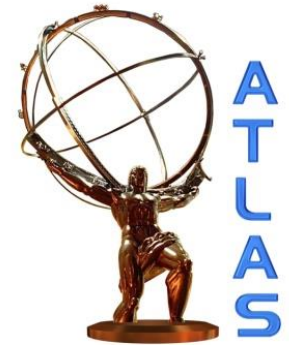


# The discovery of the Higgs boson



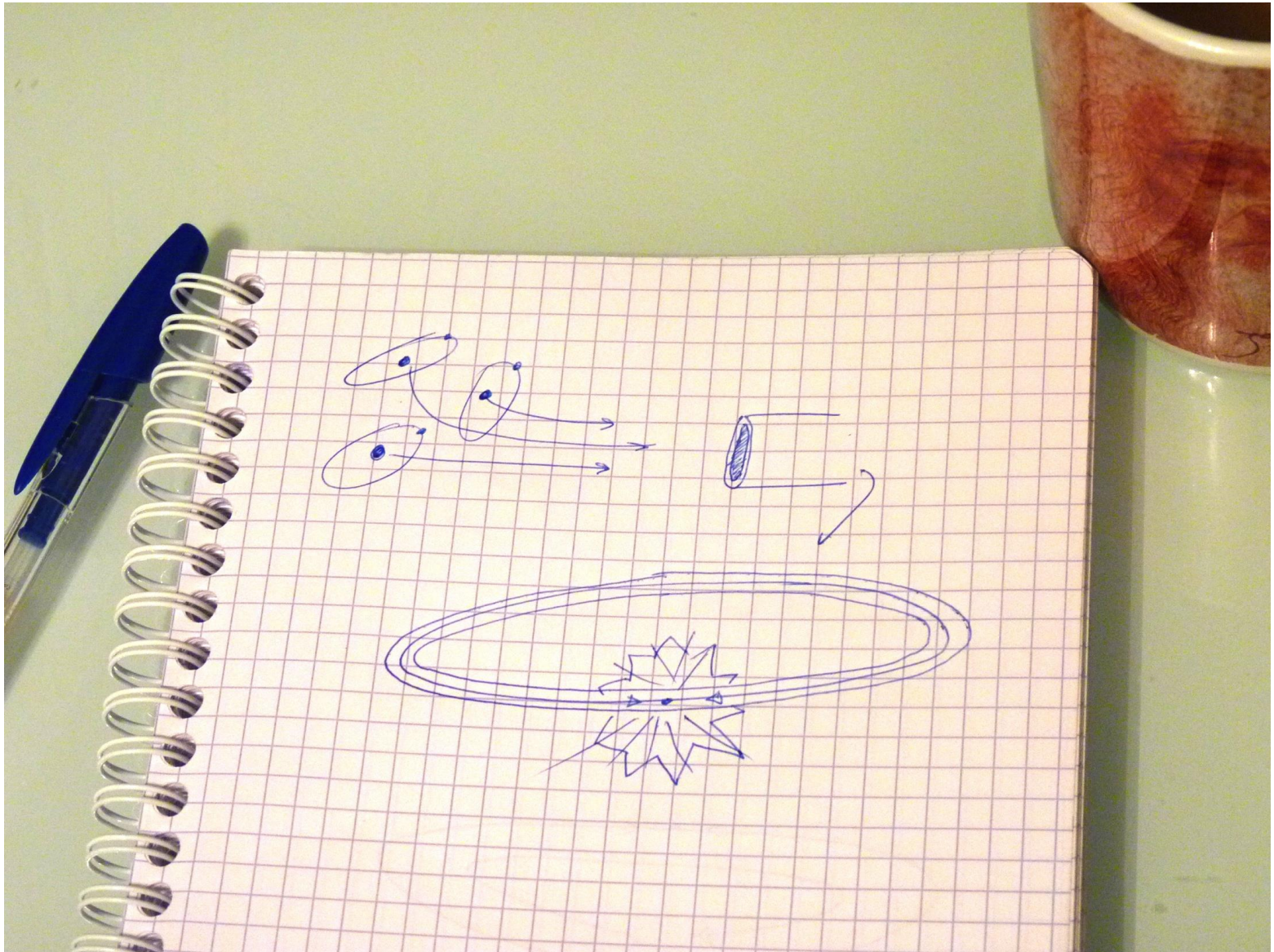
Luis Roberto Flores Castillo  
The Chinese University of Hong Kong



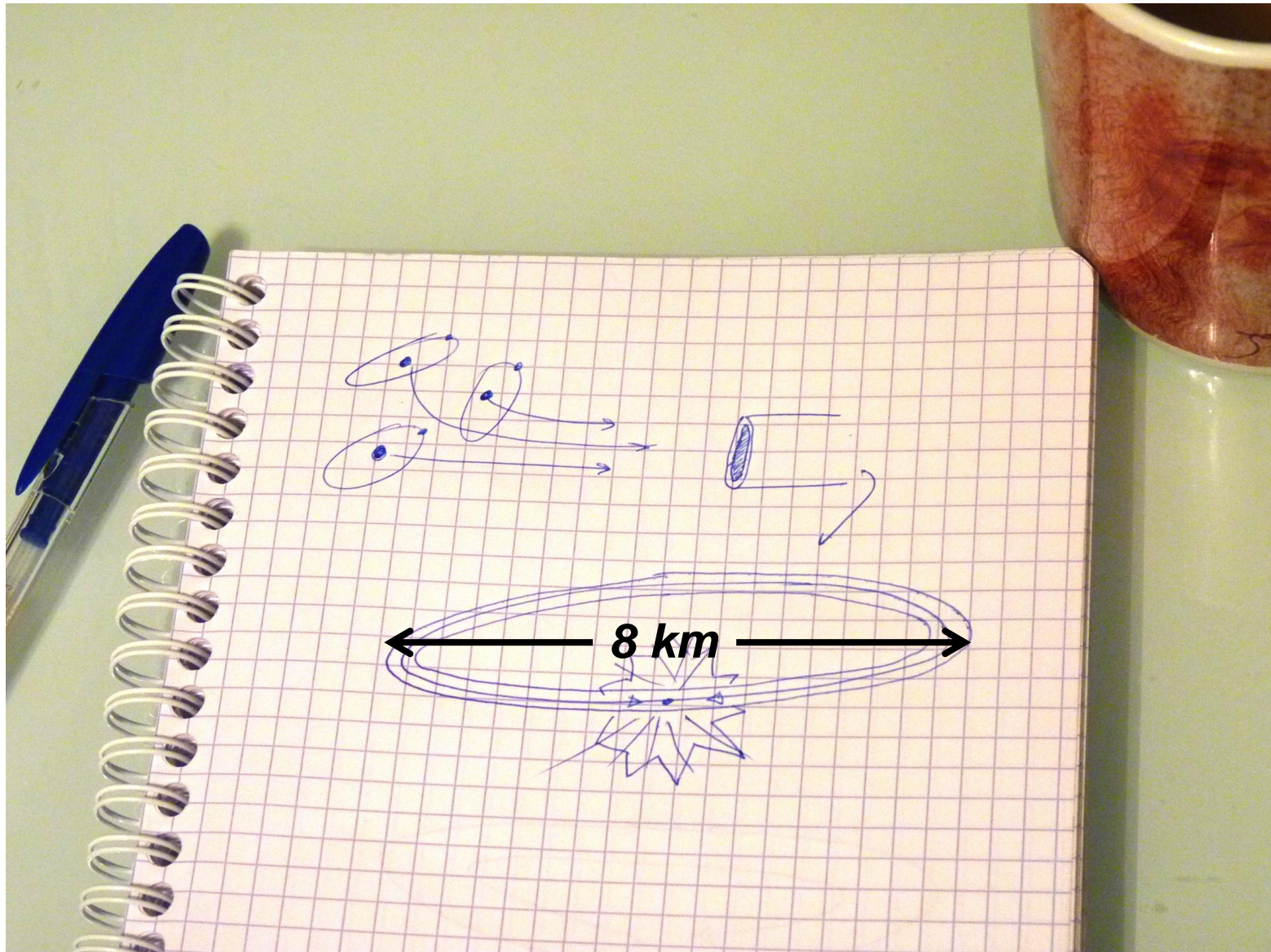
International Teacher Weeks Program 2018  
CERN, Switzerland

August 14, 2018

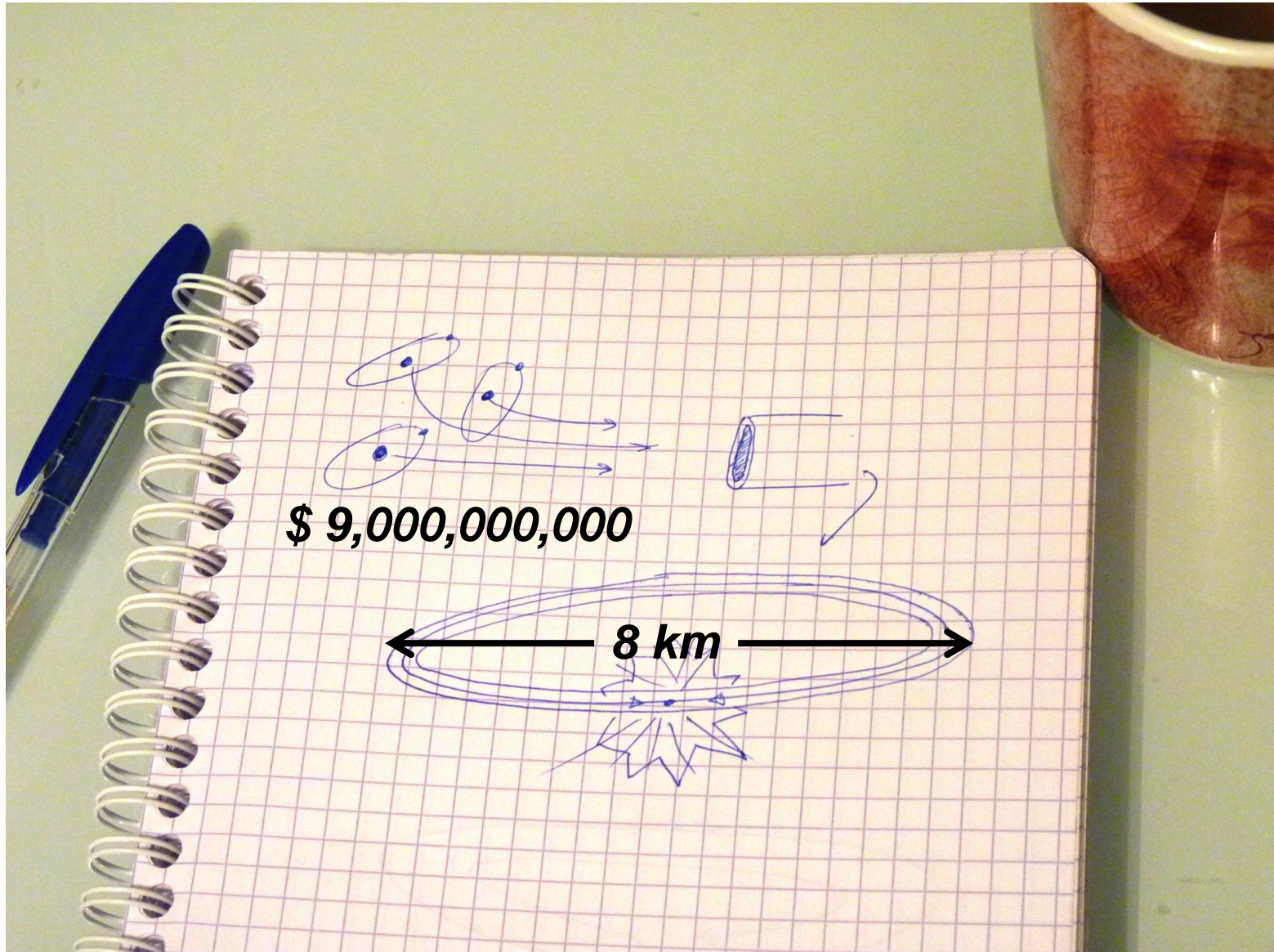
# Aiming high



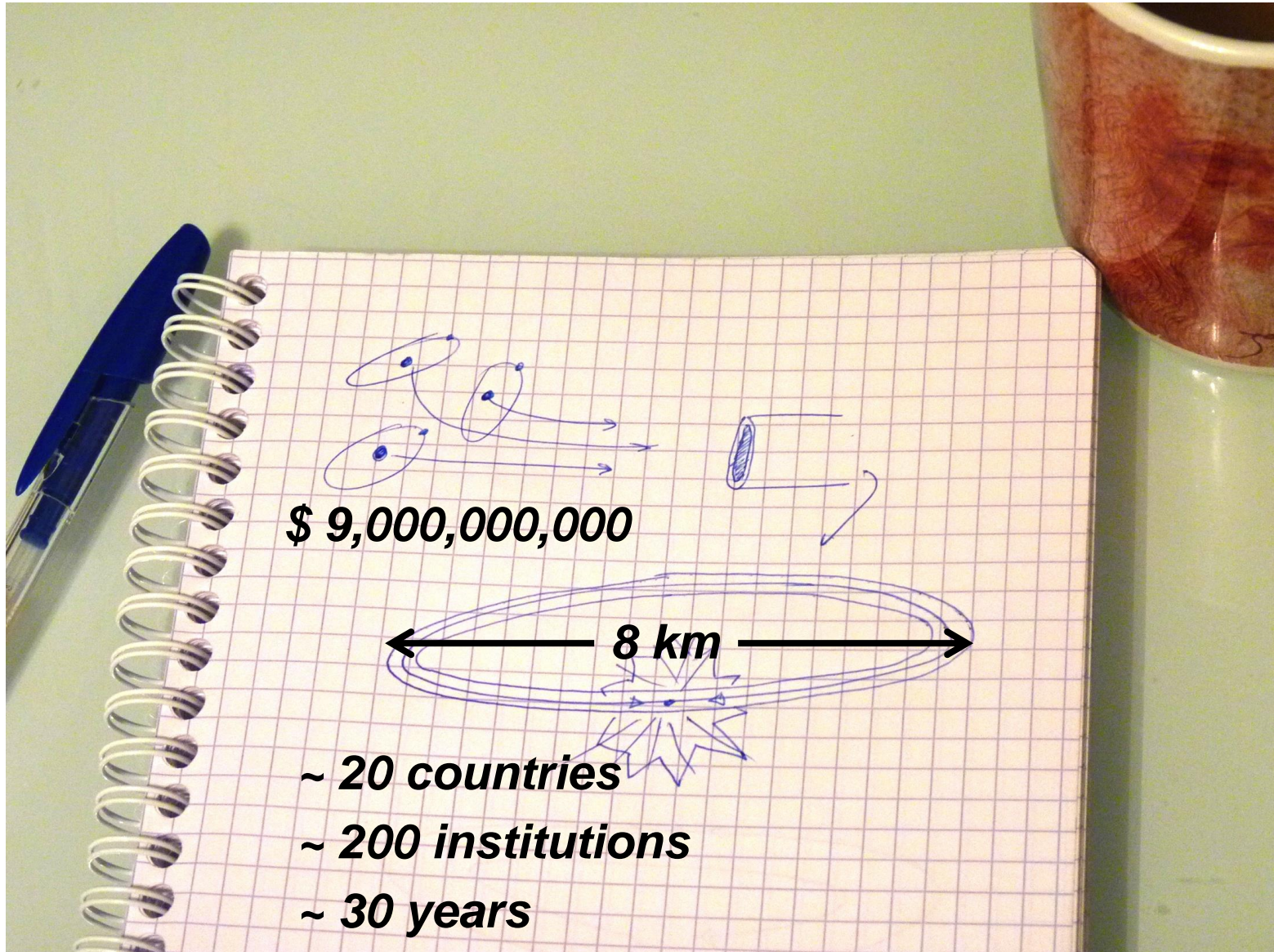
# Aiming high



# Aiming high



# Aiming high





July 4, 2012

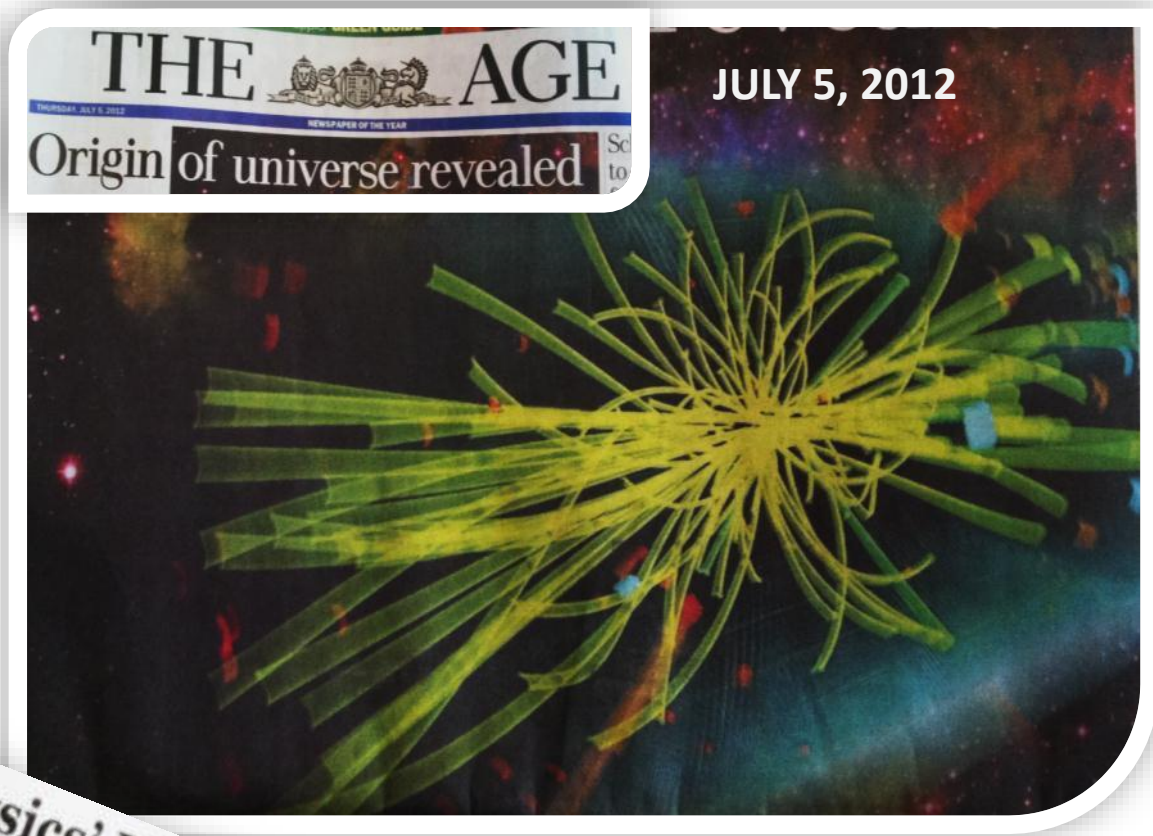


***“I think we have it” – Rolf Heuer, CERN’s Director General***

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

# 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'

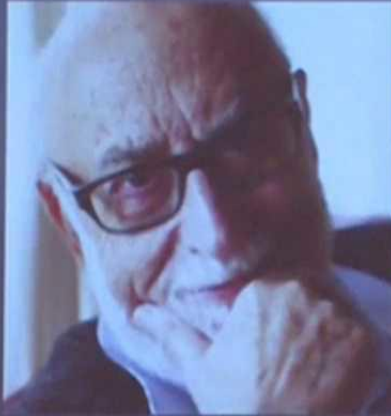
A computer-generated image shows proton collisions expected from the decay of a Higgs boson

- '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		

<b>H - Gas</b>	<b>Li - Solid</b>	<b>Br - Liquid</b>	<b>Tc - Synthetic</b>
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”

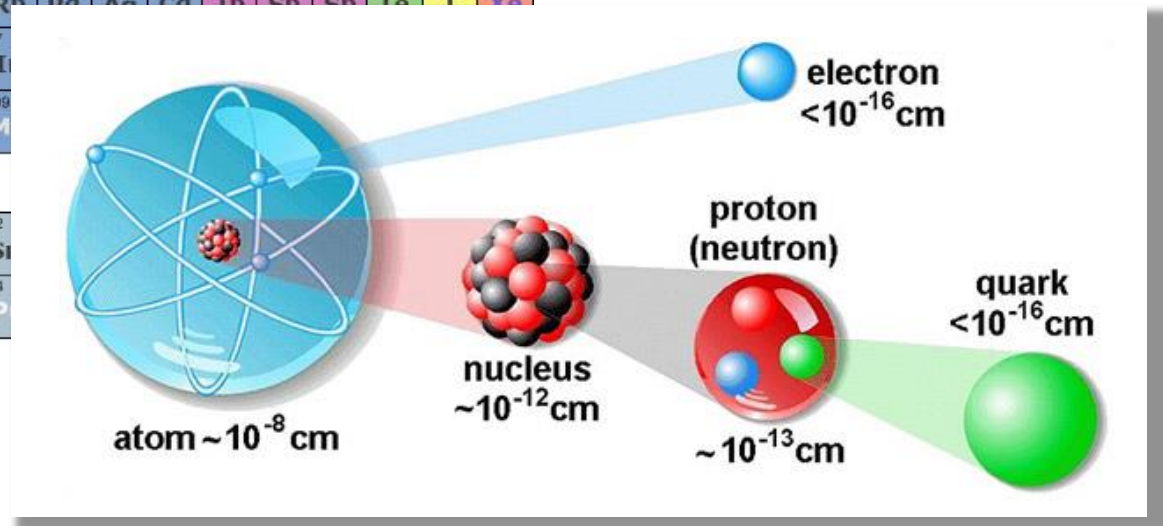


# Fundamental building blocks?

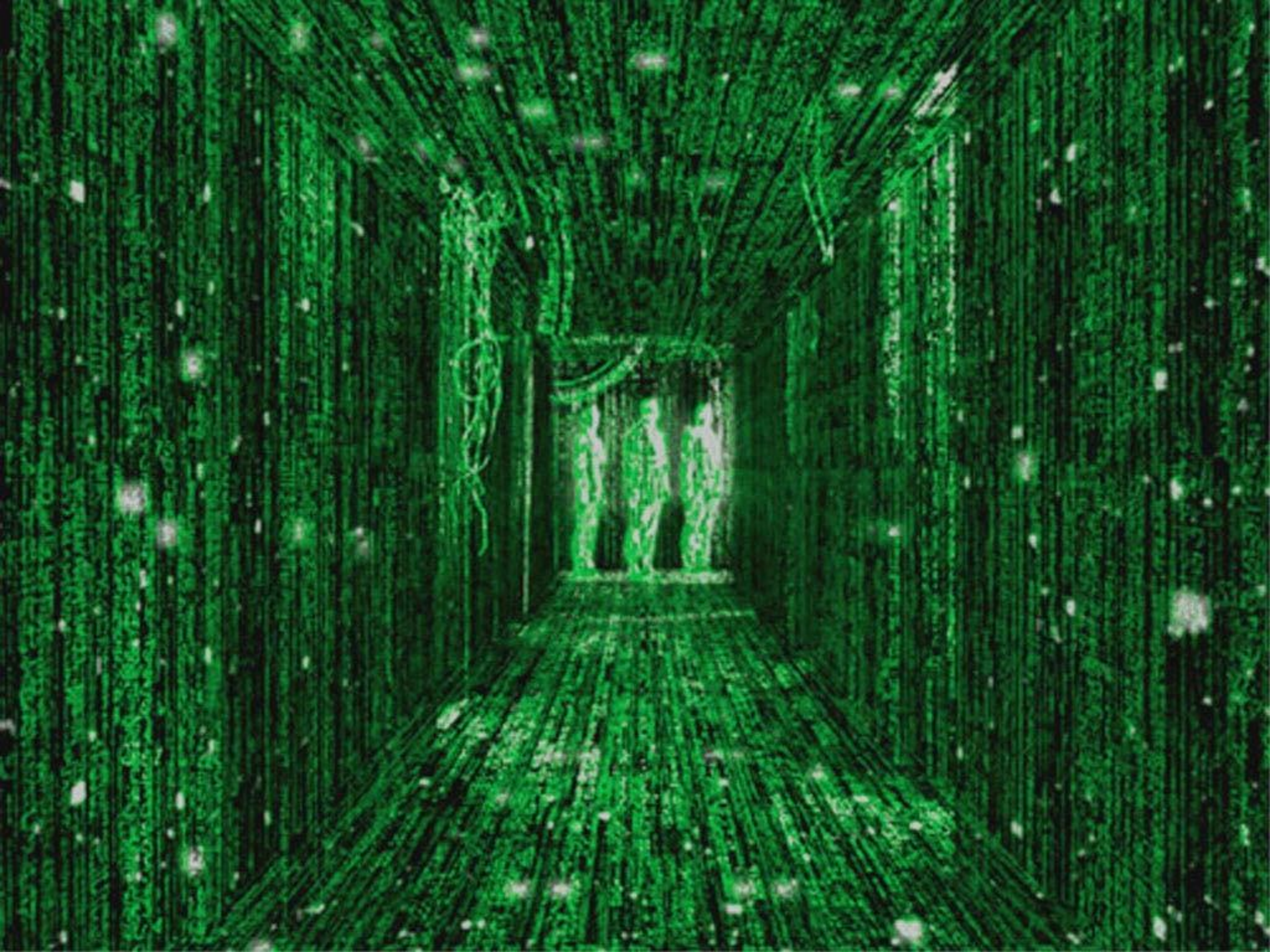
Periodic Table of Elements  
© AllAboutGemstones.com

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 *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
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** (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

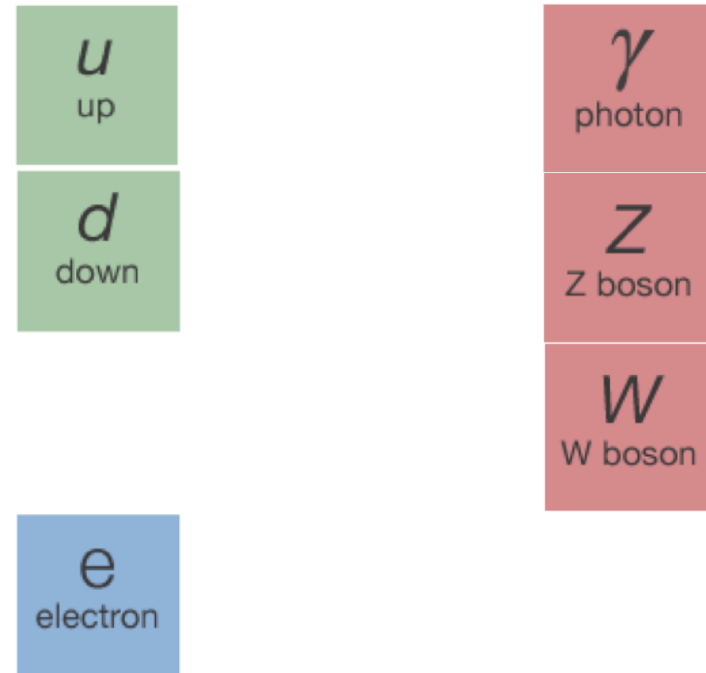
$d$   
down

$e$   
electron

$\gamma$   
photon

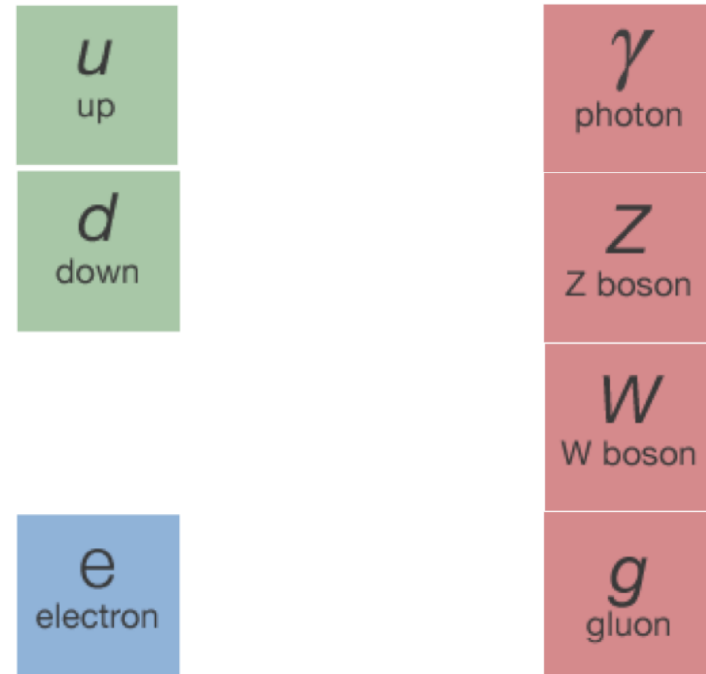
# Fundamental building blocks?

- Besides those three, ...



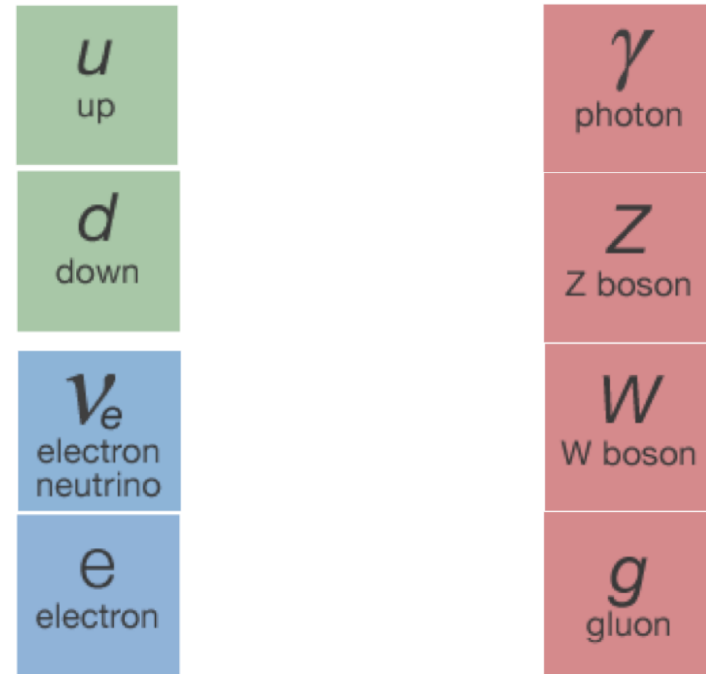
# Fundamental building blocks?

- Besides those three, ...



# Fundamental building blocks?

- Besides those three, ...



# Fundamental building blocks?

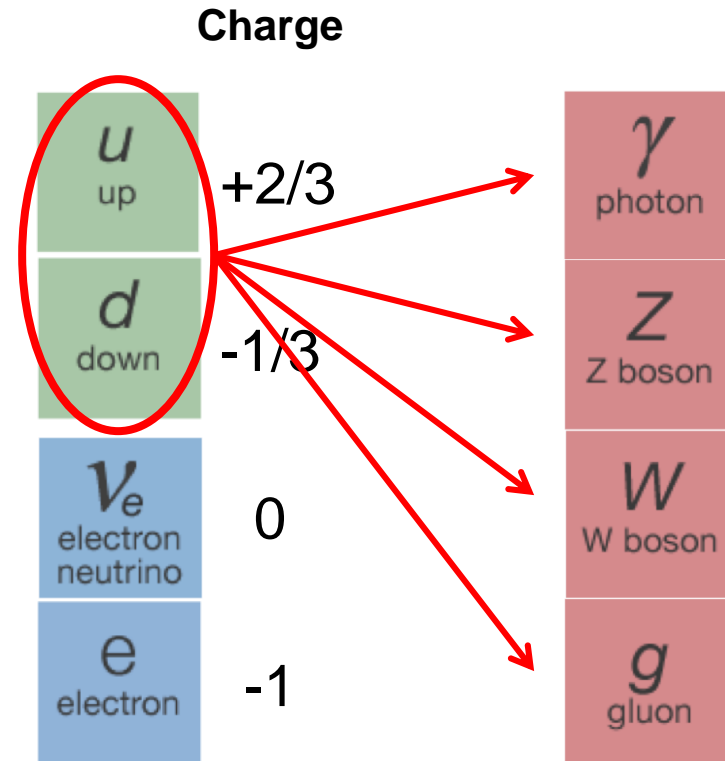
- Besides those three, ...

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	



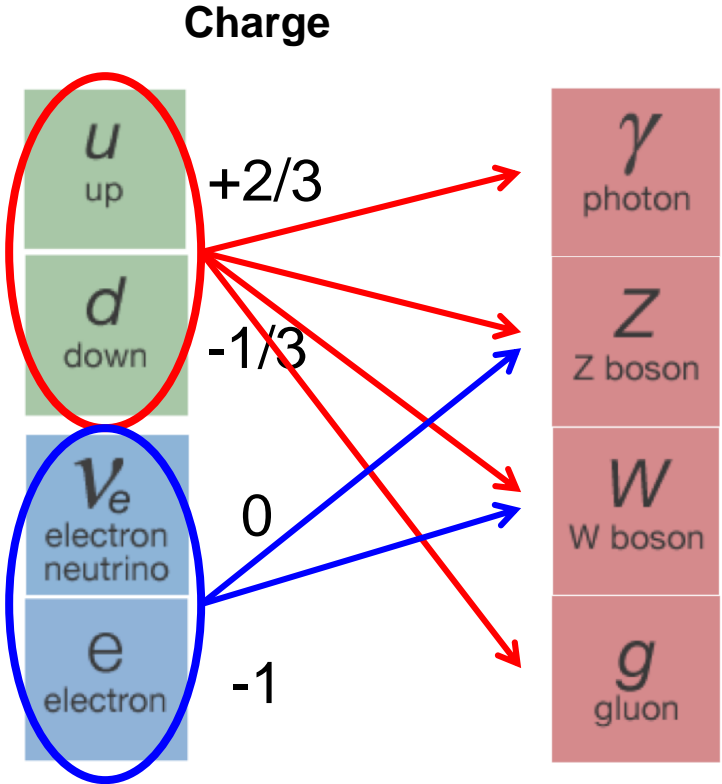
# Fundamental building blocks?

- Besides those three, ...



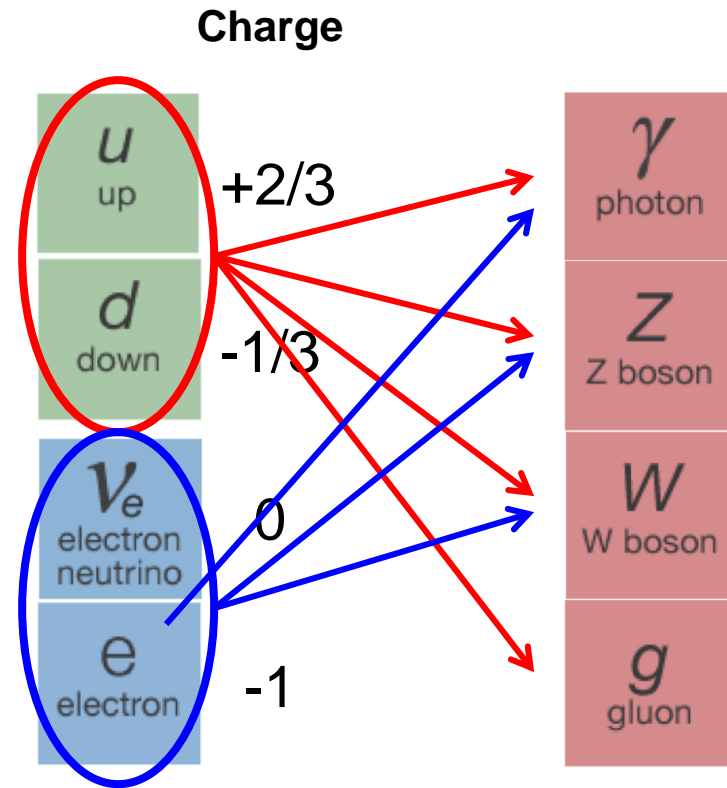
# Fundamental blocks?

- 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

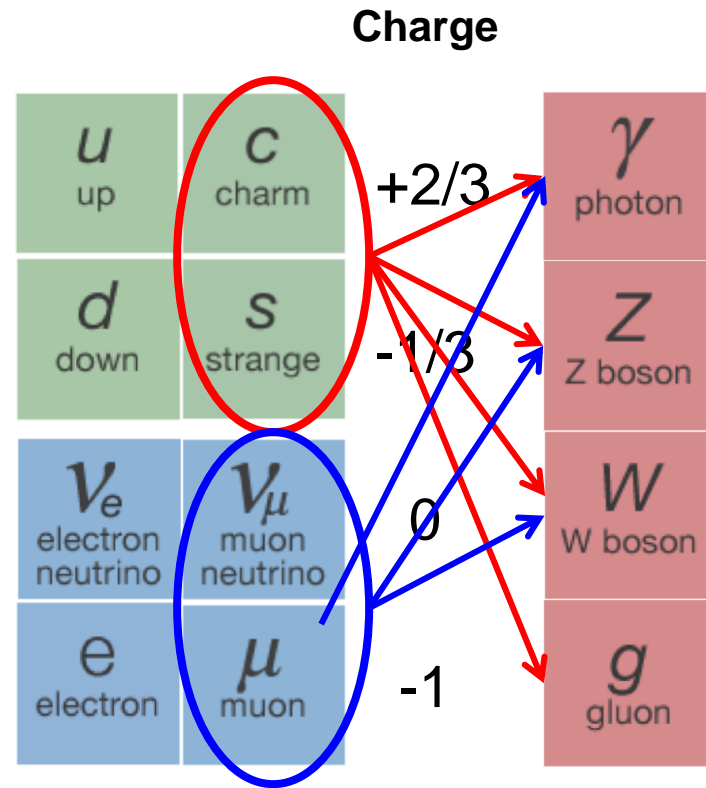
# Fundamental building blocks?

- Besides those three, ...

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

	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?

- 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	

- 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

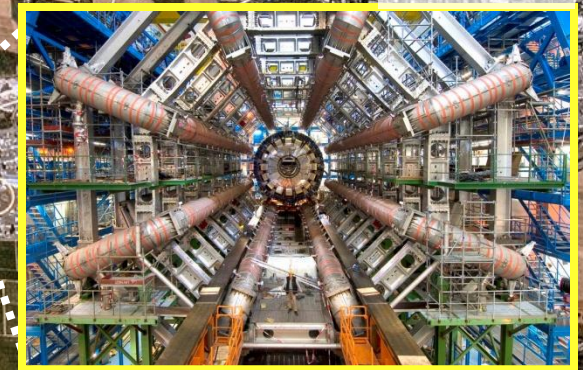
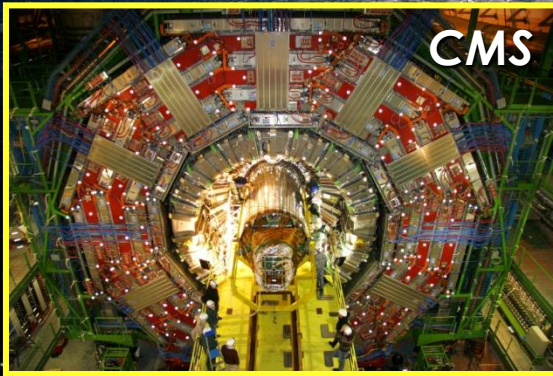
- 27 km circumference, 50-150 m below ground
- Two proton beams close to the speed of light
- Stored energy: 350 MJ (~TGV at 155 km/h)

# The Large Hadron Collider



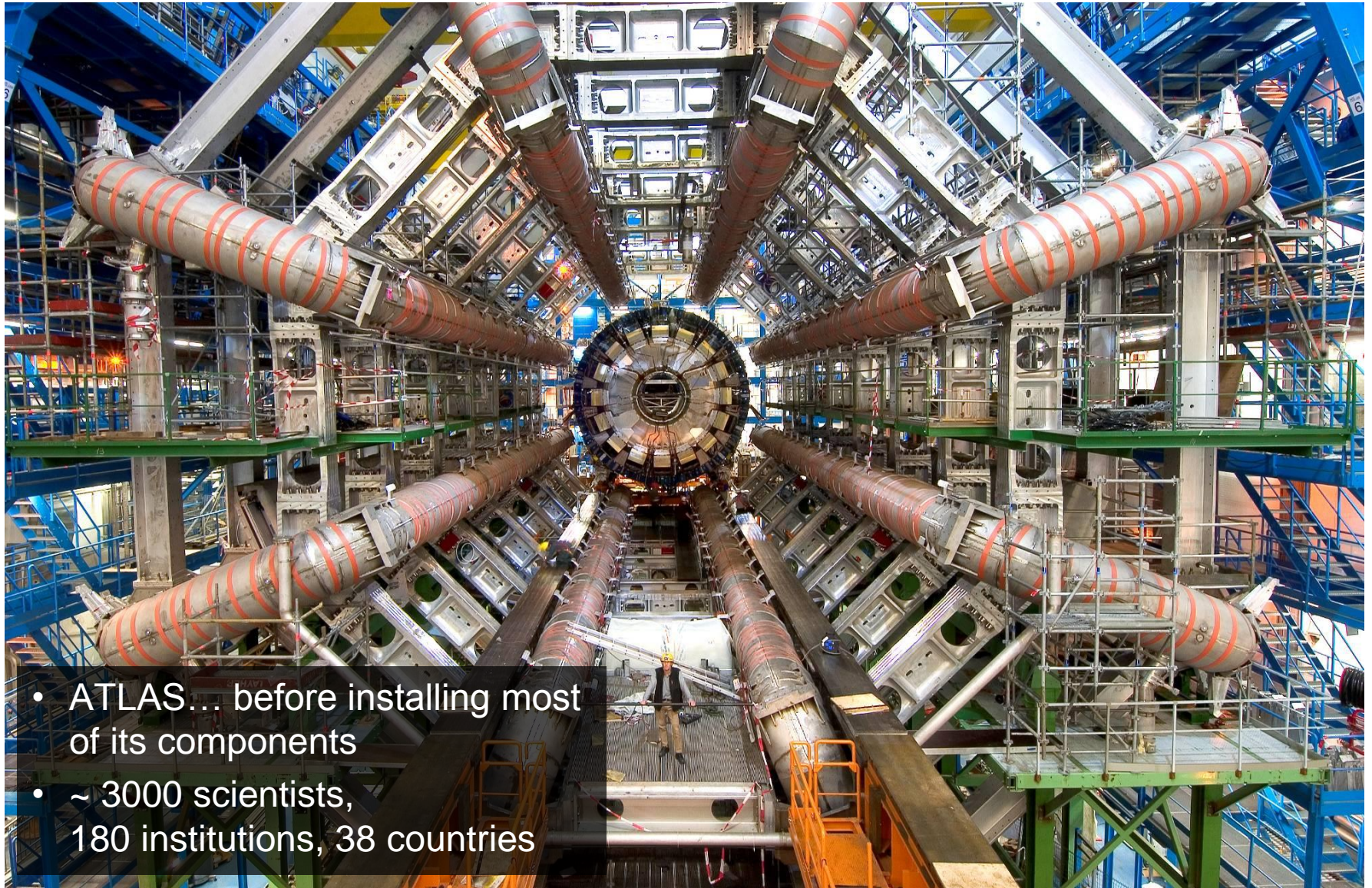
- ~1600 superconducting magnets
- “Bunches” of  $1.15 \times 10^{11}$  protons: 30 microns x several cm
- 40 million bunch crossings per second

# The Large Hadron Collider



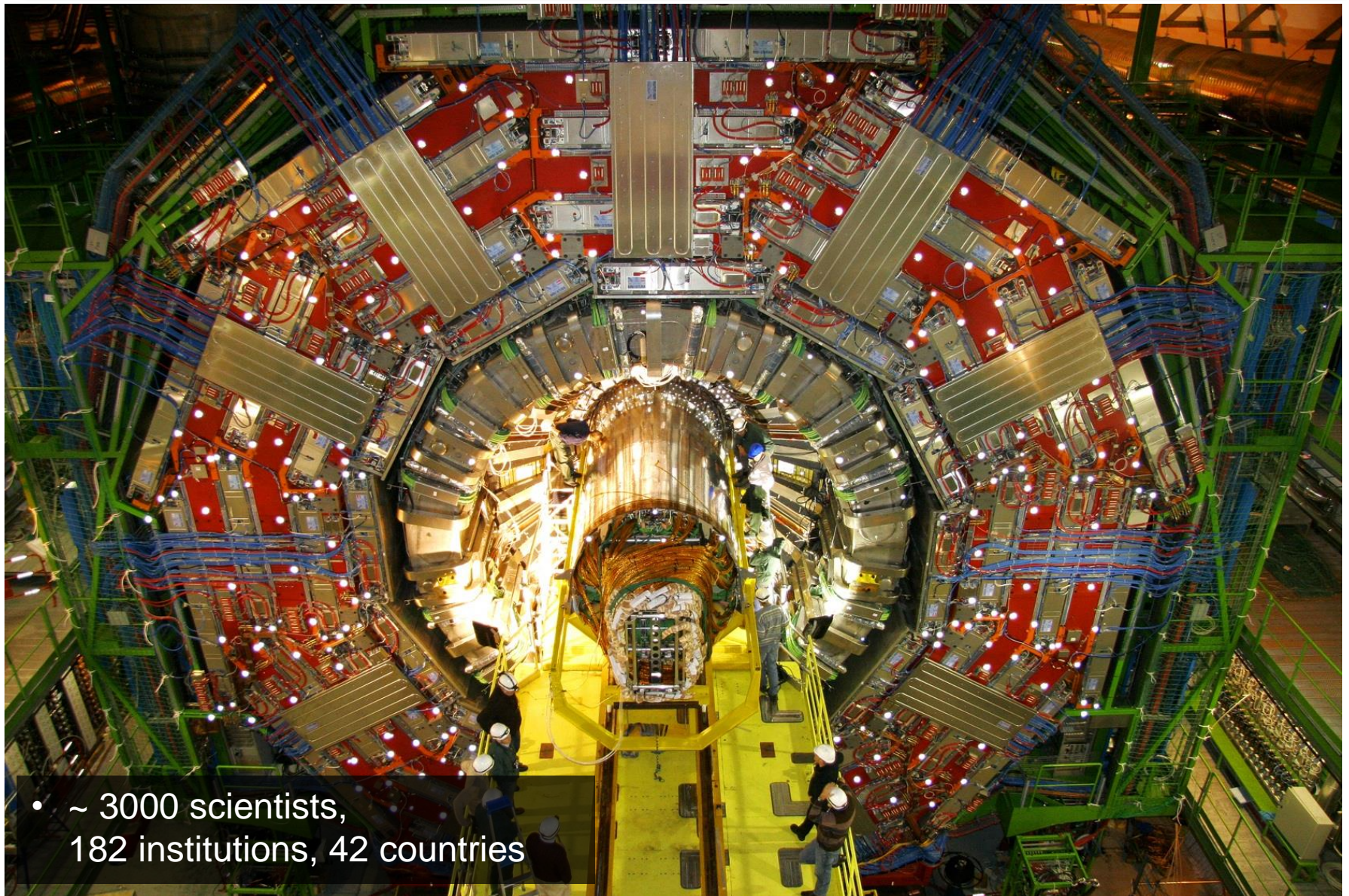
- Four collision points
- One detector on each
- Discovery: ATLAS, CMS

# ATLAS



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

# CMS



- ~ 3000 scientists,  
182 institutions, 42 countries

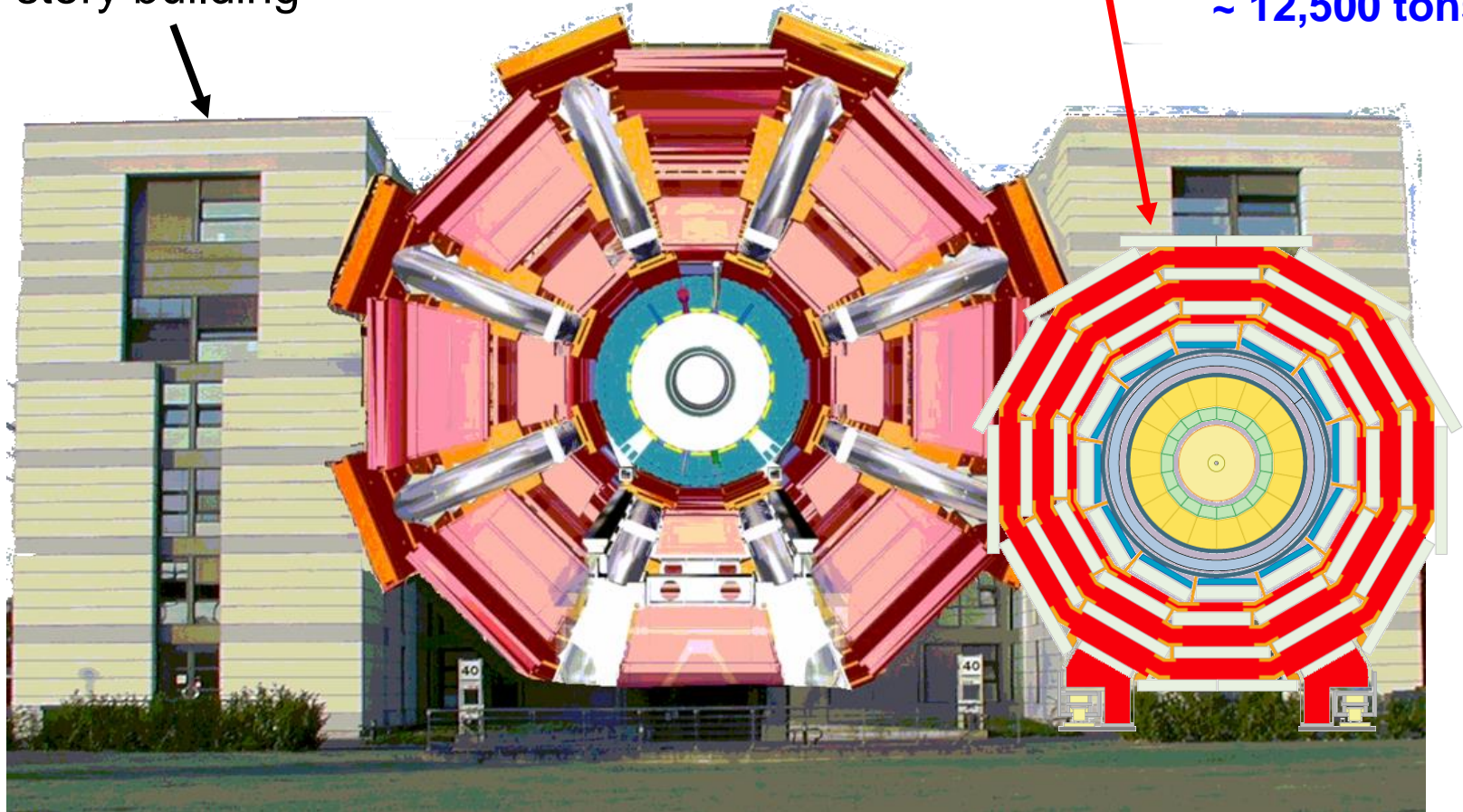


# Detectors

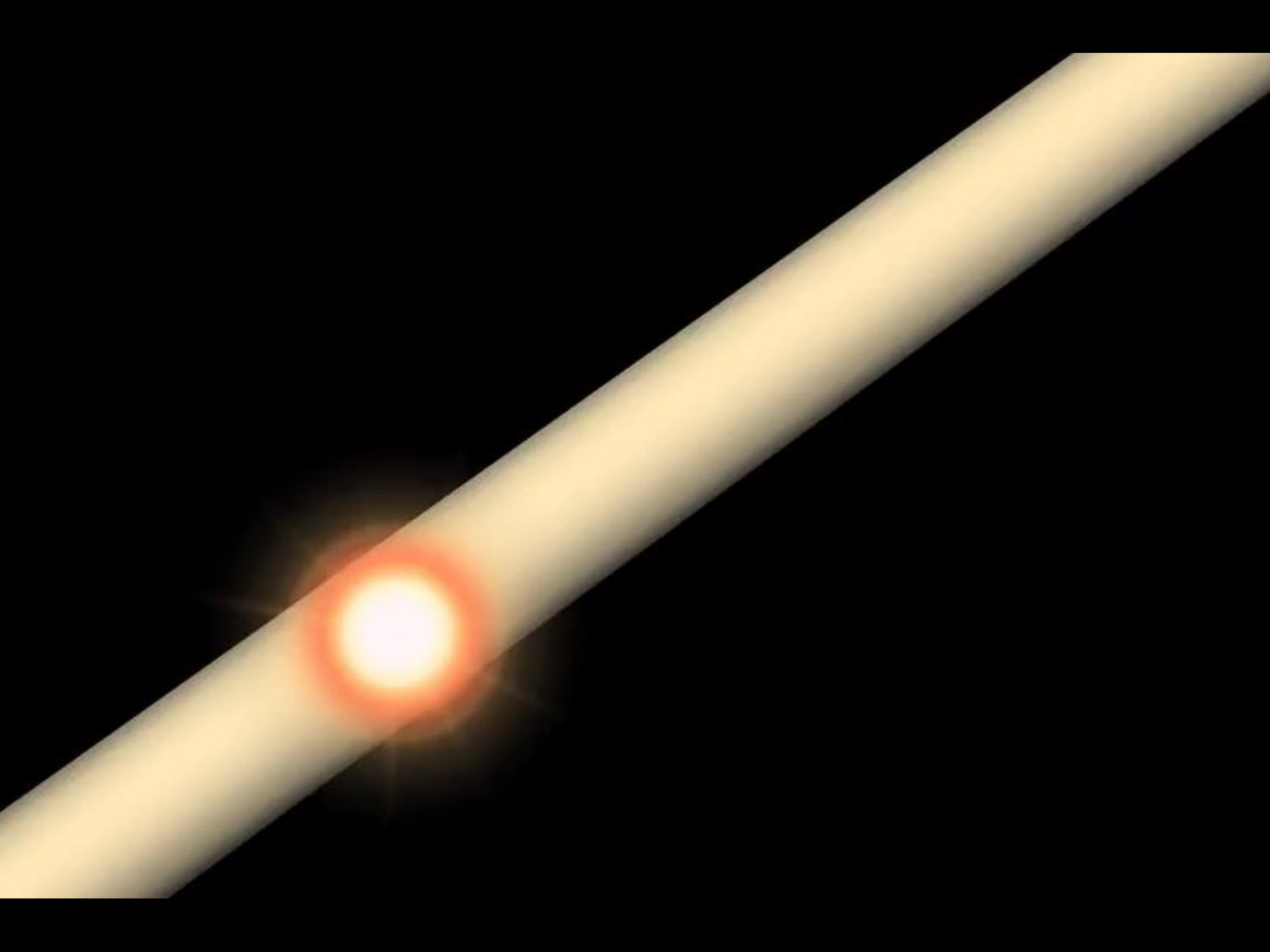
**ATLAS** ~ 25 m × 45 m  
~ 7,000 tons

**CMS** ~ 15 m × 21.5 m  
~ 12,500 tons

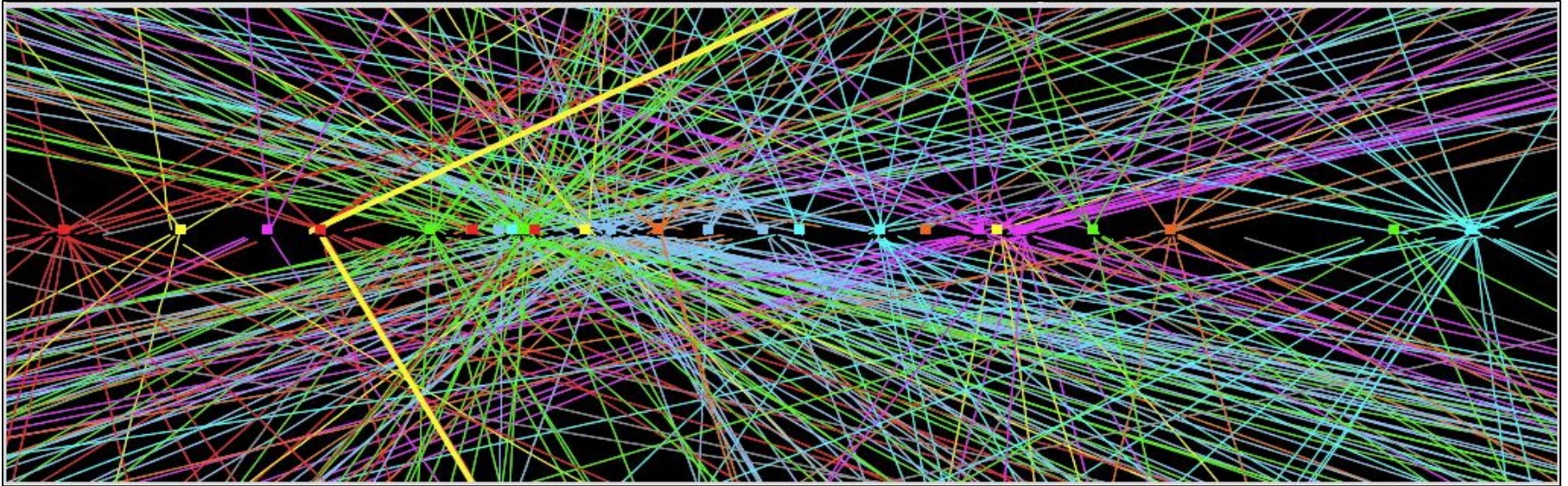
Five-story building



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



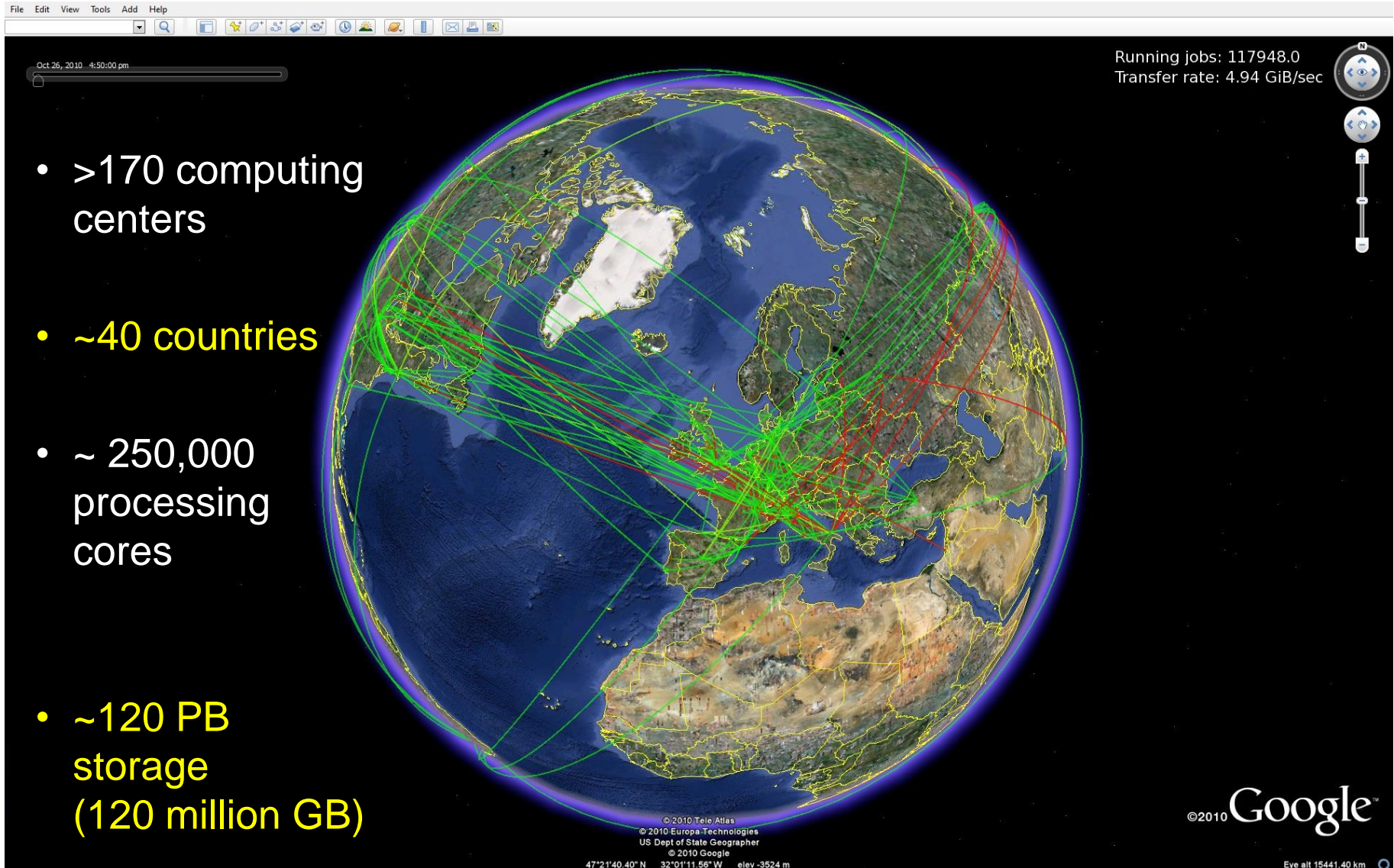
# Data



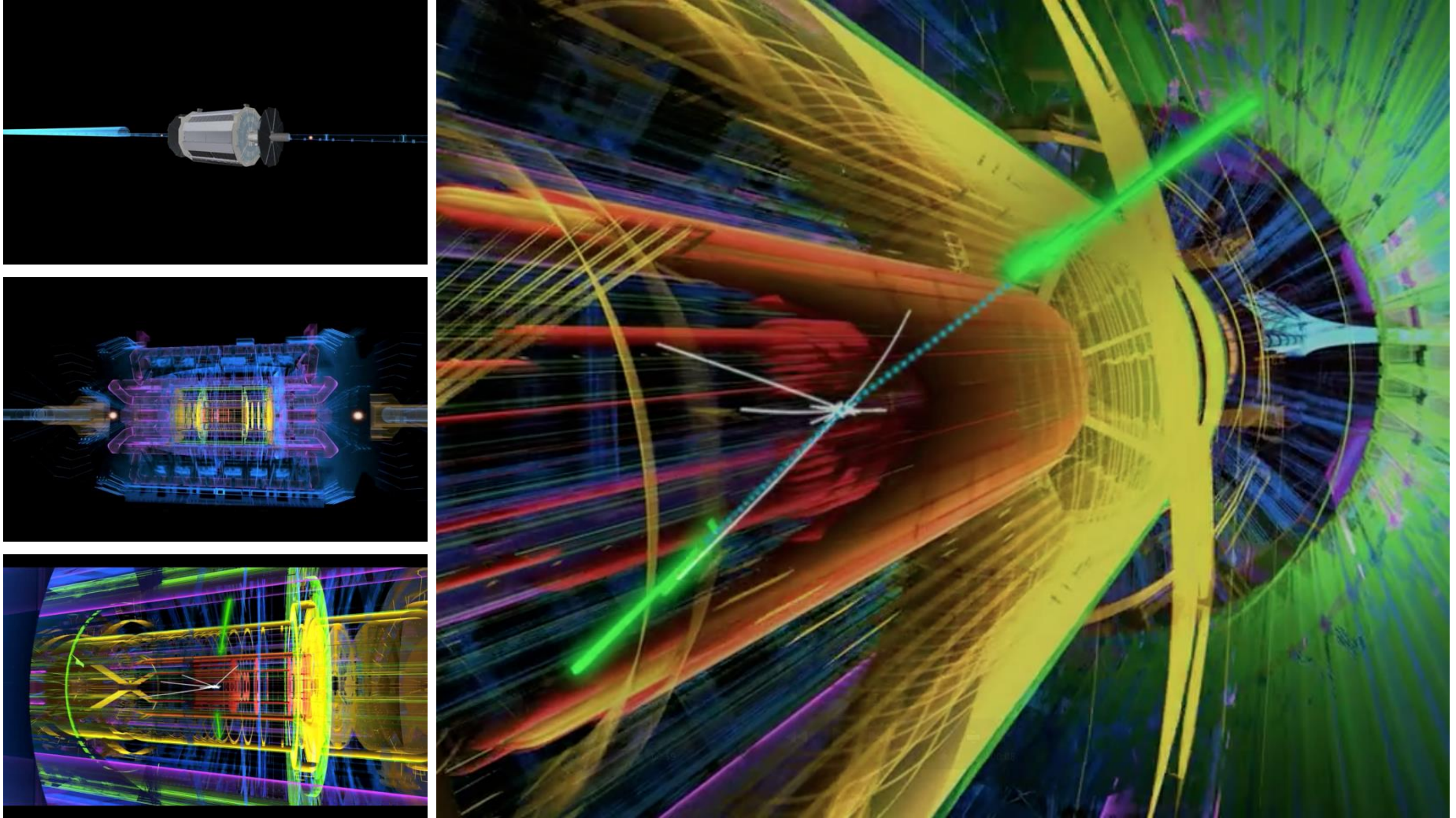
$Z \rightarrow \mu\mu$  event from 2012, with 25 reconstructed vertices

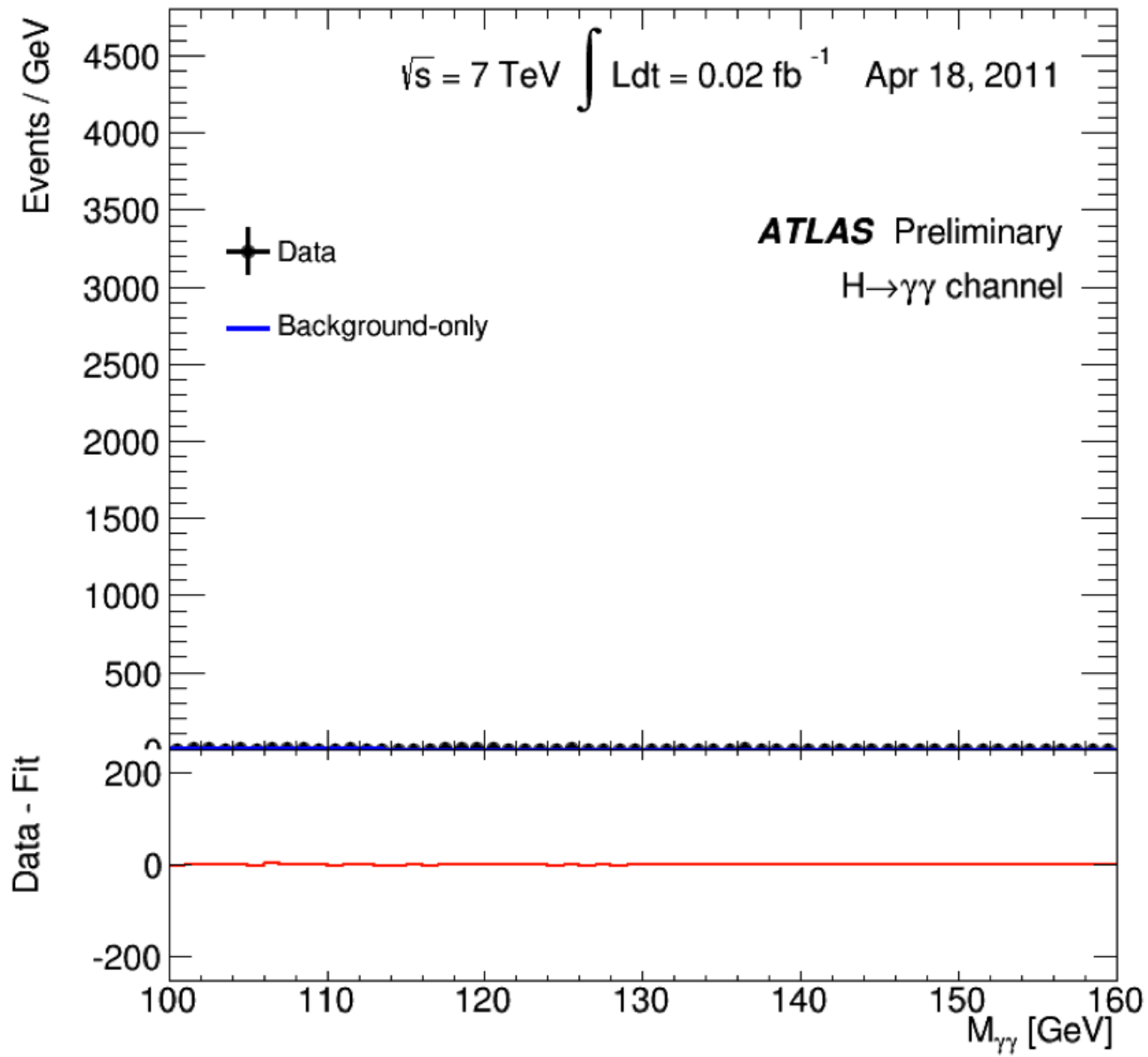
- Each bunch crossing  $\sim 20$   $pp$  interactions
- 40 M crossings per second  $\times$  20  $pp$  per crossing, spacing: 600 M  $pp/s$
- Fast selection systems (“trigger systems”) keep only 400 collisions/s
- Each  $pp$  collision produces hundreds of particles
- If stored in musing CD's, ...

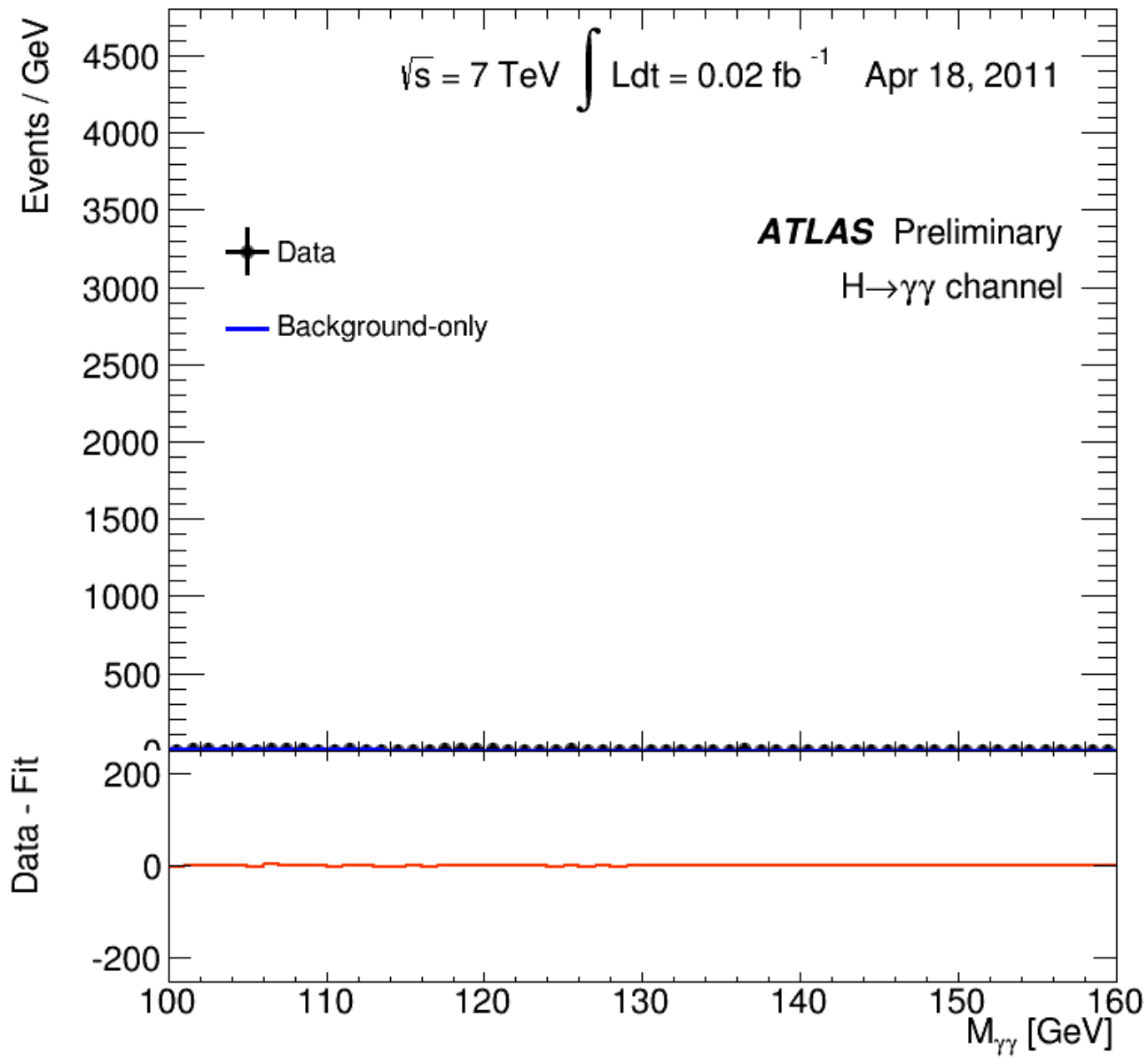
# Worldwide LHC Computing Grid



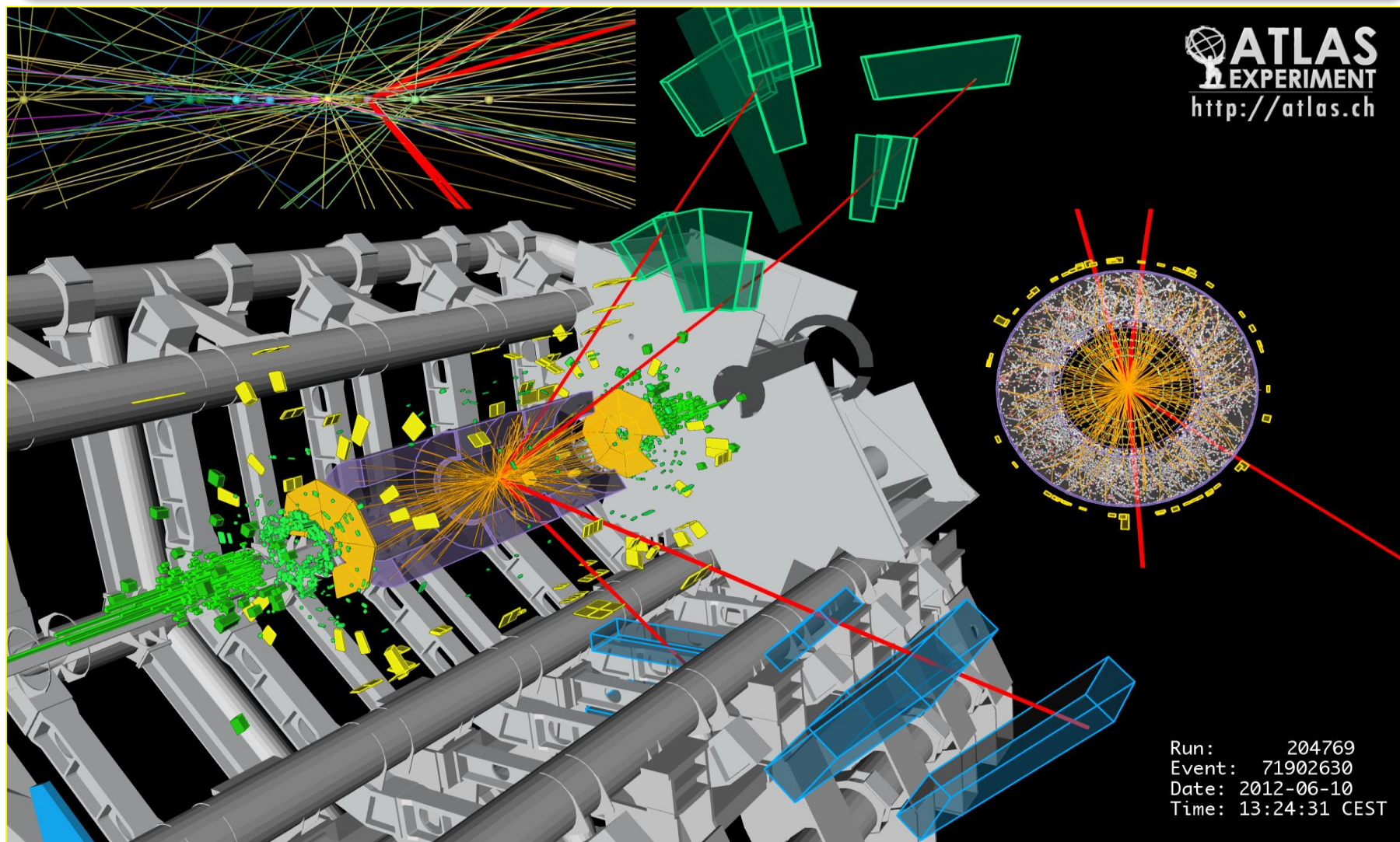
$$H \rightarrow \gamma\gamma$$







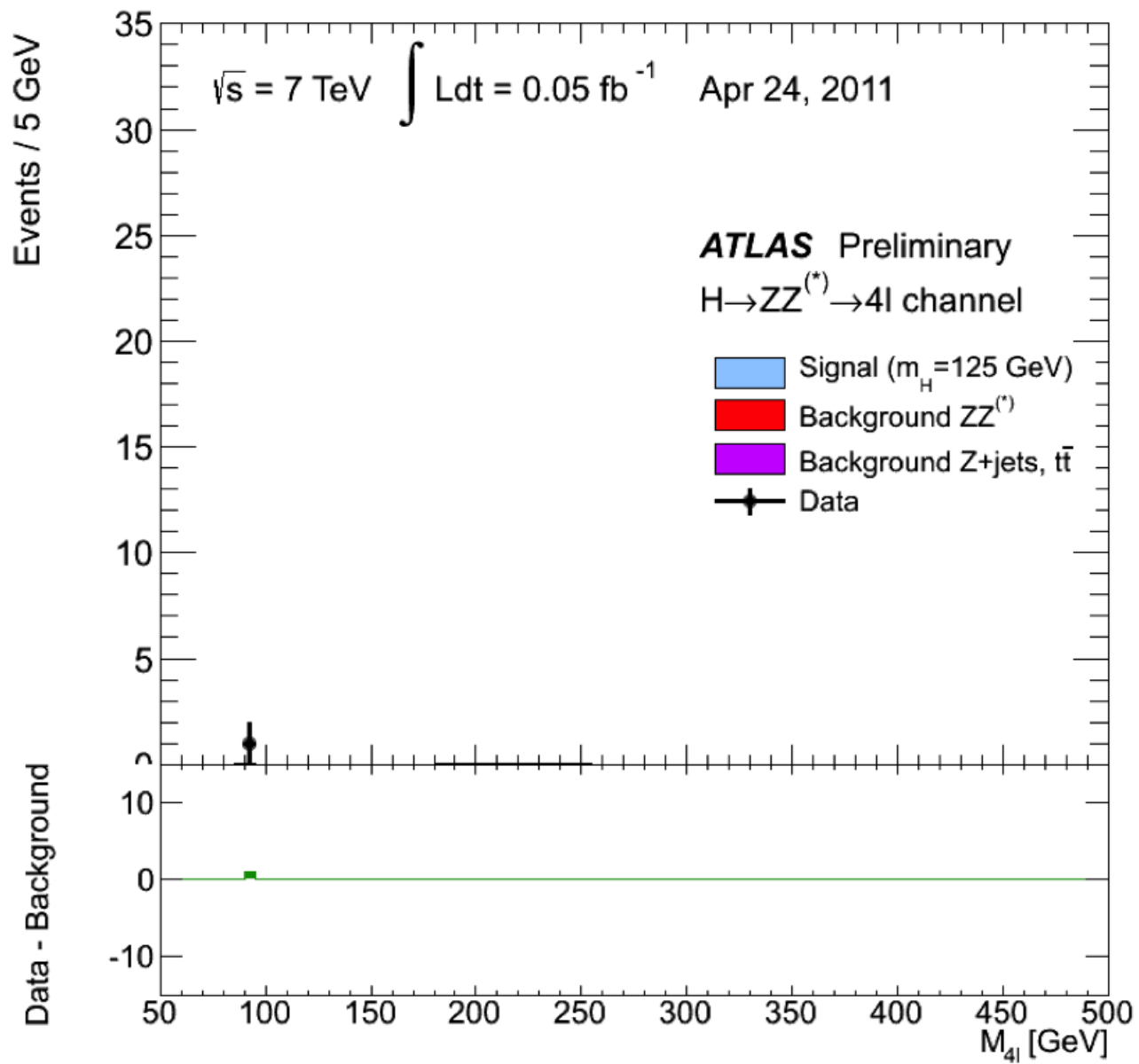
$$H \rightarrow ZZ^{(*)} \rightarrow 4\mu$$

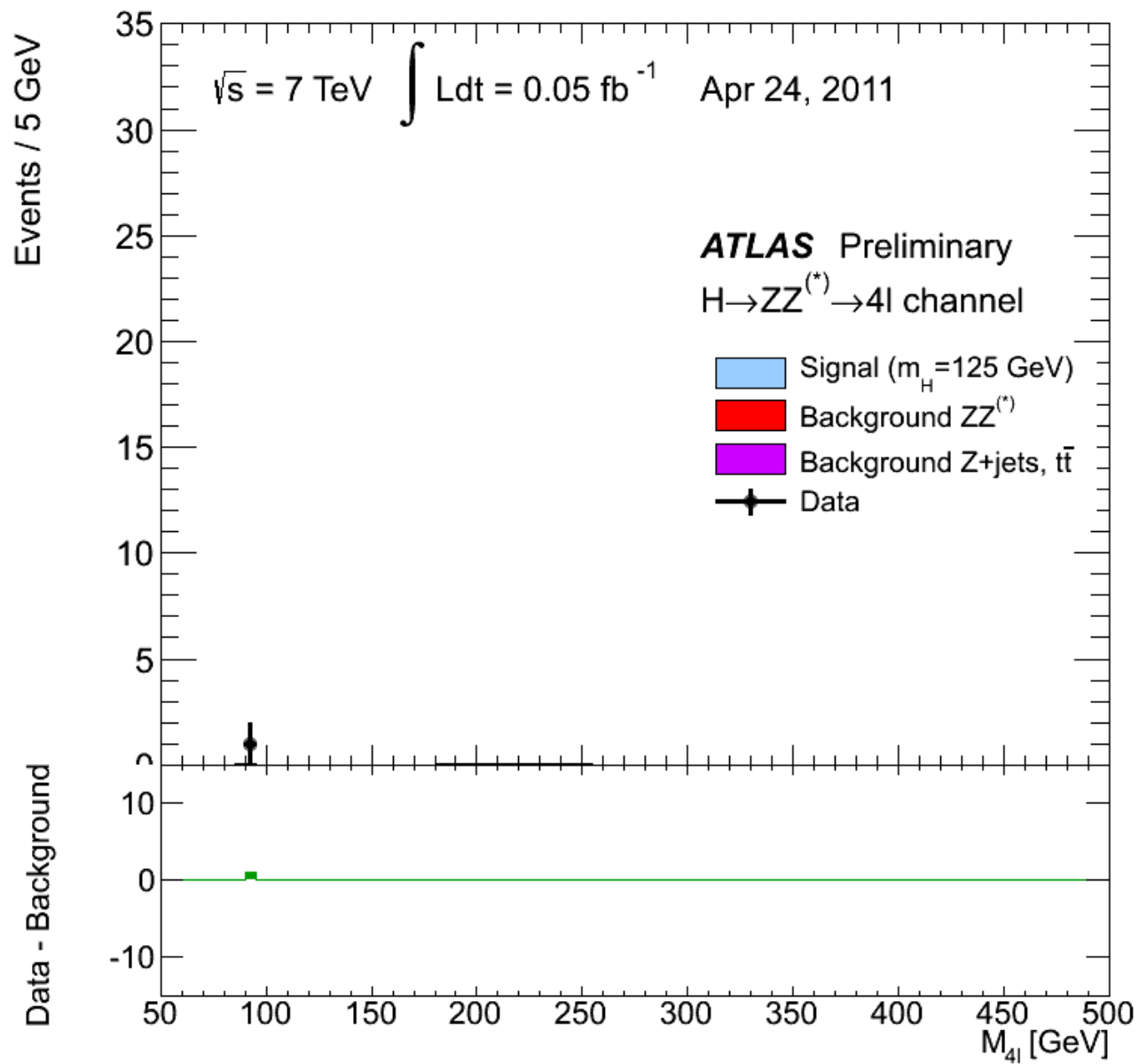


***H to 4 $\mu$  candidate, with  $m_{4\mu}=125.1$  GeV***

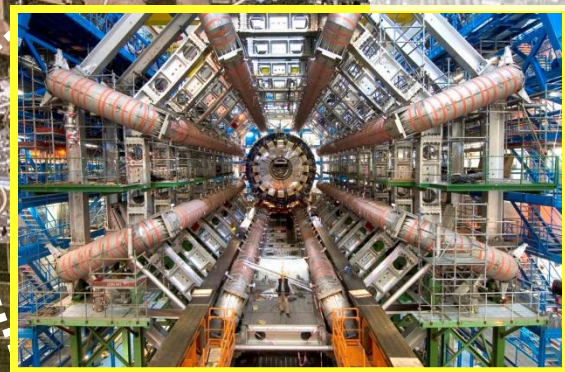
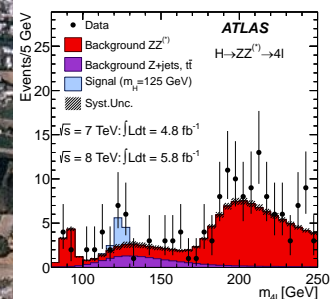
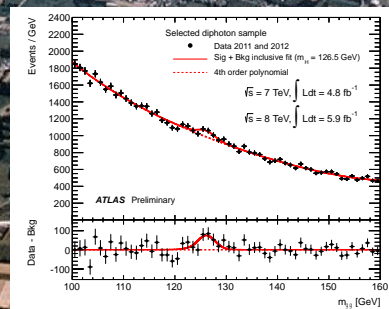
$p_T$  (muons) = 36.1, 47.5, 26.4, 71.7 GeV    $m_{12}=86.3$  GeV,  $m_{34}=31.6$  GeV. 15 reconstructed vertices



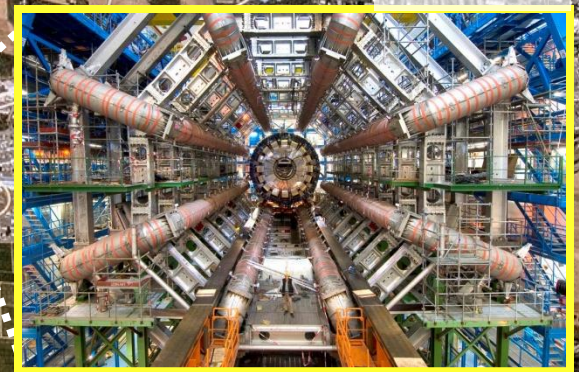
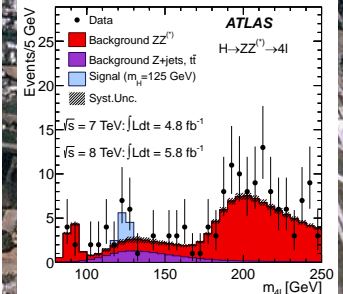
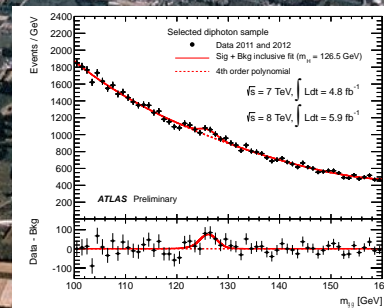
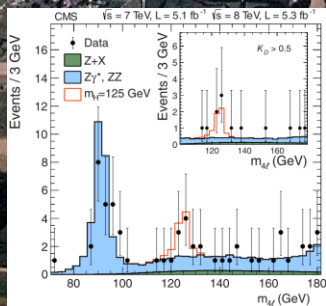
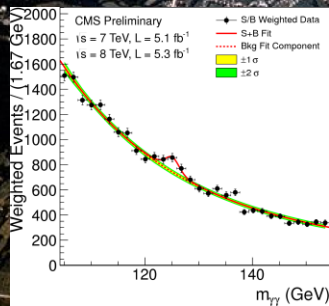
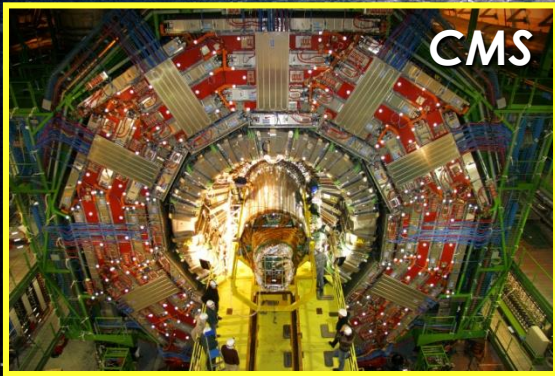




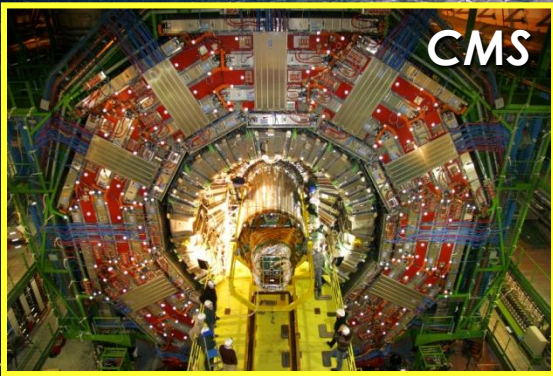
# Independent confirmation



# Independent confirmation

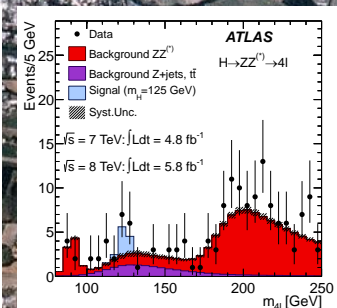
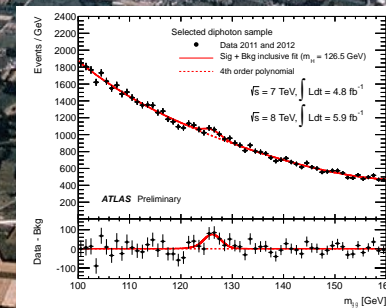
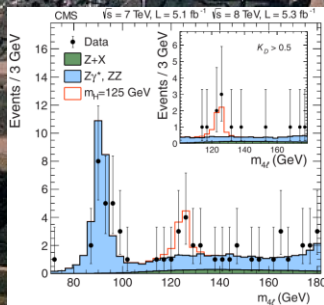
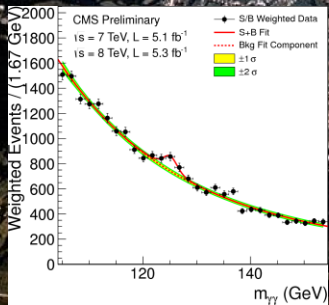


# Combination

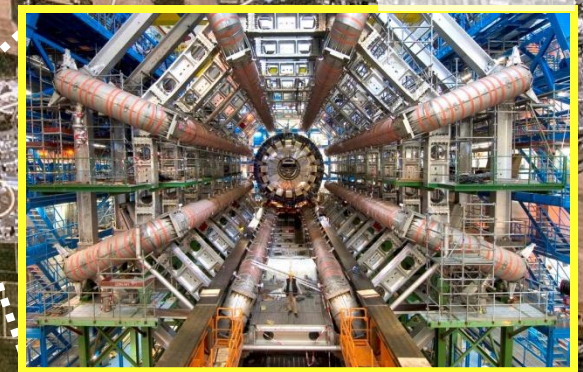


CMS

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



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



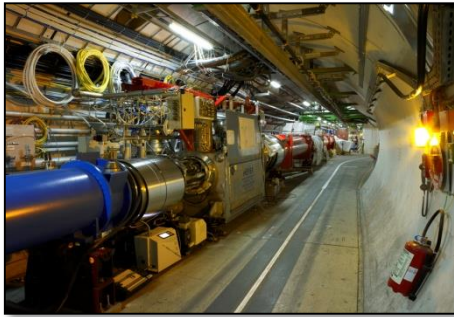
ATLAS

July 4, 2012



**From fundamental science  
to our daily life**

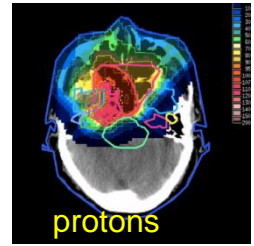
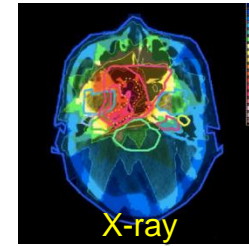
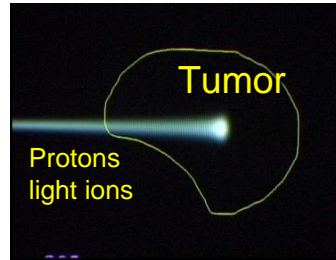
# From fundamental physics to daily life



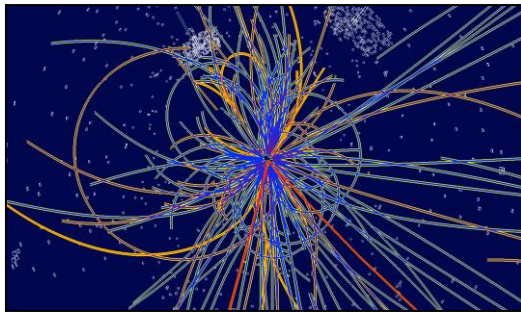
~30'000 accelerators worldwide  
~17'000 for medical applications



## Hadronic therapy for cancer

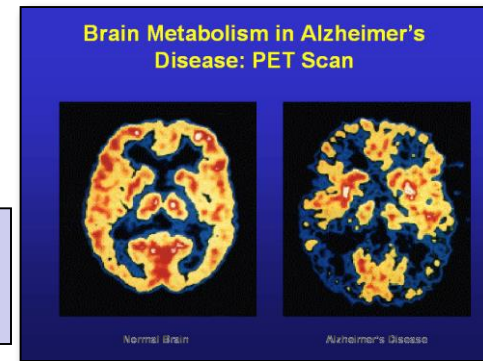


>90,000 patients treated (30 facilities)



## Medical imaging

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



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



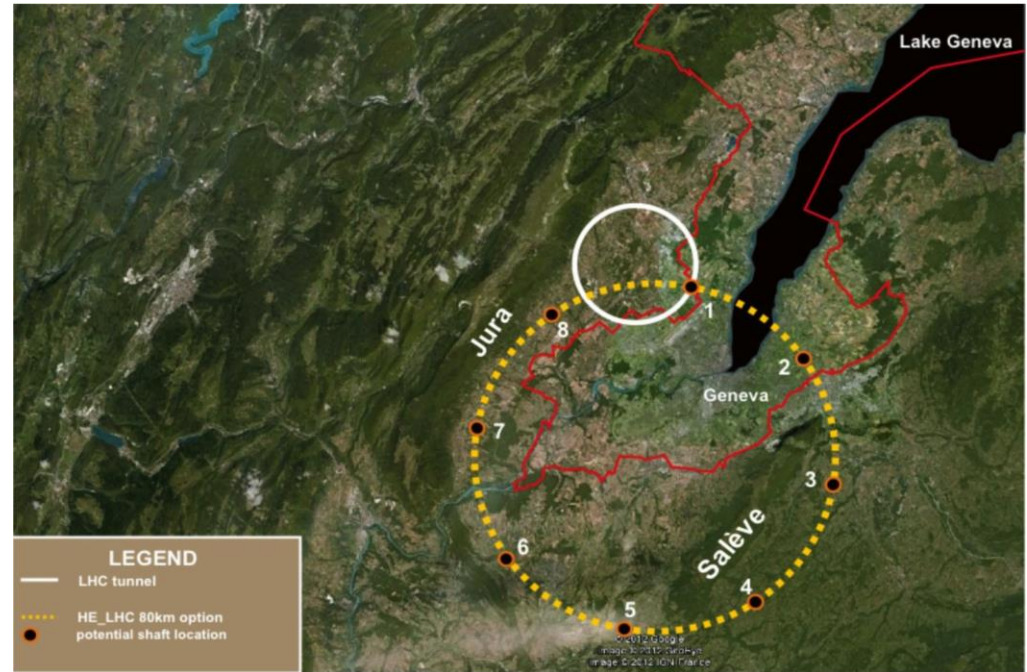


... and beyond

# Future colliders

## CERN

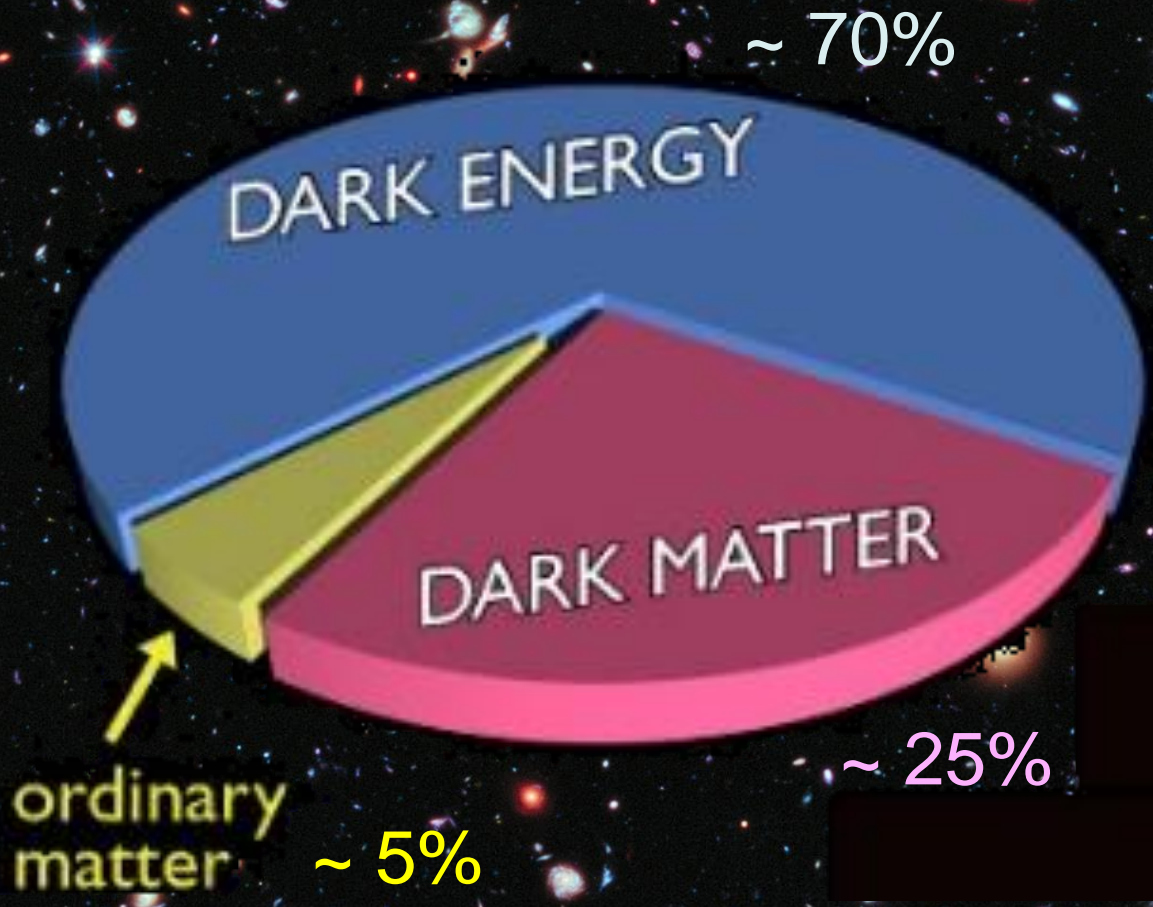
- Also in the Geneva area
- *Conceptual Design Study* in preparation

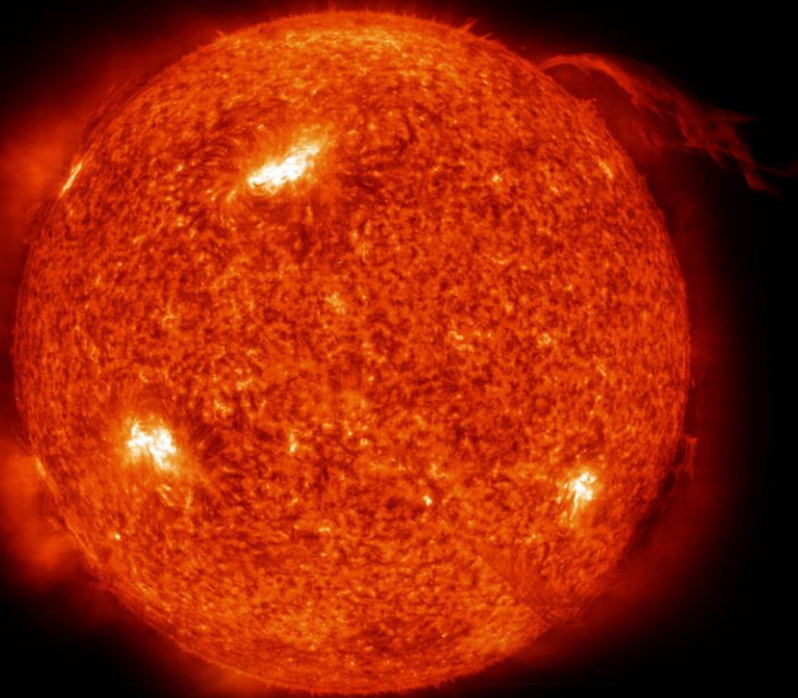


## China

- Evaluating possible sites
- Strong local support





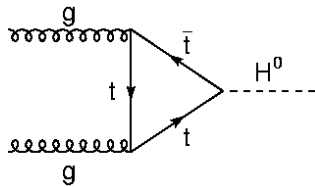




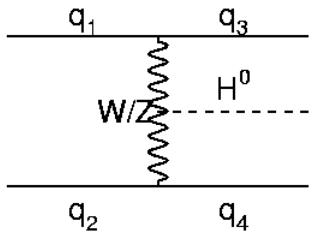
# SM Higgs production

## SM Higgs production

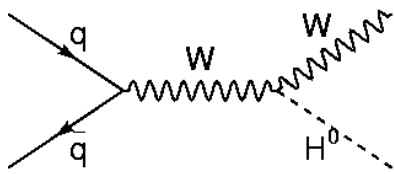
**Gluon fusion**  
(dominant at LHC)



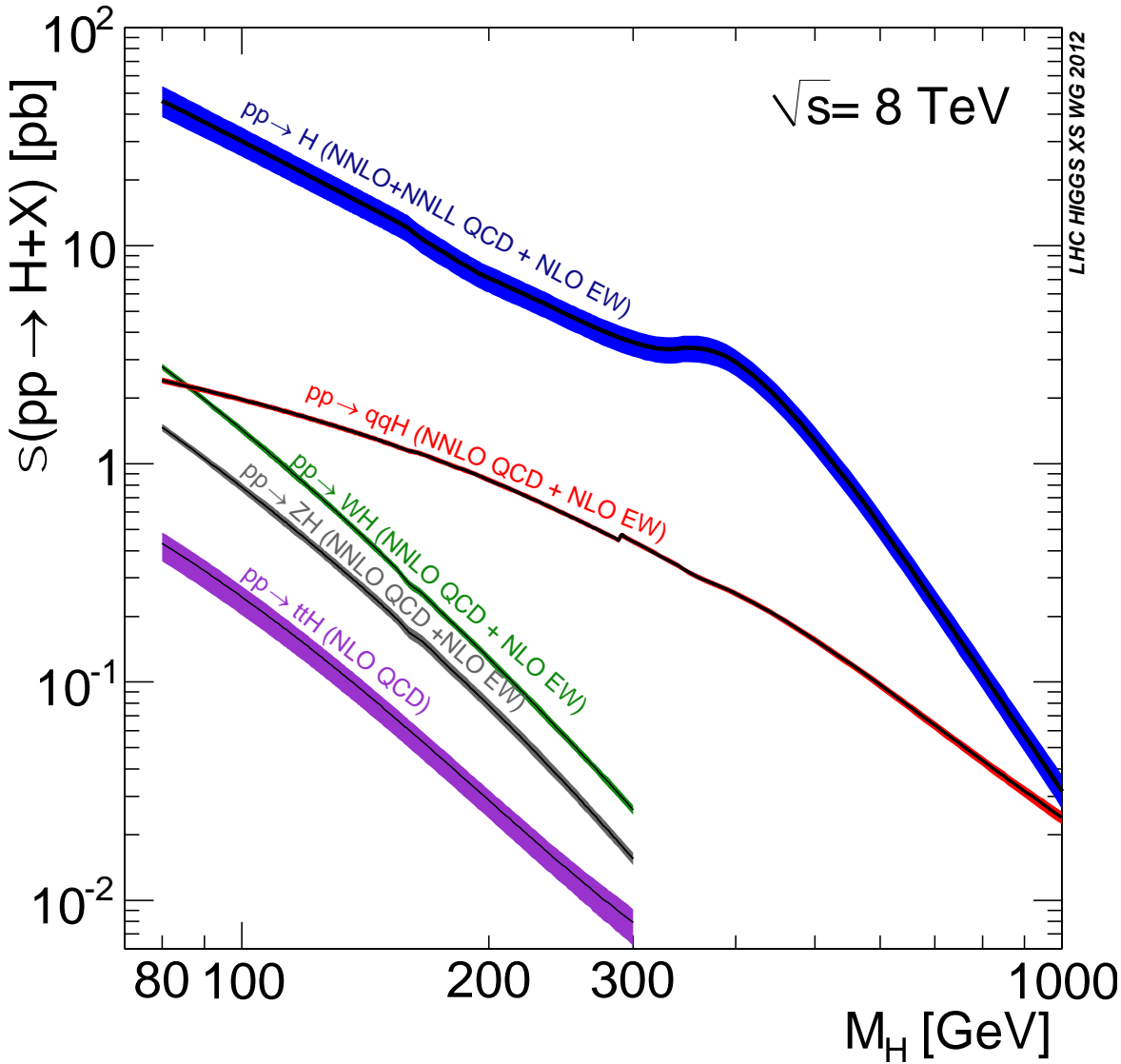
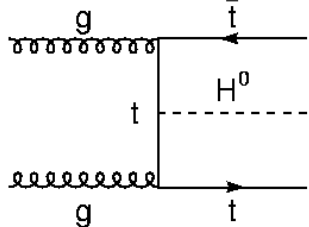
**Vector boson fusion**



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



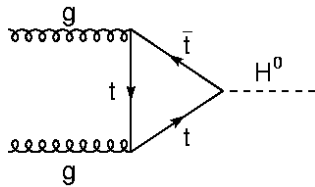
**Associated production with top**



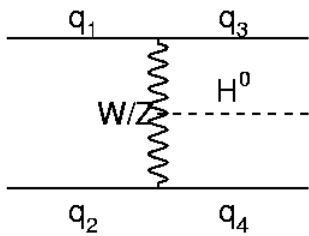
# SM Higgs production

## SM Higgs production

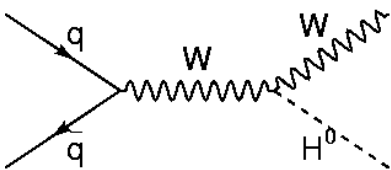
**Gluon fusion  
(dominant  
at LHC)**



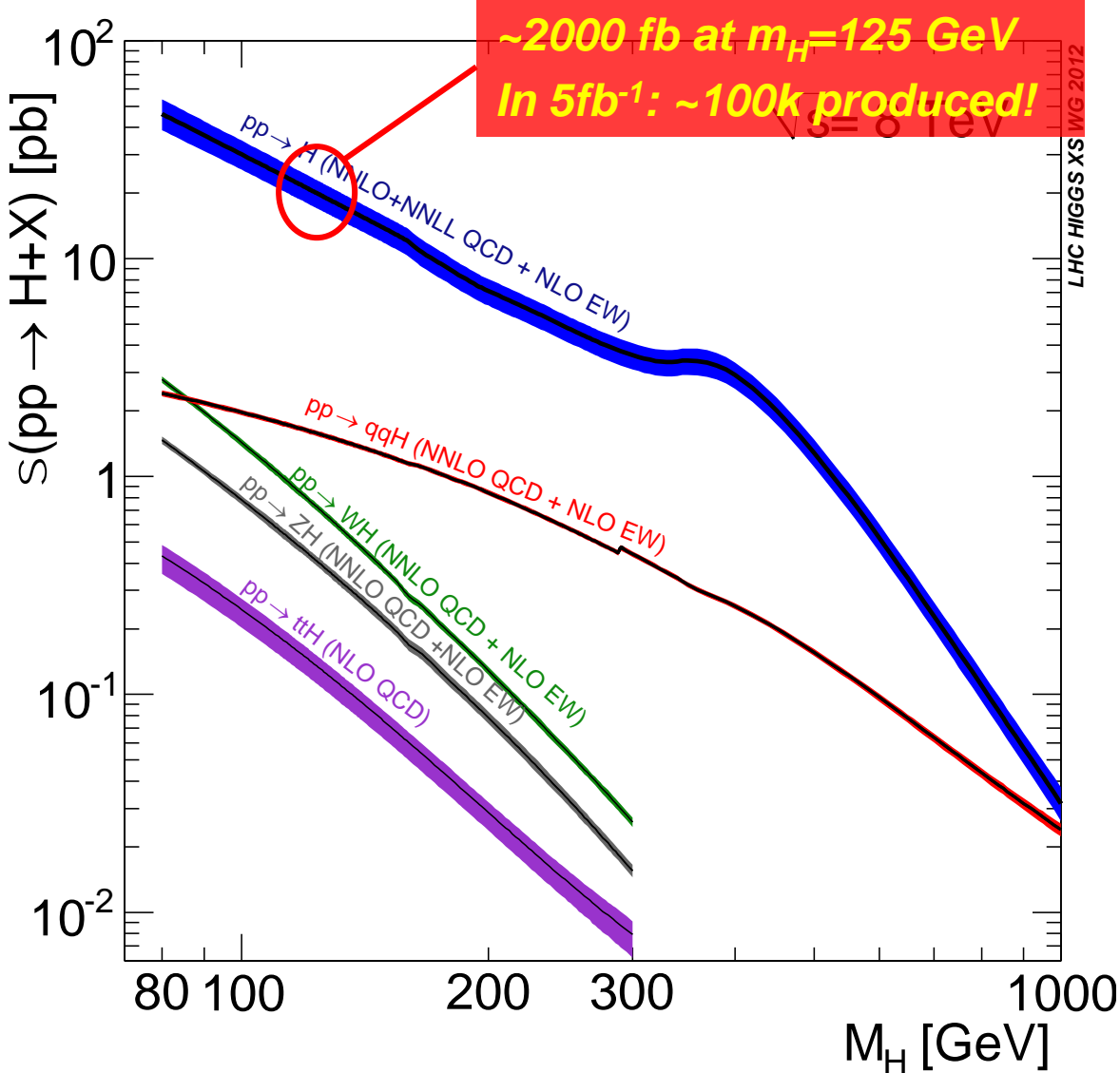
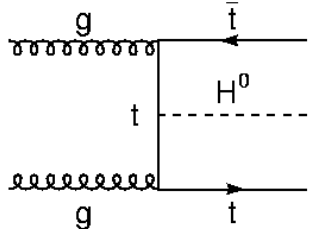
**Vector  
boson  
fusion**



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



**Associated  
production  
with top**

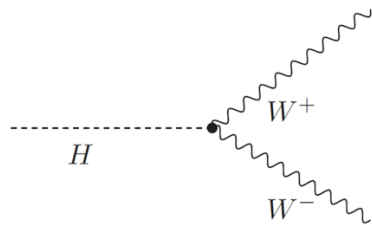




# Branching ratios

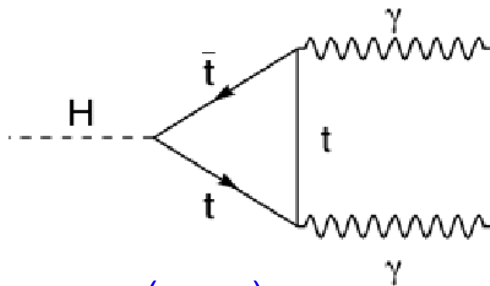
## SM Higgs decays

Direct coupling to massive particles

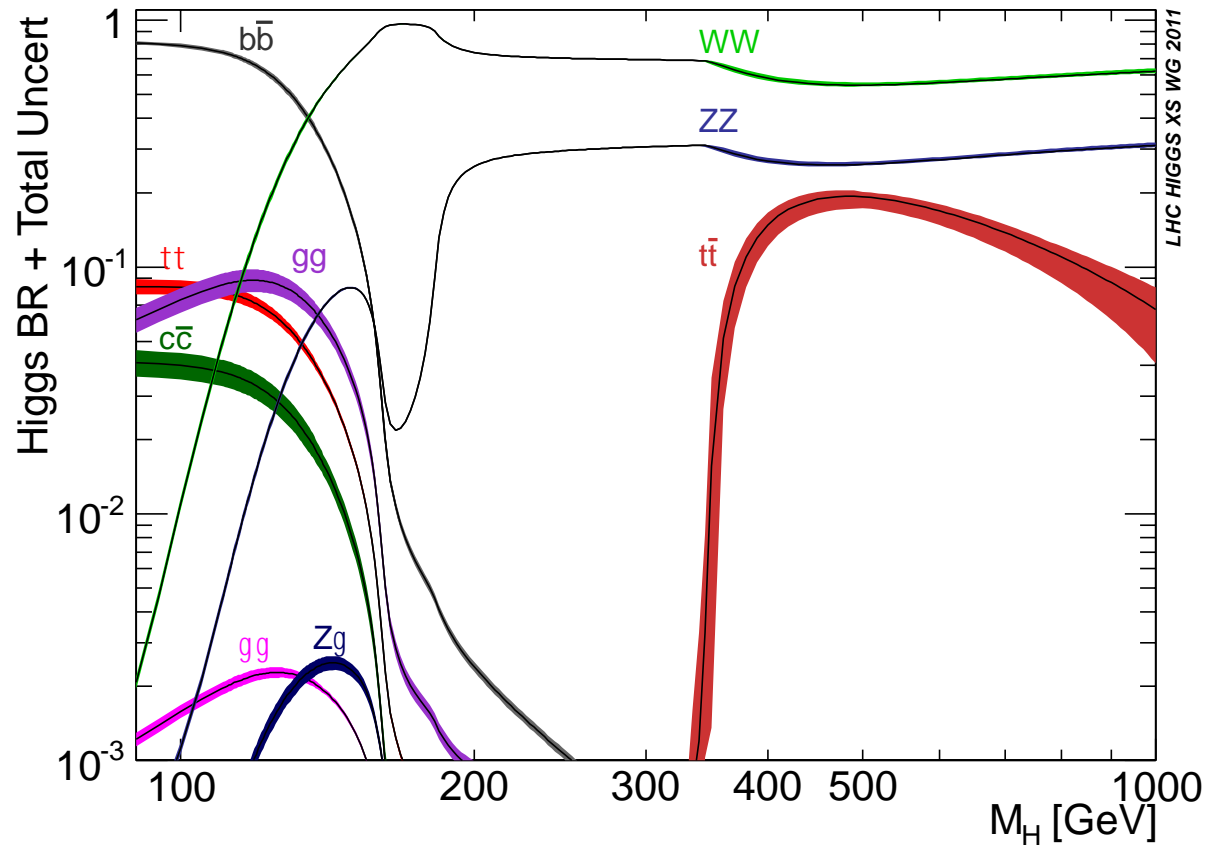


( $WW$ ,  $ZZ$ ,  $tt$ ,  $bb$ ,  $\tau\tau$ )

Through a triangle loop to massless ones



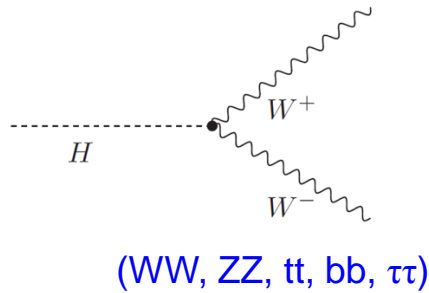
( $gg$ ,  $\gamma\gamma$ )



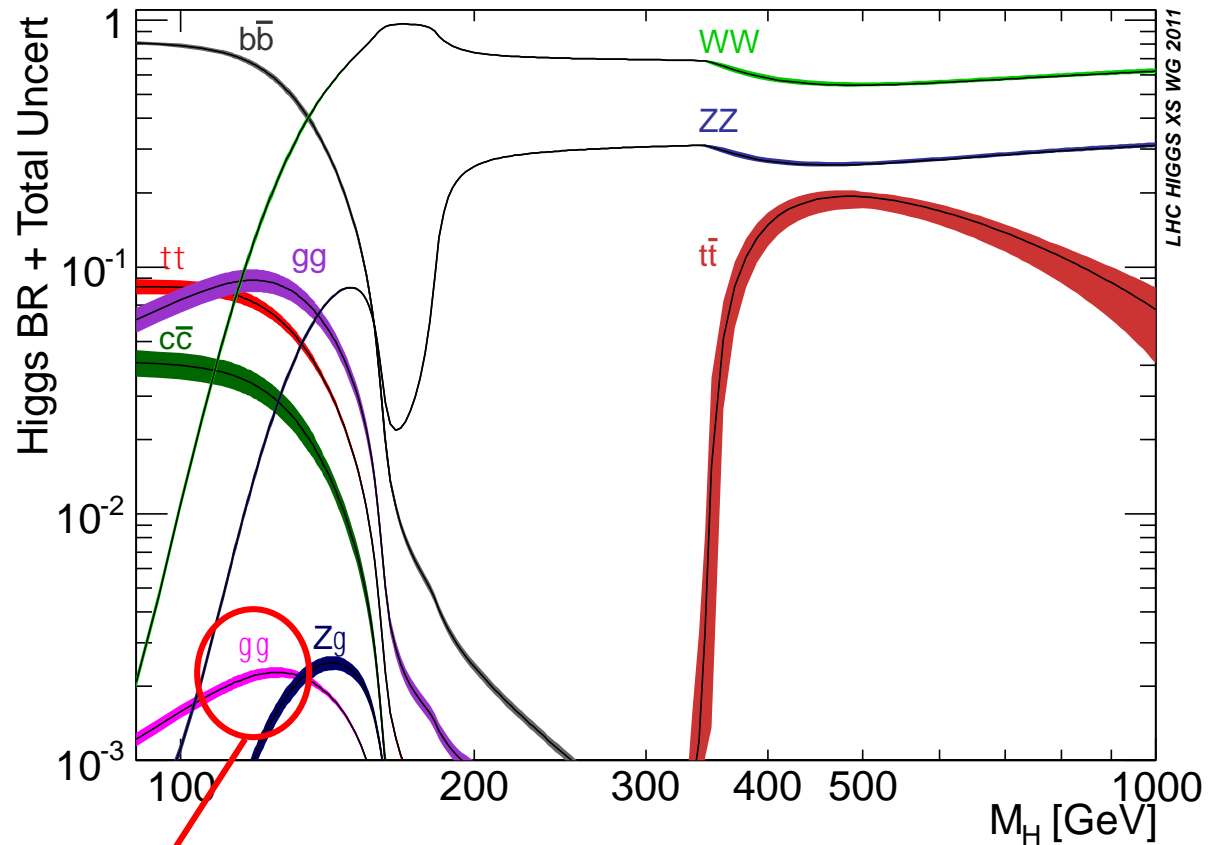
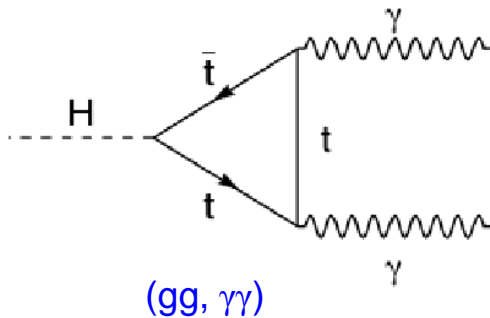
# Branching ratios

## SM Higgs decays

Direct coupling to massive particles



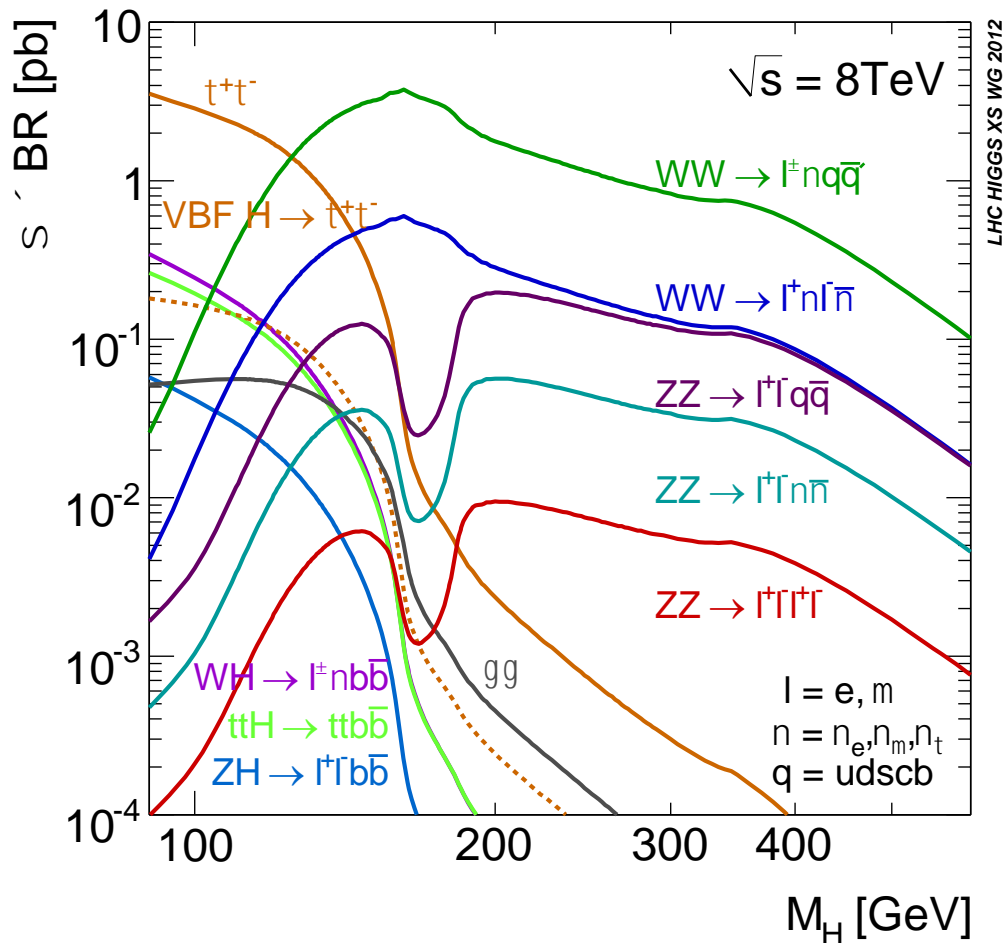
Through a triangle loop to massless ones



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

# Introduction

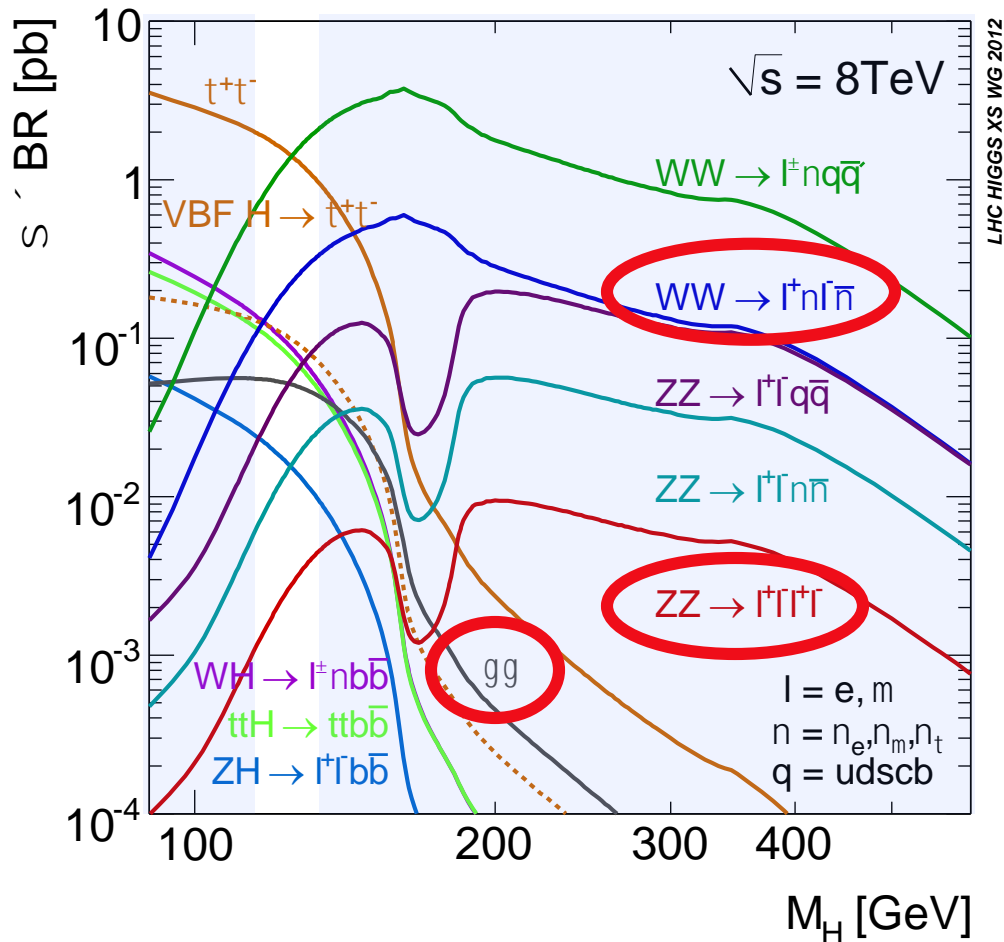
## Cross section times BR



- 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

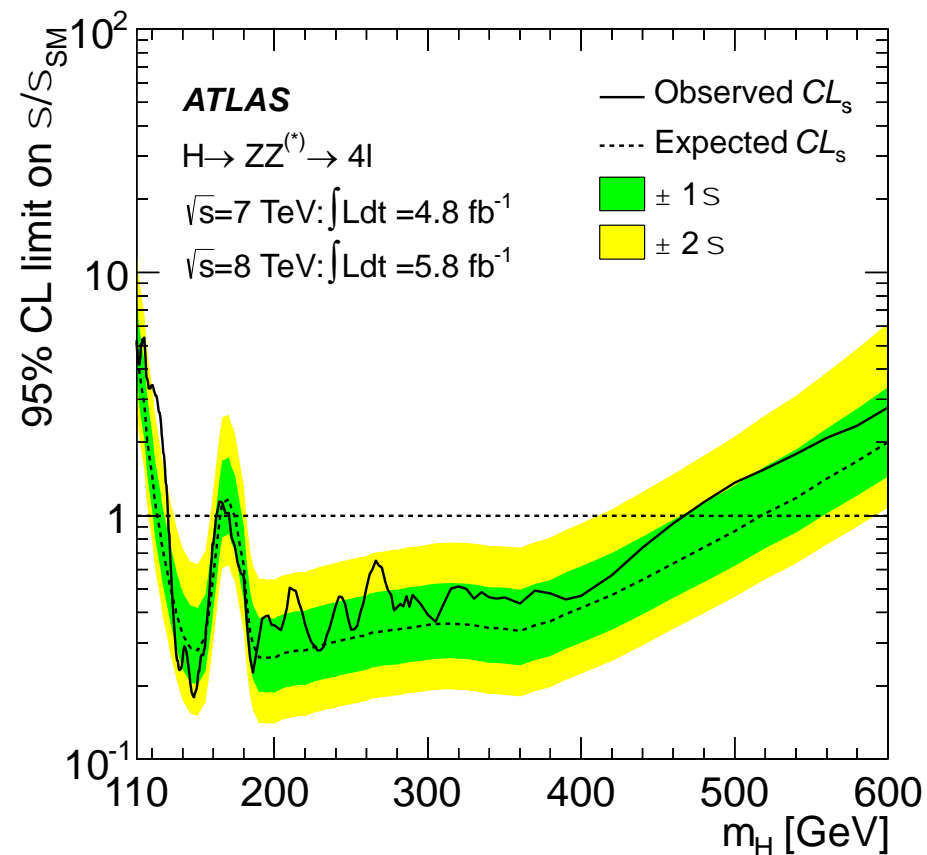
## Cross section times BR



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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?

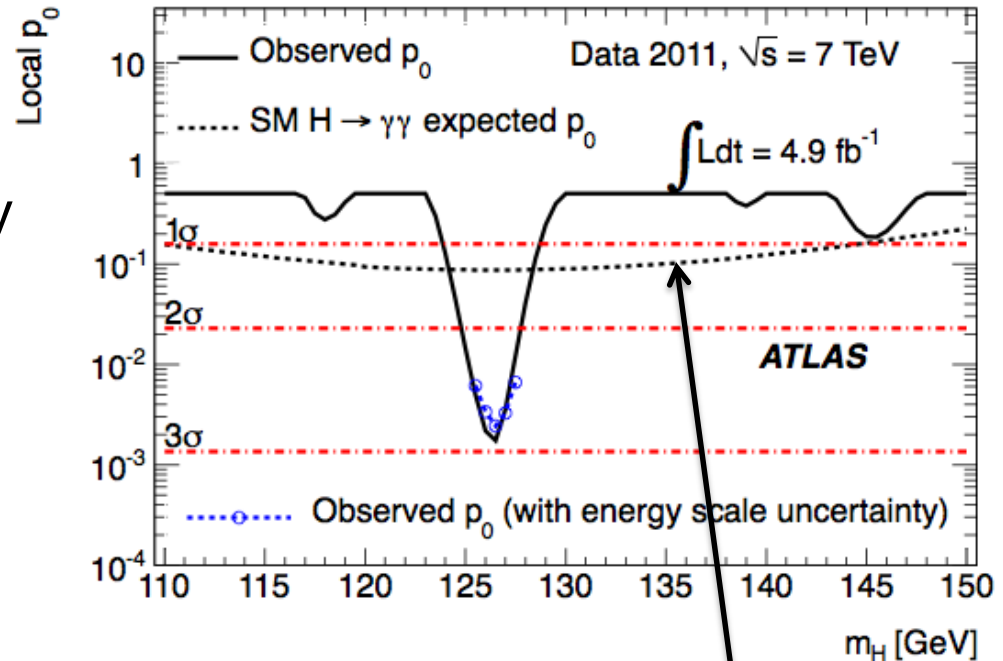
We quantify it by the probability that **background alone** would produce an excess as large as observed (or larger)

→ “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  $m_H$

