The discovery of the Higgs particle

Luis Roberto Flores Castillo

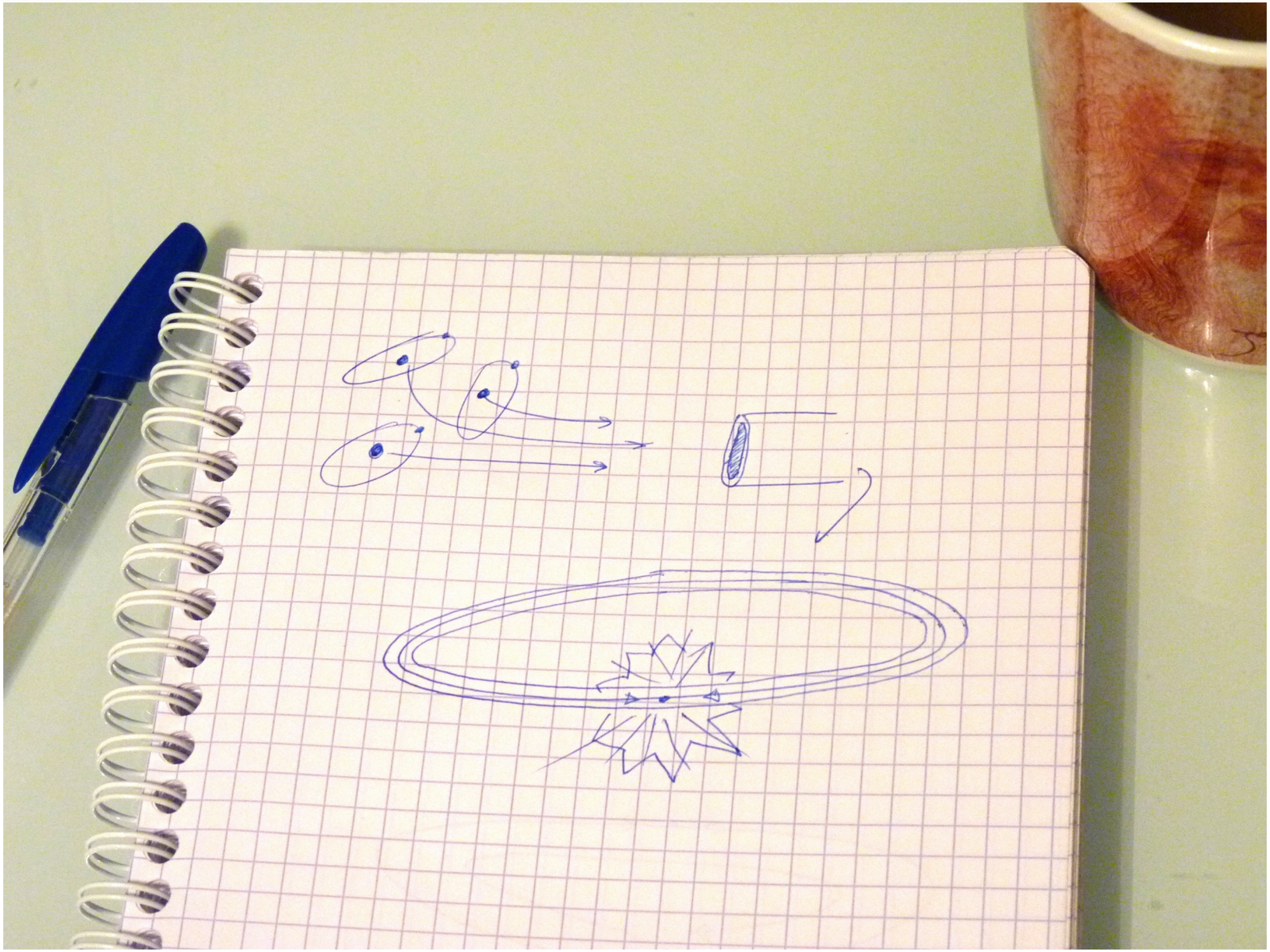
The Chinese University of Hong Kong

S’Cool LAB Summer Camp 2017

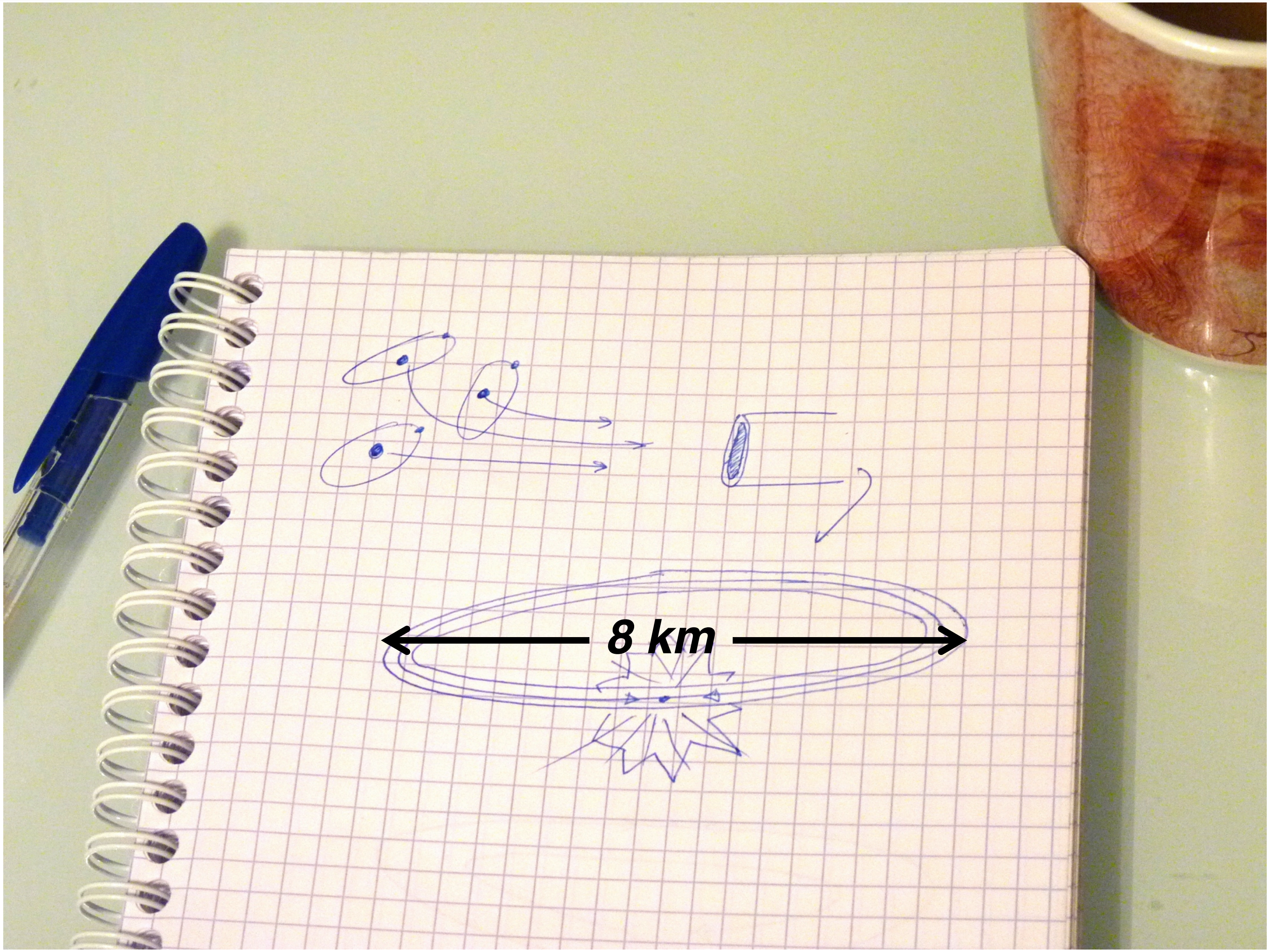
CERN, Switzerland

July 28, 2017

Aiming high



Aiming high



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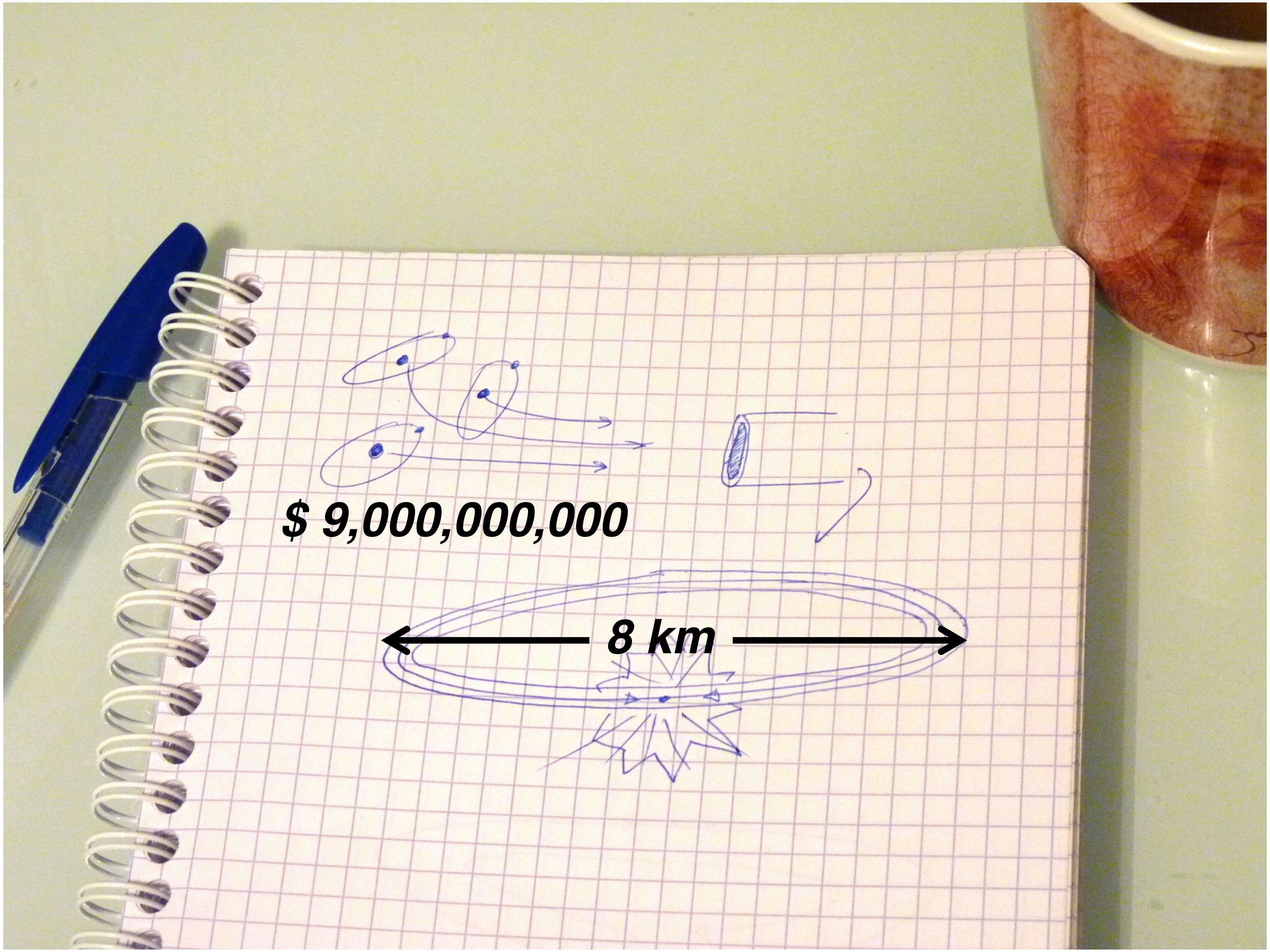
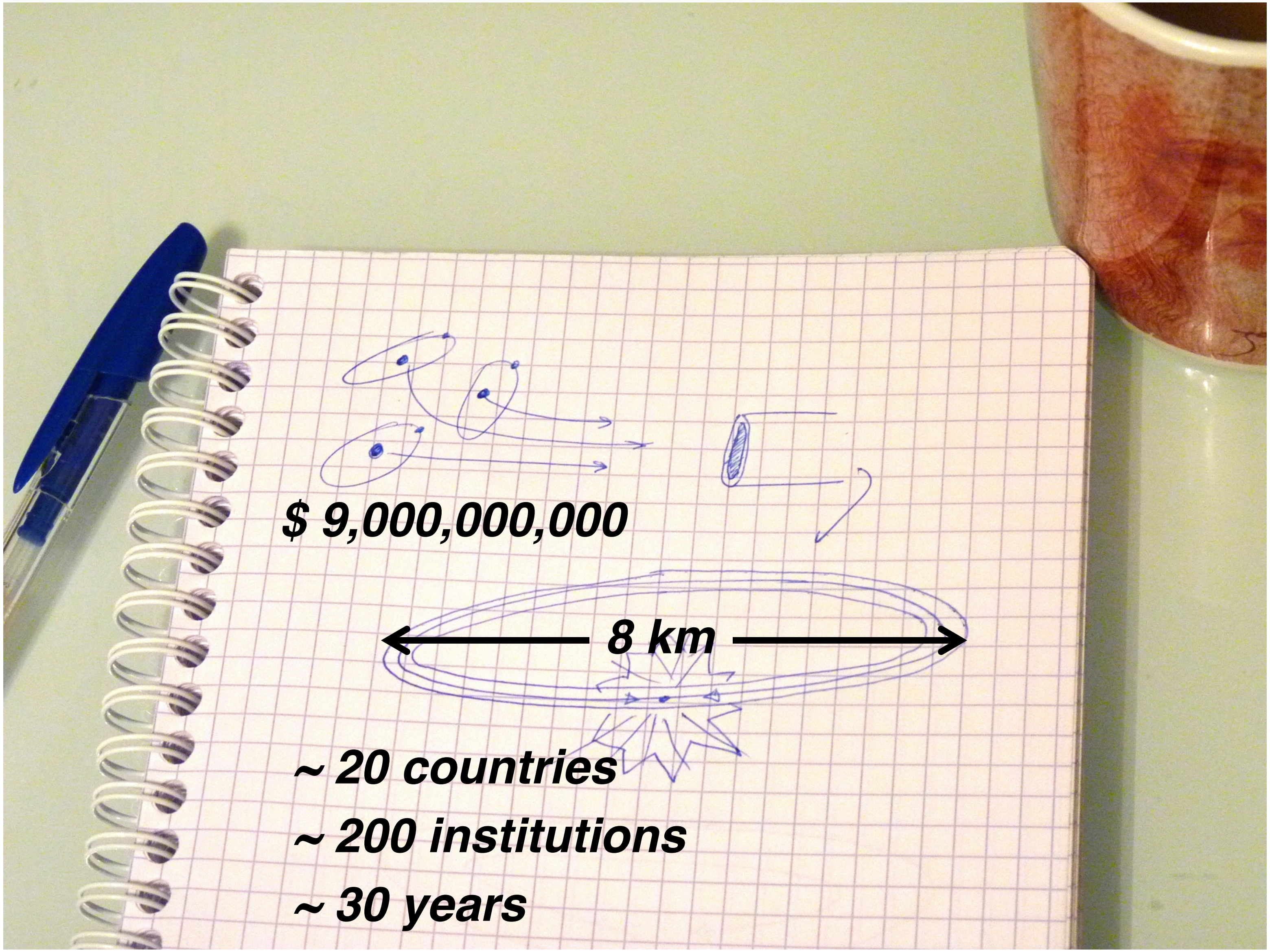


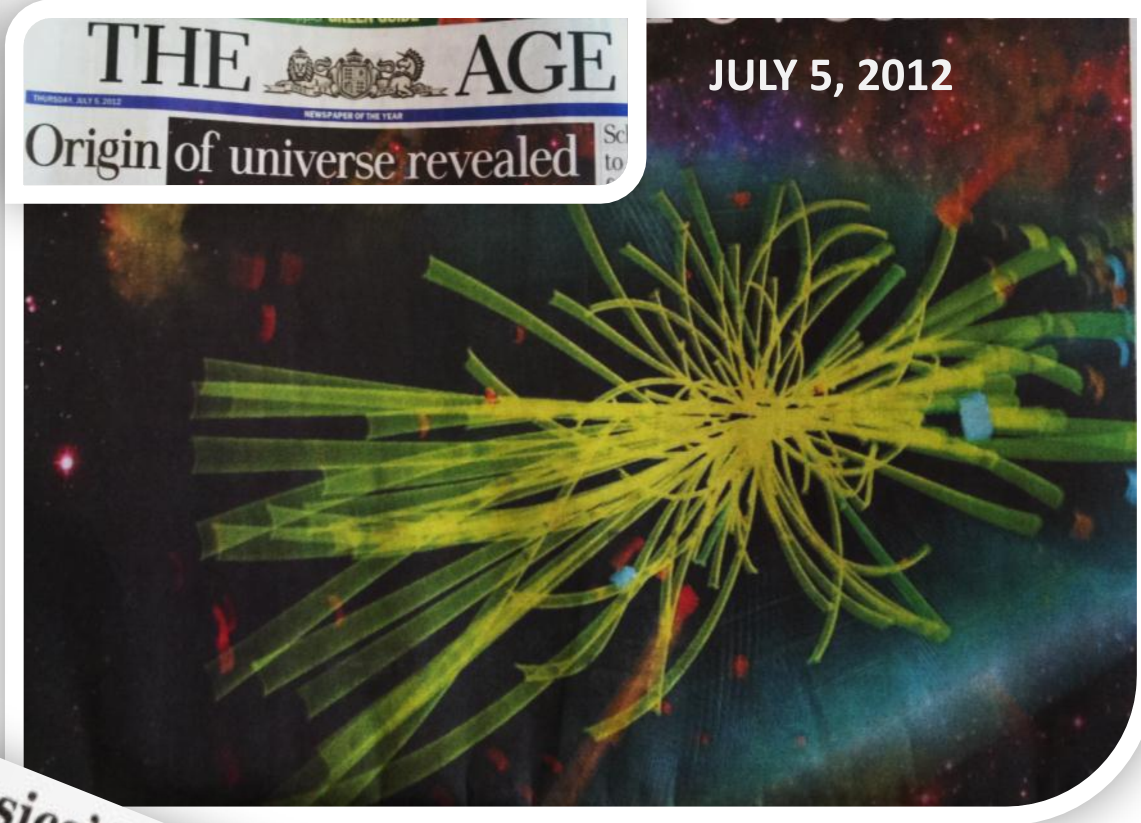
Aiming high



July 4, 2012

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

International Herald Tribune
Discovery upends world of physics
JULY 5, 2012



The New York Times
A New Particle Could Be Physics' Holy Grail
JULY 4, 2012

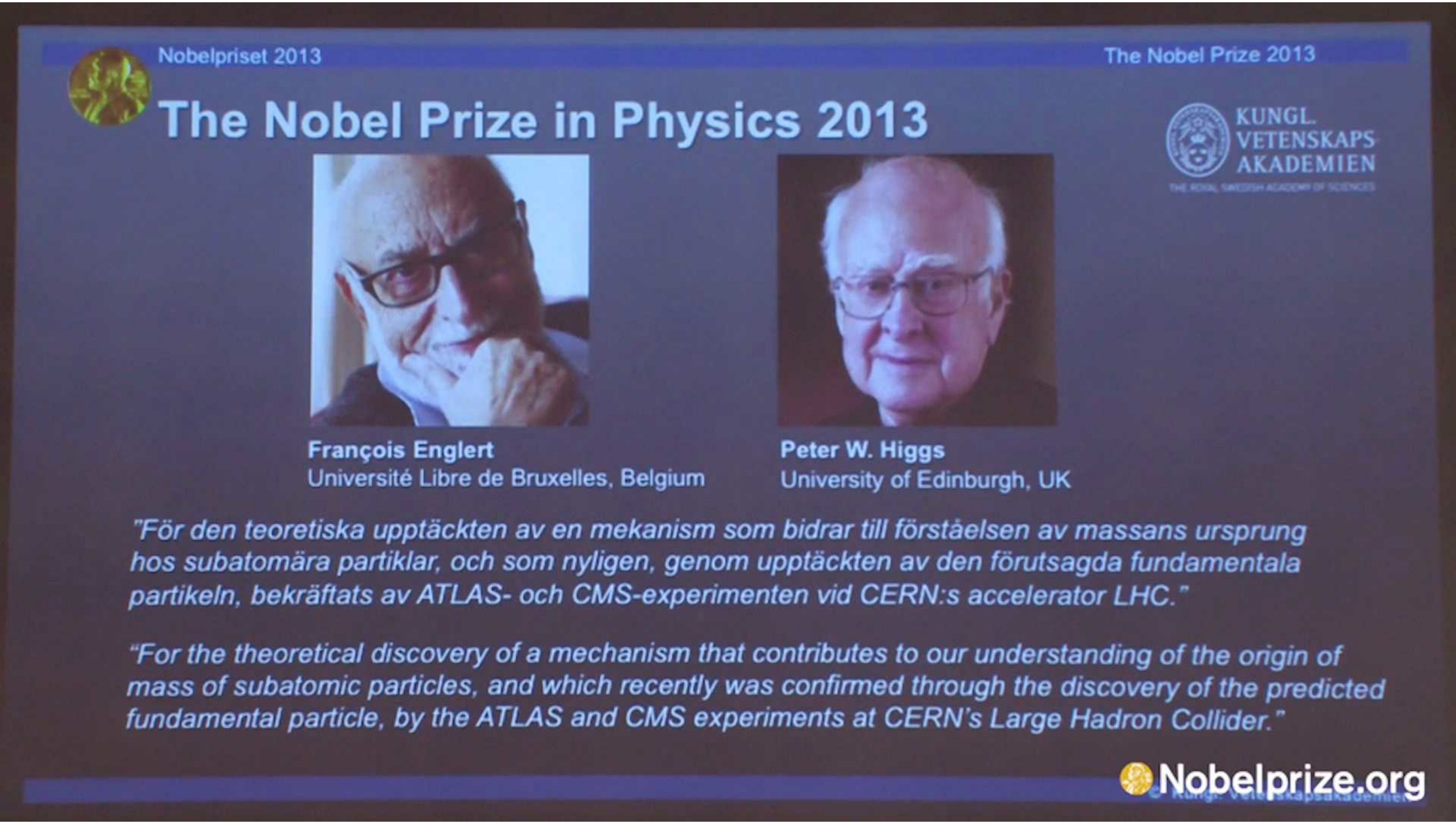
AUSTRALIAN
After 50 years – and billions of dollars the God particle is no longer a theory
JULY 4, 2012

TIME
The elusive Higgs boson is at last found—and the universe gets a little less mysterious
BY JEFFREY KLUGER
JULY 23, 2012


The Economist
In praise of charter schools
Britain's banking scandal spreads
Volkswagen overtakes the rest
A power struggle at the Vatican
When Lonesome George met Nora
A giant leap for science
Finding the Higgs boson
Worldwide excluding UK
JULY 7TH - 13TH 2012

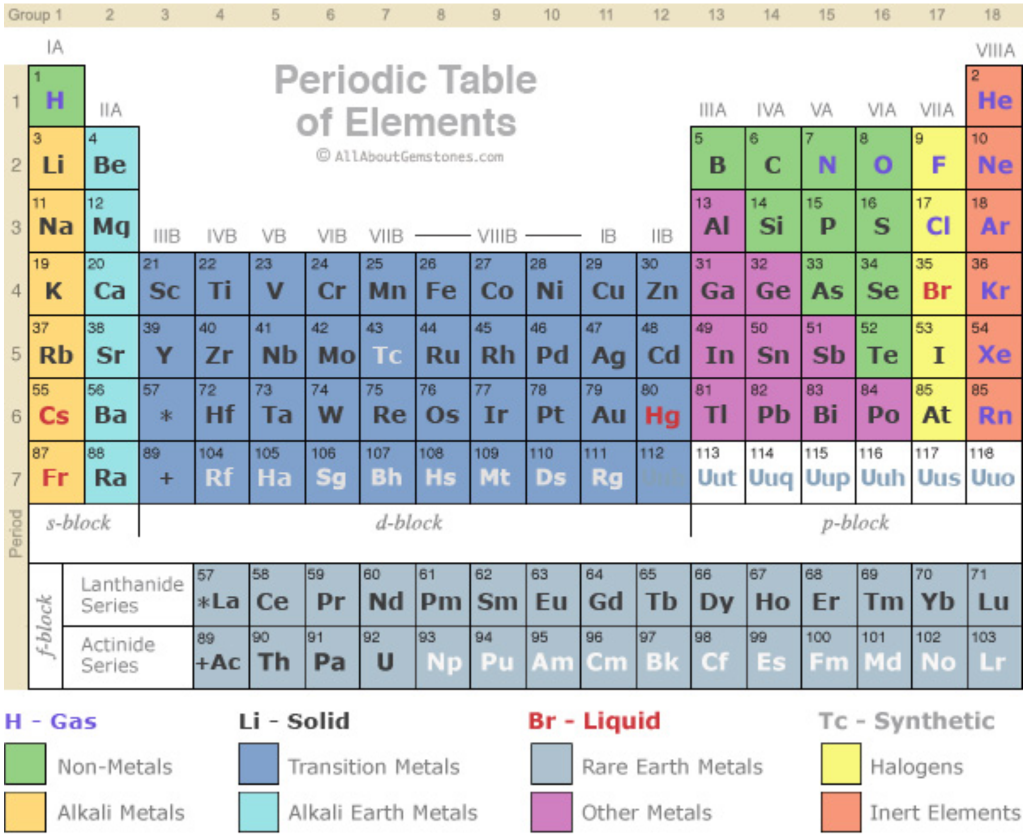

NEWSPAPER OF THE YEAR
Wimbledon 2012
Dramatic victory takes Murray through to semi-finals
Scientists prove existence of 'God particle'
'Momentous' find after 45-year hunt for Higgs boson
Professor weeps as his life's work finally bears fruit
Physicist deserves the Nobel Prize, says Hawking

October 8, 2013



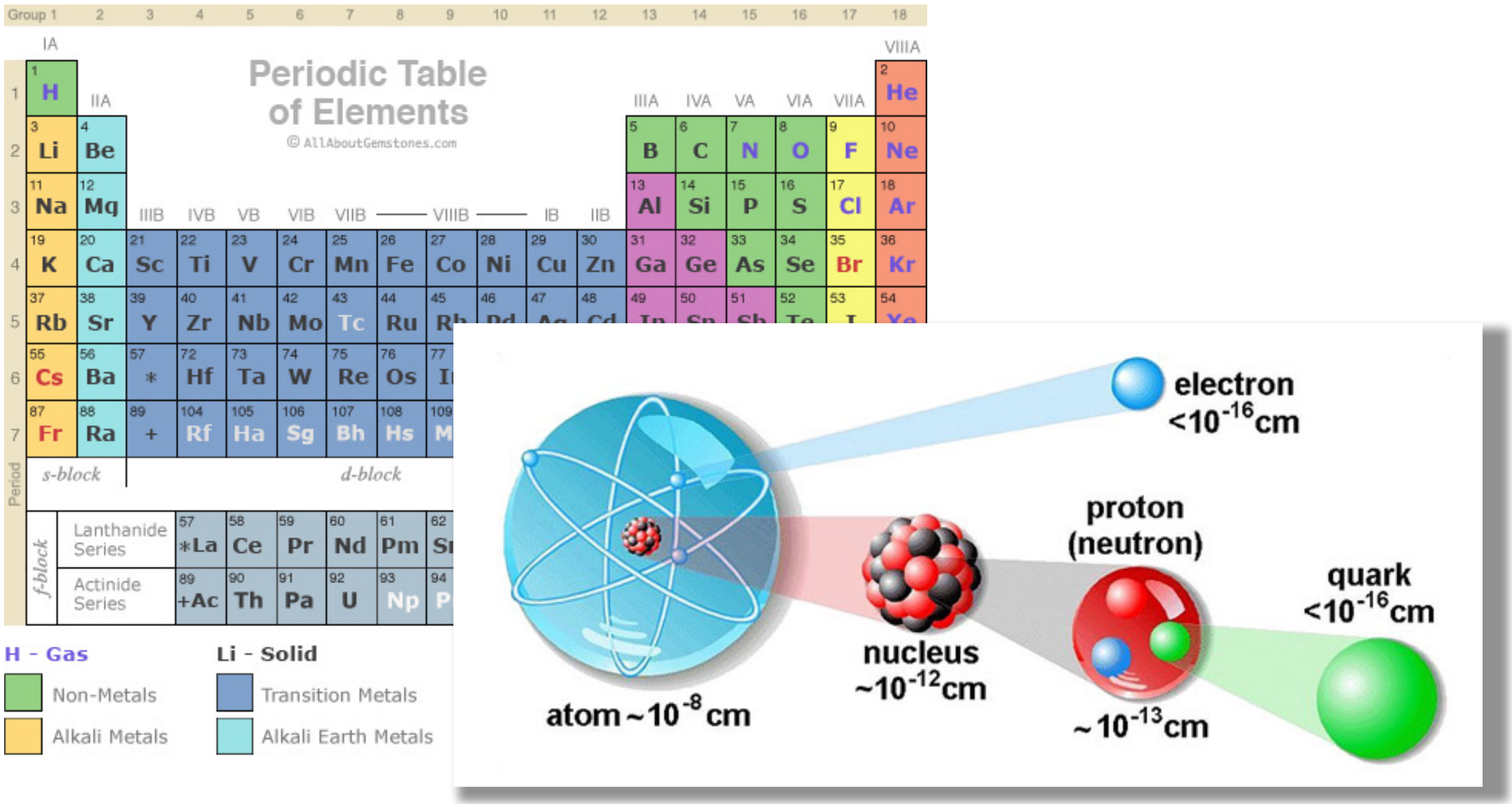
What is the Higgs boson?

Fundamental building blocks?

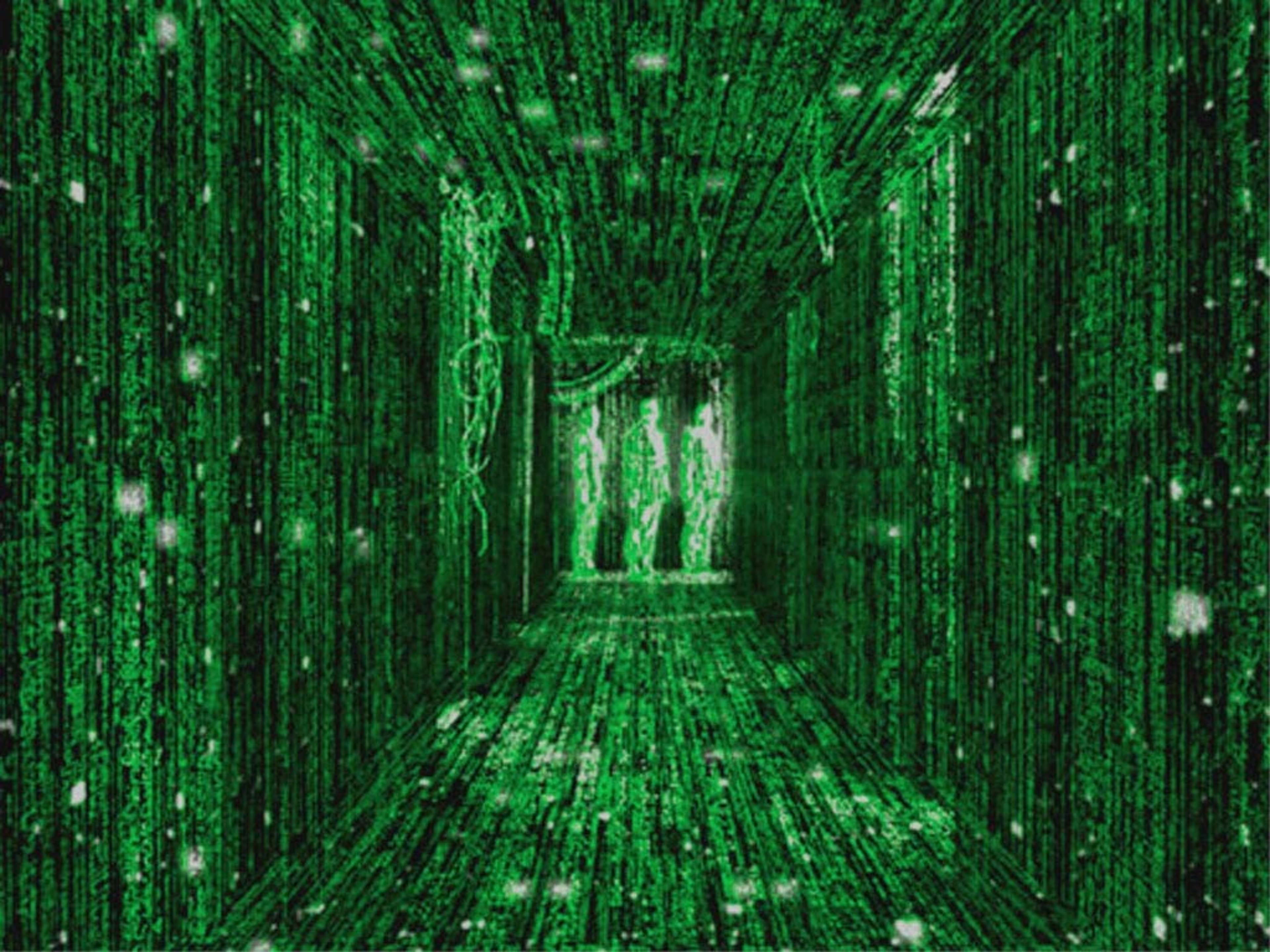


- ~1869, Mendeleyev published **“Principles of Chemistry”**
- All that complexity from ~100 “elements”

Fundamental building blocks?



… but all of them are combinations of THREE particles.



Fundamental building blocks?

- Besides those three, …

Fundamental building blocks?

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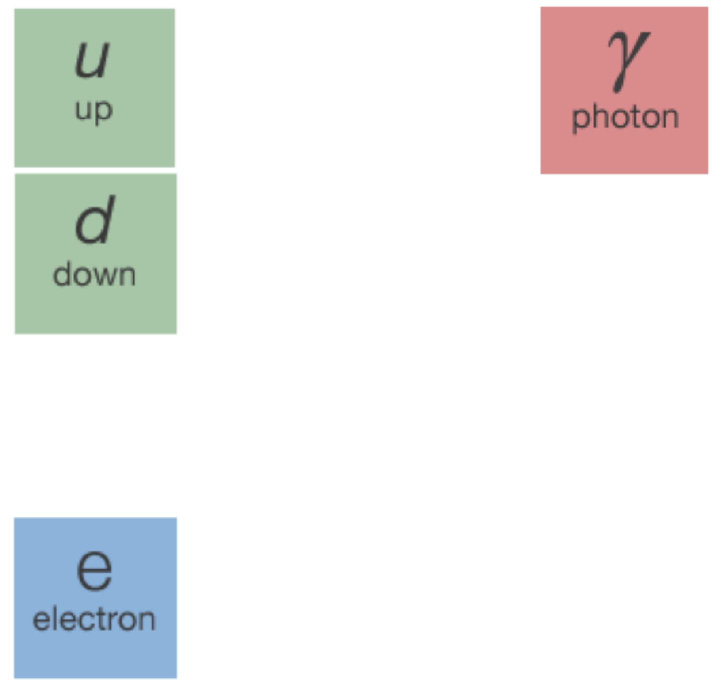
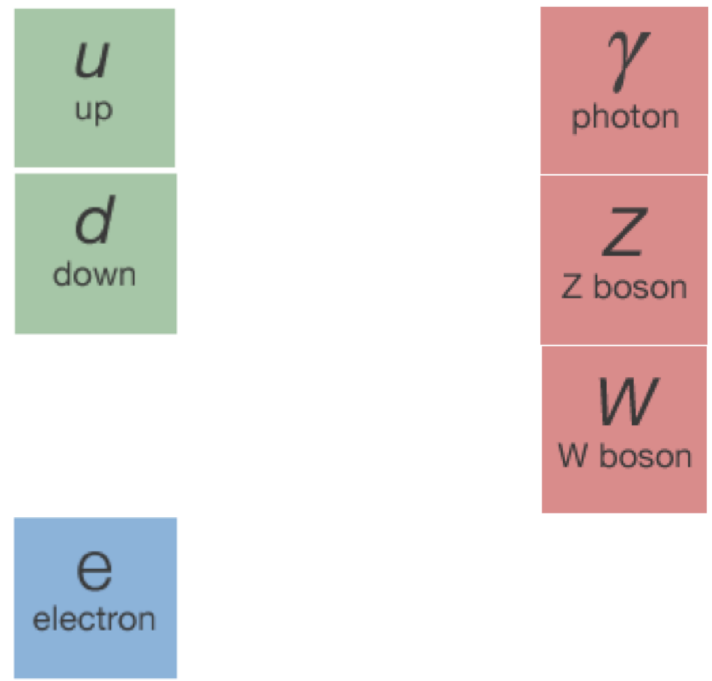


Fundamental building blocks?

- Besides those three, …



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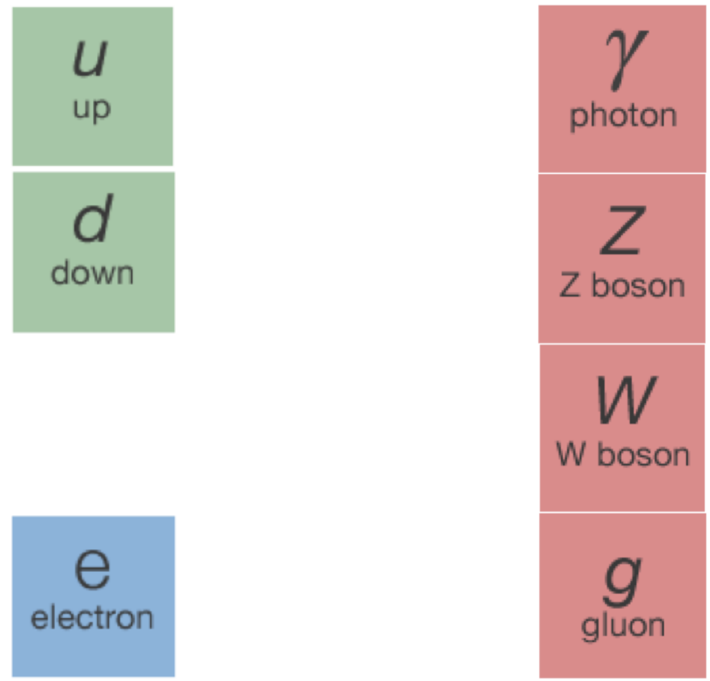

Fundamental building blocks?

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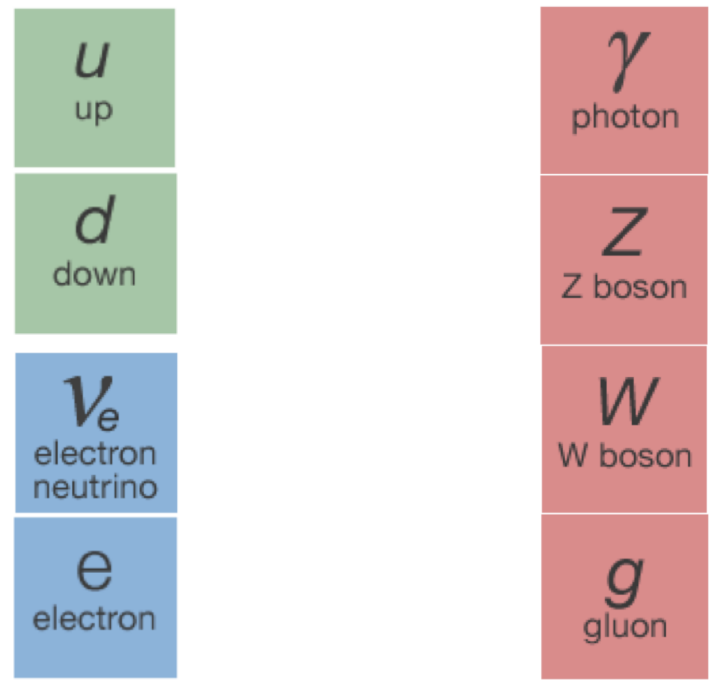


Fundamental building blocks?

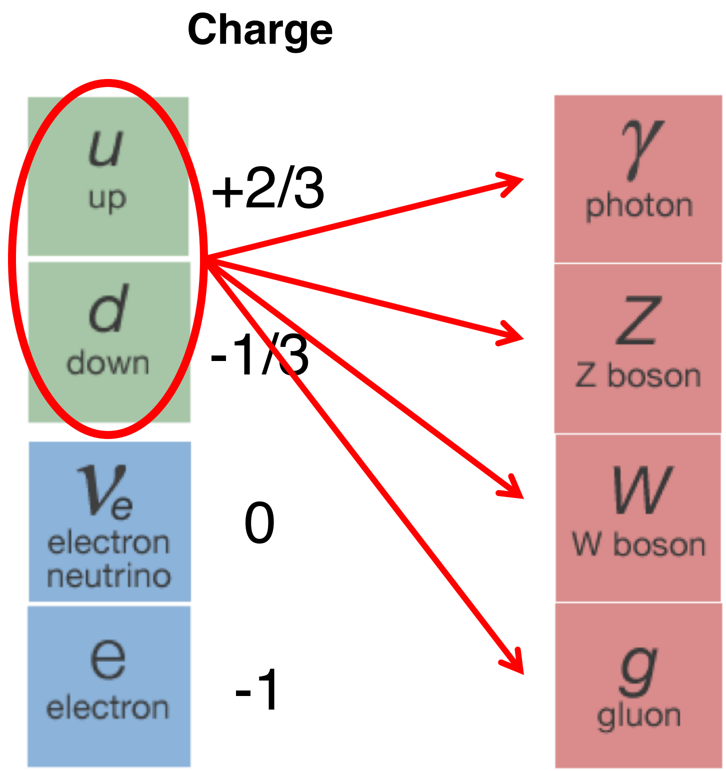
- Besides those three, …

Particle	Charge
u up	+2/3
d down	-1/3
ν_e electron neutrino	0
e electron	-1

γ photon
Z Z boson
W W boson
g gluon

Fundamental building blocks?

- Besides those three, …



Fundamental blocks?

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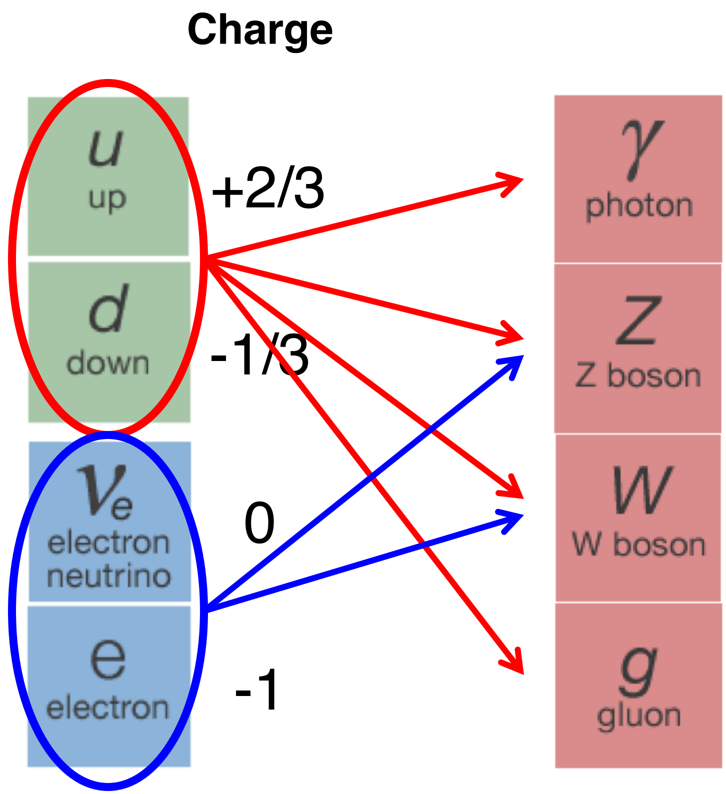
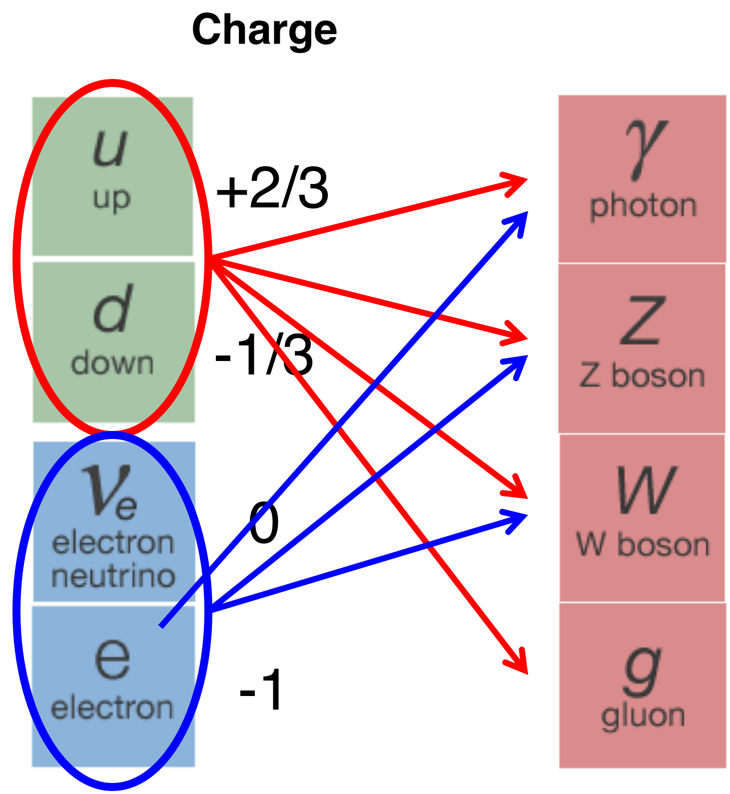


Fundamental building blocks?

- Besides those three, …



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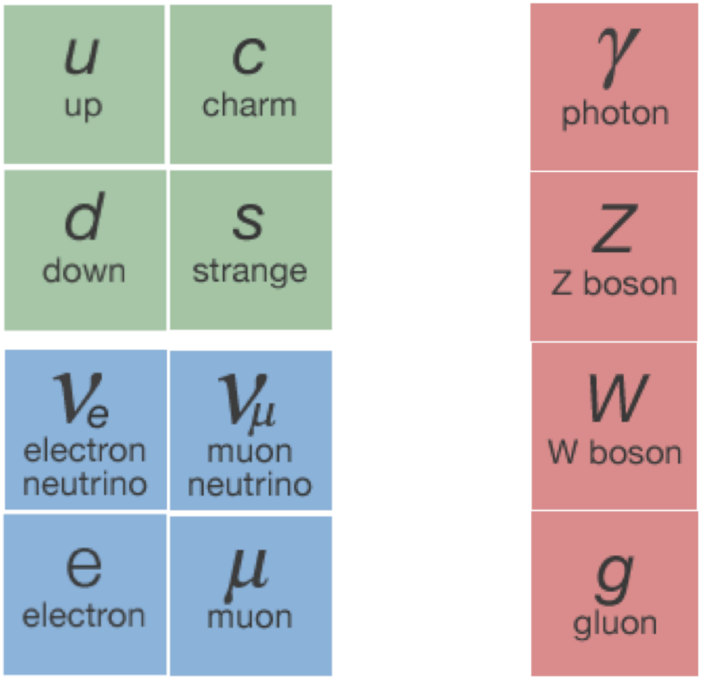


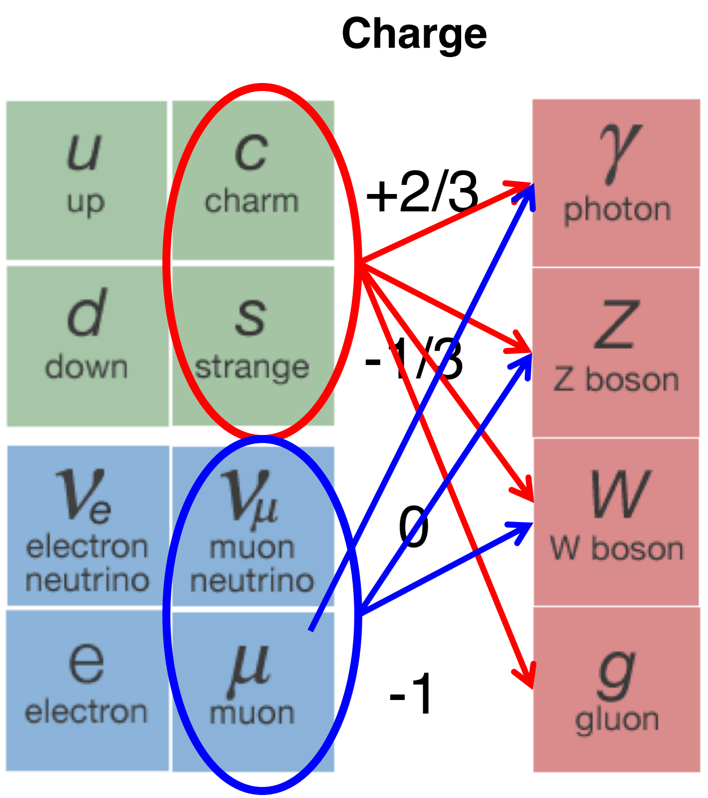
Fundamental building blocks?

- Besides those three, …

		Charge	
u up	c charm	+2/3	γ photon
d down	s strange	-1/3	Z Z boson
ν_e electron neutrino	ν_μ muon neutrino	0	W W boson
e electron	μ muon	-1	g gluon

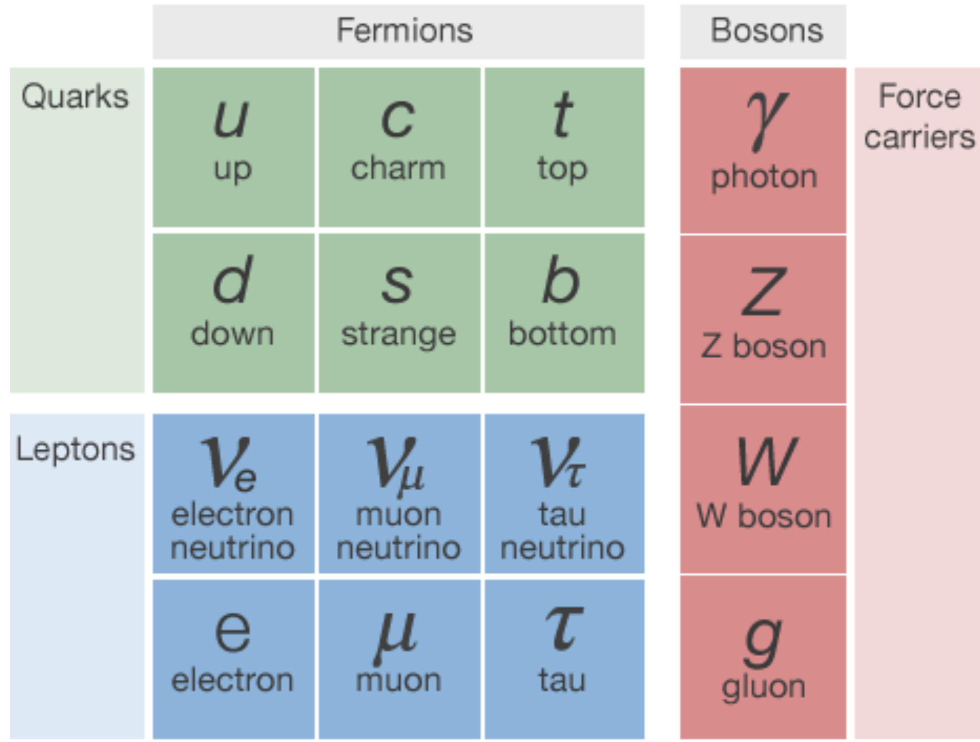
Fundamental building blocks?

- Besides those three, …



Fundamental building blocks?

- Besides those three, there are 14 more
- They describe almost all known physical phenomena



Source: AAAS

Fundamental building blocks?

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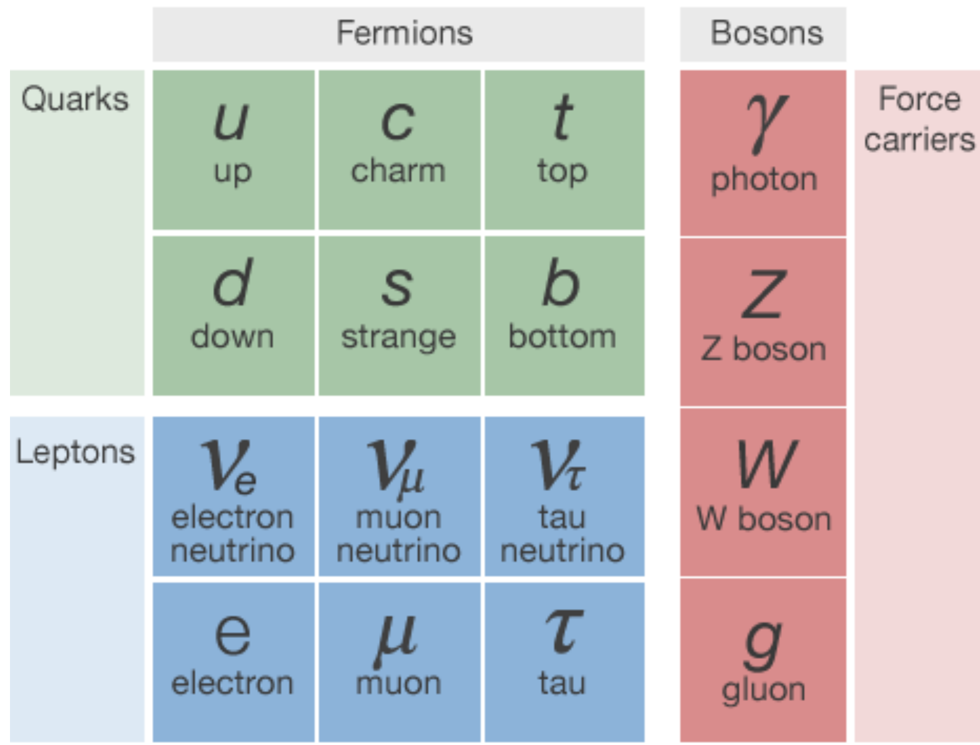


Source: AAAS

- In 1964, there was a problem: the model worked only for elementary particles with 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 y gluons travel at the speed of light

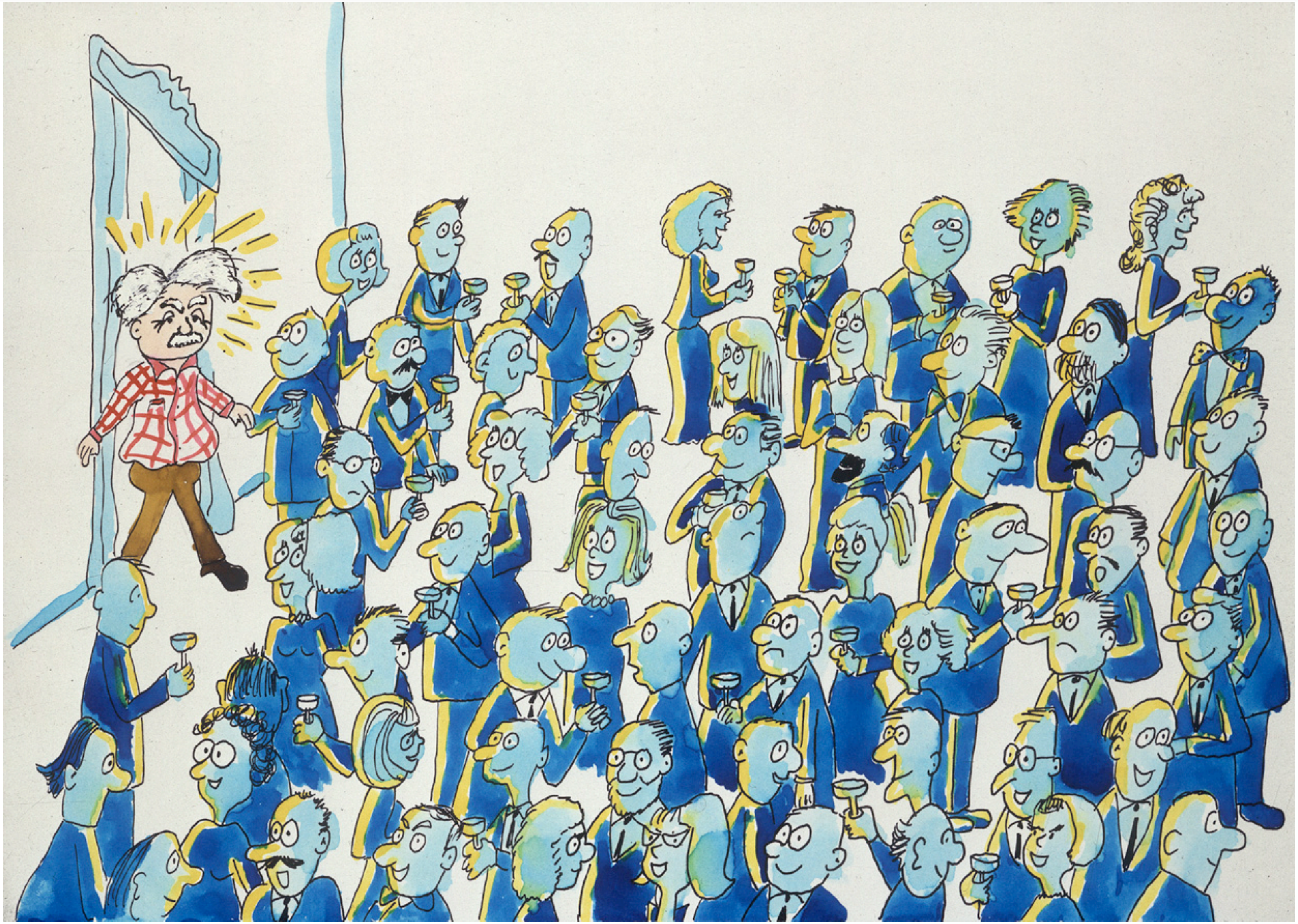
– What if **all elementary particles** traveled at light speed?
  - There would be no atoms
  - No clusters of matter (hence: no stars, no planets)
  - No life as we know it

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

What is the Higgs boson?

Prof. David J. Miller

What is the Higgs boson?



Prof. David J. Miller

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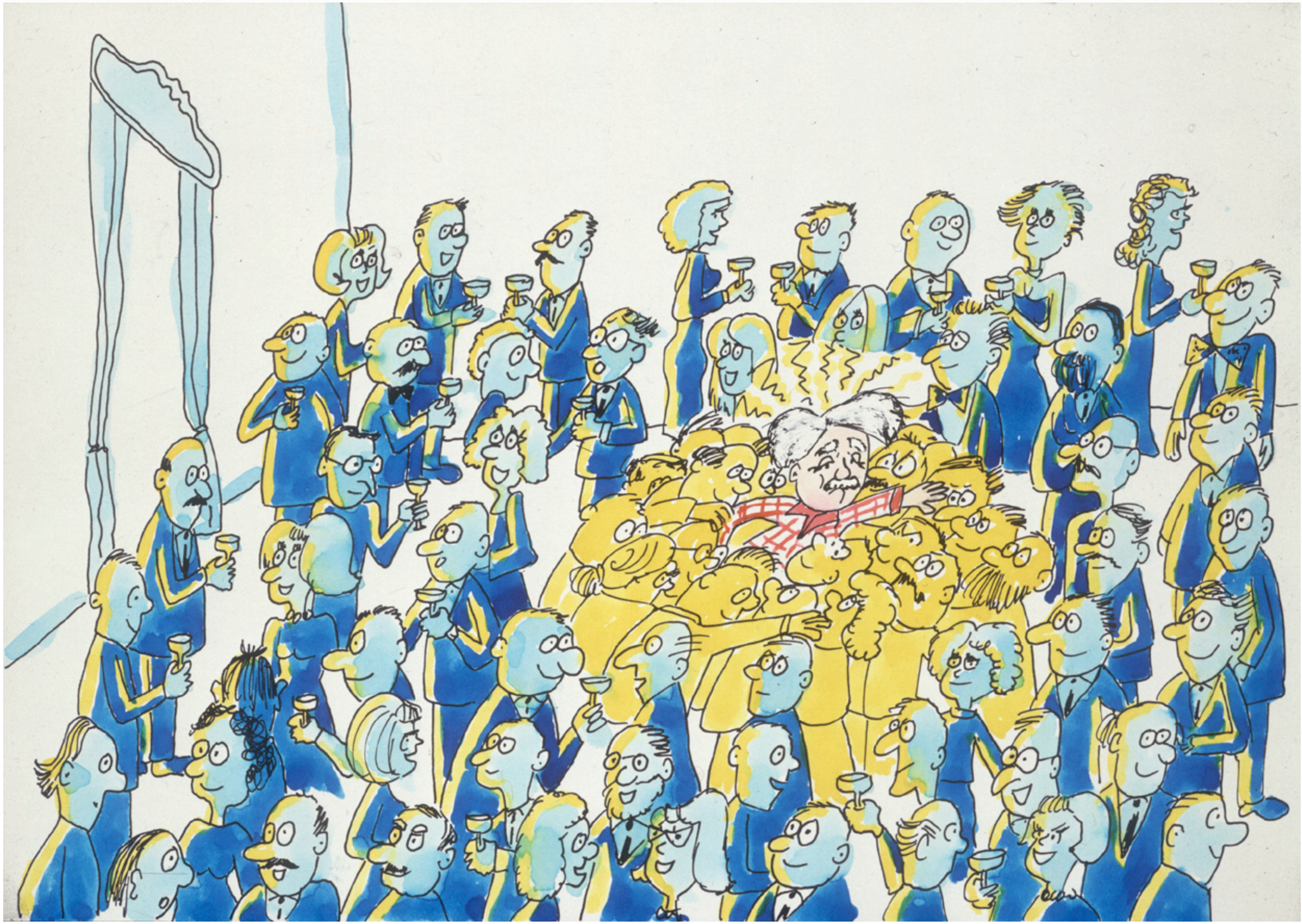

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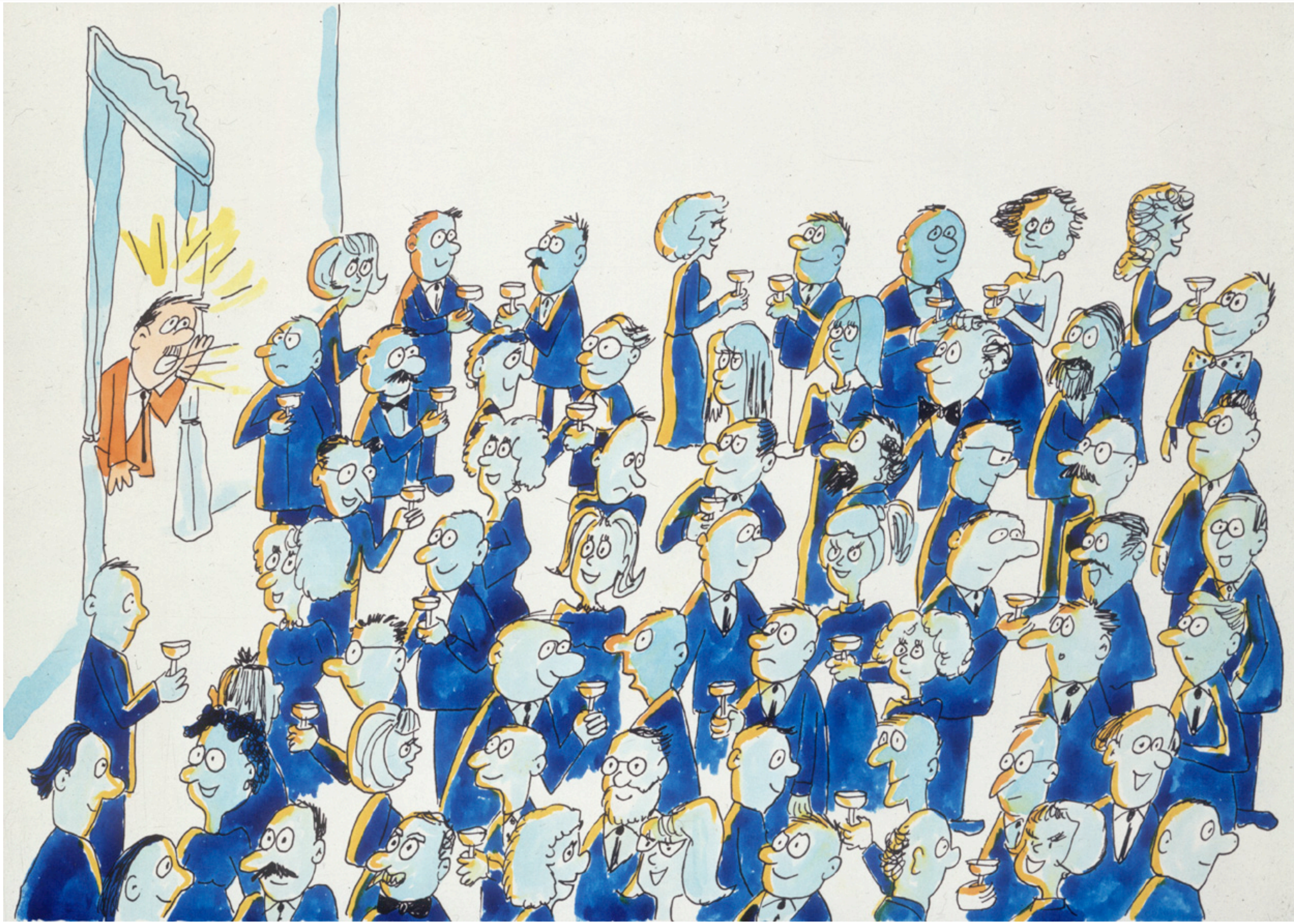

Prof. David J. Miller

What is the Higgs boson?

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“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?

Experimental search and discovery

The discovery was achieved in the *European Organization for Nuclear Physics (CERN)*.

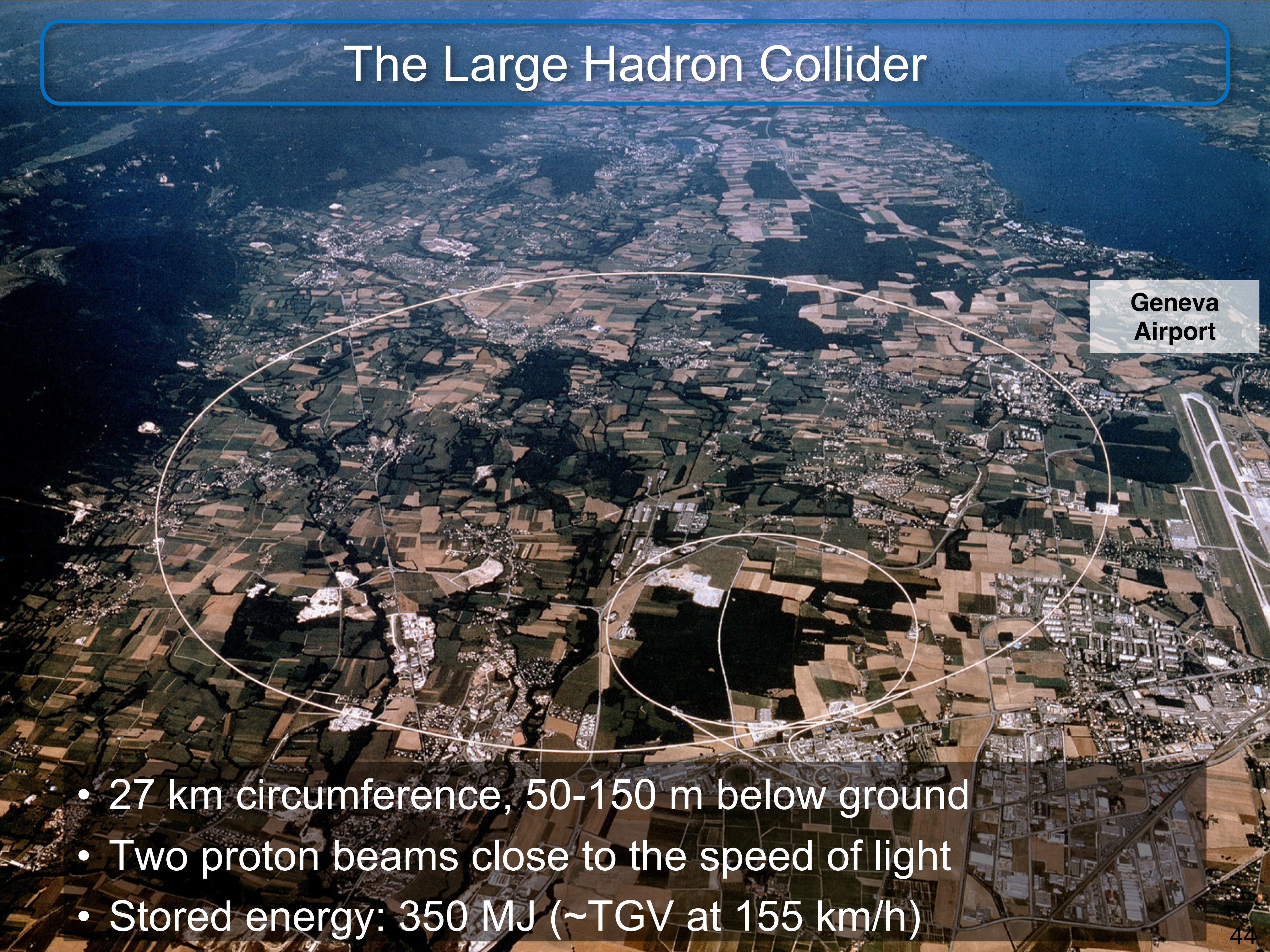
CERN: Conseil Européen pour la Recherche Nucléaire
[temporary body, but the name stayed]

Founded in 1954 with 12 european countries.

Currently 21 member states.

Home to the world's largest and most powerful particle accelerator

The Large Hadron Collider

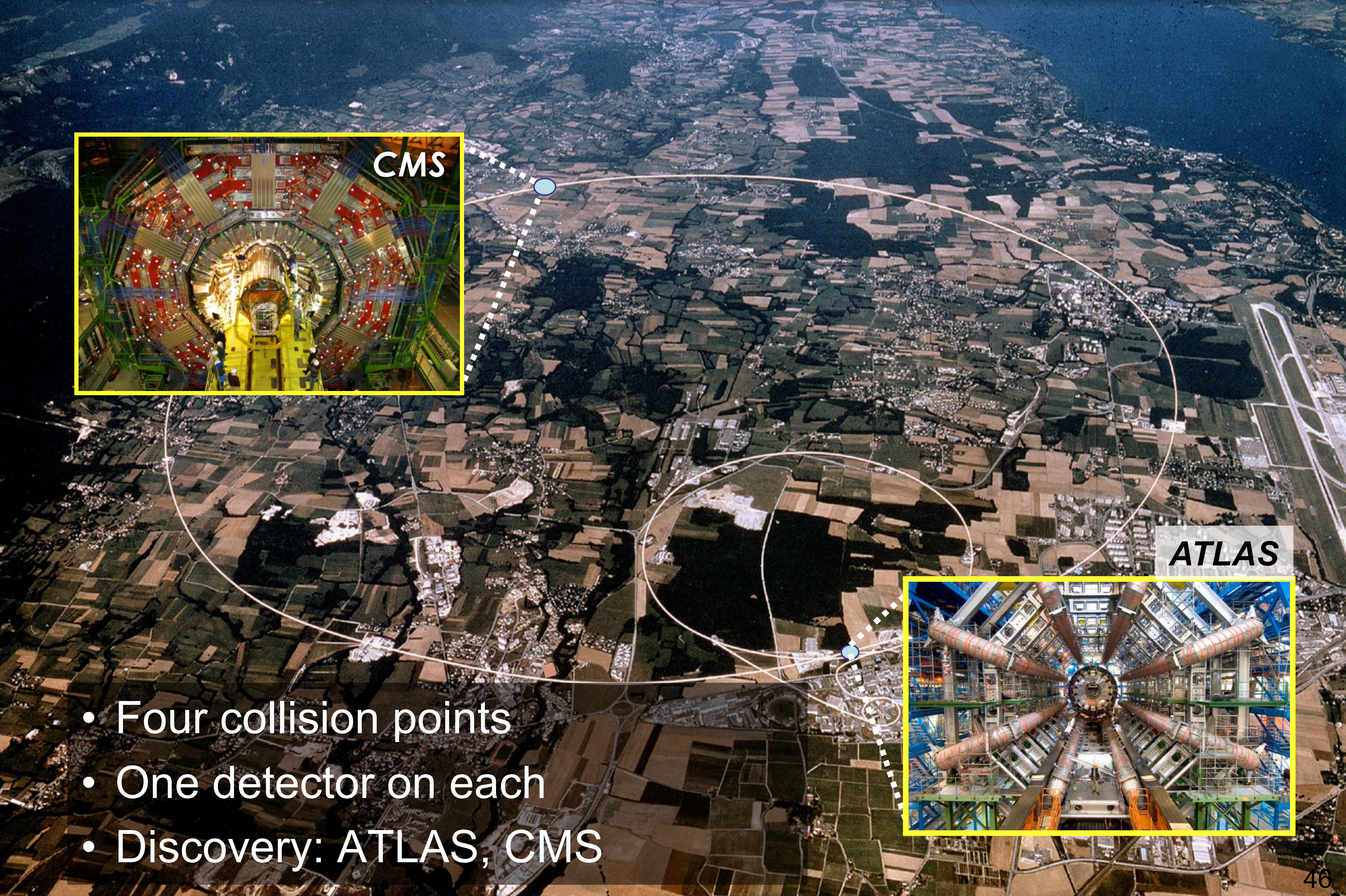


- 27 km circumference, 50-150 m below ground
- Two proton beams close to the speed of light
- Stored energy: 350 MJ (~TGV at 155 km/h)

The Large Hadron Collider

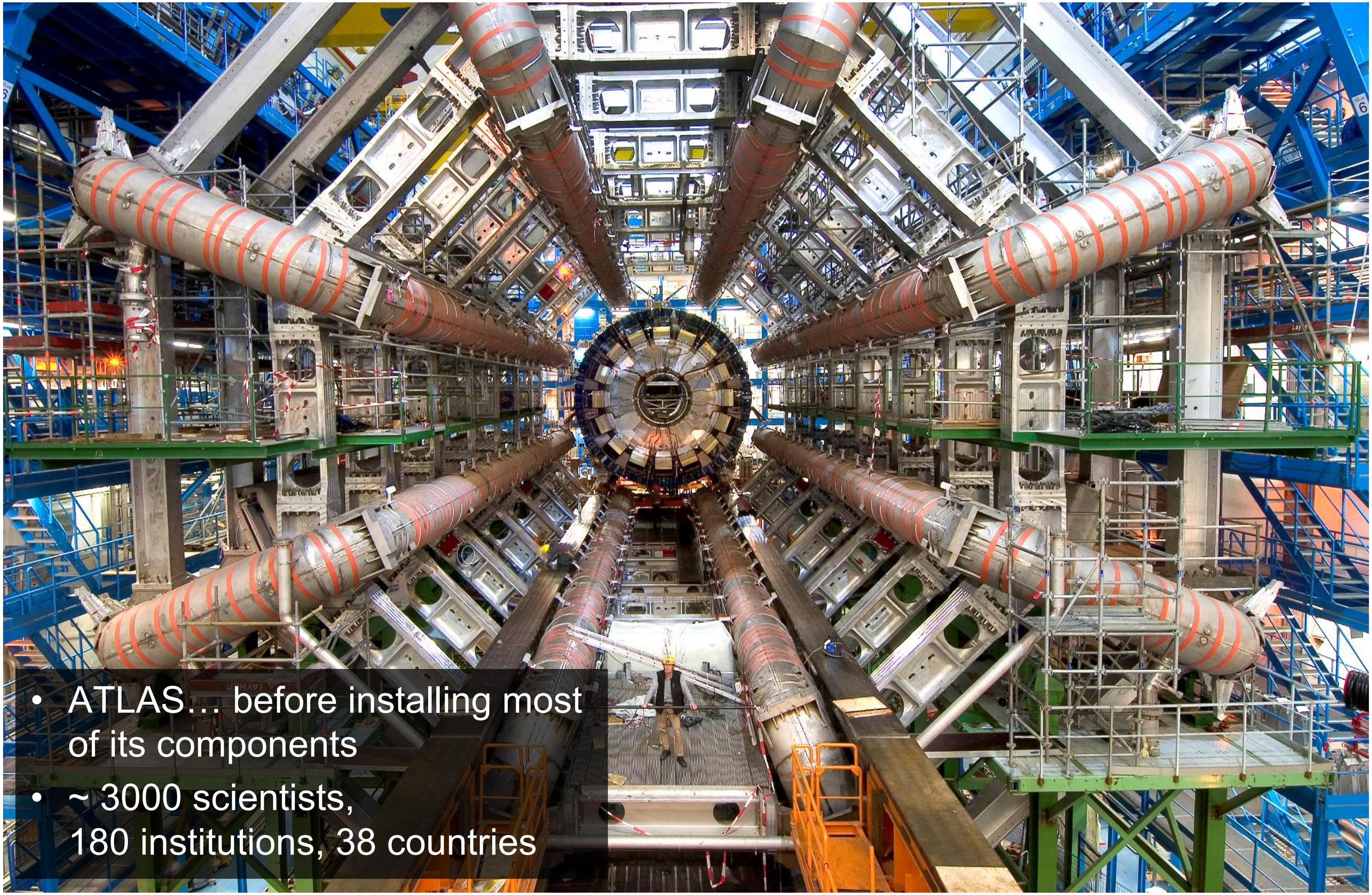
- ~1600 superconducting magnets
- "Bunches" of 1.15×10^{11} protons: 30 microns x several cm
- 40 million bunch crossings per second

The Large Hadron Collider

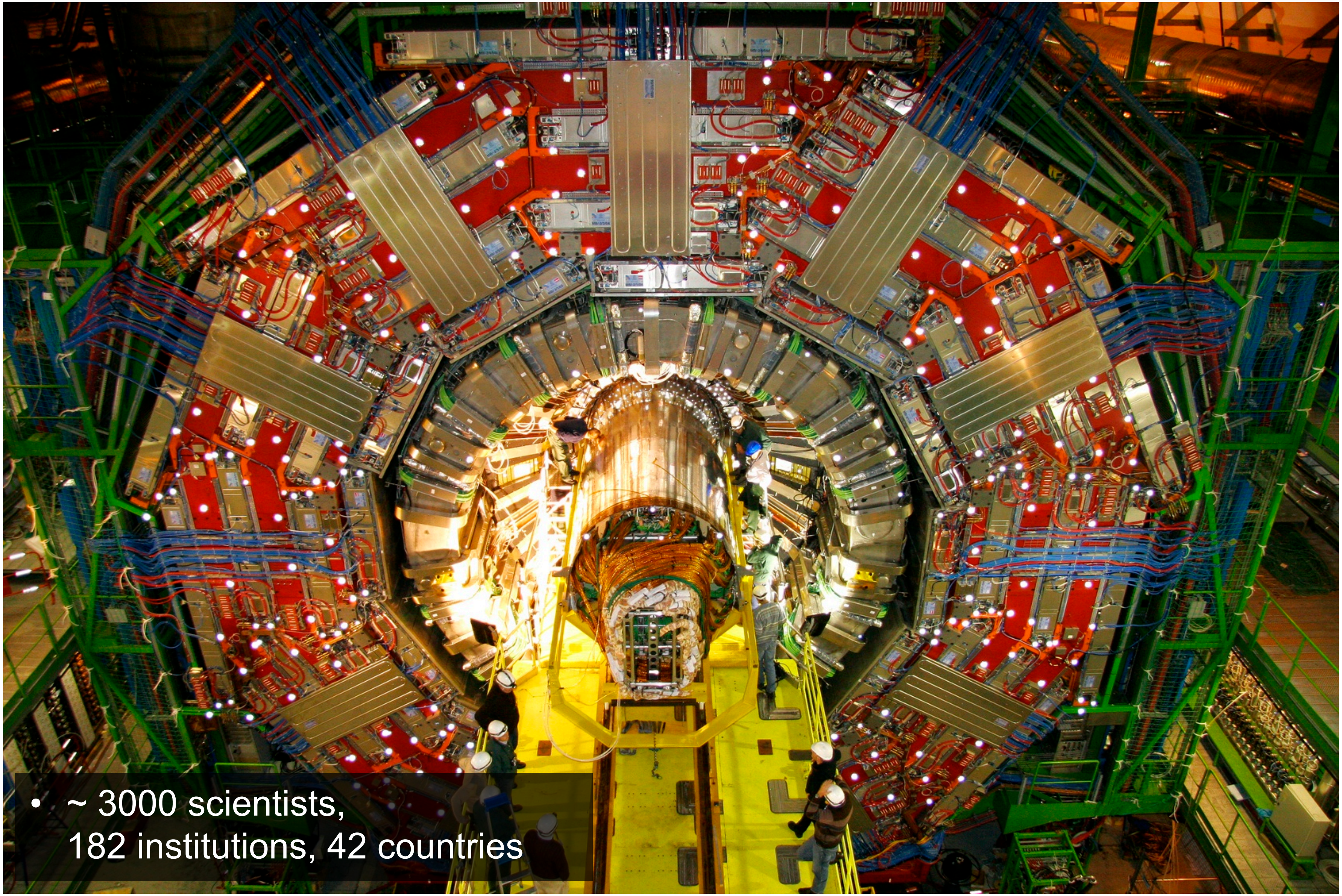


- Four collision points
- One detector on each
- Discovery: ATLAS, CMS

ATLAS

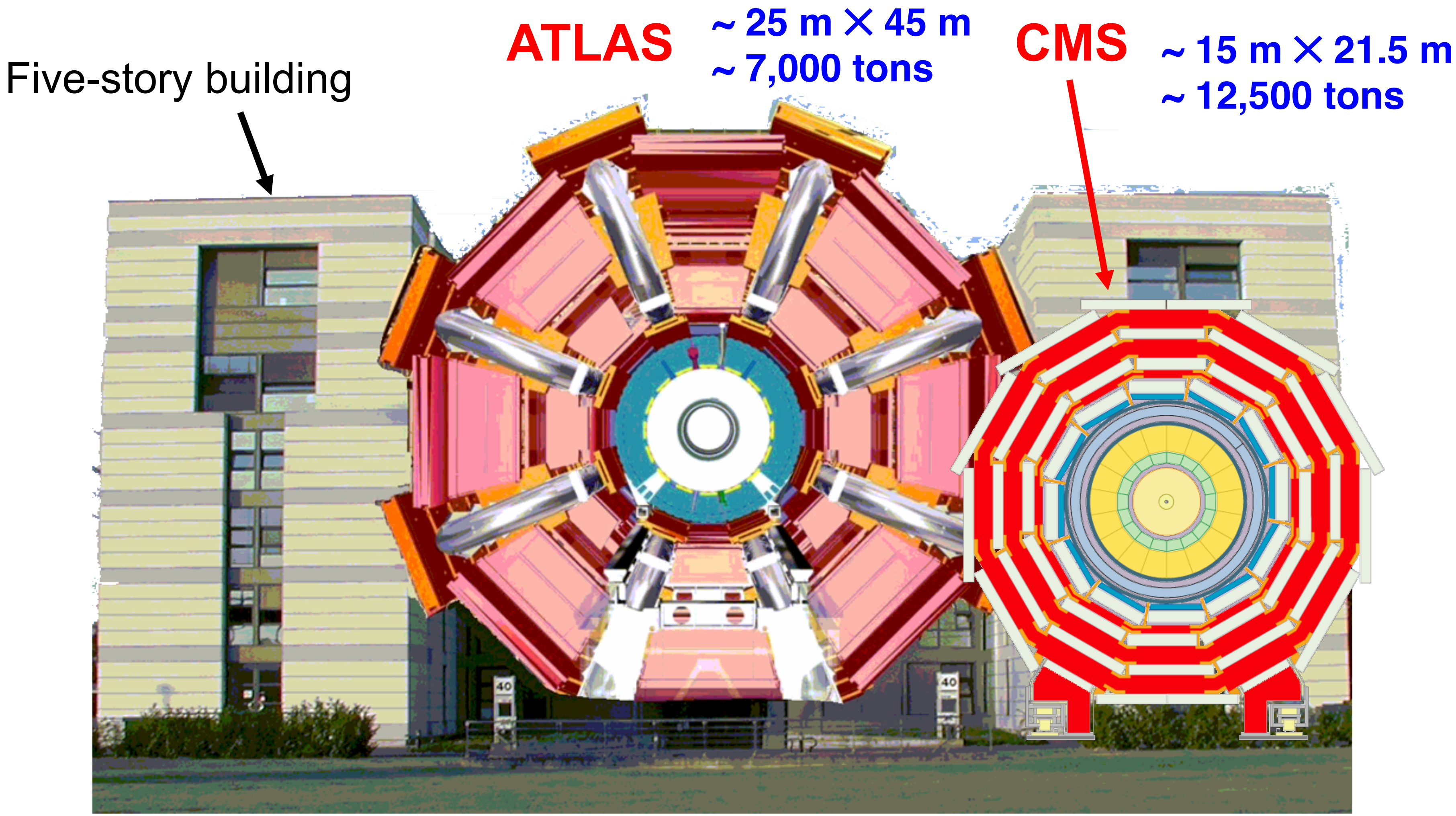

• ATLAS… before installing most of its components
• ~ 3000 scientists, 180 institutions, 38 countries

CMS



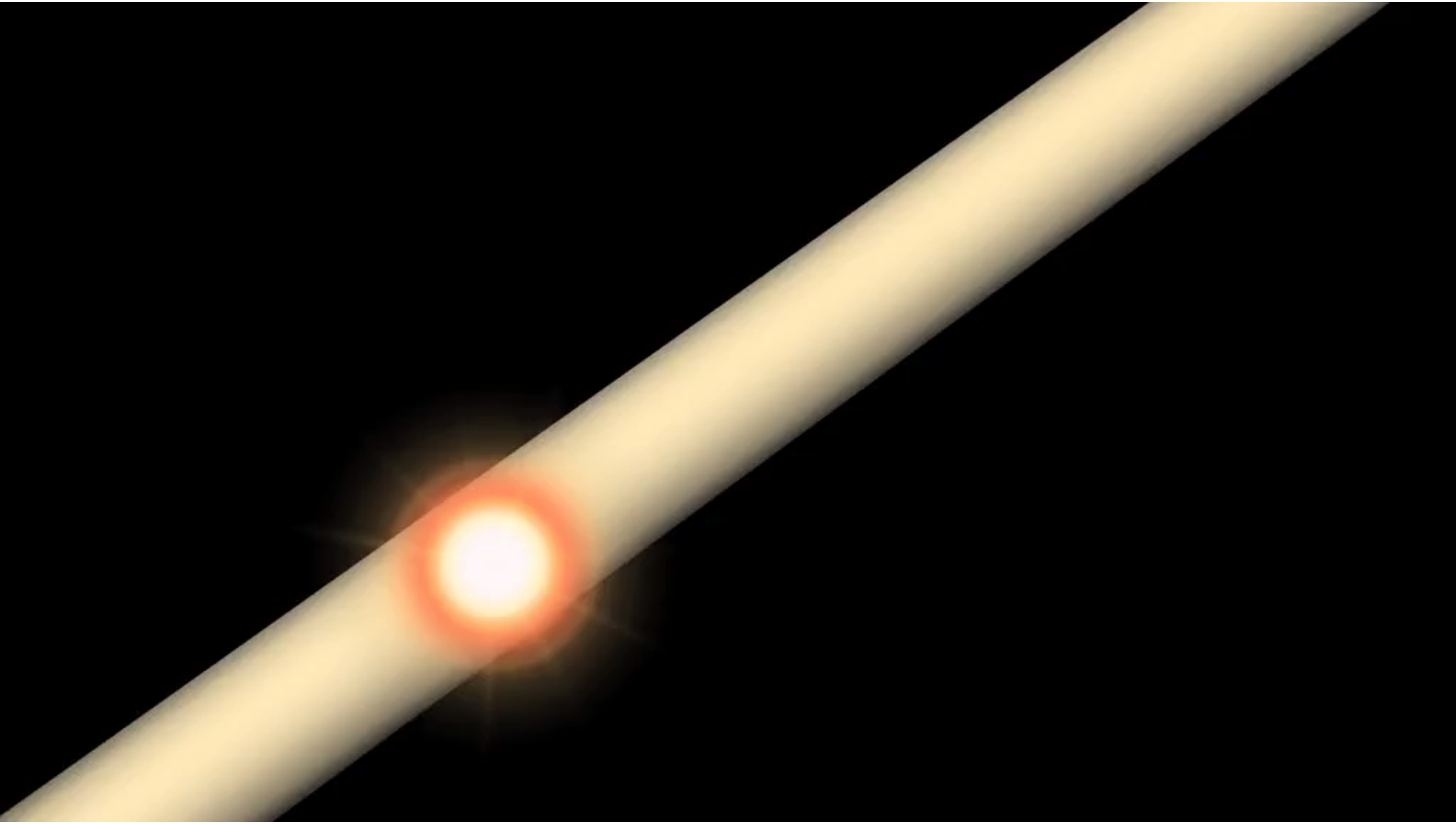
- ~ 3000 scientists,
  182 institutions, 42 countries

Detectors

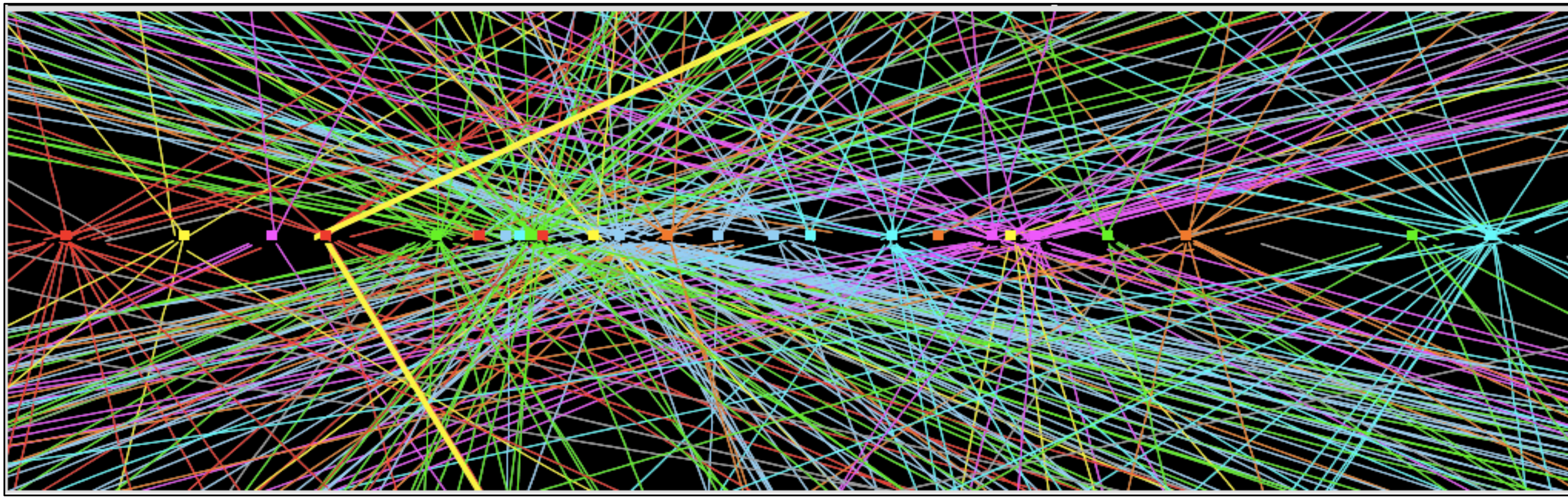


- About 100 millions sensors each
- Much beyond a 12-megapixel camera, 40 million pictures/second

One “event”



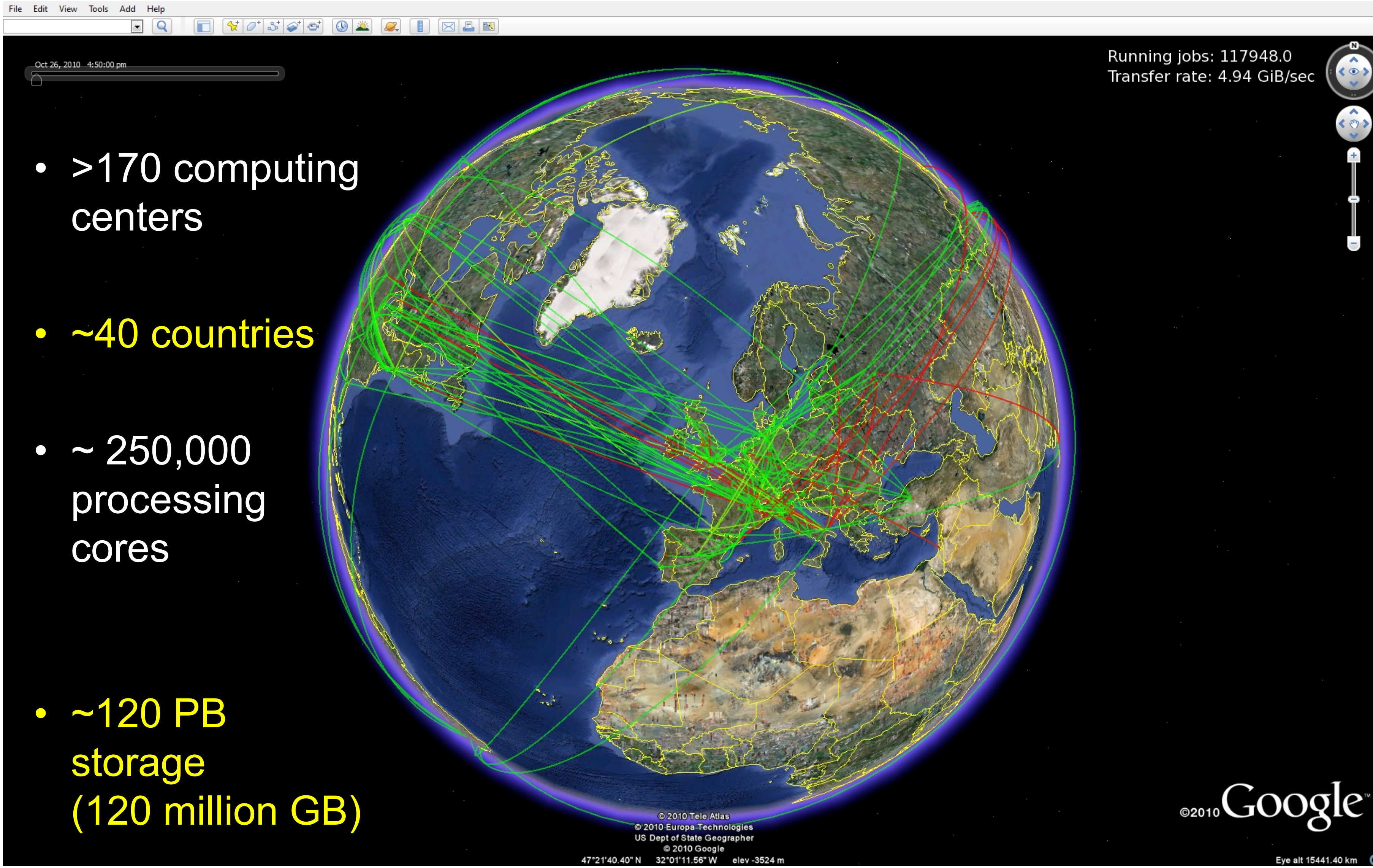
Data



Z→μμ event from 2012, with 25 reconstructed vertices

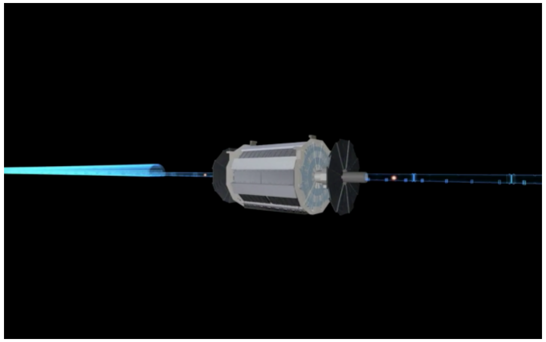
- Each bunch crossing ~20 *pp* interactions
- 40 M crossings per second × 20 pp por crossing, spacing: 600 M pp/s
- Fast selection systems ("trigger systems") keep only 400 colisions/s
- Each pp collision produces hundreds of particles
- If stored in musing CD's, …

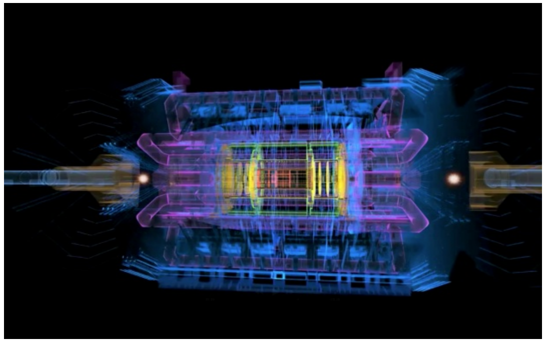
Worldwide LHC Computing Grid

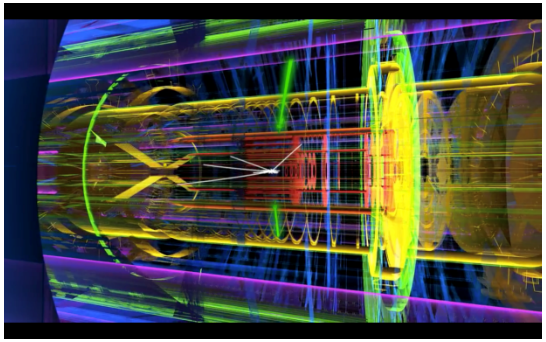


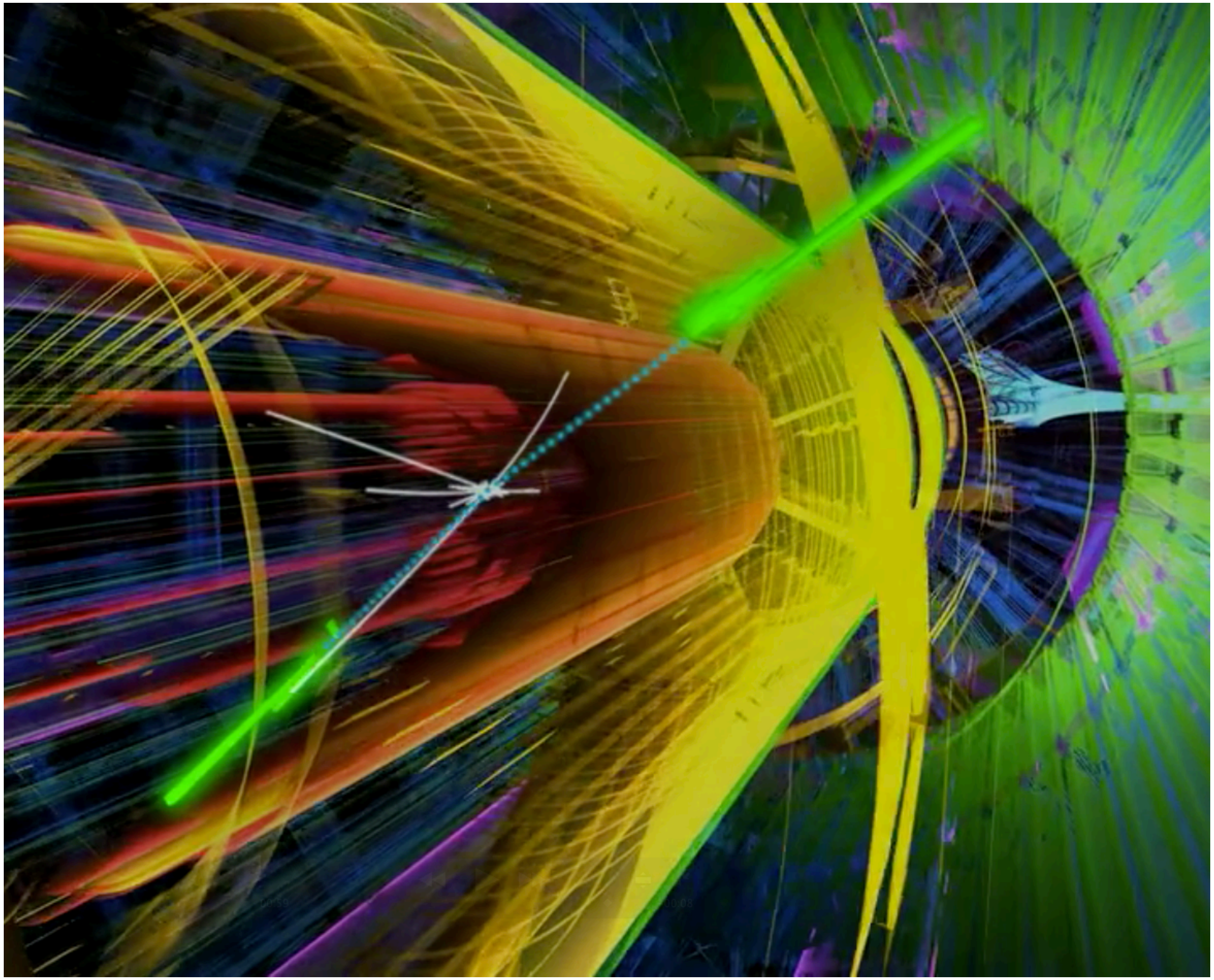
- >170 computing centers
- ~40 countries
- ~ 250,000 processing cores
- ~120 PB storage (120 million GB)

H→γγ

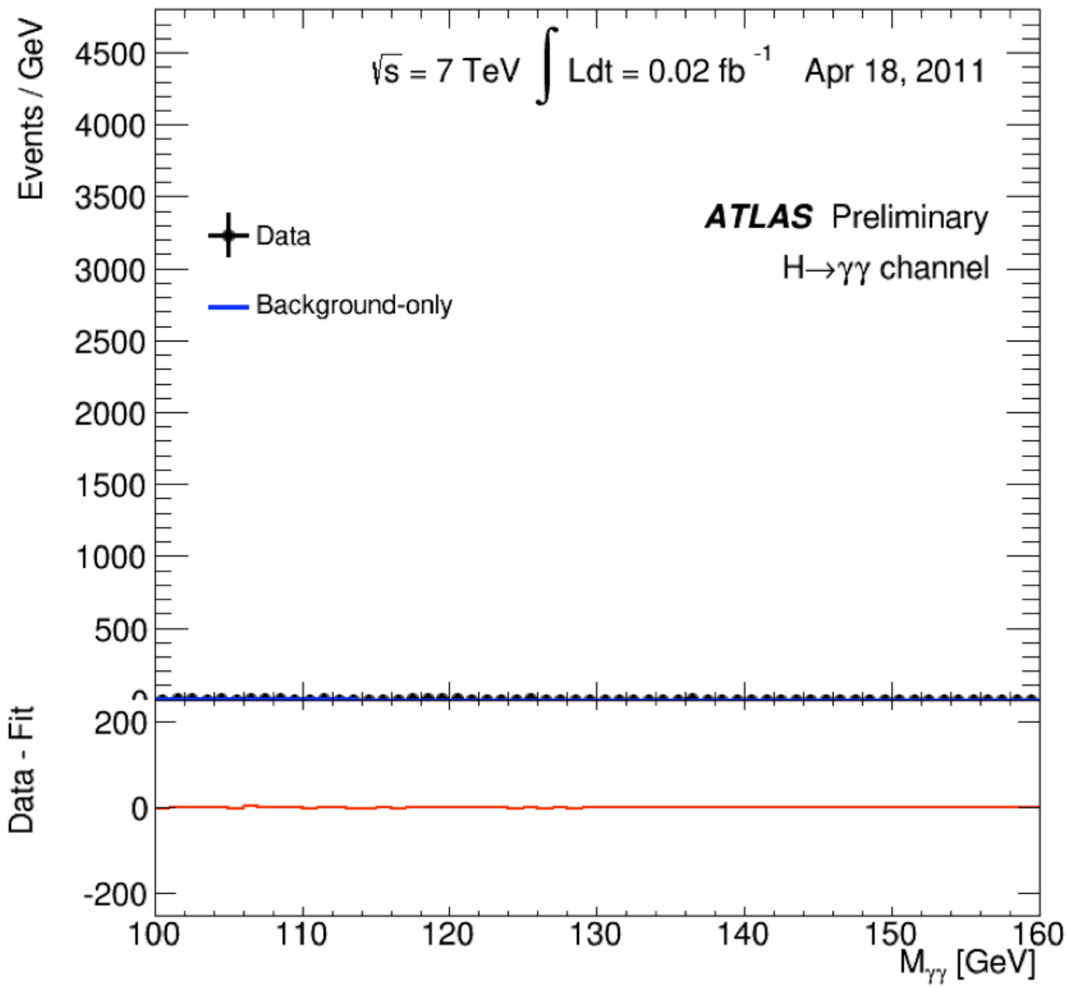






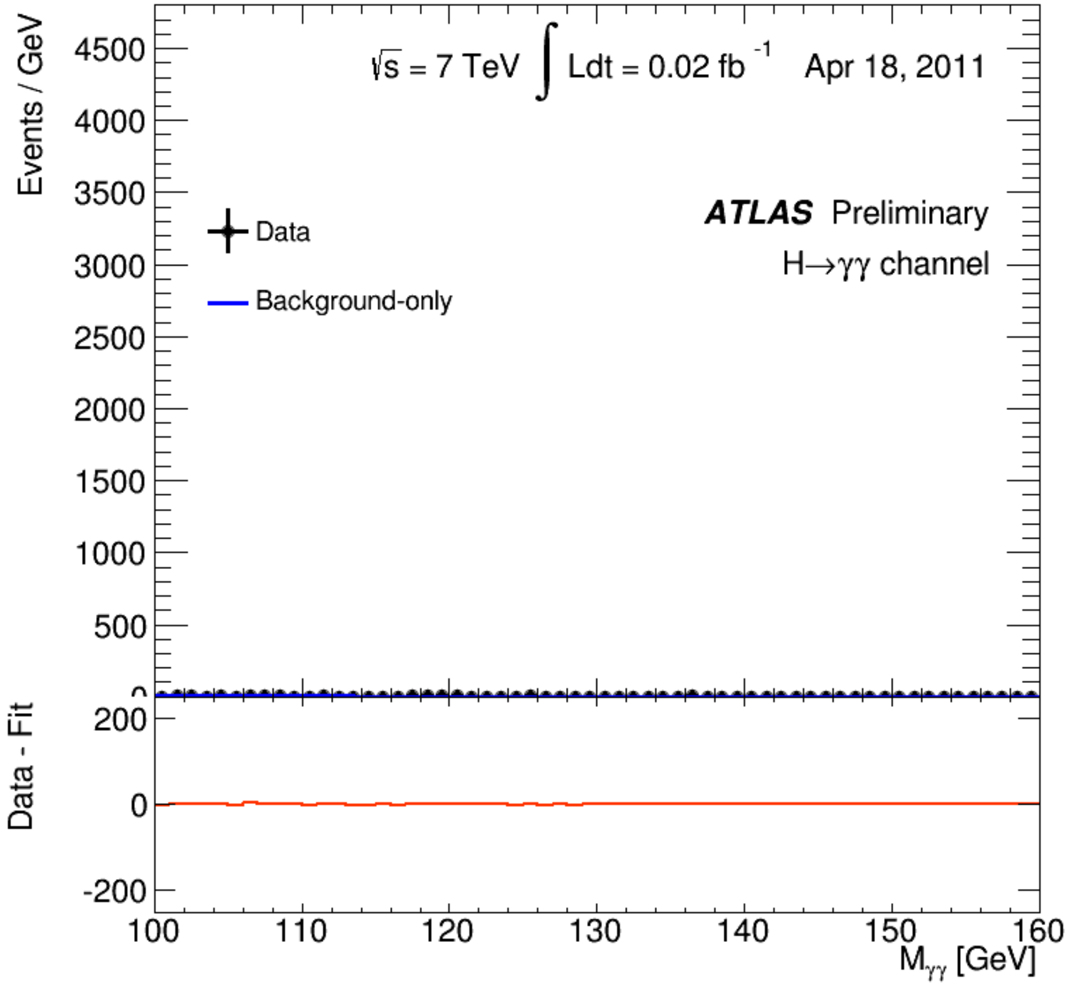


H→γγ



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

H→γγ



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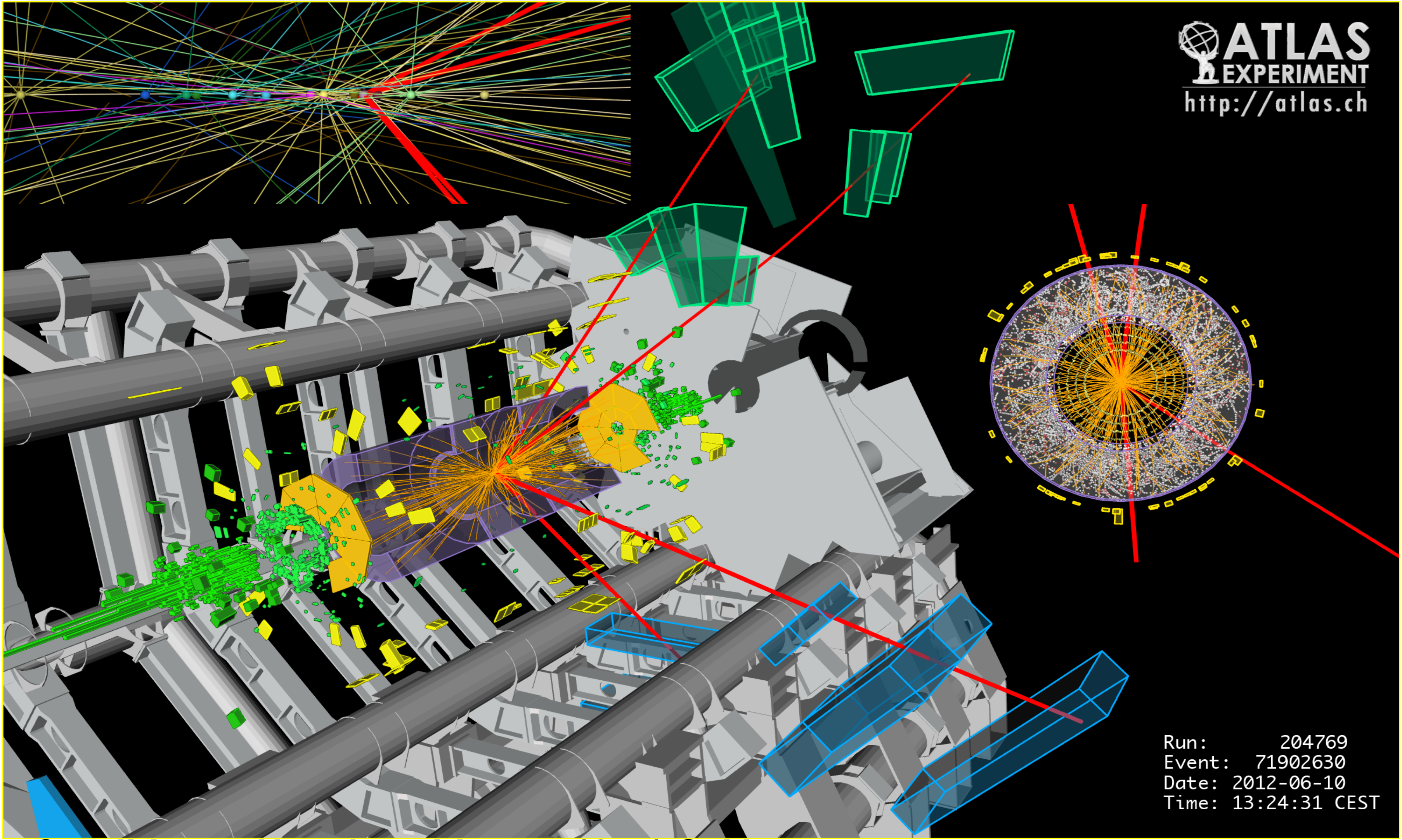
160
Mγγ [GeV]

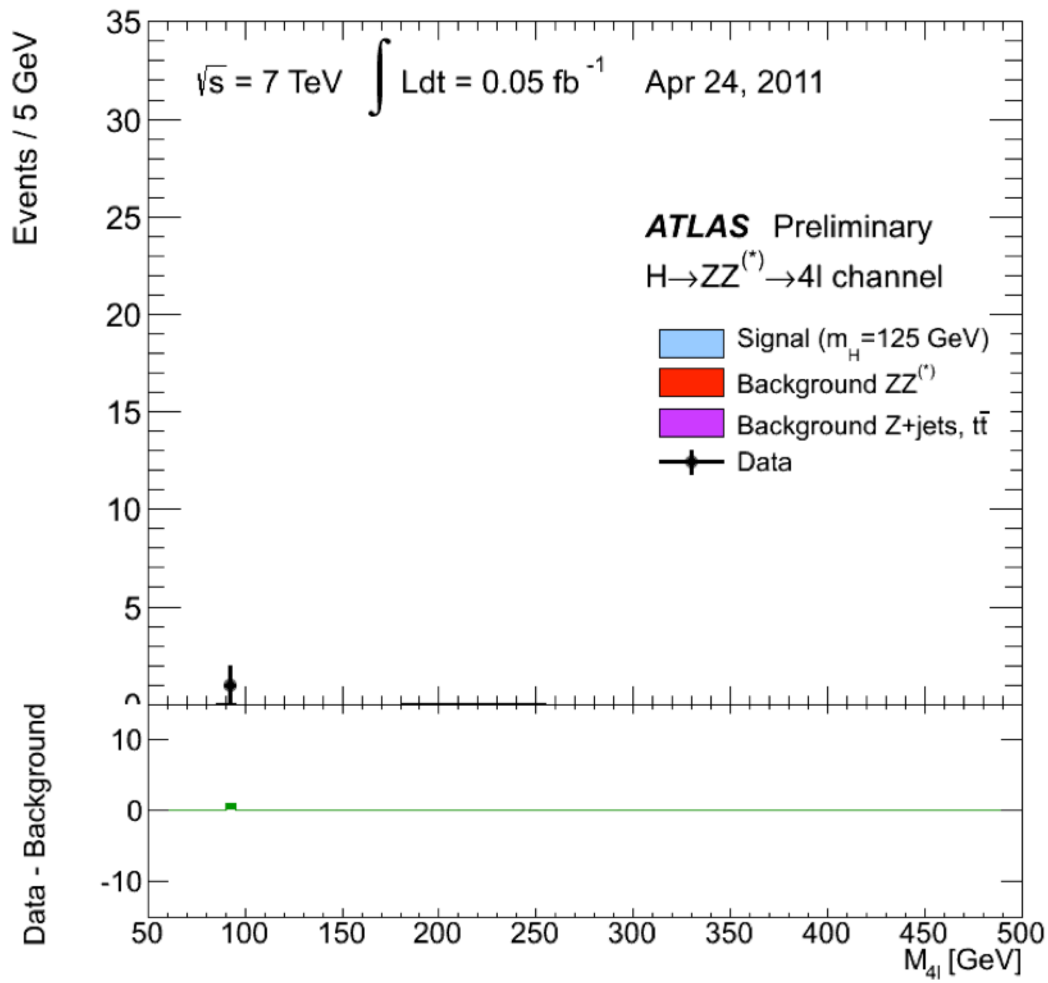
$H \rightarrow ZZ^{(*)} \rightarrow 4l$



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

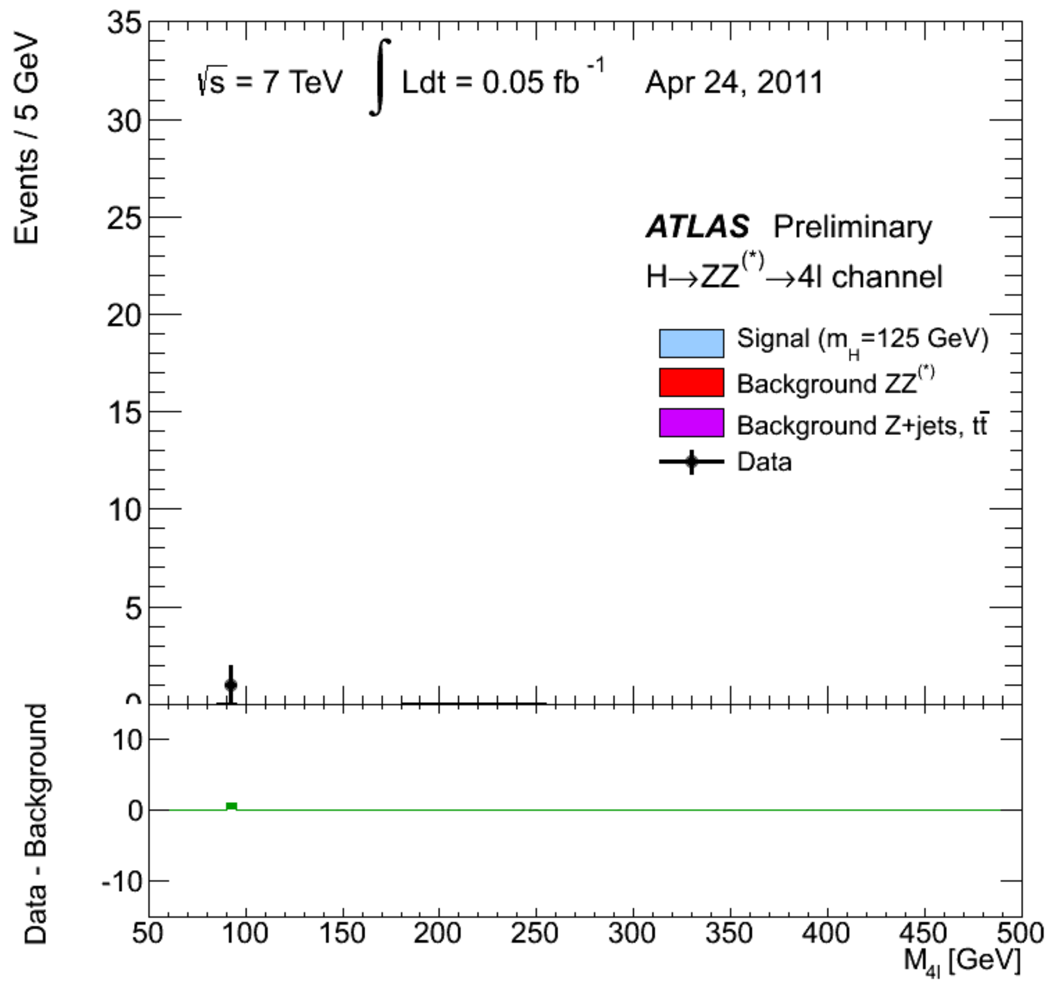
p_T (muones)= 36.1, 47.5, 26.4, 71 .7 GeV m_{12}= 86.3 GeV, m_{34}= 31.6 GeV. 15 vértices reconstruídos

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



√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]

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



Events / 5 GeV
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ATLAS Preliminary
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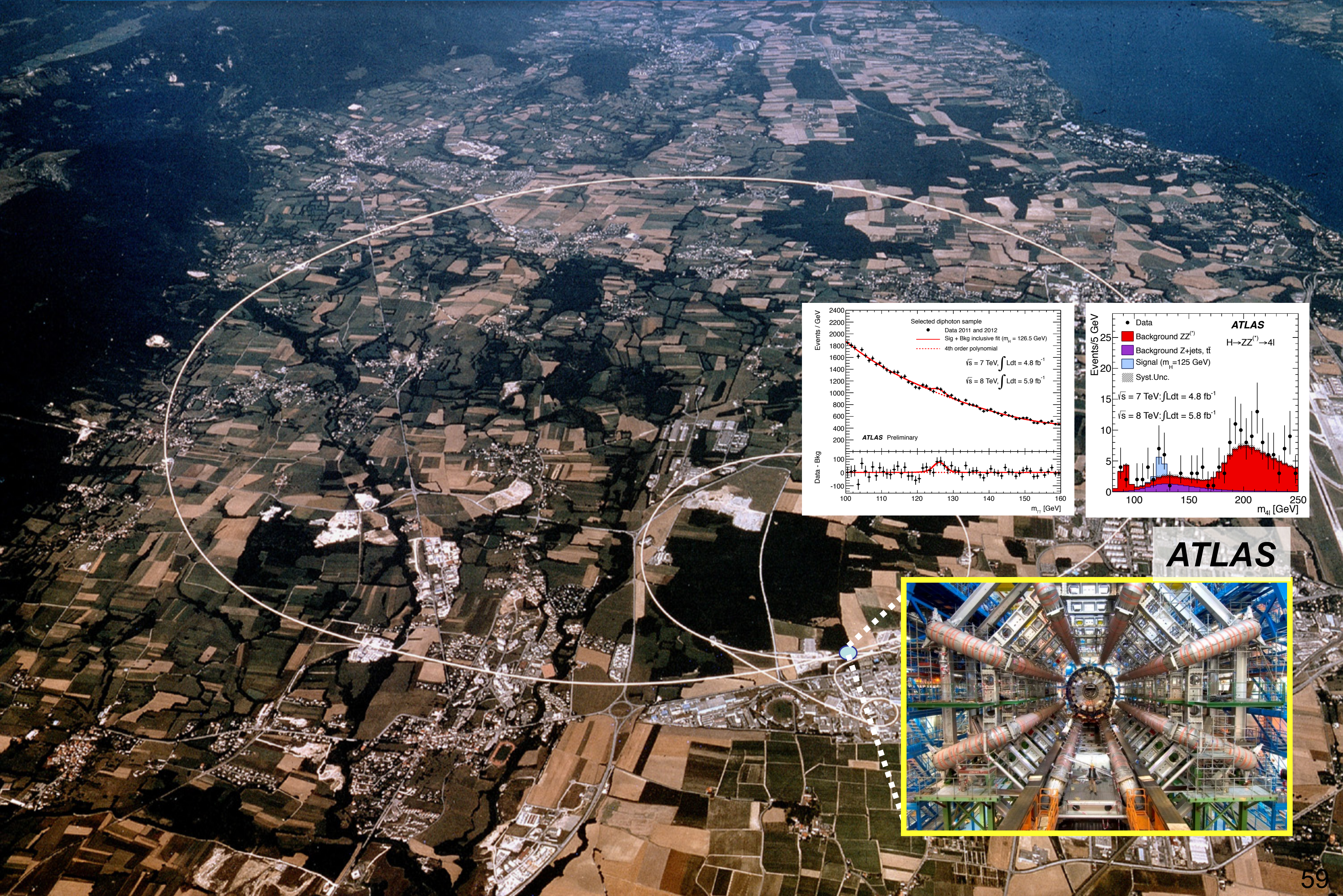
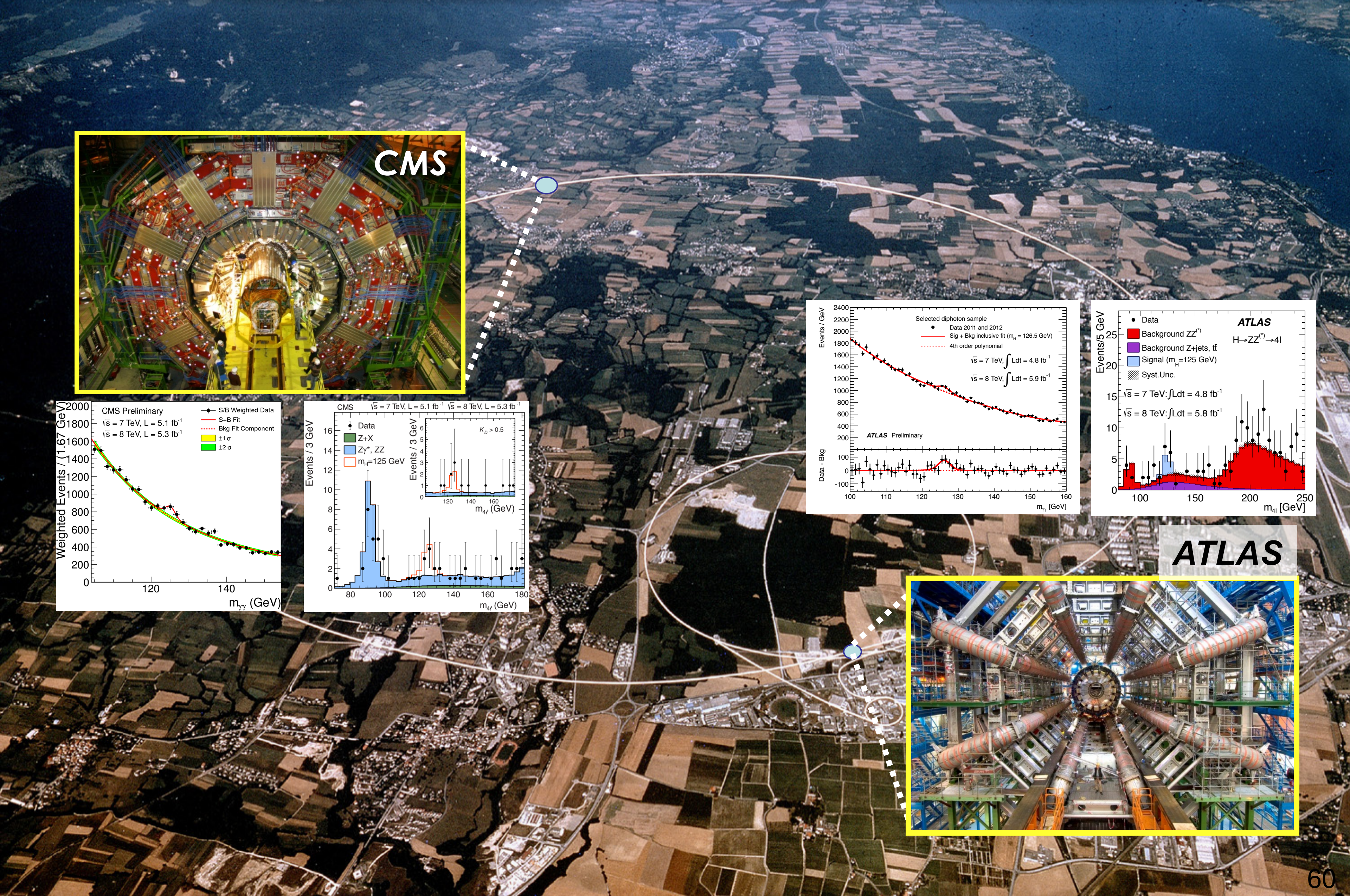
Data
Data - Background
M4l [GeV]

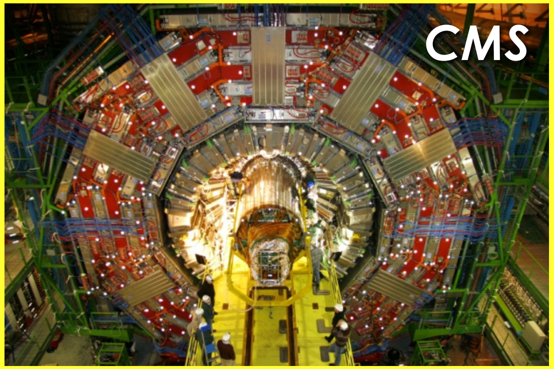
Independent confirmation

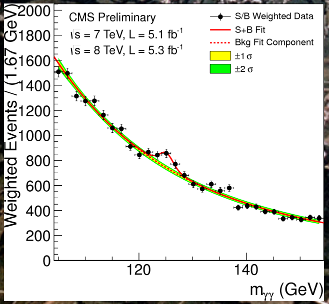


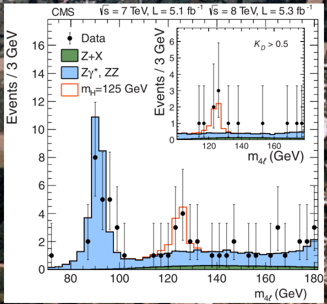
Independent confirmation

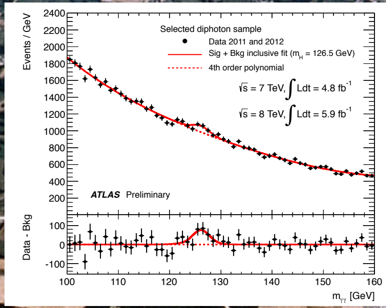


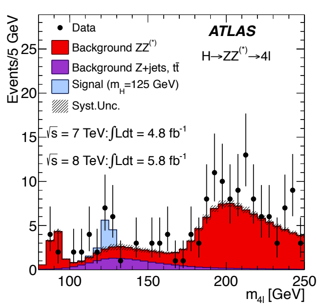
Combination



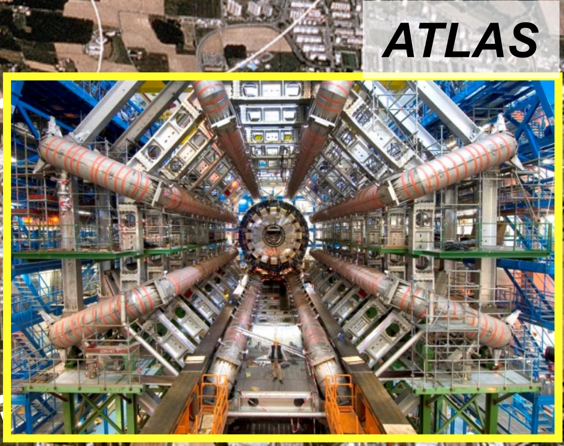








Probability < 0.00003%
= "5σ" → Discovery!

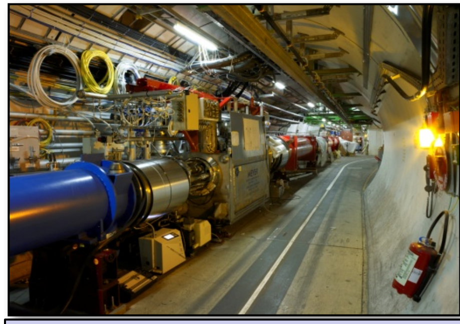


Probability < 0.00003%
= "5σ" → Discovery!

July 4, 2012

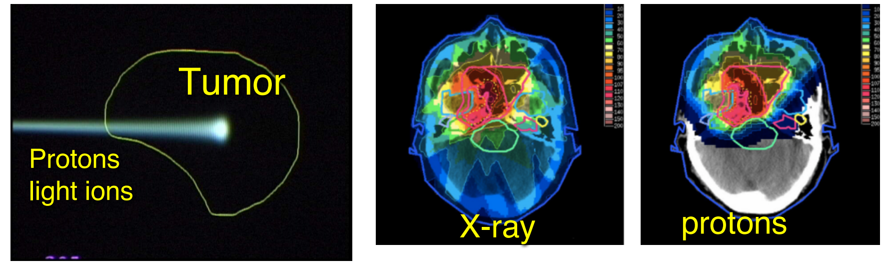
From fundamental science to our daily life

From fundamental physics to daily life

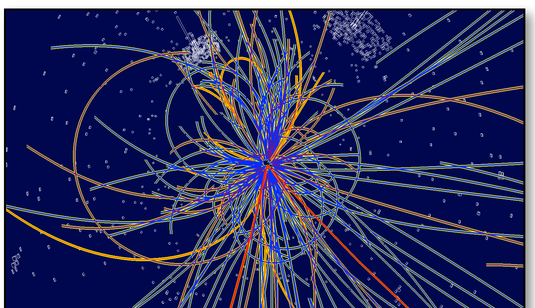


~30’000 accelerators worldwide
~17’000 for medical applications

Hadronic therapy for cancer

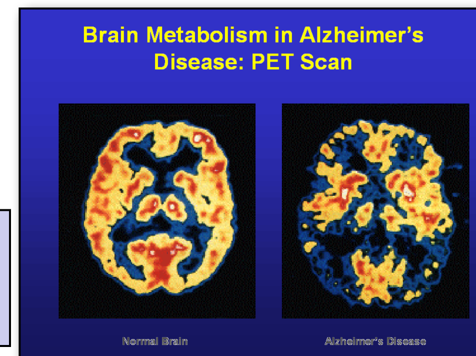


>90,000 patients treated (30 facilities)



Medical imaging

e.g. CAT & PET, airport scaners, etc.



- *www, GPS, cloud computing.*
- **In the long term, unexpected applications**: 1897: the electron.

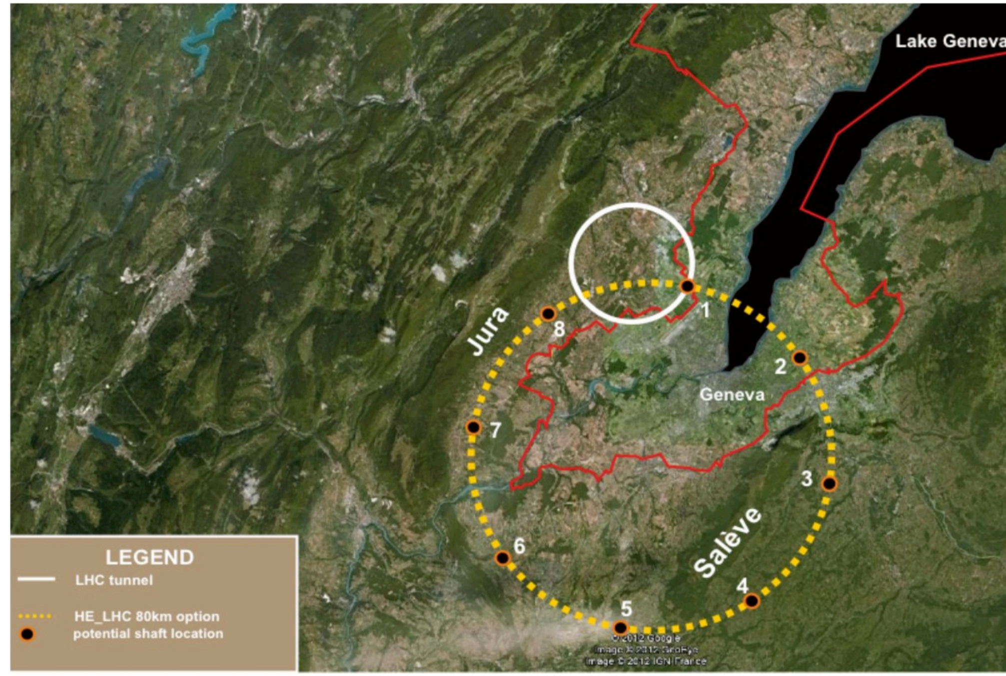



… and beyond

What is next?

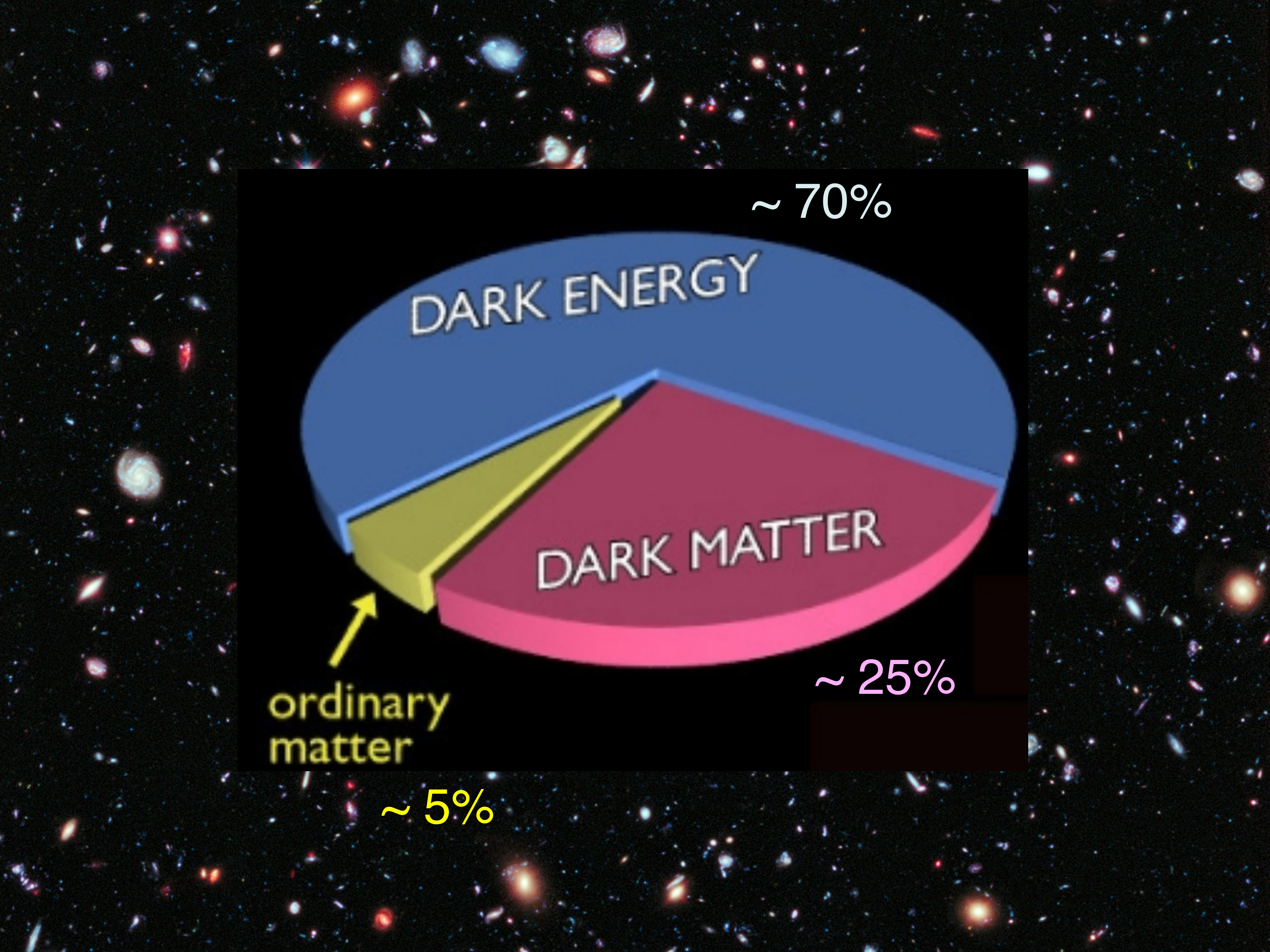
CERN:

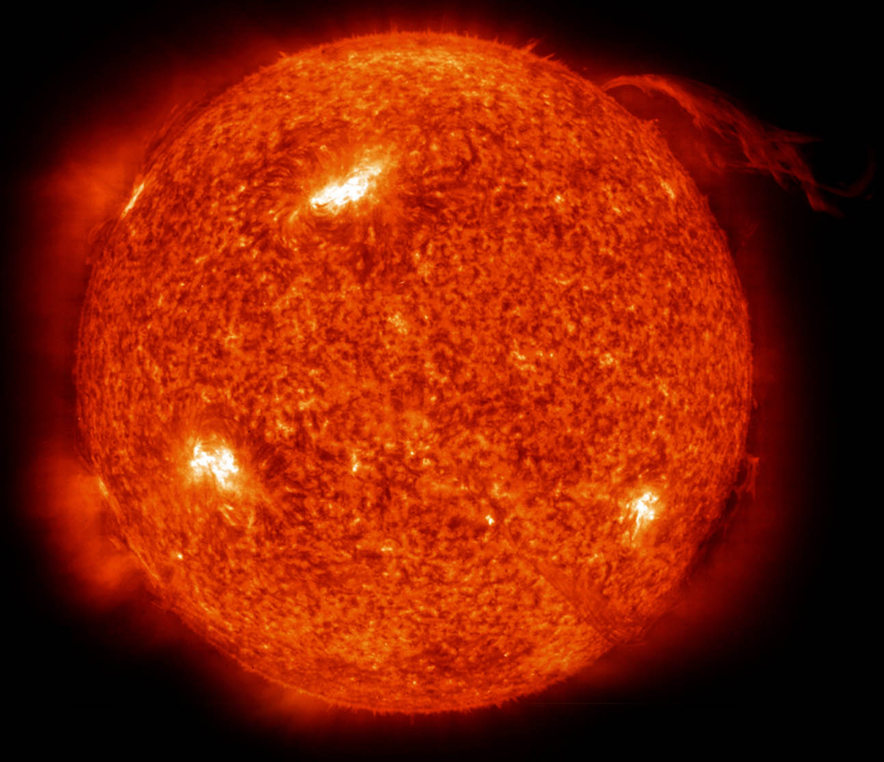
- Below the Geneva area
- *Conceptual Design Study* in preparation
- 80 – 100 km



China:

- Qinhuangdao (秦皇岛)
- Strong local support


~ 70%
DARK ENERGY
DARK MATTER
ordinary
matter
~ 25%
~ 5%



The financial case

Source: Jonh Womersley slides, FCC Kickoff Meeting, Geneva

R.o.I. of large science projects?

Example: The Fermilab collider (Tevatron)

- Accelerator: $120M (1983) = $277M (2012)
- "Main injector": $290M (1994) = $450M (2012)
- Detectors, upgrades: 2x$500M + $300M = $1,300M
- Operations: ~ 20 years x $100M/year = $2B

- TOTAL: **$4B**

Economic Impact

Source: Jonh Womersley slides, FCC Kickoff Meeting, Geneva

- PhD graduates:
  - $2.2M (US Census Bureau, 2002) = $2.8M (2012)
  - 1414 graduados: **$3.96 B**

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  - Mass-produced for the first time for the Tevatron
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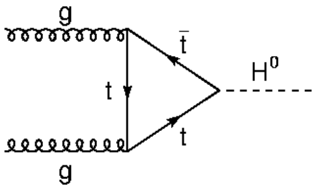
- Cloud computing: $150B/year (Gartner)
  - Large investment in linux, PC clusters, networking, etc.
  - Assuming Tevatron gave only a *3-month* speed-up: **$40B**

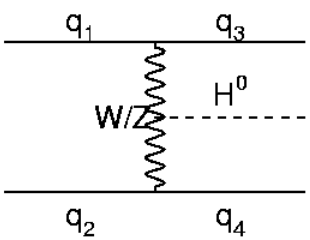
SM Higgs production

SM Higgs production

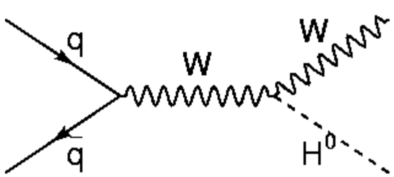
Gluon fusion (dominant at LHC)



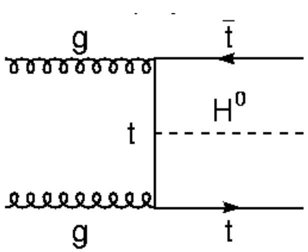
Vector boson fusion

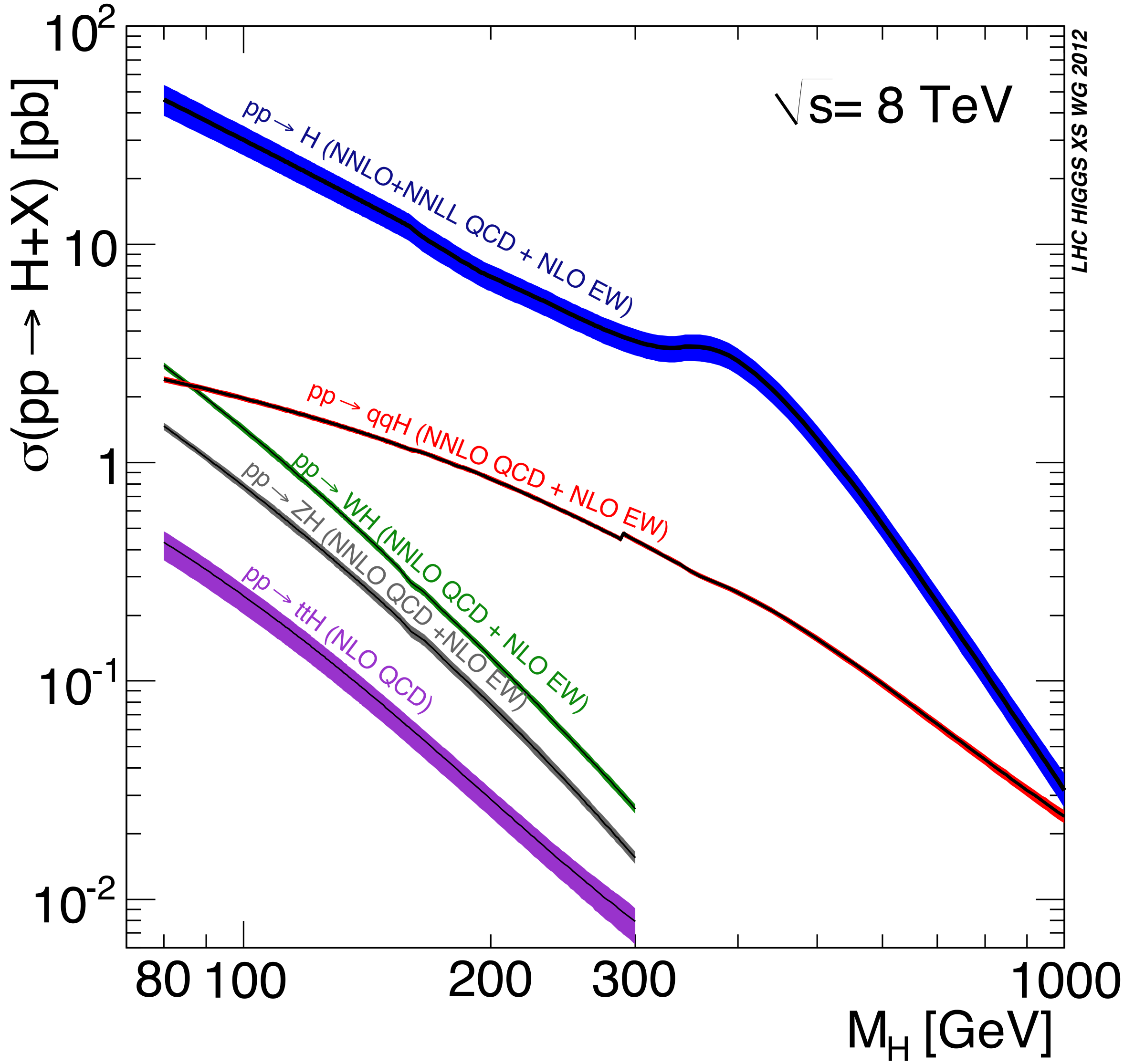


Associated production with Z/W
(Higgs-strahlung)



Associated production with top





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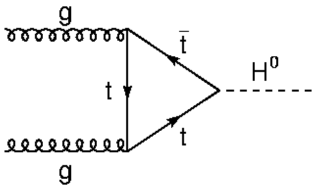

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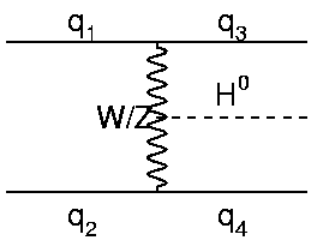

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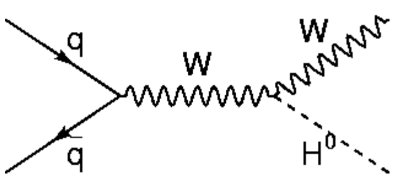

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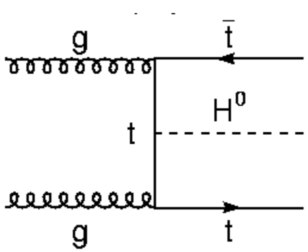
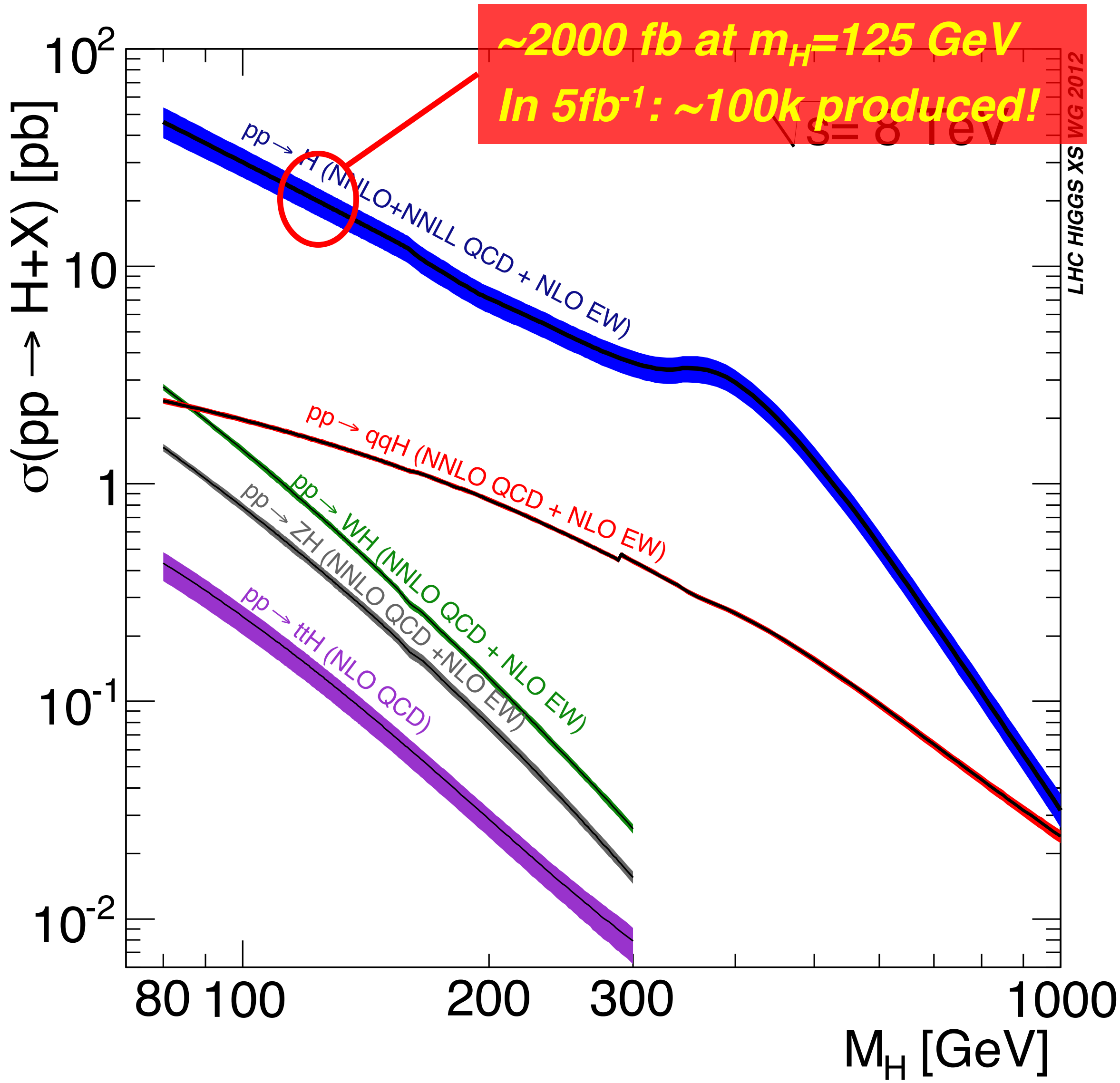
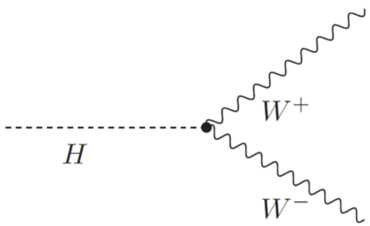




Branching ratios

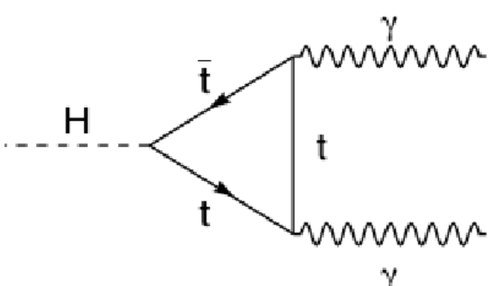
SM Higgs decays

Direct coupling to massive particles

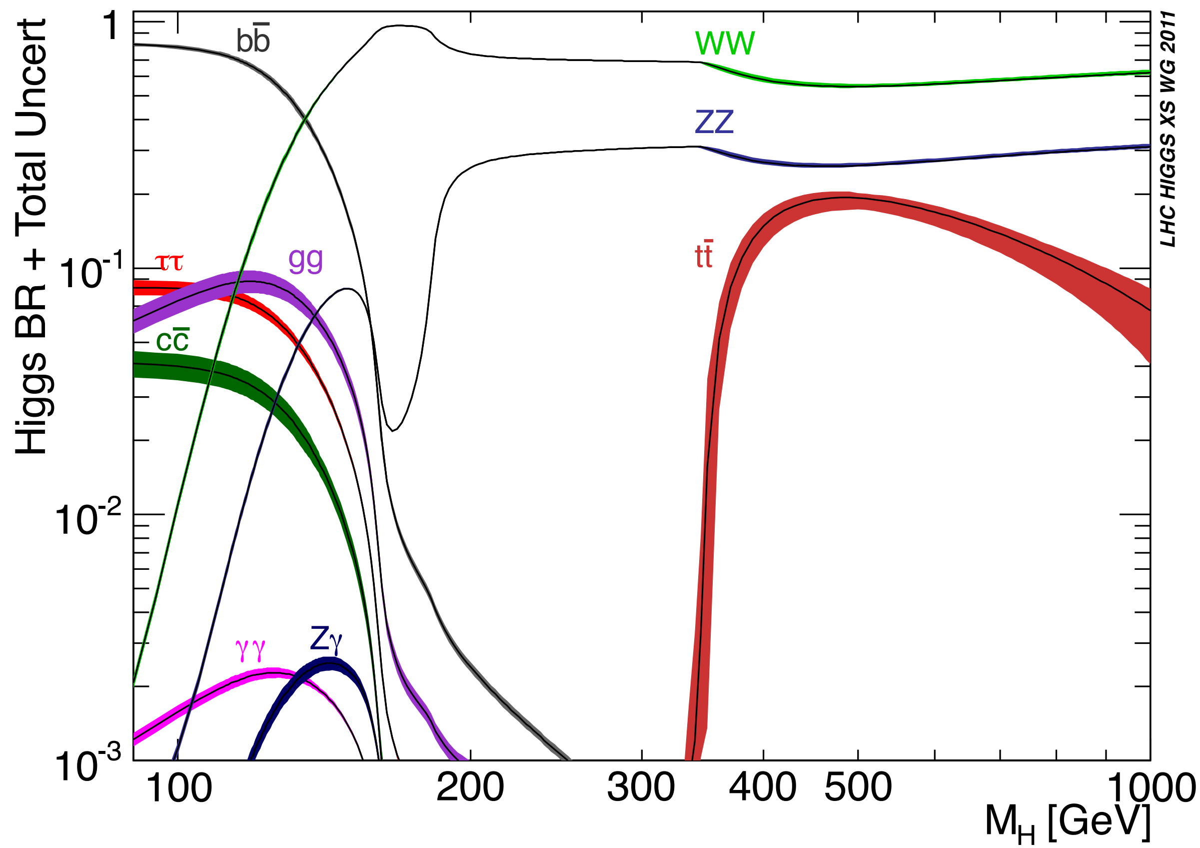


(WW, ZZ, tt, bb, ττ)

Through a triangle loop to massless ones



(gg, γγ)



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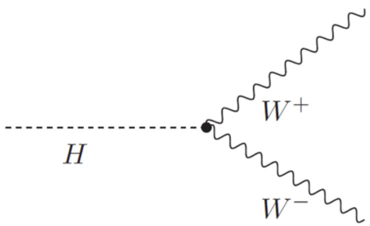

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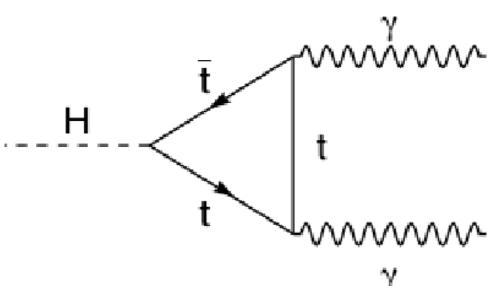

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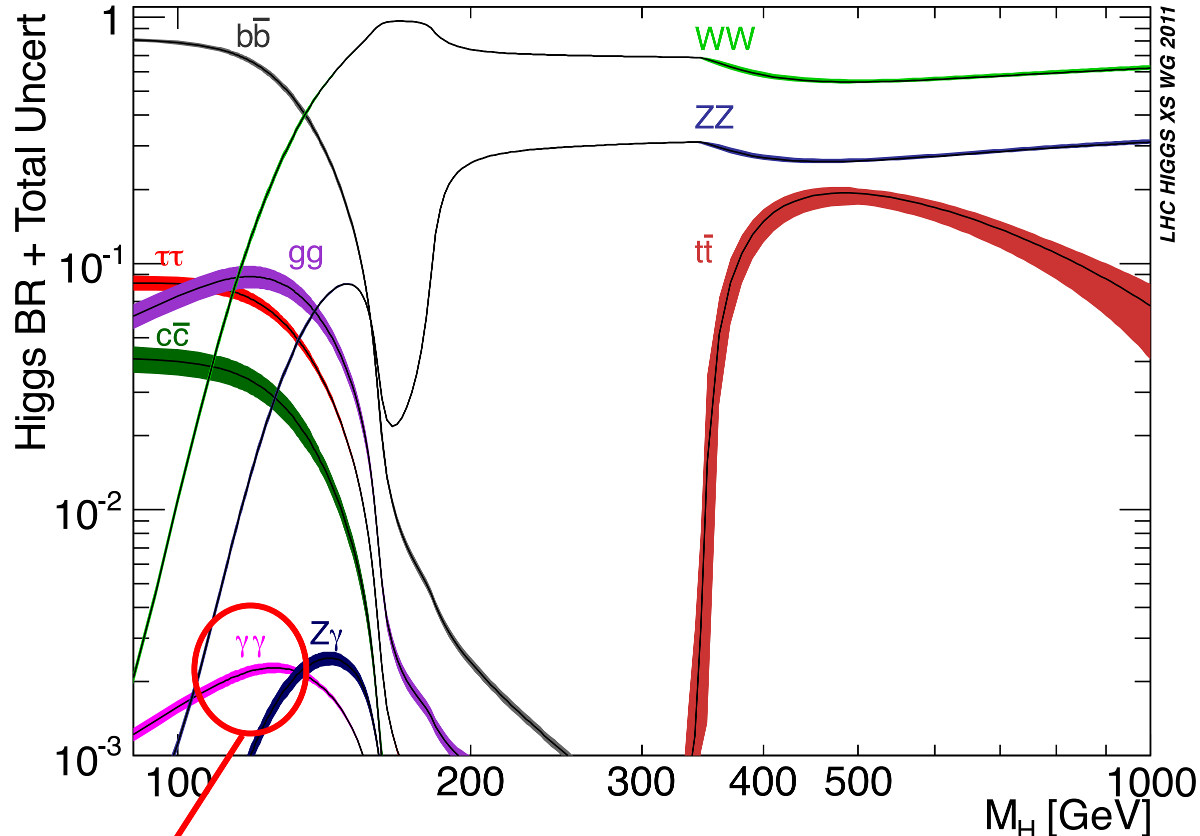
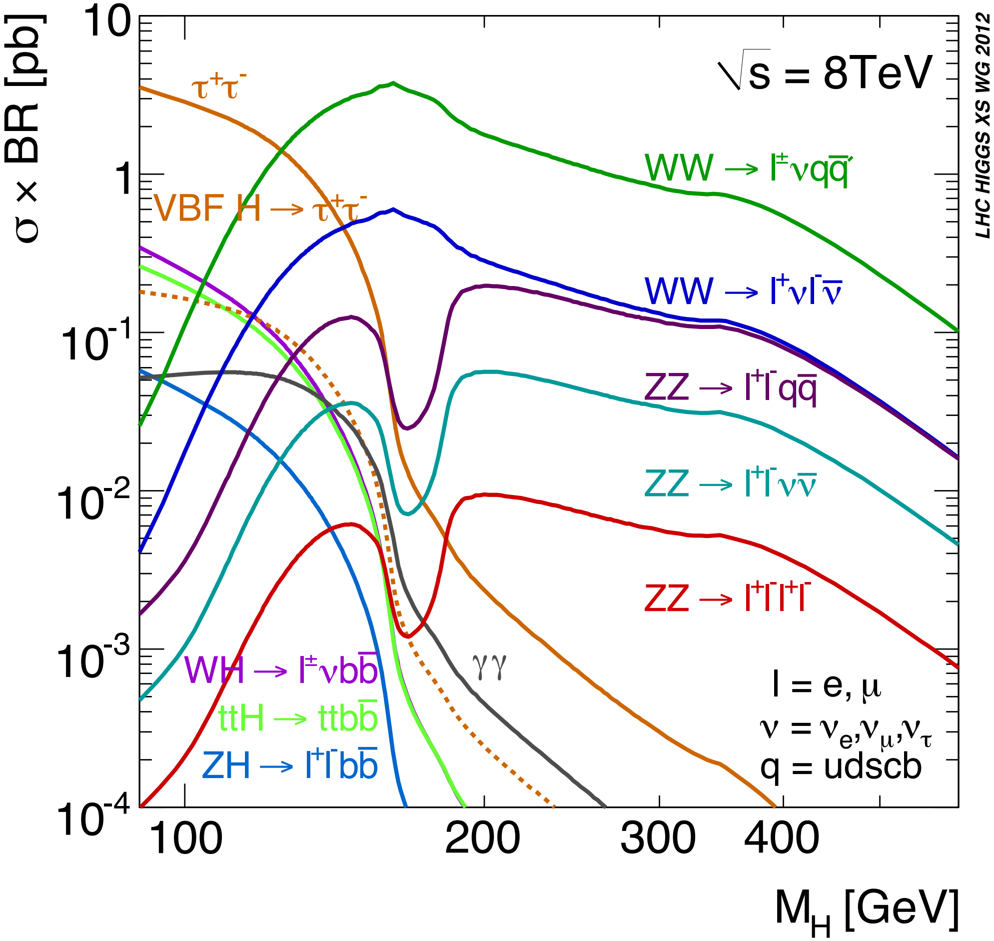


100,000 Higgs bosons produced… times ~0.002 BR to γγ, ~ 200 Higgs to be found via γγ search

Introduction

Cross section times BR



https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSectionsFigures

- WW, ZZ split into decay modes
- Targeting production modes can improve sensitivity
- Not yet the full story!
  - Missing: triggers, efficiencies, resolutions, background cross sections, rejection for each, etc.
  - Low m_H: $\tau\tau$ is largest (cons: detection and backgrounds)
  - High m_H: llvv most sensitive
- Experimentally, 100<m_H<200 is accessible in the most ways
- All modes labeled in the plot (and more) have been studied; here, we'll focus on three

Introduction

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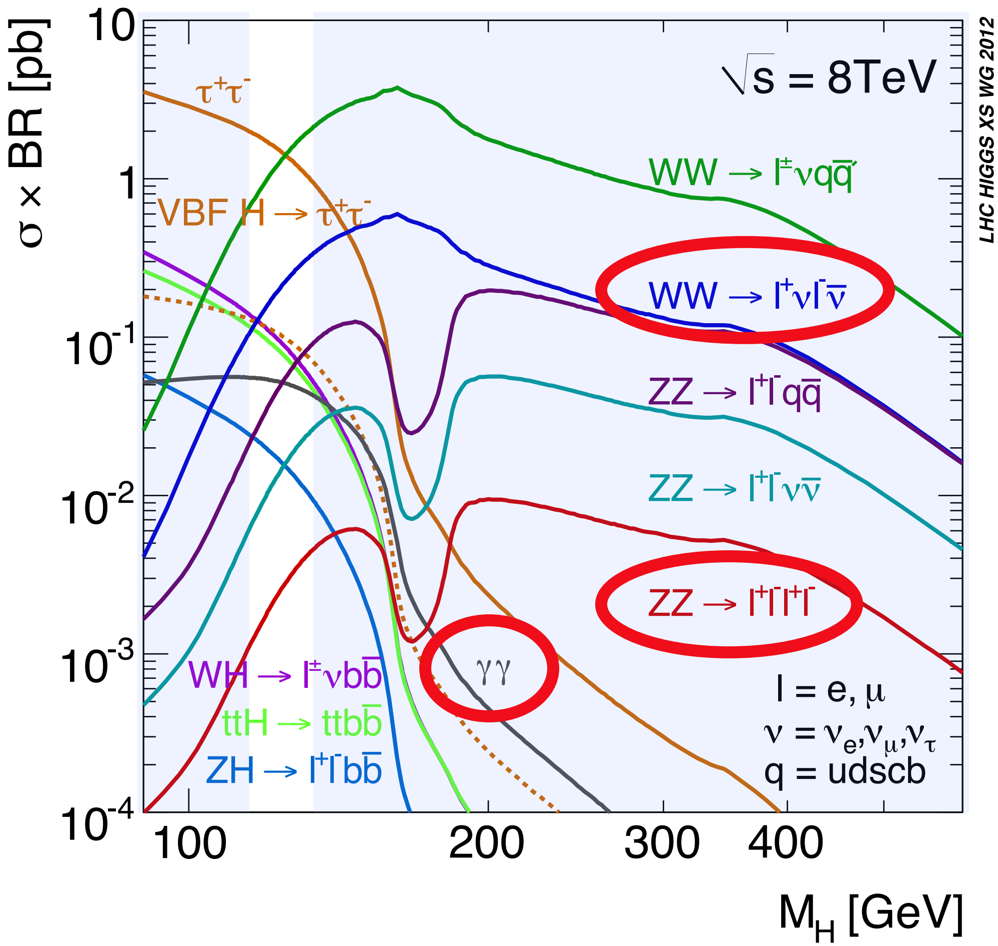

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Limits and p_0 plots

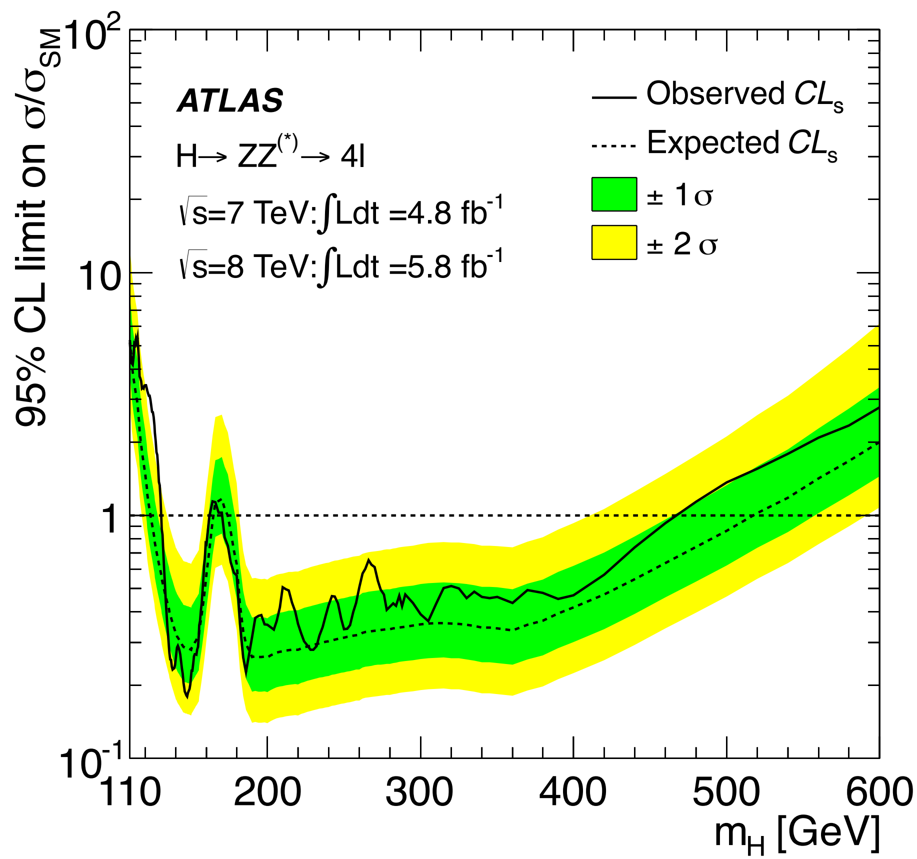
- Null search results do provide valuable information:

  What signal sizes can be ruled out?

- Need reliable background estimations

- Always a probabilistic statement
  - Need to state the "CL" (95%)

- Being a random process, uncertainty bands are needed
- "Expected": median of limits if the signal does not exits
- Observed: from the actual dataset



- Too few events → "strong" limit
- Too many events → "weak" limit

Limits and p_0 plots

- *Too many events* may also, instead, represent a signal
- … do they?

  We quantify it by the probability that background alone would produce an excess as large as observed (or larger)

  → *"Local" p_0*

- Instead of quoting p_0, we refer to it using the "number of sigmas" that it would represent in a Gaussian tail.
  - 1 sigma → p_0 = 16%
  - 3 sigma → p_0 = 0.13%
  - 5 sigma → $p_0 = 2.9\times10^{-7}$

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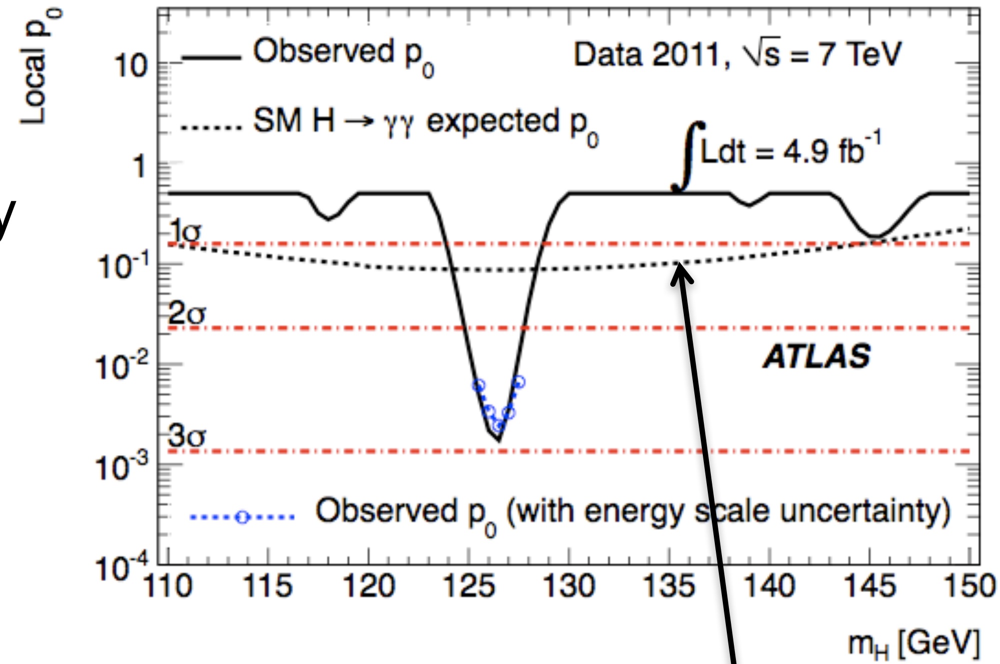

Expected from SM Higgs at given m_H