With support from Fondecyt 11220237, 1201673 and ANID – Millennium Science Initiative Program ICN2019_044

The LHC is back in business !

Anomalies, the Standard Model and novel opportunities for the discovery of new physics

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News › News › Topic: Accelerators

Voir en français

Large Hadron Collider restarts

Beams of protons are again circulating around the collider's 27-kilometre ring, marking the end of a multiple-year hiatus for upgrade work

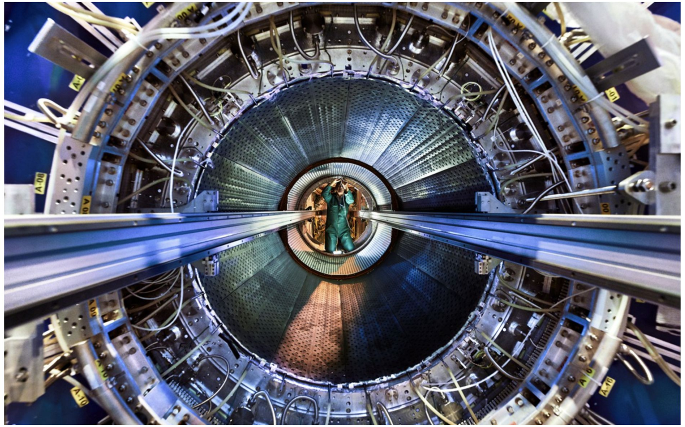
22 APRIL, 2022

NEWS FEATURE | 25 May 2022

How the revamped Large Hadron Collider will hunt for new physics

The particle-smashing machine has fired up again – sparking fresh hope it can find unusual results.

Elizabeth Gibney



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Scientists restart Large Hadron Collider in quest for dark matter

By Sara Spary, CNN
Updated 1304 GMT (2104 HKT) April 22, 2022

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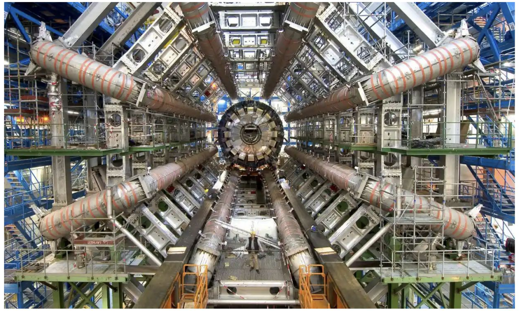
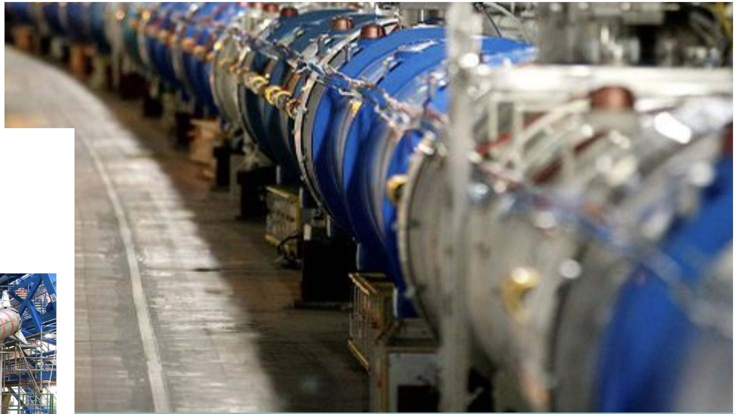
Large Hadron Collider to restart and hunt for a fifth force of nature

Latest run is expected to scrutinise findings from last year that may turn into another blockbuster discovery



The Large Hadron Collider has been given an upgrade ahead of its latest run, including the addition of powerful magnets designed to squeeze protons into finer, denser beams. Photograph: Cern/PA

The Large Hadron Collider (LHC) will restart on Friday after a three-year hiatus and is expected to resolve a scientific cliffhanger on whether a mysterious anomaly could point to the existence of a fifth fundamental force of nature.



Giovanna Cottin*
26 ABR 2022 01:57 PM
Tiempo de lectura: 3 minutos

El esperado reinicio del Gran Colisionador de Hadrones

QUÉ PASA Opinión Física

CERN video on LHC restart : https://www.youtube.com/watch?v=I5WYRo17LIs
CERN News : https://home.cern/news/news/accelerators/large-hadron-collider-restarts
Nature : https://www.nature.com/articles/d41586-022-01388-6
The Guardian UK: https://www.theguardian.com/science/2022/apr/21/large-hadron-collider-restart-fifth-force-nature
G. Cottin @QuePasa: https://www.latercera.com/que-pasa/noticia/el-esperado-reinicio-del-gran-colisionador-de-hadrones/

Outline

- LHC selected upgrades and measurements, *why* they *matter?*

- Theory meets reality : *how* could we ensure new physics won't be missed at the LHC?

- A case study : *if* new particles are long-lived, *what* could their discovery say about fundamental open questions in particle physics?

Background image @CMS, CERN

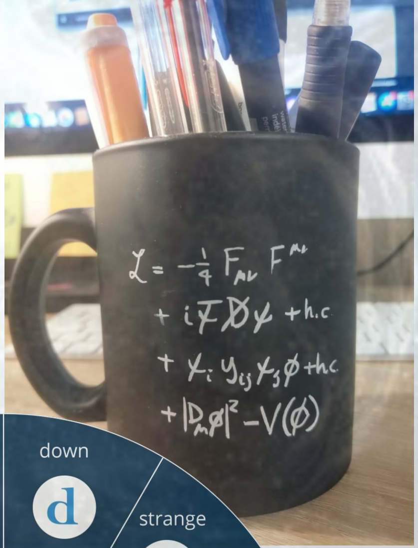
LHC selected upgrades and measurements, *why* they *matter?*

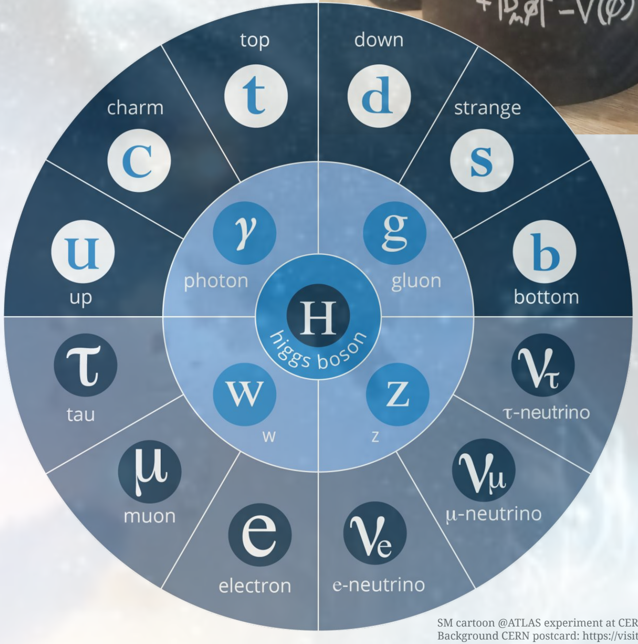
New physics beyond the Standard Model of particle physics is needed to explain small neutrino masses and the nature of particle dark matter, among others

New particles and interactions are predicted in several theoretical models to address the above

The LHC was built with the goal to find them !

“A machine built for the pursuit of pure knowledge”,
quote from *Nobel Dreams by Gary Taubes*

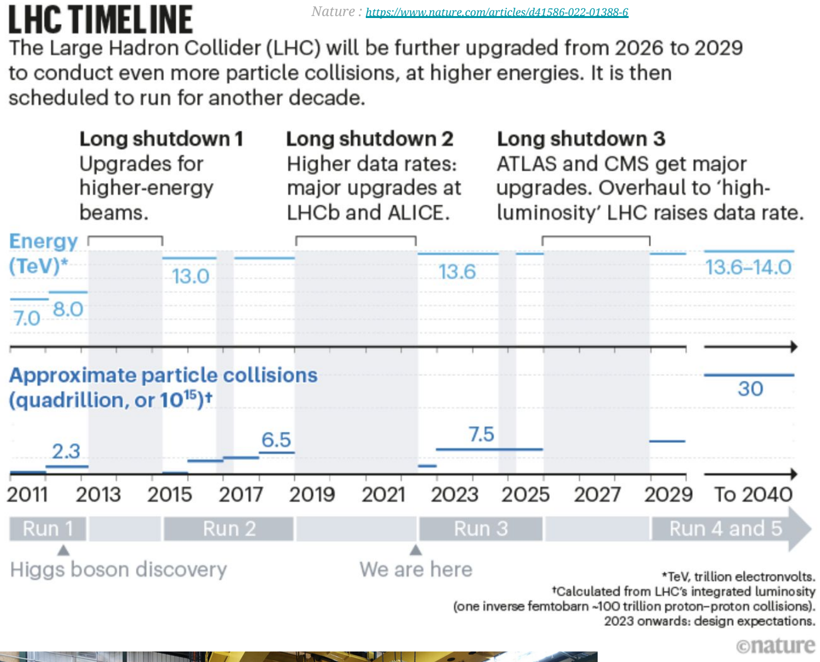




For a deep pedagogical explanation of this formula, see:
J. Woithe, G.J. Wiener, F. Van der Veken, Let's have a coffee with the Standard Model of particle physics!, Phys. Educ. 52 (2017) 034001

SM cartoon @ATLAS experiment at CERN
Background CERN postcard: https://visit.cern/node/614

Nature : https://www.nature.com/articles/d41586-022-01388-6



Limitations of this hunt

- New particles are too heavy to be produced
- Lack of precision/technology to detect them
- Lack of data to make discoveries
- Backgrounds from known particles are often huge

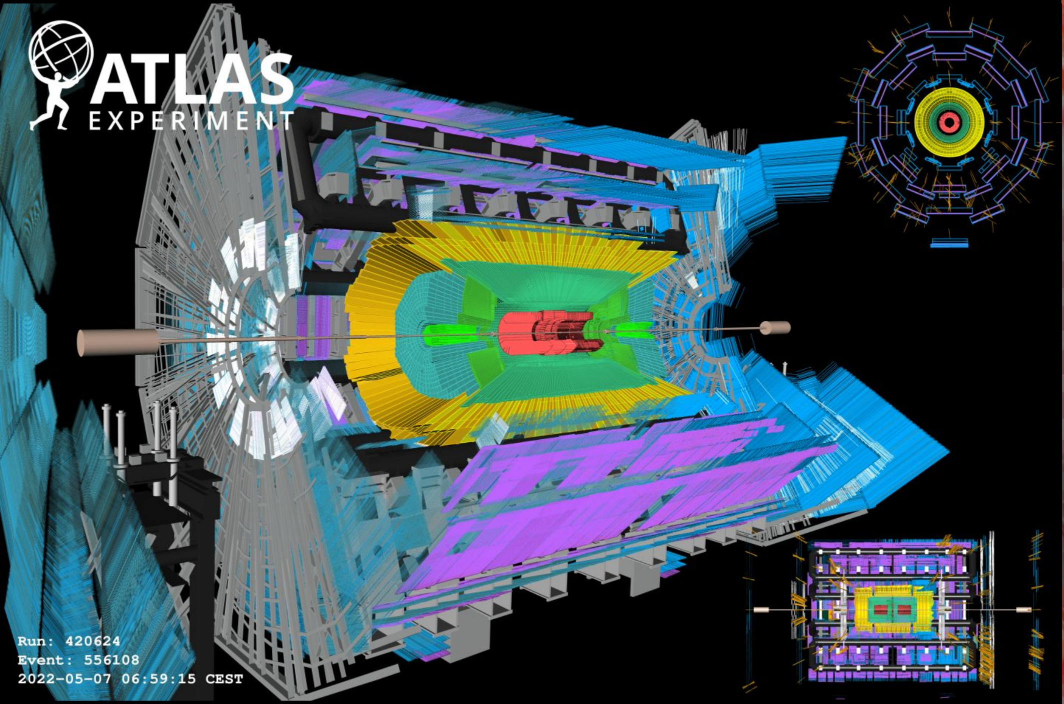
LHC upgrades to beat them

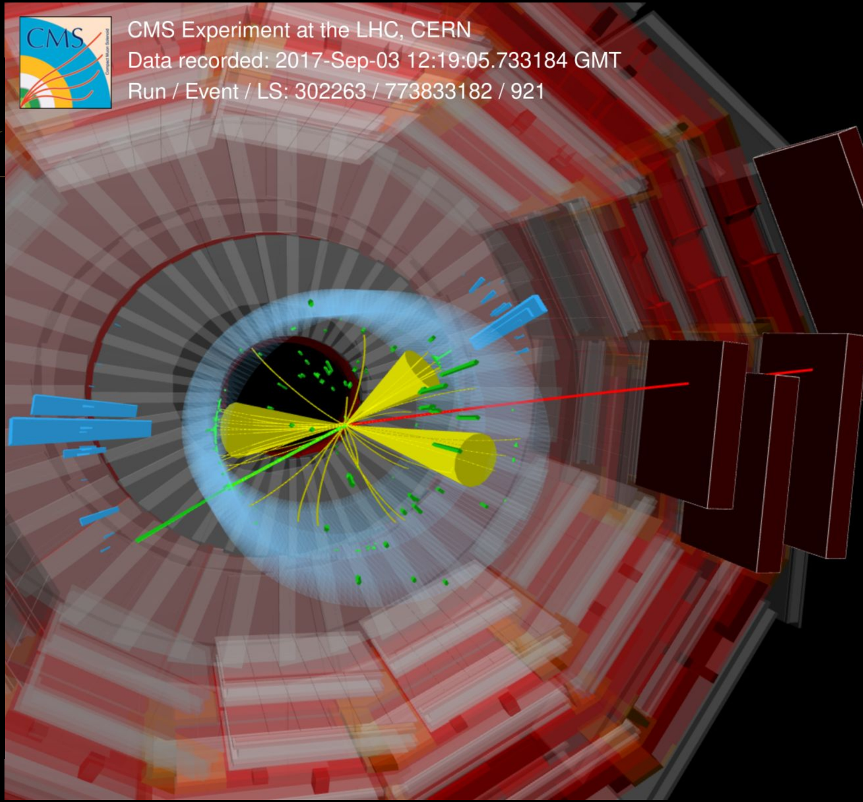
- Increase in *pp* c.o.m energies (to 13.6 trillion electron volts (TeV))
- Updated electronics and hardware, even entire new detectors
- More compact proton bunches, increasing the probability of collisions
- New triggers to select which events to save/new algorithms to process/analyze and reconstruct data

ATLAS New Small Wheel lowering @ Julien Marius Ordan, CERN

The experimental particle physics group at SAPHIR in Chile constructed part of the ATLAS muon detector !

SAPHIR Millennium Institute: https://www.institutosaphir.cl/
For more technical details on the upgrades, see Symmetry Magazine: https://www.symmetrymagazine.org/article/whats-new-for-lhc-run-3



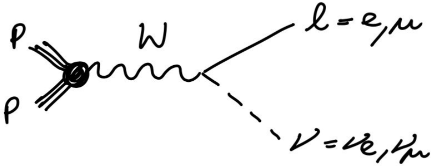


CERN Document Server: https://cds.cern.ch/
CMS-PHO-EVENTS-2022-002
ATLAS-PHOTO-2022-028

Examples of two LHC measurements: anomalies in the data could already be pointing to new physics?

W boson mass, measured in 2018 by the ATLAS collaboration, *Eur.Phys.J.C 78 (2018) 2*, arXiv:1701.07240

$$pp \to W^\pm \to \ell^\pm \nu$$

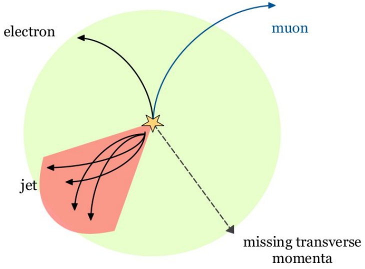


$$m_e^2 = E_e^2 - p_e^2$$
$$m_\nu^2 = E_\nu^2 - p_\nu^2$$

$$p_T = (p_x, p_y)$$

$$m_W^2 = m_e^2 + m_\nu^2 + 2(E_e E_\nu - 2\vec{p}_e \cdot \vec{p}_\nu)$$
$$m_W^2 = \underbrace{(E_e + E_\nu)^2 - (\vec{p}_{Te} + \vec{p}_{T\nu})^2}_{\equiv\, m_T^2} - (p_{ze} + p_{z\nu})^2$$

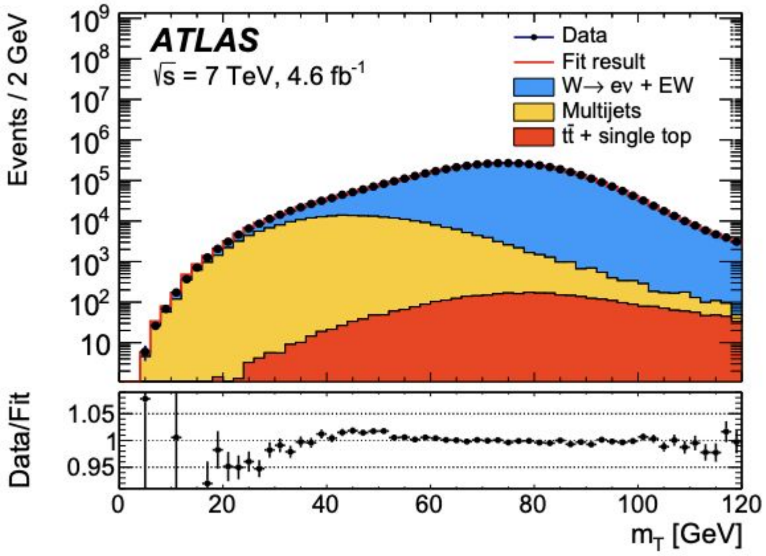
$$\vec{p}_T^{\,miss} \equiv -(\vec{p}_{Te} + \sum_i \vec{E}_i) \quad \text{with } i \text{ all visible}$$



$$m_T^2 \equiv 2 p_{Te}\, p_T^{miss} (1 - \cos\Delta\phi) \to$$ this can be experimentally reconstructed from data

$$m_T^2 \leq m_W^2$$

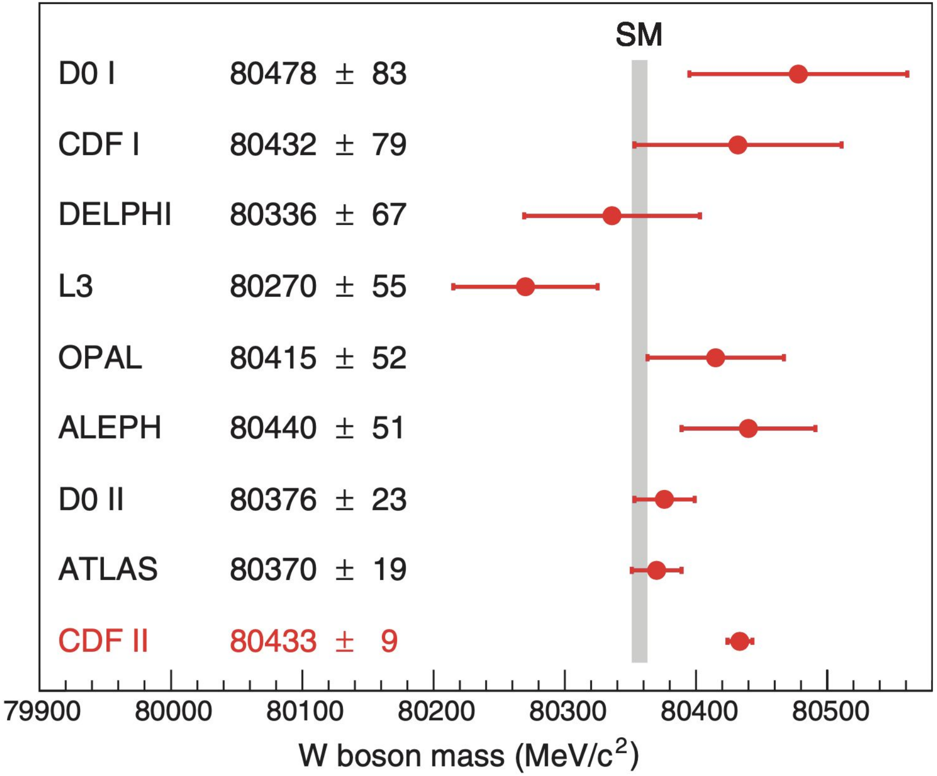
Mass extraction from templates that fit the kinematics, i.e.



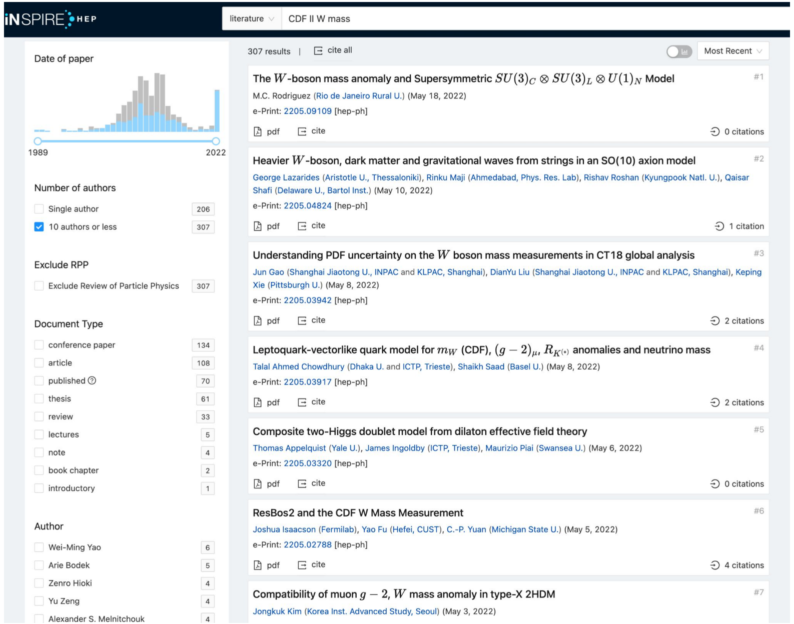
Run 3 of the LHC of top importance to elucidate this world tension

CDF result reports a difference with a significance of 7sigma w.r.t the SM prediction

High-precision measurement of the W boson mass with the CDF II detector, CDF Collaboration, [Science 376, 170–176 (2022)]



“Ambulance chasing” with over 300 theory interpretations!



Can read more about the tension in: [https://www.symmetrymagazine.org/article/whats-up-with-the-w-boson-mass]

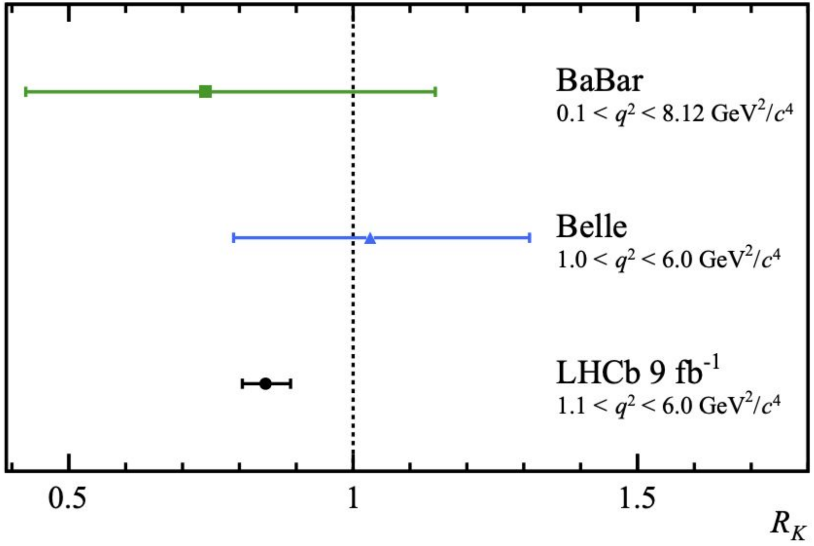
Sane words about the statistical confusion of the measurements in: http://resonaances.blogspot.com/

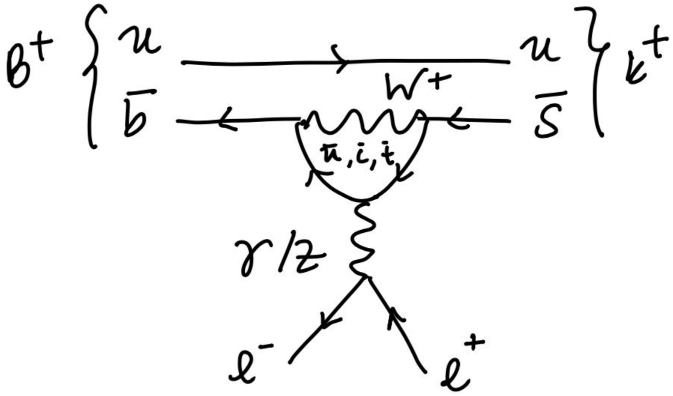
Run 3 of the LHC important to elucidate longstanding B anomalies

Latest Rk measurement in 2022 by the LHCb collaboration reports a 3.1sigma deviation w.r.t the SM

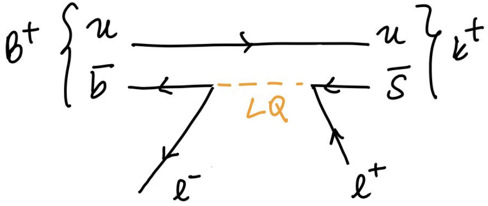
Test of lepton universality in beauty-quark decays, LHCb collaboration, Nature Phys. 18 (2022) 3, 277-282, [arXiv:2103.11769]

$$R_K = \frac{Br(B^+ \to K^+ \mu^+ \mu^-)}{Br(B^+ \to J/\psi(\to \mu^+\mu^-) K^+)} \Big/ \frac{Br(B^+ \to K^+ e^+ e^-)}{Br(B^+ \to J/\psi(\to e^+ e^-) K^+)}$$





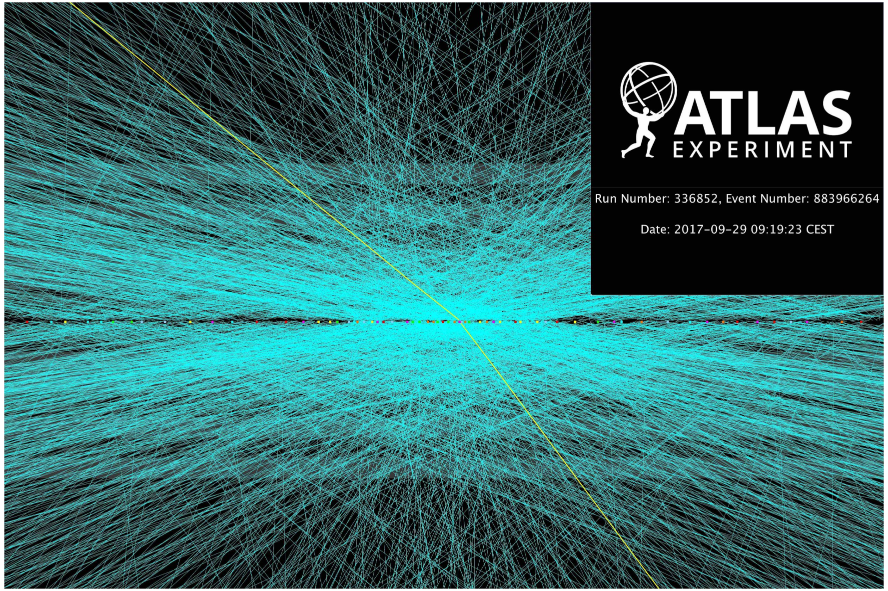
Popular theoretical models to explain this include LQ and *Z', just browse Inspire :)*



a leptoquark LQ could have diff. couplings with SM leptons

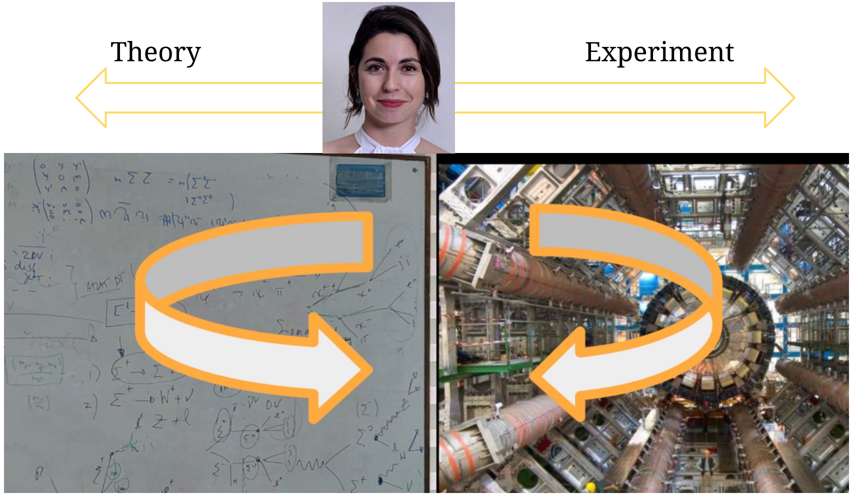
Theory meets reality : *how* could we ensure new physics won't be missed at the LHC?

Particularly if the LHC looks like this?



A complex scenario

A particle theorist/phenomenologist answer: By focusing on well motivated theoretical models with *exotic predictions* in terms of the experimental signatures they could yield



Make (one type of) lemonade to address the scenario, or "bottom-up" approach when choosing your favourite BSM model

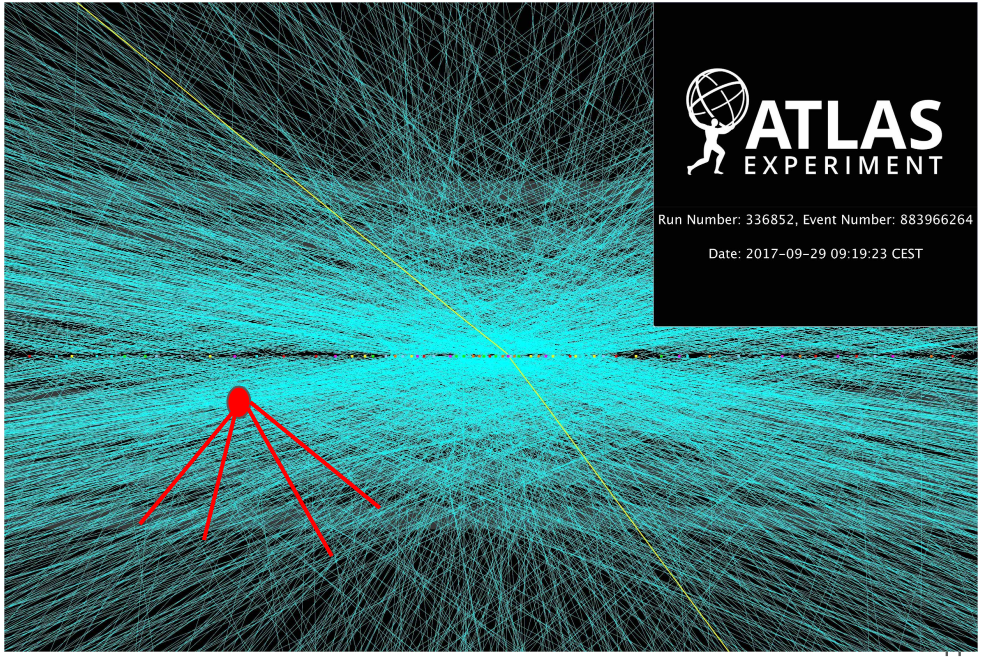
An exotic prediction: If new hypothetical particles have macroscopic lifetimes, they would decay displaced from the primary proton-proton interaction collision, yielding something exotic and more straightforwardly identifiable at the LHC

This is ONE motivation for defining a new lifetime or long-lived particle (LLP) physics frontier at the LHC. *For plenty more, see Long-lived Particle Community White Paper, J. Alimena , G. Cottin, et al, J.Phys.G 47 (2020) 9, 09050, arXiv:1903.04497 and MATHUSLA physics case motivating theoretical models, D. Curtin et al, arXiv:1806.07396*

Do not miss Ivania's talk for a motivation driven purely by dark matter !

LLPs are predicted in the Standard Model and in almost all our theories beyond the Standard Model (just need to get a small total decay width)

$$\Gamma \sim \lambda^2 \left(\frac{\Delta m}{\Lambda}\right)^n \Delta m \qquad c\tau \sim \Gamma^{-1}$$



Many LLP efforts worldwide!

https://lpcc.web.cern.ch/lhc-llp-wg

symmetry topics follow +

Illustration by Sandbox Studio, Chicago with Ariel D

Long-lived particles get their moment

08/18/20 | By Sarah Charley

Scientists on experiments at the LHC are redesigning their methods and buildin supplemental detectors to look for new particles that might be evading them.

CERNCOURIER | Reporting on high-energy physics

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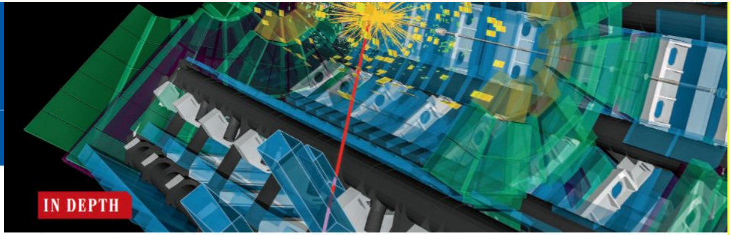
SEARCHES FOR NEW PHYSICS | MEETING REPORT

Long-lived particles gather interest

21 July 2021



IN DEPTH

In a simulated event, the track of a decay particle called a muon (red), displaced slightly from the center of particle collisions, could be a sign of new physics.

PARTICLE PHYSICS

A hunt for long-lived particles ramps up

The Large Hadron Collider could be making new particles that are hiding in plain sight

By **Adrian Cho**

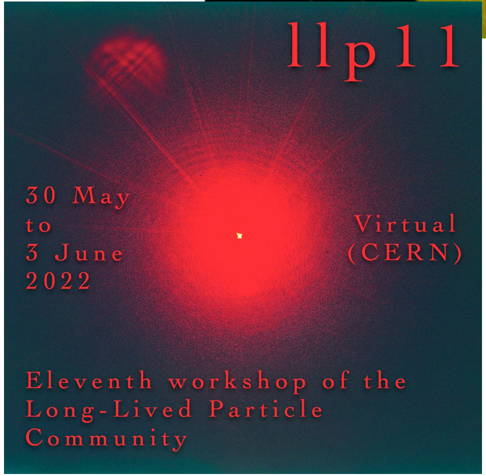
...alizing right ...s and going ...s great atom ...ron Collider ...g long-lived ...gh its detec- ...xt week, they ...e, CERN, the ...oratory near ...uss how to ...e LHC's next ...earches, and ...etectors that ...ticles. ...2012, experi- ...C discovered ...cle predicted

simple strategy to look for new particles: Smash together protons or electrons at ever-higher energies to produce heavy new particles and watch them decay instantly into lighter, familiar particles within the huge, barrel-shaped detectors. That's how CMS and its rival detector, A Toroidal LHC Apparatus (ATLAS), spotted the Higgs, which in a trillionth of a nanosecond can decay into, among other things, a pair of photons or two "jets" of lighter particles.

Long-lived particles, however, would zip through part or all of the detector before decaying. That idea is more than a shot in the dark, says Giovanna Cottin, a theorist at National Taiwan University in Taipei. "Almost all the frameworks for beyond-the-standard-model physics predict the existence of long-lived particles," she

of subsystems—trackers that trace charged particles, calorimeters that measure particle energies, and chambers that detect penetrating and particularly handy particles called muons—all arrayed around a central point where the accelerator's proton beams collide. Particles that fly even a few millimeters before decaying would leave unusual signatures: kinked or offset tracks, or jets that emerge gradually instead of all at once.

Standard data analysis often assumes such oddities are mistakes and junk, notes Tova Holmes, an ATLAS member from the University of Chicago in Illinois who is searching for the displaced tracks of decays from long-lived supersymmetric particles. "It's a bit of a challenge because the way we've designed things, and the software people have written, basically rejects these



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LHC LLP WG: Long-lived Particles at the LHC

To subscribe to the general WG mailing list, used to distribute announcements about WG meetings and available documents, go to http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=lhc-llpwg

Mandate:

The LHC Long-lived Particles Working Group (LHC LLP WG) brings together experimentalists and theorists to discuss the physics of new long-lived particles at the LHC. It also covers physics with unconventional experimental signatures. The WG builds on the experience of the LLP LHC Community and, preserving its main scientific objectives, it serves as a formal bridge with the relevant physics groups of the LHC experiments, to streamline the official endorsement of the WG's recommendations to the experiments. The WG will hold open meetings, typically at CERN, complementing the Workshops organized by the LLP LHC Community. The formation of dedicated subgroups, and possible closed meetings (restricted

Dark Matter WG
- WG documents
- WG Meetings

Electroweak WG
- WG Documents
- WG meetings

Forward Physics WG
- WG documents
- WG meetings

Conveners:

- ATLAS: Javier Montejo Berlingen and Emma Torro Pastor
- CMS: Juliette Alimena and Albert de Roeck
- FASER: Dave Casper
- LHCb: Federico Leo Redi and Carlos Vázquez Sierra
- MoEDAL: James Pinfold
- Theory: Giovanna Cottin, Nishita Desai and José Zurita
- Reach all through lhc-llpwg-admin@cern.ch

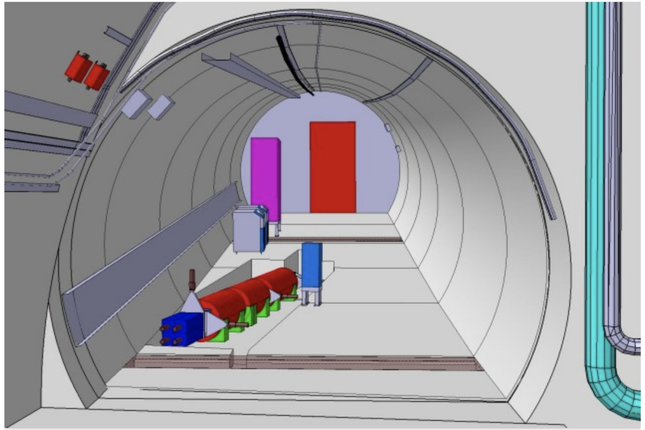
Even new dedicated LLP approved detectors at the LHC will operate in Run 3!

ABOUT NEWS

FASER: CERN approves new experiment to look for long-lived, exotic particles

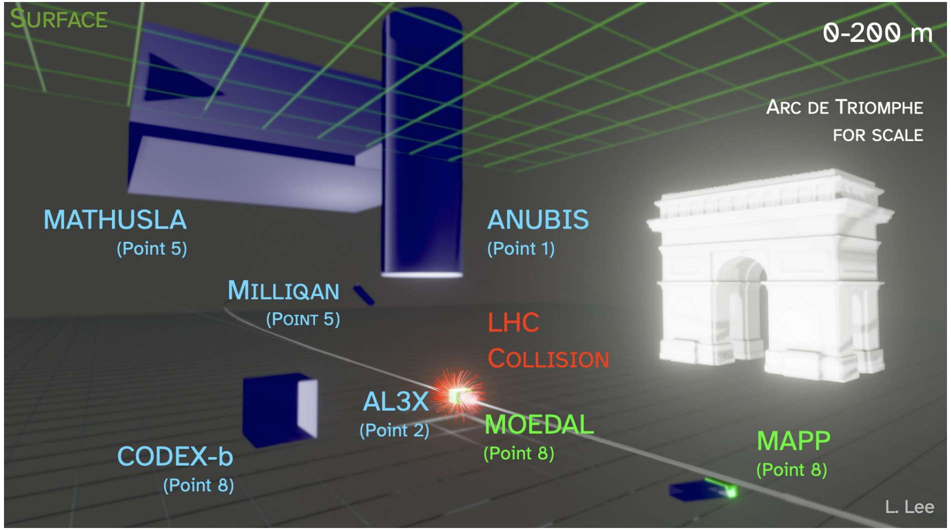
The experiment, which will complement existing searches for dark matter at the LHC, will be operational in 2021

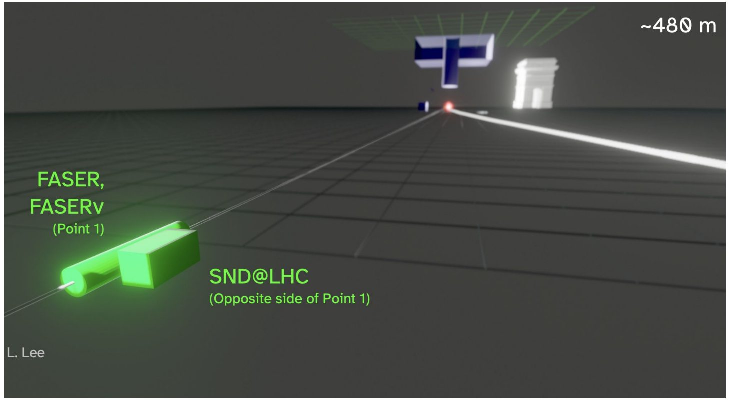
7 MARCH, 2019 | By Cristina Agrigoroae



A 3D picture of the planned FASER detector as seen in the TI12 tunnel. The detector is precisely aligned with the collision axis in ATLAS, 480 m away from the collision point. (Image: FASER/CERN)

Geneva. Today, the CERN Research Board approved a new experiment designed to look for light and weakly





Slide from L. Lee @ LHCPC2021

https://indico.cern.ch/event/905399/contributions/4282550/attachments/2261167/3837992/060921_LLee_NeutralFIPs.pdf

A case study : *if* new particles are long-lived, what could their discovery say about fundamental open questions in particle physics?

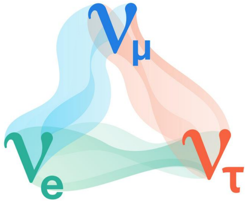
They could give an answer for neutrino mass generation mechanism

See review in A. Atre, T. Han, S. Pascoli, B. Zhang, JHEP 05 (2009) 030, arXiv:0901.3589

Seesaw
P. Minkowski, Phys. Lett. 67B (1977)
R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. 44 (1980)
J. Schechter and J. W. F. Valle, Phys. Rev. D22, 2227 (1980)
Inverse seesaw
R. Mohapatra and J. Valle, Phys. Rev. D34 (1986) 1642

Known

- Neutrino oscillations happen therefore neutrinos in the SM have mass



Neutrino oscillations is the first experimental evidence for new physics beyond the Standard Model !
See P. F. de Salas et al., JHEP 02 (2021) 071, arXiv:2006.11237

Unknowns

- Neutrino Mass Mechanism involving HNL (i.e seesaw mechanism, inverse seesaw, ...)
- Specific BSM Model of neutrino mass generation (i.e new interactions of HNL beyond Yukawa ones?)
- HNL nature (Dirac or Majorana)
- HNL mass

Source: https://www.symmetrymagazine.org/article/neutrinos-on-a-seesaw

- Many BSM models predicts long-lived HNLs
- HNLs mix with SM neutrinos, and can decay to other known particles via mixing

$$\Gamma \sim G_F^2 \, |V_{eN}|^2 \, m_N^5$$

Small mixings and ~ GeV scale HNL → LLP!

A systematic way to study non-minimal HNL models is to invoque effective field theory, adding NRO which are suppressed by a (unknown) new physics scale Λ

$$\mathcal{L}_{N_R\,SMEFT} = \mathcal{L}_{SM+N_R} + \sum_{d\geq 5} \frac{1}{\Lambda^{d-4}} \sum_i c_i^{(d)} \mathcal{O}_i^{(d)}$$

First developed in
F. del Aguila, S. Bar-Shalom, A. Soni, J. Wudka, 0806.0876 (Phys.Lett.B670, 2008)
A. Aparici, K. Kim, A. Santamaria, J. Wudka, 0904.3244 (Phys.Rev.D80, 2009)
Basis for d<=9 in
H.-L. Li, Z. Ren, M.-L. Xiao, J.-H. Yu, Y.-H. Zheng, 2105.09329

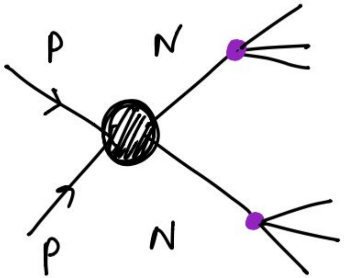
Additional HNLs in EFT with LLPs at the LHC studies
d=5 in A. Caputo, P. Hernandez, J. Lopez-Pavon, J. Salvado, JHEP 06 (2017)
d=6, diff. mass regime in Jordy de Vries, H. K. Dreiner, J. Y. Günther, Z. S. Wang, G. Zhou, JHEP 03 (2021)

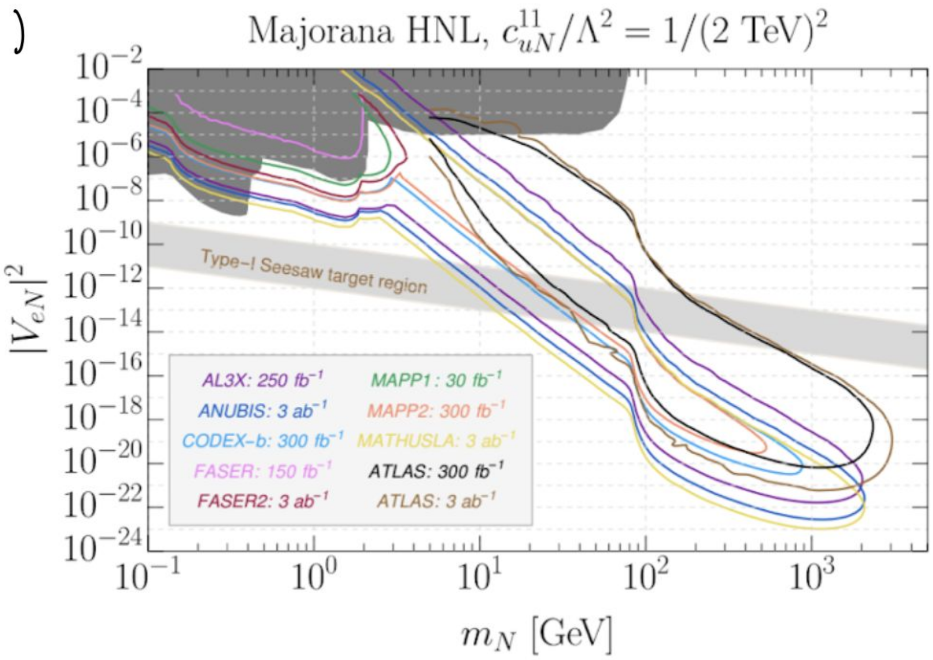
d=6 four-fermion operators with quarks and HNLs that are LLP

G. Cottin, J. C. Helo, M. Hirsch, A. Titov, Z. S. Wang, 2105.13851, (JHEP 09 (2021) 039)
R. Beltrán, G. Cottin, J.C. Helo, M. Hirsch, A. Titov, Z.S. Wang, 2110.15096 (JHEP 01 (2022) 044)

$$\mathcal{L}_6 \supset \frac{1}{\Lambda^2}\left(c_{dN} O_{dN} + c_{uN} O_{uN} + c_{QN} O_{QN}\right)$$

$$O_{dN} \quad (\bar{d}_R \gamma^\mu d_R)(\bar{N}_R \gamma_\mu N_R)$$
$$O_{uN} \quad (\bar{u}_R \gamma^\mu u_R)(\bar{N}_R \gamma_\mu N_R)$$
$$O_{QN} \quad (\bar{Q} \gamma^\mu Q)(\bar{N}_R \gamma_\mu N_R)$$





We propose dedicated search strategies (at several LHC current and proposed far detectors) in order to constrain these models in previously unexplored regions of parameter space.

We also provide estimates on the values of the new physics scale that could be probed !

- I hope my research can give concrete insights as to *how* neutrinos in the SM have mass. Such mechanisms predicts new, long-lived hypothetical particles yet to be discovered

- I hope my work can help design optimal LHC searches, and help make the physics case for new proposed LLP experiments at the LHC, as these could detect long-lived particles that current LHC experiments can not

- I want to focus my efforts in novel directions / models / optimal particle physics search strategies driven by concrete theoretical predictions that could be tested and could provide breakthroughs within my own lifetime! LHC plans to run until 2040 !

"… Precision is the keystone to consolidate our description of nature, increase the sensitivity to SM deviations, give credibility to discovery claims, and to constrain models when evaluating different microscopic origins of possible anomalies [..] The LHC has also proven to be a discovery machine […] it delivered results that could not have been obtained otherwise, immensely enriching our understanding of nature. " Michelangelo Mangano, CERN Theory Department.

Let's squeeze the LHC lemons from all fronts !