

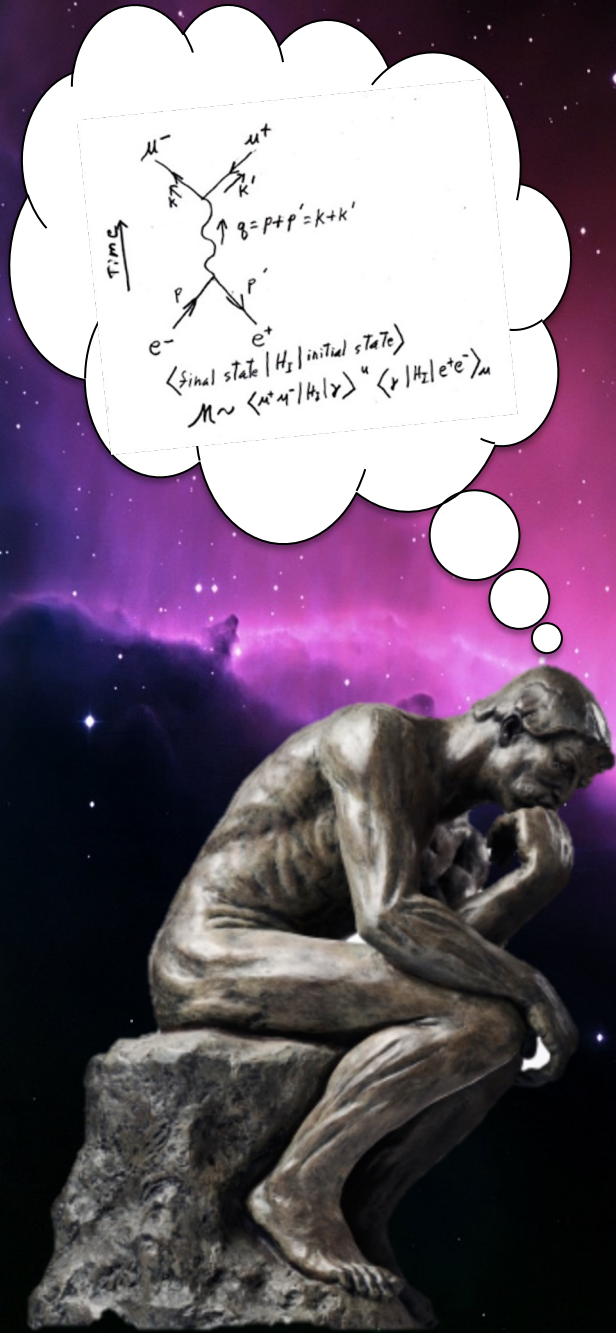
A FÍSICA EXPERIMENTAL DE PARTÍCULAS

Workshop da PHYSIS
Universidade de Coimbra – 25 de outubro de 2025

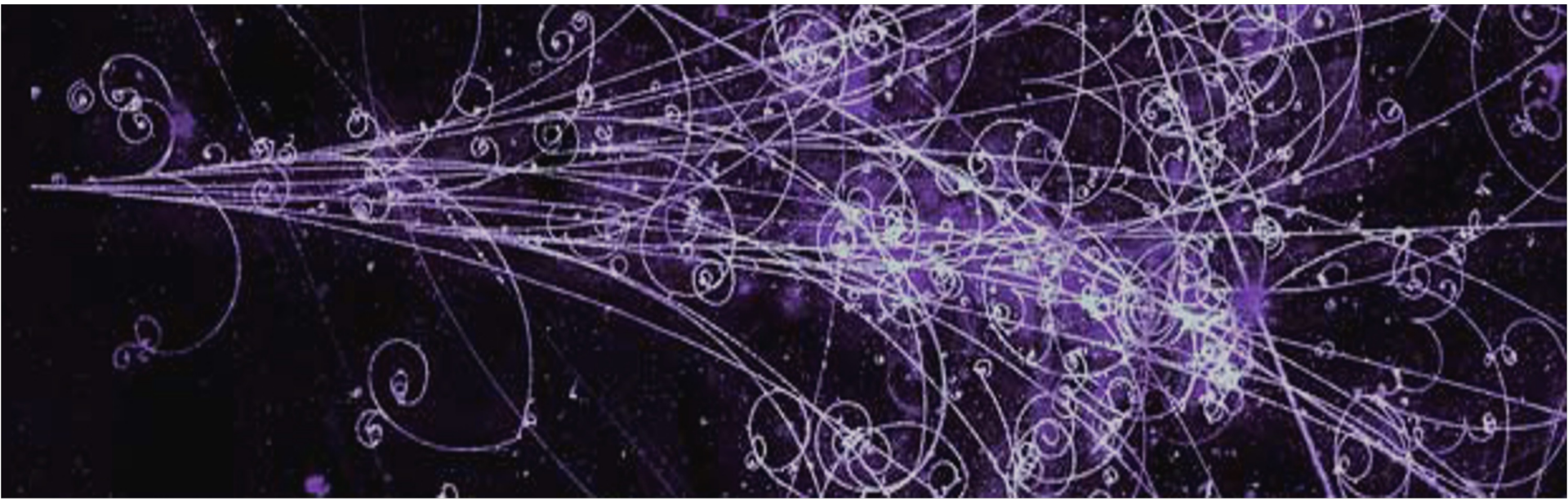
Ricardo Gonalo
Universidade de Coimbra / LIP

Sumário

- Viagem pela física de partículas
 - Partículas e forças fundamentais
 - O que sabemos e o que não sabemos...
- Física Experimental de Partículas
 - Como ver partículas invisíveis!
 - Experiências atuais ponta
 - Experiências do LHC
 - Análise de dados
- Benefícios para a sociedade
 - Partículas para o espaço e a saúde

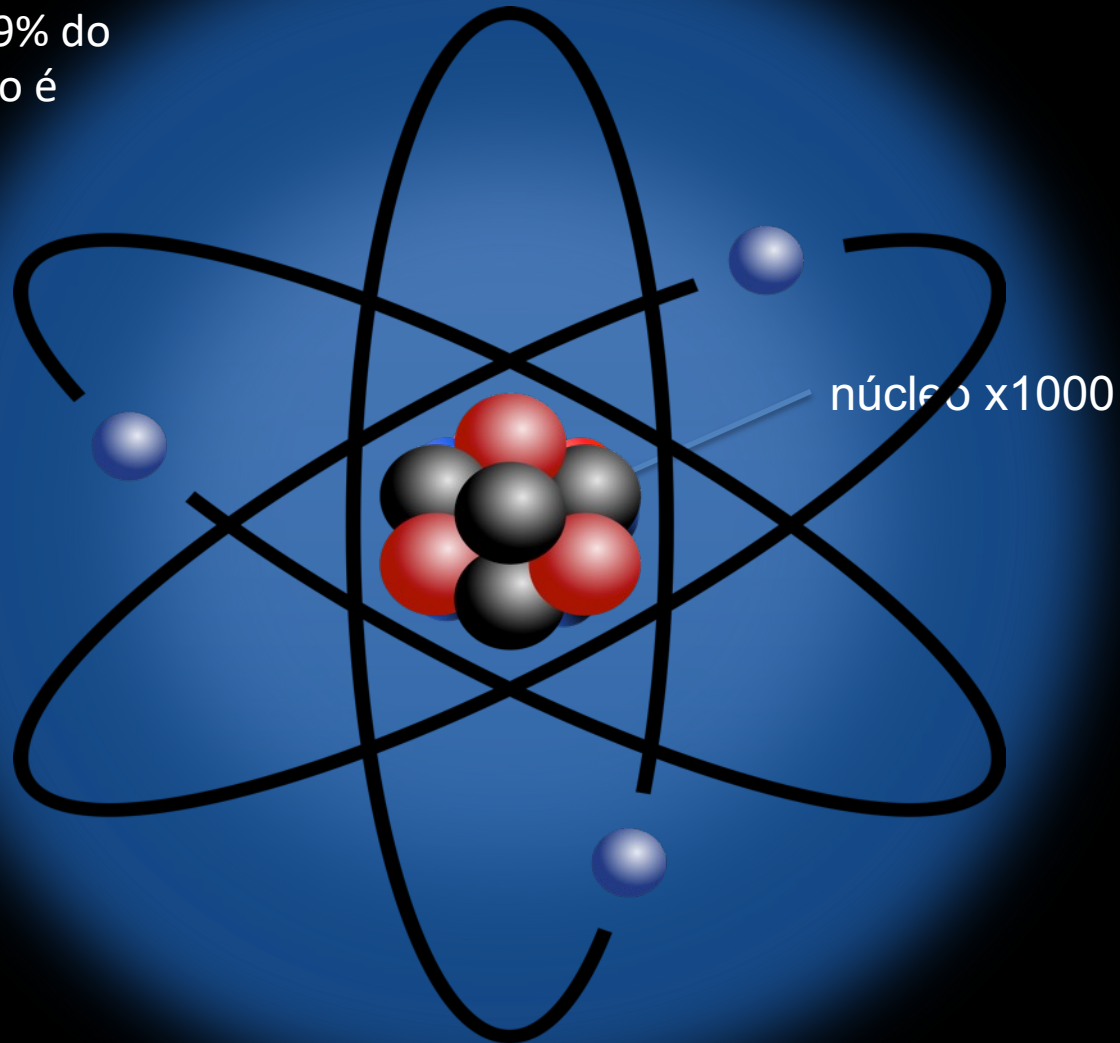


A física de partículas

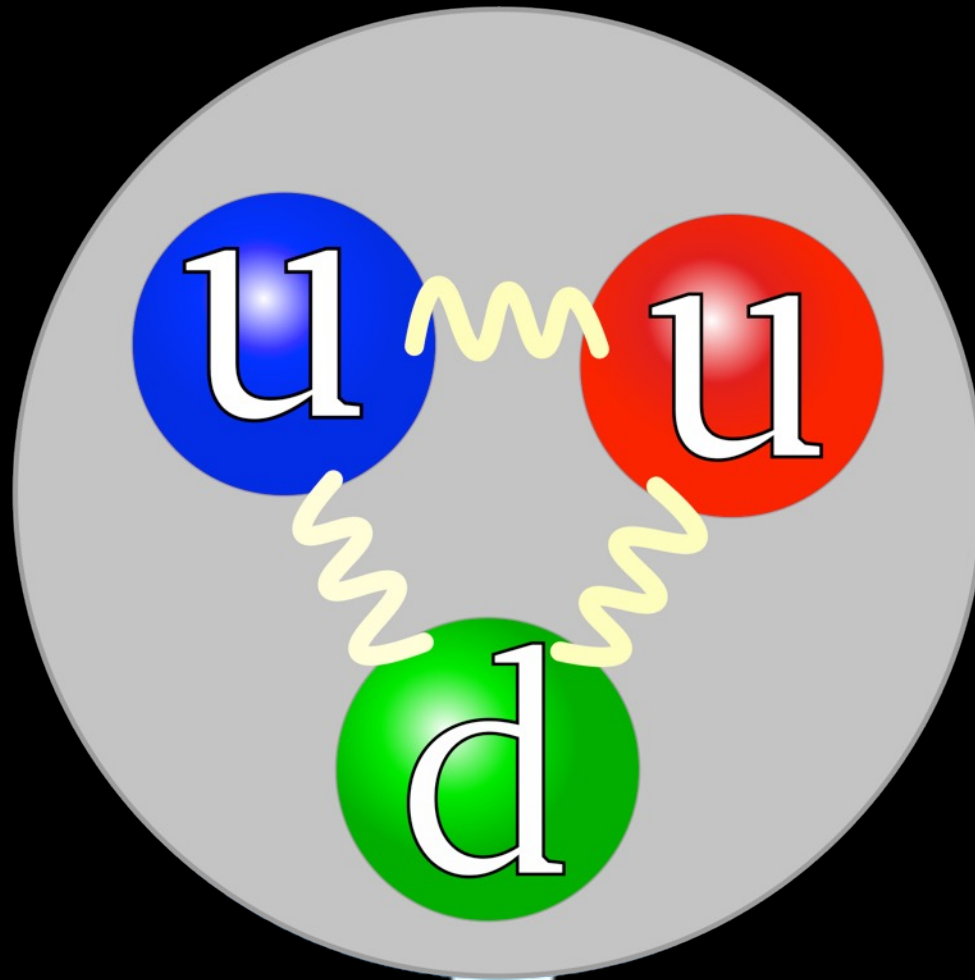


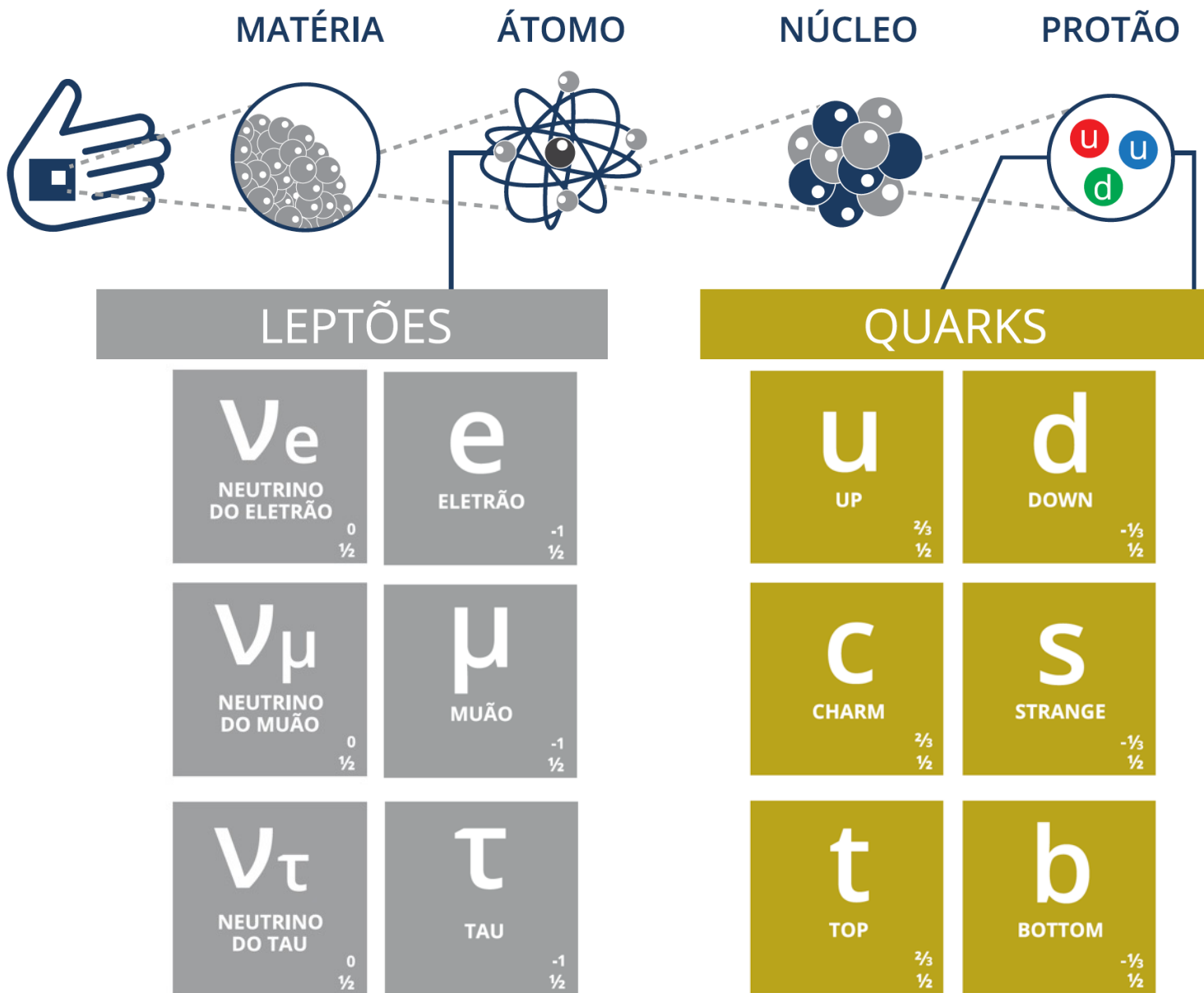
O átomo

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

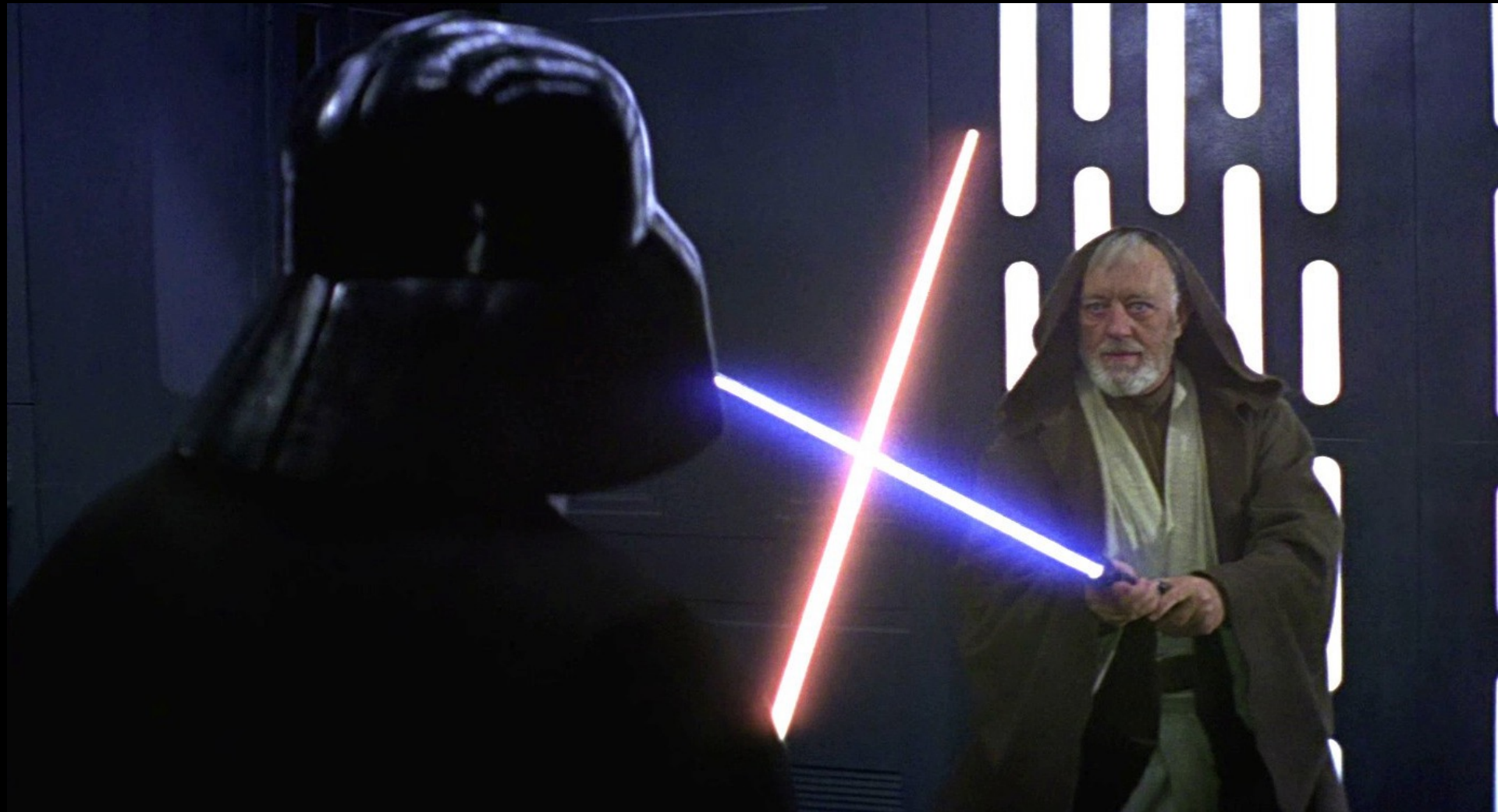


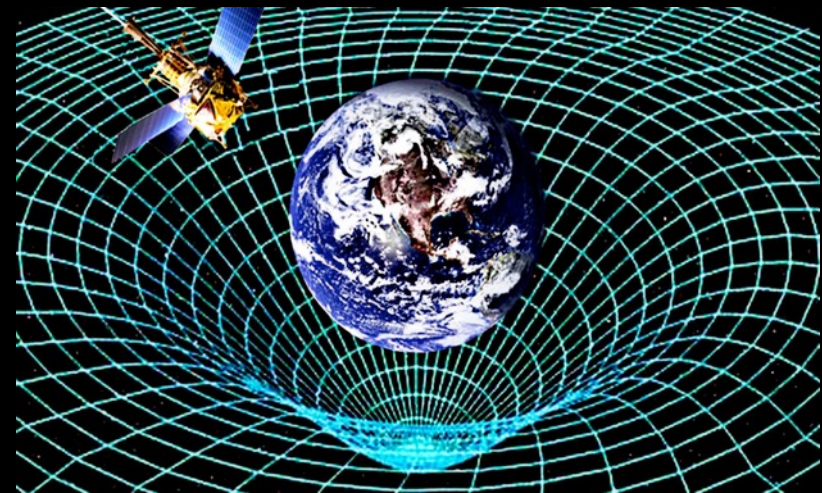
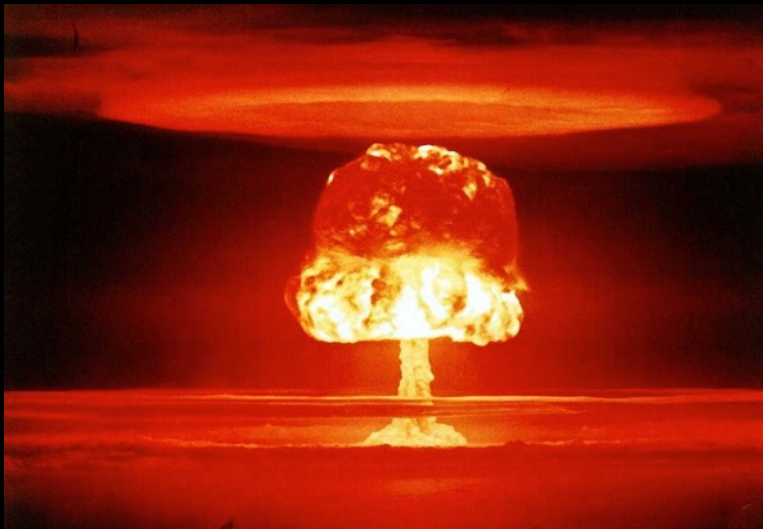
O protão no modelo dos quarks





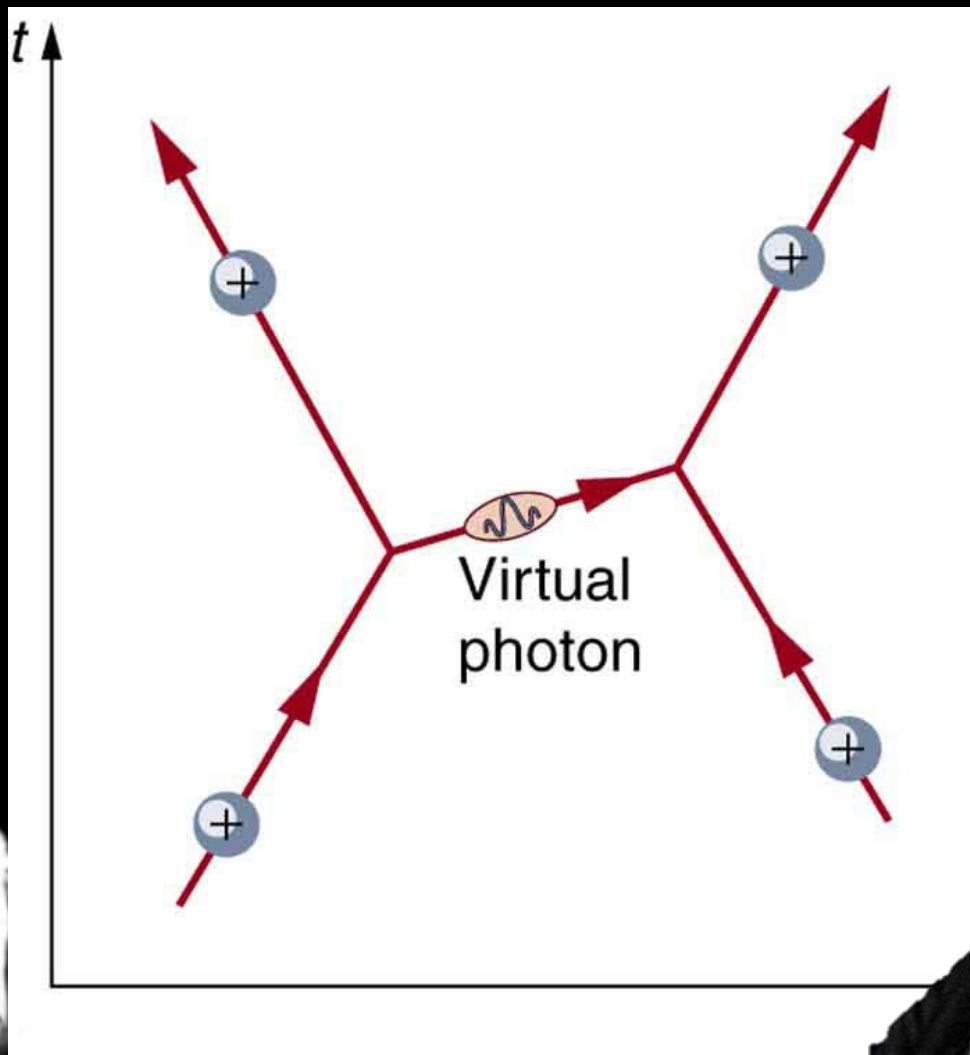
E as forças fundamentais?



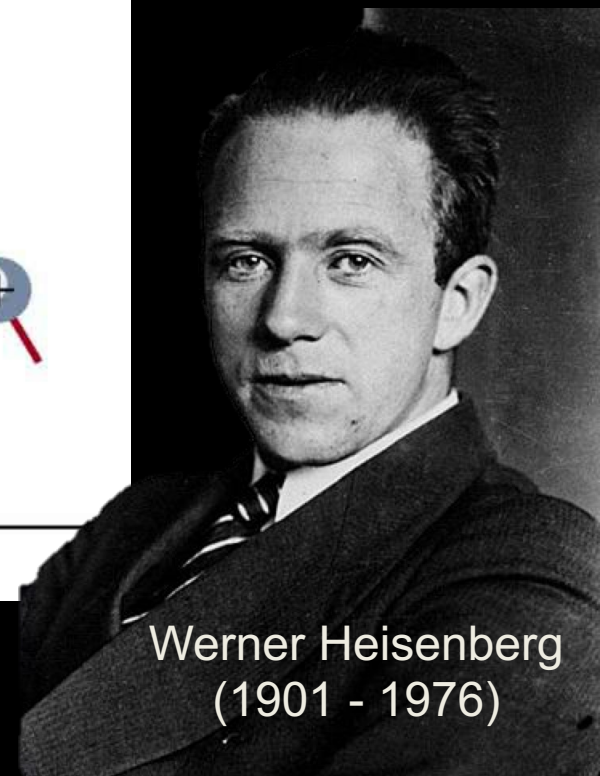


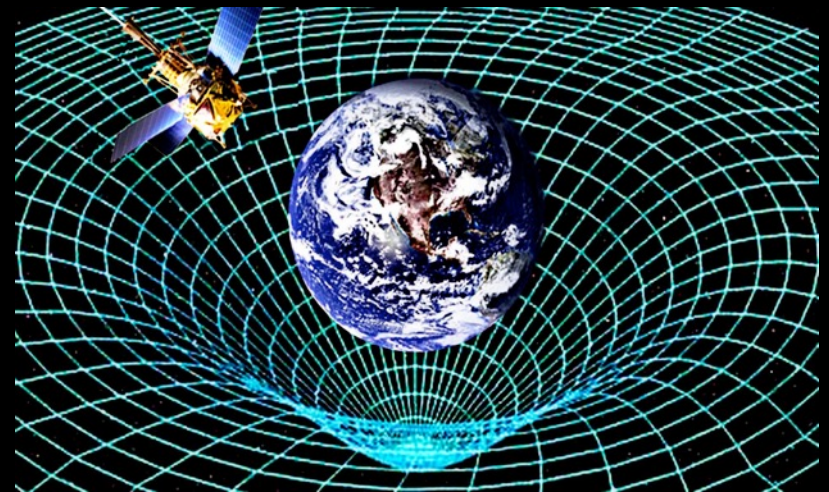
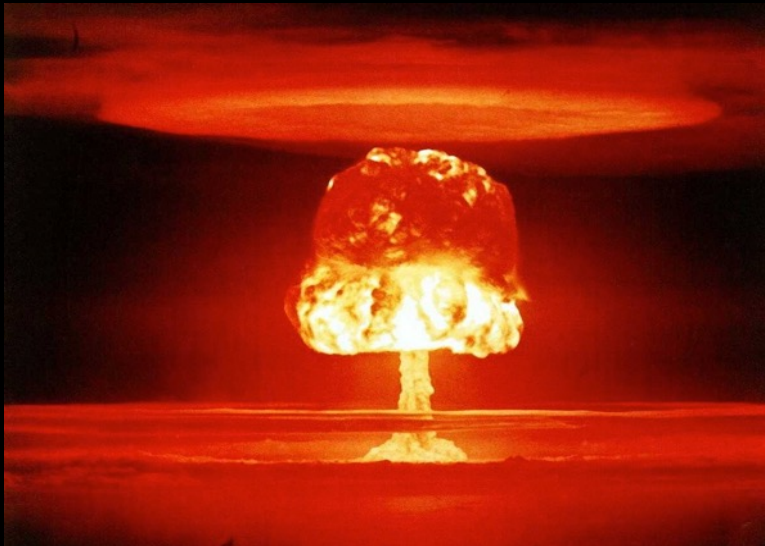
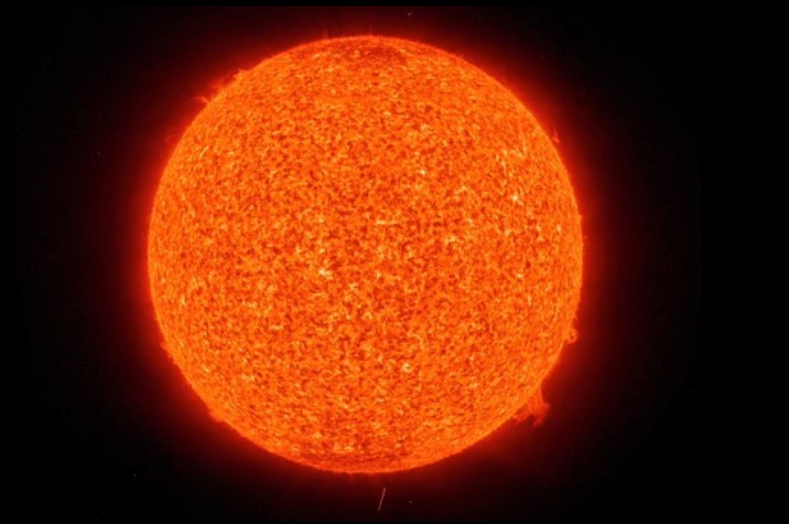
$$\Delta E \cdot \Delta t = h/4\pi$$

Richard Feynman
(1918 - 1988)



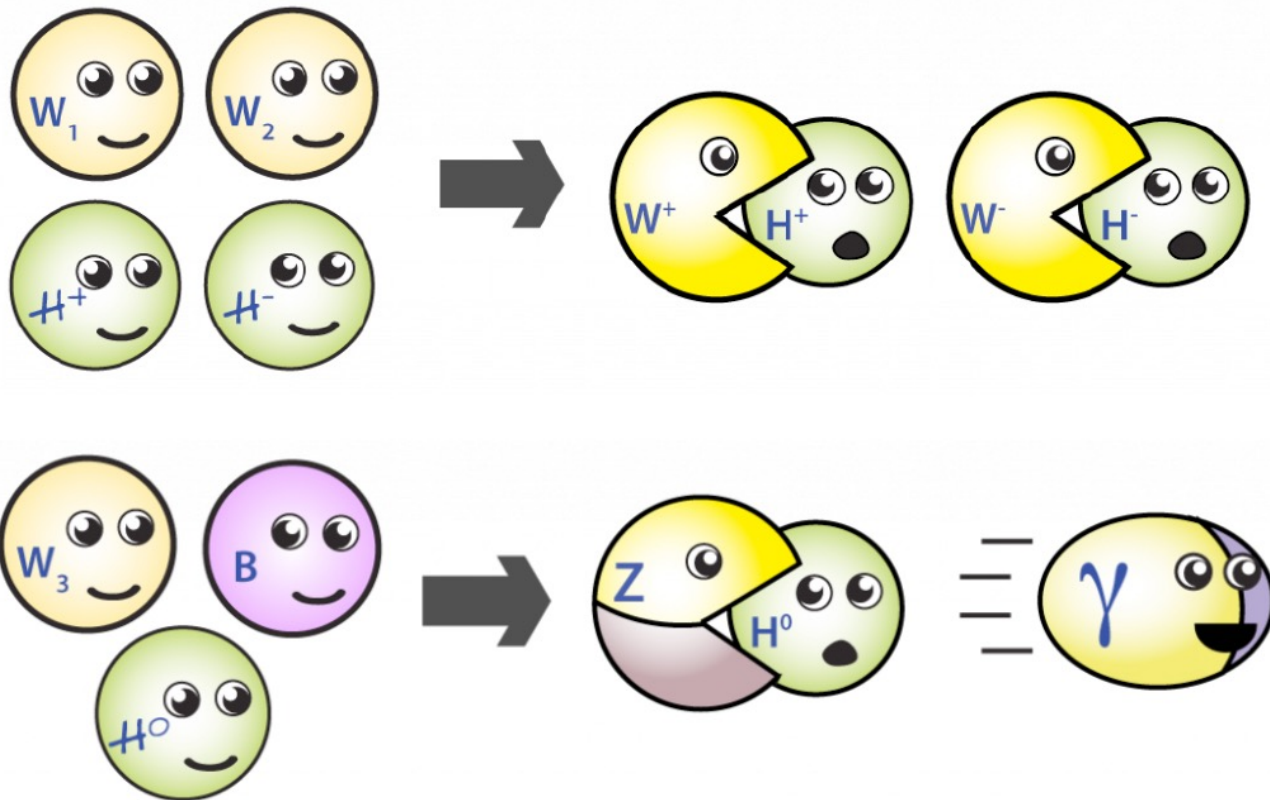
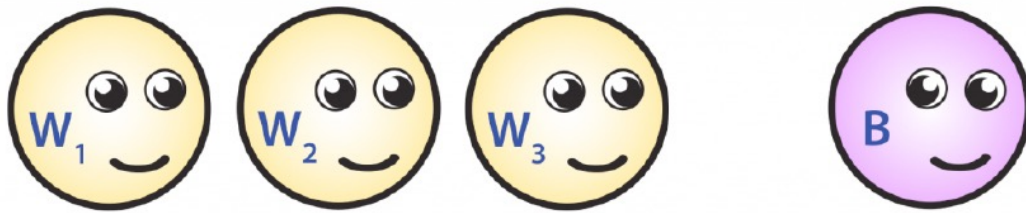
Werner Heisenberg
(1901 - 1976)





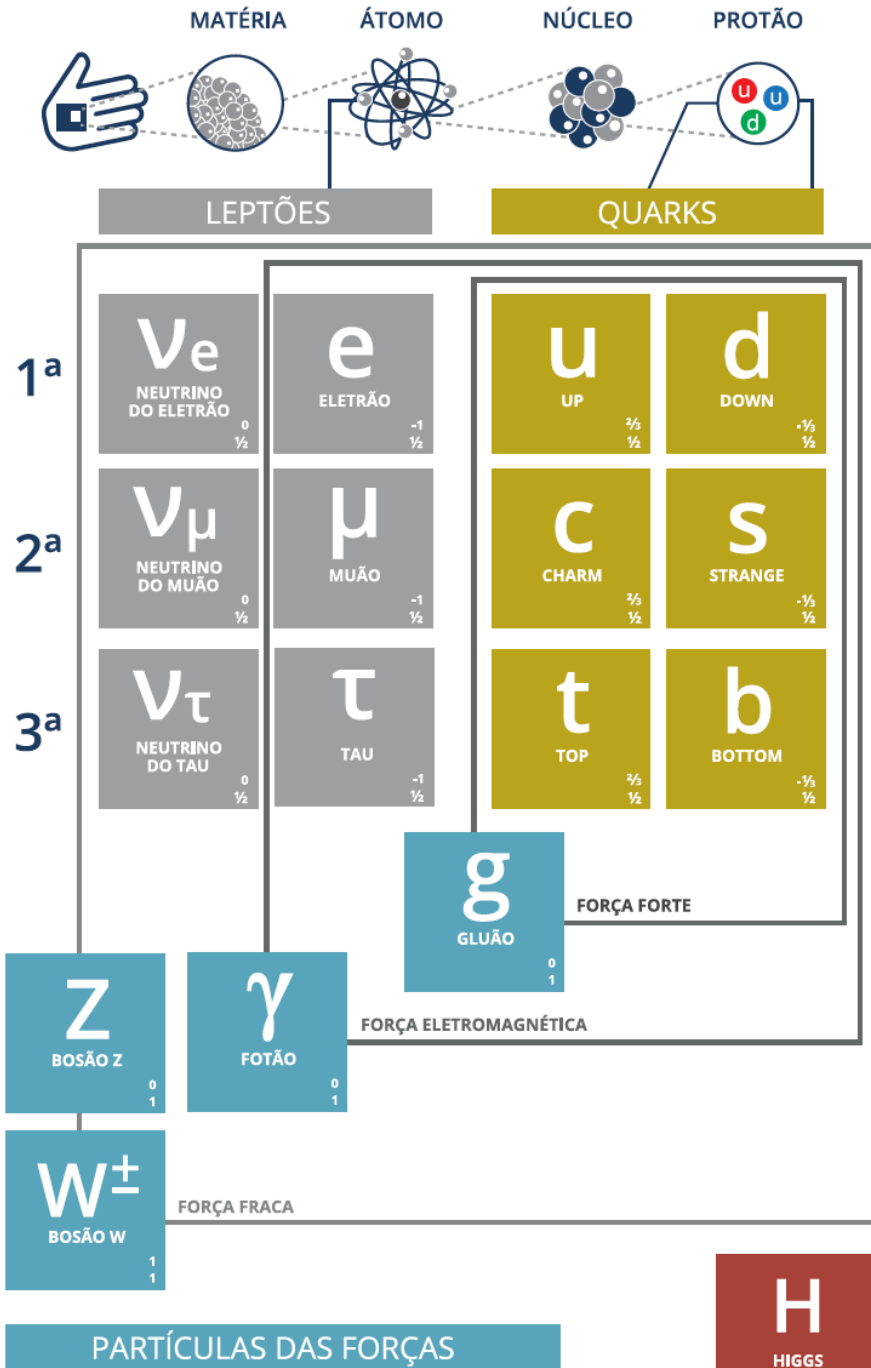
Isto não devia funcionar!...





O Modelo Padrão da Física de Partículas

$$\begin{aligned} \mathcal{L}_{SM} = & -\frac{1}{2}\partial_\nu g_\mu^a g_\nu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\ & M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - ig_{cw}(\partial_\nu Z_\mu^0(W_\mu^+ W_\nu^- - \\ & W_\nu^+ W_\mu^-) - Z_\nu^0(W_\mu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\mu W_\mu^+) + Z_\mu^0(W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\mu W_\mu^+)) - \\ & ig_{sw}(\partial_\nu A_\mu(W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu(W_\mu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\mu W_\mu^+) + A_\mu(W_\nu^+ \partial_\nu W_\mu^- - \\ & W_\nu^- \partial_\mu W_\mu^+)) - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^- W_\nu^+ + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - \\ & Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w (A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\ & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-) - \frac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\ & \beta_h \left(\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right) + \frac{2M^4}{g^2} \alpha_h - \\ & g\alpha_h M (H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-) - \\ & \frac{1}{8}g^2 \alpha_h (H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2) - \\ & gMW_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w} Z_\mu^0 Z_\mu^0 H - \\ & \frac{1}{2}ig (W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)) + \\ & \frac{1}{2}g (W_\mu^+ (H\partial_\mu \phi^- - \phi^- \partial_\mu H) + W_\mu^- (H\partial_\mu \phi^+ - \phi^+ \partial_\mu H)) + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H\partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\ & M (\frac{1}{c_w} Z_\mu^0 \partial_\mu \phi^0 + W_\mu^+ \partial_\mu \phi^- + W_\mu^- \partial_\mu \phi^+)) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + ig s_w M A_\mu (W_\mu^+ \phi^- - \\ & W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\ & \frac{1}{4}g^2 W_\mu^+ W_\mu^- (H^2 + (\phi^0)^2 + 2\phi^+ \phi^-) - \frac{1}{8}g^2 \frac{1}{c_w} Z_\mu^0 (H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-) - \\ & \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\ & W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w^2}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\ & g^2 s_w^2 A_\mu A_\nu \phi^+ \phi^- + \frac{1}{2}ig_s \lambda_{ij}^a (g_\mu^i g_\nu^j - g_\nu^i g_\mu^j) g_\mu^a - \bar{e}^\lambda (\gamma^\mu + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda (\gamma^\mu + m_\nu^\lambda) \nu^\lambda - \bar{u}_j^\lambda (\gamma^\mu + \\ & m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma^\mu + m_d^\lambda) d_j^\lambda + ig s_w A_\mu (-\bar{e}^\lambda \gamma^\mu e^\lambda + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)) + \\ & \frac{ig}{4c_w} Z_\mu^0 \{ (\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}_j^\lambda \gamma^\mu (\frac{2}{3}s_w^2 - 1 - \gamma^5) d_j^\lambda) + \\ & (\bar{u}_j^\lambda \gamma^\mu (1 - \frac{2}{3}s_w^2 + \gamma^5) u_j^\lambda) \} + \frac{ig}{2\sqrt{2}} W_\mu^+ ((\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) U^{lep}_{\lambda\kappa} e^\kappa) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)) + \\ & \frac{ig}{2\sqrt{2}} W_\mu^- ((\bar{e}^\kappa U^{lep\dagger}_{\kappa\lambda} \nu^\lambda (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\kappa\lambda}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)) + \\ & \frac{ig}{2M\sqrt{2}} \phi^+ (-m_e^\kappa (\bar{\nu}^\lambda U^{lep}_{\lambda\kappa} (1 - \gamma^5) e^\kappa) + m_\nu^\kappa (\bar{\nu}^\lambda U^{lep}_{\lambda\kappa} (1 + \gamma^5) e^\kappa) + \\ & \frac{ig}{2M\sqrt{2}} \phi^- (m_e^\lambda (\bar{e}^\lambda U^{lep\dagger}_{\lambda\kappa} (1 + \gamma^5) \nu^\kappa) - m_\nu^\kappa (\bar{e}^\lambda U^{lep\dagger}_{\lambda\kappa} (1 - \gamma^5) \nu^\kappa) - \frac{g}{2} \frac{m_\lambda}{M} H (\bar{\nu}^\lambda \nu^\lambda) - \\ & \frac{g}{2} \frac{m_\lambda}{M} H (\bar{e}^\lambda e^\lambda) + \frac{ig}{2} \frac{m_\lambda}{M} \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \frac{ig}{2} \frac{m_\lambda}{M} \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) - \frac{1}{4} \bar{\nu}_\lambda M_\lambda^R (1 - \gamma_5) \bar{\nu}_\kappa - \\ & \frac{1}{4} \bar{\nu}_\lambda M_\lambda^R (1 - \gamma_5) \bar{\nu}_\kappa + \frac{ig}{2M\sqrt{2}} \phi^+ (-m_\nu^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa) + \\ & \frac{ig}{2M\sqrt{2}} \phi^- (m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_\nu^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa) - \frac{g}{2} \frac{m_\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \\ & \frac{g}{2} \frac{m_\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G_\mu^b g_\mu^c + \\ & \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + ig_{cw} W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \\ & \partial_\mu \bar{X}^+ X^0) + ig_{sw} W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + ig_{cw} W_\mu^- (\partial_\mu \bar{X}^- X^0 - \\ & \partial_\mu \bar{X}^0 X^+) + ig_{sw} W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + ig_{cw} Z_\mu^0 (\partial_\mu \bar{X}^+ X^- - \\ & \partial_\mu \bar{X}^- X^+) + ig_{sw} A_\mu (\partial_\mu \bar{X}^+ X^- - \\ & \partial_\mu \bar{X}^- X^+) - \frac{1}{2}gM (\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H) + \frac{1-2c_w^2}{2c_w} igM (\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-) + \\ & \frac{1}{2c_w} igM (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + igM s_w (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + \\ & \frac{1}{2}igM (\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0) . \end{aligned}$$



Para cada uma destas partículas, existe uma antipartícula de carga oposta (antimatéria)

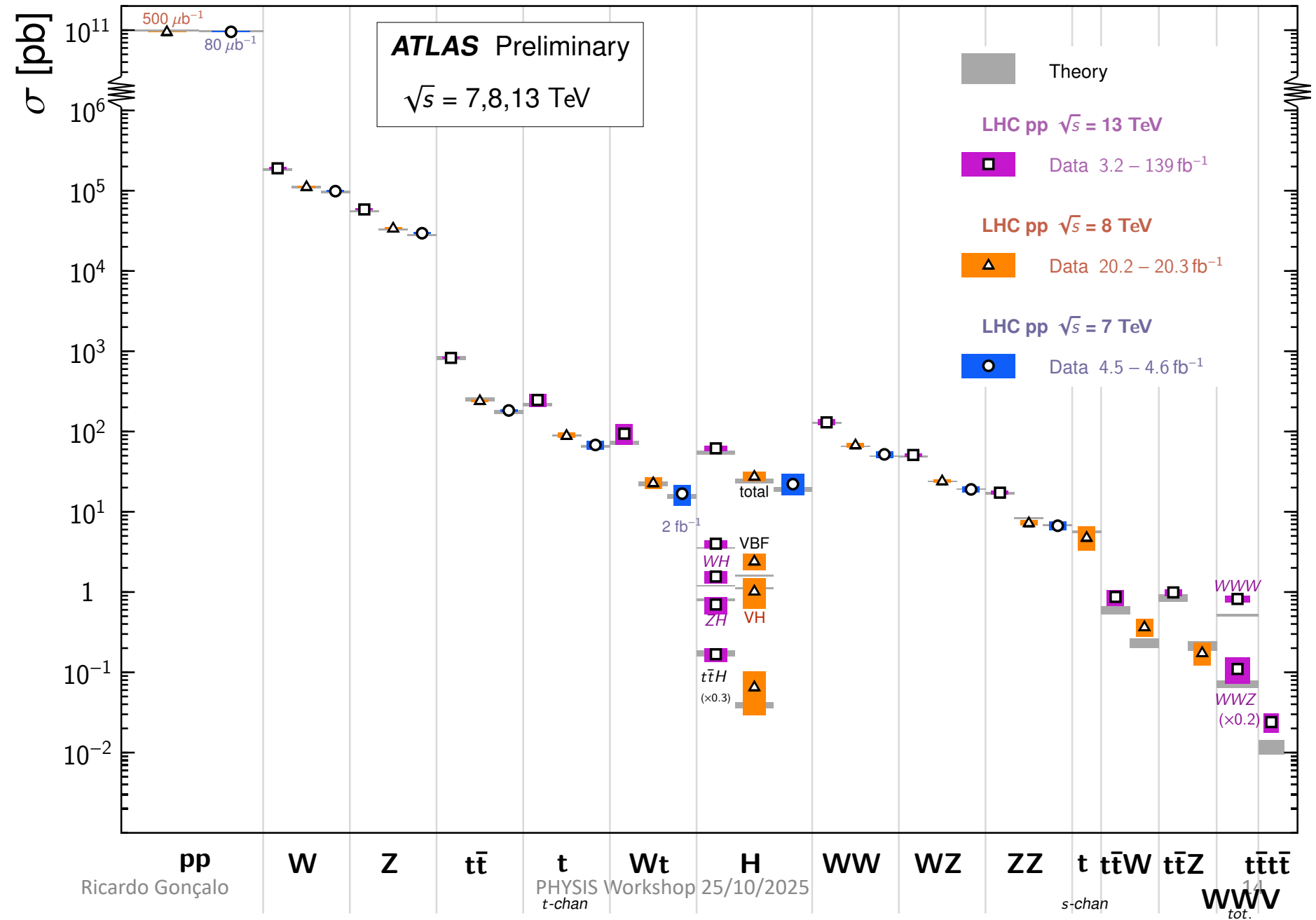
PARTÍCULAS DE MATÉRIA

Legenda

símbolo
NOME
Carga Spin

Standard Model Total Production Cross Section Measurements

Status: February 2022

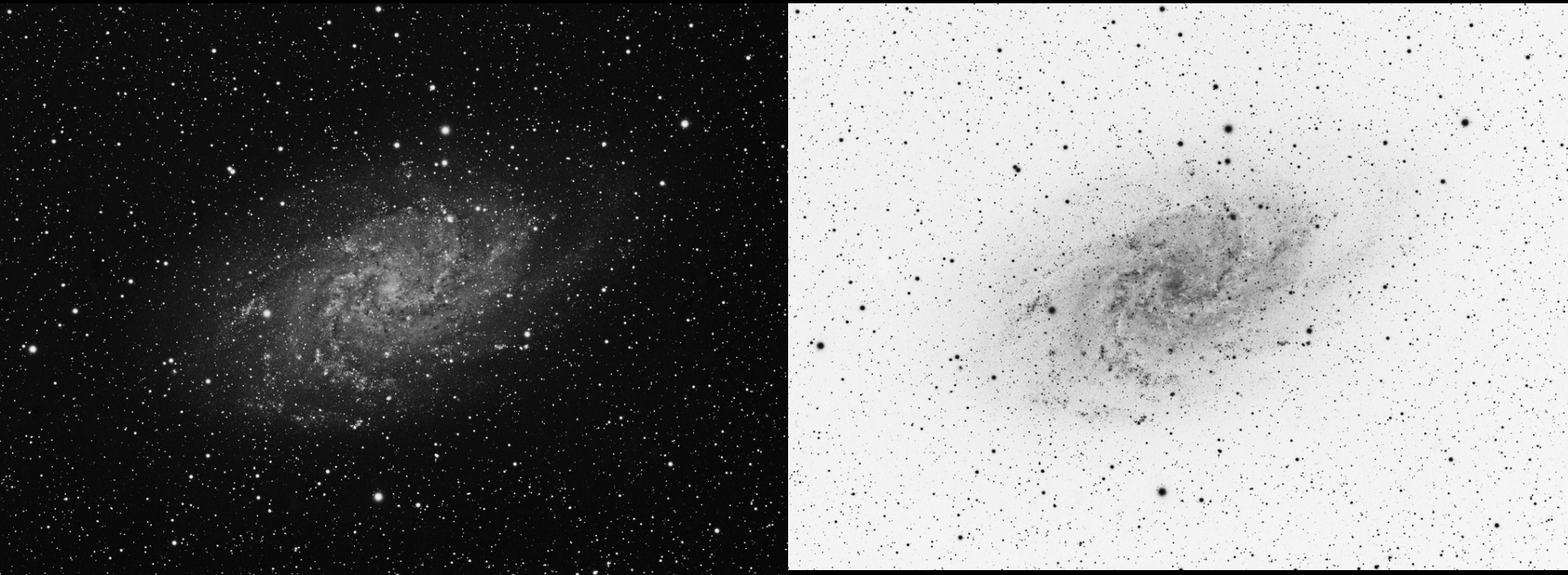


O que (ainda) não sabemos

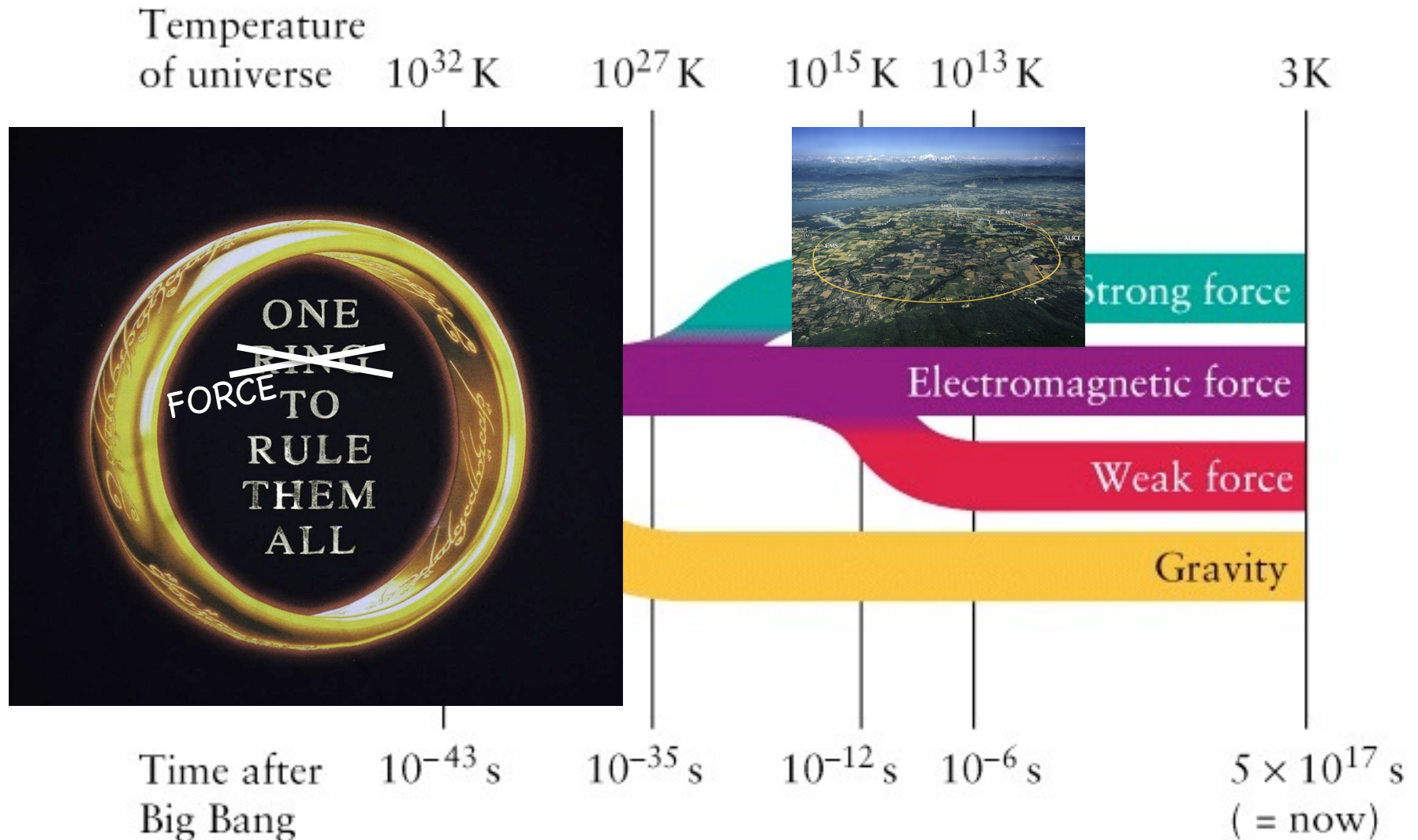


“Há mais coisas no
céu e na terra,
Horácio, do que sonha
a nossa filosofia??”

Para onde foi a antimatéria?



Uma força única?

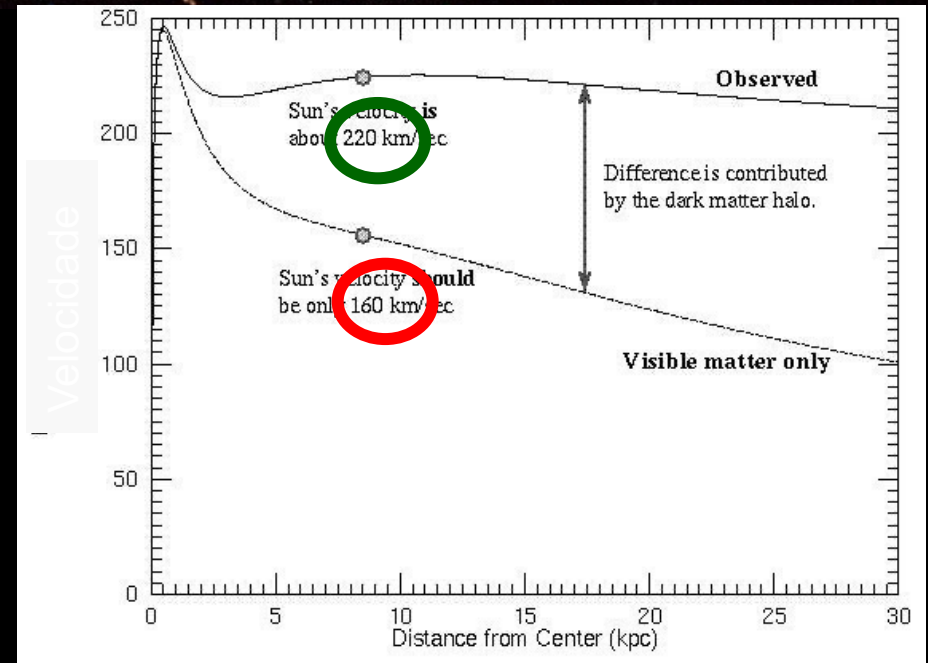


O Que é a Matéria Escura?

Você
está
aqui

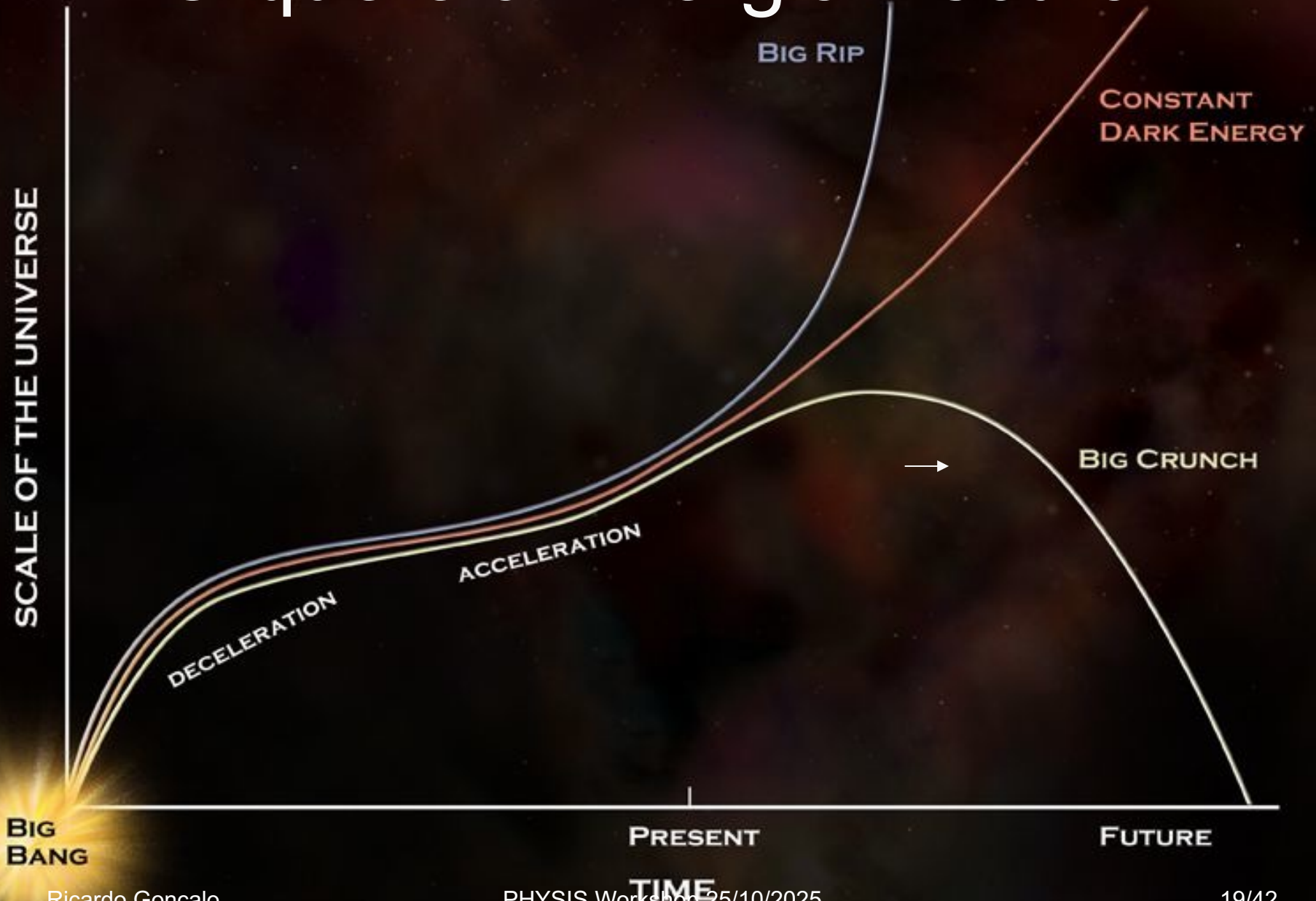


Via Láctea



Nenhuma forma de matéria conhecida!

O que é a Energia Escura



Existem
dimensões
extra?

Origem da
massa dos ν 's

Novas
interações
?

Natureza
dos ν 's?

Teoria
do sabor

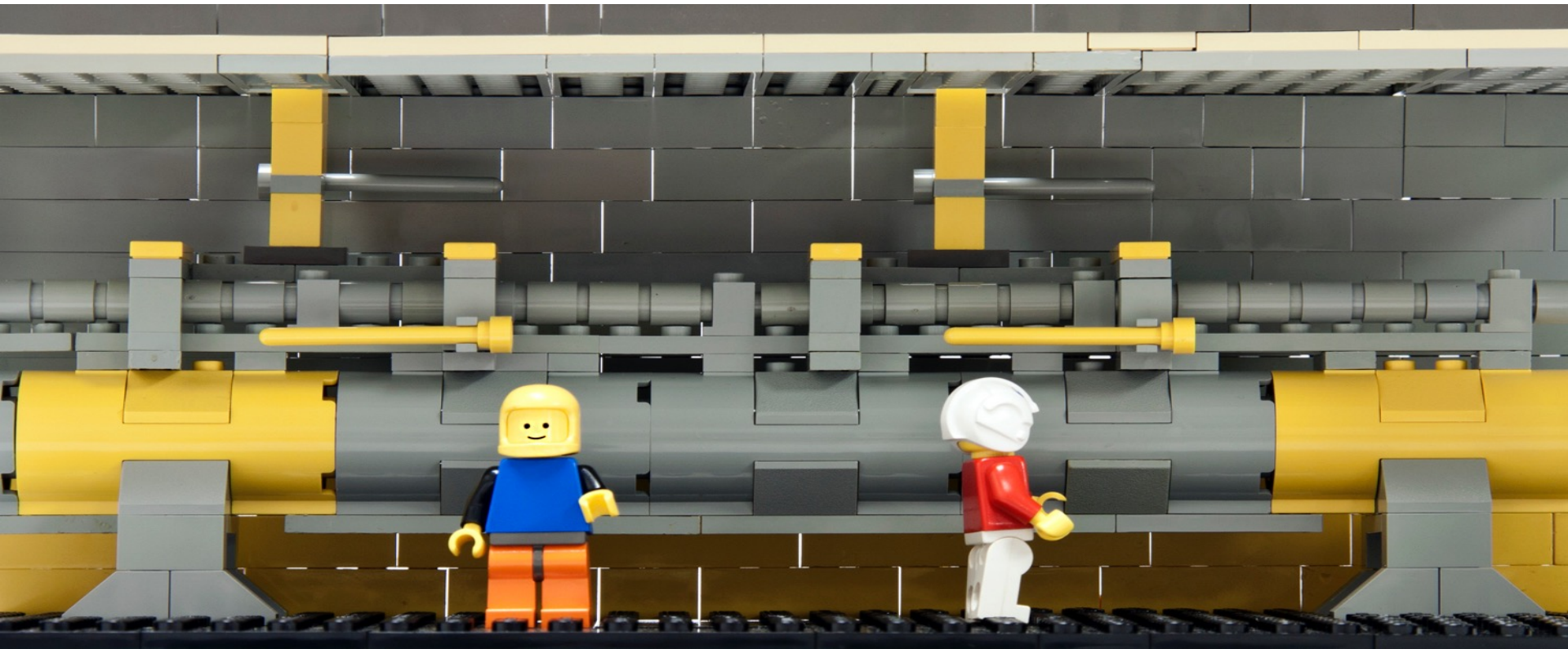
SUSY
(supersimetria)

Gravidade

QCD
(cromodinâmica
quântica)

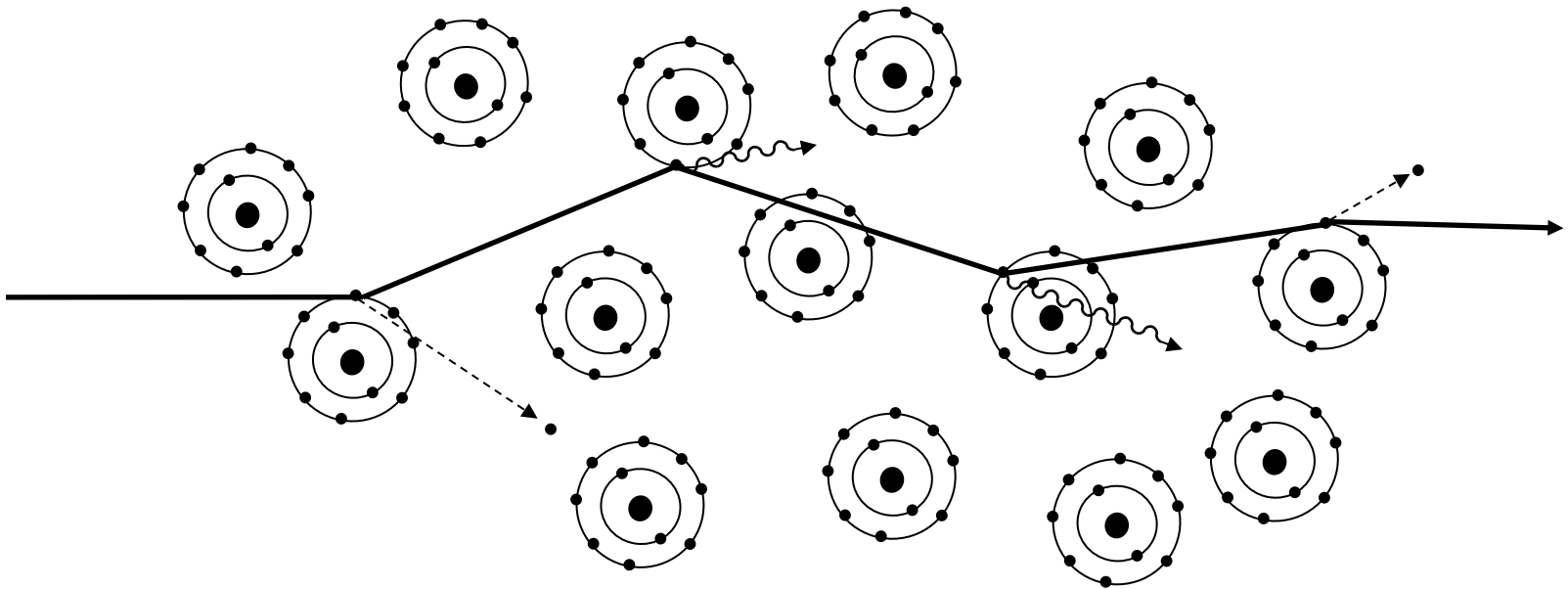
Mais bósons
de Higgs
?

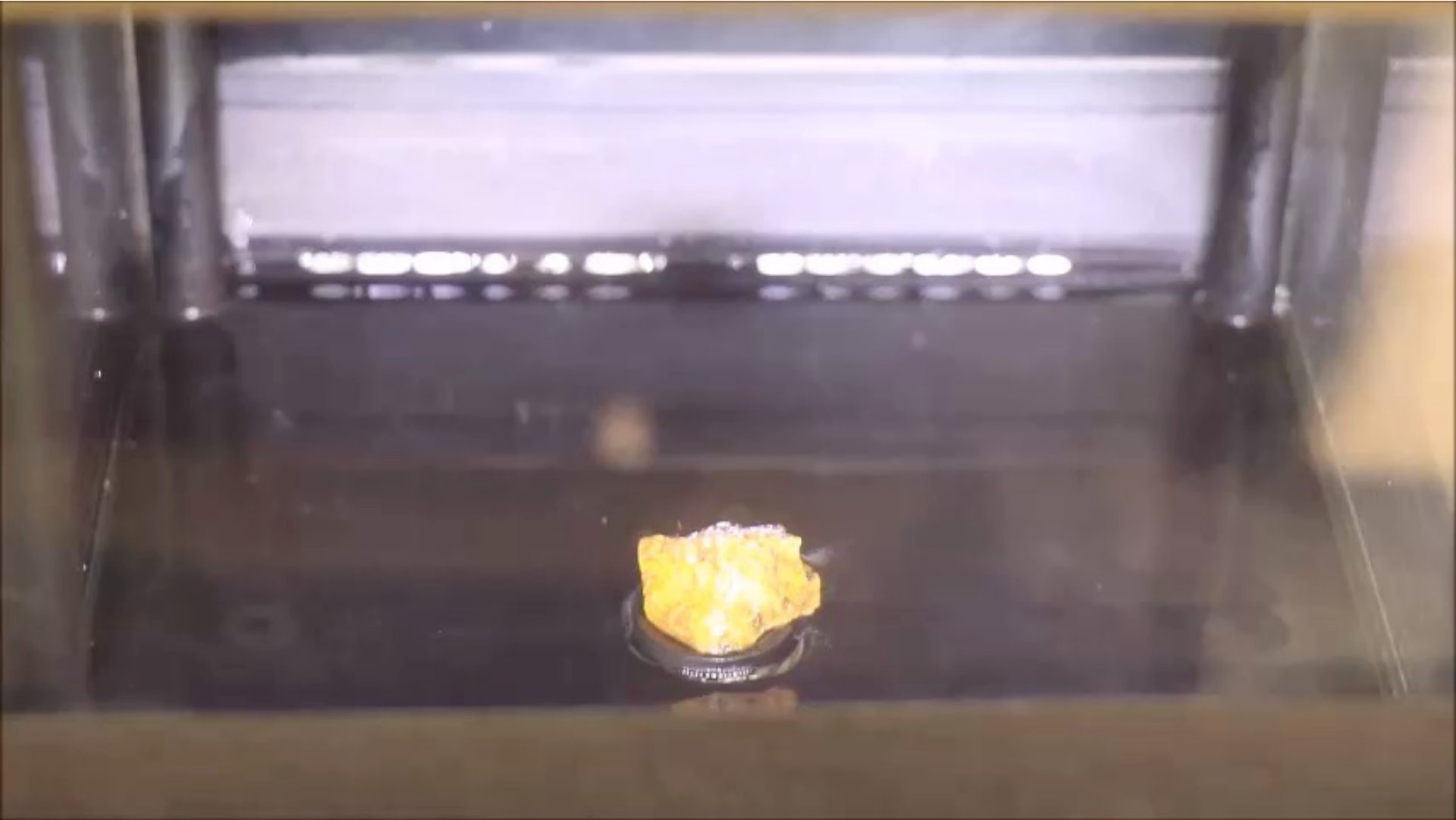
Detectores para ver o invisível



Detetores de partículas

Para detetarmos uma partícula, ela tem de **interagir com o material do detetor** e ser convertida num sinal mensurável



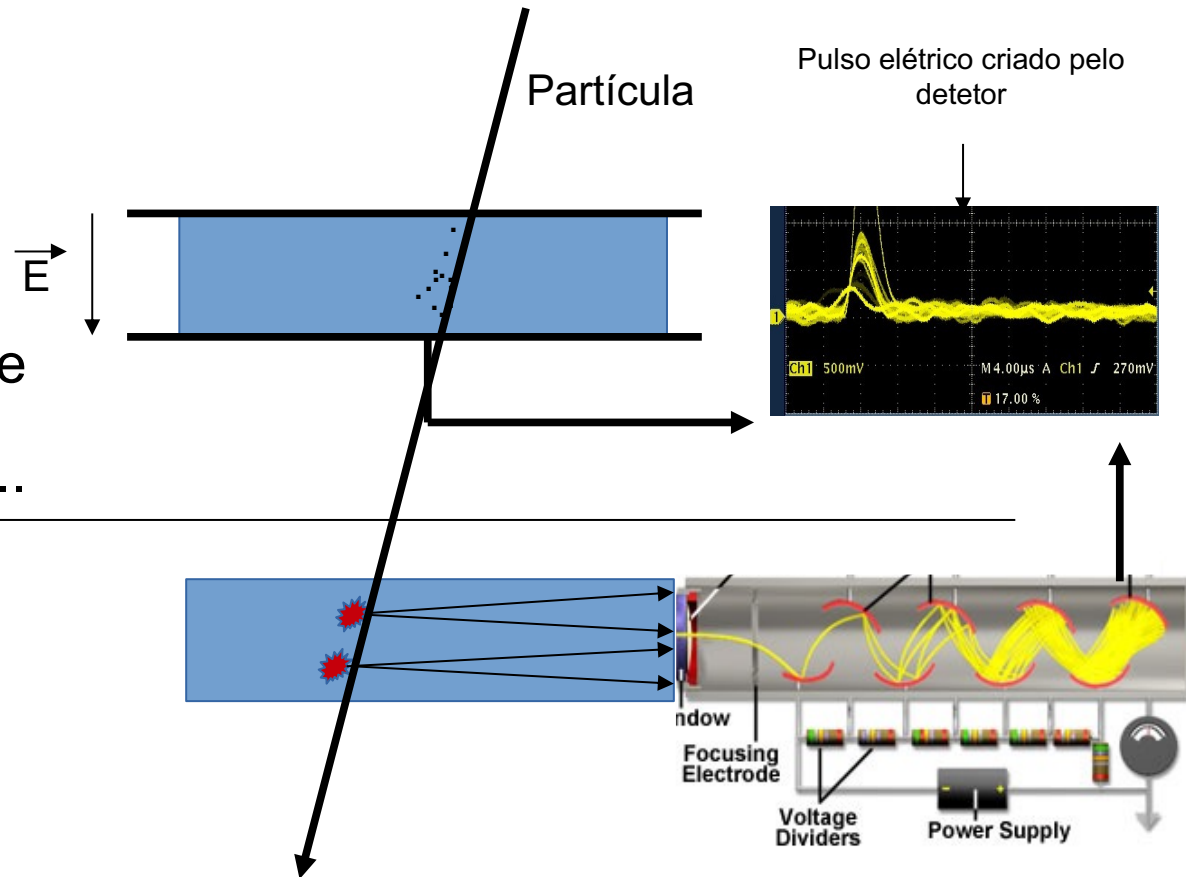


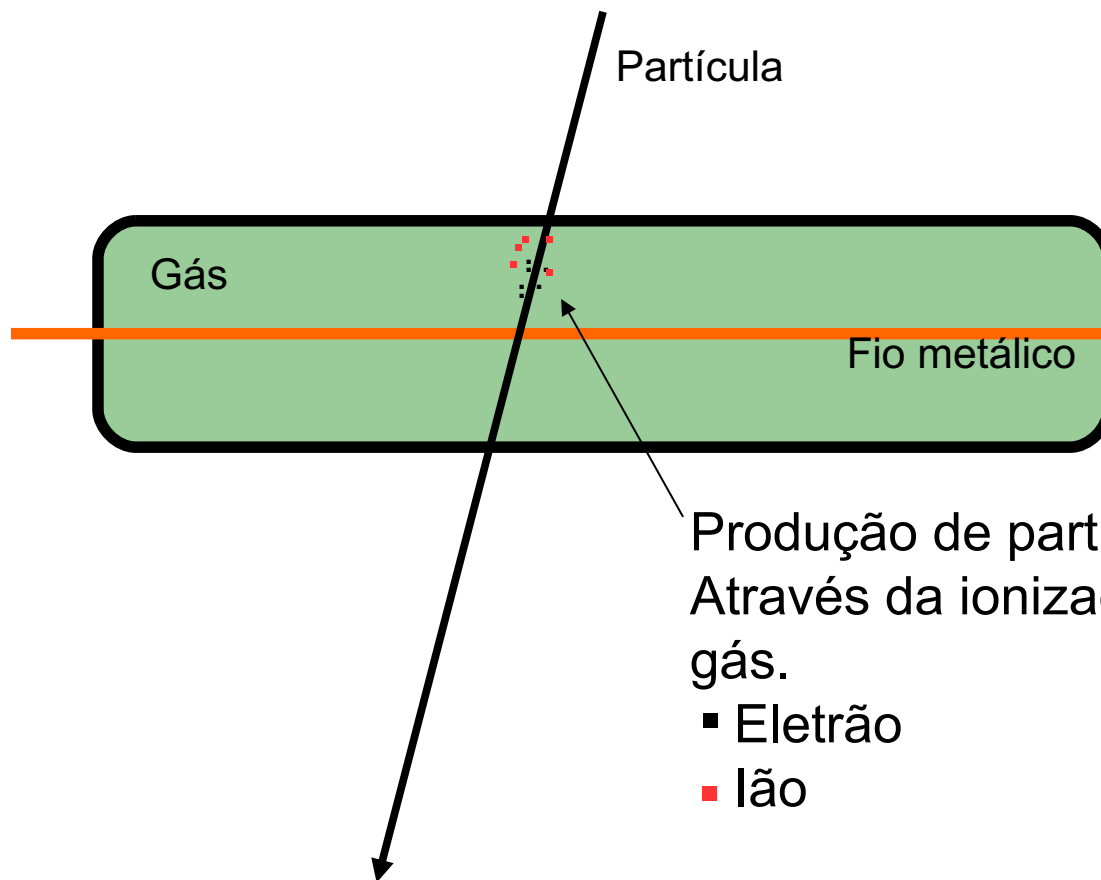
- **Produção de partículas secundárias**

- Ionização, radiação de transição, dispersão elástica e inelástica, ...

- **Produção de luz**

- Cintilação, luz Cherenkov, ...

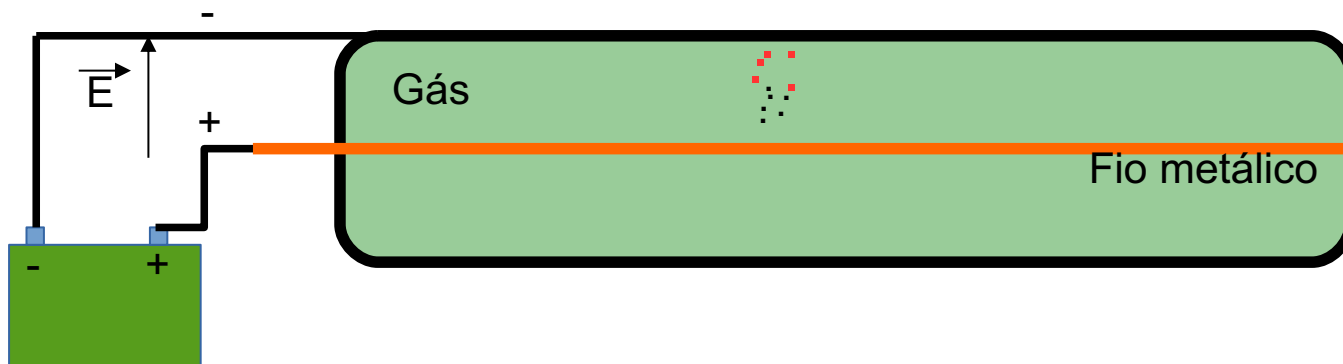




Produção de partículas secundárias
Através da ionização dos átomos do
gás.

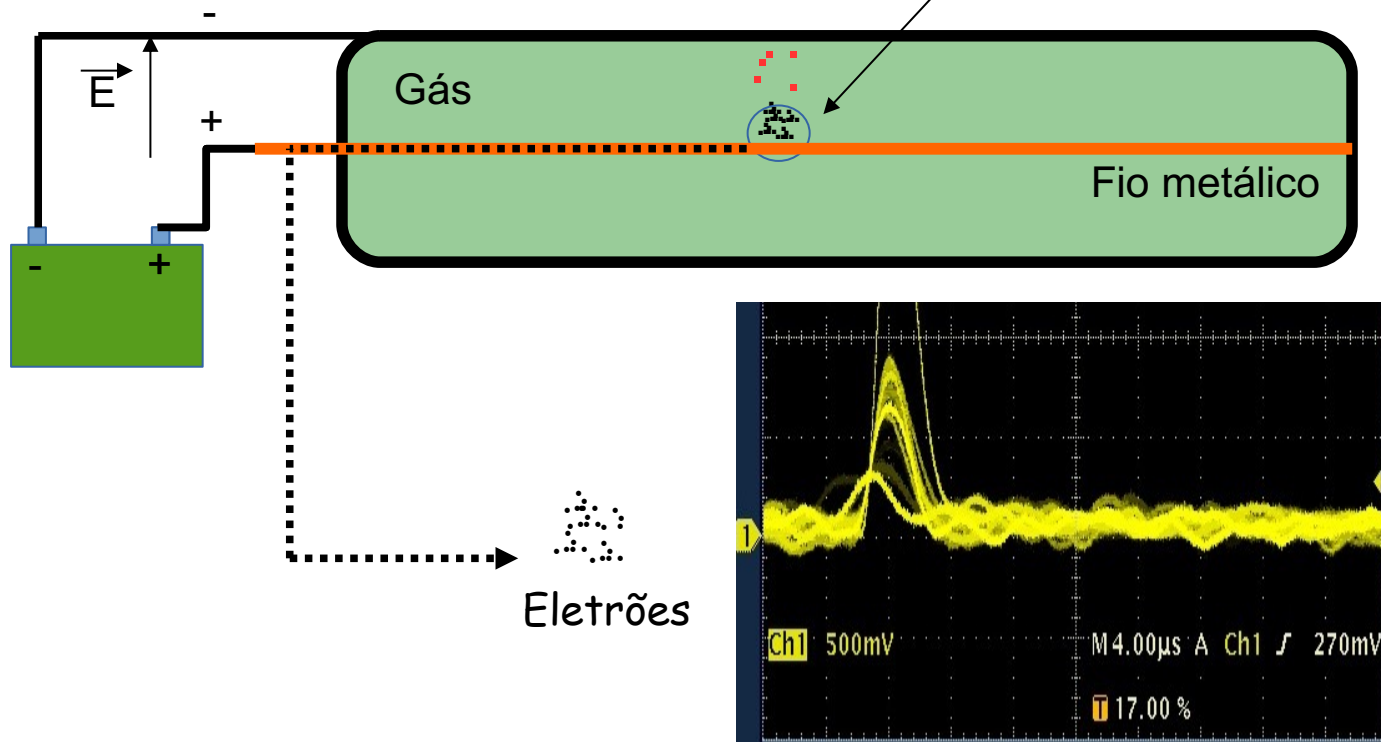
▪ Eletrão

▪ Ião

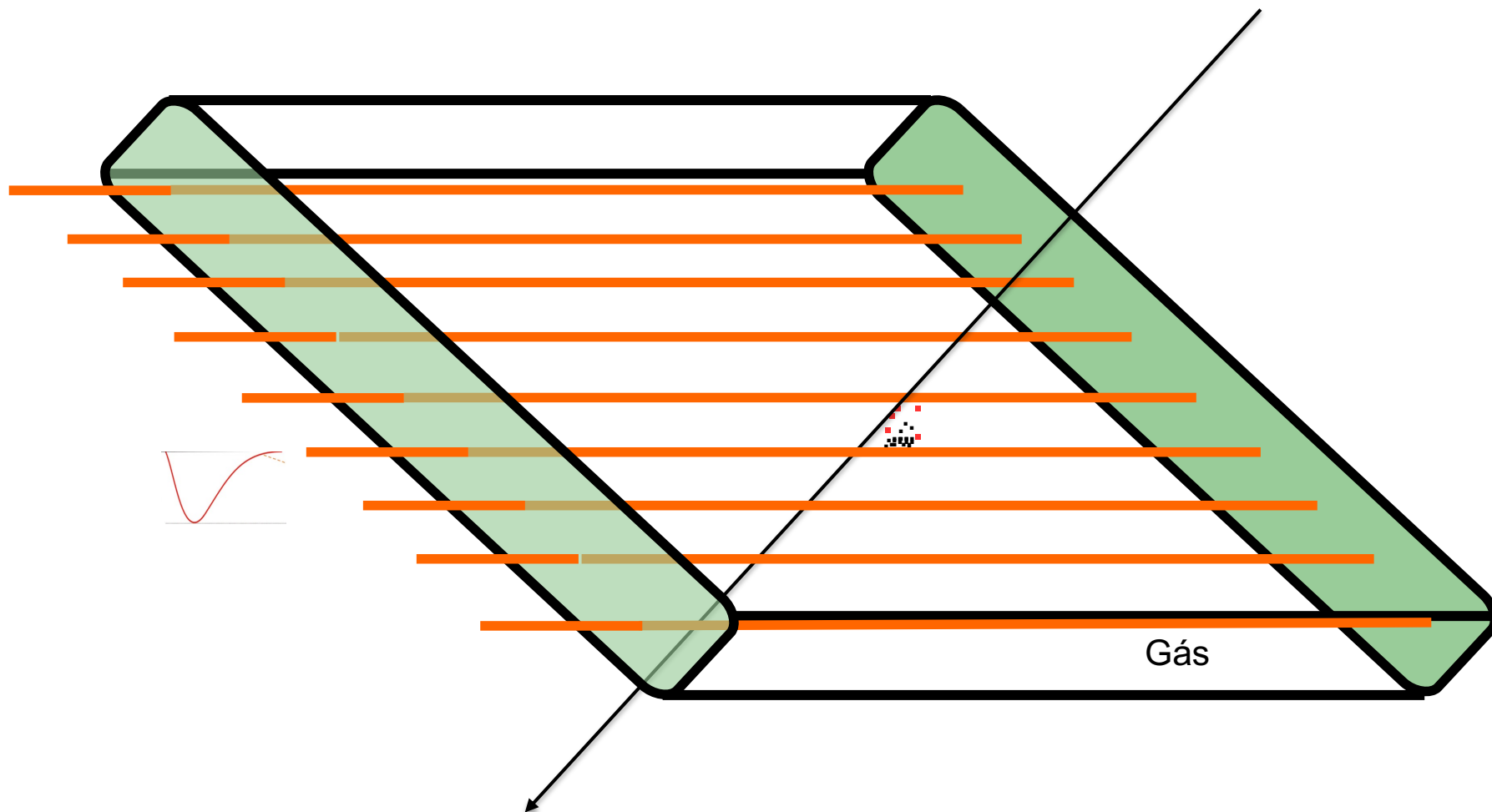


O **campo elétrico** dá aos eletrões energia suficiente para causar multiplicação de carga

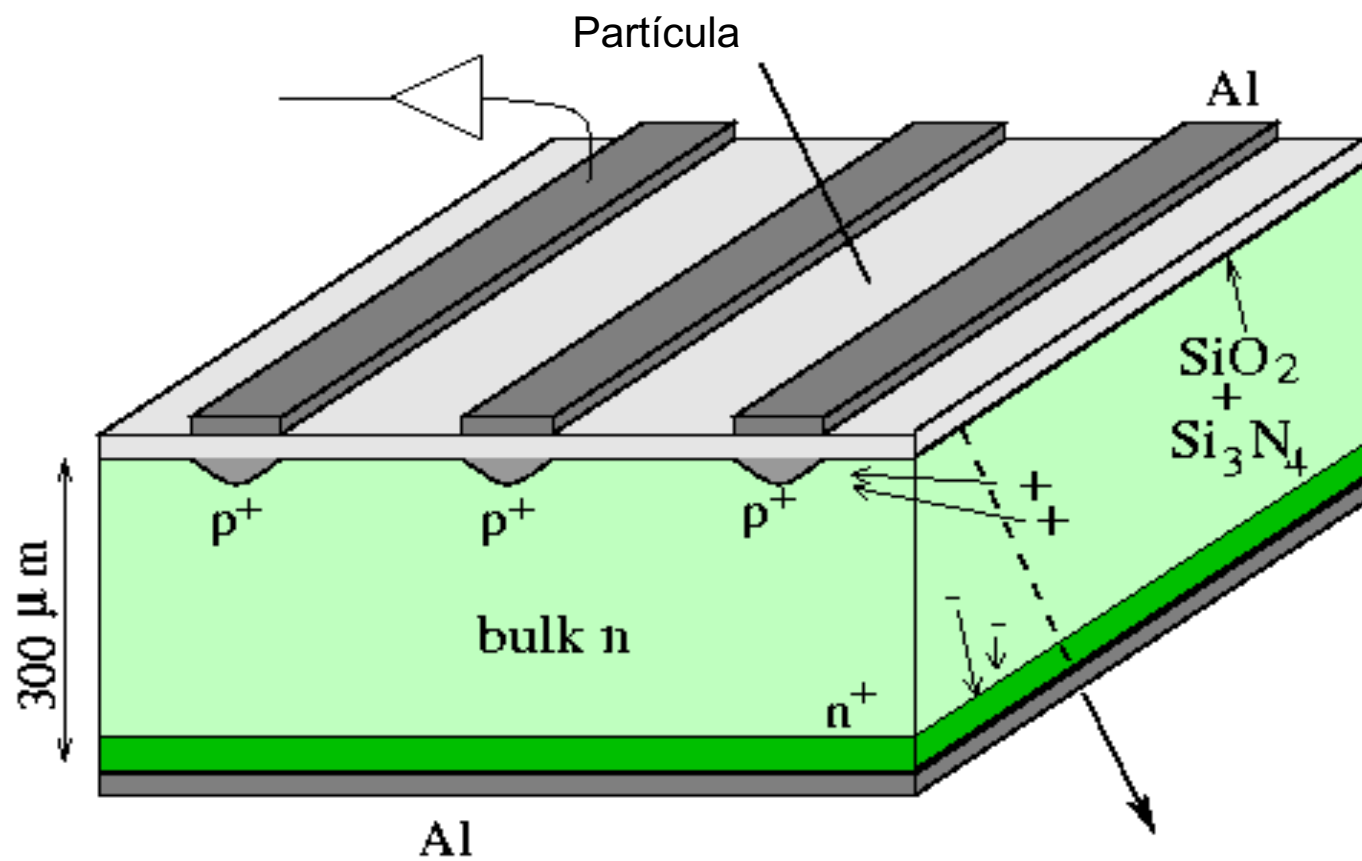
Depois da multiplicação os eletrões produzem um sinal elétrico que mensurável



Partícula

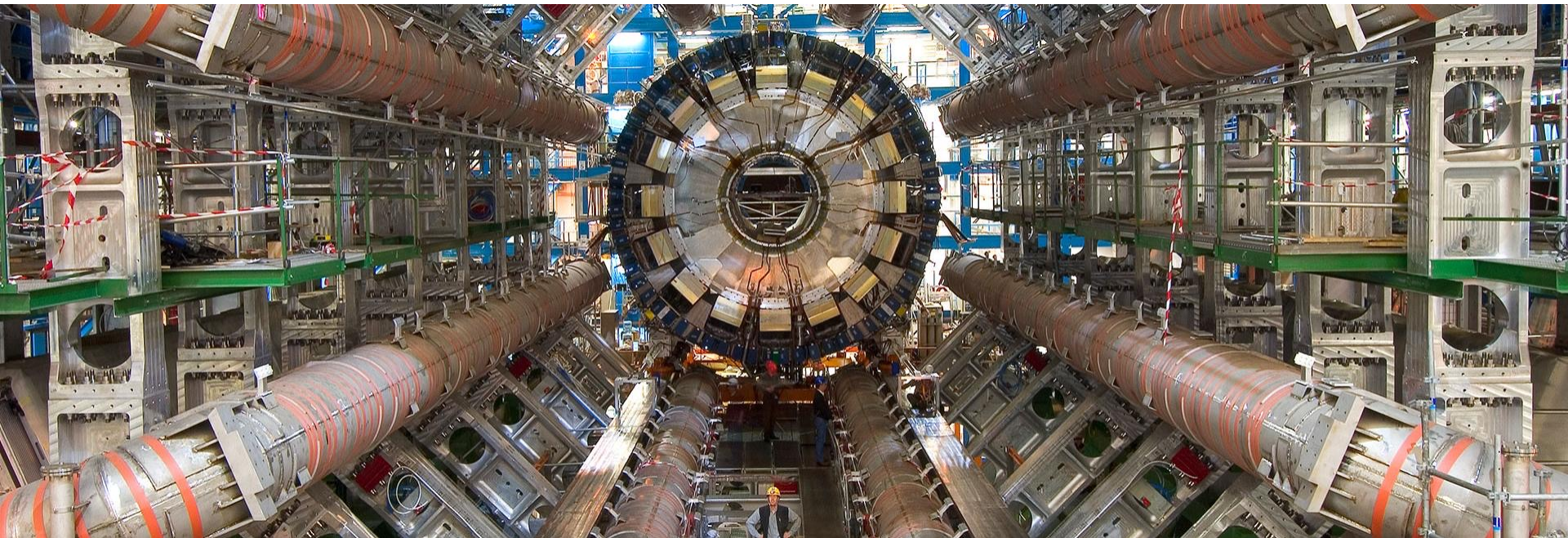


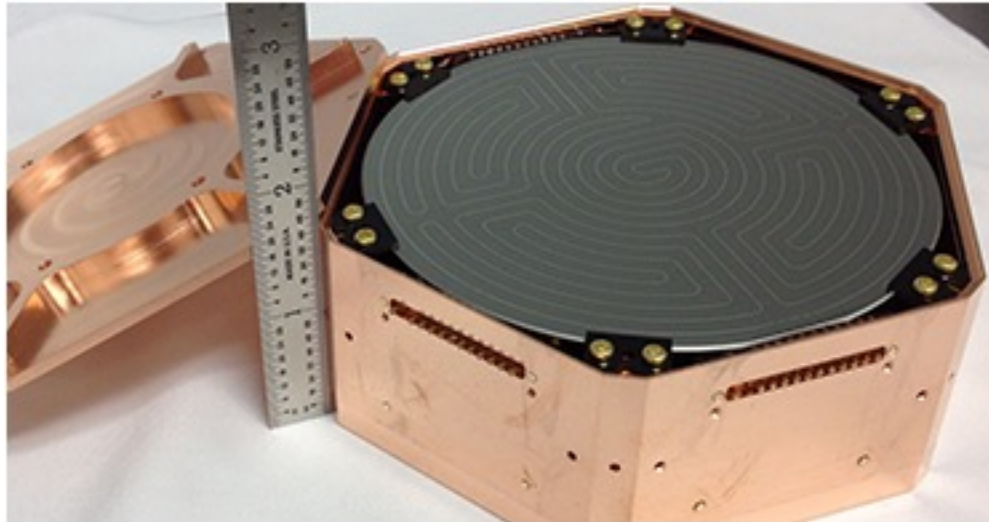
Gás



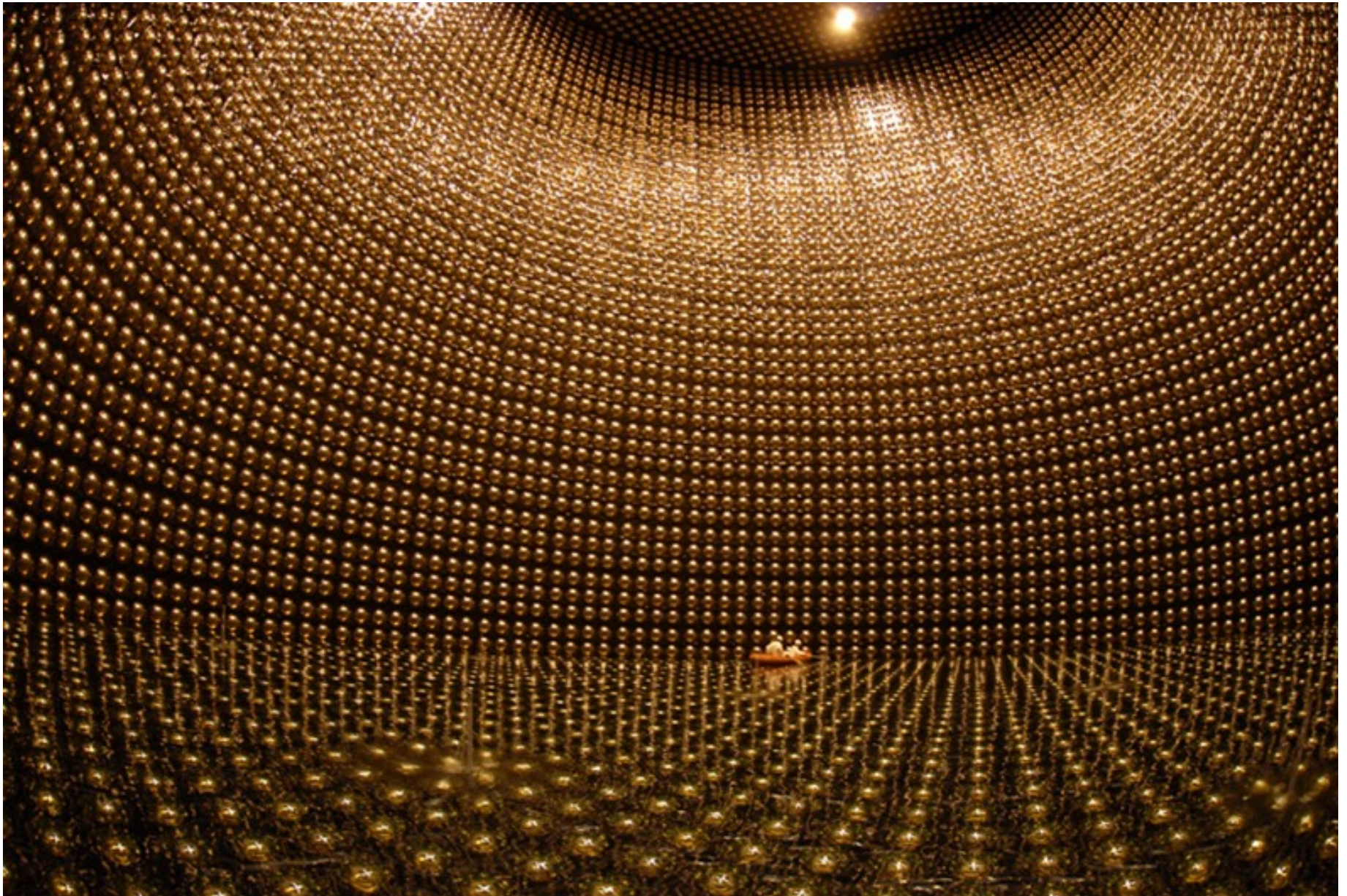


EXPERIÊNCIAS DE FÍSICA DE PARTÍCULAS



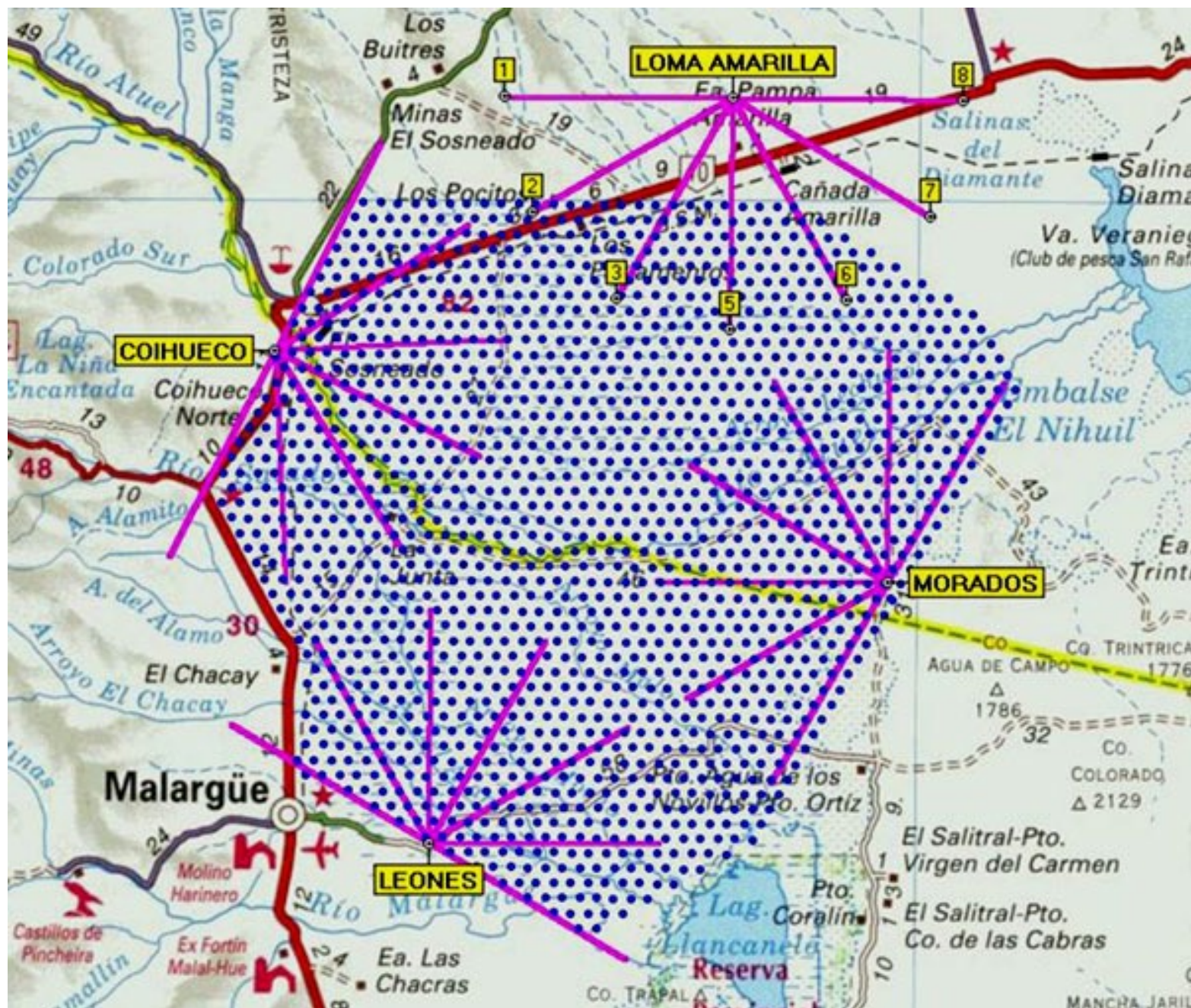


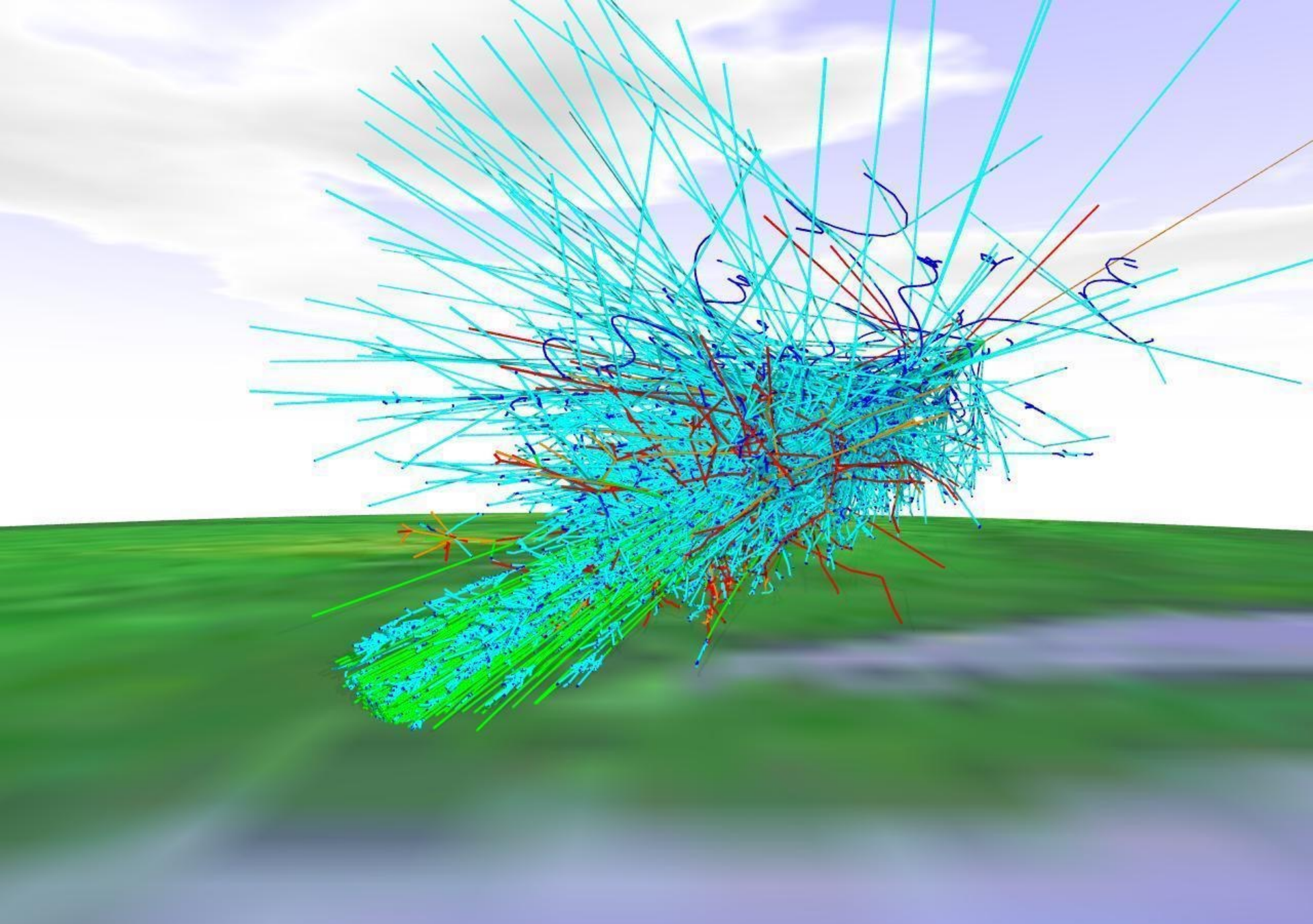




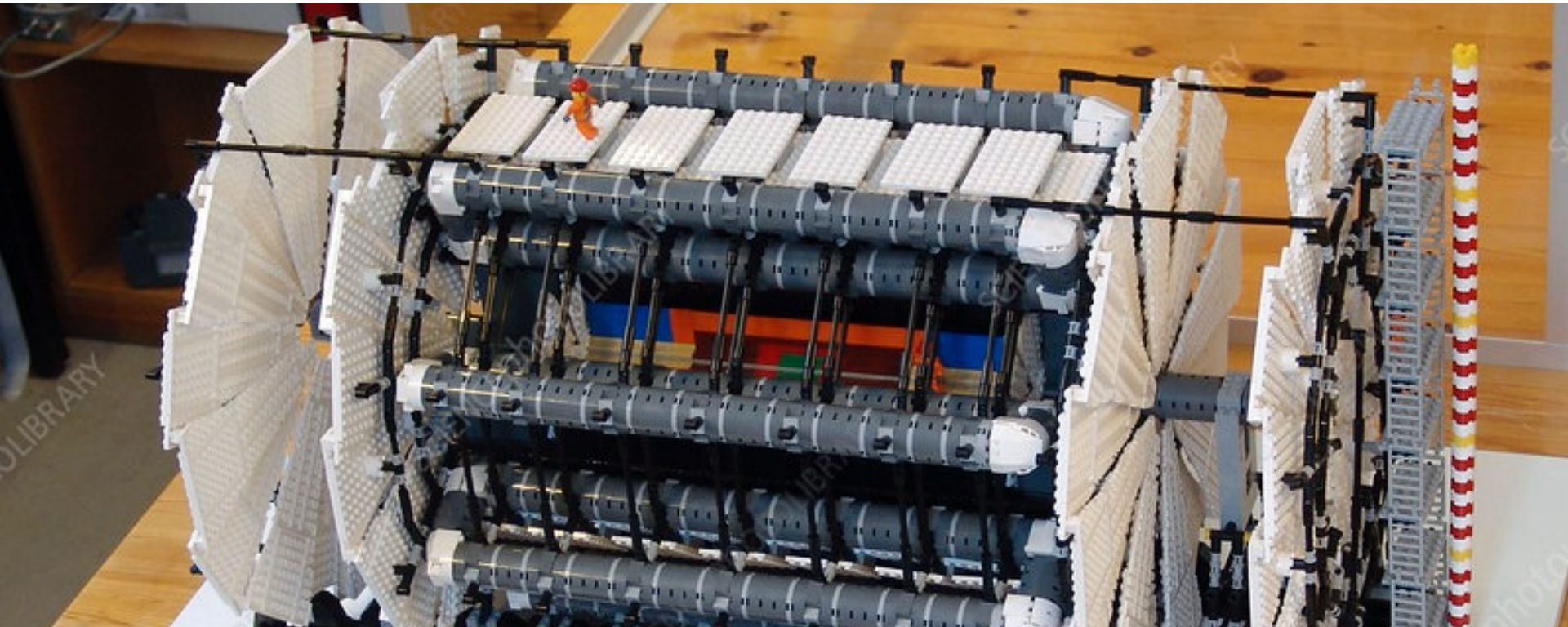




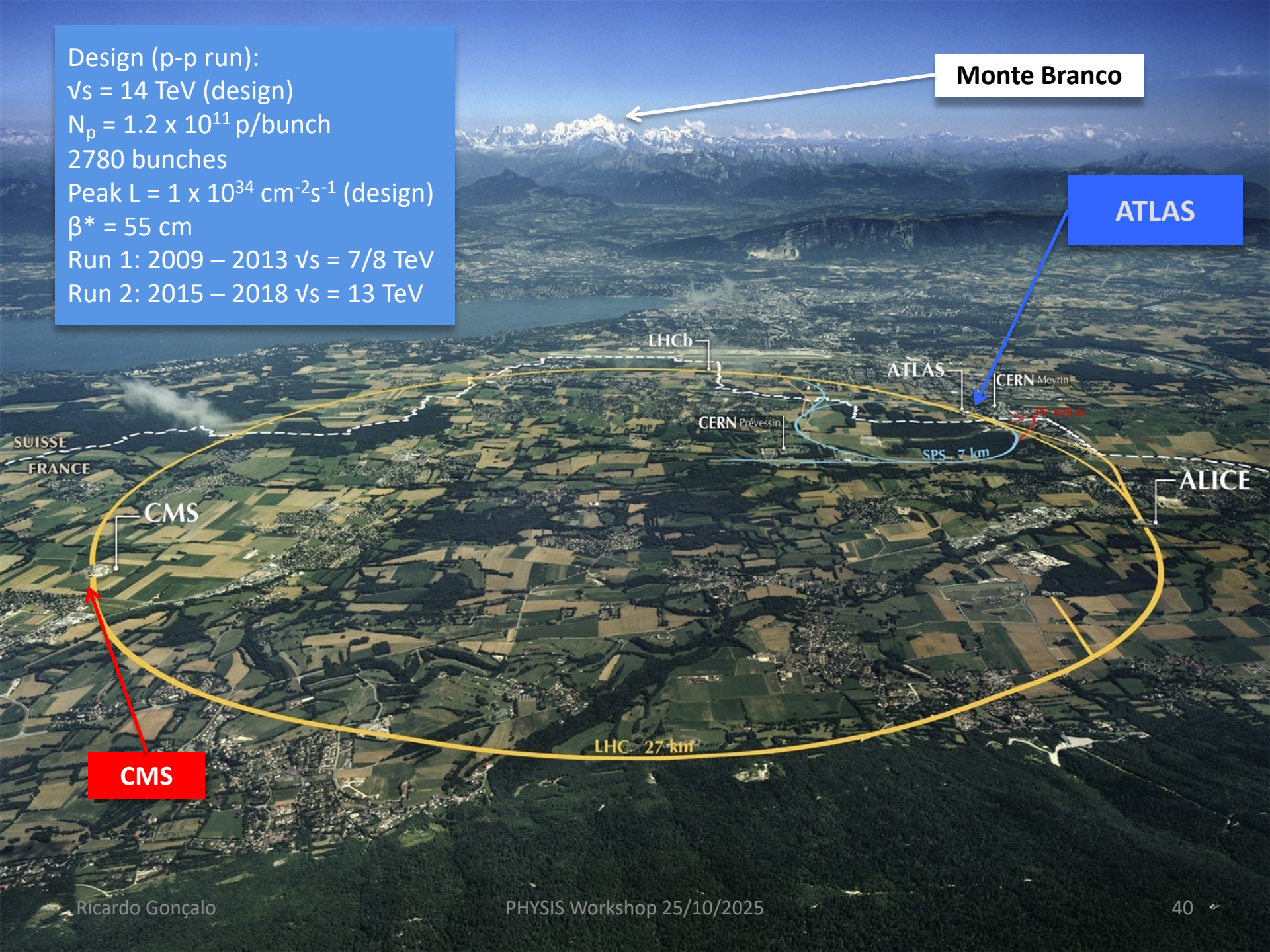




EXPERIÊNCIAS DE COLISIONADOR: O LHC

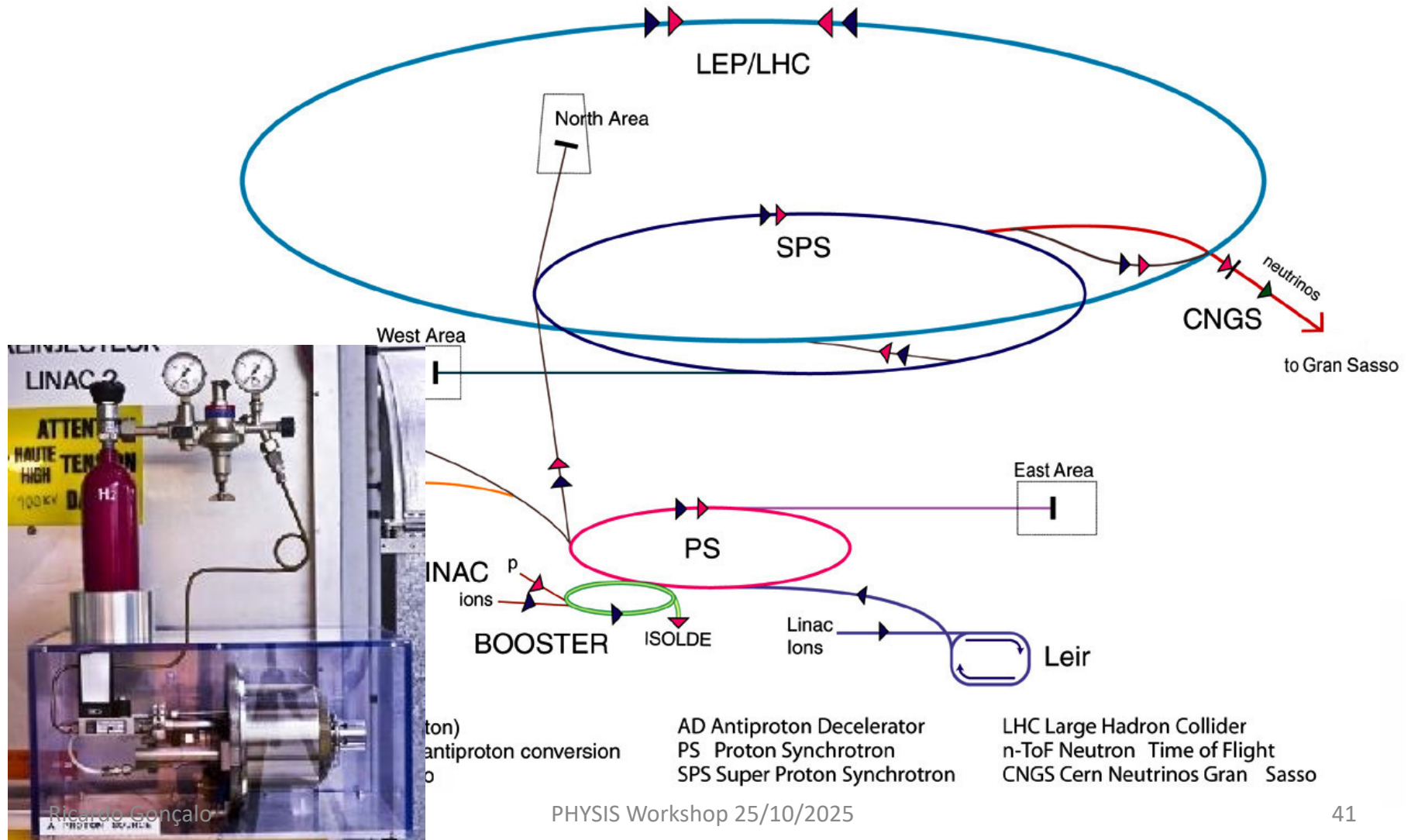


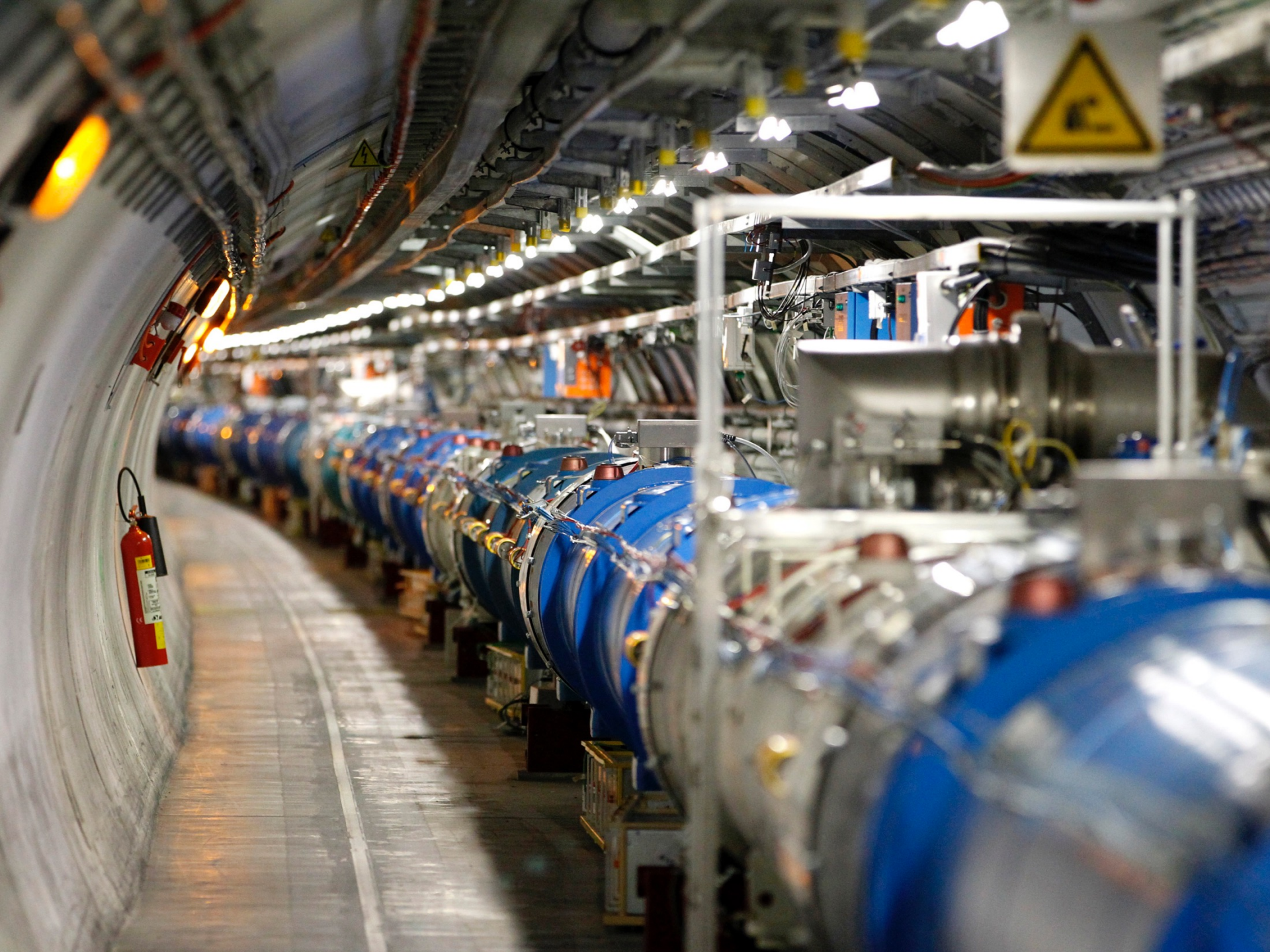
Design (p-p run):
 $\sqrt{s} = 14 \text{ TeV}$ (design)
 $N_p = 1.2 \times 10^{11} \text{ p/bunch}$
2780 bunches
Peak $L = 1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ (design)
 $\beta^* = 55 \text{ cm}$
Run 1: 2009 – 2013 $\sqrt{s} = 7/8 \text{ TeV}$
Run 2: 2015 – 2018 $\sqrt{s} = 13 \text{ TeV}$



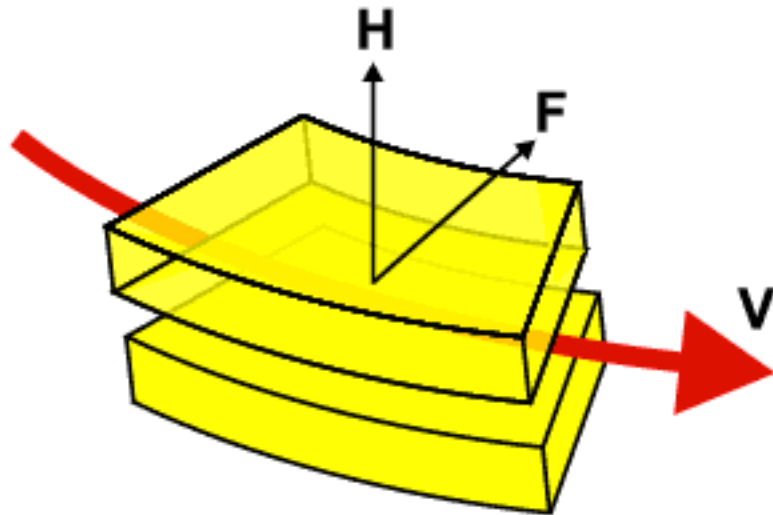
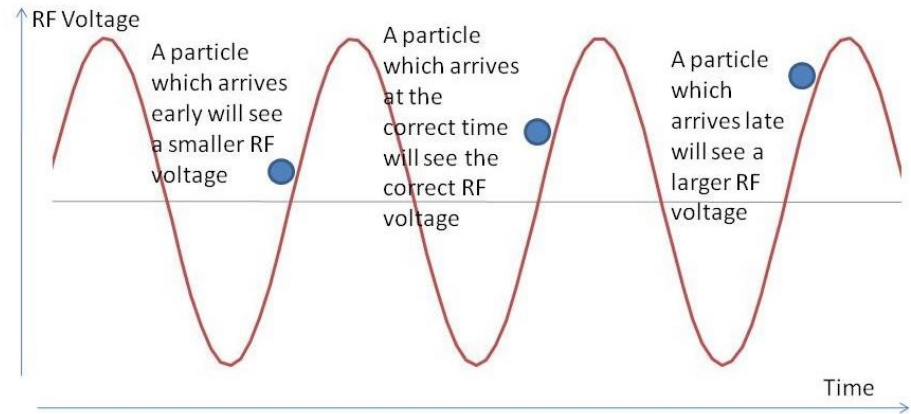
LINAC2 → **50 MeV**
Booster → **1.4 GeV**

Proton Synchrotron (PS) → **25 GeV**
Super Proton Synchrotron (SPS) → **450 GeV**
Large Hadron Collider (LHC) → **7 TeV**

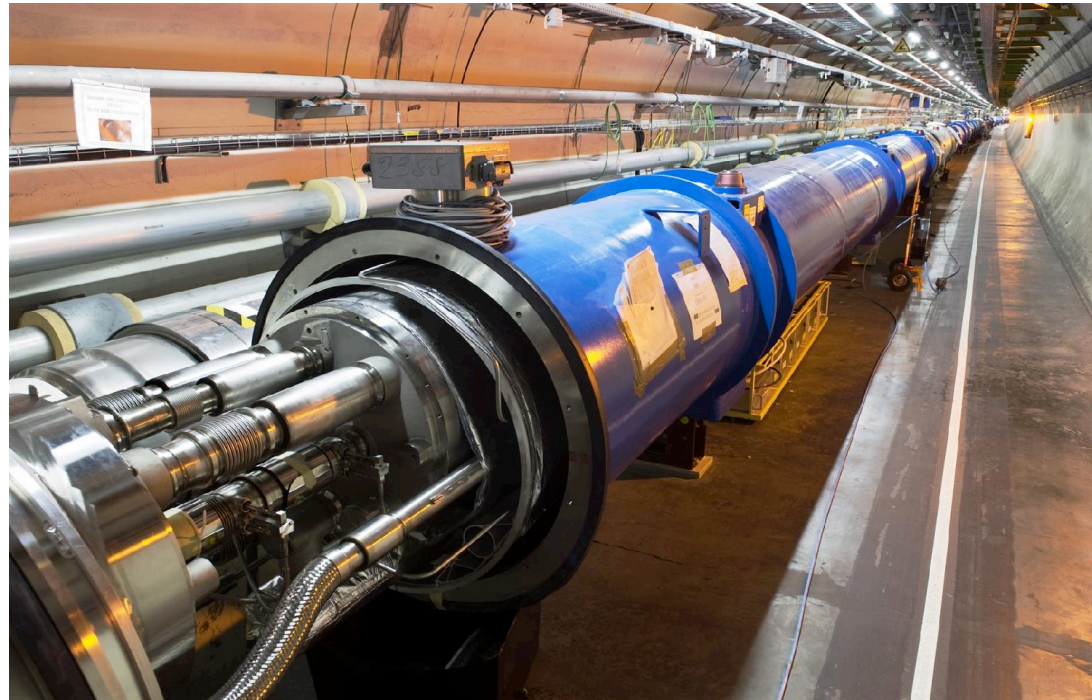




Beam acceleration



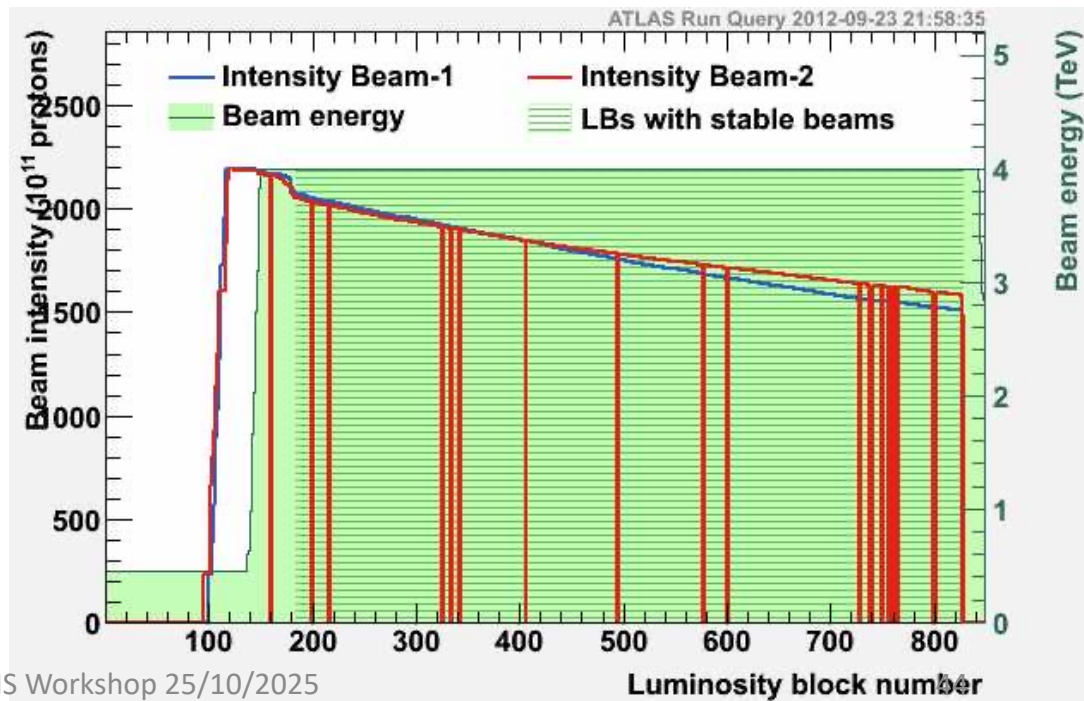
dipole





- Energia do feixe:
- 2802 bunches de 1.15×10^{11} prótons
- $7\text{TeV} / \text{próton (2015)} = 7 \times 10^{12} \times 1.602 \times 10^{-19} \text{ J}$
- 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 $\approx 16\mu\text{m}$
- Runs típicos duram cerca de 24 horas
- Intensidade diminui devido a perdas
- Depois voltamos a injectar novos feixes



Muon Spectrometer: $|\eta| < 2.7$

Air-core toroids and gas-based muon chambers
 $\sigma/p_T = 2\% @ 50\text{GeV}$ to $10\% @ 1\text{TeV}$ (ID+MS)

EM calorimeter: $|\eta| < 3.2$

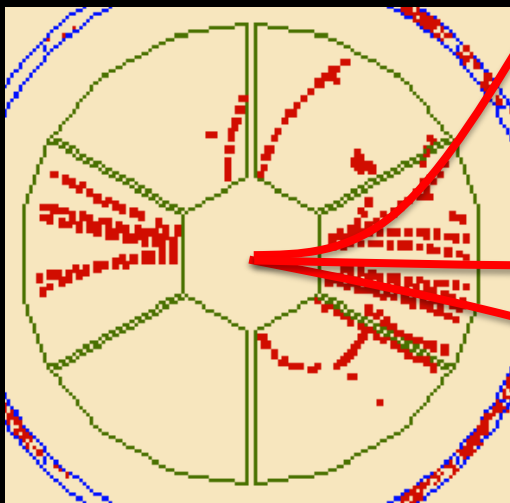
Pb-LAr Accordion
 $\sigma/E = 10\%/\sqrt{E} \oplus 0.7\%$

Hadronic calorimeter:

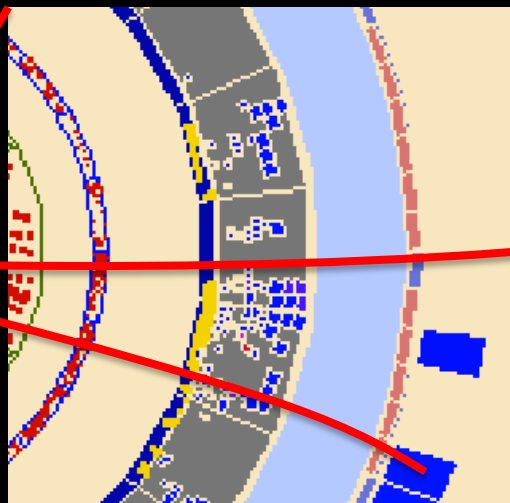
$|\eta| < 1.7$ Fe/scintillator
 $1.3 < |\eta| < 4.9$ Cu/W-Lar
 $\sigma/E_{\text{jet}} = 50\%/\sqrt{E} \oplus 3\%$

- $L = 44\text{ m}$, $\varnothing \approx 25\text{ m}$
- 7000 tonnes
- $\approx 10^8$ electronic channels
- 3-level trigger reducing 40 MHz collision rate to 200 Hz of events to tape

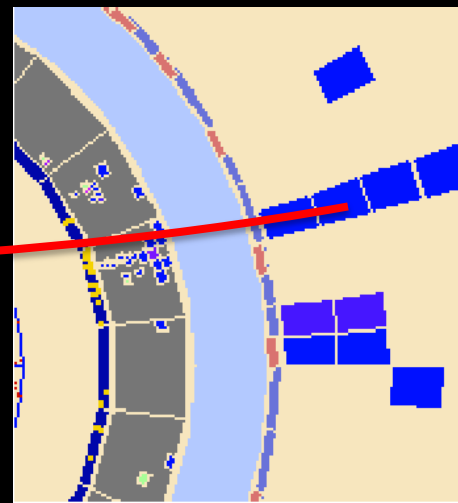
Inner Tracker: $|\eta| < 2.5$, $B=2\text{T}$
Si pixels/strips and Trans. Rad. Det.
 $\sigma/p_T = 0.05\% p_T (\text{GeV}) \oplus 1\%$



Detetor de Traços



Calorímetro
Eletromagnético



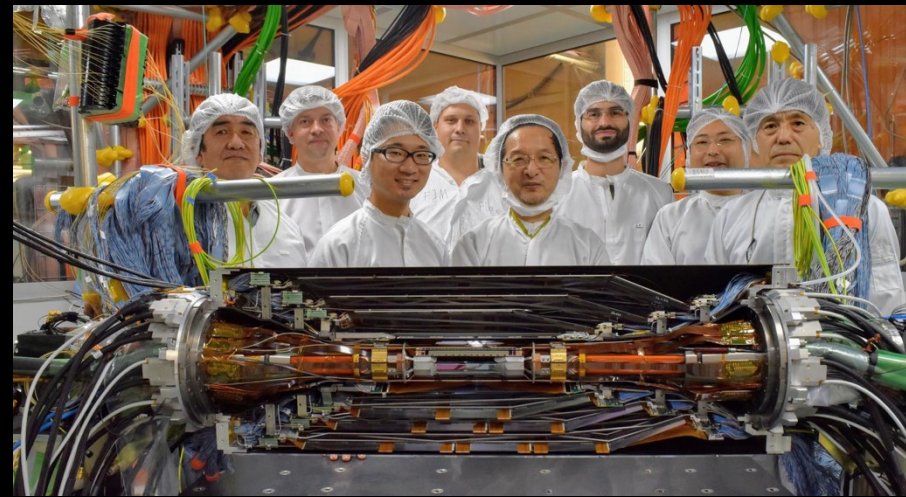
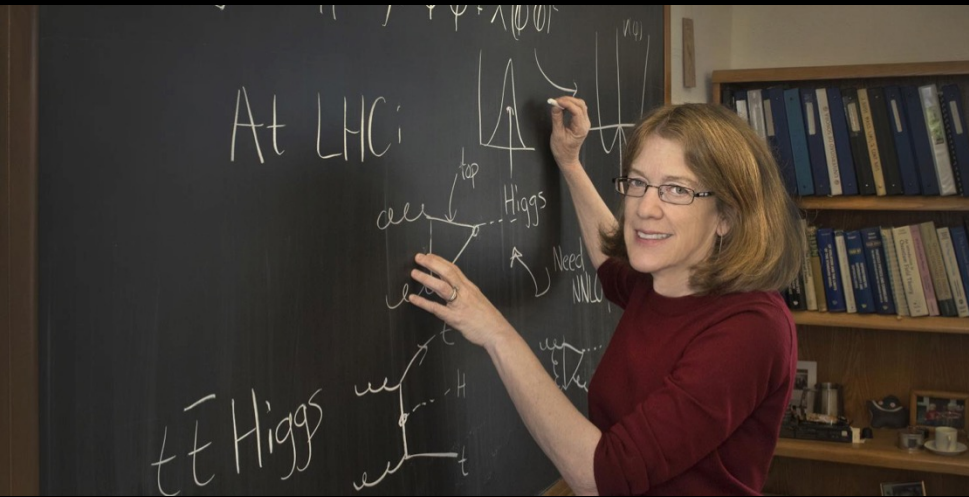
Calorímetro
Hadrónico

Os FÍSICOS DE PARTÍCULAS

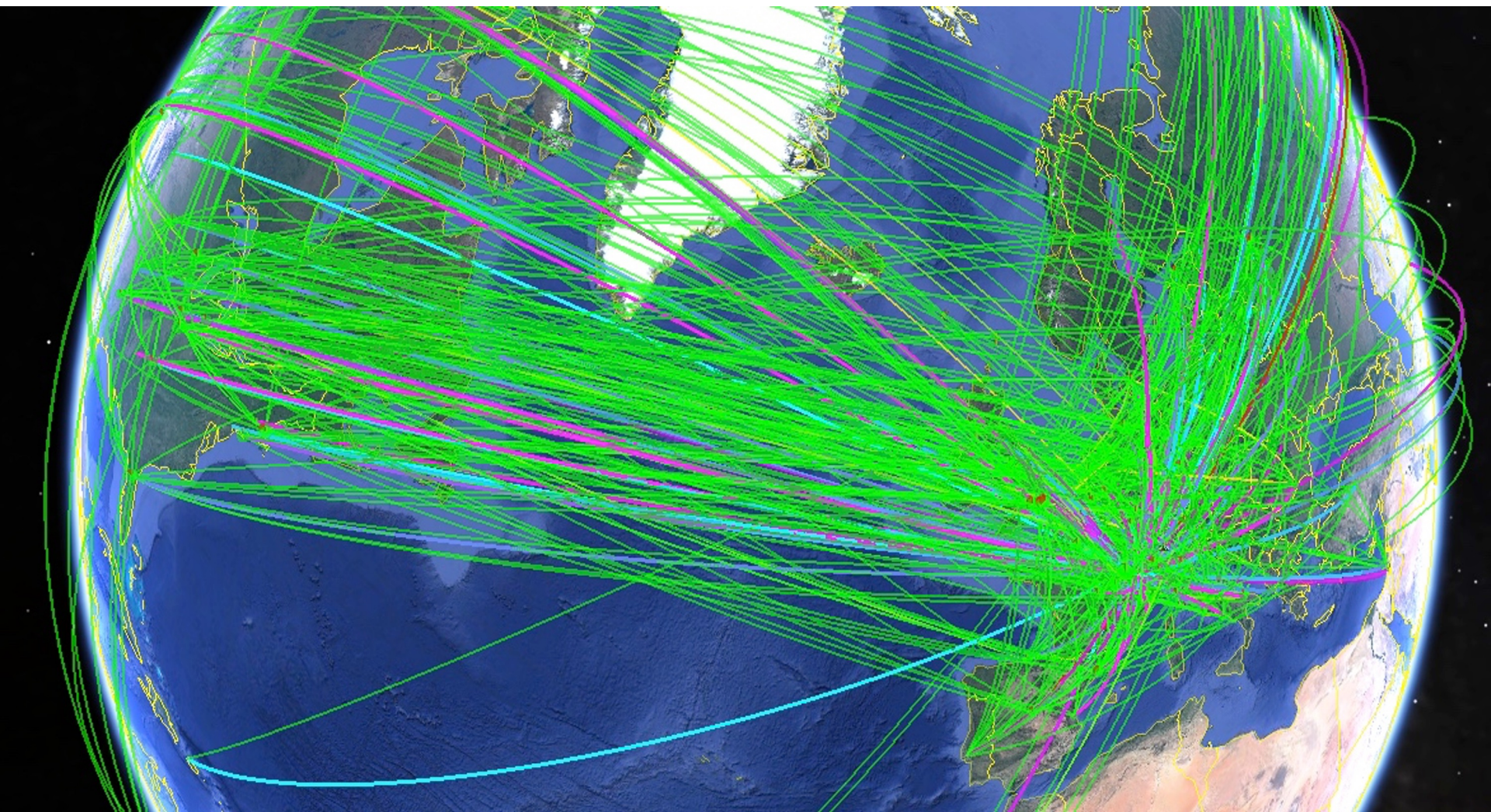




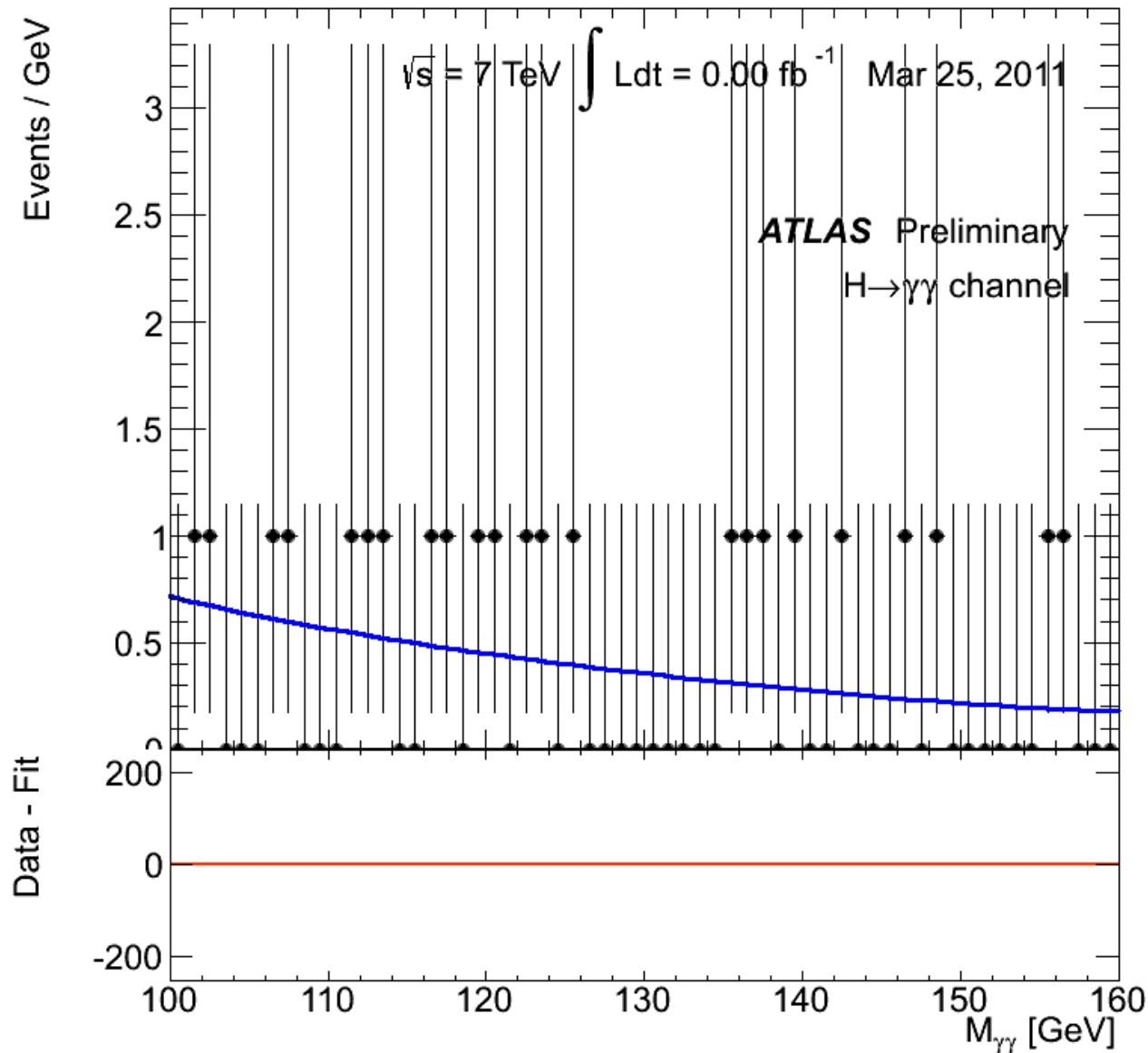
Os caçadores de partículas



Como analisar os dados?



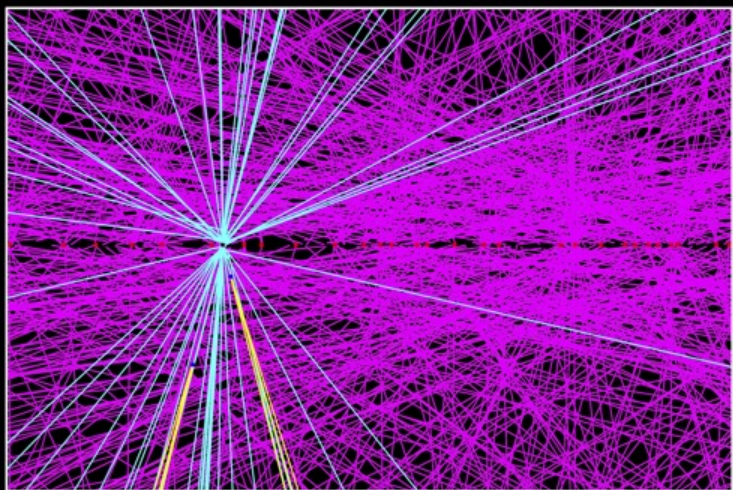
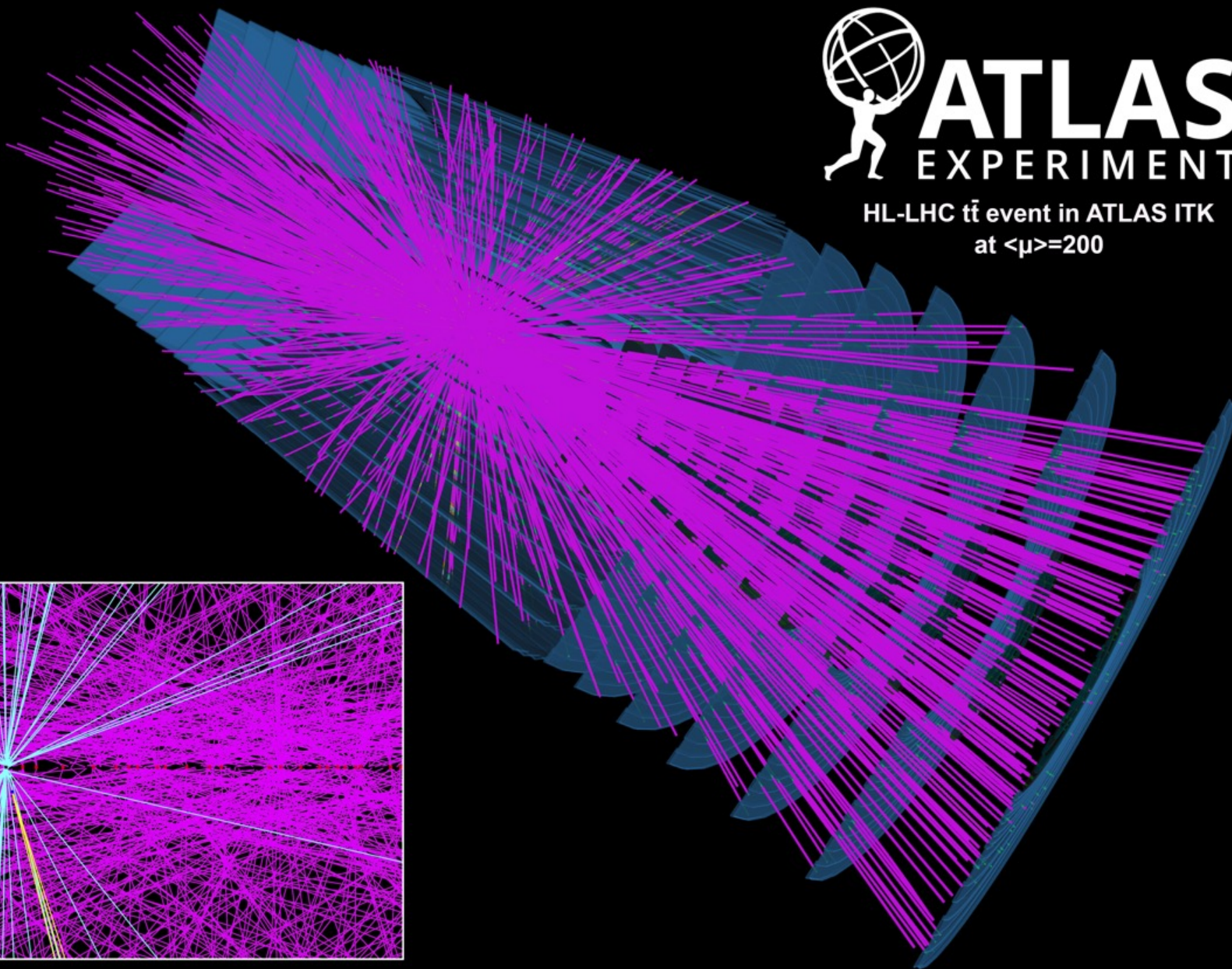
Descoberta do bóson de Higgs: $H \rightarrow \gamma\gamma$

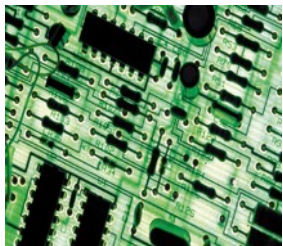


O futuro

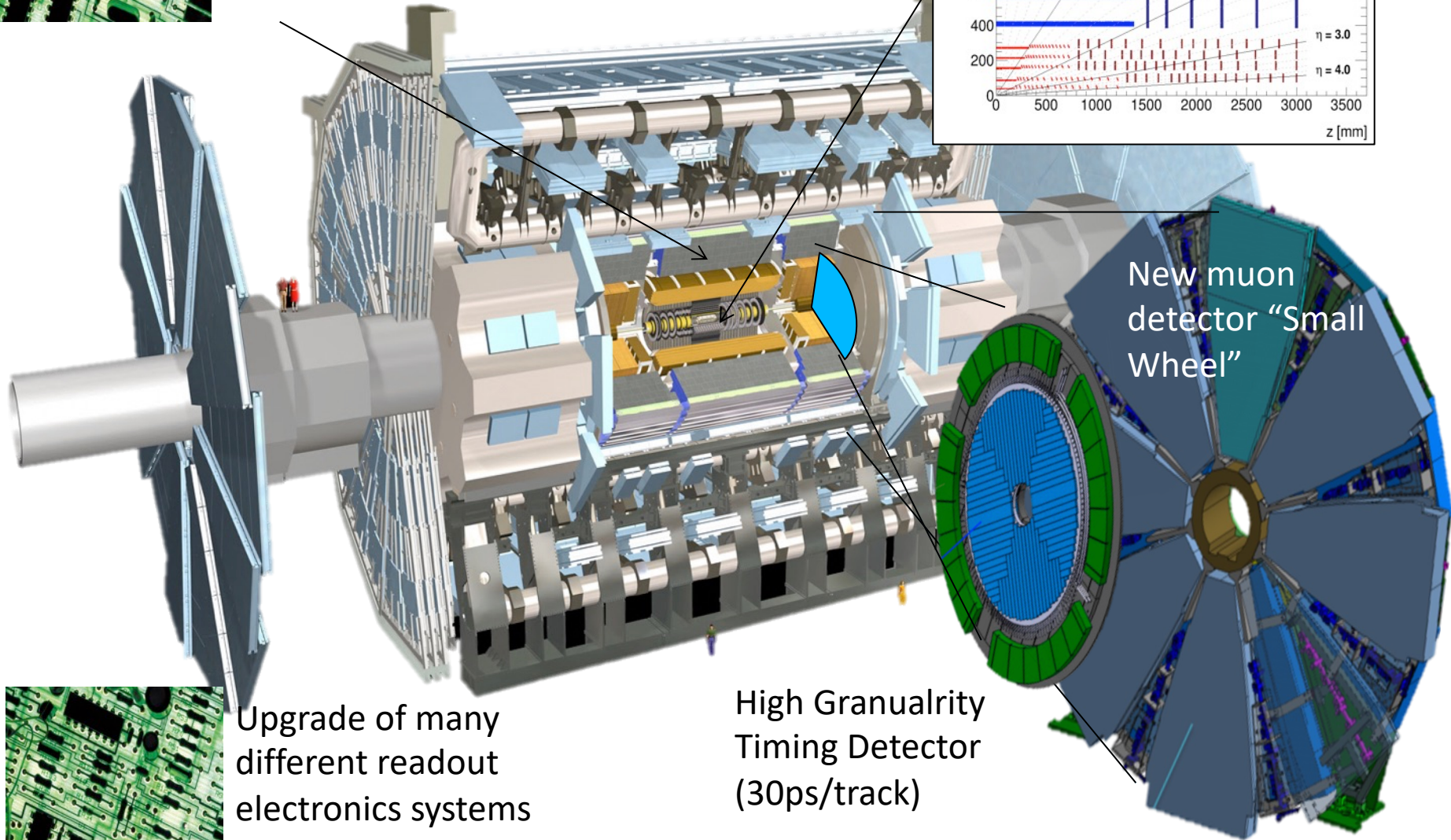
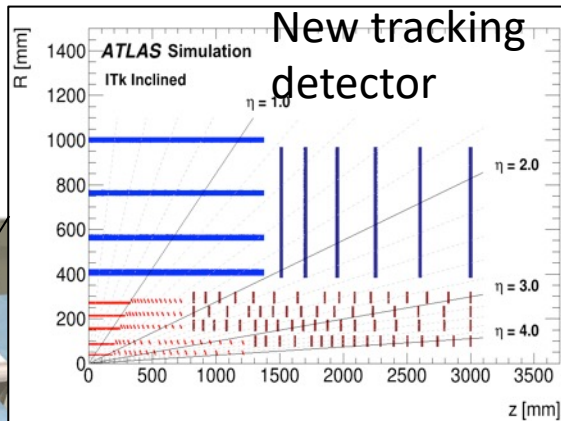


HL-LHC $t\bar{t}$ event in ATLAS ITK
at $\langle\mu\rangle=200$





Calorimeter: new DAQ electronics, **HV sources** and gap scintillators

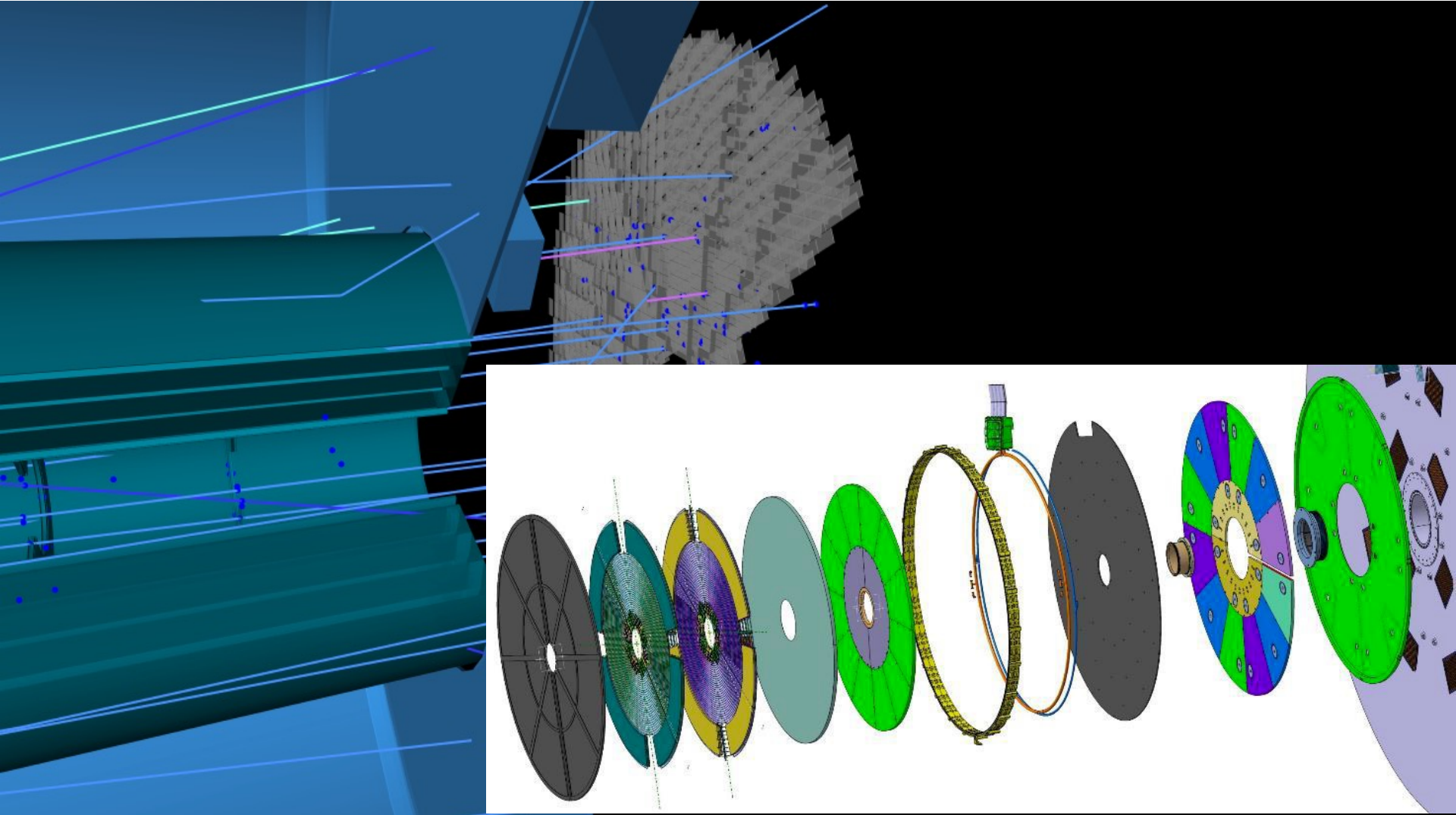


Upgrade of many different readout electronics systems

High Granualrity Timing Detector (30ps/track)

New muon detector "Small Wheel"

High Granularity Timing Detector



O Future Circular Collider - FCC



IMPACTO DIRETO NA SOCIEDADE



Impacto na Sociedade

Prototerapia

Computação
na grid

Imagiologia médica

Radioterapia

Tomografia de muões
(Pirâmide de Gizé)

Ciclo Solar

Exploração do espaço

World Wide Web

Aplicações à medicina

Desenvolvimento de muitas aplicações na área biomédica

Por exemplo:

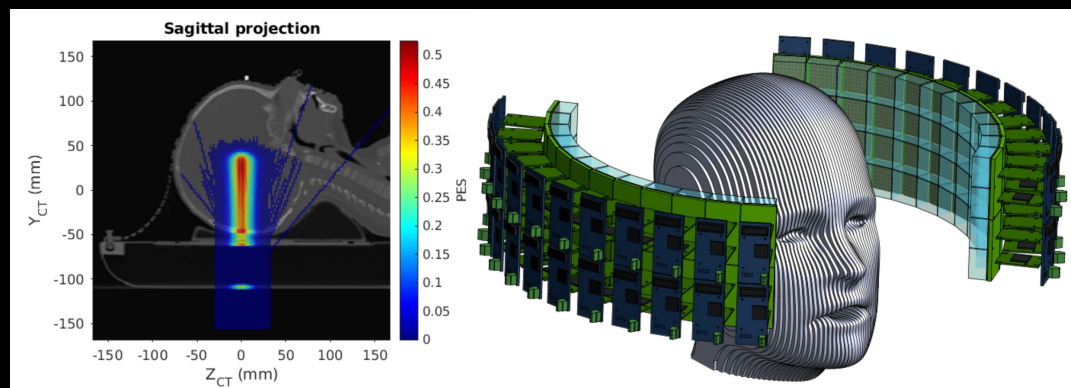
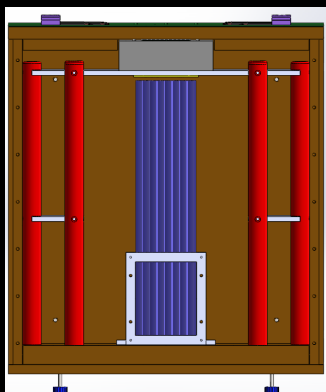
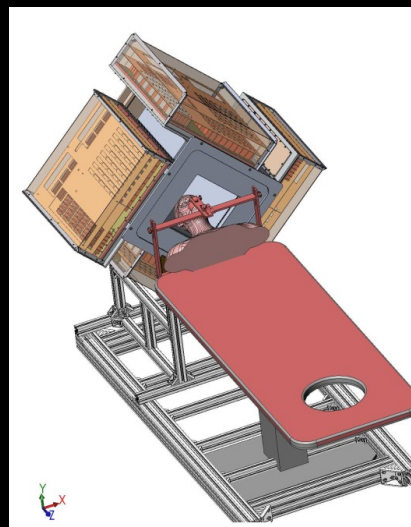
Positron Emission Tomography (PET / ToF-PET)

Orthogonal Imaging para terapias com feixes

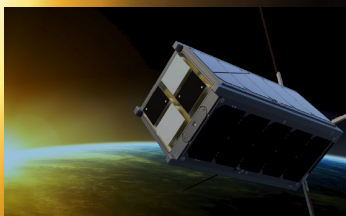
Dosimetria e microdosimetria

Instrumentação para medições biológicas

etc



Tecnologia da radiação na fronteira do espaço



Missão JUICE (ESA, EFCEC, PSI, IDEAS)

- RADEM – Rad. Hard Electron Mon.
- Teste de componentes EEE para ambiente de Júpiter

Projeto MarsREM – Mars Energetic Radiation Environment Models (ESA)

Efeitos da radiação espacial:

- Teste de componentes EEE (Technology Test Bed)
- Envelhecimento de sensores de CdZnTe para o espaço (GLOSS, ESA/CNES)

Gamma ray polarimetry, Earth observation:

- COMcube (ESA); AMEGO (NASA)
- STRATOSPOLCA (ESA)
- THOR - Space Rider: Terrestrial Gamma Flashes (Active Space, Advacam, ESA)



Perguntas?

Obrigado
pelo vosso
interesse!

jgoncalo@lip.pt



BACKUP Slides



Física Experimental de Partículas em Portugal

- Lisboa, Coimbra, Minho
- 200 membros
- 90 doutorados
- 75 estudantes
- 25 engenheiros e administrativos

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