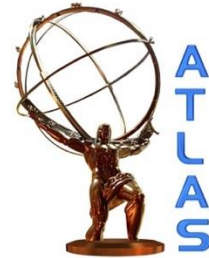


# The discovery of the Higgs boson



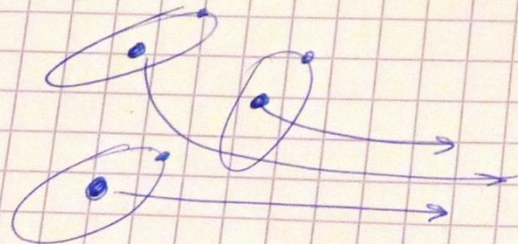
Luis Roberto Flores Castillo  
The Chinese University of Hong Kong



International Teacher Weeks 2024  
CERN, Switzerland

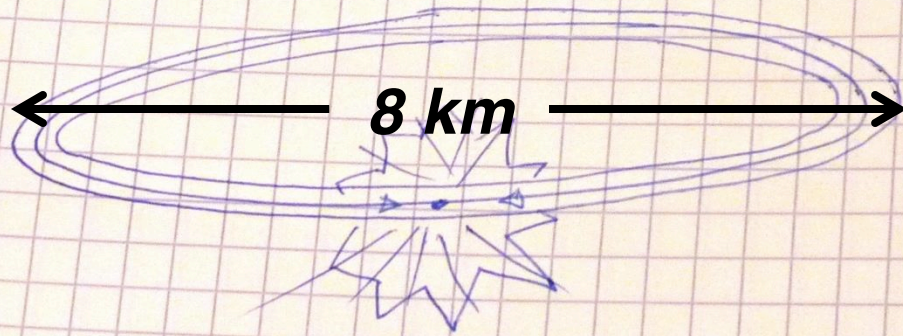
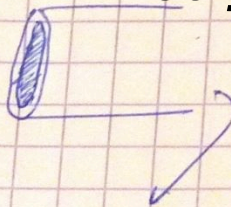
August 6, 2024

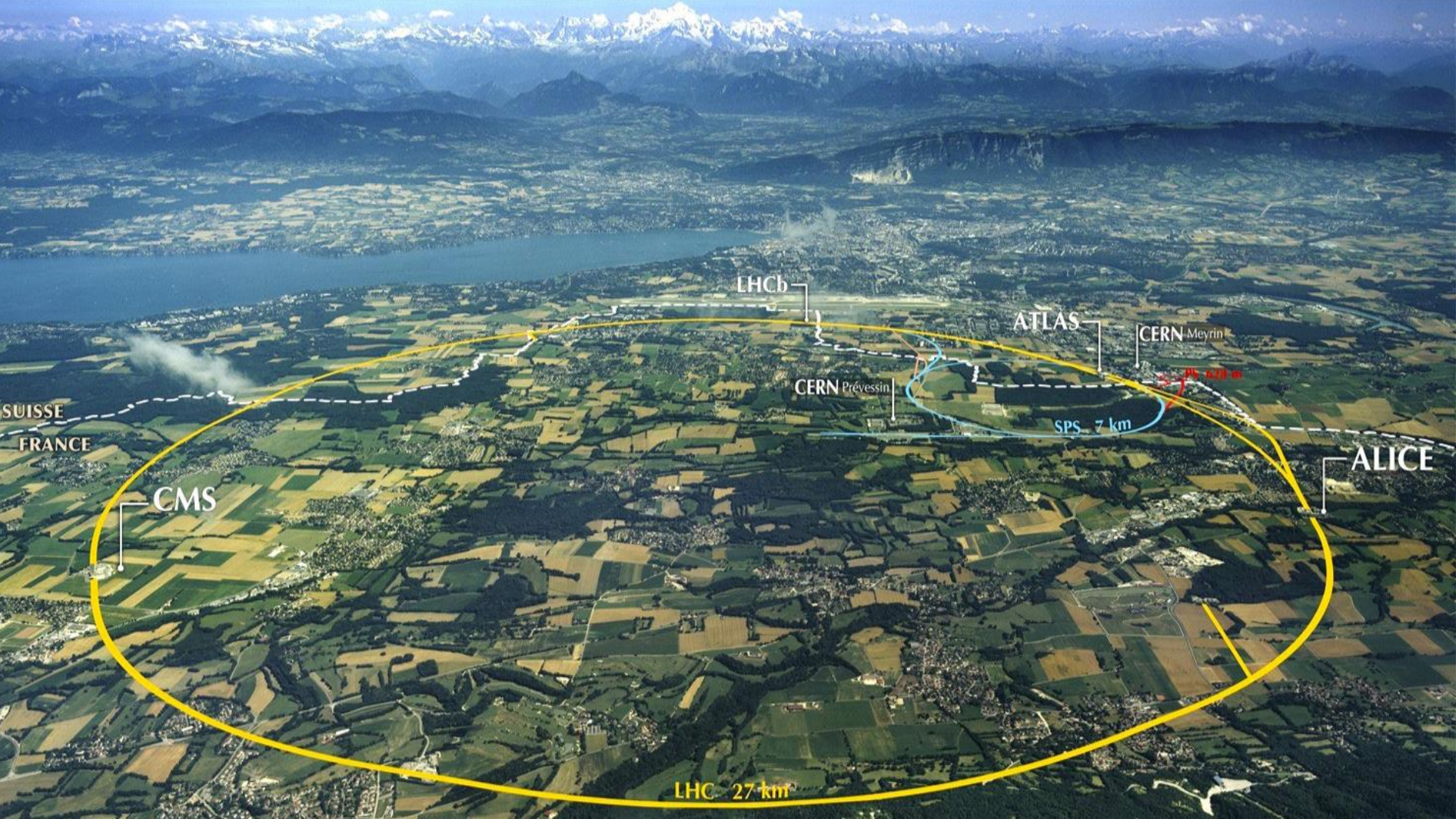
# Aiming high



*~ 20 countries*  
*~ 200 institutions*  
*~ 30 years*

**\$ 9,000,000,000**





SUISSE  
FRANCE

CMS

LHCb

ATLAS

CERN Meyrin

CERN Prévessin

SPS 7 km

ALICE

LHC 27 km

July 4, 2012

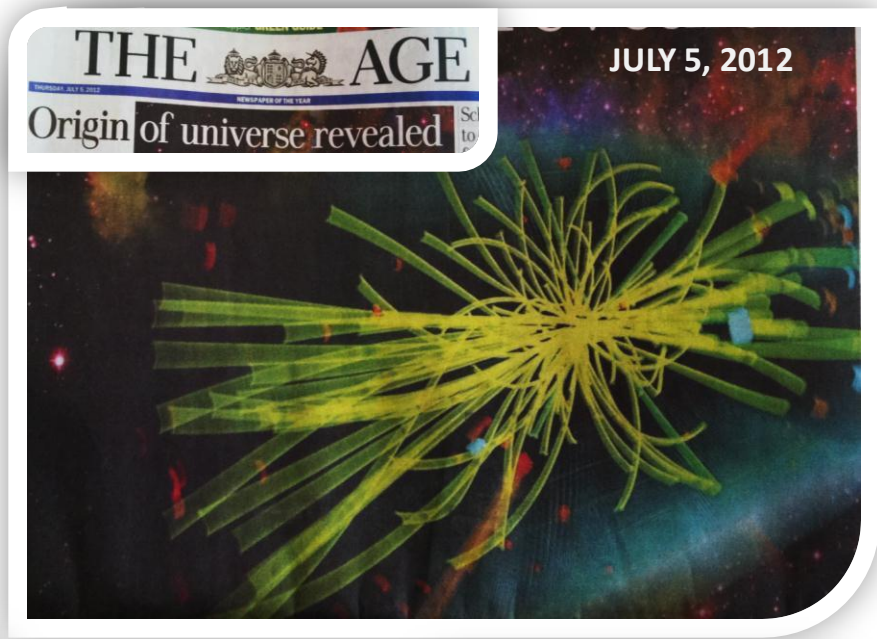


***“I think we have it” – Rolf Heuer, CERN’s Director General***

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

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

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

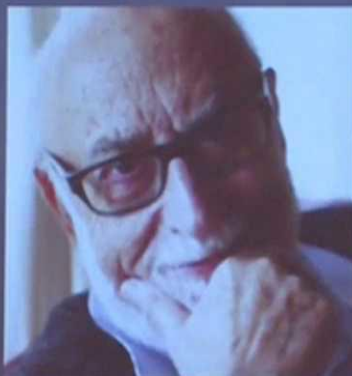


**TIME**  
The elusive Higgs boson is at last found—and  
the universe gets a little less mysterious  
BY JEFFREY KLUGER  
JULY 23, 2012

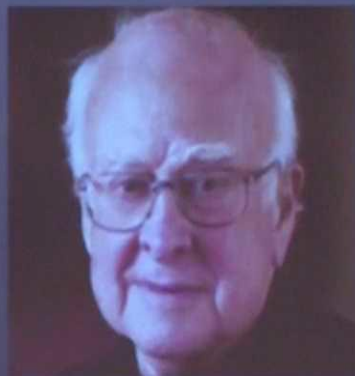




# The Nobel Prize in Physics 2013



**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."*

What is the Higgs boson?













# Fundamental building blocks?

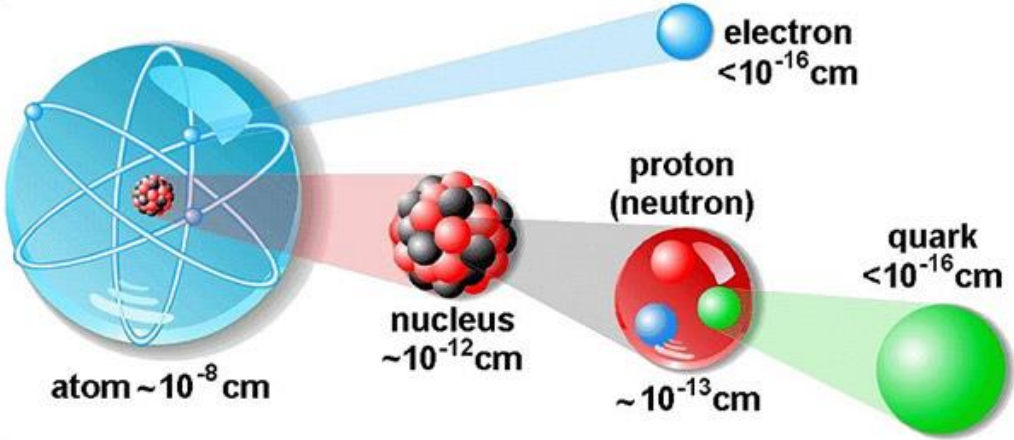
Periodic Table of Elements

© AllAboutGemstones.com

Group 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
IA												IIIA	IVA	VA	VIA	VIIA	VIIIA
1	2											3	4	5	6	7	8
H	He											B	C	N	O	F	Ne
3	4											6	7	8	9	10	
Li	Be											Al	Si	P	S	Cl	Ar
11	12											13	14	15	16	17	18
Na	Mg											Ga	Ge	As	Se	Br	Kr
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	31	32	33	34	35	36
37	38	39	40	41	42	43	44	45	46								
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd								
55	56	57	72	73	74	75	76	77	78								
Cs	Ba	*	Hf	Ta	W	Re	Os	Ir	Pt								
87	88	89	104	105	106	107	108	109	110								
Fr	Ra	+	Rf	Ha	Sg	Bh	Hs	Mt	Ds								
Period	s-block		d-block														
f-block	Lanthanide Series		57	58	59	60	61	62	63								
	*La		Ce	Pr	Nd	Pm	Sm	Eu									
	Actinide Series		89	90	91	92	93	94	95								
	+Ac		Th	Pa	U	Np	Pu	Am									

■ Non-Metals    ■ Transition Metals    ■   
■ Alkali Metals    ■ Alkali Earth Metals    ■

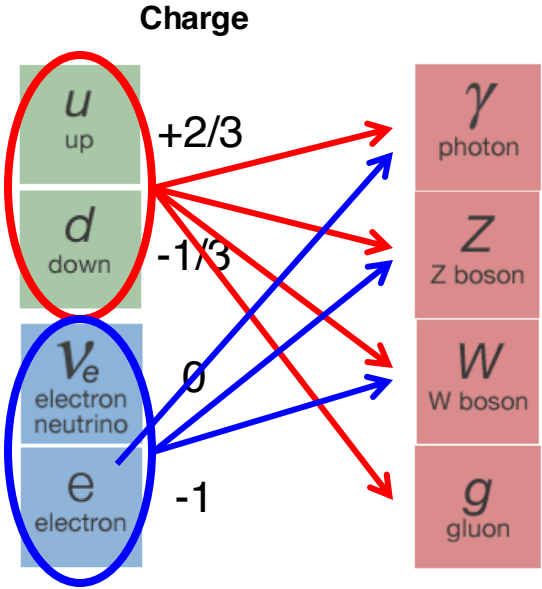
- ~1869, Mendeleev published “Principles of Chemistry”
- All that complexity from ~100 “elements”



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

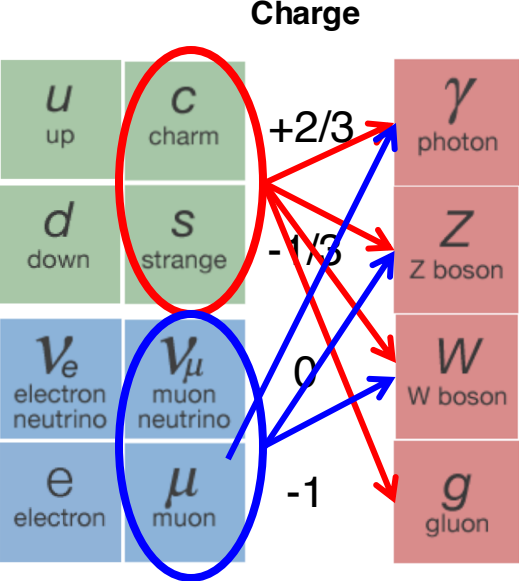


# Fundamental building blocks?





# Fundamental building blocks?



# Fundamental building blocks?

$u$ up	$c$ charm	$\gamma$ photon
$d$ down	$s$ strange	$Z$ Z boson
$\nu_e$ electron neutrino	$\nu_\mu$ muon neutrino	$W$ W boson
$e$ electron	$\mu$ muon	$g$ gluon

# Fundamental building blocks?

	Fermions			Bosons	
Quarks	$u$ up	$c$ charm	$t$ top	$\gamma$ photon	Force carriers
	$d$ down	$s$ strange	$b$ bottom	$Z$ Z boson	
Leptons	$\nu_e$ electron neutrino	$\nu_\mu$ muon neutrino	$\nu_\tau$ tau neutrino	$W$ W boson	
	$e$ electron	$\mu$ muon	$\tau$ tau	$g$ gluon	

They describe **almost all known physical phenomena**

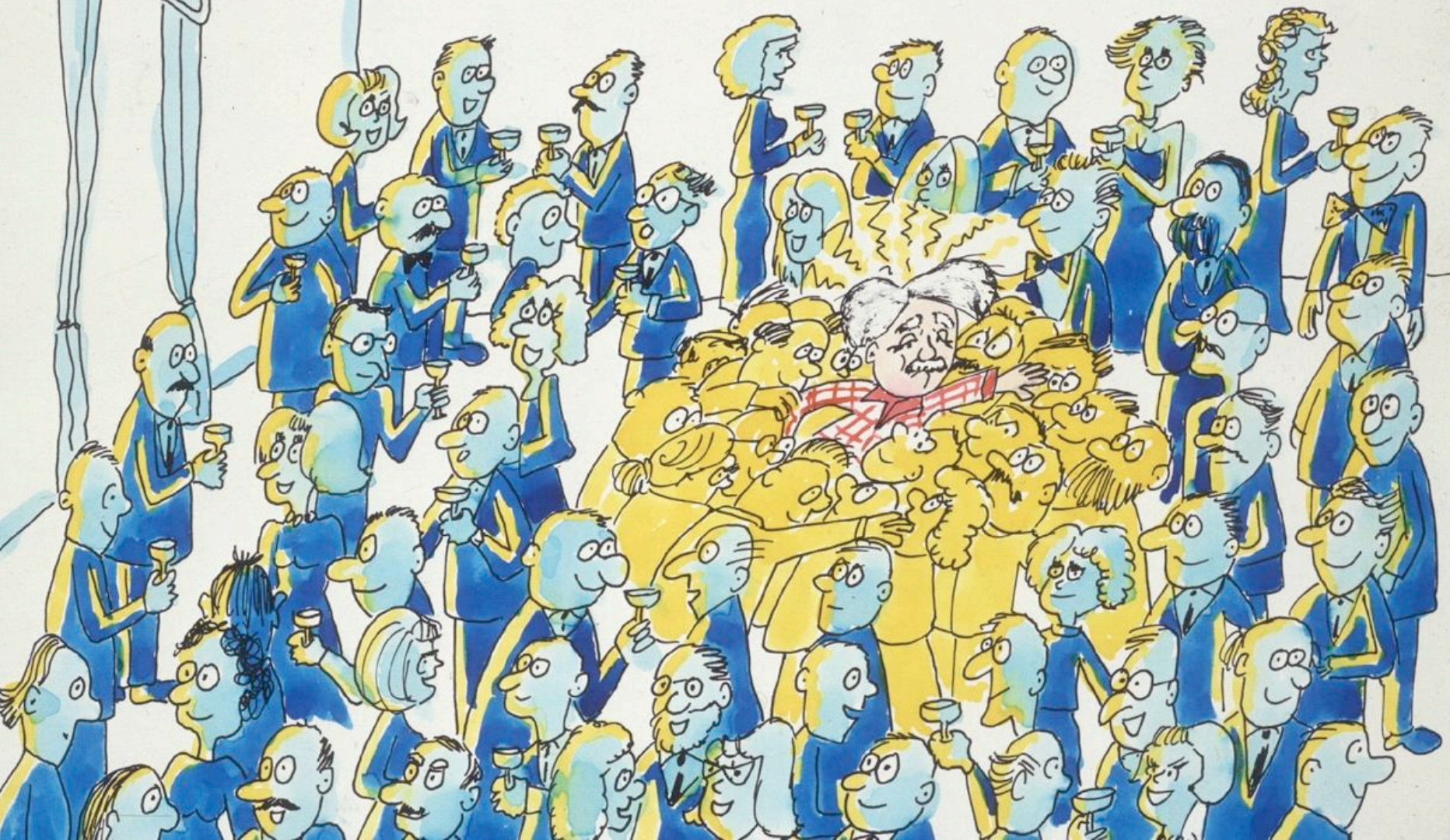
In 1964, there was a problem: the model worked **only if all elementary particles had ZERO mass**

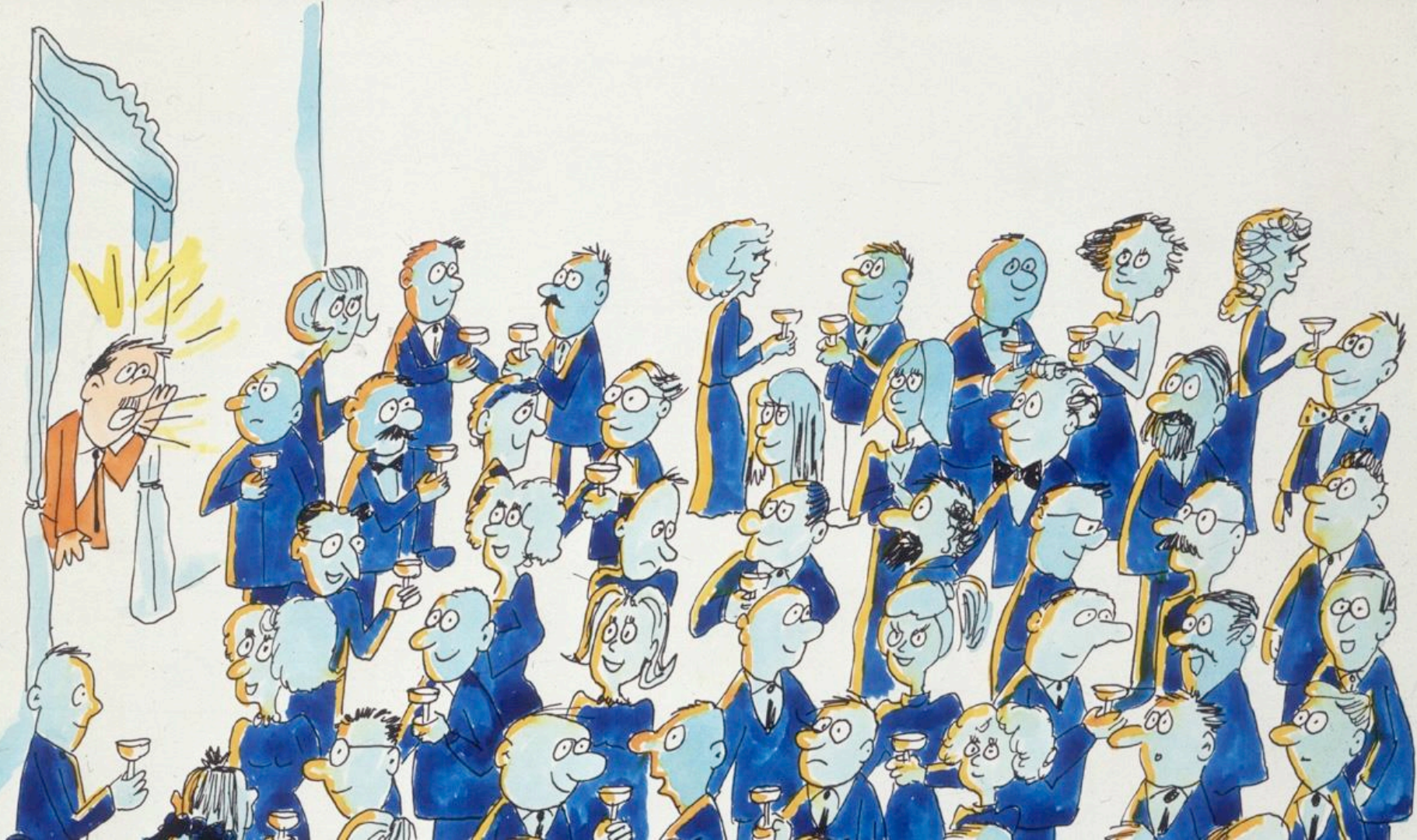
# “Zero mass”?

- “Mass” is the resistance to transform **energy** into **motion**  
**Beach ball vs bowling ball** : the lower the mass, the larger the speed acquired
- Can there be *anything* with no mass?  
Yes: **photons** and **gluons**
- 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, postulating a new field,  
**... and a new elementary particle.**

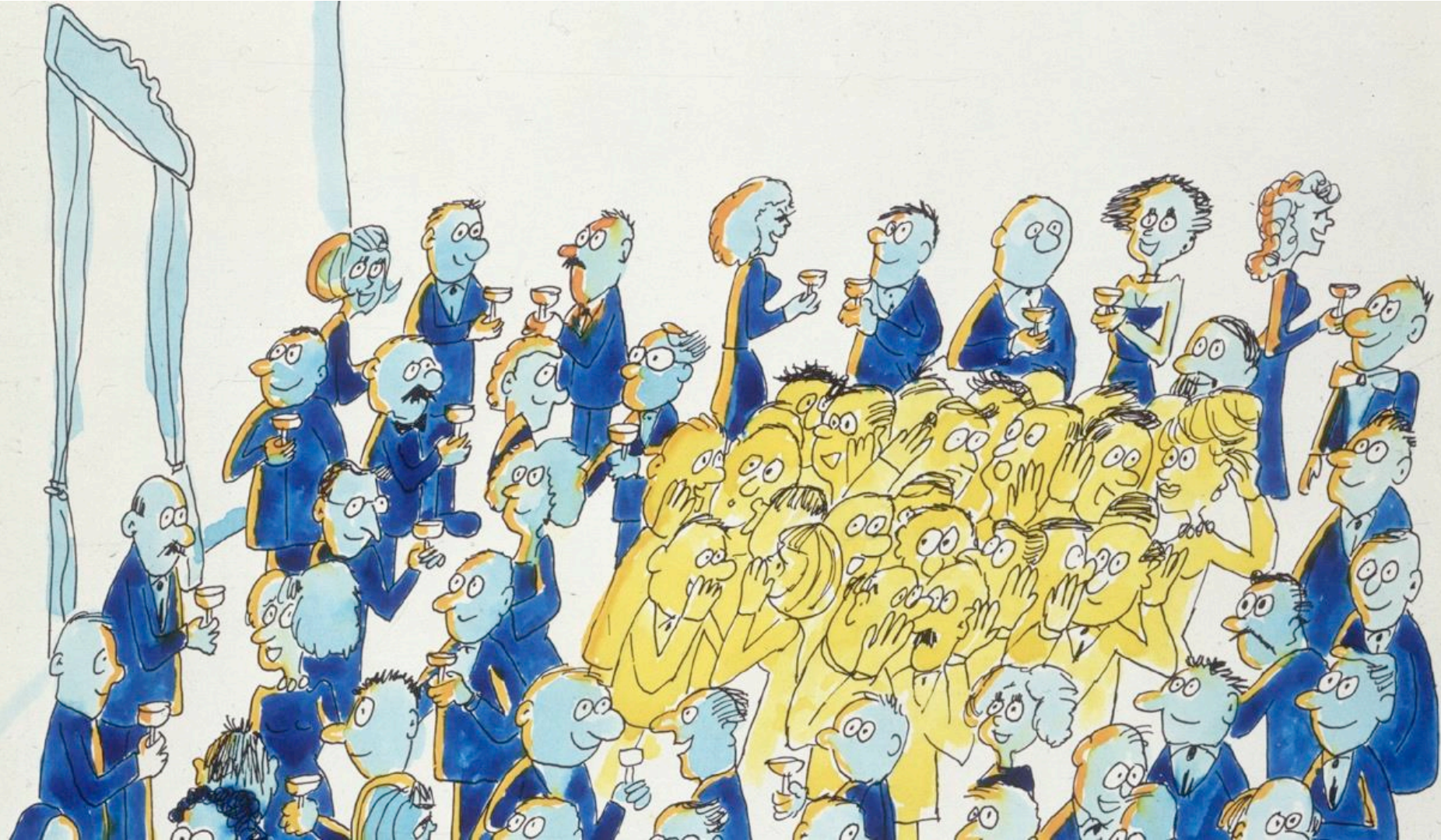








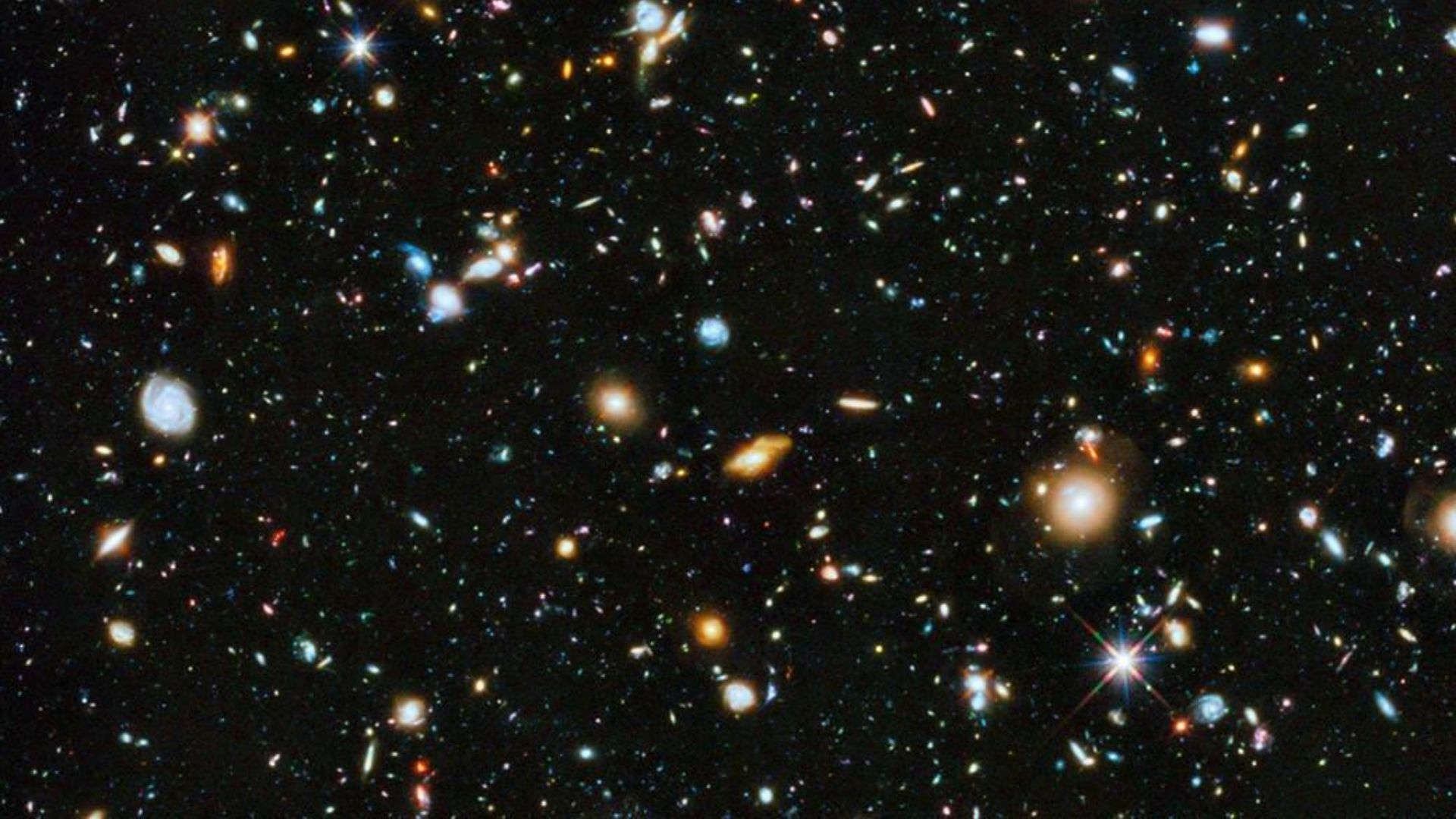




“For every complex problem there is an answer that is clear, simple, ...

“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

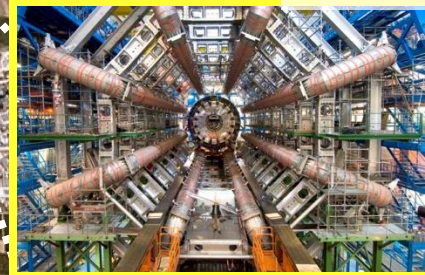
- 27 km circumference, 50-150 m below ground
- Two proton beams close to the speed of light
- Stored energy: 350 MJ (~TGV at 155 km/h)



# The Large Hadron Collider

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

# Detectors



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

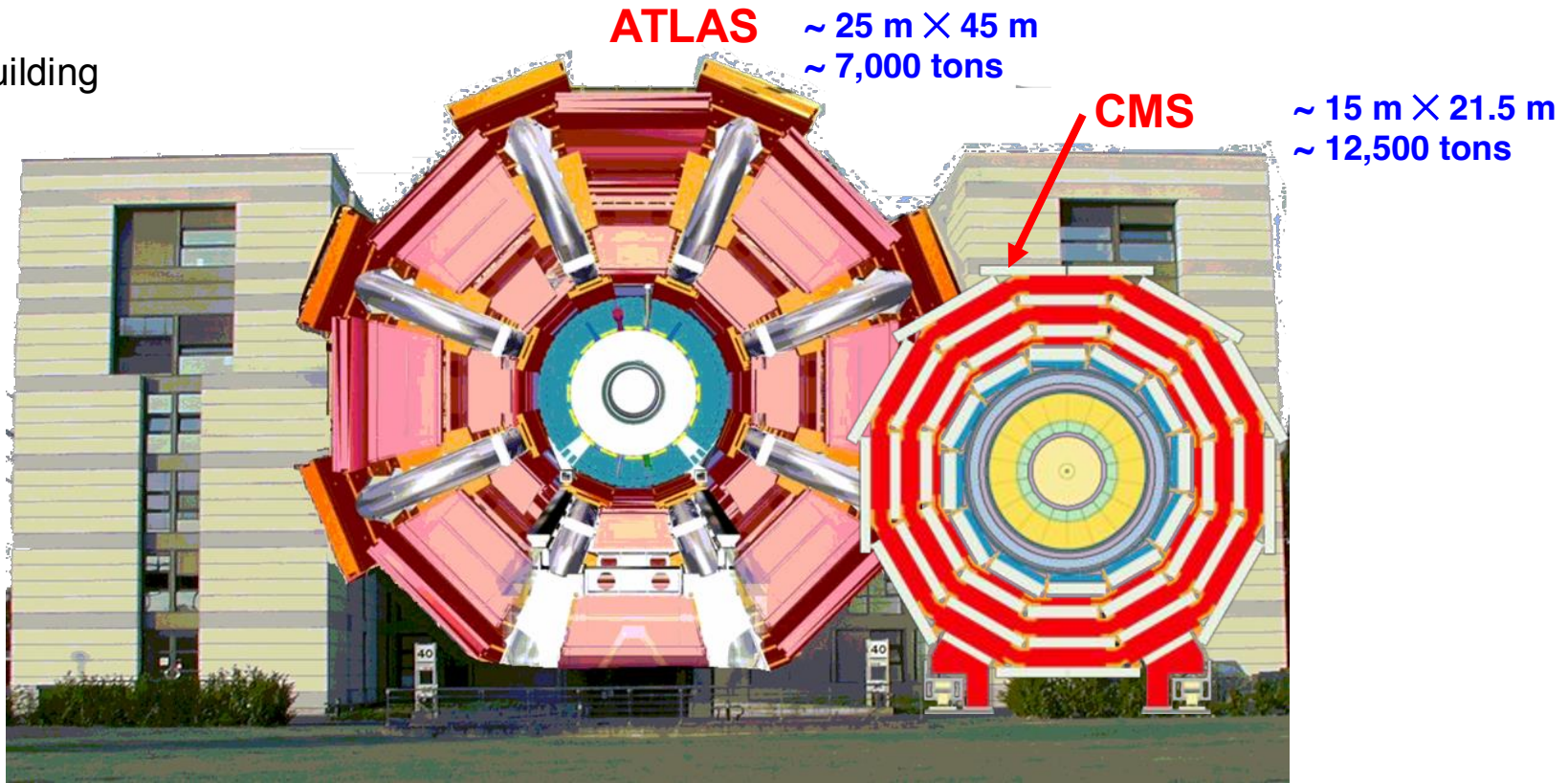
# ATLAS

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

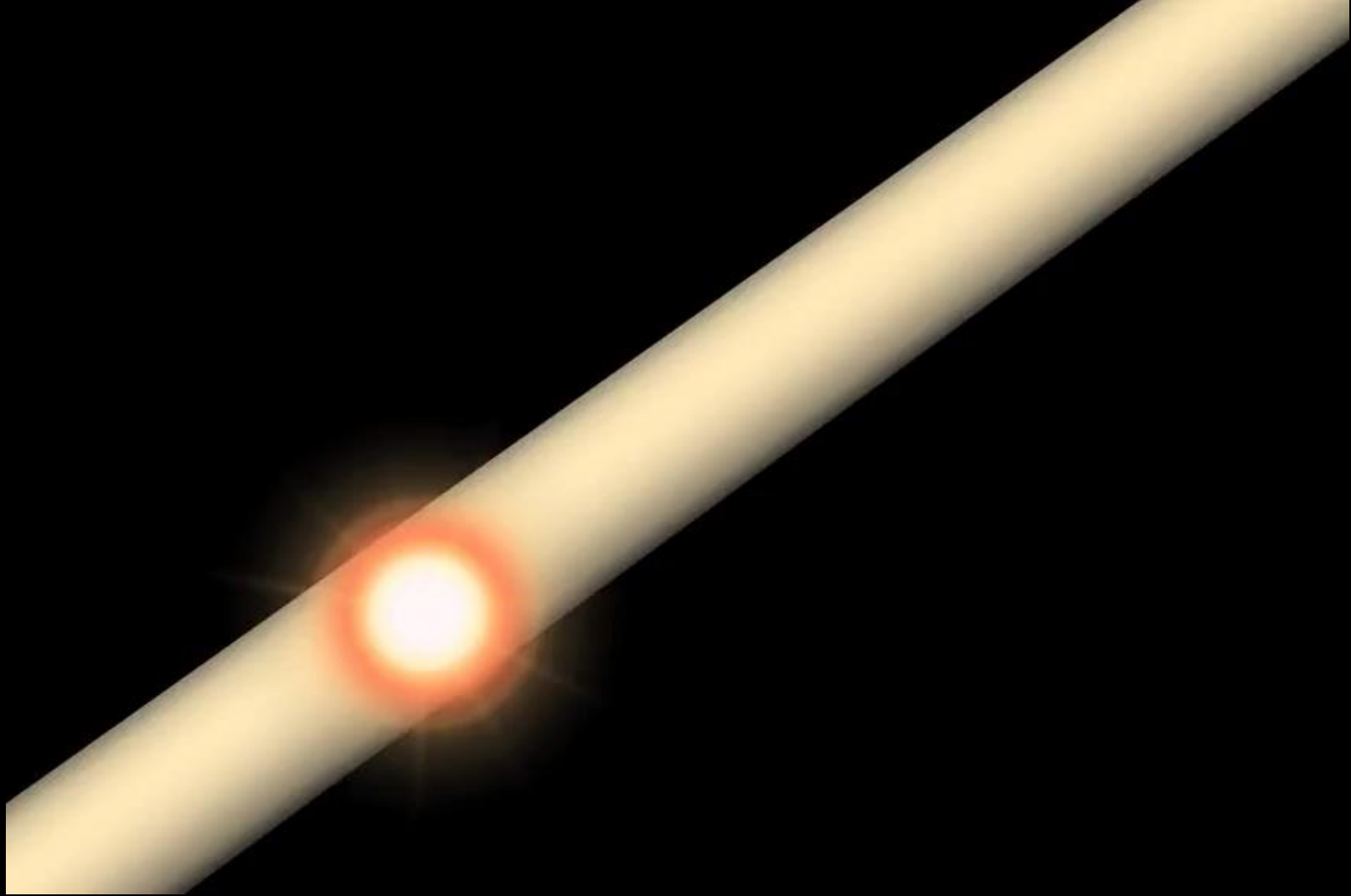
CMS

~ 3000 scientists, 182 institutions, 42 countries

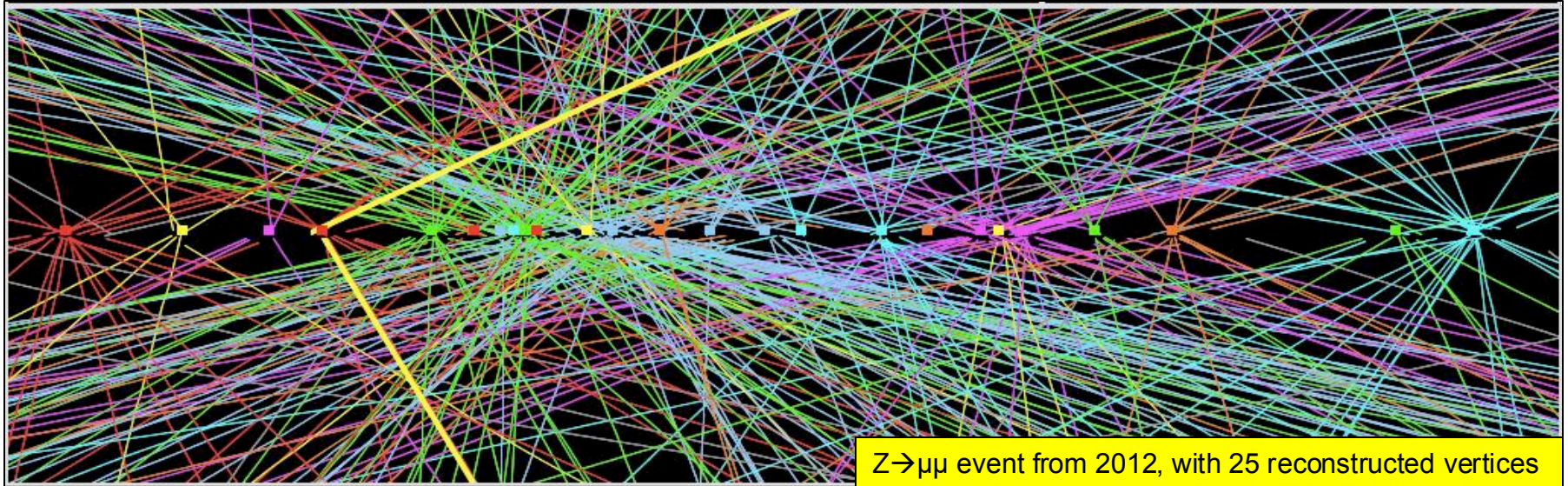
Five-story building



- About 100 millions sensors each
- Much beyond a 60-megapixel camera: **40 million pictures/second**



# Data

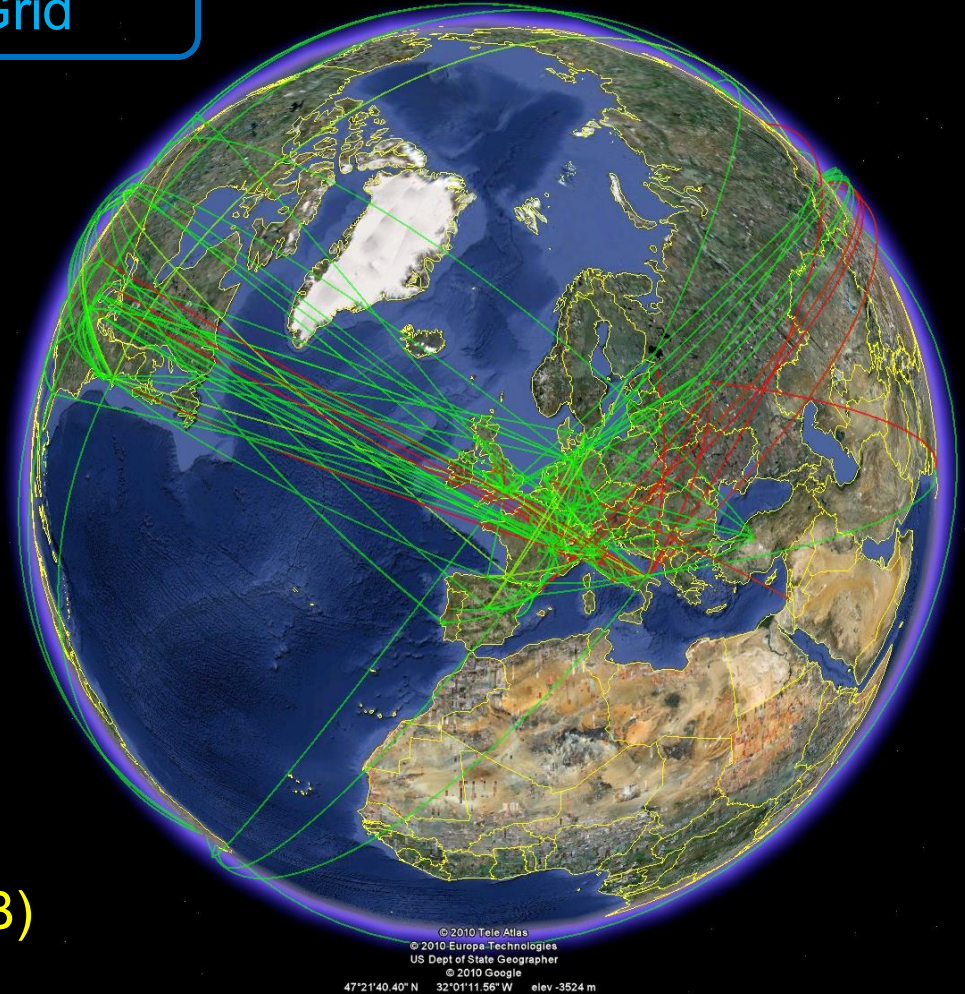


- Each bunch crossing: **~20**  $pp$  interactions
- 40 M crossings *per second*  $\times$  20  $pp$  per crossing (– some spacing): **600 M**  $pp/s$
- Fast selection systems (“trigger systems”) keep only **~ 400 collisions/s**
- Each  $pp$  collision produces **hundreds** of particles
- If stored in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

# Worldwide LHC Computing Grid

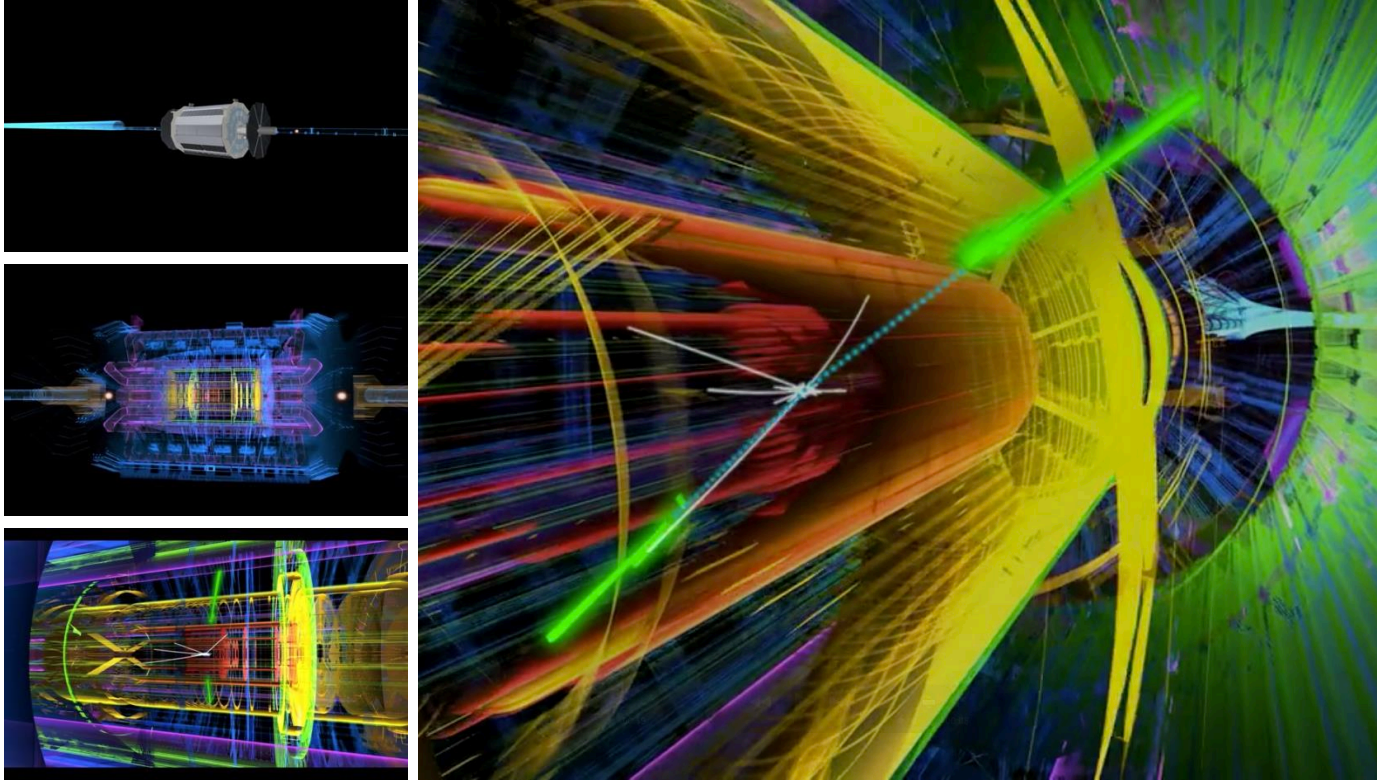
At the time of discovery:

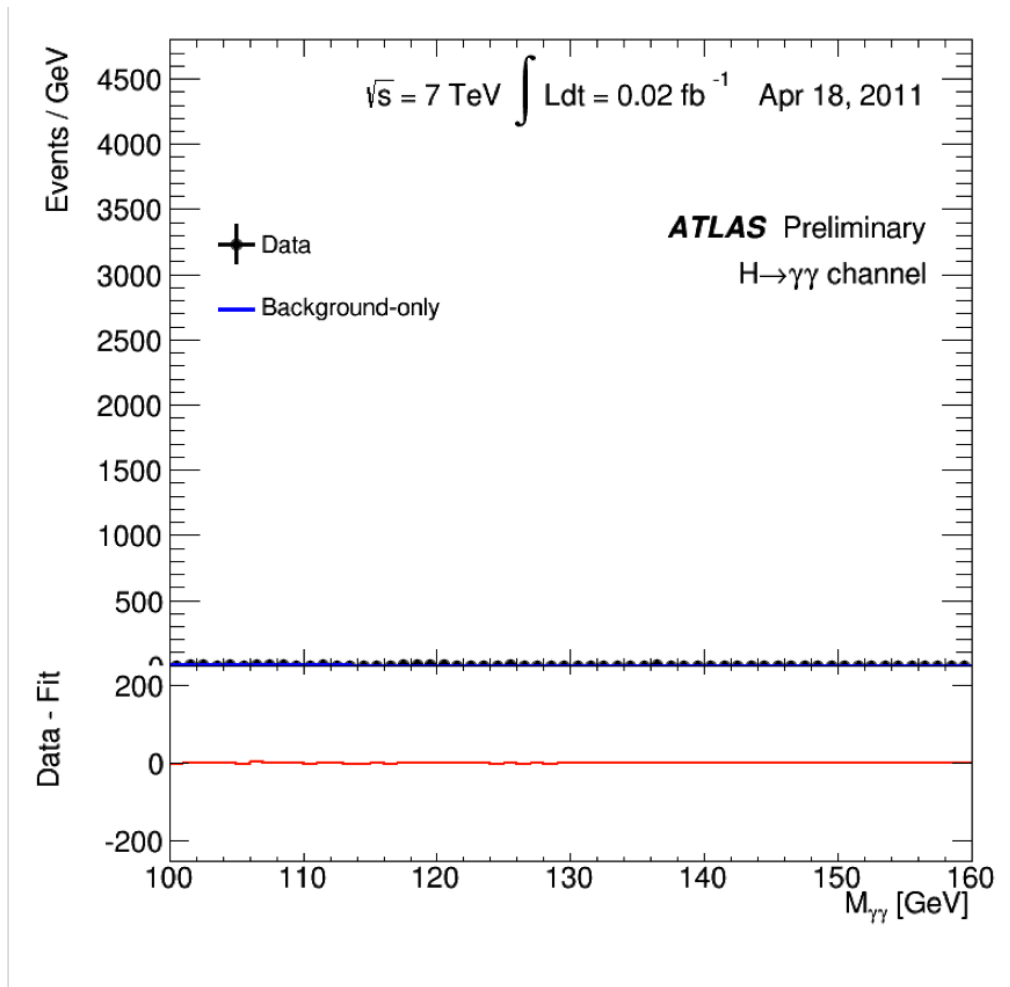
- > 170 computing centers
- ~ 40 countries
- ~ 250,000 processing cores
- ~ 120 PB storage (120 million GB)

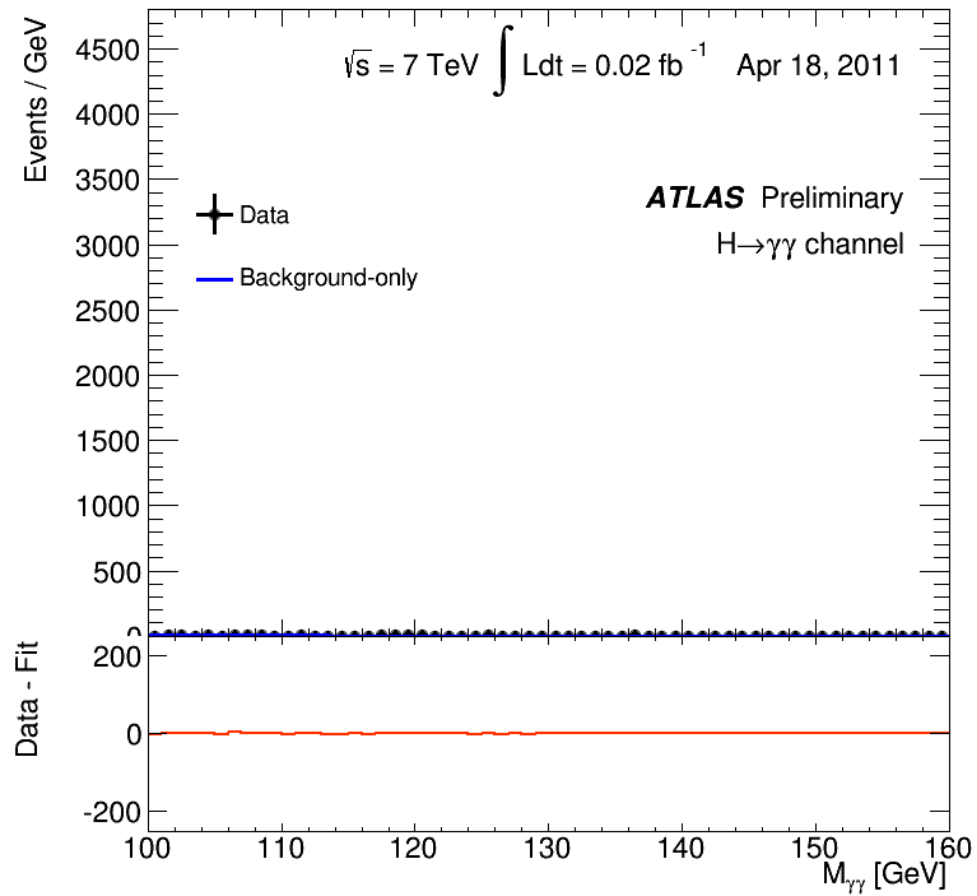




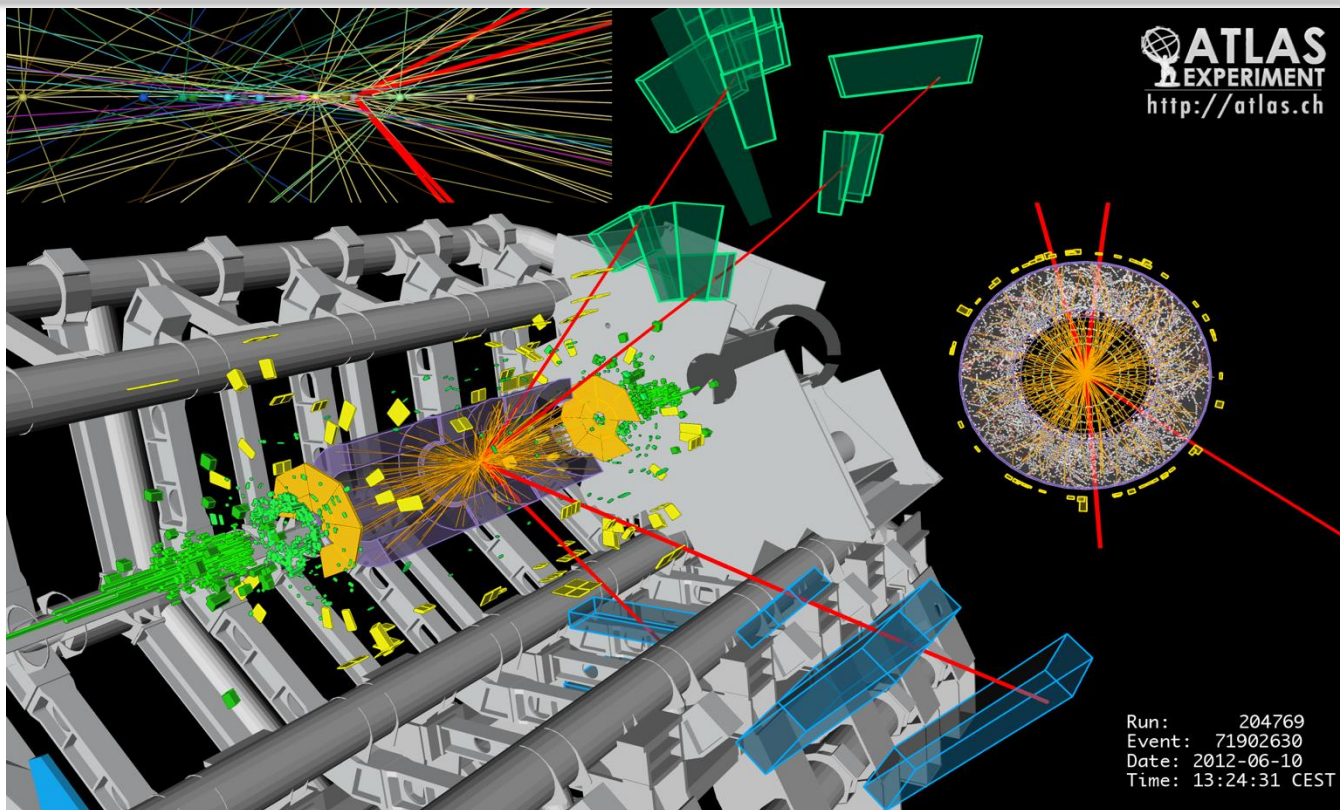
$$H \rightarrow \gamma\gamma$$





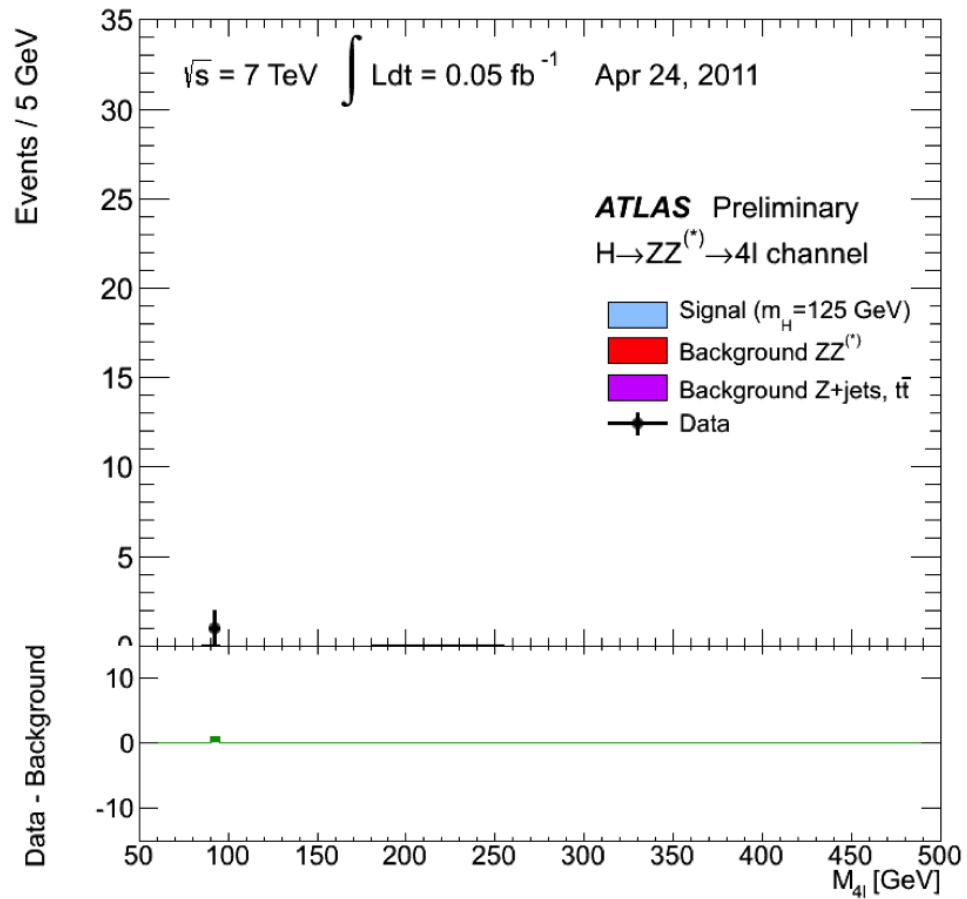


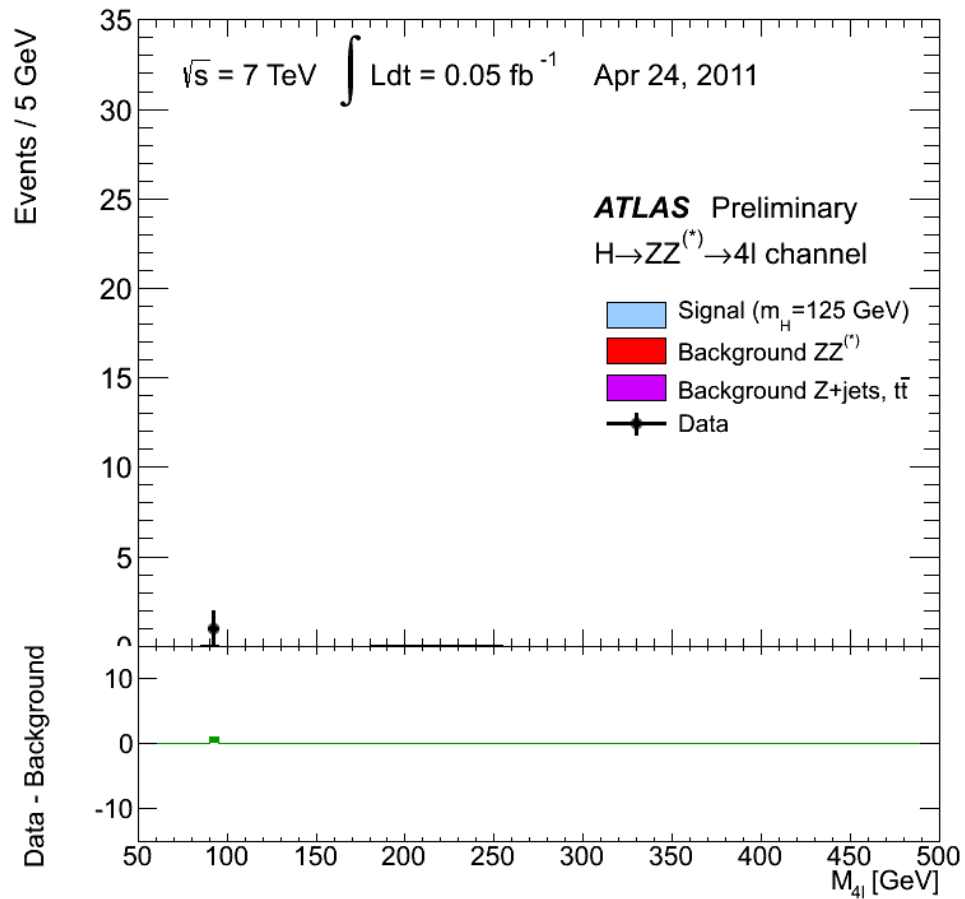
$$H \rightarrow ZZ^{(*)} \rightarrow 4\ell$$



***H to 4 $\mu$  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

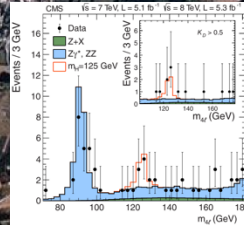
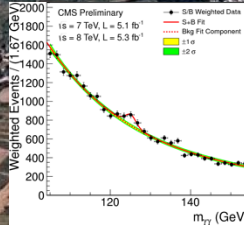




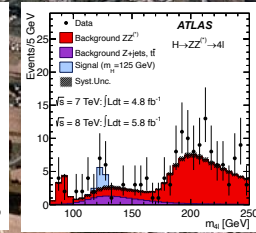
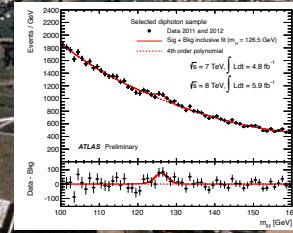
# Independent confirmation



CMS



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



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



ATLAS

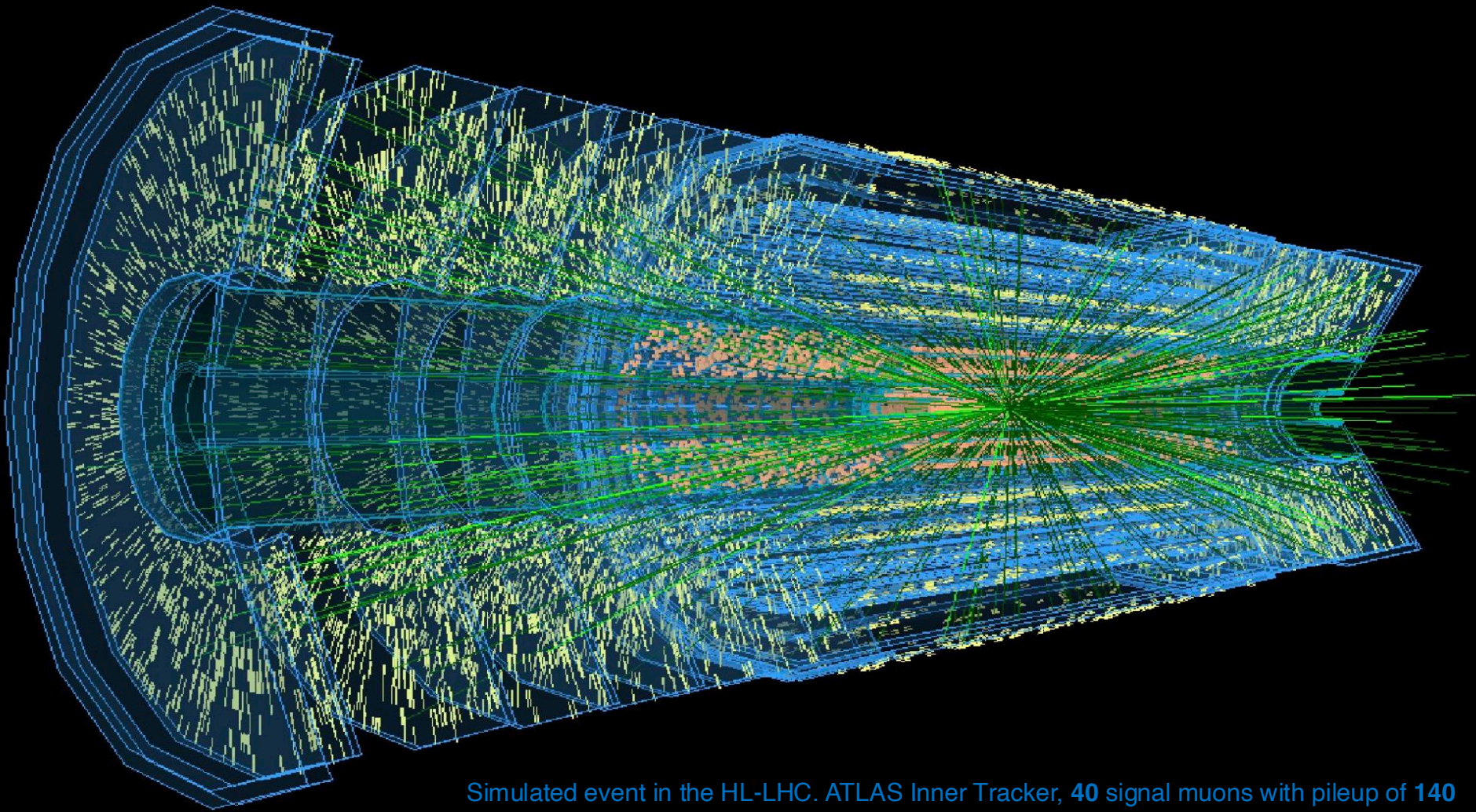
July 4, 2012



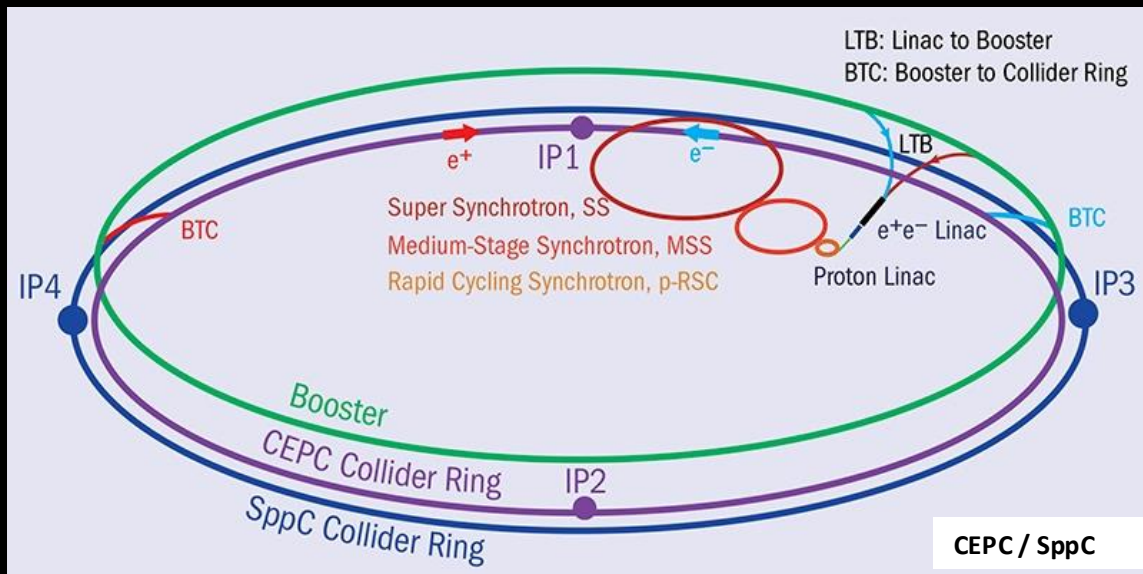
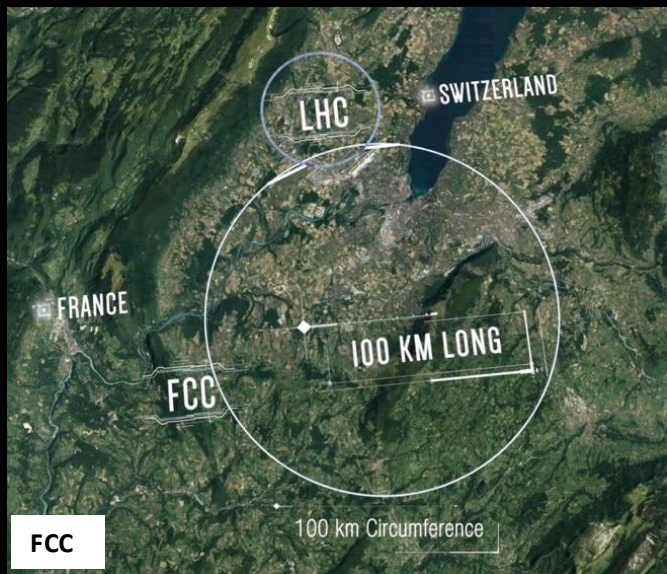
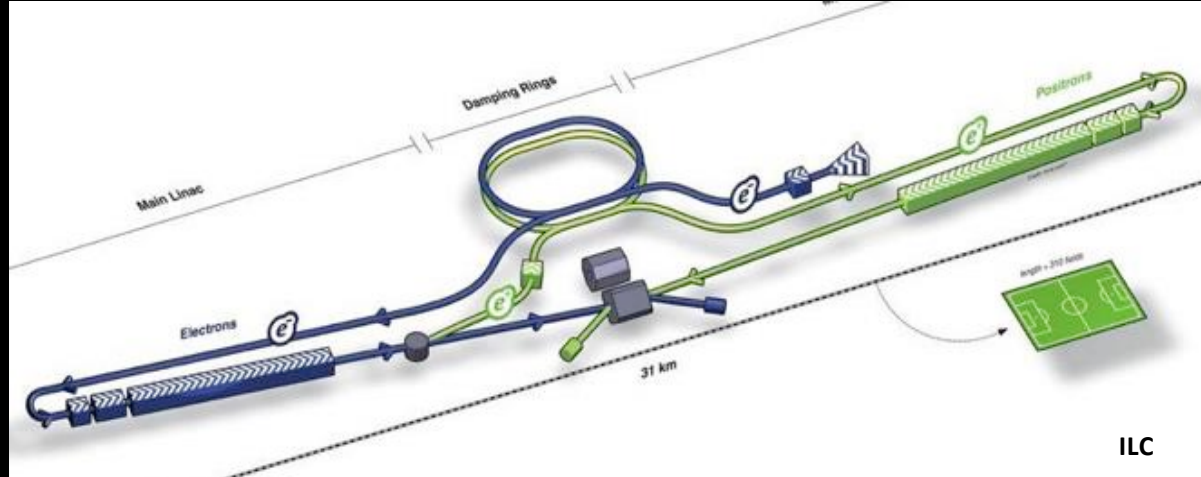
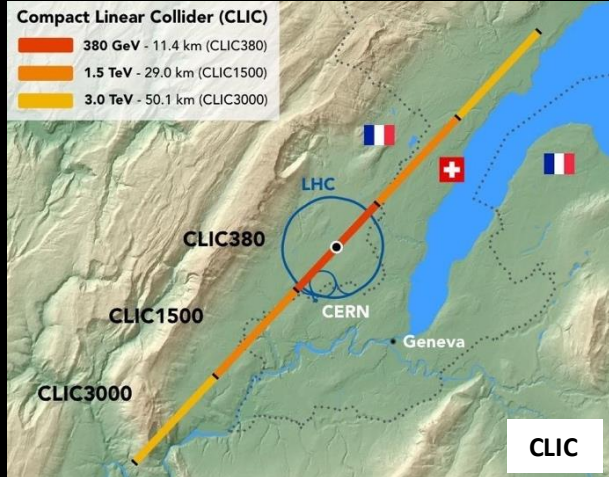
***“I think we have it” – Rolf Heuer, CERN’s Director General***



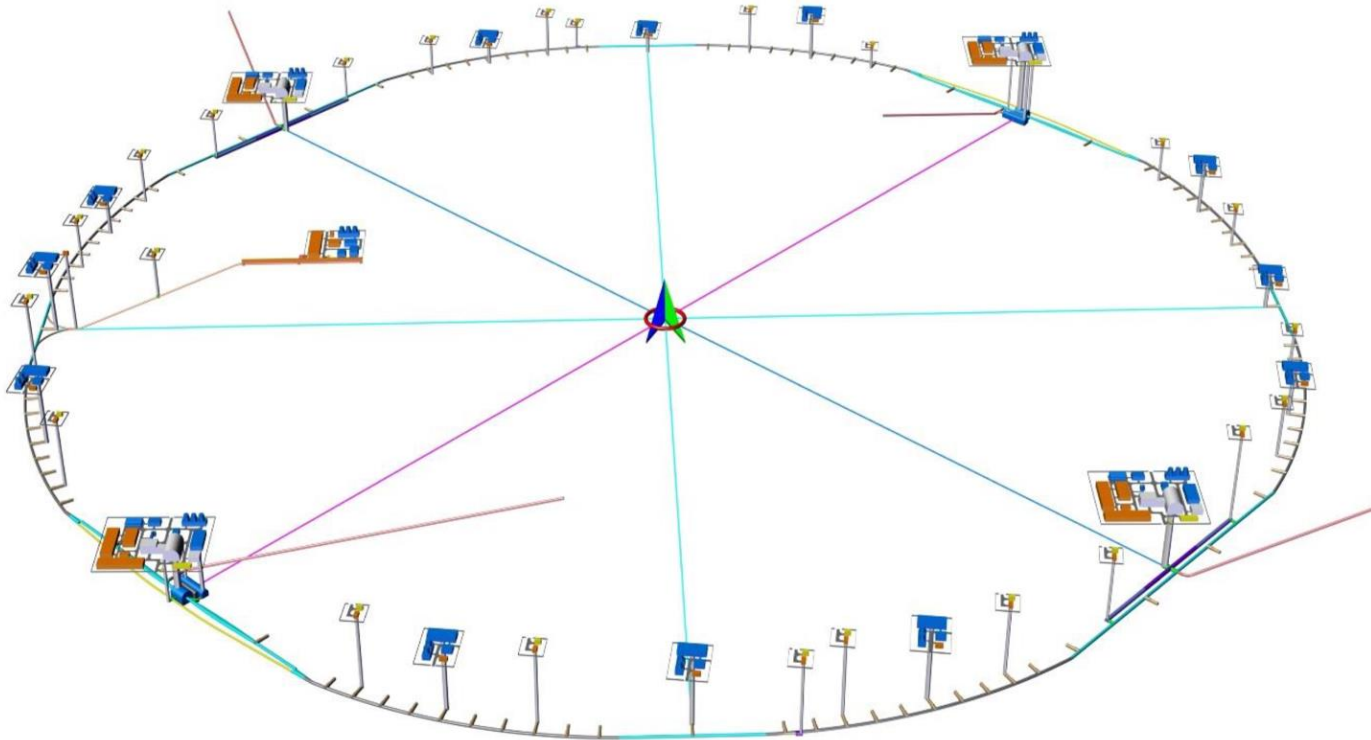
What is next?



Simulated event in the HL-LHC. ATLAS Inner Tracker, 40 signal muons with pileup of 140



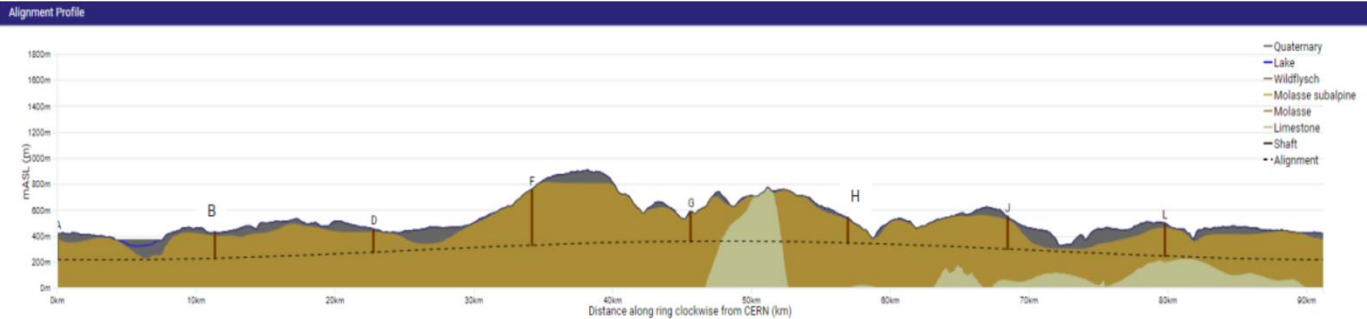
# CEPC Conceptual Design Report



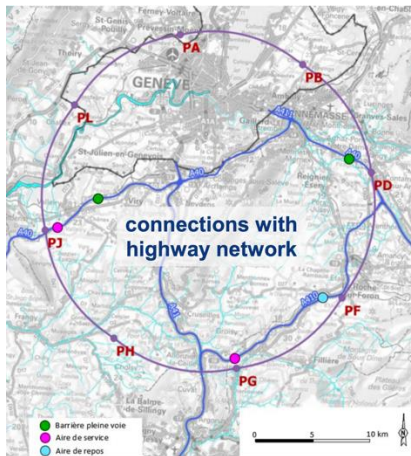
Diseño de estructuras superficiales y subterráneas del CEPC.

Imagen: CEPC CDR, Vol 1.

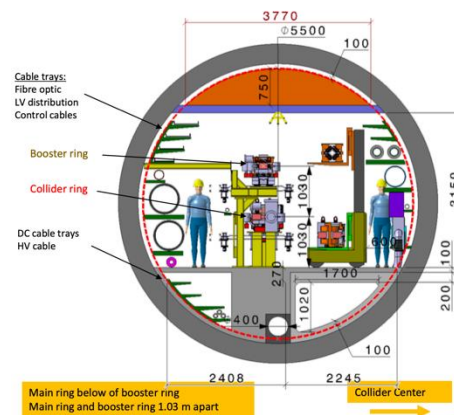
# FCC Feasibility Study



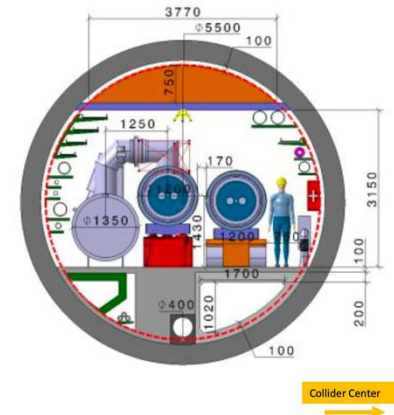
Geology Intersected by Tunnel    Geology Intersected by Section



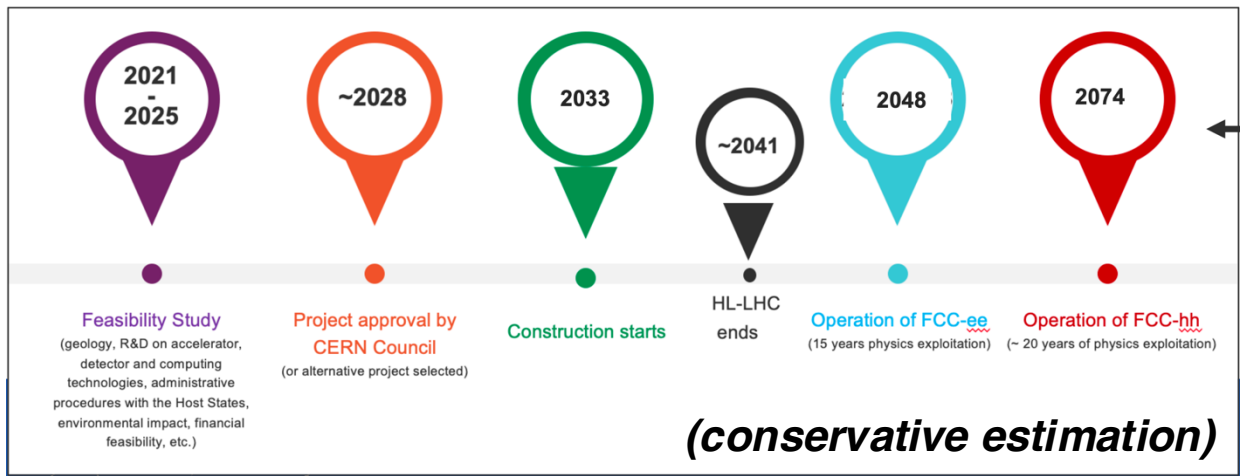
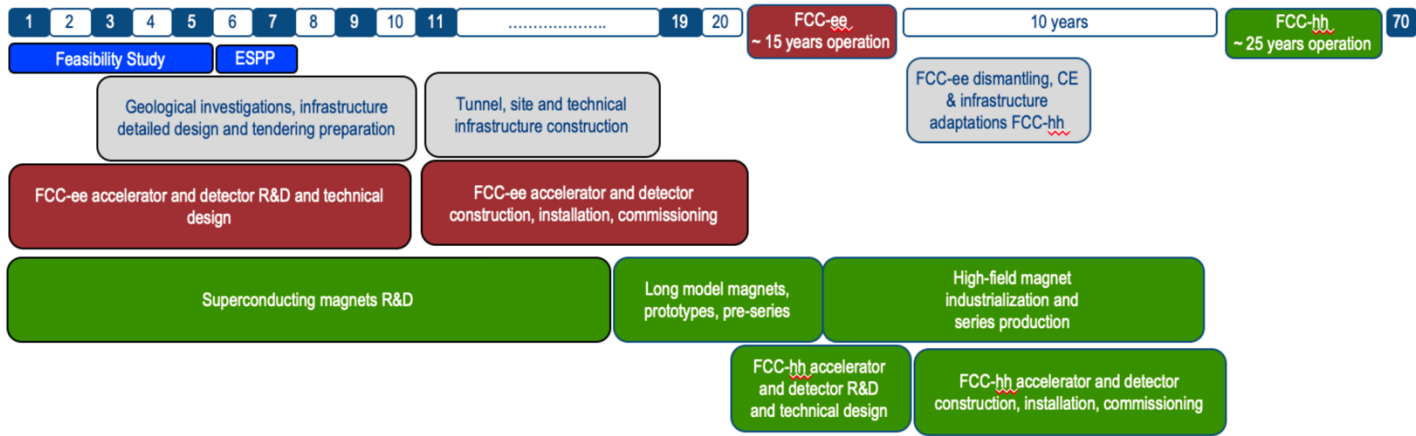
FCC-ee



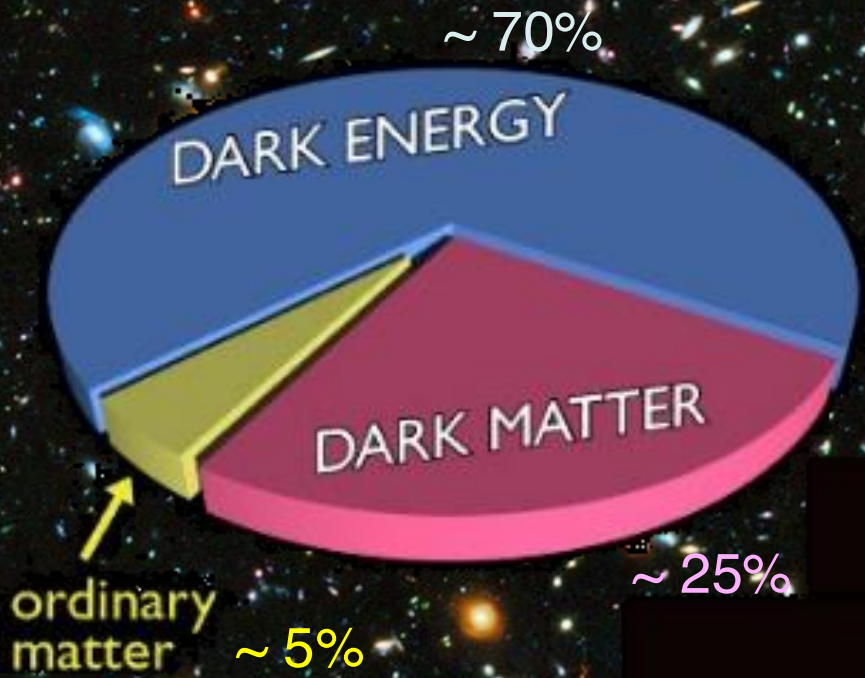
FCC-hh

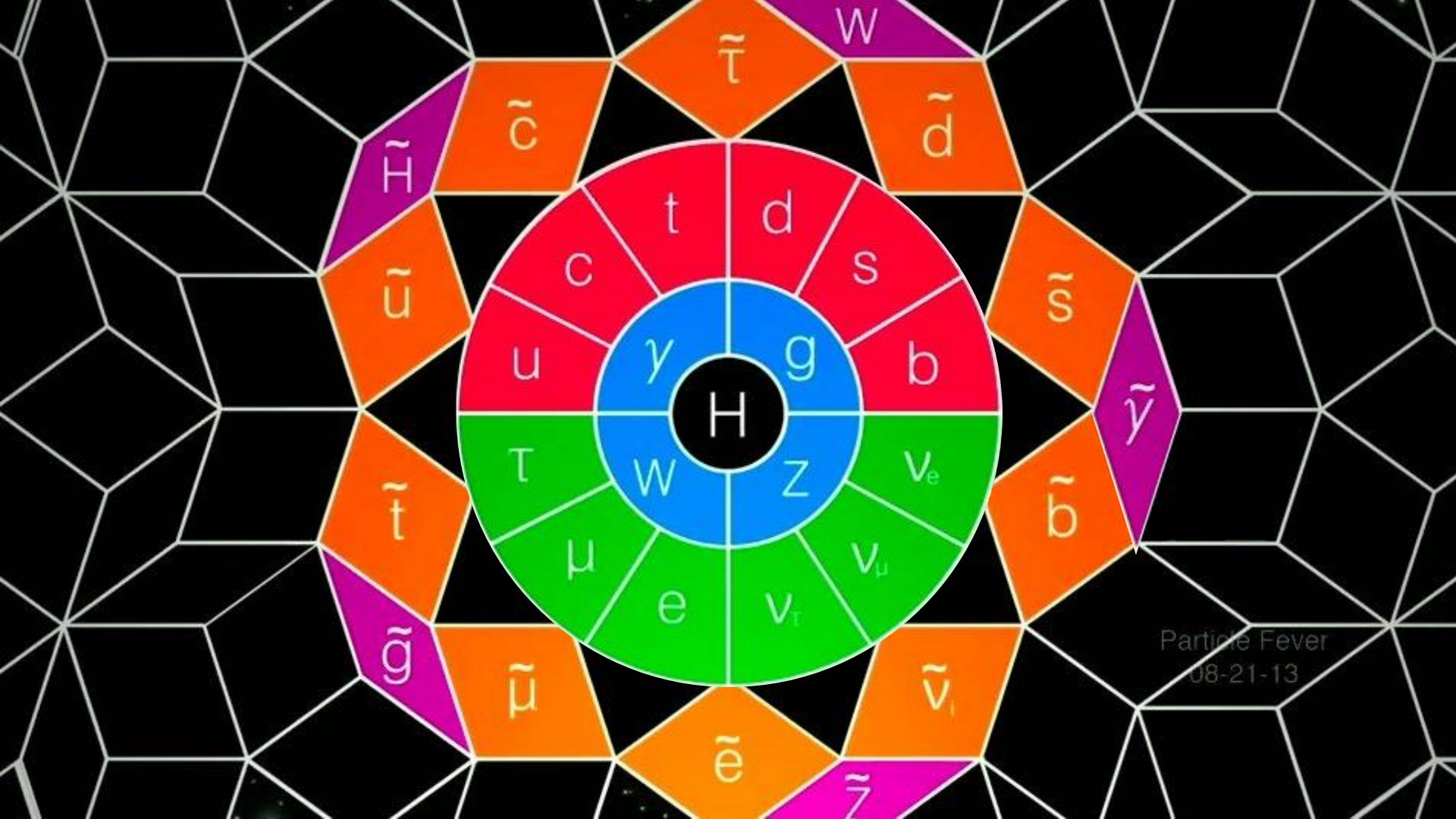


Source: Michael Benedikt, Status of the FCC Feasibility Study, CERN, 13 February 2024



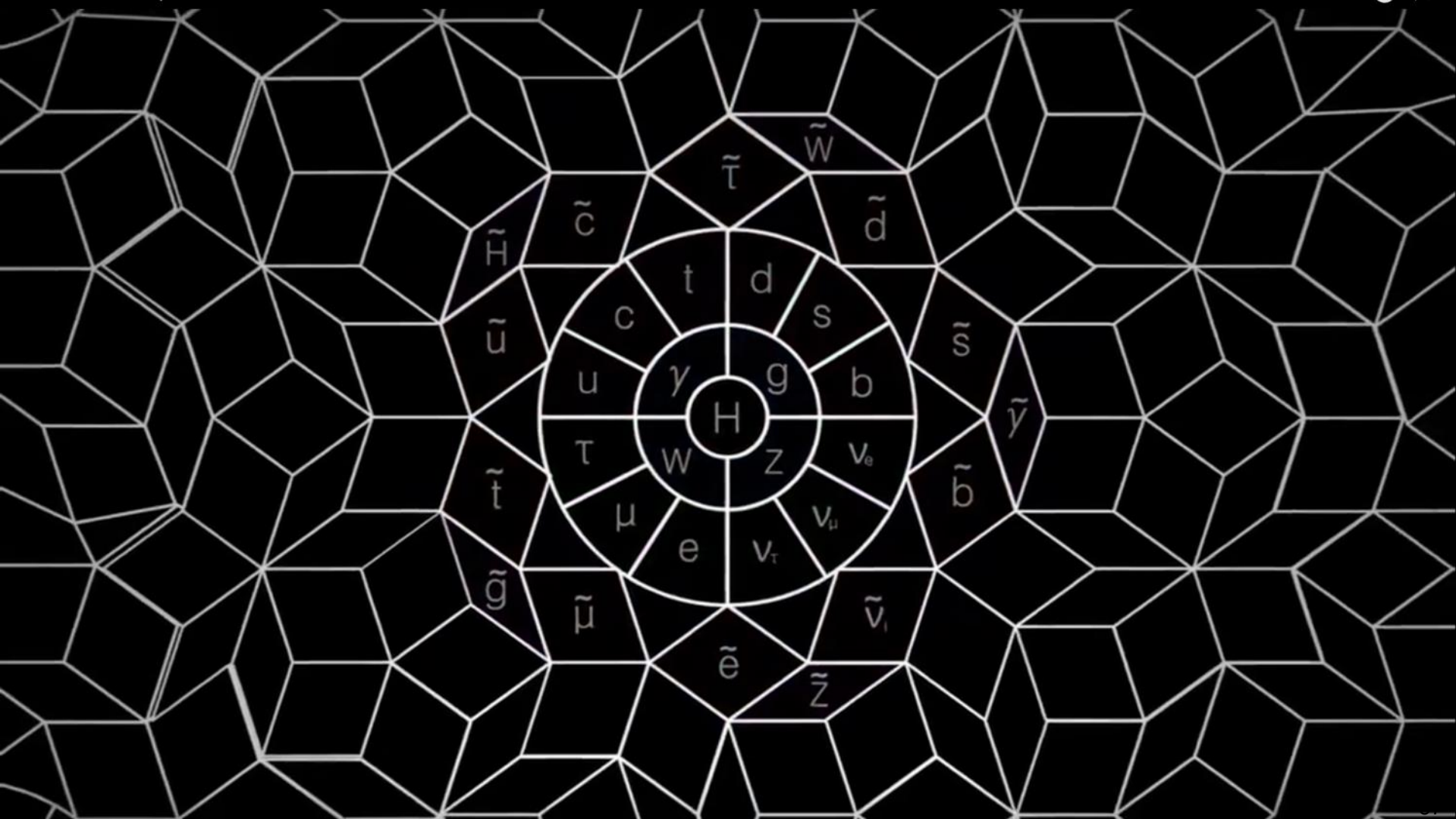
Source: Michael Benedikt, Status of the FCC Feasibility Study, CERN, 13 de febrero de 2024

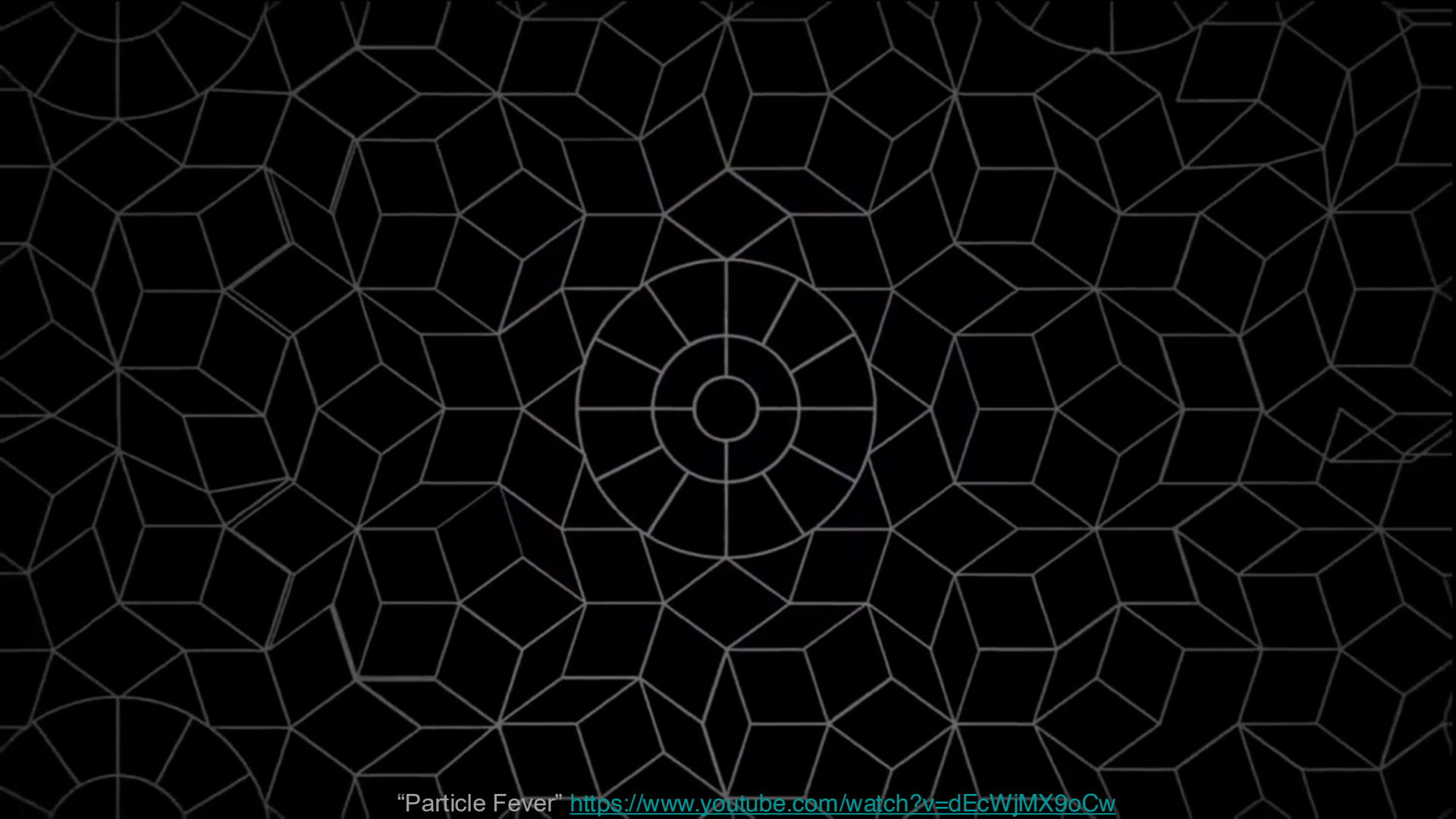




Particle Fever  
08-21-13







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

