

Physics Beyond the Standard Model with the Large Hadron Collider

Inês Ochoa

7th Lisbon mini-school on Particle and Astroparticle Physics May 10, 2022

The Standard Model of Particle Physics



The Standard Model of Particle Physics



Then, in 2012...



The Higgs boson: the last piece of the Standard Model



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The Large Hadron Collider at CERN

CERN: Organisation européenne pour la recherche nucléaire Swiss/French border





What comes out of a proton-proton collision?



... for example, a pair of top-quarks





The detectors



The detectors





A pair of top-quarks as seen by the ATLAS detector



A pair of top-quarks as seen by the ATLAS detector



Quantum chromodynamics processes producing gluons and quarks that originate jets of particles



Quantum chromodynamics processes producing gluons and quarks that originate jets of particles



Run: 282712 Event: 474587238 2015-10-21 06:26:57 CEST

EXPERIMENT

Pile-up: collisions don't come one by one...



A Z boson decaying to two muons is recorded in a beam crossing with 65 (!) additional pile-up collisions.

 $\sqrt{\hat{s}} = 13 \text{ TeV}$

Pile-up: collisions don't come one by one...

Transverse momenta of tracks > 100 MeV

Transverse momenta of tracks > 1 GeV

Transverse momenta of tracks > 5 GeV



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 $\sqrt{\hat{s}} = 13 \text{ TeV}$

Physics with the LHC data



Physics with the LHC data

First step: rediscovering the Standard Model



Physics with the LHC data

Precisely measuring the Standard Model



Physics with the LHC data Measuring the Higgs Boson properties



Decay modes of the Higgs Boson



Physics with the LHC data Measuring the Higgs Boson properties



The Standard Model is not enough

The Higgs boson discovery was a groundbreaking achievement.

... but the Standard Model is an <u>incomplete</u> description of our Universe.

Plenty of open questions...

- What happened to all the antimatter?
- What is dark matter?
- What is dark energy?
- How does gravity come in?
- No explanation for masses of particles.
- No explanation for the number of generations.





What else could there be?



Heavy W' and Z' bosons and composite Higgs bosons to alleviate the naturalness problem?



Additional Higgs bosons to help explain the matter antimatter imbalance?



Dark matter candidates, such as sterile neutrinos, axions, supersymmetric particles, ...?



tau

electron neutrino

muon neutrino neutrino

sterile neutrino?





higgstan.com

https://arxiv.org/abs/1707.06958 https://arxiv.org/abs/2007.05293

How to make a search?

For example, search for a **new particle** (resonance) in a particular final state, e.g. W' into WH \rightarrow qqbb:



Small signals on top of large backgrounds: take advantage of advanced analysis methods such as **machine learning**



Perform a **statistical analysis** to determine whether the data is compatible with the presence of signal or not



For example, search for a **new particle** (resonance) in a particular final state, e.g. W' into $WH \rightarrow qqbb$:

How to make a search?



Small signals on top of large backgrounds: take advantage of advanced analysis methods such as **machine learning**



Perform a **statistical analysis** to determine whether the data is compatible with the presence of signal or not



Exciting hint / statistical fluctuation?30

New: anomaly detection

y

Weak supervision

https://arxiv.org/abs/2005.02983

CERN seminar

CWoLa

mixed sample 2 dN/dm_{res} sample background mixeg B (jet) signal C (jet)

Features of B, C

m_{res}





New: anomaly detection

Unsupervised learning





3-Prong: Leading Jet Anomaly Score After Transformation





"Beam splashes" to check that all instruments and software is running as expected

The LHC is back on!

Run 1 (2010-2012) @ 7, 8 TeV
Run 2 (2015-2018) @ 13 TeV
Run 3 (2022-2025) @ 13.6 TeV

New energy record! First stable beams expected in July.





How to stay up-to-date on CMS and ATLAS physics news





SEARCH FOR RARE PRODUCTION OF VECTOR BOSON PAIRS

READ MORE

The biggest achievement of the LHC so far has been the observation of a Higgs boson in 2012. This is an outstanding confirmation of what today is the established theory that describes the fundamental interactions of particles, known as the standard...

CERN Accelerating science IN A DETECTOR FAR. FAR SEARCHING FOR ELUSIVE TRAVELLERS BY TRACING

MUONS

"The important thing", said Einst questioning", and we, as human What is it all made up of? How c together? We've been yearning questions for aeons, with our co culminating.. READ MORE

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Briefings

9×10⁻⁶

ATLAS

√s_{NN} = 5.02 TeV Pb+Pb 2.2 nb⁻¹

04 0.5

an 260 nh

ATLAS



8 0-10% 8(T__)=0.9% 10-20% 8(T__)=1%

- 20-40% a(T)=2% - 40-80% a(T)=5% 60-80% &(T):e8% = co 8Lur 200 < p_ < 224 GeV

Mass matters - but it isn't the only thing!

The ATLAS Collaboration finds evidence of parton mass, colour-charge and radiation-pattern dependence in guark-gluon-plasma induced energy loss.

Physics Briefing I 27 April 2022

ATLAS gives new insight into dijet suppression in heavy-ion collisions

At the recent Quark Matter 2022 conference in Krakow, Poland, members of the ATLAS Collaboration presented a new study of "jets" of particles travelling through the QGP. The result provides new insight into dijet suppression due to interactions with the nuclear medium.

Physics Briefing | 22 April 2022

anti-k, R = 0.4

|y| < 2.1 $|\phi_1 - \phi_2| > 7\pi/8$ 0.6 0.7

Stay tuned for Run 3 results!

- Run 3 and beyond will deliver a much larger data rate.
- Unexpected surprises may still be around the corner...

Run: 207620 Event: 101402870 Date: 2012-07-29 Time: 00:05:11 UTC

Backup

e de trop

CERN open data



An Educational project in High Energy Physics

Physics with the LHC data ... including the W boson mass



Recent Tevatron result:

'Extraordinary' W boson particle finding contradicts understanding of how universe works Higgs Boson production at the LHC



The LHC datasets



Superconducting magnets to bend and focus the beam





Radio-frequency cavities to bunch and accelerate the protons



