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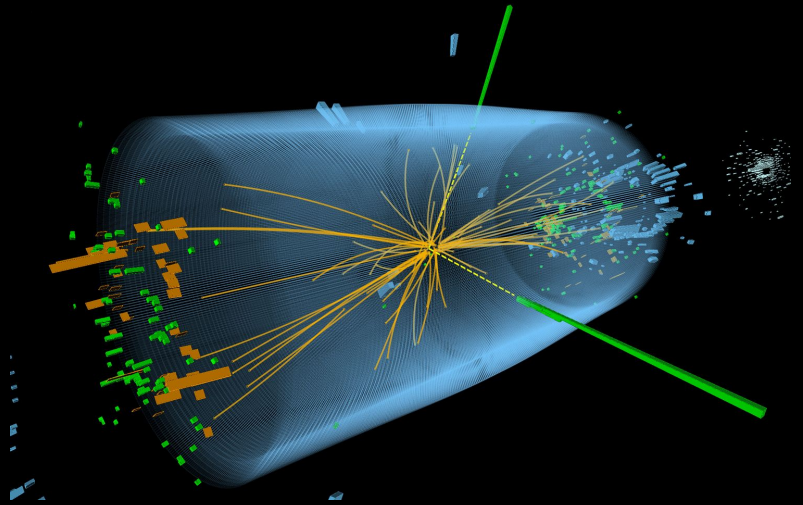
Particle Physics Phenomenology

Lecture I

Introduction and motivations to search for New Physics



@ CERN, CMS

Giovanna Cottin

Mini Curso, Universidad de La Serena
December 2019

“Realms of Physics”

SMALL

FAST

Classical Mechanics
Classical Electromagnetism
Newton, Maxwell

Relativistic Mechanics
Einstein’s Special Relativity

Gravity
Einstein’s General Relativity

@ Berlin Wall with Einstein :)

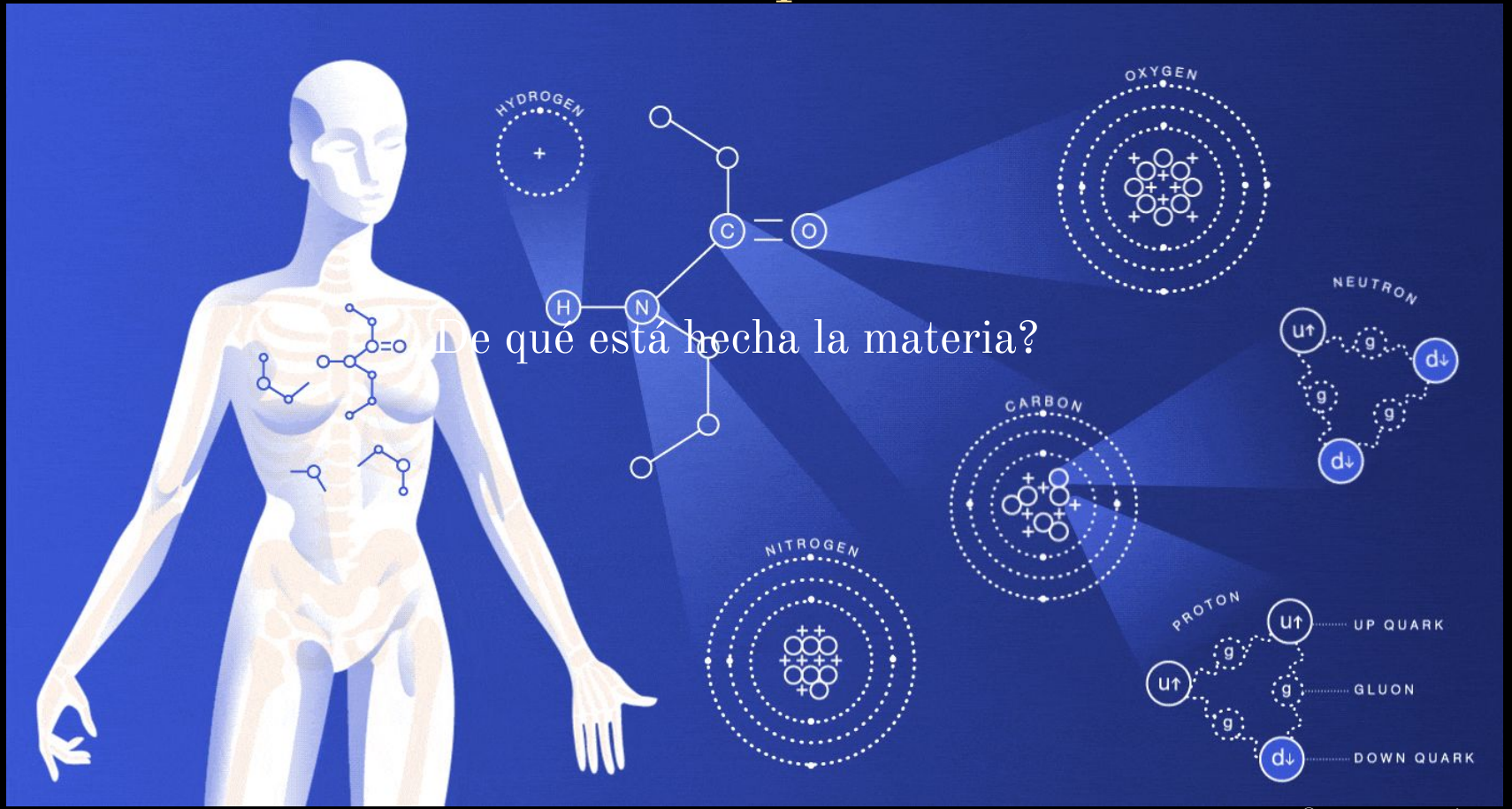
Quantum Mechanics
Planck, Rutherford, Schrodinger
Bohn, Dirac, Pauli, Heisenberg

Quantum Field Theory
Feynman, Yang, Mills, Wilczek, Gross
Politzer, Weinberg, Salam, Glashow

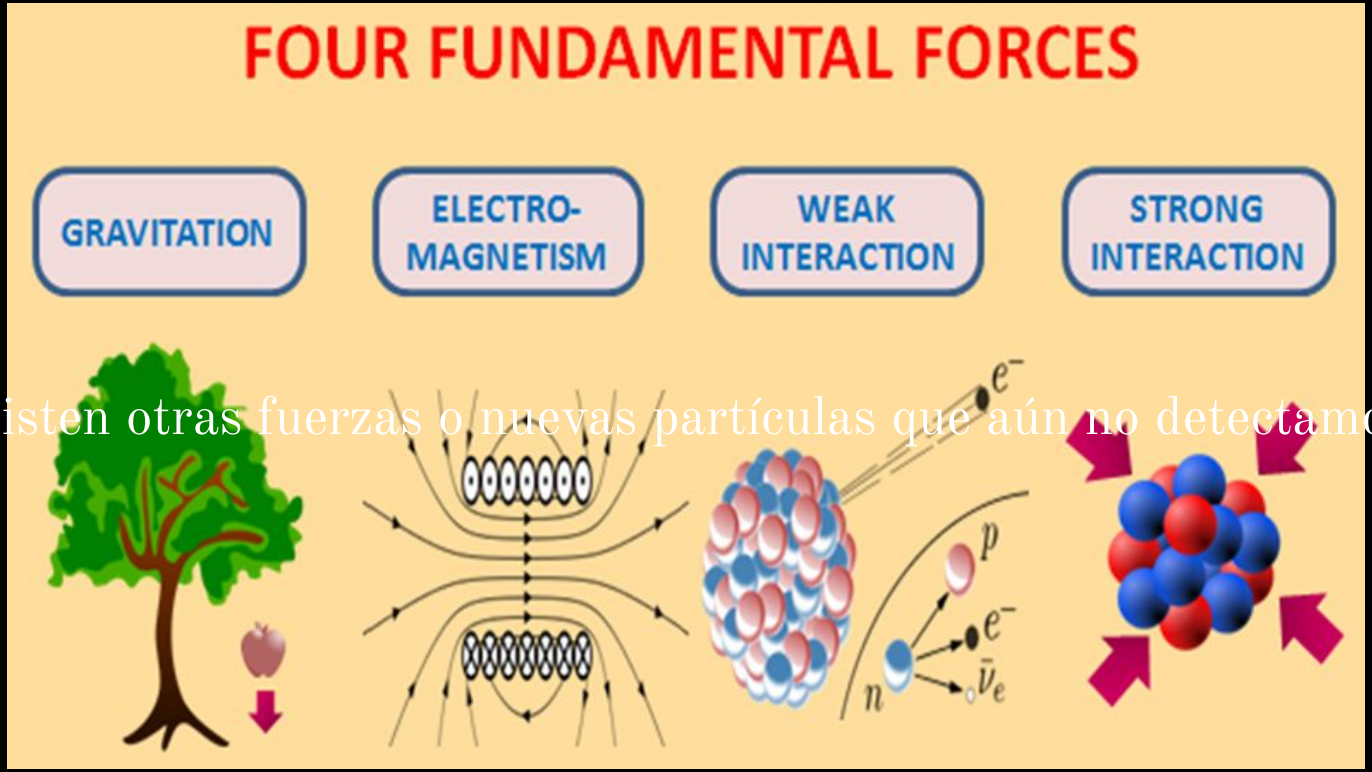
Particle Physics lives here !
This Course !

??? A Theory of Everything? String Theory? Loop Quantum Gravity?

La materia está hecha de partículas elementales!



Existen 4 fuerzas fundamentales conocidas en la naturaleza !



Existen otras fuerzas o nuevas partículas que aún no detectamos?

Fundamental Force Particles

Force	Particles Experiencing	Force Carrier Particle	Range	Relative Strength*
Gravity acts between objects with mass	all particles with mass	graviton (not yet observed)	infinity	much weaker
Weak Force governs particle decay	quarks and leptons	W^+, W^-, Z^0 (W and Z)	short range	
Electromagnetism acts between electrically charged particles	electrically charged	γ (photon)	infinity	
Strong Force** binds quarks together	quarks and gluons	g (gluon)	short range	much stronger

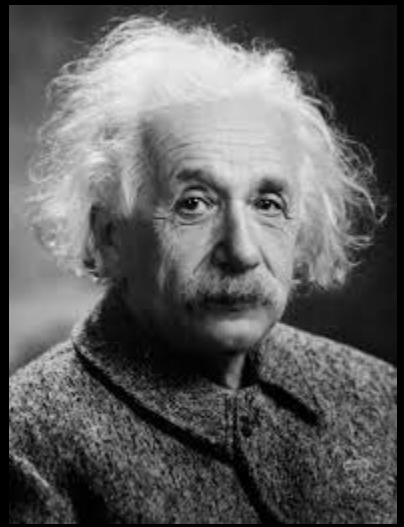
https://www.clearias.com/four-fundamental-forces-of-nature/

En detalle: Fuerzas e Interacciones

Entes o cuerpos usualmente masivos interactúan entre sí. Pero qué es la masa?

$$F = ma$$

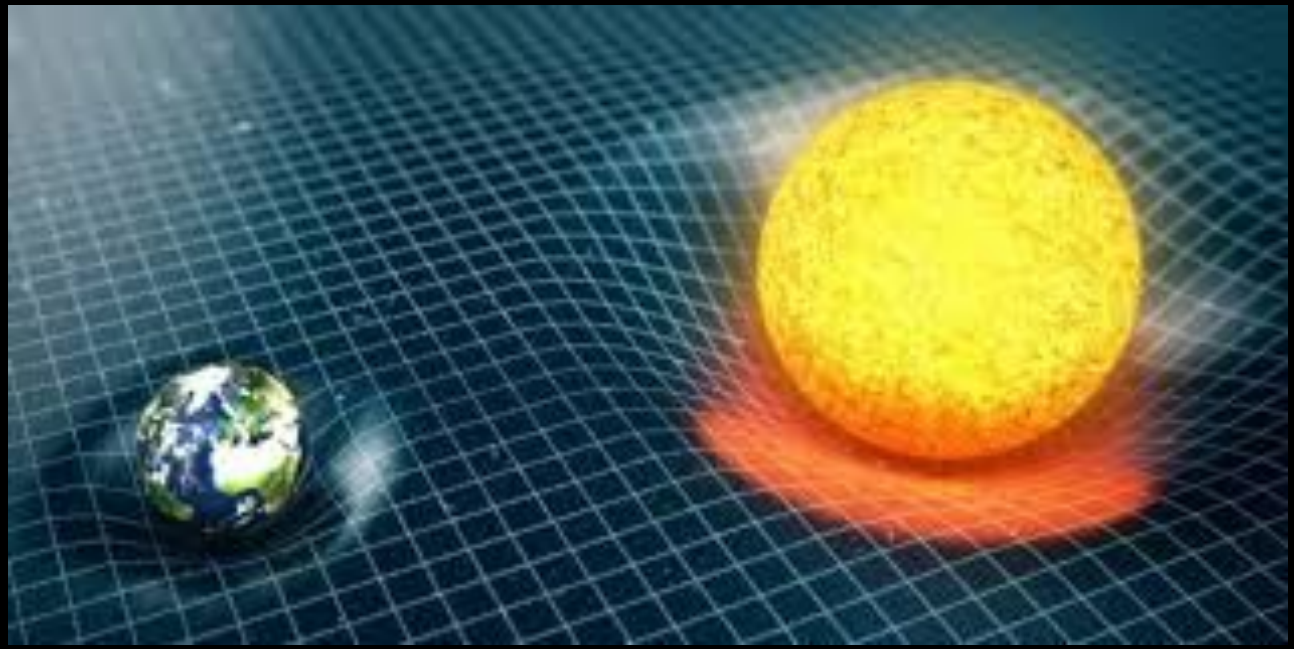
$$E = mc^2$$



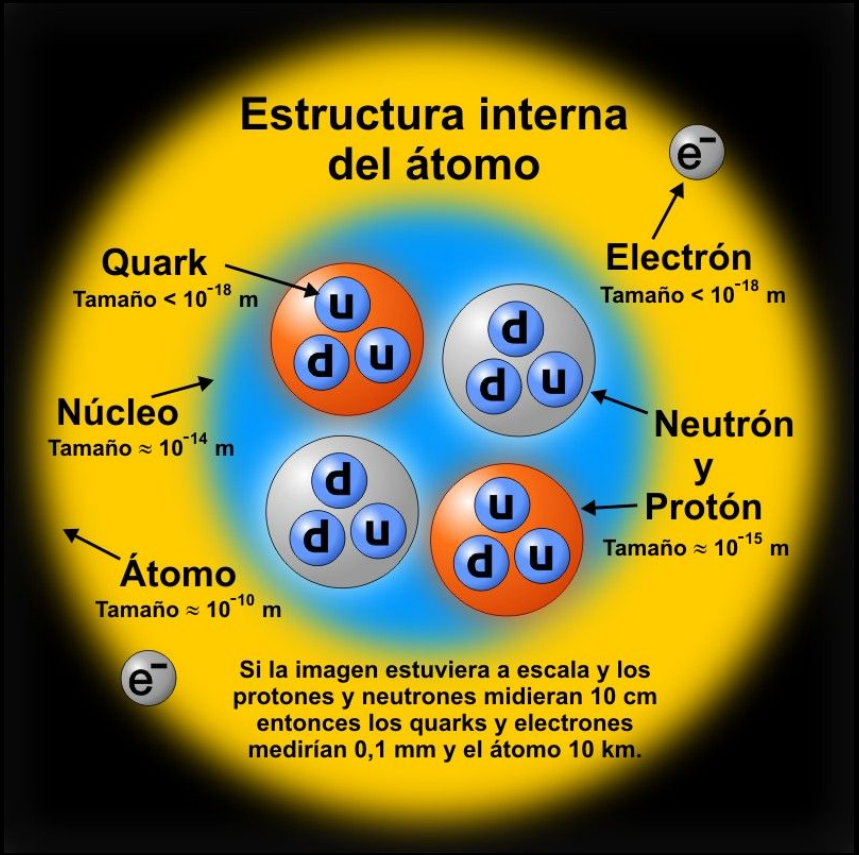
Probablemente estas son las ecuaciones más famosas de la Física. En ninguna de ellas se da una explicación de masa !

Idea de Gravedad

La masa es “algo” que deforma el espacio tiempo



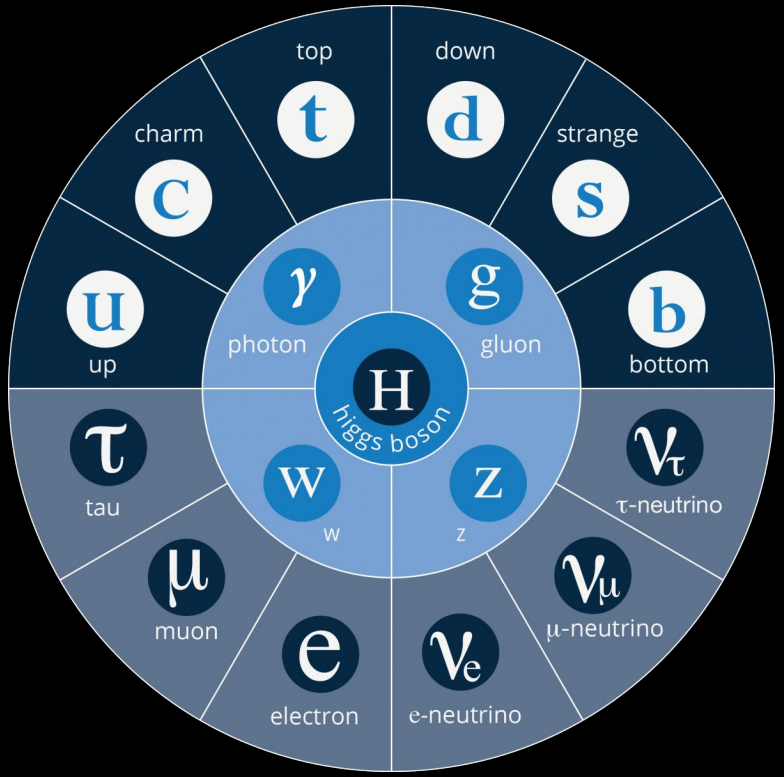
Como entendemos hoy ese algo



Las partículas fundamentales tienen masa pero no volumen. Son entes puntuales. Las partículas elementales interactúan entre ellas ! El modelo matemático que mejor las describe es el Standard Model de fisica de particulas !

Mecánica Cuántica + Relatividad Especial =
Teoría Cuántica de Campos

El Modelo Estándar de física de partículas



Teoria de Campos

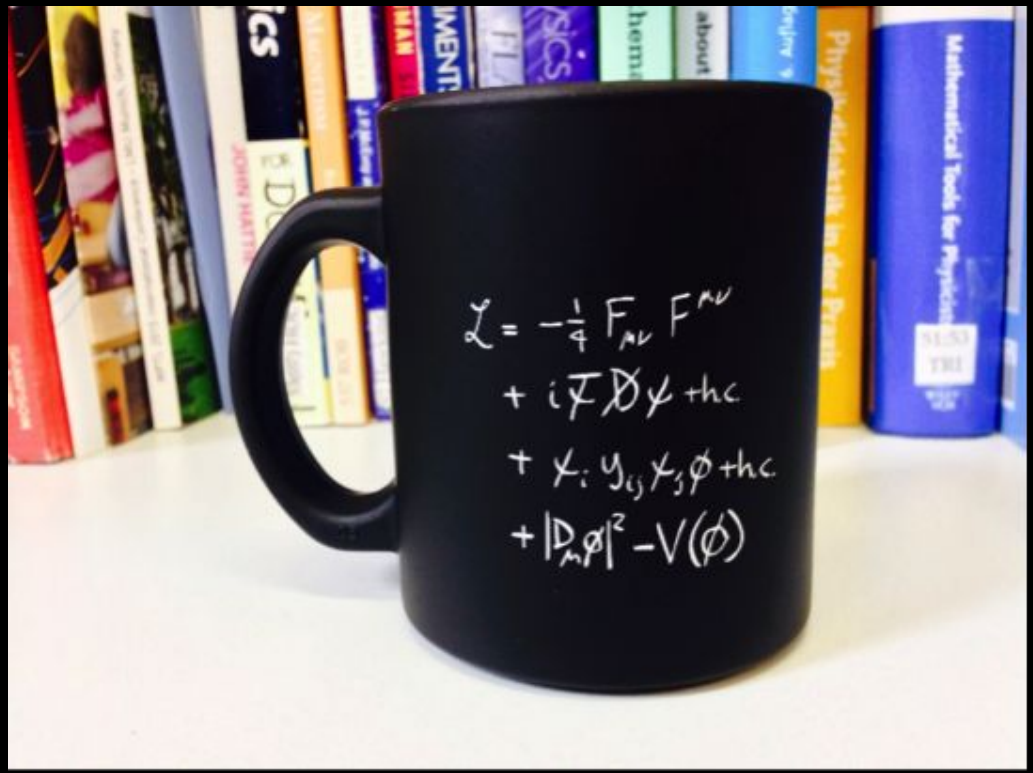
Un campo es una cantidad física asociada a cada punto del espacio-tiempo, como el campo Electromagnético o el campo Gravitacional.

$$\psi(x)$$

Desde la mecánica cuántica entendemos que la fluctuación o “quantum” de dicho campo corresponden a las partículas elementales !

Mecánica Cuántica + Relatividad Especial =
Teoría Cuántica de Campos

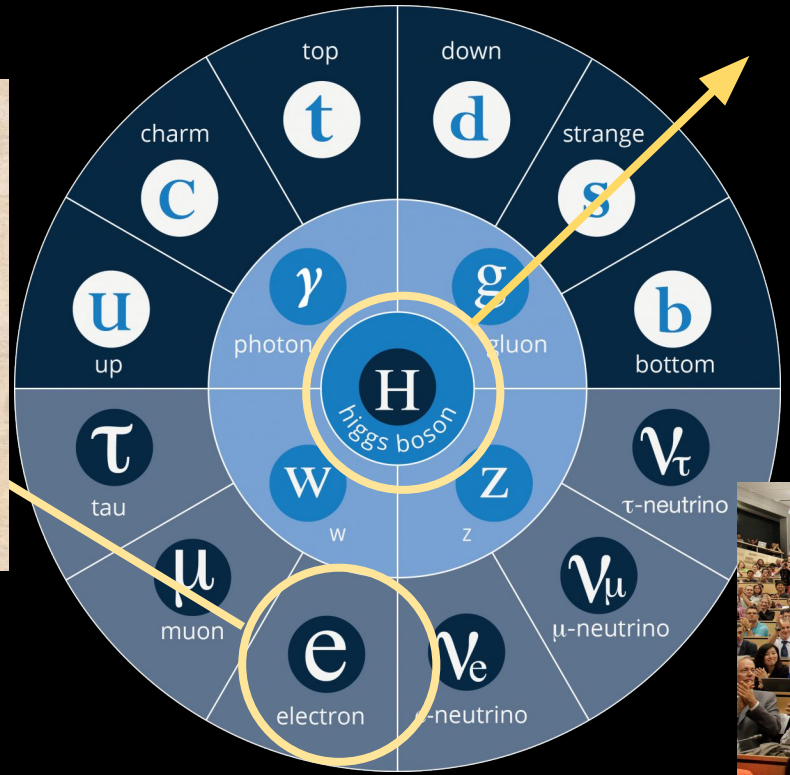
El Modelo Estándar de física de partículas



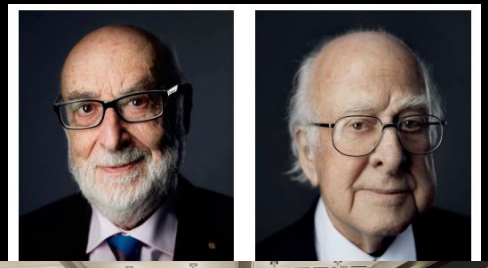
Del electrón al bosón de Higgs

Primera partícula descubierta en (1897) por Joseph Thompson en el Laboratorio Cavendish, Cambridge. Premio Nobel de Física en 1906

Outside the Old Cavendish Lab in 2017

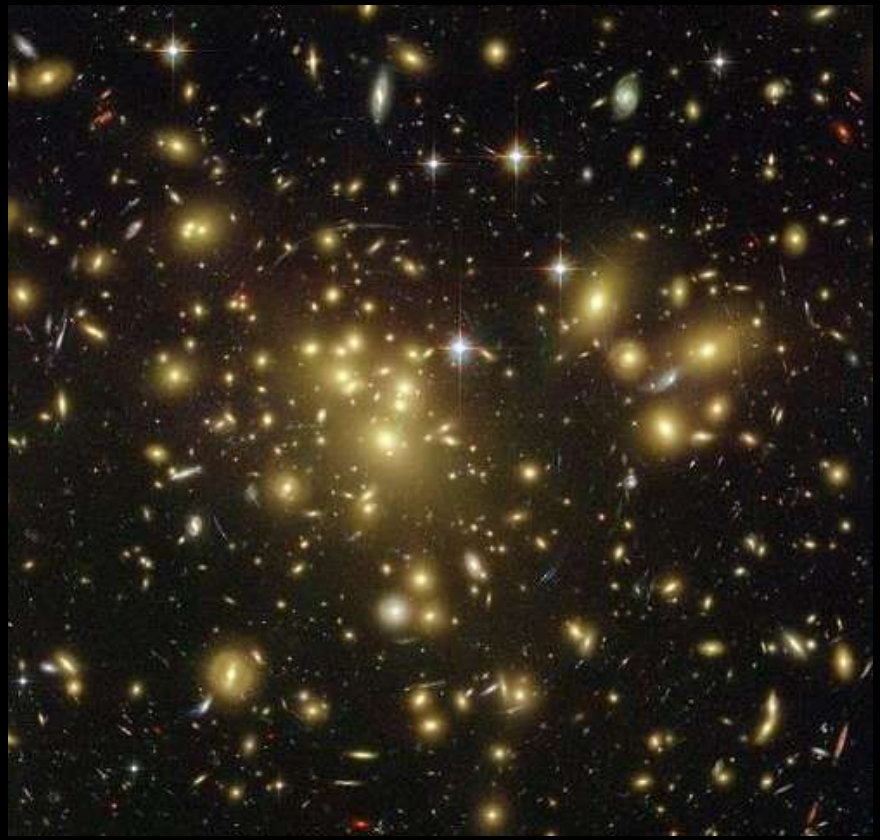


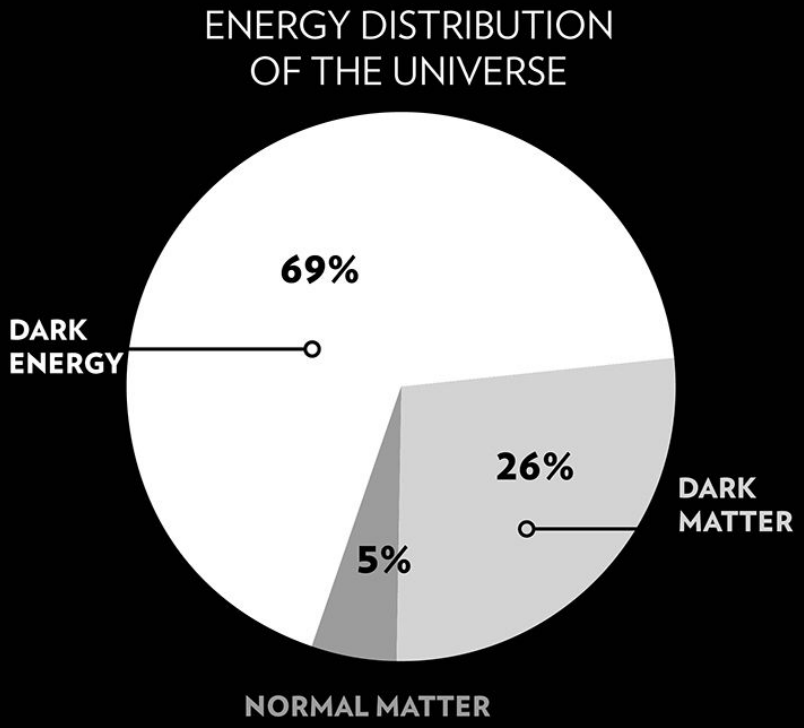
Última partícula descubierta en (2012) por las colaboraciones ATLAS y CMS en el laboratorio CERN. Premio Nobel de Física en 2013 a F. Englert y P. Higgs



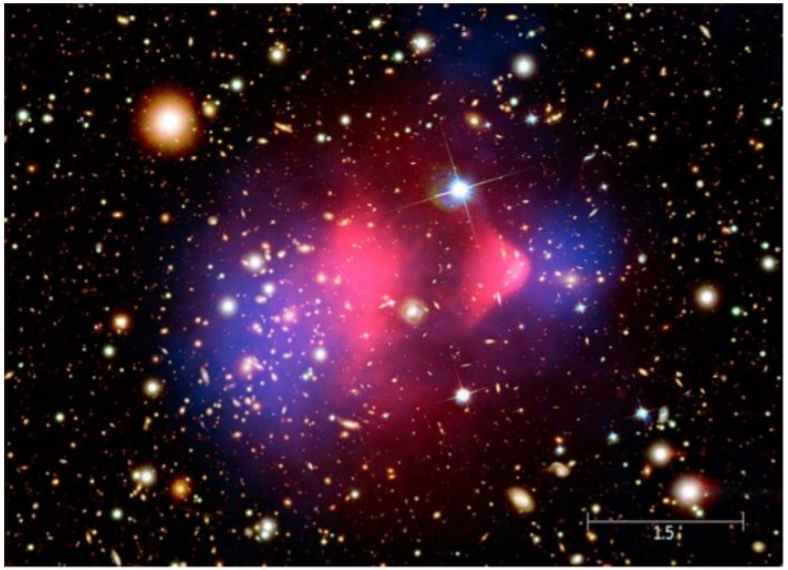
Se completa el Modelo Estándar !!!

Hay algo más allá del Modelo Estándar ?



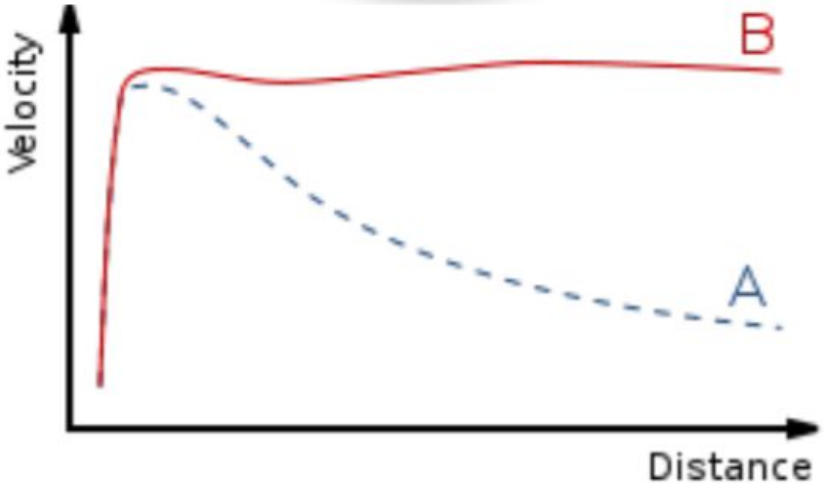


@ phys.org



Bullet Cluster: In the crossing of two galaxies, since Dark Matter (in blue) does not interact by electromagnetic forces, is not slowed in the same way as the X-ray visible gas (in red).

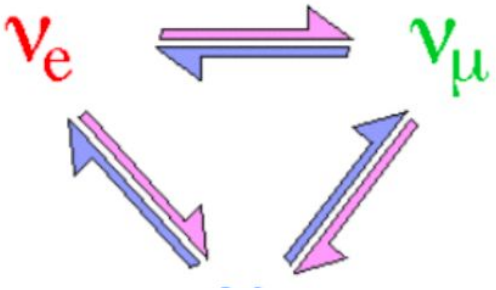
Source : https://en.wikipedia.org/wiki/Dark_matter



Predicted (A) and observed (B) galaxy rotation curve. Dark matter can explain the 'flat' behaviour in (B) at large distance.

En el Standard Model no existe una partícula candidata a Materia Oscura ...

... tampoco podemos explicar la masa de los neutrinos ...

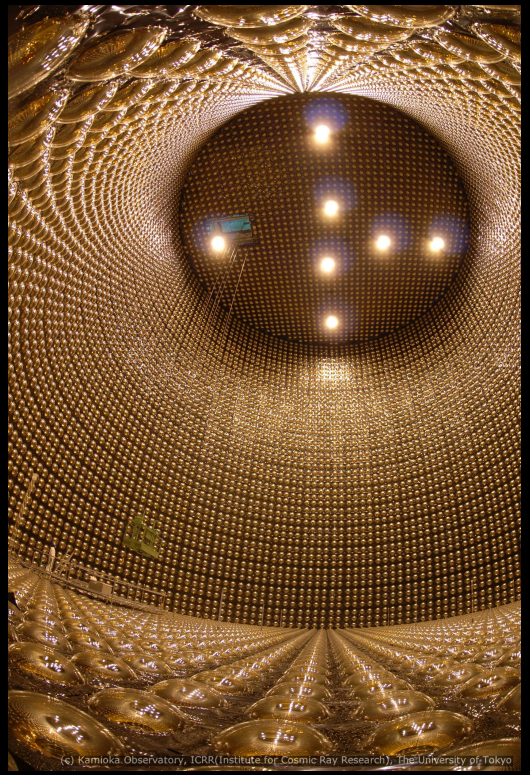


$$P_{\nu_\alpha \to \nu_\beta}(t) = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2$$

$$= \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

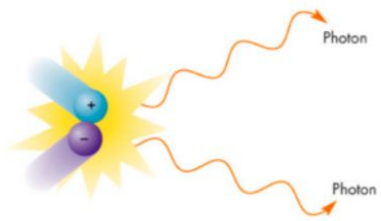
$$+ 2 \sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin\left(\frac{\Delta m^2_{ij} L}{4E}\right),$$

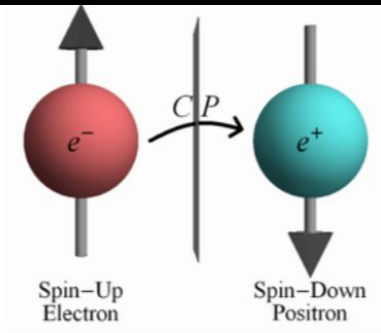
Where does neutrino mass come from?



… ni el porqué de la cantidad de materia por sobre antimateria en el Universo !!!

matter and antimatter particles have opposite charge.





One would expect the Big Bang to produce equal amounts of matter and antimatter, but this is not the case, as we see a matter dominated Universe.

There must've been a symmetry violation that allowed matter to be produced more commonly than antimatter. This is known as CP violation (charge conjugation-parity).

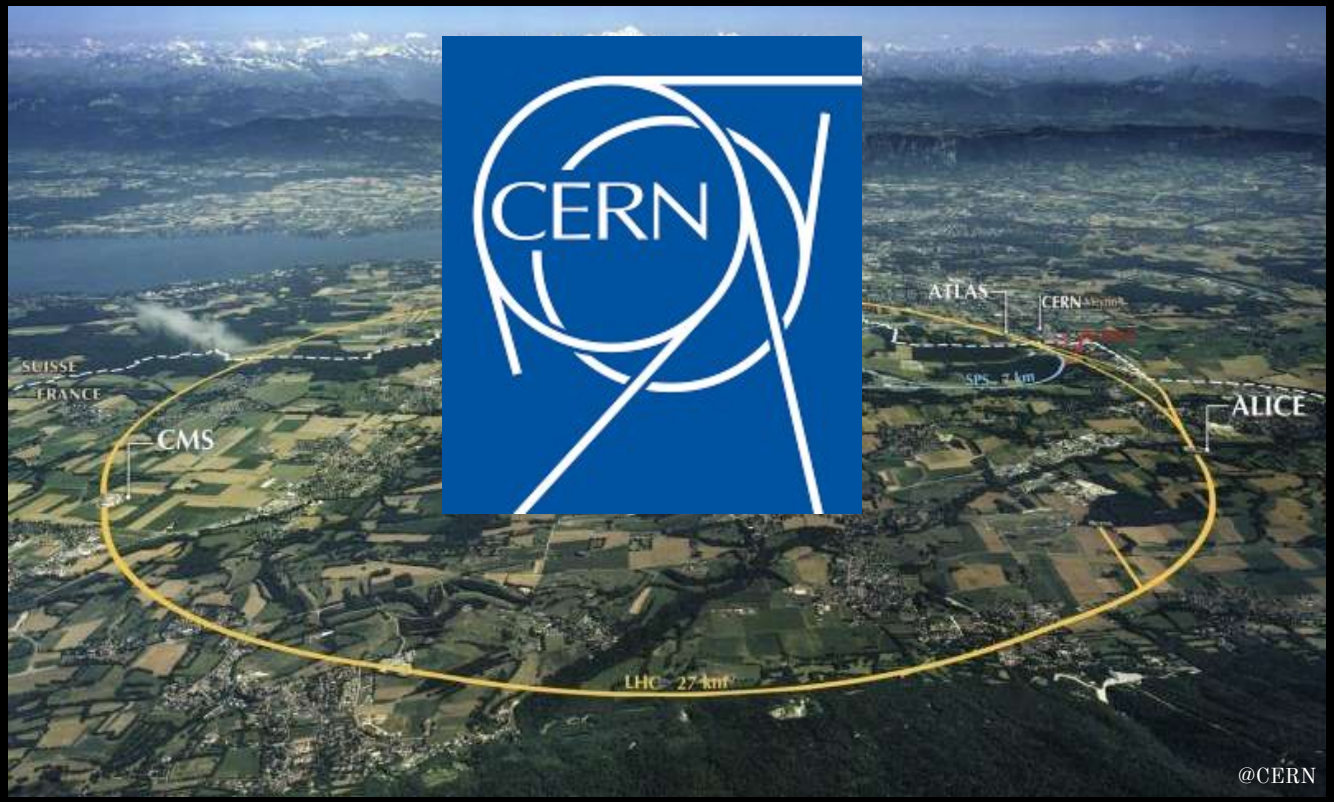
In the Standard Model, the amount of CP violation is too small to account for the matter-antimatter asymmetry !!!

Source : http://hepoutreach.syr.edu/HEP_Tour/lhcbexperiment/index.html

Source : http://www.mhhe.com/physsci/astronomy/fix/fix_splash

Para entender el Universo como hoy lo vemos, necesitamos de nueva física !

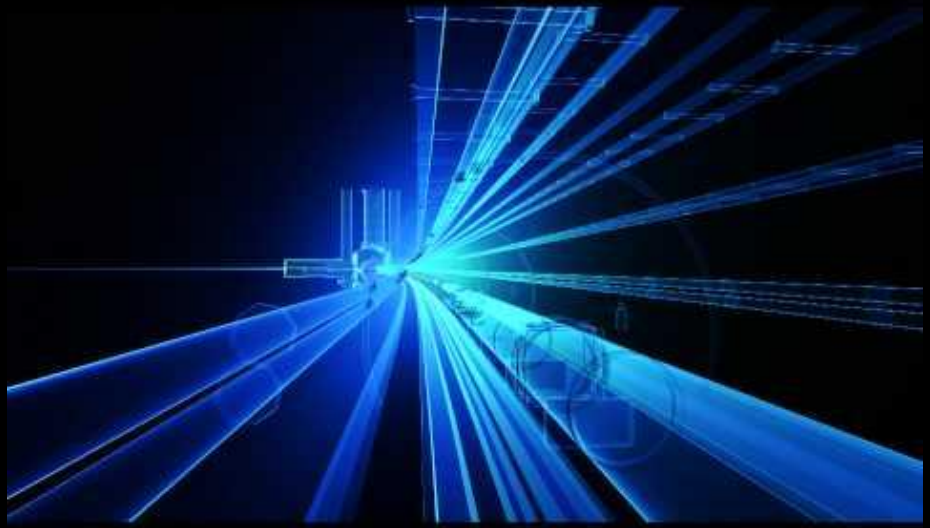
CERN y el Gran Colisionador de Hadrones



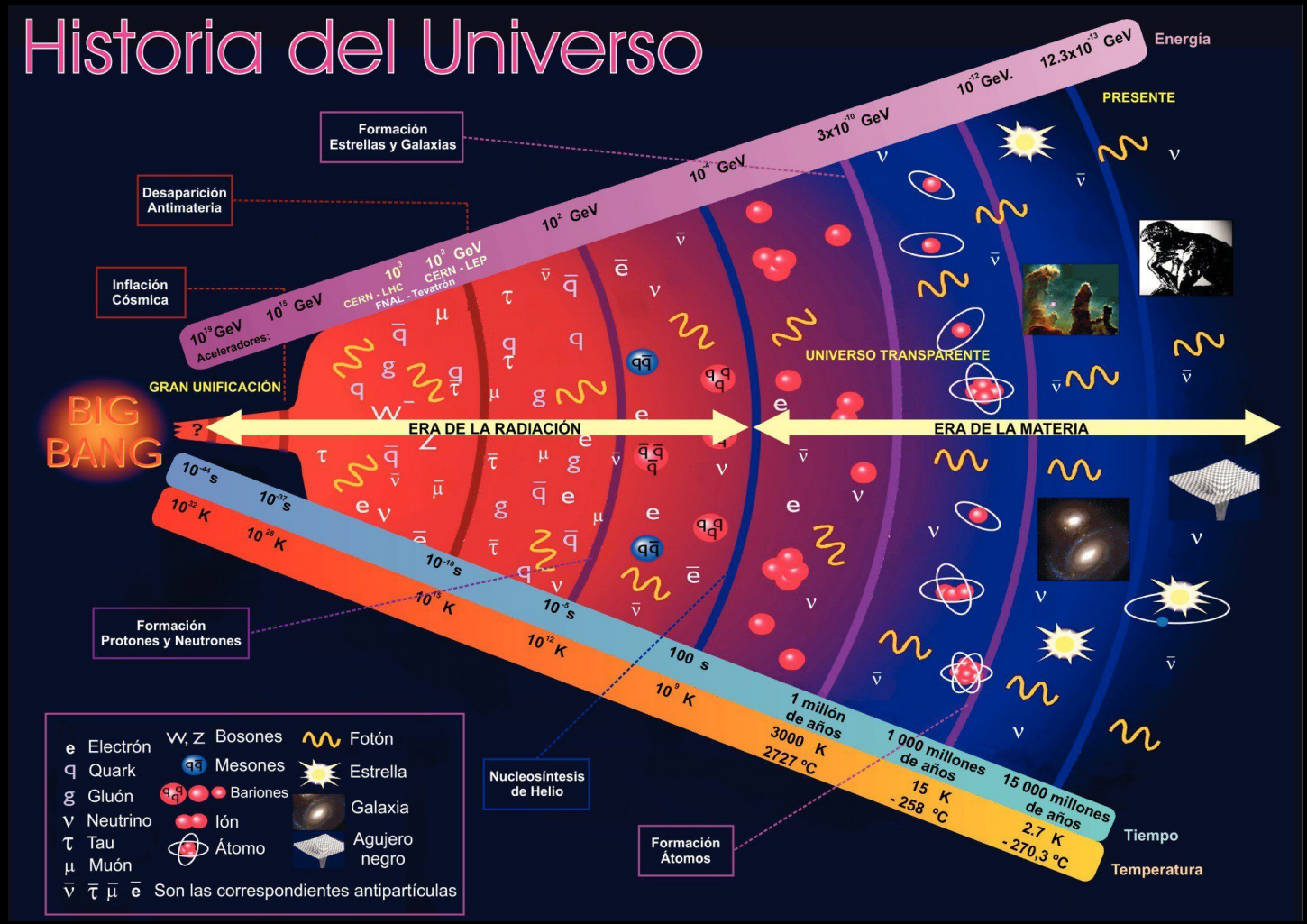
CERN y el Gran Colisionador de Hadrones

Gran Acelerador de partículas. Grandes Cantidades de Datos

Buscar una partícula de Materia Oscura es como buscar una aguja en un pajar !



Historia del Universo



Particle Phenomenology: From Theory to Experiment

1) Motivation

Dark Matter

Baryogenesis

Neutrino Masses

Naturalness

2) Theory Models

SUSY Multiple NP with SM gauge charges RPV, split SUSY

Higgs Portal NP predominantly coupled to the Higgs Hidden Valley

Gauge Portal New vector mediators can produce NP Z', dark photon

Dark Matter Non SUSY, hidden sector DM produced as final state at colliders EWK Multiplets, FIMP, SIMPs

RH Neutrinos RHnu masses in the GeV to TeV range SM+N, Left-Right Symmetry

3) Phenomenology

Search strategies

Identify signatures

Model reinterpretation

4) Experiment

Implement and reconstruct those signatures

Hunt them in the Data

Experimental results

Coffee??

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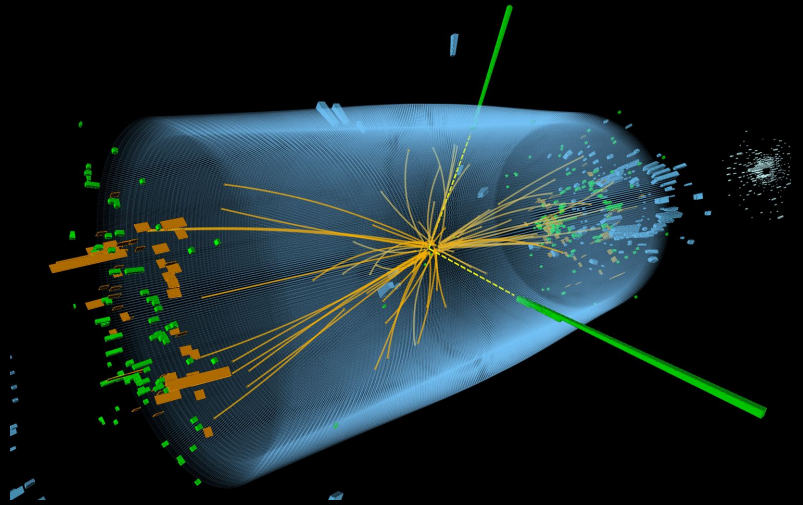
Particle Physics Phenomenology

Lecture II

Hunting for new physics at the LHC

Giovanna Cottin

Mini Curso, Universidad de La Serena
December 2019



@ CERN, CMS

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FIMP, SIMPs

RH Neutrinos RHnu masses in the GeV to TeV rang

Focus on LHC in this course !

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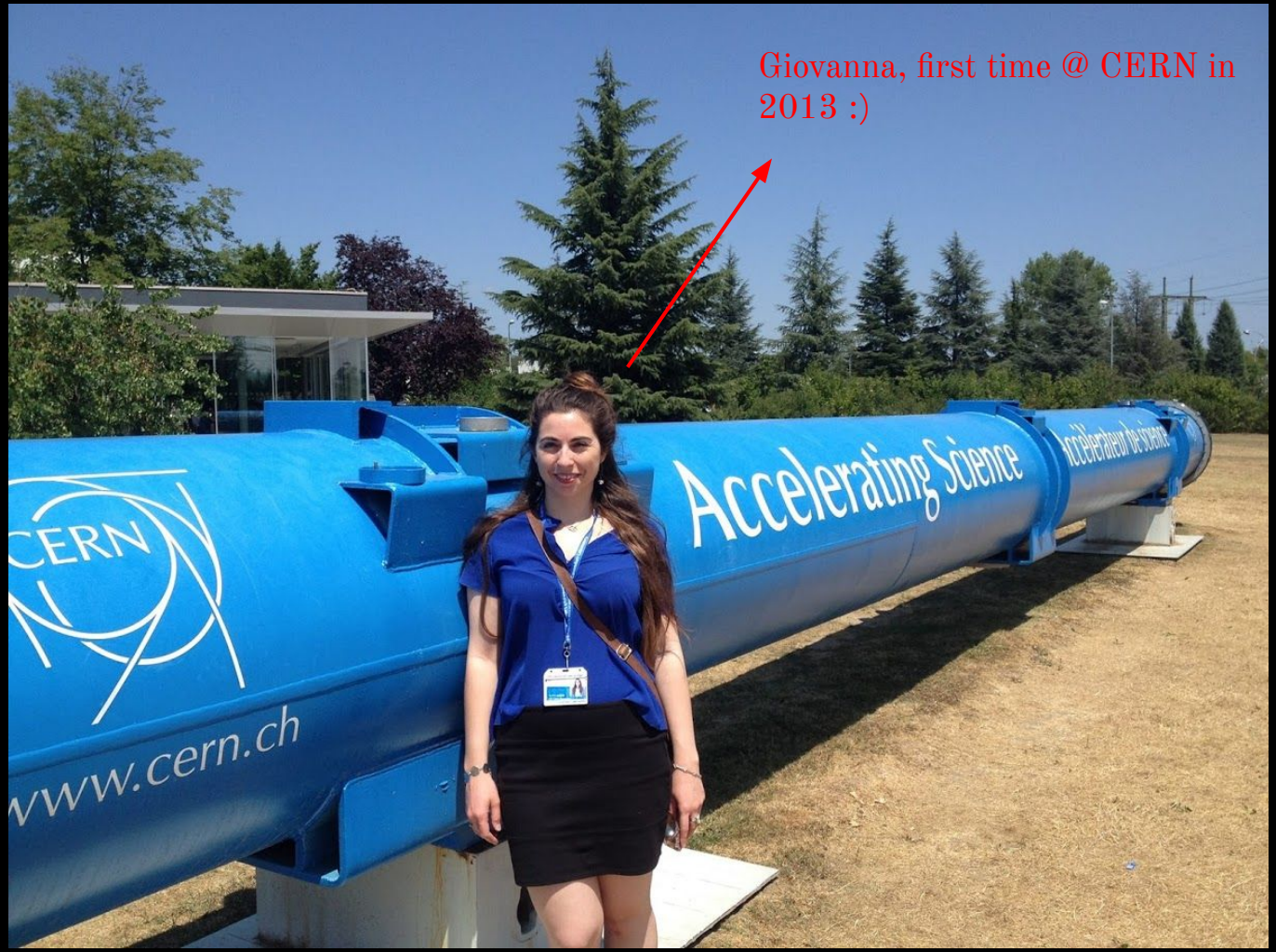

Giovanna, first time @ CERN in 2013 :)
CERN
www.cern.ch
Accelerating Science

Collider Detection

The Large Hadron Collider (LHC) at CERN was built with the hope to find New Physics (i.e new particles) that help explain the things the Standard Model can't

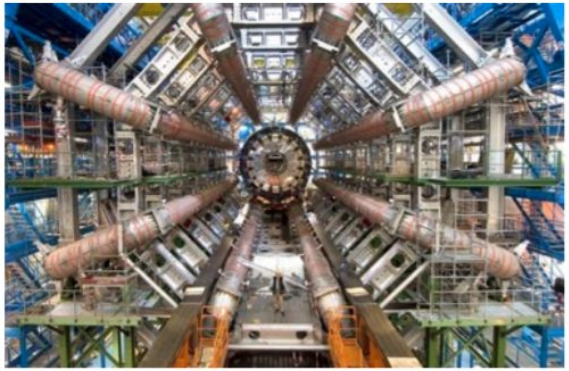
Source : http://www.atlas.ch/photos/lhc.html, Image credit, CERN

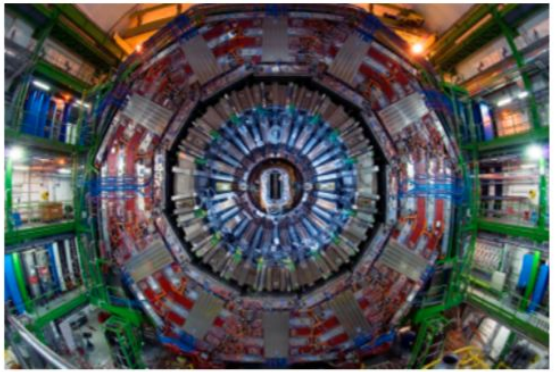
- 27 Km ring !
- Emptiest space (vacuum) in the solar system !
- Magnets cooler than outer space !

"A machine built for the pursuit of pure knowledge" quote from *Nobel Dreams*

Four major LHC experiments, designed for different purposes

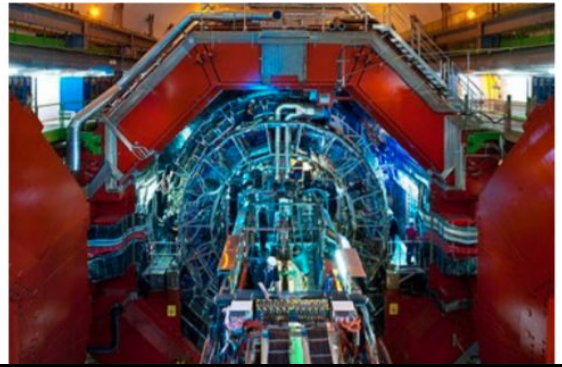
ATLAS and CMS : Higgs + Dark Matter





Source : Image credit, CERN

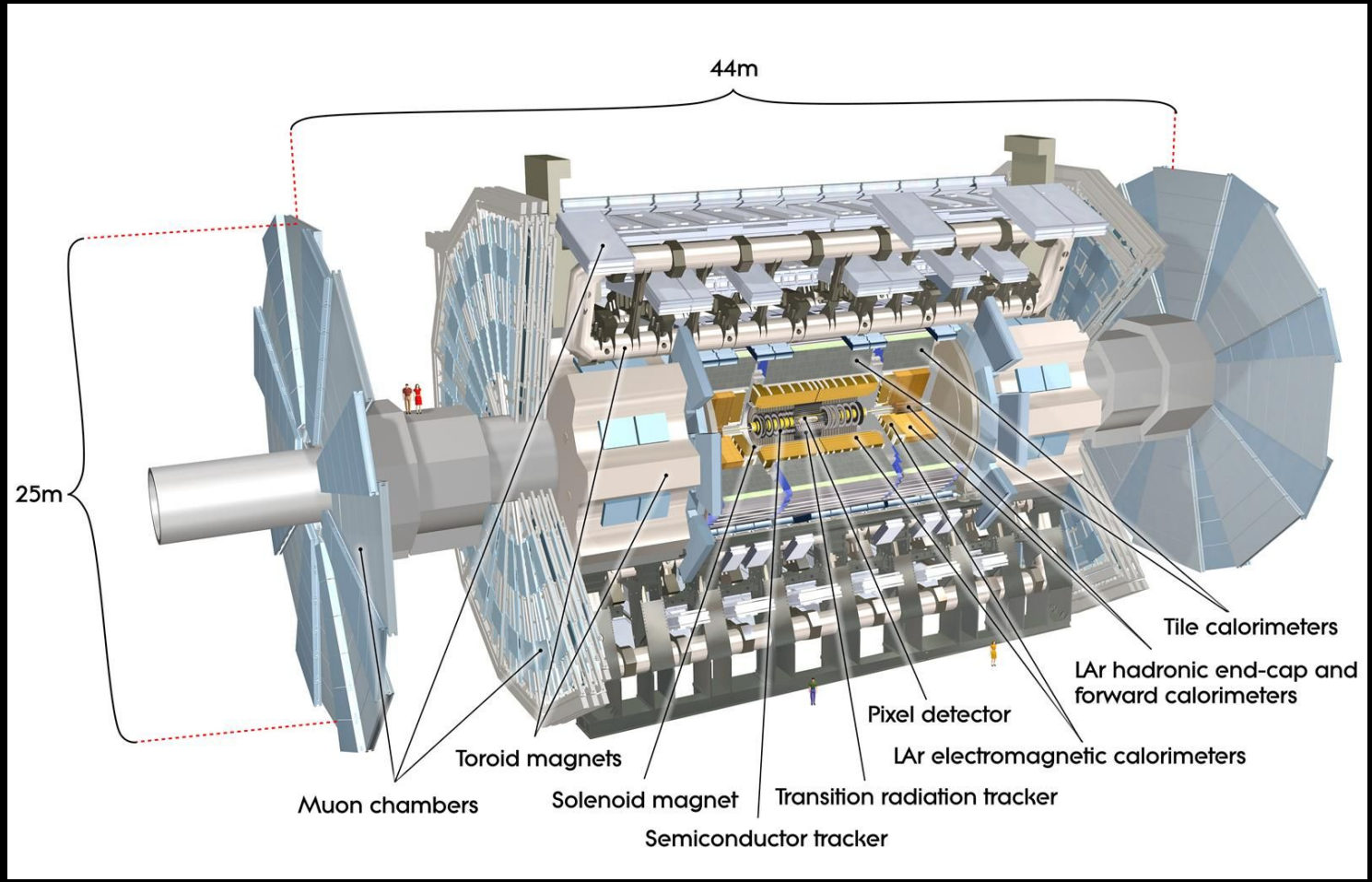
ALICE: Quark-gluon plasma

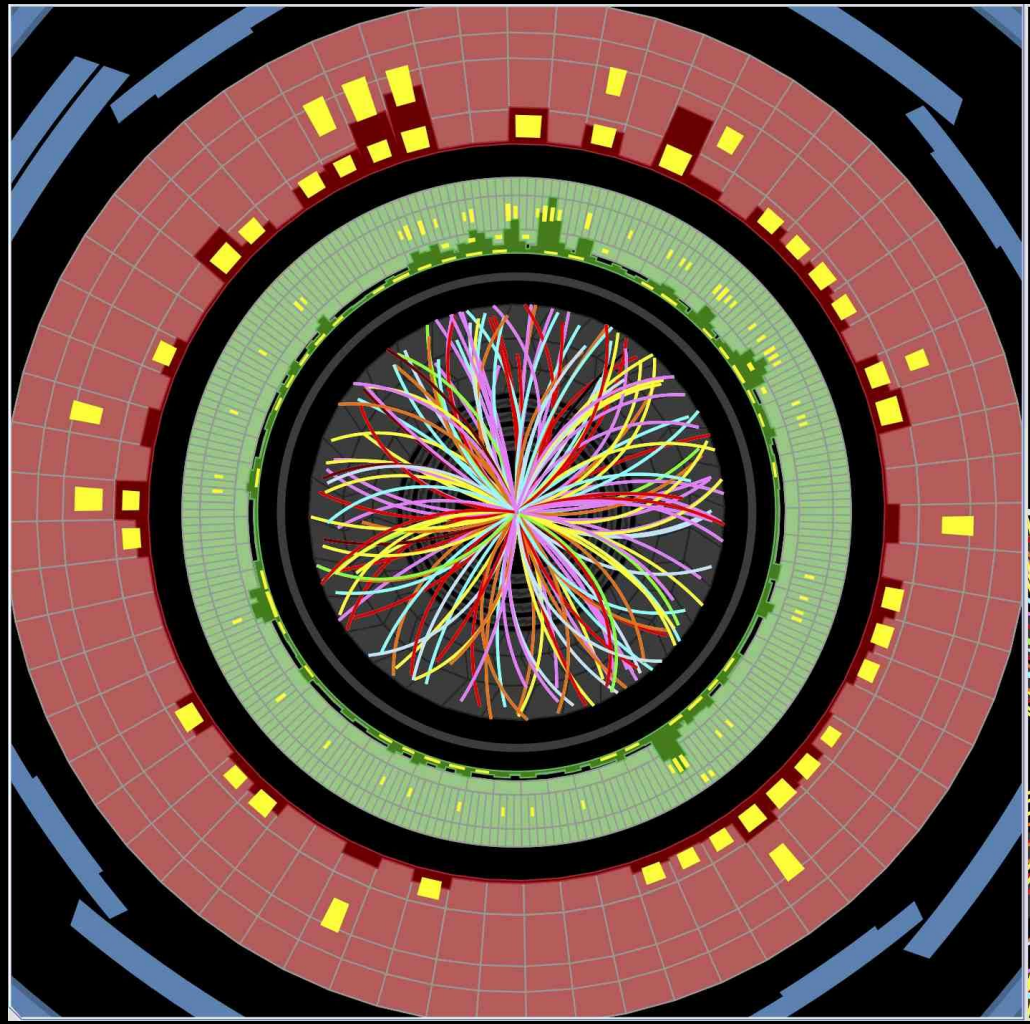


LHCb : Matter-Antimatter asymmetry


Argentina
Armenia
Australia
Austria
Azerbaijan
Belarus
Brazil
Canada
Chile
China
Colombia
Czech Republic
Denmark
France
Georgia
Germany
Greece
Israel
Italy
Japan
Morocco
Netherlands
Norway
Poland
Portugal
Romania
Russia
Serbia
Slovakia
Slovenia
South Africa
Spain
Sweden
Switzerland
Taiwan
Turkey
UK
USA
CERN
JINR
ATLAS
Collaboration
July 2010

The ATLAS Detector



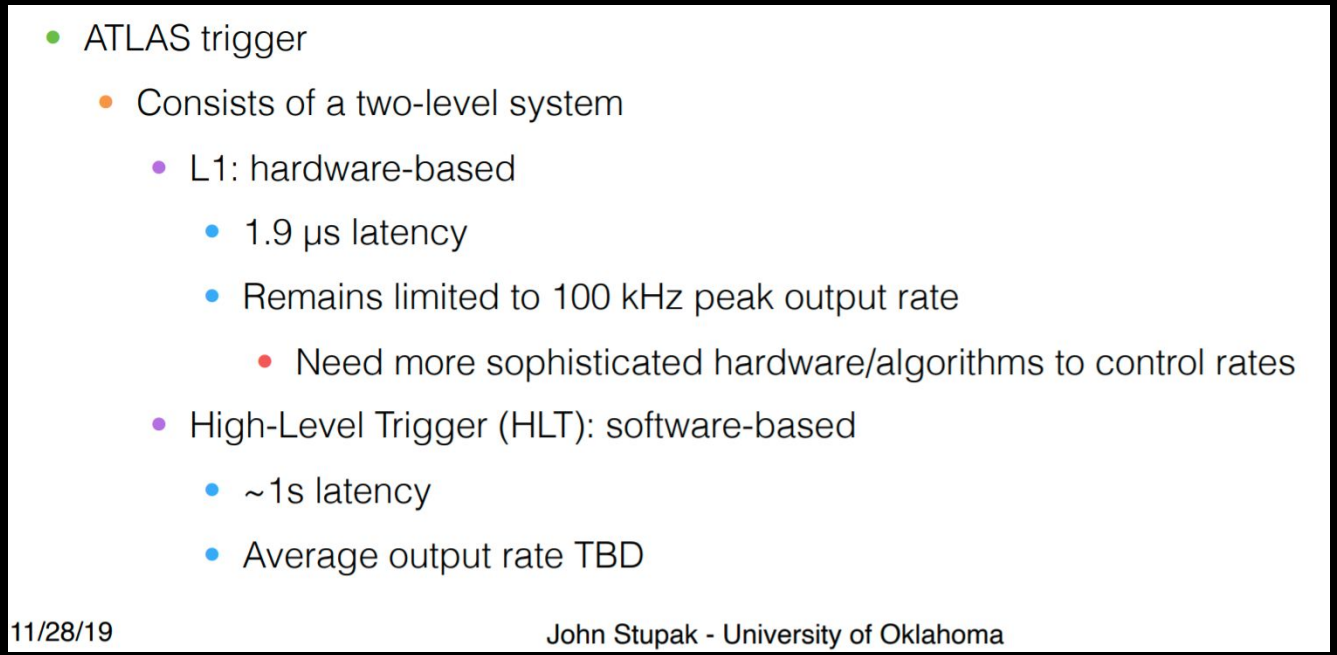



ATLAS
EXPERIMENT
Run Number: 266904, Event Number: 25884352
Date: 2015-06-03 13:41:54 CEST

ATLAS Trigger

The information produced in each collision is too high to be able to record everything (40 MHz collision frequency in Run 3, roughly 25 petabytes per year) !

A trigger system is needed to filter events

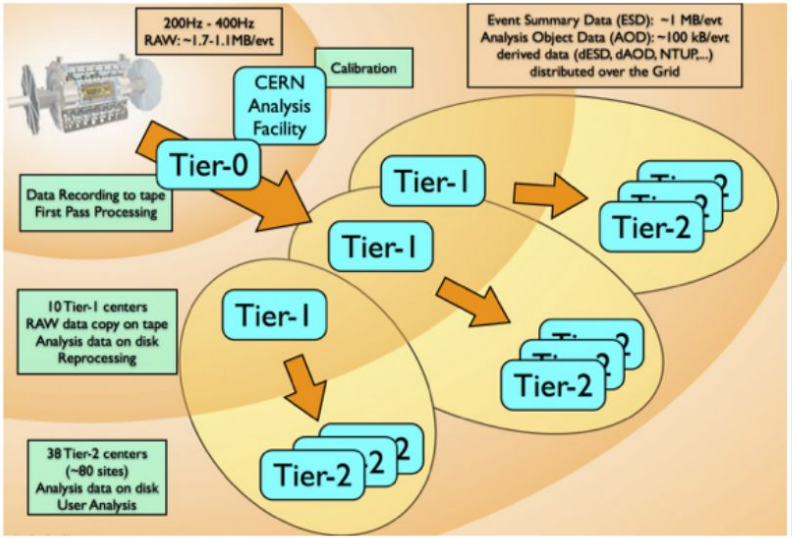


The triggered data that comes out from the collisions is analysed by physicist around the world in the search for the unknown!

The World Wide Web was created at CERN !

During 2011 and 2012 ATLAS alone generated roughly six petabytes of raw data!

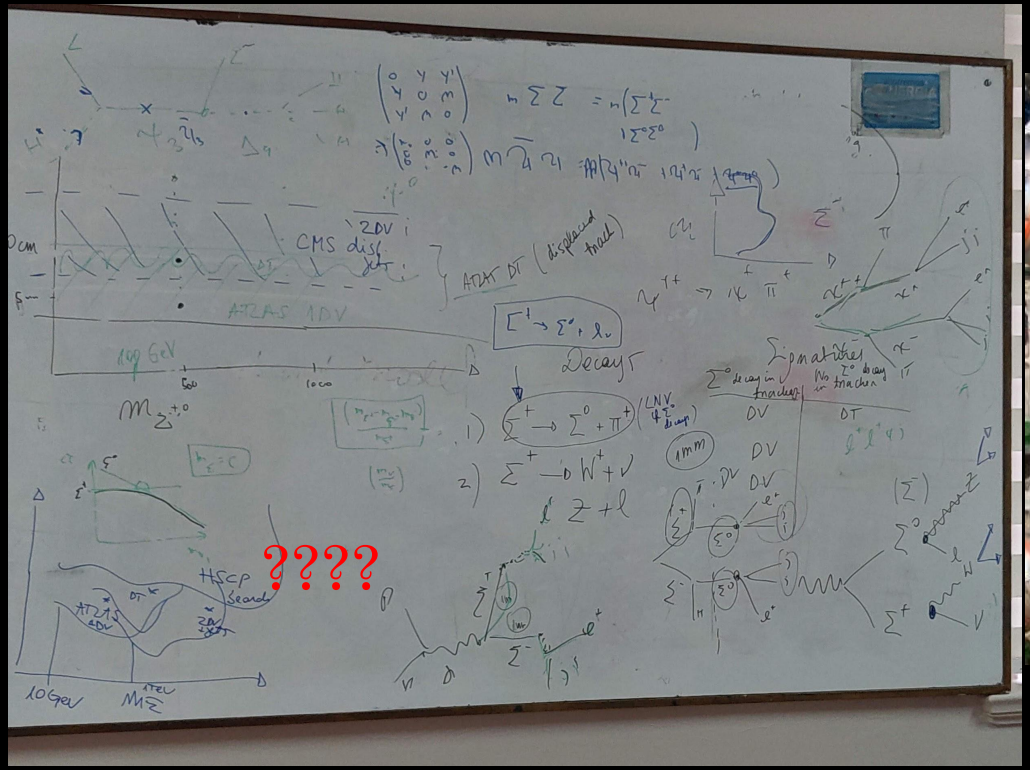
Giovanna outside Tim Berners-Lee office @ CERN

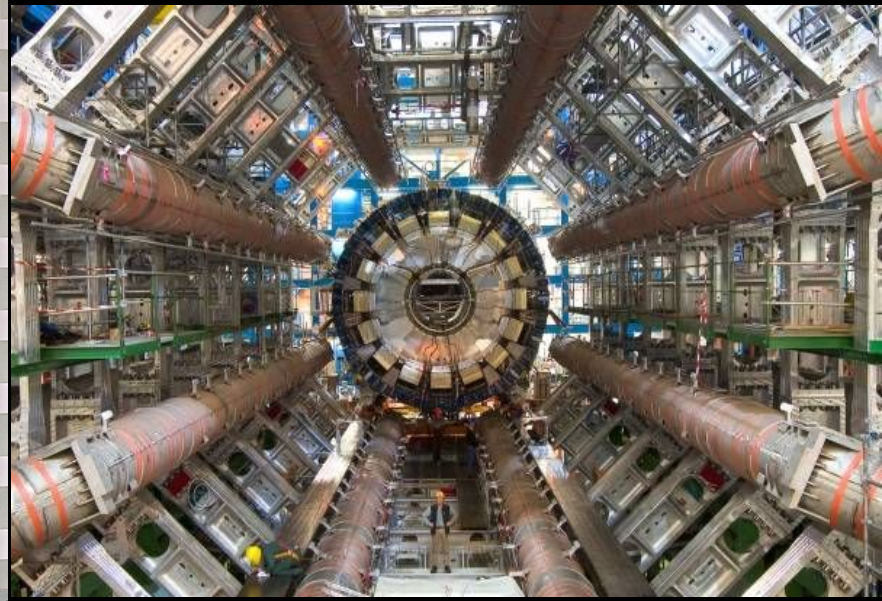


Source : http://hep.uchicago.edu/atlas/nwt2/

Source : https://sciencenode.org/feature/how-grid-computing-helped-cern-hunt-higgs.php

Theory ⟷ Experiment





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Hunt them in the Data

Experimental results

Ejemplo de Teoría que queremos probar !

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Neutrino Masses

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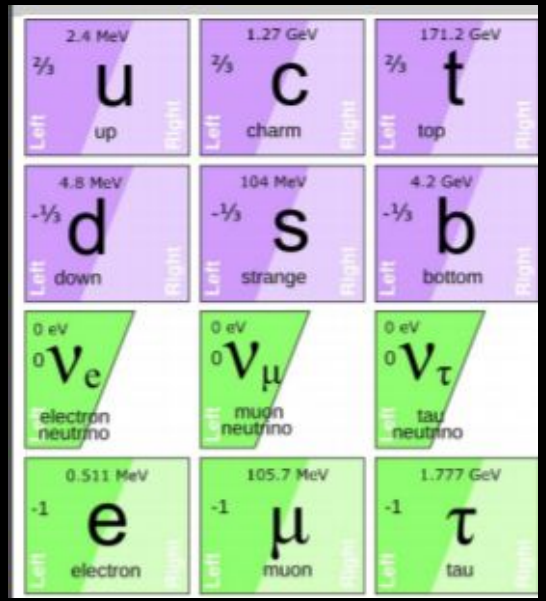
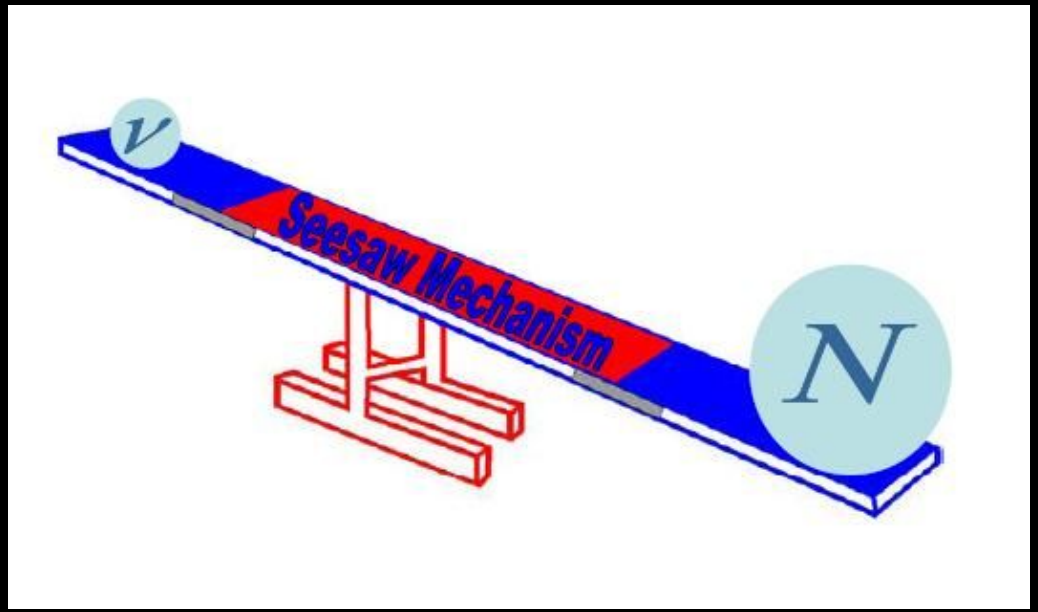
2) Theory

Standard Model + N

See-saw:
P. Minkowski, Phys. Lett. 67B (1977)
R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. 44 (1980)
J. Schechter and J. W. F. Valle, Phys. Rev. D22, 2227 (1980)





$$m_\nu \simeq -M_D M_N^{-1} M_D^T.$$

$$\nu_\ell \simeq U_{\ell m}\nu^m + V_{\ell n}N^n,$$

$$V_{\ell n} \simeq M_D M_N^{-1}$$

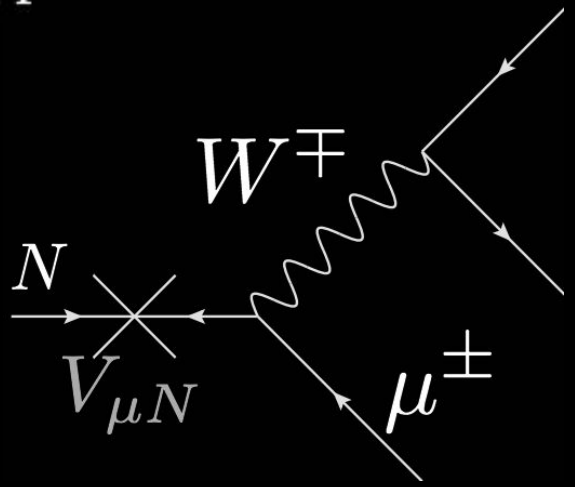
2) Theory

Standard Model + N

$$pp \to W^{\pm} \to N l^{\pm}$$

$$N \to l^{\pm} q \bar{q}$$

$$N \to l'^{\mp} l^{\pm} \nu_l \qquad N \to \nu_l q \bar{q}$$



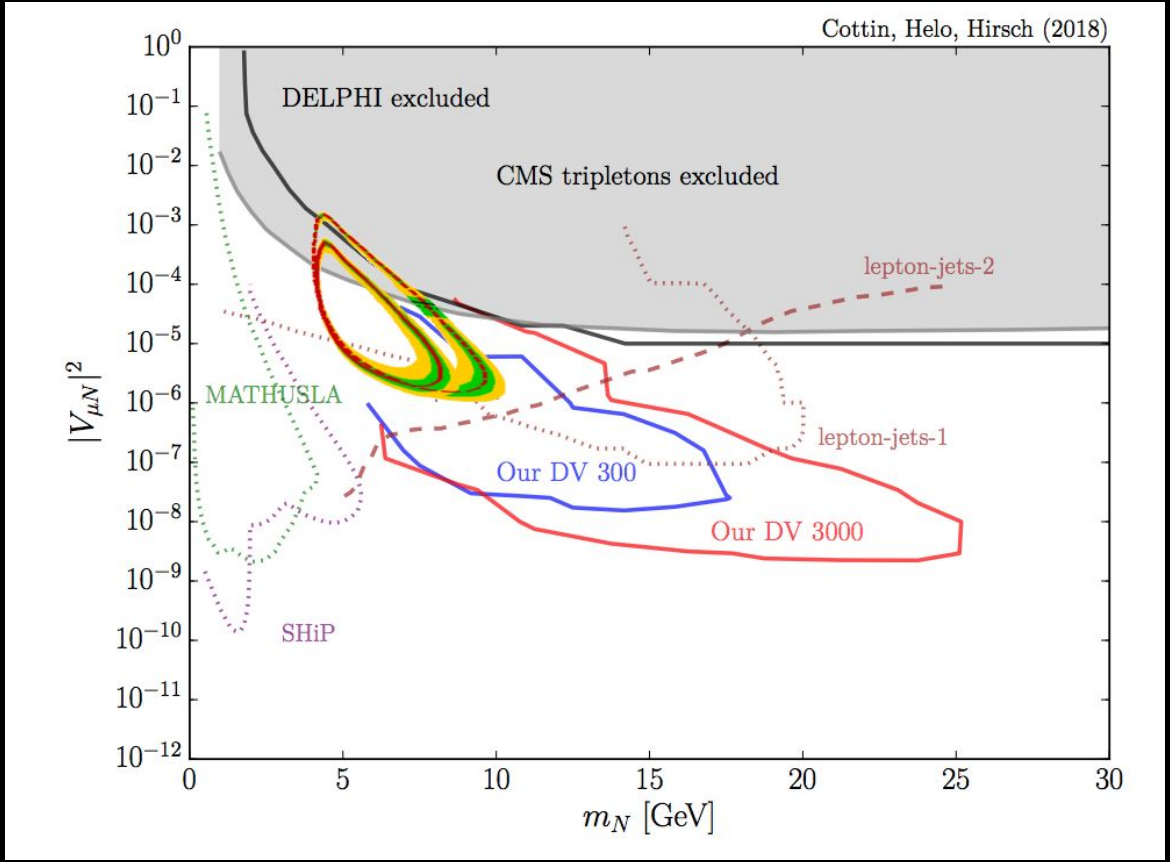
$$c\tau_N \sim 3.7 \left(\frac{1\,\text{GeV}}{m_N} \right)^5 \left(\frac{0.1}{|V_{lN}|^2} \right) \text{ [mm]}$$

Sterile N mixes with SM neutrino.
Large lifetime due to off-shell decay

displaced N studies in:

G. Cottin, J.C. Helo, M. Hirsch, D. Silva, Phys. Rev. D.99 (2019)
G. Cottin, J.C. Helo and M. Hirsch, Phys. Rev. D97 (2018)
G. Cottin, J.C. Helo and M. Hirsch, Phys. Rev. D98 (2018)
E. Izaguirre and B. Shuve, Phys. Rev. D91 (2015)
S. Dube, D. Gadkari, and A. M. Thalapillil, Phys. Rev. D96 (2017)
J. C. Helo, M. Hirsch, and S. Kovalenko, Phys. Rev. D89 (2014)

The LHC can probe this model with a displaced vertex search strategy and reach regions of parameter space that other searches and even other experiments can NOT !



ATLAS
arXiv:1905.09787

Theory

Phenomenology

Experiment