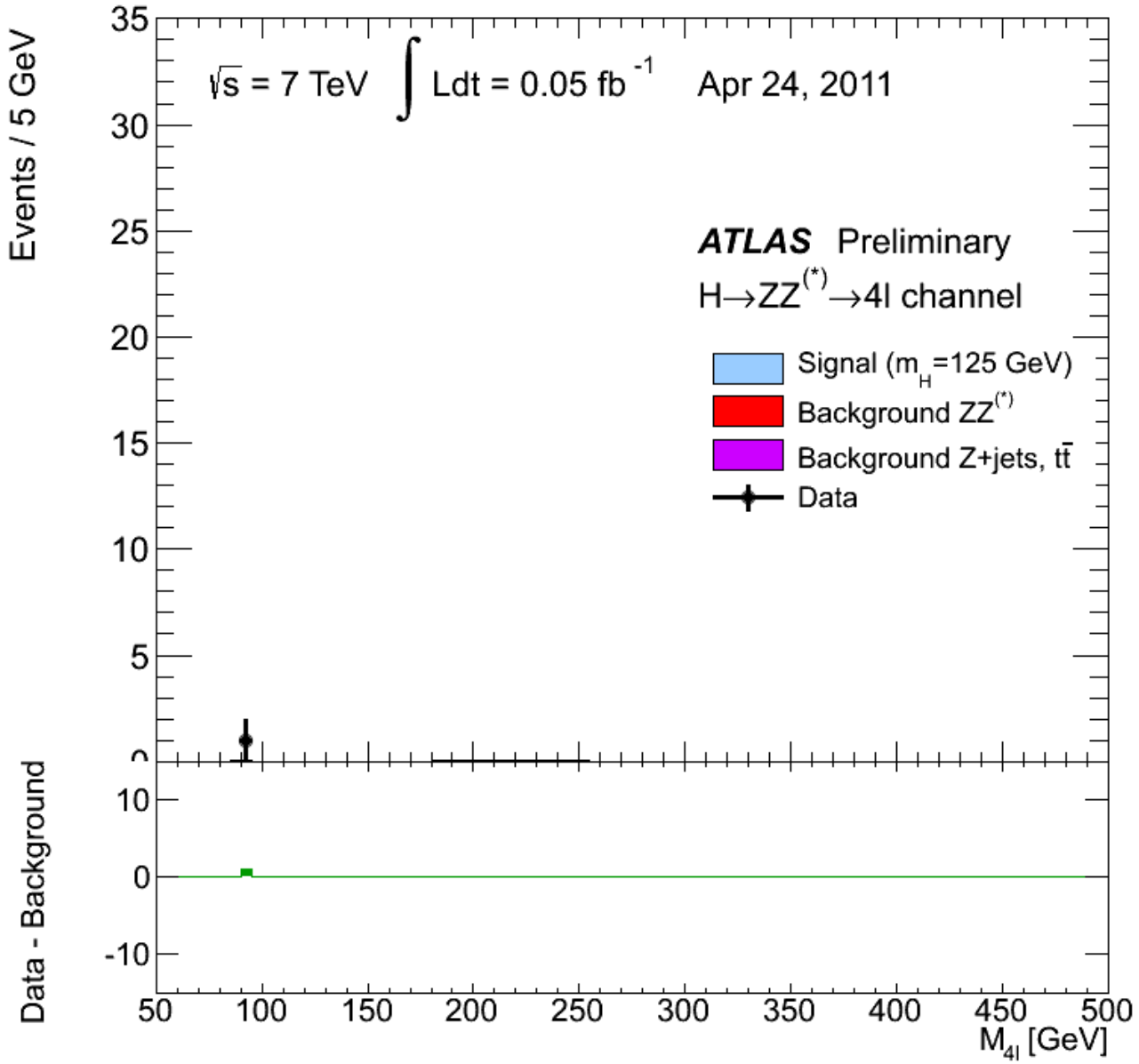
$H \rightarrow ZZ^{(*)} \rightarrow 4l$



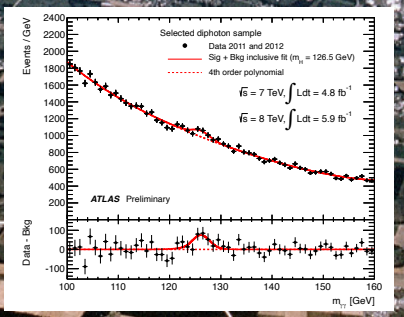
H to 4μ candidate, with $m_{4\mu}$=125.1 GeV

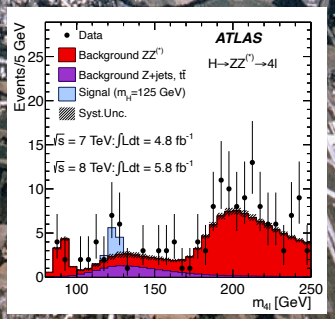
p_T (muons) = 36.1, 47.5, 26.4, 71 .7 GeV m_{12}= 86.3 GeV, m_{34}= 31.6 GeV. 15 reconstructed vertices


√s = 7 TeV ∫ Ldt = 0.05 fb -1 Apr 24, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (mH=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Events / 5 GeV
Data - Background
M4l [GeV]

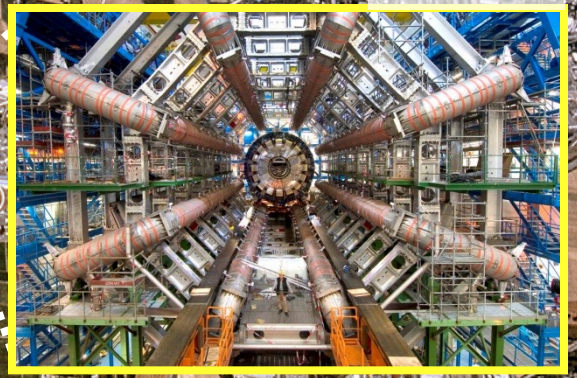

Events / 5 GeV
√s = 7 TeV ∫ Ldt = 0.05 fb -1 Apr 24, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (m_H=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Data - Background
M_4l [GeV]

Independent confirmation

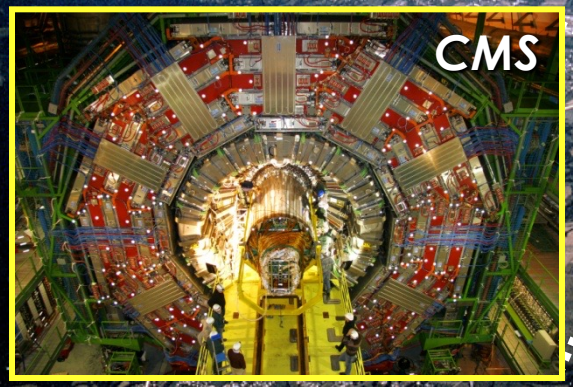


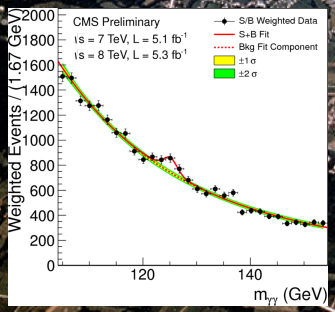


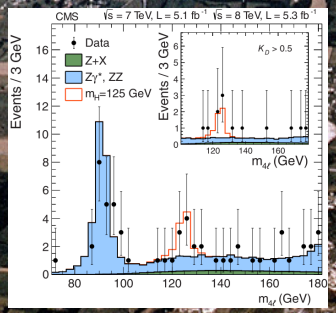
ATLAS

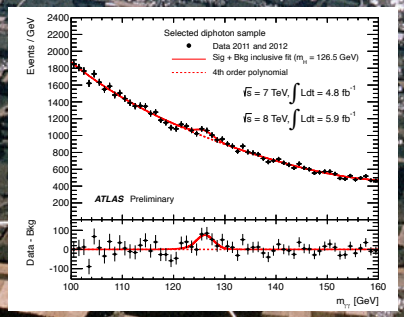


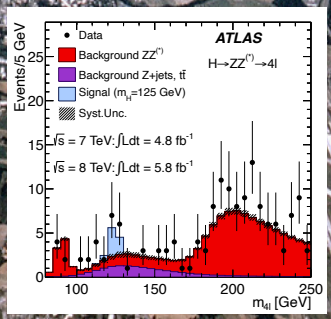
Independent confirmation



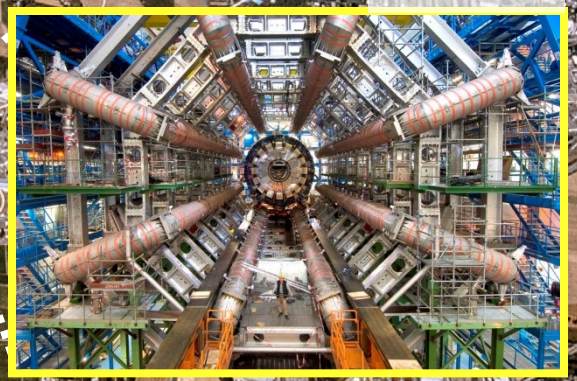




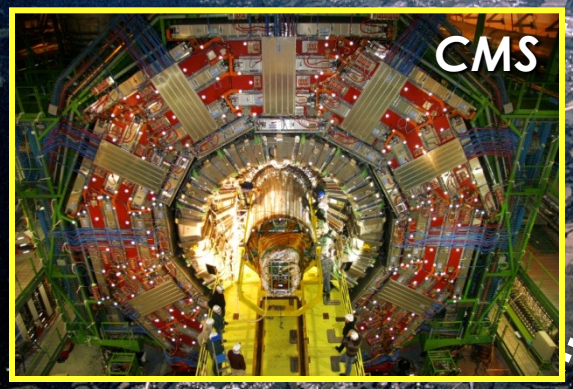




ATLAS

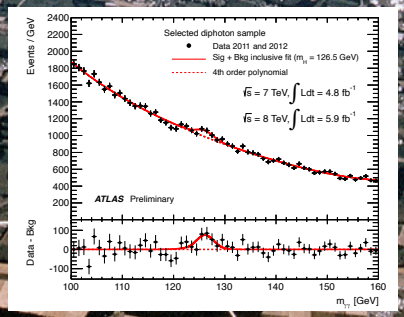


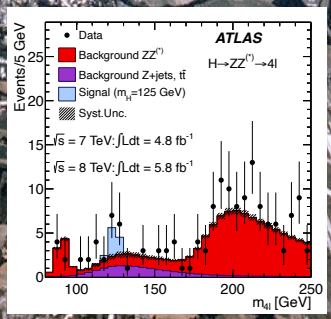
Combination

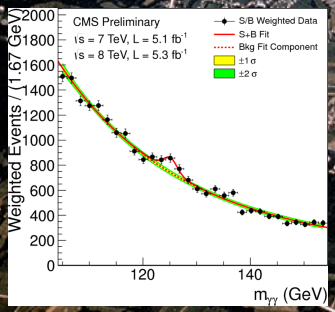


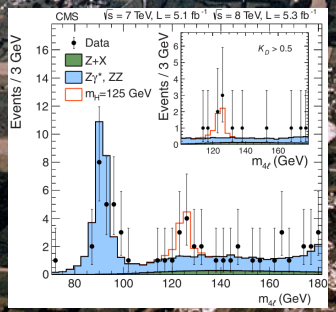
Probability < 0.00003%

= “5σ” → Discovery!

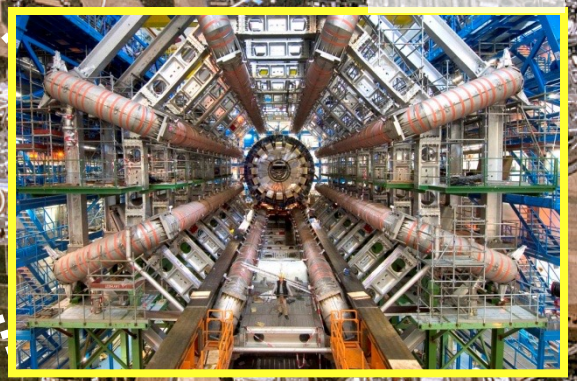








ATLAS



Probability < 0.00003%

= “5σ” → Discovery!

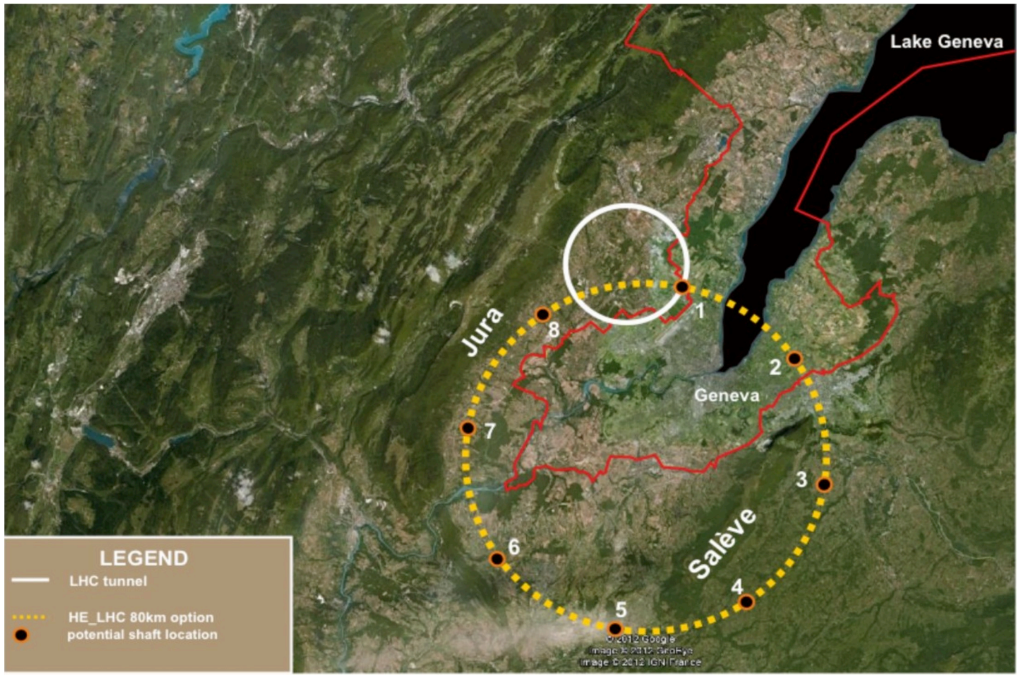
July 4, 2012

What is next?

Future colliders

CERN

- Also in the Geneva area
- *Conceptual Design Report* : January 2019



China

- Evaluating possible sites
- Strong local support

Imagen: CEPC CDR, Vol 1.

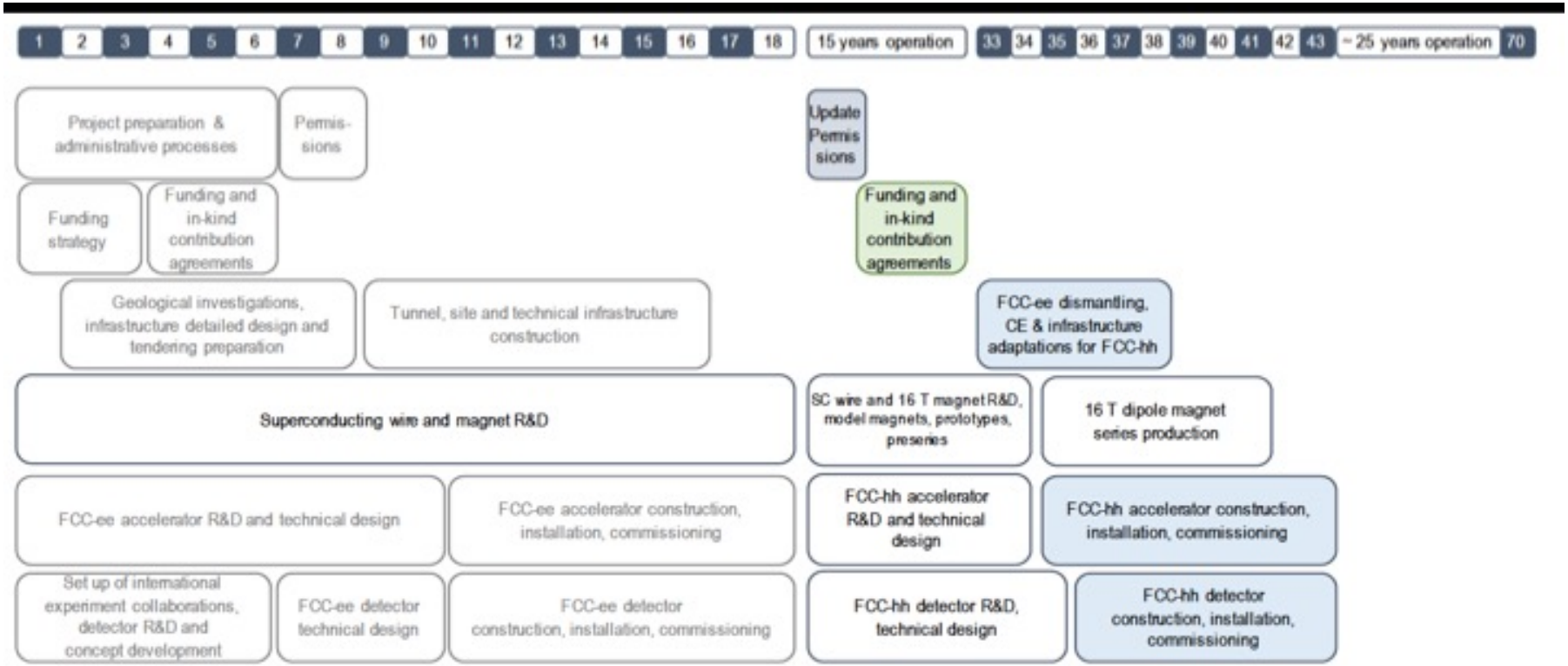
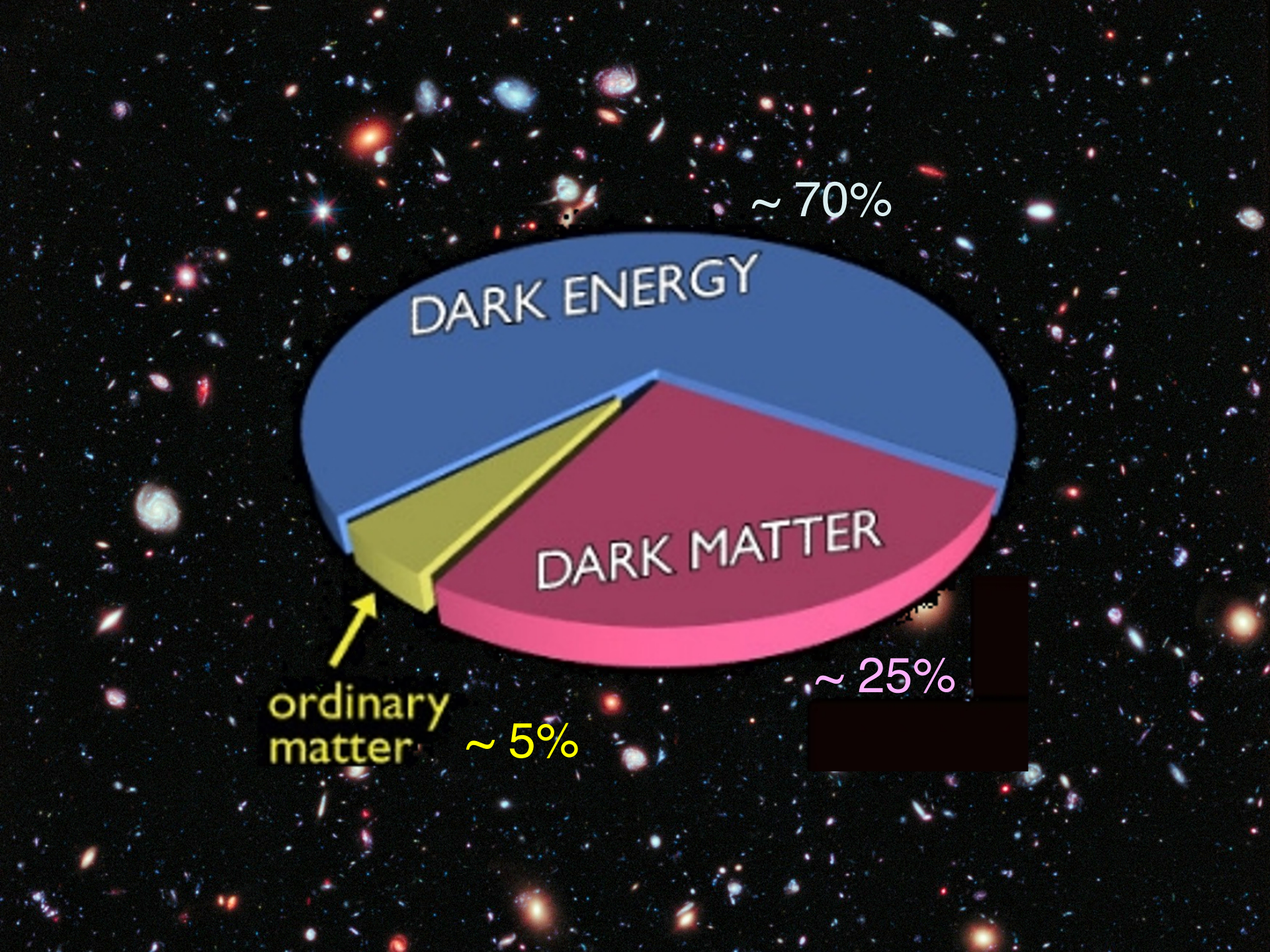
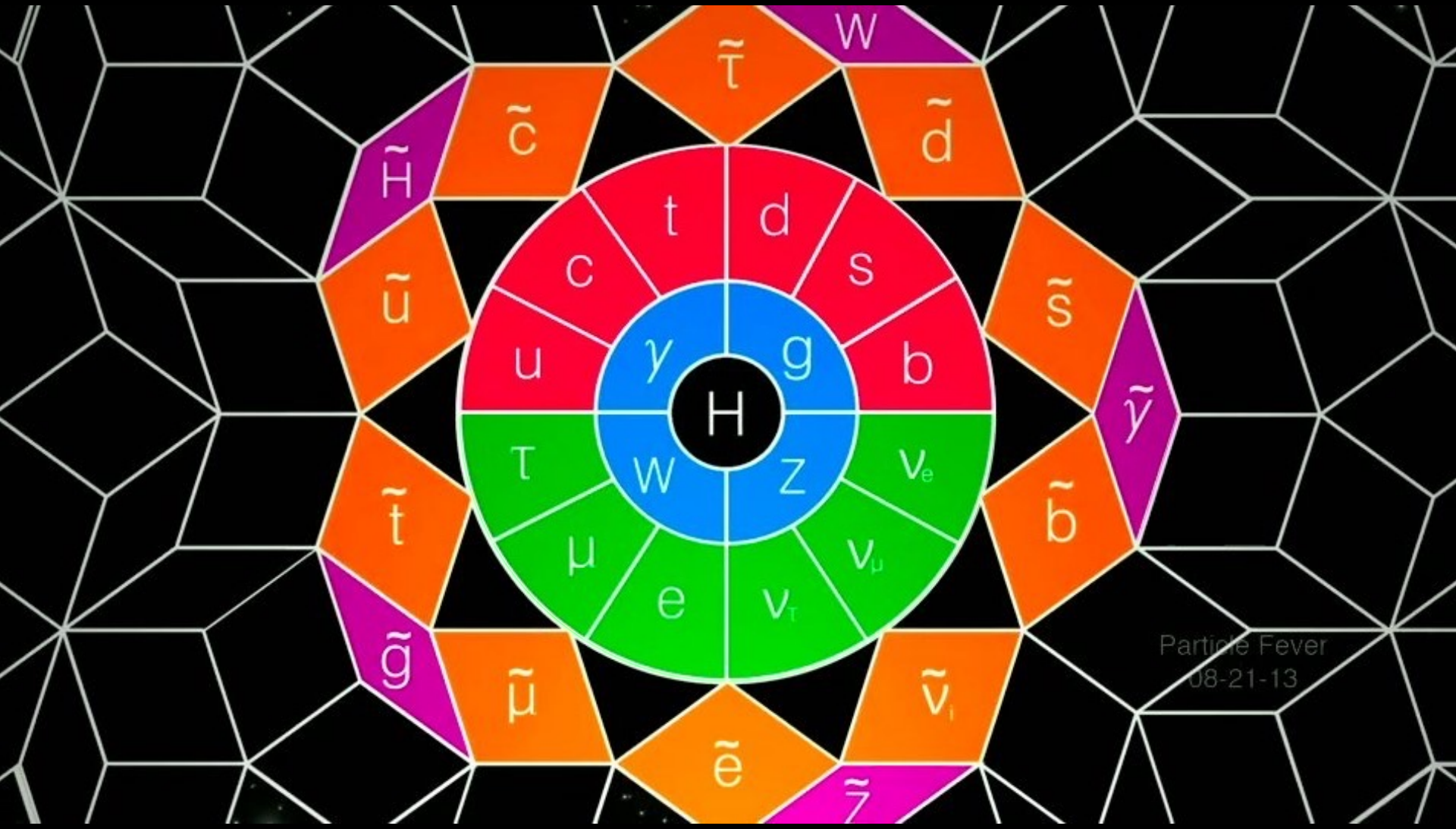


Imagen: Jorgen D'Hondt @ HK IAS Workshop 2019


~ 70%
DARK ENERGY
DARK MATTER
~ 25%
ordinary matter
~ 5%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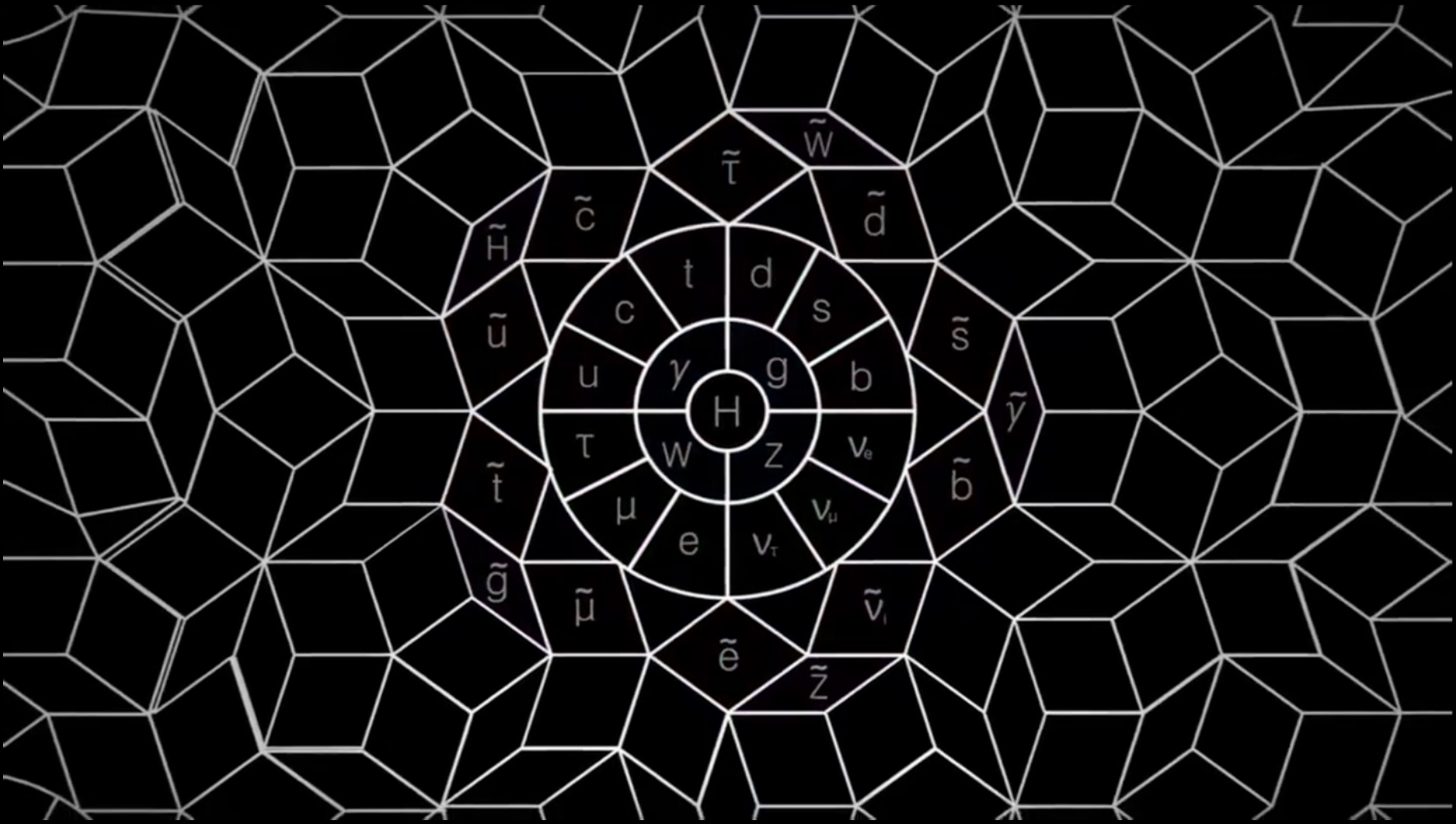
Particle Fever
08-21-13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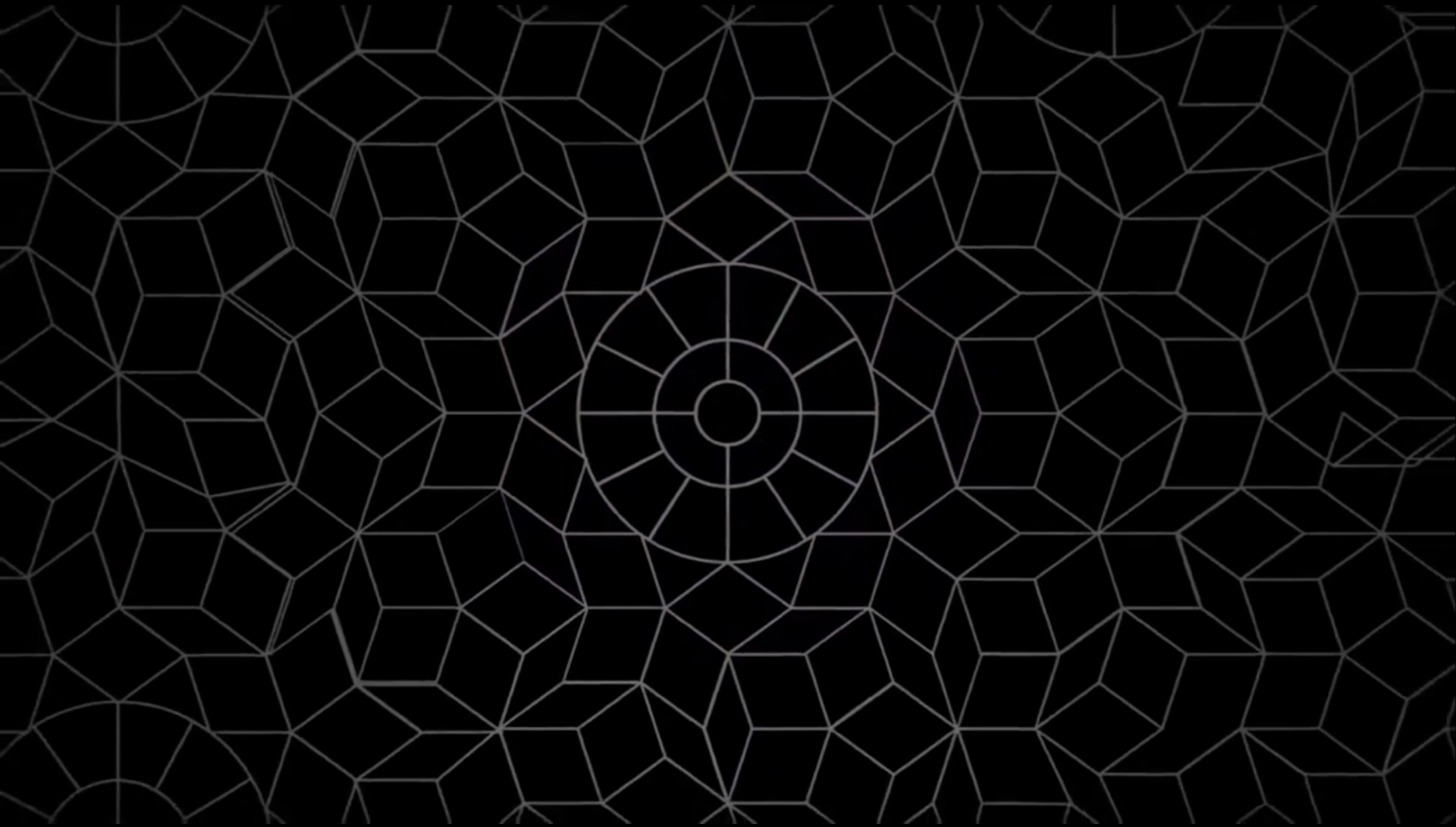
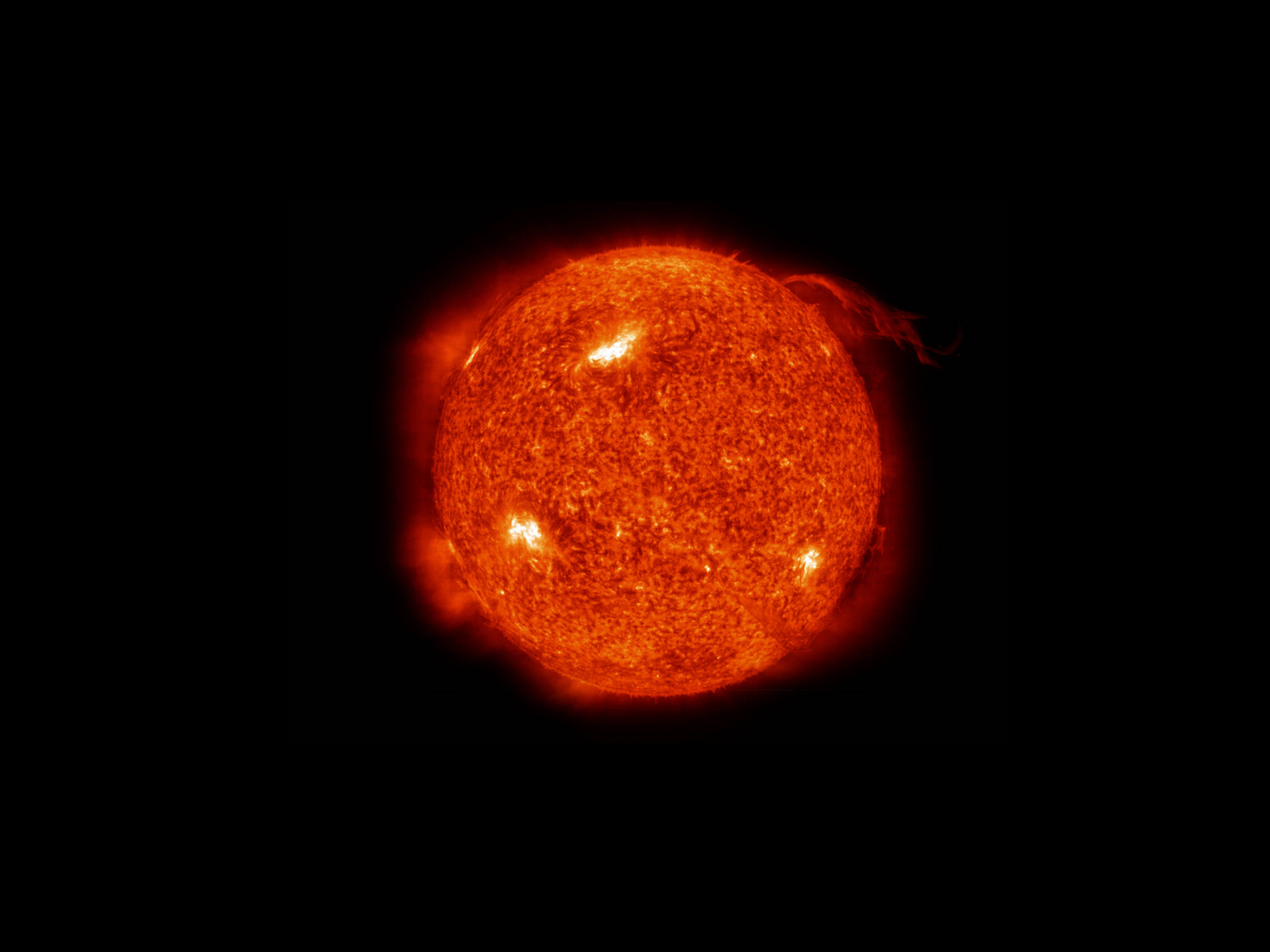


“Particle Fever” https://www.youtube.com/watch?v=dEcWjMX9oCw



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- Stephen Hawking, “A brief history of time”
- Carlo Rovelli, “Seven brief lessons on Physics”
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- Lee Smolin, “The life of the cosmos”
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Youtube channels:

- PBS Spacetime, https://www.youtube.com/c/pbsspacetime
- Fermilab, https://www.youtube.com/c/fermilab/videos