

Universidade do Minho Escola de Ciências LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTÍCULAS partículas e tecnologia



Probing the Standard Model and Beyond at the LHC

Nuno Castro nfcastro@lip.pt

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Lisb@20







The Standard Model of Particle Physics particles & interactions



 $\begin{aligned} \mathcal{L} - (D_{\mu\nu} \phi)^{\dagger} D^{*} \phi - \mathcal{U}(\phi) - \frac{i}{4} F_{\mu\nu} F^{\mu\nu} F^{\mu\nu} \\ D_{\mu\nu} \phi = \partial_{\mu\nu} \phi - i a A_{\mu\nu} \phi \\ f_{\mu\nu} = \partial_{\mu\nu} A_{\nu} - \partial_{\nu\nu} A_{\mu\nu} \\ f_{\mu\nu} = \partial_{\mu\nu} A_{\nu} - \partial_{\nu\nu} A_{\mu\nu} \\ \mathcal{U}(\phi) = i a \phi^{\dagger} \phi + \beta (\phi^{*} \phi)^{2} \\ \mathcal{K} = \partial_{\mu\nu} \phi + \beta (\phi^{*} \phi)^{2} \\ \mathcal{K} = \partial_{\mu\nu} \phi + \beta (\phi^{*} \phi)^{2} \\ \mathcal{K} = \partial_{\mu\nu} \phi + \beta (\phi^{*} \phi)^{2} \\ \mathcal{K} = \partial_{\mu\nu} \phi + \beta (\phi^{*} \phi)^{2} \\ \mathcal{K} = \partial_{\mu\nu} \phi + \beta (\phi^{*} \phi)^{2} \\ \mathcal{K} = \partial_{\mu\nu} \phi + \beta (\phi^{*} \phi)^{2} \\ \mathcal{K} = \partial_{\mu\nu} \phi + \beta (\phi^{*} \phi)^{2} \\ \mathcal{K} = \partial_{\mu\nu} \phi + \beta (\phi^{*} \phi)^{2} \\ \mathcal{K} = \partial_{\mu\nu} \phi + \beta (\phi^{*} \phi)^{2} \\ \mathcal{K} = \partial_{\mu\nu} \phi + \beta (\phi^{*} \phi)^{2} \\ \mathcal{K} = \partial_{\mu\nu} \phi + \beta (\phi^{*} \phi)^{2} \\ \mathcal{K} = \partial_{\mu\nu} \phi + \beta (\phi^{*} \phi)^{2} \\ \mathcal{K} = \partial_{\mu\nu} \phi + \beta (\phi^{*} \phi)^{2} \\ \mathcal{K} = \partial_{\mu\nu} \phi + \beta (\phi^{*} \phi)^{2} \\ \mathcal{K} = \partial_{\mu\nu} \phi + \beta (\phi^{*} \phi)^{2} \\ \mathcal{K} = \partial_{\mu\nu} \phi + \beta (\phi^{*} \phi)^{2} \\ \mathcal{K} = \partial_{\mu\nu} \phi + \beta (\phi^{*} \phi)^{2} \\ \mathcal{K} = \partial_{\mu\nu} \phi + \beta (\phi^{*} \phi)^{2} \\ \mathcal{K} = \partial_{\mu\nu} \phi + \beta (\phi^{*} \phi)^{2} \\ \mathcal{K} = \partial_{\mu\nu} \phi + \beta (\phi^{*} \phi)^{2} \\ \mathcal{K} = \partial_{\mu\nu} \phi + \beta (\phi^{*} \phi)^{2} \\ \mathcal{K} = \partial_{\mu\nu} \phi + \beta (\phi^{*} \phi)^{2} \\ \mathcal{K} = \partial_{\mu\nu} \phi + \beta (\phi^{*} \phi)^{2} \\ \mathcal{K} = \partial_{\mu\nu} \phi + \beta (\phi^{*} \phi)^{2} \\ \mathcal{K} = \partial_{\mu\nu} \phi + \beta (\phi^{*} \phi)^{2} \\ \mathcal{K} = \partial_{\mu\nu} \phi + \beta (\phi^{*} \phi)^{2} \\ \mathcal{K} = \partial_{\mu\nu} \phi + \partial_{\mu\nu} \phi$

The Standard Model of Particle Physics probing it at colliders



The Large Hadron Collider and its detectors



The Large Hadron Collider and its detectors



The Large Hadron Collider and its detectors



The Large Hadron Collider and its detectors



The Large Hadron Collider and its collaborations





The Large Hadron Collider experiments what do we see?







The Large Hadron Collider experiments how to interpret what we see?







probe the Standard Model!

Comparing with theory predictions

excellent agreement

















probe the Standard Model - Higgs boson properties

machine learning:

decision trees







probe the Standard Model - and search for new phenomena beyond it!

- Why should we search for new physics beyond the Standard Model?
 - we *must* leave no stone unturned in data
 - ... and we have good motivations to think that new physics exists
 - mass hierarchy of the fermions
 - matter/anti-matter asymmetry
 - dark matter
 - I ...

probe the Standard Model - and search for new phenomena beyond it!

fγ .lete≑				$\int dt = 0$	3.2 - 79.8 th ⁻¹	1/c = 8 13 10/
f v lote:				J200 - (0.2 70.0) 10	γ ³ = 0, 10 10 V
r, y ueta	ET	∫£ dt[fb⁻	¹] Limit			Reference
$\begin{array}{cccc} 0 \ e, \mu & 1-4 \ j \\ 2 \ \gamma & - \\ - & 2 \ j \\ 2 \ 1 \ e, \mu & \geq 2 \ j \\ - & \geq 3 \ j \\ 2 \ \gamma & - \\ multi-channel \\ 1 \ e, \mu & \geq 1 \ b, \geq 1 \ J, \\ 1 \ e, \mu & \geq 2 \ b, \geq 3 \ . \end{array}$	Yes - - - 2j Yes j Yes	36.1 36.7 37.0 3.2 3.6 36.7 36.1 36.1 36.1	Ma Ma Ma Ma Ma Ma Ma Ma Ma Ma Ma Ma Ma M	7.7 TeV 8.6 TeV 8.9 TeV 8.2 TeV 9.55 TeV	$\begin{array}{l} n=2 \\ n=3 \; \text{HLZ NLO} \\ n=6 \\ n=6, M_D=3 \; \text{TeV, rot BH} \\ n=6, M_D=3 \; \text{TeV, rot BH} \\ k/\overline{M}_{PI}=0.1 \\ k/\overline{M}_{PI}=1.0 \\ \Gamma/m=15\% \\ \overline{\text{Tor}} \left(1,1,3 \\ k(A^{(1,1)} \to tt) = 1 \right. \end{array}$	1711.03301 1707.04147 1703.09127 1606.02265 1512.02586 1707.04147 CERN-EP-2018-179 1804.10823 1803.09678
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	- 2j Yes Yes Yes -	36.1 36.1 36.1 79.8 36.1 79.8 36.1 36.1 36.1	2' mass 45 TeV 2' mass 2.42 TeV 2' mass 2.1 TeV 2' mass 2.1 TeV 2' mass 2.1 TeV W mass 2.1 TeV V mass 3.0 TeV V mass 3.7 TeV V mass 2.30 TeV V mass 2.30 TeV	TeV	$\Gamma/m = 1\%$ $g_V = 3$ $g_V = 3$	1707.02424 1709.07242 1805.09299 1804.10823 ATLAS-CONF-2018-017 1801.08992 ATLAS-CONF-2018-016 1712.08518 CERN-EP-2018-142
- 2 j 2 e,μ - ≥1 e,μ ≥1 b,≥1 j	- Yes	37.0 36.1 36.1	Λ Λ Λ 2.57 TeV		21.8 TeV η_{lL}^- 40.0 TeV η_{lL}^- $ C_{4t} = 4\pi$	1703.09127 1707.02424 CERN-EP-2018-174
$\begin{array}{llllllllllllllllllllllllllllllllllll$	Yes Yes Yes	36.1 36.1 3.2	m _{med} 1.55 TeV m _{med} 1.67 TeV M, 700 GeV		$\begin{array}{l} g_{\rm q}{=}0.25, \ g_{\rm \chi}{=}1.0, \ m(\chi) = 1 \ {\rm GeV} \\ g{=}1.0, \ m(\chi) = 1 \ {\rm GeV} \\ m(\chi) < 150 \ {\rm GeV} \end{array}$	1711.03301 1711.03301 1608.02372
$\begin{array}{ccc} 2 \ e & \geq 2 \ j \\ 2 \ \mu & \geq 2 \ j \\ 1 \ e, \mu & \geq 1 \ b, \geq 3 \ j \end{array}$	- - Yes	3.2 3.2 20.3	LO mass 1.1 TeV LO mass 1.05 TeV LO mass 640 GeV		$egin{array}{ll} eta = 1 \ eta = 1 \ eta = 1 \ eta = 1 \ eta = 0 \end{array}$	1605.06035 1605.06035 1508.04735
multi-channel multi-channel X $2(SS)/\ge 3 e, \mu \ge 1 b, \ge 1 j$ $1 e, \mu \ge 1 b, \ge 1 j$ $0 e, \mu, 2 \gamma \ge 1 b, \ge 1 j$ $1 e, \mu \ge 4 j$	Yes Yes Yes Yes	36.1 36.1 36.1 3.2 79.8 20.3	T mass 1.37 TeV B mass 1.34 TeV Tugi mass 1.64 TeV W mass 1.44 TeV B mass 1.21 TeV G mass 69 GeV		$\begin{split} & \text{SU(2) doublet} \\ & \text{SU(2) doublet} \\ & \mathcal{B}(T_{5/3} \rightarrow Wt) = 1, \ c(T_{5/3} Wt) = 1 \\ & \mathcal{B}(Y \rightarrow Wb) = 1, \ c(YWb) = 1/\sqrt{2} \\ & \kappa_B = 0.5 \end{split}$	ATLAS-CONF-2018-032 ATLAS-CONF-2018-032 CERN-EP-2018-171 ATLAS-CONF-2016-072 ATLAS-CONF-2018-024 1509.04261
$\begin{array}{cccc} - & 2 \mathrm{j} \\ 1 \gamma & 1 \mathrm{j} \\ - & 1 \mathrm{b}, 1 \mathrm{j} \\ 3 \mathrm{e}, \mu & - \\ 3 \mathrm{e}, \mu, \tau & - \end{array}$		37.0 36.7 36.1 20.3 20.3	e' mas 60 e' mas 2.5 TeV 53 7 mas 2.6 TeV 2' mas 3.0 TeV * mas 1.6 TeV	D TeV TeV	only u^* and d^* , $\Lambda = m(q^*)$ only u^* and d^* , $\Lambda = m(q^*)$ $\Lambda = 3.0 \text{ TeV}$ $\Lambda = 1.6 \text{ TeV}$	1703.09127 1709.10440 1805.09299 1411.2921 1411.2921
$\begin{array}{cccc} 1 \ e, \mu & \geq 2 \ j \\ 2 \ e, \mu & 2 \ j \\ 2.3.4 \ e, \mu (SS) & - \\ 3 \ e, \mu, \tau & - \\ 1 \ e, \mu & 1 \ b \\ - & - \\ - & - \end{array}$	Yes - - Yes -	79.8 20.3 36.1 20.3 20.3 20.3 7.0	N ^A mass 550 GeV 2.0 TeV A ^A mass 870 GeV 147 mass 147 mass H ^A mass 657 GeV 147 mass 147 mass H ^A mass 757 GeV 147 mass 147 mass H ^A mass 785 GeV 147 mass 147 mass		$\begin{split} m(W_{\rm K}) &= 2.4 \text{ TeV, no mixing} \\ {\rm DY \ production} \\ {\rm DY \ production, \ } (H_{\ell^{\rm M}}^{\rm train} \to \ell \tau) = 1 \\ s_{\rm resort-m} &= 0.2 \\ {\rm DY \ production, \ } q = 5e \\ {\rm DY \ production, \ } g = 1 \\ g_{\rm C}, \ {\rm spin \ } 1/2 \end{split}$	ATLAS-CONF-2018-020 1506.08020 1710.09748 1411.2921 1410.5404 1504.04188 1509.08059
	$\begin{array}{ccccccc} & 0 & c, \mu & 1 & - & z \\ & 2 & & & & & & & & \\ & 2 & & & & & &$	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$0 \in [n]$ $1 = 4$ y_0 (k_1, k_2) $2 \neq n = 2$ -2 (k_1, k_2) (k_2, k_2) $1 = (p + 2)$ $2 = 3$ (k_1, k_2) (k_2, k_2) $2 \neq n = 3$ -32 (k_1, k_2) (k_2, k_2) $2 = 2$ -32 (k_1, k_2) (k_2, k_2) $n = 2$ $2 = 3$ $n = 32$ (k_1, k_2) (k_2, k_2) $1 = (\mu_1 + 2) k_2 = 31$ (k_2, k_3) (k_3, m_3) (k_2, m_3) $1 = (\mu_1 + 2) k_2 = 31$ (k_3, m_3) (k_3, m_3) (k_3, m_3) $2 = (\mu_1 36)$ $2 m_3$ (k_3, m_3) (k_3, m_3) $1 = (\mu_1 + 2) k_2 = 1/2$ (k_3, m_3) (k_3, m_3) (k_3, m_3) $1 = (\mu_1 + 2) k_2 = 1/2$ (k_3, m_3) (k_3, m_3) (k_3, m_3) $n = (1 + 1) k_3 = 1/2$ (k_3, m_3) (k_3, m_3) (k_3, m_3) $n = (1 + 1) k_3 = 1/2$ (k_3, m_3) (k_3, m_3) (k_3, m_3) $n = (1 + 1) k_3 = 1/2$ (k_3, m_3) (k_3, m_3) (k_3, m_3) $n = (1 + 1) k_3 = 1/2$ (k_3, m_3) (k_3, m_3) (k_3, m_3) <	$ \begin{array}{cccccccccccccccccccccccccccccccccccc$

*Only a selection of the available mass limits on new states or phenomena is shown. †Small-radius (large-radius) jets are denoted by the letter j (J).

probe the Standard Model - and search for new phenomena beyond it!

- If we assume that the Standard Model is the low energy limit of a more general theory at higher energy
 - the Higgs boson mass can be calculable (and not a free parameter):

 $M_{H}^{2} = 3.2734594296342905438674964732159643$ -3.2734594296342905438674964732159645 =10^{-32} (in planck units) quantum corrections, e.g.

an example: the hierarchy problem

• The *natural* solution for this balancing in mass without fine-tuning is to have counter terms originating from new heavy particles (top partners)





an example: vector-like quarks

- Many different topologies
- Looking for extremely small signals
- Advanced analysis methods are mandatory!





an example: use of neural networks for classification problems



Each line in the graph represents a constant whose value is adjusted using the training data.

an example: use of neural networks for classification problems



an example: use of neural networks in searches





an example: use of neural networks in searches



an example: vector-like quarks



What's next? LHC and beyond







What's next? LHC and beyond





If you want to know more and keep an eye on the latest news... physics briefings



https://atlas.cern/updates/briefing https://cms.cern/cms-updates





http://opendata.atlas.cern





Thanks for your attention

Questions?

you can always reach me at nfcastro@lip.pt

When you ask for more data... ... more data is what you get!









Channel	Dataset	Reference	
ttH(bb)	36.1 fb ⁻¹ , 13 TeV	Phys. Rev. D 97, 072016	
ttH multi-lepton (mostly H→WW* and H→π)	36.1 fb ⁻¹ , 13 TeV	Phys. Rev. D 97, 072003	
ttH(ZZ*→4I) 79.8 fb ⁻¹ , 13 TeV			
ttH(ɣɣ)	79.8 fb ⁻¹ , 13 TeV	CERN-EP-2018-138 submitted to PLB	
ttH combination	36.1 - 79.8 fb⁻¹, 13 TeV		

probe the Standard Model!

Comparing with theory predictions

excellent agreement



probe the Standard Model - and search for new phenomena beyond it!



Ano

an example: vector-like quarks

