Overview of Particle Physics and its Applications

Reina Camacho Toro
CNRS-LPNHE

US-ATLAS Education and Outreach Event
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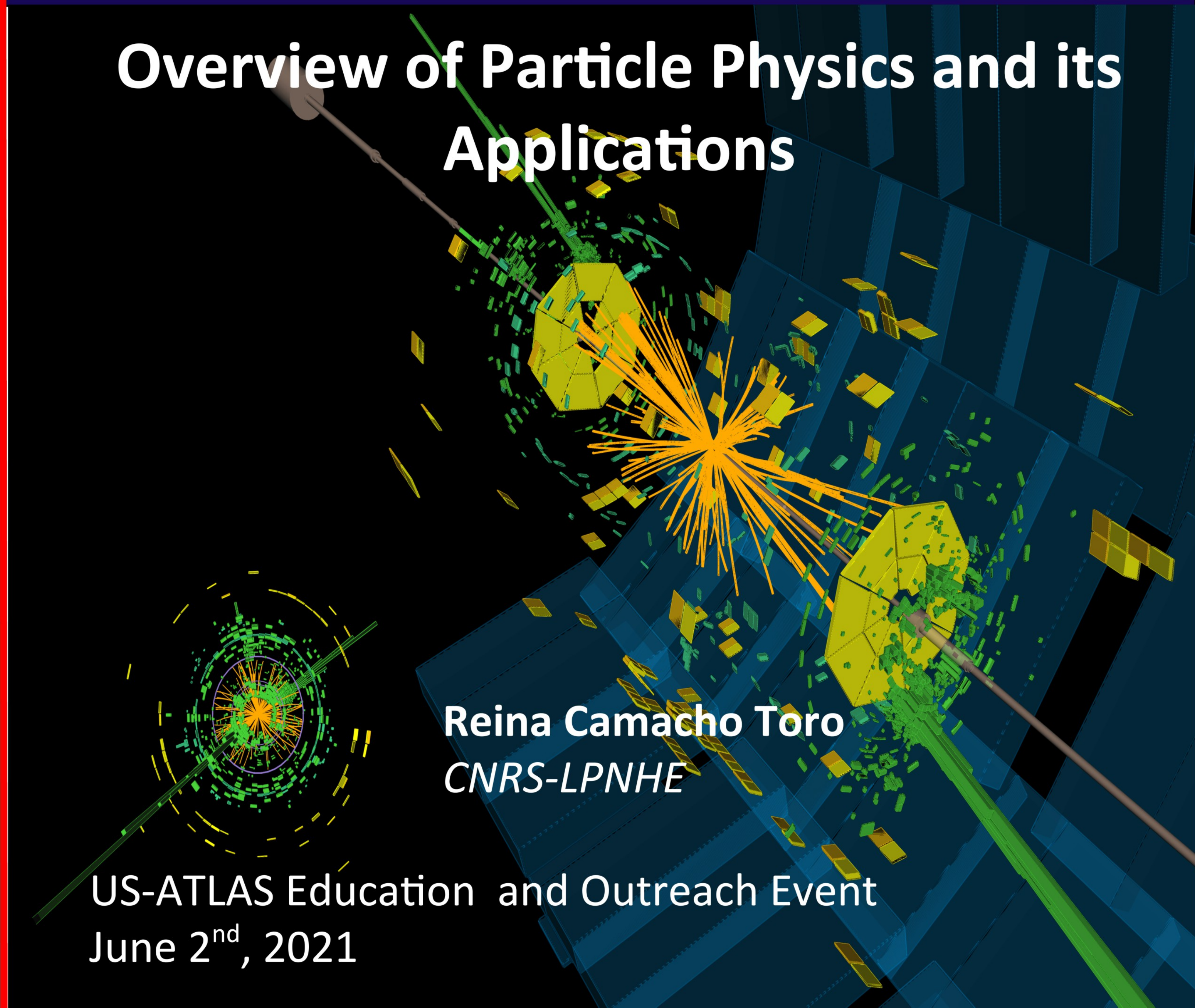
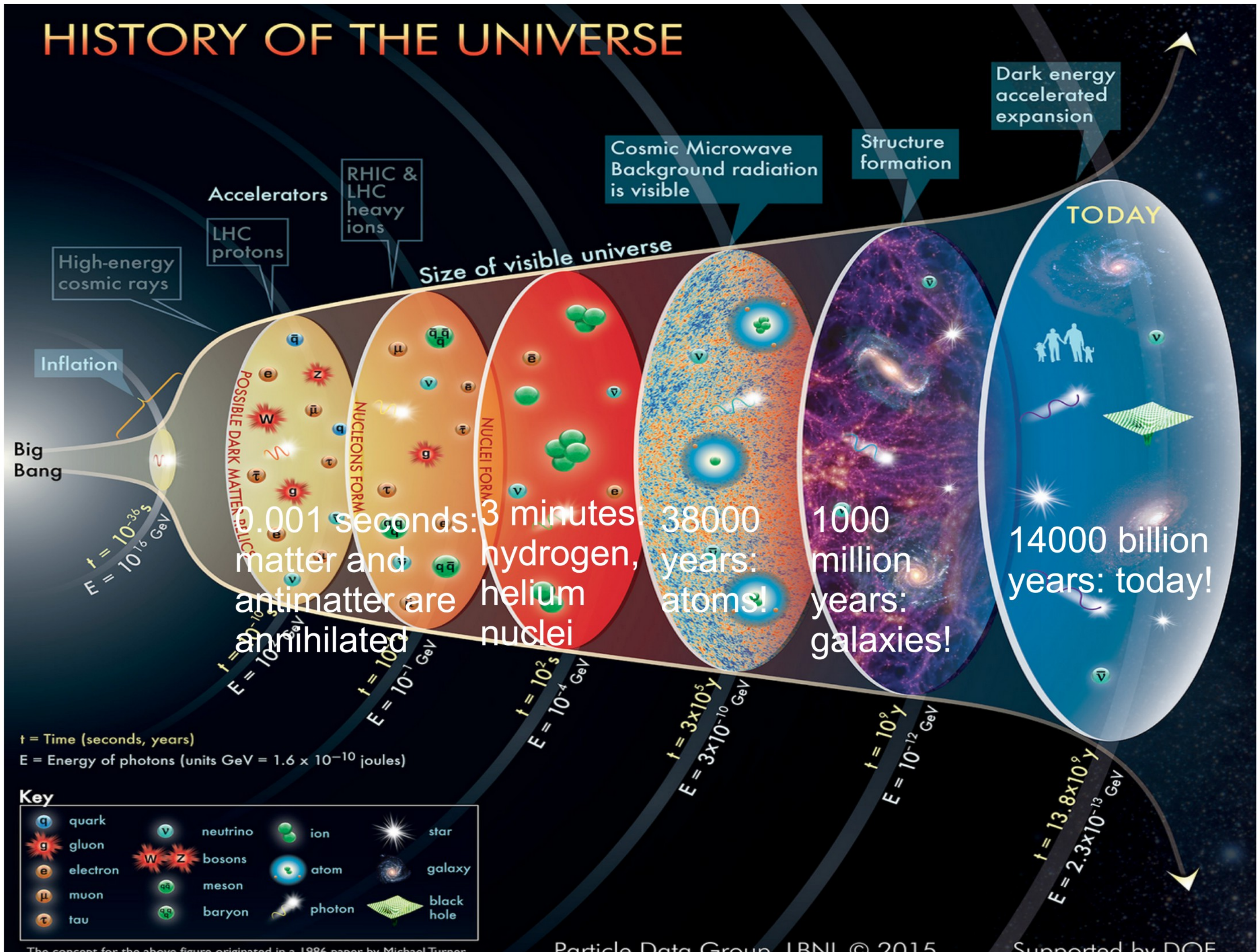


ATLAS EXPERIMENT

cnrs dépasser les frontières IN2P3 Les deux infinis

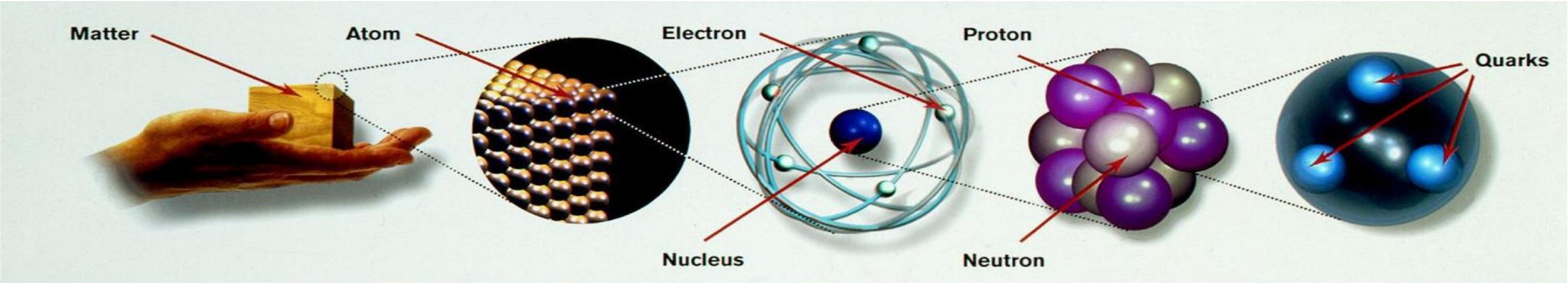
The history of the universe through particle physics

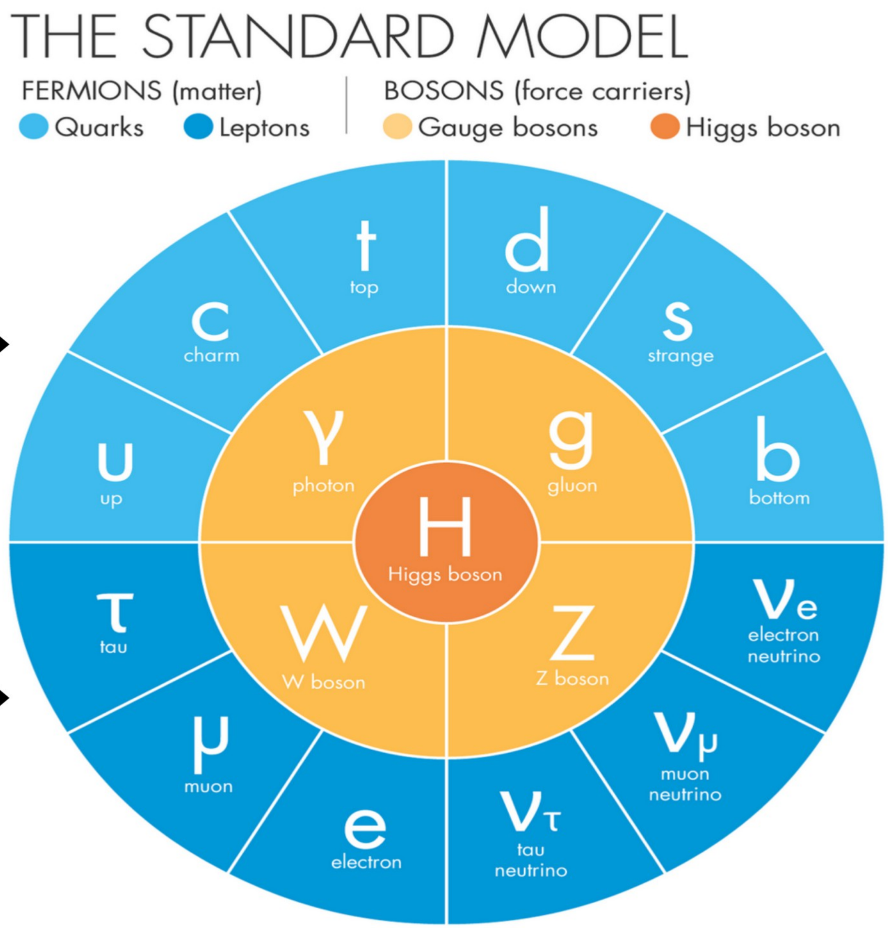
It is the key to solving fundamental questions: What is the physics that governs our universe? Is there a theory that explains all natural phenomena in a fundamental way?



As we go back in the history of the universe it becomes denser and hotter (energy) and the distance scales become smaller

What do we know today about matter?
The standard model, a model to unify everything (or almost everything)





Particles of matter (outer ring)

Particles of forces (inner ring)

** Every fundamental particle has a corresponding antiparticle, same mass and opposite electric charge*

What do we know today about matter?
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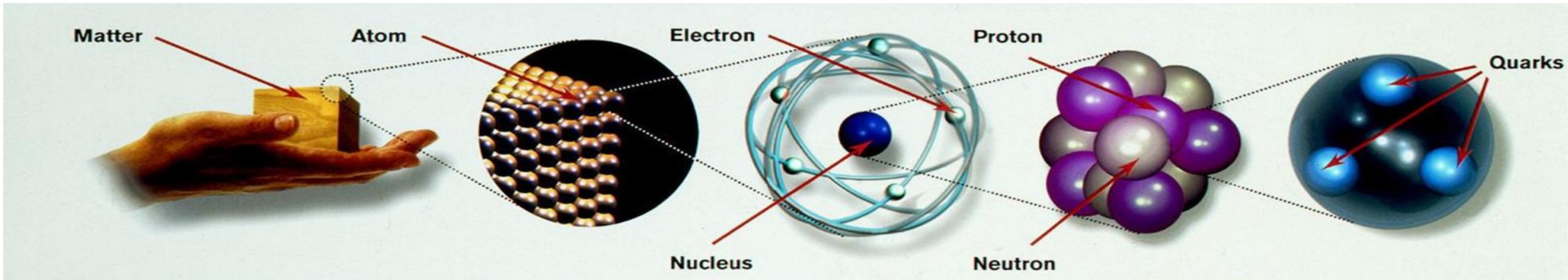
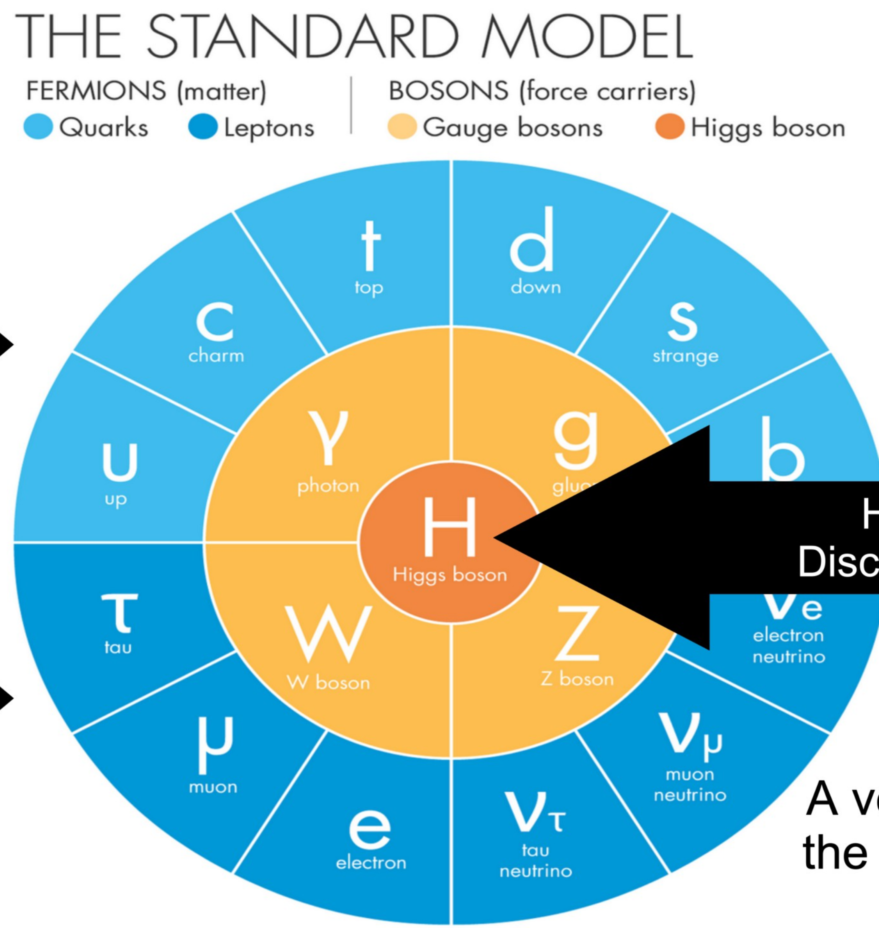




Particles of matter (outer ring)

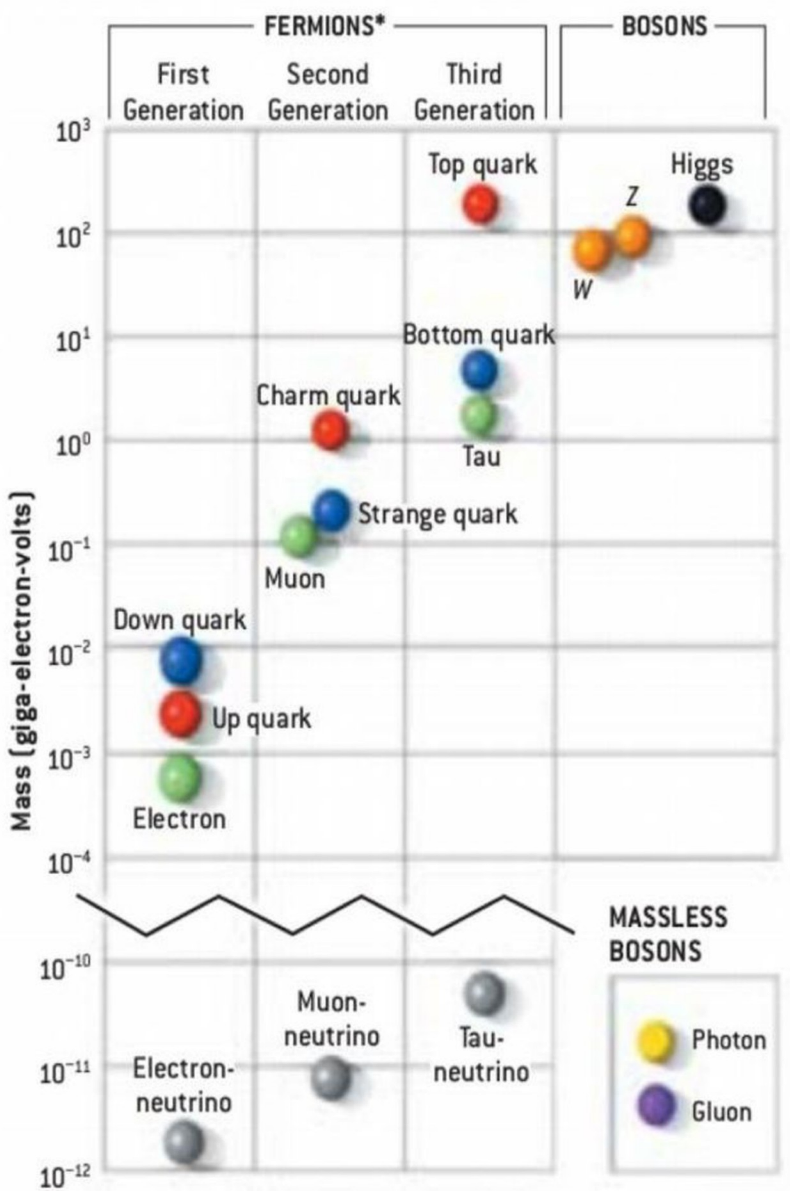
Particles of forces (inner ring)

Higgs boson
Discovered in 2012

A very successful model from the experimental point of view

** Every fundamental particle has a corresponding antiparticle, same mass and opposite electric charge*

The Higgs boson: the origin of particle masses



Explanation proposed by Brout, Englert, Higgs et al., 1964

- "Brout-Englert-Higgs mechanism (BEH)" → origin of masses
- ~ 10^{-11} s after the Big Bang, when Higgs field became active, particles acquired masses proportional to the strength of their interactions with this Higgs field

Consequence: existence of a Higgs boson

- The Higgs boson is the quantum of the new postulated field
- It has been searched for > 30 years at accelerators all over the world
- Finally discovered at the LHC in 2012

The formula of the universe?

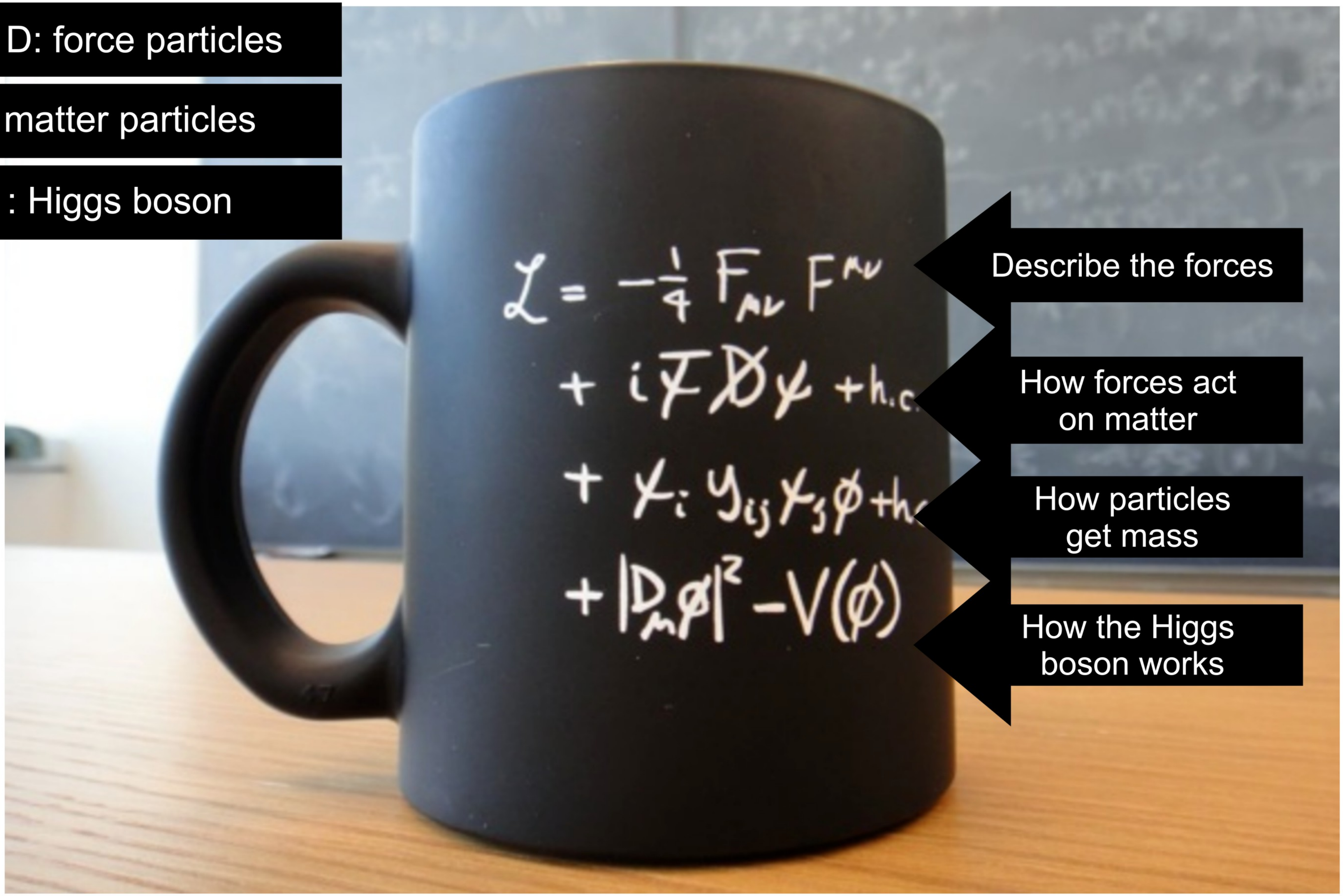
$$\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$
$$M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) -$$
$$igs_w(\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu -$$
$$W^-_\nu \partial_\nu W^+_\mu)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu -$$
$$Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu (W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 -$$
$$\beta_h\left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h -$$
$$g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) -$$
$$\tfrac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) -$$
$$gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H -$$
$$\tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) +$$
$$\tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) +$$
$$M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- -$$
$$W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) -$$
$$\tfrac{1}{4}g^2W^+_\mu W^-_\mu\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu\left(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-\right) -$$
$$\tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \tfrac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^2s_w^2A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\,\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial +$$
$$m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_wA_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) +$$
$$\tfrac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) +$$
$$(\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) +$$
$$\tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) +$$
$$\tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa)\right) +$$
$$\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa)\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) -$$
$$\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda\,M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa -$$
$$\tfrac{1}{4}\overline{\bar{\nu}_\lambda\,M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa} + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j)\right) +$$
$$\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j)\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) -$$
$$\tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5d^\lambda_j) + \bar{G}^a\partial^2G^a + g_sf^{abc}\partial_\mu\bar{G}^aG^bg^c_\mu +$$
$$\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- -$$
$$\partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 -$$
$$\partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ -$$
$$\partial_\mu\bar{X}^-X^-) + igs_wA_\mu(\partial_\mu\bar{X}^+X^+ -$$
$$\partial_\mu\bar{X}^-X^-) - \tfrac{1}{2}gM\left(\bar{X}^+X^+H + \bar{X}^-X^-H + \tfrac{1}{c_w^2}\bar{X}^0X^0H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-\right) +$$
$$\tfrac{1}{2c_w}igM\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + igMs_w\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) +$$
$$\tfrac{1}{2}igM\left(\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0\right).$$

The formula of the universe?

F or D: force particles

ψ : matter particles

ϕ : Higgs boson



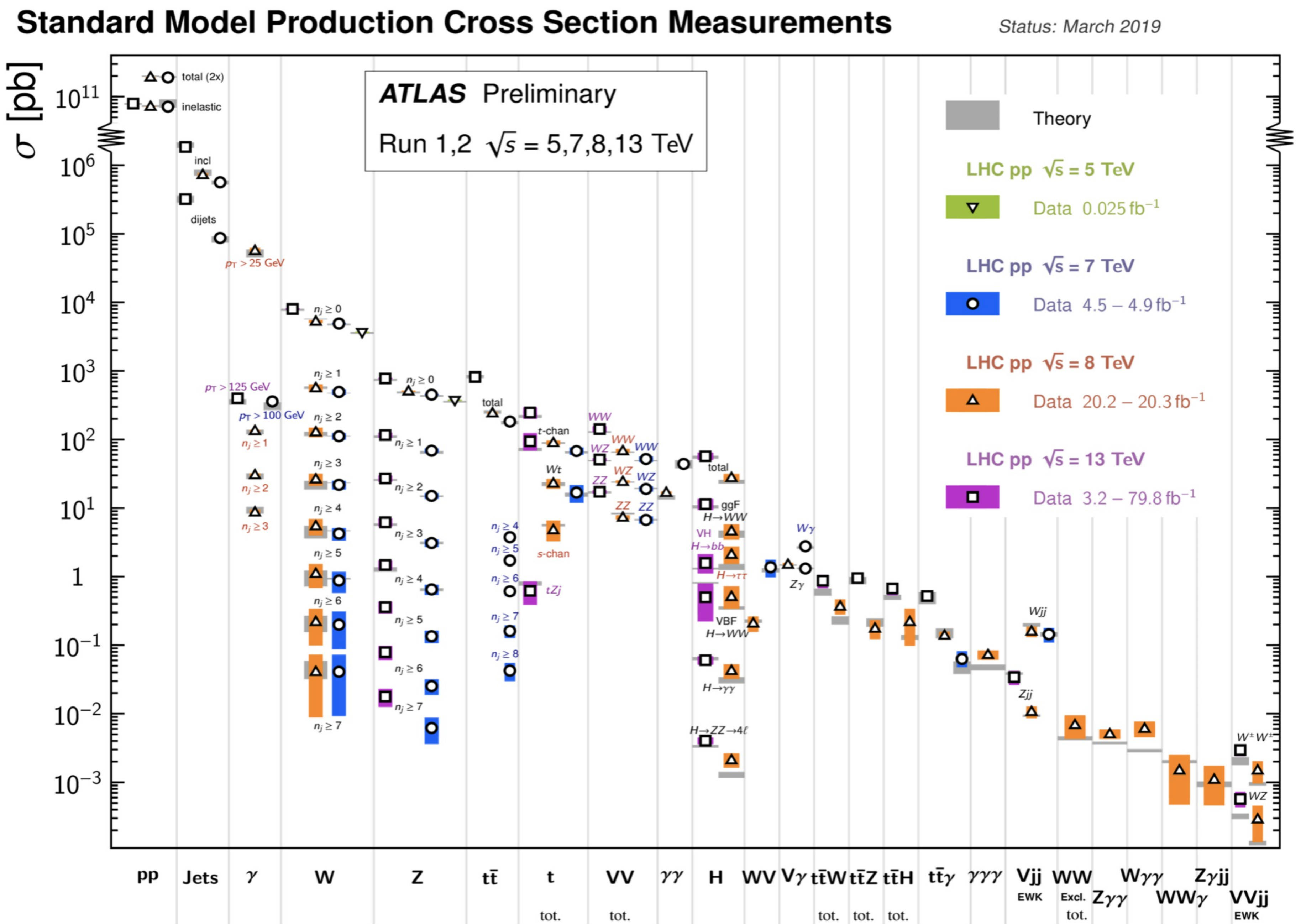
Describe the forces

How forces act on matter

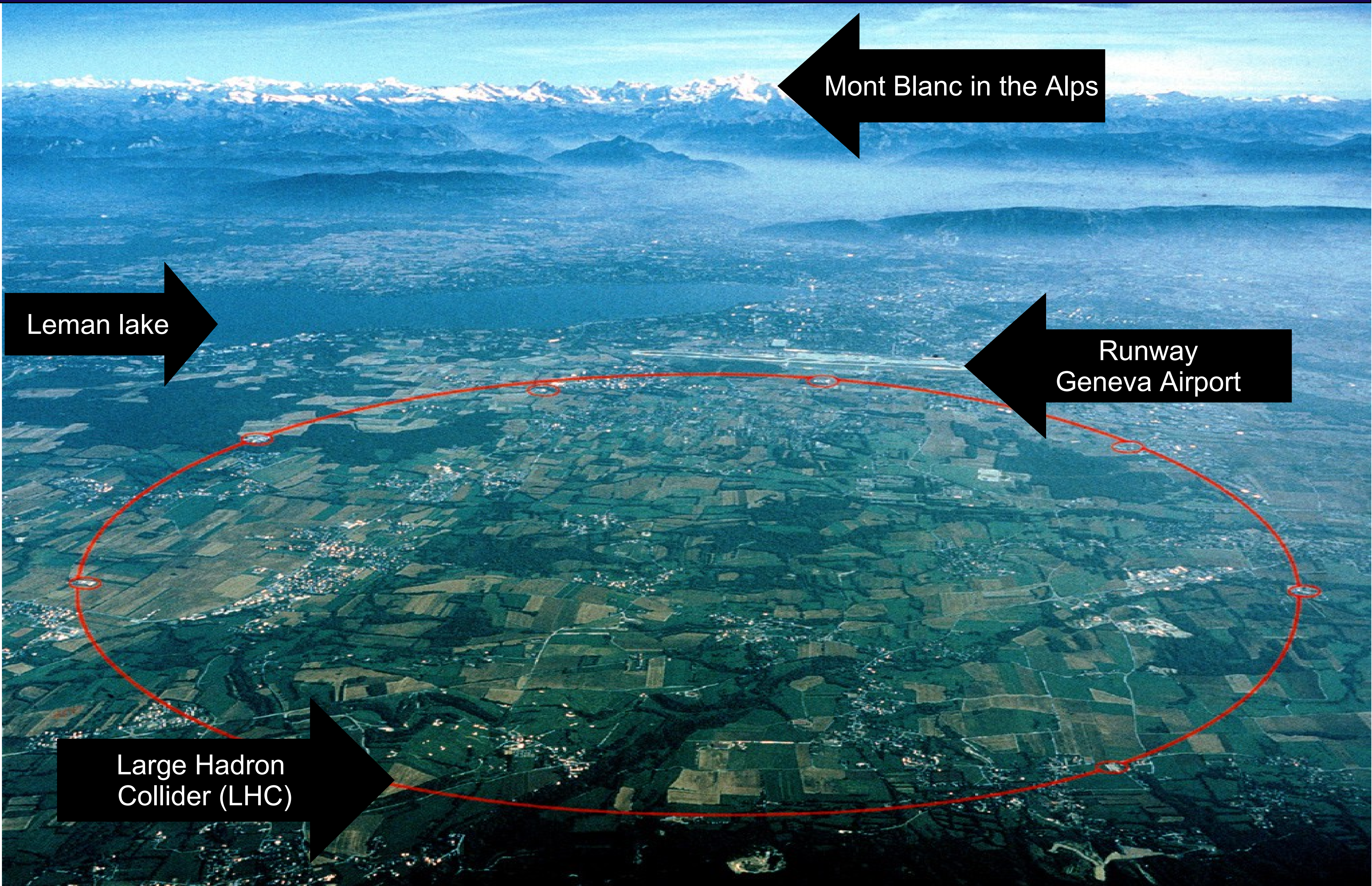
How particles get mass

How the Higgs boson works

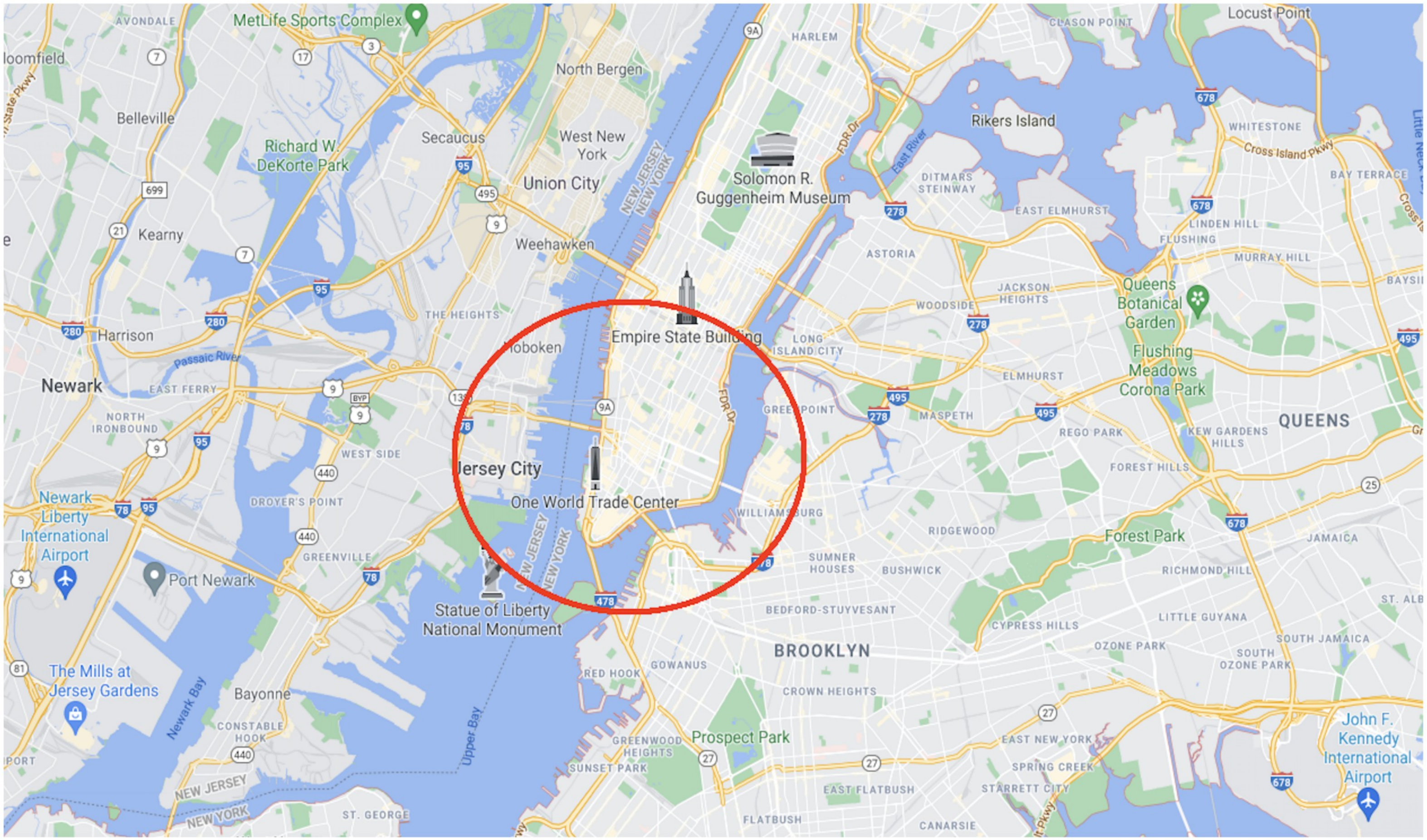
A very successful model



An example in our tool box



The Large Hadron Collider (LHC)

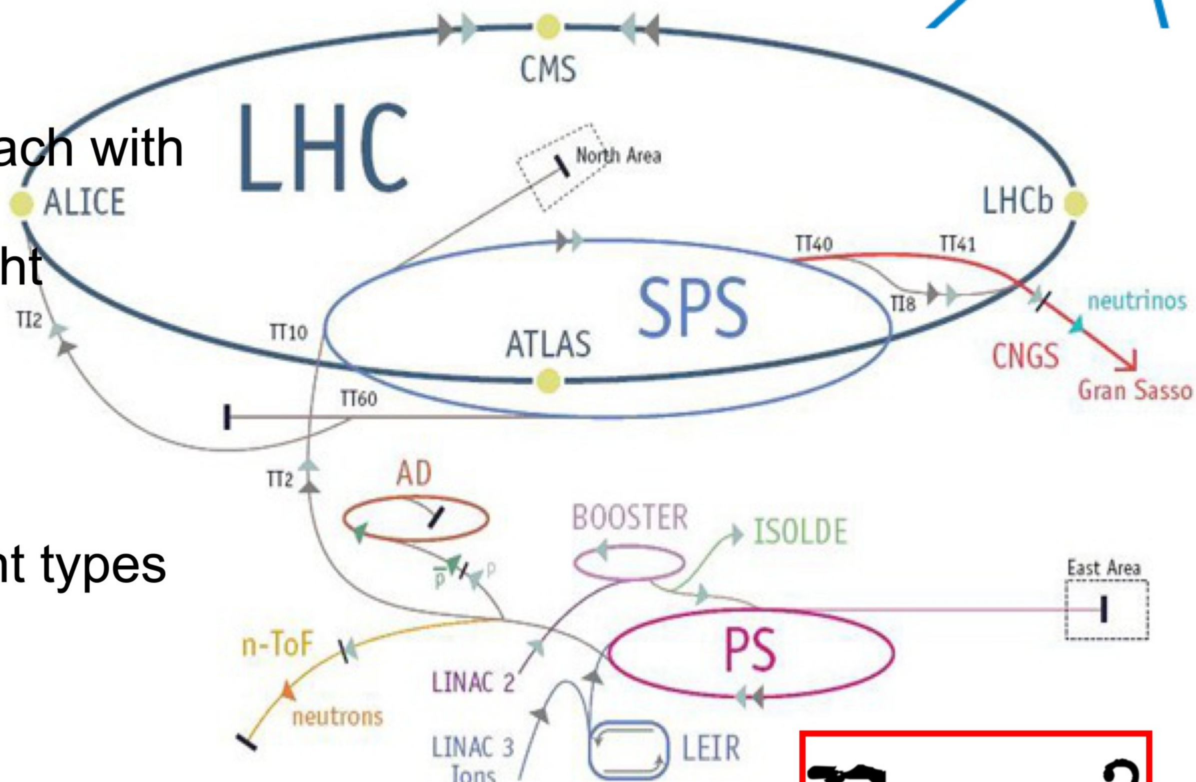


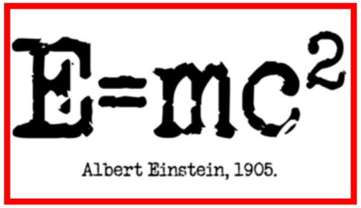
Exploring the small scales:

- **Resolving structures:** Use particle beam like light in a microscope. Need very short wavelength, i.e. particles at very high energies $E = hc/\lambda$
- **Creating new particles:** collide particles with ‘available’ collision energy corresponding to at least the rest mass of the new particle $E = mc^2$

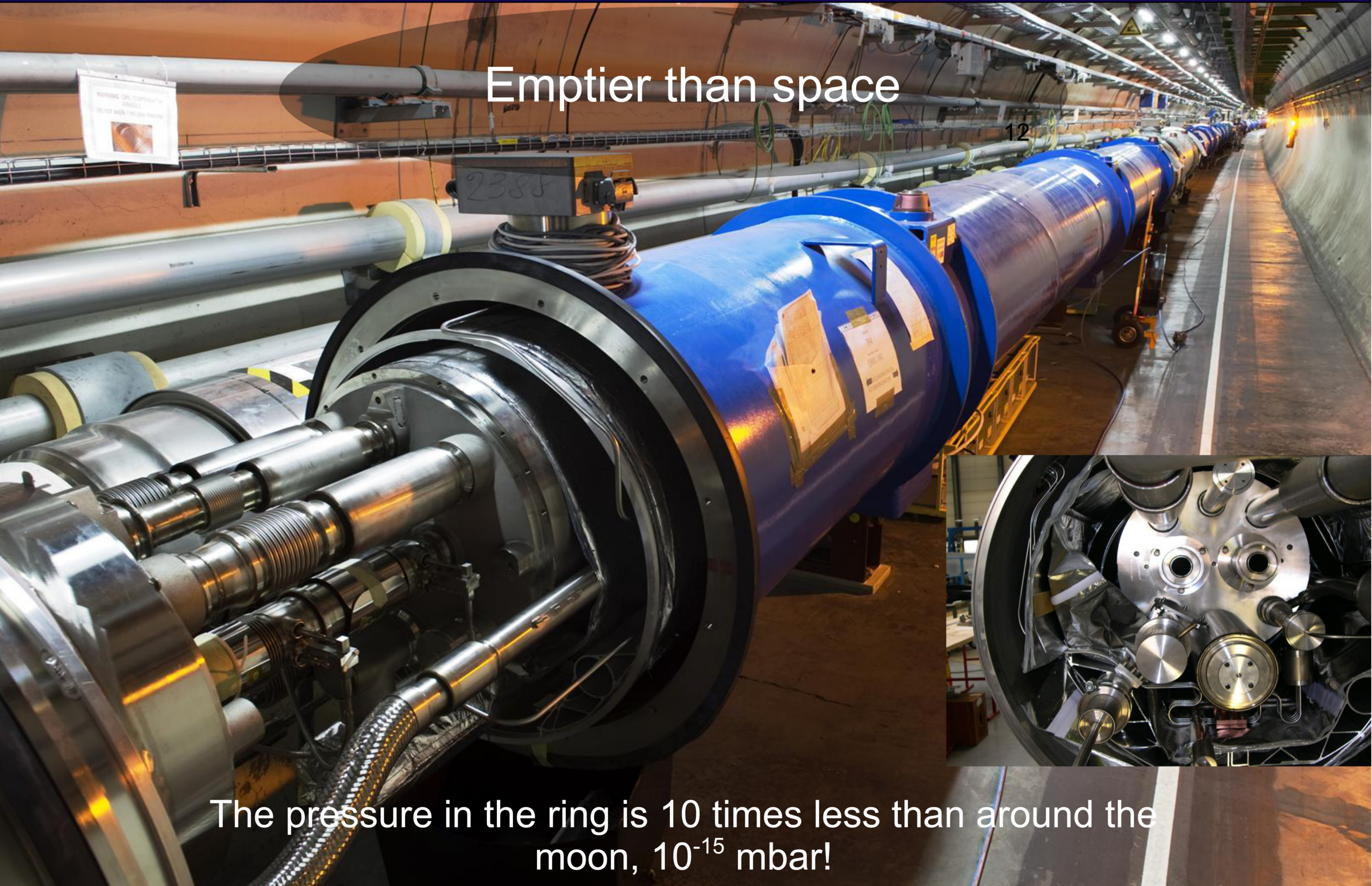
The Large Hadron Collider (LHC)

- Located on the French-Swiss border at CERN
- Higher energy than any other particle collider (protons)
- Millions of millions of protons , each with the energy of a mosquito at 99.9999991% of the speed of light circulate the 27km ring 11 000 times/second
- Driven inside the accelerator by thousands of magnets of different types and sizes
- 600 million collisions per second
- 4 high precision detectors built to record data: ATLAS, CMS, LHCb and ALICE





The last stage/ring : the LHC



Emptier than space

The pressure in the ring is 10 times less than around the moon, 10^{-15} mbar!

The last stage/ring : the LHC

Cooler than space

LHC 1.9 degrees above absolute zero = - 271 C
Space 2.7 degrees above absolute zero = - 270 C

In order to maintain a temperature suitable for the superconductivity of the magnets and the radio-frequency cavities

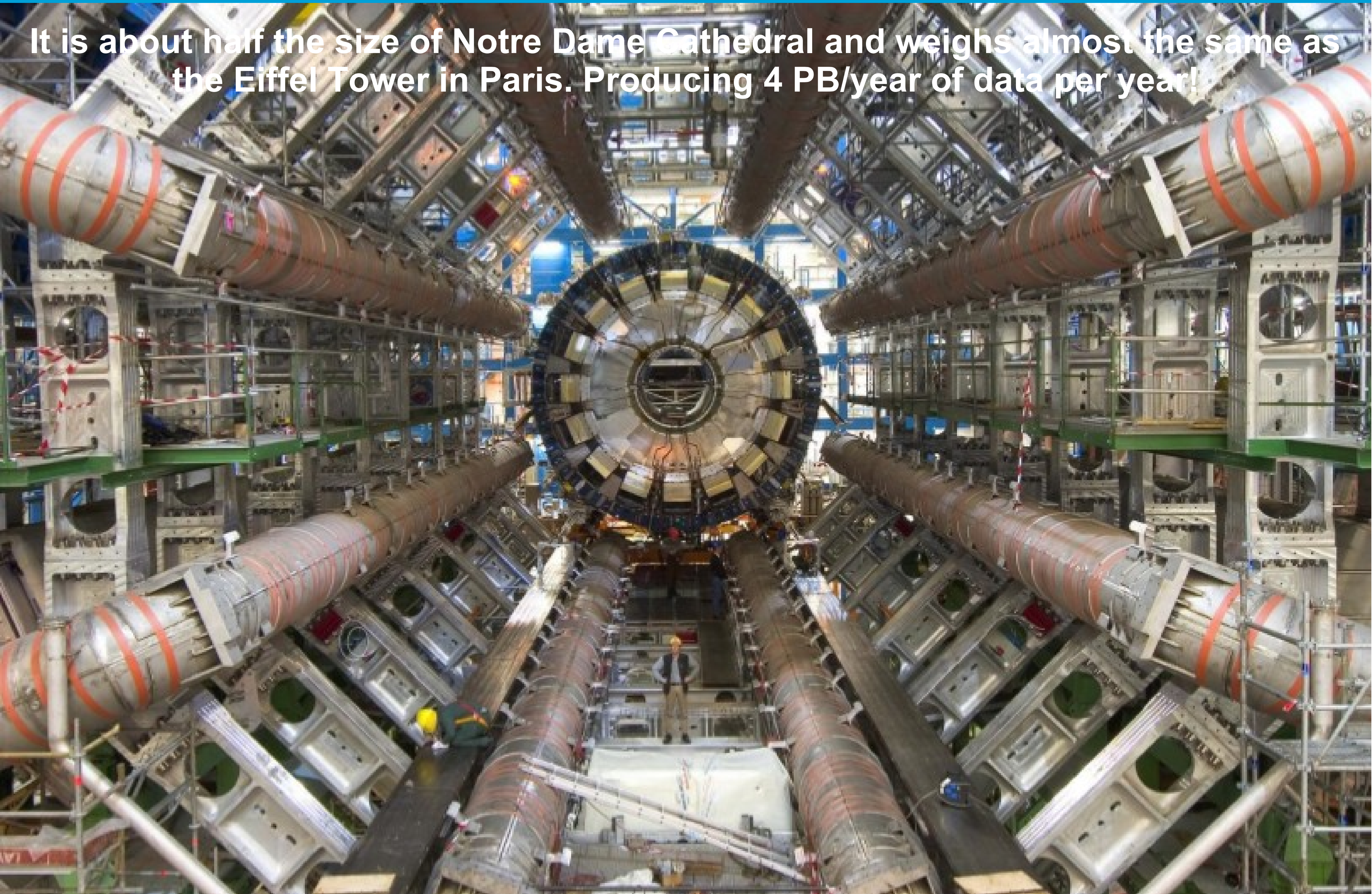
LHC: 4 main detectors

Needs VERY high:

- Precision
- Statistics
- selectivity
- background suppression

An example: ATLAS

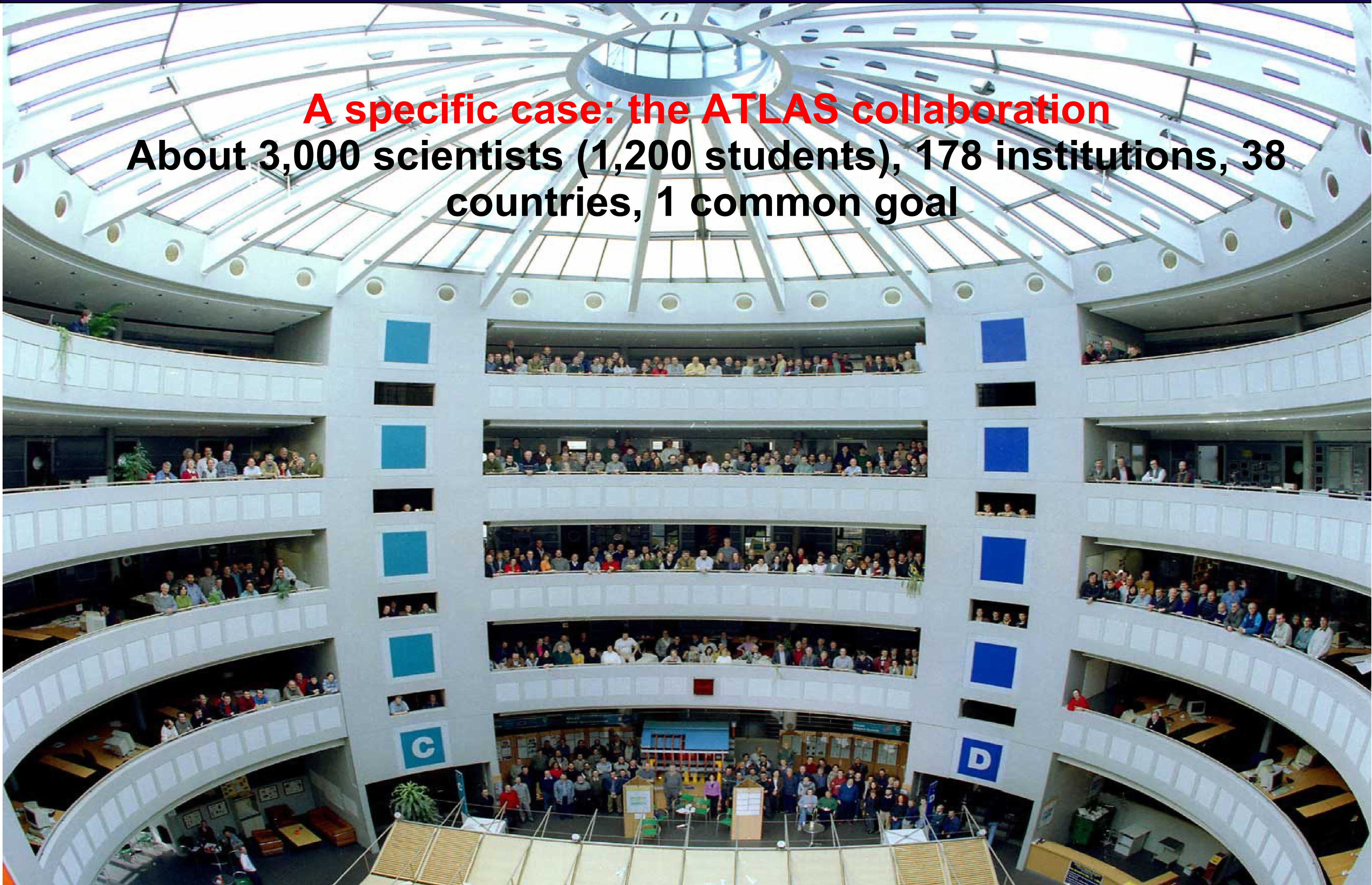
It is about half the size of Notre Dame Cathedral and weighs almost the same as the Eiffel Tower in Paris. Producing 4 PB/year of data per year!



The human part of a particle physics experiment

A specific case: the ATLAS collaboration

About 3,000 scientists (1,200 students), 178 institutions, 38 countries, 1 common goal

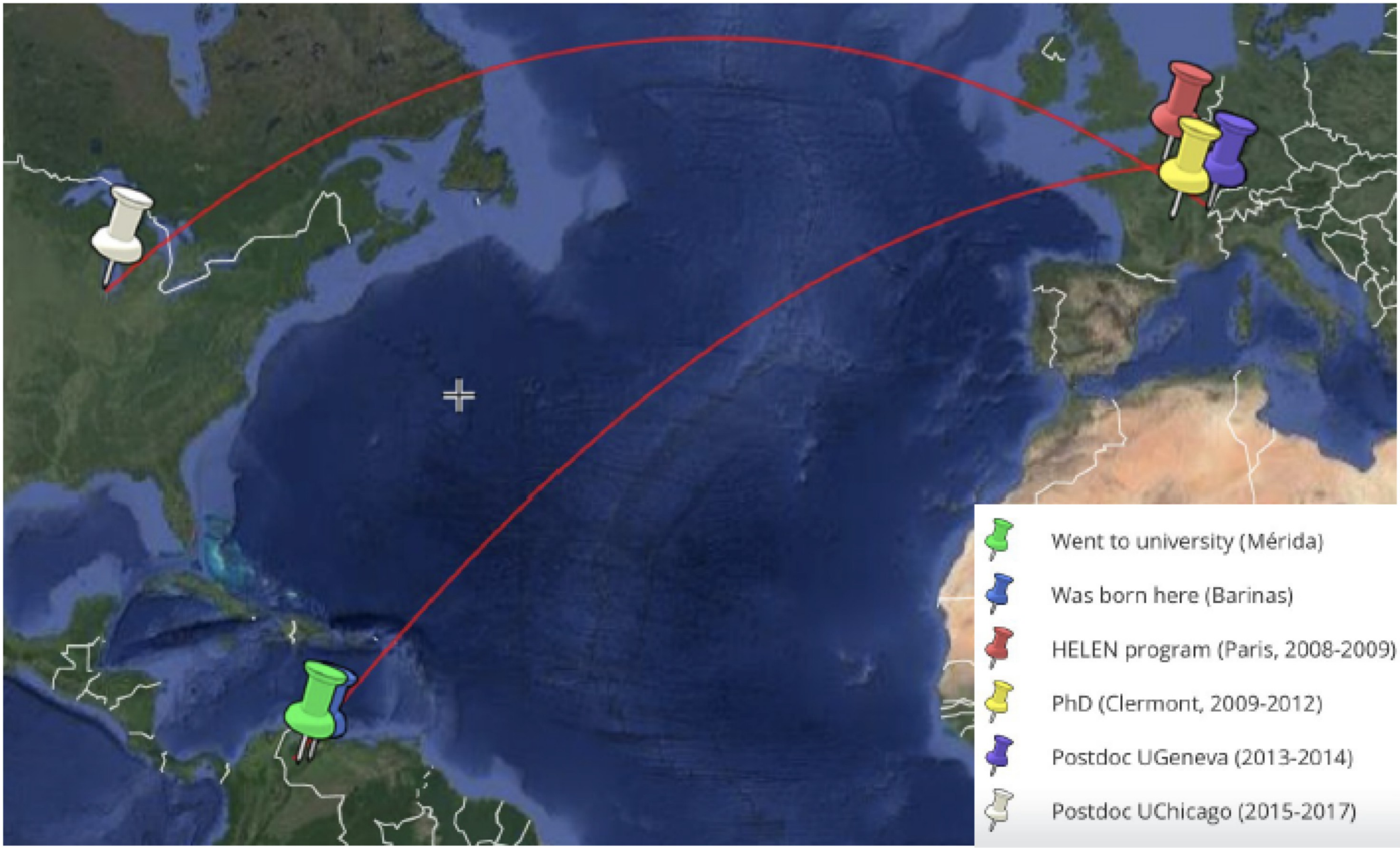


The human part of a particle physics experiment

The human part of a particle physics experiment

**Just another normal day in the ATLAS experiment control room:
Data analysis, detector development, detector operations....**

The human part of a particle physics experiment: One of 3000 stories

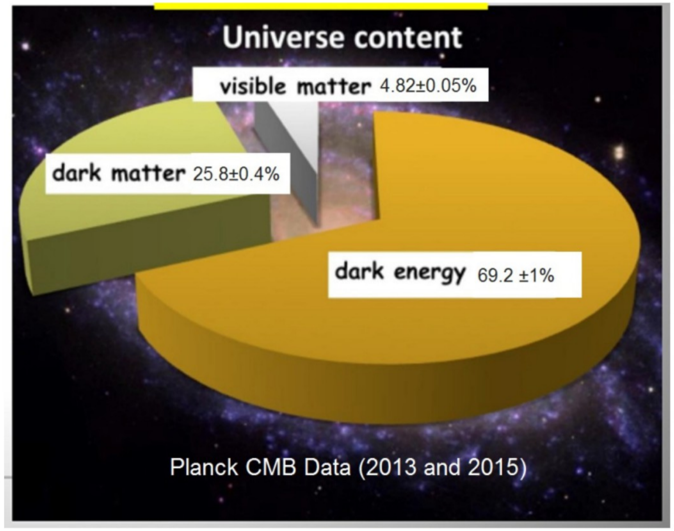


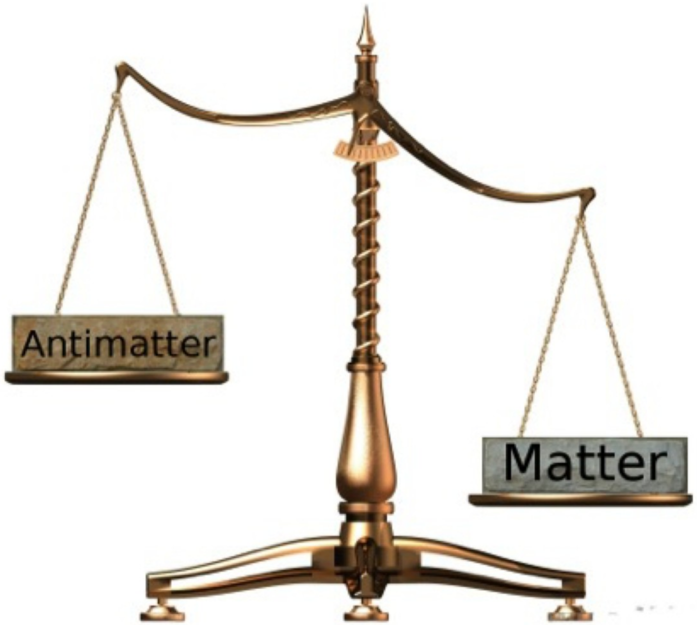
Work as a researcher at the French National Research Center (CNRS) in Paris since 2018

My work: Higgs physics, silicon detector R&D, capacity building Europe-Latin America

But there are still many questions without answers!

- Today:
  - Numerous predictions of the Standard Model have been experimentally verified with high accuracy
- Some unanswered questions:
  - And the gravitation?
  - How to unify all the particle interactions?
  - What is the nature of dark matter and dark energy?
  - The SM does not include enough CP violation to account for the matter-antimatter asymmetry observed in nature
- Is the SM an approximation of a more general theory?
  - Increase our experiment's precision to reach its limits!





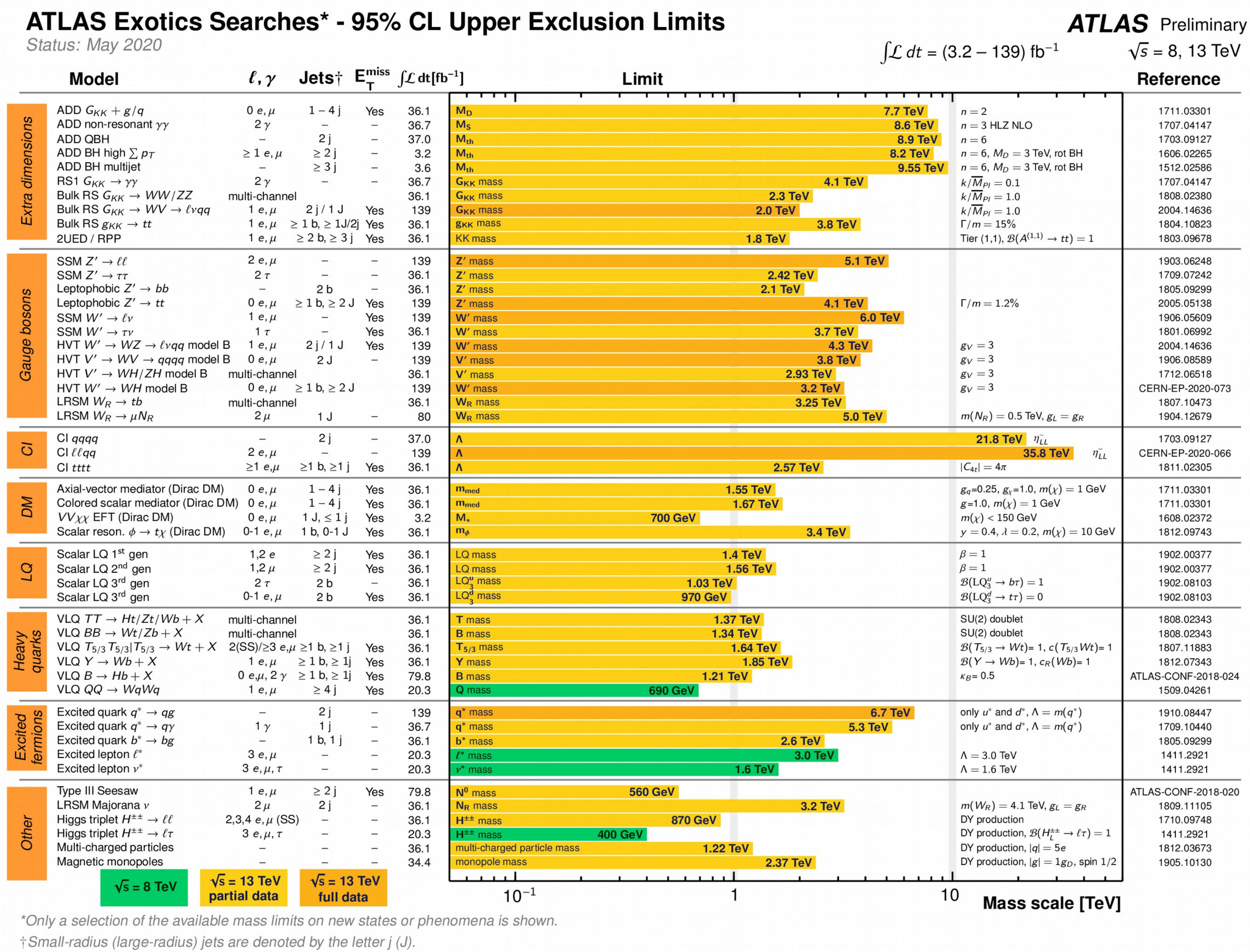
Where are going now?
Particle physicists are explorers

Known friends

Known strangers

Unknown strangers

New physics so far?

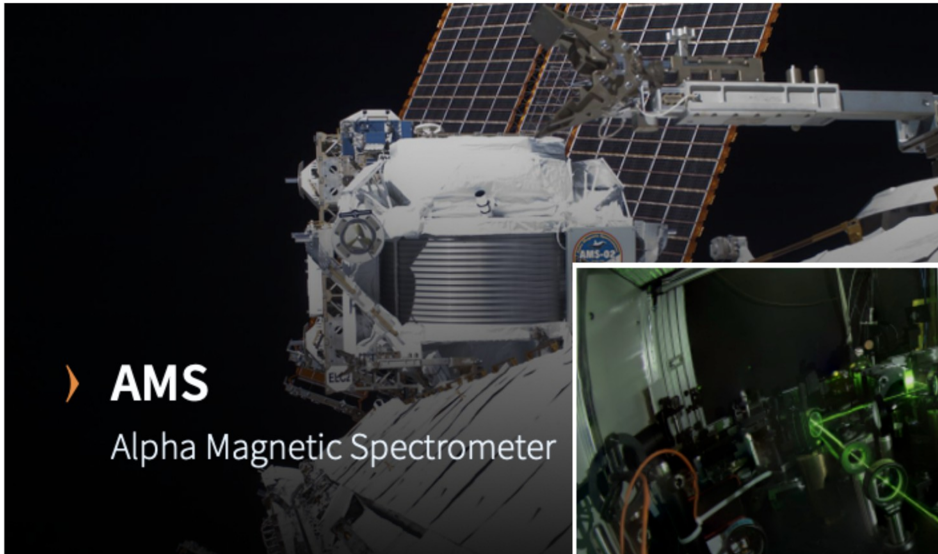


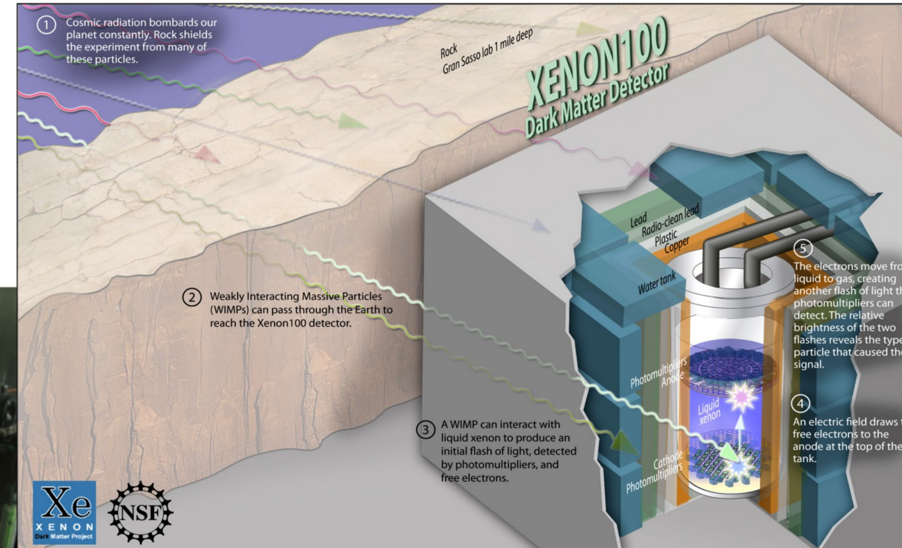
New physics may appear now or after several years of exploration

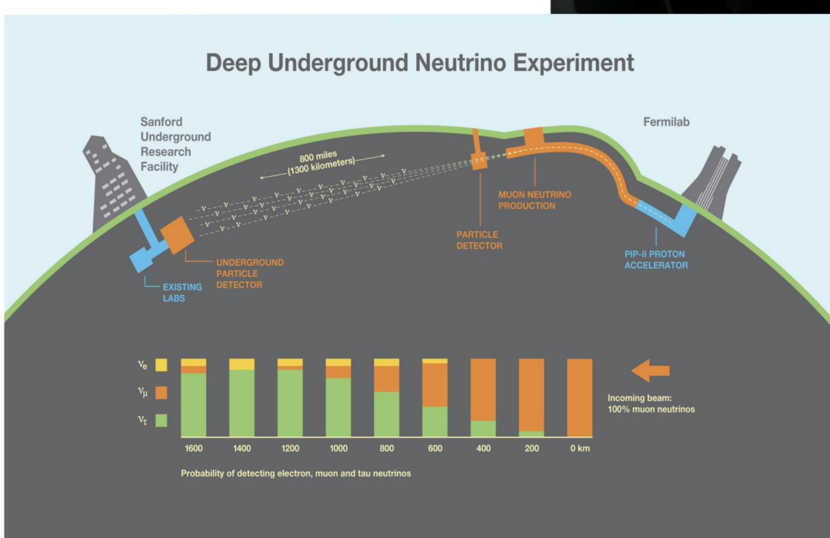
We don't decide where new physics will appear, but we decide to keep exploring:

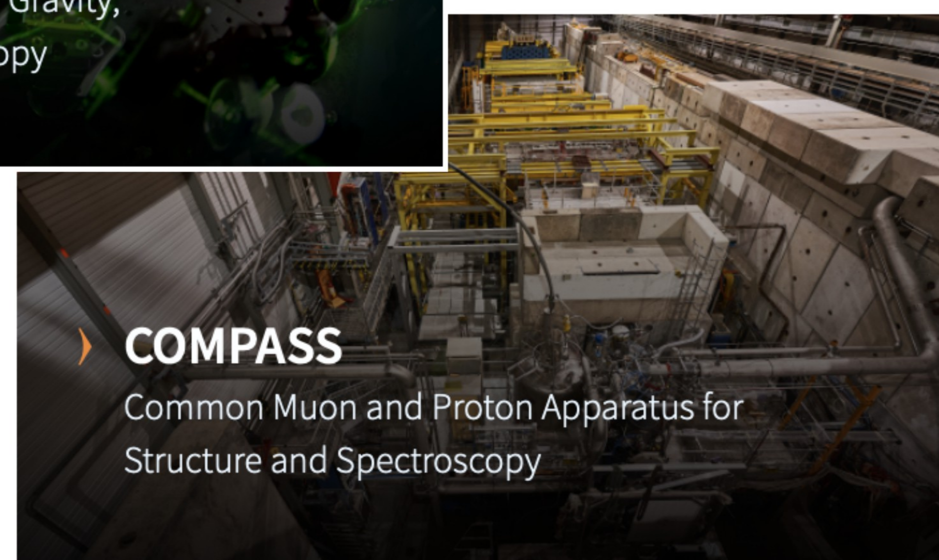
- Improving our data analysis techniques
- Taking advantage of new technologies and/or developing new ones
- Collaborating with other scientific fields and industry
- New eyes, new people, new collaborations

Many more tools in our box







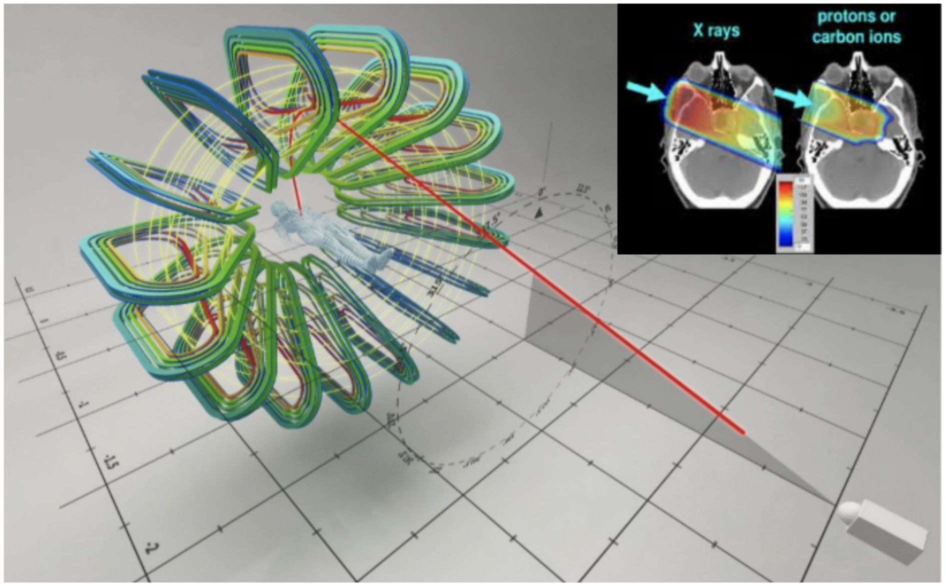


Technology transfer: from particle physics labs to society

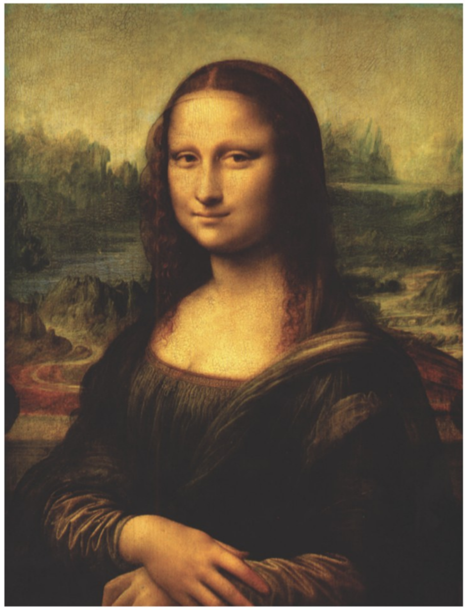
- From Rutherford's experiment: the structure of the atom
- To the most powerful accelerator ever built: the LHC
- All these experiments reveal to us mysteries of nature
- But they also take us to the limit of what we can build, what we can do, measure
- Driving technological developments of high impact

Technology transfer: from particle physics labs to society

- An accelerator can be used to:
  - treat a tumor
  - provide a sustainable and cleaner source of energy
  - burn nuclear waste
  - harden materials for better tyres and more resistant plastic foils
  - implant ions in semi-conductor
  - map proteins
  - design new drugs
  - date archaeological findings
  - ...among others



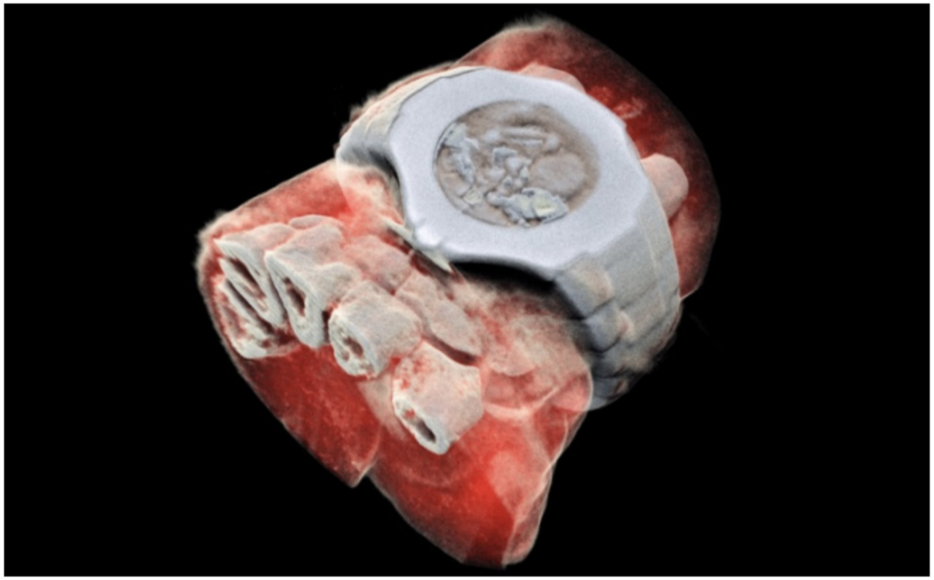
Hadrontherapy: more than 100,000 cancer patients treated worldwide (45 facilities)



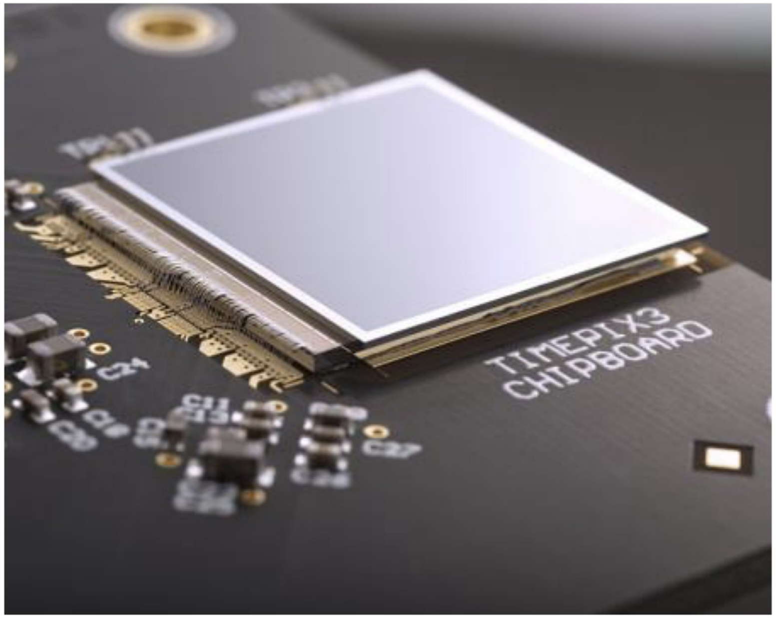
Accelerator Mass Spectroscopy can be used to date paintings and detect fraudulent copies

Technology transfer: from particle physics labs to society

- A particle detector can be used to:
  - visualise the brain activity
  - validate new drugs in preclinical trials
  - confirm the efficacy of cancer treatment
  - spot the location and content of suspicious cargo
  - detect contraband radioactive materials
  - … among others



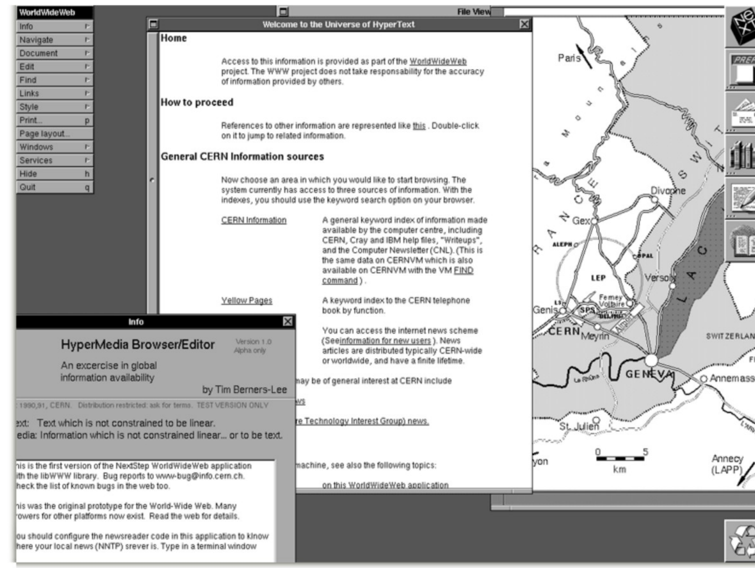
Medical imaging sensors. Image by MARS startup



Dosimetry: Real-time measurement of radiation exposure

Technology transfer: from particle physics labs to society

- Information technology developed for particle physics can be used to:
  - for financial and investment forecasting
  - to provide seamless platforms for e-commerce, e-health and e-administration
  - to separate bio-molecules
  - to monitor and analyse climate change
  - In particular through the use of the Grid computing applications
  - … among others



In 1989 Tim Beners-Lee invented the WWW. Sharing information between researchers and universities

European Grid Infrastructure provide access to high-throughput computing resources across Europe using grid computing techniques

Technology transfer: from particle physics labs to society

- Capacity building
- Education & training
- An unique way of thinking, to approach and solve problems
- Invaluable inside and outside of academia

CERN summer student program

Fermilab education high schools tours

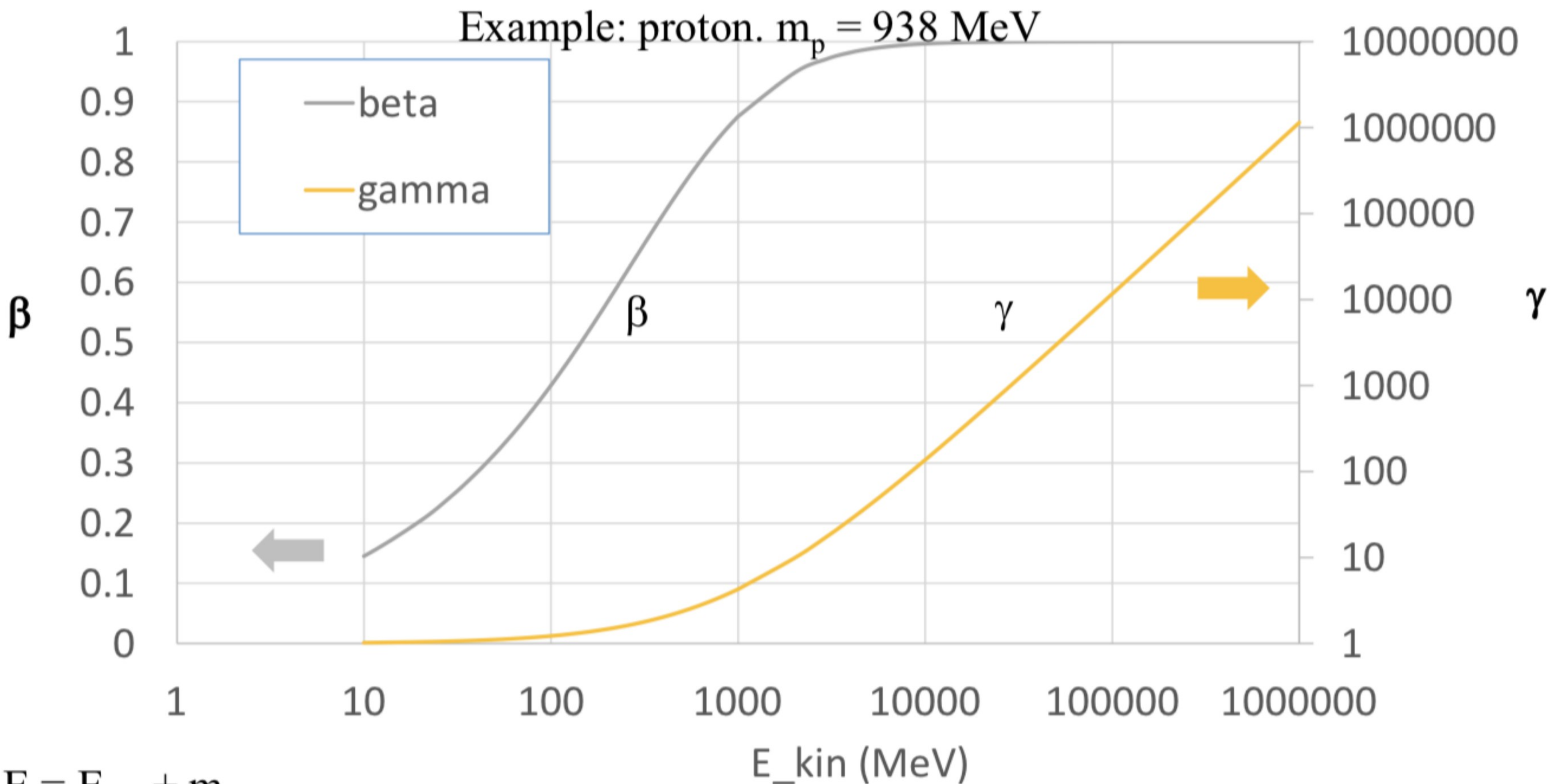
One of the events of the ATLAS Early Career Scientist Board

Thanks!

¡Gracias!

Backup

Relativistic kinematics



$E = E_{kin} + m_0$

$E^2 = p^2c^2 + m_0{}^2c^4$

$E = mc^2 = m_0\gamma c^2$

$\beta = v/c = pc/E$

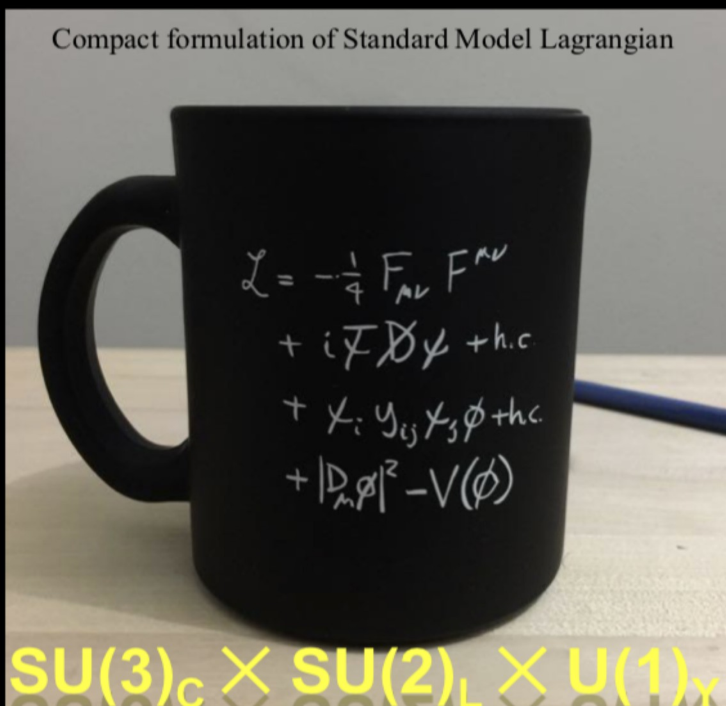
$\gamma = 1/(1-\beta^2)$

$\gamma = m/m_0$

Energy accelerates particles <u>towards</u> speed of light (v=c, $\beta = 1$) and increases their relativistic mass!

The Standard Model

The Standard Model is much more than an order scheme for elementary particles. It's the theory of <u>almost</u> everything.



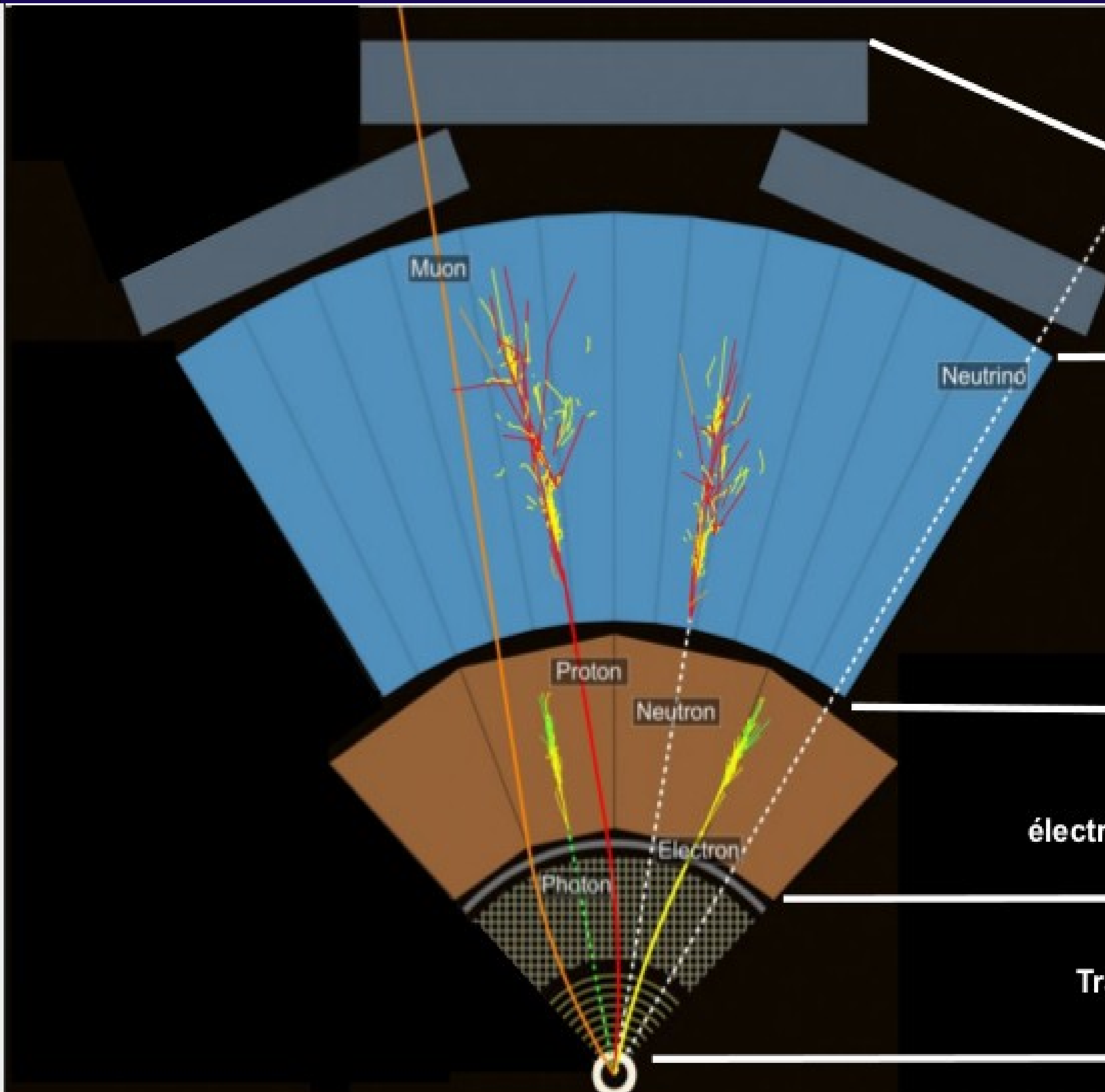
Compact formulation of Standard Model Lagrangian

Unfortunately it has ~20 free parameters which need to be measured.

Neutrinos remain massless!

Parameters of the Standard Model [hide]			
Symbol	**Description**	**Renormalization scheme (point)**	**Value**
m_e	Electron mass		511 keV
m_μ	Muon mass		105.7 MeV
m_τ	Tau mass		1.78 GeV
m_u	Up quark mass	$\mu_{\overline{MS}}$ = 2 GeV	1.9 MeV
m_d	Down quark mass	$\mu_{\overline{MS}}$ = 2 GeV	4.4 MeV
m_s	Strange quark mass	$\mu_{\overline{MS}}$ = 2 GeV	87 MeV
m_c	Charm quark mass	$\mu_{\overline{MS}} = m_c$	1.32 GeV
m_b	Bottom quark mass	$\mu_{\overline{MS}} = m_b$	4.24 GeV
m_t	Top quark mass	On-shell scheme	172.7 GeV
θ_{12}	CKM 12-mixing angle		13.1°
θ_{23}	CKM 23-mixing angle		2.4°
θ_{13}	CKM 13-mixing angle		0.2°
δ	CKM CP-violating Phase		0.995
g_1 or g'	U(1) gauge coupling	$\mu_{\overline{MS}} = m_Z$	0.357
g_2 or g	SU(2) gauge coupling	$\mu_{\overline{MS}} = m_Z$	0.652
g_3 or g_s	SU(3) gauge coupling	$\mu_{\overline{MS}} = m_Z$	1.221
θ_{QCD}	QCD vacuum angle		~0
v	Higgs vacuum expectation value		246 GeV
m_H	Higgs mass		~ 125 GeV ~~(tentative)~~

Cómo se descubre una partícula?
Tomemos el ejemplo del Higgs



	Particules	Grandeurs mesurées
Spectromètre	muon	impulsion, charge
Calorimètre hadronique	hadrons (protons, neutrons, pions, kaons, etc.)	énergie
Calorimètre électromagnétique	e-, e+, photons	énergie
Trajectographe	particules chargées	impulsion, charge

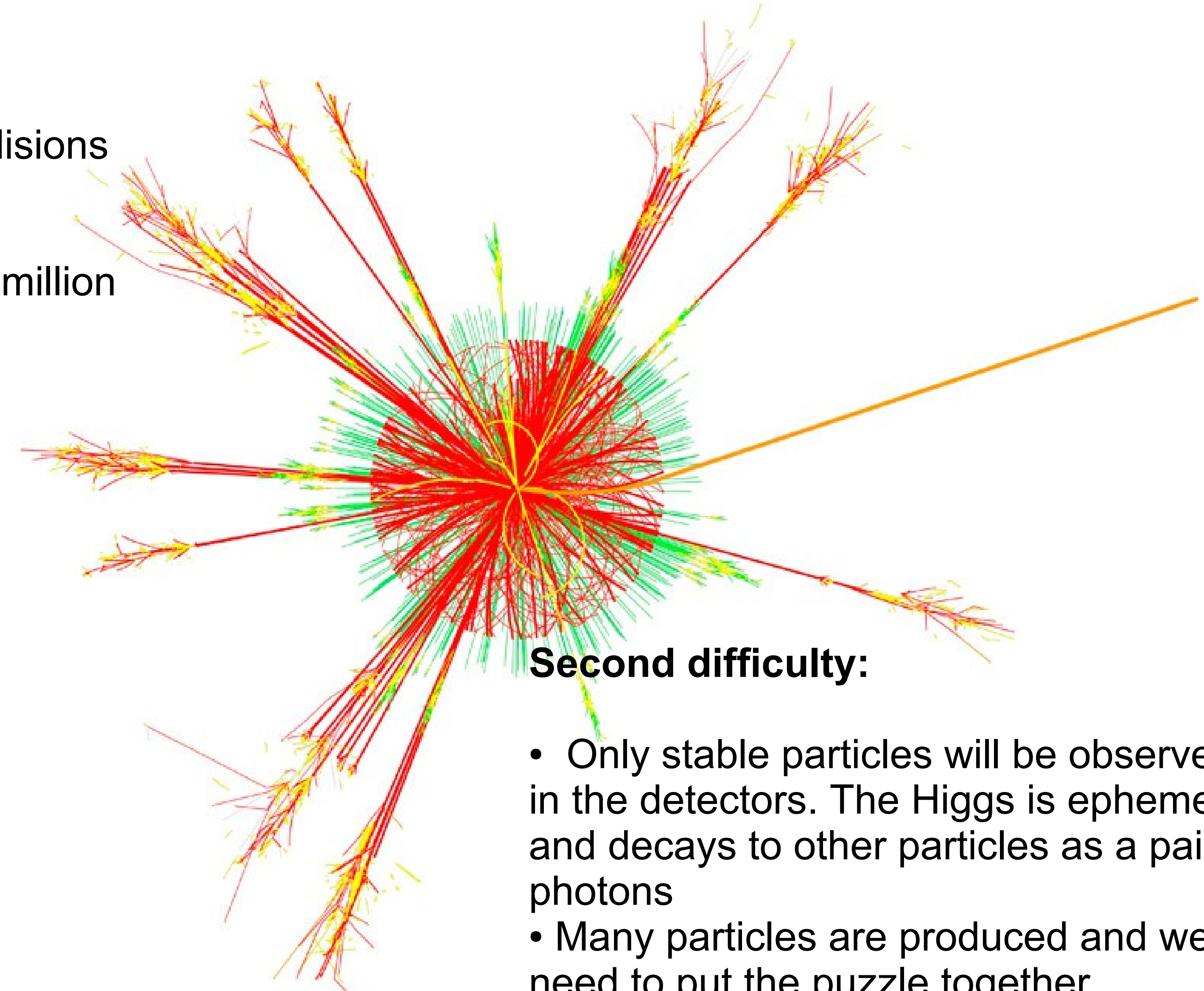
How do we discover a new particle?

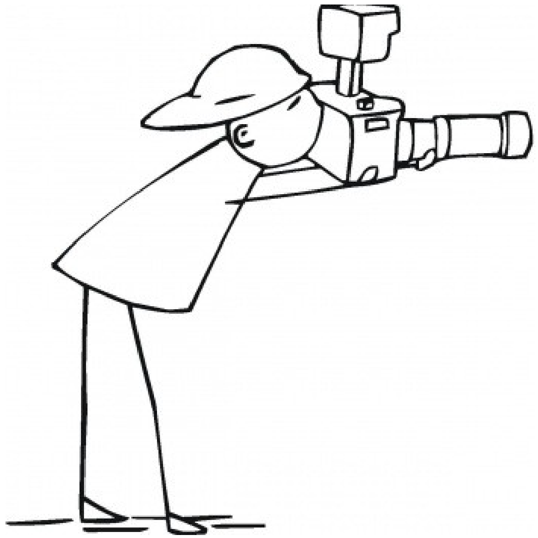
We need to produce the Higgs and then we need to be able to detect/identify it!

First difficulty:

• We would need 10^{14} collisions to observe one Higgs

• The LHC produces 600 million collisions per second



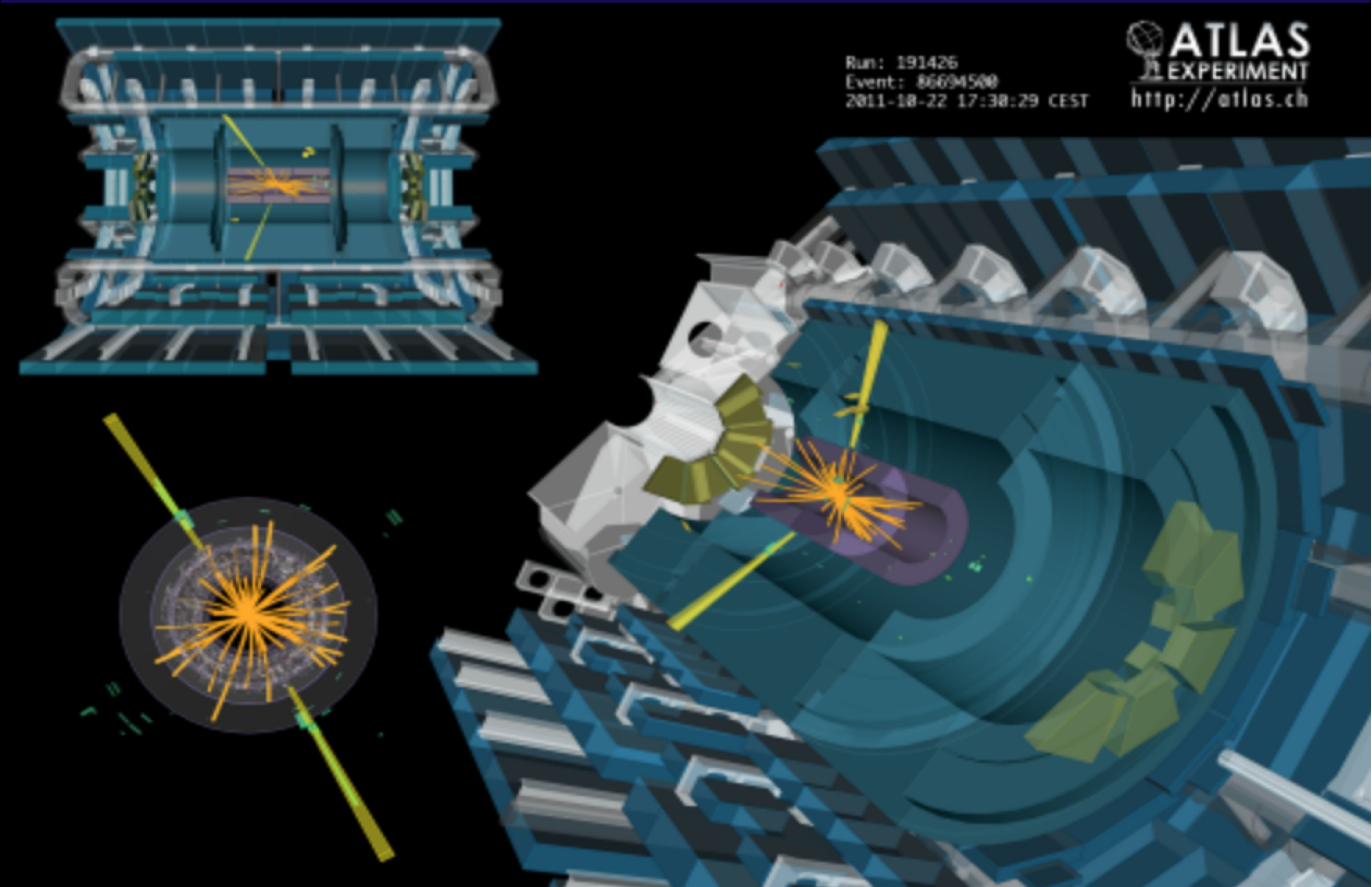


Second difficulty:

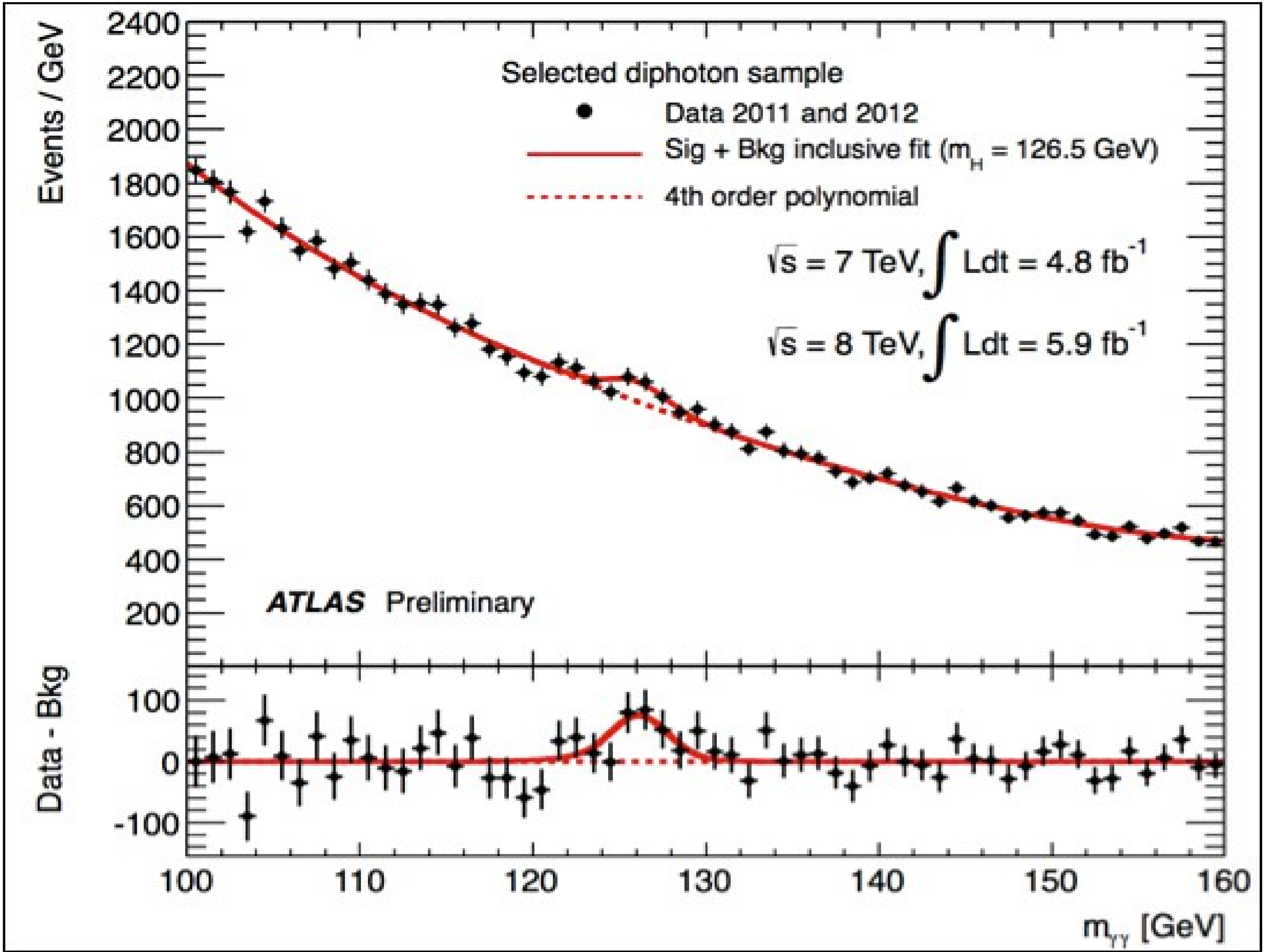
• Only stable particles will be observed in the detectors. The Higgs is ephemeral and decays to other particles as a pair of photons

• Many particles are produced and we need to put the puzzle together

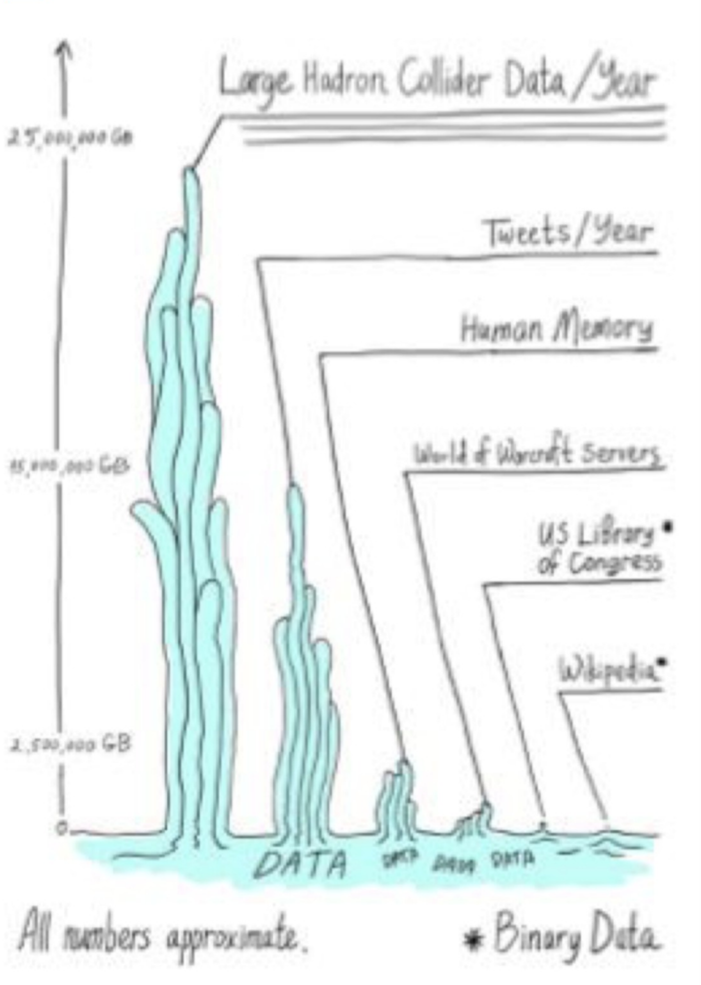
How do we discover a new particle?
The Higgs boson as an example

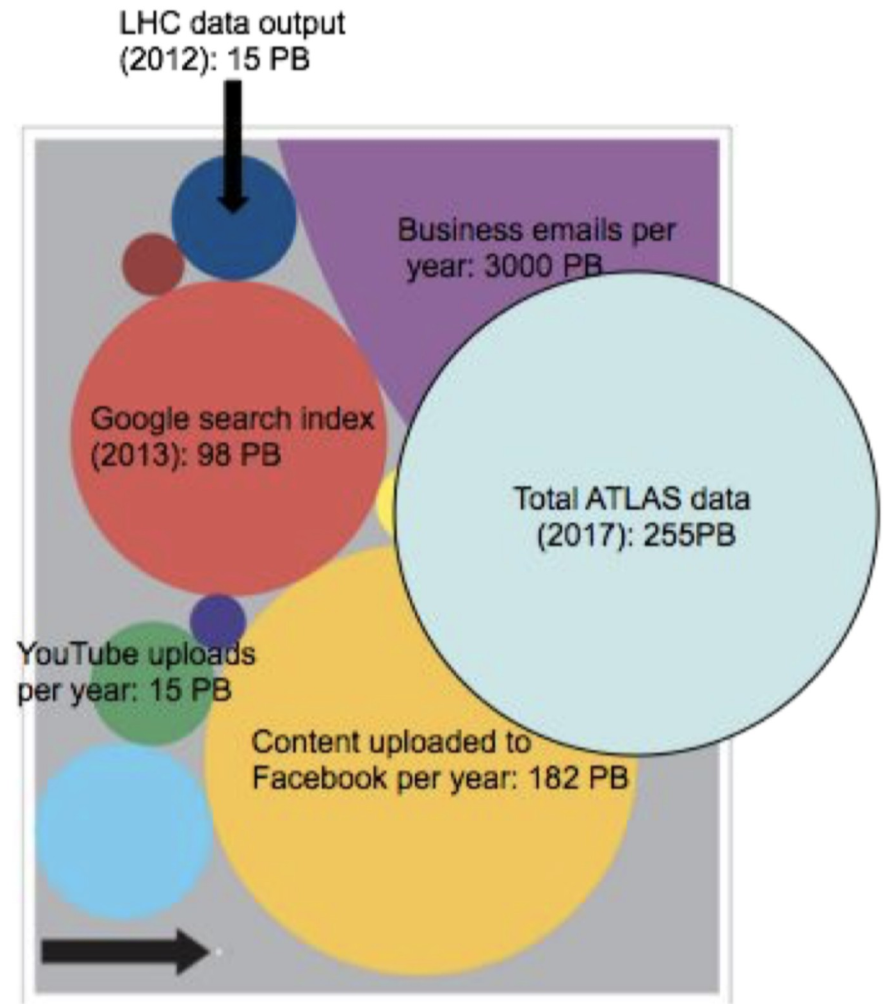


How do we discover a new particle?
The Higgs boson as an example



Big Data ?





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Taken from http://www.symmetrymagazine.org/image/august-2012-big-data

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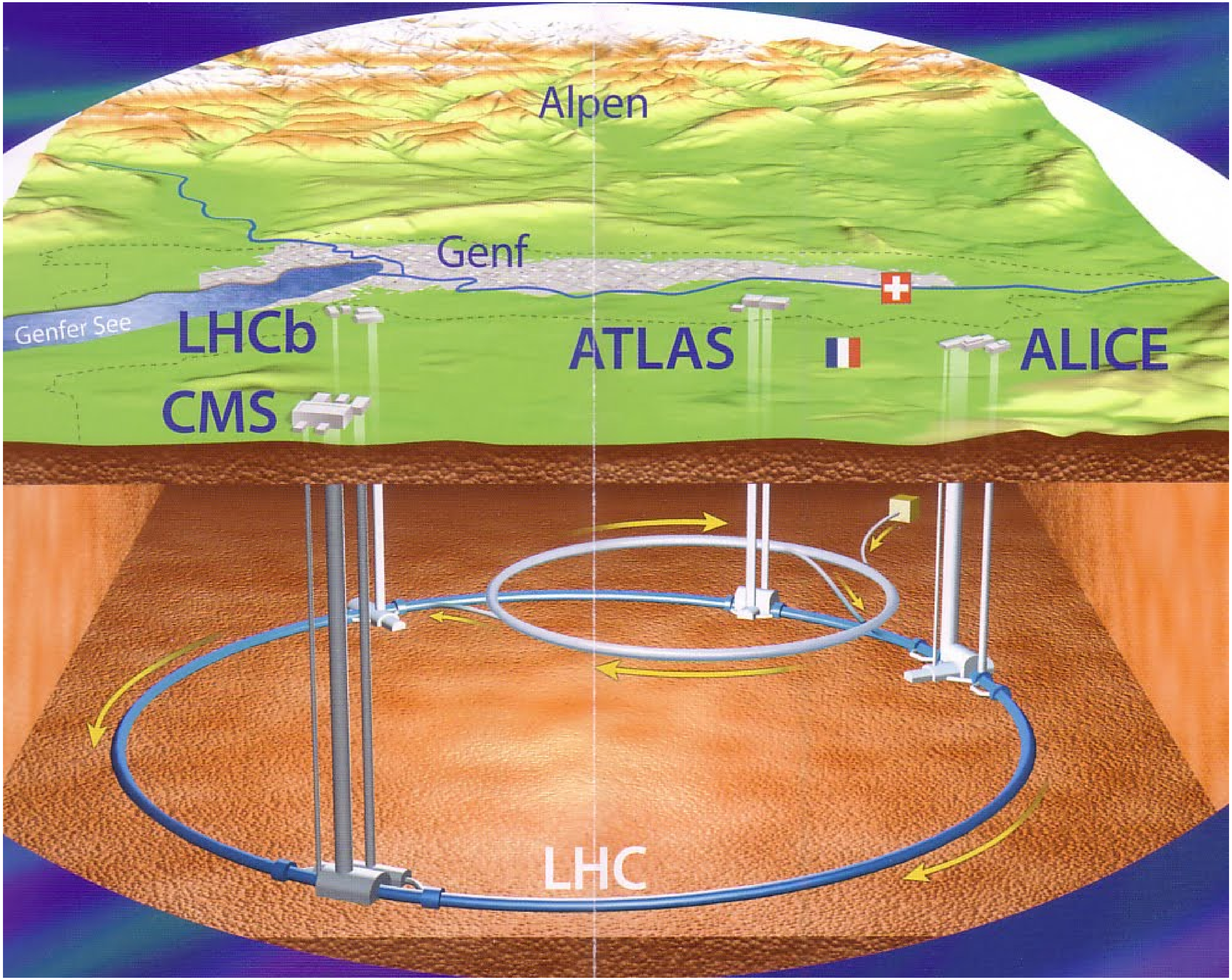
Taken from http://www.wired.com/2013/04/bigdata/

LHC: 4 detectores principales



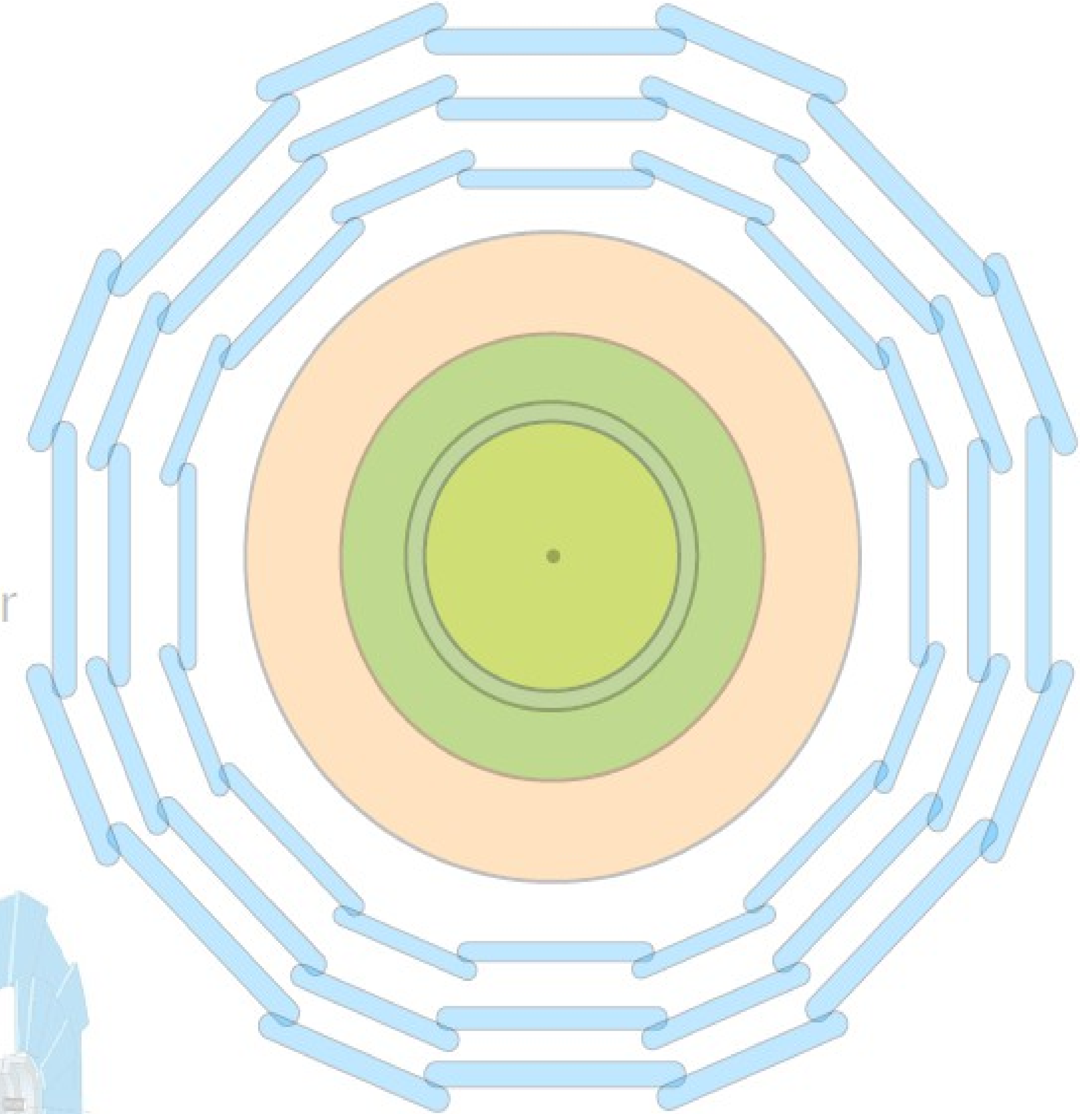
The ATLAS experiment

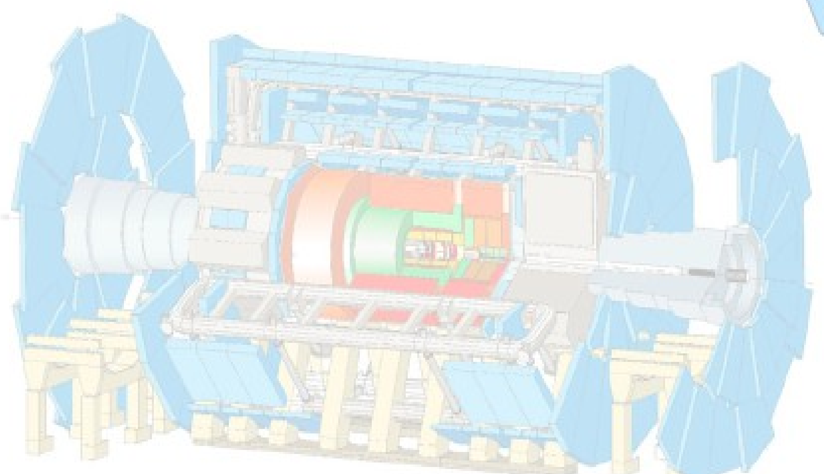
Inner Detector

Electromagnetic calorimeter

Hadronic calorimeter

Muon Spectrometer





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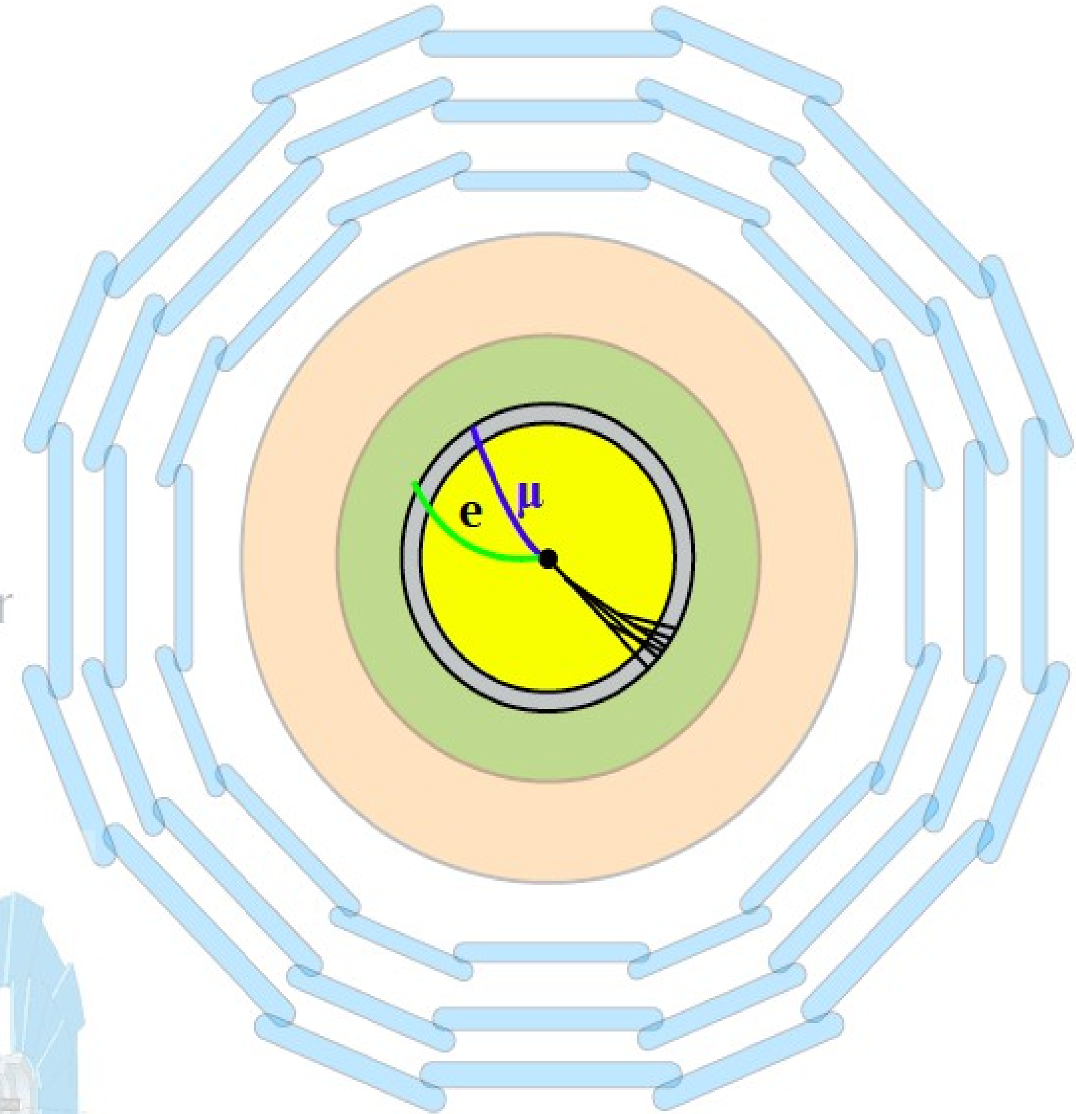

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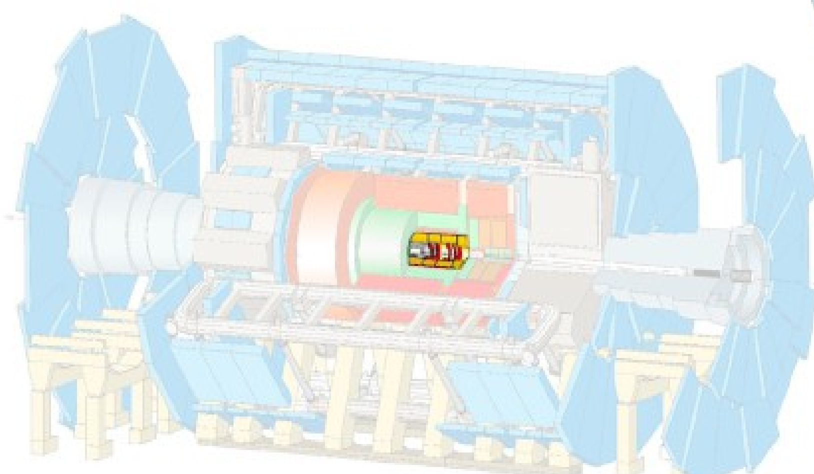

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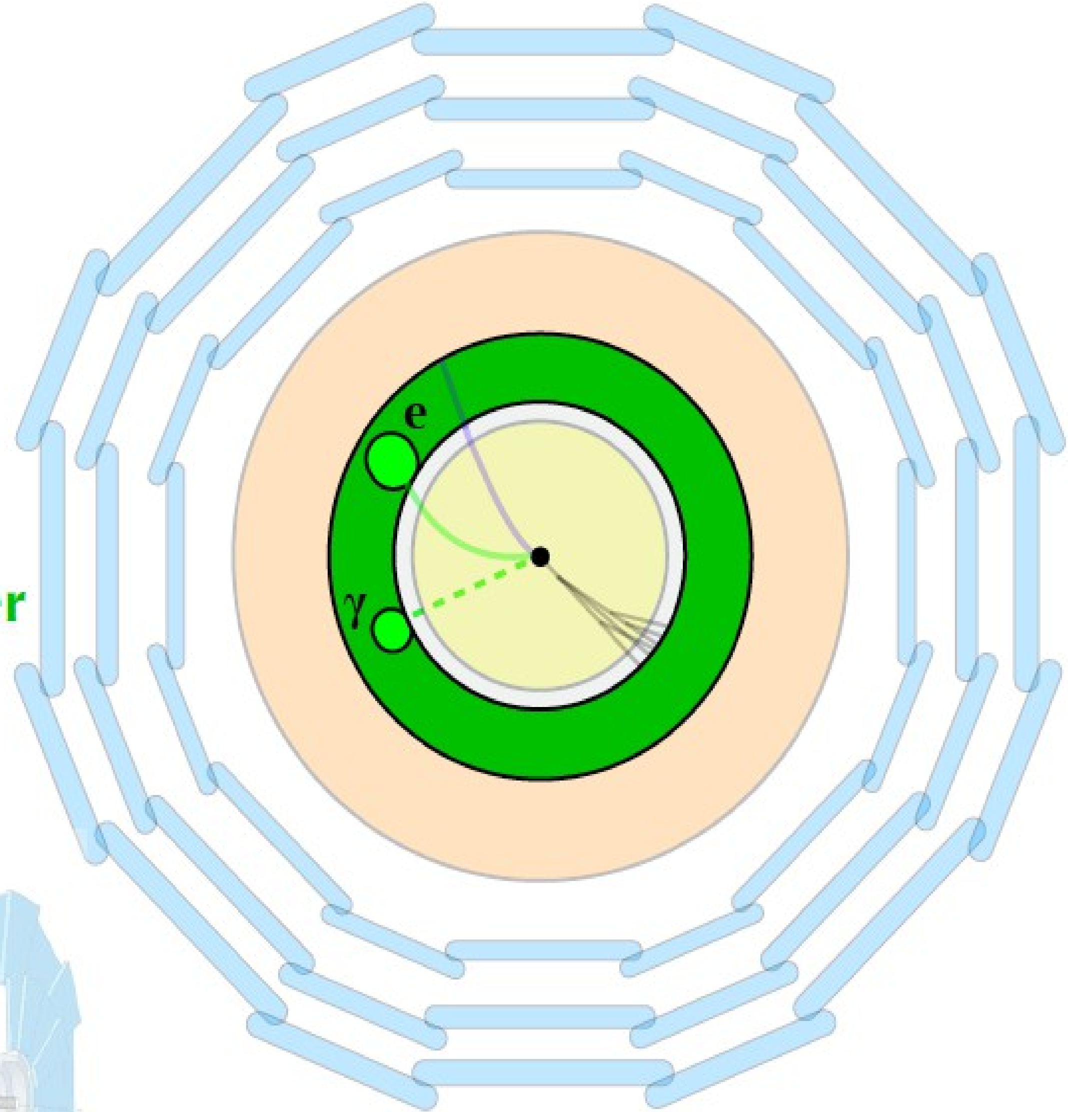

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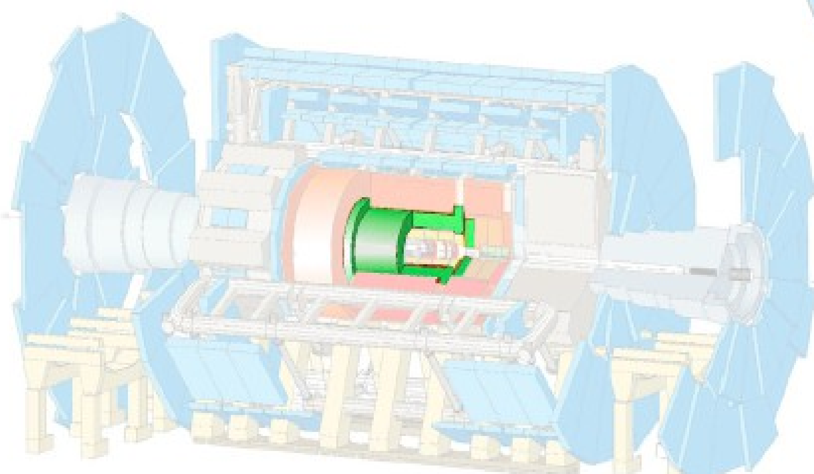

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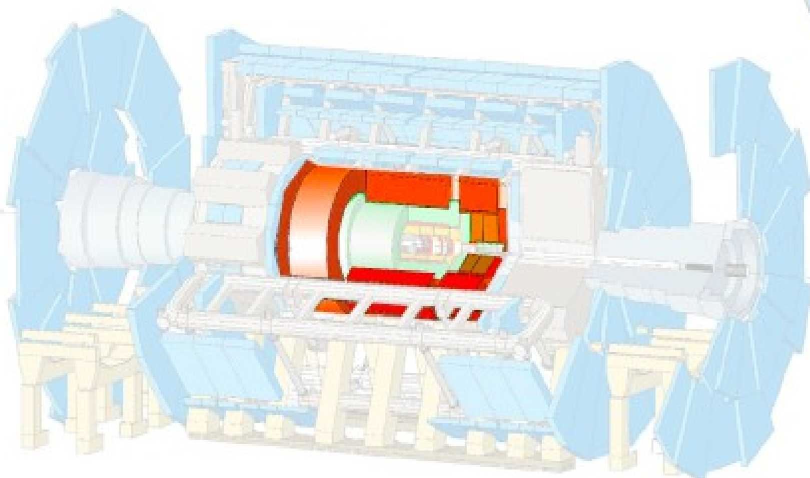

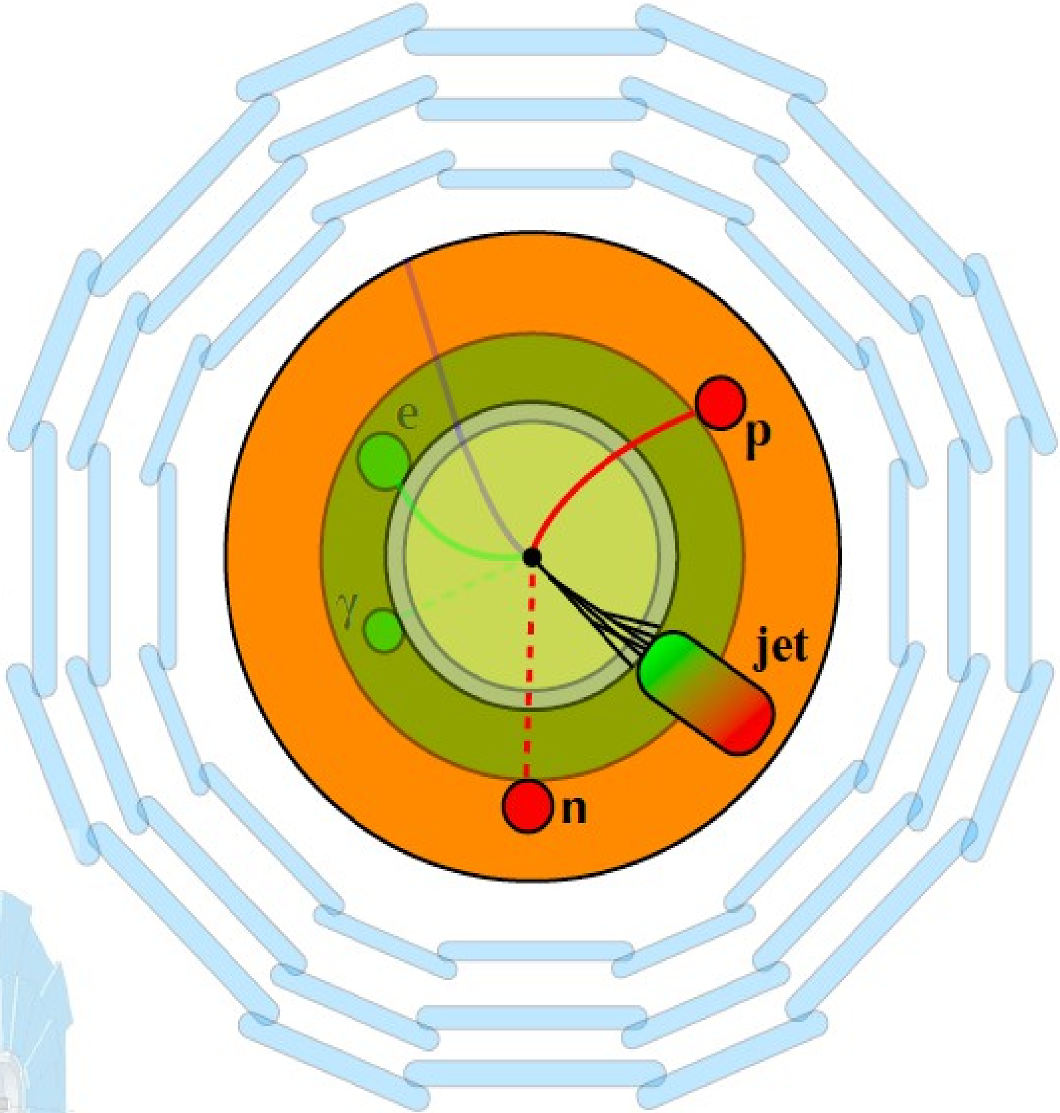

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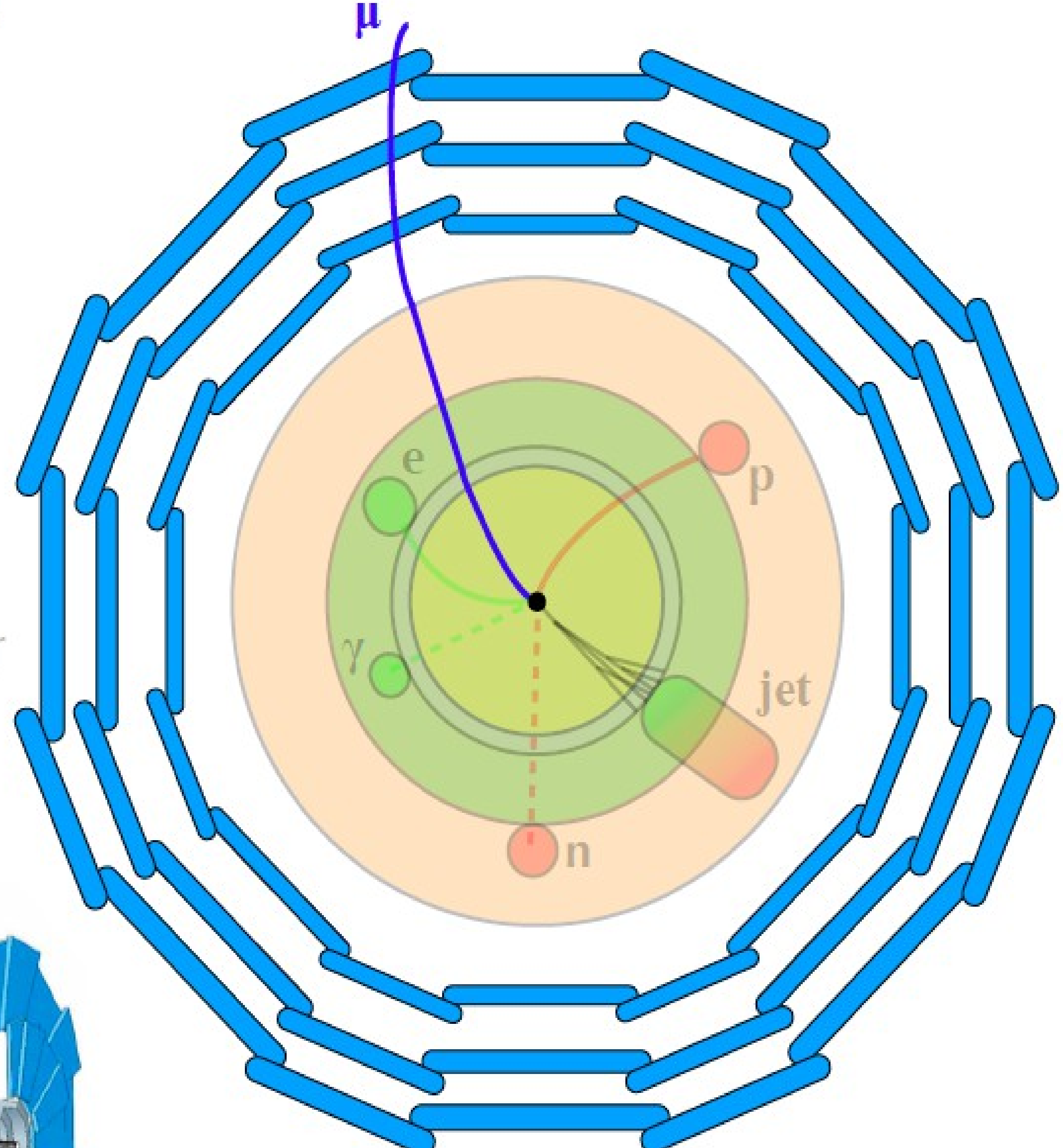

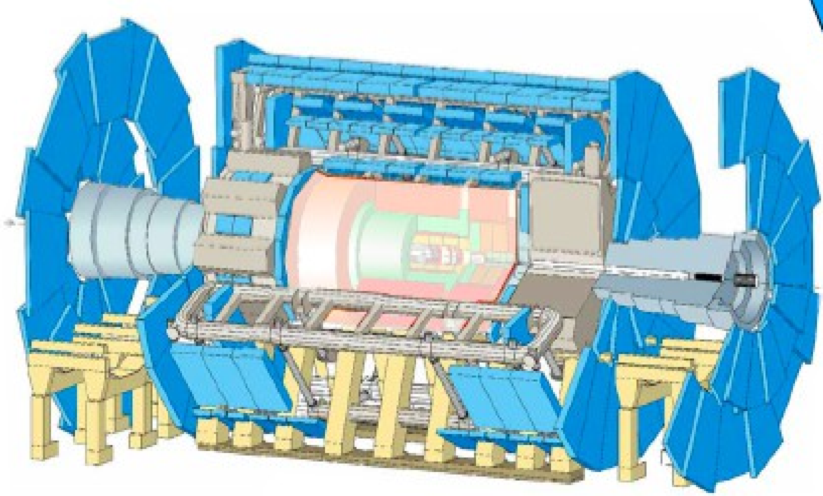

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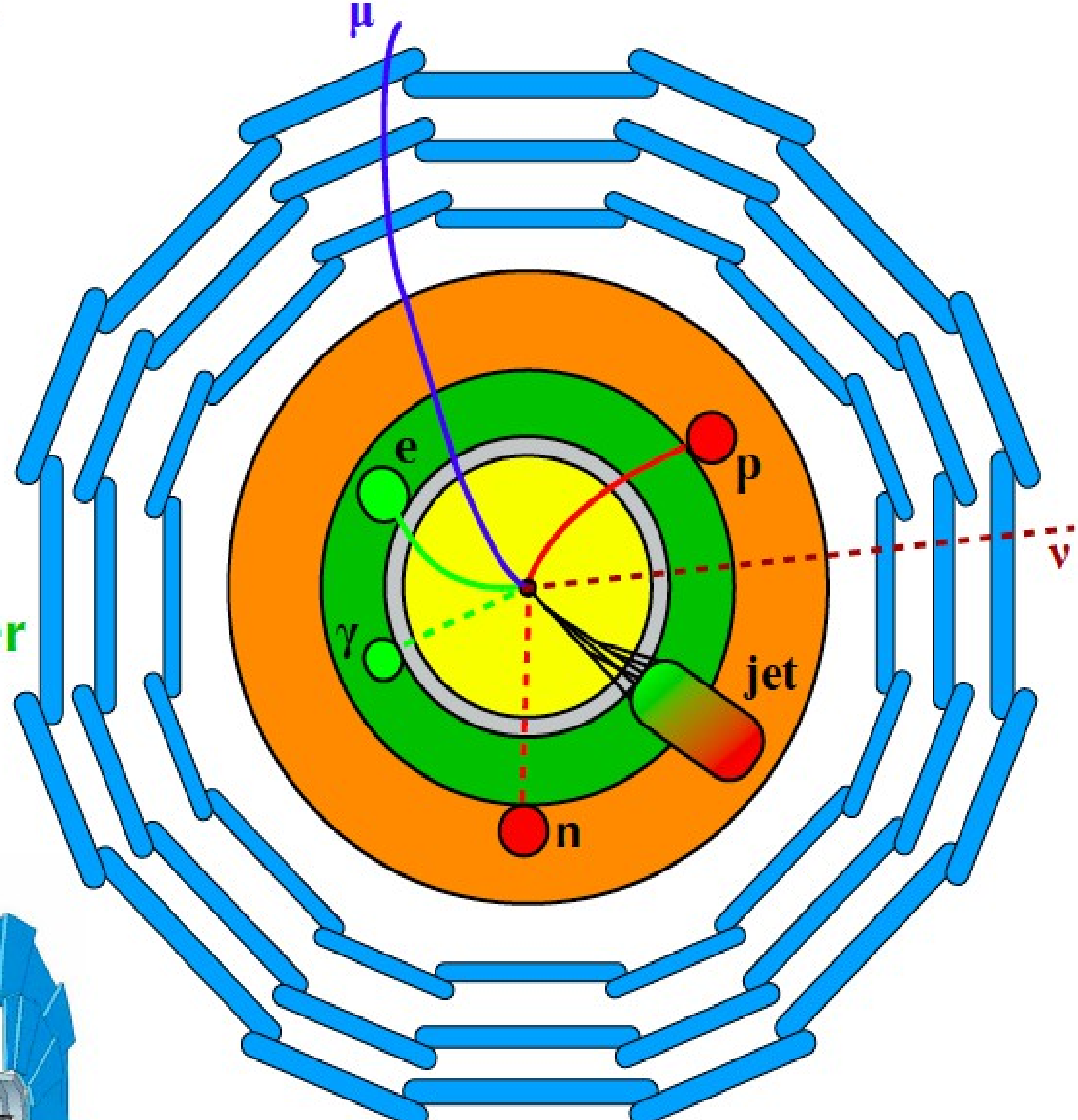

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