A experiência

ATLAS

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Ciências ULisboa
IF INVESTIGADOR FCT
LIP

Sumário

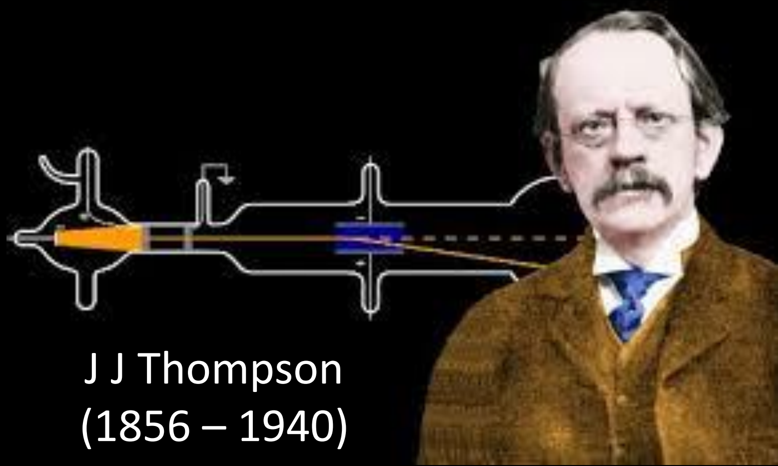
- **Revisão da matéria dada**
  - As partículas e as forças fundamentais
  - O mecanismo de Higgs
- **A experiência ATLAS**
  - O LHC e ATLAS
  - A descoberta do Higgs
- **Depois da descoberta**

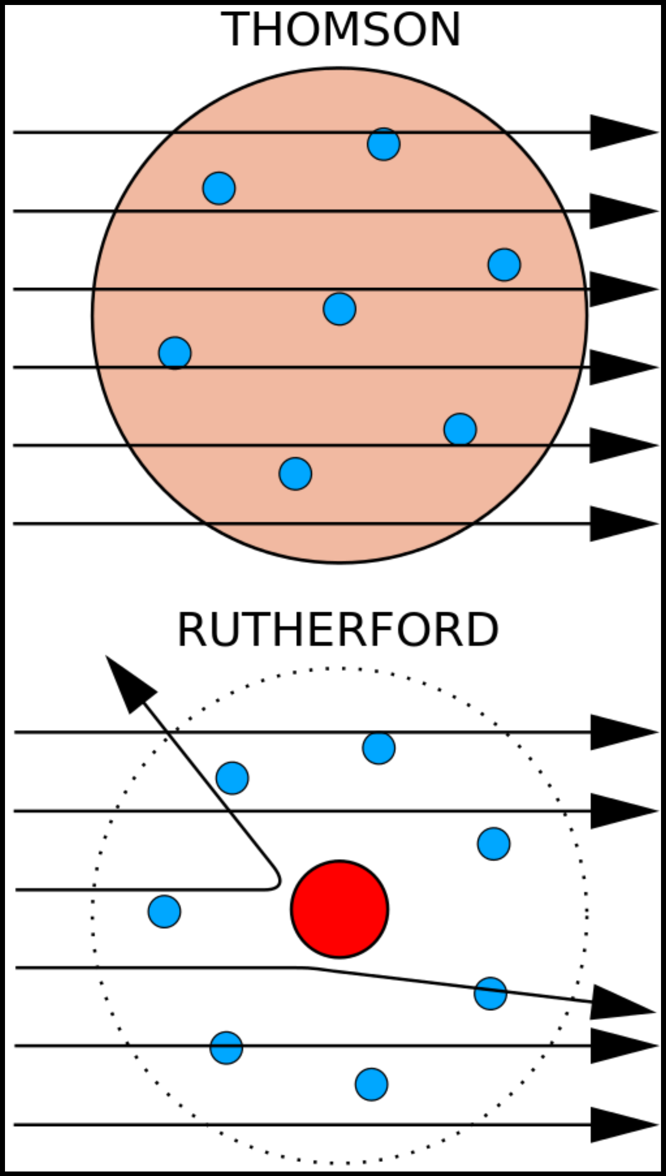
O Modelo Padrão da física de partículas

Ou

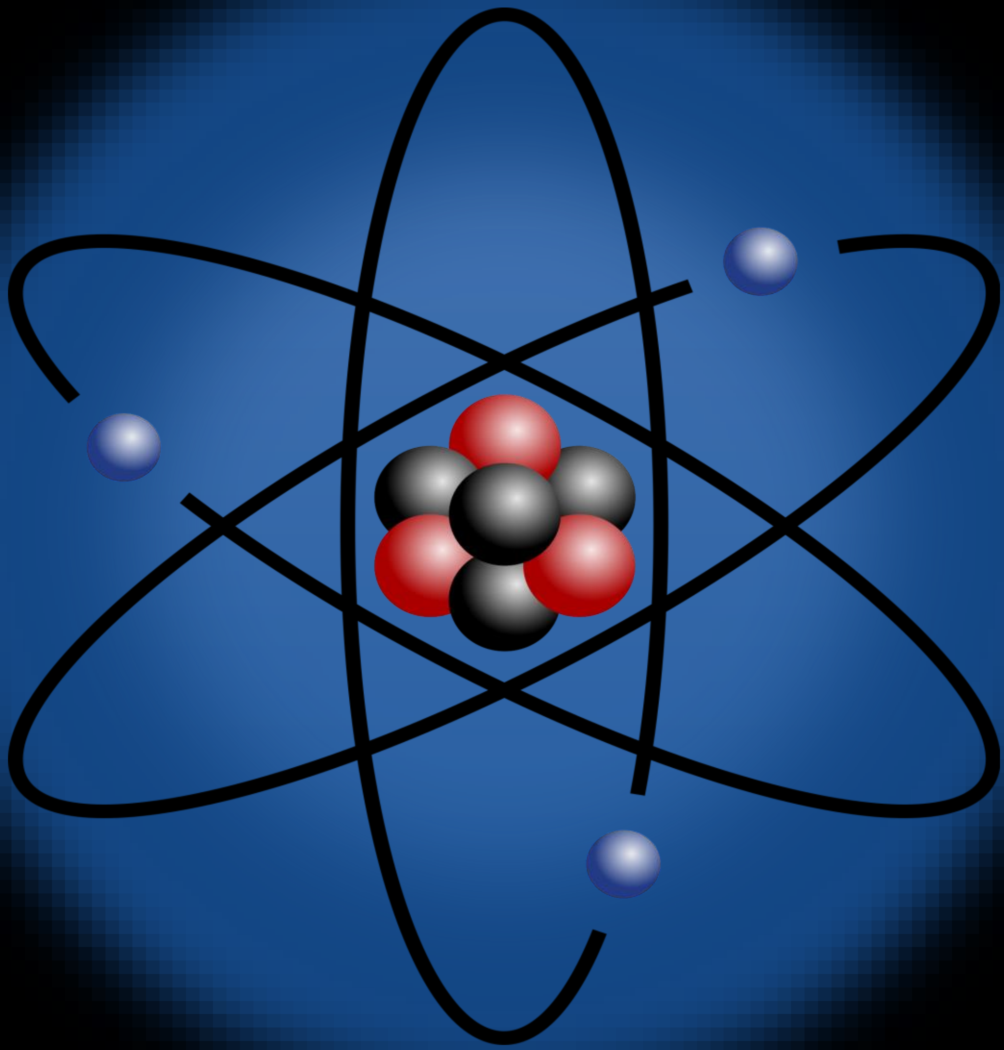
O que pensamos saber do funcionamento do Universo…

Há cerca de 100 anos...
A pré-história...



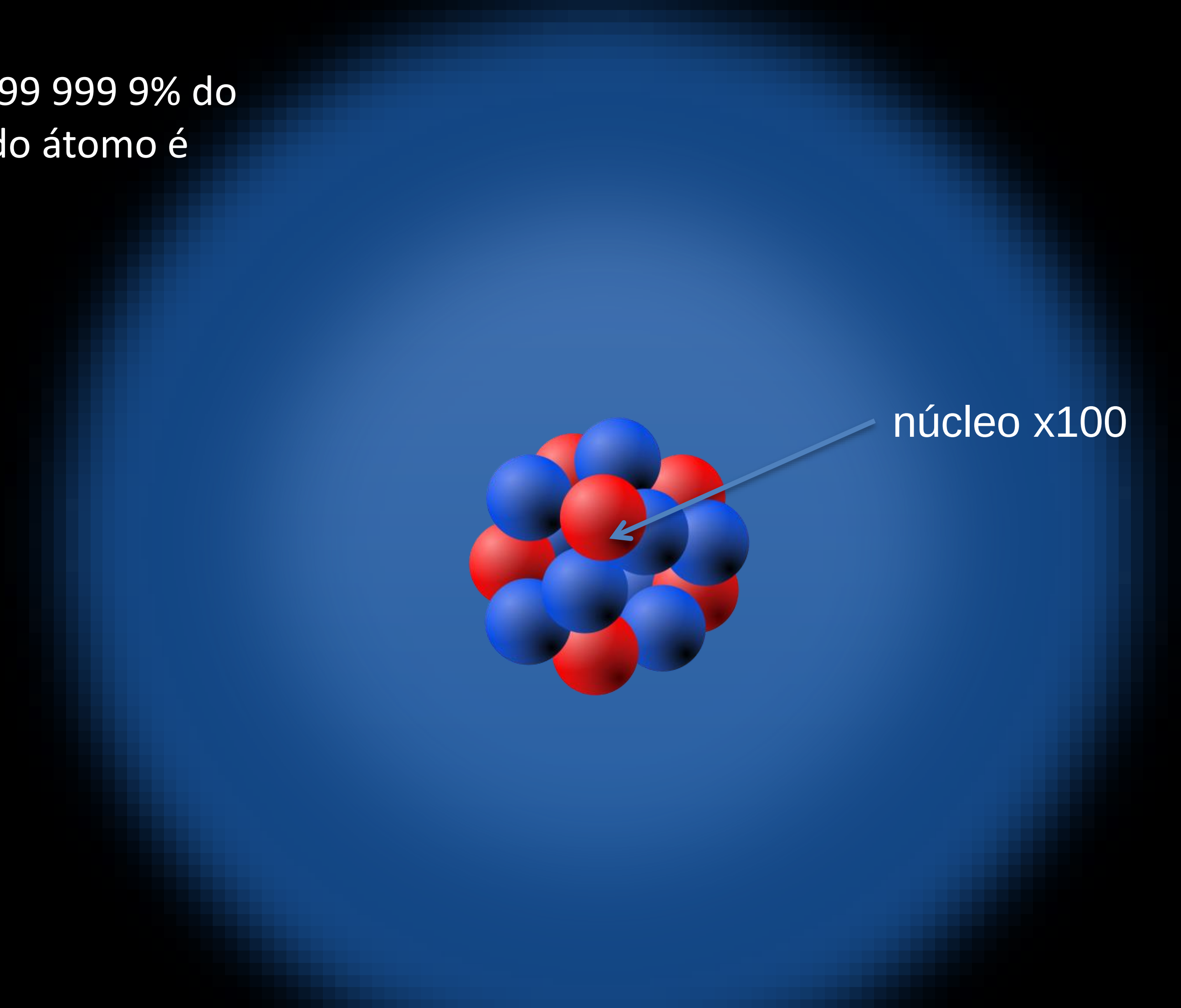


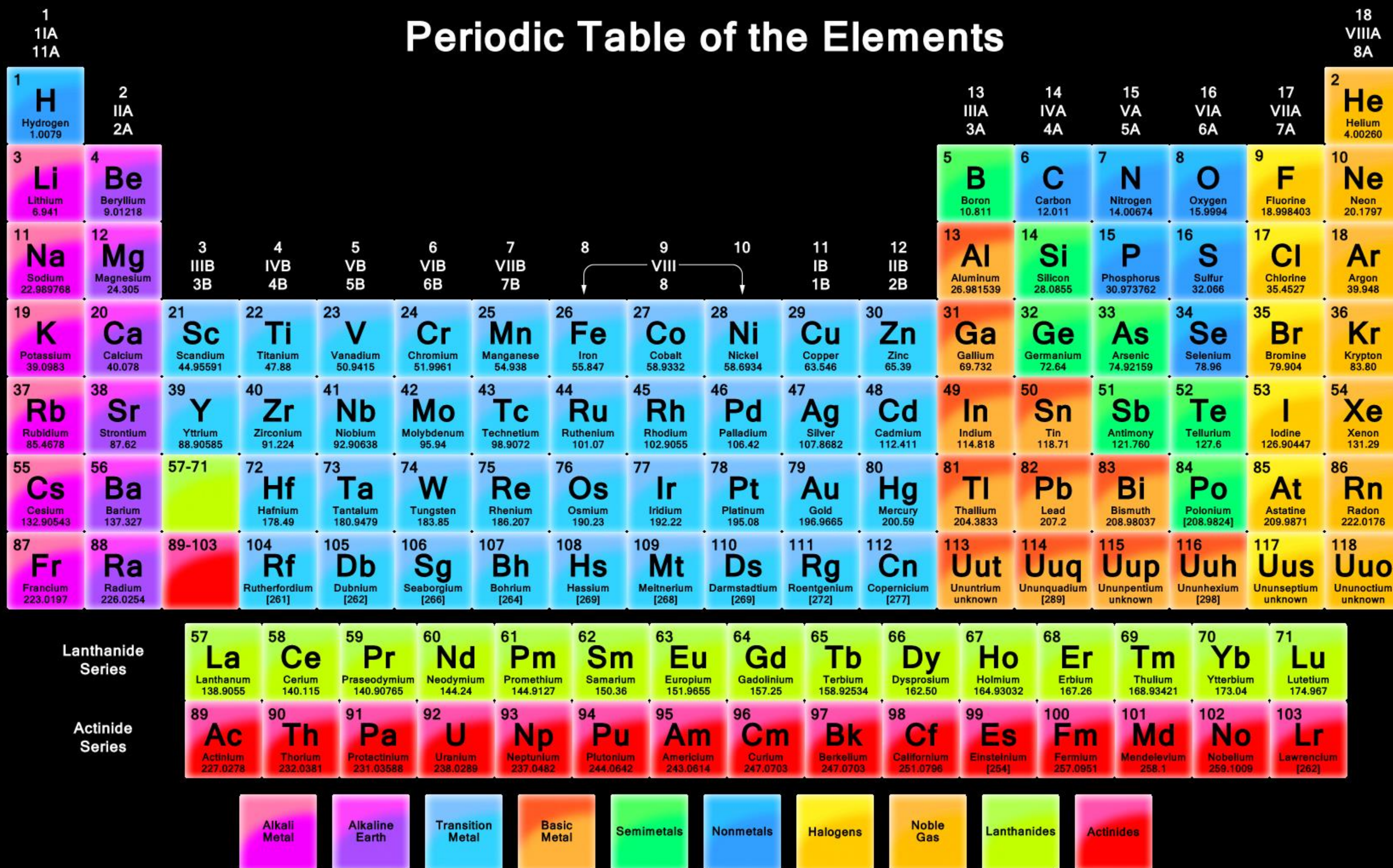
O átomo



O átomo

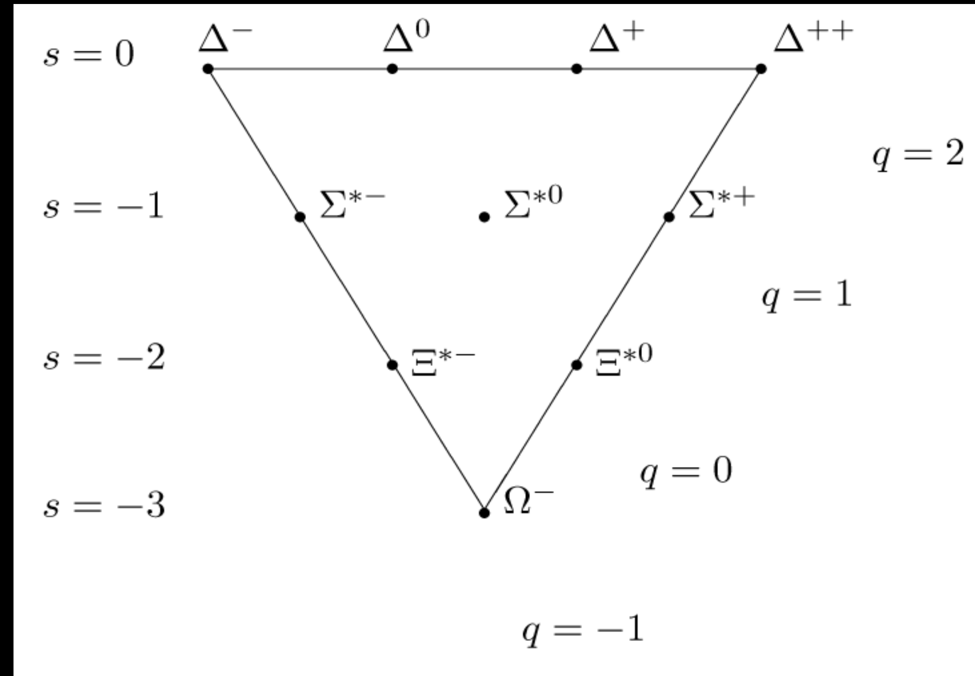
99.999 999 999 9% do volume do átomo é vazio!




Periodic Table of the Elements
1 1IA 11A
2 IIA 2A
3 IIIB 3B
4 IVB 4B
5 VB 5B
6 VIB 6B
7 VIIB 7B
8
9 VIII 8
10
11 IB 1B
12 IIB 2B
13 IIIA 3A
14 IVA 4A
15 VA 5A
16 VIA 6A
17 VIIA 7A
18 VIIIA 8A
1 H Hydrogen 1.0079
2 He Helium 4.00260
3 Li Lithium 6.941
4 Be Beryllium 9.01218
5 B Boron 10.811
6 C Carbon 12.011
7 N Nitrogen 14.00674
8 O Oxygen 15.9994
9 F Fluorine 18.998403
10 Ne Neon 20.1797
11 Na Sodium 22.989768
12 Mg Magnesium 24.305
13 Al Aluminum 26.981539
14 Si Silicon 28.0855
15 P Phosphorus 30.973762
16 S Sulfur 32.066
17 Cl Chlorine 35.4527
18 Ar Argon 39.948
19 K Potassium 39.0983
20 Ca Calcium 40.078
21 Sc Scandium 44.95591
22 Ti Titanium 47.88
23 V Vanadium 50.9415
24 Cr Chromium 51.9961
25 Mn Manganese 54.938
26 Fe Iron 55.847
27 Co Cobalt 58.9332
28 Ni Nickel 58.6934
29 Cu Copper 63.546
30 Zn Zinc 65.39
31 Ga Gallium 69.732
32 Ge Germanium 72.64
33 As Arsenic 74.92159
34 Se Selenium 78.96
35 Br Bromine 79.904
36 Kr Krypton 83.80
37 Rb Rubidium 85.4678
38 Sr Strontium 87.62
39 Y Yttrium 88.90585
40 Zr Zirconium 91.224
41 Nb Niobium 92.90638
42 Mo Molybdenum 95.94
43 Tc Technetium 98.9072
44 Ru Ruthenium 101.07
45 Rh Rhodium 102.9055
46 Pd Palladium 106.42
47 Ag Silver 107.8682
48 Cd Cadmium 112.411
49 In Indium 114.818
50 Sn Tin 118.71
51 Sb Antimony 121.760
52 Te Tellurium 127.6
53 I Iodine 126.90447
54 Xe Xenon 131.29
55 Cs Cesium 132.90543
56 Ba Barium 137.327
57-71
72 Hf Hafnium 178.49
73 Ta Tantalum 180.9479
74 W Tungsten 183.85
75 Re Rhenium 186.207
76 Os Osmium 190.23
77 Ir Iridium 192.22
78 Pt Platinum 195.08
79 Au Gold 196.9665
80 Hg Mercury 200.59
81 Tl Thallium 204.3833
82 Pb Lead 207.2
83 Bi Bismuth 208.98037
84 Po Polonium [208.9824]
85 At Astatine 209.9871
86 Rn Radon 222.0176
87 Fr Francium 223.0197
88 Ra Radium 226.0254
89-103
104 Rf Rutherfordium [261]
105 Db Dubnium [262]
106 Sg Seaborgium [266]
107 Bh Bohrium [264]
108 Hs Hassium [269]
109 Mt Meitnerium [268]
110 Ds Darmstadtium [269]
111 Rg Roentgenium [272]
112 Cn Copernicium [277]
113 Uut Ununtrium unknown
114 Uuq Ununquadium [289]
115 Uup Ununpentium unknown
116 Uuh Ununhexium [298]
117 Uus Ununseptium unknown
118 Uuo Ununoctium unknown
Lanthanide Series
57 La Lanthanum 138.9055
58 Ce Cerium 140.115
59 Pr Praseodymium 140.90765
60 Nd Neodymium 144.24
61 Pm Promethium 144.9127
62 Sm Samarium 150.36
63 Eu Europium 151.9655
64 Gd Gadolinium 157.25
65 Tb Terbium 158.92534
66 Dy Dysprosium 162.50
67 Ho Holmium 164.93032
68 Er Erbium 167.26
69 Tm Thulium 168.93421
70 Yb Ytterbium 173.04
71 Lu Lutetium 174.967
Actinide Series
89 Ac Actinium 227.0278
90 Th Thorium 232.0381
91 Pa Protactinium 231.03588
92 U Uranium 238.0289
93 Np Neptunium 237.0482
94 Pu Plutonium 244.0642
95 Am Americium 243.0614
96 Cm Curium 247.0703
97 Bk Berkelium 247.0703
98 Cf Californium 251.0796
99 Es Einsteinium [254]
100 Fm Fermium 257.0951
101 Md Mendelevium 258.1
102 No Nobelium 259.1009
103 Lr Lawrencium [262]
Alkali Metal
Alkaline Earth
Transition Metal
Basic Metal
Semimetals
Nonmetals
Halogens
Noble Gas
Lanthanides
Actinides

A idade heroica


Observação de raios cósmicos, Plaza de Mulas Argentina, 1950

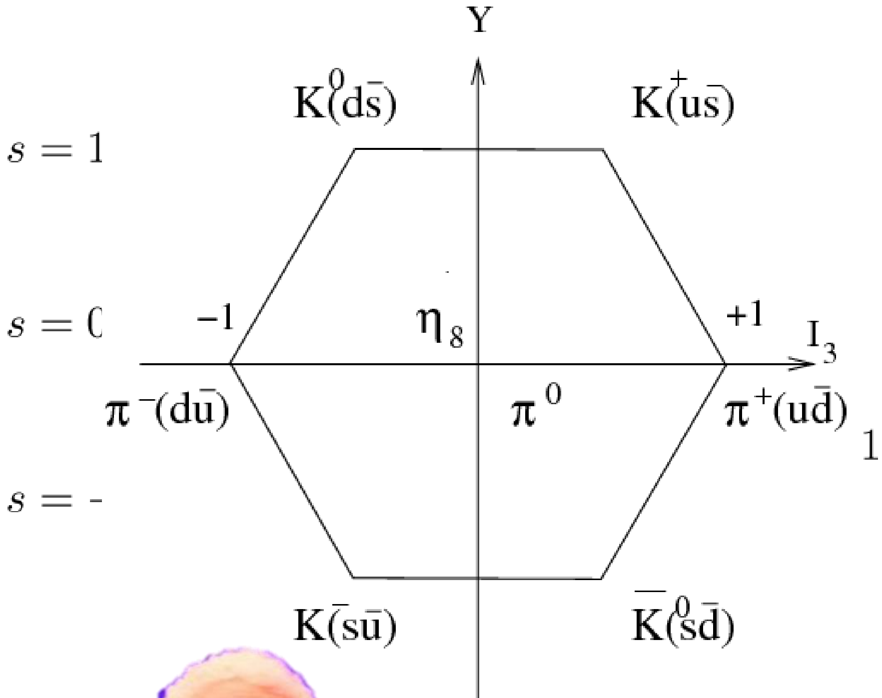



Victor Hess em 1911/1912

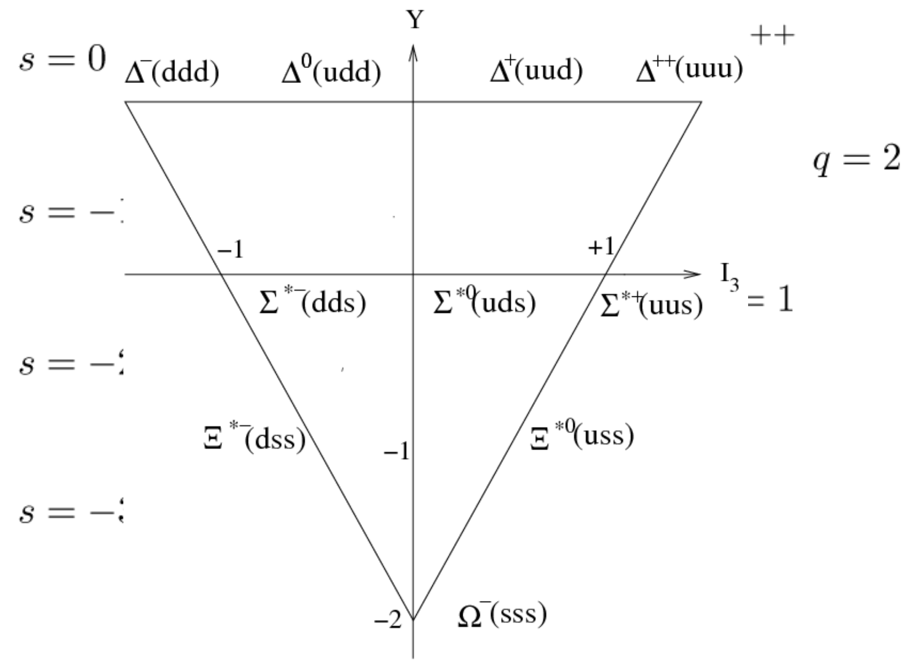

Acelerador de Van de Graaff


Um ciclotrão, cerca de 1950

MESÕES
(instáveis)



BARIÕES
(decaem até ao protão)

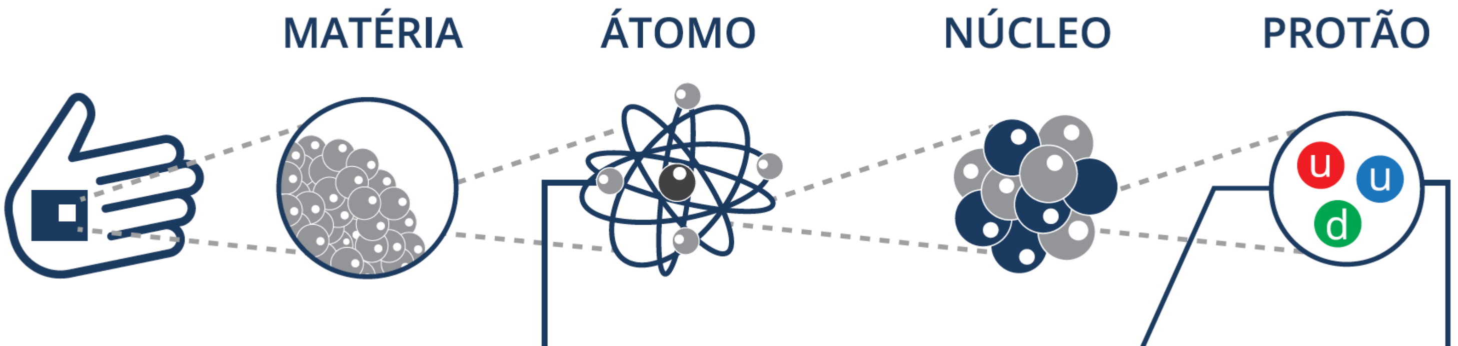


HADRÕES:

Do grego ***hadros*** (encorpado, forte)

Partículas constituídas por ***quarks***

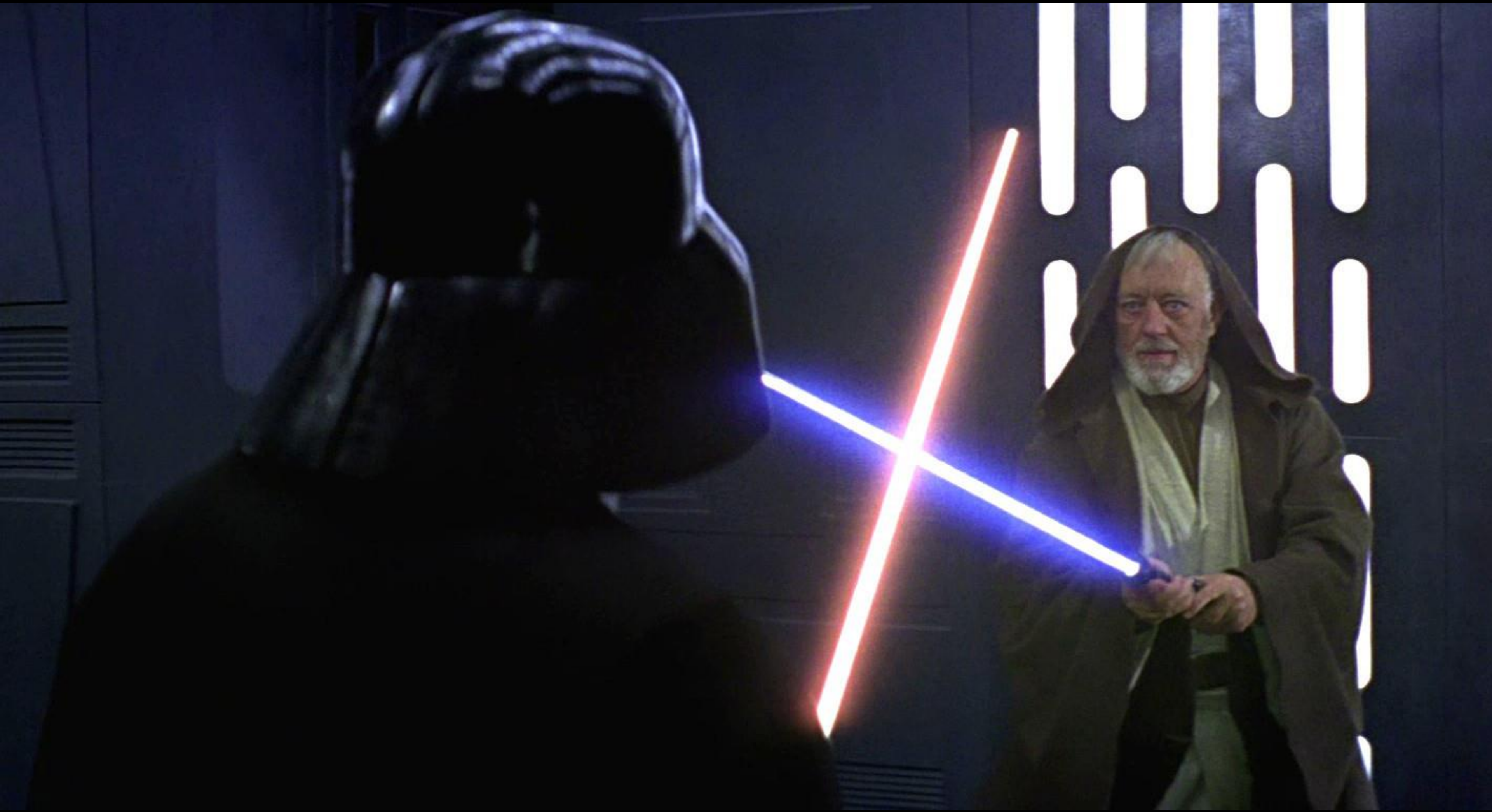
<u>Não são partículas elementares!</u>

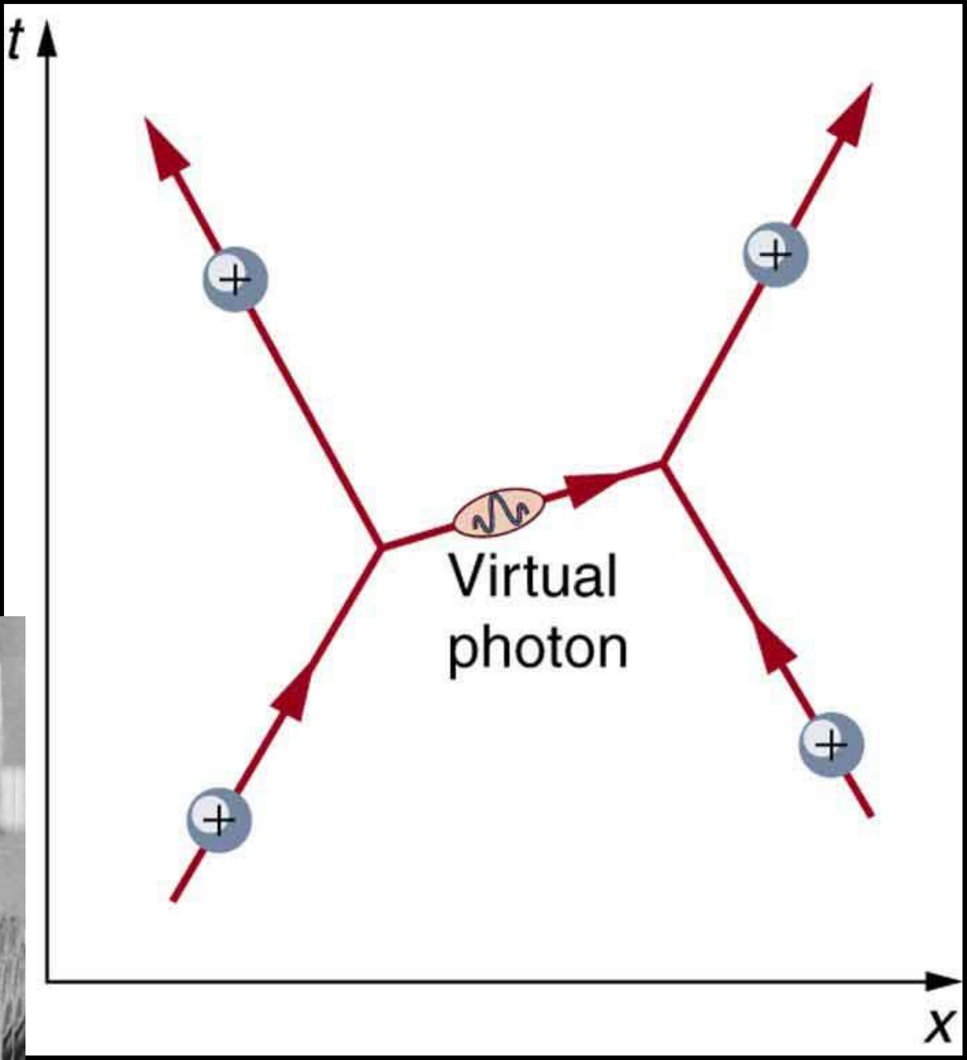


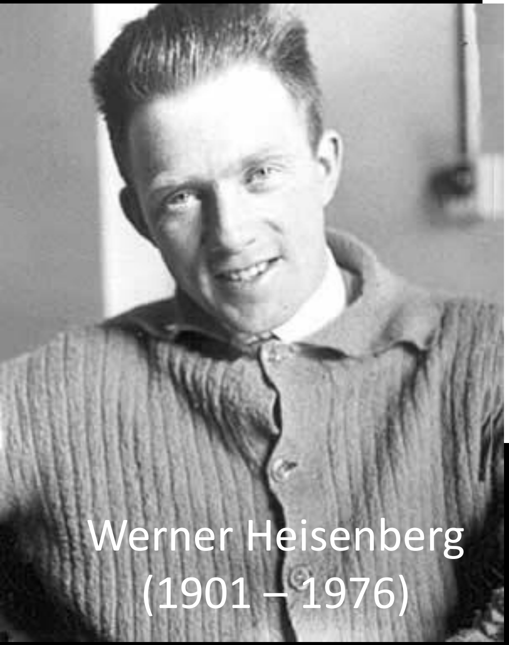
LEPTÕES	
ν_e NEUTRINO DO ELETRÃO 0 ½	e ELETRÃO -1 ½
ν_μ NEUTRINO DO MUÃO 0 ½	μ MUÃO -1 ½
ν_τ NEUTRINO DO TAU 0 ½	τ TAU -1 ½

QUARKS	
u UP ⅔ ½	d DOWN -⅓ ½
c CHARM ⅔ ½	s STRANGE -⅓ ½
t TOP ⅔ ½	b BOTTOM -⅓ ½

E as forças fundamentais?

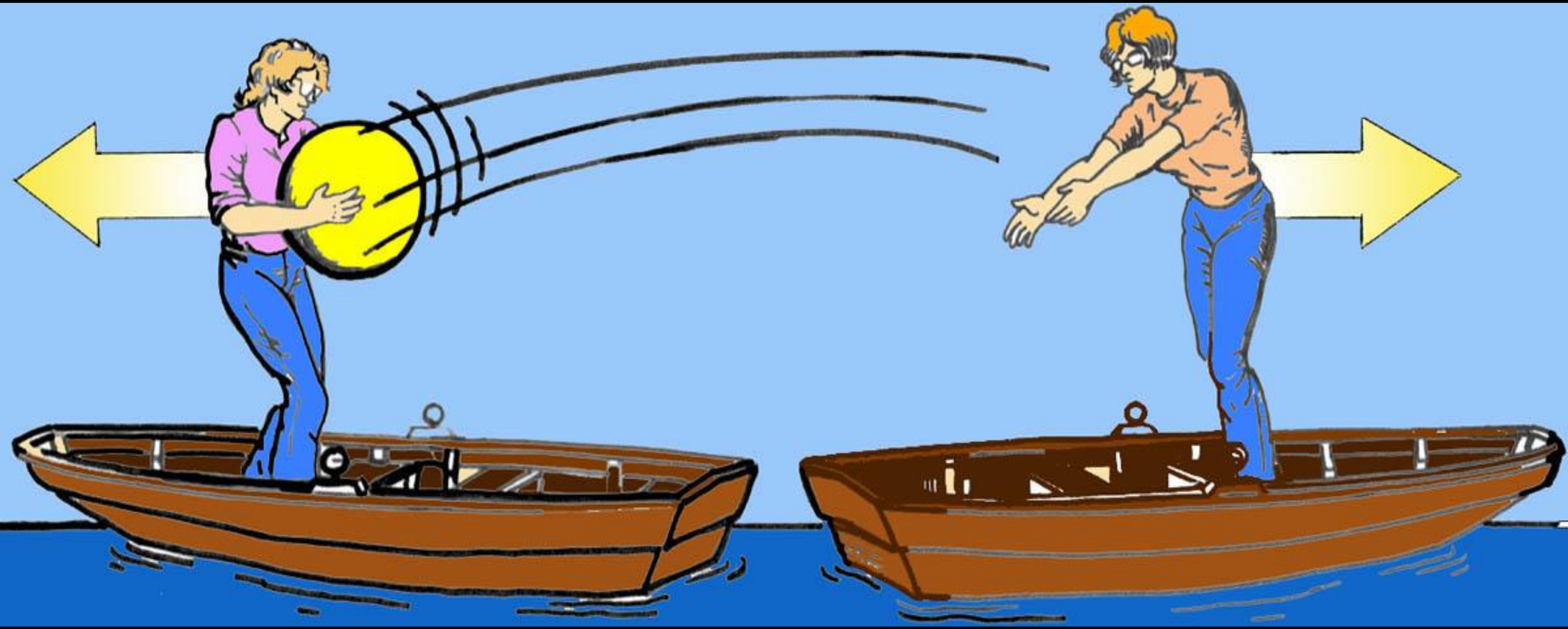


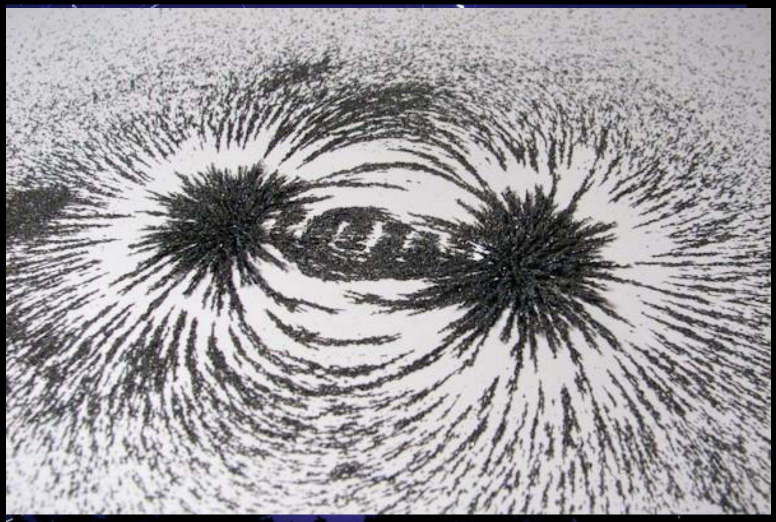


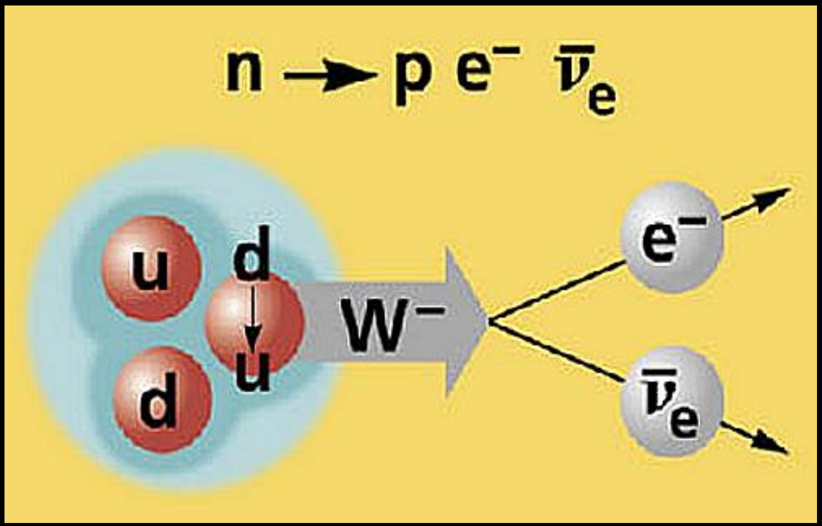


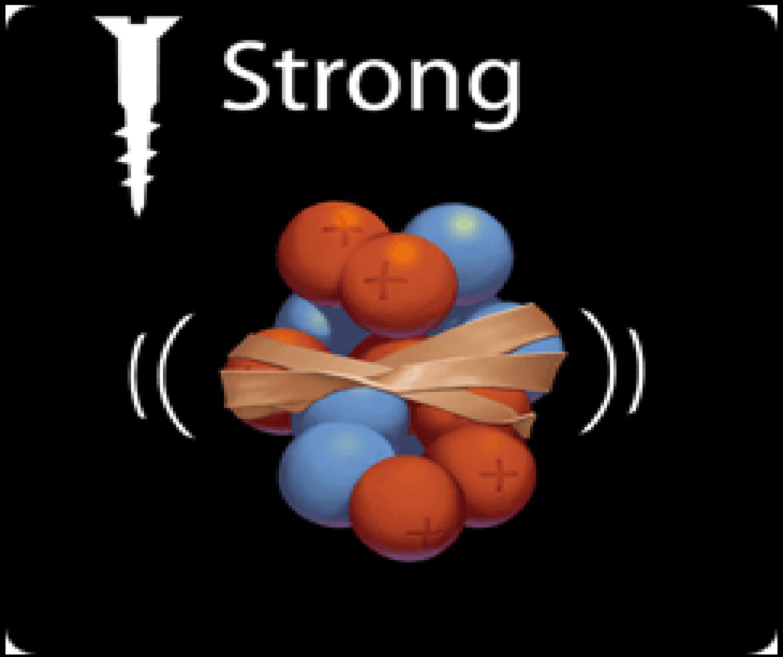
$$\Delta E \times \Delta t \approx \hbar$$

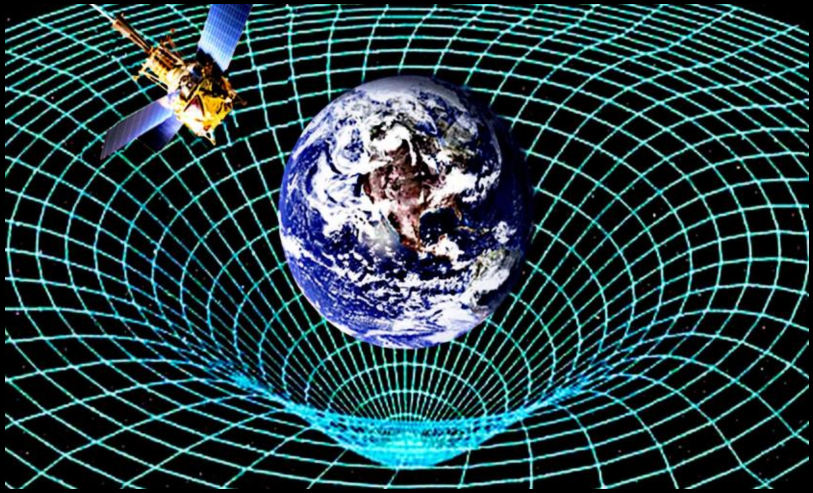
As forças fundamentais



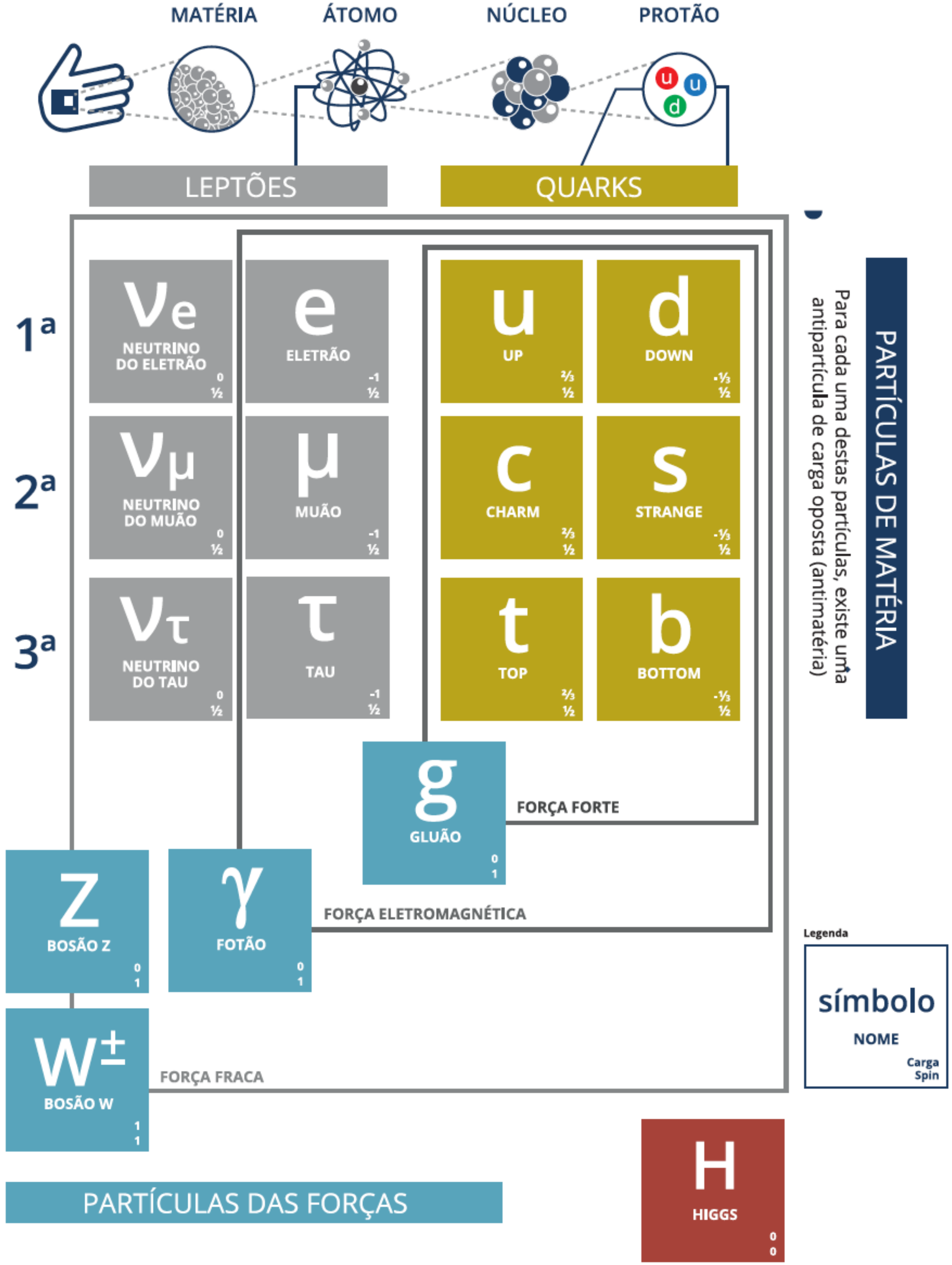



$n \rightarrow p\ e^-\ \bar{\nu}_e$
u
d
d
u
W^-
e^-
$\bar{\nu}_e$

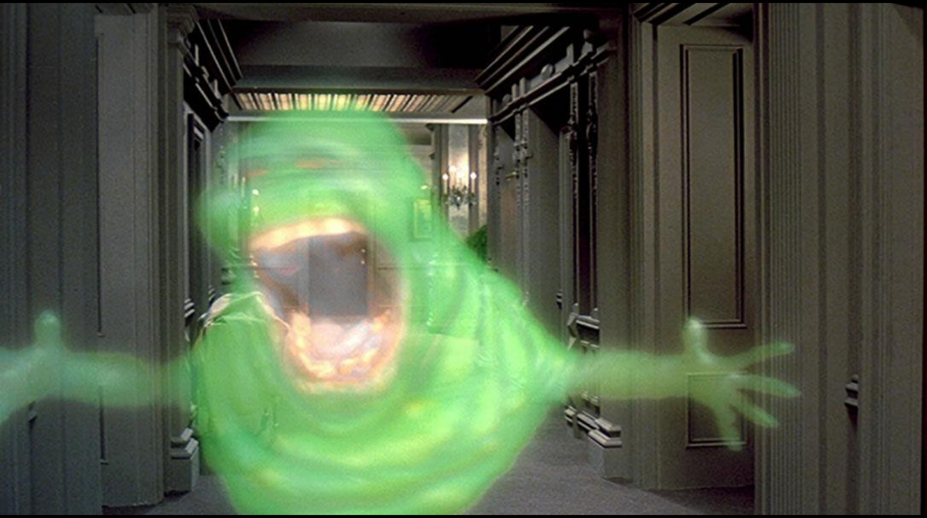

Strong



Finalmente, o Modelo Padrão da Física de Partículas!

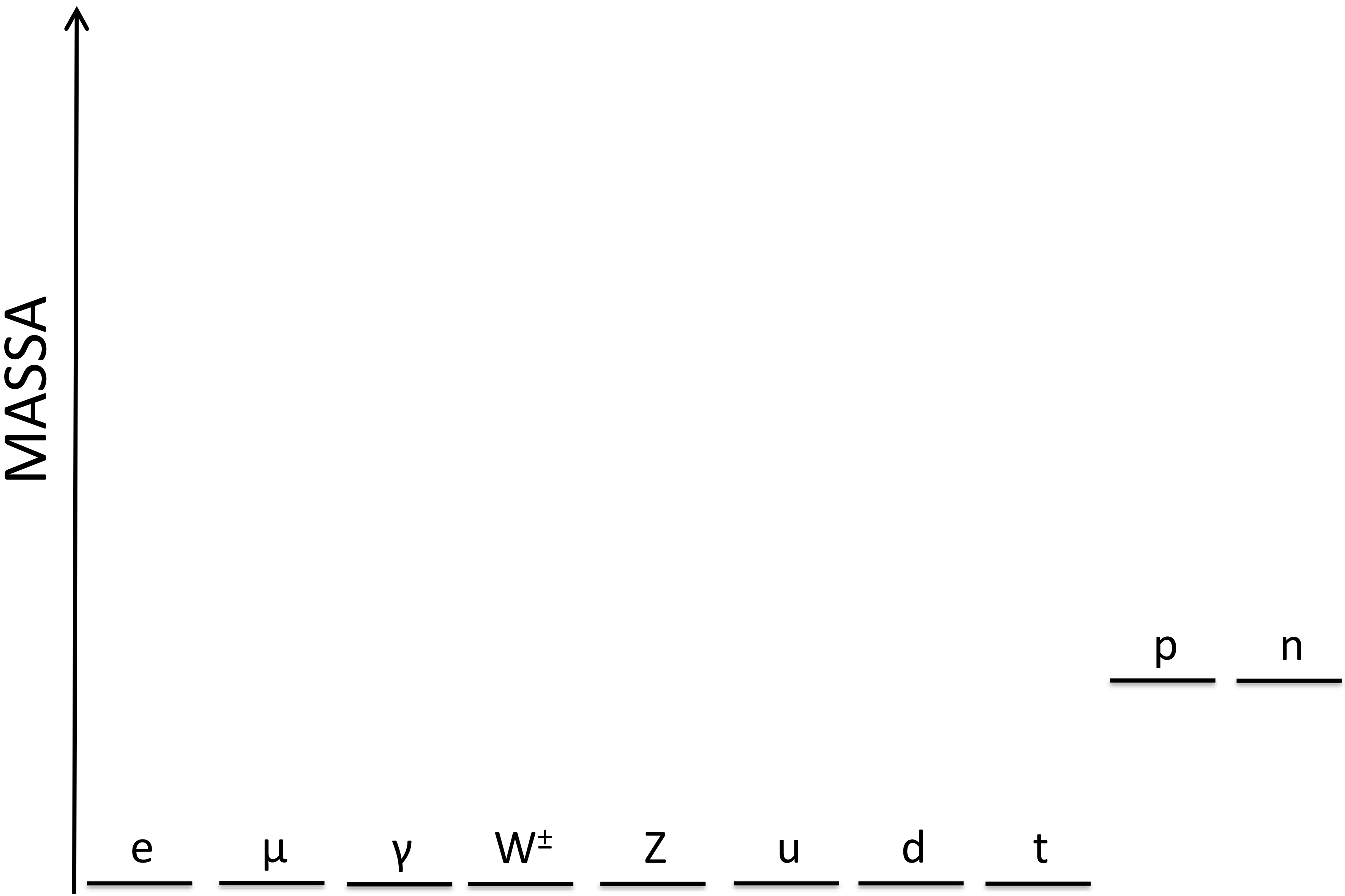


Teste de Avaliação Contínua:
O que está errado nestas imagens?

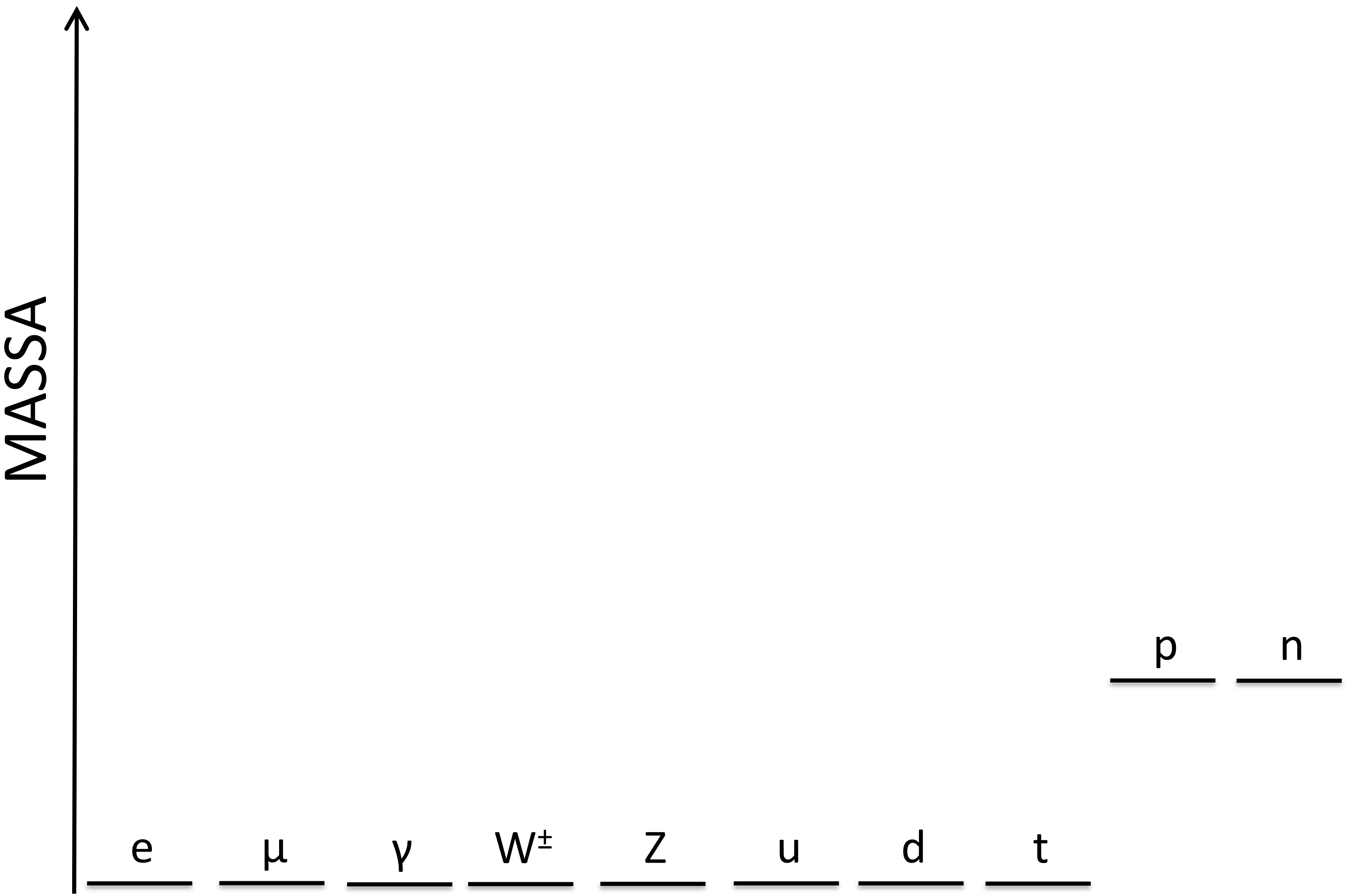


Agora chegamos aos problems...

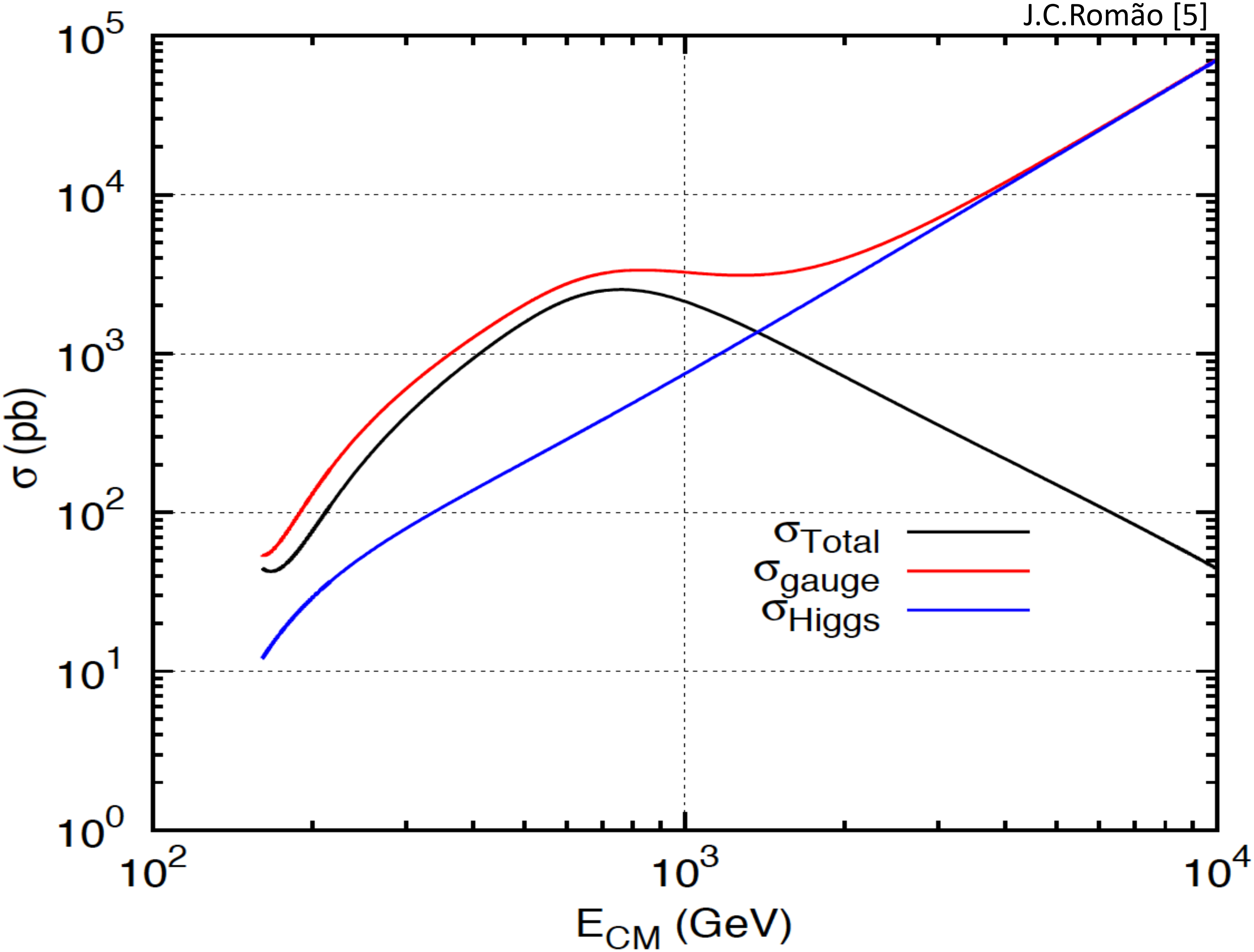
Isto não devia funcionar!...



Isto não devia funcionar!...

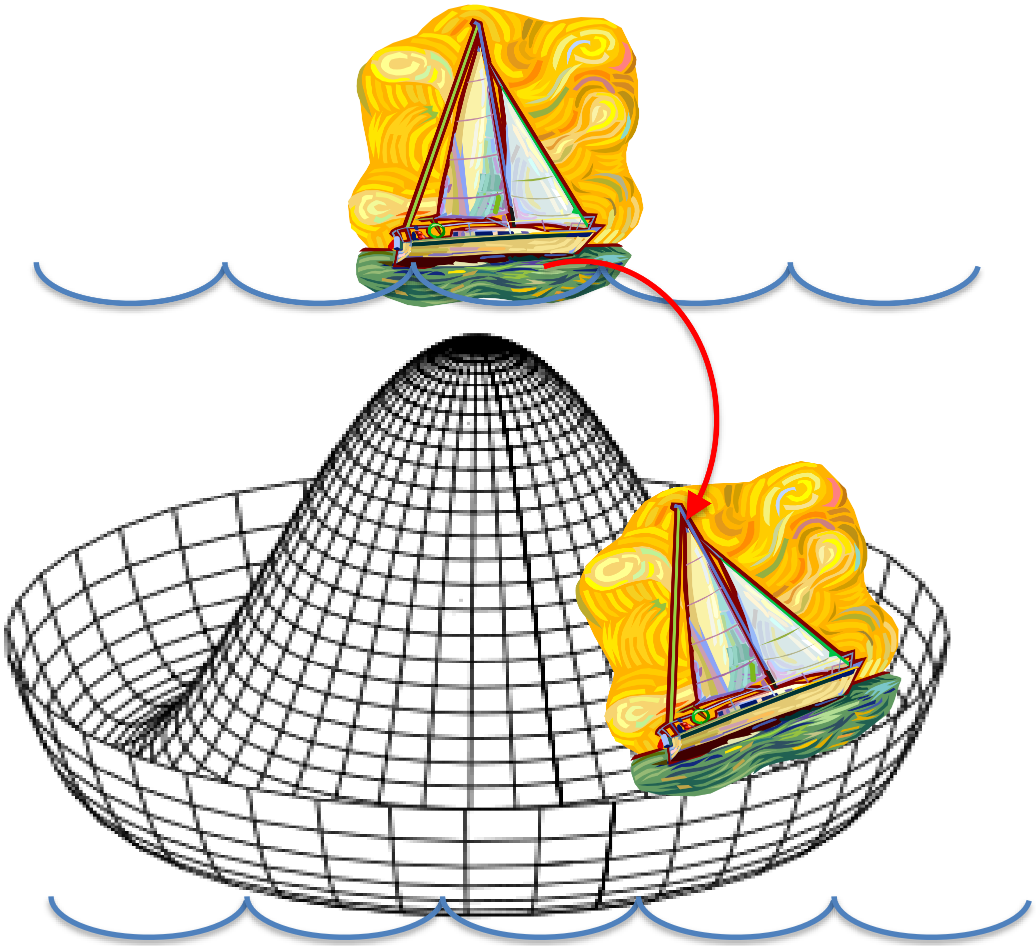


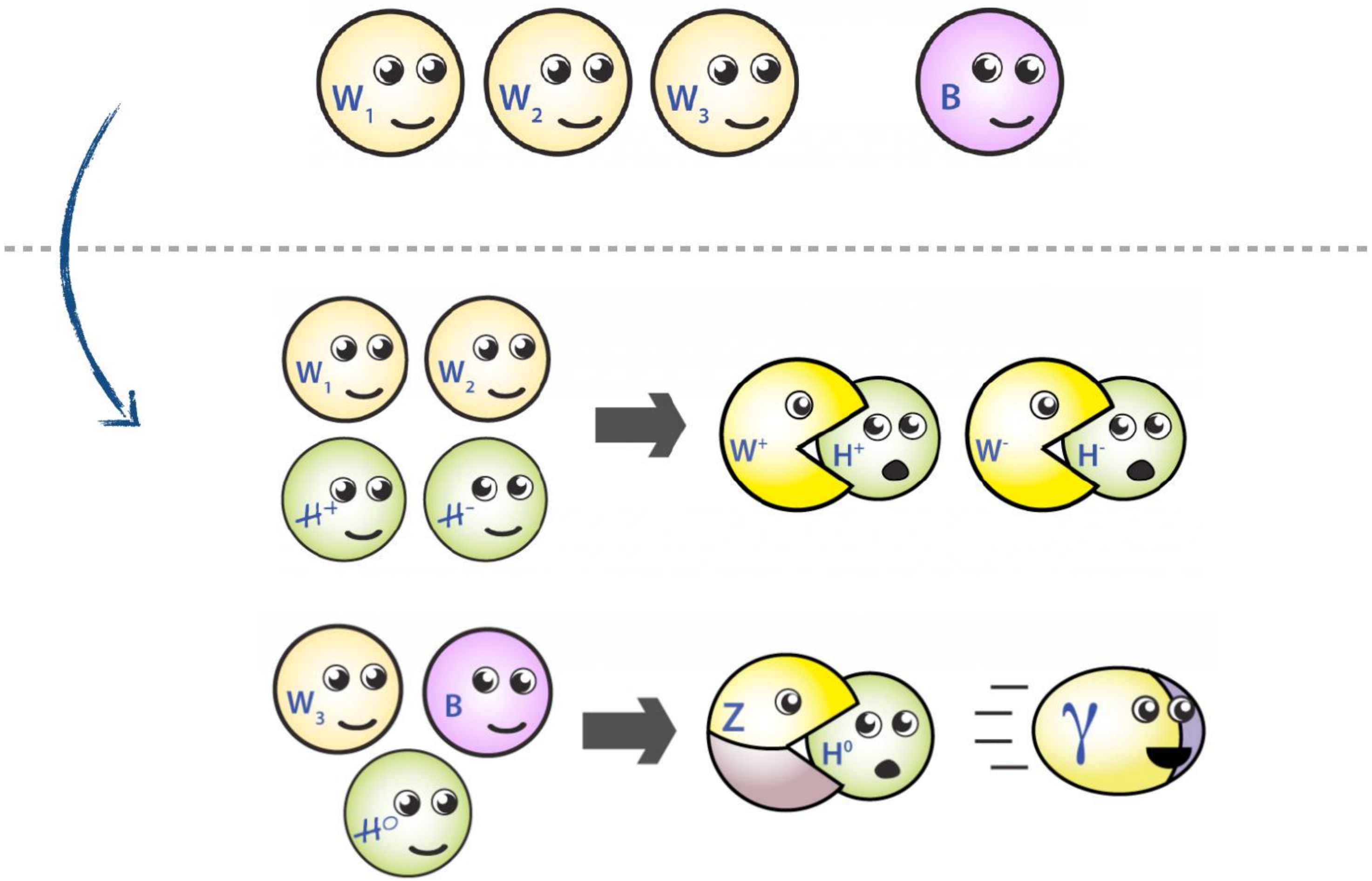
J.C.Romão [5]

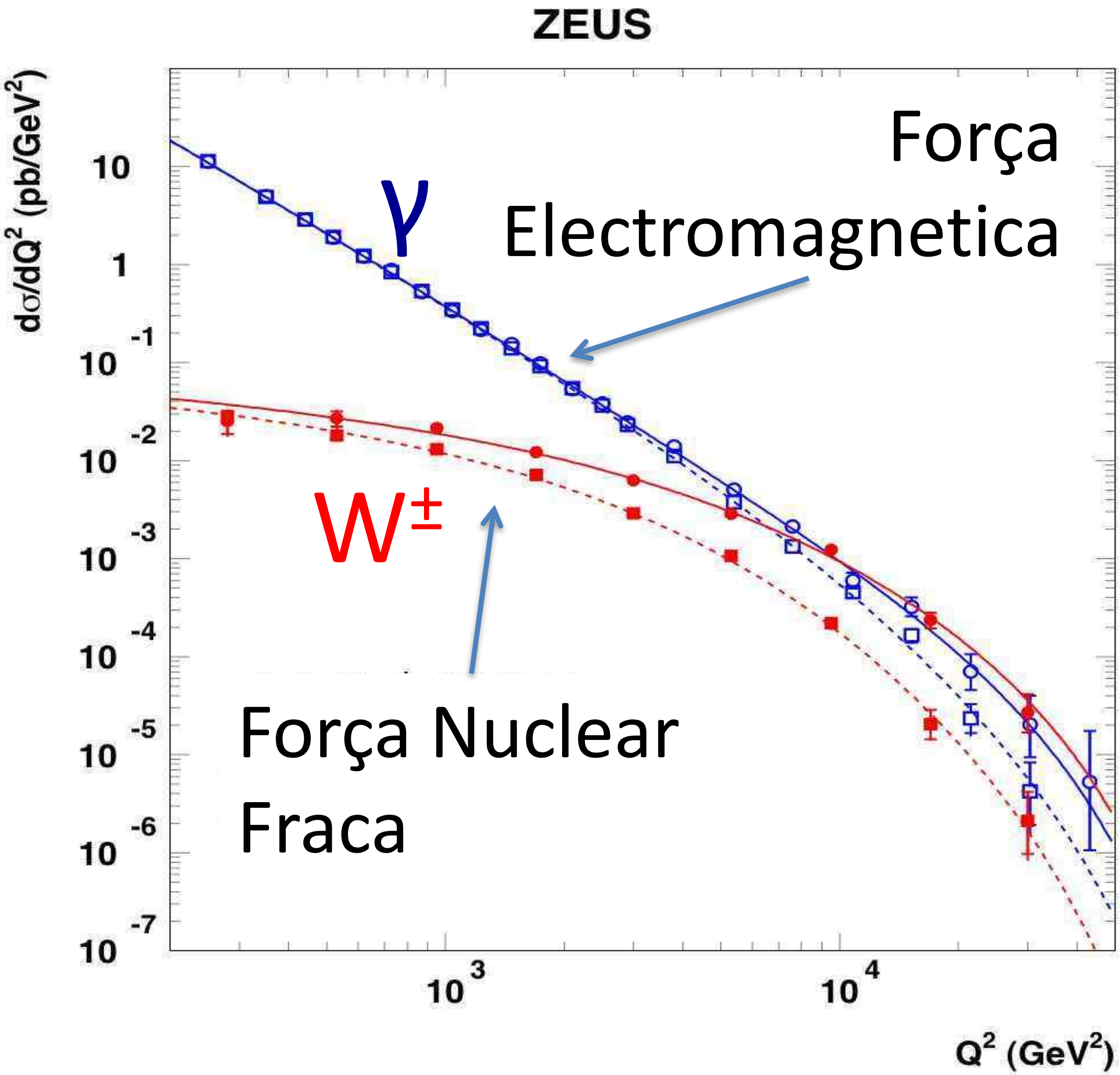


10^5
10^4
10^3
10^2
10^1
10^0
σ (pb)
10^2
10^3
10^4
E_{CM} (GeV)
σ_{Total}
σ_{gauge}
σ_{Higgs}

O Mecanismo de Higgs
em bonecos




W_1
W_2
W_3
B
W_1
W_2
H^+
H^-
W^+
H^+
W^-
H^-
W_3
B
H^0
Z
H^0
γ



ZEUS
dσ/dQ² (pb/GeV²)
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10³
10⁴
Q² (GeV²)
γ
Força
Electromagnetica
W±
Força Nuclear
Fraca

A Física Experimental de Partículas de hoje

A história começa há mais de 30 anos...

what is the origin of mass?

what kind of unification may exist beyond the standard model?

what is the origin of flavour?

is there a deeper reason for gauge symmetry?

We have simply too many a priori plausible hypotheses concerning the nature of symmetry breaking in the standard model. Experimentation in the TeV range at the constituent level is bound to provide most essential clues, and the present successes of the $p\bar{p}$ collider are a very strong encouragement to go to higher energies and to higher luminosities in hadron-hadron collisions.

PROCEEDINGS OF THE ECFA-CERN WORKSHOP

held at Lausanne and Geneva,
21–27 March 1984

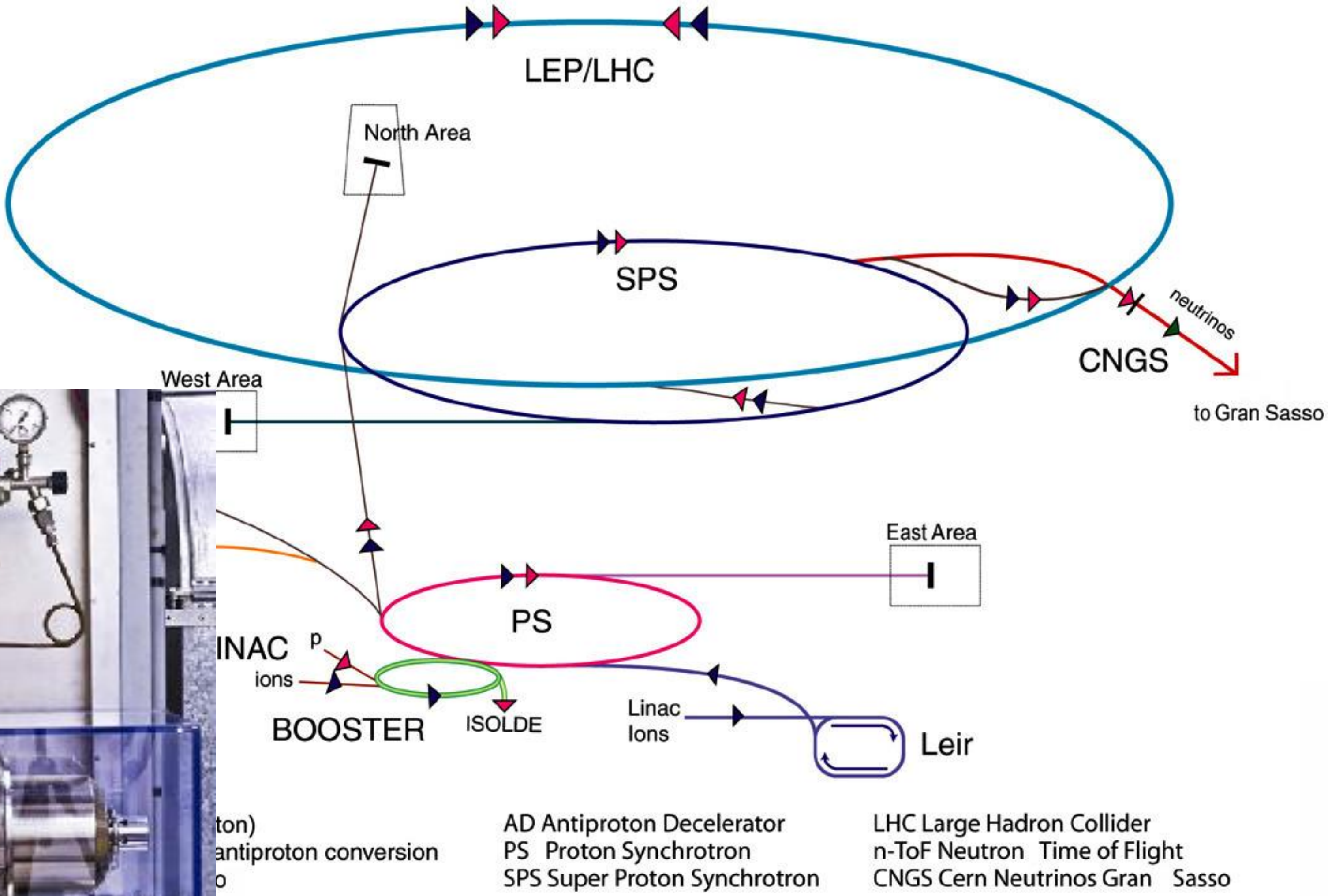
LINAC2 → **50 MeV**

Booster → **1.4 GeV**

Proton Synchroton (PS) → **25 GeV**

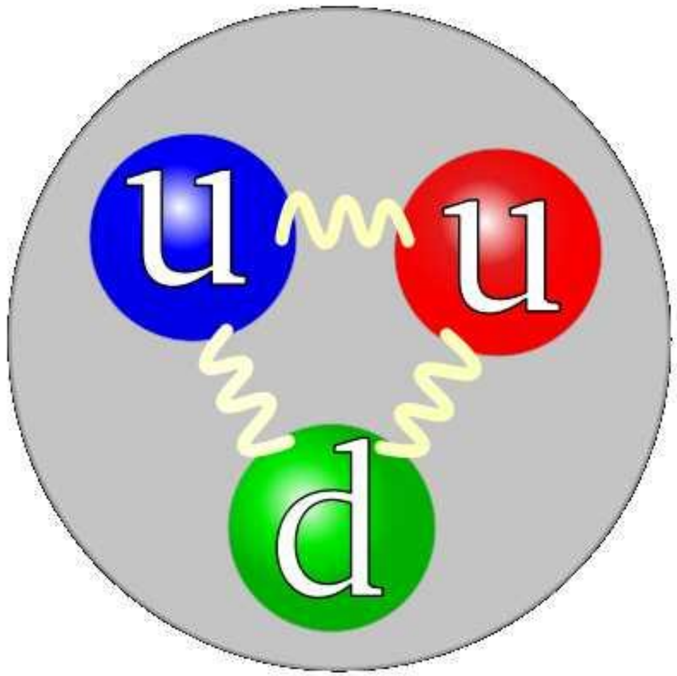
Super Proton Synchrotron (SPS) → **450 GeV**

Large Hadron Collider (LHC)→ **7 TeV**

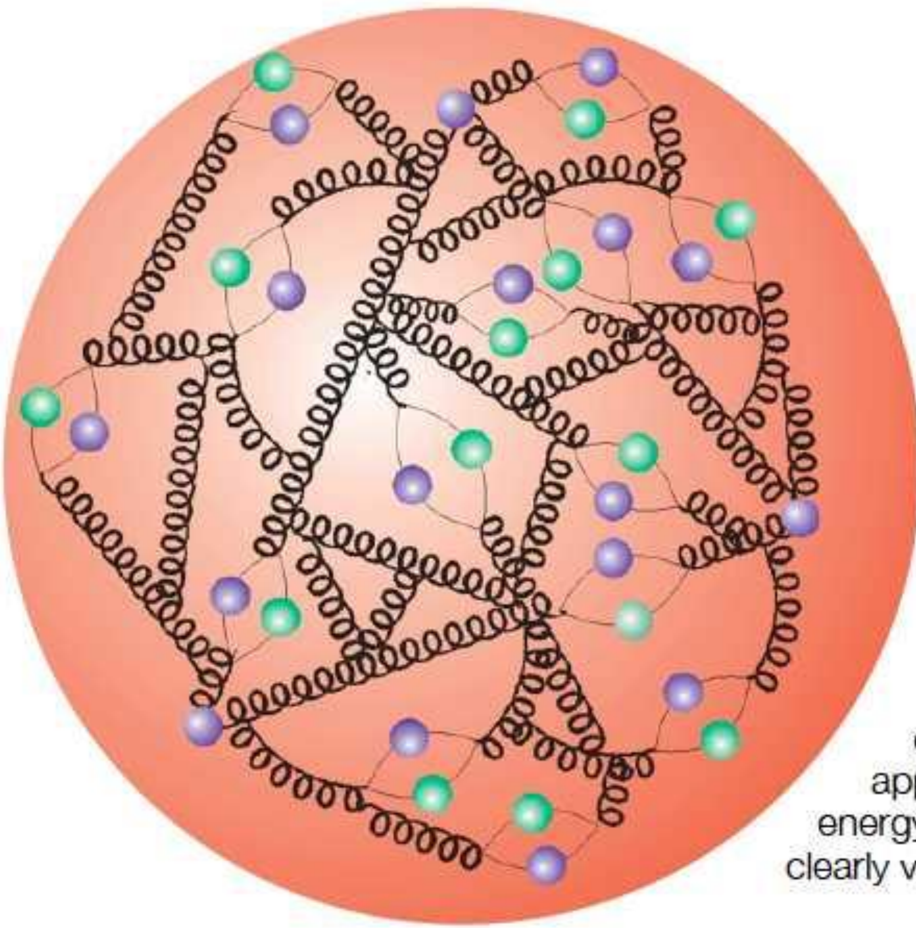


O que é um protão?

O protão no modelo dos quarks



O protão como o conhecemos hoje

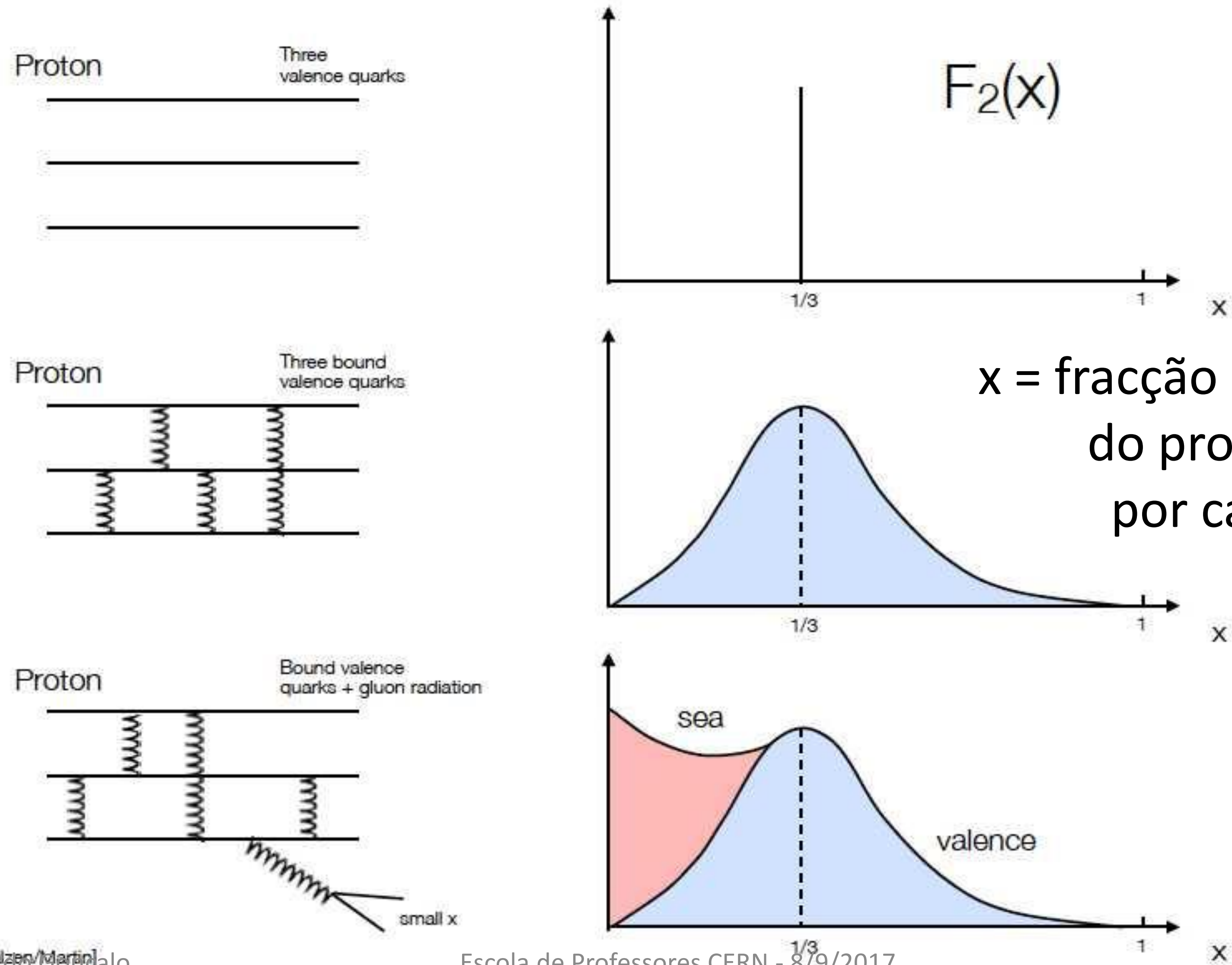


The most dramatic of these [experimental consequences], that the protons viewed at ever higher resolution would appear more and more as field energy (soft glue), was only clearly verified at HERA ...

F. Wilczek
[Nobel Prize 2004]

Como se distribui a energia dentro dos protões

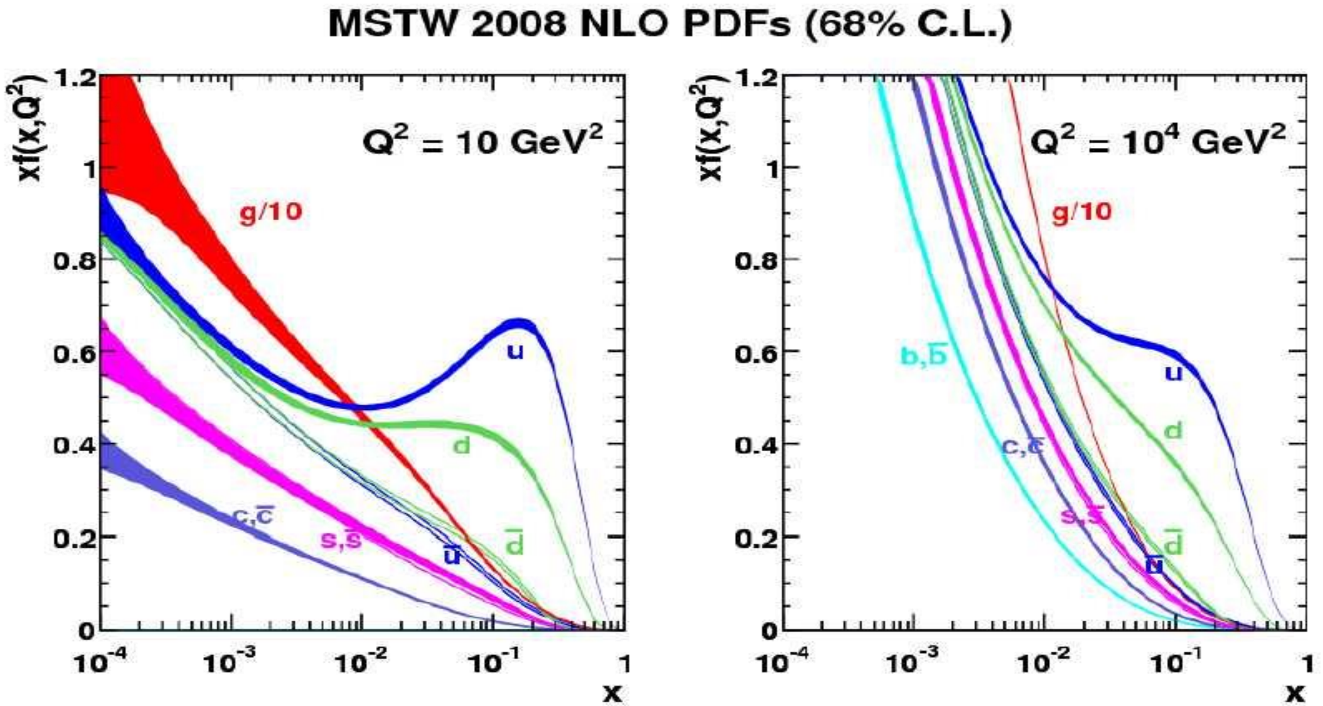
Partões: quarks e gluões constituintes dos hadrões



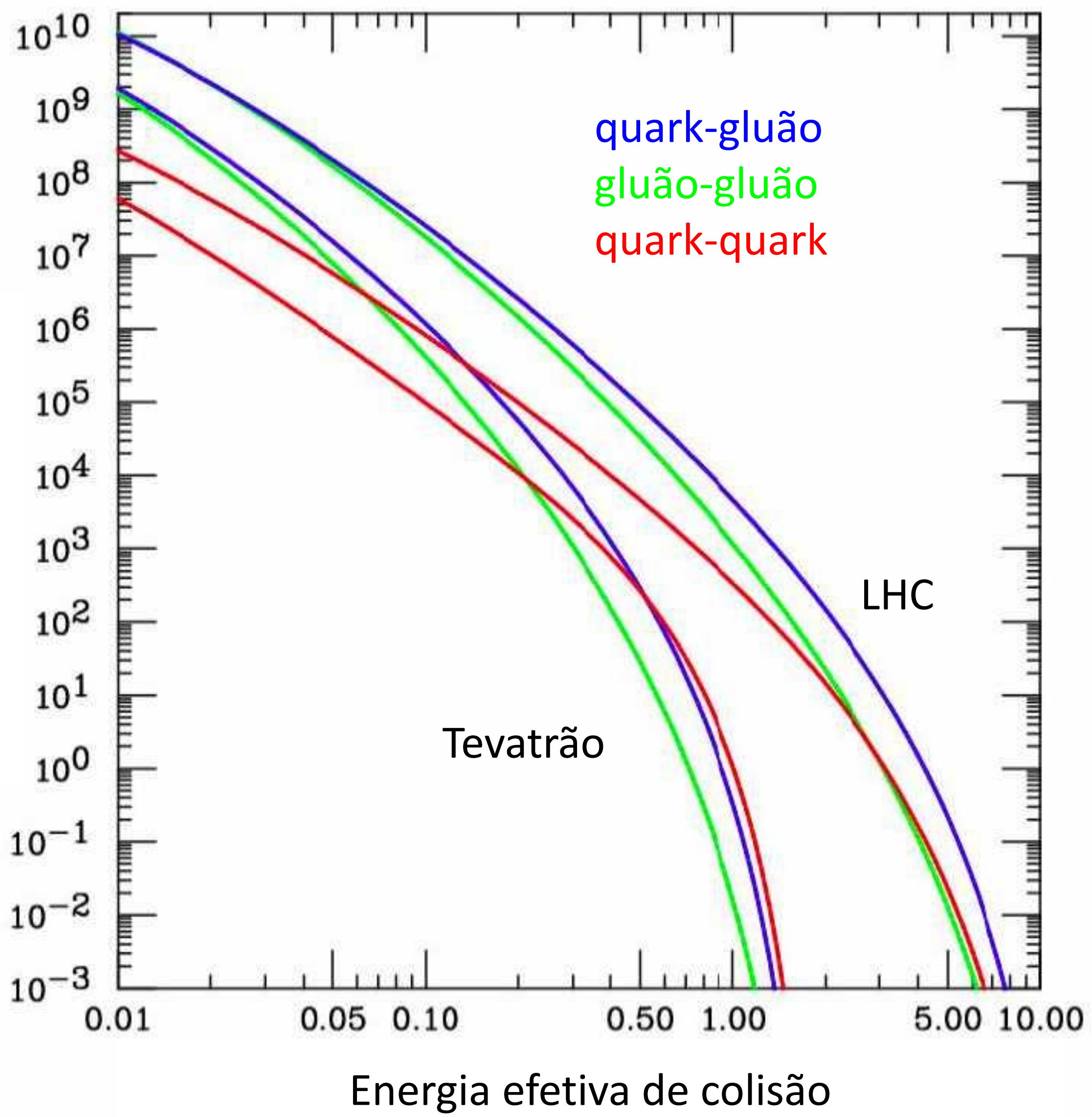
x = fracção da energia do protão levada por cada partão

[see e.g. Halzen/Martin]

Em detalhe: funções de distribuição dos partões

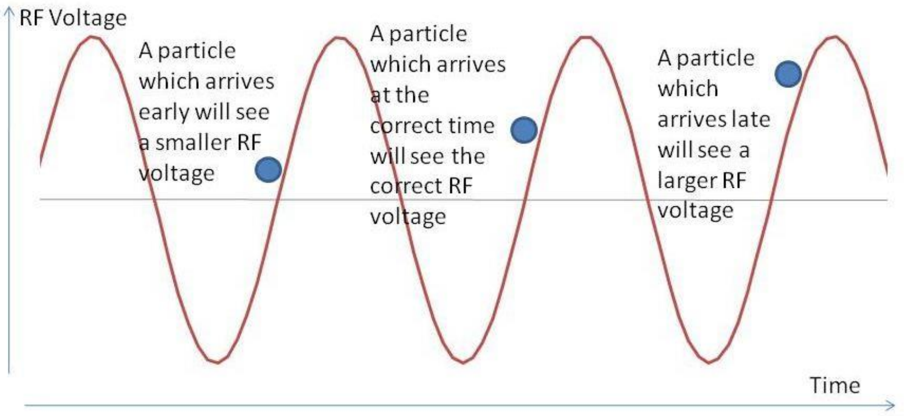


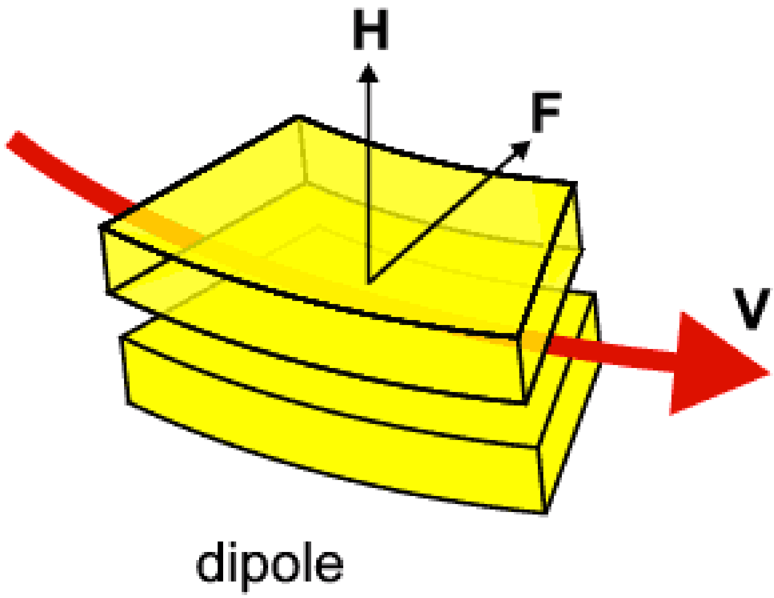
A energias maiores, como as do LHC, a contribuição dos gluões e dos quarks de "mar" aumenta – o LHC colide quarks e gluões!

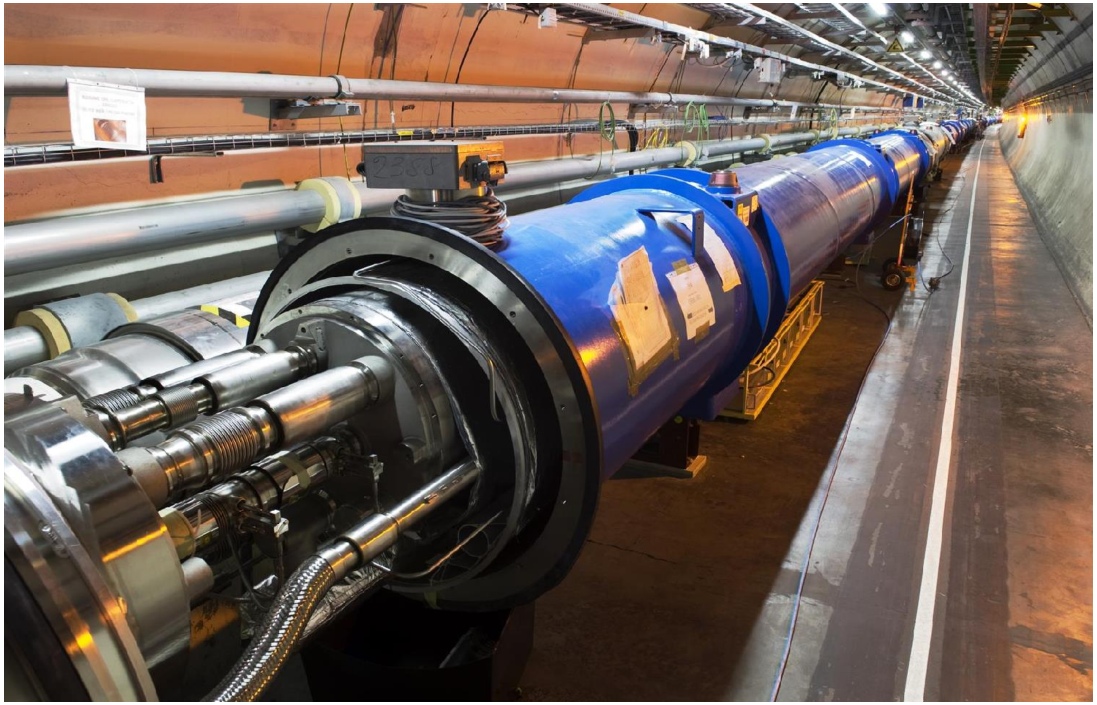


quark-glução
gluão-gluão
quark-quark
LHC
Tevatrão
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0.01
0.05
0.10
0.50
1.00
5.00
10.00
Energia efetiva de colisão

Feixes de protões

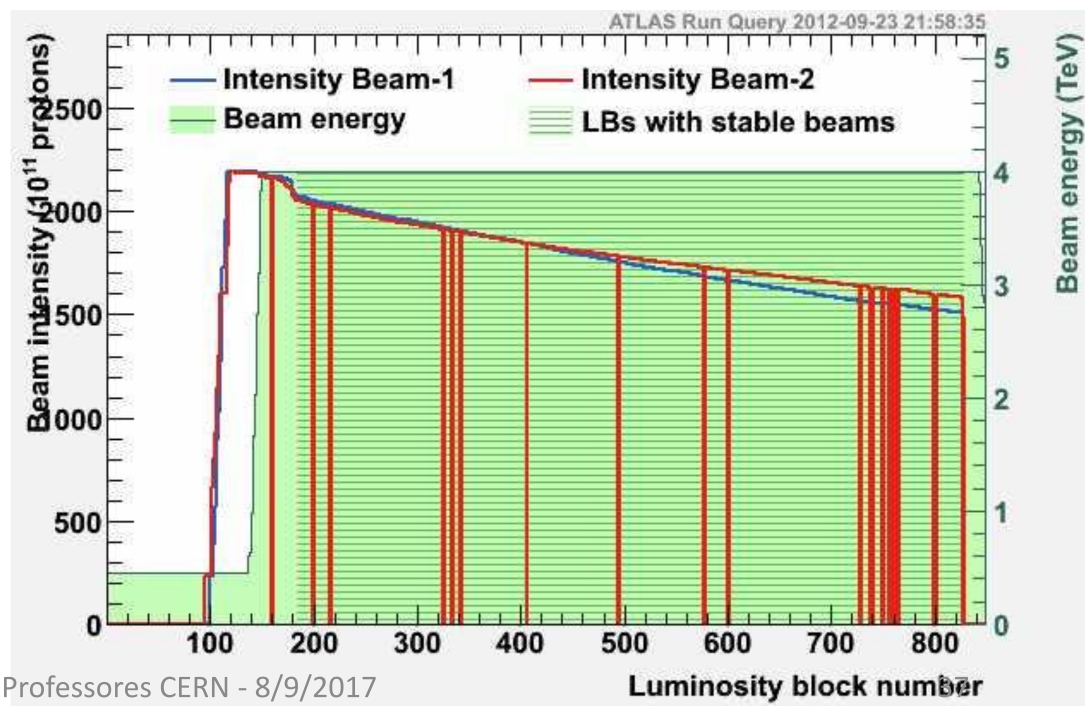




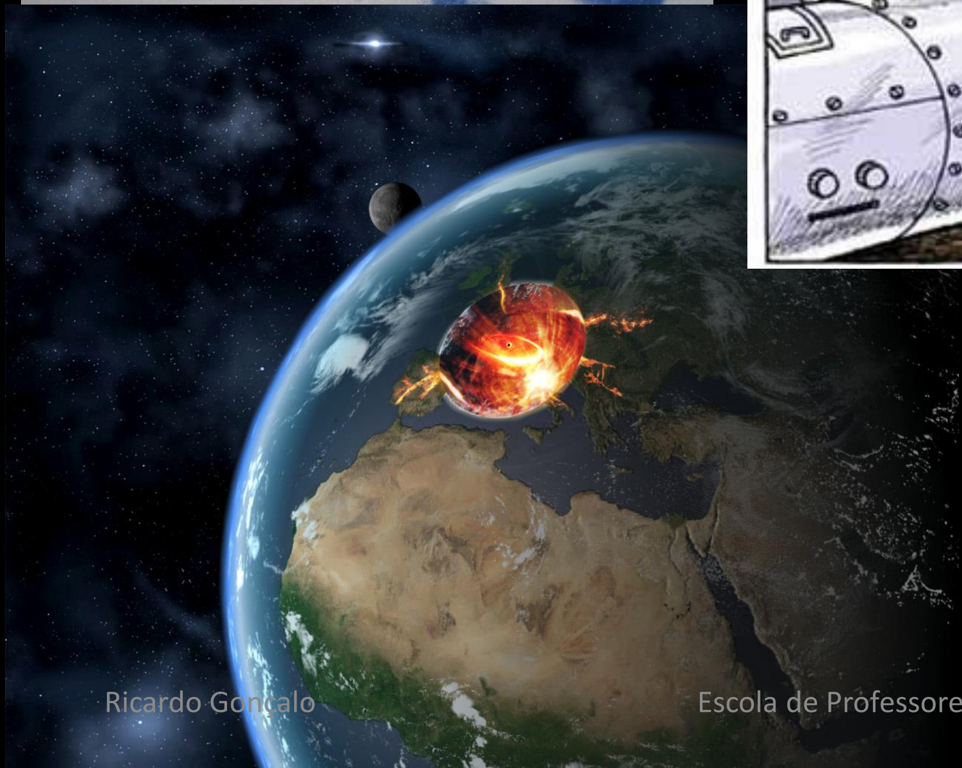


- Energia do feixe:
- 2802 bunches de 1.15×10^{11} protões
- 7TeV / protão (2015) = 7×10^{12} x 1.602×10^{-19} J
- Dá 362 MJ por feixe…
- Igual à energia cinética de um porta-aviões de 20,000t a viajar a 11,7 nós (21.7 km/h)

- Tudo contido num feixe de ≈16μm
- Runs típicos duram cerca de 8 horas
- Intensidade diminui devido a perdas
- Depois voltamos a injectar novos feixes



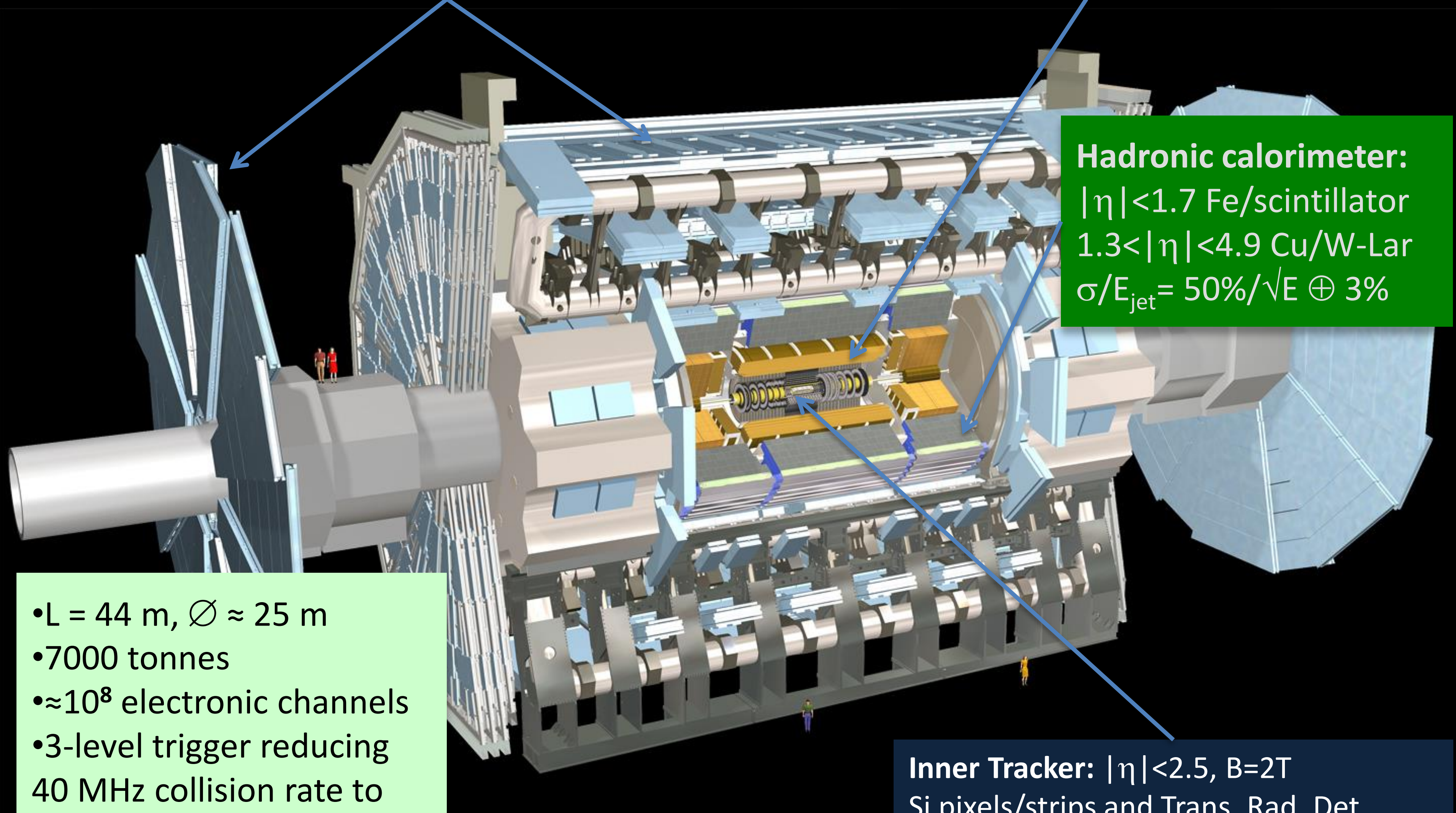

QUI A PEUR
DU
TROU NOIR




13.8 BILLION YEARS AGO, A FEW SECONDS BEFORE THE CREATION OF OUR UNIVERSE...
All set. Let's fire up this Large Hadron Particle Collider and see what happens!

Muon Spectrometer: $|\eta|<2.7$
Air-core toroids and gas-based muon chambers
σ/p_T = 2% @ 50GeV to 10% @ 1TeV (ID+MS)

EM calorimeter: $|\eta|<3.2$
Pb-LAr Accordion
$\sigma/E = 10\%/\sqrt{E} \oplus 0.7\%$

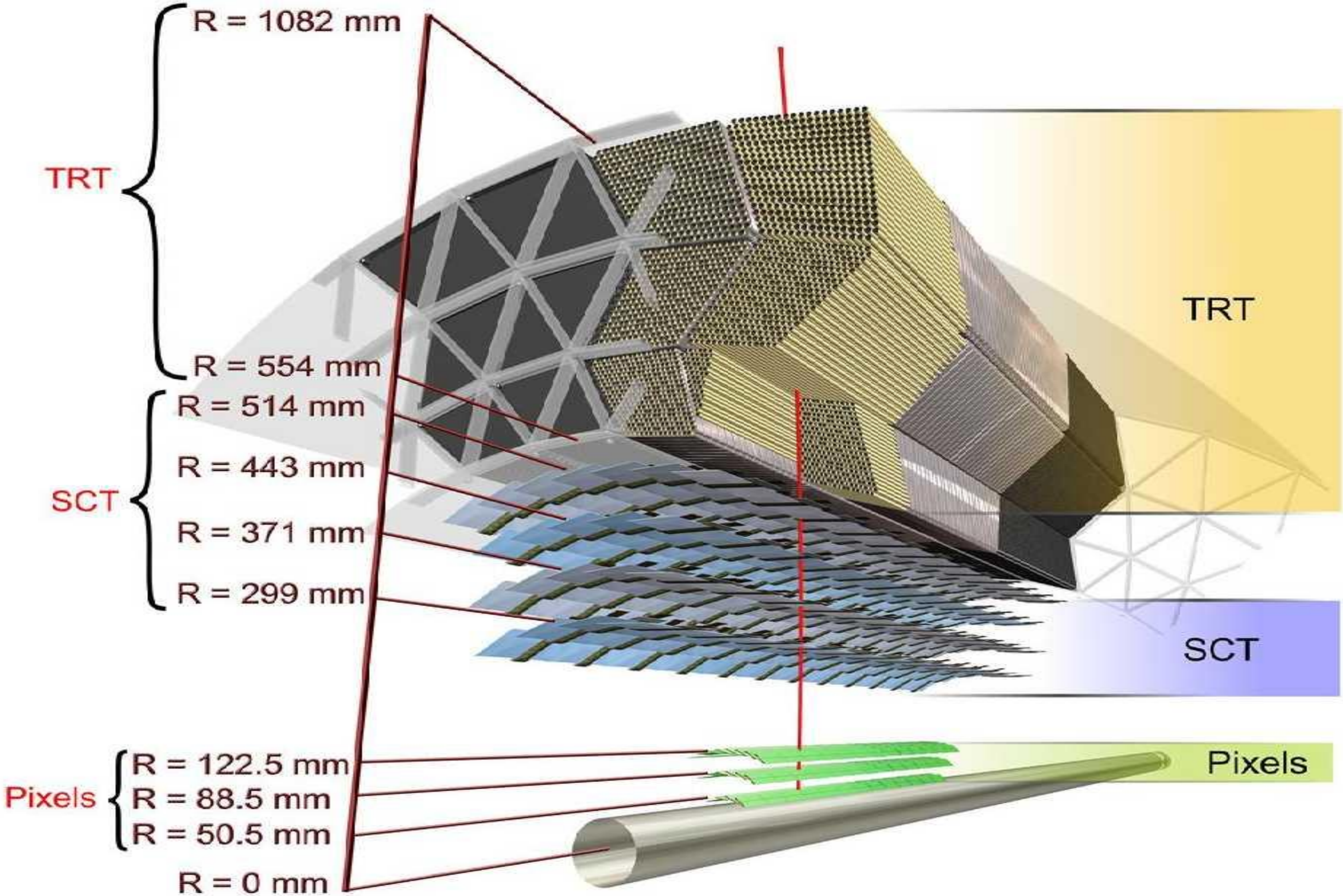


Hadronic calorimeter:
$|\eta|<1.7$ Fe/scintillator
$1.3<|\eta|<4.9$ Cu/W-Lar
$\sigma/E_{jet} = 50\%/\sqrt{E} \oplus 3\%$

- L = 44 m, ∅ ≈ 25 m
- 7000 tonnes
- ≈10^8 electronic channels
- 3-level trigger reducing 40 MHz collision rate to 200 Hz of events to tape

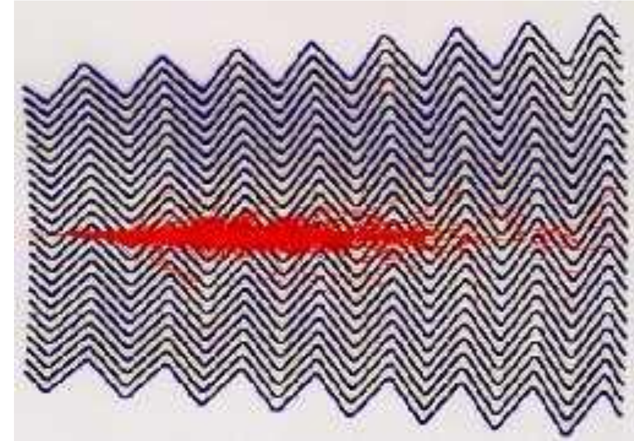
Inner Tracker: $|\eta|<2.5$, B=2T
Si pixels/strips and Trans. Rad. Det.
$\sigma/p_T = 0.05\%\ p_T\,(\text{GeV}) \oplus 1\%$

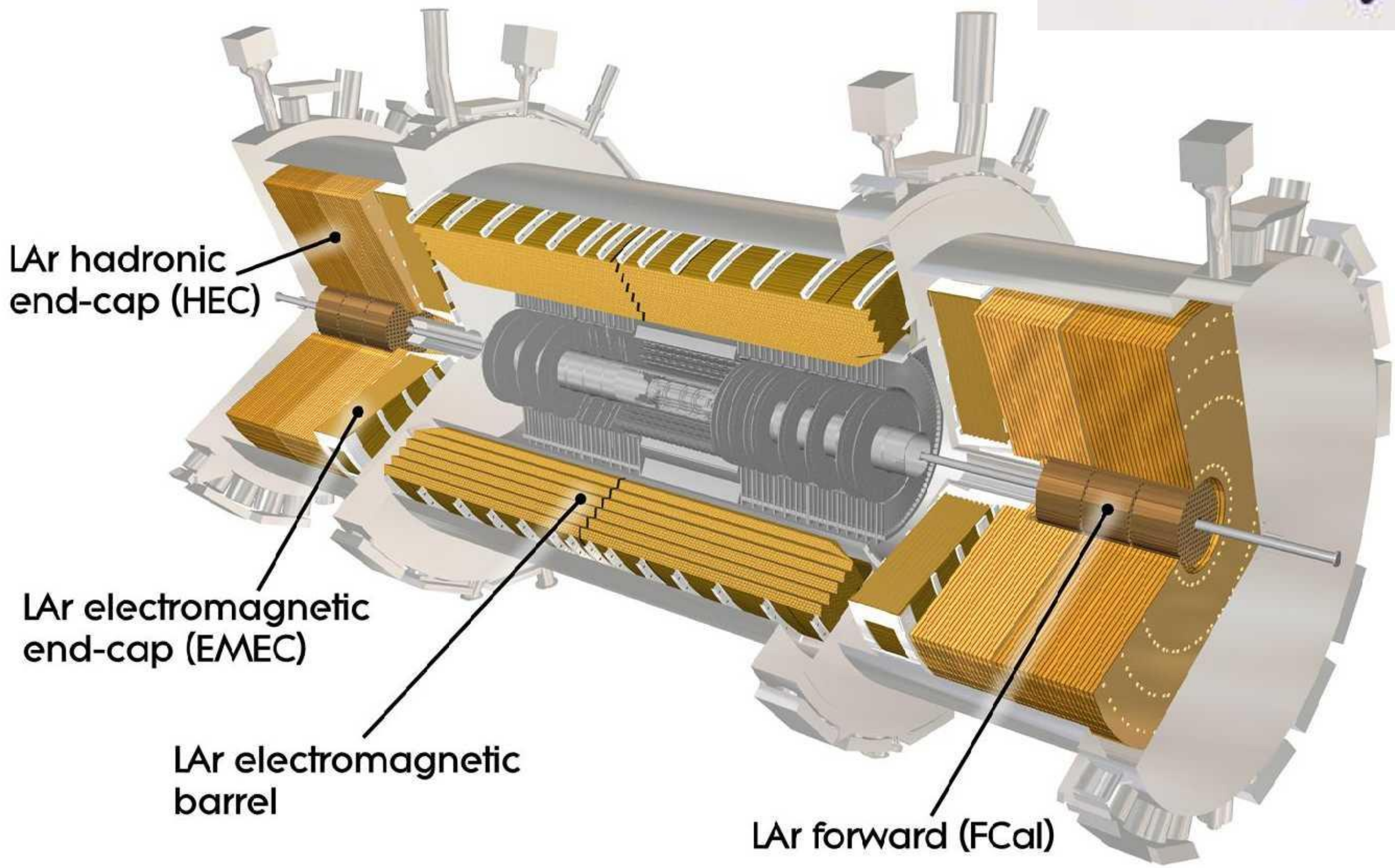
Detetores de traços



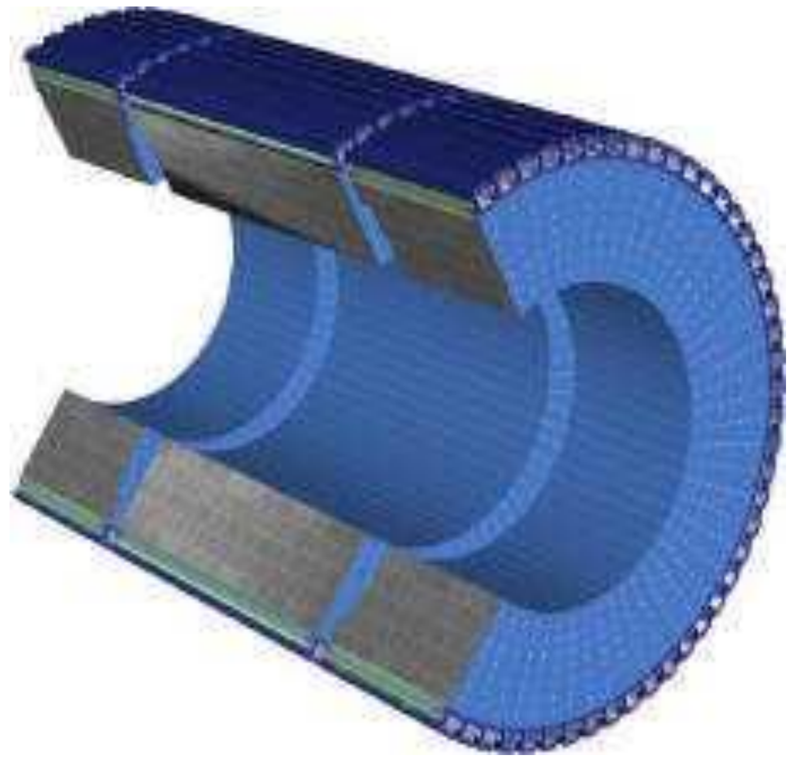
Calorímetros de Árgon Líquido

EM calorimeter: $|\eta| < 3.2$
Pb-LAr Accordion
$\sigma/E = 10\%/\sqrt{E} \oplus 0.7\%$

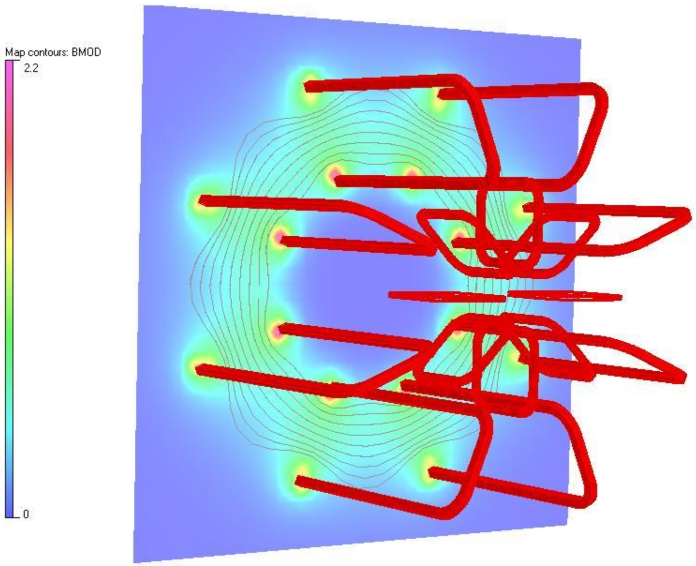


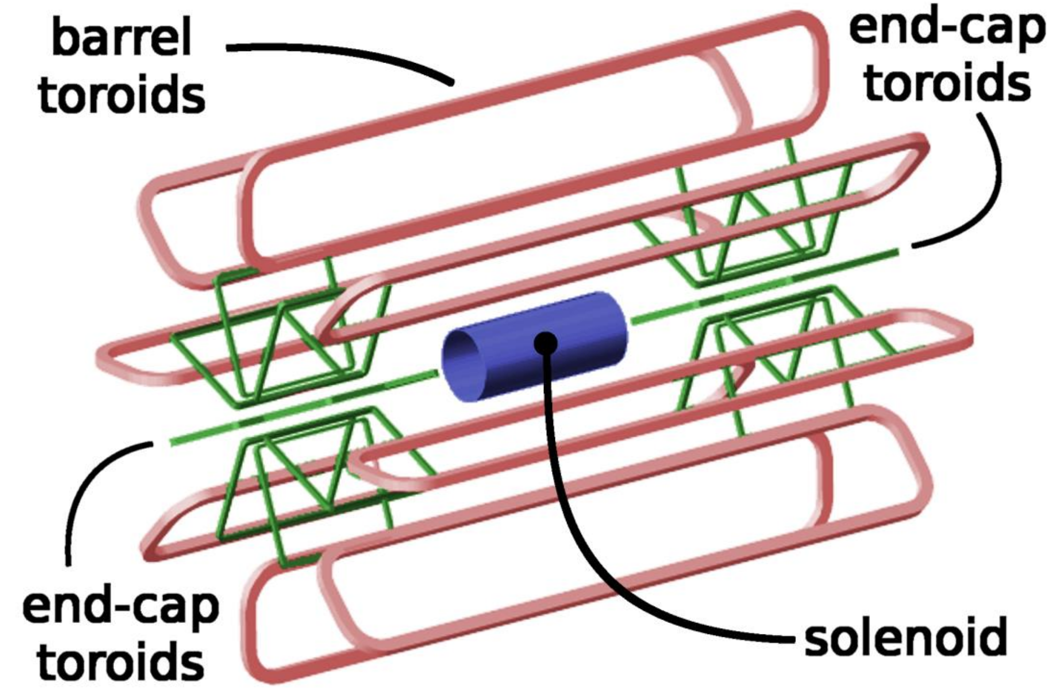


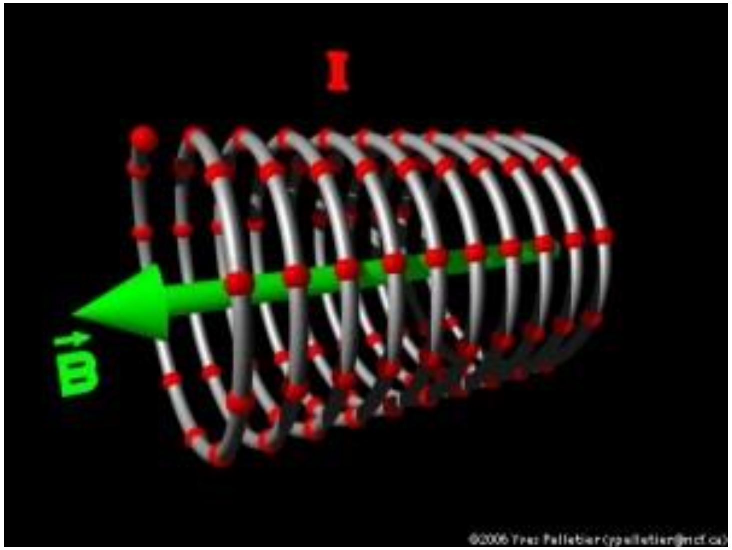
O calorímetro de telhas (TileCal)



Sistema de ímanes de ATLAS



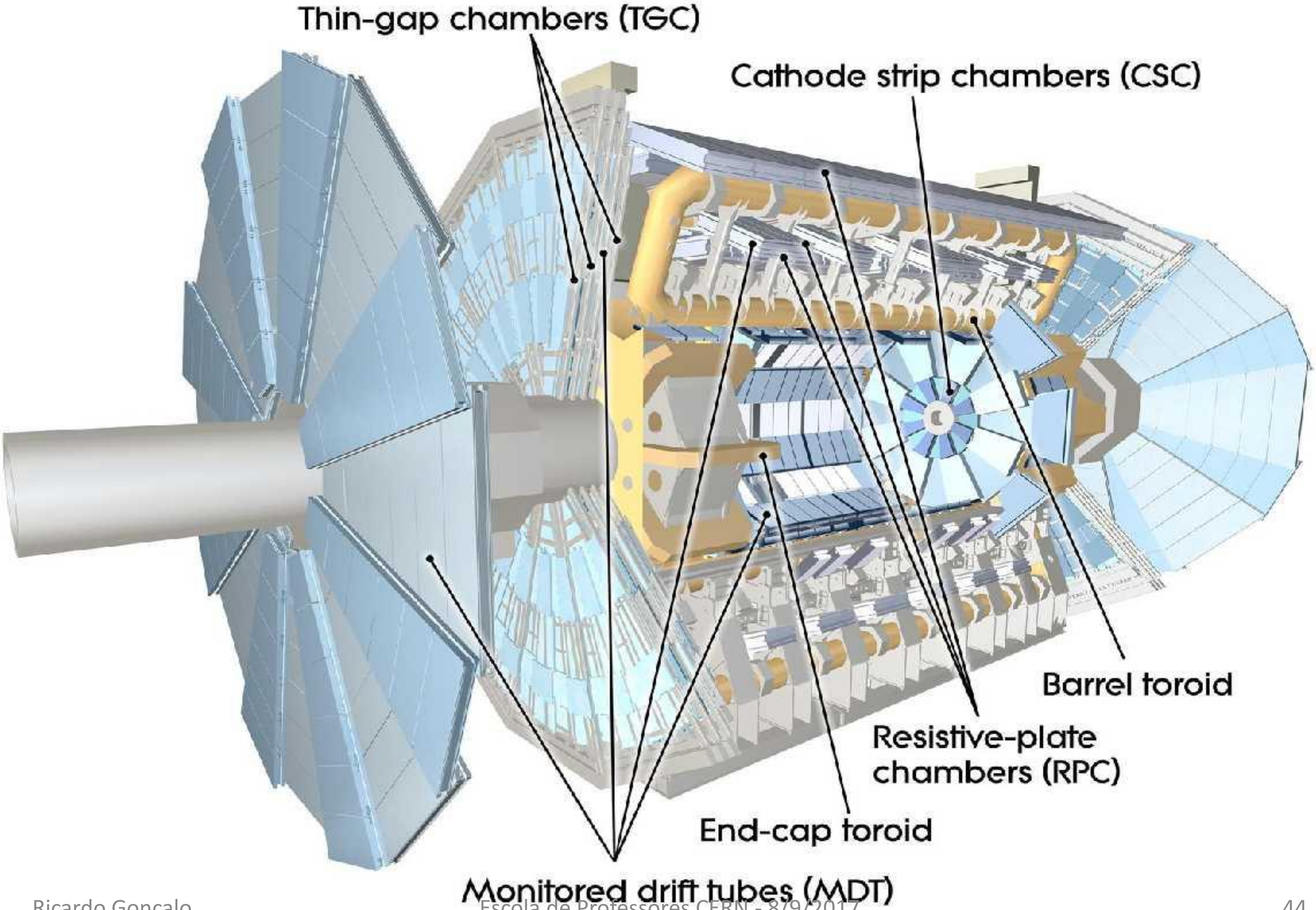




- Campos magnéticos muito intensos (2T, 4T max) gerados por ímanes supercondutores
- Curvam as partículas carregadas através da força de Lorenz:

$$\mathbf{F} = \mathbf{v} \times \mathbf{B}$$

Detetores de muões

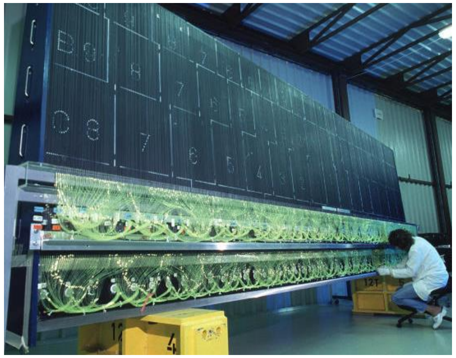


Extrato de filme:
"ATLAS Episode II: the particles strike back"
https://cds.cern.ch/record/1096390?ln=ka

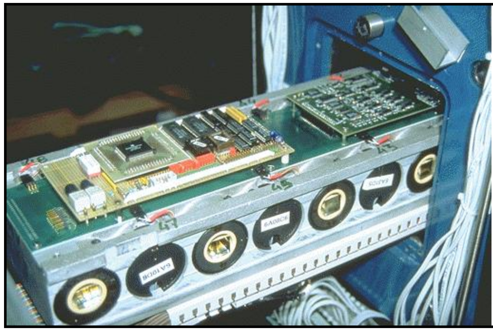
Etapas do projecto Tilecal (1993-2009)

1993-1995 R&D-protótipos

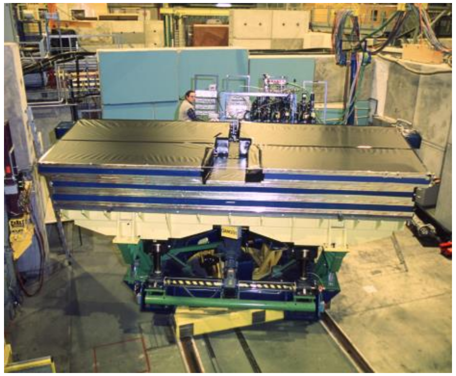
1996-2002:construção



1999-2002 Instrumentação

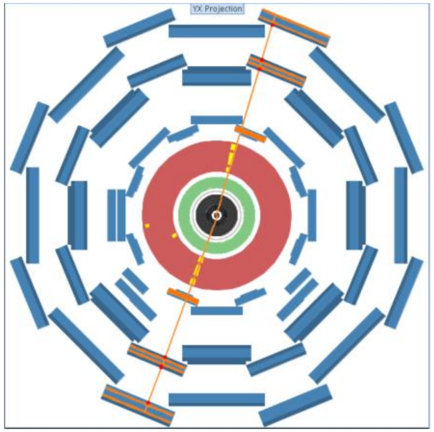


1999-2004: Electrónica



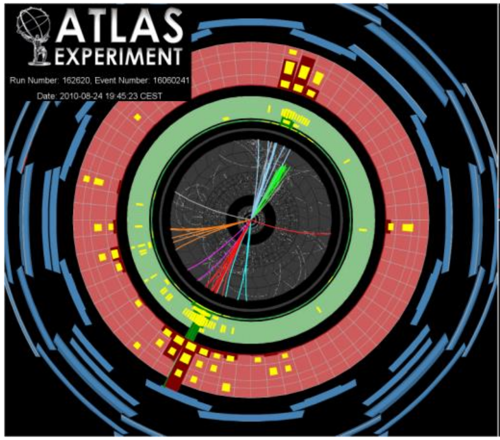
2002-2004: calibrações

2004-2006 Instalação



2007-2009 certificação

(raios cósmicos)

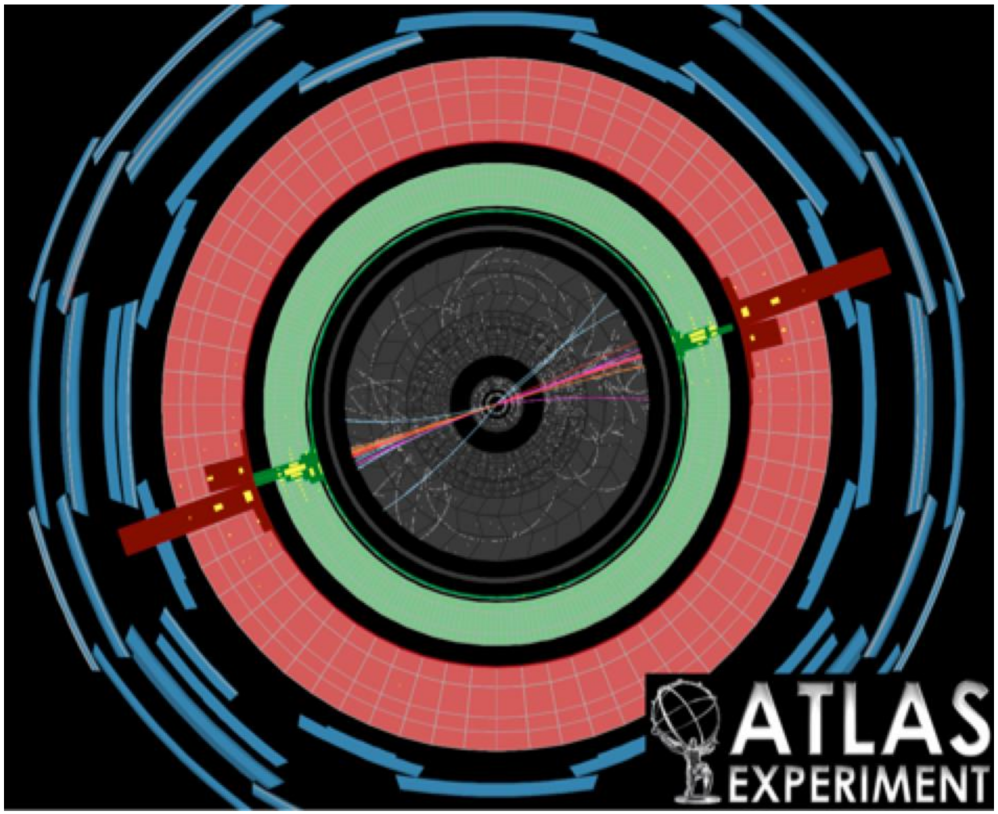


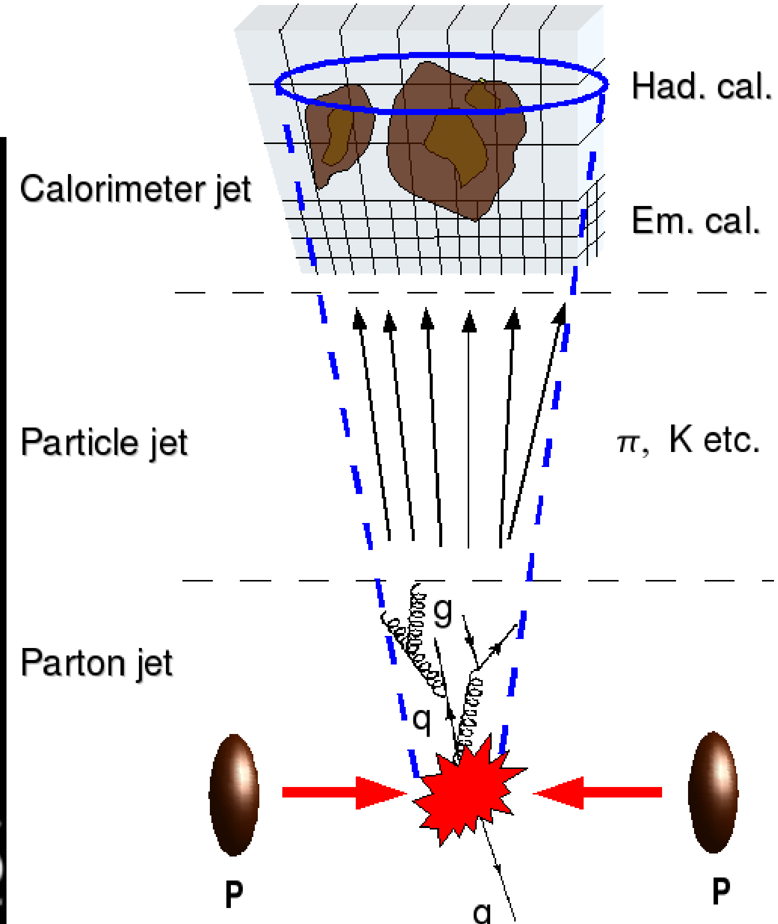
2009--→: aquisição/análise dados LHC

Um longo percurso para conseguir as excelentes características do Tilecal no detetor ATLAS

Com participação portuguesa: LIP, FCUL, UMinho

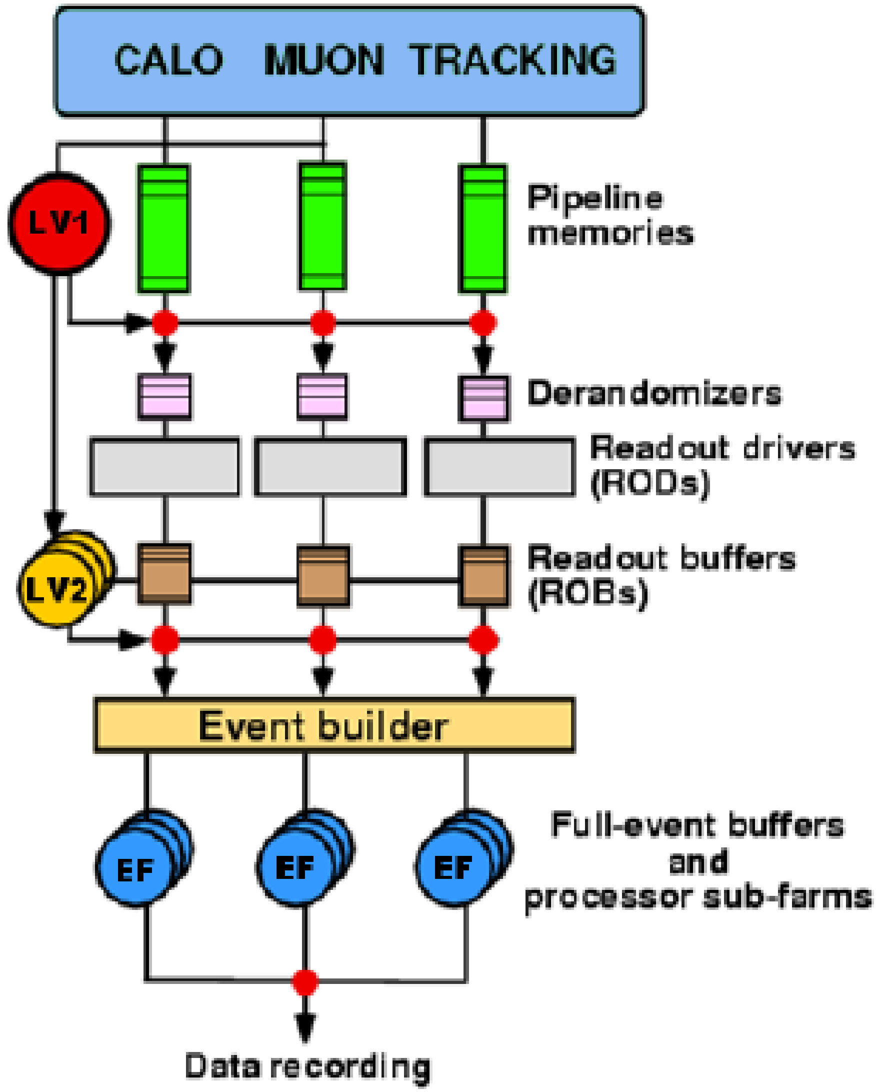
Jactos hadrónicos



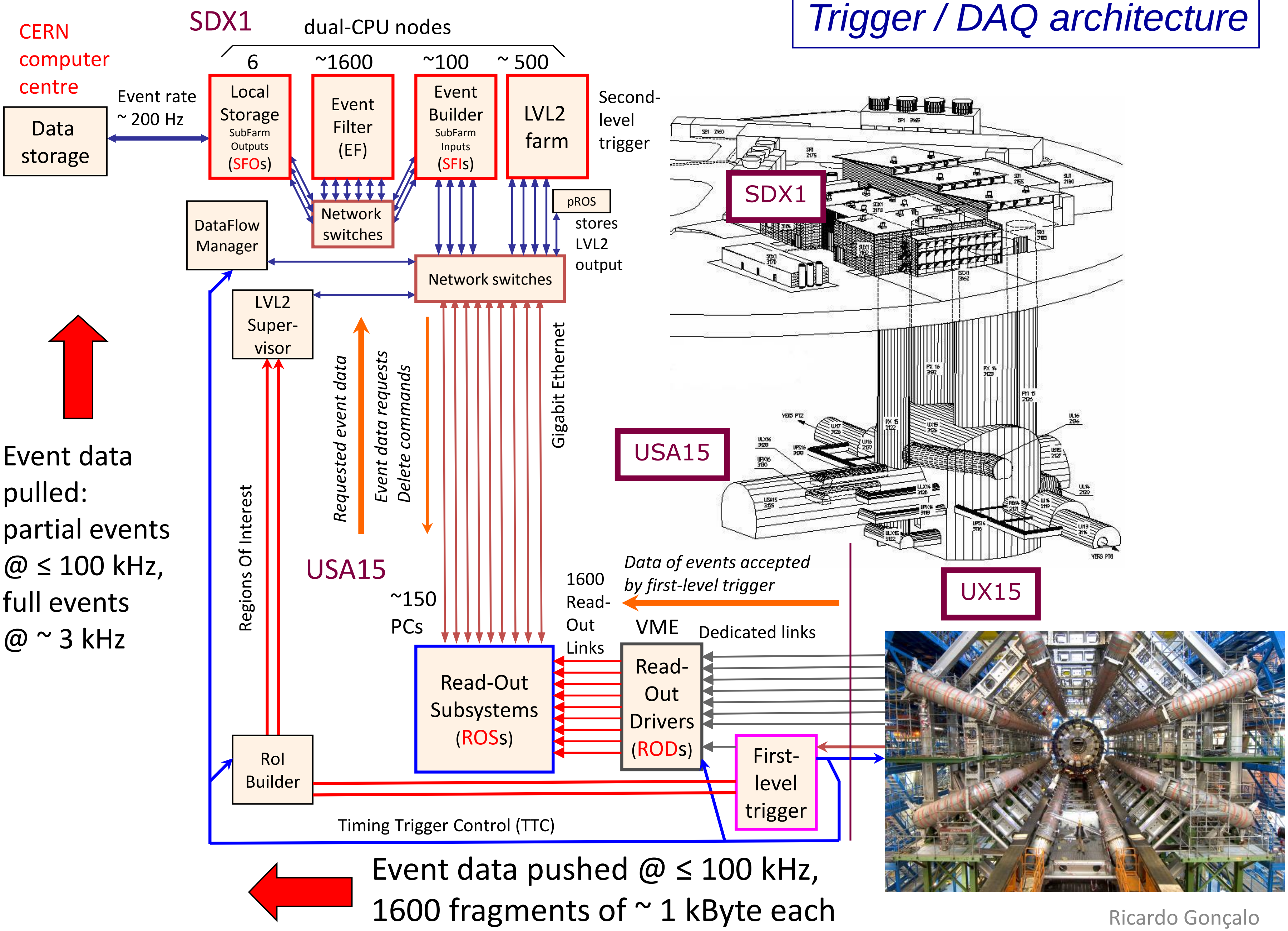


Trigger: sistema de seleção em tempo real

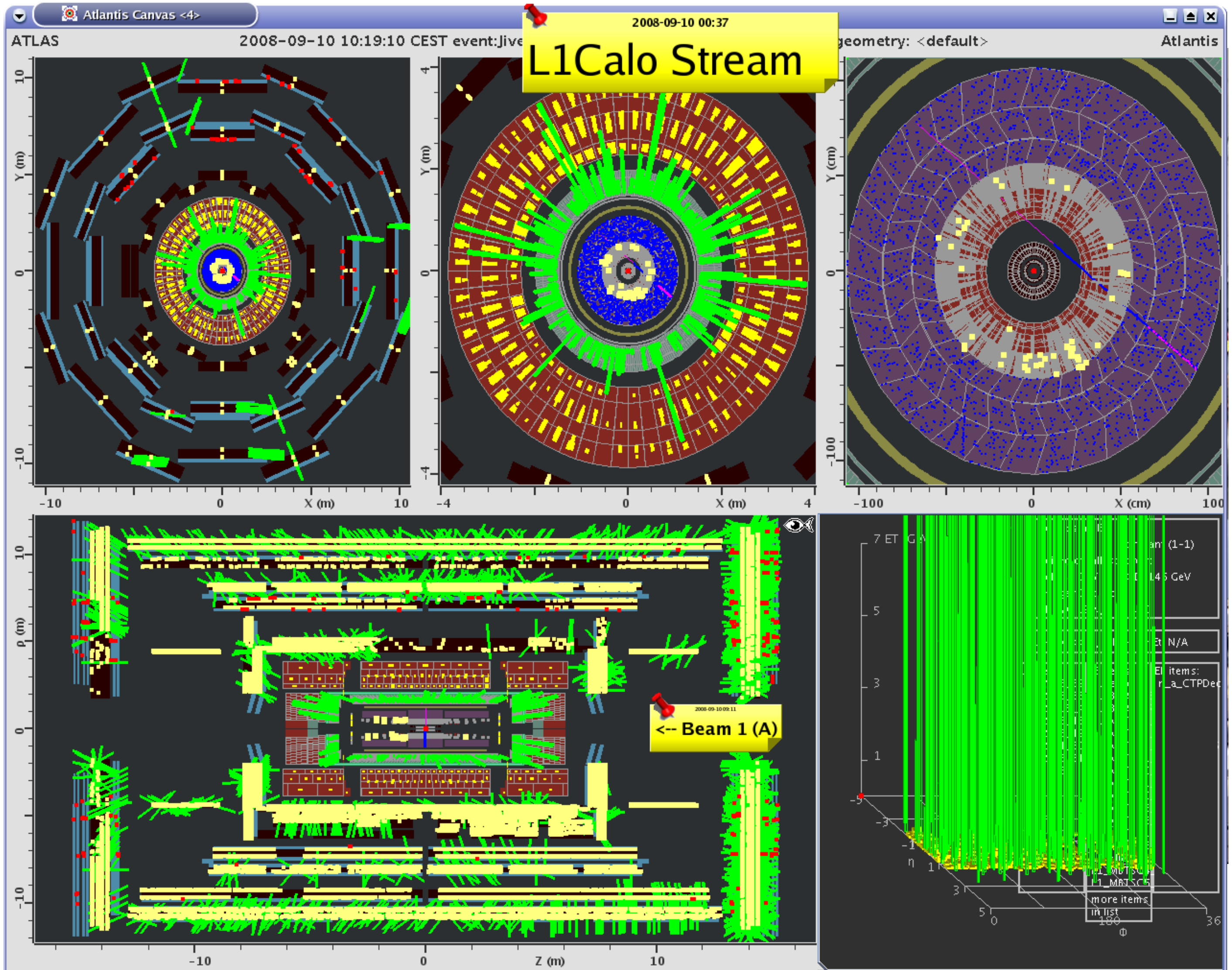
- 25 ns entre pacotes
  - (i.e. ≈7.5m à velocidade de *c*)
  - 40 milhões de cruzamentos de feixes por segundo
  - Cada colisão daria ≈1.5Mb
  - => 60Tb por segundo
- Impossível guardar todos os dados
  - E desnecessário!
  - A maioria das colisões é sem interesse
- O sistema de trigger guarda apenas ≈10-15 colisões por cada milhão
- Mas tem que decidir em 2,5μs!!



Trigger / DAQ architecture



10 de Setembro 2008: primeiros feixes!



Filme em:
https://cds.cern.ch/record/2020780?ln=en

A Colaboração ATLAS

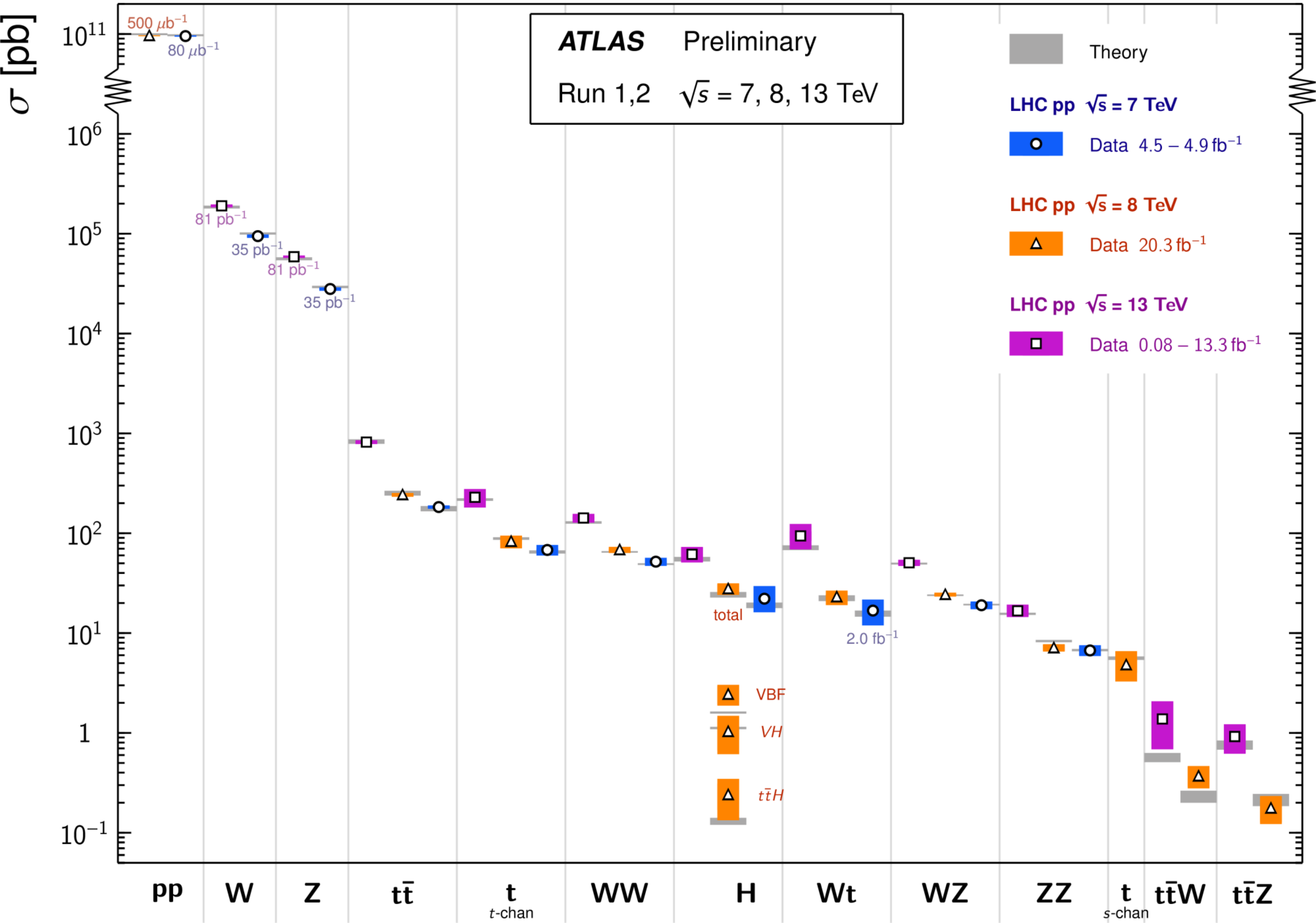
3000 cientistas
(1000 estudantes)
33 países
177 universidades
e laboratórios

ATLAS em Português

Em Portugal:
~20 investigadores, ~10 – 15 estudantes
LIP – Coimbra, Minho, Lisboa
FCUL, FCTUC, UM, CEFITEC/UNL, INESC, CFMC
Programa de treino de engenheiros no CERN

No Brasil:
Cerca de 30 colegas de várias instituições
UFRJ-COPPE, UFJF, USP, UFSJ (UFBA, CEFET-RJ, UFF)

Standard Model Total Production Cross Section Measurements *Status: August 2016*

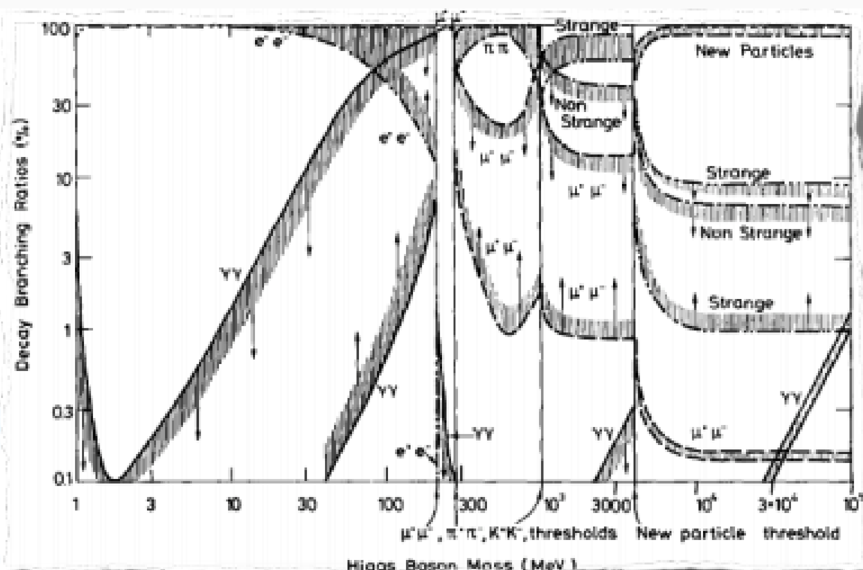


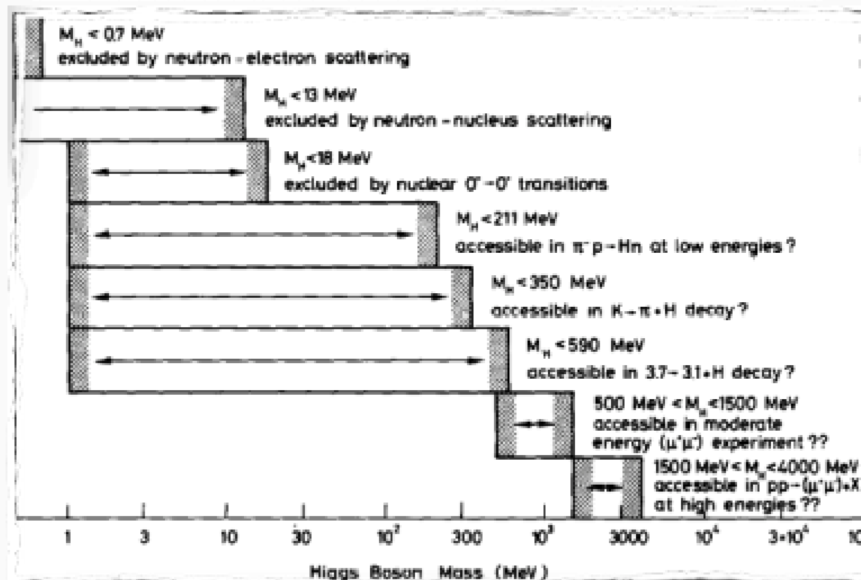
Breve história da descoberta do Higgs

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

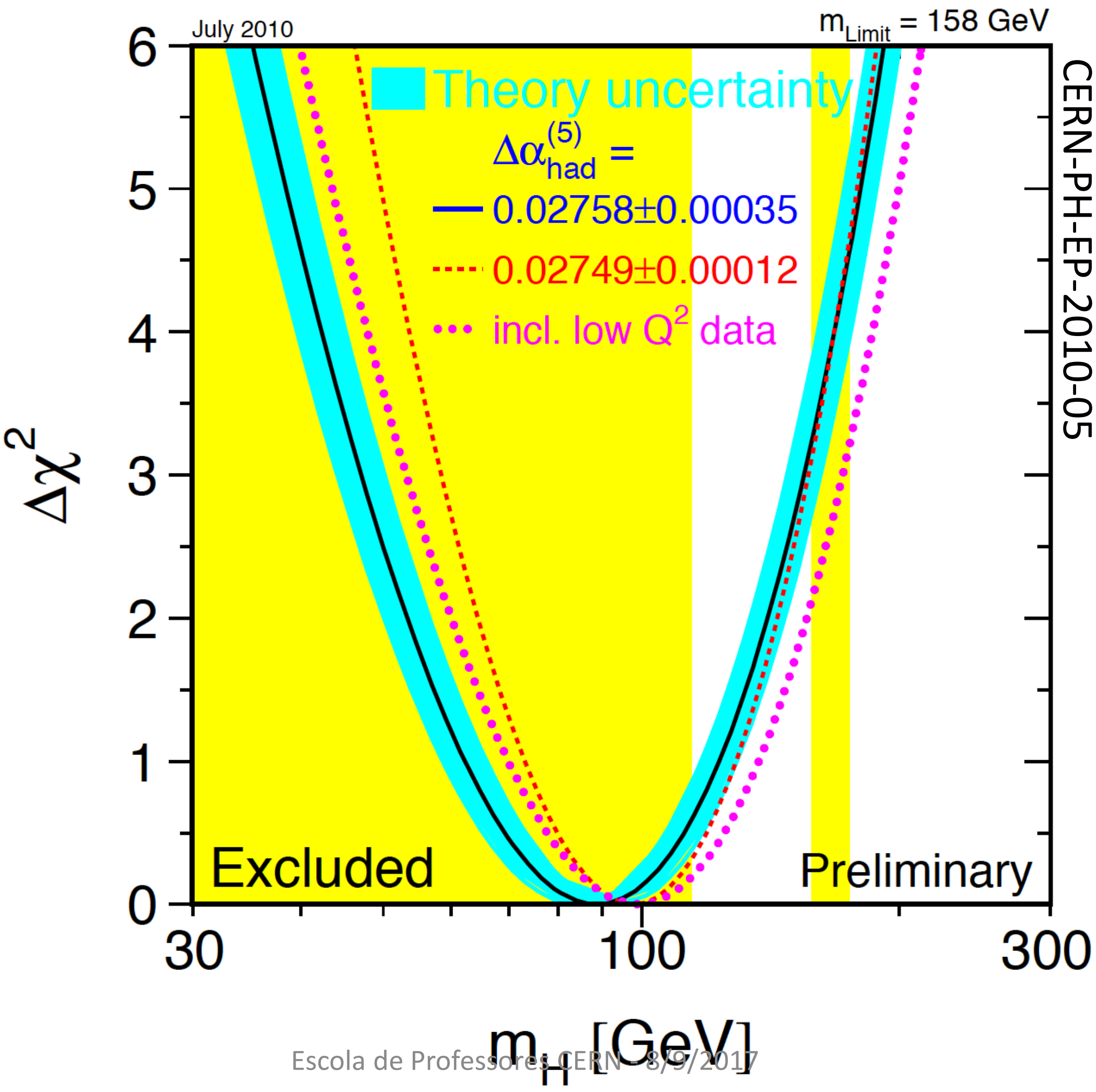
Received 7 November 1975



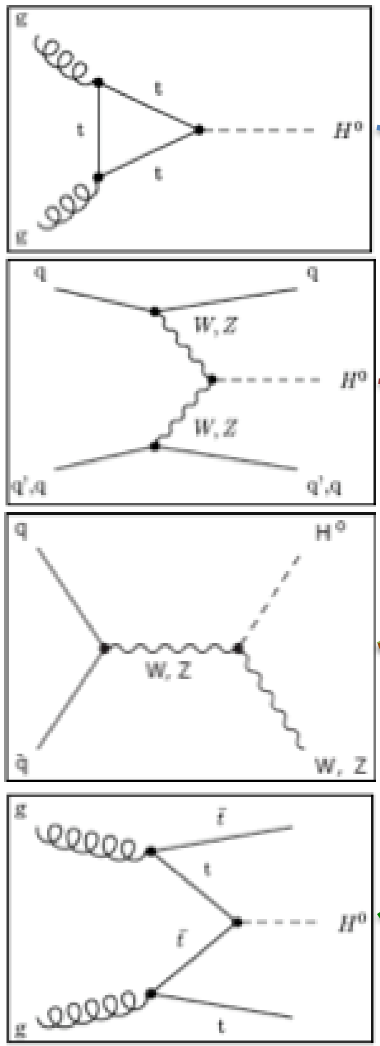


We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

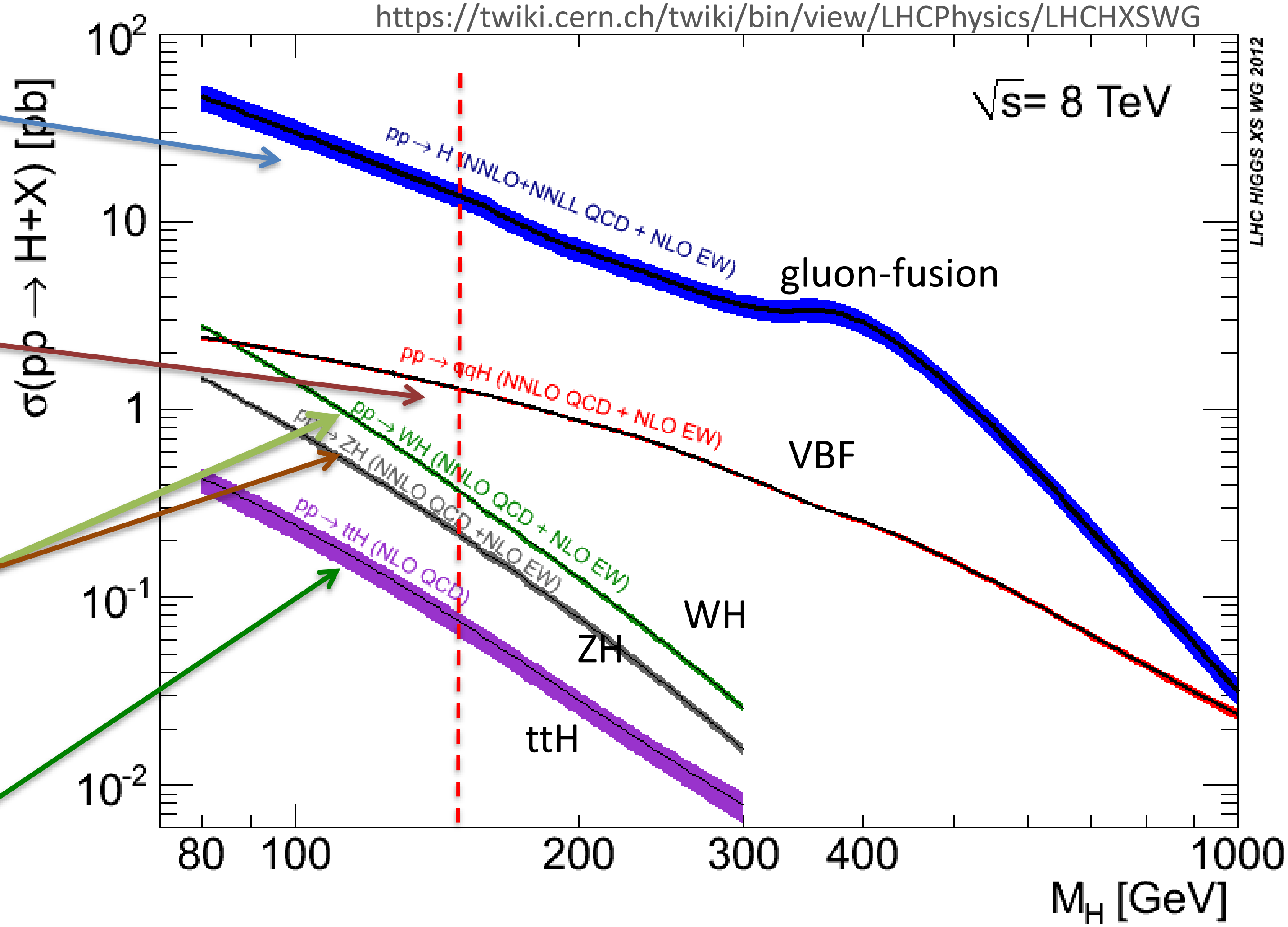
Por volta de Julho de 2010, depois de décadas de buscas...

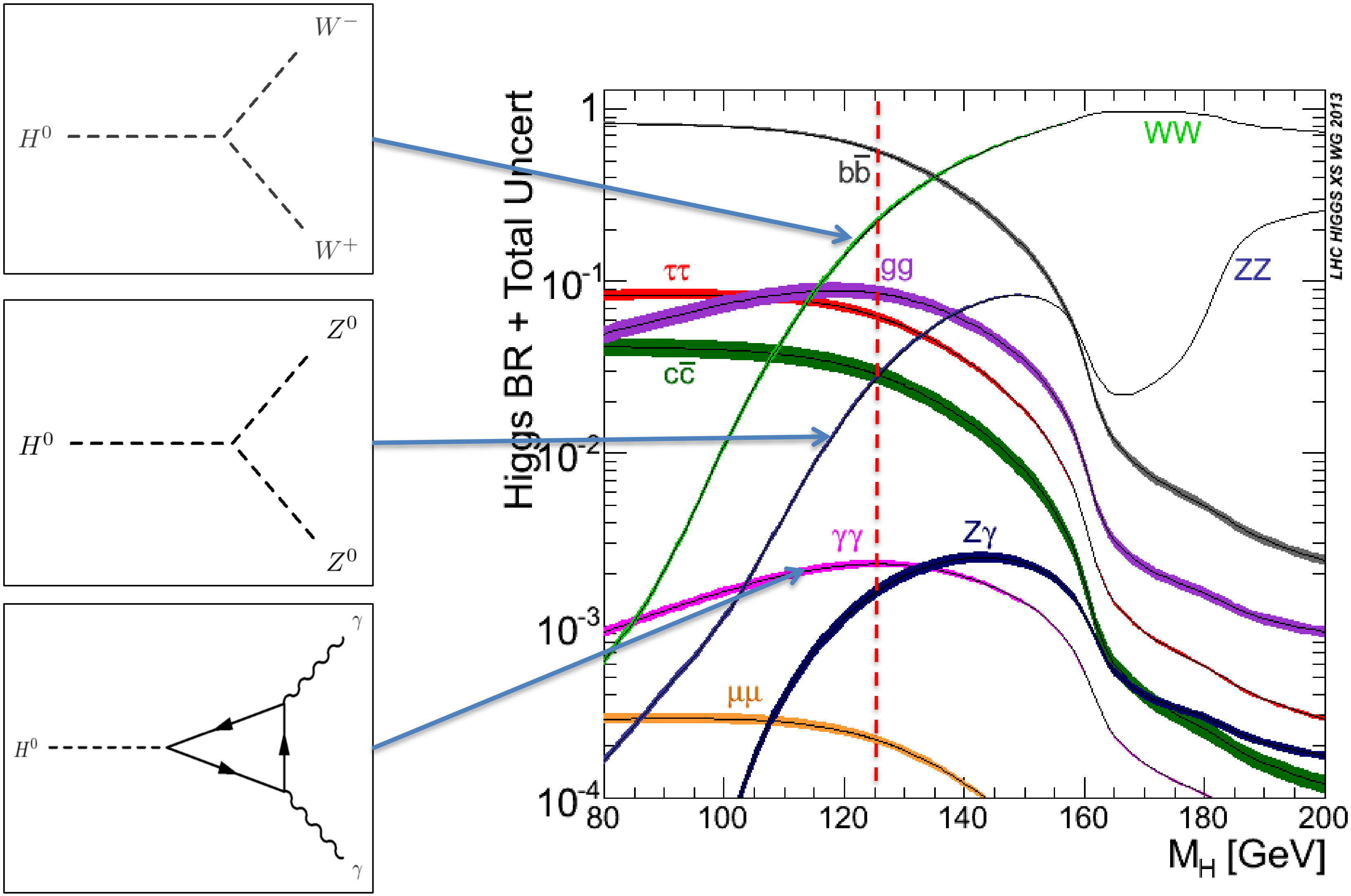


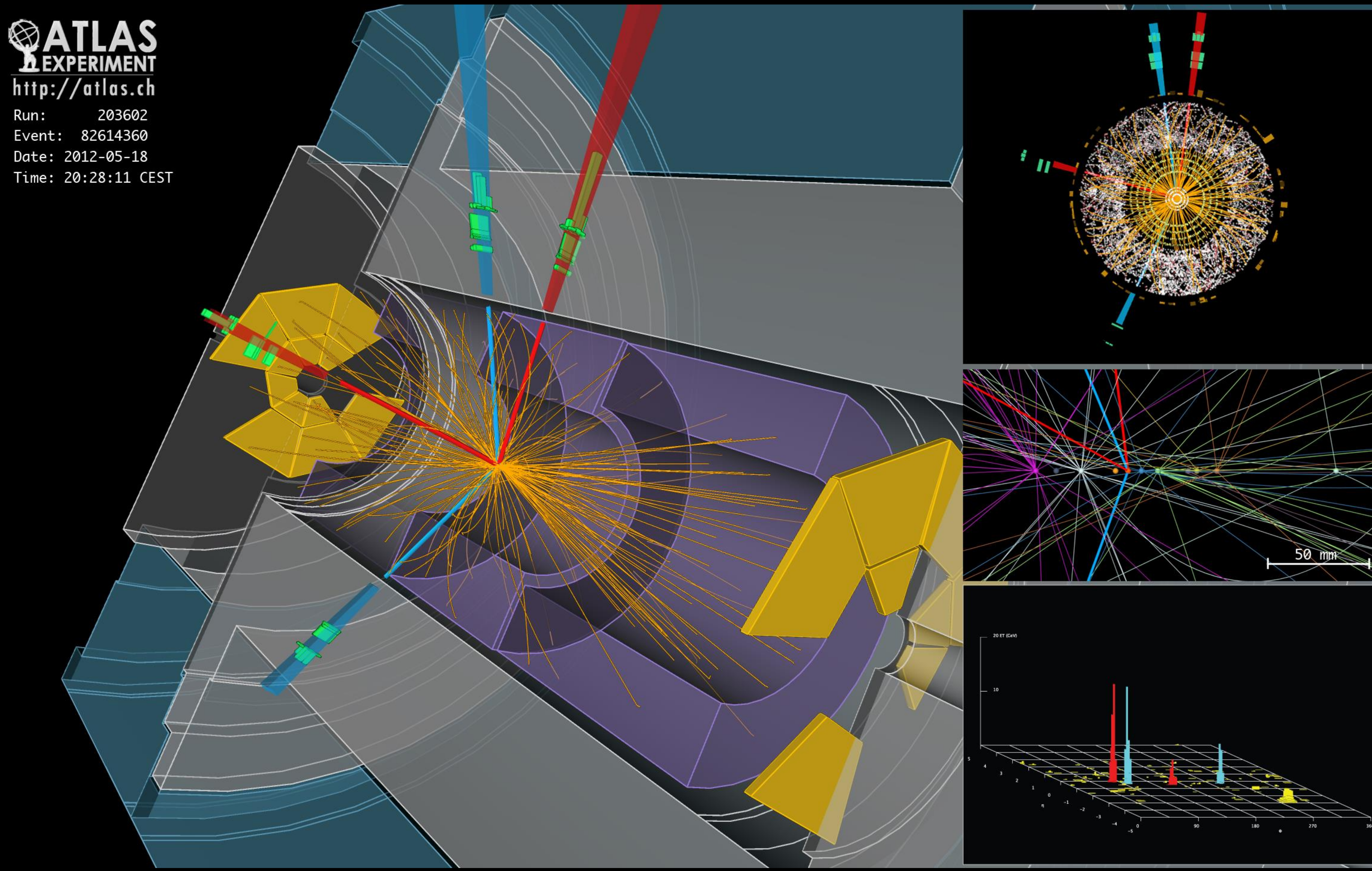
At the LHC

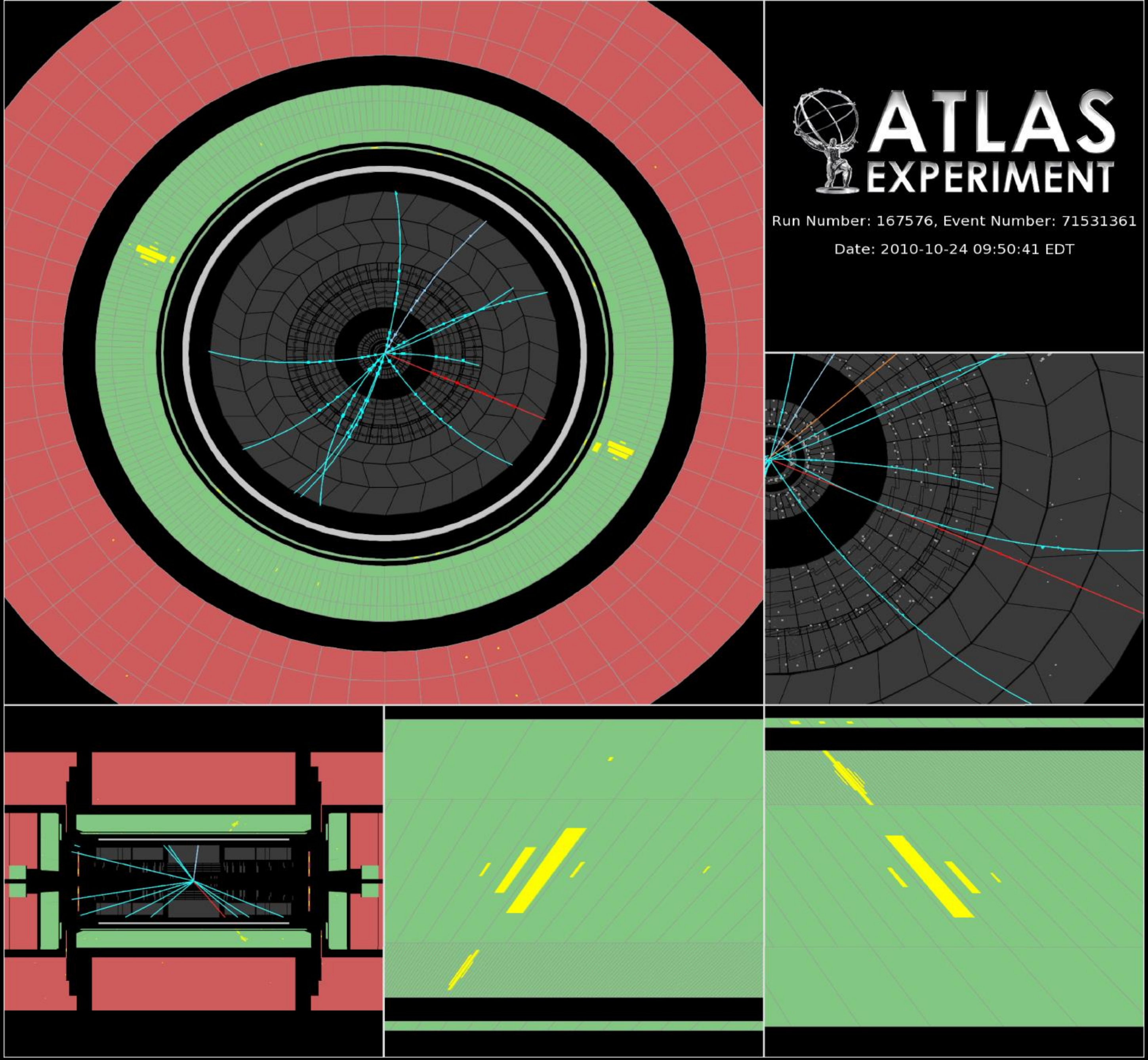


https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG

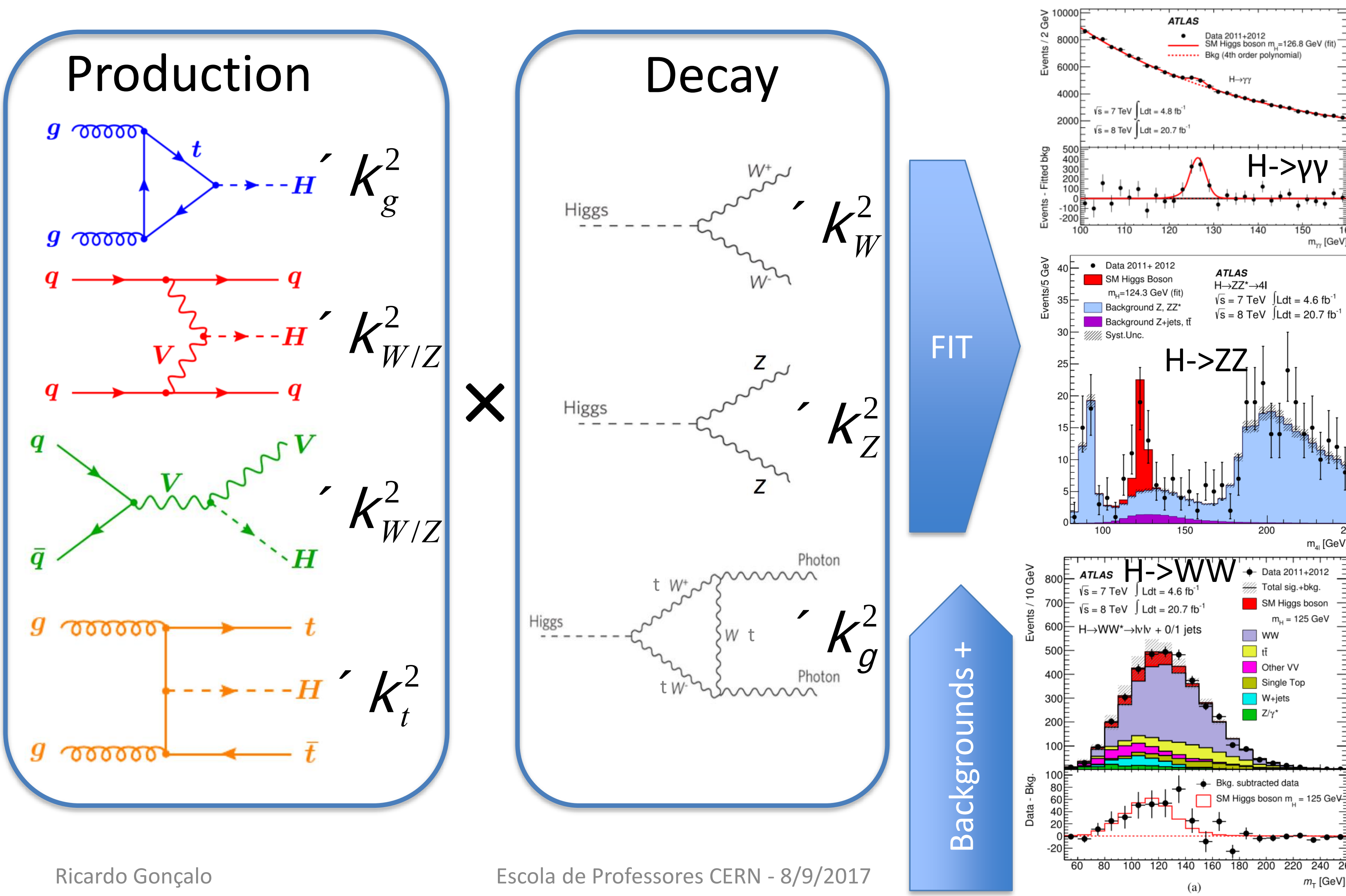



W^-
H^0
W^+
Z^0
H^0
Z^0
γ
H^0
γ
Higgs BR + Total Uncert
LHC HIGGS XS WG 2013
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
80
100
120
140
160
180
200
M_H [GeV]
WW
$b\bar{b}$
$\tau\tau$
gg
ZZ
$c\bar{c}$
$\gamma\gamma$
$Z\gamma$
$\mu\mu$


ATLAS EXPERIMENT
http://atlas.ch
Run: 203602
Event: 82614360
Date: 2012-05-18
Time: 20:28:11 CEST
50 mm

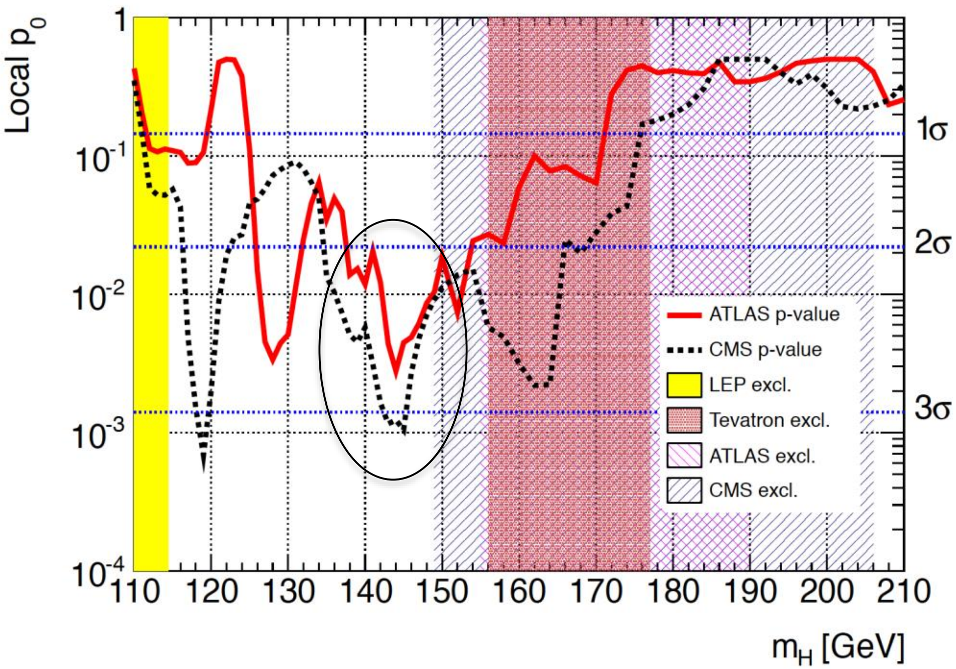

ATLAS EXPERIMENT
Run Number: 167576, Event Number: 71531361
Date: 2010-10-24 09:50:41 EDT

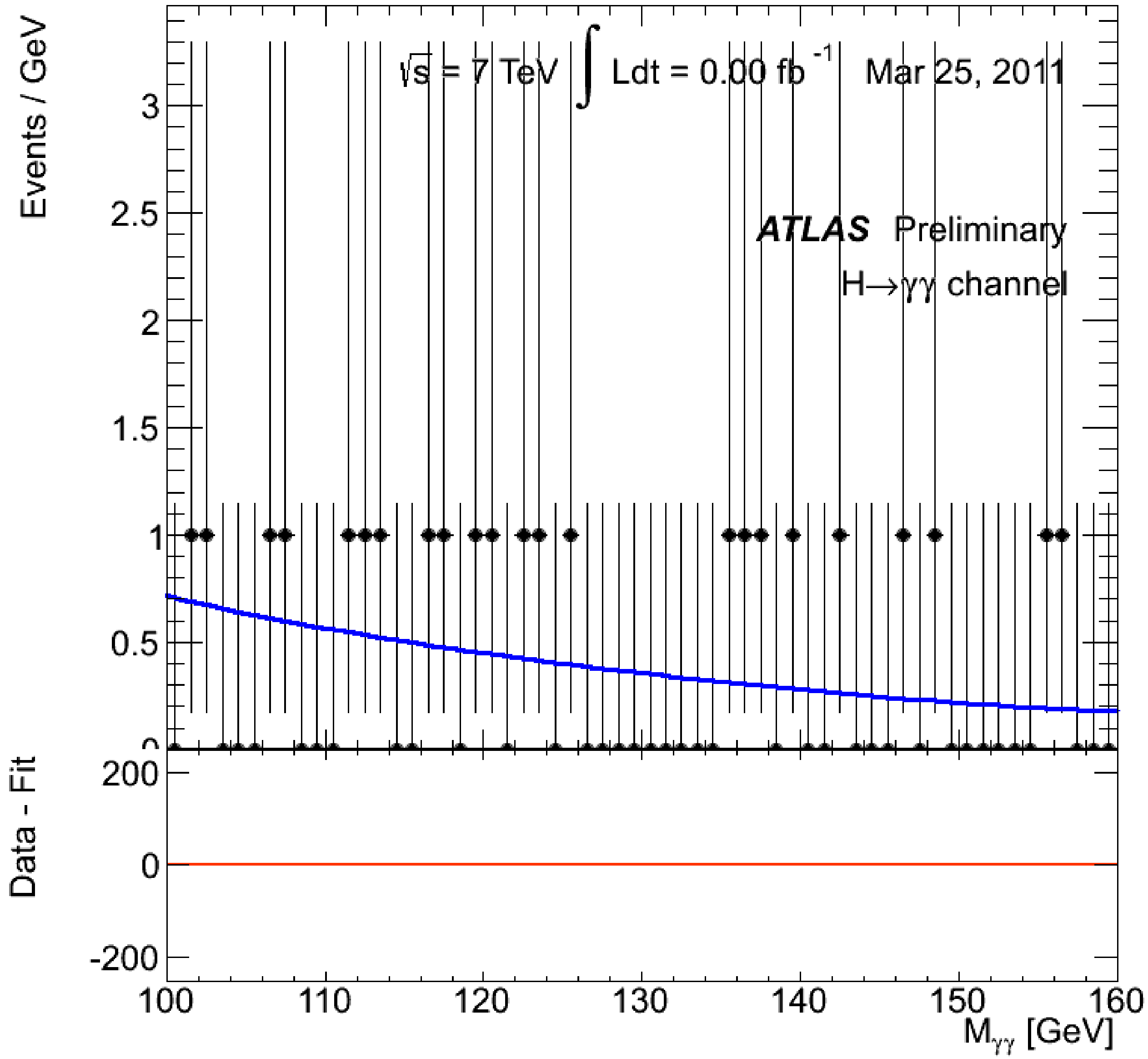
Combinação estatística



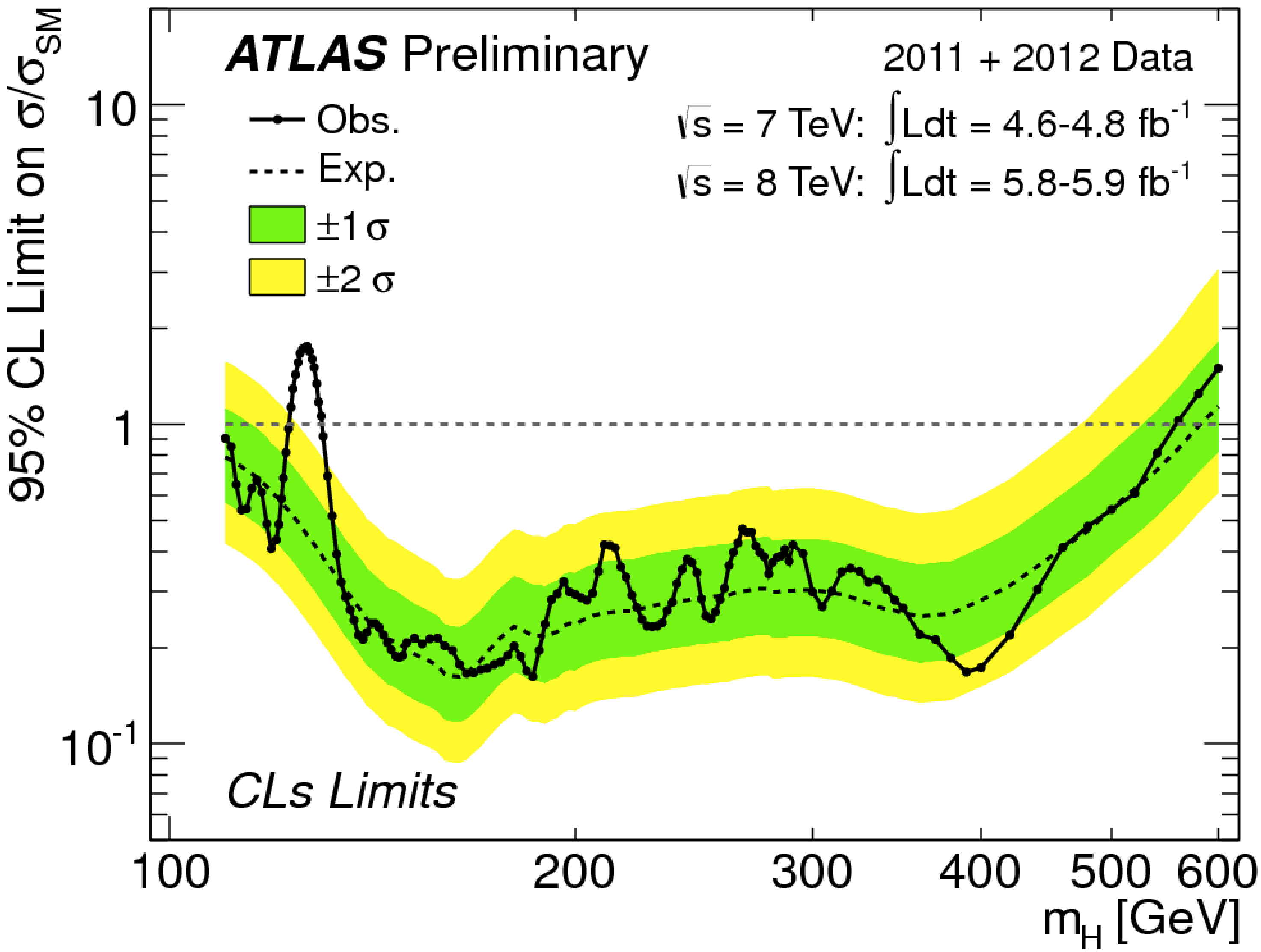
Nem sempre se acerta à primeira...

Conferência europeia de Física de Partículas (EPS-HEP) 2011 [6]

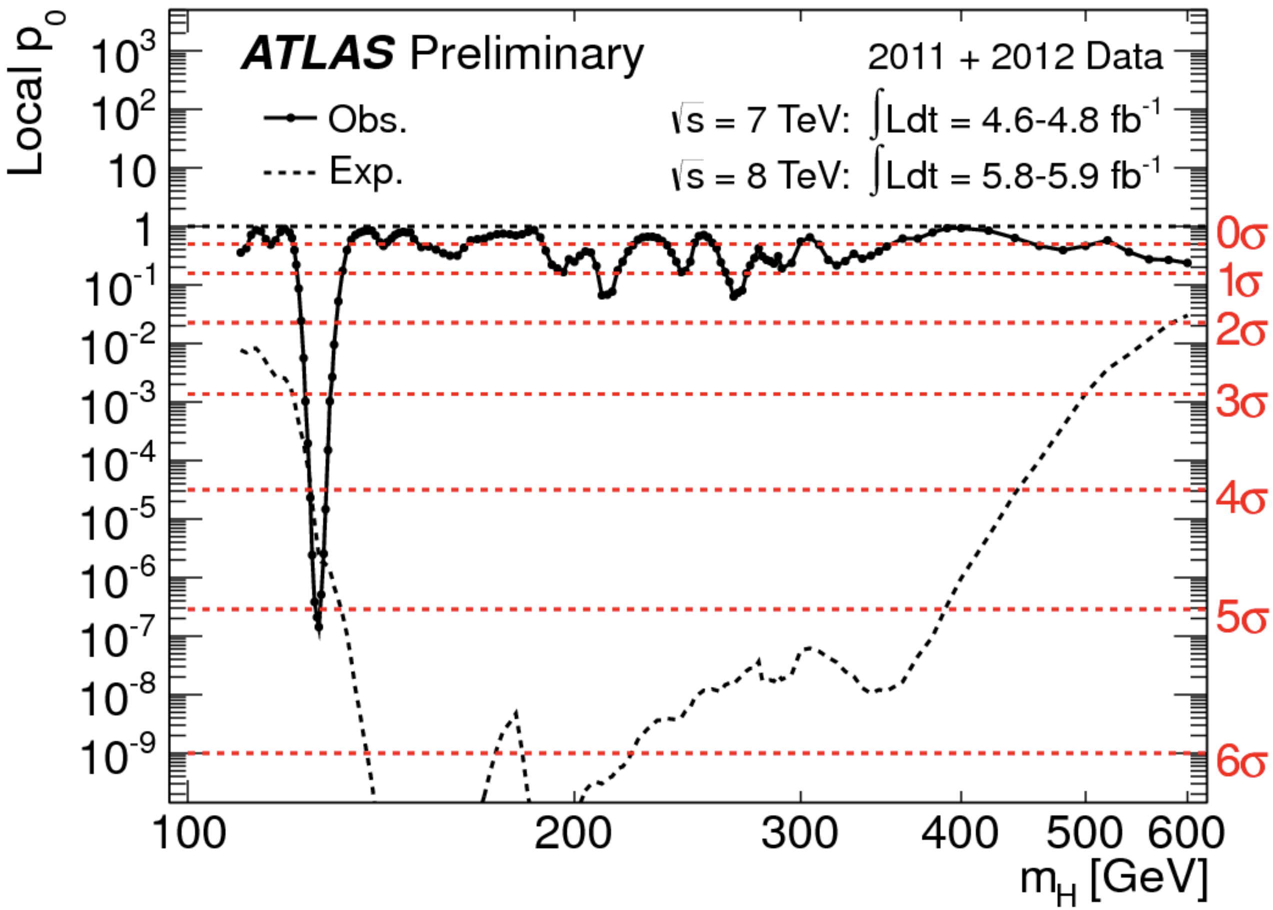



√s = 7 TeV ∫ Ldt = 0.00 fb⁻¹ Mar 25, 2011
ATLAS Preliminary
H→γγ channel
Events / GeV
Data - Fit
Mγγ [GeV]

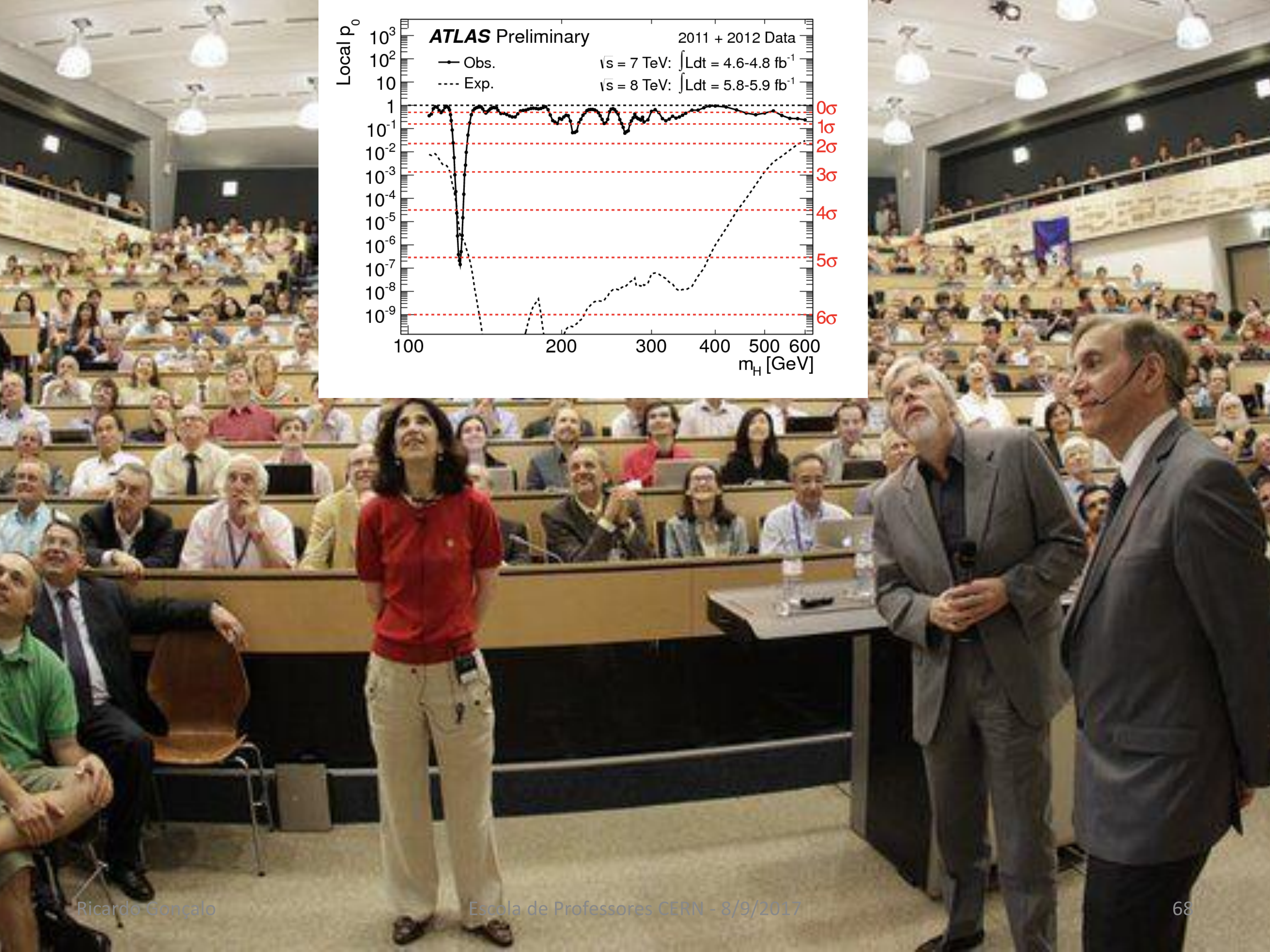
“The Brazil Plot”



O Gráfico dos 6 mil milhões de francos suíços



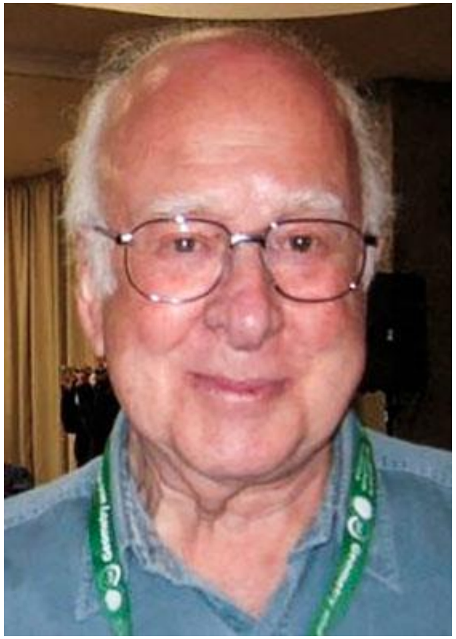
Probabilidade de 1 em 3.5 milhões de o sinal vir de uma flutuação estatística do ruído de fundo


ATLAS Preliminary
2011 + 2012 Data
Obs.
Exp.
√s = 7 TeV: ∫Ldt = 4.6-4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8-5.9 fb-1
Local p0
0σ
1σ
2σ
3σ
4σ
5σ
6σ
mH [GeV]

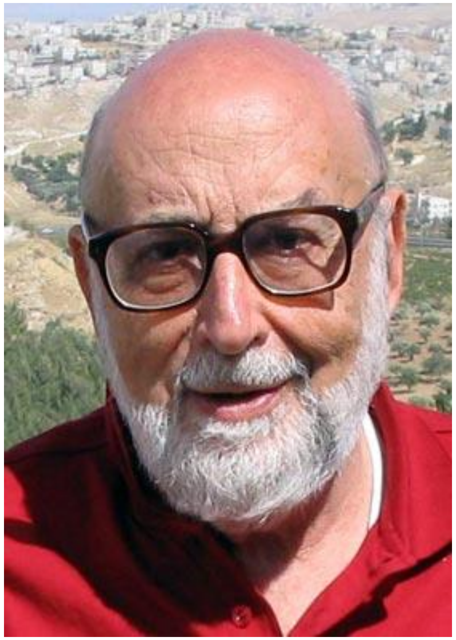
A Descoberta do bosão de Higgs

A Descoberta do bosão de Higgs...
...premiada com o Prémio Nobel 2013:

Peter Higgs,
Inglês,
nascido em 1929,
Univ. Edimburgo

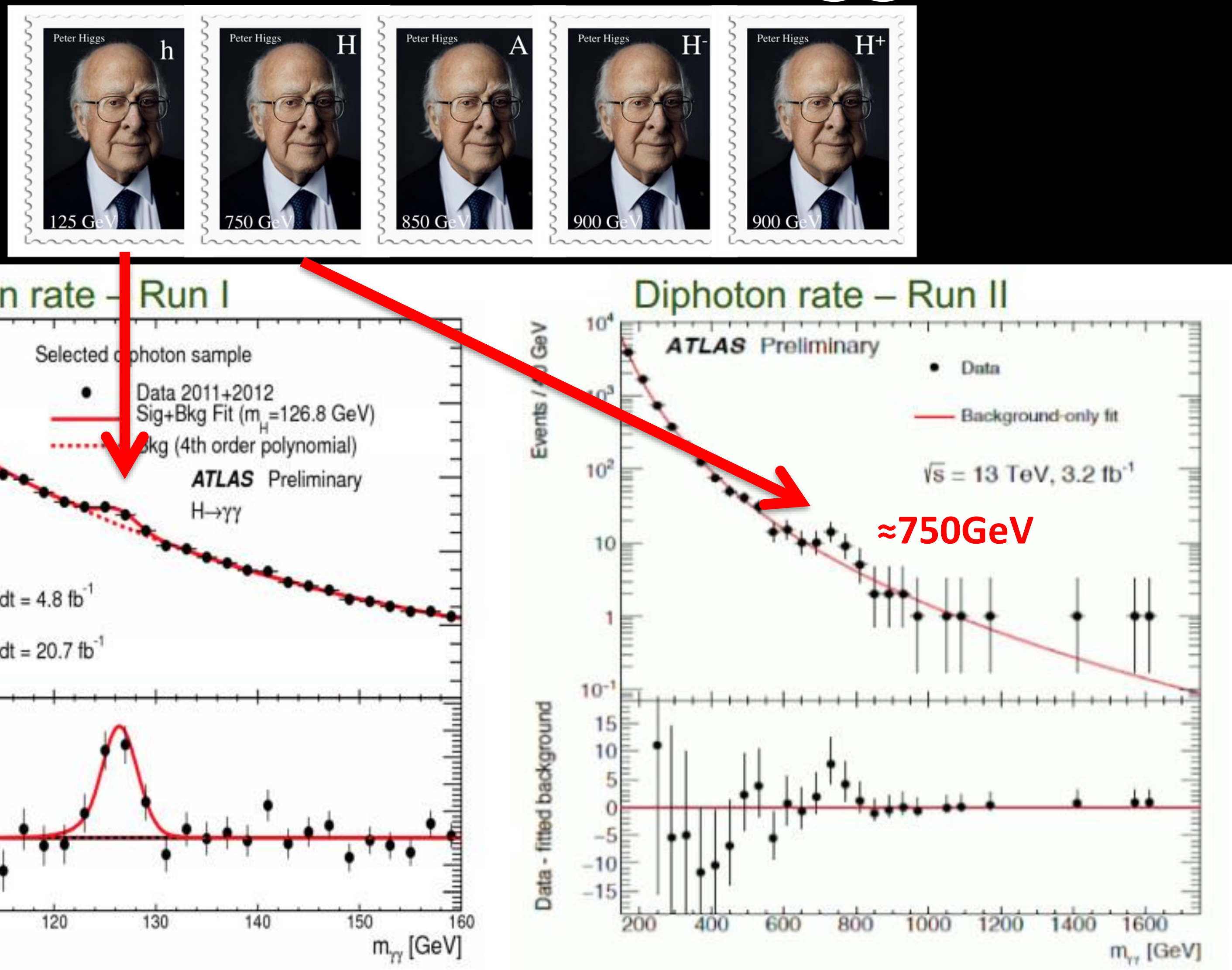


François Englert,
Belga,
nascido em 1932,
U. Libre de Bruxelles



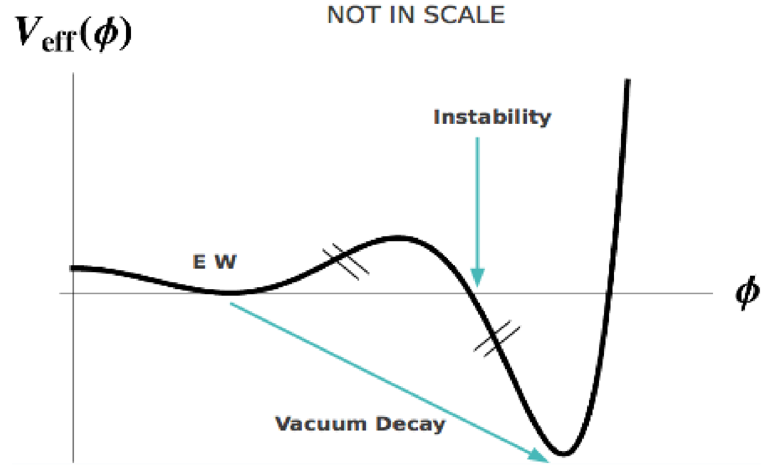
*"for the **theoretical discovery** of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the **discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider**"*

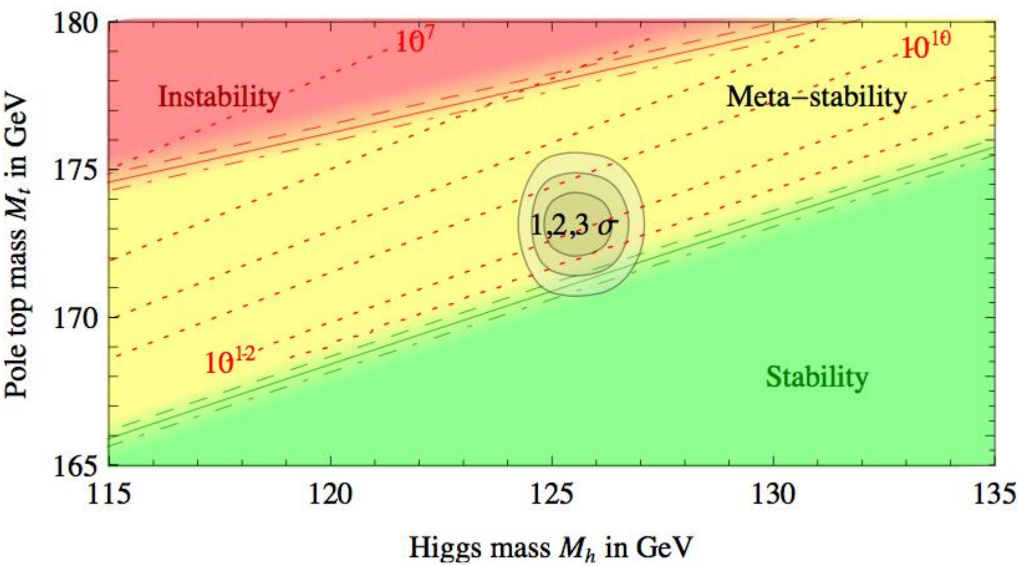
Há mais bosões de Higgs?



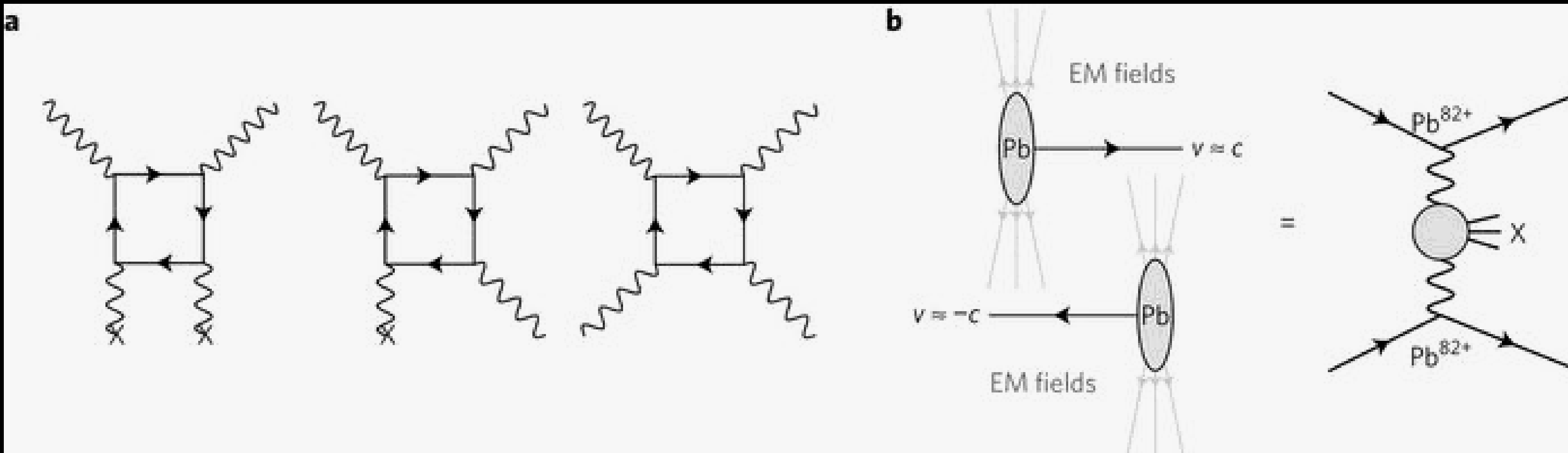
What if?...

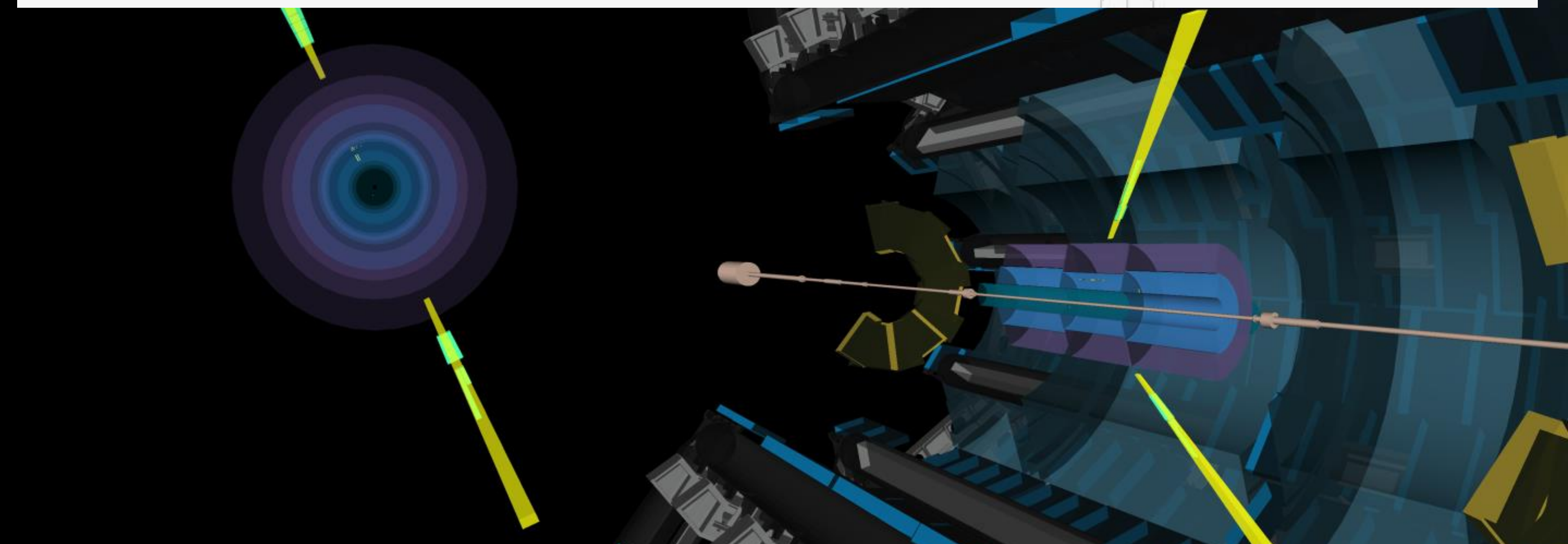
$$V^{1l}(\phi) = \frac{1}{2}m^2\phi^2 + \frac{\lambda}{24}\phi^4 + \frac{1}{64\pi^2}\Bigg[\left(m^2+\frac{\lambda}{2}\phi^2\right)^2\left(\ln\left(\frac{m^2+\frac{\lambda}{2}\phi^2}{\mu^2}\right)-\frac{3}{2}\right)$$
$$+3\left(m^2+\frac{\lambda}{6}\phi^2\right)^2\left(\ln\left(\frac{m^2+\frac{\lambda}{6}\phi^2}{\mu^2}\right)-\frac{3}{2}\right)+6\,\frac{g_1{}^4}{16}\phi^4\left(\ln\left(\frac{\frac{1}{4}g_1{}^2\phi^2}{\mu^2}\right)-\frac{5}{6}\right)$$
$$+3\,\frac{\left(g_1{}^2+g_2{}^2\right)^2}{16}\phi^4\left(\ln\left(\frac{\frac{1}{4}\left(g_1{}^2+g_2{}^2\right)\phi^2}{\mu^2}\right)-\frac{5}{6}\right)-12\,h_t^4\phi^4\left(\ln\frac{g^2\phi^2}{\mu^2}-\frac{3}{2}\right)\Bigg]$$





Notícias frescas





“Há mais coisas no céu e na terra, Horácio, do que sonha a nossa filosofia.”

Ricardo Gonçalo (LIP) Qualquer duvida: jgoncalo@lip.pt

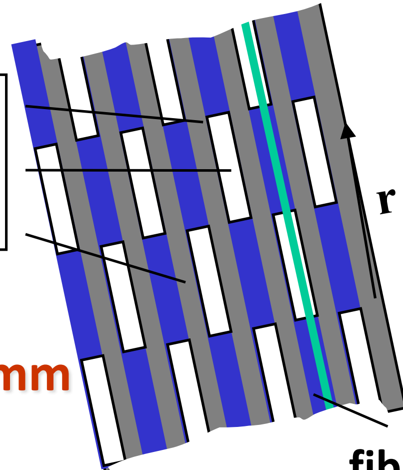

KEEP
CALM
AND
CHECK
BACKUP SLIDES

Estrutura e princípio de funcionamento do calorímetro Tilecal

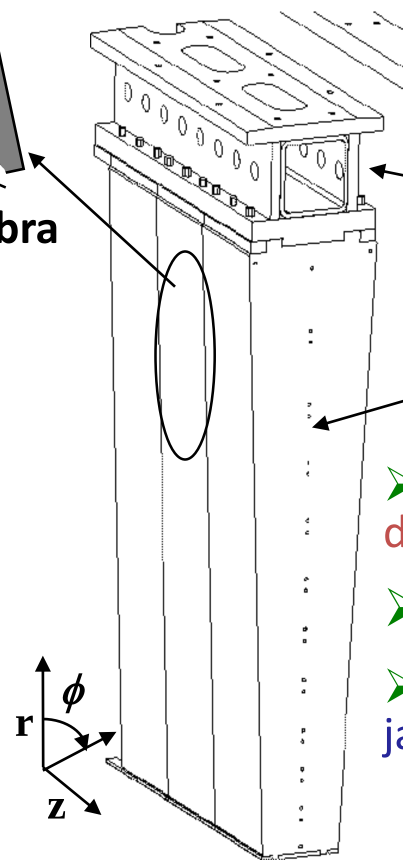
Estrutura periódica, ferro e cintiladores de plástico

placa mestra (5mm)
espaçador (4mm)
cintilador (3mm)

período básico, 18mm



- **razão Fe/cint. 4:1**
- **diâmetro ext 8.5 m**
- **comprimento 12 m**
- **peso total 2900 T**

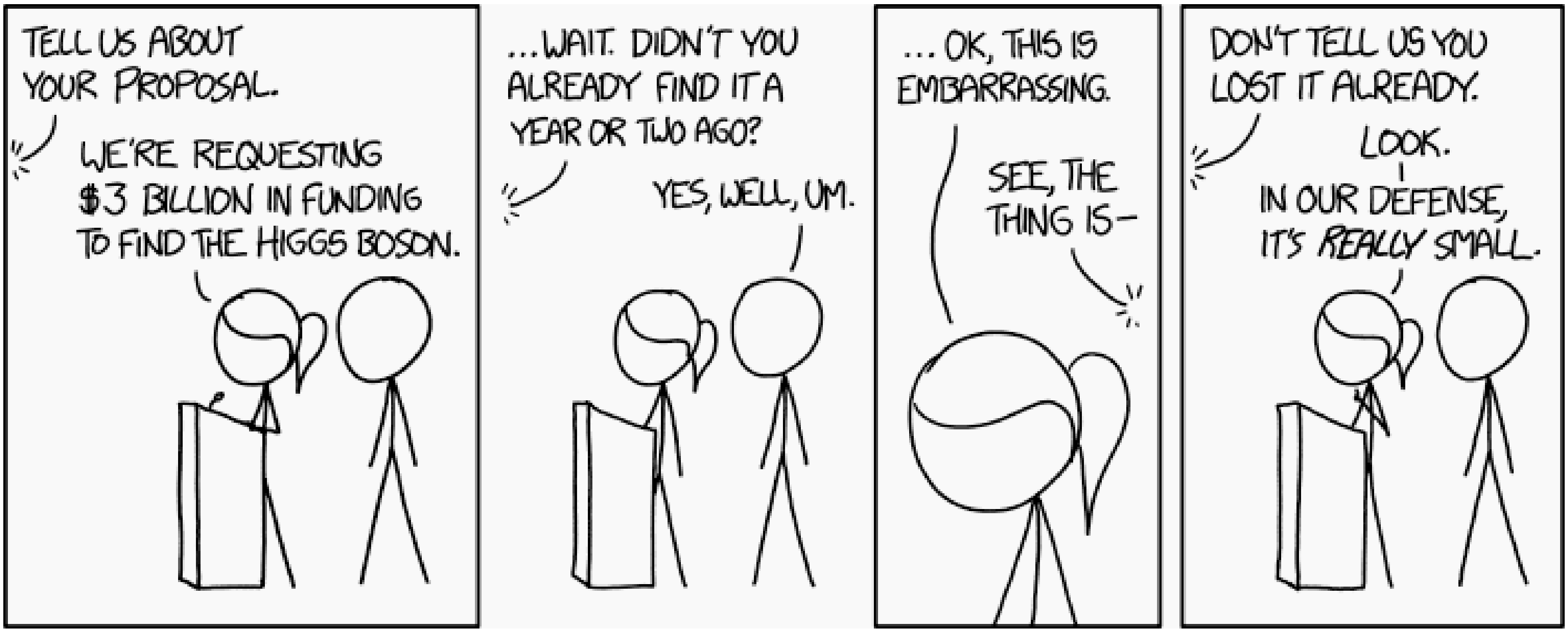


Luz produzida nos cintiladores transmitida até aos fotomultiplicadores através de fibras ópticas WLS

Fibras WLS

- Hermeticidade para detecção de jactos e E_t^{miss}
- Cobertura $|\eta| < 1.6$
- Resolução em energia para jactos

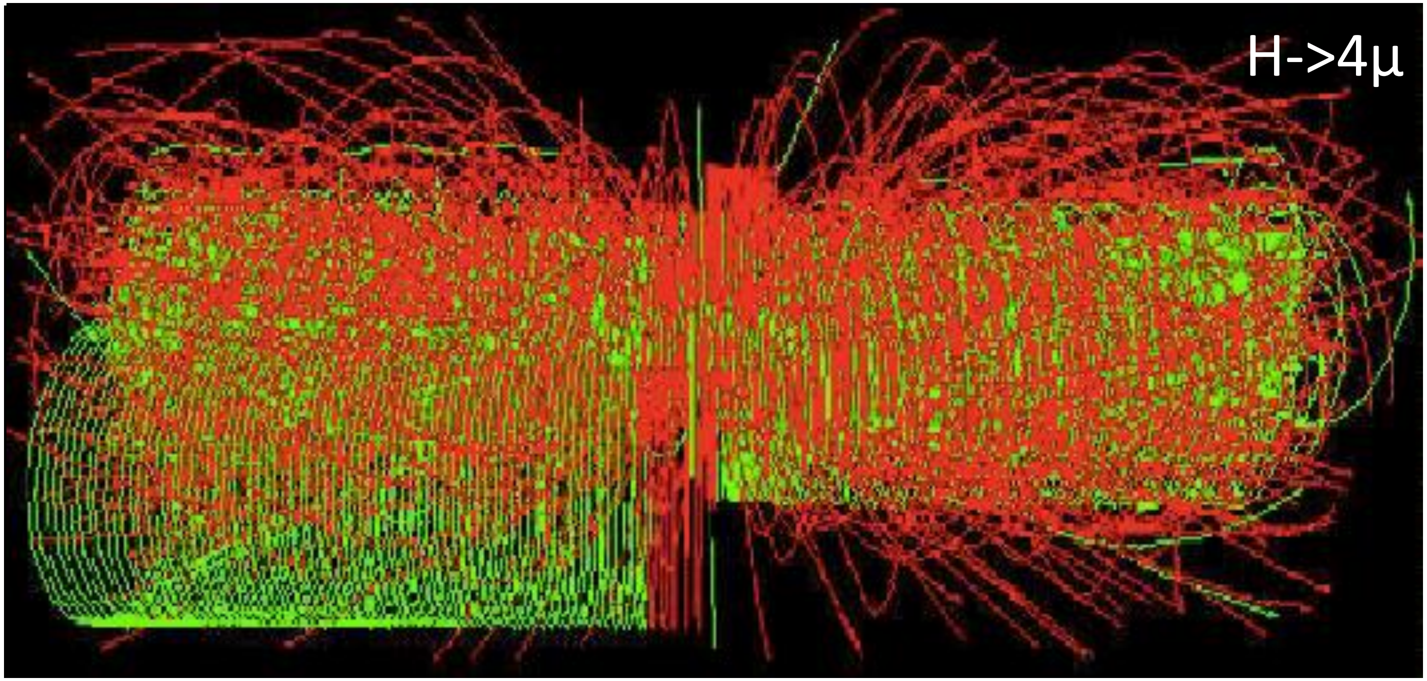
$$\frac{\Delta E}{E} \sim \frac{50\%}{\sqrt{E}} \oplus 3\%$$


TELL US ABOUT YOUR PROPOSAL.
WE'RE REQUESTING $3 BILLION IN FUNDING TO FIND THE HIGGS BOSON.
...WAIT. DIDN'T YOU ALREADY FIND IT A YEAR OR TWO AGO?
YES, WELL, UM.
... OK, THIS IS EMBARRASSING.
SEE, THE THING IS—
DON'T TELL US YOU LOST IT ALREADY.
LOOK.
IN OUR DEFENSE, IT'S *REALLY* SMALL.

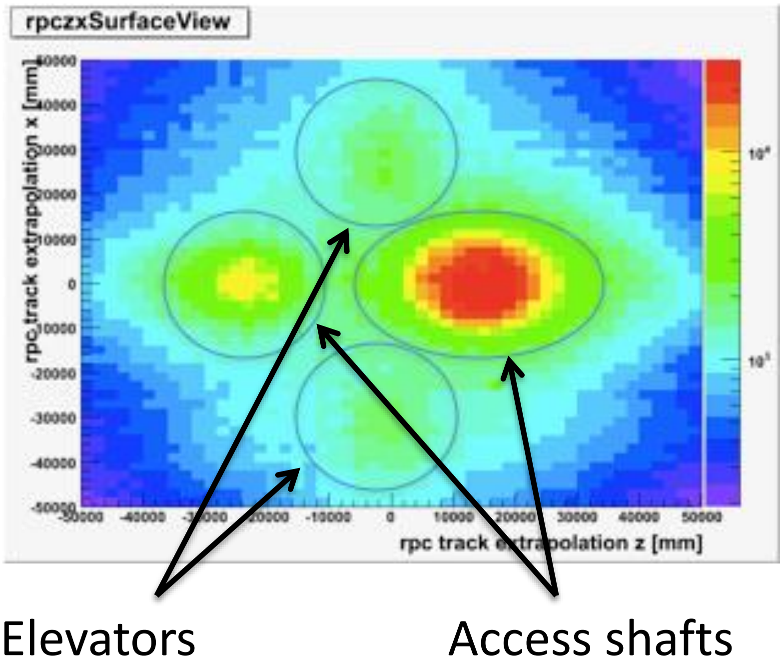
- Ok, so we reject background and take only signal events

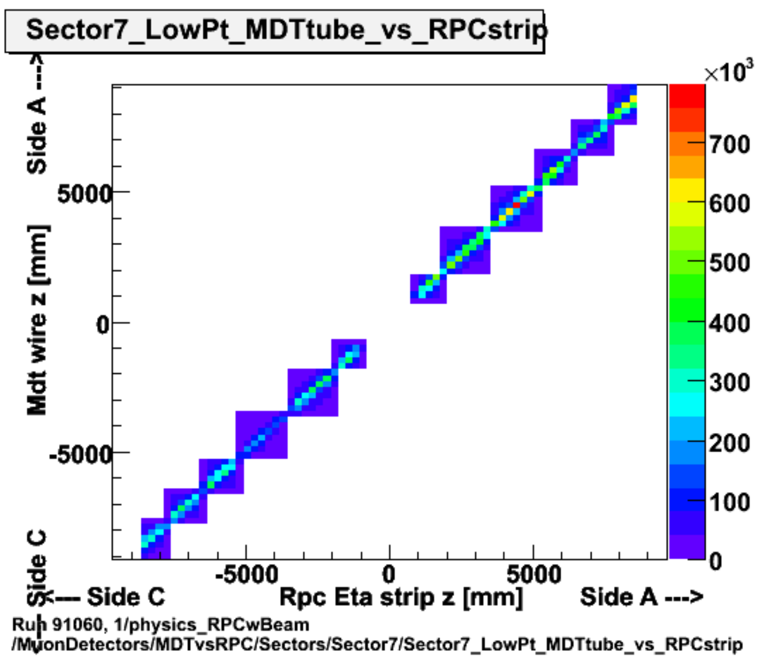
Maybe not so simple:

  - Bunch spacing is 25ns: not much time to decide! (25ns x *c* = 7.5m)
  - Put event fragments in memory pipeline to buy time for Level 1 decision
  - Pileup of minimum-bias events means longer reconstruction time and higher occupancy
  - Not only pileup from same bunch crossing! ATLAS sub-detector response varies from a few ns to about 700 ns (= 28 bunch crossings!)
  - Try to rely mostly on high-pT particles

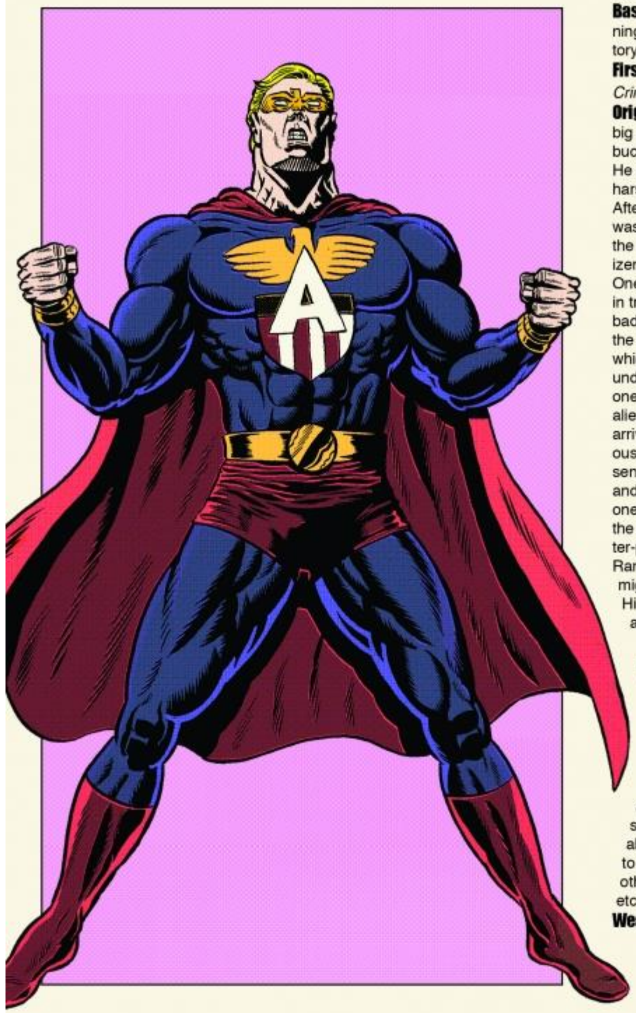


X-ray of the ATLAS cavern with cosmic muons





Very good correlation between RPC (trigger chambers) and MDT (precision chambers) hits



ATLAS

Real name: Johnny Rammond
Occupation: Head of the O.P.T.C.– Optic City Planning Committee
Identity: Known to his best friend Toby Whey
Legal status: Johnny Rammond is a United States citizen, Atlas is considered "above the law"
Place of birth: Heffield, Nebraska
Marital status: Single
Known relatives: Sturgill Rammond (father, deceased), Dorothy Rammond (mother, deceased), Toby Whey (best friend)
Base of operations: The Optic City Planning Center, as well as his secret laboratory in a hidden chamber of his house
First appearance: *All Time Comics: Crime Destroyer* #1
Origin: Johnny Rammond came to the big city from the Midwest with a couple bucks in his pocket and stars in his eyes. He soon found the reality of Optic City a harsher one than he could have dreamed. After months of hardship and difficulty, he was reduced to sleeping in the sewers of the city with the other underground denizens of the underground communities. One night he came upon a mugging and in trying to stop it, he was assaulted and badly hurt. He managed to crawl back into the sewers. He was washed into a drain which took him into a deeper level of the under city than any human had ever been, one which was constructed by ancient aliens many aeons before human beings arrived on the continent. There, mysterious, cosmic machines whirred to life and, sensing Rammond's innate good nature and well-meaning spirit, imbued him with one of the most powerful weapons on the planet, his multi-channel, anti-matter-powered communicator / signal ring. Rammond's second life as Optic City's mightiest costumed hero began that day. His only weakness is when uncertainty and fear take hold in his mind

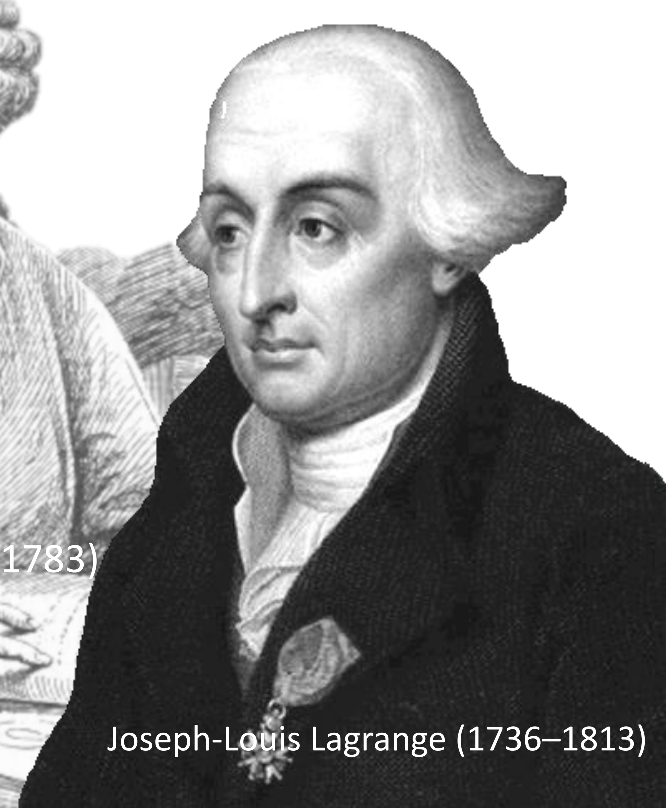
Height: 6'1"
Weight: 215 lbs.
Eyes: Blue
Hair: Blonde
Powers: Atlas's anti-matter ring gives him multiple powers, including super strength, super speed, the ability to fly, anti-matter rays which shoot out of his eyeballs, the ability to absorb tremendous trauma, the ability to communicate with whoever wears his other ring from anywhere in the universe, etc.
Weapons: Anti-matter power ring

Voltemos um pouco atrás…

Atenção! Os próximos slides contêm equações potencialmente chocantes.

Emmy Noether (1882 – 1935)

Leonhard Euler(1707–1783)



Joseph-Louis Lagrange (1736–1813)

Lagrangianos e mecânica clássica

The equations of motion of a system are derived from a scalar **Lagrangian** function of **generalized coordinates** and **velocities** (time derivatives)

$$L(q, \dot{q}) = T - V$$

and from the **Euler-Lagrange's equations**:

$$\frac{\partial L}{\partial q_j} - \frac{d}{dt}\frac{\partial L}{\partial \dot{q}_j} = 0$$

Example

Particle in a conservative potential V. The Lagrangian

$$L = \frac{1}{2}m(\dot{x}^2 + \dot{y}^2 + \dot{z}^2) - V(x, y, z)$$

has derivatives (e.g. for *x*)

$$\frac{\partial L}{\partial x} = -\frac{\partial V}{\partial x}, \frac{\partial L}{\partial \dot{x}} = m\dot{x}, \frac{d}{dt}(\frac{\partial L}{\partial \dot{x}}) = m\ddot{x}$$

and Euler-Lagrange's equations

$$\frac{\partial L}{\partial q_j} - \frac{d}{dt}\frac{\partial L}{\partial \dot{q}_j} = 0$$

finally give us Newton's familiar 2nd law!

$$m\ddot{x} = -\frac{\partial V}{\partial x}, m\ddot{y} = -\frac{\partial V}{\partial y}, m\ddot{z} = -\frac{\partial V}{\partial z} \Leftrightarrow m\vec{a} = \vec{F}$$

Symmetries and conservation laws

Noether's theorem:

If a system has a continuous symmetry property, then there are corresponding quantities whose values are conserved in time.

Simplest case: Coordinates not explicitly appearing in the Lagrangian

$\Rightarrow$ Lagrangian invariant over a continuous transformation of the coordinates

Example: mass **m** orbiting in the field of a fixed mass **M**

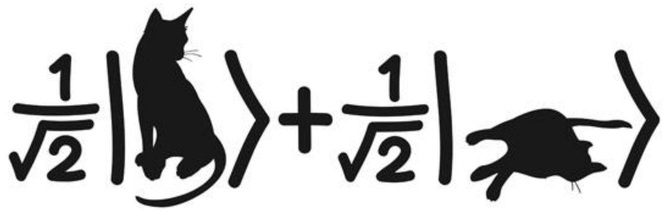
$$L(r,\phi,\dot{r},\dot{\phi}) = T - V = \frac{1}{2}m\dot{r}^2 + \frac{1}{2}mr^2\dot{\phi}^2 + \frac{GMm}{r}$$

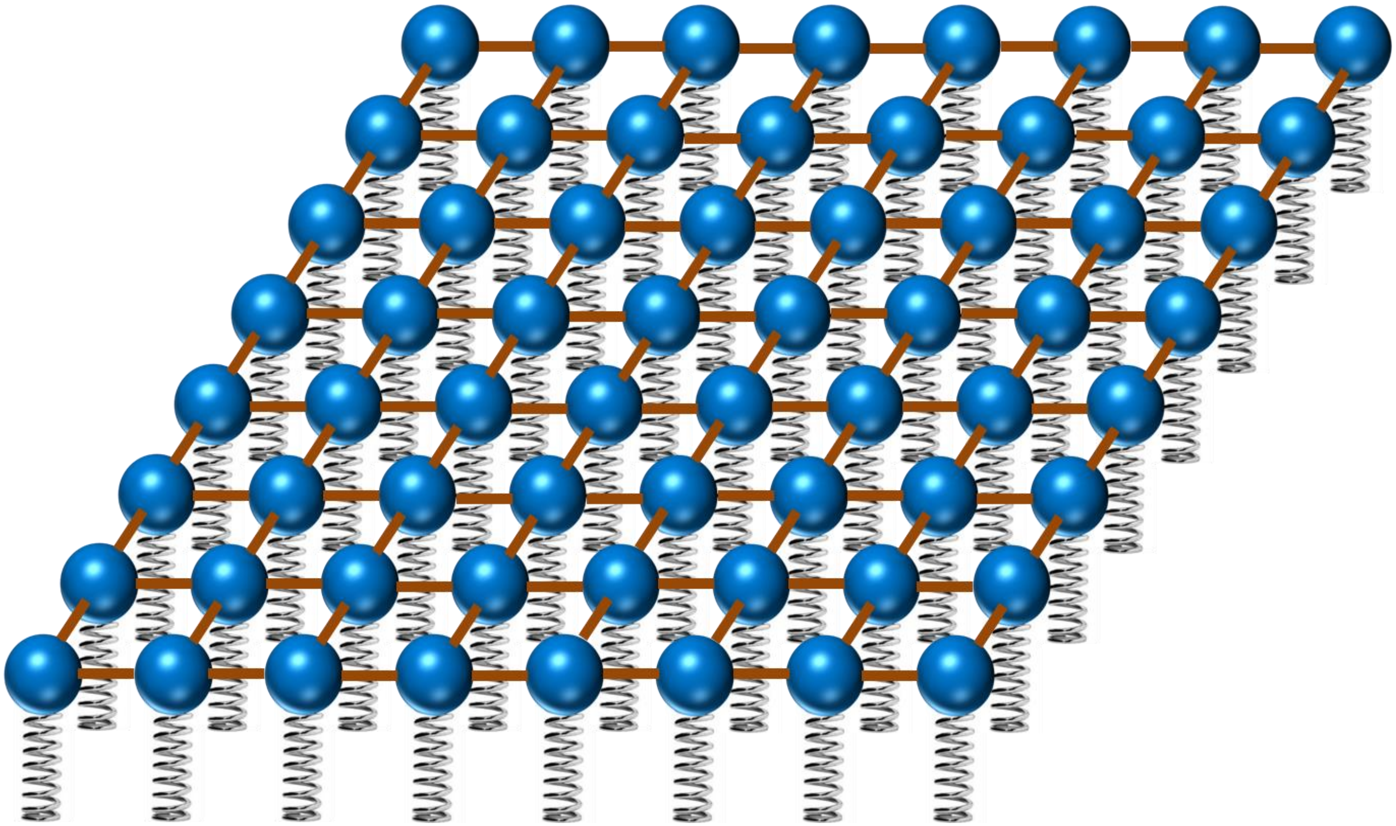
Since the lagrangian doesn't depend explicitly on **ϕ** (symmetry with respect to rotations in space), the Euler-Lagrange equation gives

$$\frac{d}{dt}\left(\frac{\partial L}{\partial\dot{\phi}}\right) = 0 \Leftrightarrow \frac{\partial L}{\partial\dot{\phi}} = mr^2\dot{\phi} = J$$

Where the **angular momentum J** is a constant of motion!

Agora nos campos quânticos...





Partículas são ondas num “mar” (campo quântico)

Generalized coordinates are now **fields** (dislocation of each spring)

$$q_i \rightarrow \phi_i(x^\mu)$$

In a relativistic theory we must treat space and time coordinates on an equal footing, so the derivatives in the classical equations are now

$$\frac{d}{dt}, \nabla \rightarrow \partial_\mu = (\frac{\partial}{\partial t}, \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z})$$

In place of a Lagrangian we have a **Lagrangian density** (we call it Lagrangian anyway, just to be confusing)

$L(q_i, \frac{dq_i}{dt}) \rightarrow \mathcal{L}(\phi_i, \partial_\mu \phi_i)$ with: $L = \int \mathcal{L} d^3\boldsymbol{x}$

The new Euler-Lagrange equation now becomes

$$\partial_\mu(\frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi_i)}) - \frac{\partial \mathcal{L}}{\partial \phi_i} = 0$$

Gauge invariance

Take the Dirac Lagrangian for a field ψ representing a spin-½ particle, for example an electron:

$$\mathcal{L} = i\hbar\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi$$

It is invariant under a global U(1) phase transformation like:

$$\psi(x) \rightarrow \psi'(x) = e^{iq\chi}\psi(x)$$

Where **χ** is a constant

$$\mathcal{L}' = e^{-iq\chi}e^{iq\chi}(i\hbar\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi) = \mathcal{L}$$

Local gauge invariance and interactions

If **χ** = **χ** (*x*) then we get extra terms in the Lagrangian:

$$\begin{aligned} \mathcal{L}' &= ie^{-iq\chi}\bar{\psi}\gamma^{\mu}[e^{iq\chi}\partial_{\mu}\psi + iq(\partial_{\mu}\chi)e^{iq\chi}\psi] - me^{-iq\chi}e^{iq\chi}\bar{\psi}\psi \\ &= \mathcal{L}' - q\bar{\psi}\gamma^{\mu}(\partial_{\mu}\chi)\psi \end{aligned}$$

But we can now make the Lagrangian invariant by adding an ***interaction term*** with a new **gauge** field $\boldsymbol{A_\mu}$ which transforms as:

$$A_{\mu} \rightarrow A'_{\mu} = A_{\mu} - \partial_{\mu}\chi$$

We get:

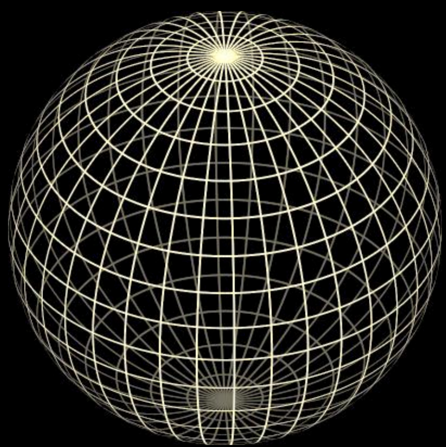
$$\mathcal{L} = i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi - q\bar{\psi}\gamma^{\mu}A_{\mu}\psi$$

A few things to note:

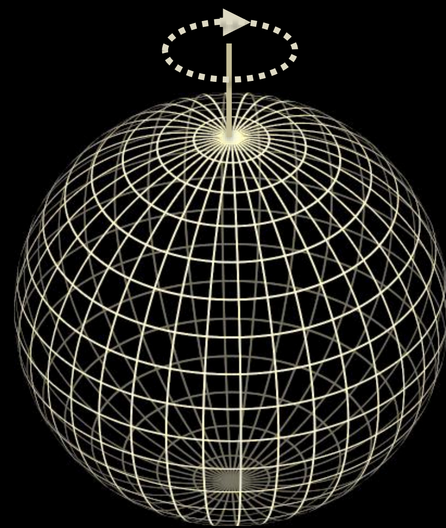
1. Gauge theories are renormalizable, i.e. calculable without infinities popping up everywhere (Nobel prize of t'Hooft and Veltman)
2. The new gauge field $\boldsymbol{A_\mu}$ is the photon in QED
3. The mass of the fermion is the coefficient of the term on $\boldsymbol{\psi\bar{\psi}}$
4. There is no term in $\boldsymbol{A_\mu A^\mu}$ (the photon has zero mass) → this is the beginning of the Higgs story…

$$\psi(x) \rightarrow \psi'(x) = e^{iq\chi}\psi(x)$$

Esfera original

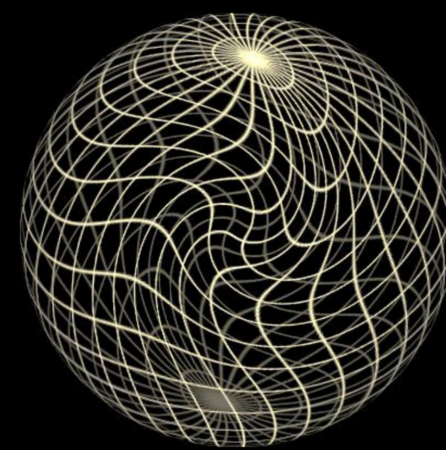


Transformação global



χ = constante

Transformação local



χ = χ (*x*)

Mass of elementary particles and gauge bosons

$$\mathcal{L}_{QED} = \bar{\psi}(i\gamma^\mu\partial_\mu - m_e)\psi - e\bar{\psi}\gamma^\mu\psi A_\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_\gamma A_\mu A^\mu$$

To keep the Lagrangian gauge invariant (against a U(1) local phase transformation) the photon field transforms as:

$$A_\mu \rightarrow A'_\mu = A_\mu - \partial_\mu\chi$$

But the ***A***$^{\mu}$ mass term breaks the invariance of the Lagrangian:

$$\frac{1}{2}m_\gamma A_\mu A^\mu \rightarrow \frac{1}{2}m_\gamma(A_\mu - \partial_\mu)(A^\mu - \partial^\mu\chi) \neq \frac{1}{2}m_\gamma A_\mu A^\mu$$

For the SU(2)$_L$ gauge symmetry transformations of the **weak interaction** the fermion mass term $\mathbf{m_e\bar{\Psi}\psi}$ also breaks invariance!

Bottom line: **the SM (without the Higgs mechanism) results in wrong calculations and breaks down for massive particles**

O Mecanismo de Higgs

Robert Brout (1928 – 2011)

Peter Higgs (b. 1929)

François Englert (b. 1932)

- Introduce a SU(2) doublet of spin-0 complex fields

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi 4 \end{pmatrix}$$

- The Lagrangian is

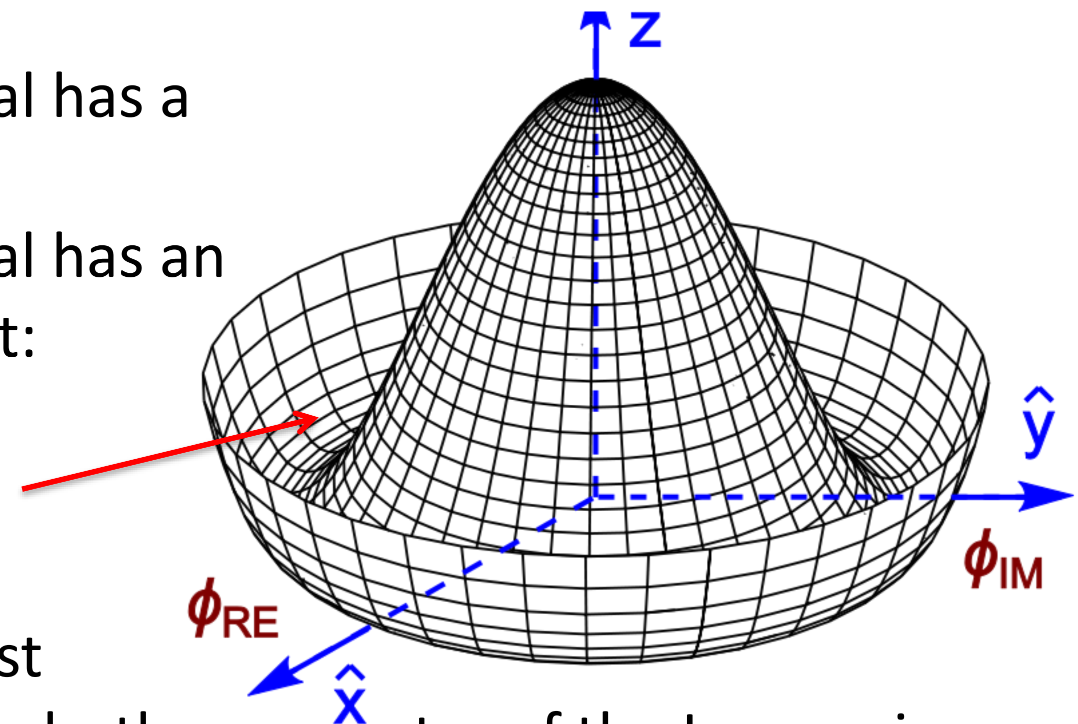
$$\mathcal{L} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi)$$

- With a potential

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$

- For $\lambda>0$, $\mu^2<0$ the potential has a minimum at the origin
- For $\lambda>0$, $\mu^2<0$ the potential has an infinite number of minima at:

$$|\phi| = \frac{v}{\sqrt{2}} = \sqrt{-\frac{\mu^2}{2\lambda}}$$

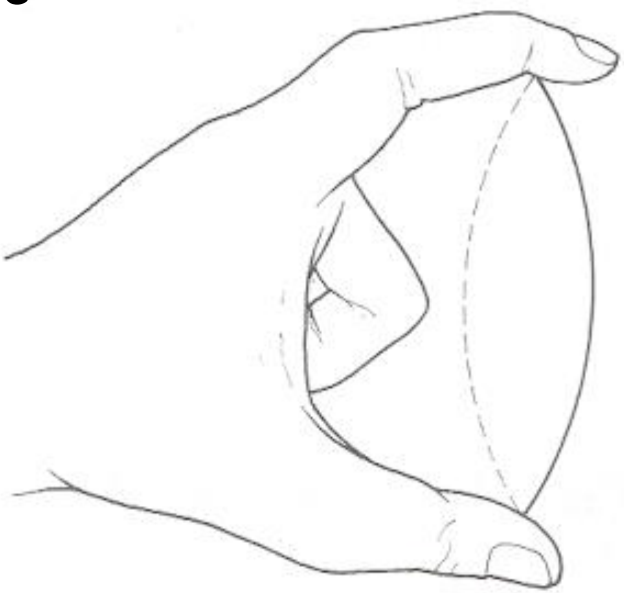


The choice of vacuum (lowest energy state of the field) breaks the symmetry of the Lagrangian

Electroweak symmetry breaking

- In the Standard Model with no Higgs mechanism, interactions are symmetric and particles do not have mass

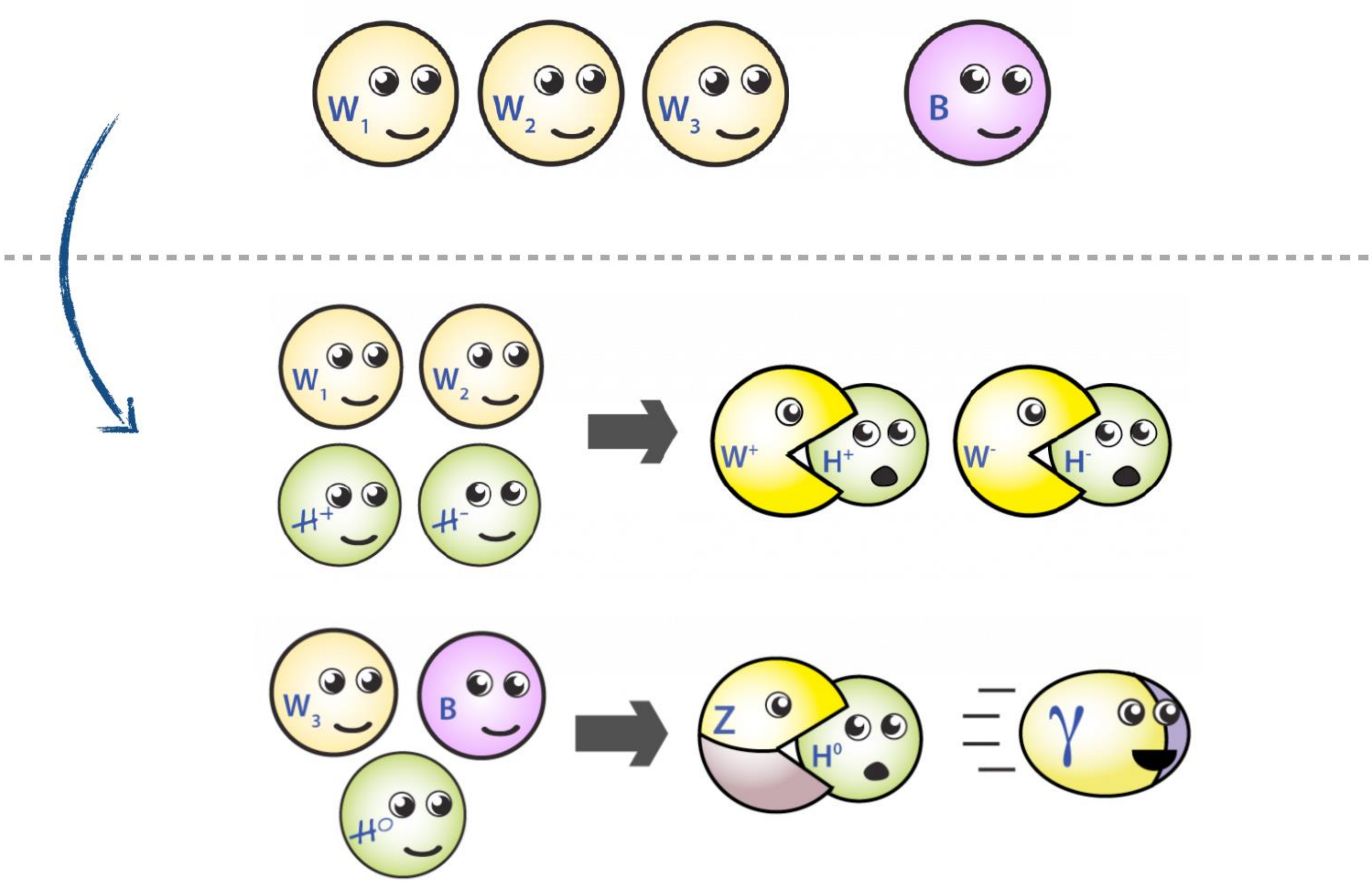
- Electroweak symmetry is broken:
  - Photon does not have mass
  - W, Z have a large mass



- Higgs mechanism: mass of W and Z results from the Higgs mechanism
- Masses of fermions come from a direct interaction with the Higgs field

see J.Varela's lecture

EWK Symmetry Breaking in Pictures



- We have at this point a massive scalar field with vacuum expectation value ***v*** and mass

$$m_h = \sqrt{2\lambda}v$$

- 4 gauge fields: $W^{(1)}$, $W^{(2)}$, $W^{(3)}$, and $B^{(1)}$ which transform to give the massive W^+, W^- and Z, and massless A (the photon)

$$m_{W^{(1)}} = m_{W^{(2)}} = m_W = \frac{1}{2} g_W v$$

$$m_A = 0 \qquad \Leftrightarrow v = 246\text{GeV}$$

$$m_Z = \frac{1}{2} v \sqrt{g_W^2 + g^2}$$

with g, g_W the couplings of electromagnetic and weak forces

- Defining the Weinberg angle as

$$\frac{g}{g_W} = \tan\theta_W$$

we also get the relation between the masses of W and Z

$$\frac{m_W}{m_Z} = \cos\theta_W$$

- Fermions get their masses from interaction terms with the Higgs field (Yukawa coupling)

Finally! What we think we know:

- Higgs mass (was) the only unknown parameter

$$m_h = \sqrt{2\lambda}v$$

- We can give mass to $W^{\pm}$ and Z while keeping the photon massless
- Relation between masses of W and Z

$$\frac{m_W}{m_Z} = \cos\theta_W$$

- Higgs couples to W and Z with strengths proportional to their masses
- Higgs couples to all fermions with a strength proportional to their mass

$$g_f = \sqrt{2}\frac{m_f}{v}$$