

# Detectando Partículas no LHC, CERN

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CMS masterclass, LIP, 14 Julho 2025



FCT

Financiamento  
para a Ciência  
& a Tecnologia



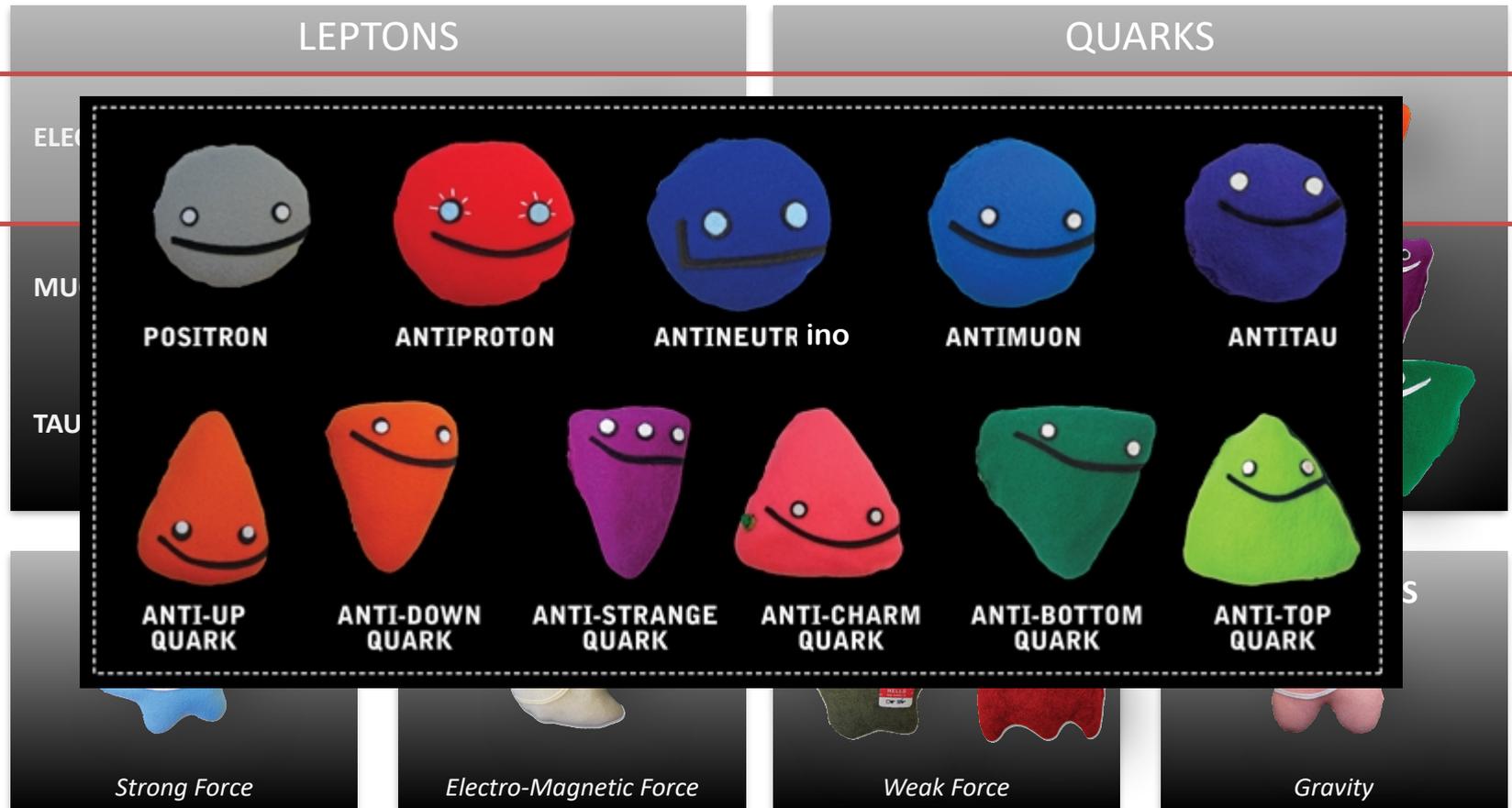
anos 1985 • 2025  
Portugal  
CERN



TÉCNICO  
LISBOA



# Tabela periódica das partículas elementares



# O Modelo Padrão da Física de Partículas

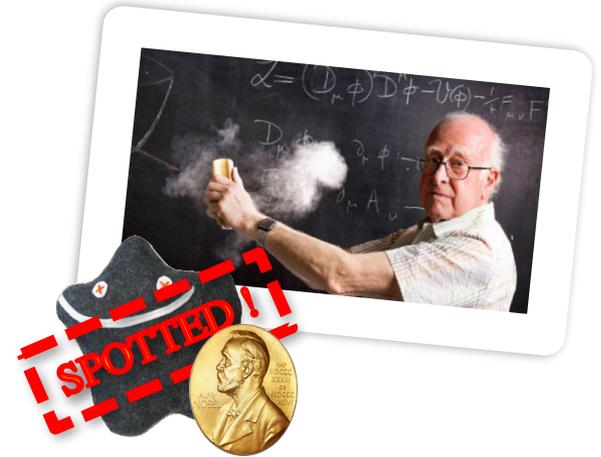
	I	II	III		
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
<b>QUARKS</b>	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> gluon	<b>H</b> higgs
	$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b><math>\gamma</math></b> photon	
<b>LEPTONS</b>	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	<b>e</b> electron	<b><math>\mu</math></b> muon	<b><math>\tau</math></b> tau	<b>Z</b> Z boson	
	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$	
	0	0	0	$\pm 1$	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	<b><math>\nu_e</math></b> electron neutrino	<b><math>\nu_\mu</math></b> muon neutrino	<b><math>\nu_\tau</math></b> tau neutrino	<b>W</b> W boson	
					<b>SCALAR BOSONS</b>
					<b>GAUGE BOSONS VECTOR BOSONS</b>
					<b>new thing</b>

Uma teoria fantástica, mas incompleta ➔ explorar novas partículas e interações!

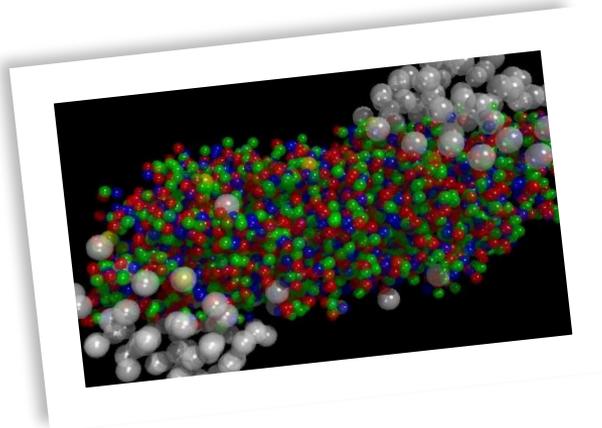
# Em busca de respostas a questões fundamentais ...



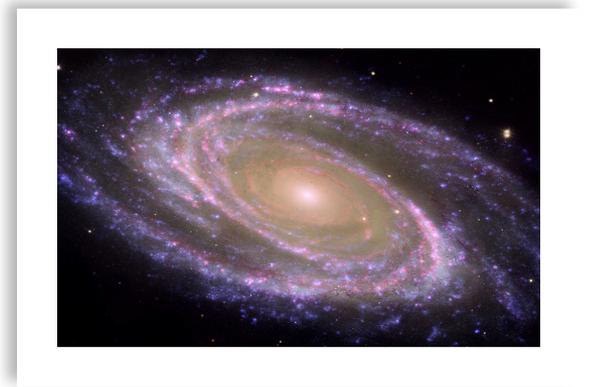
Porquê mais matéria do que antimatéria?



O que confere massa às Partículas?



Do que é feito 95% do universo?  
(matéria/energia escura)



Qual era o estado da matéria nos primeiros instantes do universo?

# o CERN, uma colaboração global

23 membros

11 associados

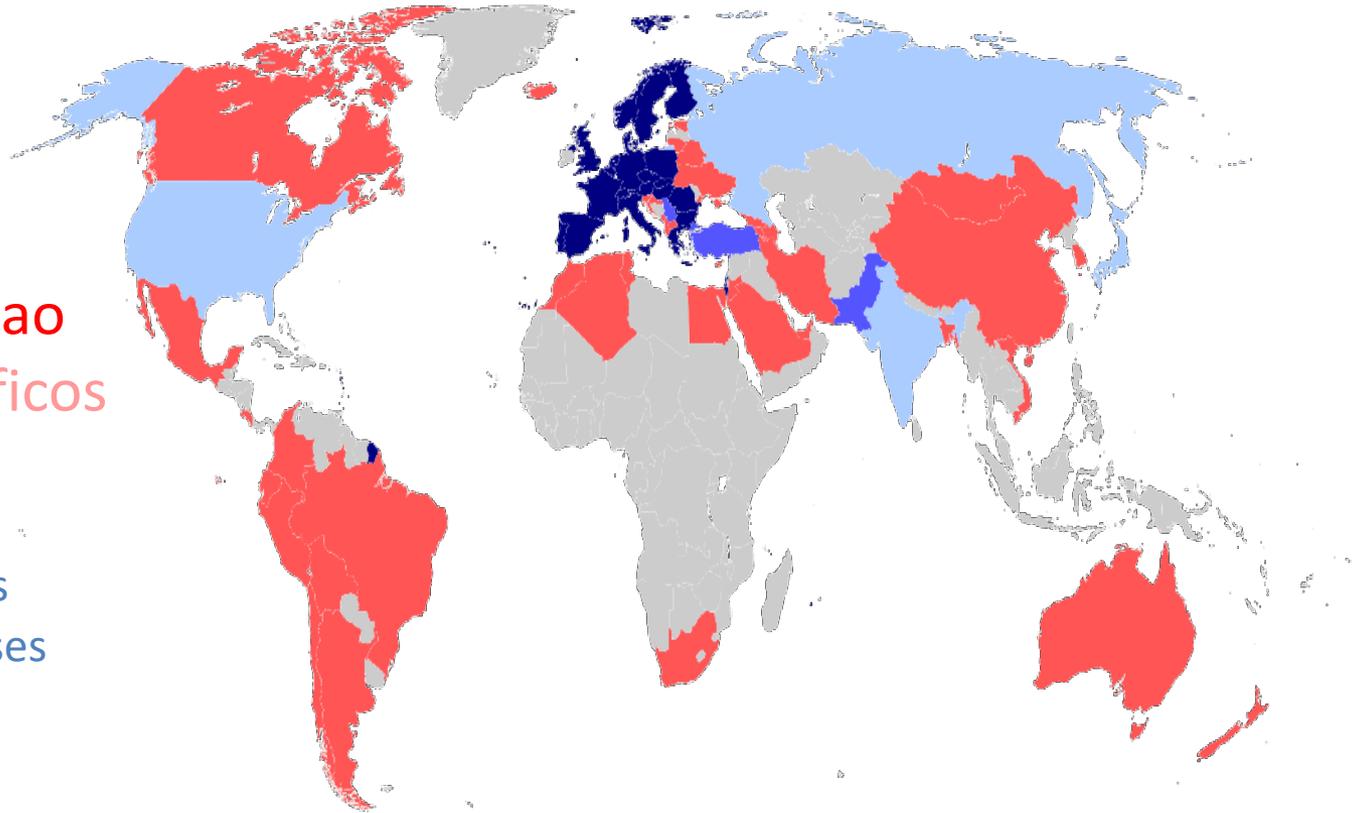
5 observadores

Acordos de cooperação

Contactos científicos

13000+ colaboradores

oriundos de 100+ países



Portugal membro desde 1986

Organização internacional fundada em 1954



ANOS **CERN** 

Acabamos de celebrar o septuagésimo aniversário do CERN: <https://cern70.cern>

# O acelerador

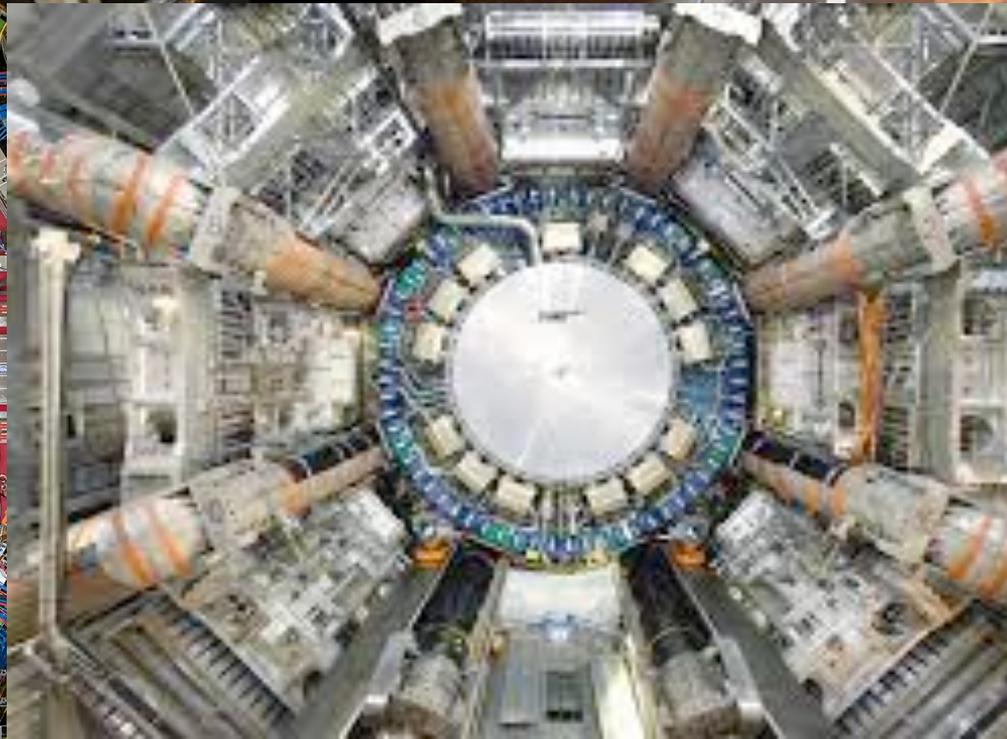
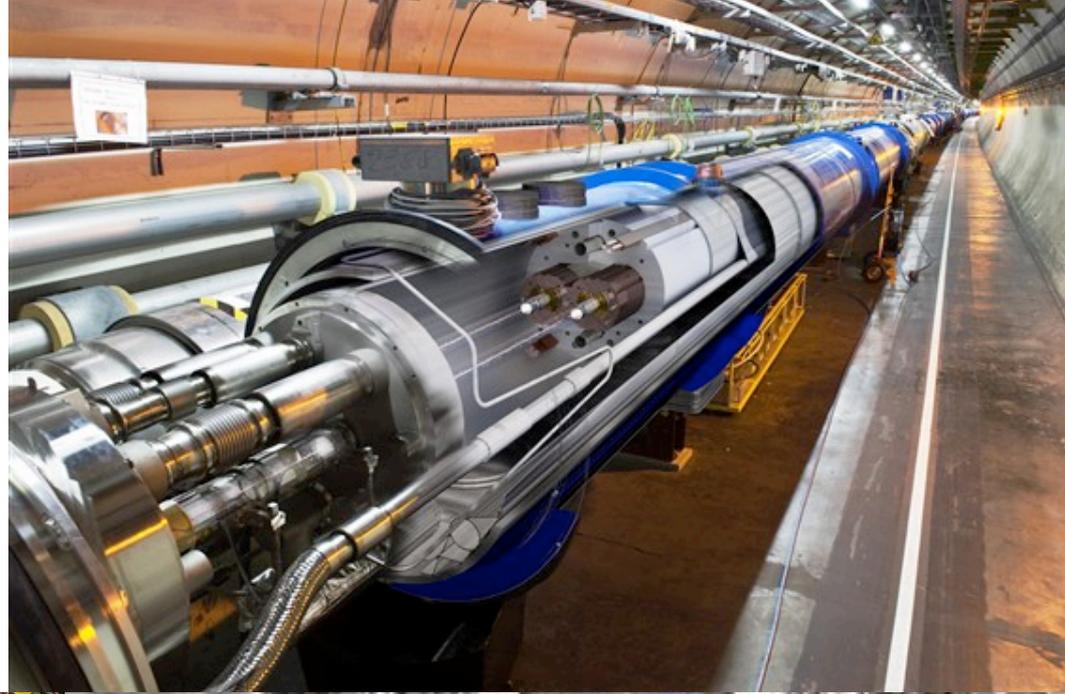


The LHC is the **world-leading** particle accelerator & collider

Delivering **unprecedented** energies and intensities

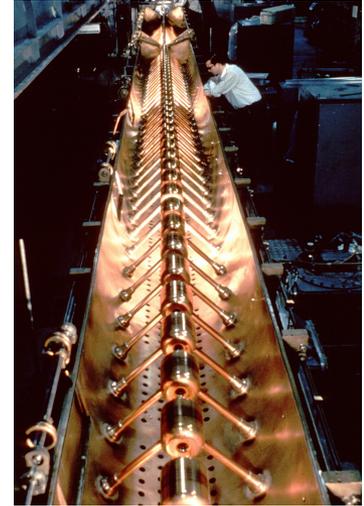
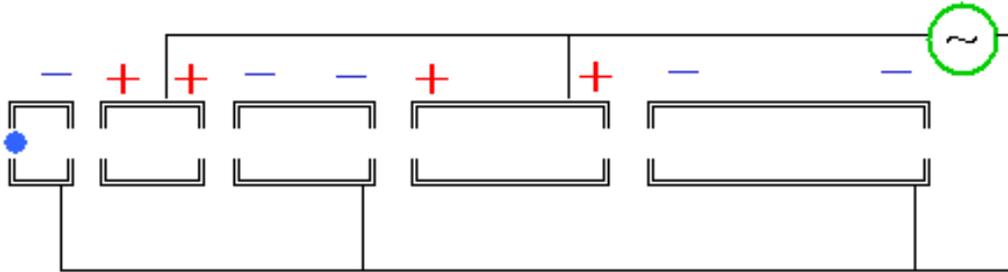
The LHC detectors are the most **sophisticated** scientific tools yet

Machine and detectors not static, systematically improved/**upgraded**



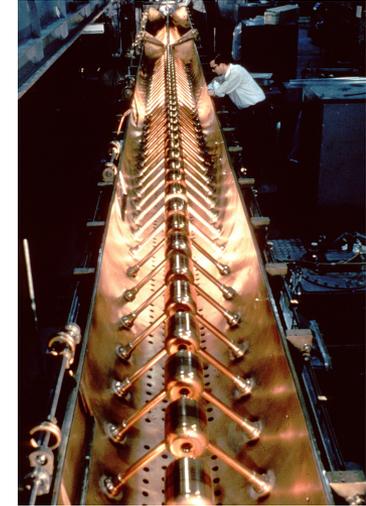
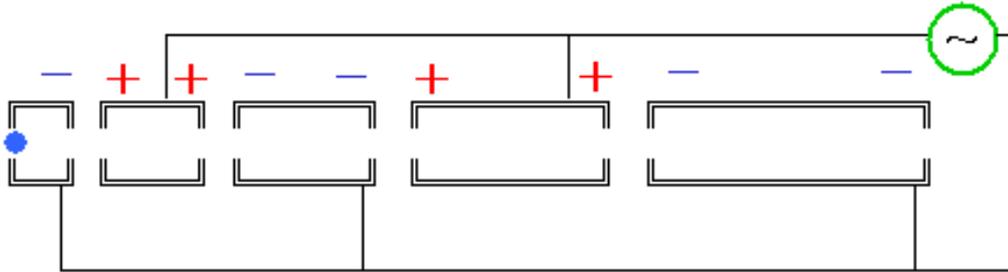
# Acelerando as partículas

## Acelerador linear

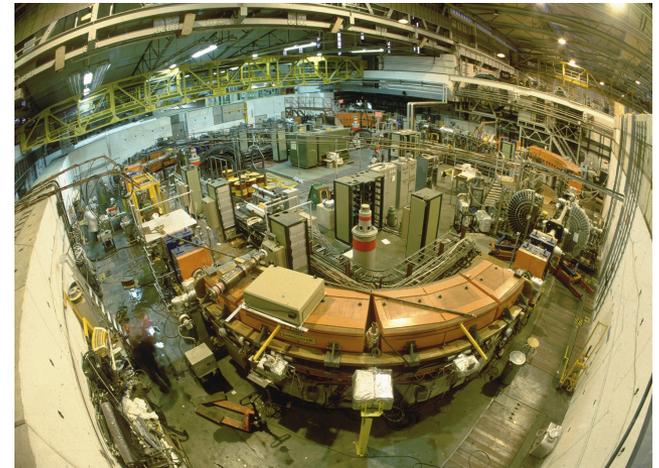
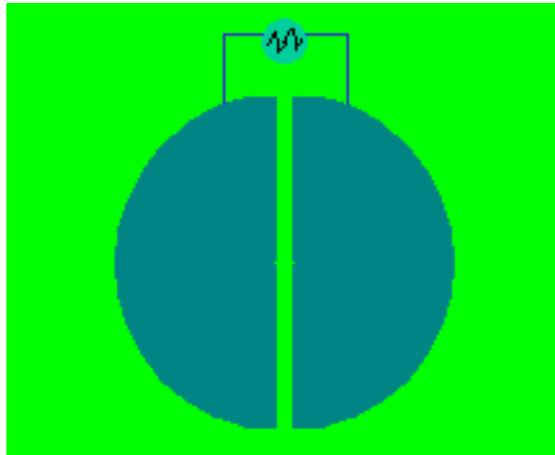


# Acelerando as partículas

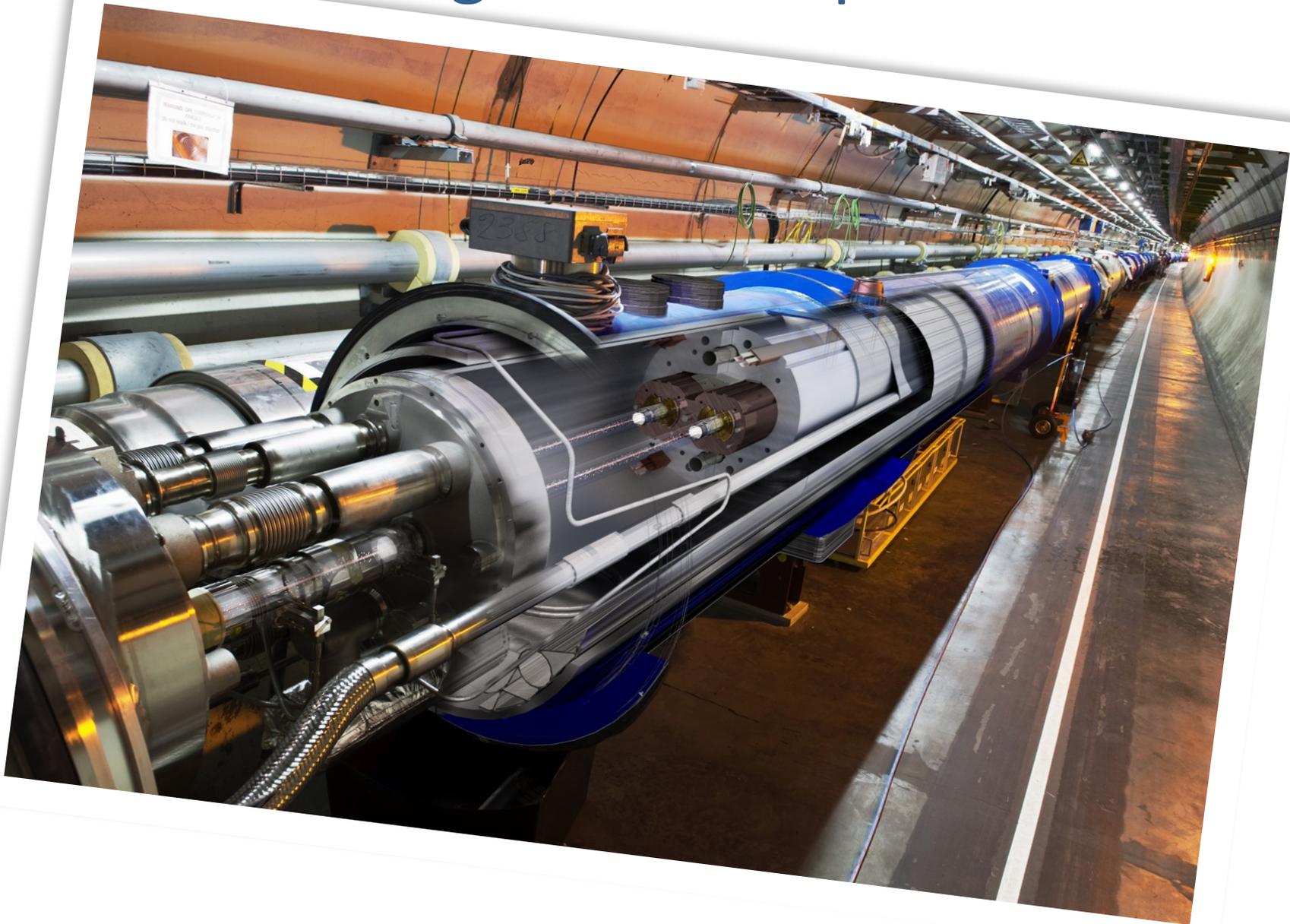
## Acelerador linear



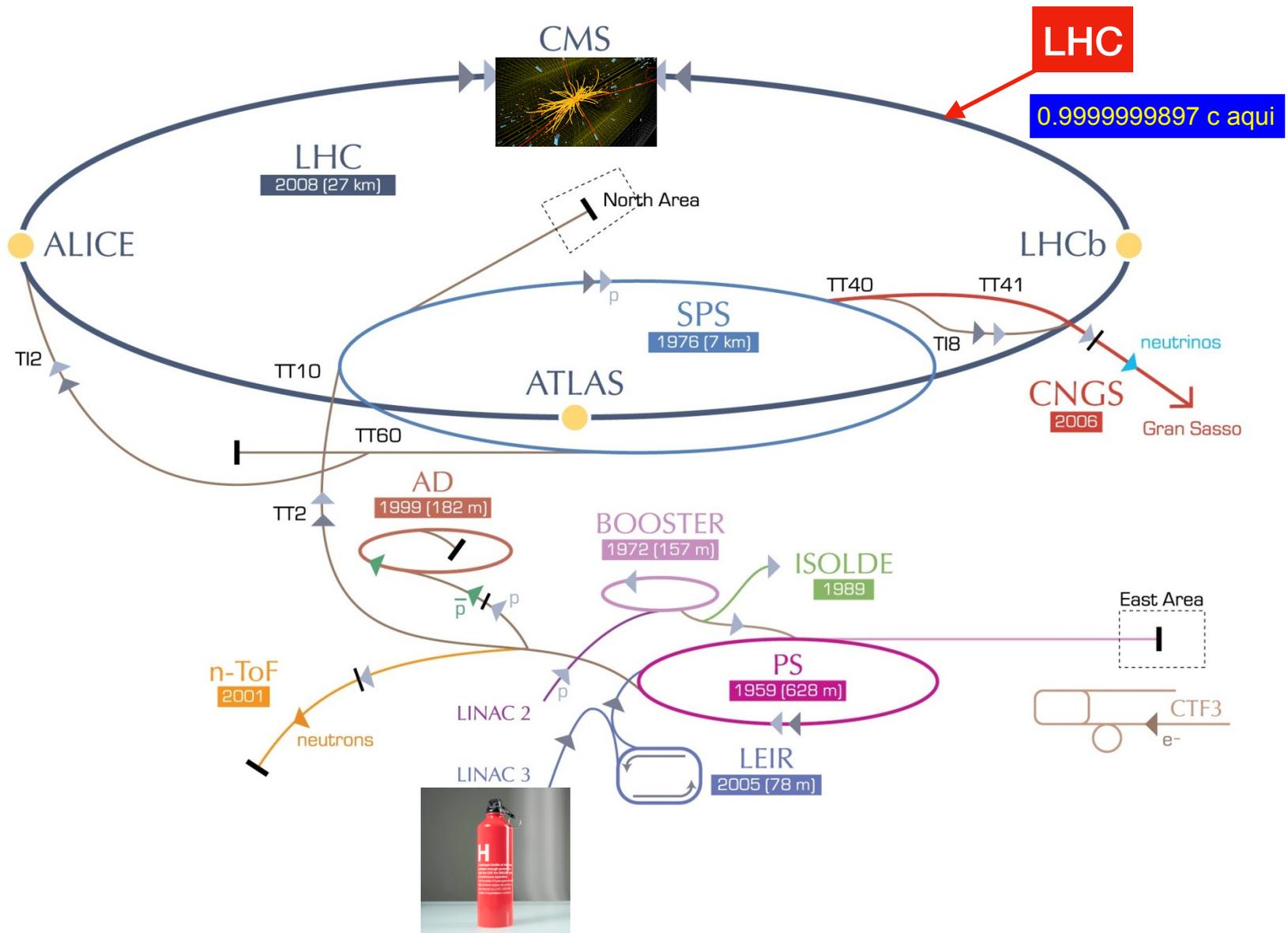
## Acelerador circular



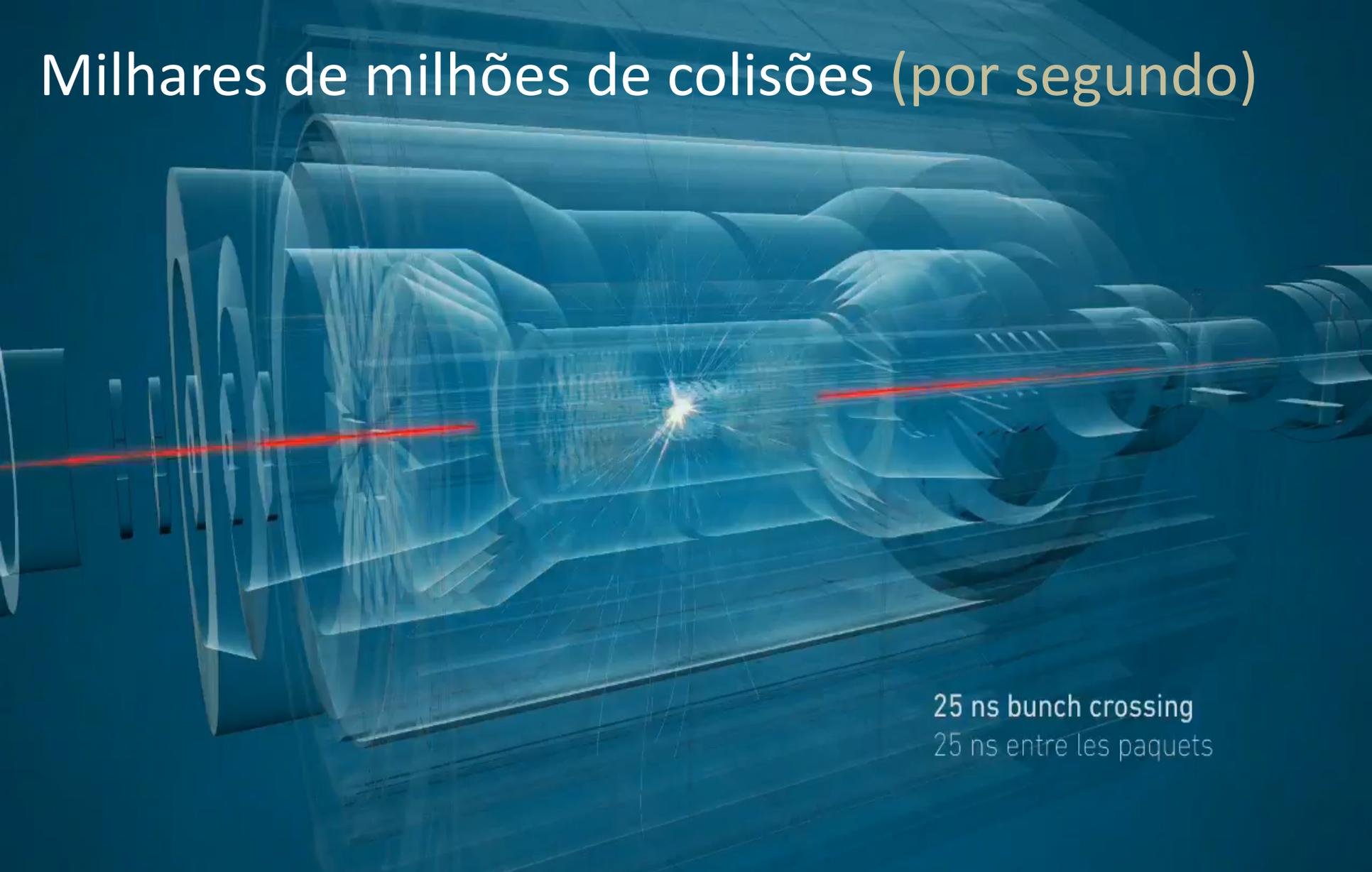
# o magneto mais potente



# a cadeia de aceleradores do CERN, e o LHC

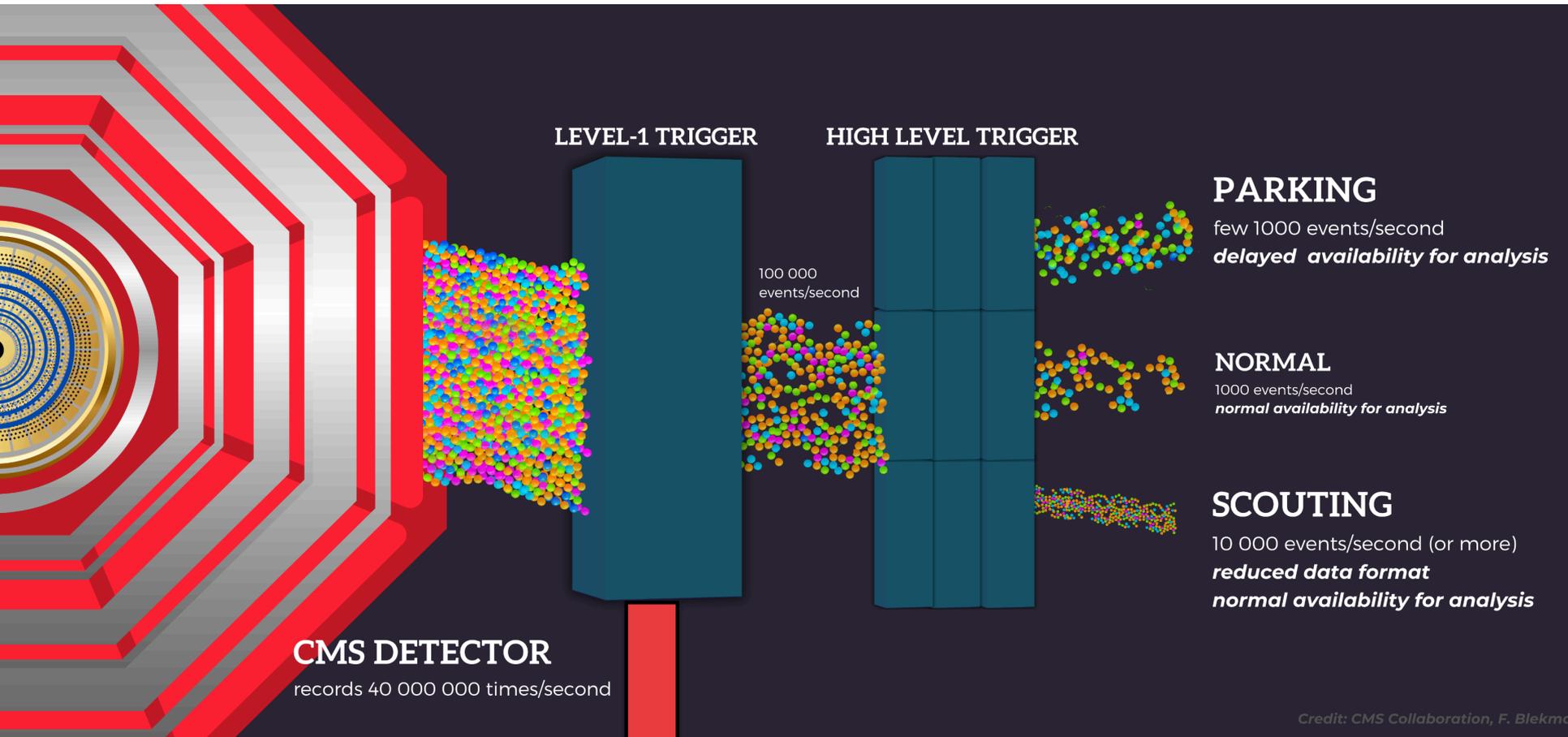


Milhares de milhões de colisões (por segundo)



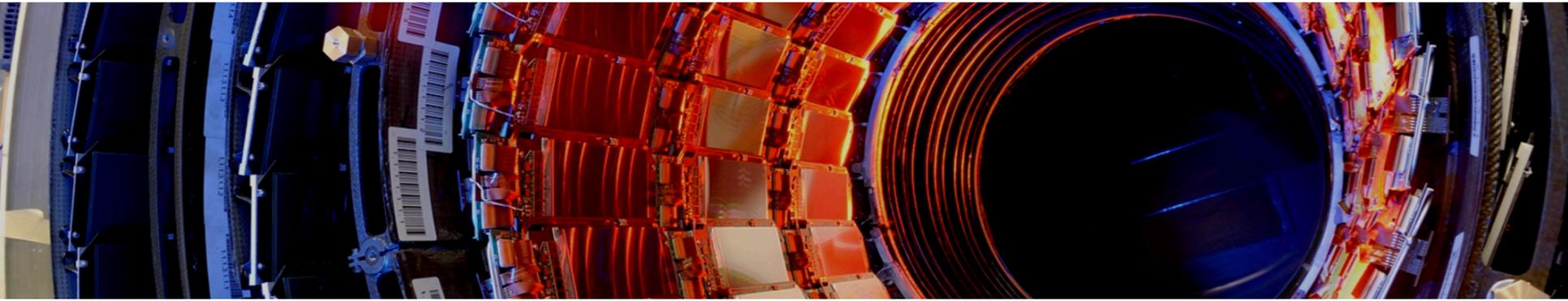
25 ns bunch crossing  
25 ns entre les paquets

# Filtrando as colisões



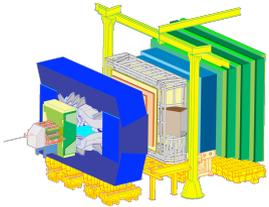
A física de interesse no LHC corresponde a **acontecimentos raros**  
É necessário **filtrar em tempo real** as colisões de interesse (trigger)

# O detector

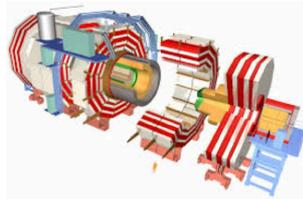


# LHC = acelerador + detectores + física

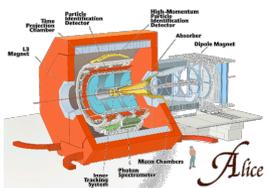
LHCb



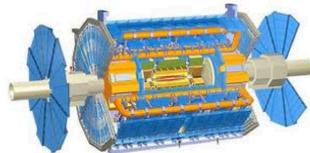
CMS



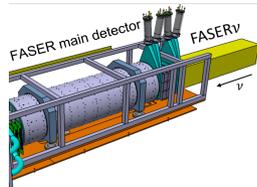
ALICE



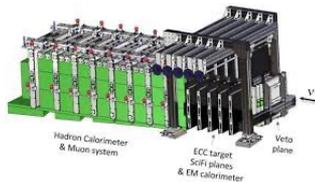
ATLAS



FASERv



SND@LHC



O LHC é o único instrumento científico que nos permite criar e detectar *todas* as partículas do MP

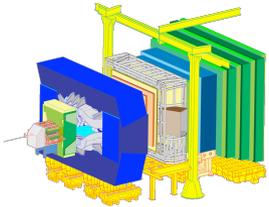
	mass $\approx 2.2 \text{ MeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ <b>u</b> up	mass $\approx 1.28 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ <b>c</b> charm	mass $\approx 173.1 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ <b>t</b> top	mass 0 charge 0 spin 1 <b>g</b> gluon	mass $\approx 124.97 \text{ GeV}/c^2$ charge 0 spin 0 <b>H</b> higgs	
QUARKS	mass $\approx 4.7 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ <b>d</b> down	mass $\approx 96 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ <b>s</b> strange	mass $\approx 4.18 \text{ GeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ <b>b</b> bottom	mass 0 charge 0 spin 1 <b><math>\gamma</math></b> photon	SCALAR BOSONS	
	mass $\approx 0.511 \text{ MeV}/c^2$ charge -1 spin $\frac{1}{2}$ <b>e</b> electron	mass $\approx 105.66 \text{ MeV}/c^2$ charge -1 spin $\frac{1}{2}$ <b><math>\mu</math></b> muon	mass $\approx 1.7768 \text{ GeV}/c^2$ charge -1 spin $\frac{1}{2}$ <b><math>\tau</math></b> tau	mass $\approx 91.19 \text{ GeV}/c^2$ charge 0 spin 1 <b>Z</b> Z boson		GAUGE BOSONS VECTOR BOSONS
	mass $< 2.2 \text{ eV}/c^2$ charge 0 spin $\frac{1}{2}$ <b><math>\nu_e</math></b> electron neutrino	mass $< 0.17 \text{ MeV}/c^2$ charge 0 spin $\frac{1}{2}$ <b><math>\nu_\mu</math></b> muon neutrino	mass $< 18.2 \text{ MeV}/c^2$ charge 0 spin $\frac{1}{2}$ <b><math>\nu_\tau</math></b> tau neutrino	mass $\approx 80.39 \text{ GeV}/c^2$ charge $\pm 1$ spin 1 <b>W</b> W boson		

+  
*antipartículas*

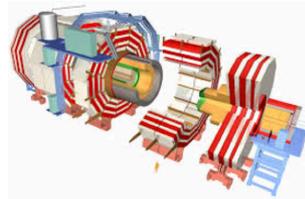
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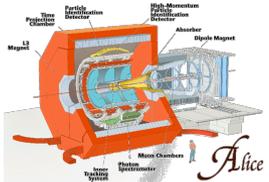
LHCb



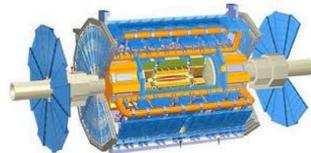
CMS



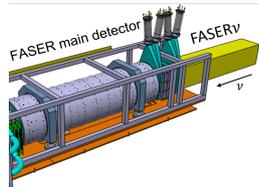
ALICE



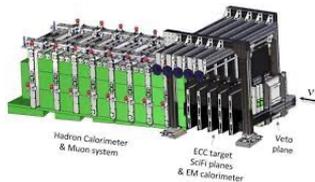
ATLAS



FASERv



SND@LHC



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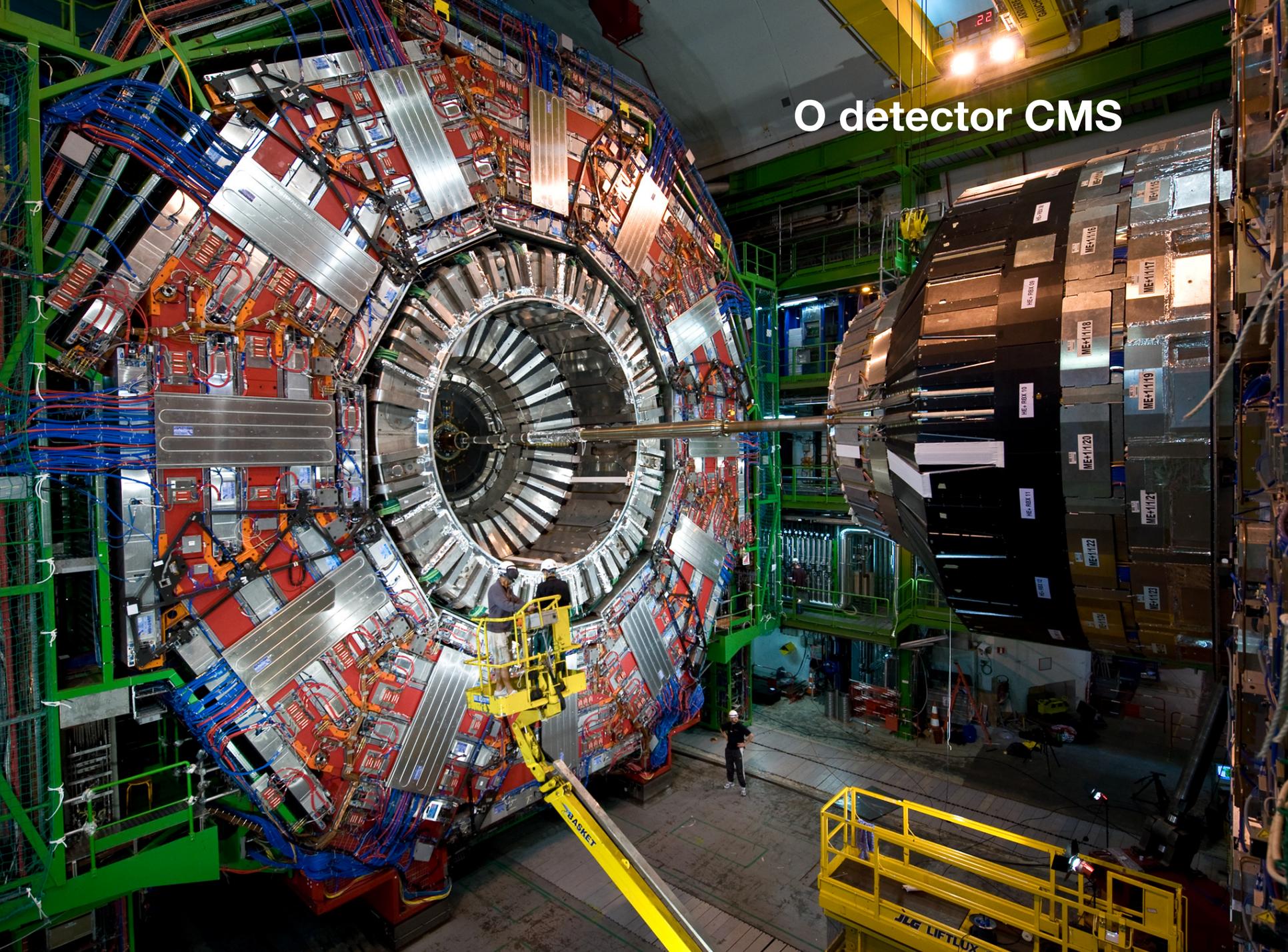
+  
*antipartículas*

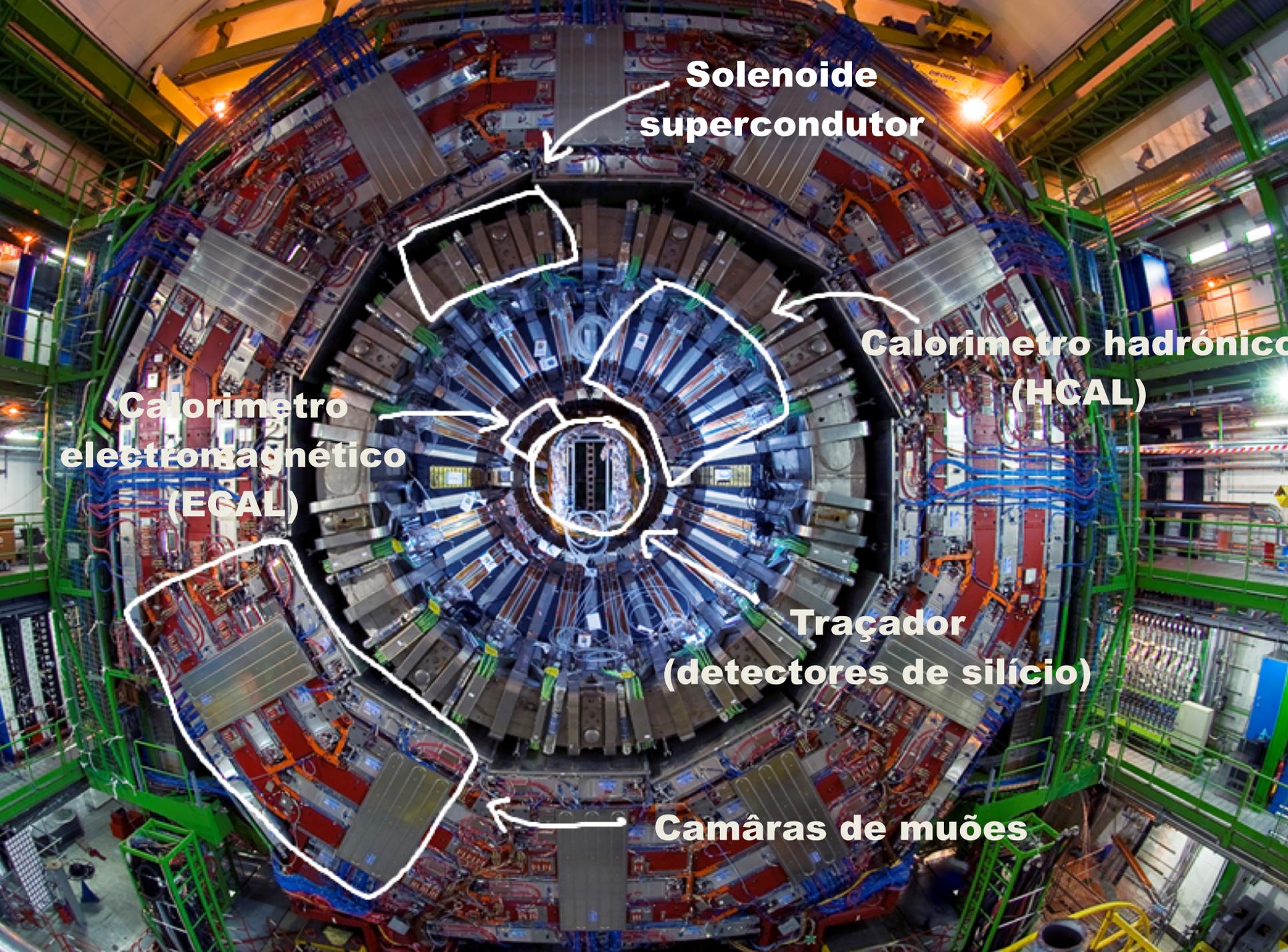
(com



participação Portuguesa / LIP)

O detector CMS





**Solenóide  
supercondutor**

**Calorímetro hadrónico  
(HCAL)**

**Calorímetro  
electromagnético  
(ECAL)**

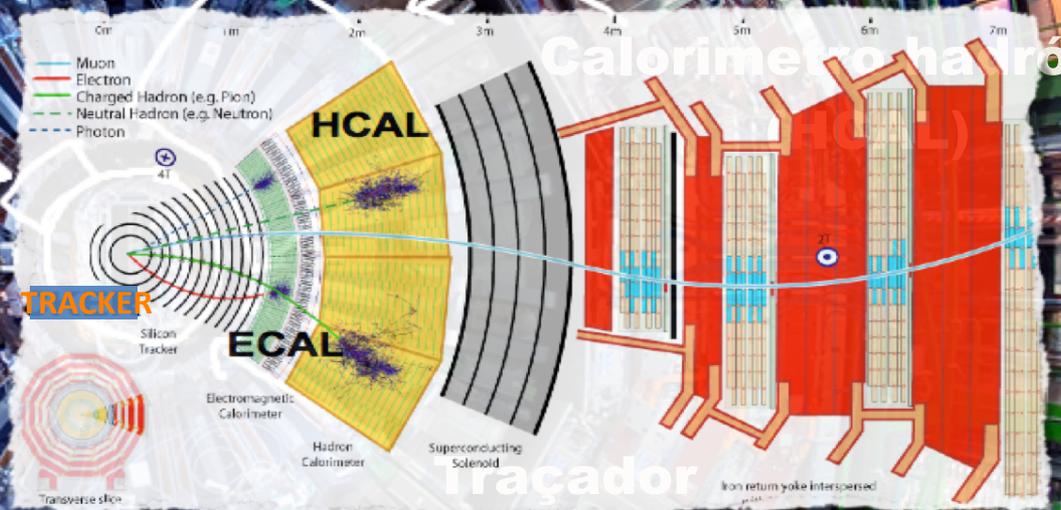
**Traçador  
(detectores de silício)**

**Camêras de muões**

**Solenóide  
supercondutor**

**Calorímetro  
electromagnético  
(ECAL)**

**Calorímetro hadrónico**

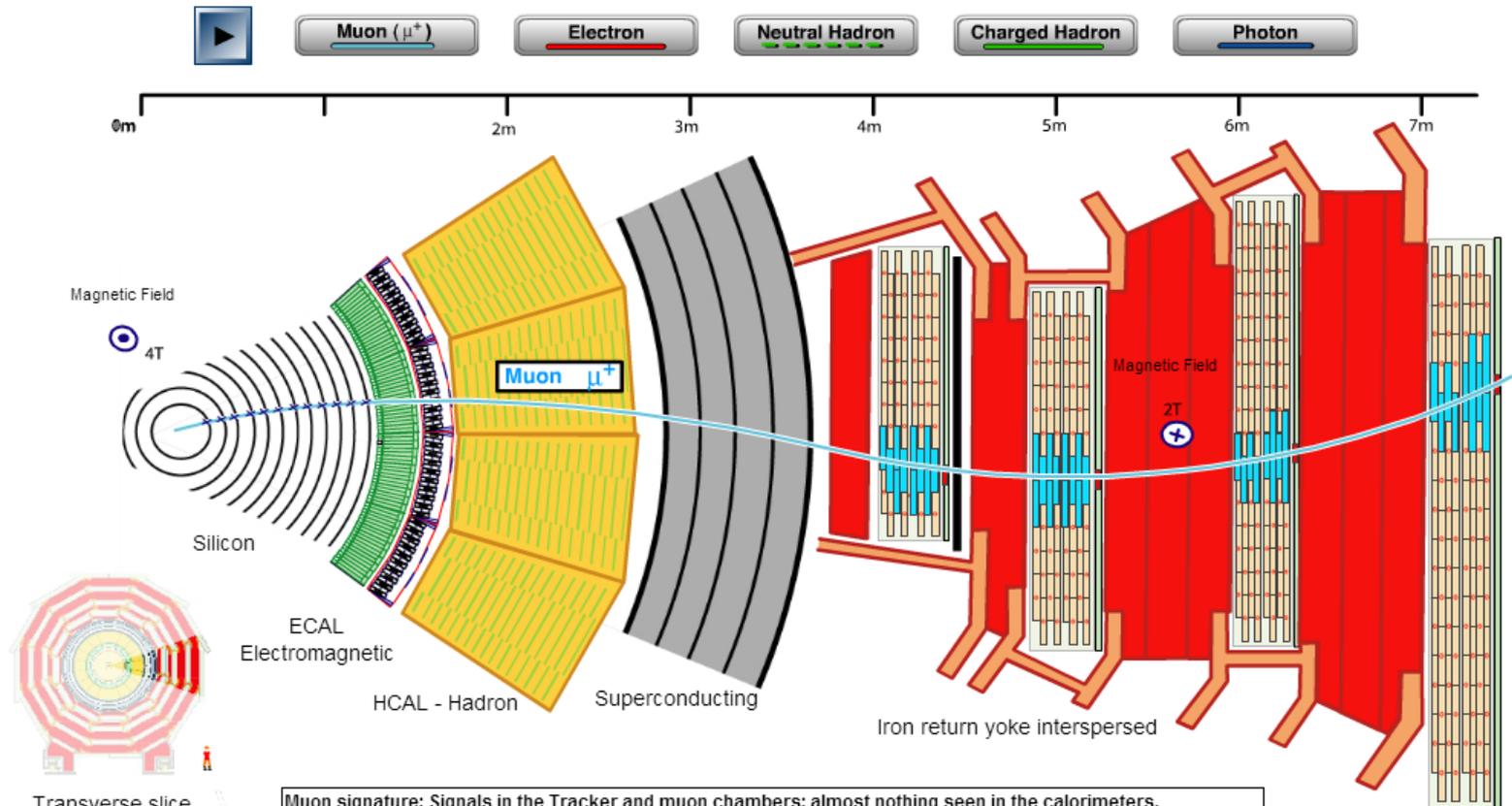


**Traçador  
(detectores de silício)**

**Camêras de muões**

# Identificando as partículas: muão

Transverse Slice of the Compact Muon Solenoid (CMS) Detector

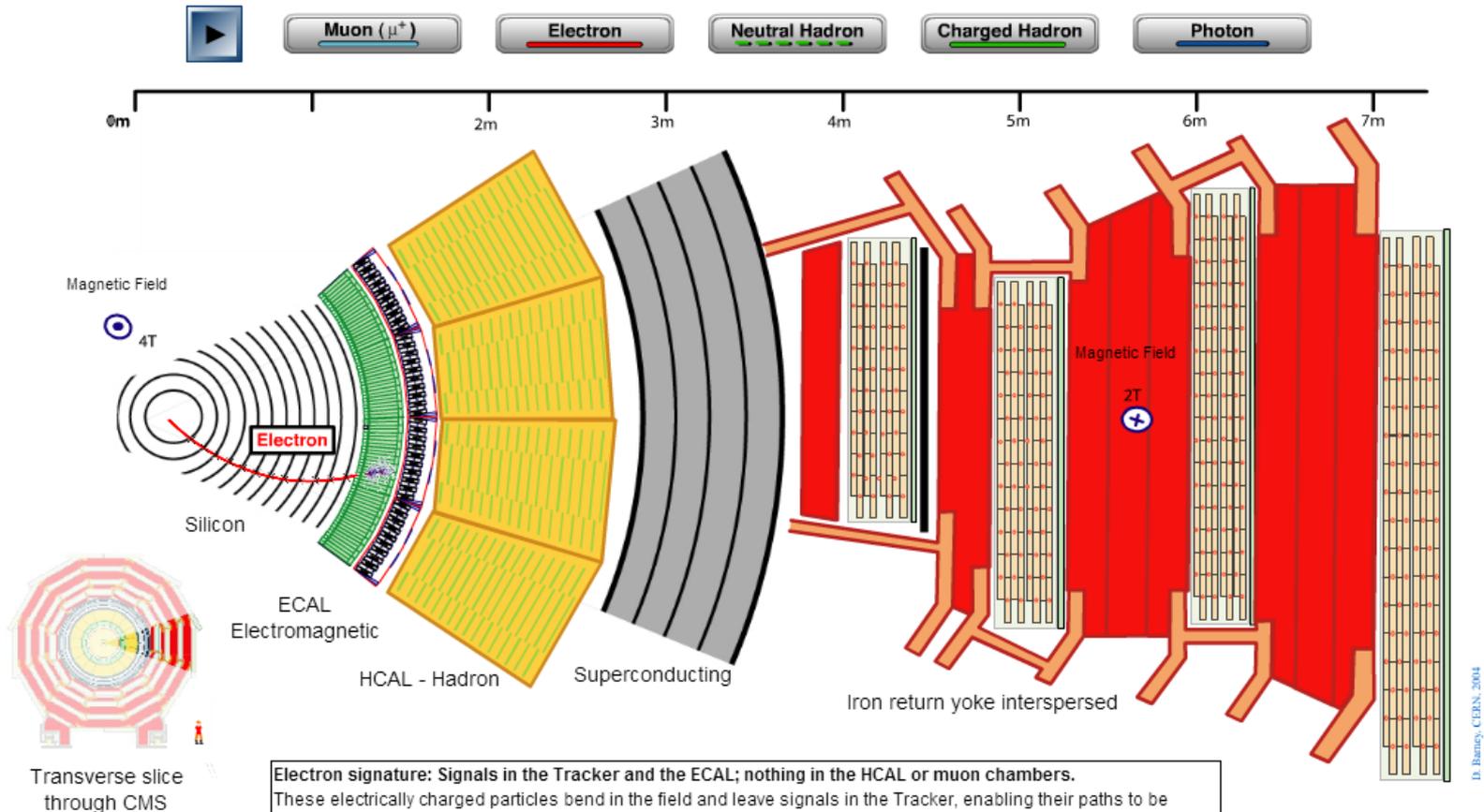


Transverse slice through CMS

**Muon signature:** Signals in the Tracker and muon chambers; almost nothing seen in the calorimeters. Muons are perhaps the easiest particles to identify in CMS: no other charged particle traverses the whole detector. Being charged, they are bent by the field in one direction inside the solenoid and in the opposite direction outside. As muons can only arise from the decay of something heavier their presence signifies that something potentially interesting has happened.

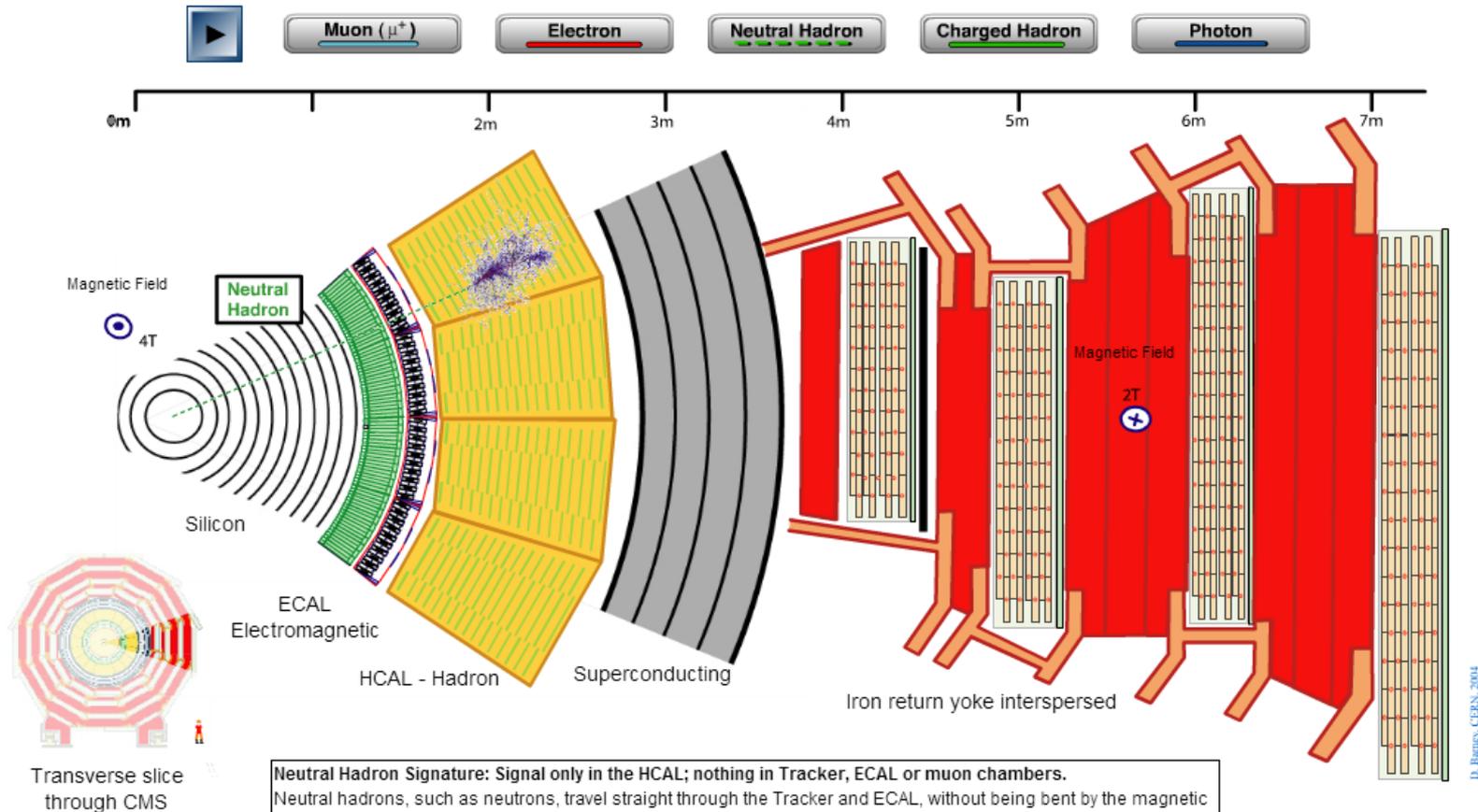
# Identificando as partículas: electrão

Transverse Slice of the Compact Muon Solenoid (CMS) Detector



# Identificando as partículas: neutrão

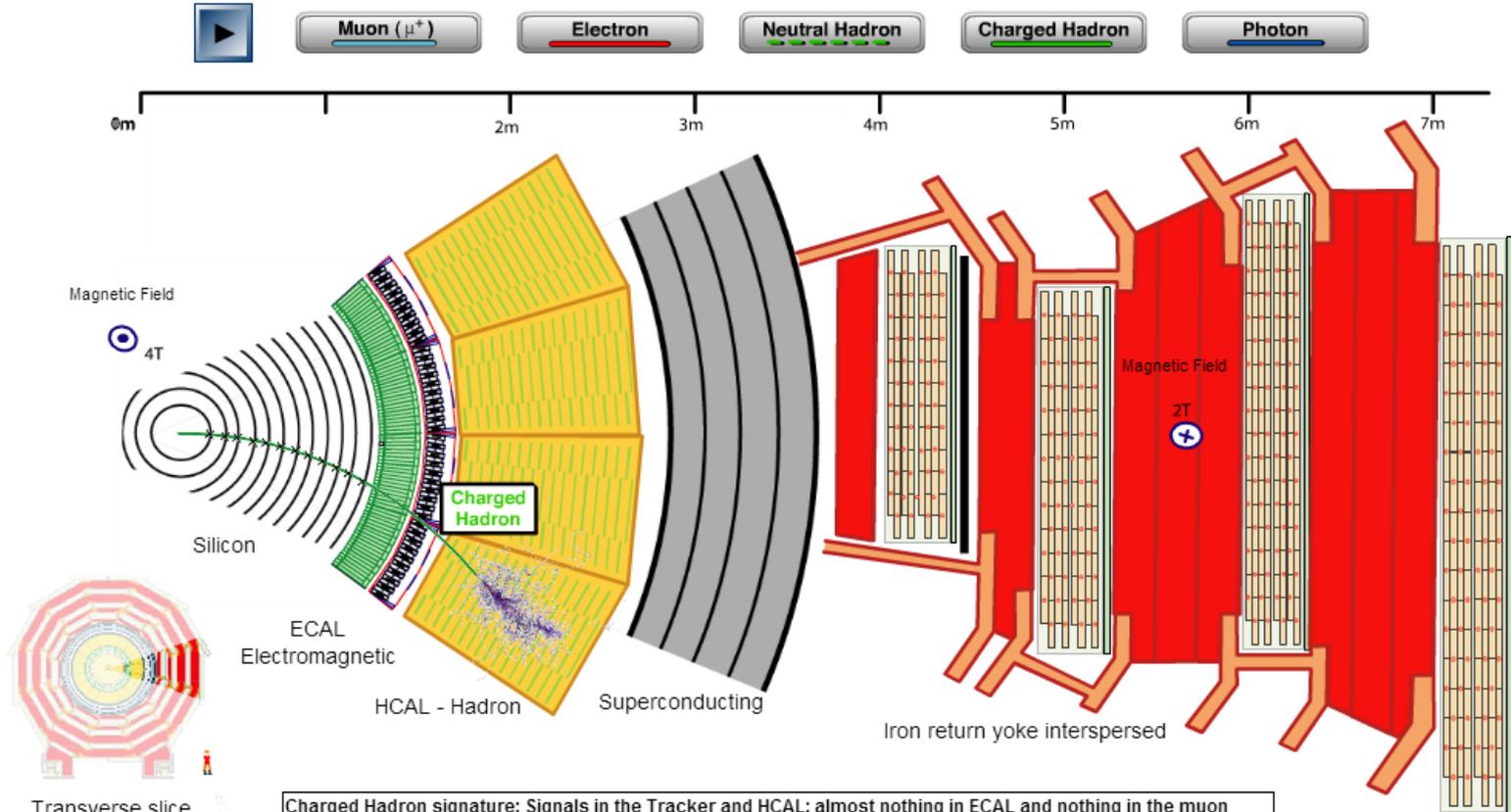
Transverse Slice of the Compact Muon Solenoid (CMS) Detector



D. Barney, CERN, 2004

# Identificando as partículas: prótão

Transverse Slice of the Compact Muon Solenoid (CMS) Detector

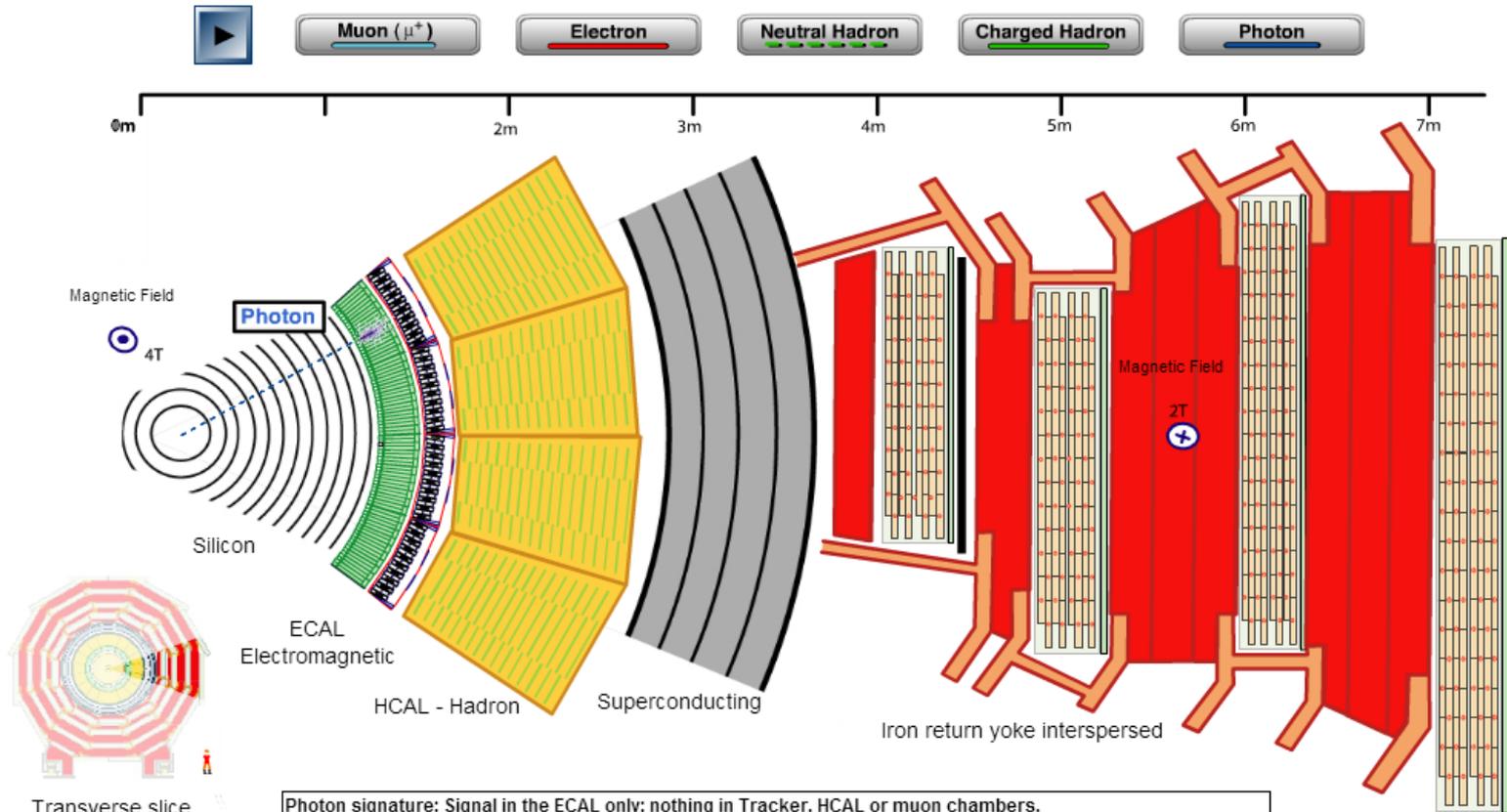


**Charged Hadron signature: Signals in the Tracker and HCAL; almost nothing in ECAL and nothing in the muon chambers.**  
 Charged hadrons, such as protons and pi plus or pi minus (made of pairs of quarks), are bent by the magnetic field and travel straight through the ECAL leaving almost no signals. Upon reaching the HCAL they are slowed to a stop by the dense materials, producing showers of secondary particles along the way that in turn produce light in thin layers of plastic **scintillator** material. The amount of light is proportional to the energy of the incoming hadron.

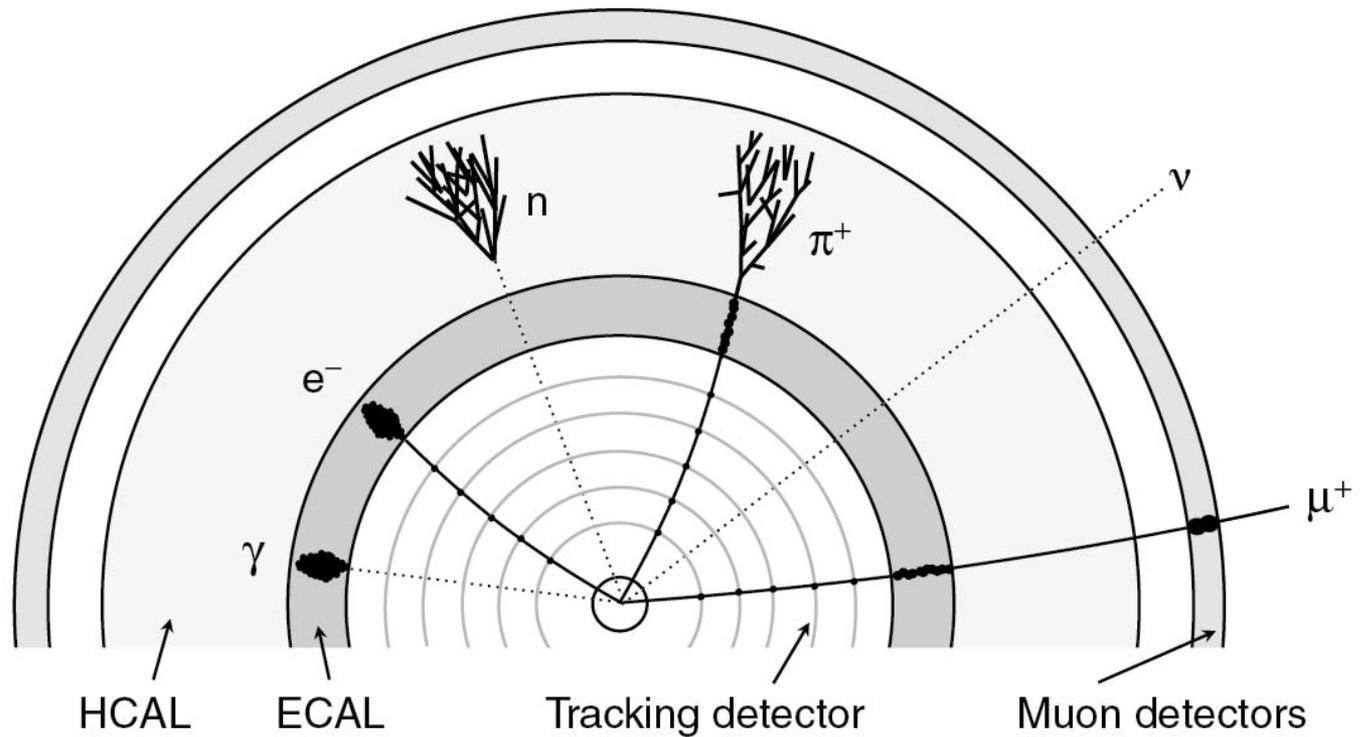
Derived from CMS Detector Slice from CERN

# Identificando as partículas: fóton

Transverse Slice of the Compact Muon Solenoid (CMS) Detector



**Photon signature: Signal in the ECAL only; nothing in Tracker, HCAL or muon chambers.**  
 Being electrically neutral, photons pass through the Tracker undetected and not bent by the magnetic field. They interact in the ECAL in a similar way to electrons, producing electromagnetic showers that leave their energies in the form of light that is detected.

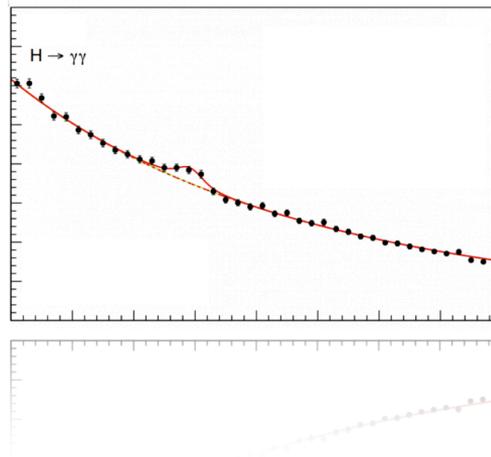


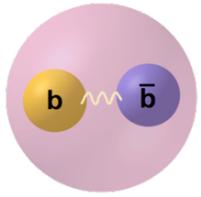
**calorímetros:** medem energia das partículas

**traçadores:** detectam trajectórias das partículas carregadas

**câmaras de muões:** os muões chegam às camadas exteriores

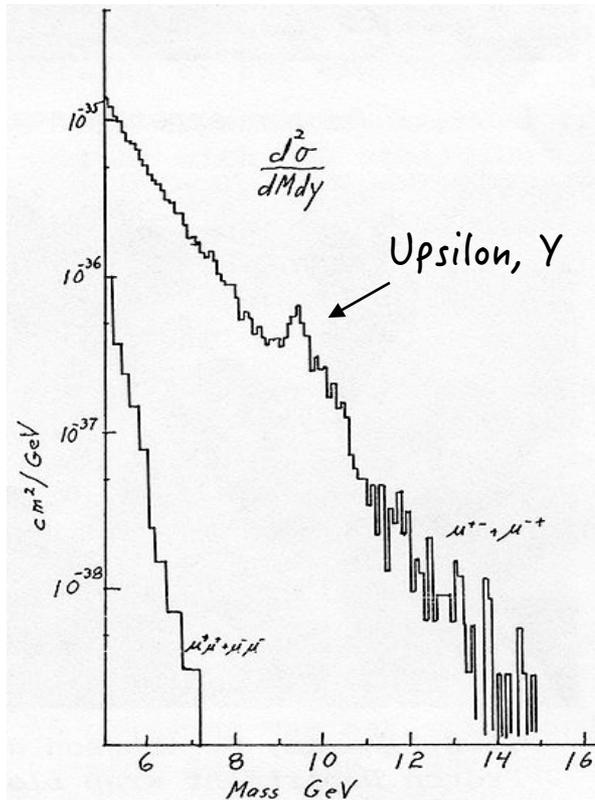
# Como é que “vemos” as partículas?





# a descoberta do SM

1977

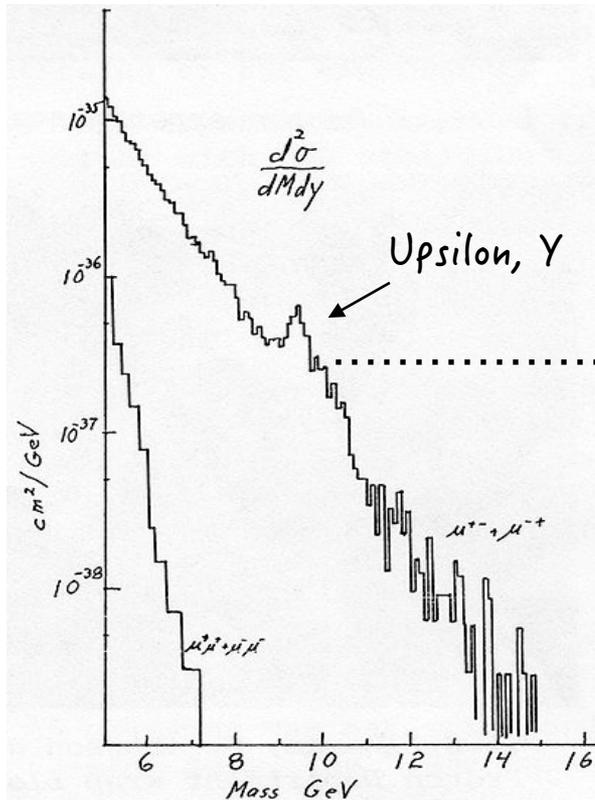


Υ, beauty

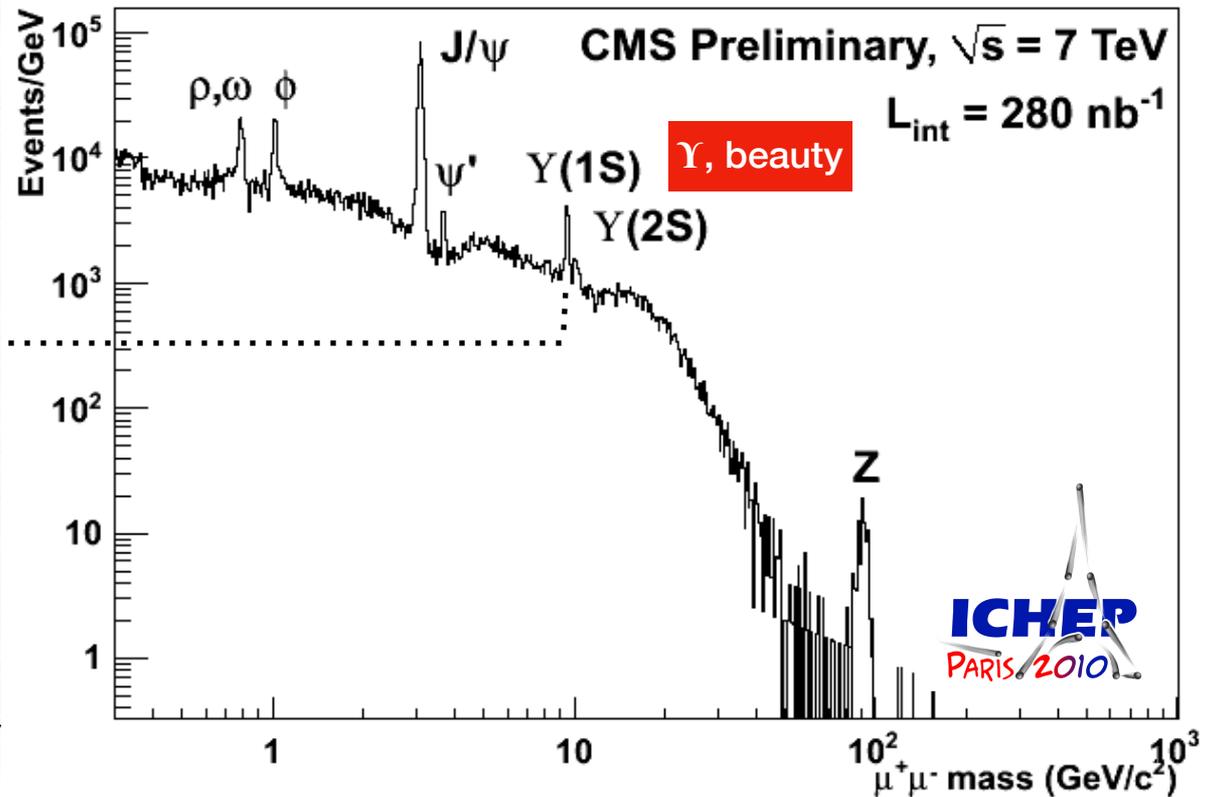
the discovery of the **b**  
quark

# a re-descoberta do SM @ LHC

1977

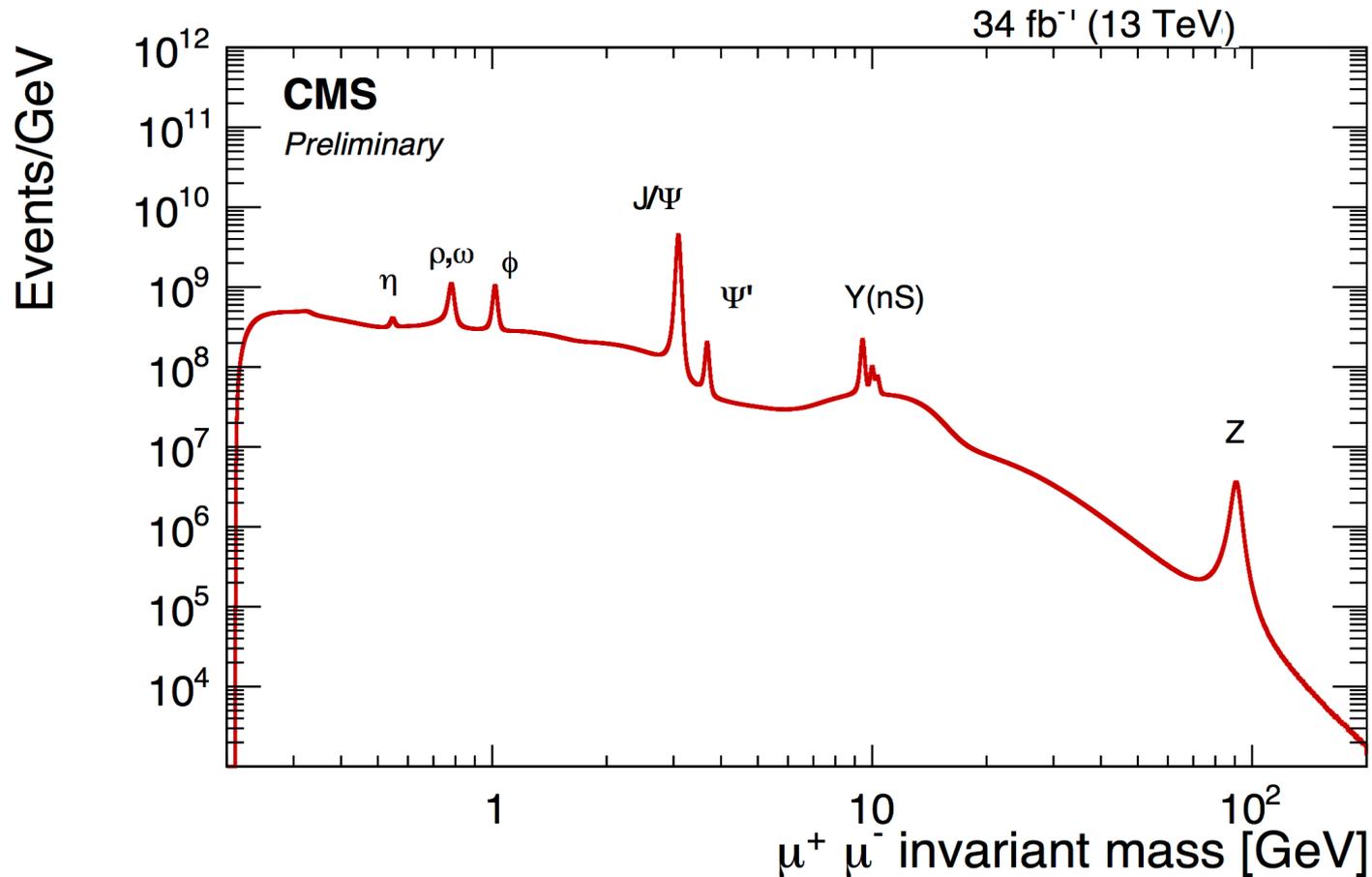


2010



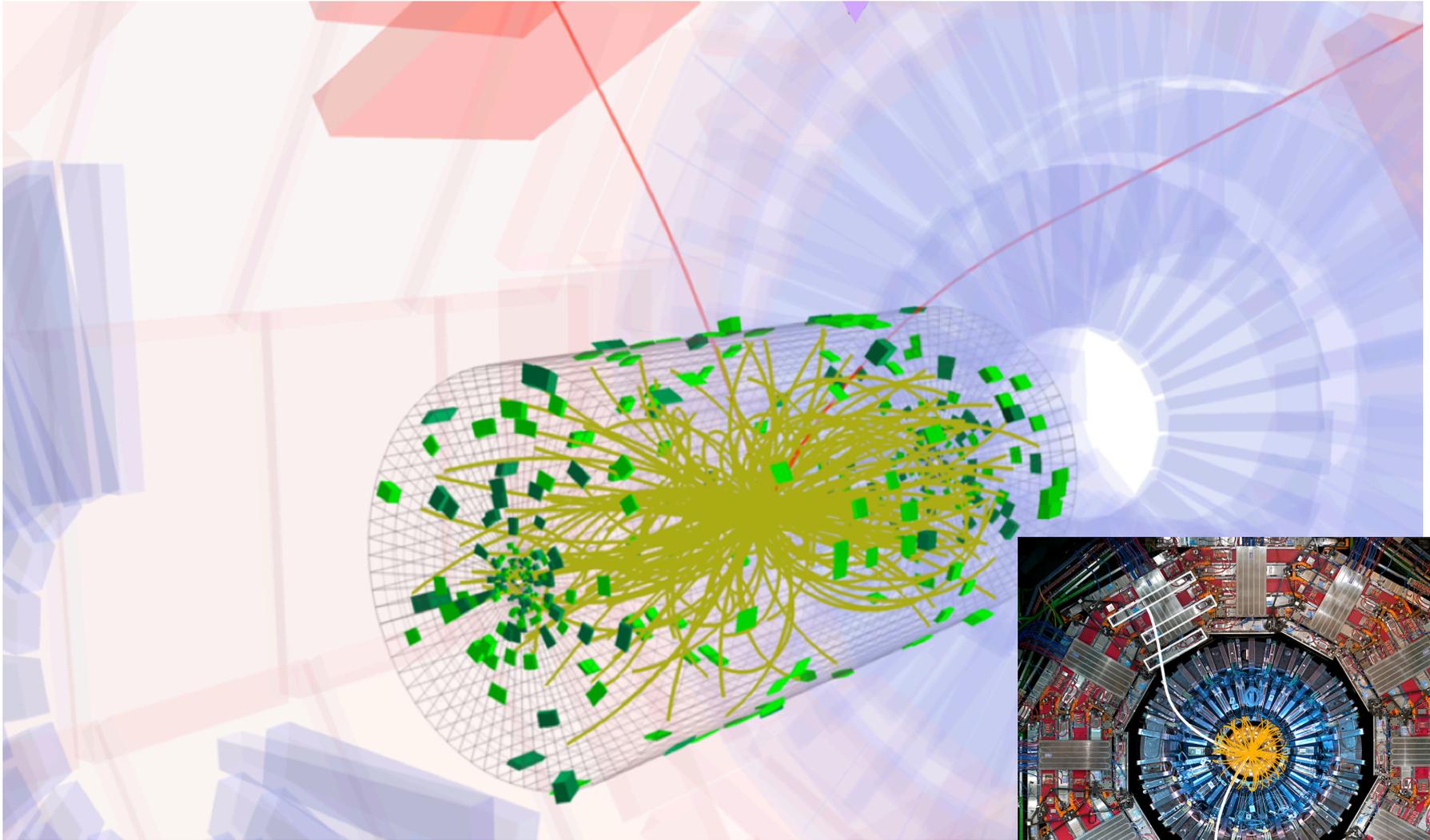
the discovery of the **b**  
quark

# a re-descoberta do SM @ LHC



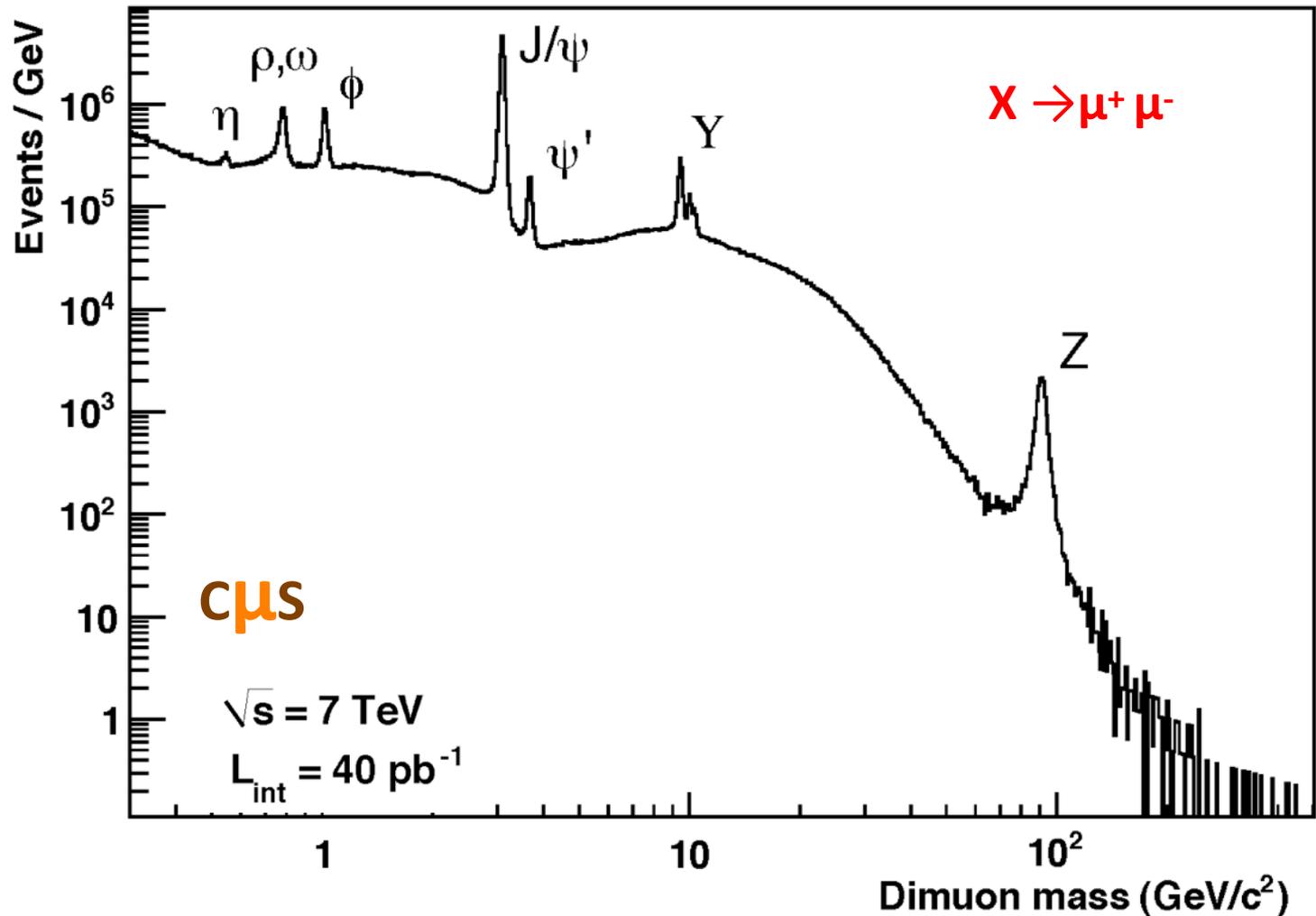
Decades worth of particle physics discovery ... in a single plot!

muão + anti-muão + (fundo)



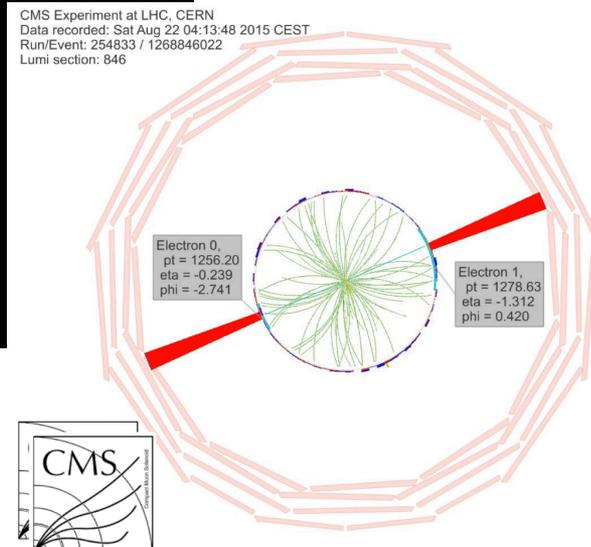
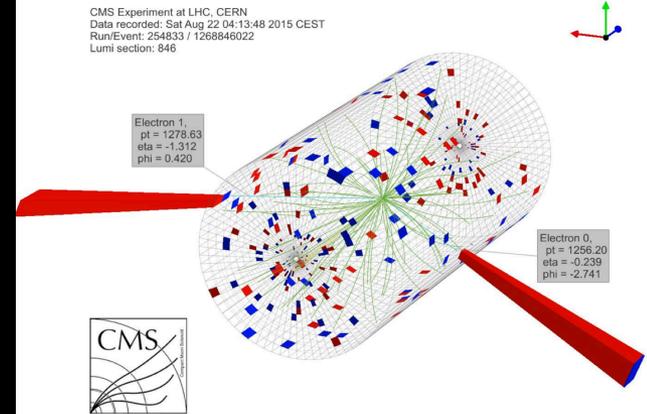
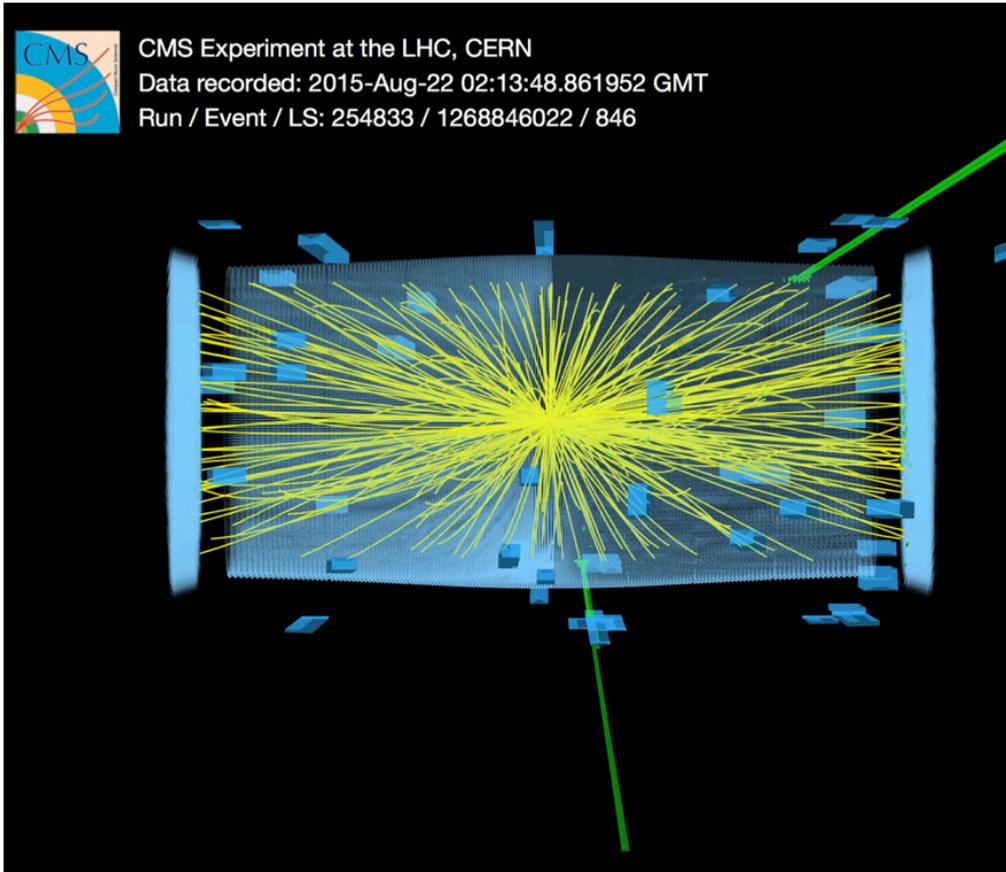
$X \rightarrow \mu^+ \mu^-$

# o espectro de massa $\mu^+\mu^-$

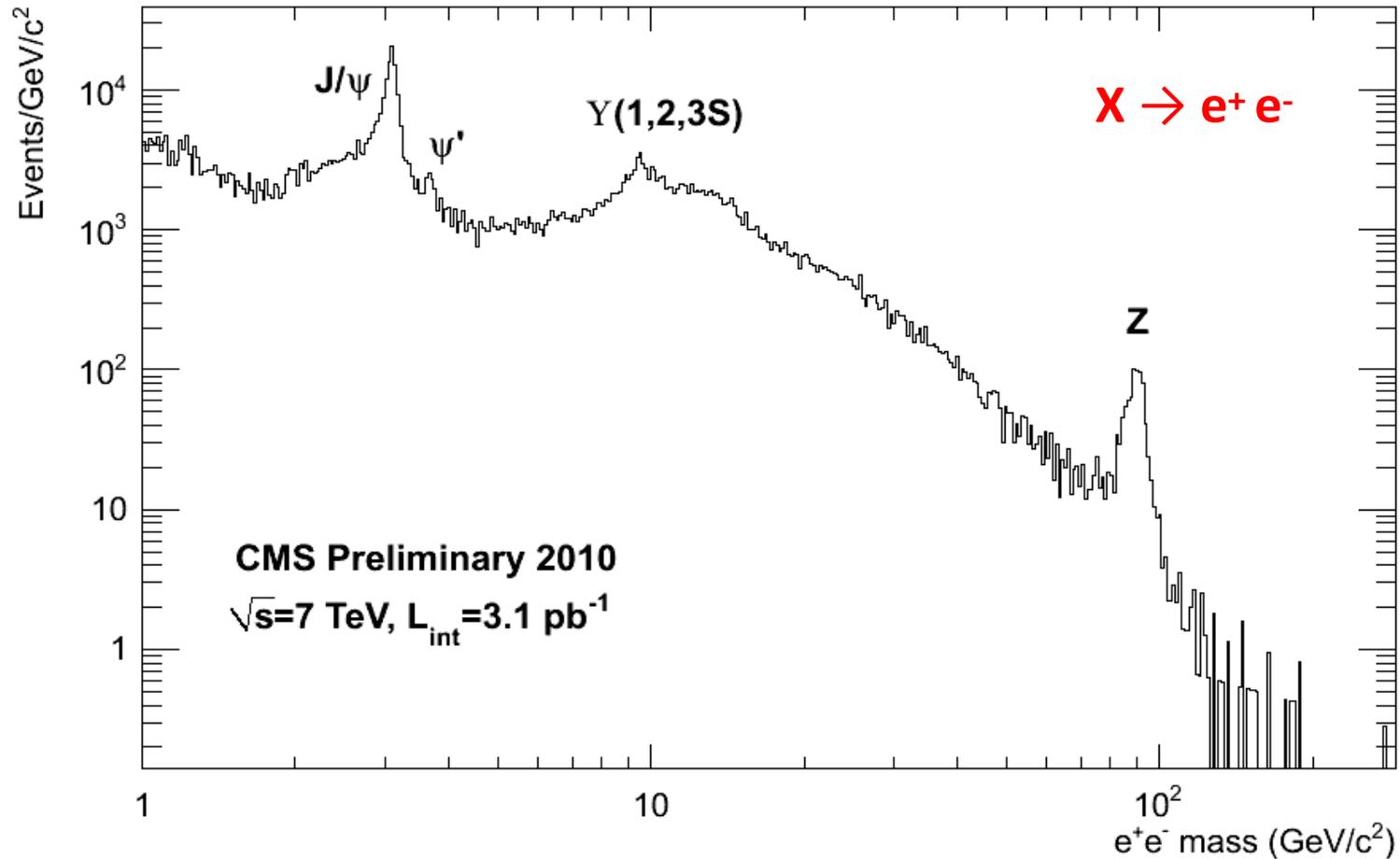


A re-descoberta do Modelo Padrão, 2010 (primeiros dados do LHC)

# electrão + positrão + (fundo)



# o espectro de massa $e^+e^-$



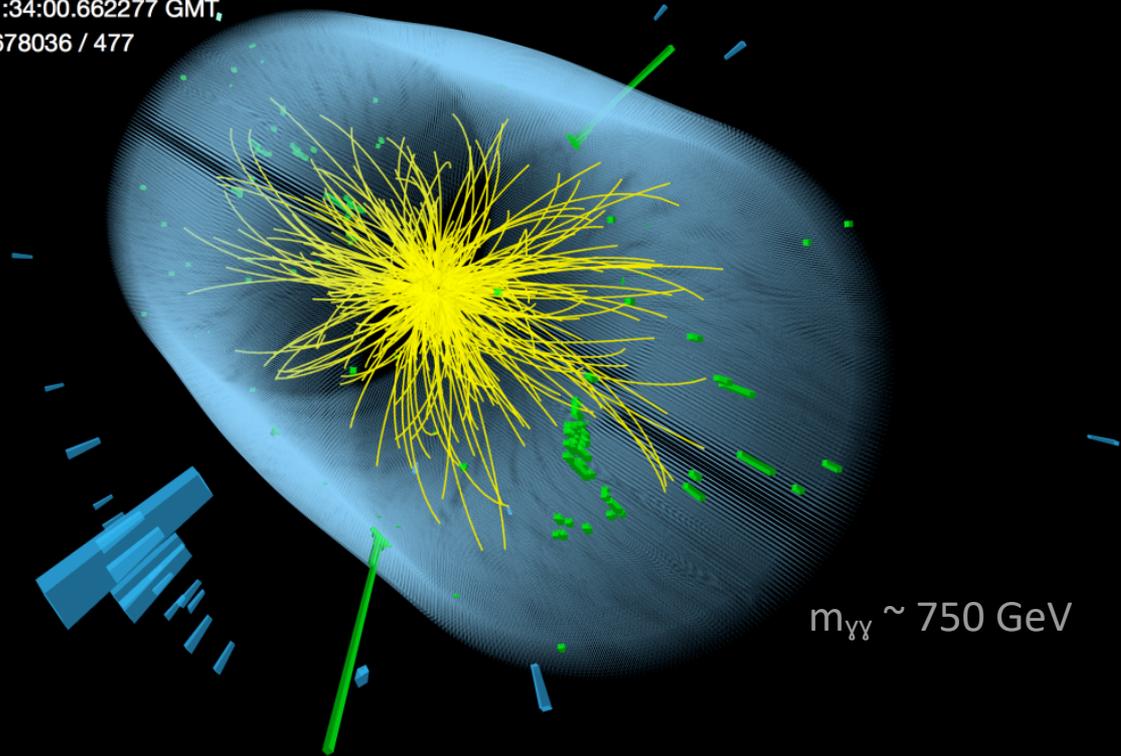
# Dois fotões + (fundo)



CMS Experiment at the LHC, CERN

Data recorded: 2015-Nov-02 21:34:00.662277 GMT,

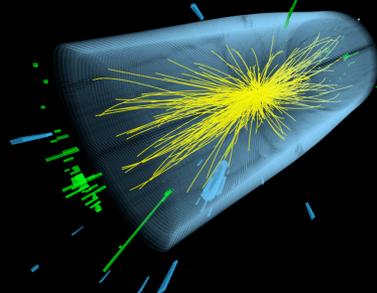
Run / Event / LS: 260627 / 854678036 / 477



CMS Experiment at the LHC, CERN

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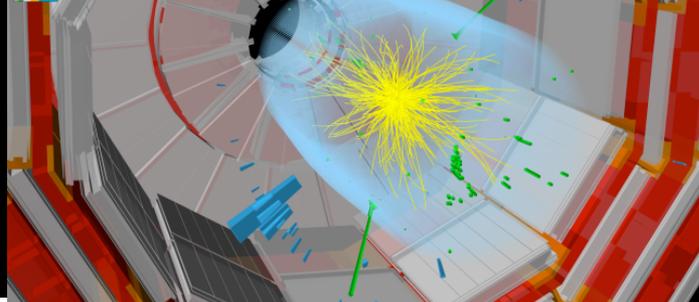
Run / Event / LS: 260627 / 854678036 / 477



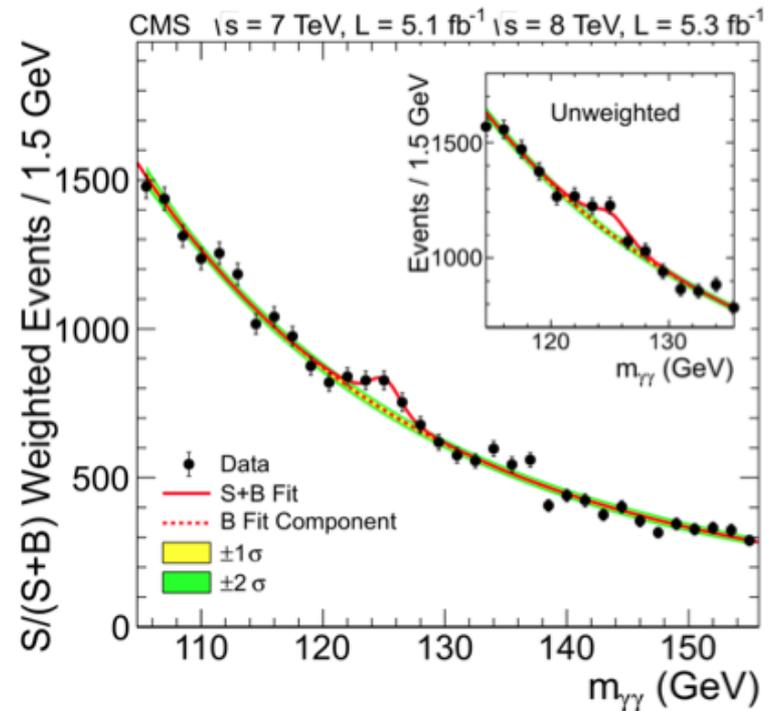
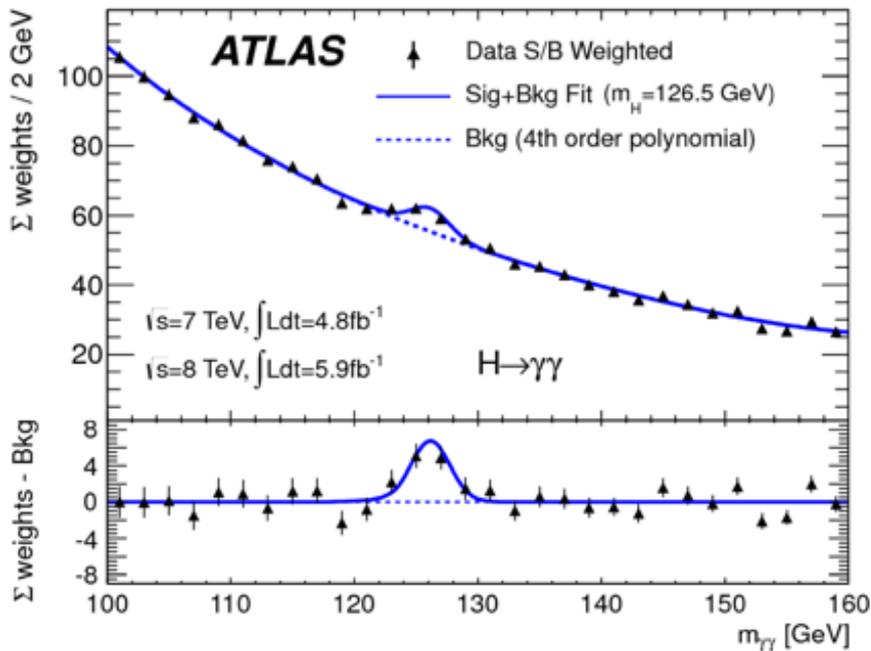
CMS Experiment at the LHC, CERN

Data recorded: 2015-Nov-02 21:34:00.662277 GMT

Run / Event / LS: 260627 / 854678036 / 477



# o espectro de massa de dois fótons

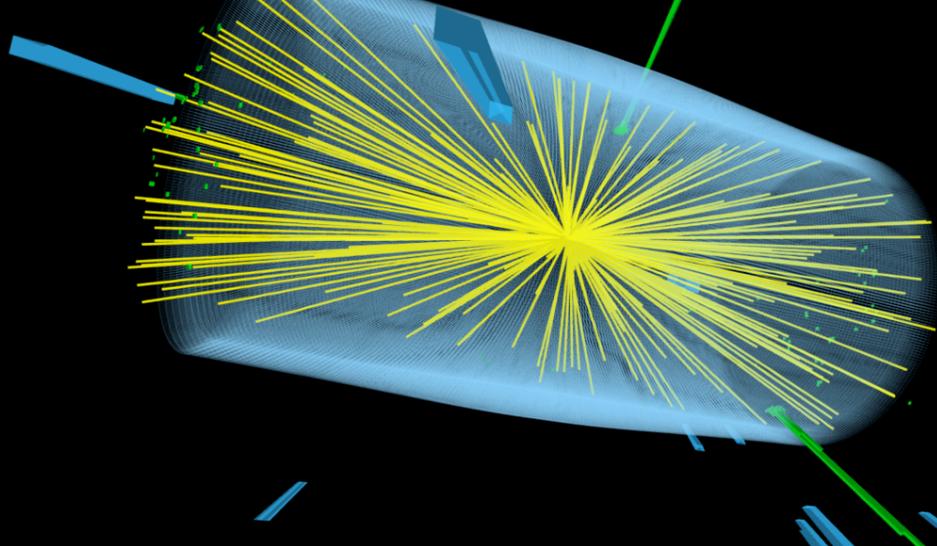


Um exemplo famoso: a descoberta do bóson de Higgs no LHC

Higgs → fóton + fóton

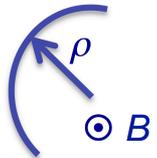
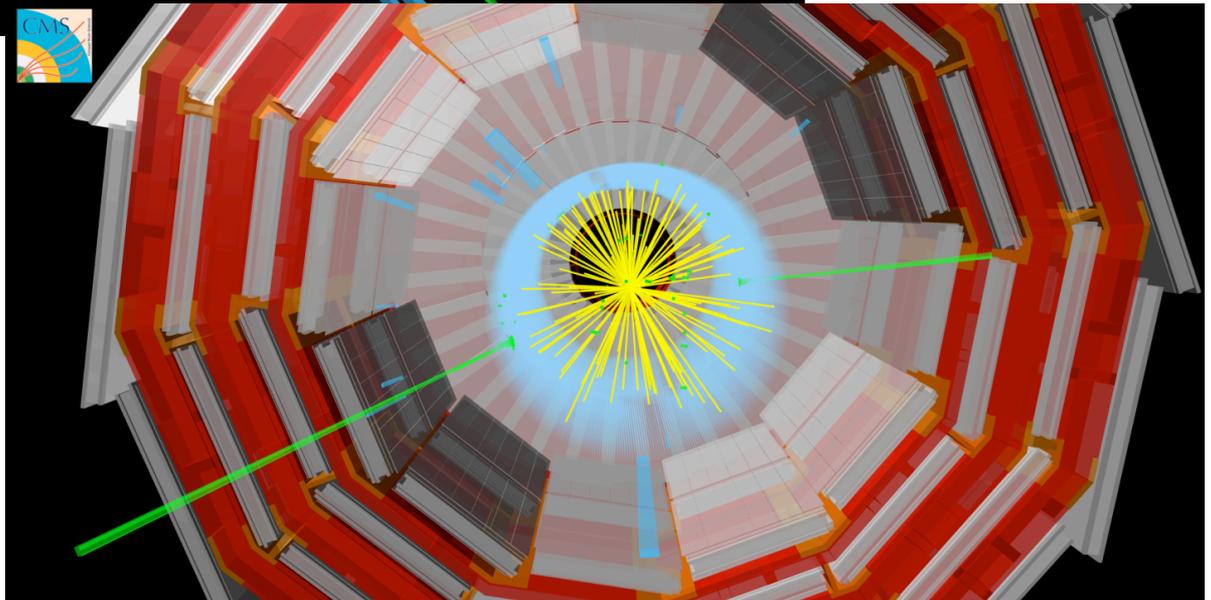
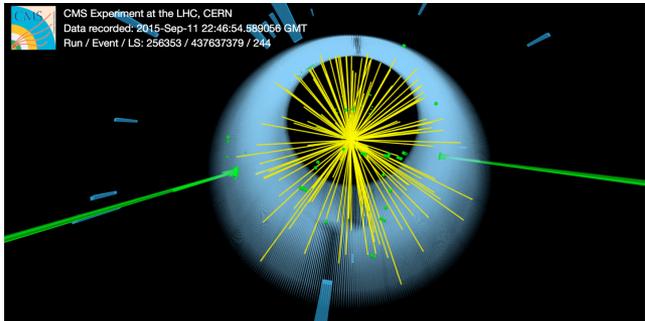


CMS Experiment at the LHC, CERN  
 Data recorded: 2015-Oct-27 11:51:17.472320 GMT  
 Run / Event / LS: 260043 / 994191540 / 754



?

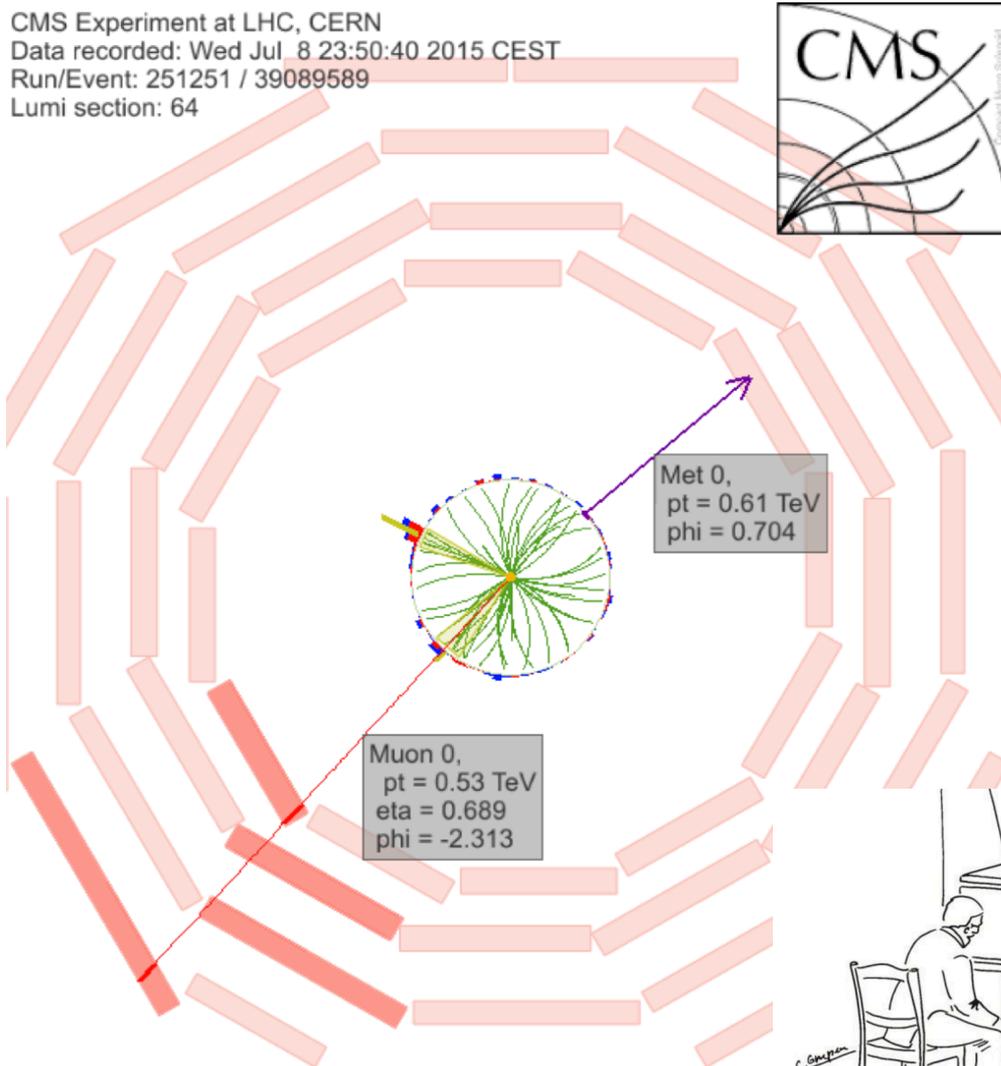
$m_{??} \sim 700 - 800 \text{ GeV}$



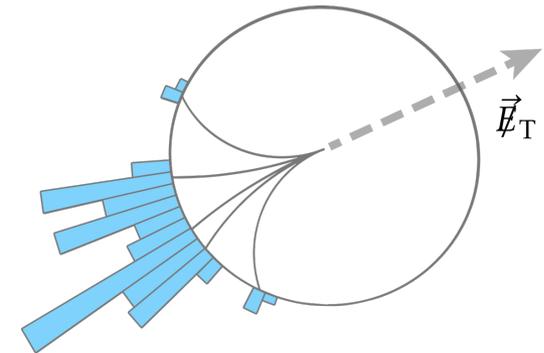
$$\rho = \frac{p}{ZeB}$$

# muão + energia-em-falta + (fundo)

CMS Experiment at LHC, CERN  
Data recorded: Wed Jul 8 23:50:40 2015 CEST  
Run/Event: 251251 / 39089589  
Lumi section: 64



• mas ... e os **Neutrinos**?

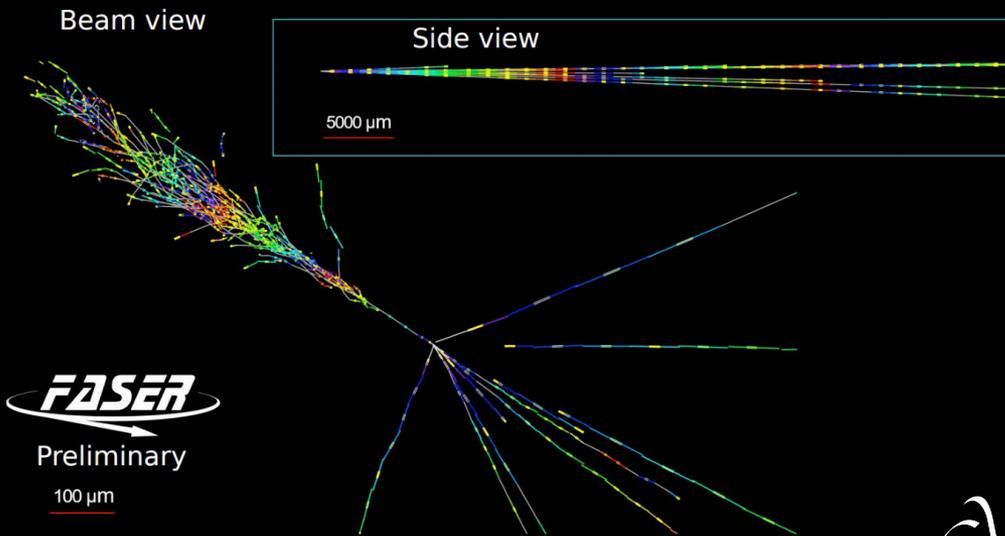
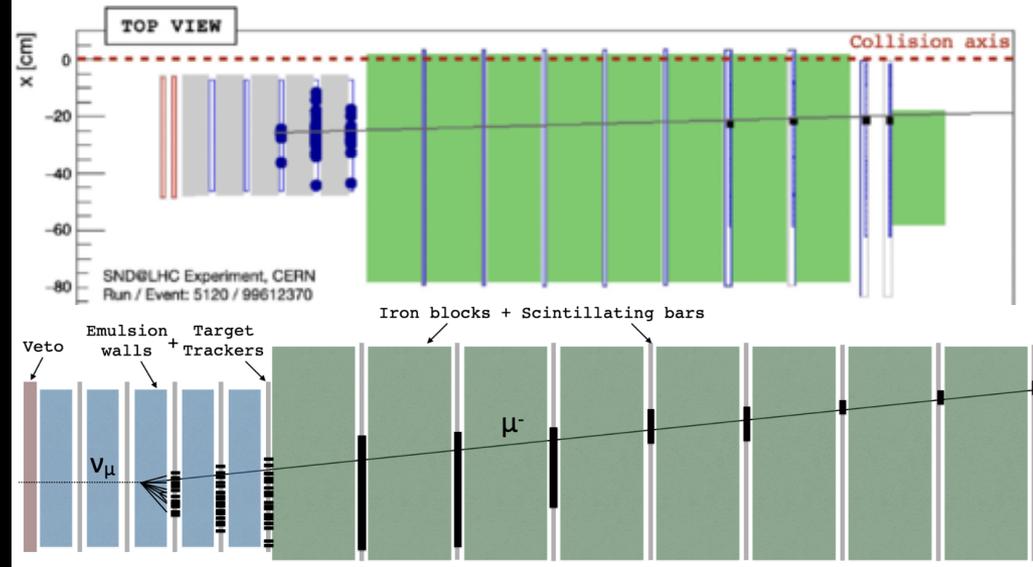


- os neutrinos atravessam os detectores sem interagirem
- a sua presença pode ser apenas revelada por **energia-em-falta**



“Did you see it?”  
“No nothing.”  
“Then it was a neutrino!”

# (extra) primeira observação de neutrinos no @LHC in 2023



**FASER**  
Preliminary  
100 μm

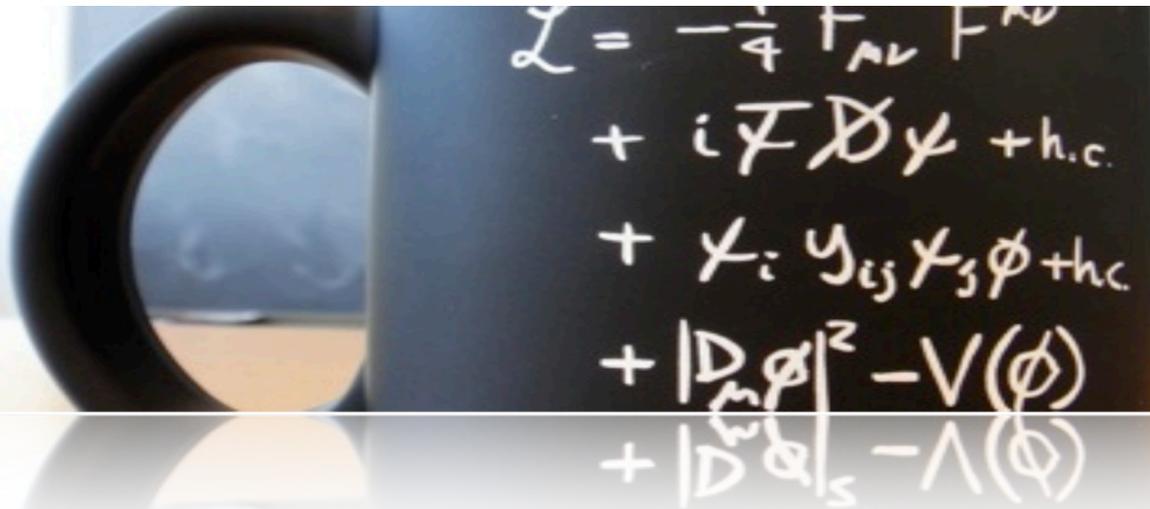


Scattering and Neutrino Detector at the LHC

SND@LHC

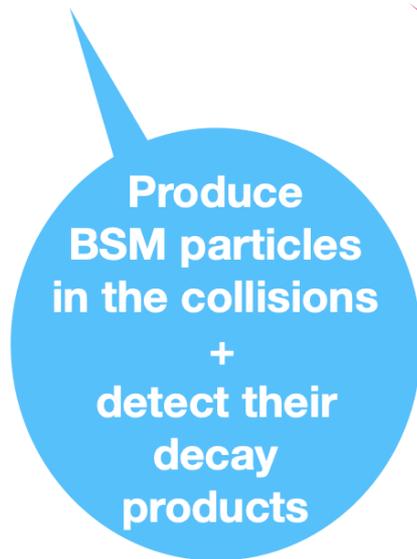


# A física

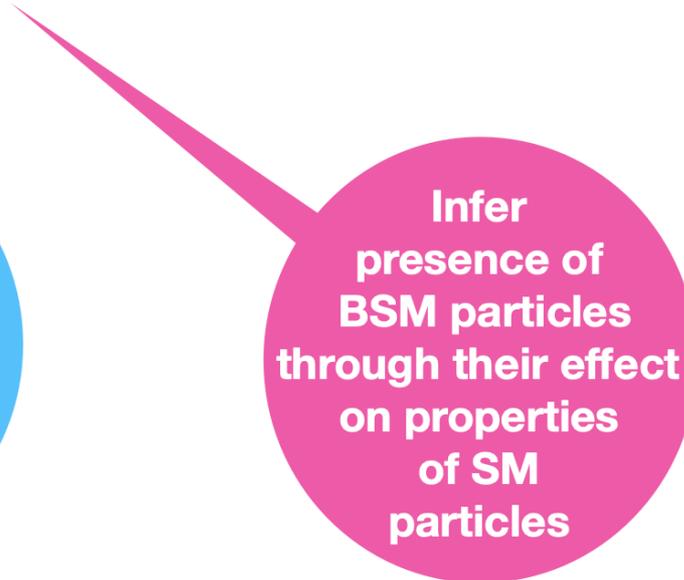

$$\begin{aligned}\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i\bar{\psi} \not{D} \psi + \text{h.c.} \\ & + \chi_i Y_{ij} \chi_j \phi + \text{h.c.} \\ & + |D_\mu \phi|^2 - V(\phi) \\ & + |D_\mu \chi_i|^2 - \Lambda(\chi_i)\end{aligned}$$

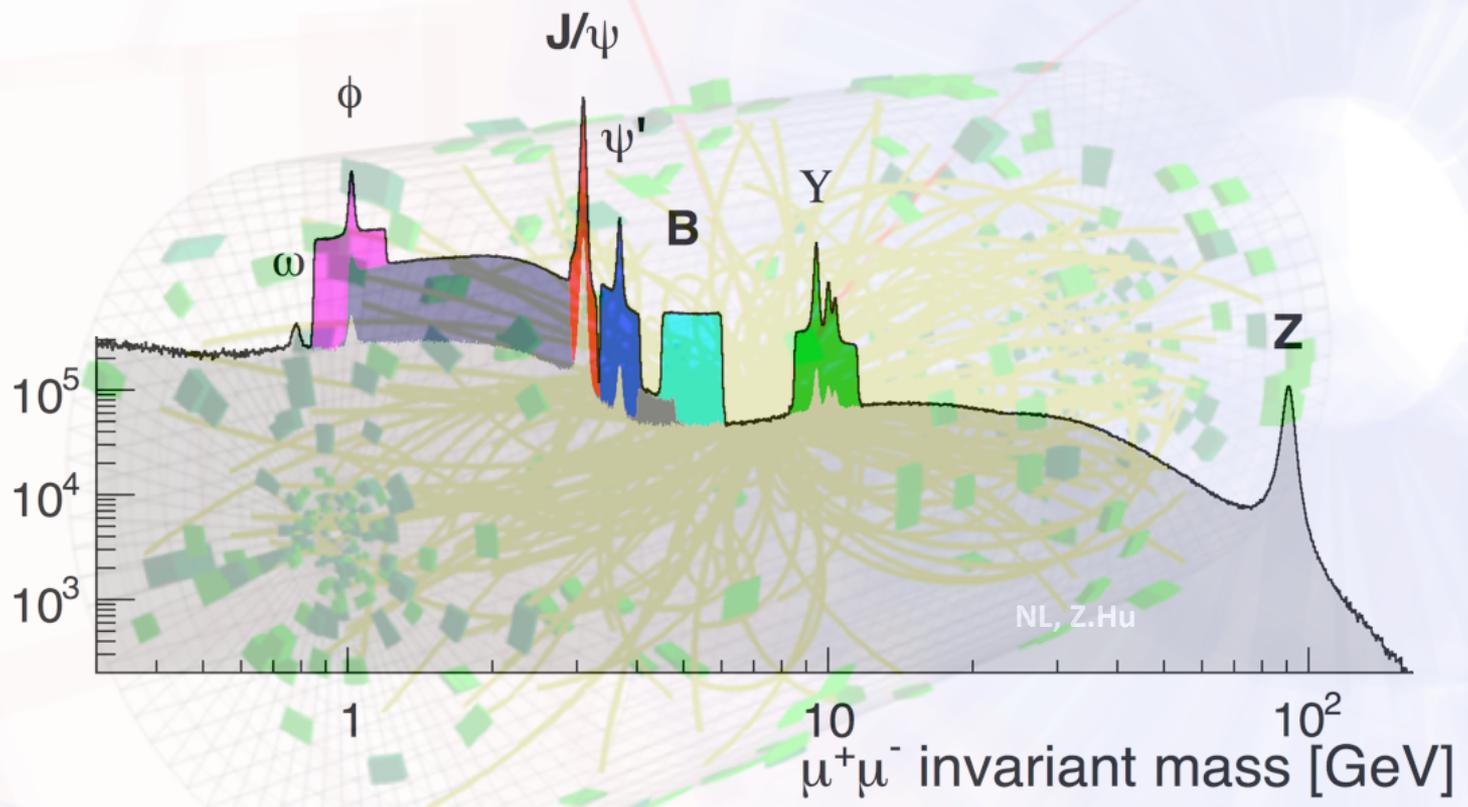
# Physics goals at the LHC?

- Test the Standard Model (SM)
  - Precision measurements + rare processes
- Find physics beyond the Standard Model (BSM)
  - Direct and indirect searches for new particles

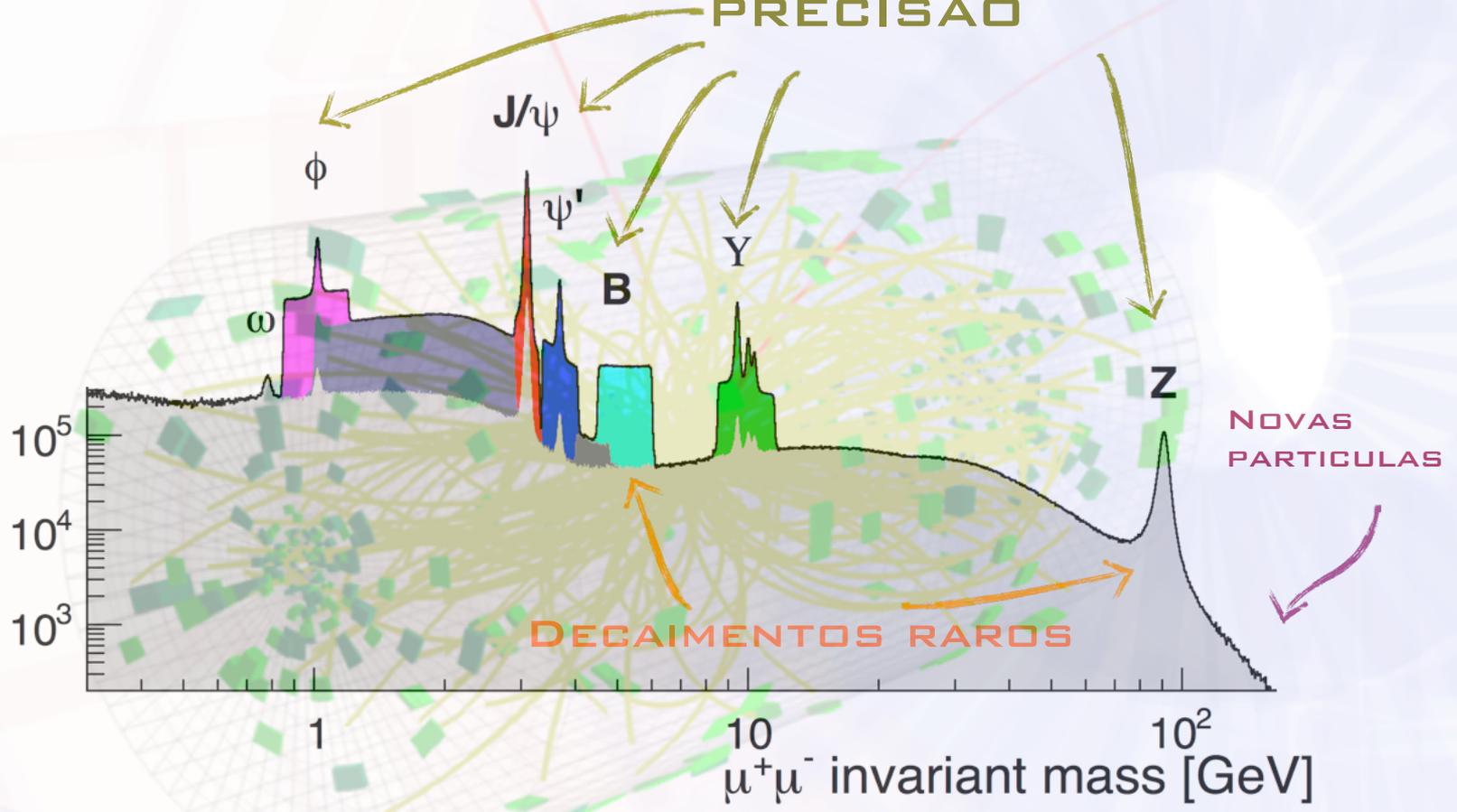


*ie "a la Higgs"*

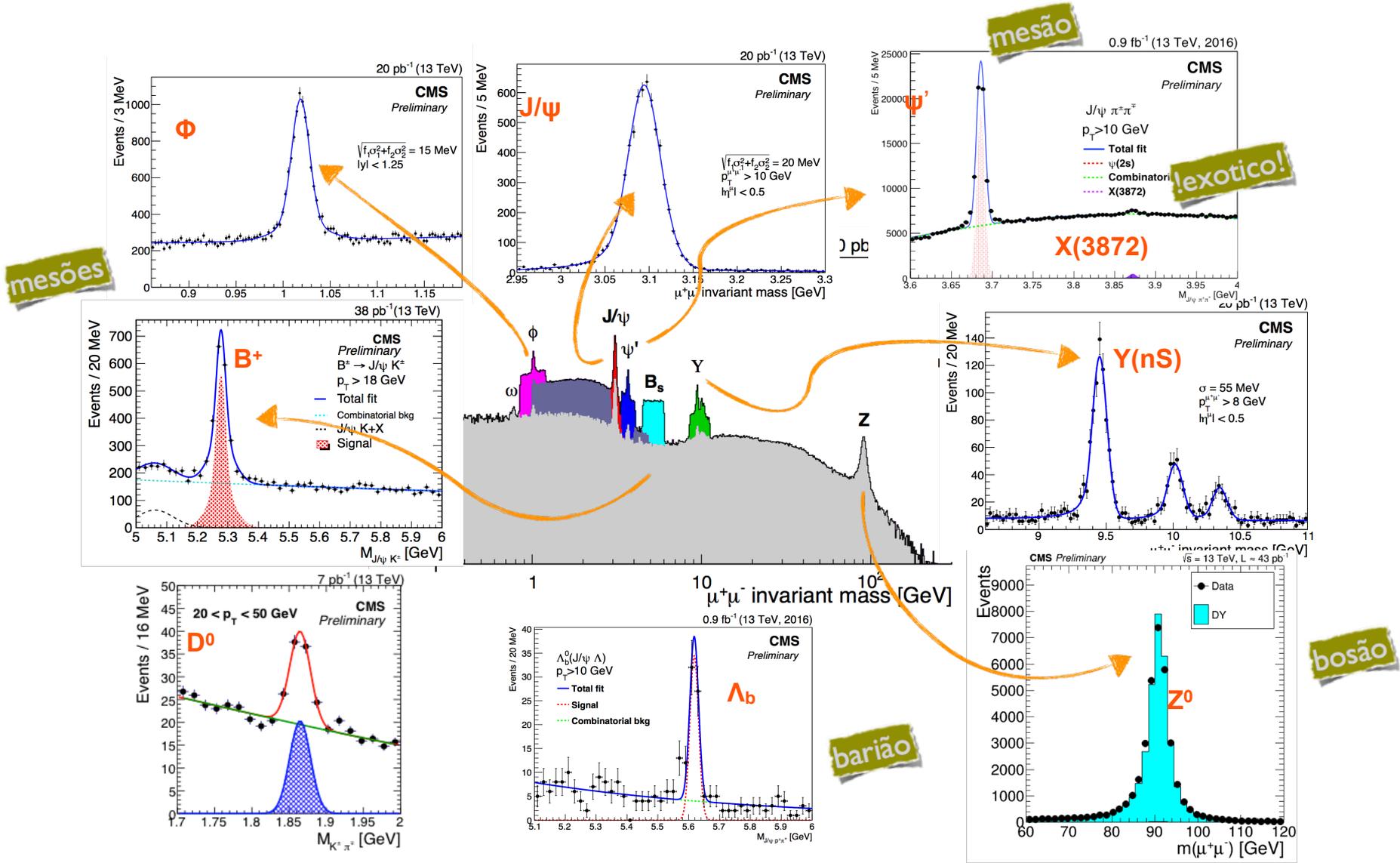




# MEDIDAS DE PRECISÃO

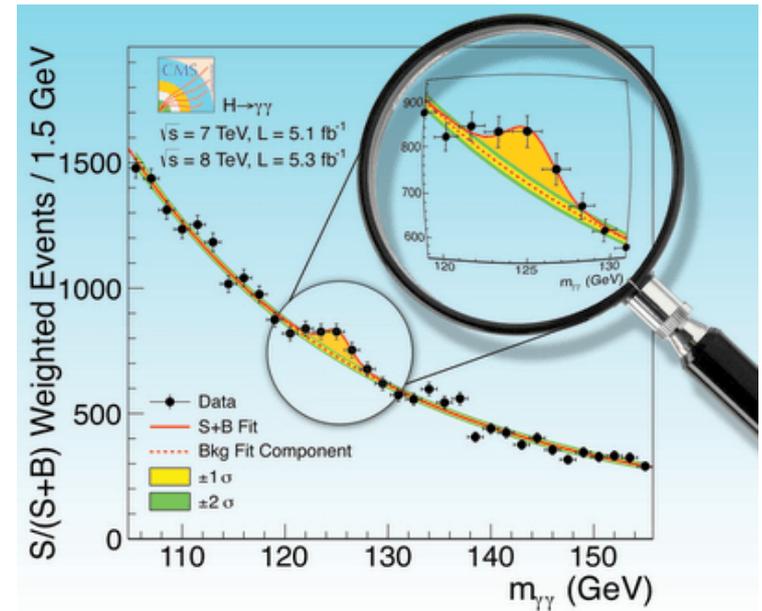
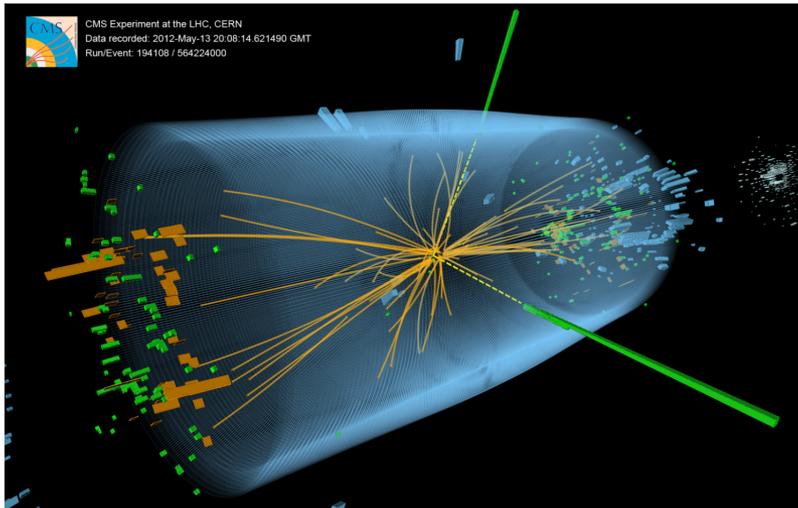


# Medidas de precisão



# Novas partículas descobertas no LHC?

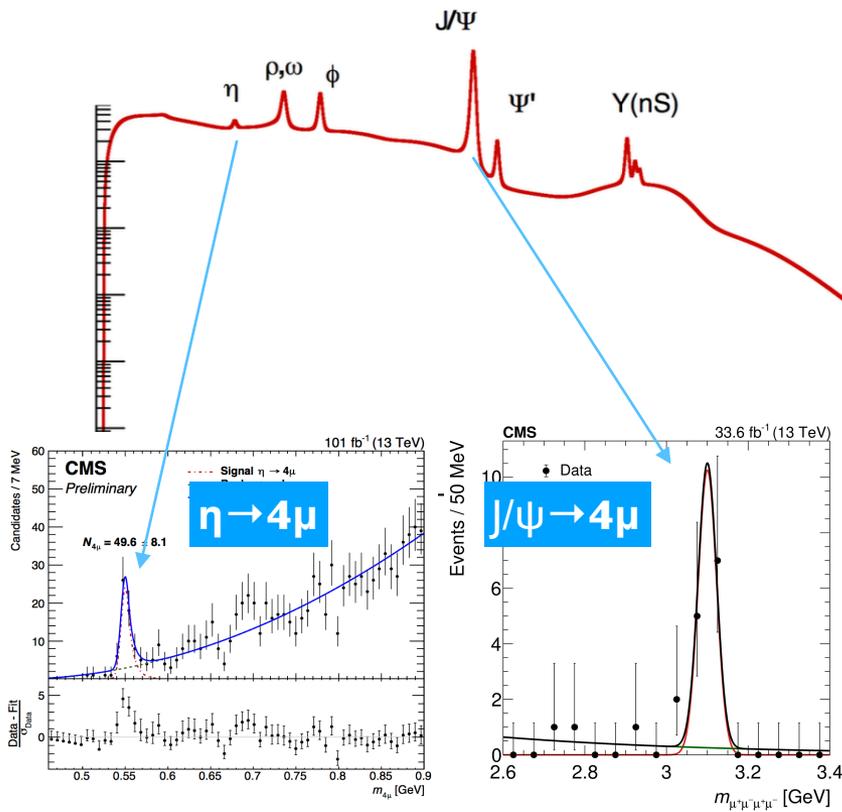
# Novas partículas descobertas no LHC?



... e para além do bóson de Higgs?

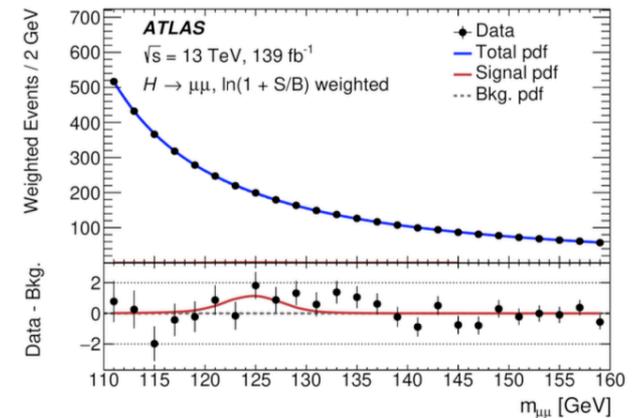
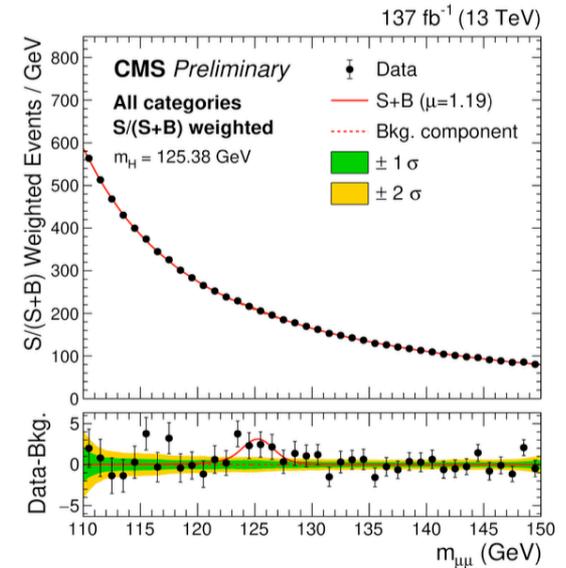
# Novas partículas descobertas no LHC?

## interações



evidence for

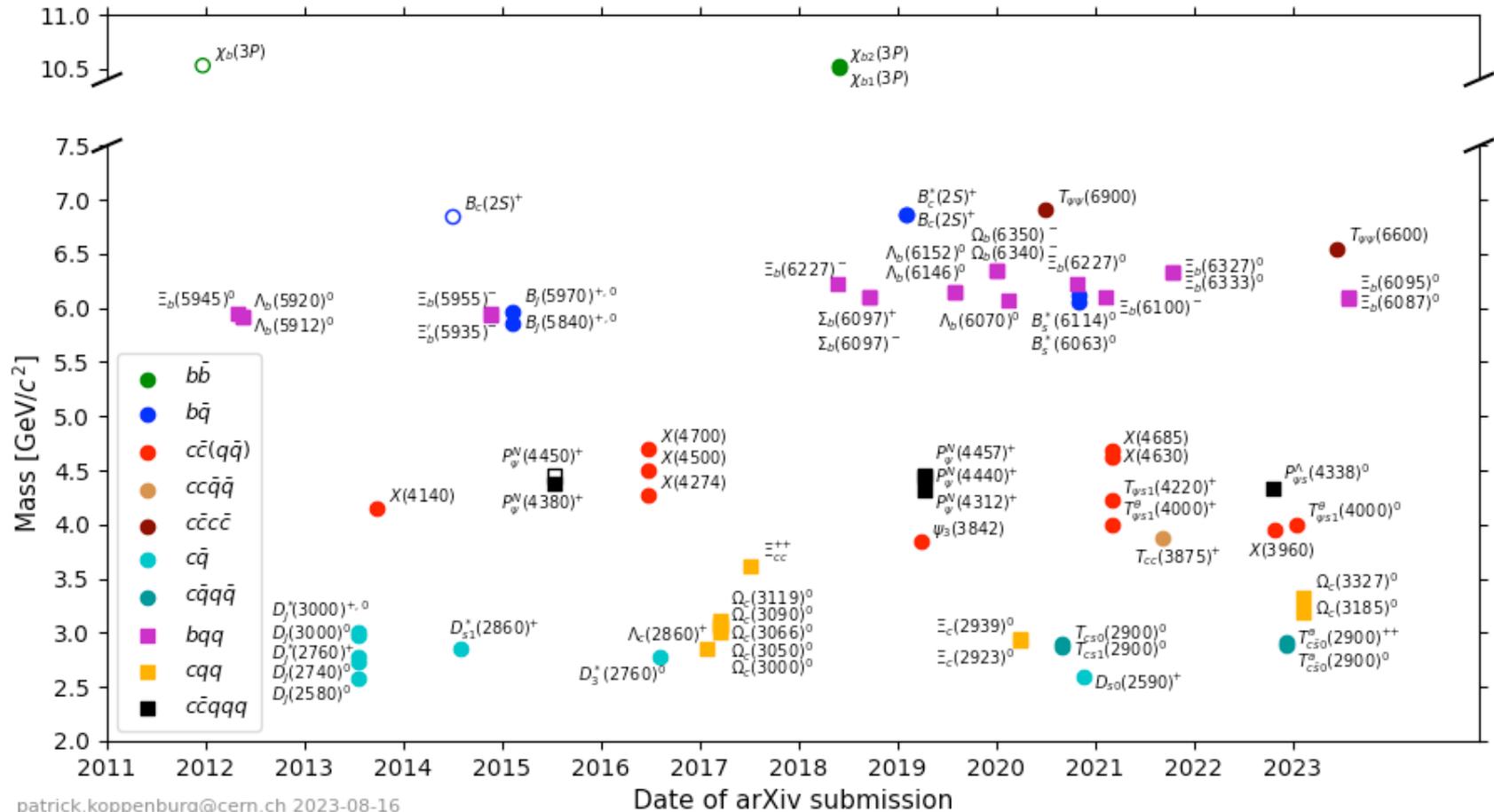
$H \rightarrow \mu\mu$



$10^2$   
nass [GeV]

Observação de novos decaimentos (raros!!!) de partículas já conhecidas

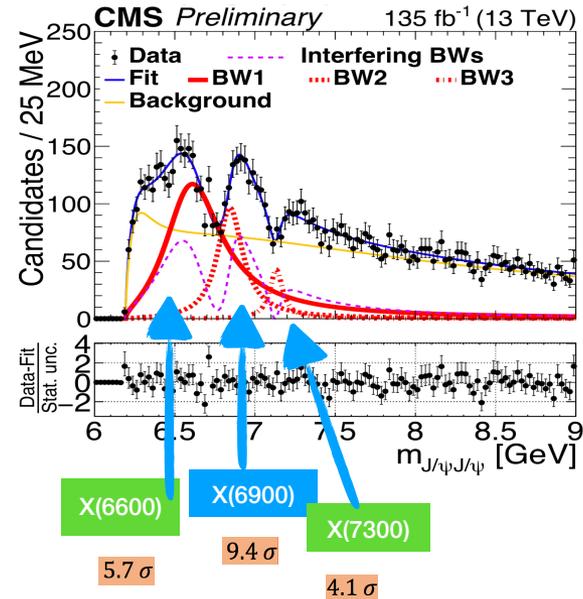
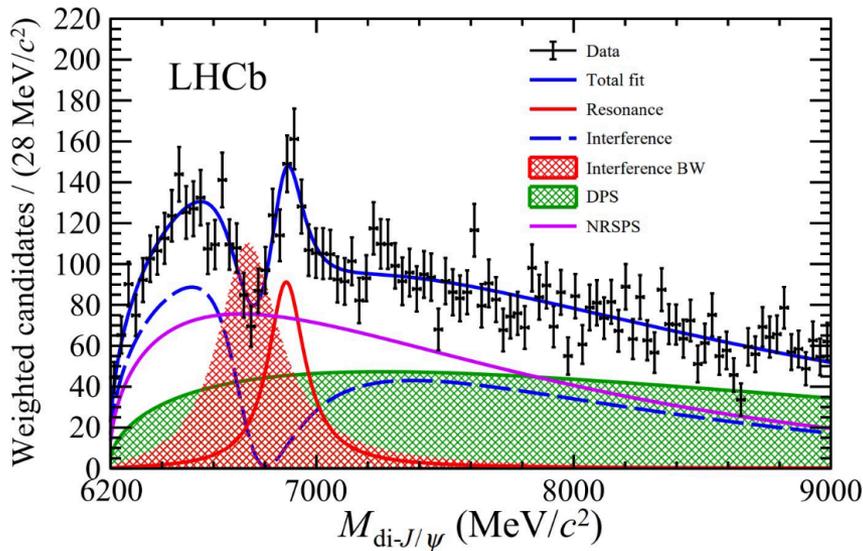
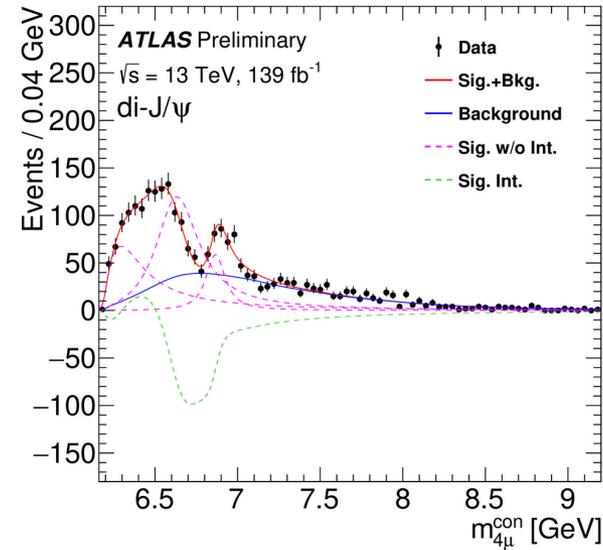
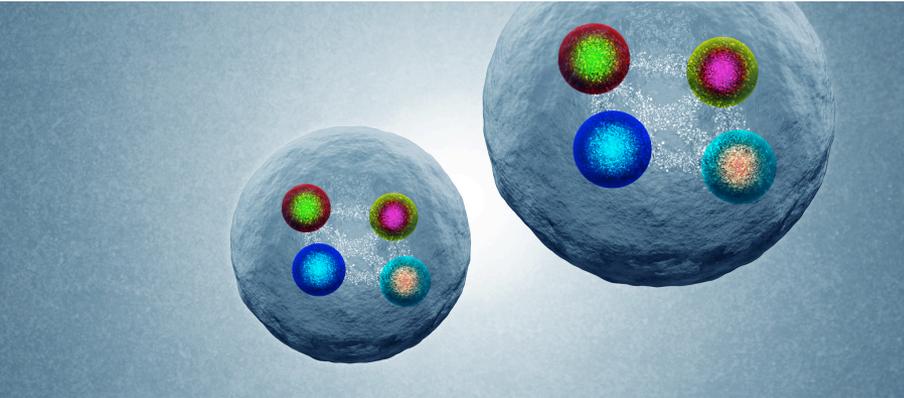
# Novas partículas descobertas no LHC?



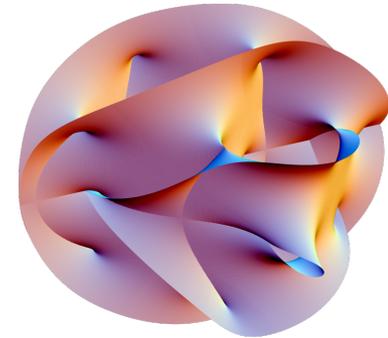
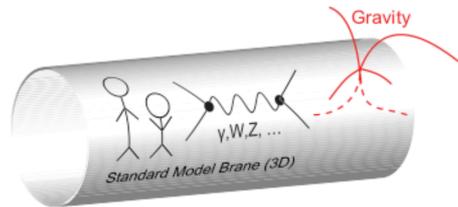
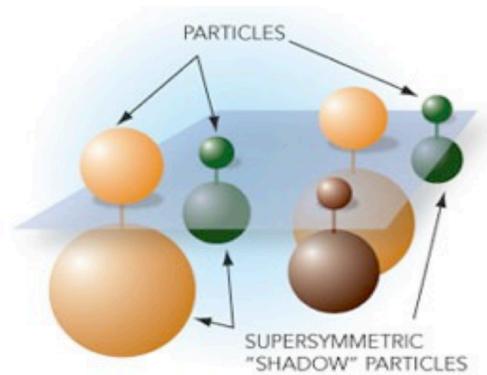
72+1 novas partículas já descobertas! — e mais estão à espera para serem descobertas !

# Novas partículas descobertas no LHC?

um tetraquark formado de quarks pesados!

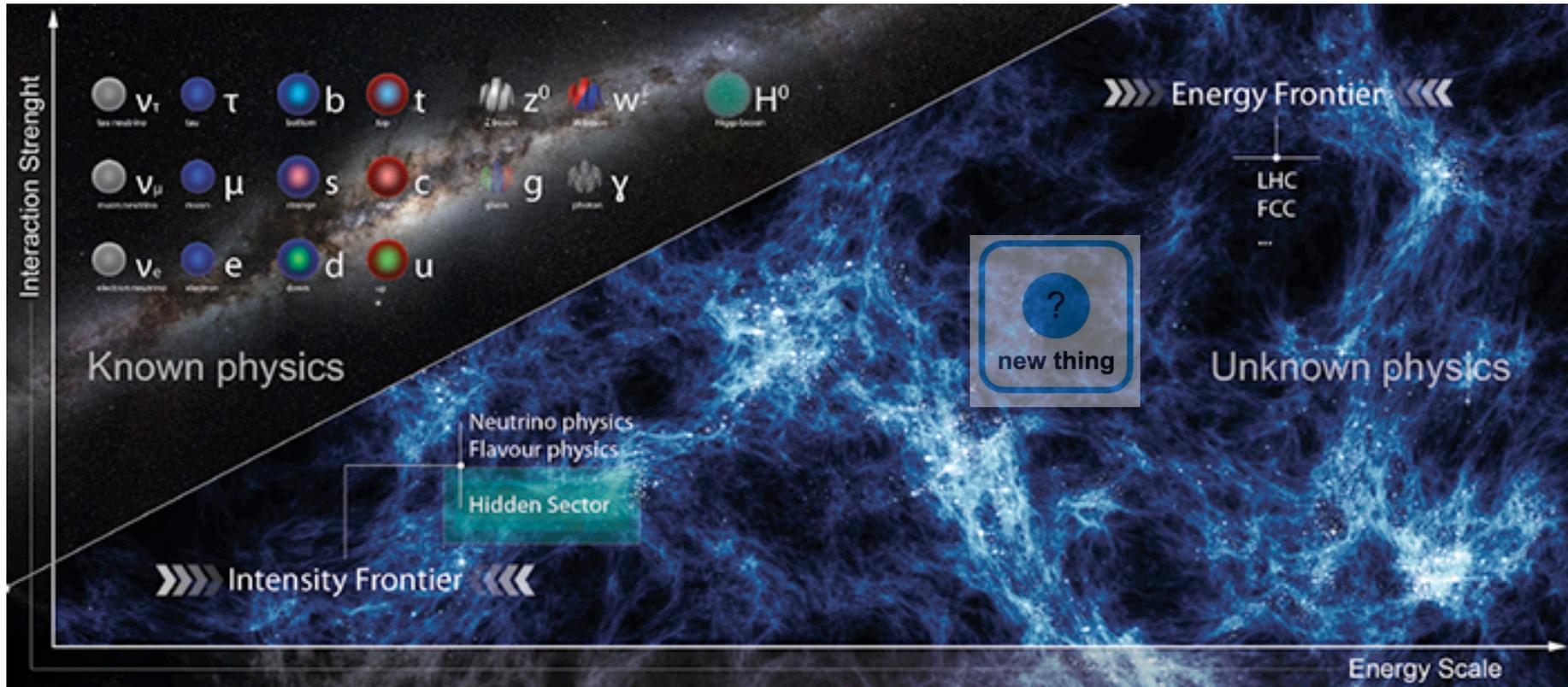


# Para além do MP



# Para além do Modelo Padrão

energy frontier 

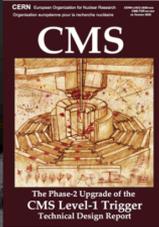


intensity frontier 

Beam intensity: high luminosity 

Beam energy:  $\sqrt{s}$  

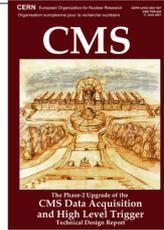
# O HL-LHC requer um 'novo' detector CMS



## L1-Trigger

<https://cds.cern.ch/record/2714892>

- Tracks in L1-Trigger at 40 MHz
- Particle Flow selection
- 750 kHz L1 output
- 40 MHz data scouting



## DAQ & High-Level Trigger

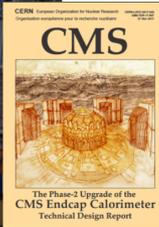
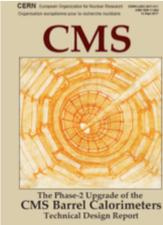
<https://cds.cern.ch/record/2759072>

- Full optical readout
- Heterogenous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

## Barrel Calorimeters

<https://cds.cern.ch/record/2283187>

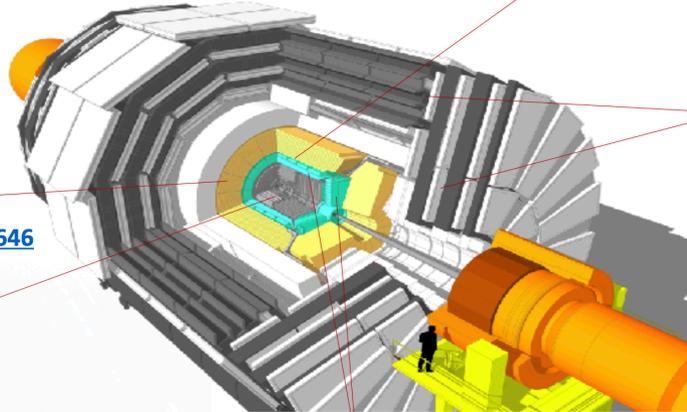
- ECAL crystal granularity readout at 40 MHz with precise timing for  $e/\gamma$  at 30 GeV
- ECAL and HCAL new Back-End boards



## Calorimeter Endcap

<https://cds.cern.ch/record/2293646>

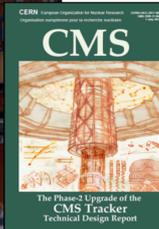
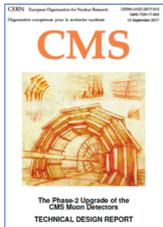
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS



## Muon systems

<https://cds.cern.ch/record/2283189>

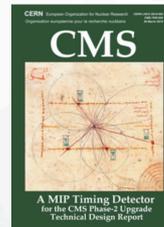
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC  $1.6 < \eta < 2.4$
- Extended coverage to  $\eta \approx 3$



## Tracker

<https://cds.cern.ch/record/2272264>

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to  $\eta \approx 3.8$



## MIP Timing Detector

<https://cds.cern.ch/record/2667167>

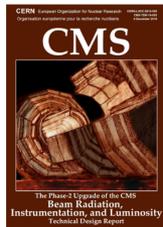
Precision timing with:

- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

## Beam Radiation Instr. and Luminosity

<http://cds.cern.ch/record/2759074>

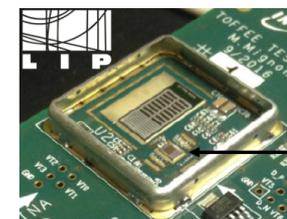
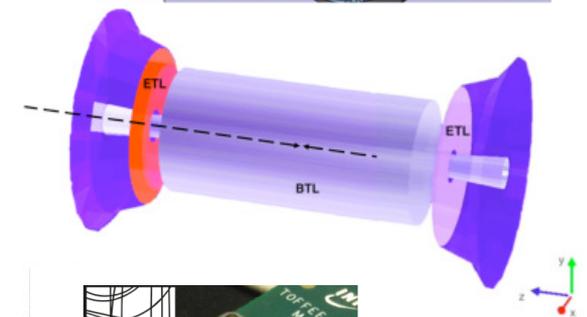
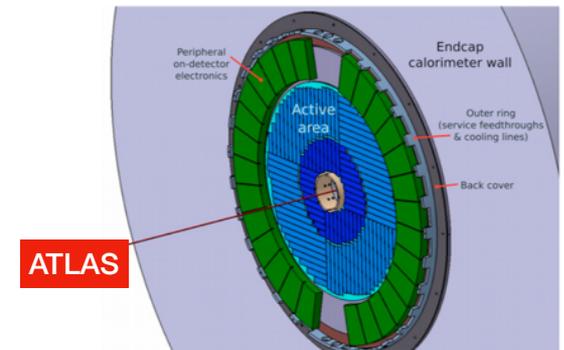
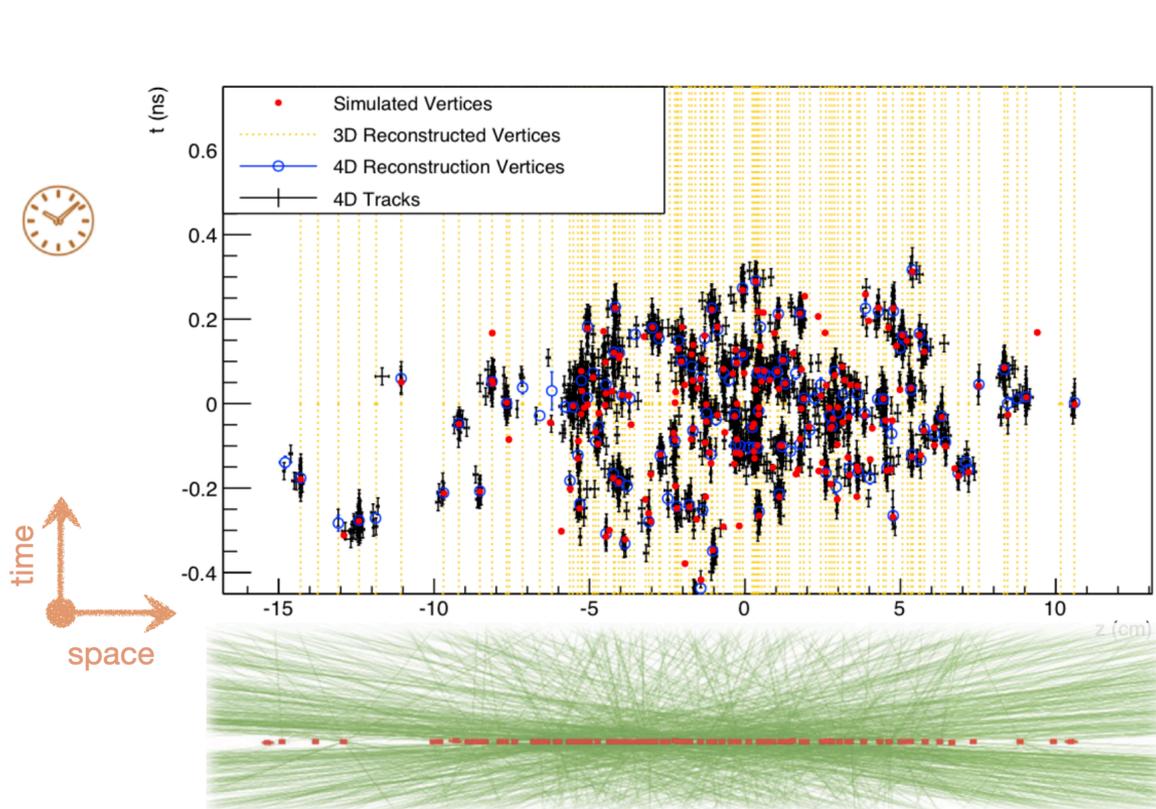
- Beam abort & timing
- Beam-induced background
- Bunch-by-bunch luminosity: 1% offline, 2% online
- Neutron and mixed-field radiation monitors



# HL-LHC: adding precision timing detectors

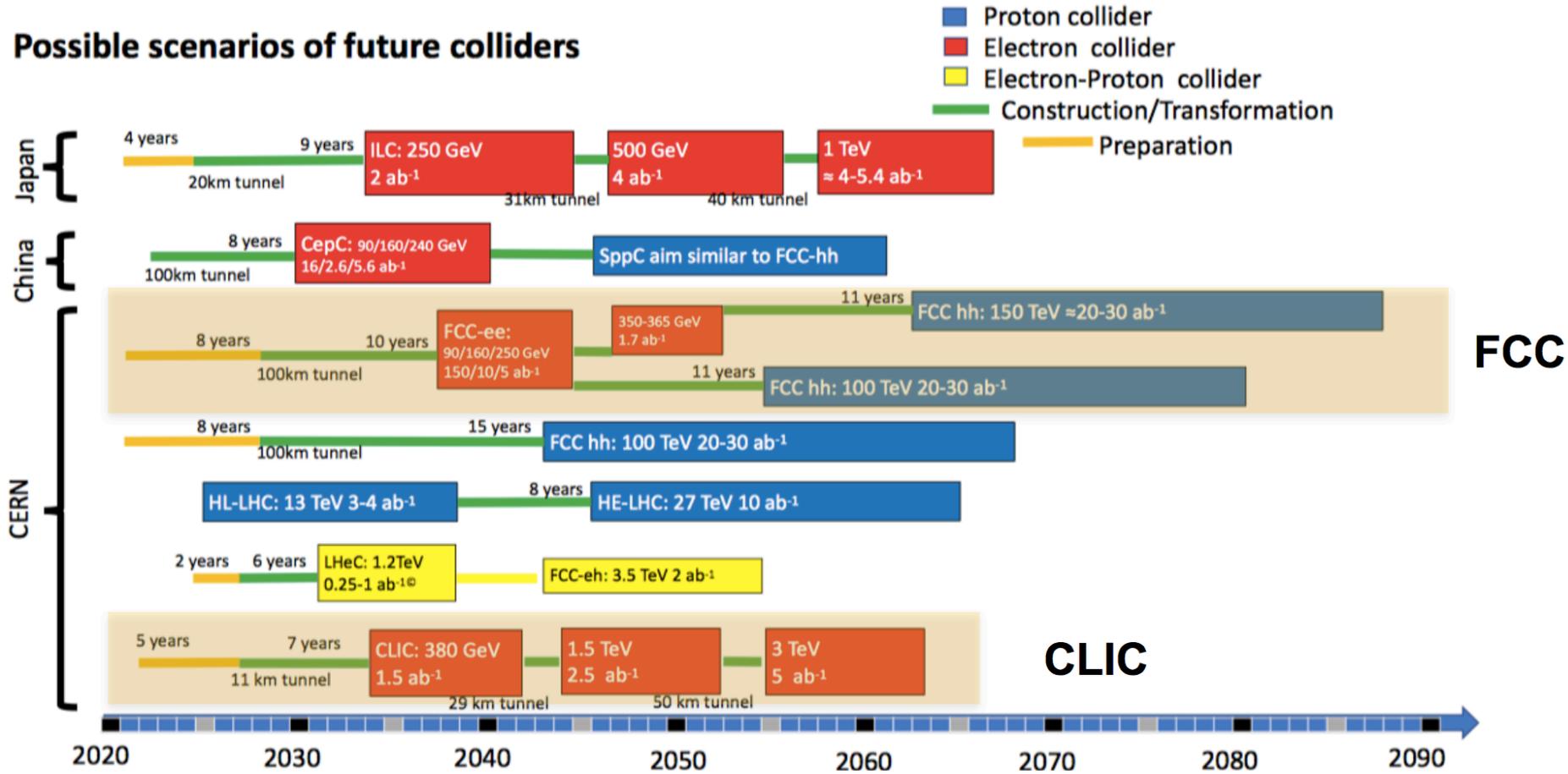
**Example challenge** for the high-luminosity LHC phase: **pile-up**

- can expect up to 200 simultaneous collisions per bunch crossing
- detectors do not have the spacial resolution to distinguish resulting vertices
- solution: **add time dimension**, i.e. develop novel precision timing detectors



CMS

# Possible scenarios of future colliders



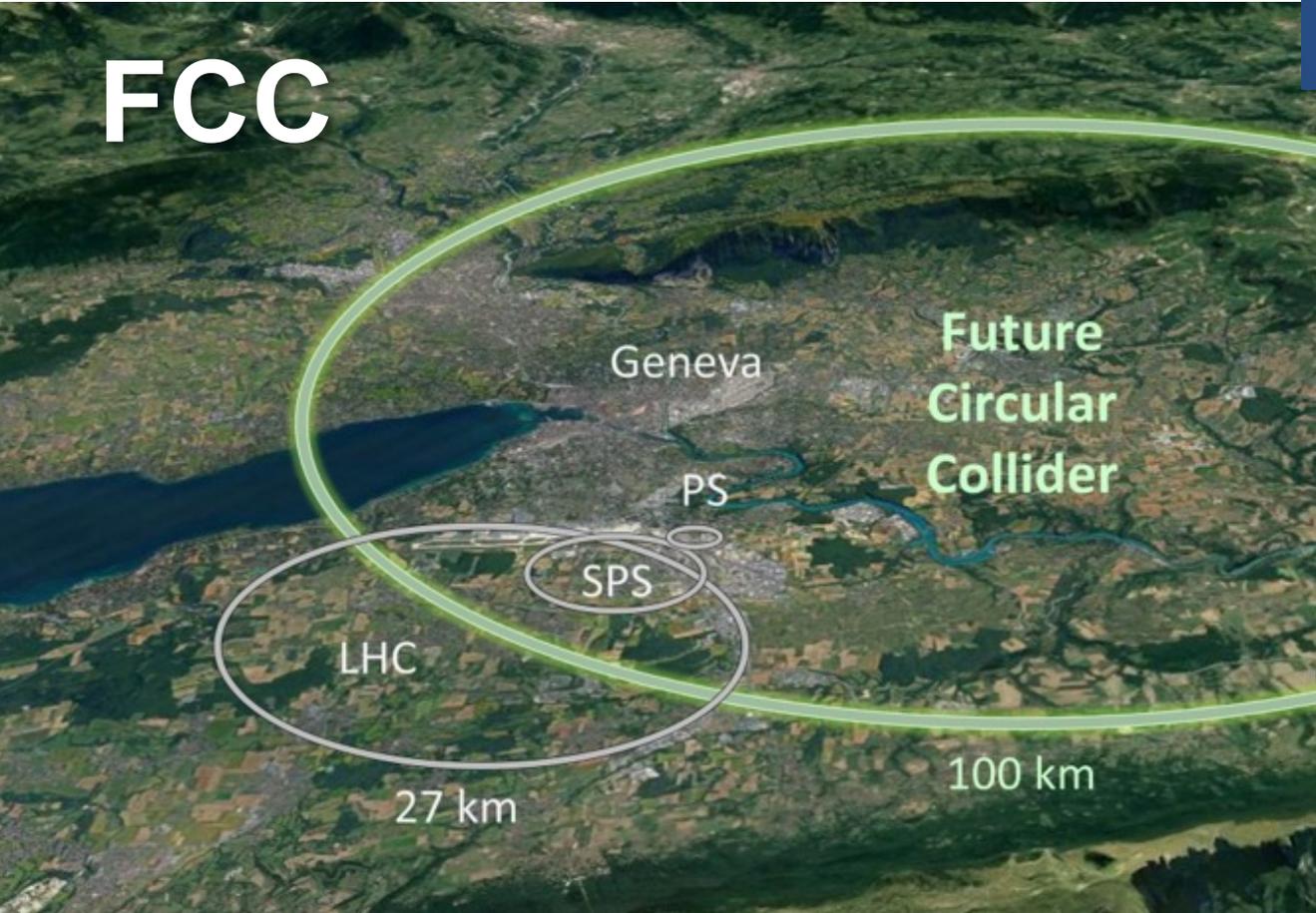
'Hoje'

'Amanhã'

'Depois de amanhã'

# European strategy priority

## FCC



### Circular collider with 100 Km circumference:

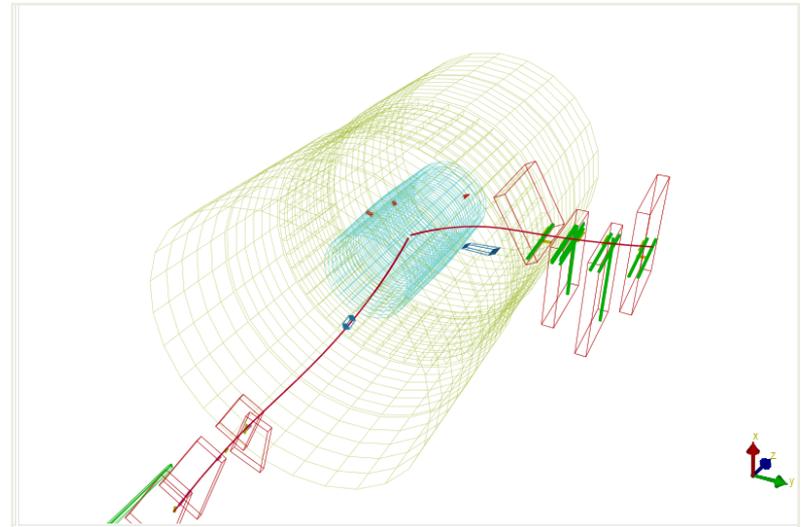
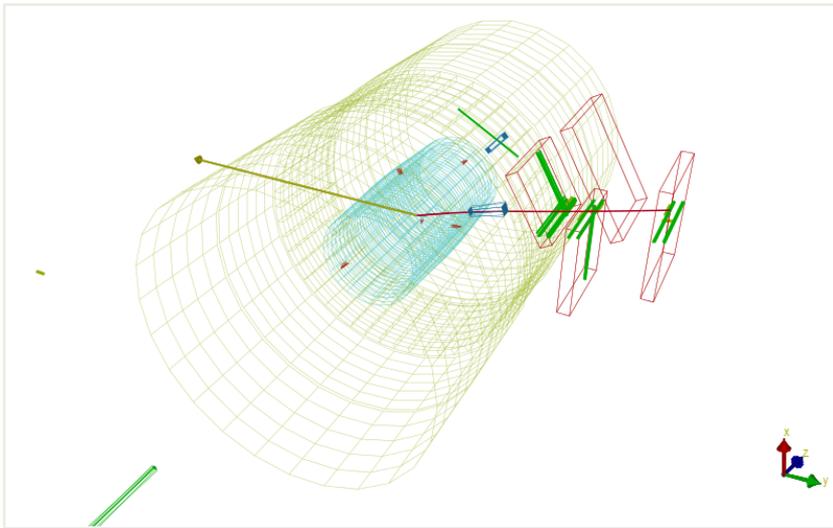
- Phase 1 (FCC-ee): electron-positron collisions at energy 90-365 GeV
- Phase 2 (FCC-hh): proton-proton collision at energy 100 TeV



# A Tarefa de hoje

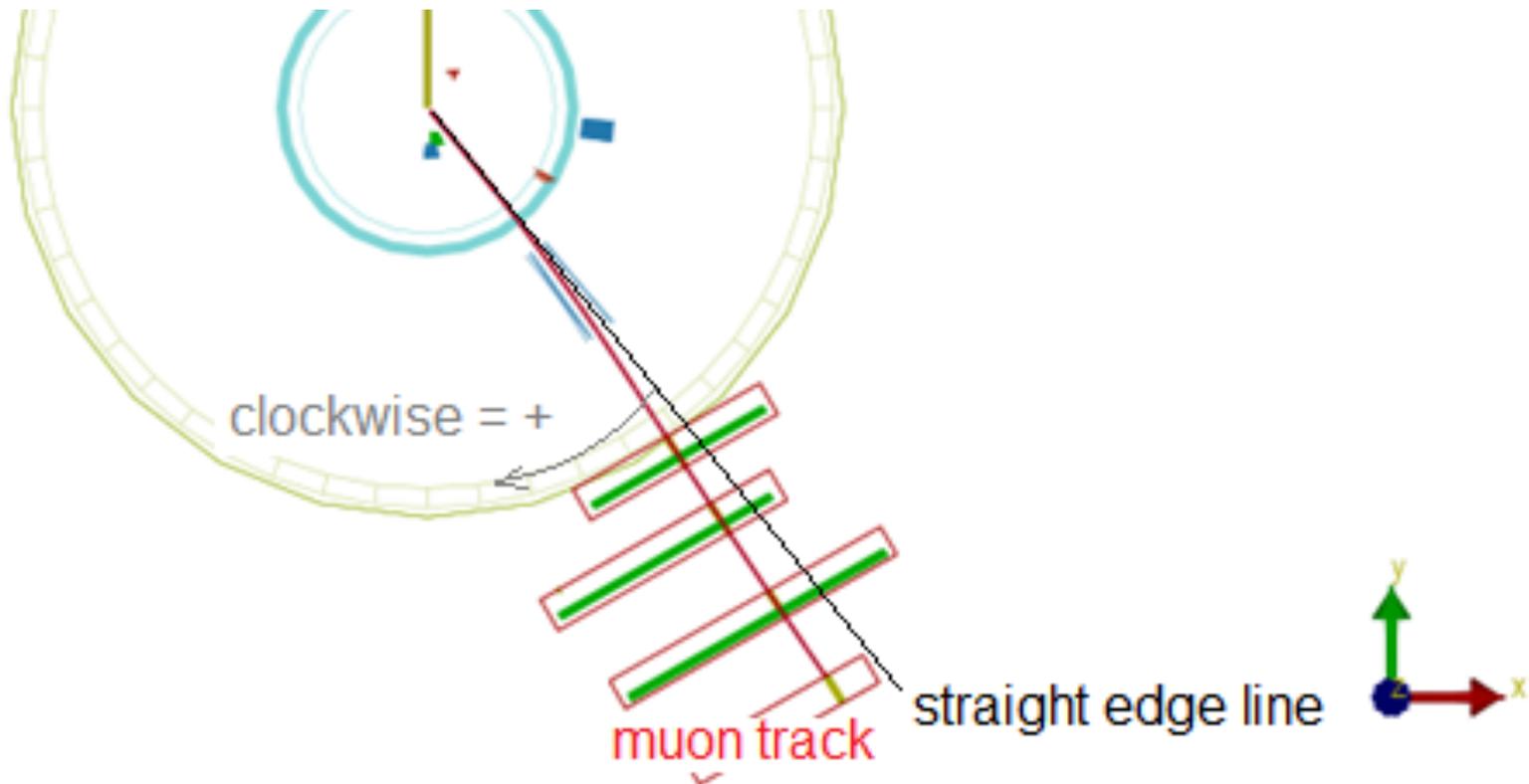
Usar dados reais de CMS no LHC em iSpy para testar o desempenho do detector CMS:

- Podemos distinguir candidatos W de Z ?



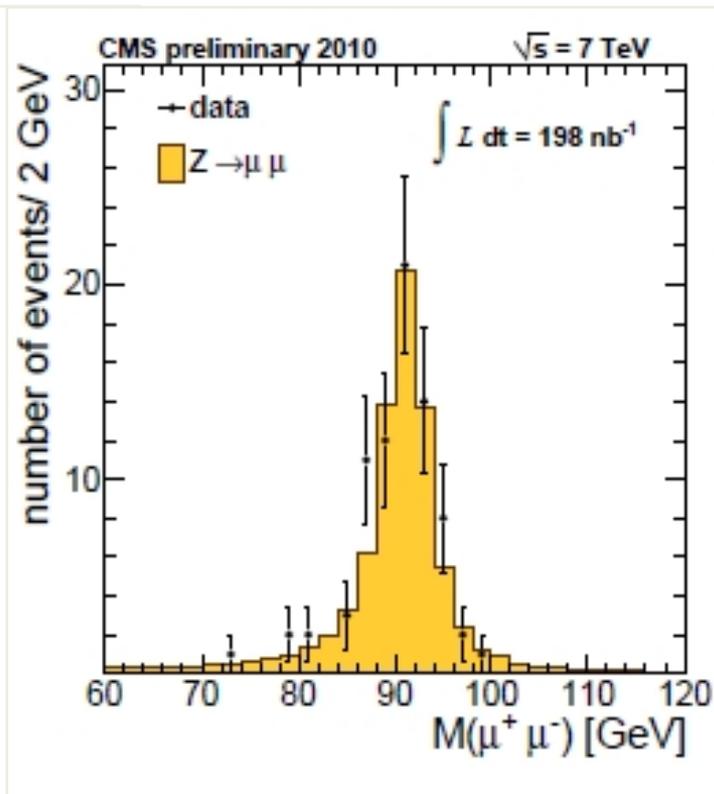
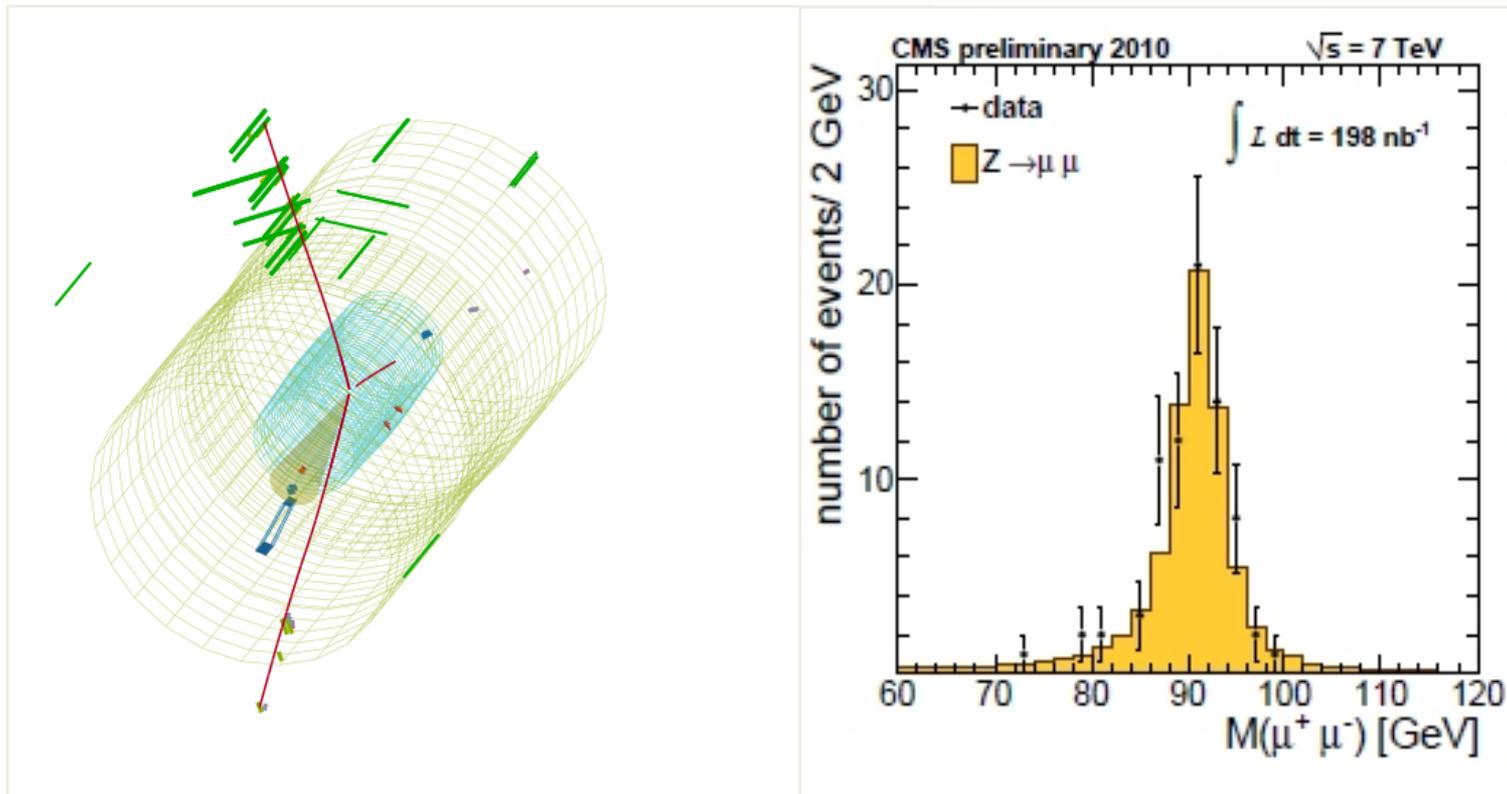
# A Tarefa de hoje

- Podemos calcular a razão  $W^+/W^-$  em CMS ?



# A Tarefa de hoje

- Podemos ter uma distribuição de massa dos candidatos Z?



EvNo	E1	px1	py1	pz1	pt1	eta1	phi1	Q1	E2	px2	py2	pz2	pt2	eta2	phi2	Q2	M	
128943239	72.89895	13.36098	-26.087	66.74727	29.3095	1.5612	-1.09746		1	37.6277	-10.9181	35.80517	-3.82334	37.3966	-0.10197	1.86677	-1	90.31227

# A Tarefa de hoje

## Histogramas de massas e páginas de Resultados

