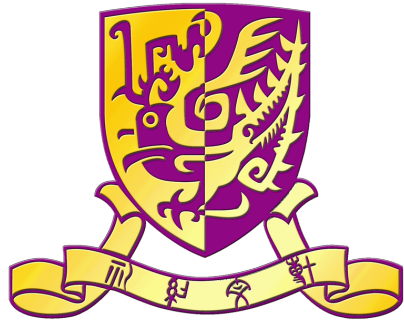


The discovery of the Higgs boson



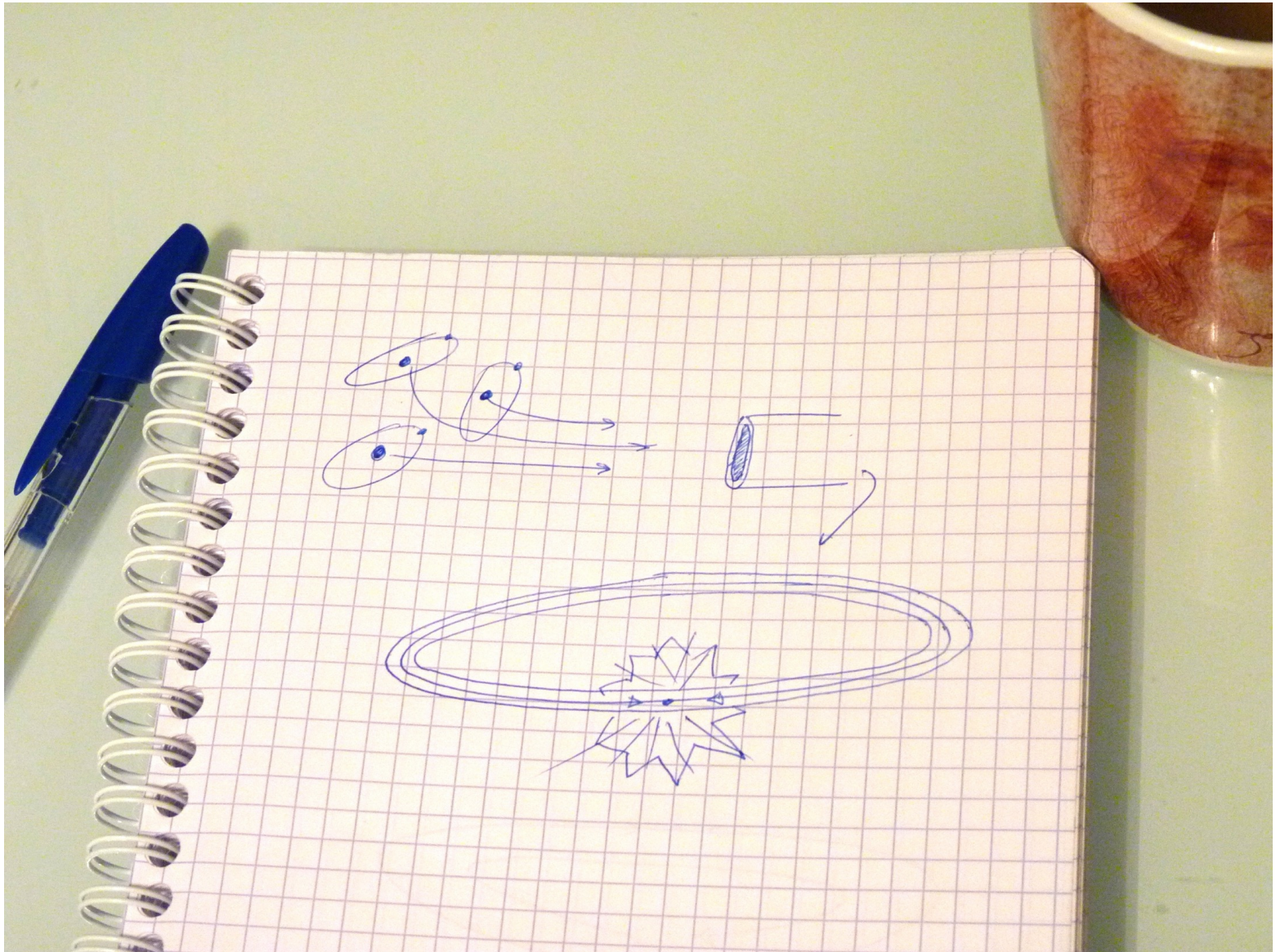
Luis Roberto Flores Castillo
The Chinese University of Hong Kong



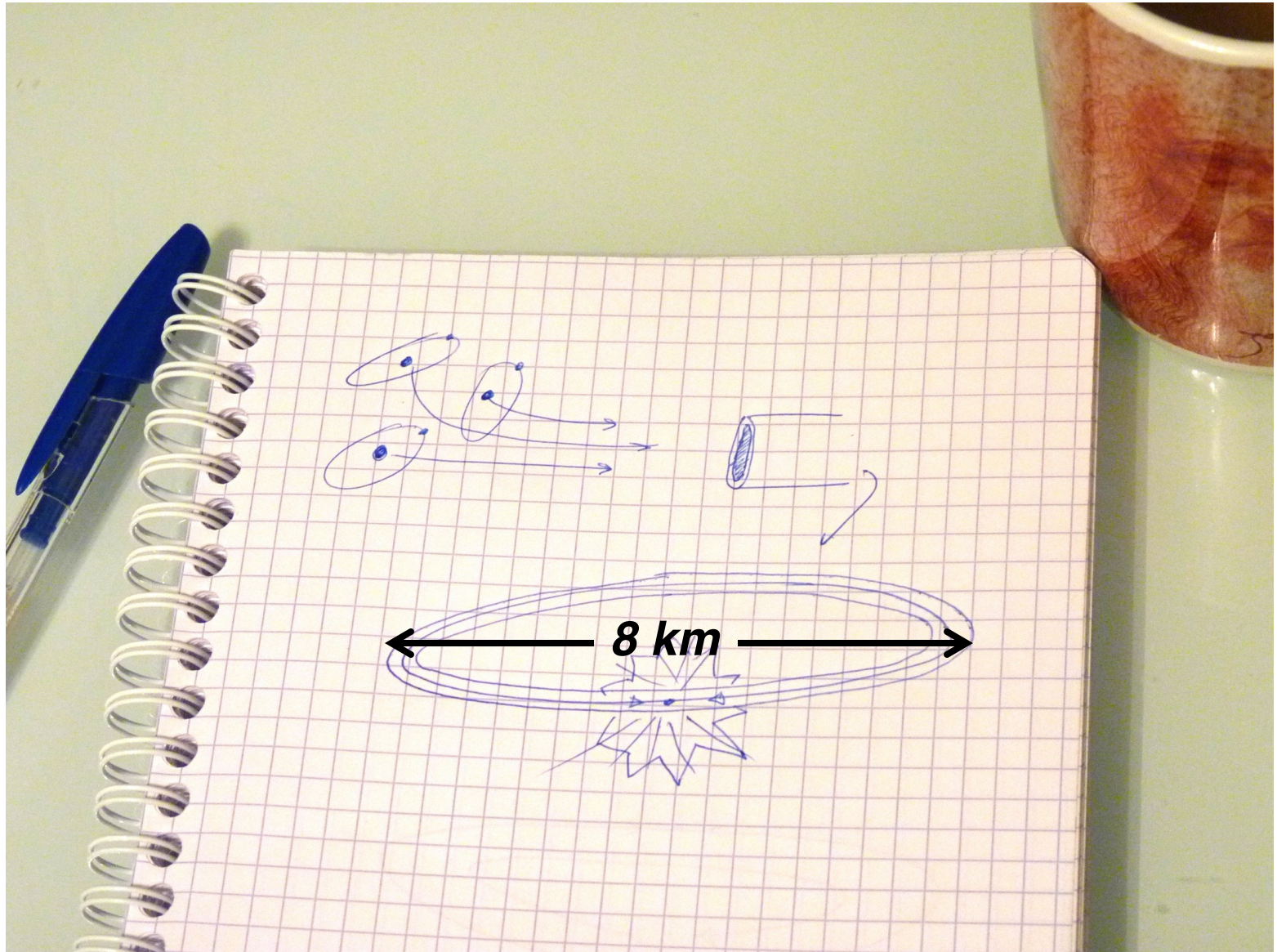
International High School Teachers Program 2024
CERN, Switzerland

July 2, 2024

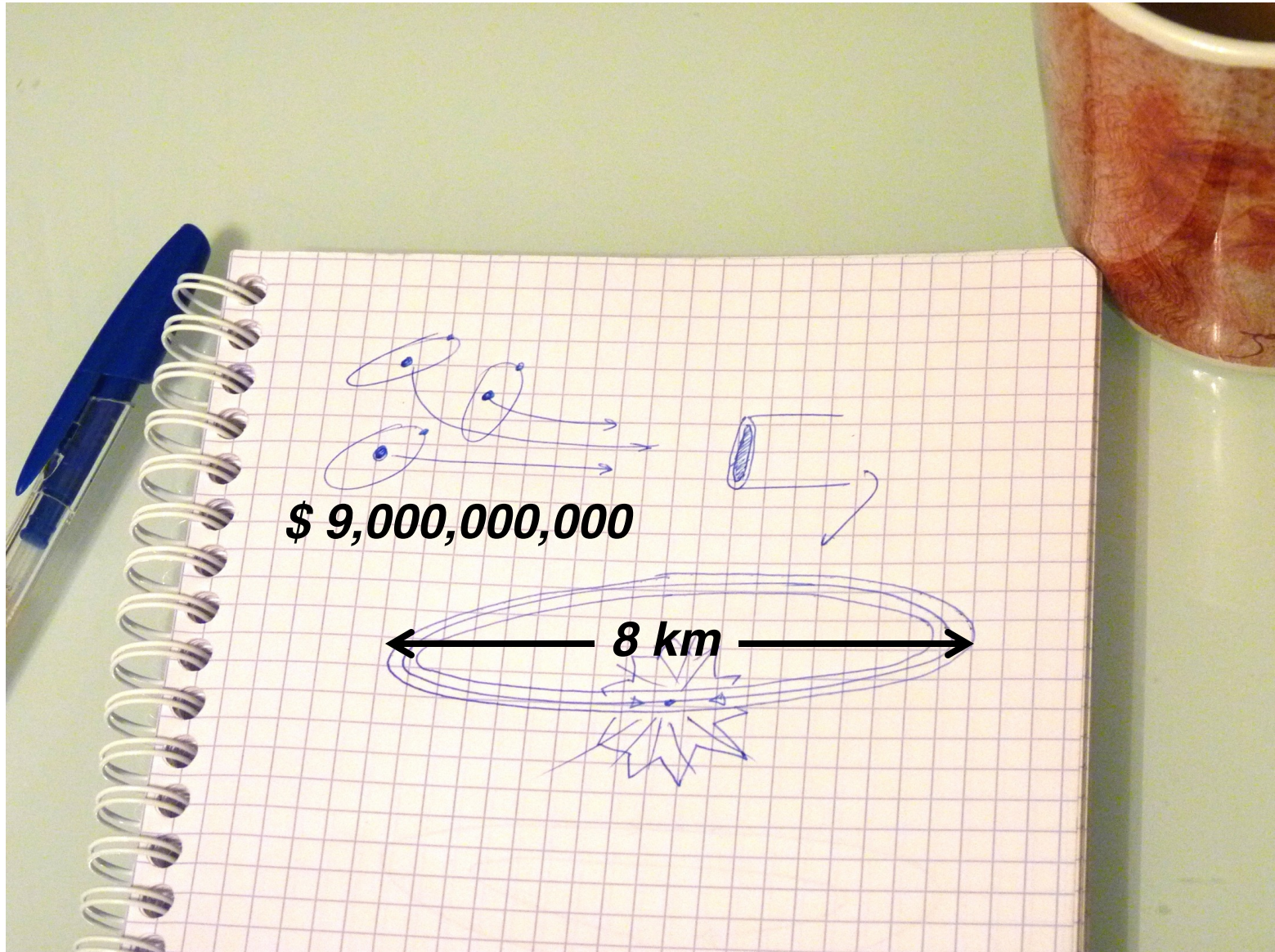
Aiming high



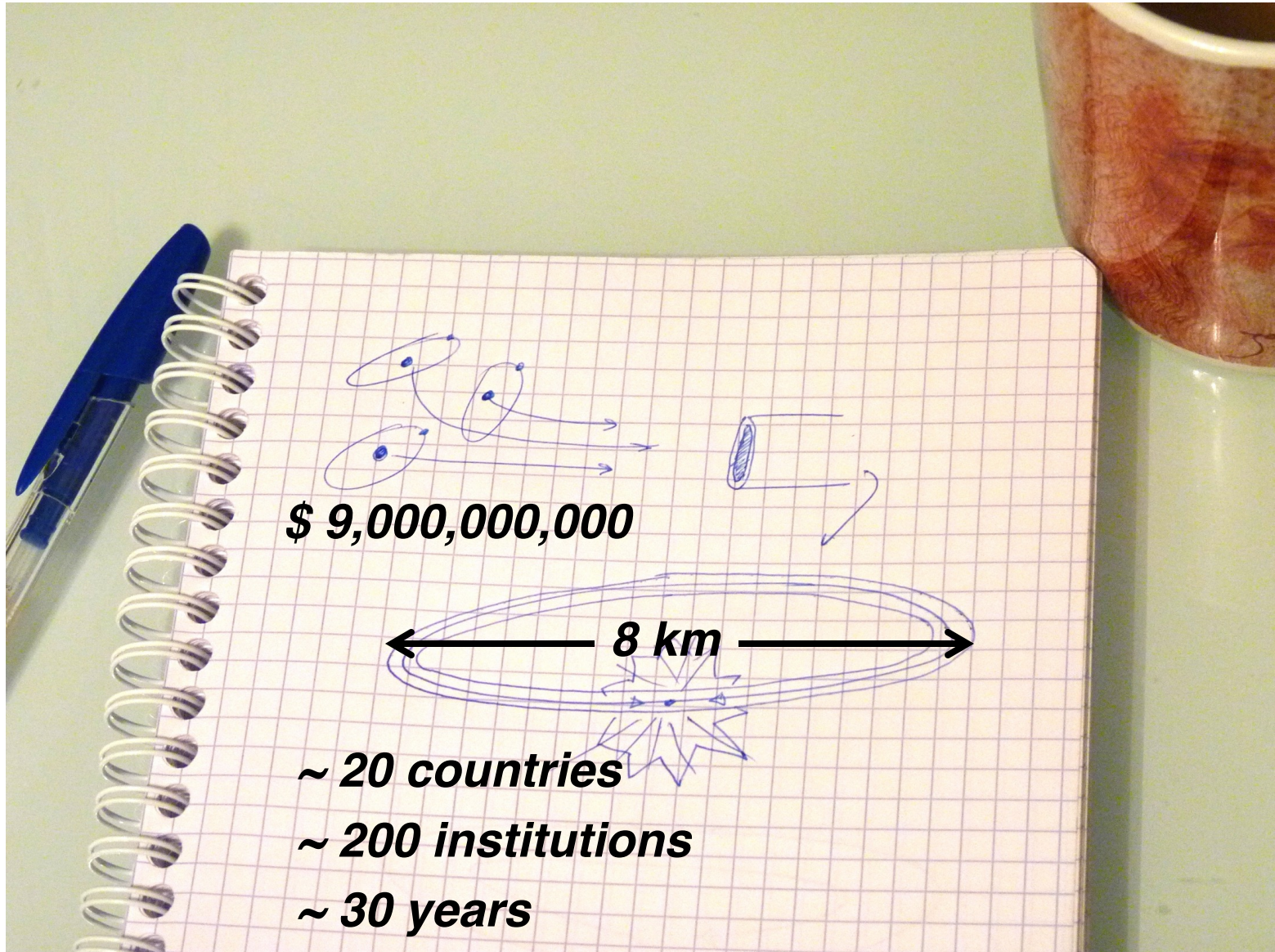
Aiming high

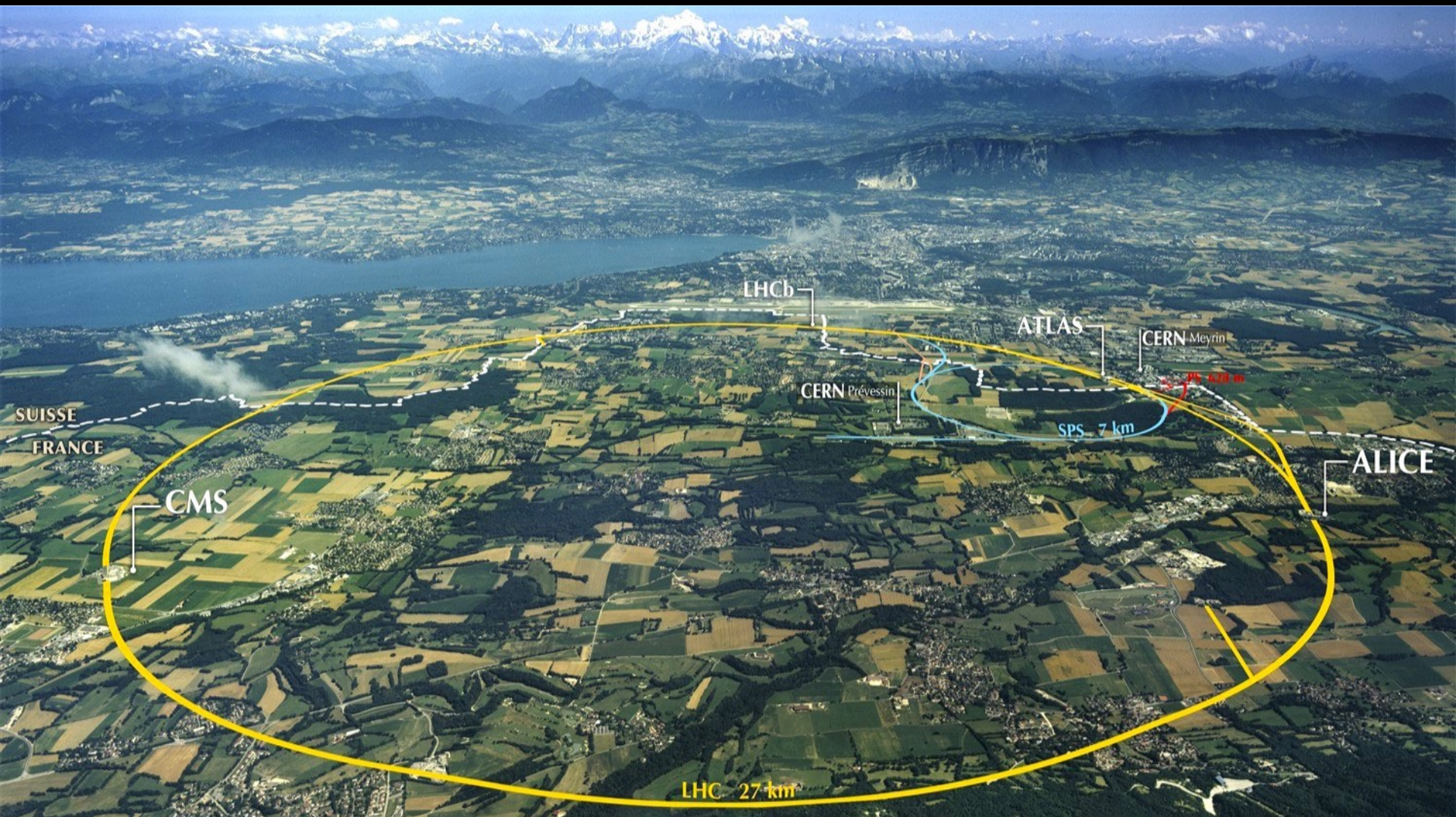


Aiming high



Aiming high





July 4, 2012

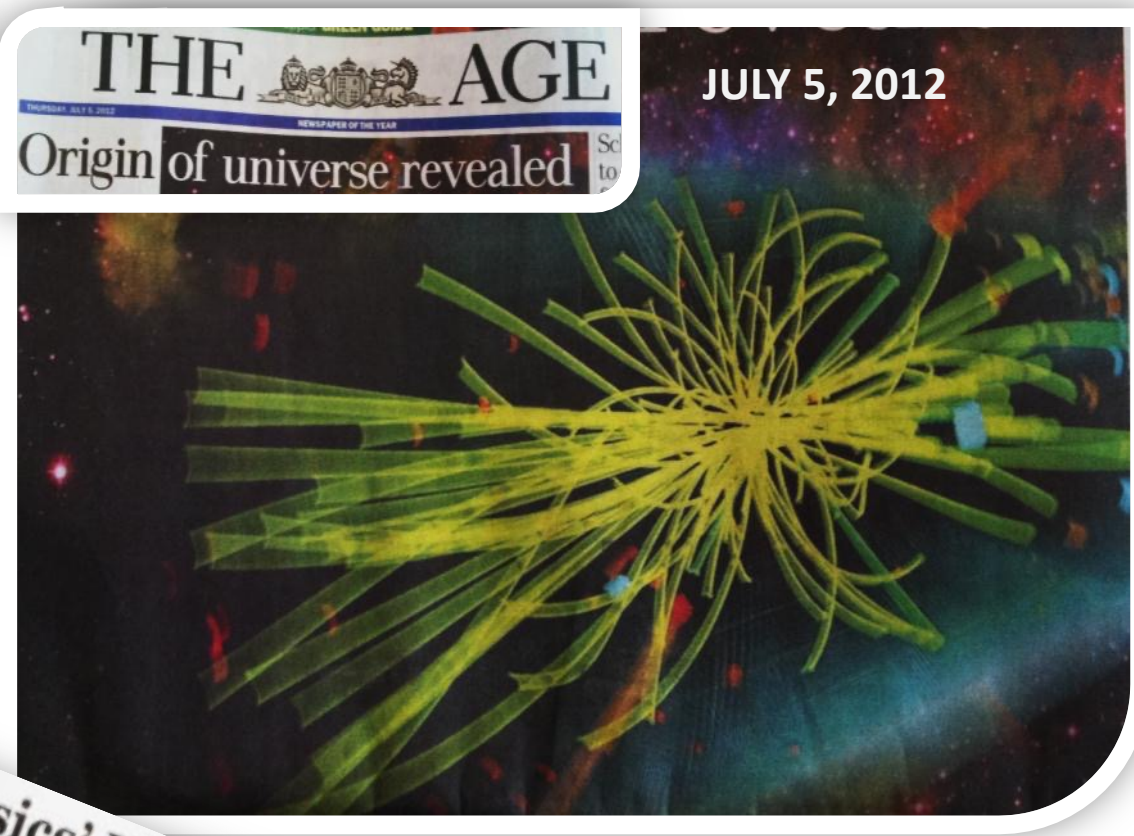


“I think we have it” – Rolf Heuer, CERN’s Director General

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

The 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

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

JULY 7TH - 13TH 2012

Economist.com

A giant leap for science



Finding the
Higgs boson

JULY 7TH - 13TH 2012

Worldwide excluding UK

NEWSPAPER OF THE YEAR

Wimbledon 2012

Dramatic victory takes
Murray through to semi-finals



Scientists prove existence of 'God particle'

A computer-generated
image shows particle
collisions expected from
the decay of a Higgs boson

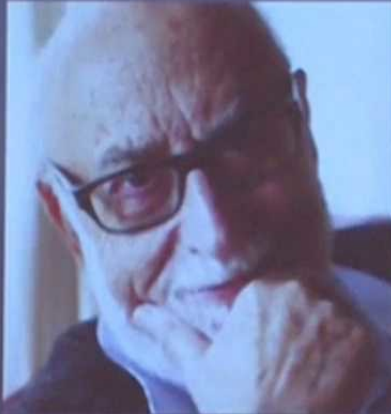


- 'Momentous' find after 45-year hunt for Higgs boson
- Professor weeps as his life's work finally bears fruit
- Physicist deserves the Nobel Prize, says Hawking





The Nobel Prize in Physics 2013



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."

October 8, 2013

What is the Higgs boson?











Fundamental building blocks?

Periodic Table of Elements
© AllAboutGemstones.com

Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Period 1	1 H																	2 He
Period 2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
Period 3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
Period 4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
Period 5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
Period 6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
Period 7	87 Fr	88 Ra	89 +	104 Rf	105 Ha	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
	<i>s-block</i>		<i>d-block</i>										<i>p-block</i>					
<i>f-block</i>	Lanthanide Series		57 *La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
	Actinide Series		89 +Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

H - Gas **Li - Solid** **Br - Liquid** **Tc - Synthetic**
■ Non-Metals ■ Transition Metals ■ Rare Earth Metals ■ Halogens
■ Alkali Metals ■ Alkali Earth Metals ■ Other Metals ■ Inert Elements

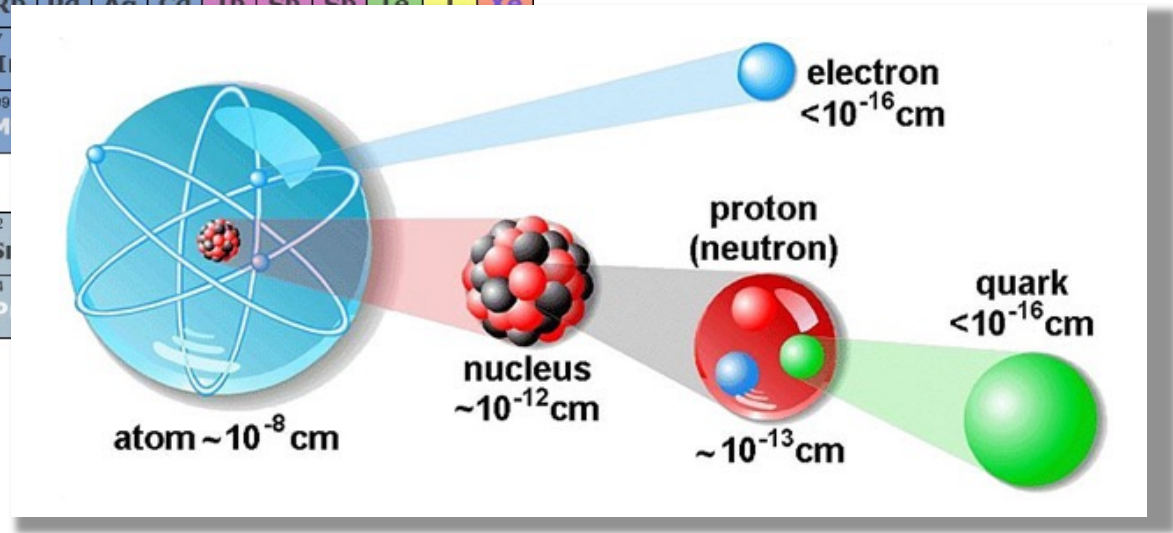
- ~1869, Mendeleev published “Principles of Chemistry”
- All that complexity from ~100 “elements”

Fundamental building blocks?

Periodic Table of Elements
© AllAboutGemstones.com

Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +	104 Rf	105 Ha	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

H - Gas **Li - Solid**
■ Non-Metals ■ Transition Metals
■ Alkali Metals ■ Alkali Earth Metals

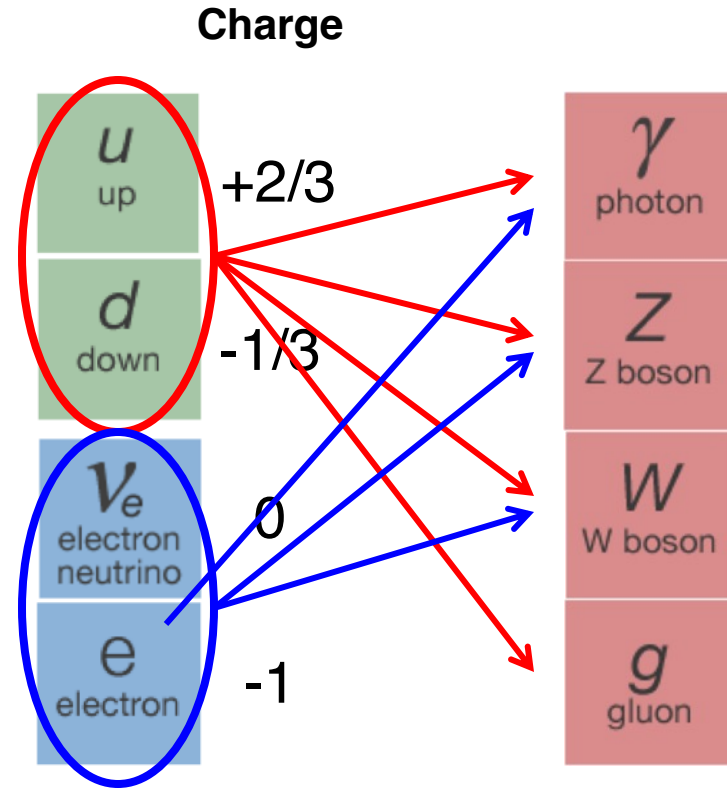


... but all of them are combinations of THREE particles.



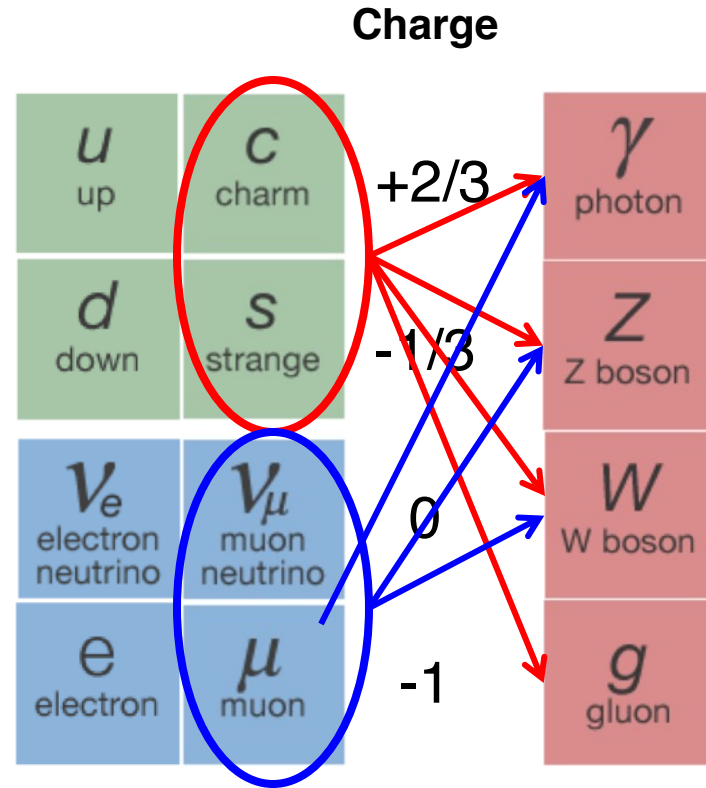
Fundamental building blocks?

- 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**

	Fermions			Bosons	
Quarks	u up	c charm	t top	γ photon	Force carriers
	d down	s strange	b bottom	Z Z boson	
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
	e electron	μ muon	τ tau	g gluon	

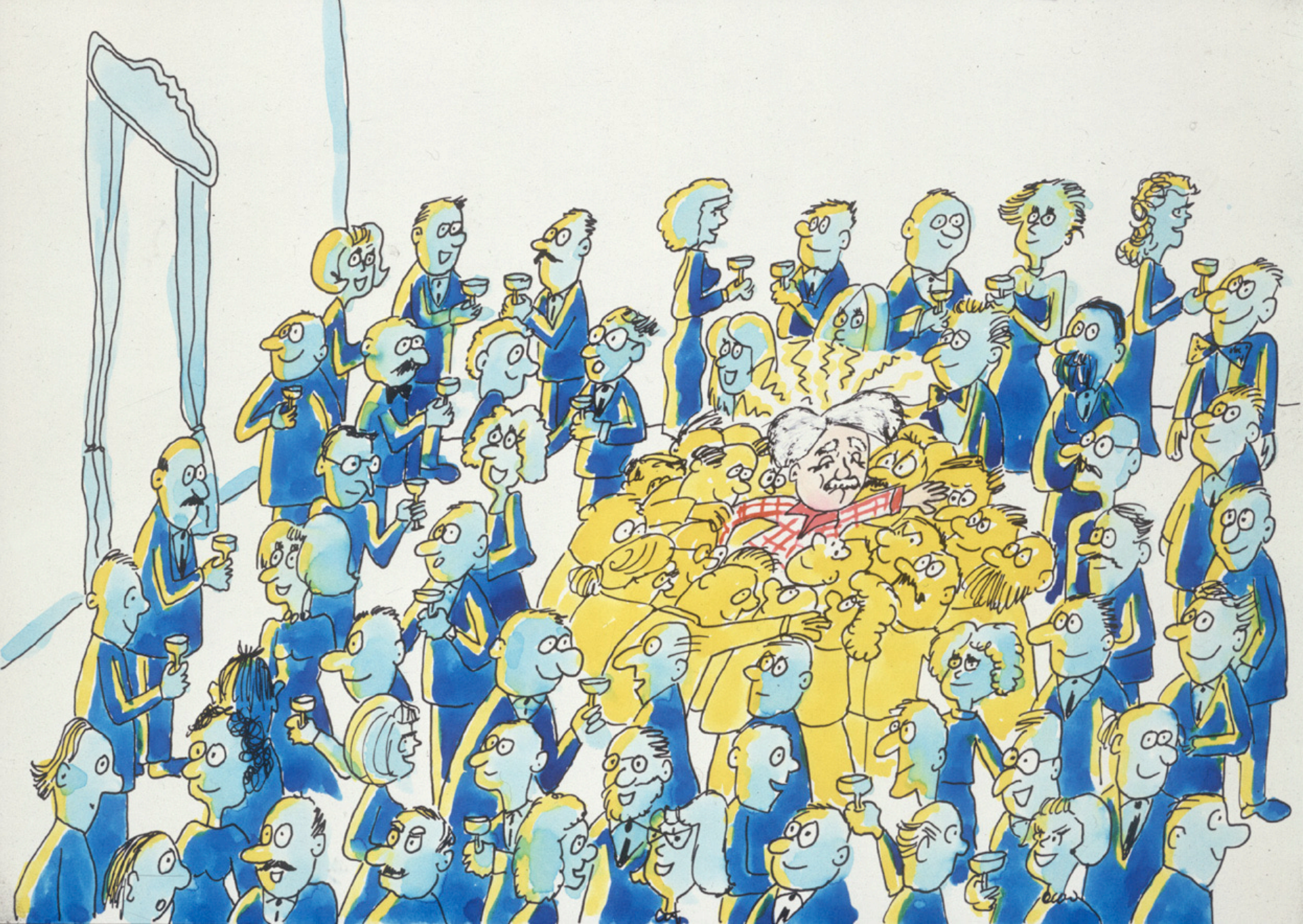
- In 1964, there was a problem: the model worked **only if all elementary particles had ZERO mass**

“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.







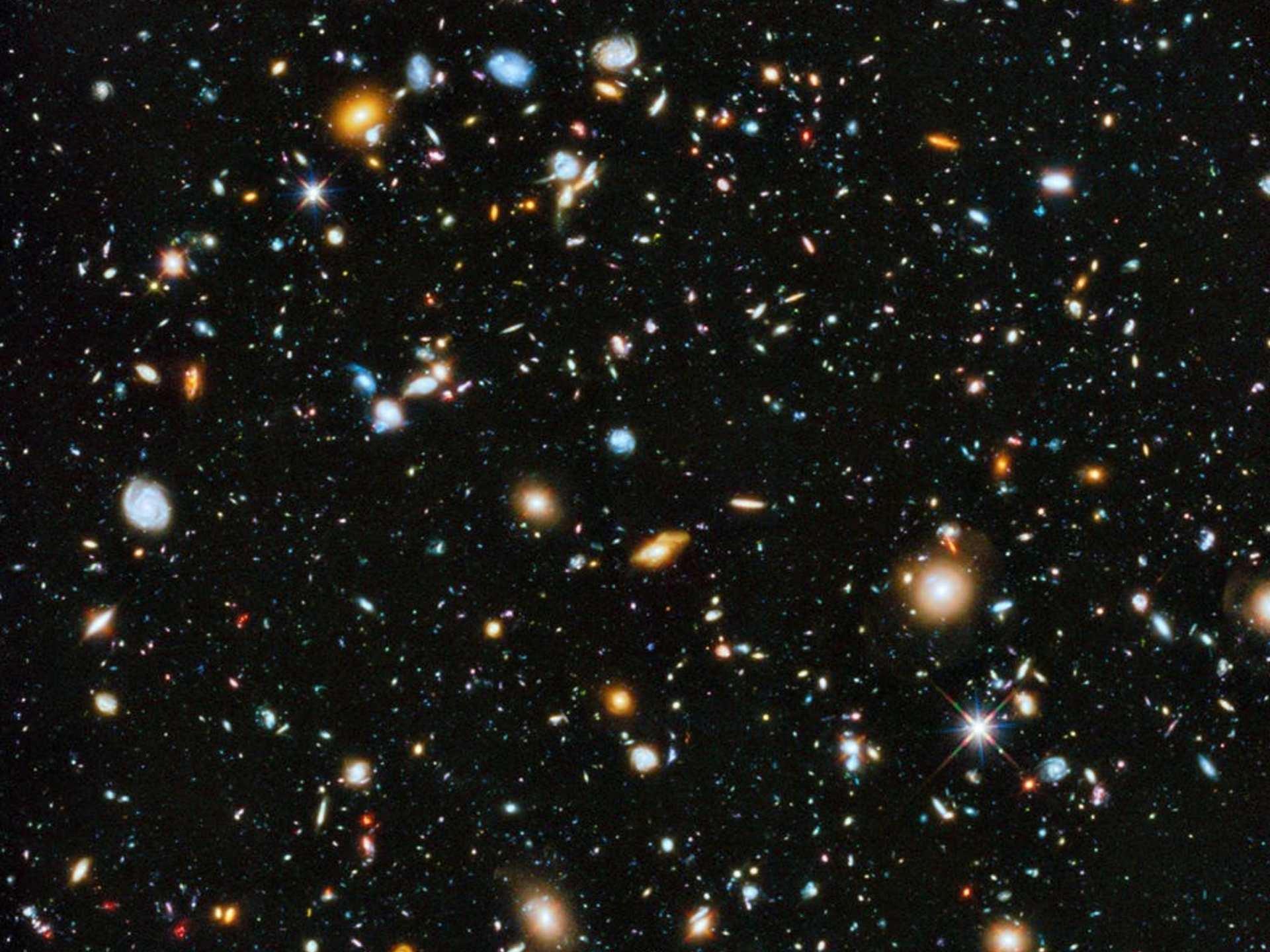




“For every complex problem there is an answer that is clear, simple, ...

“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

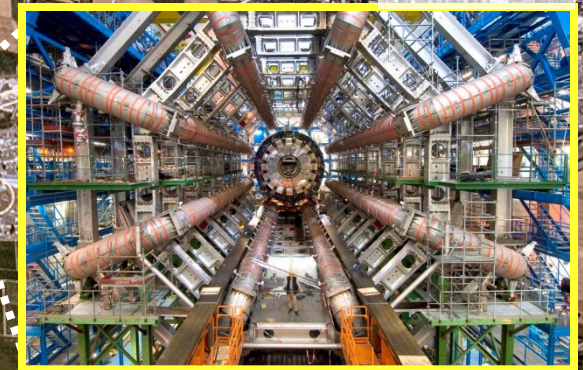
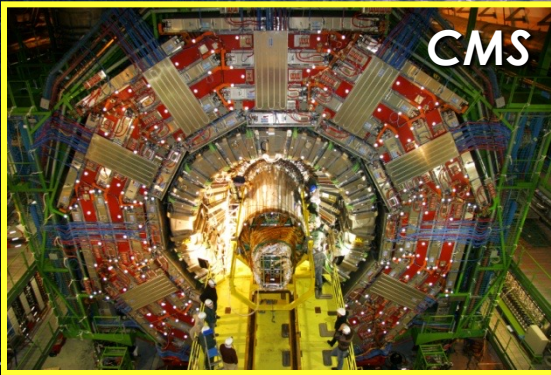
Geneva
Airport

- 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

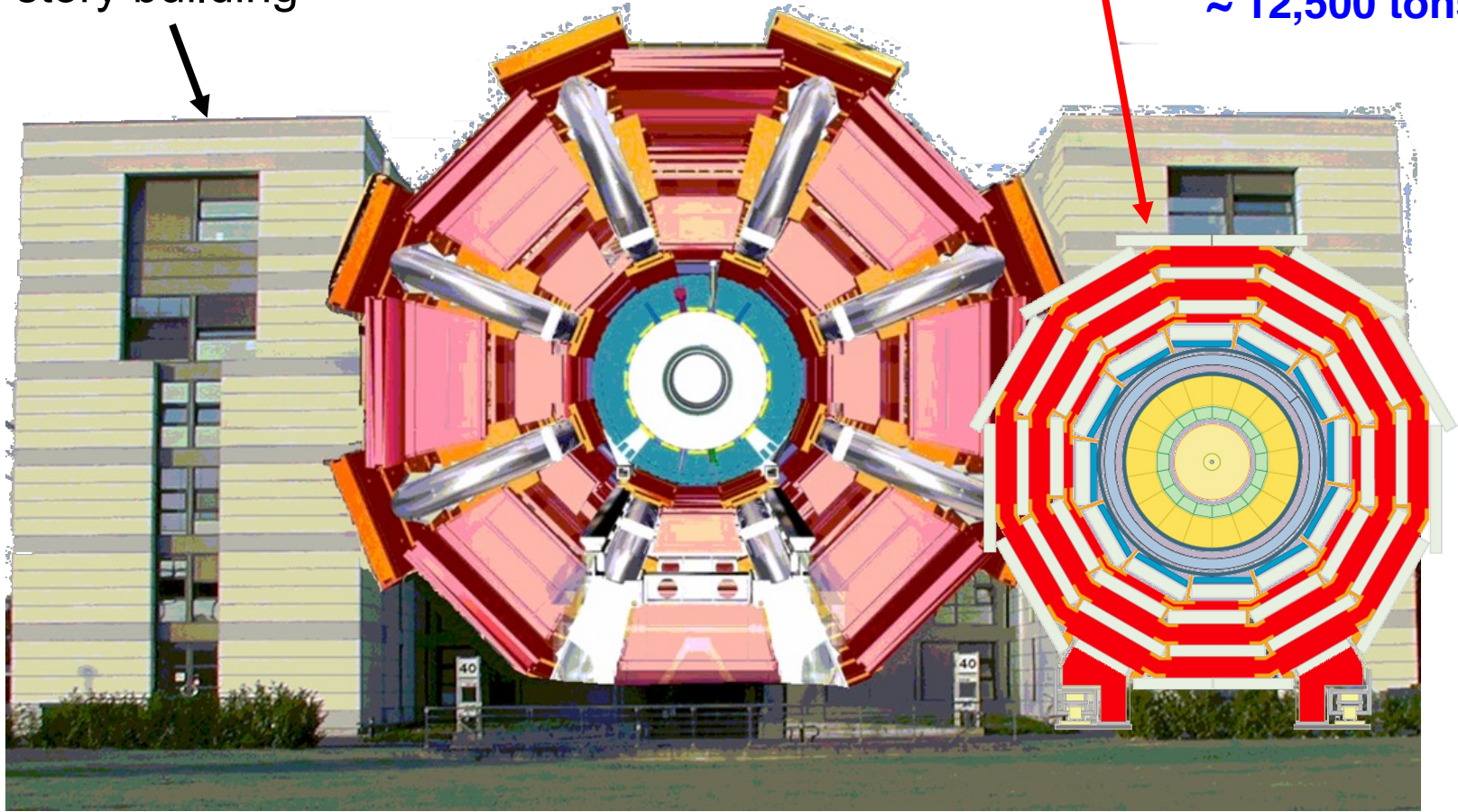


~ 3000 scientists, 182 institutions, 42 countries

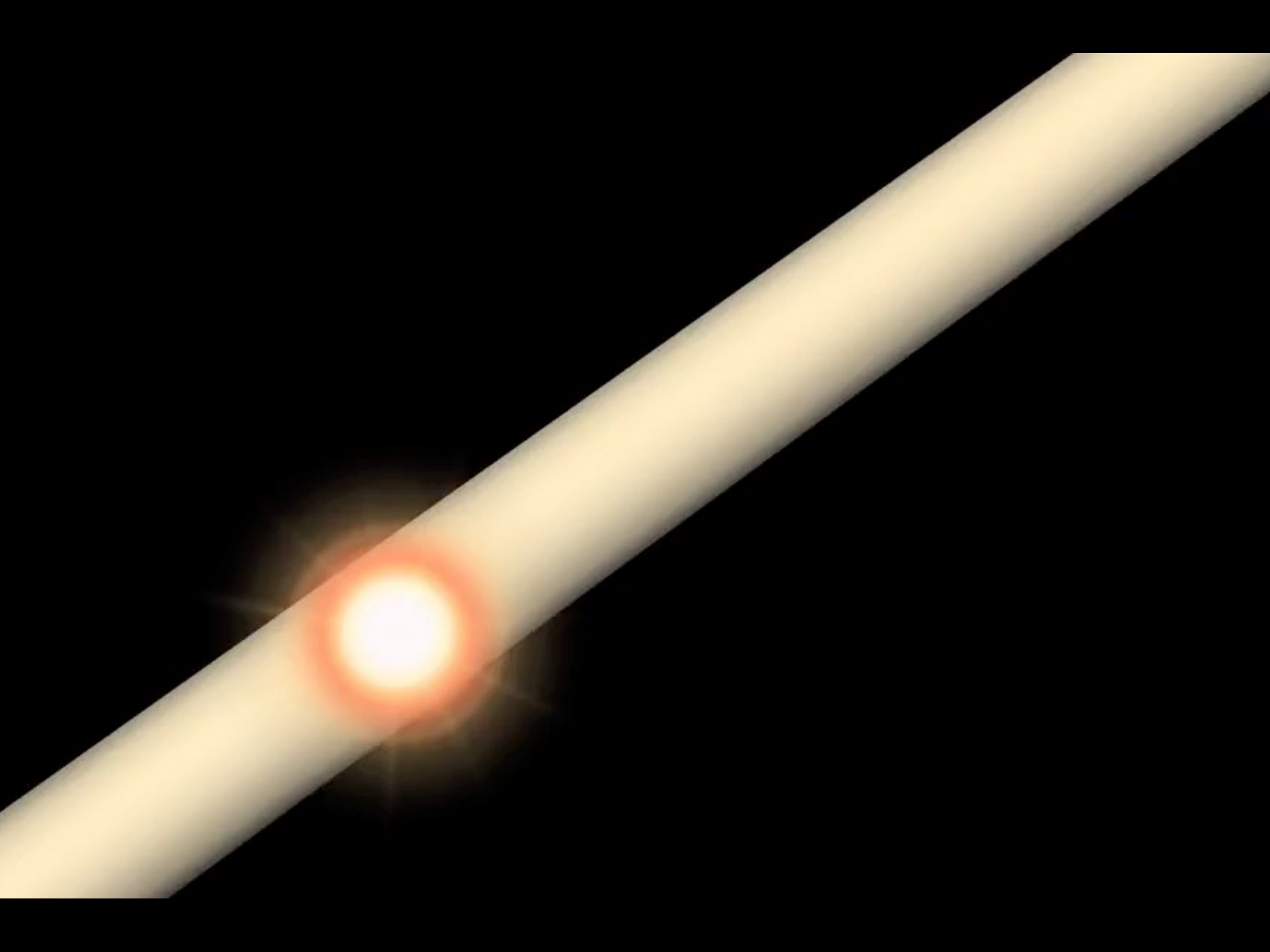
Five-story building

ATLAS ~ 25 m × 45 m
~ 7,000 tons

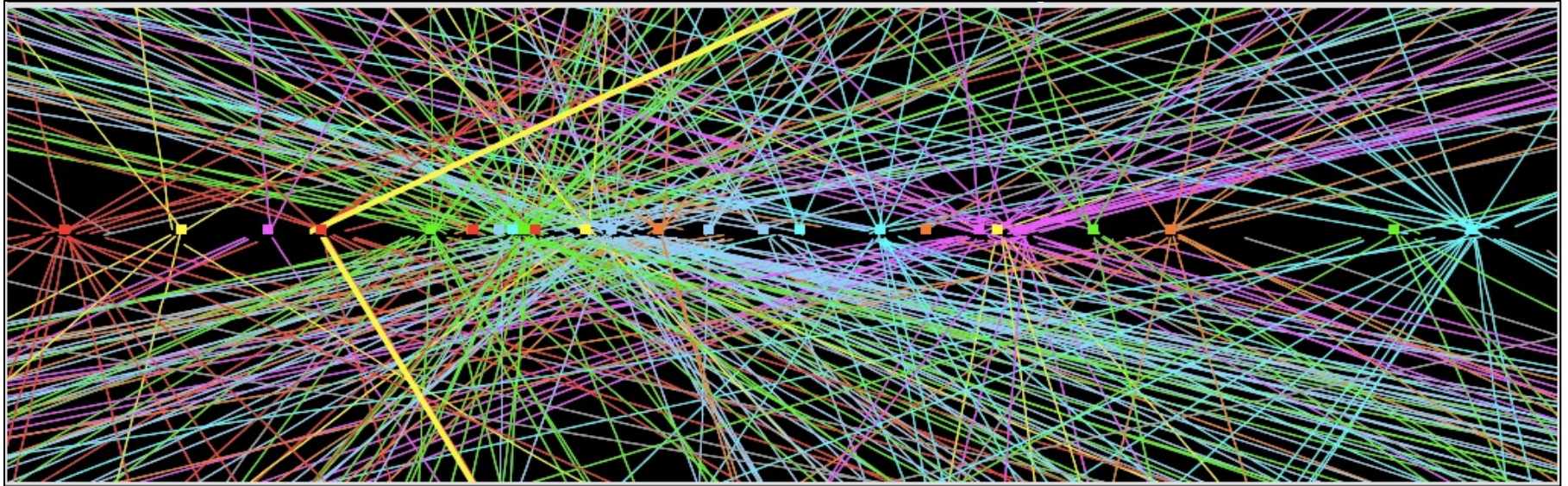
CMS ~ 15 m × 21.5 m
~ 12,500 tons



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



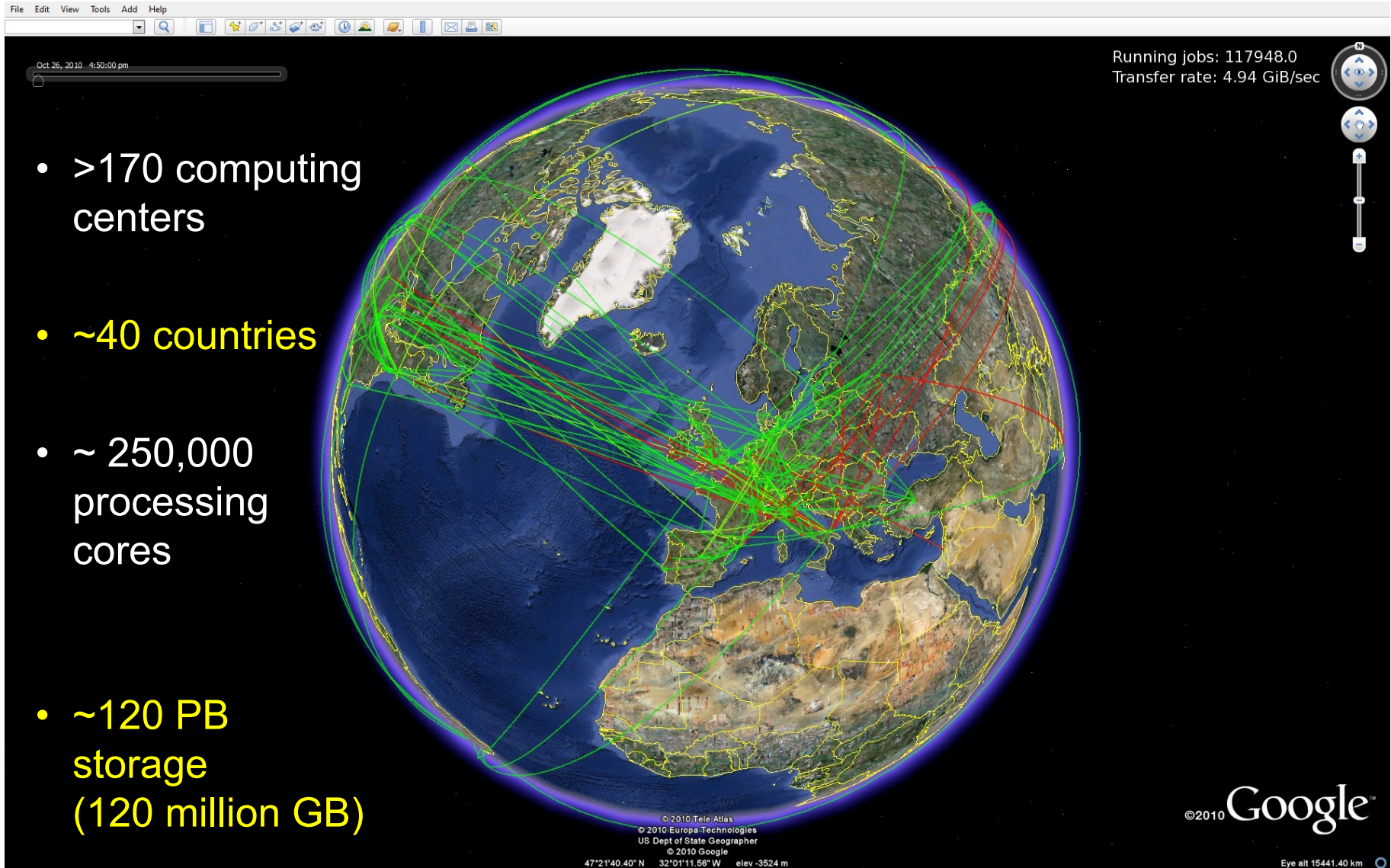
Data



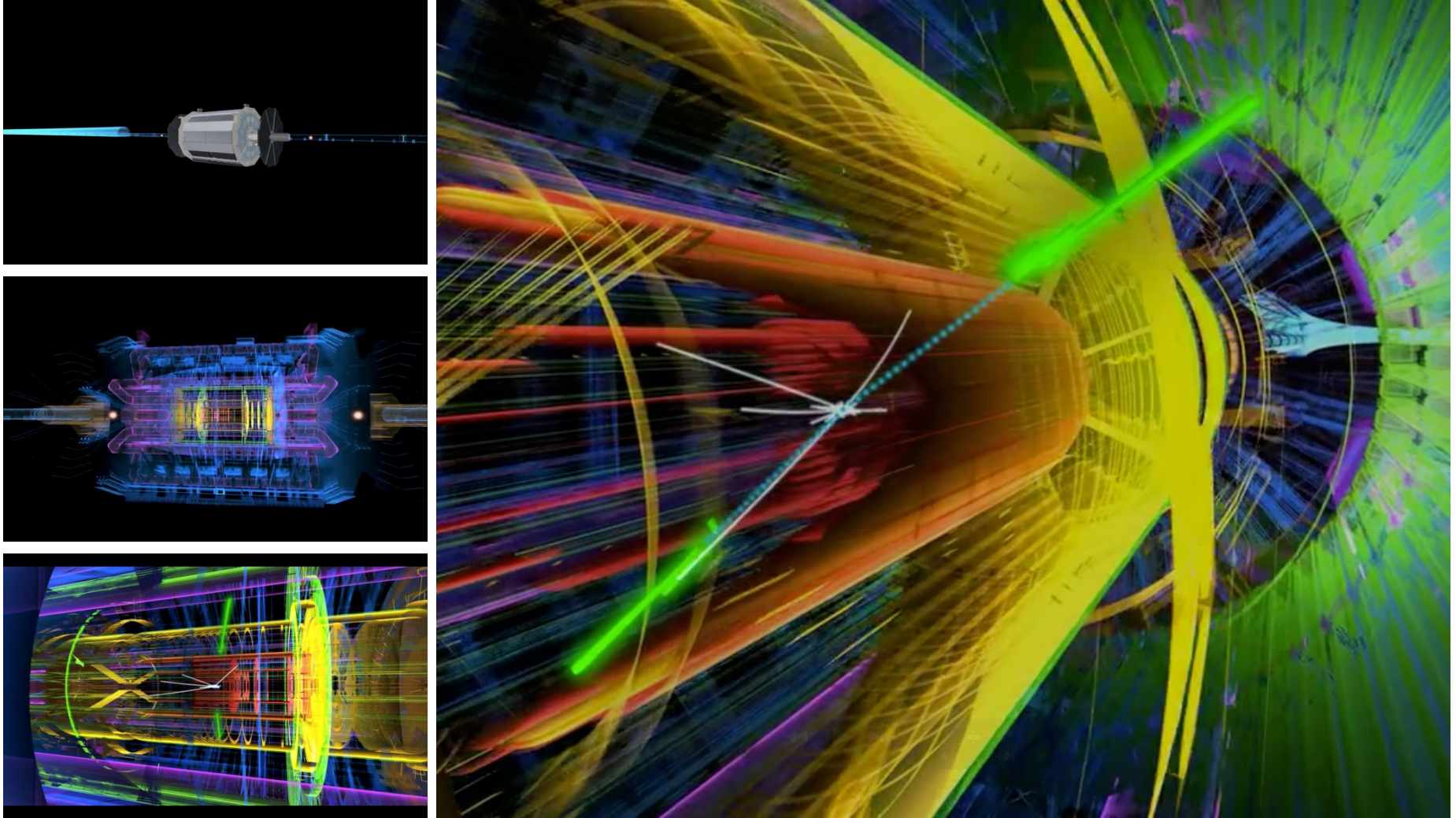
$Z \rightarrow \mu\mu$ event from 2012, with 25 reconstructed vertices

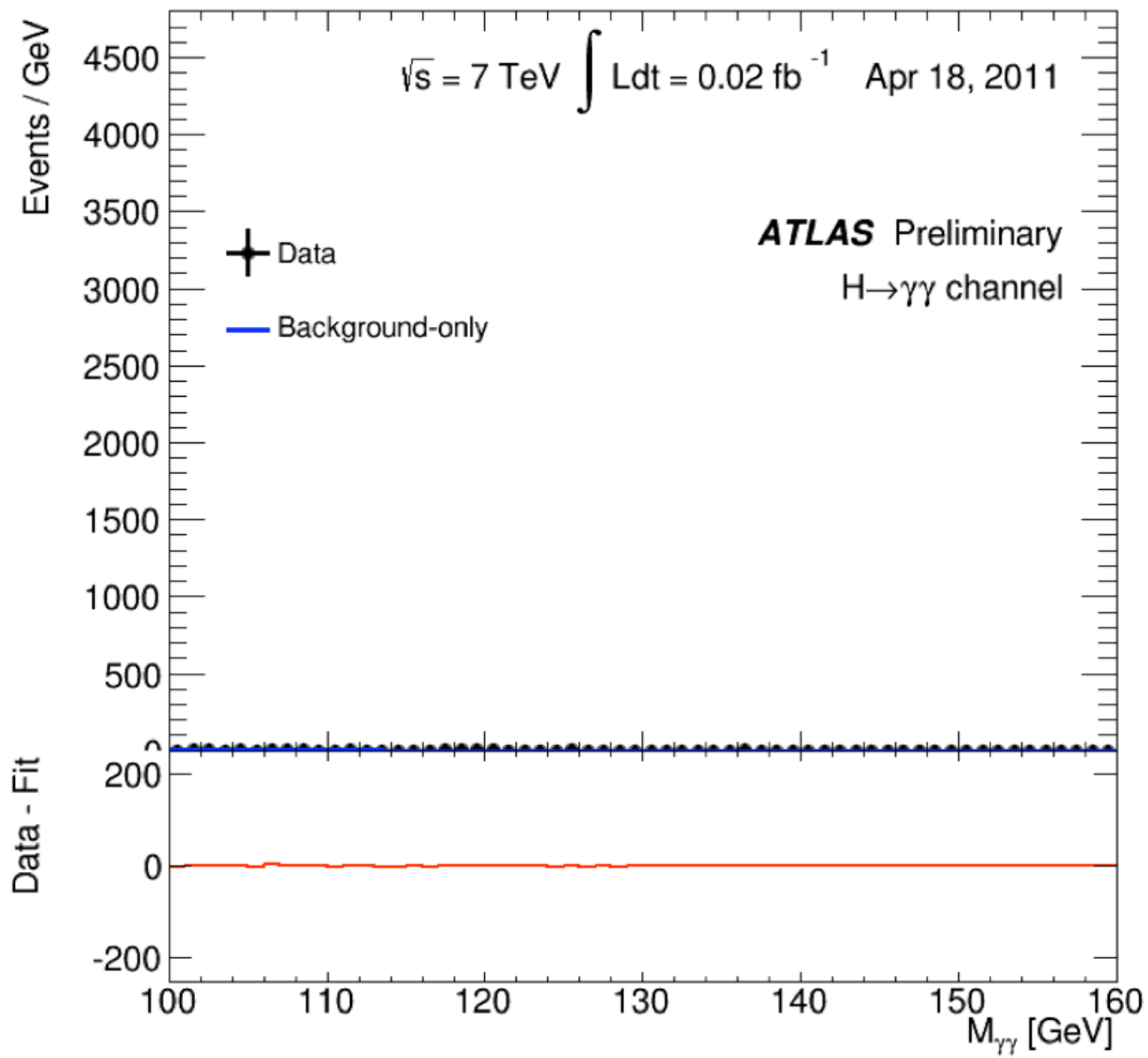
- Each bunch crossing ~ 20 pp interactions
- 40 M crossings per second \times 20 pp per crossing, spacing: 600 M pp/s
- Fast selection systems (“trigger systems”) keep only 400 collisions/s
- Each pp collision produces hundreds of particles
- If stored in using CD's, ...

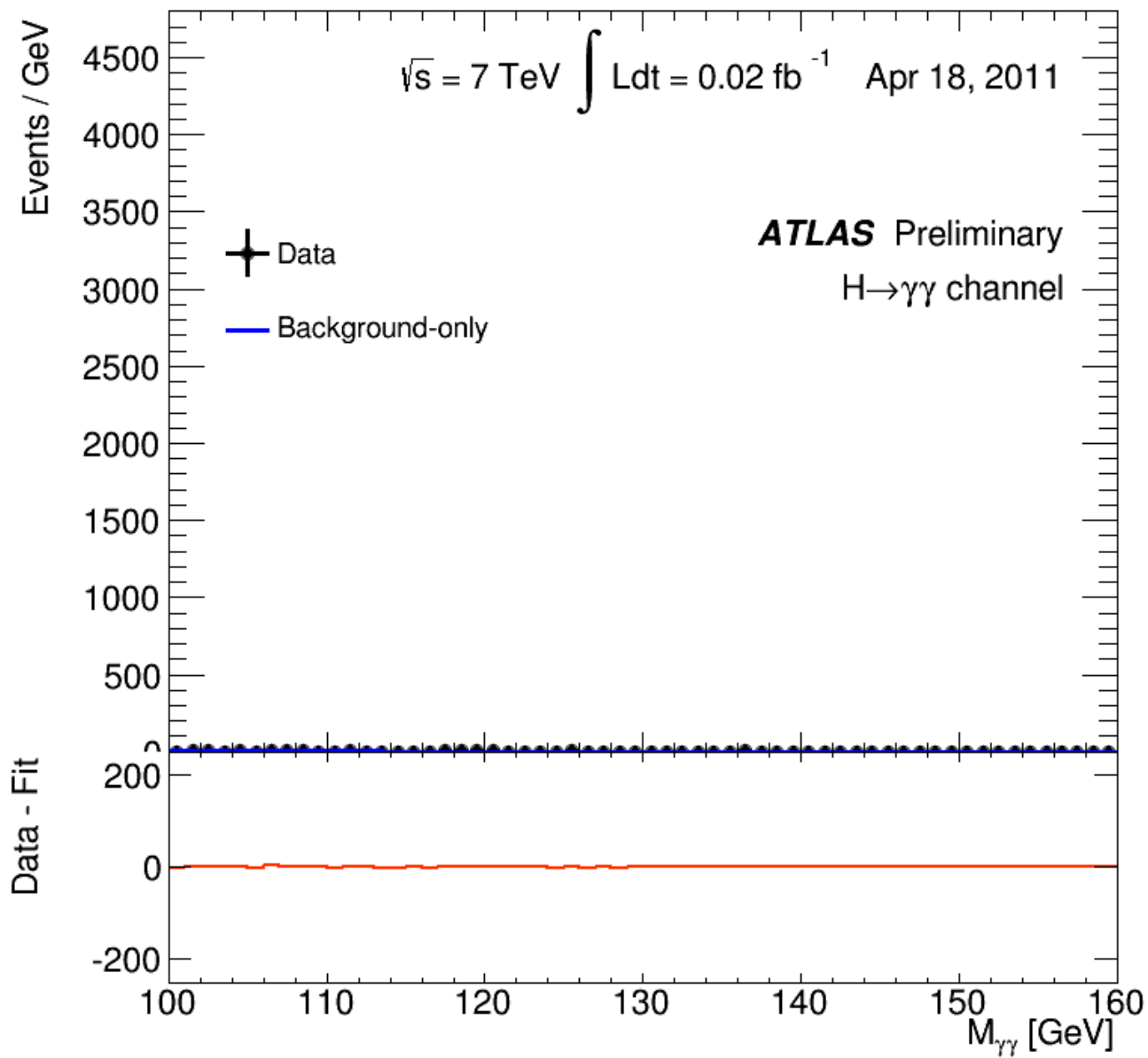
Worldwide LHC Computing Grid



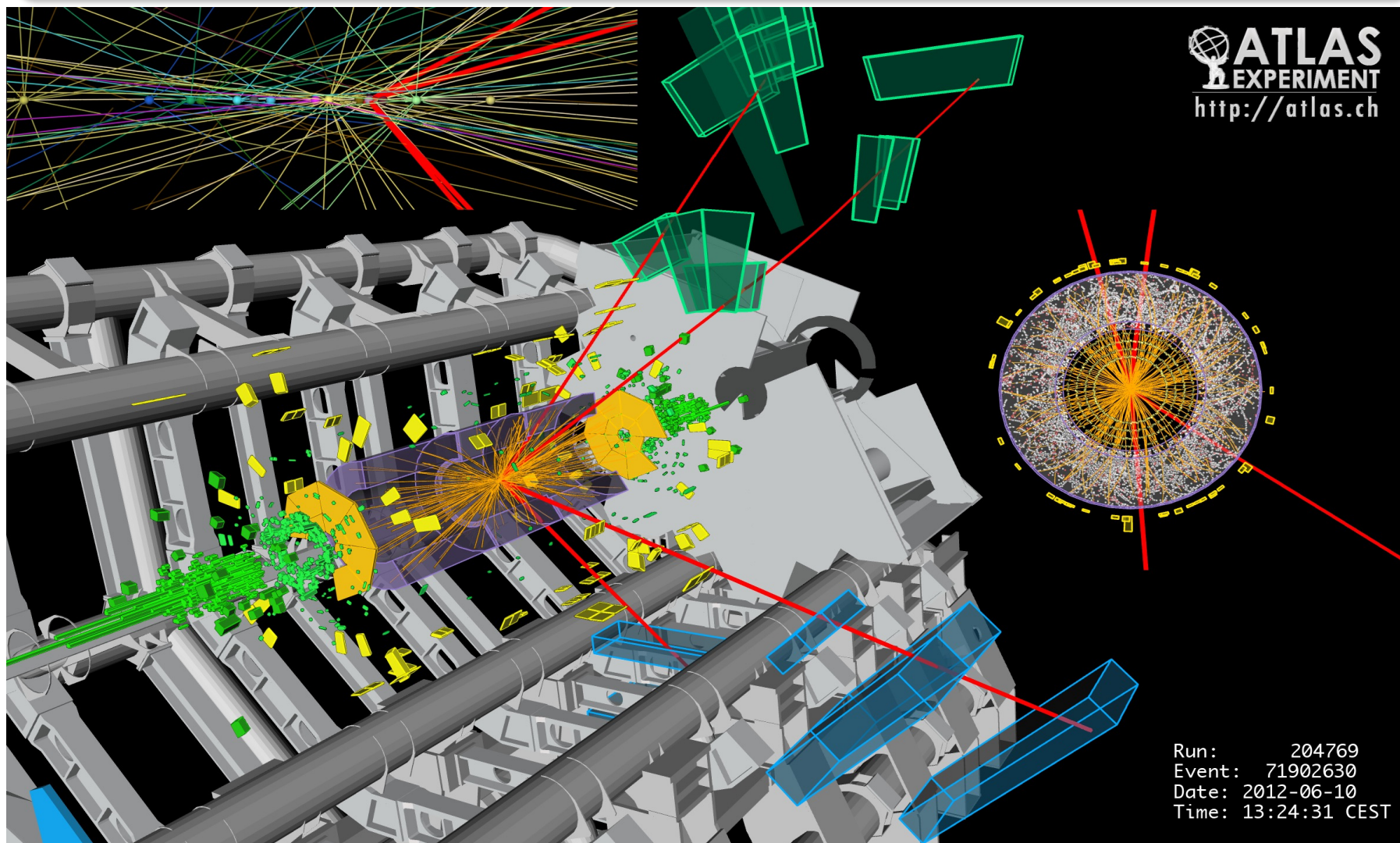
$$H \rightarrow \gamma\gamma$$





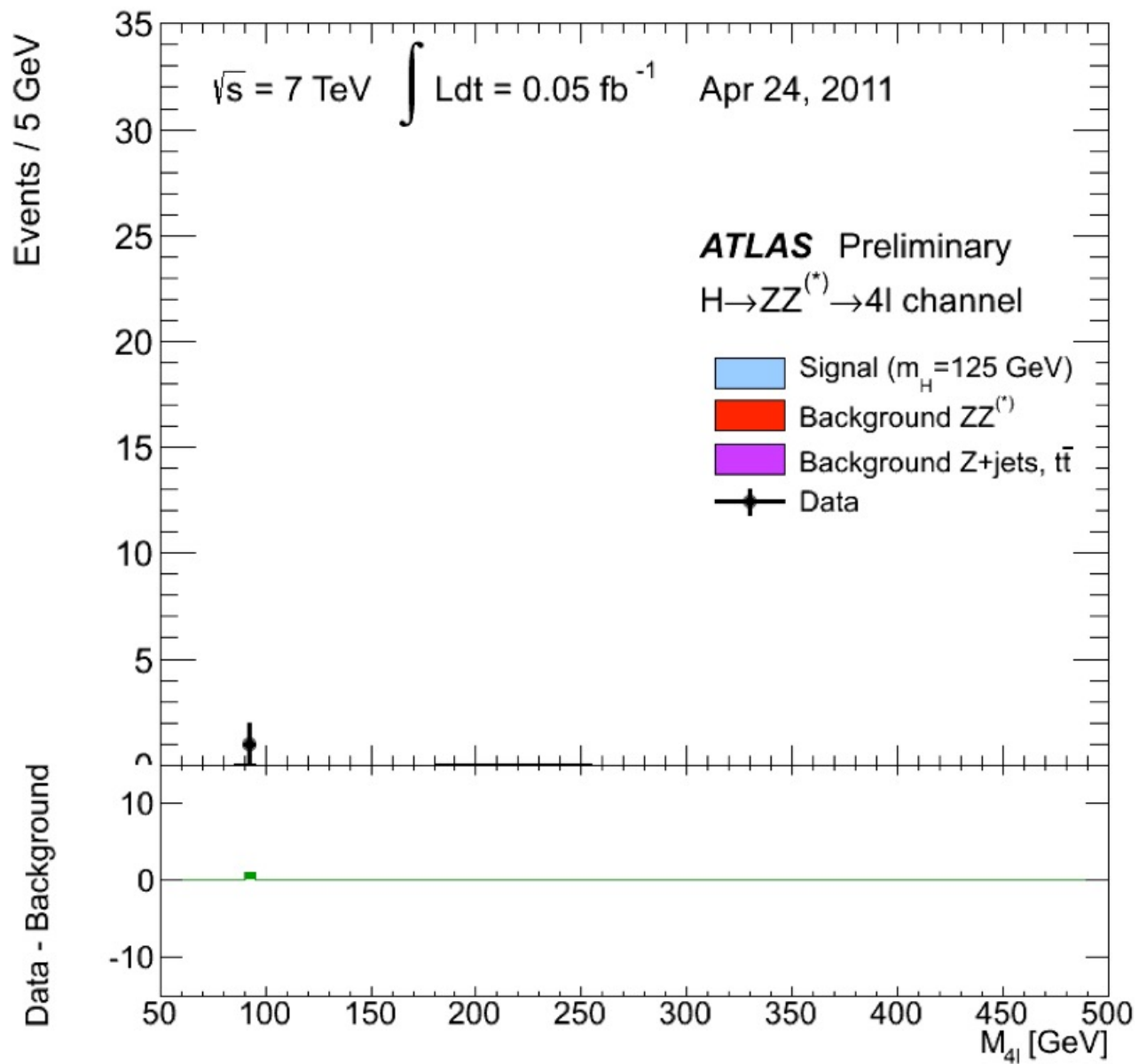


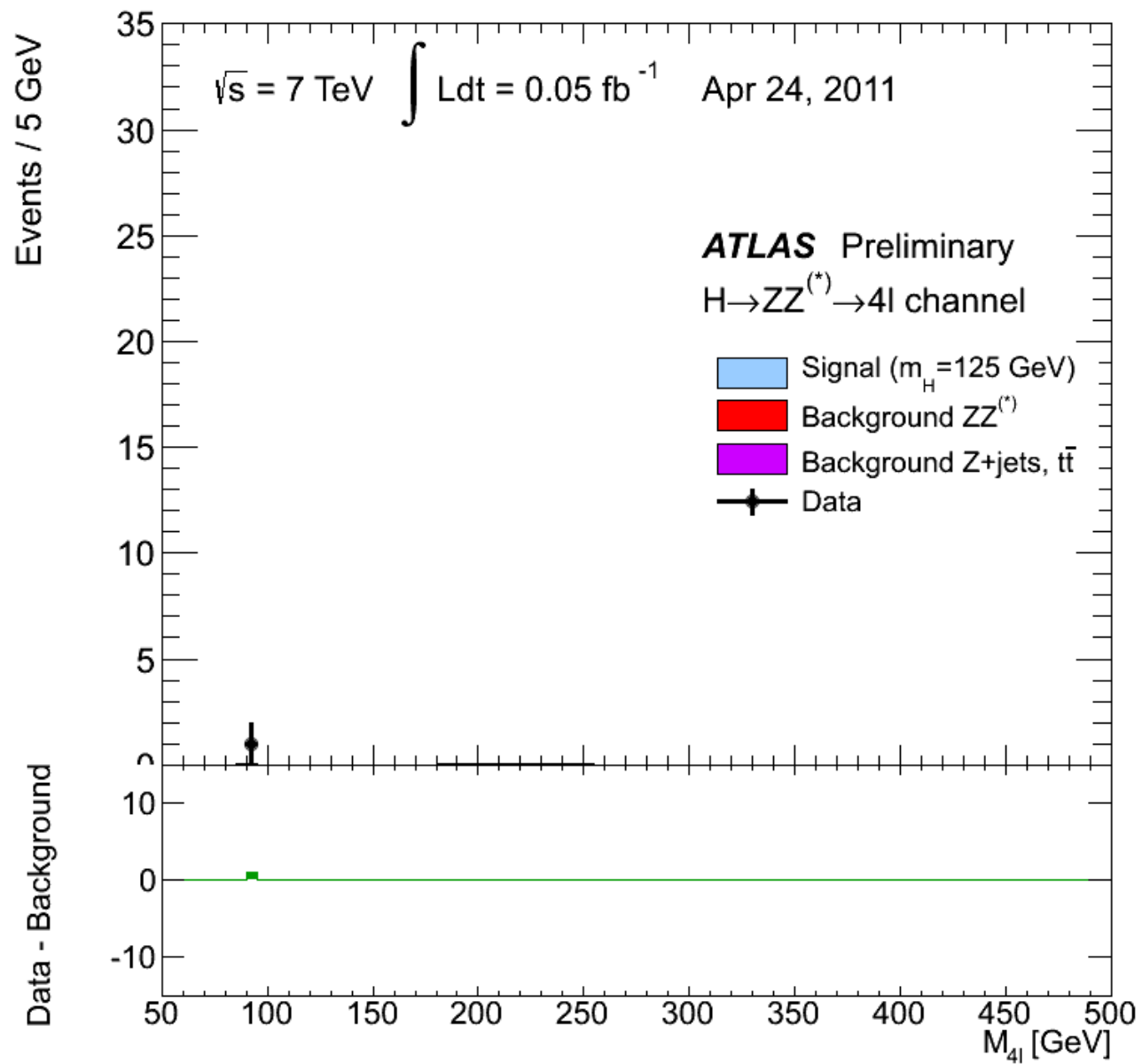
$$H \rightarrow ZZ^{(*)} \rightarrow 4\mu$$



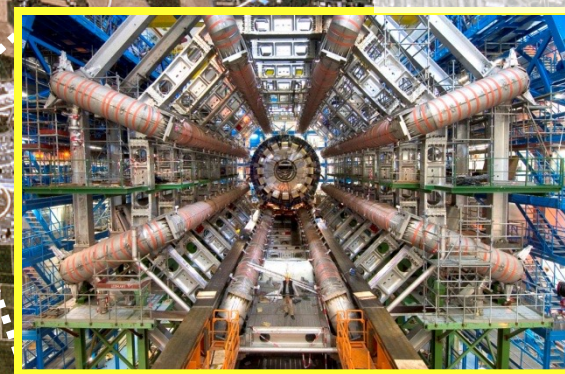
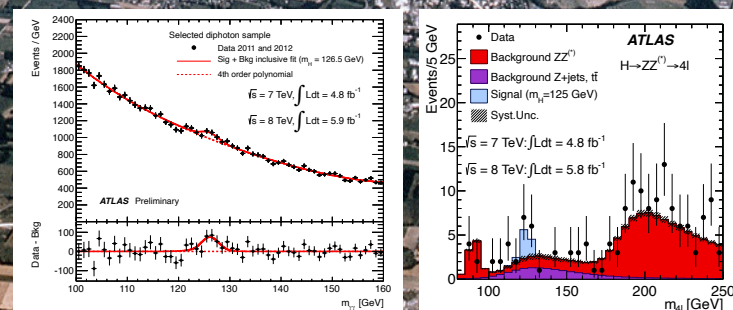
H to 4 μ candidate, with $m_{4\mu}=125.1$ GeV

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

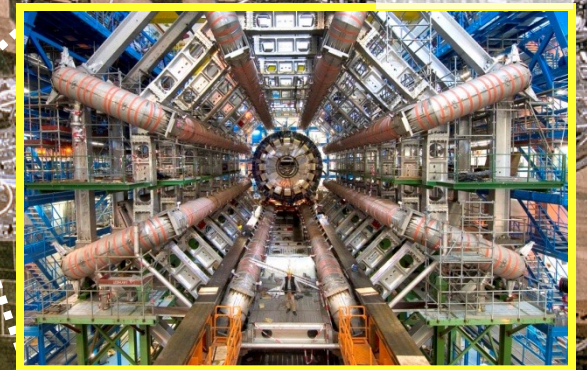
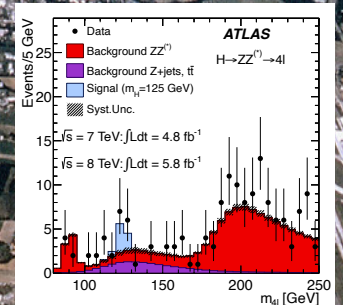
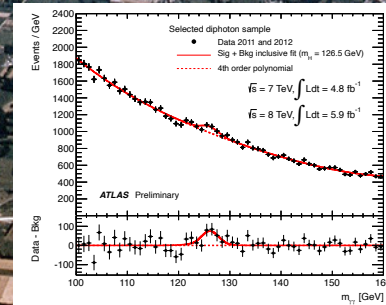
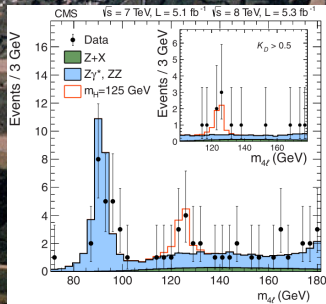
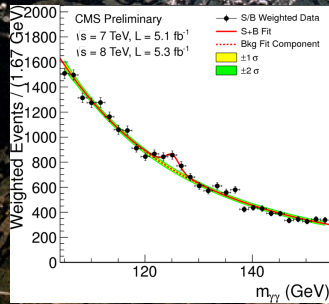
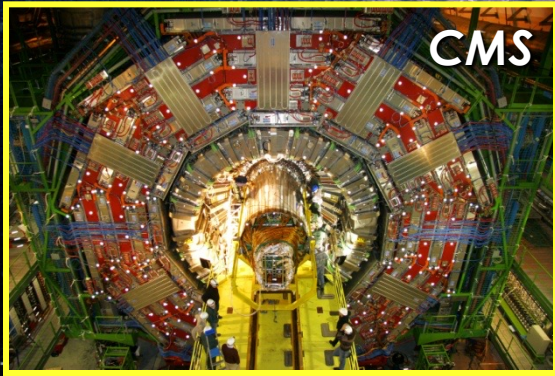




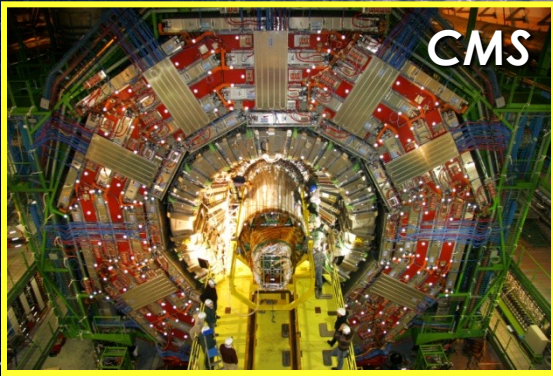
Independent confirmation



Independent confirmation

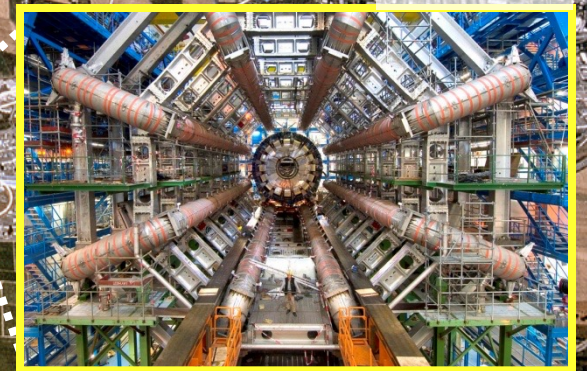
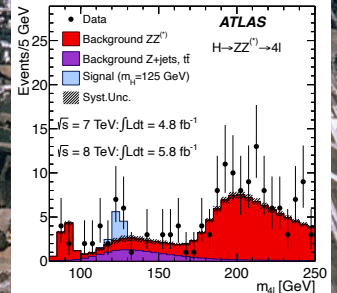
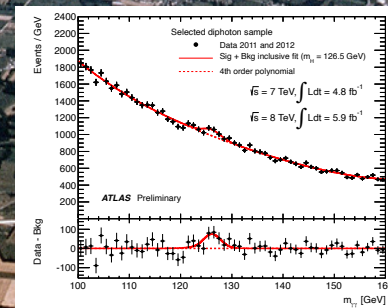
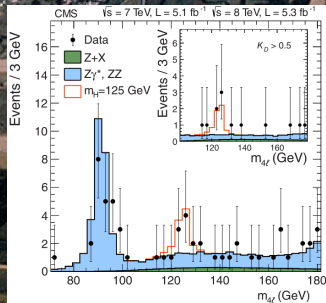
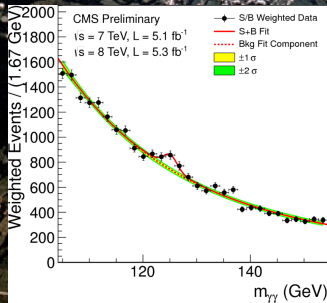


Combination



CMS

Probability $< 0.00003\%$
 = “ 5σ ” \rightarrow Discovery!



ATLAS

Probability $< 0.00003\%$
 = “ 5σ ” \rightarrow Discovery!

July 4, 2012

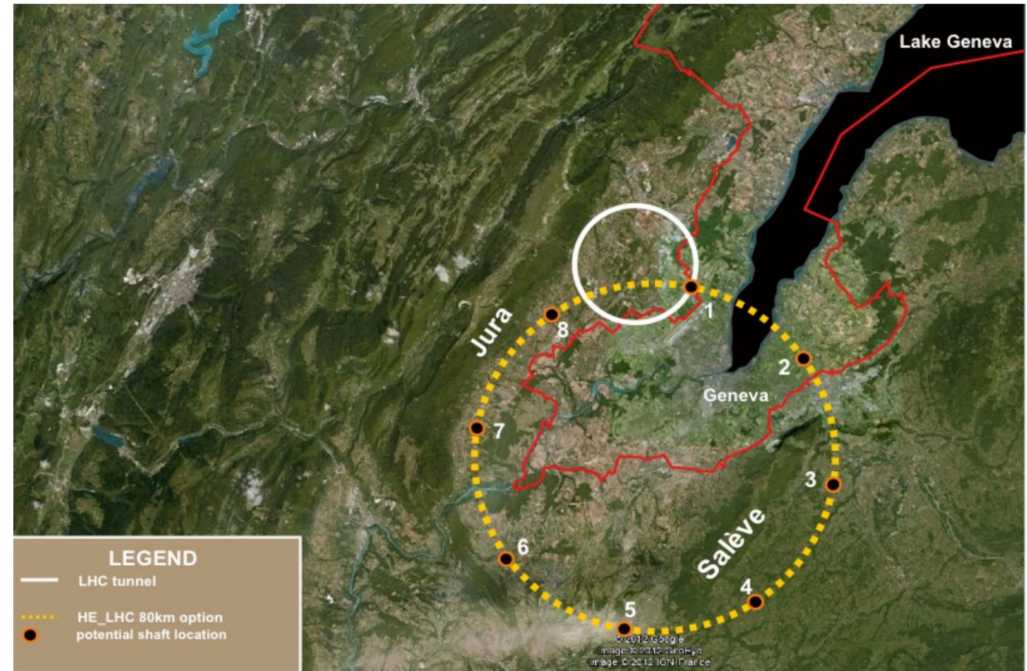


What is next?

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.

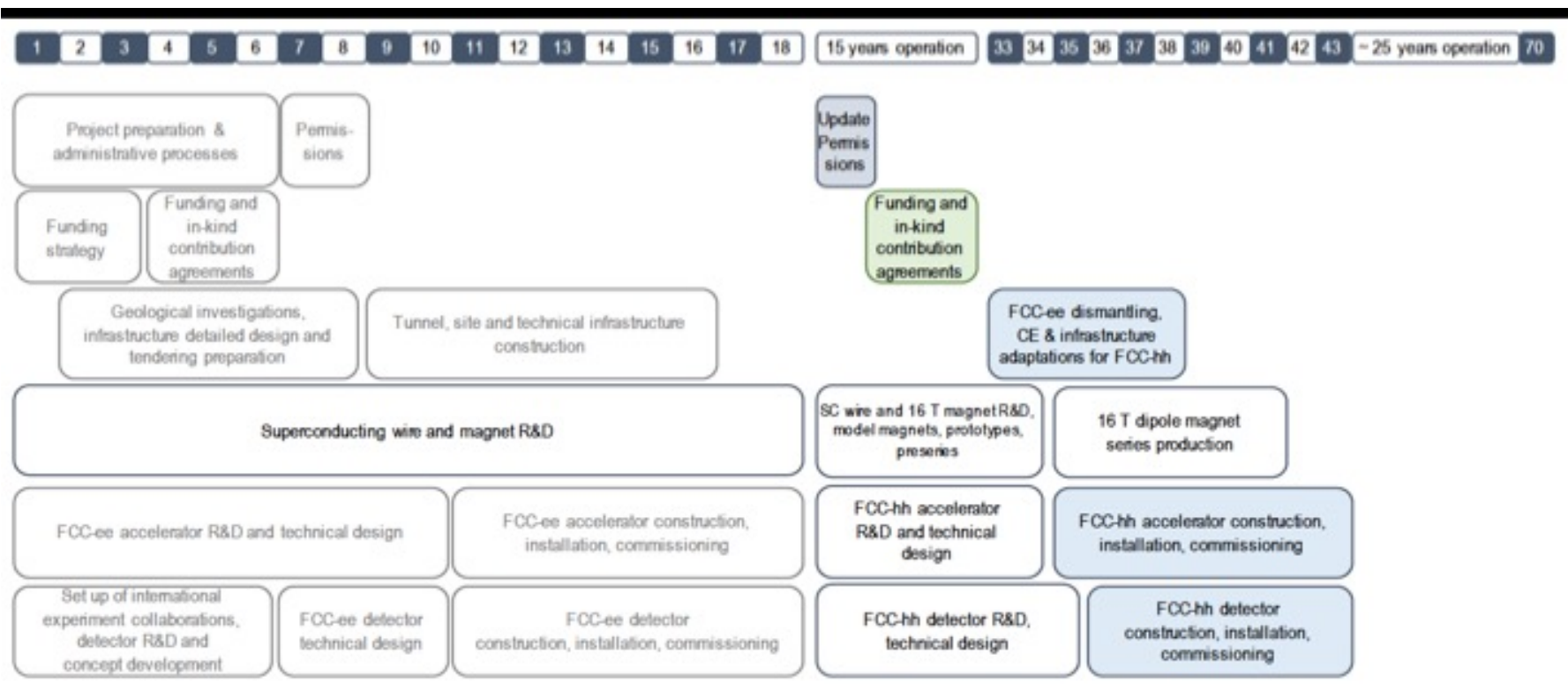
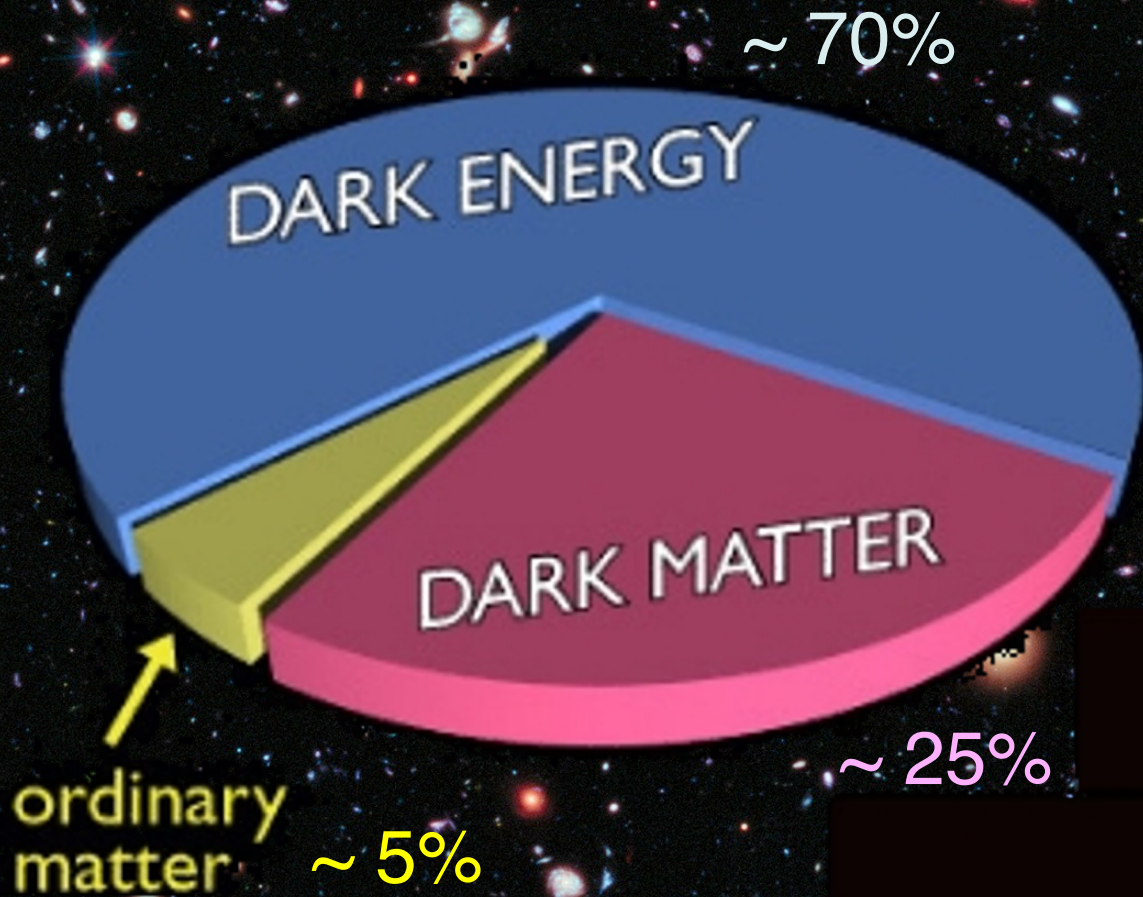
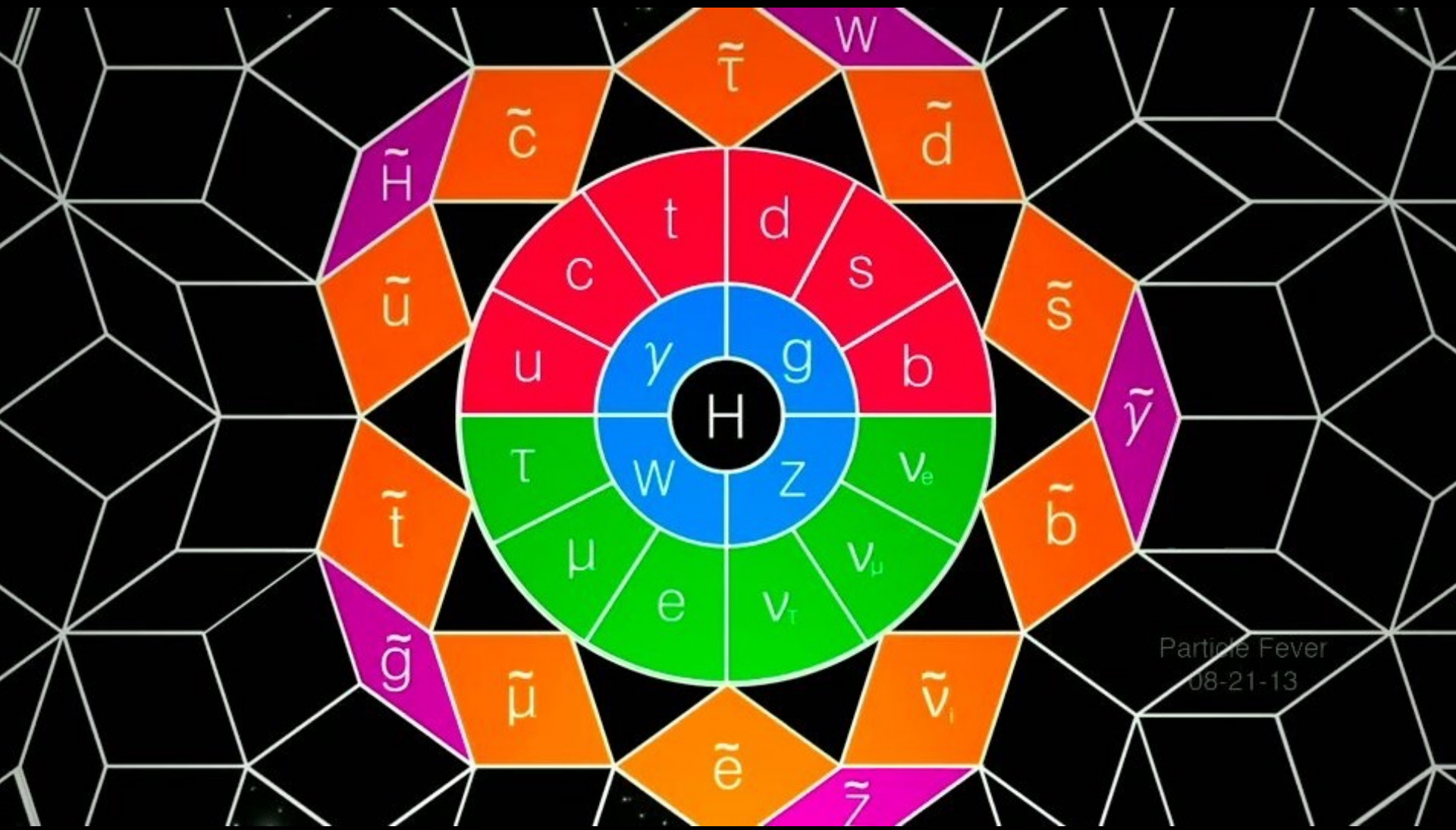
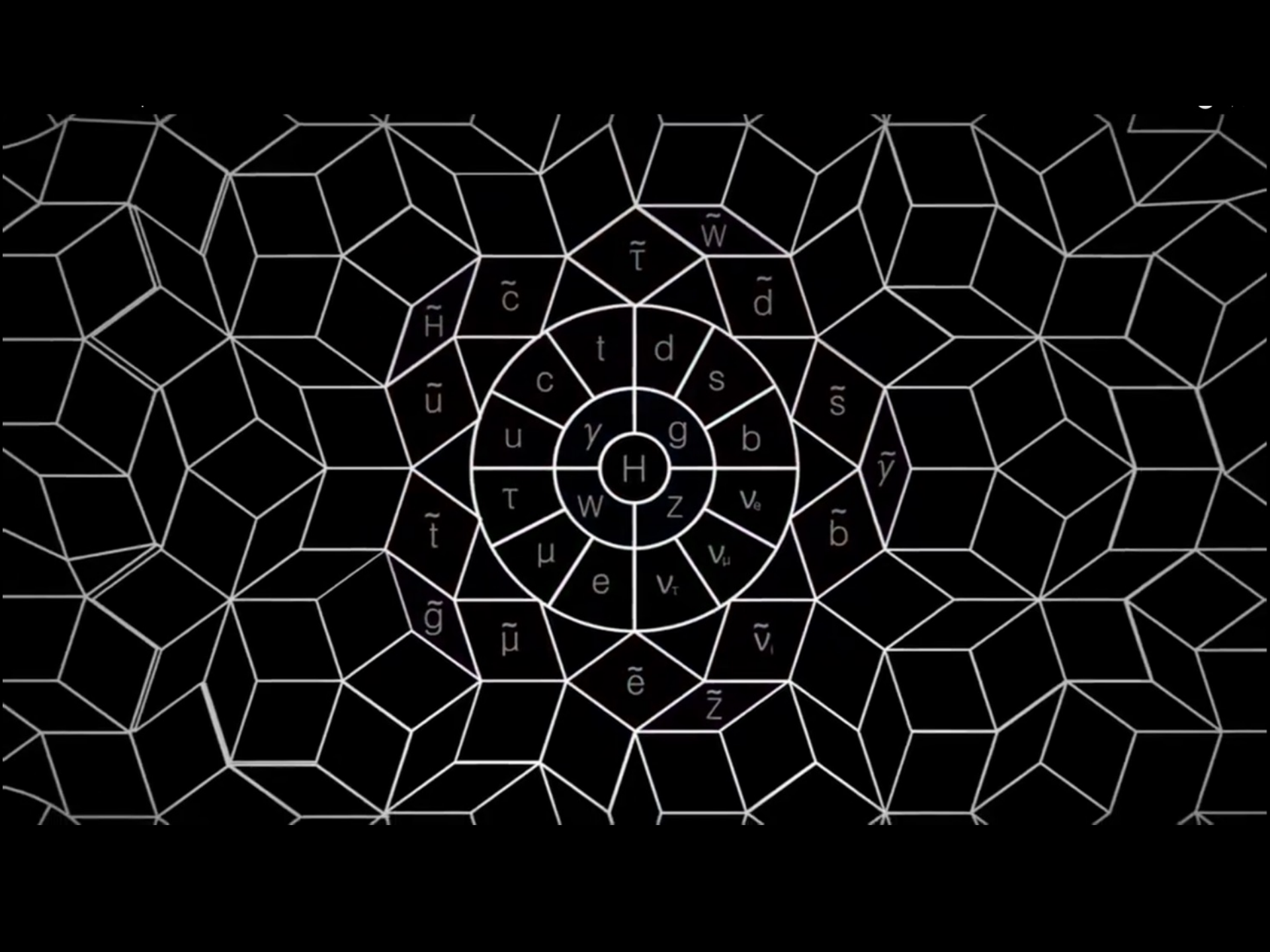


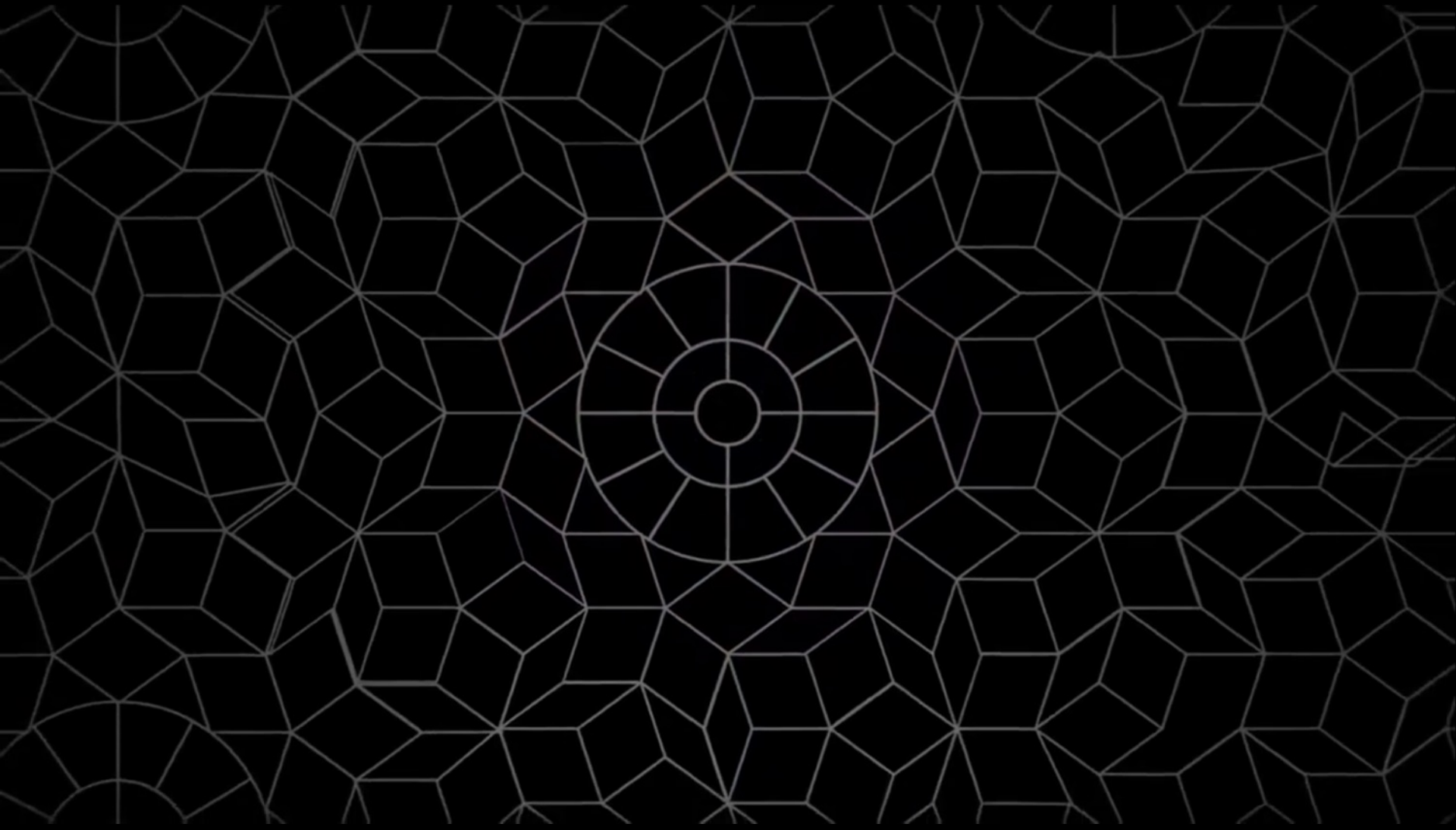
Imagen: Jorgen D'Hondt @ HK IAS Workshop 2019



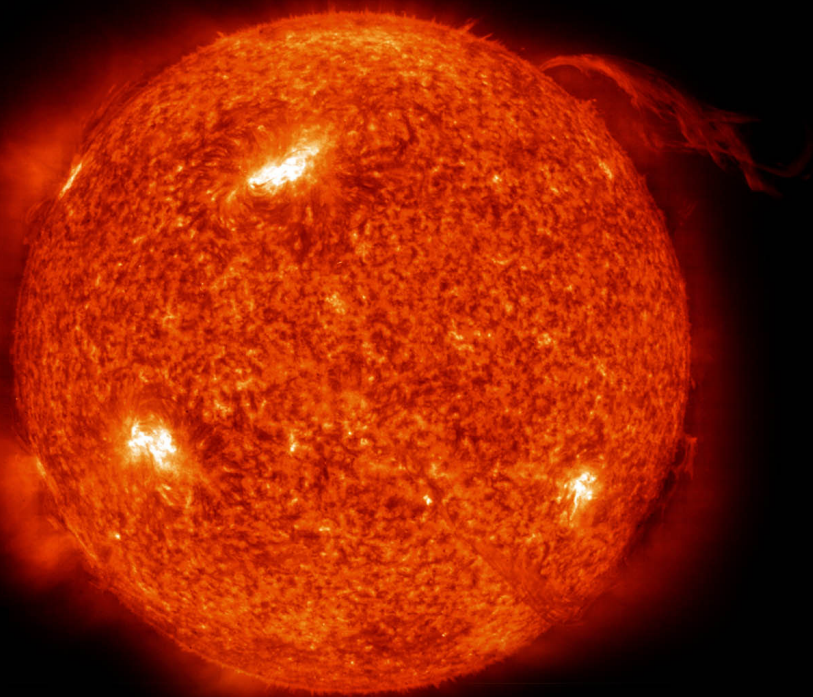


Particle Fever
08-21-13





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



Minimal bibliograhya

- Richard Rhodes, “The making of the Atomic Bomb”
- David Griffiths, “Introduction to elementary particles”, Ch. 1
- Steven Weinberg, “Dreams of a final theory”
- John Gribbin, “In search of Schrodinger’s cat”
- Stephen Hawking, “A brief history of time”
- Carlo Rovelli, “Seven brief lessons on Physics”
- Carlo Rovelli, “The order of time”
- Lee Smolin, “The life of the cosmos”
- Luis R Flores Castillo, “The search and discovery of the Higgs boson”

Youtube channels:

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