

Cálculo da Massa Invariante em processos no LHC

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18ª Escola de Verão de Física





Conteúdos a abordar



01

O Modelo Padrão

02

Espaço-tempo

03

O cálculo da Massa Invariante

04

A experiência e o LHC

05

Análise dos dados

06

Conclusão



O Modelo Padrão

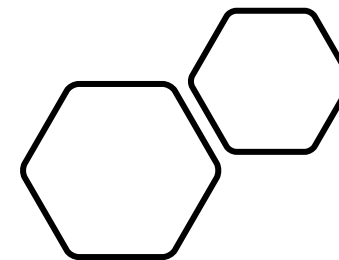


Standard Model of Elementary Particles

	three generations of matter (fermions)			interactions / force carriers (bosons)	
	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
QUARKS	u up	c charm	t top	g gluon	H higgs
	d down	s strange	b bottom	γ photon	
	e electron	μ muon	τ tau	Z Z boson	
LEPTONS	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

GAUGE BOSONS
VECTOR BOSONS

SCALAR BOSONS



INTERACT WITH THE ELECTROMAGNETIC FIELD

UP	CHARM	TOP	GLUON	HIGGS BOSON
DOWN	STRANGE	BOTTOM	PHOTON	
ELECTRON	MUON	TAU	Z BOSON	
ELECTRON NEUTRINO	MUON NEUTRINO	TAU NEUTRINO	W BOSON	

INTERACT WITH THE STRONG FIELD

UP	CHARM	TOP	GLUON	HIGGS BOSON
DOWN	STRANGE	BOTTOM	PHOTON	
ELECTRON	MUON	TAU	Z BOSON	
ELECTRON NEUTRINO	MUON NEUTRINO	TAU NEUTRINO	W BOSON	

INTERACT WITH THE WEAK FIELD

UP	CHARM	TOP	GLUON	HIGGS BOSON
DOWN	STRANGE	BOTTOM	PHOTON	
ELECTRON	MUON	TAU	Z BOSON	
ELECTRON NEUTRINO	MUON NEUTRINO	TAU NEUTRINO	W BOSON	

INTERACT WITH THE HIGGS FIELD

UP	CHARM	TOP	GLUON	HIGGS BOSON
DOWN	STRANGE	BOTTOM	PHOTON	
ELECTRON	MUON	TAU	Z BOSON	
ELECTRON NEUTRINO	MUON NEUTRINO	TAU NEUTRINO	W BOSON	

INTERACT WITH THE WEAK FIELD

UP	CHARM	TOP	GLUON	HIGGS BOSON
DOWN	STRANGE	BOTTOM	PHOTON	Z BOSON
ELECTRON	MUON	TAU	W BOSON	
ELECTRON NEUTRINO	MUON NEUTRINO	TAU NEUTRINO		

INTERACT WITH THE HIGGS FIELD

UP	CHARM	TOP	GLUON	HIGGS BOSON
DOWN	STRANGE	BOTTOM	PHOTON	Z BOSON
ELECTRON	MUON	TAU	W BOSON	
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INTERACT WITH THE ELECTROMAGNETIC FIELD

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INTERACT WITH THE STRONG FIELD

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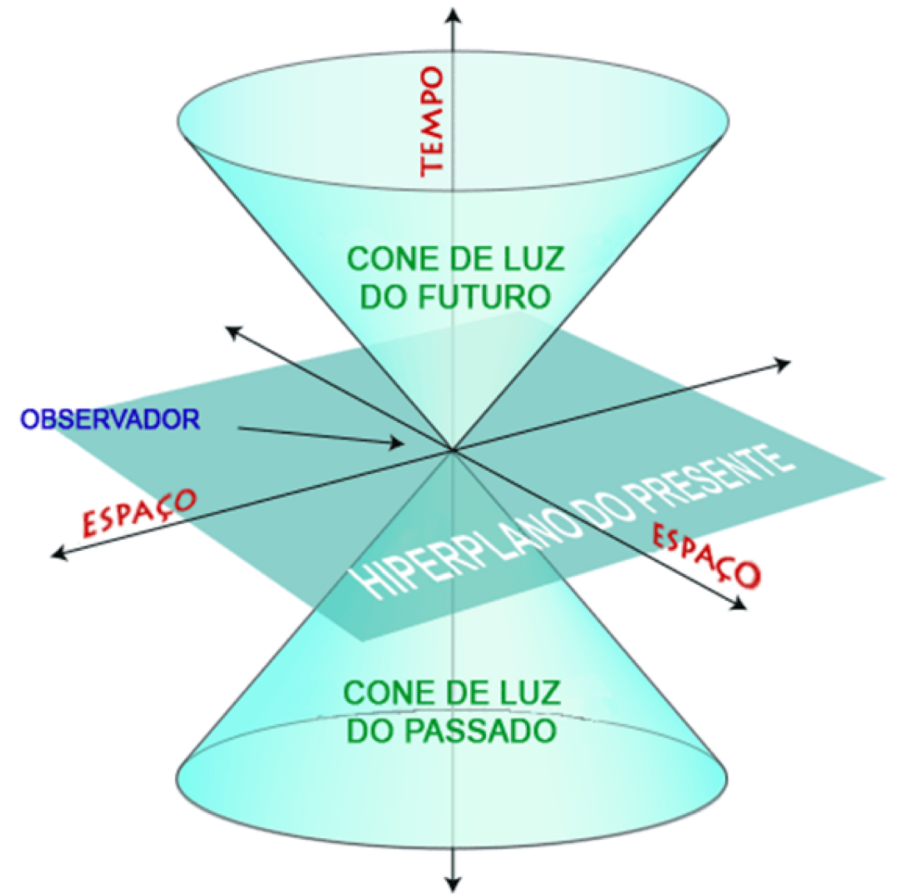


Espaço-tempo de Minkowski



$$x^\mu = (x^0, x^1, x^2, x^3) = (ct, X, Y, Z)$$

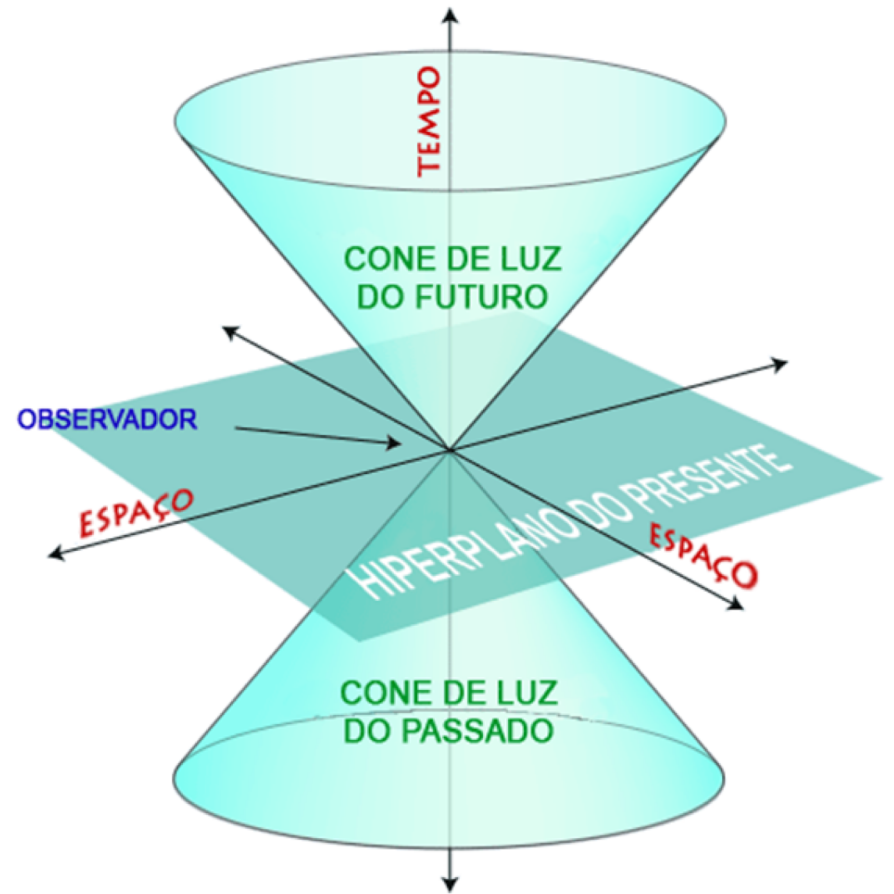
$$x_\mu = (x_0, x_1, x_2, x_3) = (ct, -x, -y, -z)$$



$$x^\mu = (x^0, x^1, x^2, x^3) = (ct, X, Y, Z)$$

$$x_\mu = (x_0, x_1, x_2, x_3) = (ct, -x, -y, -z)$$

$$s^2 = \sum_{\mu=0}^3 (x^\mu \cdot x_\mu) = c^2t^2 - x^2 - y^2 - z^2$$



O cálculo da Massa Invariante



$$\begin{aligned} &\bullet \vec{p} = m \cdot \vec{v} \\ &\bullet \vec{v} = \frac{\Delta \vec{r}}{\Delta t} \end{aligned}$$

Espaço Euclidiano



$$\begin{aligned} &\bullet p^\mu = m v^\mu \\ &\bullet v^\mu = \frac{\Delta x^\mu}{\Delta t'} \end{aligned}$$

Espaço de Minkowski

$$\begin{aligned} p^\mu &= \underbrace{m \gamma}_{M} (c; \vec{v}') \\ &= (Mc; M\vec{v}') \\ &= \left(Mc \cdot \frac{c}{c}; \vec{p}' \right) \\ &= \left(\frac{E}{c}; \vec{p}' \right) \end{aligned}$$

$$\begin{aligned} v^\mu &= \gamma \frac{\Delta x^\mu}{\Delta t} \\ &= \gamma \left(\frac{ct}{\Delta t}; \frac{\Delta \vec{r}}{\Delta t} \right) \\ &= \gamma (c; \vec{v}') \end{aligned}$$

$\Delta t = \gamma \Delta t'$

$$P^{\mu} \cdot P_{\mu} = (Mc; M\vec{v}) \cdot (Mc; -M\vec{v})$$

$$= M^2 (c^2 - \vec{v}^2)$$

$$= m^2 \gamma^2 (c^2 - \vec{v}^2)$$

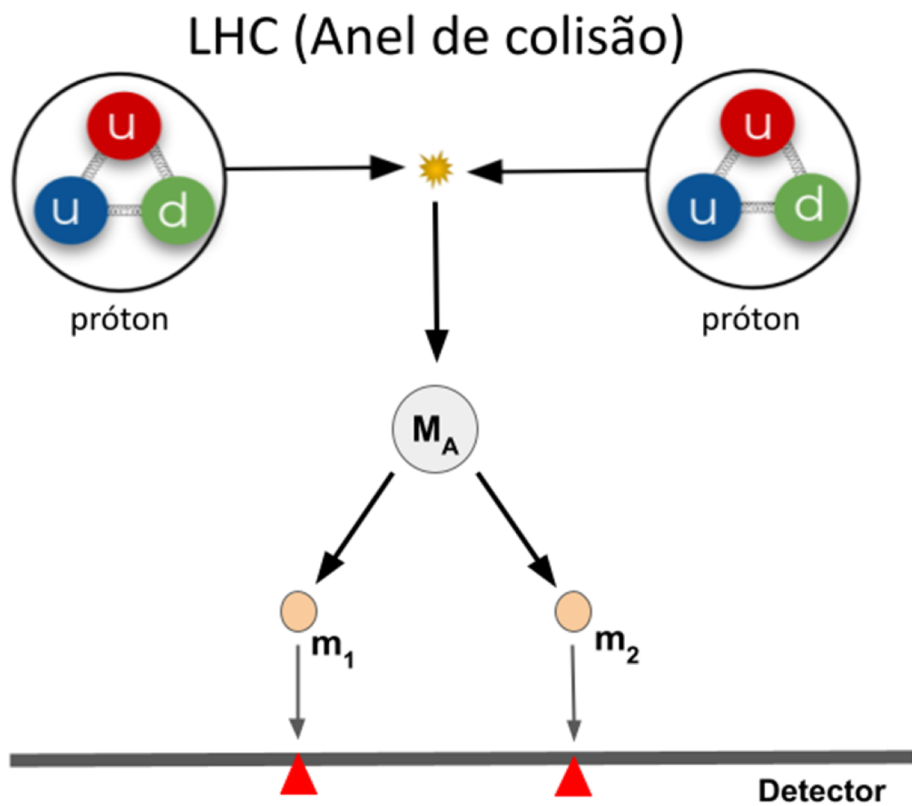
$$= m^2 c^2$$

$$P^{\mu} \cdot P_{\mu} = \left(\frac{E}{c}; \vec{p}\right) \cdot \left(\frac{E}{c}; -\vec{p}\right)$$

$$= \frac{E^2}{c^2} - \vec{p}^2$$

$$m^2 c^2 = \frac{E^2}{c^2} - \vec{p}^2$$

$$\Leftrightarrow E^2 = m^2 c^4 + \vec{p}^2 c^2$$



Conservação de momento

$$P_i = P_f$$

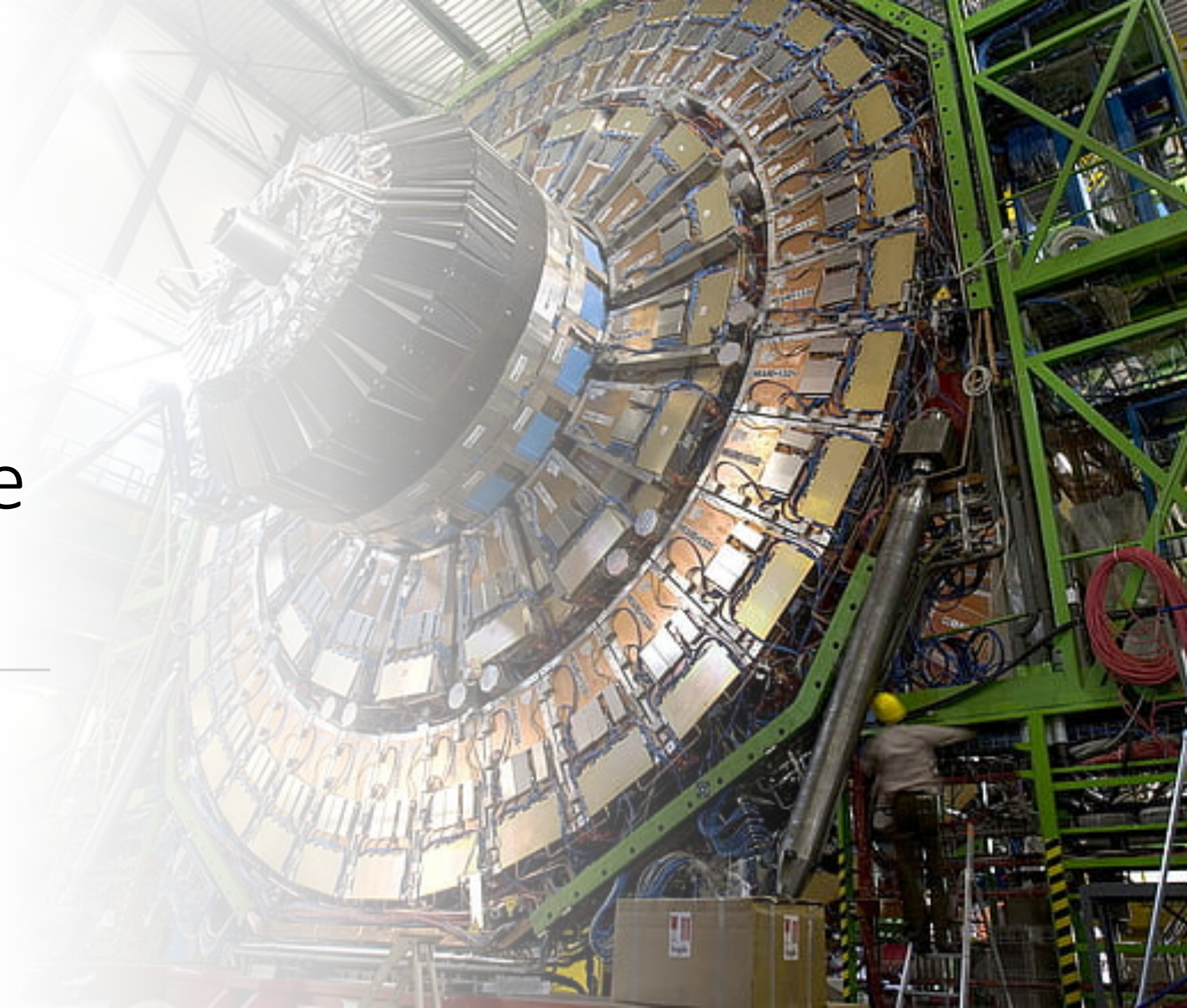
$$P_A^\mu = P_1^\mu + P_2^\mu$$

$$P_A^\mu \cdot P_{A\mu} = (P_1^\mu + P_2^\mu) \cdot (P_{1\mu} + P_{2\mu})$$

$$m_A = \left[m_1^2 + 2 \left(\frac{E_1 E_2}{c^4} - \frac{\vec{P}_1 \cdot \vec{P}_2}{c^2} \right) + m_2^2 \right]^{1/2}$$



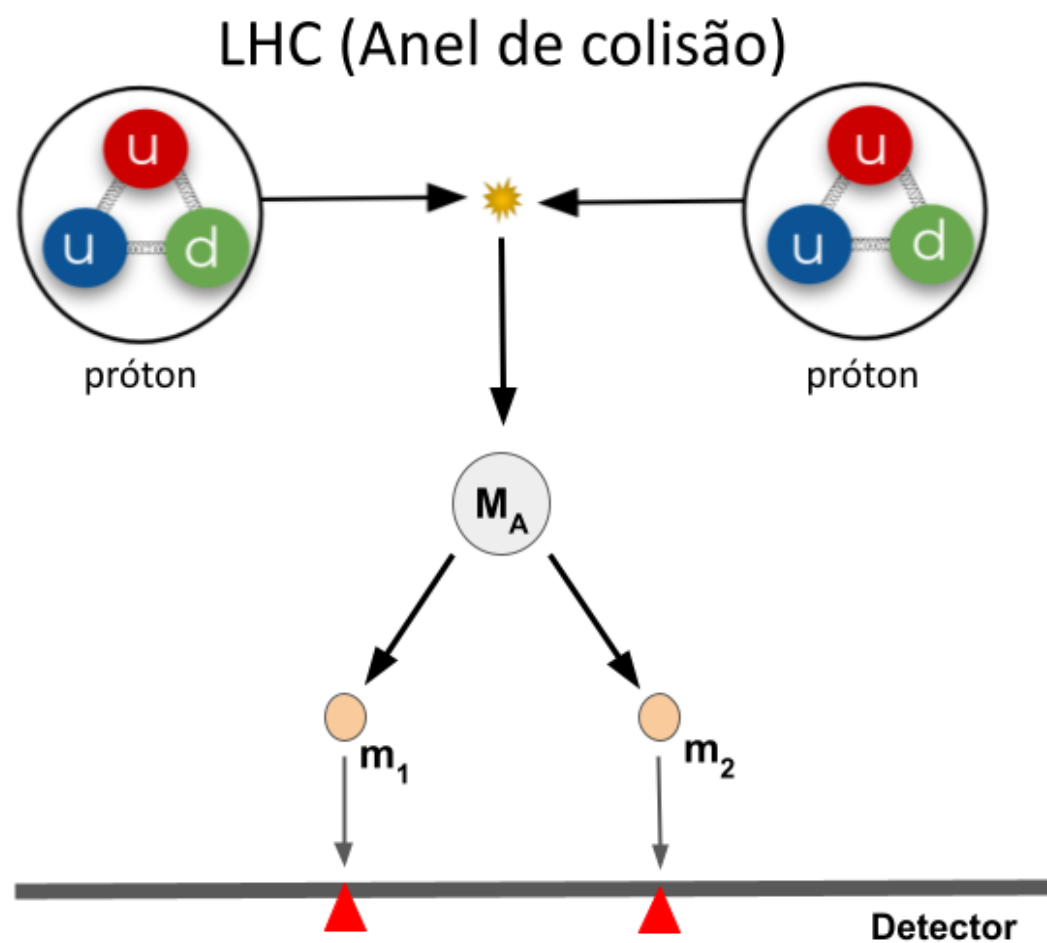
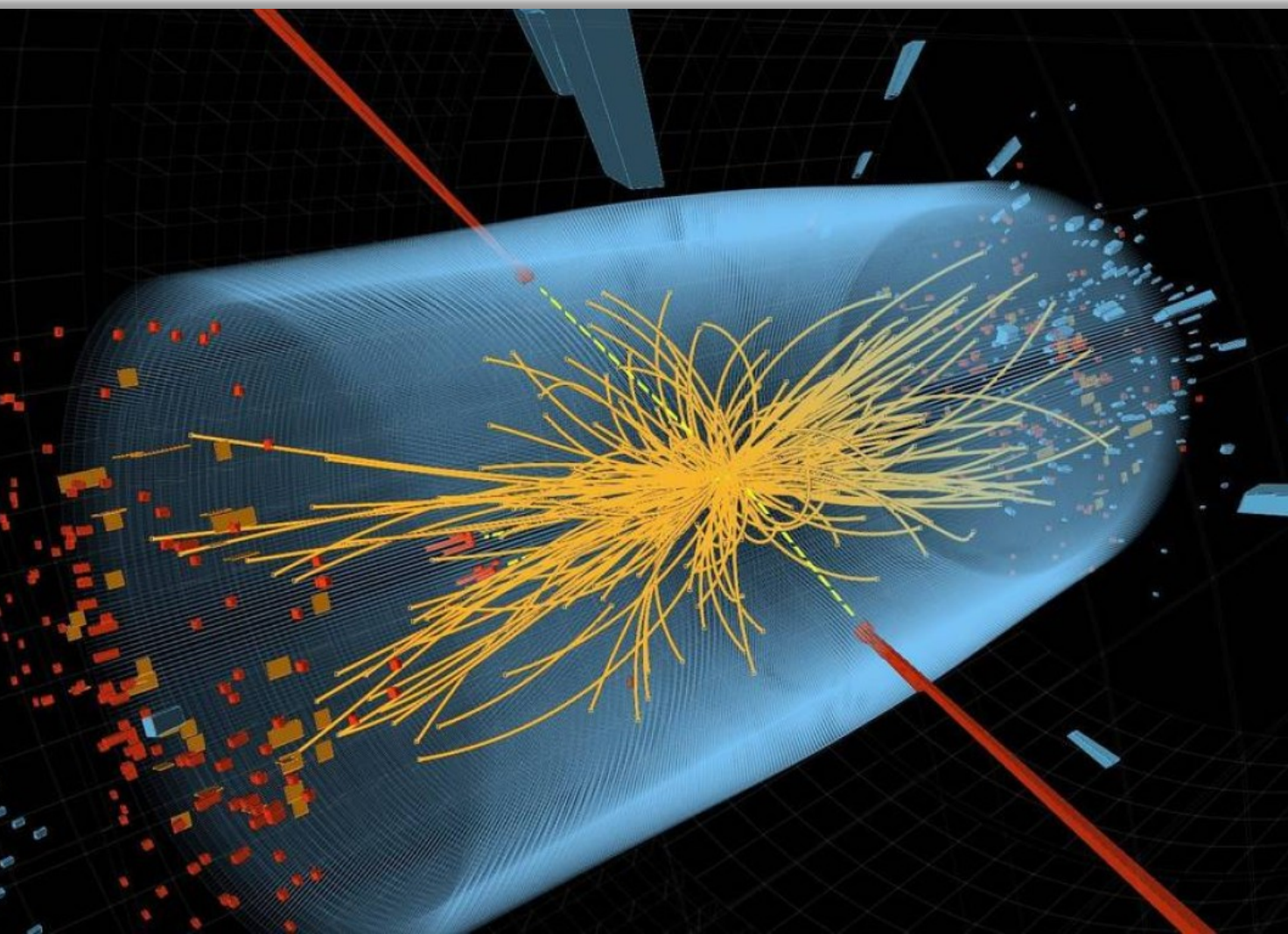
A experiência e o LHC

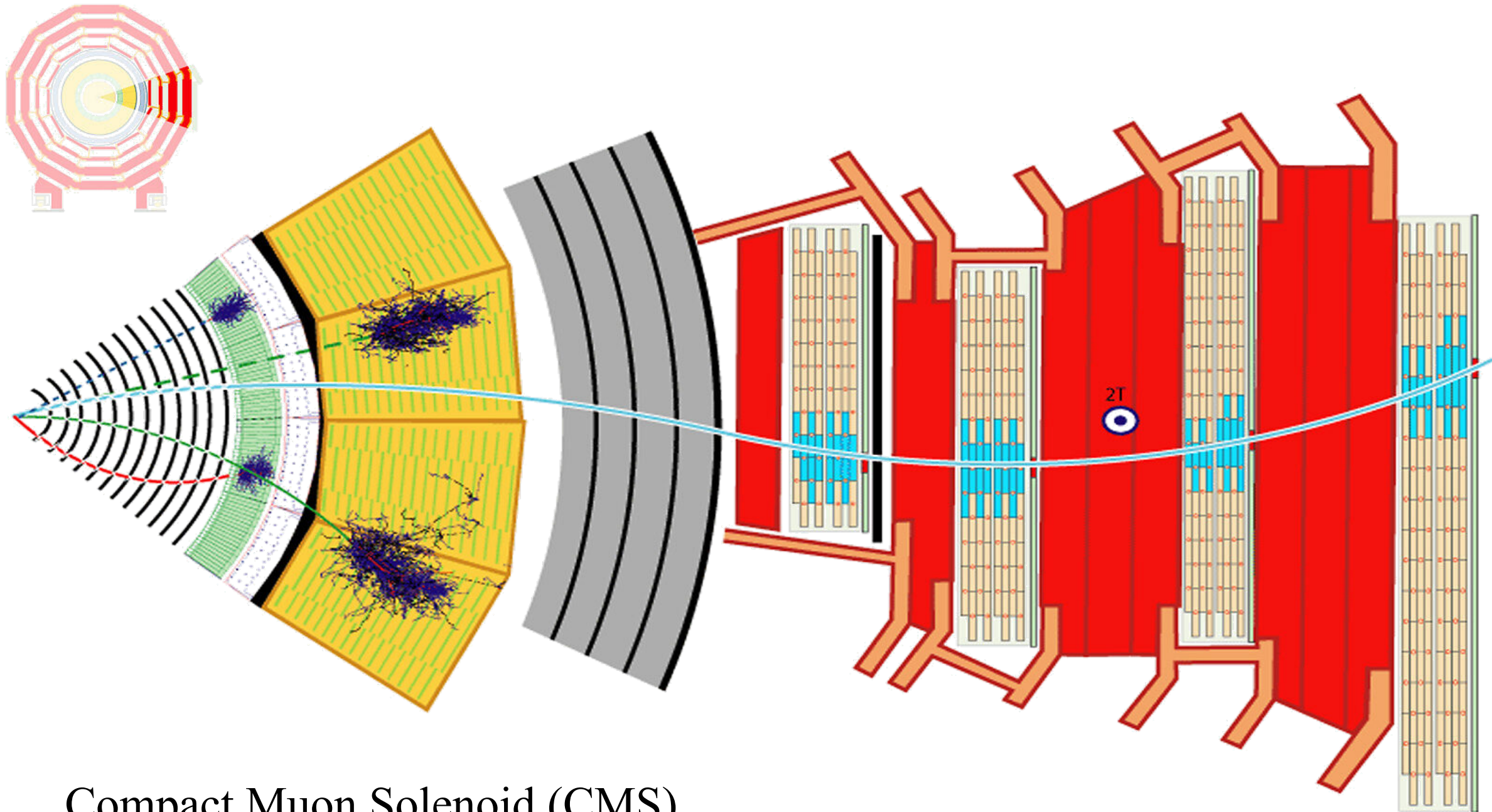


CERN - G enebra, Su ica



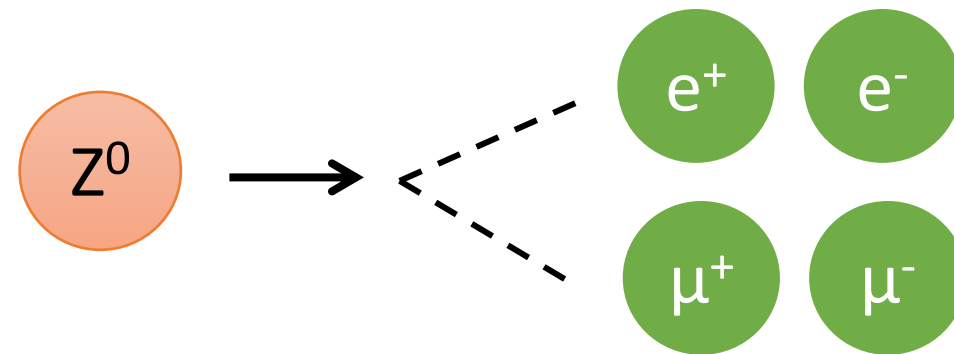
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- Organiza o Europeia de Pesquisas Nucleares -





Compact Muon Solenoid (CMS)

Decaimento do Bosão Z

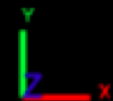




CMS Experiment at the LHC, CERN

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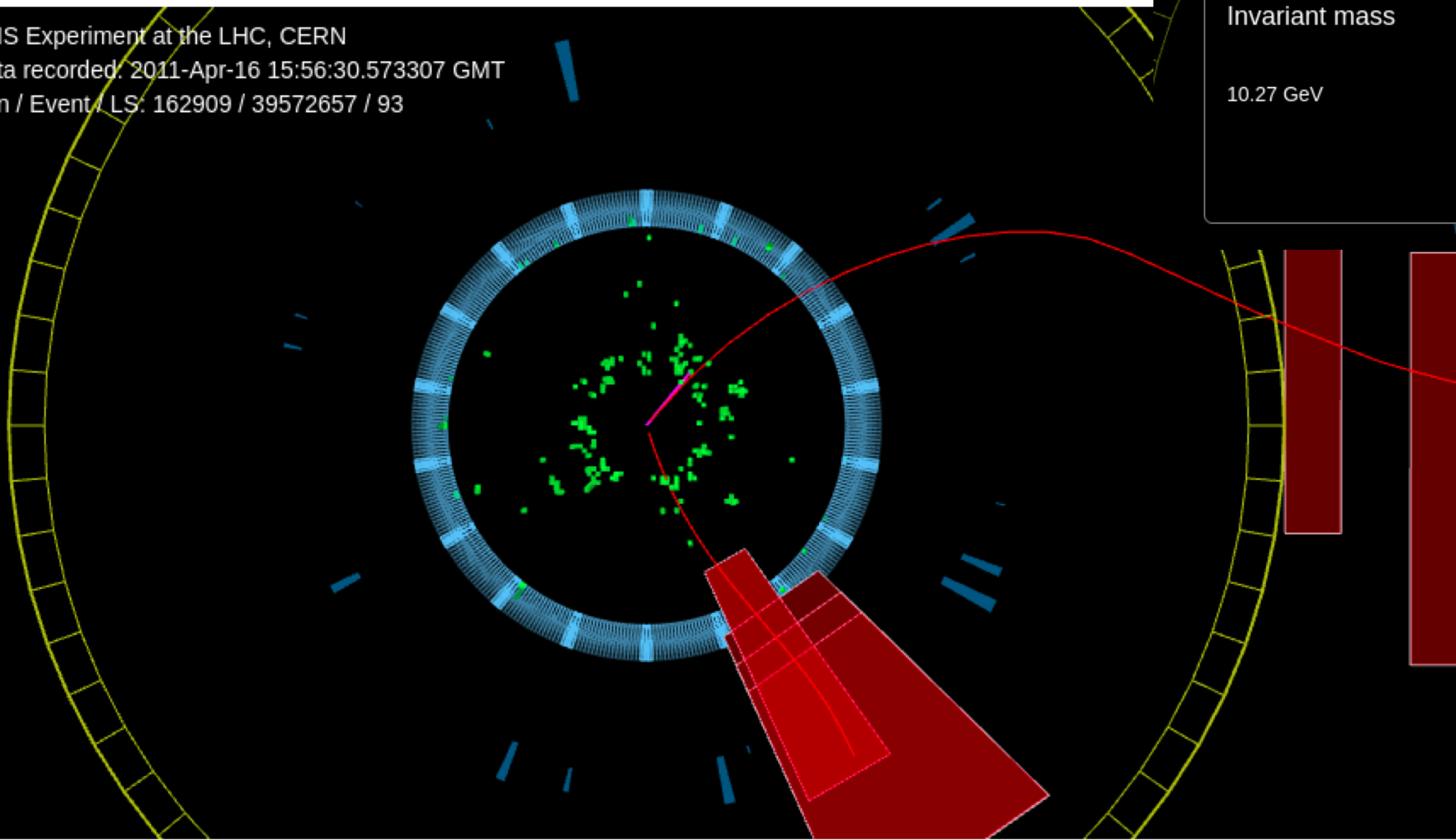
Run / Event / LS: 162909 / 39572657 / 93



Invariant mass ✖

10.27 GeV

Close





CMS Experiment at the LHC, CERN

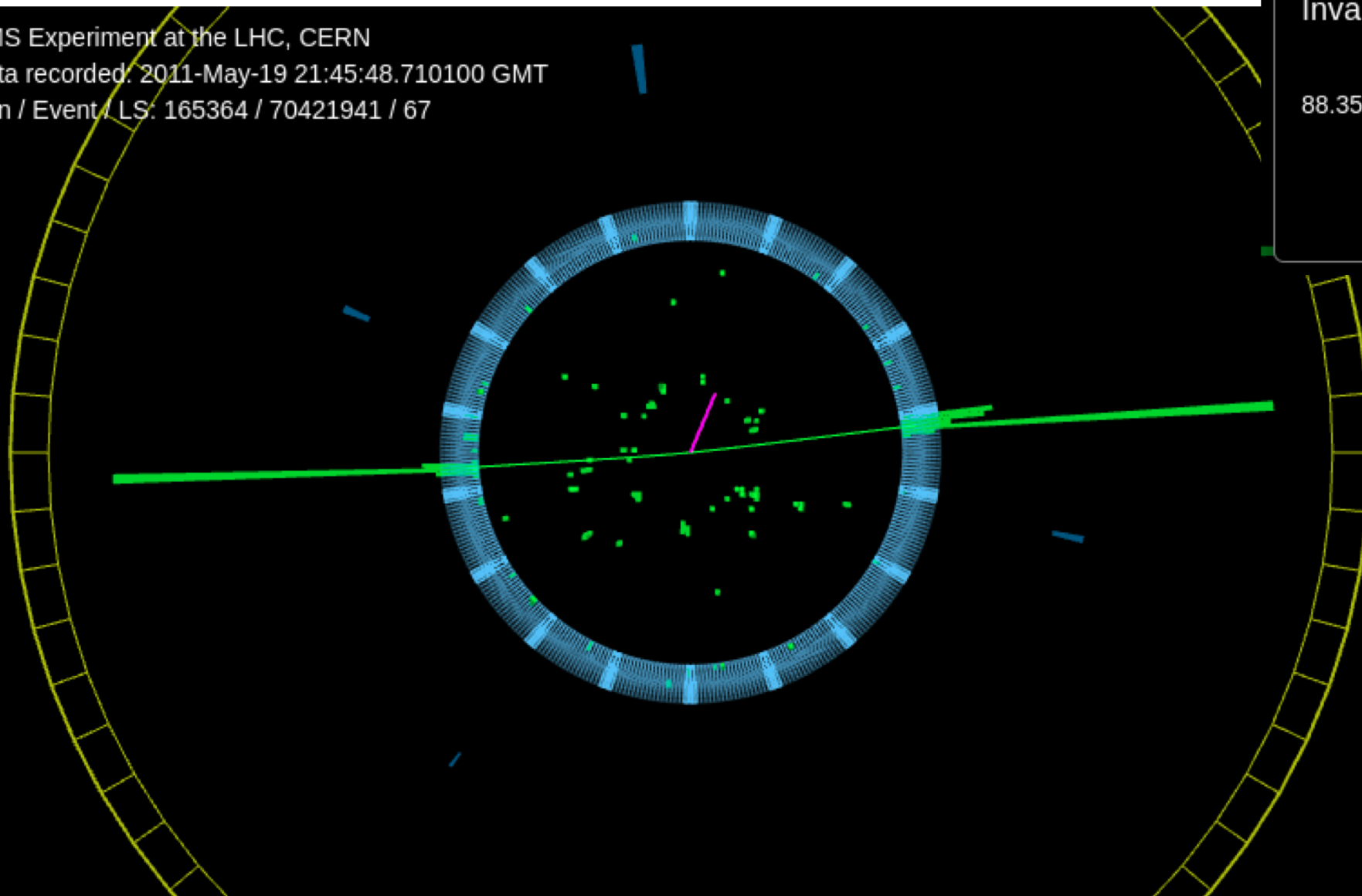
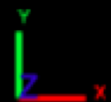
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Run / Event / LS: 165364 / 70421941 / 67

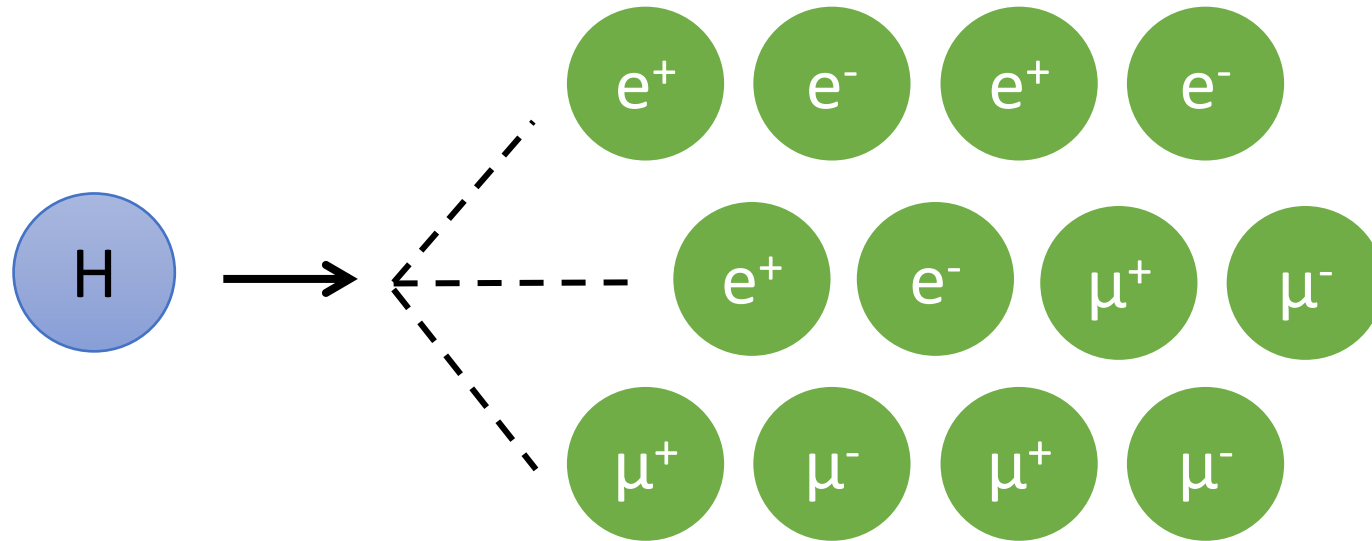
Invariant mass ✖

88.35 GeV

Close



Decaimento do Bosão de Higgs

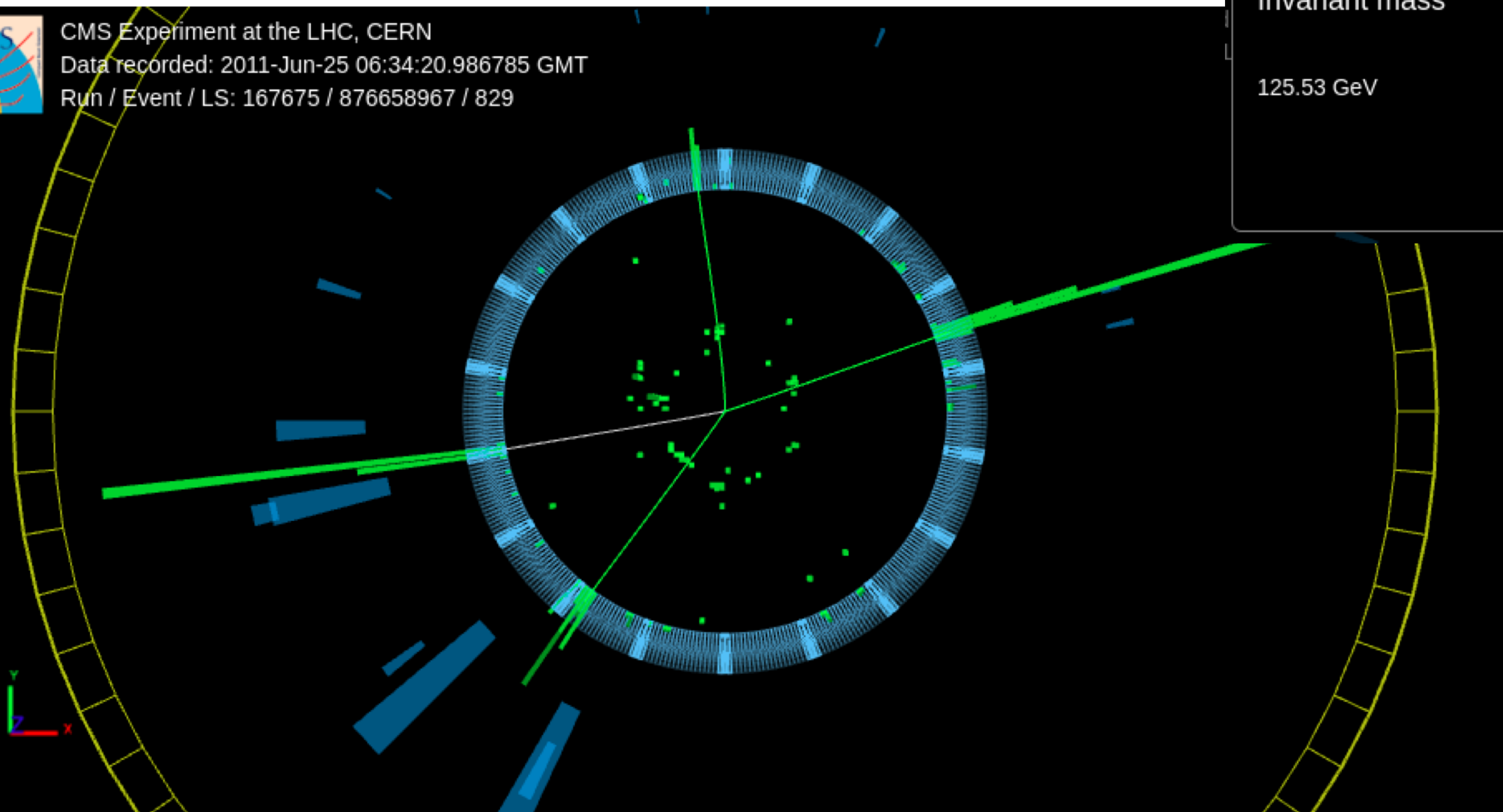




CMS Experiment at the LHC, CERN

Data recorded: 2011-Jun-25 06:34:20.986785 GMT


Run / Event / LS: 167675 / 876658967 / 829



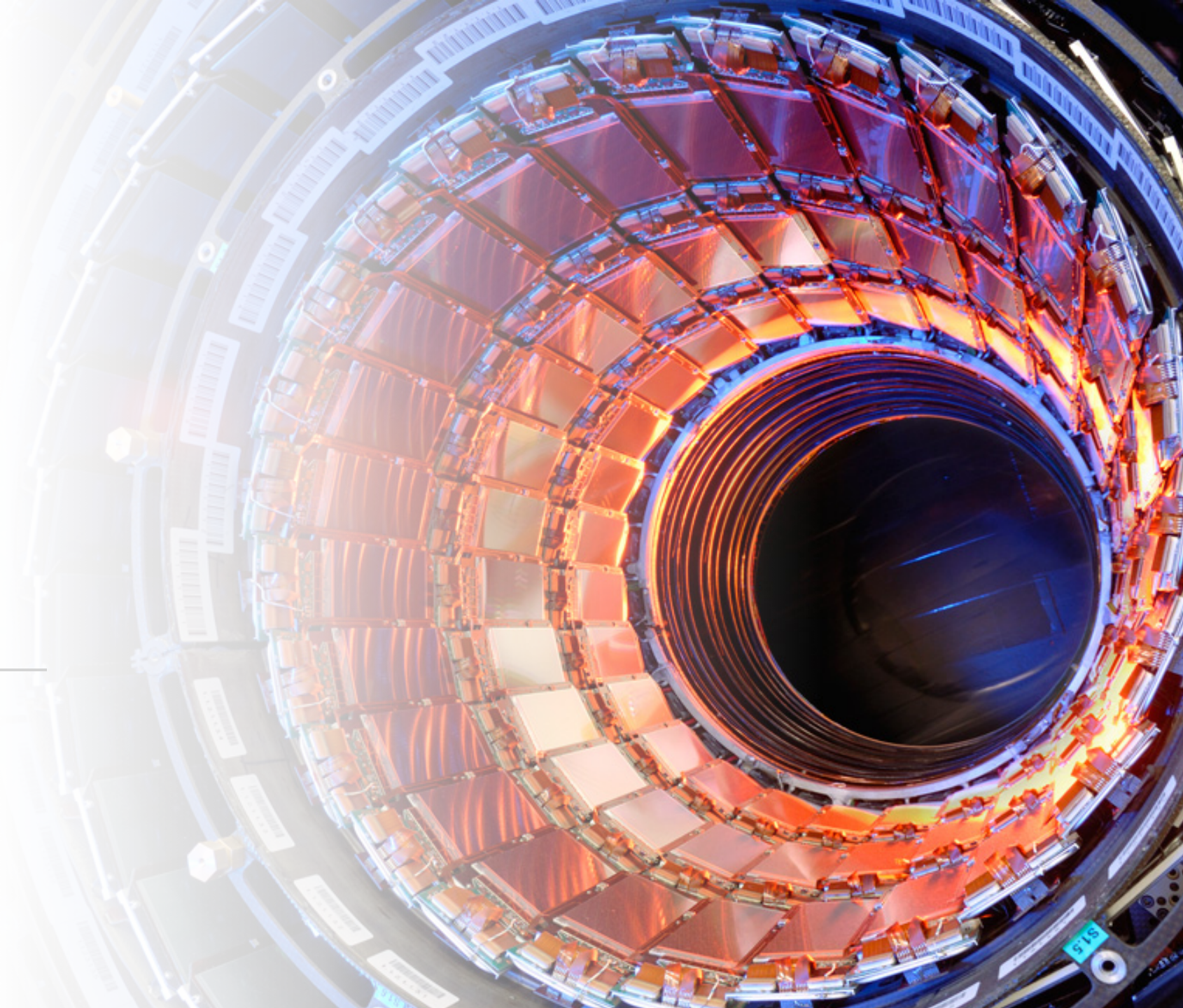
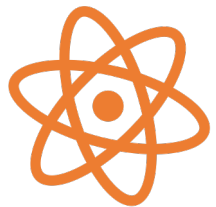
Invariant mass ✖

125.53 GeV

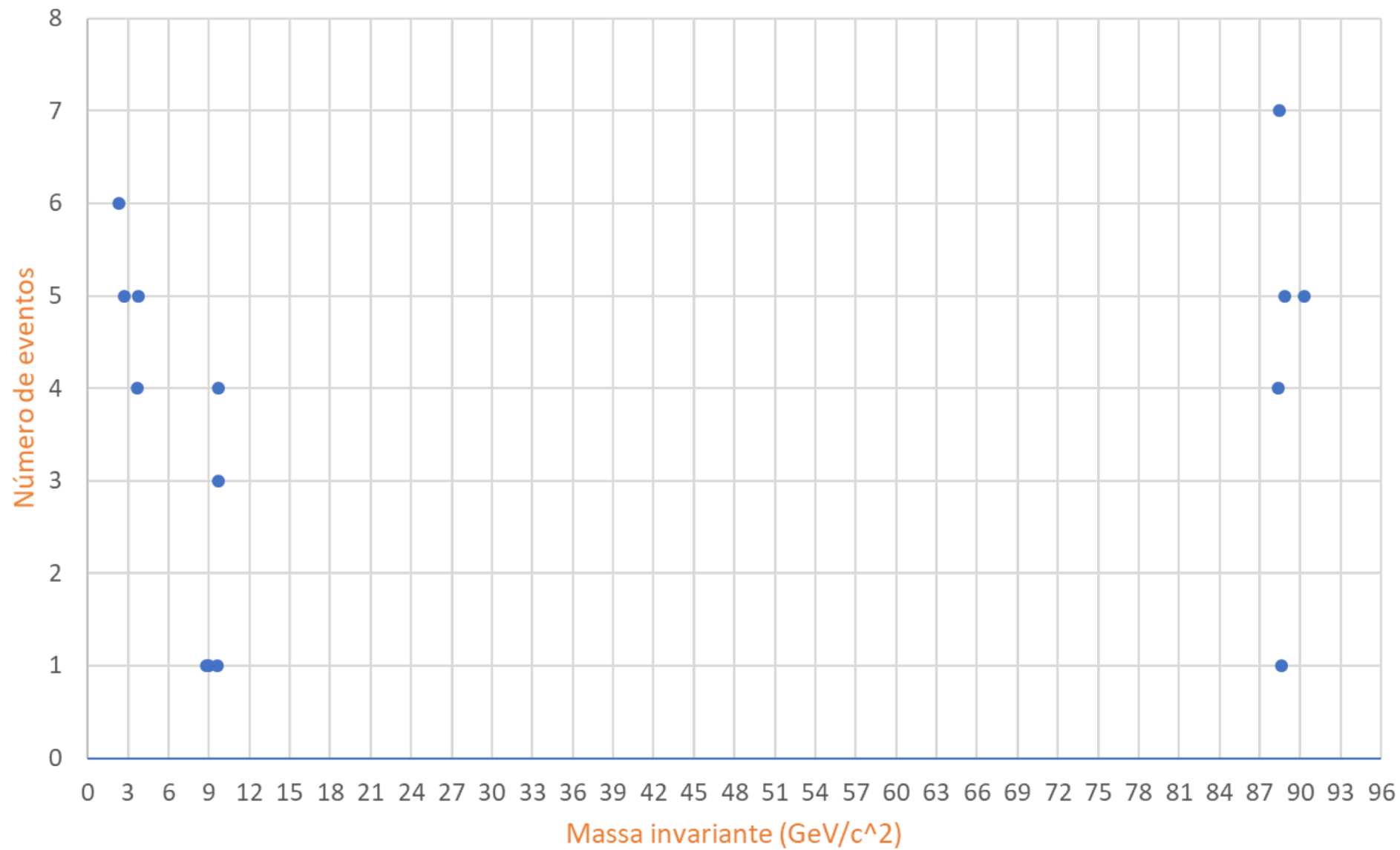
Close



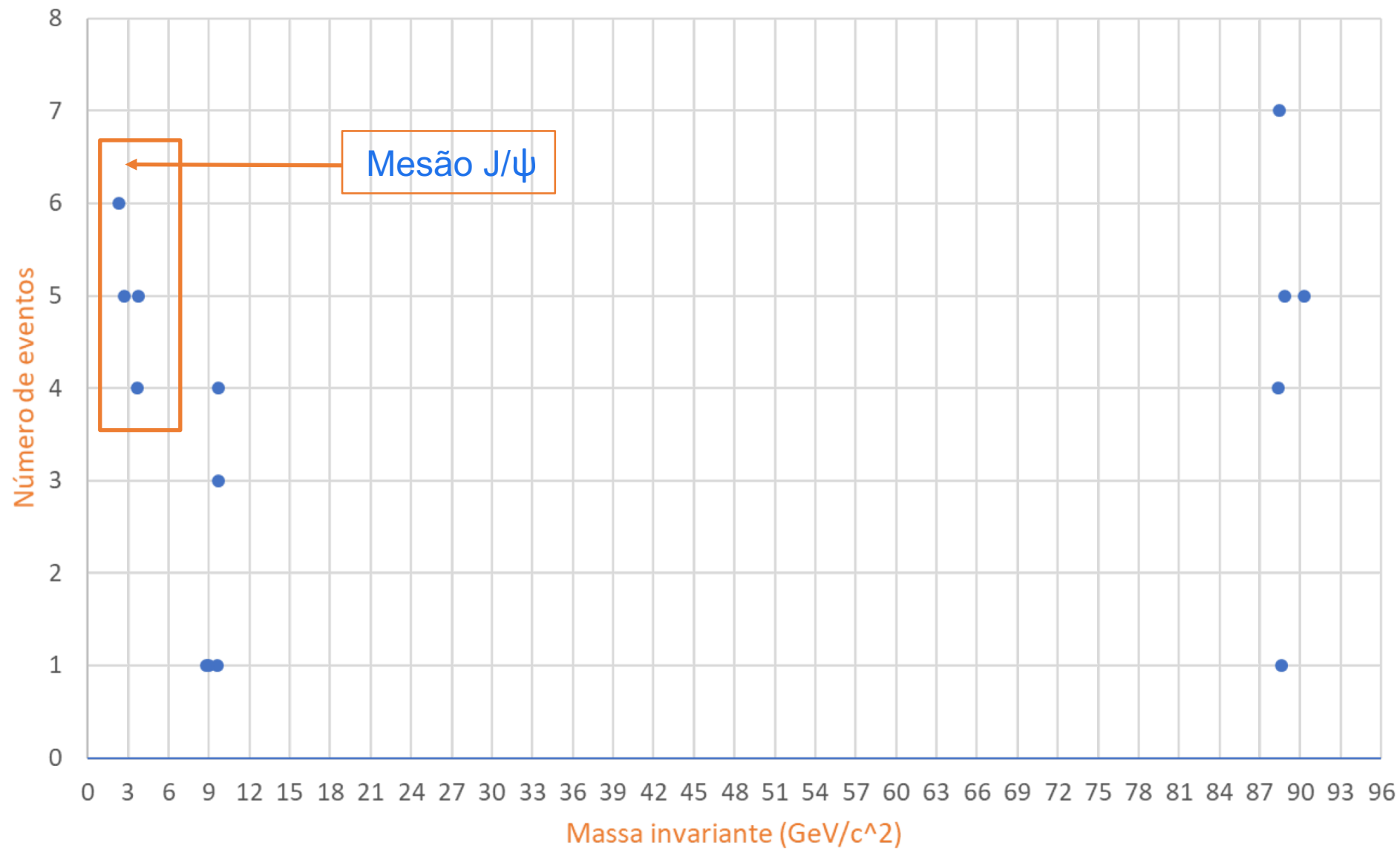
Dados
recolhidos e
respetiva
análise



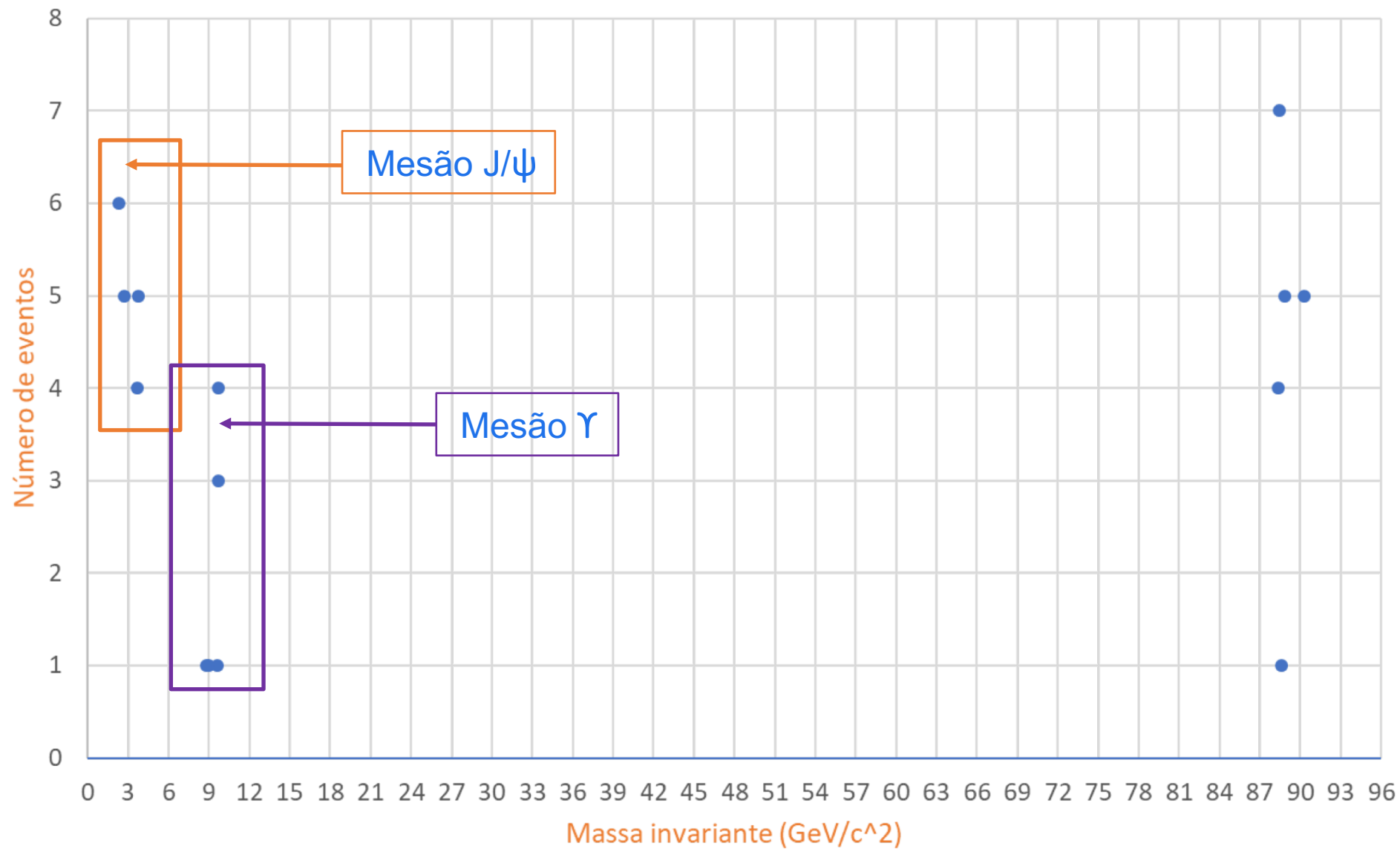
Eventos que decaíram em dois leptões



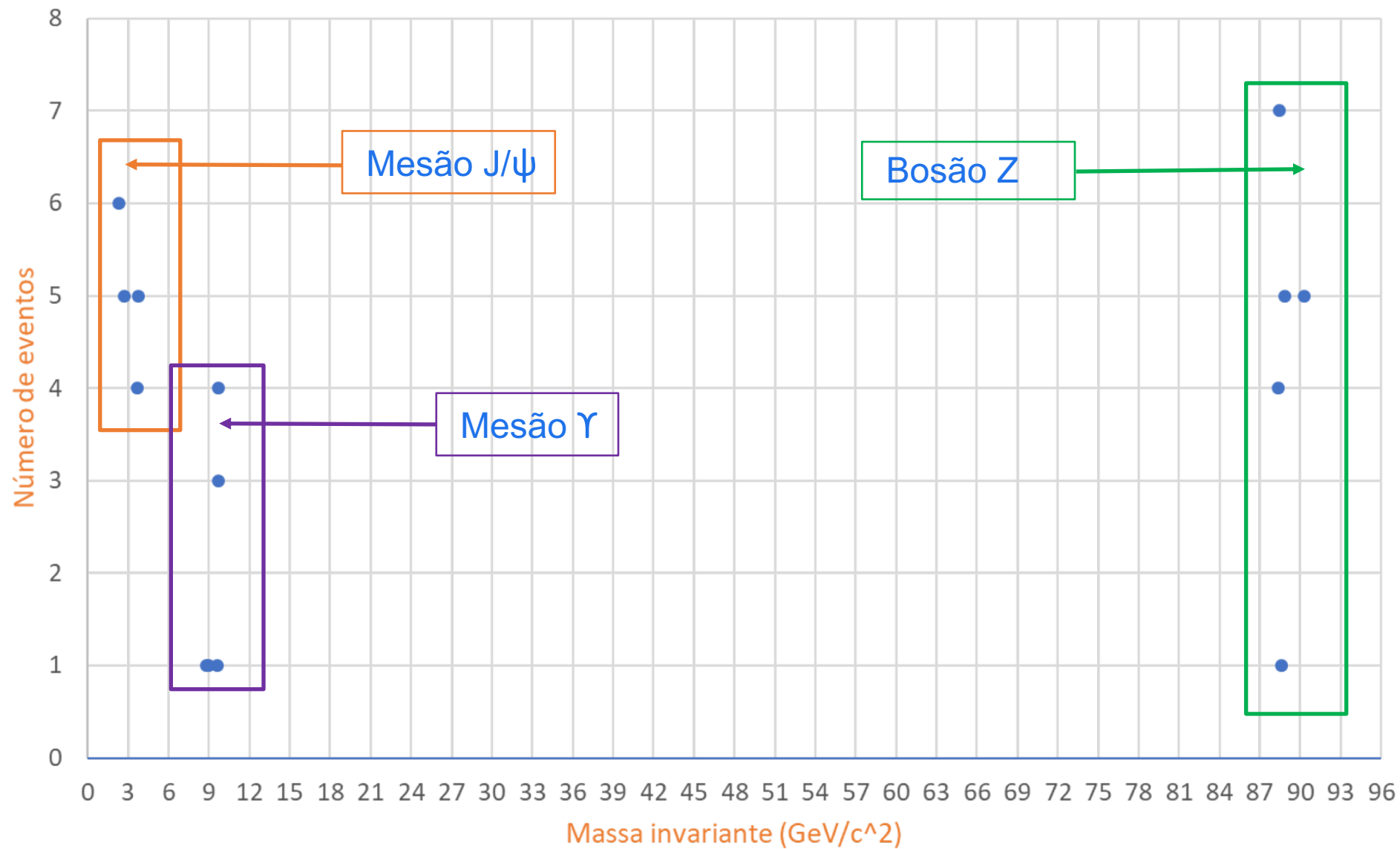
Eventos que decaíram em dois leptões



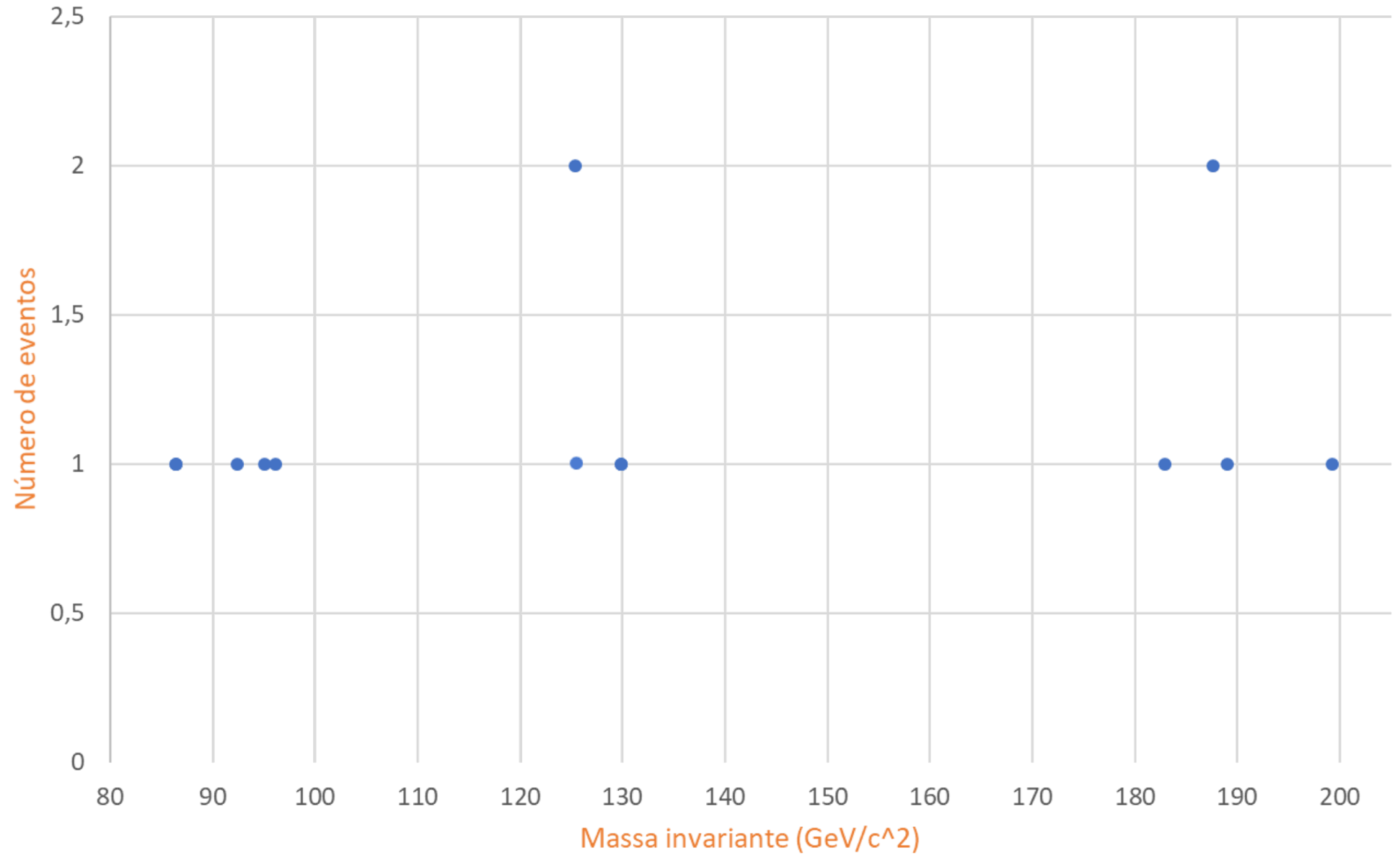
Eventos que decaíram em dois leptões



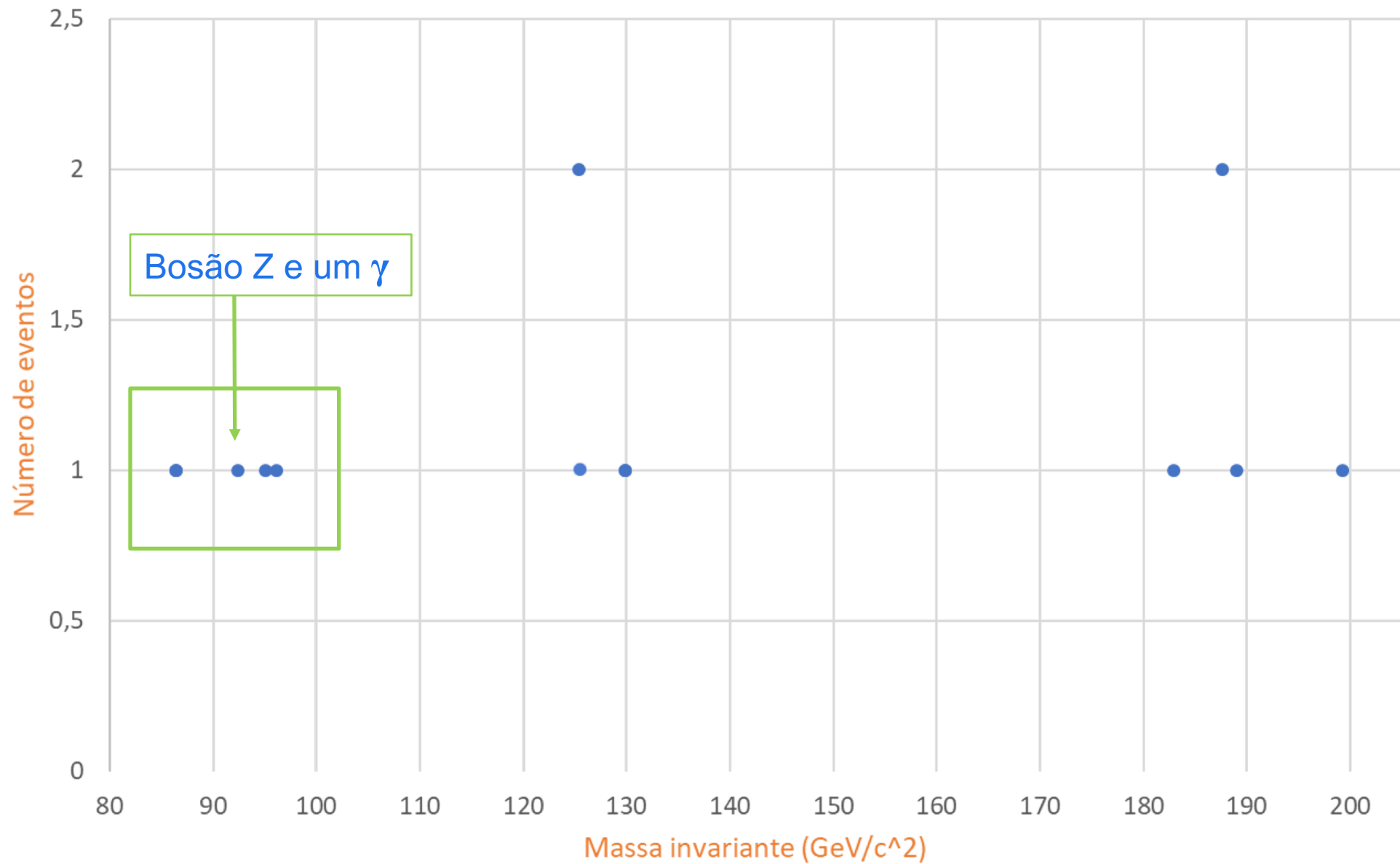
Eventos que decaíram em dois leptões



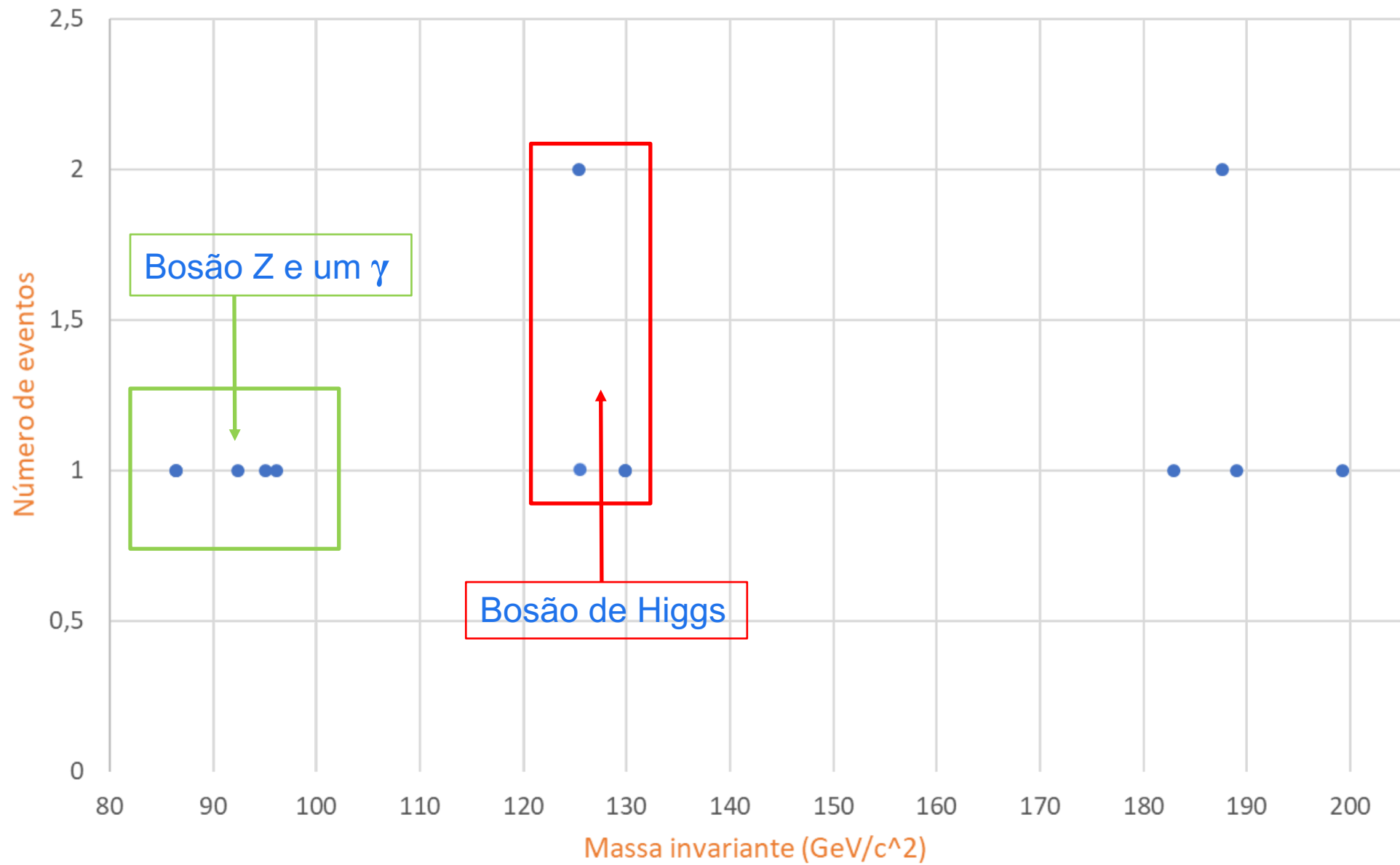
Eventos que decaíram em quatro leptões



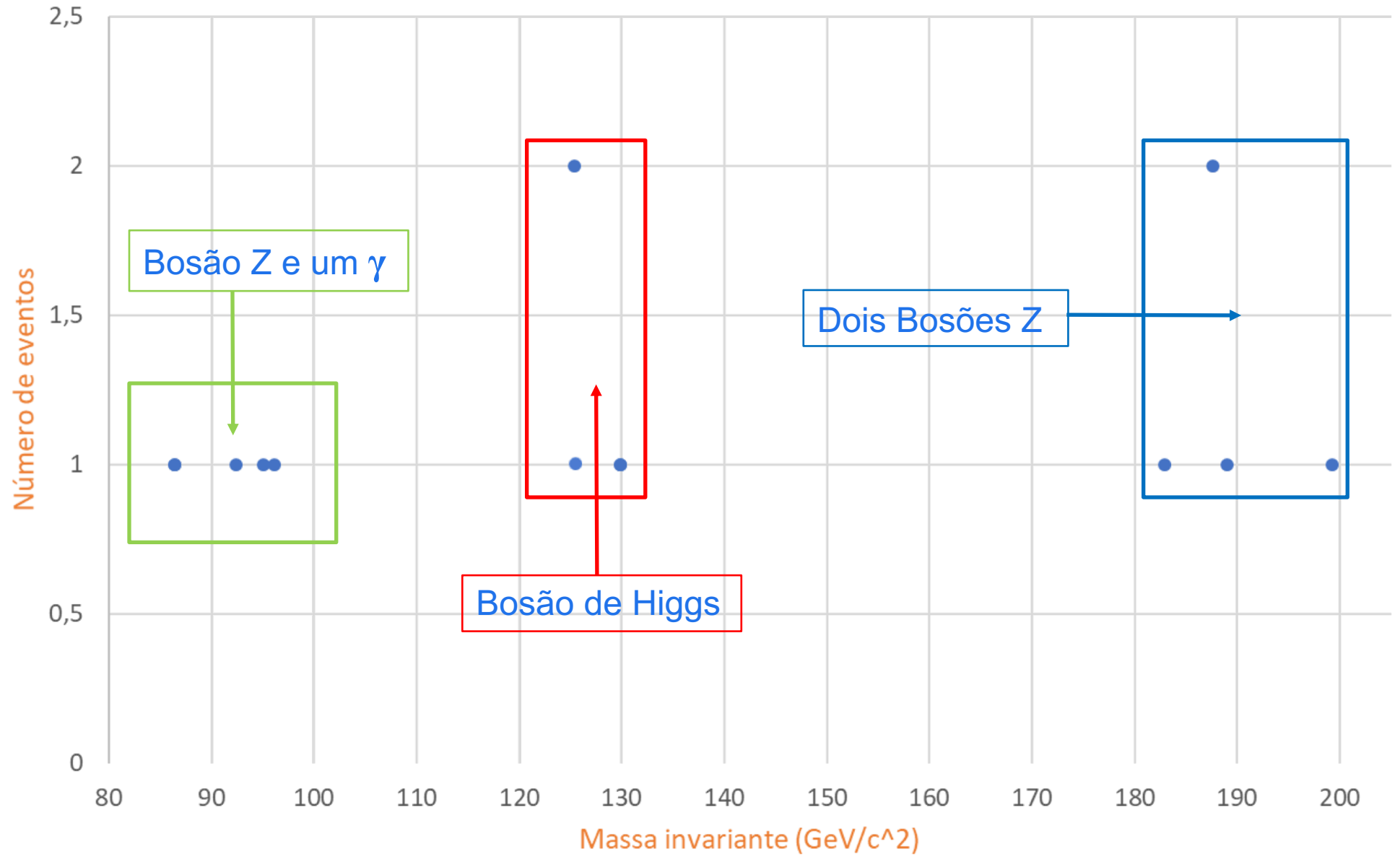
Eventos que decaíram em quatro leptões



Eventos que decaíram em quatro leptões

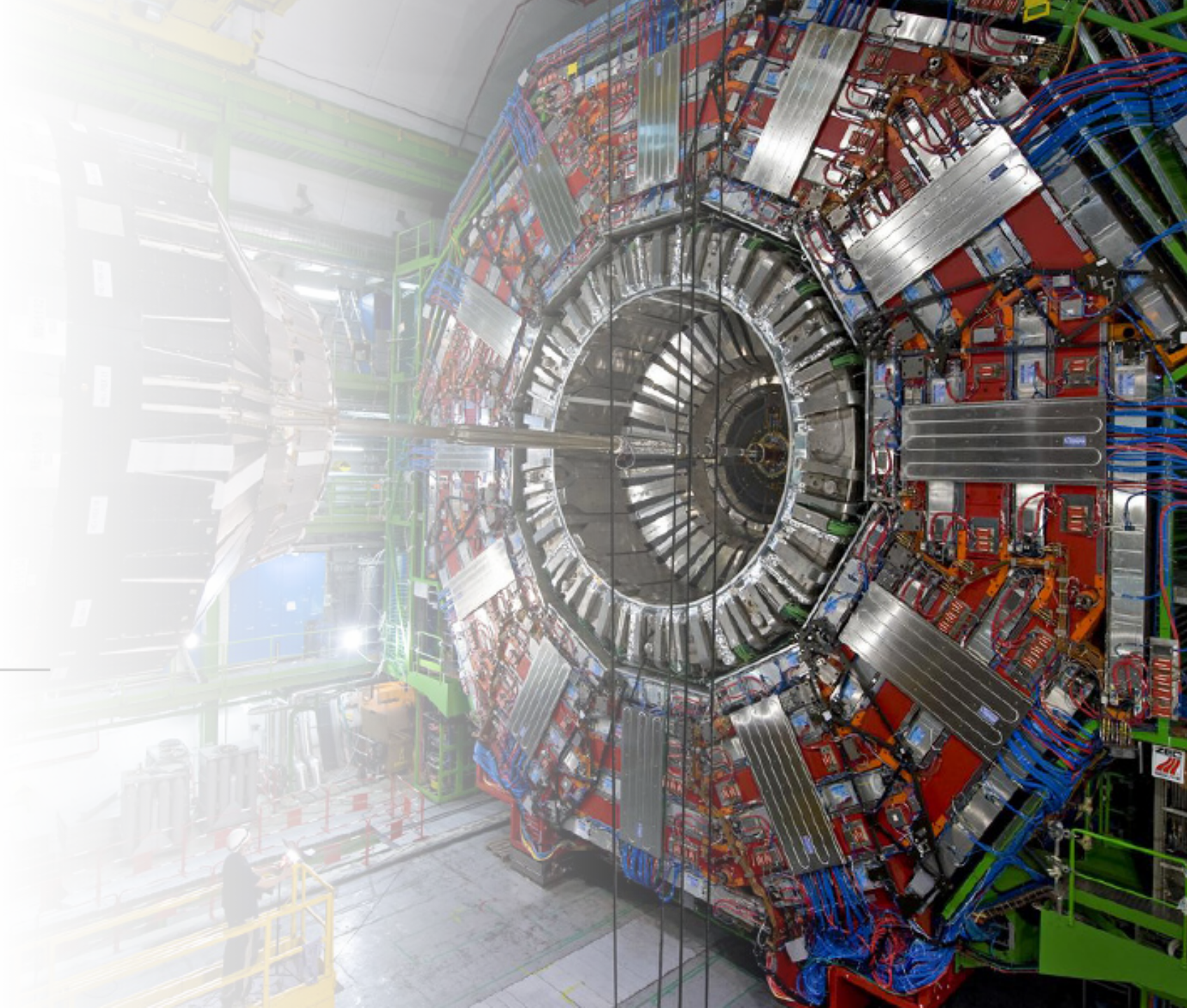


Eventos que decaíram em quatro leptões





Valores de massa invariante



Partícula	Bosão Z	Bosão de Higgs	Mesão J/ψ	Mesão Υ
Massa tabelada	91.1876 GeV	125.25 GeV	3.096 GeV	9.46 GeV
Massa experimental	88.9938 GeV	126.54 GeV	3.034 GeV	9.55 GeV
Erro experimental	0.7655 GeV	1.93 GeV	0.637 GeV	0.29 GeV

The background image shows a complex industrial environment, possibly a particle accelerator or a large-scale manufacturing plant. It features a series of large, blue, cylindrical components arranged in a line, with various pipes, cables, and mechanical parts. A yellow warning sign with a black symbol is visible in the upper center. The lighting is dim, with some warm, yellowish lights illuminating the scene.

Conclusão/Agradecimentos