Higgs boson and physics Beyond the Standard Model

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Who am I?

Ana Peixoto

- From Paredes de Coura to Braga
- PhD student in experimental particle physics
    - New physics interactions in the top quark sector
- Member of the ATLAS Collaboration at CERN since 2015

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Outline

Higgs boson and Beyond the Standard Model theories

Higgs boson

- → Mechanism
- → Discovery
- → Decays
- → Other channels discoveries
- → Couplings
- → Production in association with two top quarks

Beyond the Standard Model

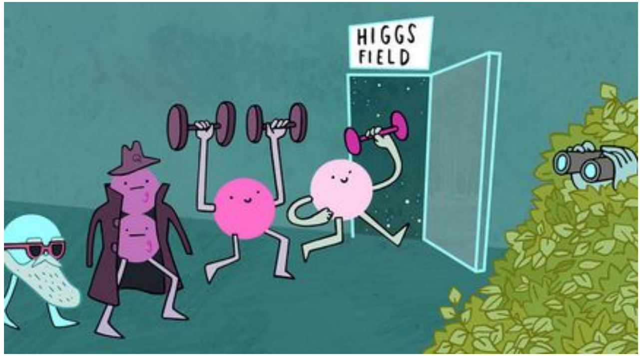
- → Motivation
- → Top quark
- → Additional Higgs bosons
- → Supersymmetry
- → Dark matter
- → Long-lived particles
- → Considerations while doing a search

Higgs boson

Mechanism, decays and couplings

Brout-Englert-Higgs mechanism
Higgs boson

Essential to explain the generation of the mass of gauge bosons through the addition of a quantum field named Higgs field that is everywhere around us (and it has the Higgs boson as its particle).



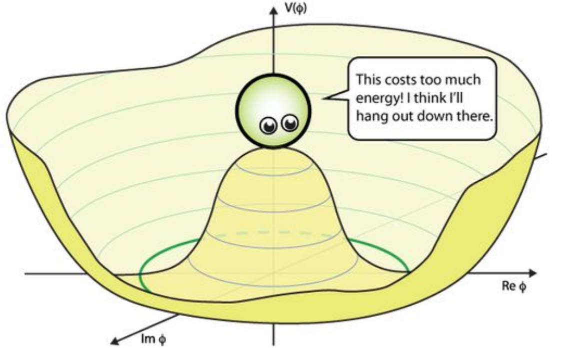
Proposed by three independent groups around 1964, the BEH mechanism solved the contradiction between massive particles and the requirement of gauge invariance. Such mechanism was incorporated into the Standard Model (SM) formulation by Steven Weinberg and Abdus Salam.

Brout-Englert-Higgs mechanism
Higgs boson

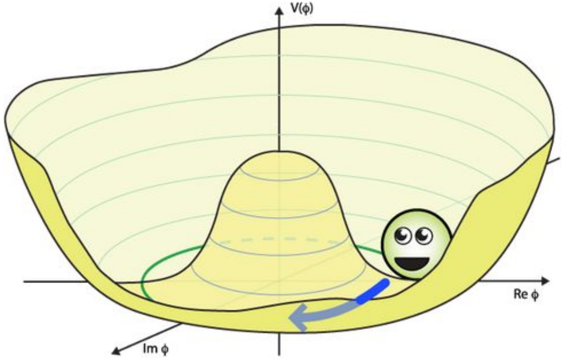
The masses of the weak gauge bosons ($W^{\pm}$ and Z) are generated by a electroweak symmetry breaking.

Fermions (quarks and leptons) also acquire mass as result of their interaction with the Higgs field (but not in the same way as the gauge bosons).

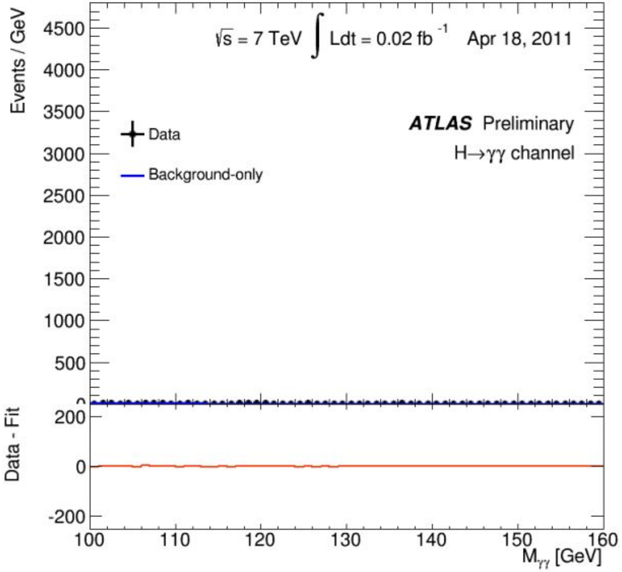
The Higgs field has a non-zero vacuum expectation value while not having a unique minimum.



$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2$$



Discovery
Higgs boson



After a successful Run-1 of the Large Hadron Collider (LHC), both ATLAS and CMS experiments discovered the final piece of the SM: the Higgs boson.

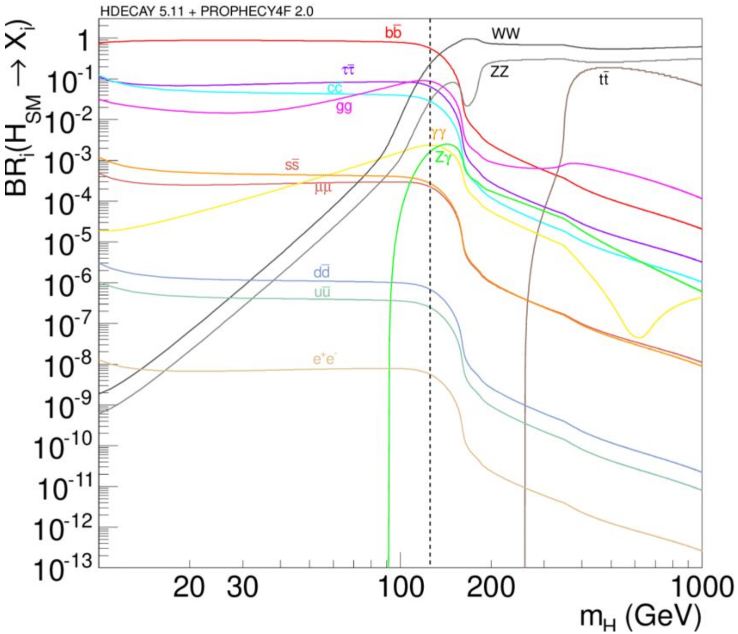
The observation of a Higgs boson-like particle was announced by both collaborations on 4 July 2012 through the diphoton channel with a mass around 125 GeV.

On 8 October 2013, the [Nobel prize in Physics] was awarded to François Englert and Peter Higgs for “the theoretical discovery of the origin of mass of subatomic particles”.

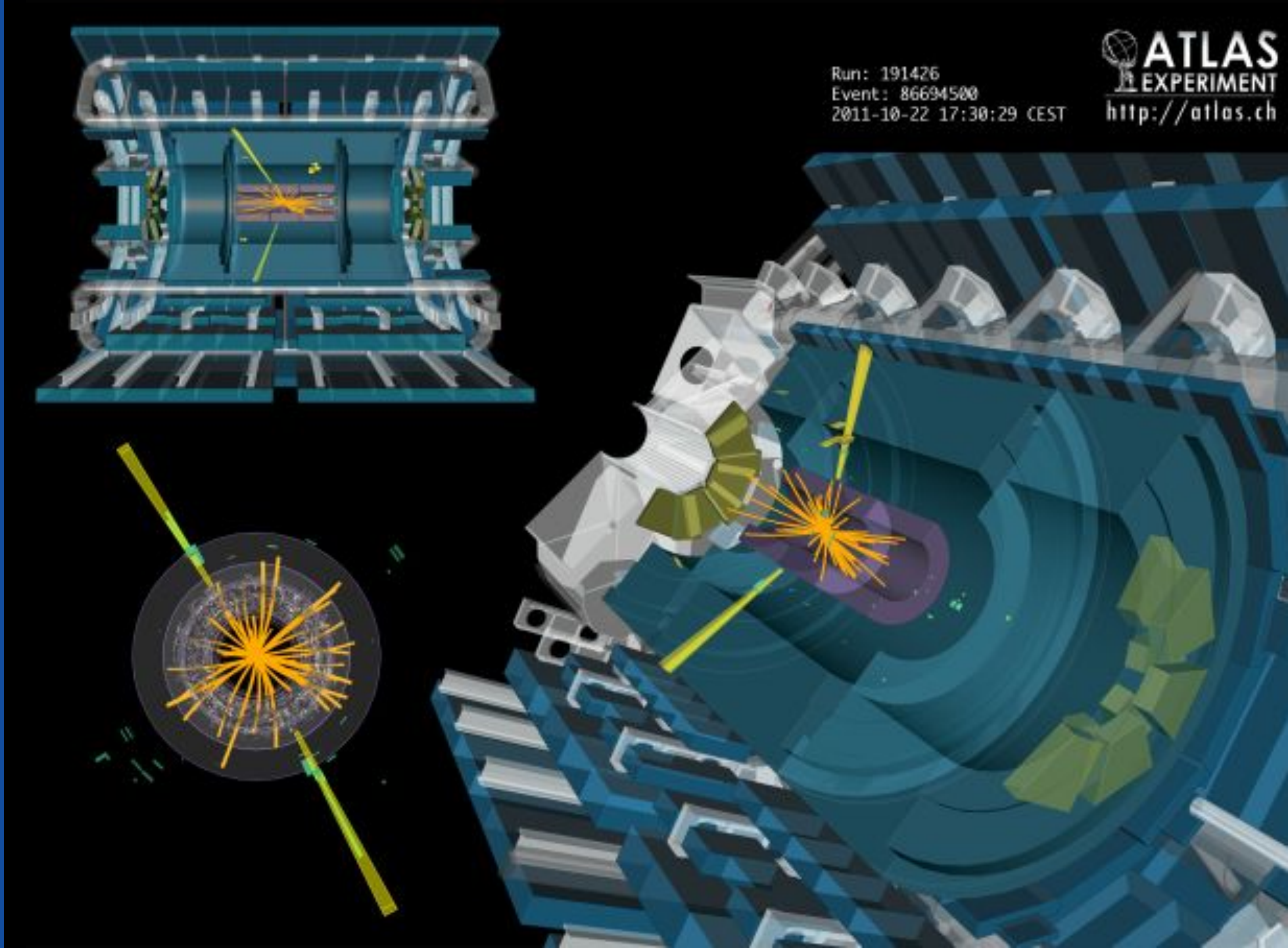
Decays
Higgs boson

There are distinct ways to produce and decay the Higgs:

- Significant difference between cross-sections and branching ratios with more than three orders of magnitude;
- Some channels with a “clean” final state but with a low branching ratio (*ZZ*, γγ);
- Some difficult to isolate but with a high probability to detect (*WW*, ττ, *bb*).



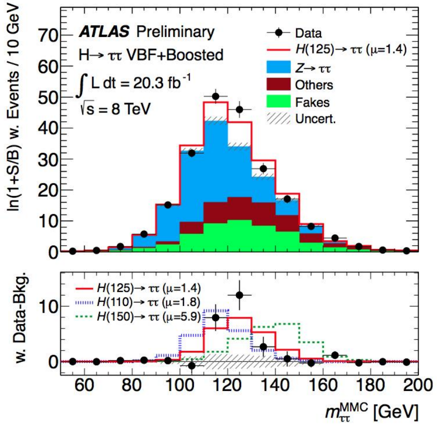
Higgs to two photons

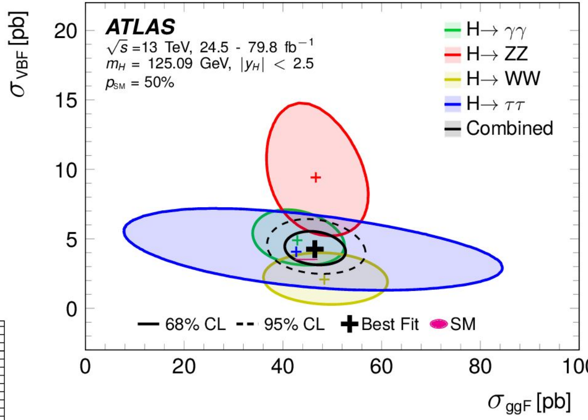


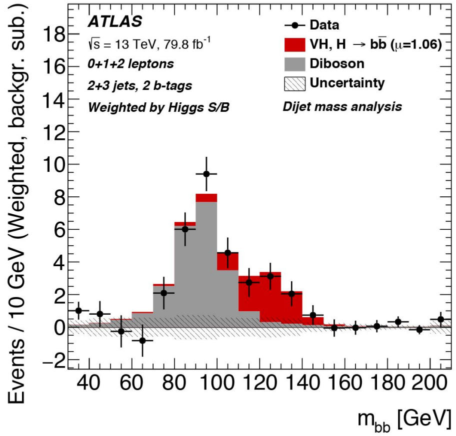
Discovery
Higgs boson

The Higgs boson decaying to *WW* and *ZZ* bosons and to taus were the following discoveries, revealing an exciting agreement with the SM expectation: 1.09 ± 0.07 (stat) ± 0.08 (syst) (by comparing data and prediction yields).

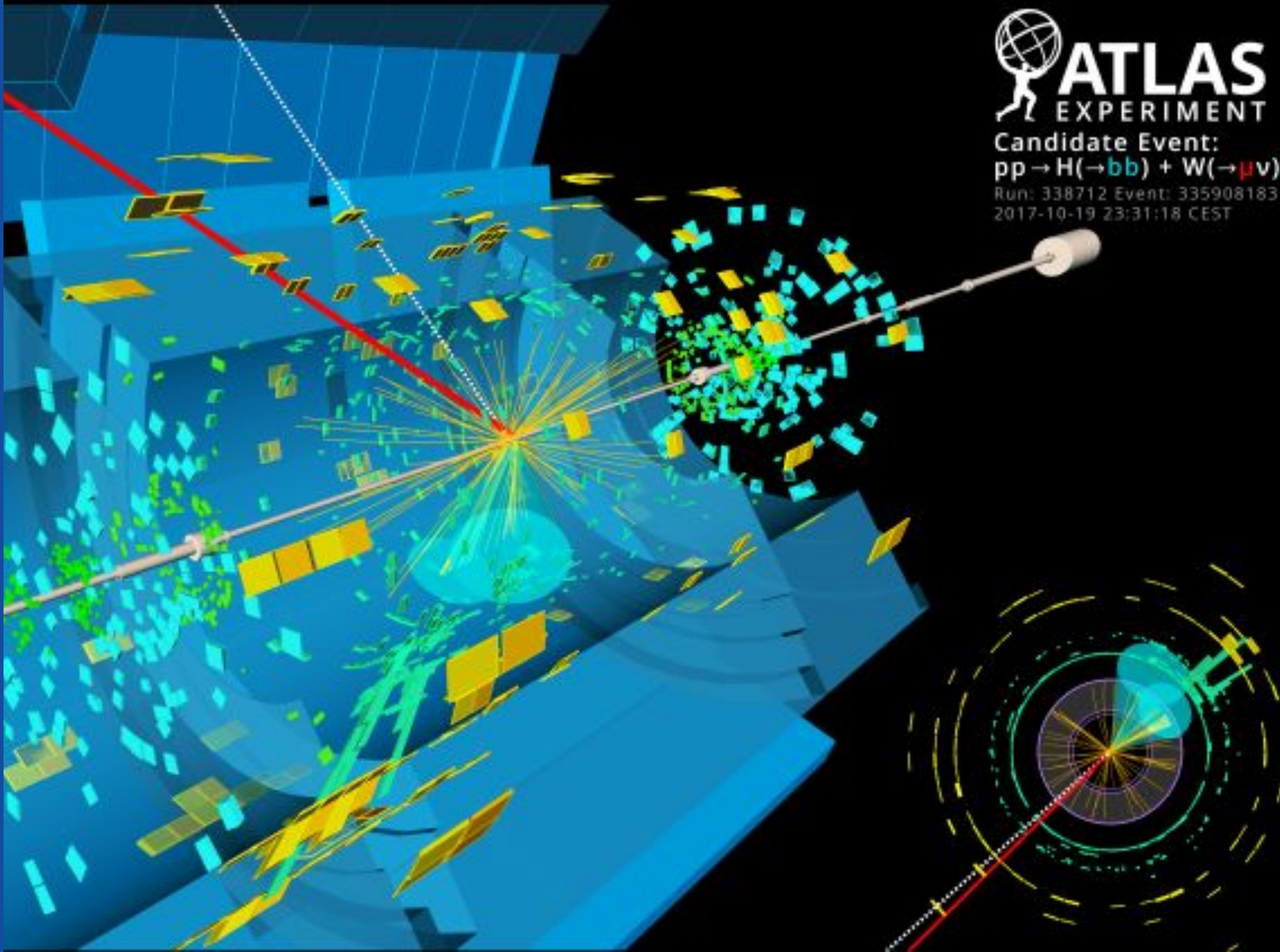
Decay to two bottom quarks is very challenging but its discovery was possible looking into the production of the Higgs boson in association with a vector boson.







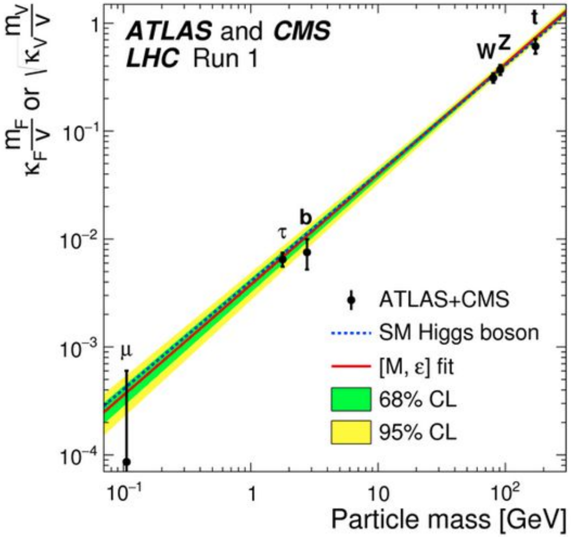
Higgs to two bottoms

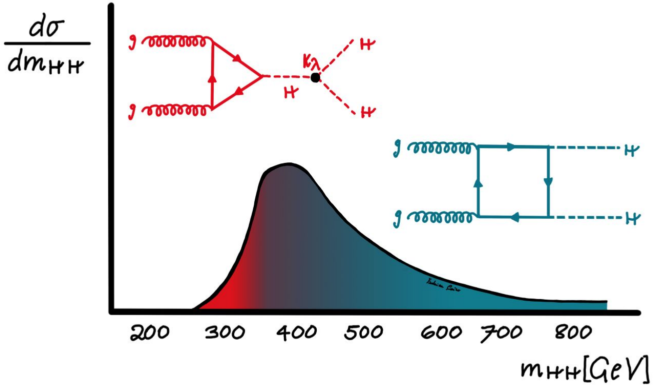


Couplings
Higgs boson

The BEH mechanism considers three distinct couplings with this scalar boson:

1) Coupling to the electroweak gauge bosons proportional to their square masses
   ⇒ Better measured coupling at the moment
2) Couplings to fermions proportional to the fermion mass named Yukawa couplings
   ⇒ Measured to muon (μ), taus (τ), bottom (*b*) and top (*t*) quarks
3) Self-coupling that can be triple or quadruple, which depends on the Higgs potential
   ⇒ Twice the Higgs, twice the challenge!

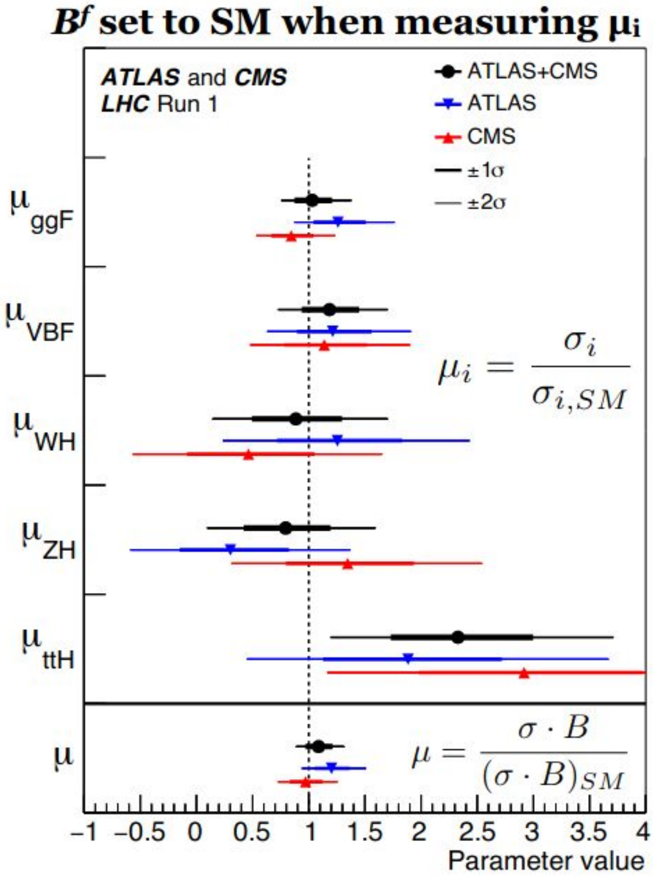




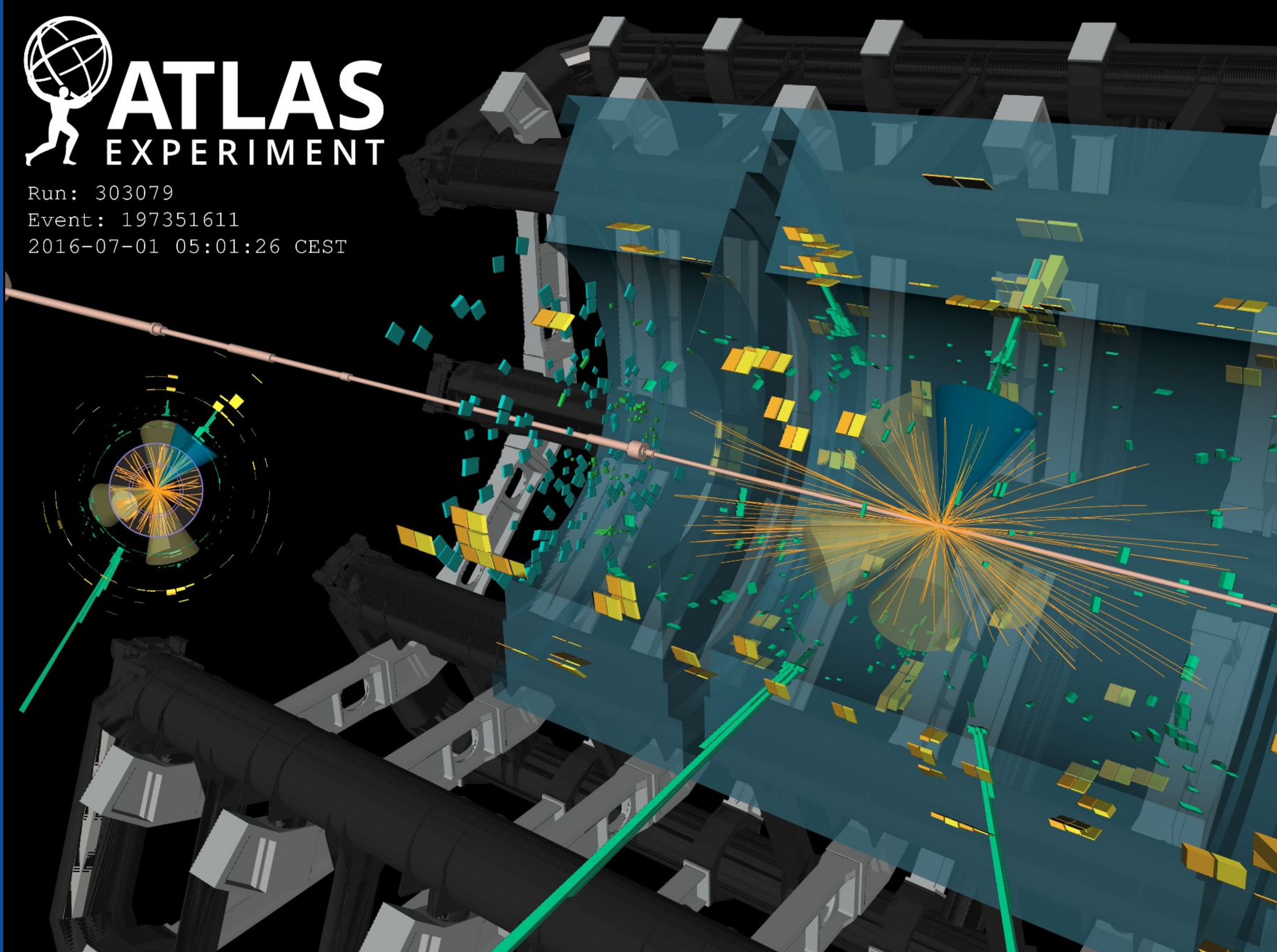
Measurements
Higgs boson

The discovery of the Higgs boson provided a new tool to search for new physics through precision measurements, while specific new physics scenarios are considered in direct searches.

A good example of these measurements is one of the most sensitivity tests of the Higgs mechanism, where the production of the Higgs boson together with a top quark pair (*ttH*) is studied.



Higgs with two tops



Beyond the Standard Model

Top quark, Higgs boson(s), Supersymmetry, Dark matter and Long-lived particles (but many more theories are predicted and being tested!)

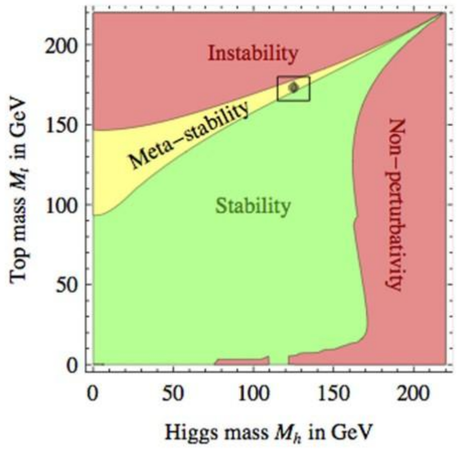
Why?

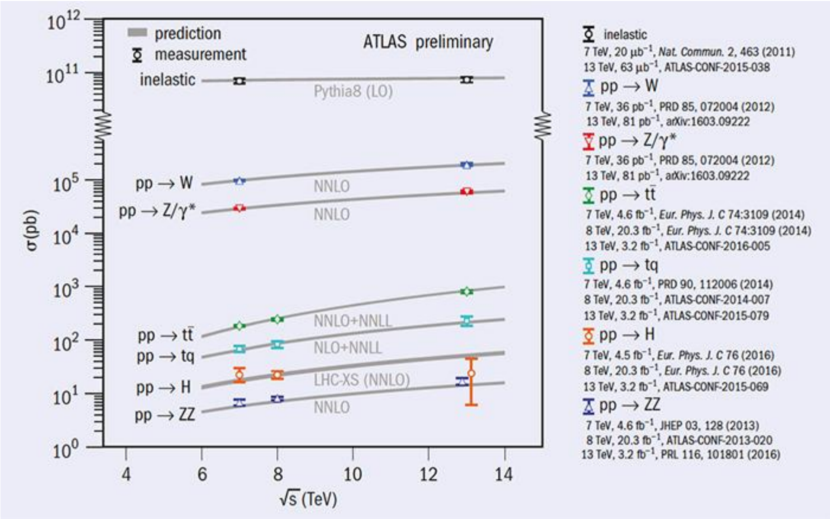
- ➔ Gravitational lensing and measurements of the rotation curves of galaxies leading to dark matter
- ➔ Matter and anti-matter asymmetry
- ➔ Neutrinos oscillations show that these particles are massive in contradiction with the SM formulation
- ➔ No particular reason to only have three generations
- ➔ Hierarchy mass of the fermions with significant difference between the three generations
- ➔ Why is the difference between the Higgs and other energy scales is so significant?

Top quark
Beyond the Standard Model

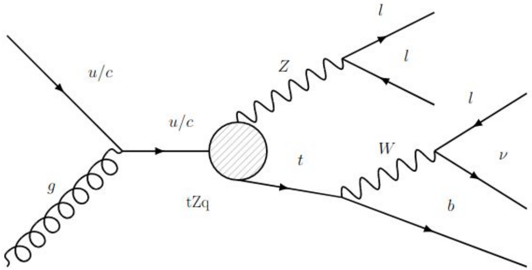
Largest correction to the Higgs boson mass comes from the top quark ⇒ Top quark might play a special role in the electroweak symmetry breaking mechanism and the mass hierarchy pattern.

Moreover, the top quark is one of the most produced particles at the LHC, around 275 million during LHC Run-2, providing crucial data to a thorough research.

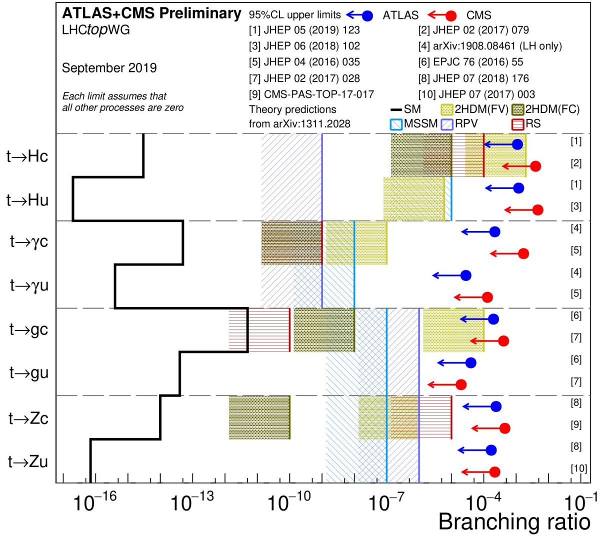




Top quark
Beyond the Standard Model

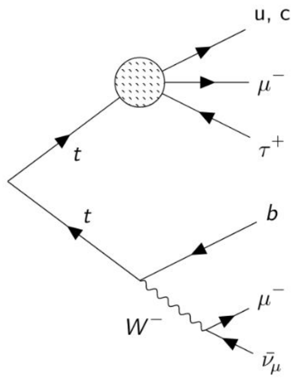


A fermion can change its flavour without changing its charge. Such interactions are forbidden at tree level and heavily suppressed at loop level by GIM mechanism in SM. Nonetheless, several BSM models lead to FCNC contributions, often at tree level.



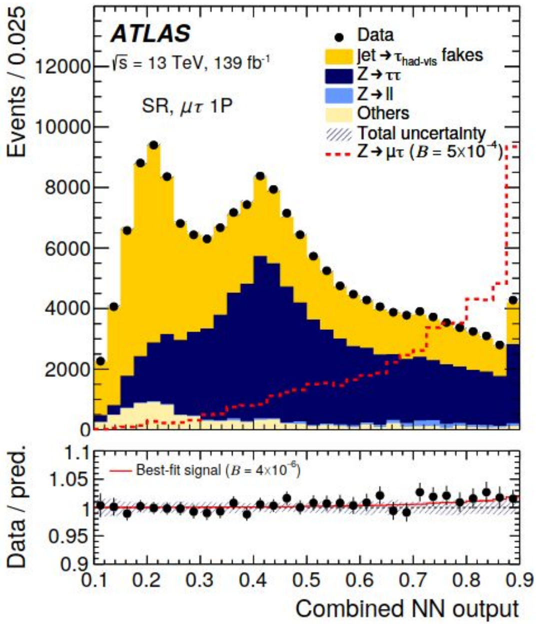
Top quark decays via FCNC presents a powerful probe of new physics since limits on these interactions can exclude or validate BSM models while their observation would be a direct proof of new physics.

Top quark
Beyond the Standard Model



Number of leptons in each family is conserved in interactions even though there is no fundamental principles imposing it. The observation of neutrinos oscillations has demonstrated that the lepton flavour in neutrino weak interactions is not conserved.

Therefore, searches for new physics can also consider charged lepton flavour violating decays. More specifically, searching for Z boson decays into a tau lepton and another lepton of different flavour (electron or muon) with opposite electric charge.

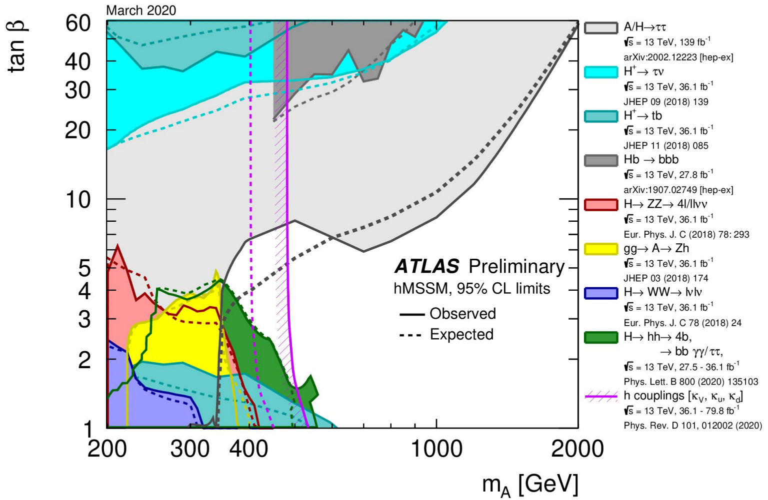


Higgs boson(s)

Beyond the Standard Model

While the SM predicts a Higgs boson, there are several BSM theories, as the Two Higgs Doublet Model (2HDM) and Minimal Supersymmetric Standard Model (MSSM), assuming additional Higgs bosons that can be charged or even pseudo-scalars.

The possibility of having a composite Higgs can be considered as well by providing the answers to the shortcomings of the SM and considering dark matter contributions.

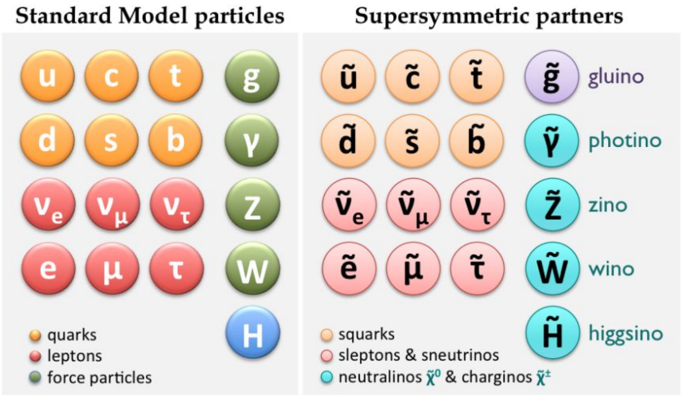


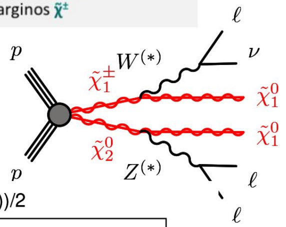
Supersymmetry
Beyond the Standard Model

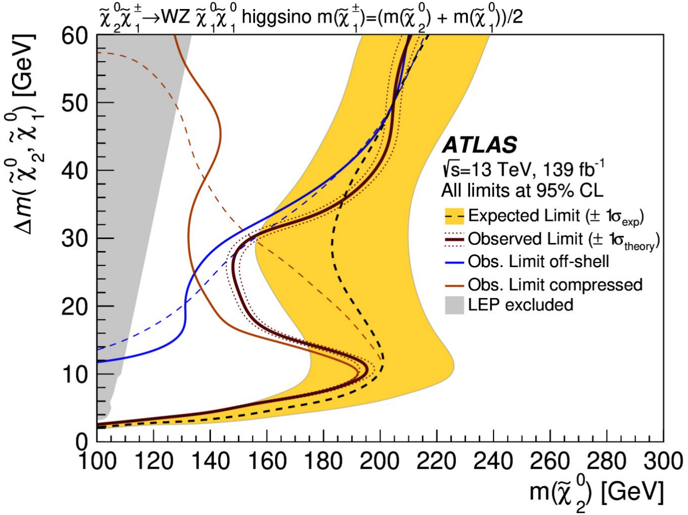
Probably the most famous BSM theory that postulates that each SM particle has a superpartner with a spin differing by a half-integer
⇒ A lot of particles to be discovered!

No evidence for these particles was discovered until the moment but an enormous effort is underway exploring all the different scenarios.

Besides the neutralinos, the supersymmetric partner of the bottom quark (the scalar bottom) is one of most sought-after new particles at the Large Hadron Collider.







Supersymmetry
Beyond the Standard Model

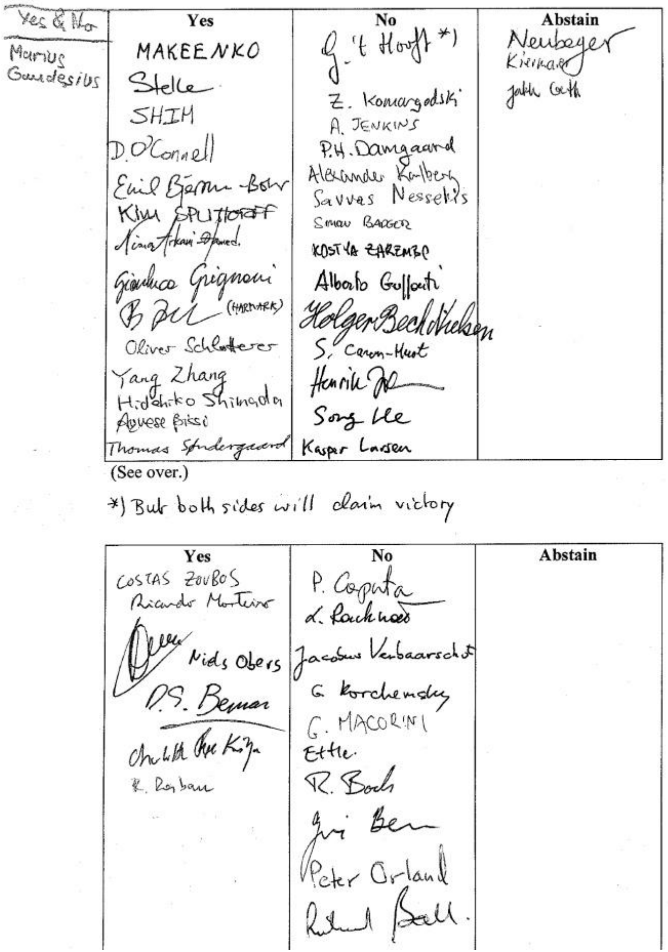
The expectation to such discovery at the Large Hadron Collider even motivated a curious wager:

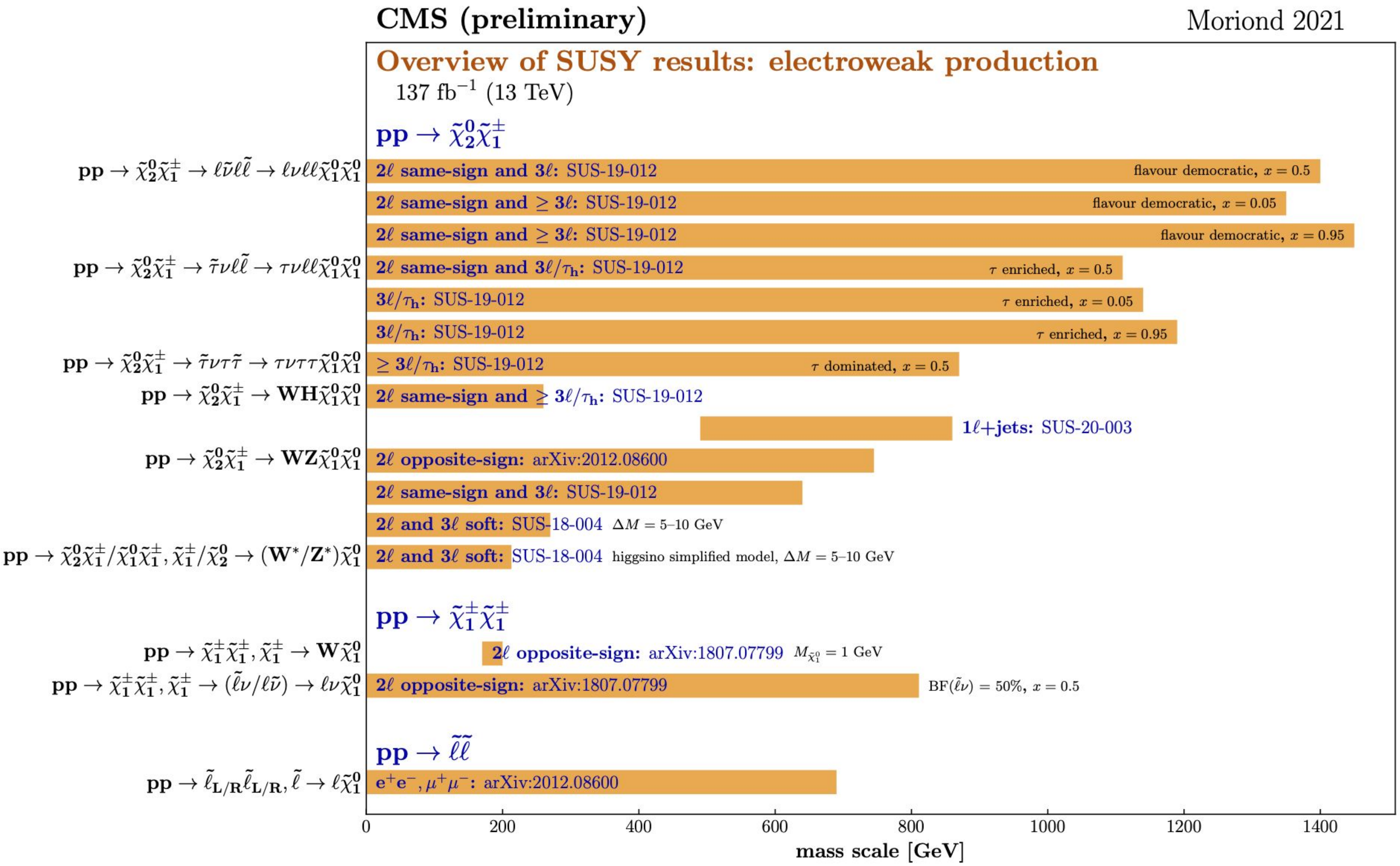
Wager on Supersymmetry

Question: Do you believe that by noon CET on June 16th, 2016, that at least one supersymmetric partner of any of the known particles will be experimentally discovered?

By signing "yes" or "no" you promise to deliver a bottle (75cl) of good cognac at a price not less than $100, in case you are wrong.

This is an addendum to the 2000 Wager on Supersymmetry. Those who signed the previous wager may either sign again (at a forfeit of two bottles of cognac) or accept they have suffered ignominious defeat.



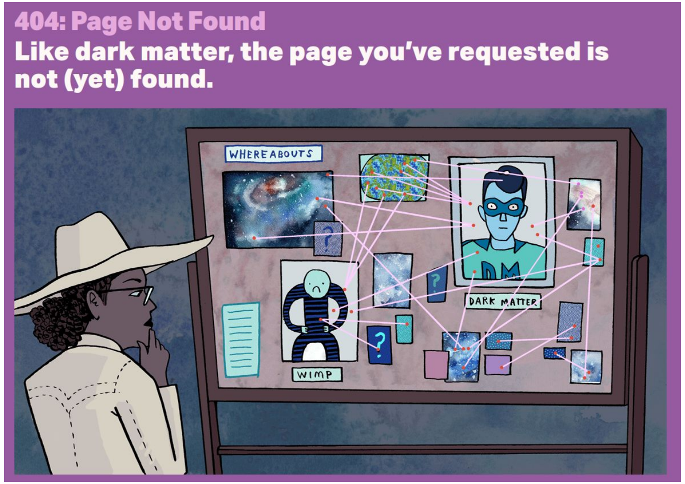


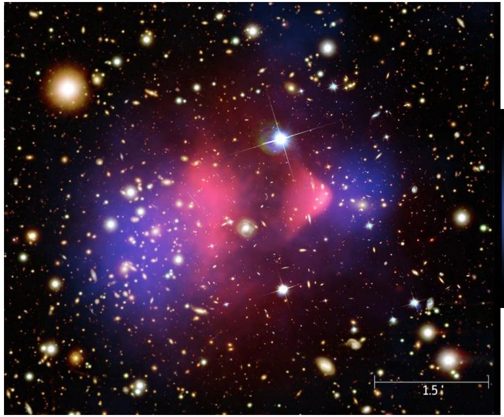
Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.

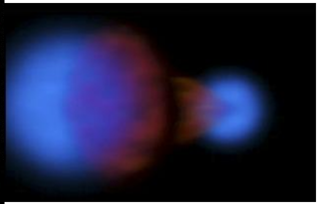
Dark matter
Beyond the Standard Model

Dark matter constitutes 26% of our universe while the known matter composes only 5%! Even knowing that the dark matter seems to be formed very early on in the universe history, there is no evidence of its decay yet. Therefore, it can be that dark matter particles are the most stable particles with a new kind of charge.

In fact, the dark matter is so non-reactive that it may not even interact with itself. As example, during the merge of two galaxies, the respective dark matter halos appears to simply pass through one another like ghosts.



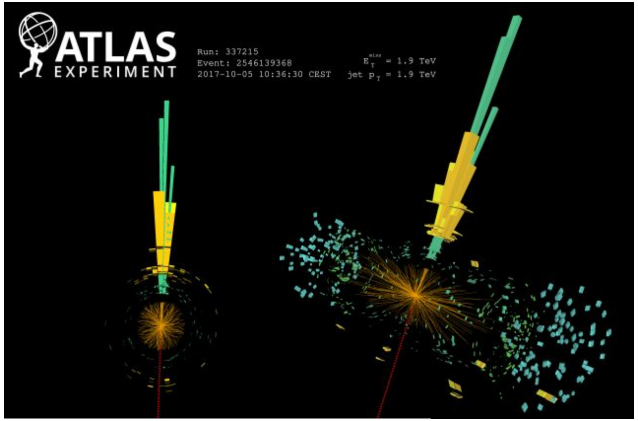


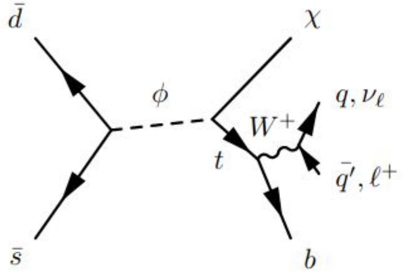


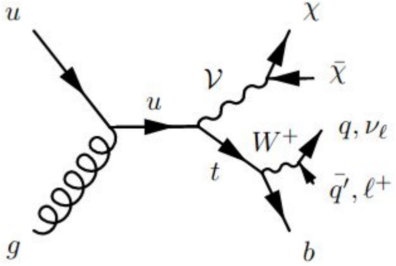
Dark matter
Beyond the Standard Model

While dark matter would escape the LHC detectors unseen, it could occasionally be accompanied by a visible jet of particles radiated from the interaction point, thus providing a detectable signal.

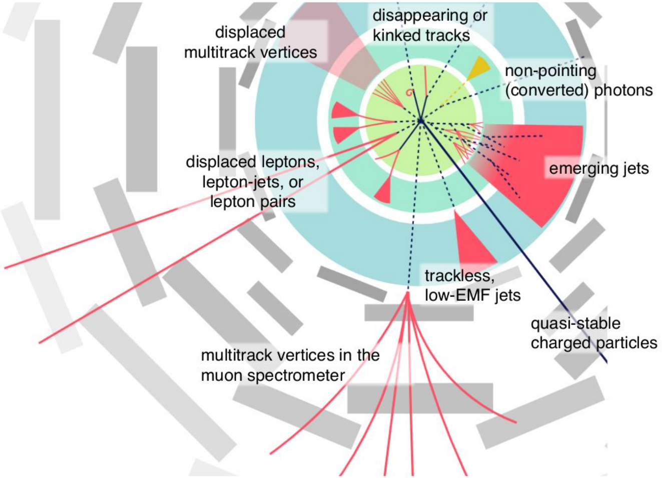
To identify such events, physicists can exploit the principle of momentum conservation in the transverse detector plane looking for visible jets recoiling from something invisible. As events with jets are common at the LHC, physicists further refined their parameters: the events had to have at least one highly energetic jet and significant missing energy, generated by the momentum imbalance of the “invisible” particles.







Long-lived particles
Beyond the Standard Model

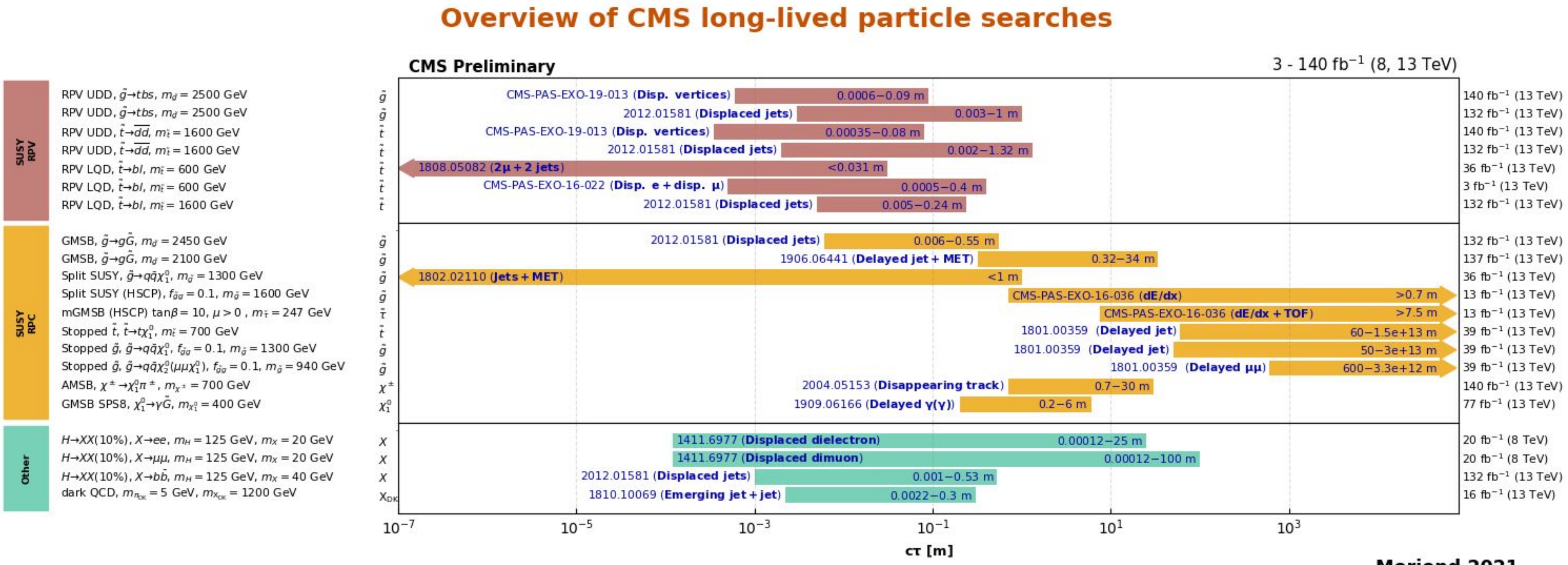


More unusual signatures of unknown physics, such as long-lived particles (LLPs), can be exploited by our particle physics detectors as well. These new particles would have lifetimes of 0.01 to 10 nanoseconds; for comparison, the Higgs boson has a lifetime of 10^{-22} seconds.

Since the particles created by the decay of a long-lived particle would appear away from the collision, unusual background sources can arise: photons mis-identified as electrons, muons that are mis-measured, and poorly measured cosmic-ray muons.

Long-lived particles - Current limits

Beyond the Standard Model

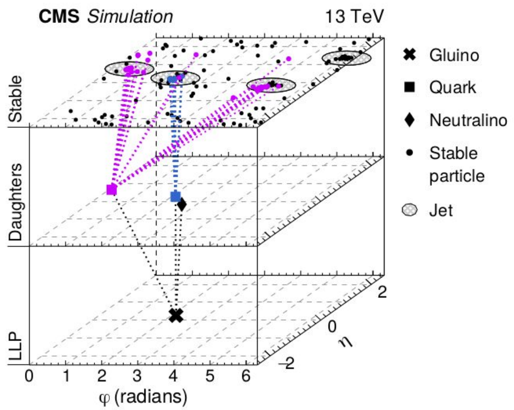


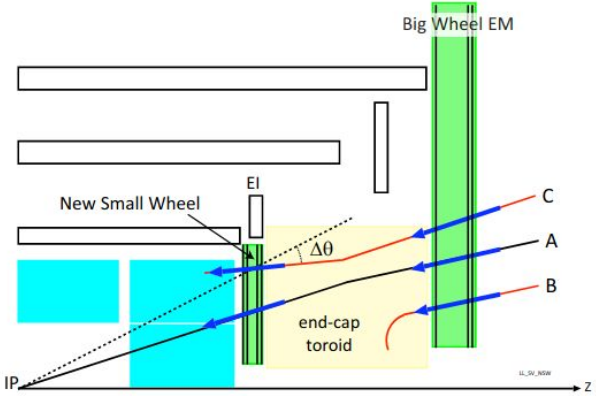
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

Long-lived particles
Beyond the Standard Model

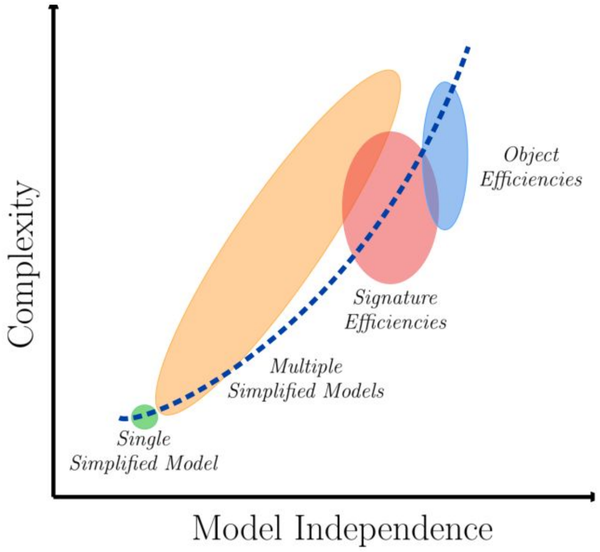
The development of machine learning techniques to improve the identification of the LLP particles is one of the biggest efforts in our community at the moment accompanied by important upgrades to the ATLAS, CMS and LHCb detectors on the tracker, calorimetry, muon, timing and trigger systems.

The data collected at the LHC during Run-1 and Run-2 constitutes the biggest dataset of the particle physics. Such data should be exploited in the best and distinct ways as possible. Simultaneously, the upgrades both on hardware and software of the experiments should remain to improve the measurements precision and provide hints for new physics.





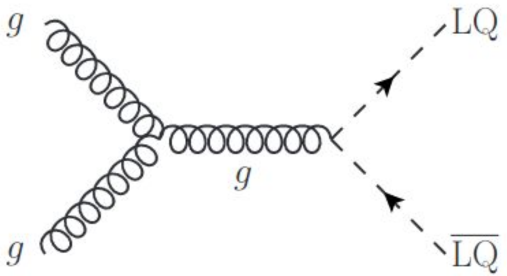
Considerations while doing a search
Beyond the Standard Model



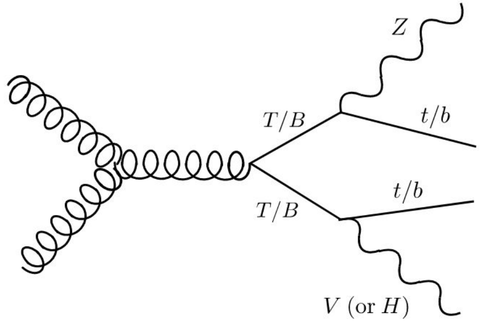
Every step of a search is crucial to the final result:

- Not every trigger can be used for all analyses;
- Detectors are not perfect: Mis-identification can happen and have a significant contribution to the event yields;
- Theory predictions may not be as precise as desired: Example of the *ttW* production;
- Object efficiencies, background normalisations and Monte Carlo simulation variations, among others, should be considered as systematic uncertainties.

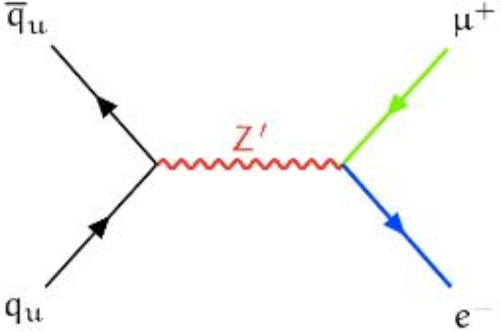
More New Physics models!
Beyond the Standard Model



The discussed scenarios of New Physics only reveal a small part of the several models currently being tested at the LHC Collaborations!

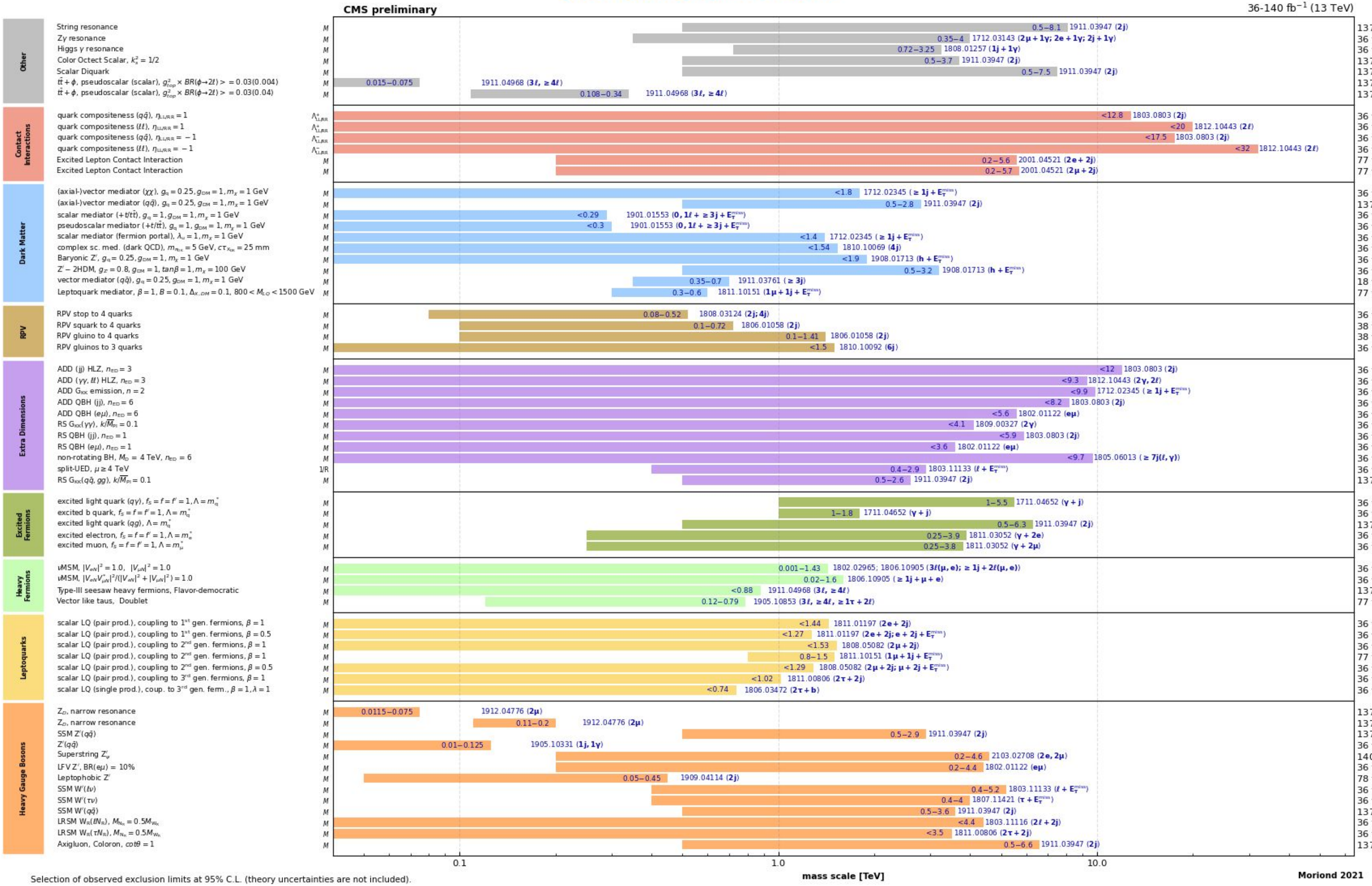


A wide range of BSM models (and equally exciting) also try to tackle the open questions caused by our experimental observations, such as leptoquarks, extra dimensions, excited fermions, heavy fermions (as Vector Like Quarks) and heavy gauge bosons (as *Z'* or *W'*), among others.



If no evidence for new physics is found after the data analysis, experimental limits on the masses and couplings are obtained for all these models and respective new particles.

Overview of CMS EXO results



Conclusions

- ➔ The current measurements of the Higgs boson properties indicate an agreement with the SM predictions, while a wide range of studies are underway to learn even more about this particle.
- ➔ New physics is here: both the Higgs boson and top quark opens the window for new interactions while models beyond the SM predict new particles.
- ➔ Improvements on the analysis methods and development of new Machine Learning algorithms to better distinguish signal from background are an important effort for all the LHC collaborations
- ➔ The High-Luminosity LHC is the future of CERN with crucial upgrades both from higher magnetic fields and new detectors, among others.

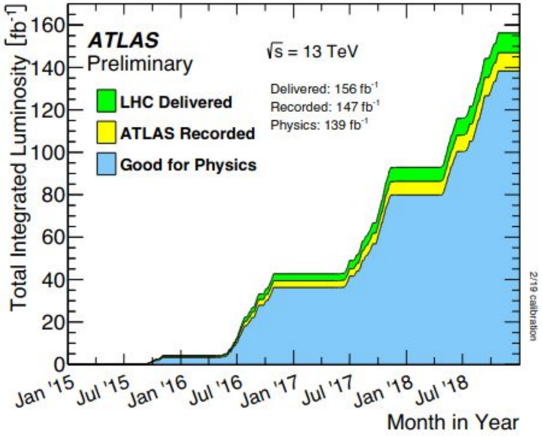
Thanks!

ATLAS Collaboration: https://atlas.cern/
CMS Collaboration: https://cms.cern/collaboration
CERN Courier: https://cerncourier.com/
Symmetry Magazine: https://www.symmetrymagazine.org/
LIP Youtube channel (with very interesting seminars):
https://www.youtube.com/user/webmasterlippt/videos

Curiosities
LHC Run-2

Run-2 dataset (2015–2018)

Excellent data-taking (94.2%) and data quality (94.6%) efficiency



Particle	Produced in 140 fb^{-1} pp at $\sqrt{s}$ = 13 TeV	
Higgs boson	7.8 million	
Top quark	275 million	(115 million $t\bar{t}$)
Z boson	8 billion	($\rightarrow \ell\ell$, 270 million per flavour)
W boson	26 billion	($\rightarrow \ell\nu$, 2.8 billion per flavour)
Bottom quark	~160 trillion	(significantly reduced by acceptance)

After an outstanding Run 2 — we have in our hands the richest hadron collision data sample ever recorded