

# The discovery of the Higgs particle



Luis Roberto Flores Castillo  
The Chinese University of Hong Kong

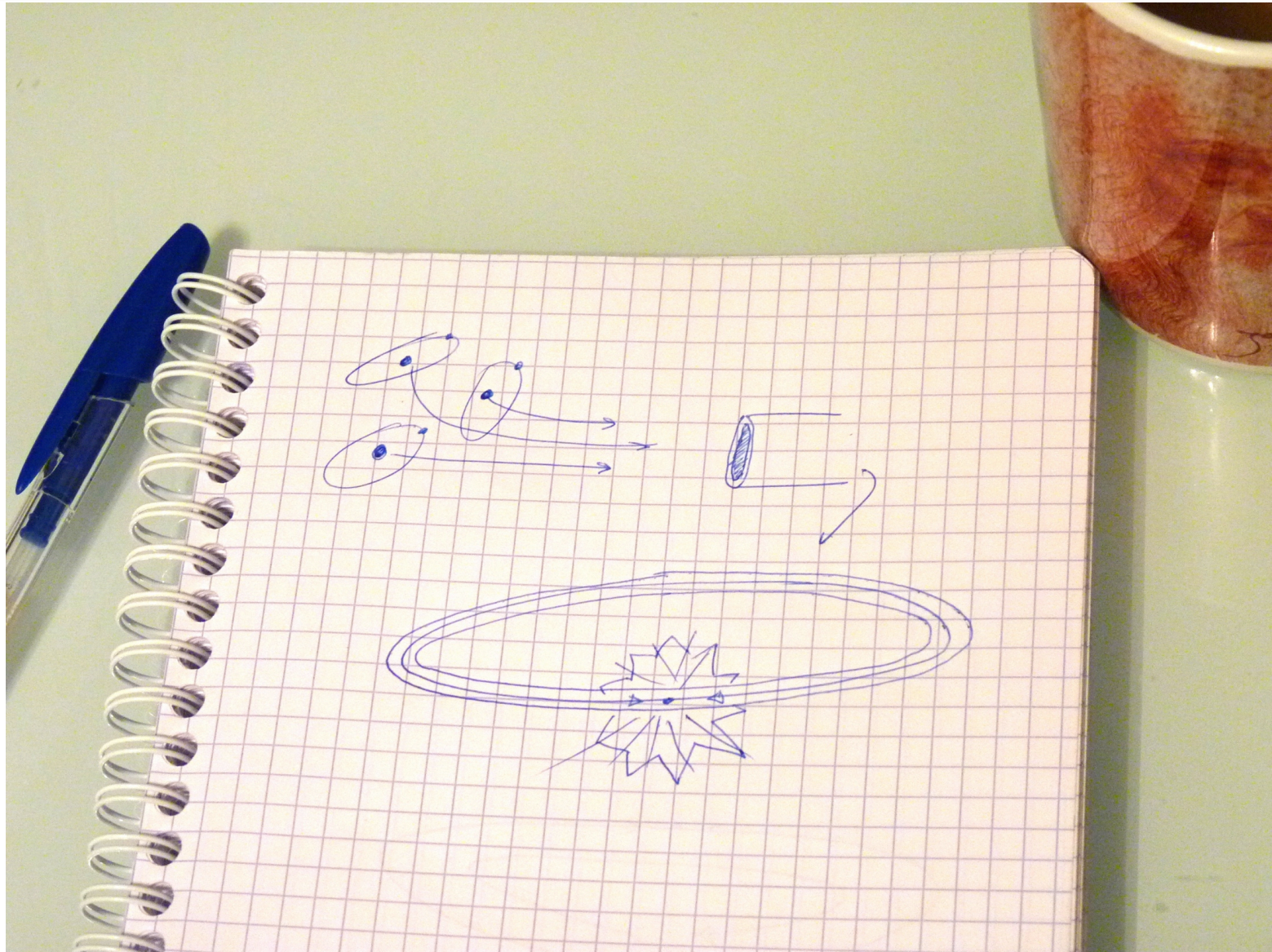


International Teacher Weeks Program 2017

CERN, Switzerland

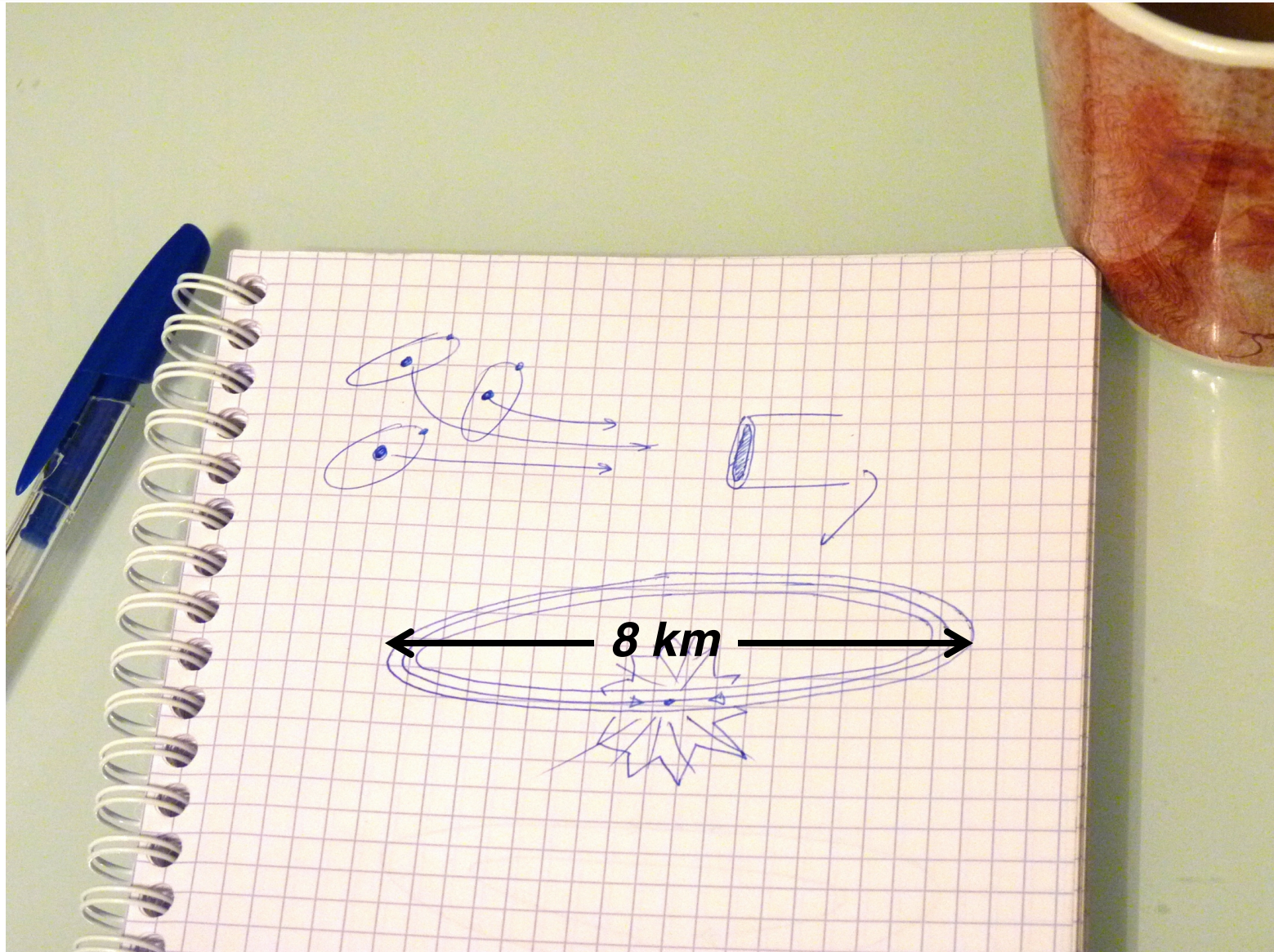
August 15, 2017

# Aiming high



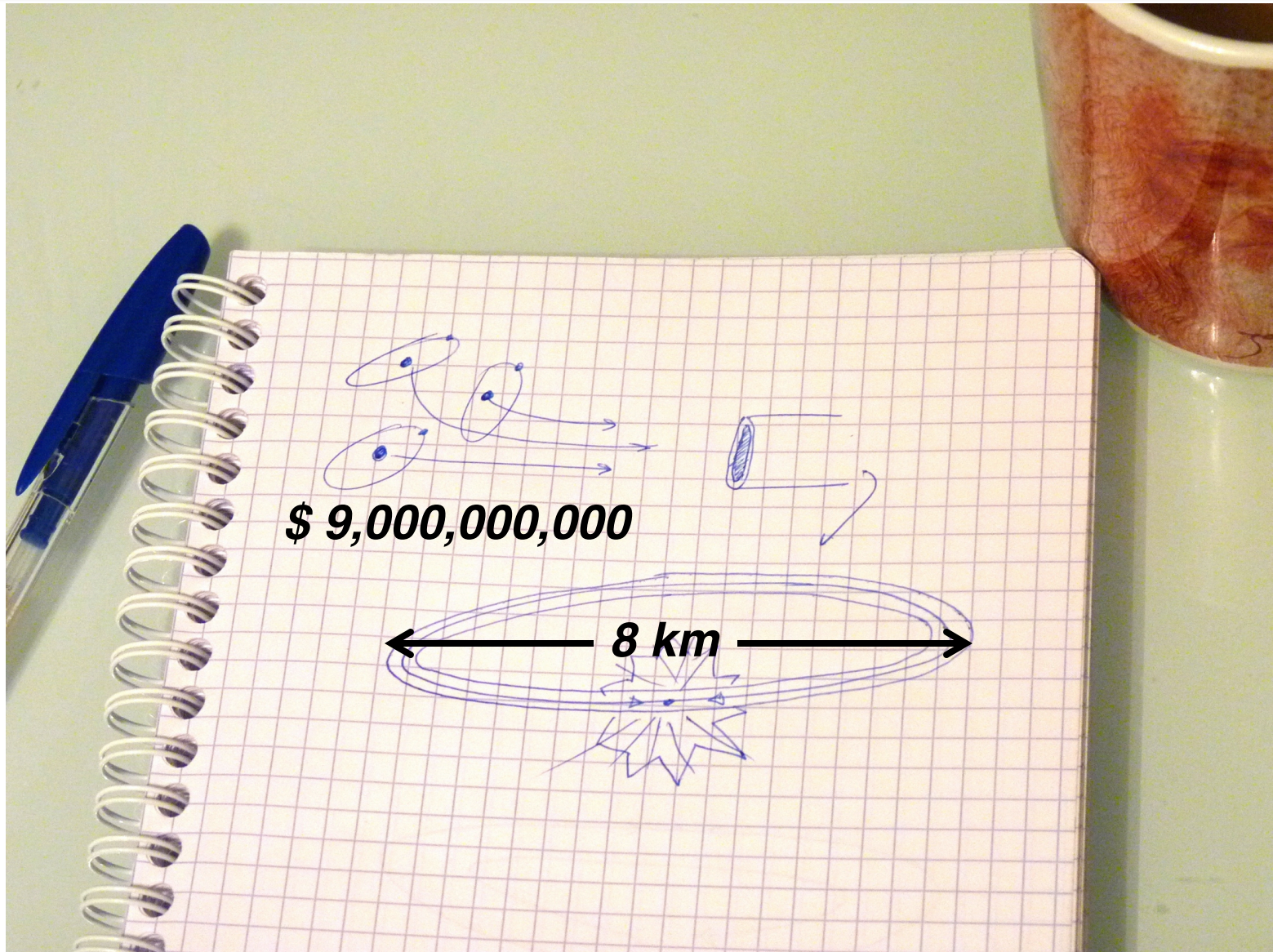


# Aiming high



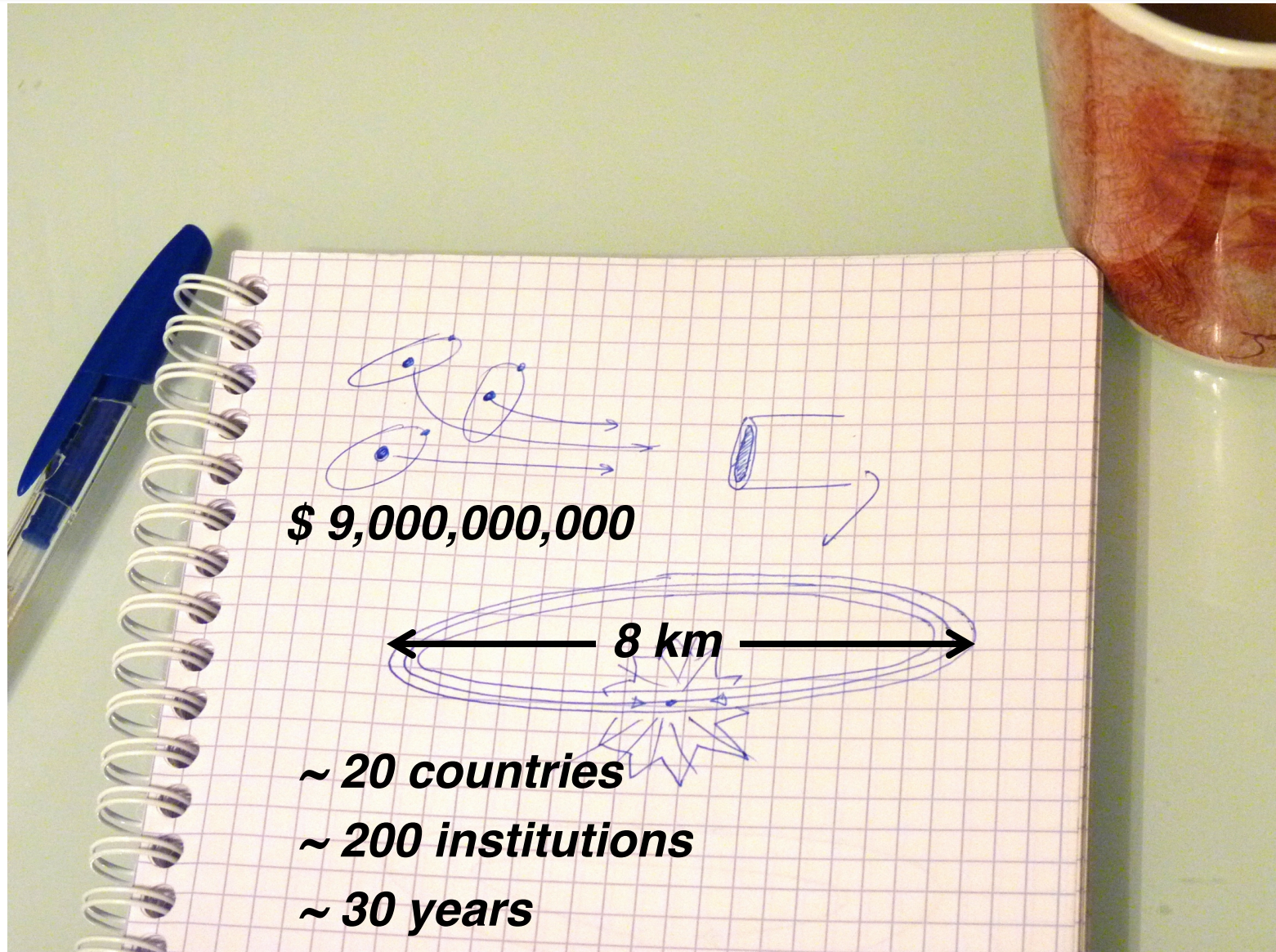


# Aiming high





# Aiming high









July 4, 2012



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



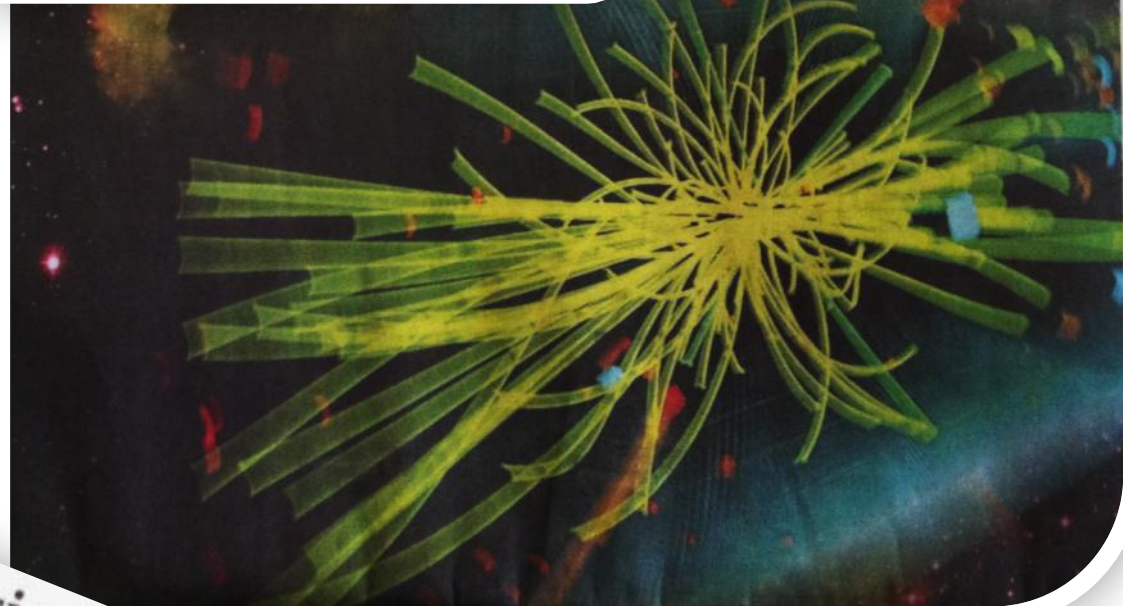
International Herald Tribune  
Discovery upends  
world of physics  
JULY 5, 2012

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

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

THE AGE  
THURSDAY, JULY 5, 2012  
NEWSPAPER OF THE YEAR  
Origin of universe revealed

JULY 5, 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

JULY 7TH - 13TH 2012

Economist.com

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

JULY 7TH - 13TH 2012

Worldwide excluding UK

NEWSPAPER OF THE YEAR

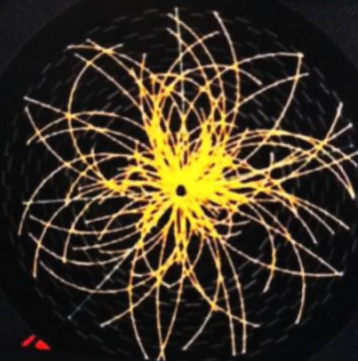
Wimbledon 2012

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



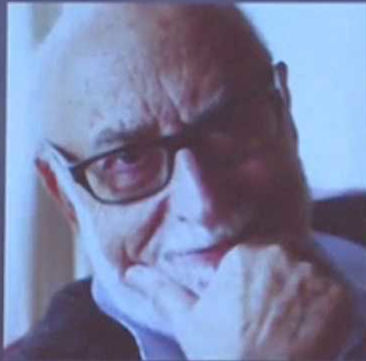
October 8, 2013



Nobelpriset 2013

The Nobel Prize 2013

## 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."*

**Nobelprize.org**  
© Kungl. Vetenskapsakademien



**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	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	H																	He
2	Li	Be											B	C	N	O	F	Ne
3	Na	Mg											Al	Si	P	S	Cl	Ar
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
6	Cs	Ba	*	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
7	Fr	Ra	+	Rf	Ha	Sg	Bh	Hs	Mt	Ds	Rg		Uut	Uuq	Uup	Uuh	Uus	Uuo
	s-block		d-block										p-block					
f-block	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”



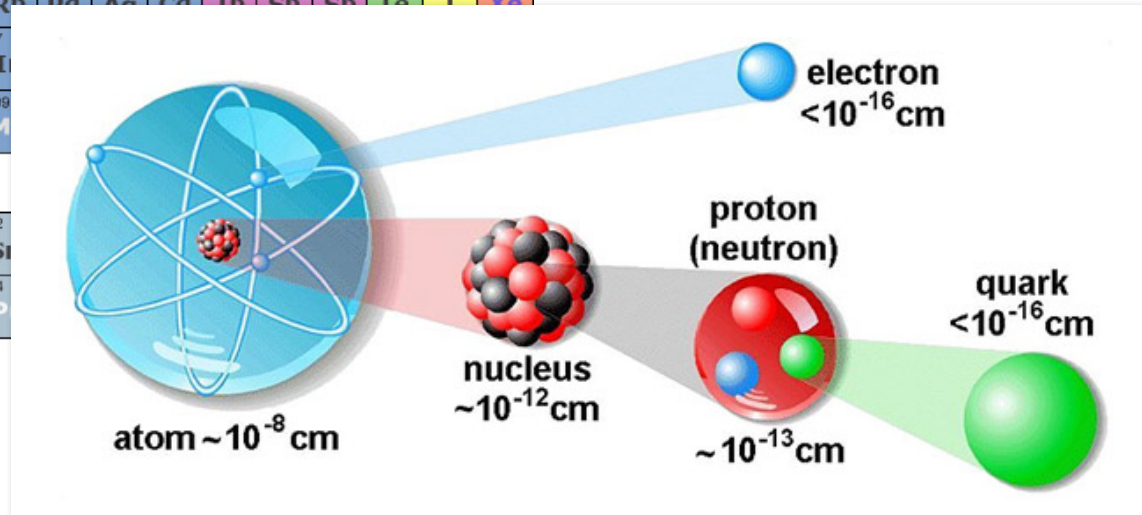
# Fundamental building blocks?

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
1A	1 H																	2 He
2A		4 Be																
3A	3 Li																	
4A																		
5A	11 Na	12 Mg																
6A																		
7A	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
8A																		
9A	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
10A																		
11A	55 Cs	56 Ba	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	72 Hf
12A																		
13A	87 Fr	88 Ra	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	104 Rf
14A																		
15A																		
16A																		
17A																		
18A																		

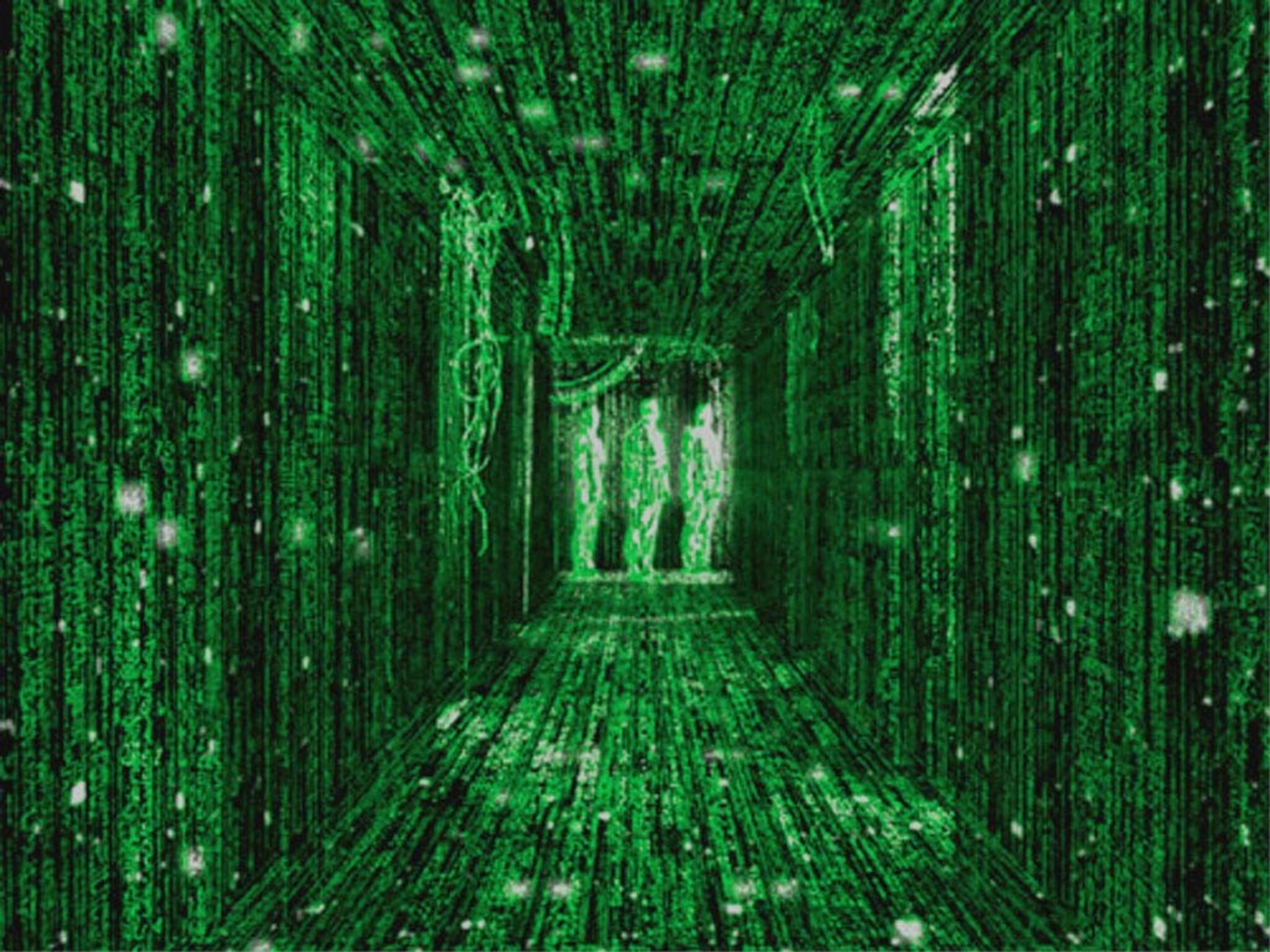
**Legend:**

- H - Gas** (Green)
- Li - Solid** (Blue)
- Non-Metals** (Green)
- Alkali Metals** (Yellow)
- Transition Metals** (Blue)
- Alkali Earth Metals** (Cyan)



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







# Fundamental building blocks?

- Besides those three, ...

$u$   
up

$d$   
down

$e$   
electron



# Fundamental building blocks?

- Besides those three, ...

$u$   
up

$d$   
down

$e$   
electron

$\gamma$   
photon



# Fundamental building blocks?

- Besides those three, ...

$u$   
up

$d$   
down

$e$   
electron

$\gamma$   
photon

$Z$   
Z boson

$W$   
W boson



# Fundamental building blocks?

- Besides those three, ...

$u$   
up

$d$   
down

$e$   
electron

$\gamma$   
photon

$Z$   
Z boson

$W$   
W boson

$g$   
gluon



# Fundamental building blocks?

- Besides those three, ...





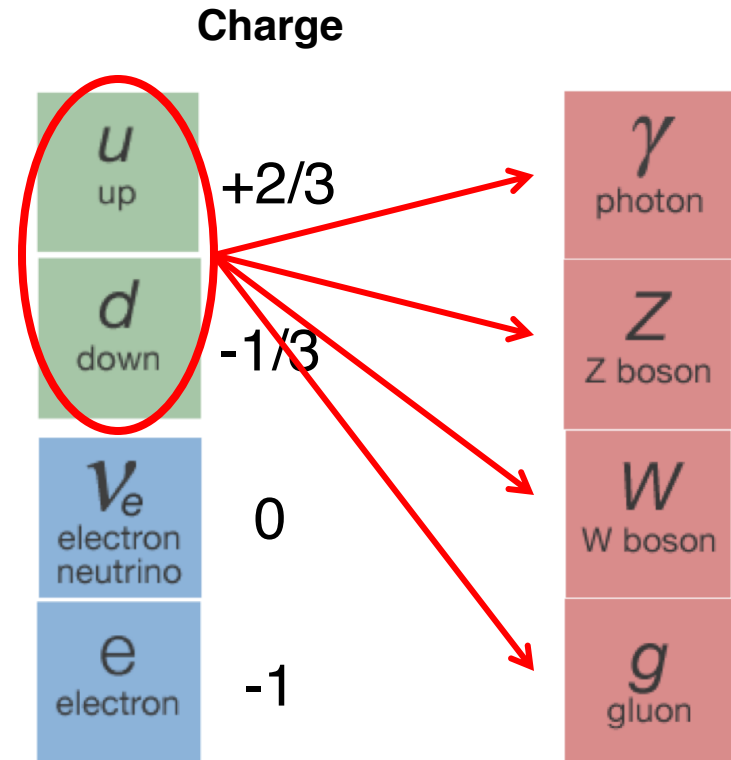
# Fundamental building blocks?

- Besides those three, ...

Charge	
$u$ up	$+2/3$
$d$ down	$-1/3$
$\nu_e$ electron neutrino	$0$
$e$ electron	$-1$
$\gamma$ photon	
$Z$ Z boson	
$W$ W boson	
$g$ gluon	

# Fundamental building blocks?

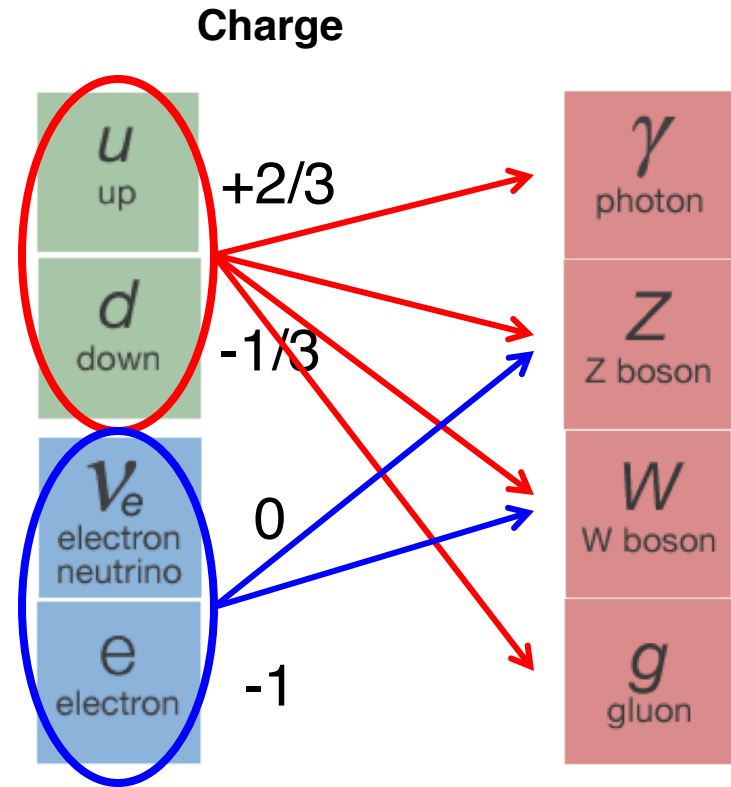
- Besides those three, ...





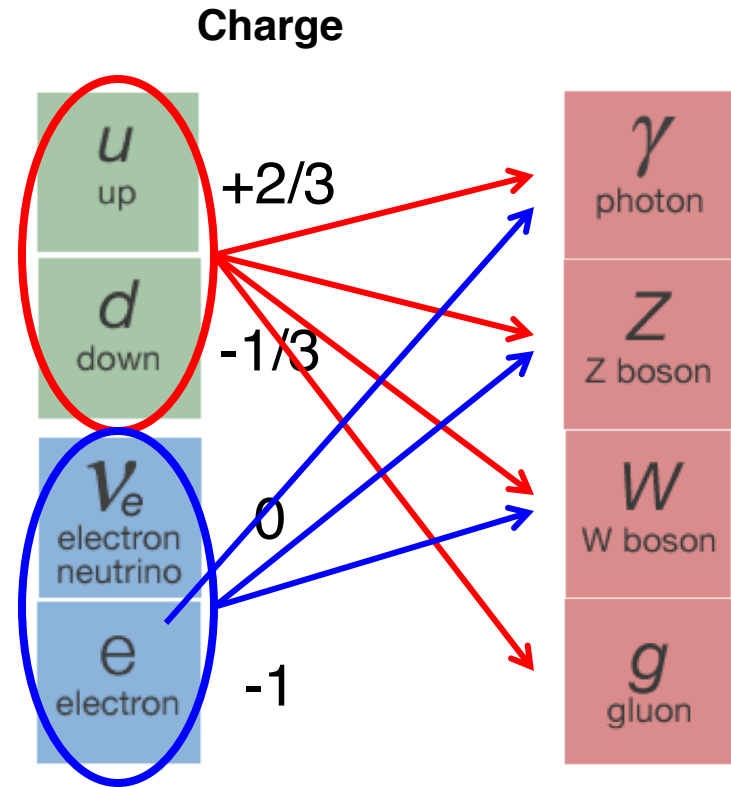
# Fundamental blocks?

- Besides those three, ...



# Fundamental building blocks?

- Besides those three, ...





# Fundamental building blocks?

- Besides those three, ...

$u$ 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?

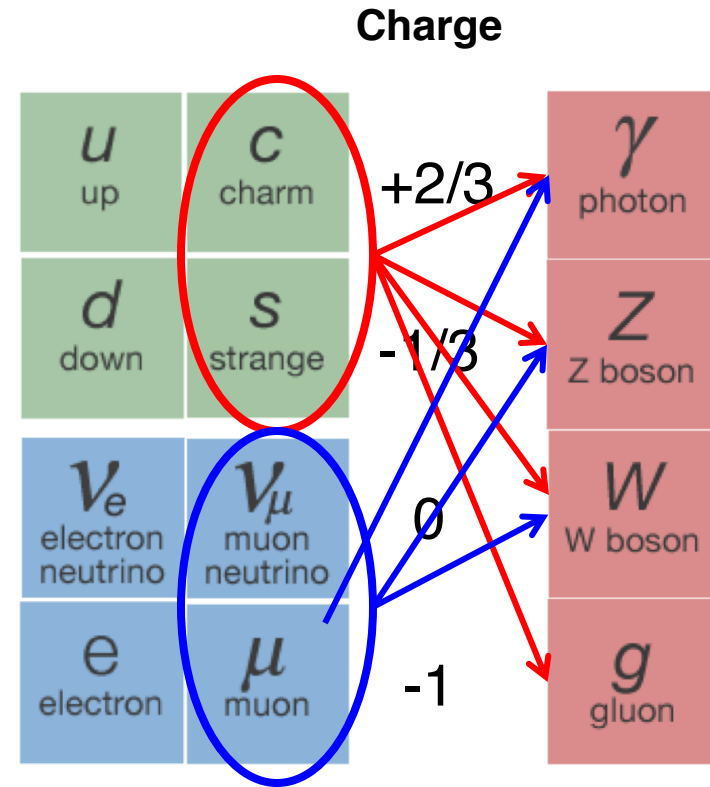
- Besides those three, ...

		Charge	
$u$ up	$c$ charm	$+2/3$	$\gamma$ photon
$d$ down	$s$ strange		$Z$ Z boson
$\nu_e$ electron neutrino	$\nu_\mu$ muon neutrino	0	$W$ W boson
$e$ electron	$\mu$ muon		$g$ gluon
		$-1/3$	
		$-1$	



# Fundamental building blocks?

- Besides those three, ...



# Fundamental building blocks?

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

	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	

Source: AAAS



# Fundamental building blocks?

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	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	

- In 1964, there was a problem: the model worked **only for elementary particles with ZERO mass**

Source: AAAS

# “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.



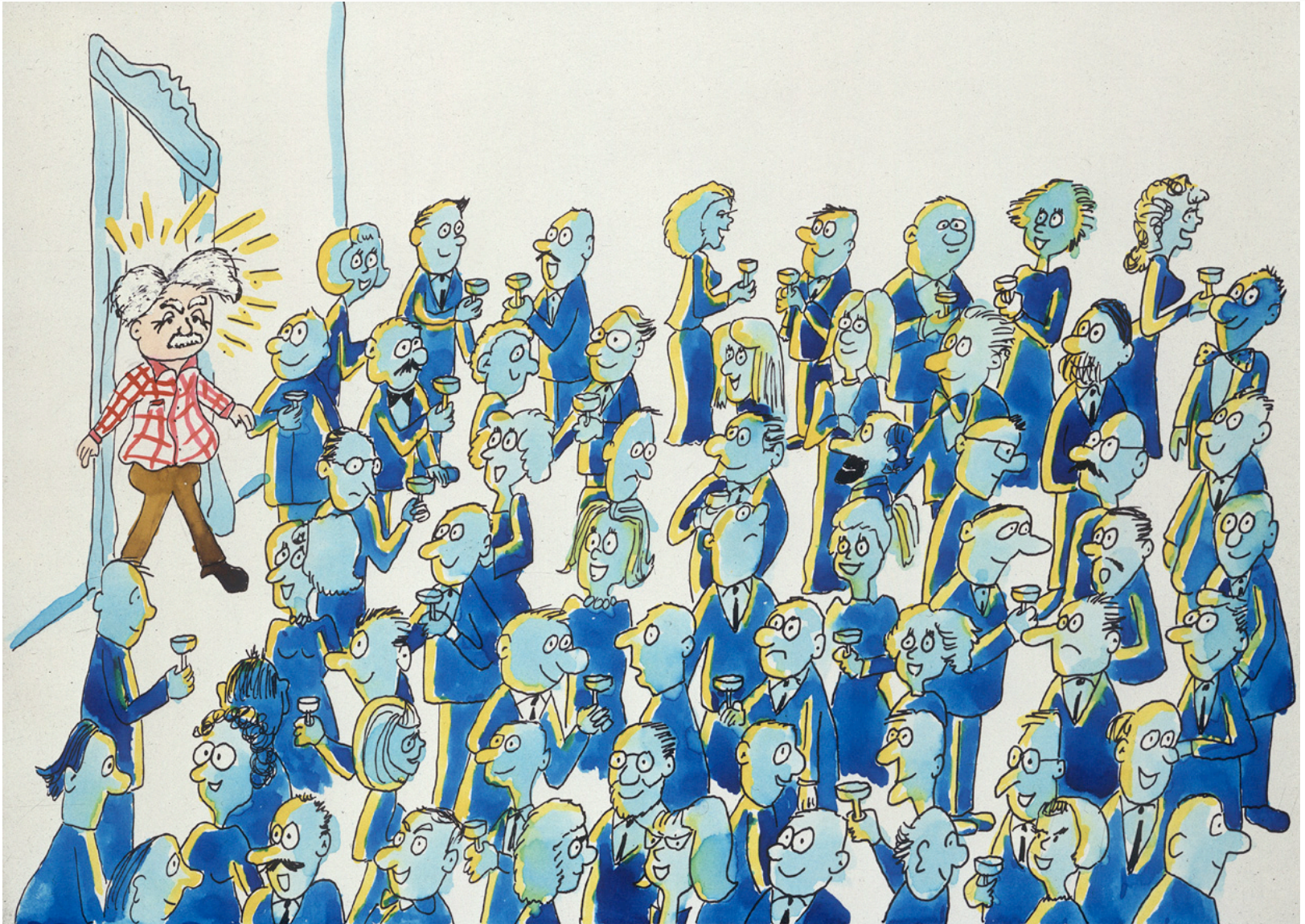
# What is the Higgs boson?



Prof. David J. Miller



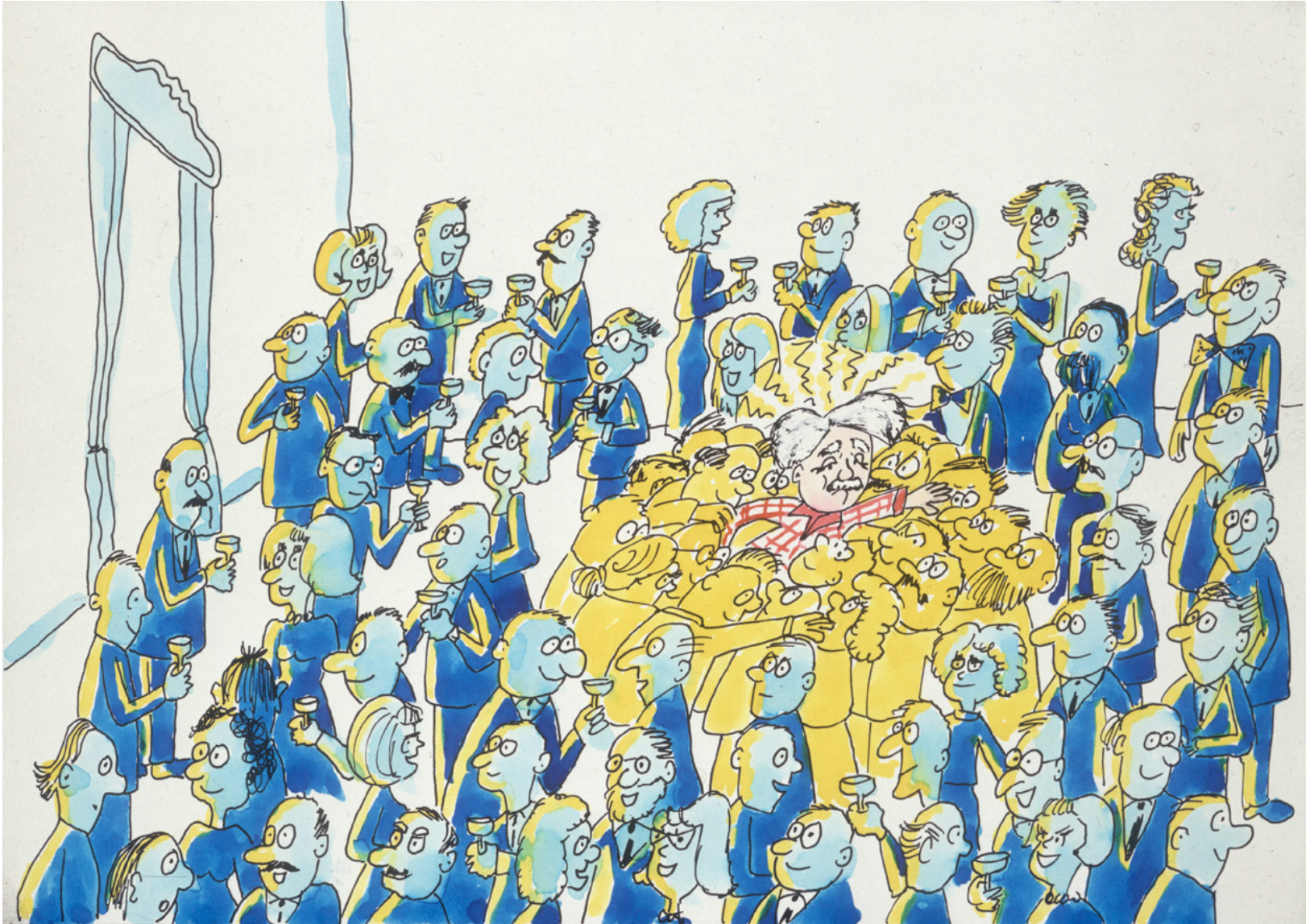
# What is the Higgs boson?



Prof. David J. Miller



# What is the Higgs boson?



Prof. David J. Miller



# What is the Higgs boson?



Prof. David J. Miller



# What is the Higgs boson?



Prof. David J. Miller

“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

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)



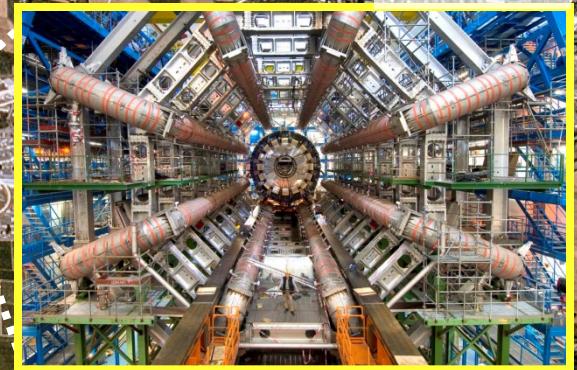
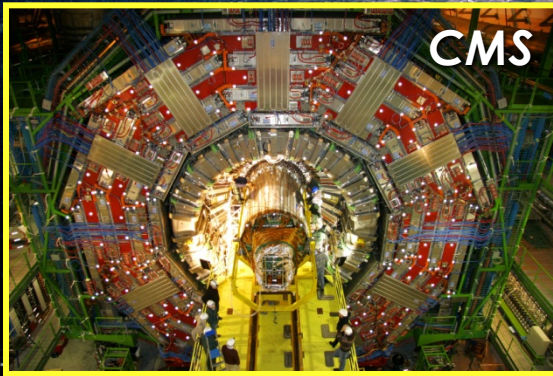
# The Large Hadron Collider



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



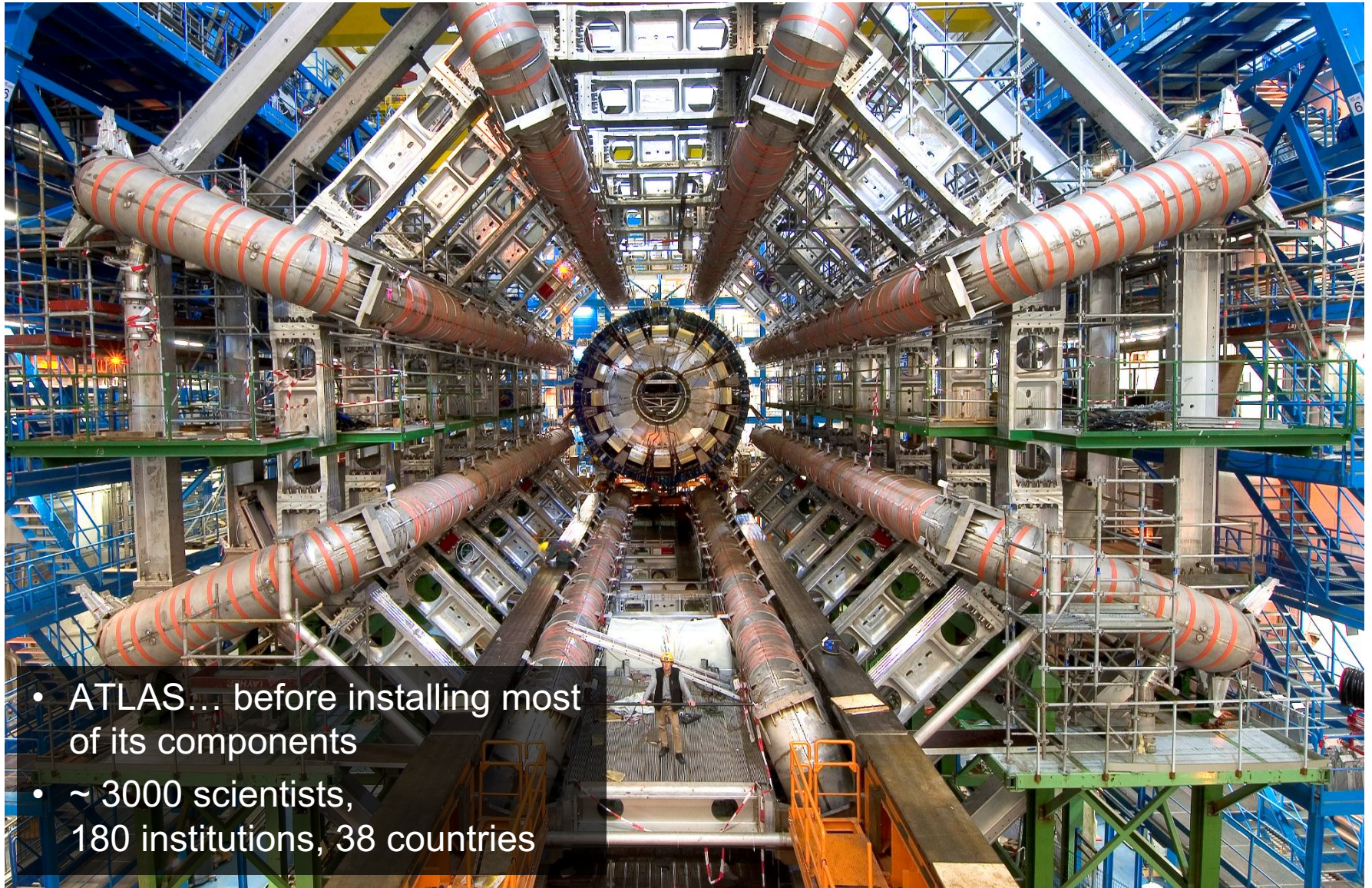
# The Large Hadron Collider



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



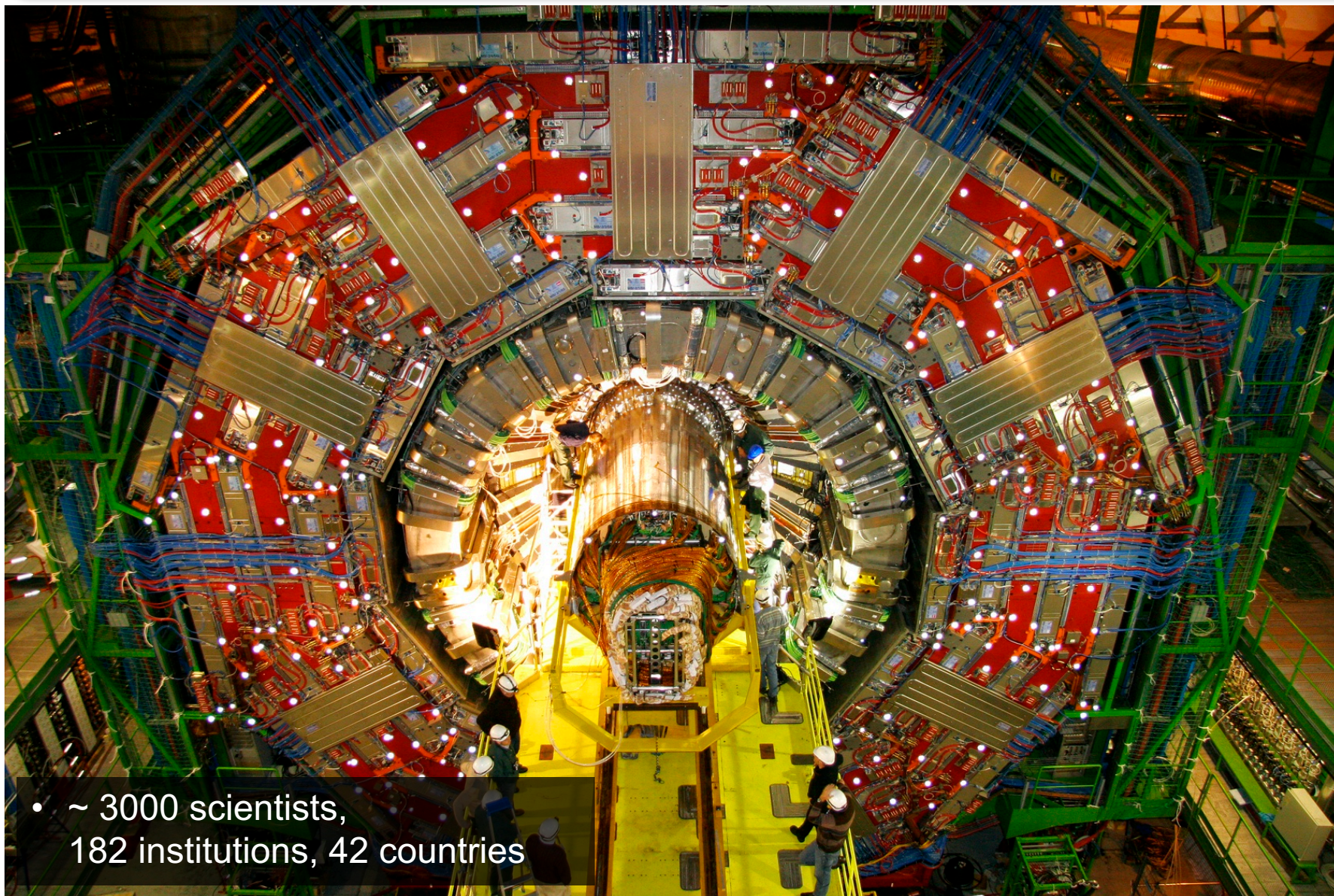
# ATLAS



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



# CMS



- ~ 3000 scientists,  
182 institutions, 42 countries

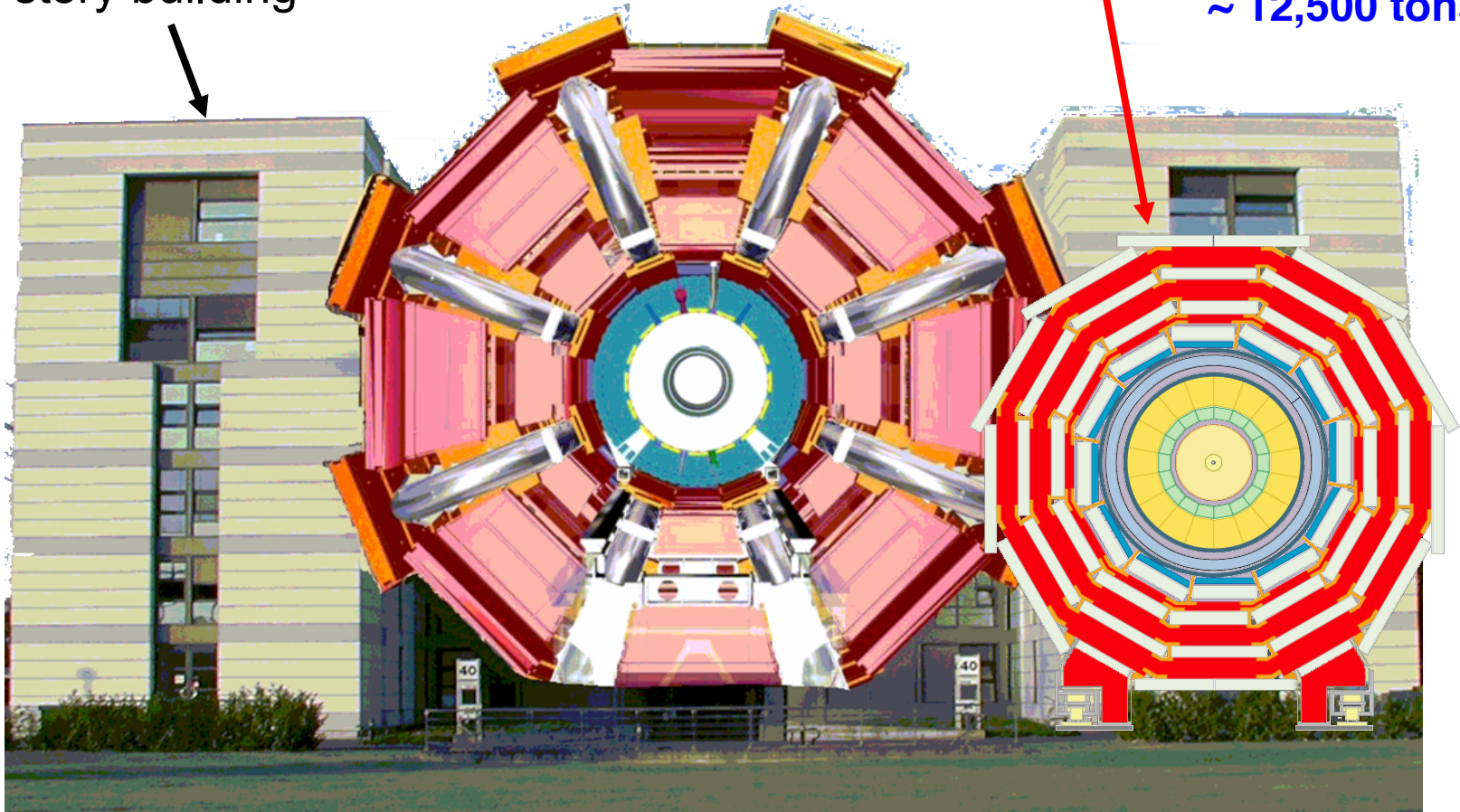


# Detectors

Five-story building

**ATLAS**  $\sim 25 \text{ m} \times 45 \text{ m}$   
 $\sim 7,000 \text{ tons}$

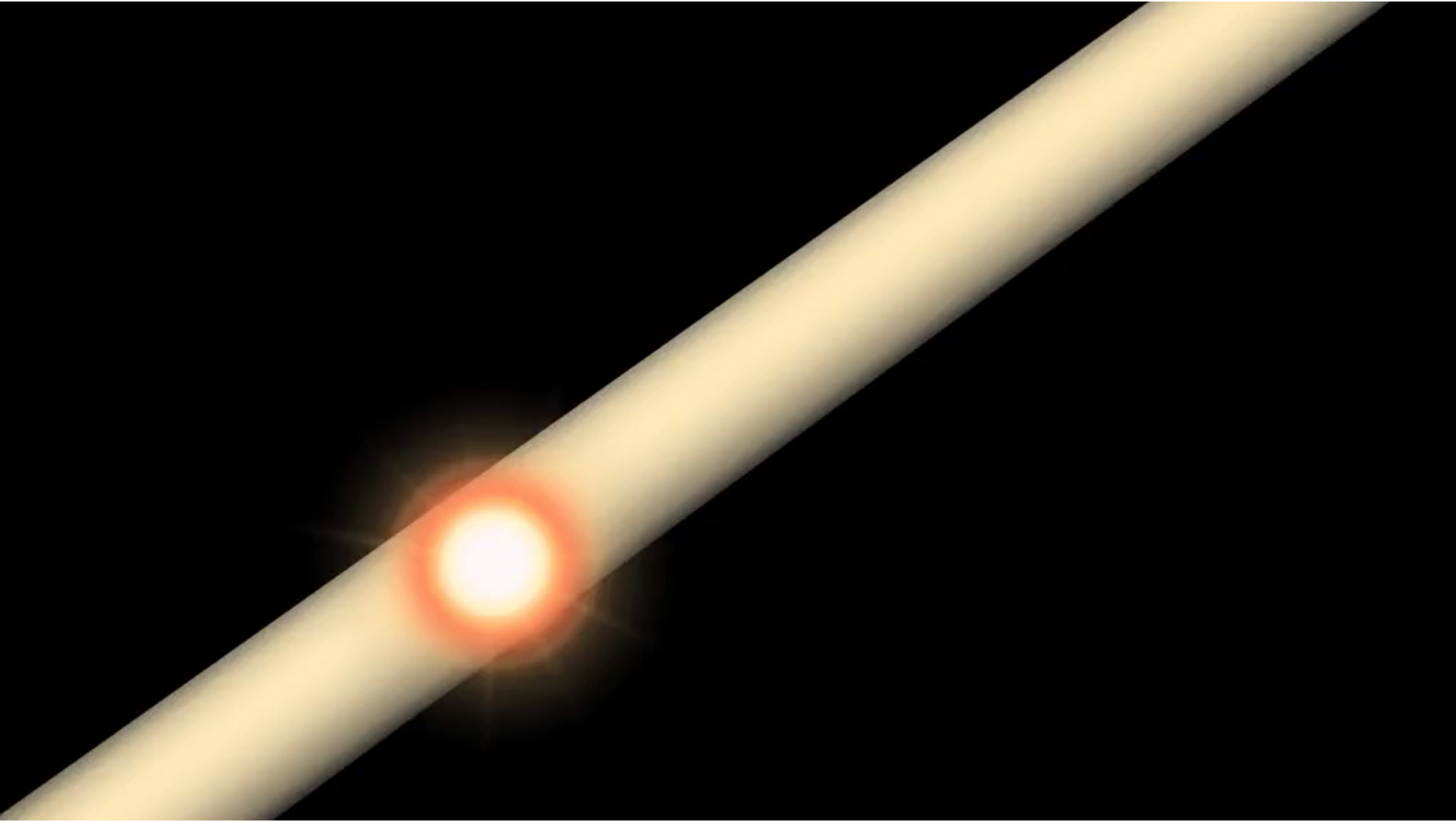
**CMS**  $\sim 15 \text{ m} \times 21.5 \text{ m}$   
 $\sim 12,500 \text{ tons}$



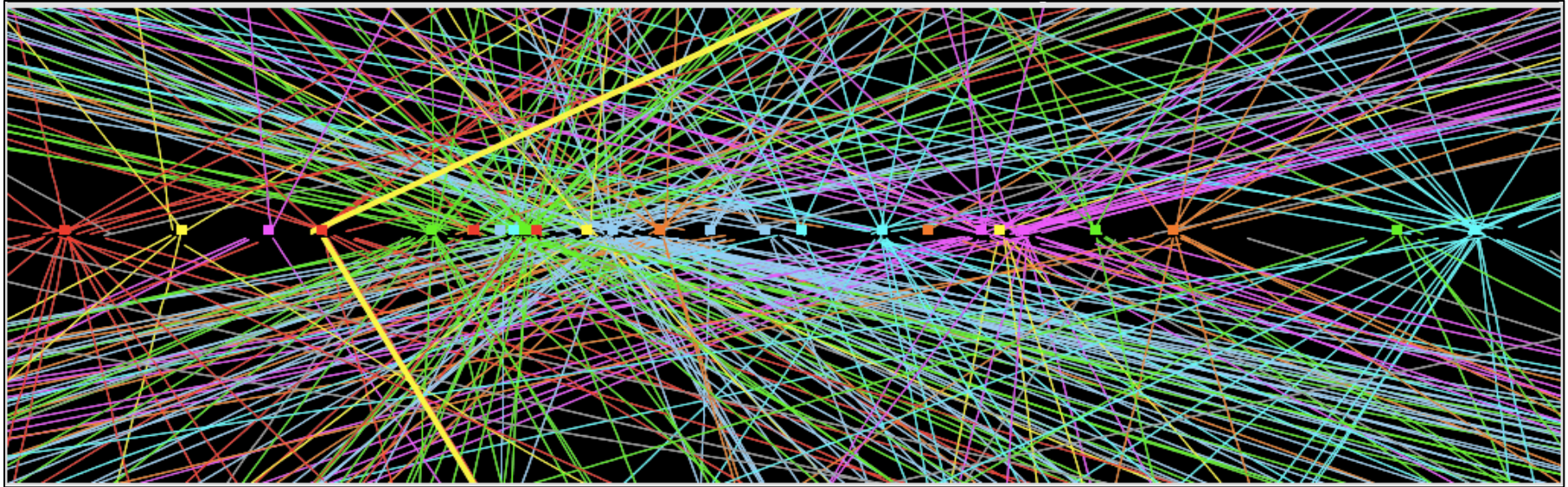
- About 100 millions sensors each
- Much beyond a 12-megapixel camera, 40 million pictures/second



# One “event”



# Data

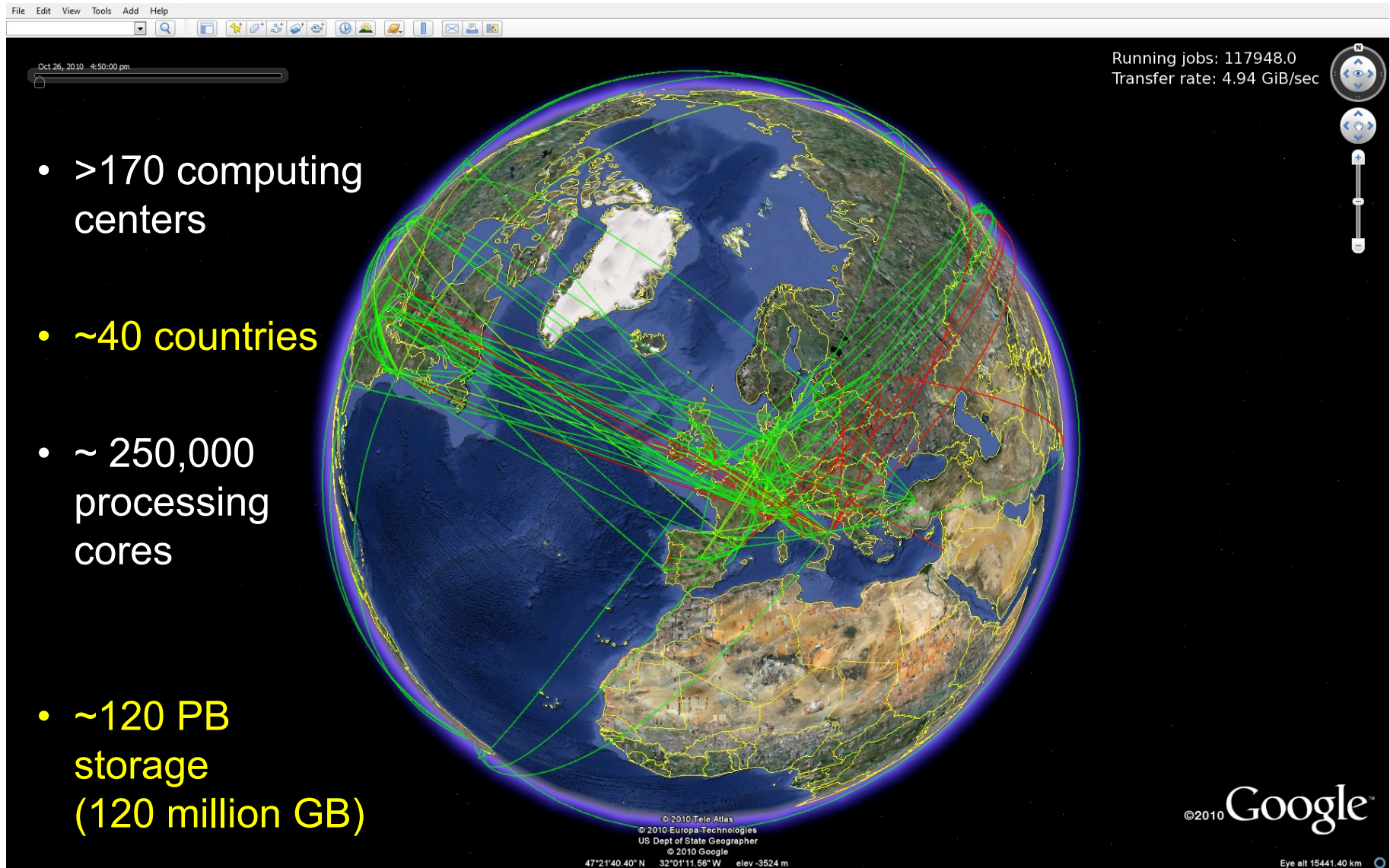


$Z \rightarrow \mu\mu$  event from 2012, with 25 reconstructed vertices

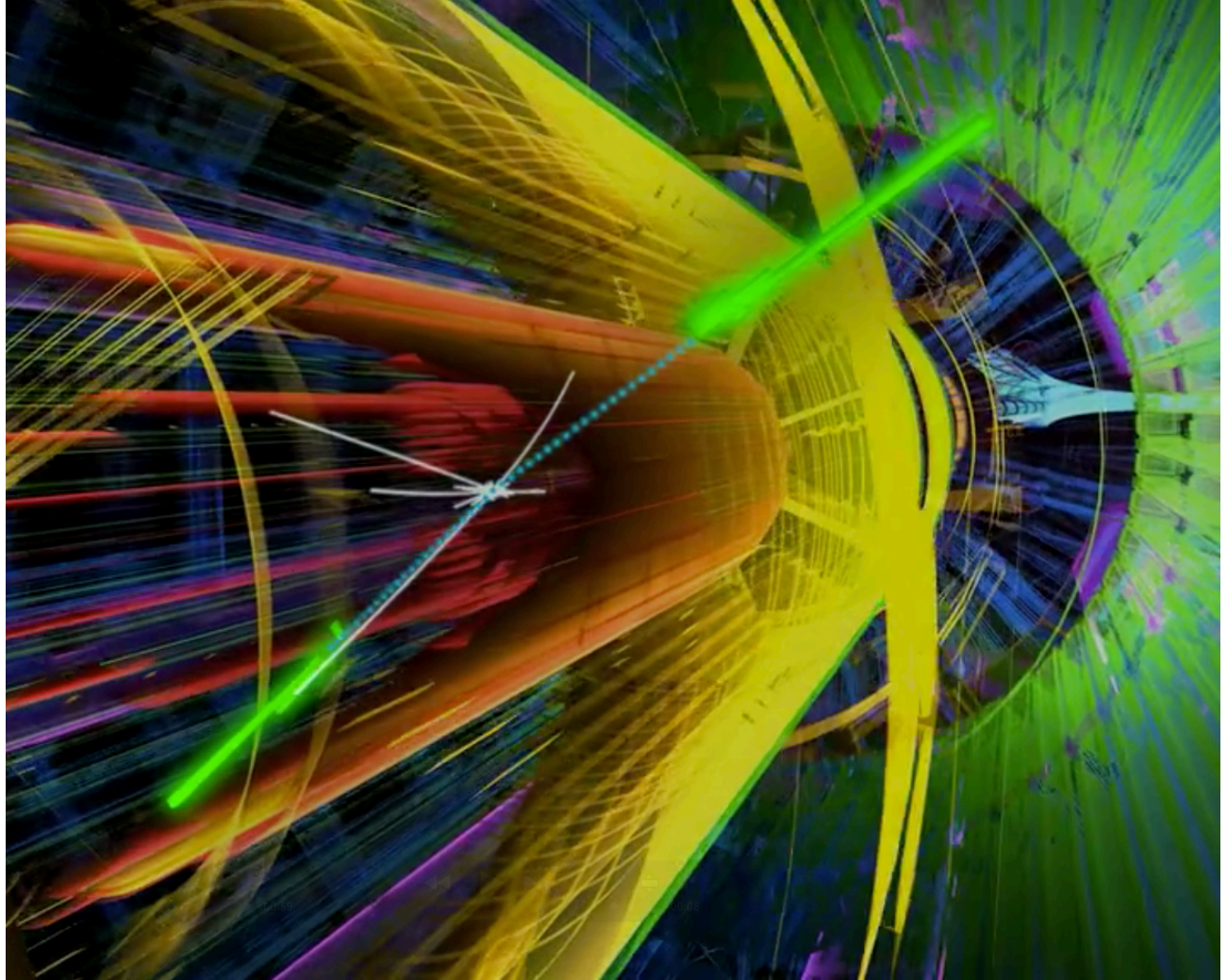
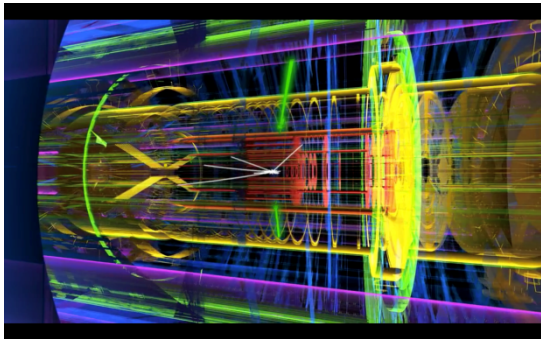
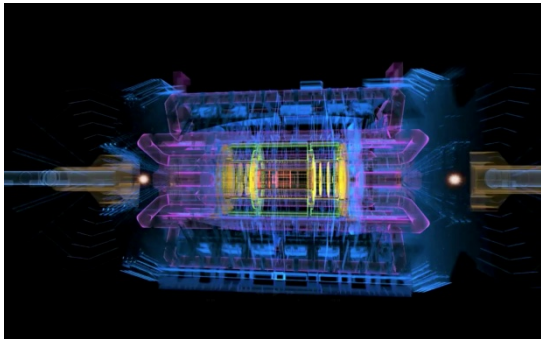
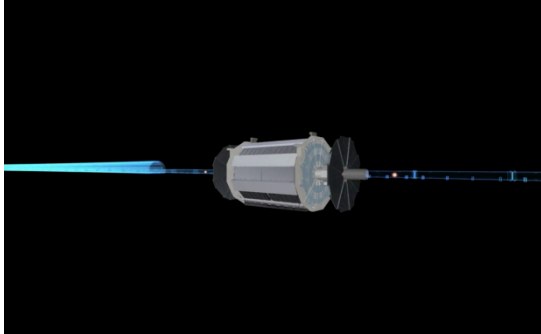
- Each bunch crossing  $\sim 20$   $pp$  interactions
- 40 M crossings per second  $\times$  20  $pp$  per crossing, spacing: 600 M  $pp/s$
- Fast selection systems (“trigger systems”) keep only 400 collisions/s
- Each  $pp$  collision produces hundreds of particles
- If stored in using CD's, ...



# Worldwide LHC Computing Grid

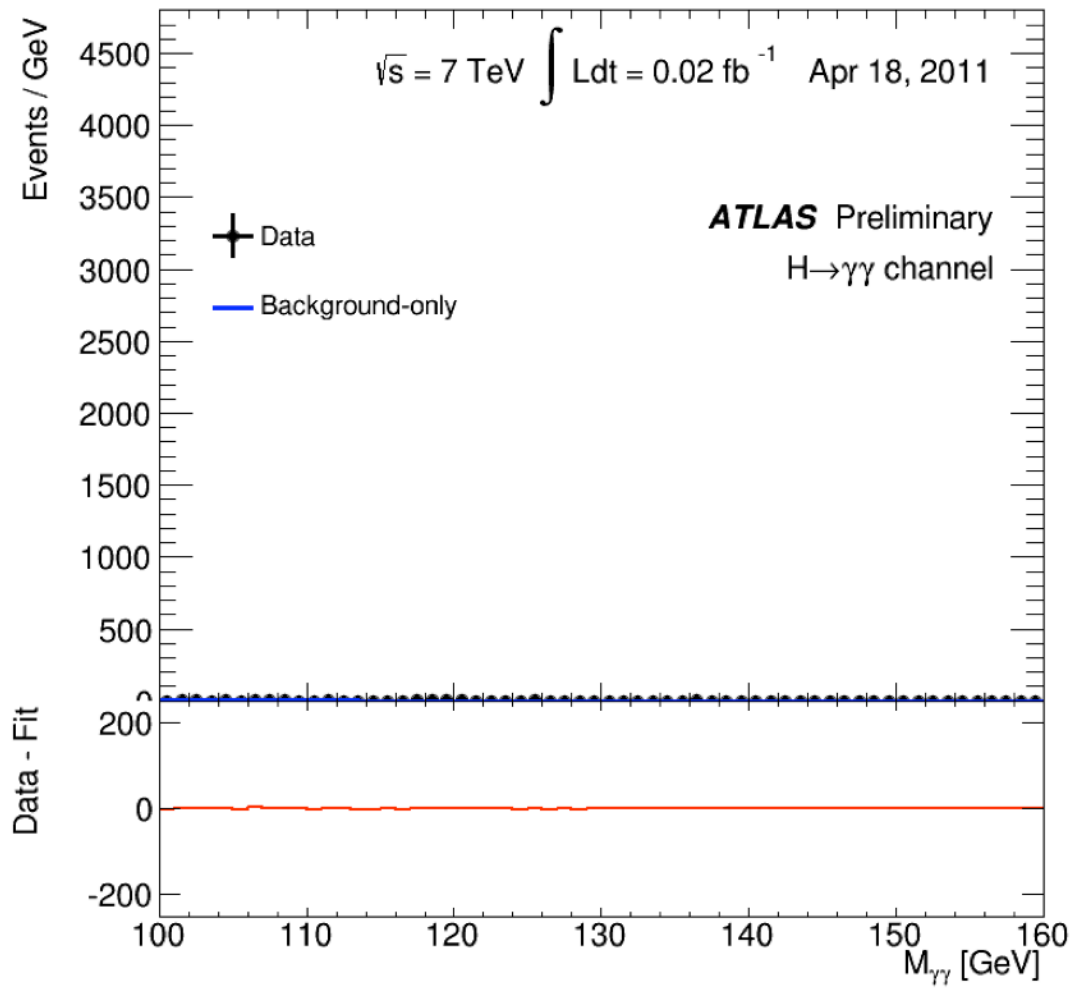


$$H \rightarrow \gamma\gamma$$

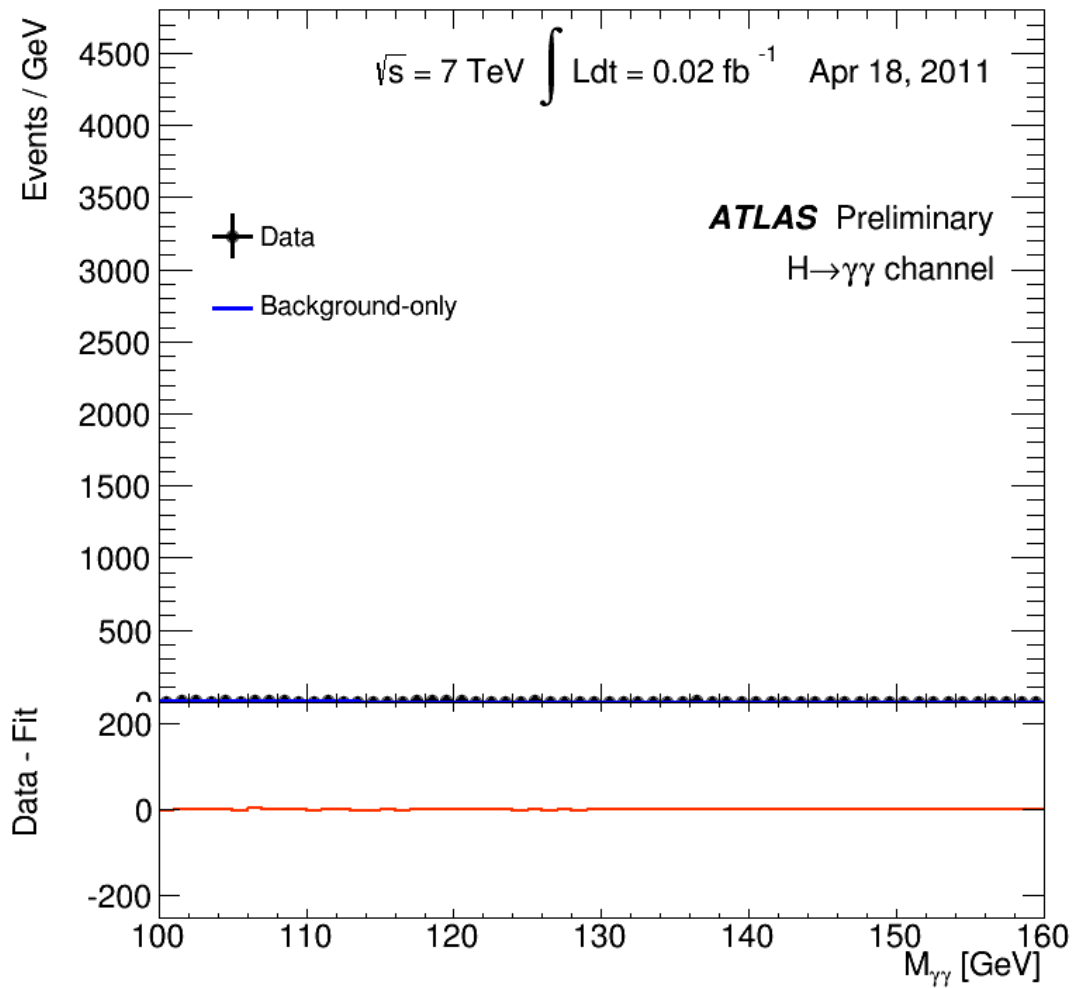




# $H \rightarrow \gamma\gamma$

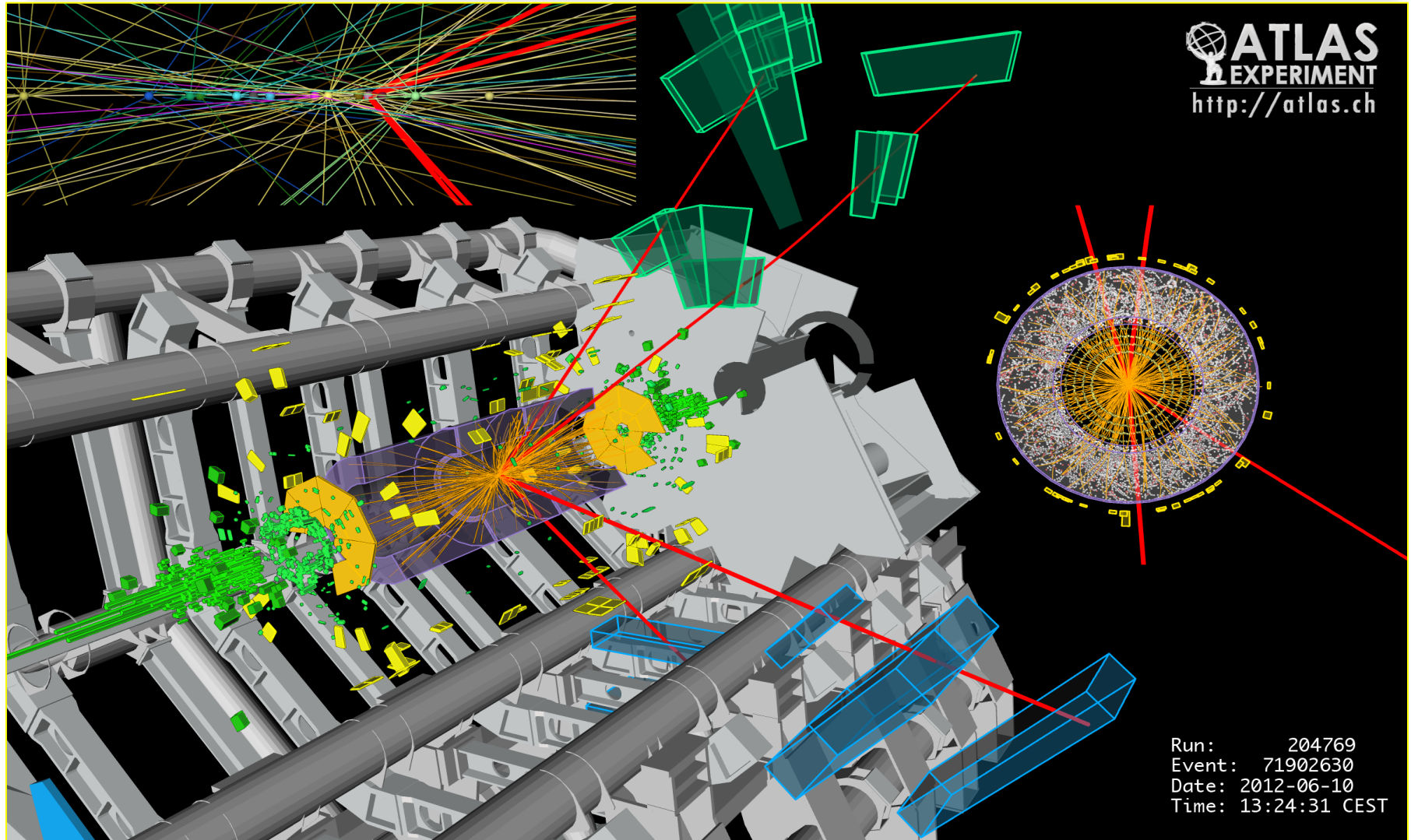


# $H \rightarrow \gamma\gamma$





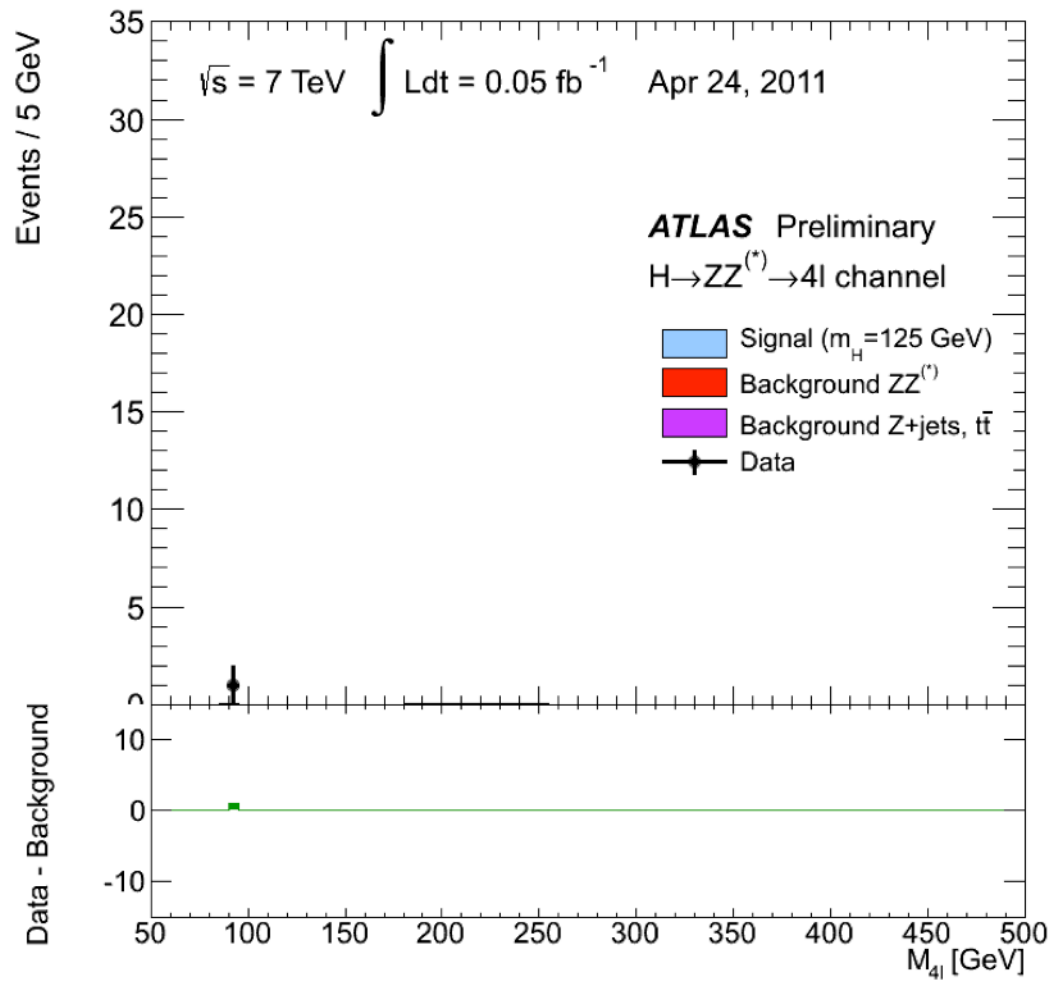
$$H \rightarrow ZZ^{(*)} \rightarrow 4l$$



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

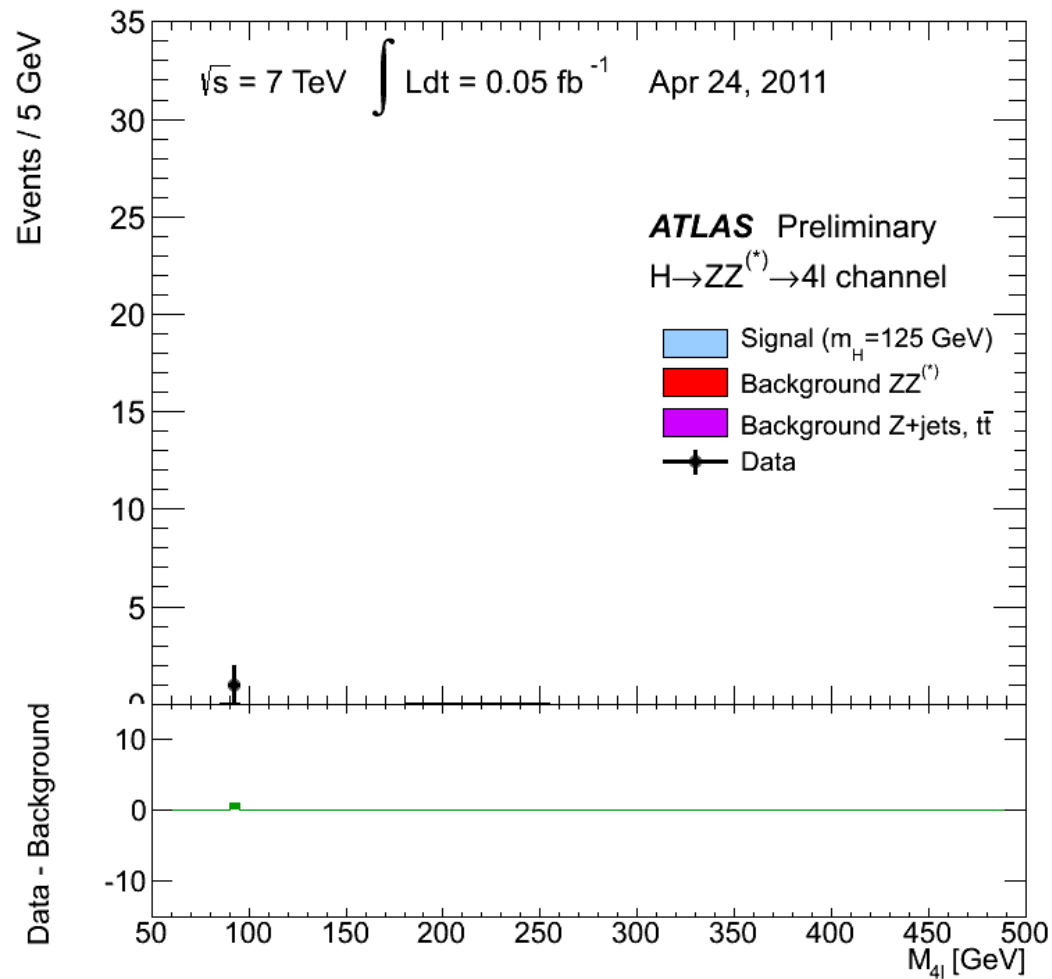
$p_T$  (muones)= 36.1, 47.5, 26.4, 71.7 GeV  $m_{12}=86.3$  GeV,  $m_{34}=31.6$  GeV. 15 vértices reconstruídos

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



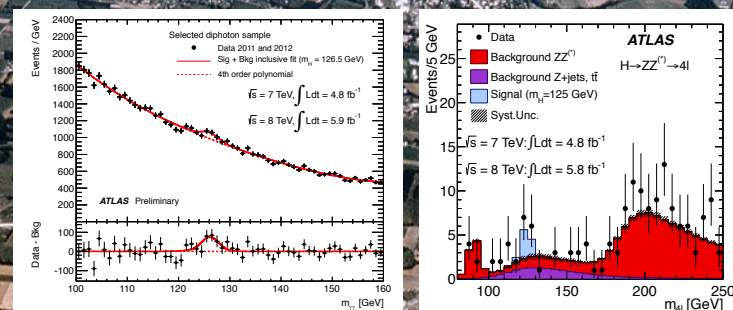


$$H \rightarrow ZZ^{(*)} \rightarrow 4l$$

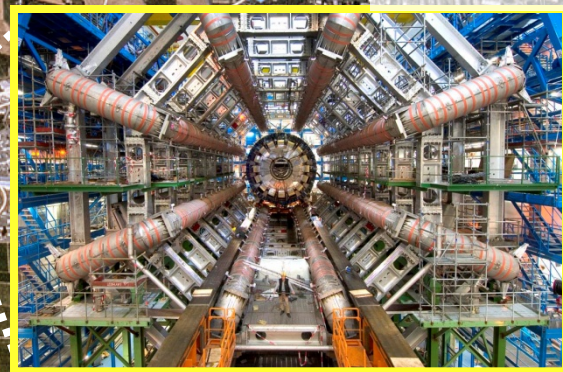




# Independent confirmation

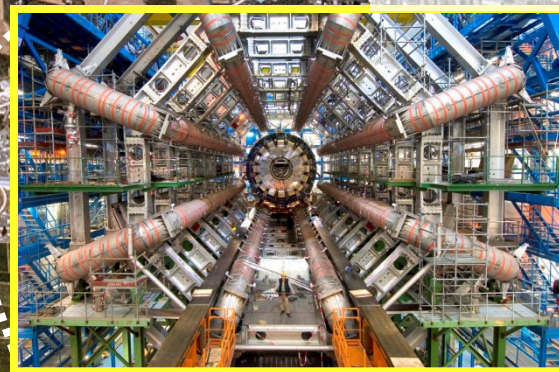
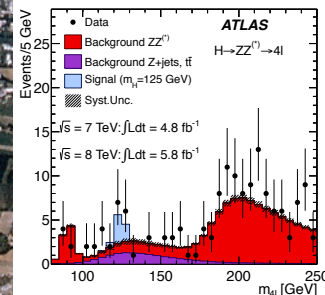
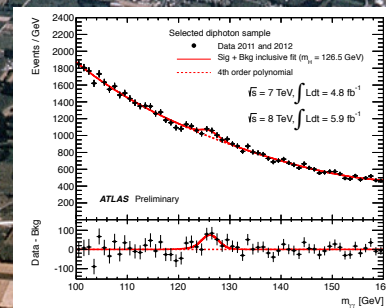
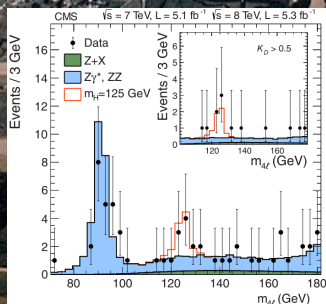
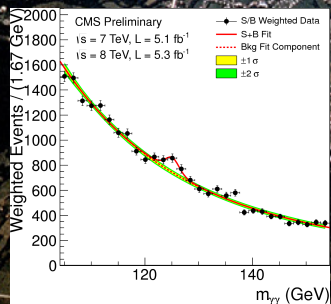
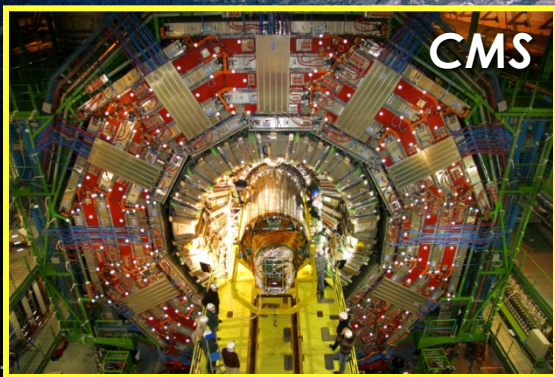


ATLAS





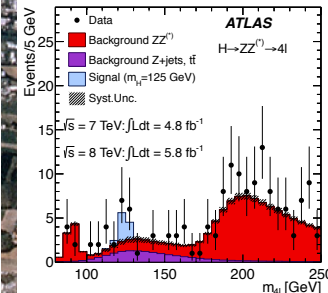
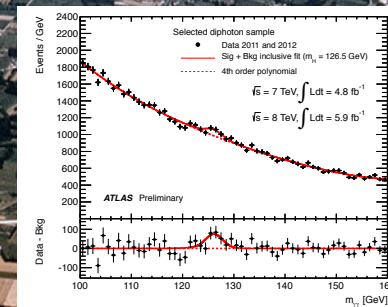
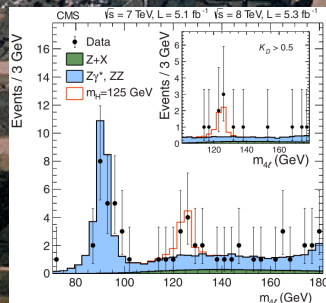
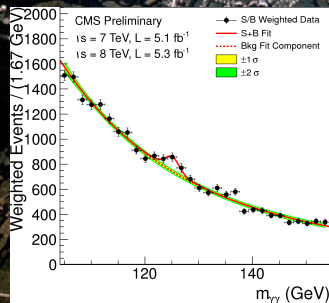
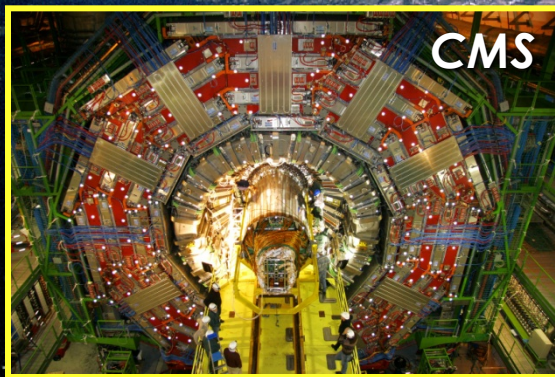
# Independent confirmation



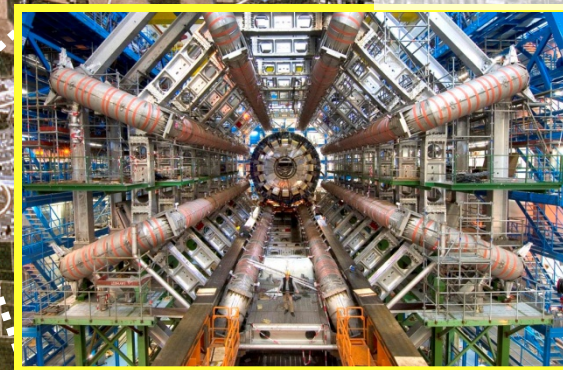


# Combination

Probability  $< 0.00003\%$   
 $= "5\sigma" \rightarrow \text{Discovery!}$



Probability  $< 0.00003\%$   
 $= "5\sigma" \rightarrow \text{Discovery!}$





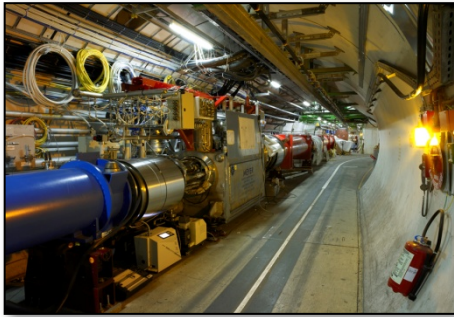
July 4, 2012



**From fundamental science  
to daily life**

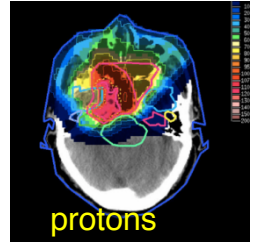
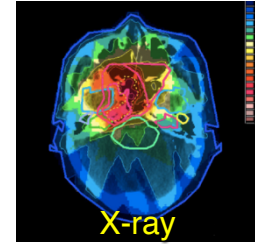
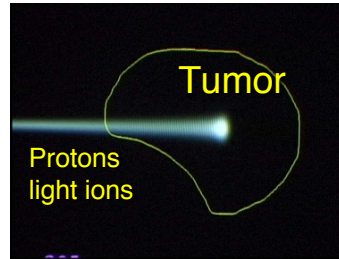


# From fundamental physics to daily life

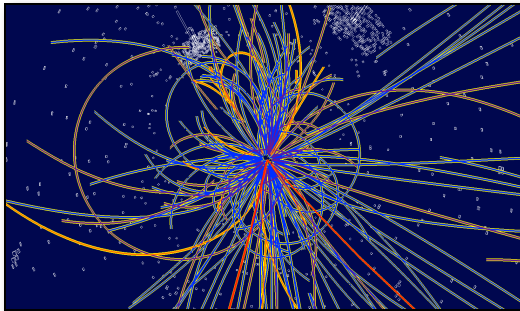


~30'000 accelerators worldwide  
~17'000 for medical applications

## Hadronic therapy for cancer

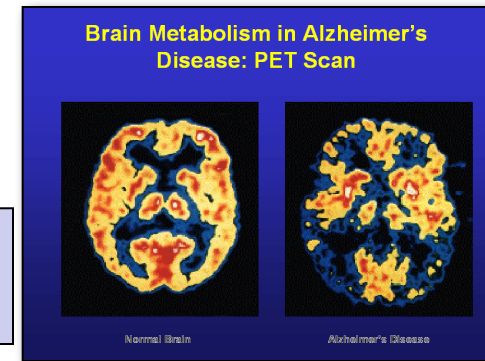


>90,000 patients treated (30 facilities)



## Medical imaging

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



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



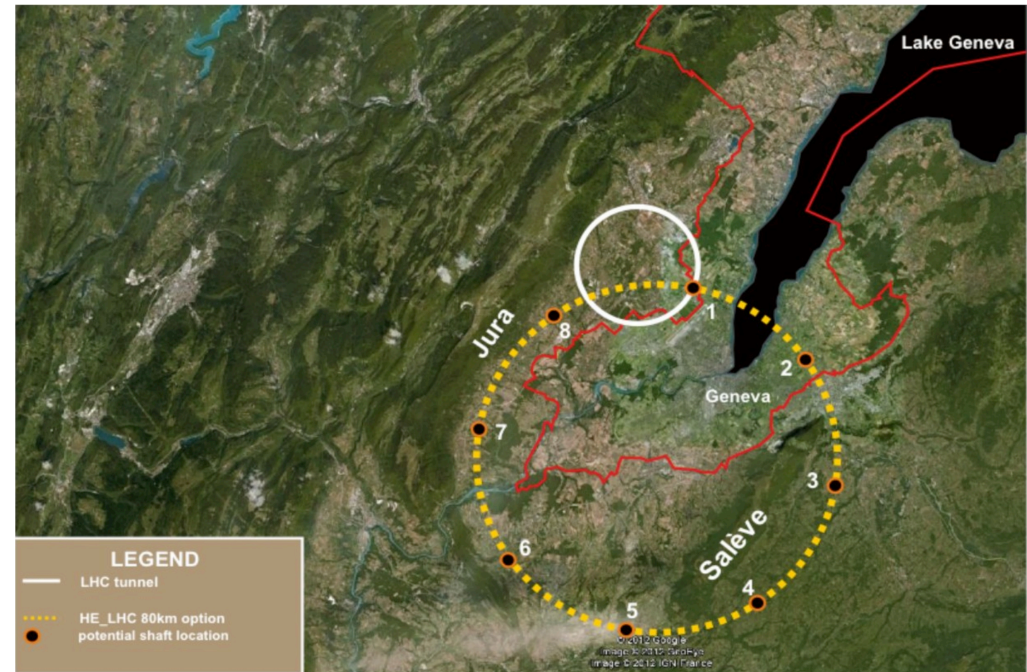


... and beyond

# What is next?

## CERN:

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



## China:

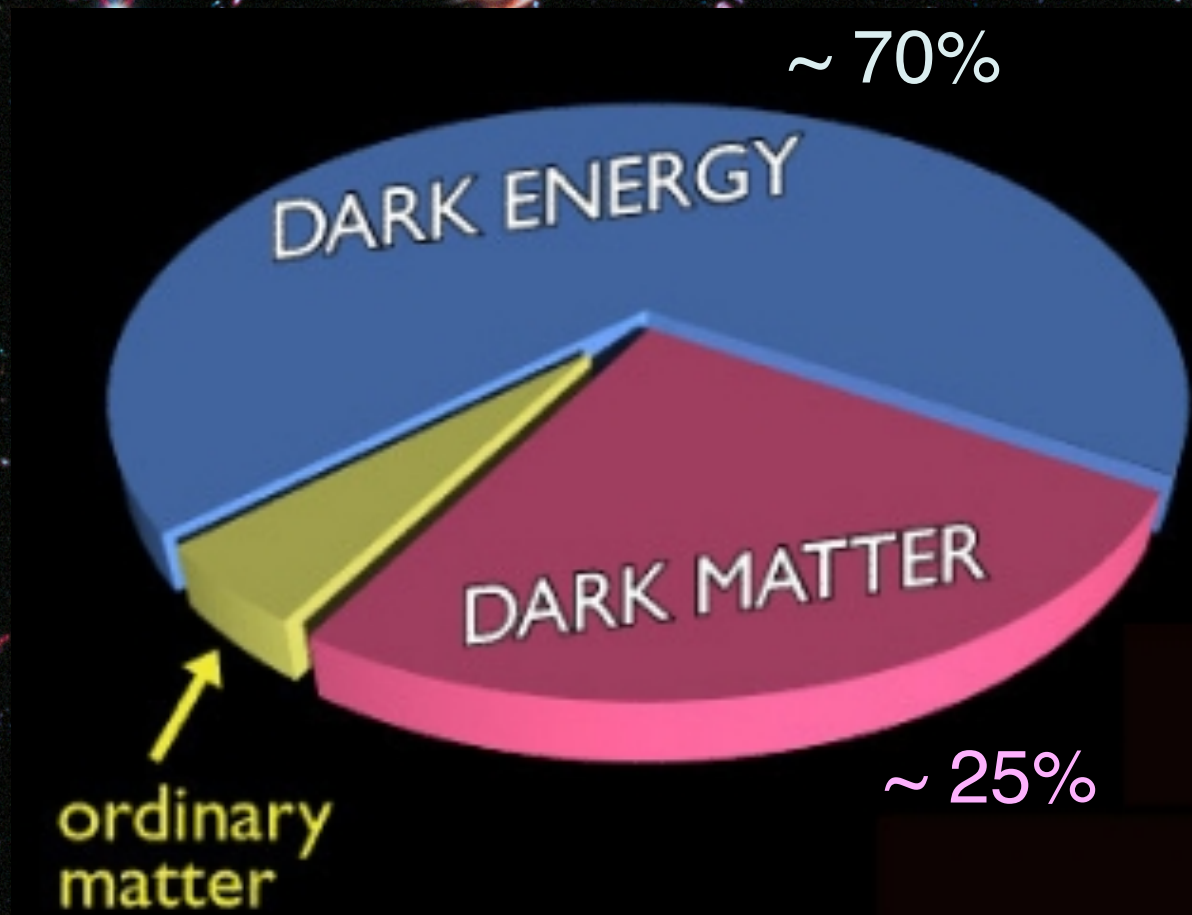
- Qinhuangdao (秦皇岛)
- Strong local support



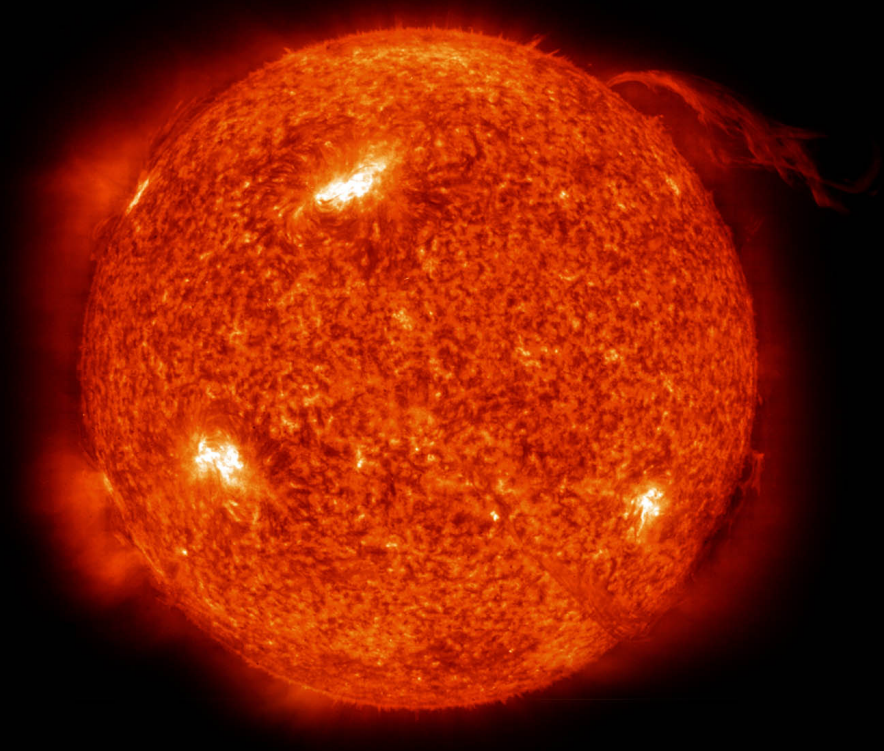
















# The financial case

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:  $2 \times \$500\text{M} + \$300\text{M} = \$1,300\text{M}$
- Operations:  $\sim 20 \text{ years} \times \$100\text{M}/\text{year} = \$2\text{B}$

• **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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- Superconducting magnets
  - Mass-produced for the first time for the Tevatron
  - Current value of the SCM industry: **\$1.5B/year**
  - MRI industry (the major costumer of SCM): **\$5B/year**
  - It would likely have succeeded anyway, but it is fair to claim an acceleration of 1-2 years: **\$5B - \$10B**

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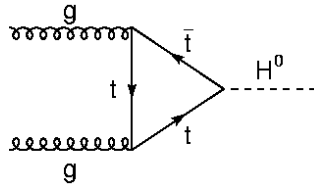
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- Cloud computing: **\$150B/year** (Gartner)
  - Large investment in linux, PC clusters, networking, etc.
  - Assuming Tevatron gave only a *3-month* speed-up: **\$40B**



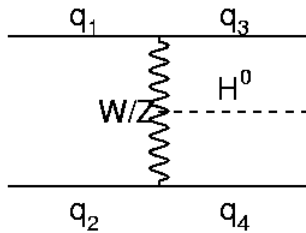
# SM Higgs production

## SM Higgs production

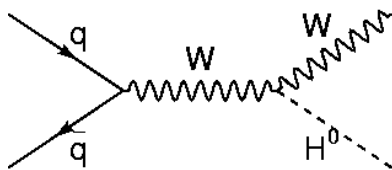
**Gluon fusion**  
(dominant  
at LHC)



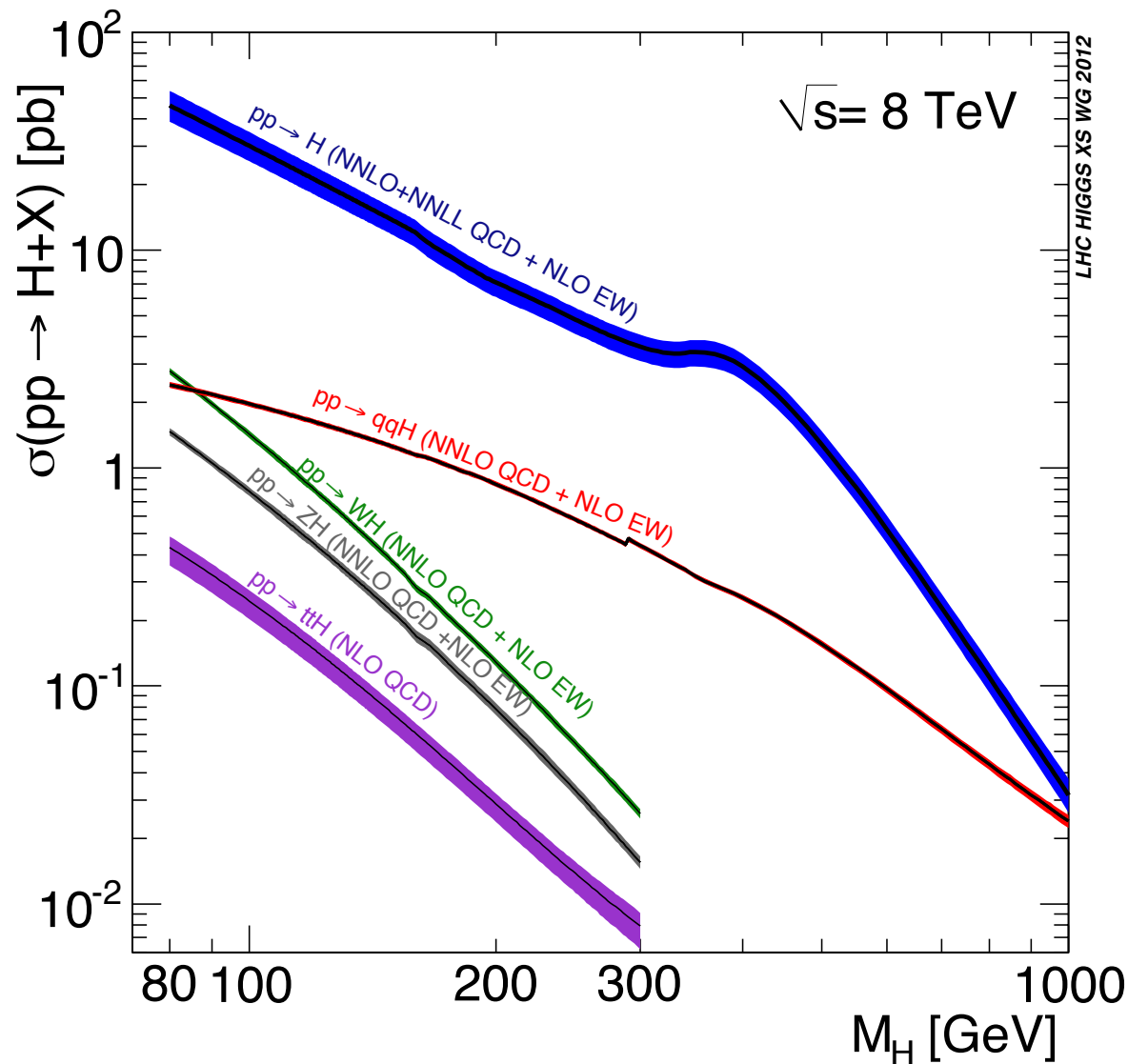
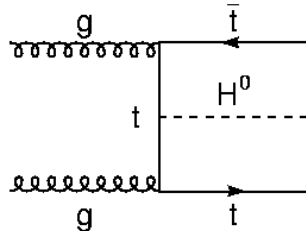
**Vector  
boson  
fusion**



**Associated  
production  
with Z/W**  
(Higgs-strahlung)



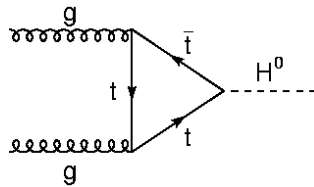
**Associated  
production  
with top**



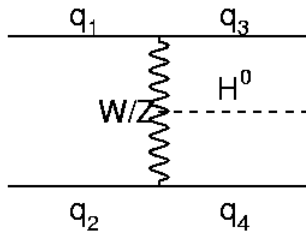
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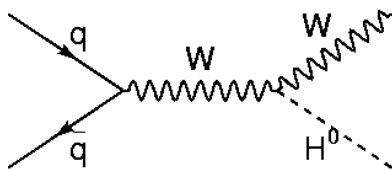
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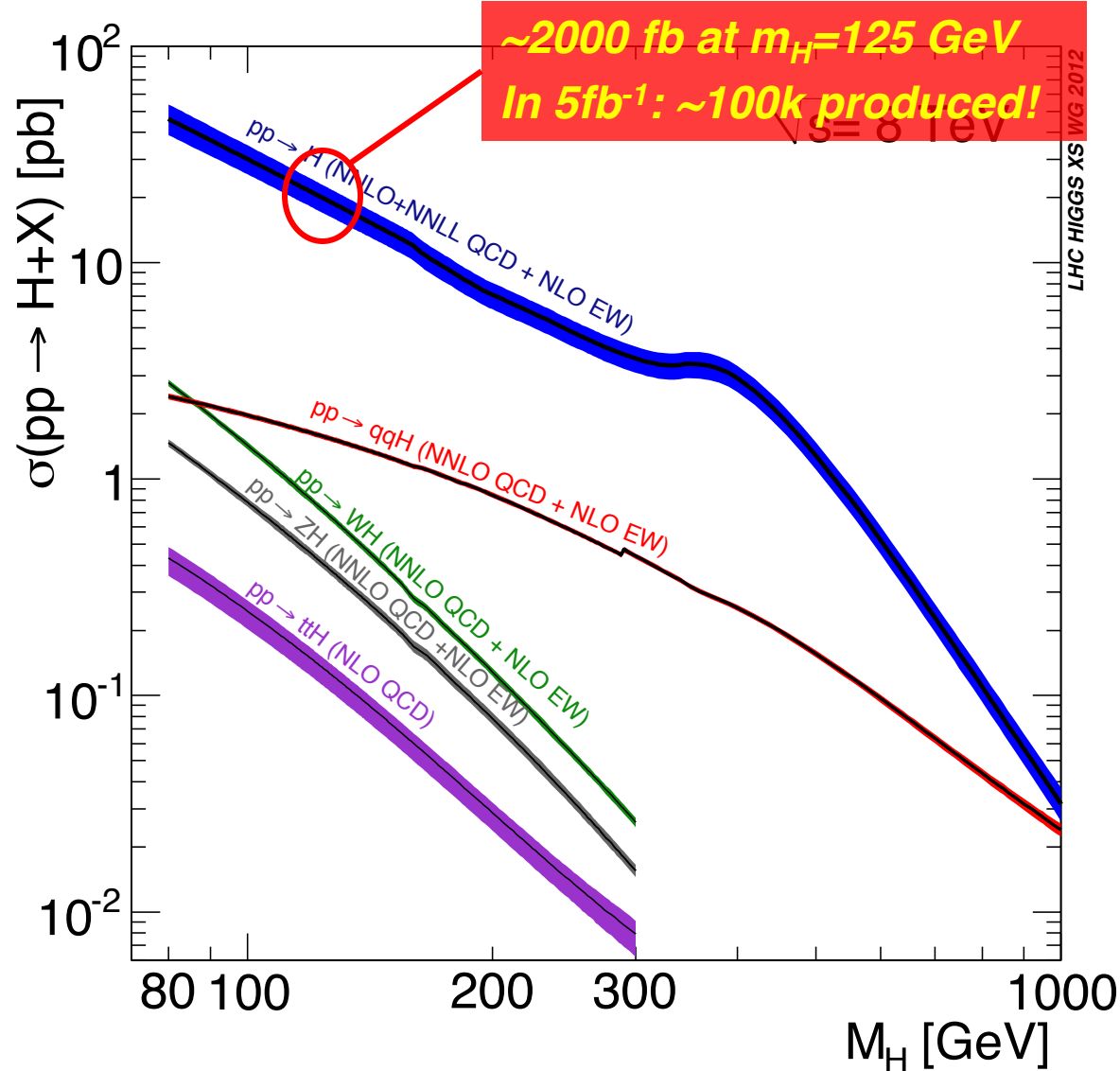
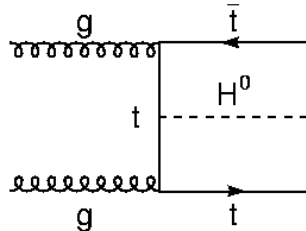
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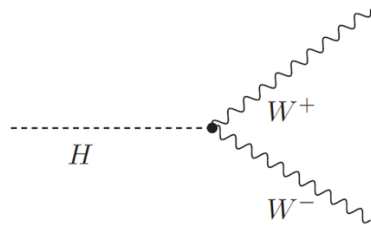




# Branching ratios

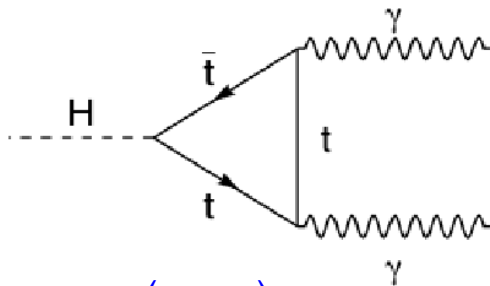
## SM Higgs decays

Direct coupling to massive particles

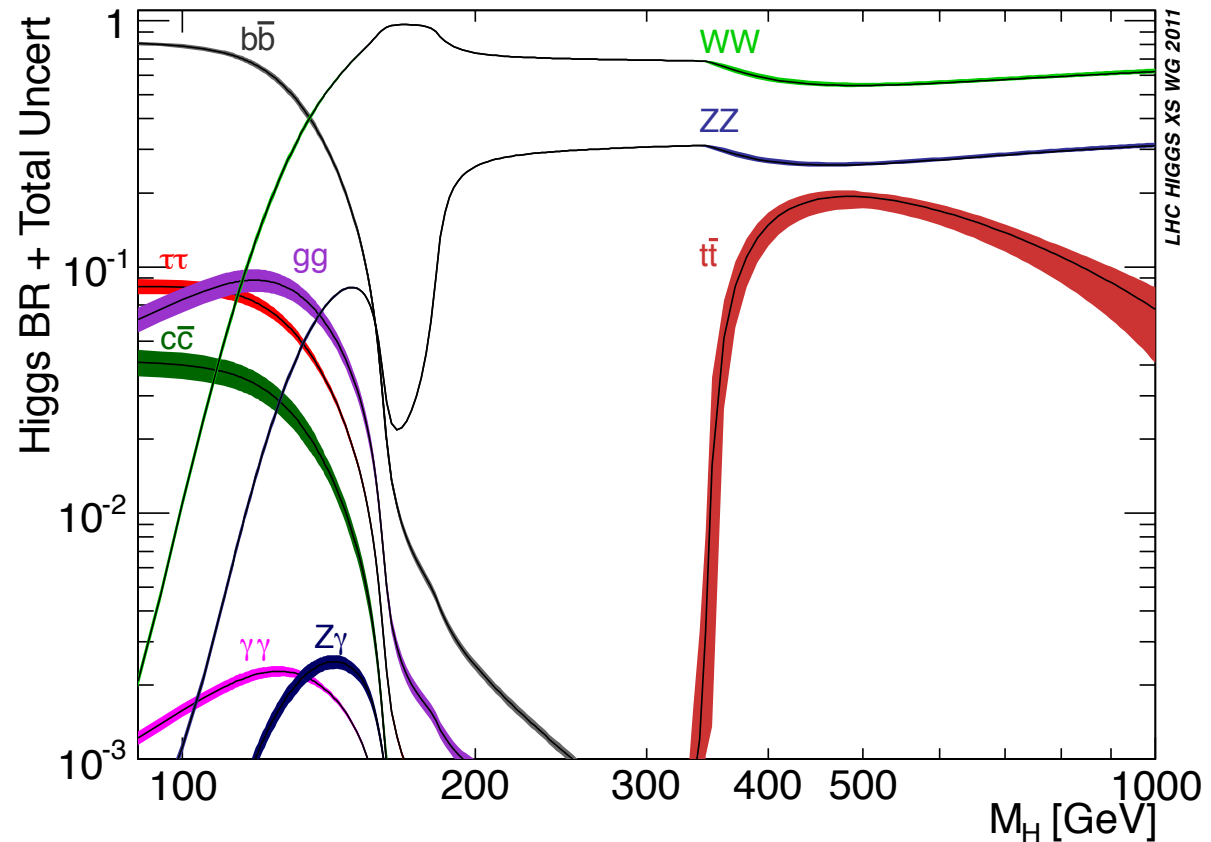


(WW, ZZ, tt, bb,  $\tau\tau$ )

Through a triangle loop to massless ones



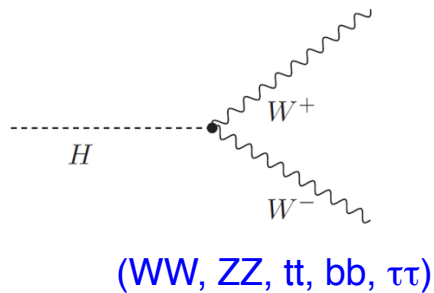
(gg,  $\gamma\gamma$ )



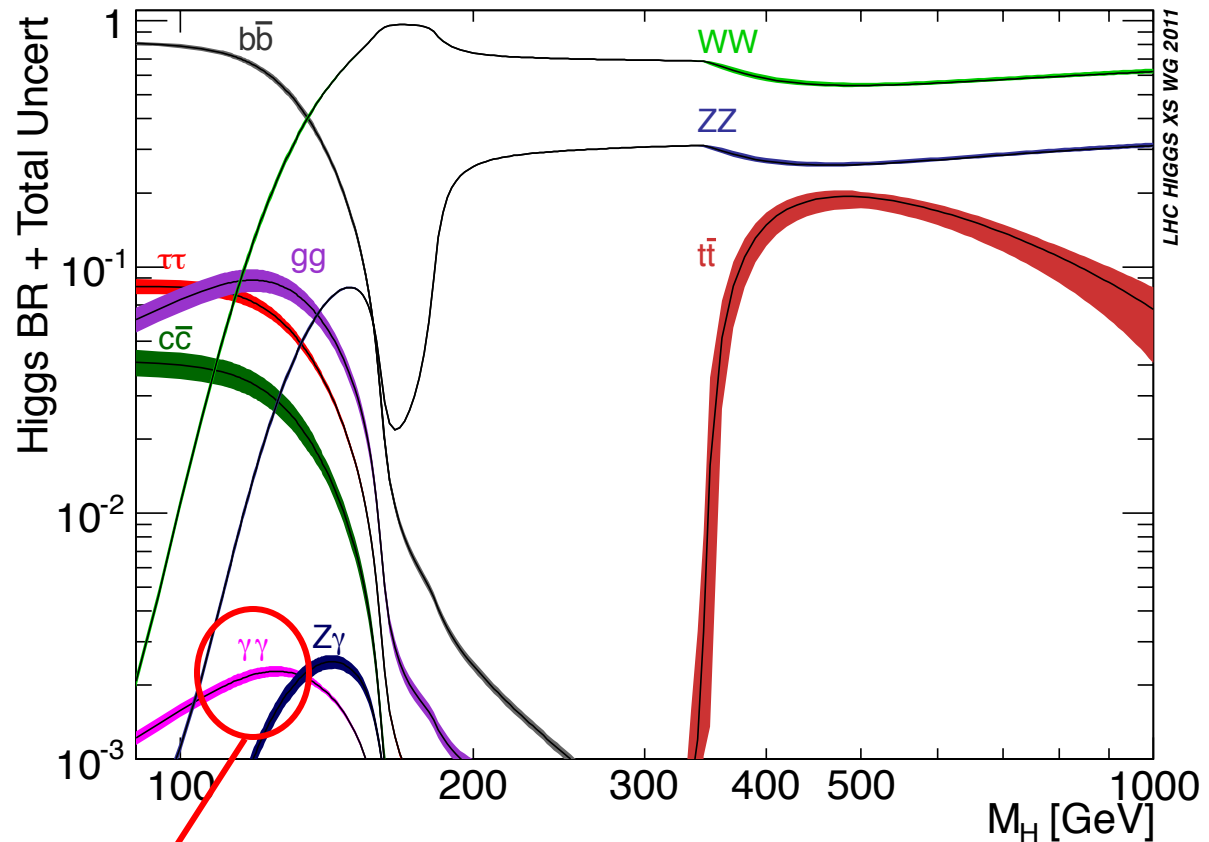
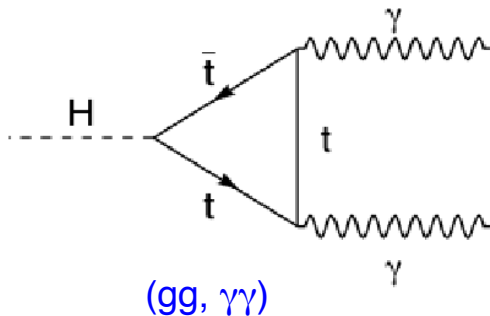
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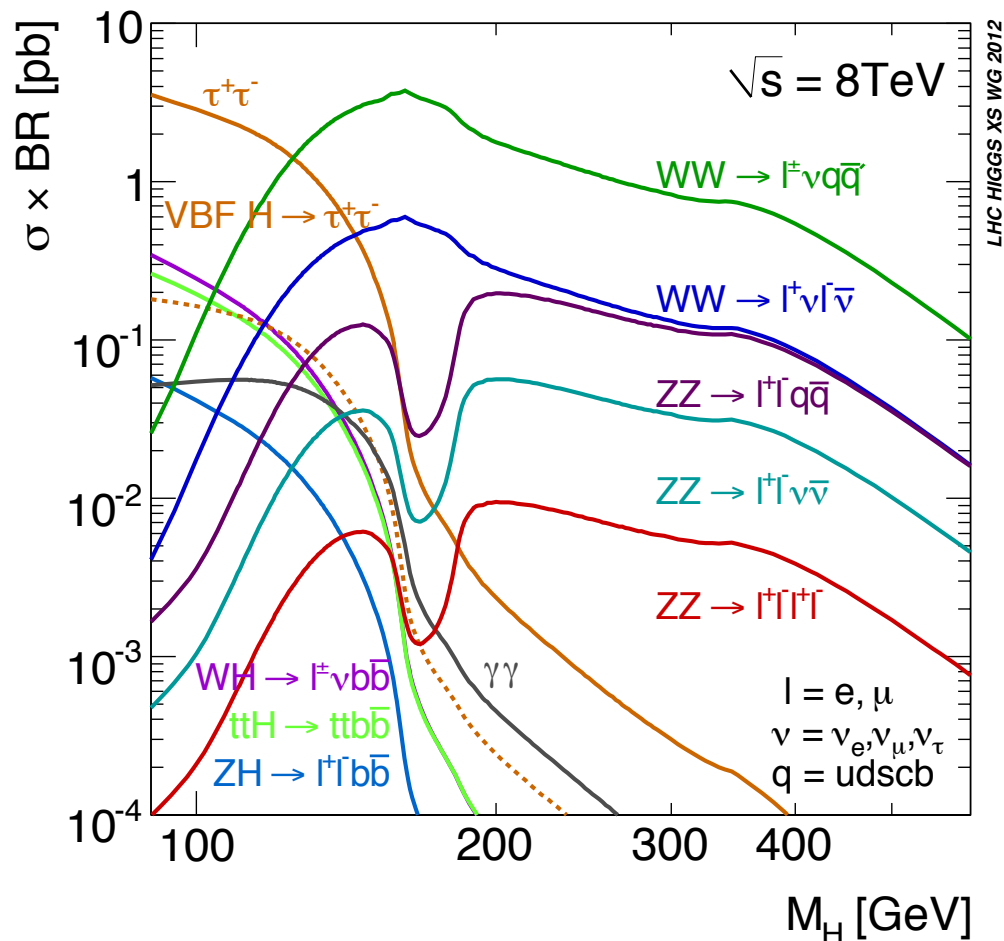


**100,000 Higgs bosons produced... times  $\sim 0.002$  BR to  $\gamma\gamma$ ,  $\sim 200$  Higgs to be found via  $\gamma\gamma$  search**



# Introduction

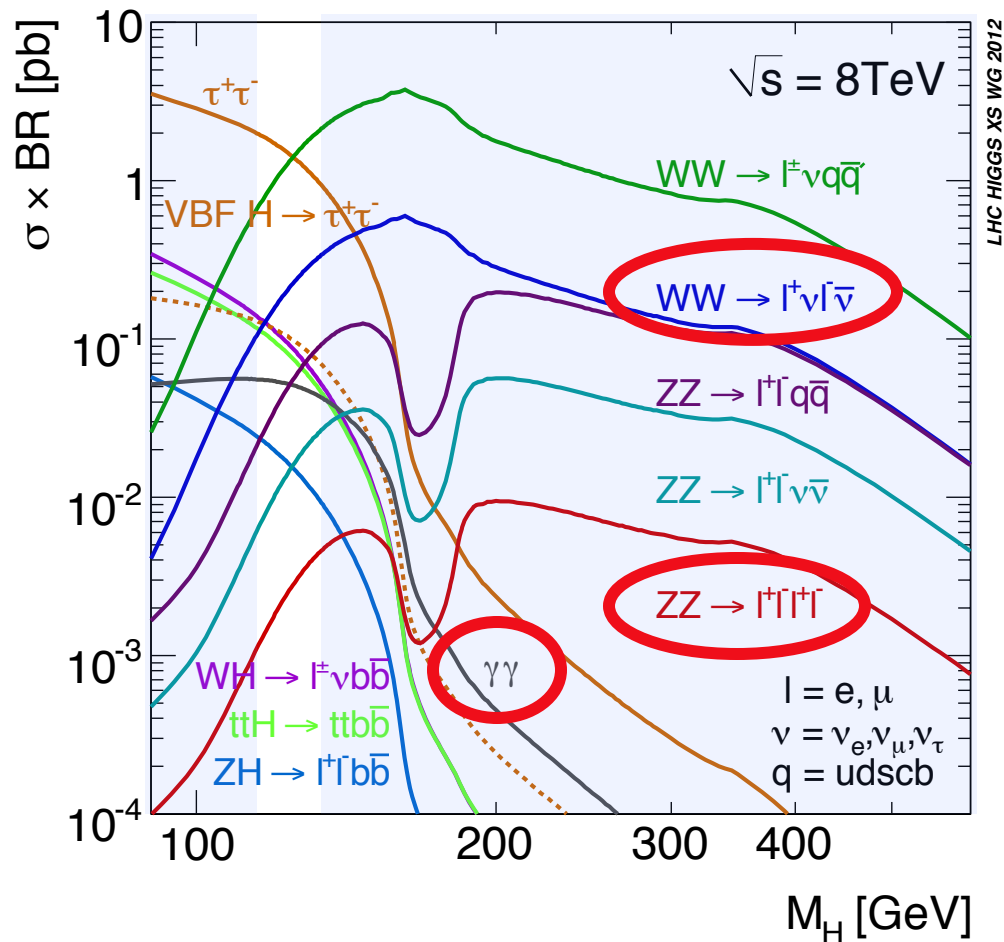
## Cross section times BR



- 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  $m_H$ :  $ll\nu\nu$  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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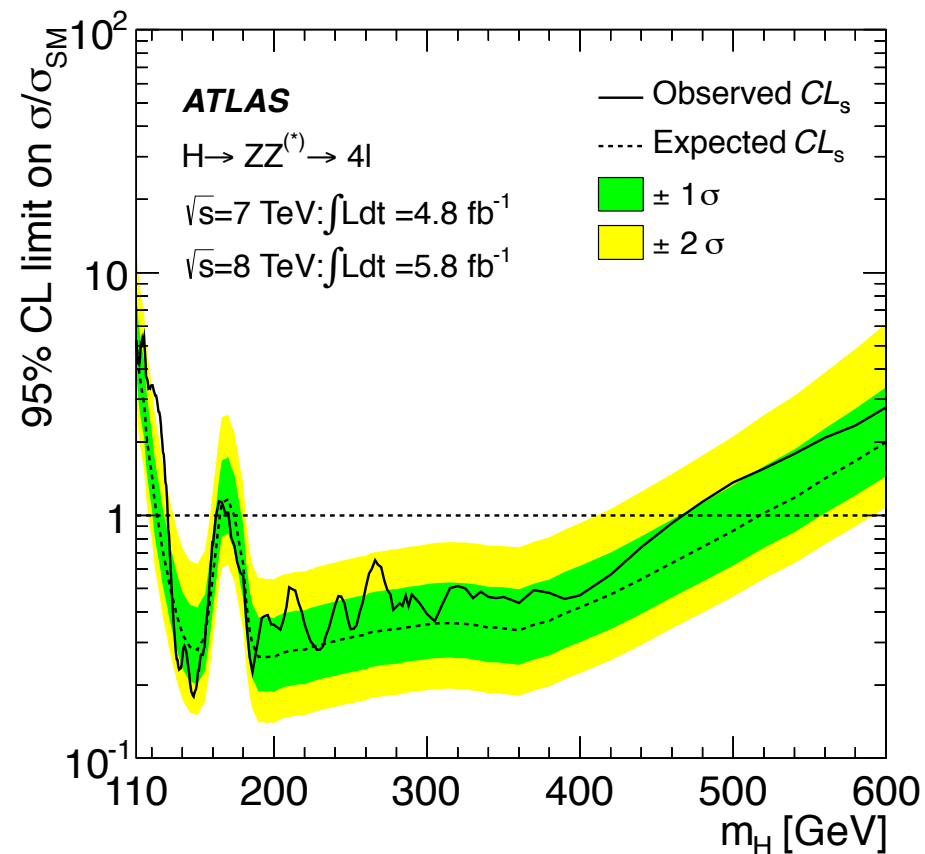


# Limits and $p_0$ plots

- 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 exist
- Observed: from the actual dataset



- Too few events  $\rightarrow$  “strong” limit
- Too many events  $\rightarrow$  “weak” limit

# Limits and $p_0$ plots

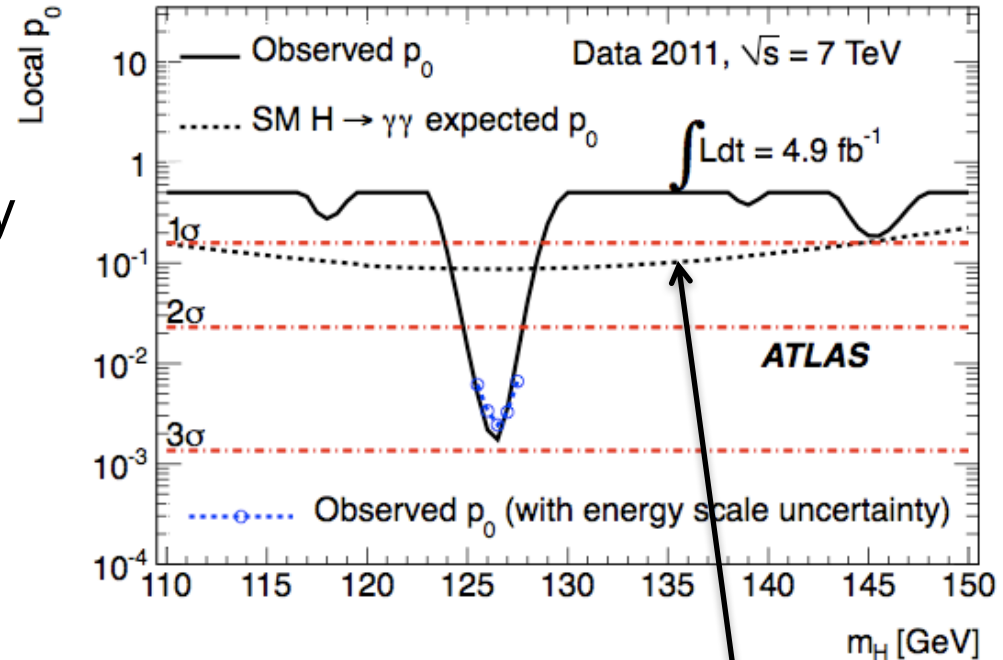
- *Too many events* may also, instead, represent a signal
- ... do they?

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 →  $p_0 = 2.9 \times 10^{-7}$

January 2012 PRL Publication



Expected from SM Higgs at given  $m_H$

