RIGA TECHNICAL UNIVERSITY

Institute of Particle Physics and Accelerator Technologies

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Conversation with CERNies

A crash course in High-Energy Particle Physics

COMETA

COST Action CA22130

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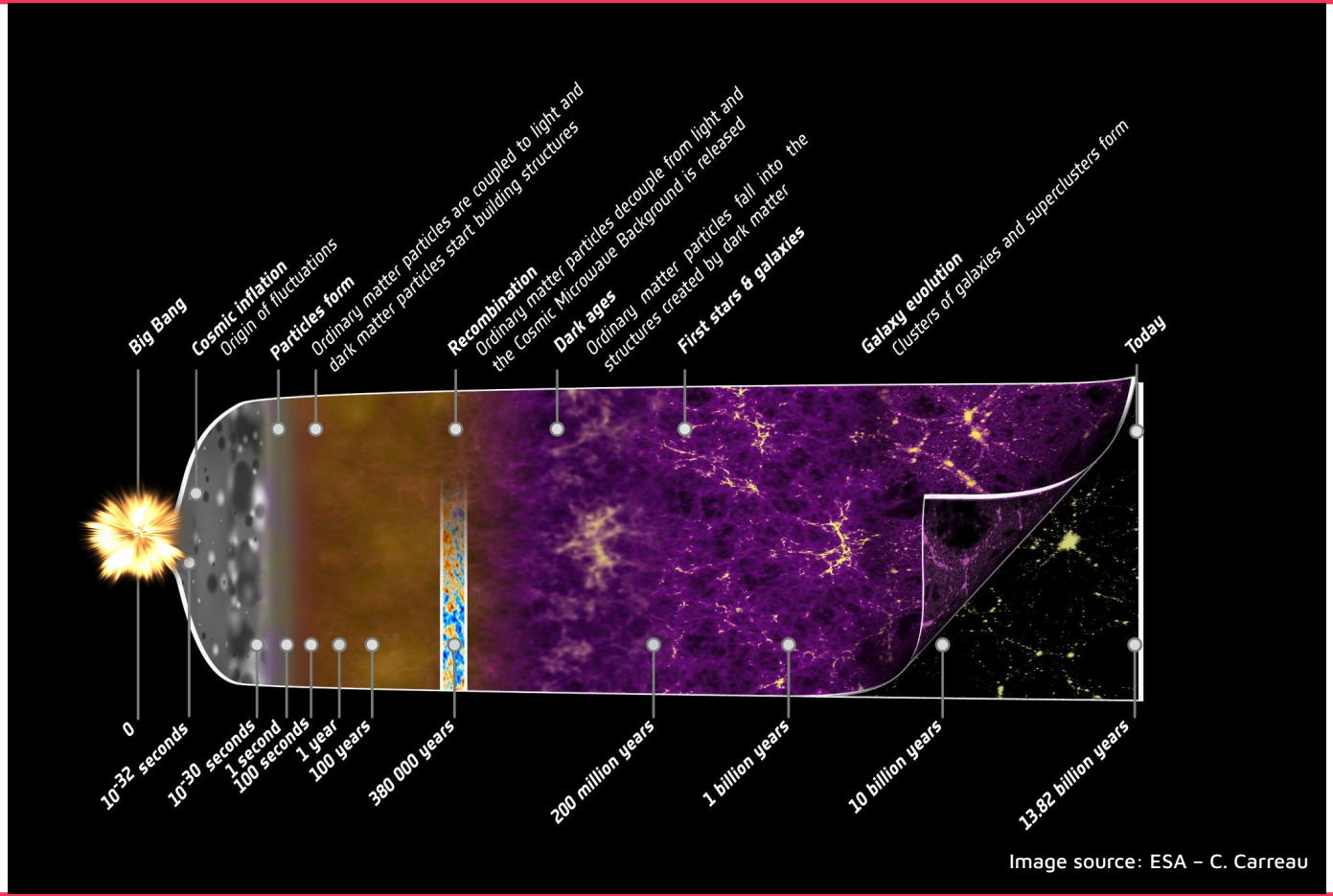
Riga Technical University

28th of February, 2024
İzmir, Türkiye

Welcome

- Thank you for joining us today for the COMETA panel discussion and the Q&A session !
- We will spent approximately the next hour discussing particle physics and attempt to answer any questions you might have !
- After the event, there should be some refreshments made available.
- To begin with, let me give you a very short summary of particle physics …

History of our Universe



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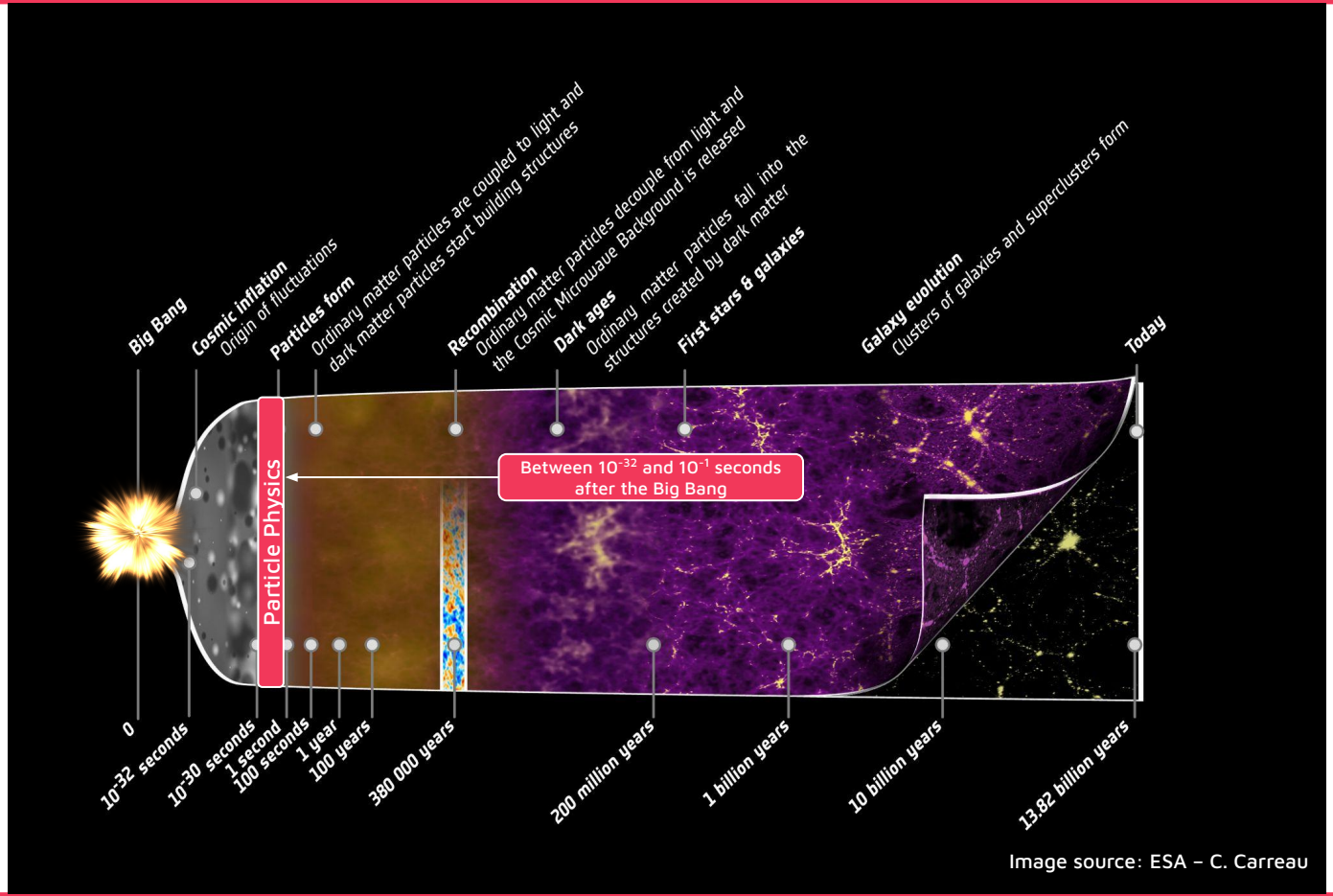


Known fundamental forces

- The nature of our Universe is governed by the four known fundamental forces.

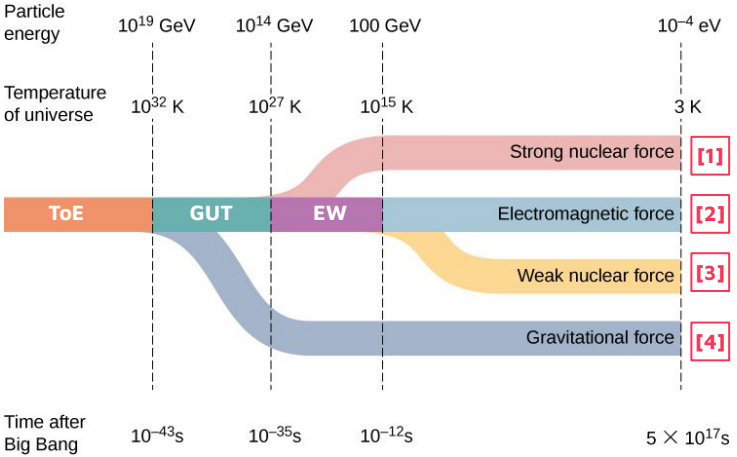


Image source: University of Central Florida

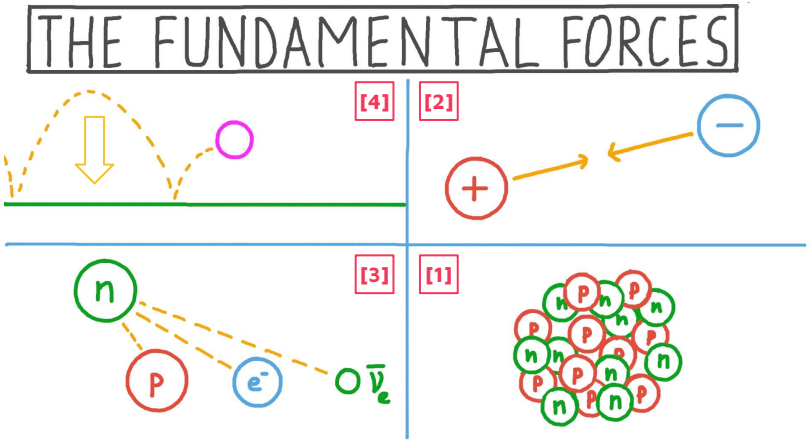


Image source: nagwa

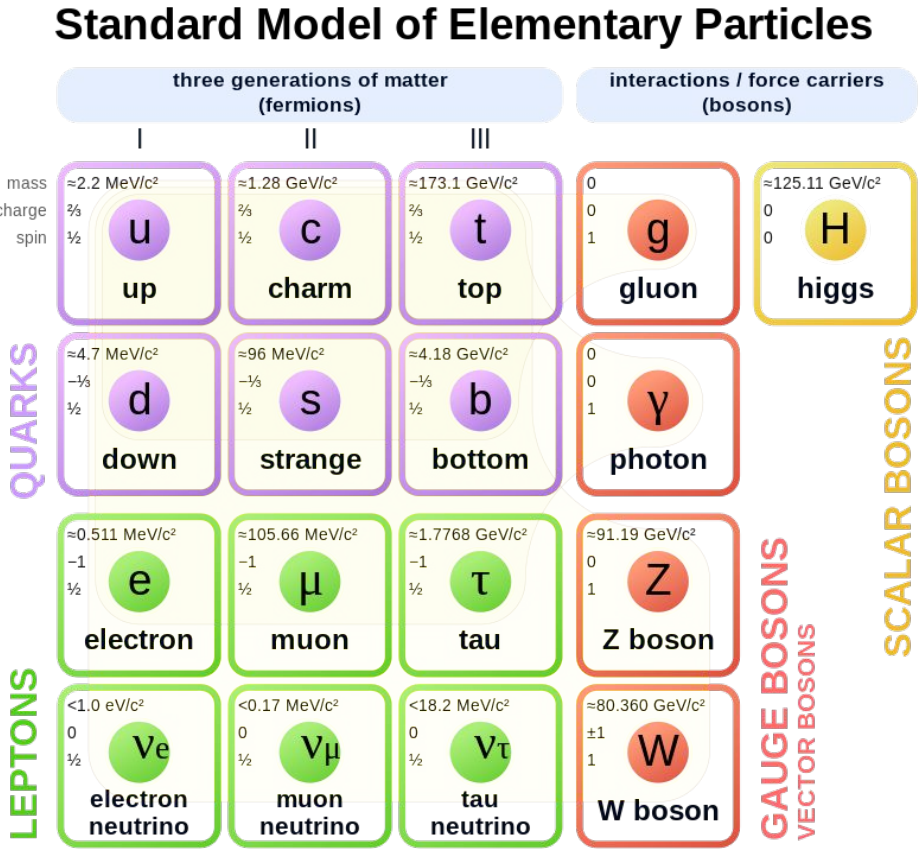
- It is hoped that these forces could be unified at higher energies (**Grand Unified Theory [GUT]**, **Theory of Everything [ToE]**).

- As with electric and magnetic phenomena before, we have learned how to describe two of the interactions, the weak and the electromagnetic forces, into a single, **Electroweak** (**EW**) force !

- We have managed to describe 3 ([1],[2] & [3]) of the 4 fundamental interactions in a single framework – the Standard Model !

The Standard Model of Particle Physics

- The Standard Model (SM) is a Quantum Field Theory (QFT), and is, arguably, the most successful theory in all of physics (and maybe all of science)!
- SM has an incredible predictive power, culminating with the discovery of the Higgs boson in 2012 !
- The existence of the Higgs particle was predicted in 1964, by Peter Higgs.
- It was introduced into the theory, to allow for the carriers of the weak force, the vector bosons, to *acquire* mass.



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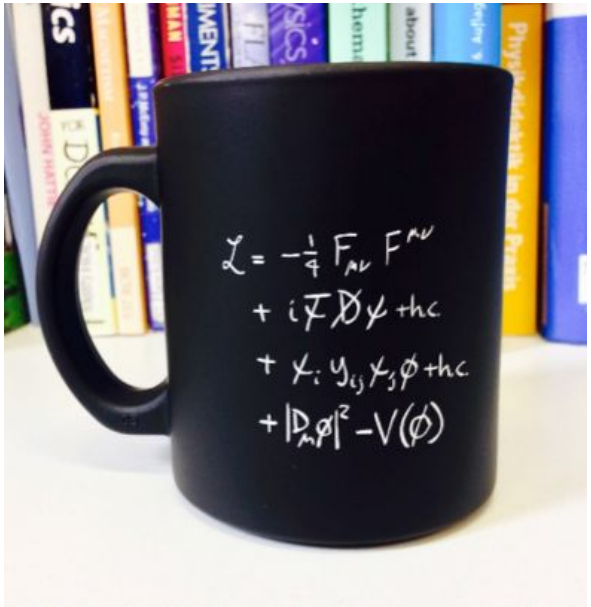
- The SM is incredible, yet the mathematics of it fits on a coffee cup !!!



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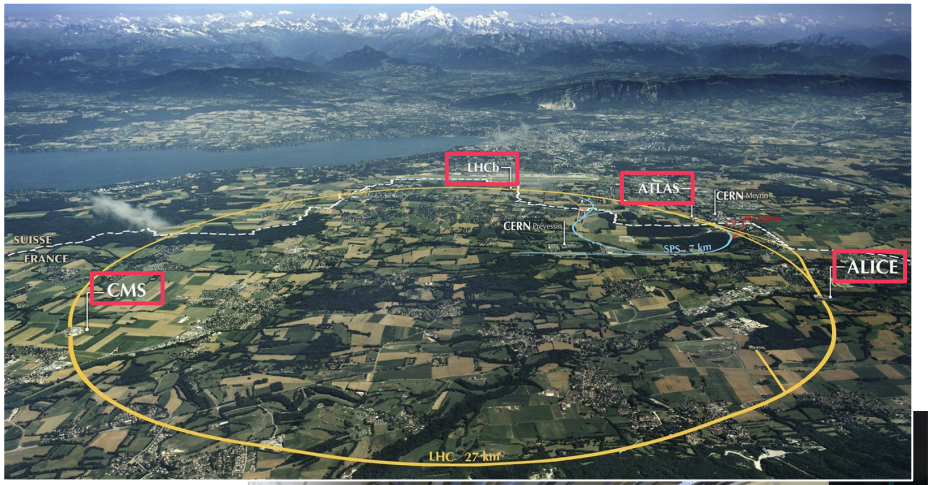
- The SM is incredible, yet the mathematics of it fits on a coffee cup !!! *[sort of]*

$$\begin{aligned}
\mathcal{L}_{SM} = & -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4} g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
& \tfrac{1}{2} i g_s^2 (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
& M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \\
& \tfrac{1}{2} m_h^2 H^2 - \partial_\mu \bar{\phi}^+ \partial_\mu \phi^- - M^2 \bar{\phi}^+ \phi^- - \tfrac{1}{2}\partial_\mu \bar{\phi}^0 \partial_\mu \phi^0 - \tfrac{1}{2c_w^2} M \bar{\phi}^0 \phi^0 - \beta_h [\tfrac{2M^2}{g^2} + \\
& \tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \bar{\phi}^0 \phi^0 + 2\bar{\phi}^+ \phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - ig c_w [\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
& W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
& W^-_\nu \partial_\nu W^+_\mu)] - igs_w [\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - \\
& W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
& \tfrac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\nu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
& g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
& W^+_\nu W^-_\mu) - 2 A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha [H^3 + H\bar{\phi}^0 \phi^0 + 2H\bar{\phi}^+ \phi^-] - \\
& \tfrac{1}{8} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\bar{\phi}^+ \phi^-)^2 + 4(\bar{\phi}^0)^2 \bar{\phi}^+ \phi^- + 4H^2 \bar{\phi}^+ \phi^- + 2(\bar{\phi}^0)^2 H^2] - \\
& g M W^+_\mu W^-_\mu H - \tfrac{1}{2} g \tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \tfrac{1}{2} ig [W^+_\mu (\bar{\phi}^0 \partial_\mu \phi^- - \phi^- \partial_\mu \bar{\phi}^0) - \\
& W^-_\mu (\bar{\phi}^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \bar{\phi}^0)] + \tfrac{1}{2} g [W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W^-_\mu (H \partial_\mu \phi^+ - \\
& \phi^+ \partial_\mu H)] + \tfrac{1}{2} g \tfrac{1}{c_w} (Z^0_\mu (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \tfrac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + \\
& igs_w M A_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) - ig \tfrac{1 - 2c_w^2}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
& igs_w A_\mu (\bar{\phi}^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \tfrac{1}{4} g^2 W^+_\mu W^-_\mu [H^2 + (\phi^0)^2 + 2\bar{\phi}^+ \phi^-] - \\
& \tfrac{1}{4} g^2 \tfrac{1}{c_w^2} Z^0_\mu Z^0_\mu [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \bar{\phi}^+ \phi^-] - \tfrac{1}{2} g^2 \tfrac{s_w^2}{c_w} Z^0 \bar{\phi}^0 (W^+_\mu \phi^- + \\
& W^-_\mu \phi^+) - \tfrac{1}{2} ig^2 \tfrac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \tfrac{1}{2} g^2 s_w A_\mu \bar{\phi}^0 (W^+_\mu \phi^- + \\
& W^-_\mu \bar{\phi}^+) + \tfrac{1}{2} ig^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \tfrac{s_w}{c_w} (2c_w^2 - 1) Z^0_\mu A_\mu \bar{\phi}^+ \phi^- - \\
& g^1 s_w^2 A_\mu A_\mu \bar{\phi}^+ \phi^- - \bar{e}^\lambda (\gamma \partial + m^\lambda_e) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}^\lambda_j (\gamma \partial + m^\lambda_u) u^\lambda_j - \\
& \bar{d}^\lambda_j (\gamma \partial + m^\lambda_d) d^\lambda_j + igs_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j \gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j \gamma^\mu d^\lambda_j)] + \\
& \tfrac{ig}{4c_w} Z^0_\mu [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu (\tfrac{4}{3} s_w^2 - \\
& 1 - \gamma^5) u^\lambda_j) + (\bar{d}^\lambda_j \gamma^\mu (1 - \tfrac{8}{3} s_w^2 - \gamma^5) d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}} W^+_\mu [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + \\
& (\bar{u}^\lambda_j \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}} W^-_\mu [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa} \gamma^\mu (1 + \\
& \gamma^5) u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}} \tfrac{m^\lambda_e}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \\
& \tfrac{g}{2} \tfrac{m^\lambda_e}{M} [H (\bar{e}^\lambda e^\lambda) + i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}} \phi^+ [-m^\kappa_d (\bar{u}^\lambda_j C_{\lambda\kappa} (1 - \gamma^5) d^\kappa_j) + \\
& m^\lambda_u (\bar{u}^\lambda_j C_{\lambda\kappa} (1 + \gamma^5) d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}} \phi^- [m^\lambda_d (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 + \gamma^5) u^\kappa_j) - m^\kappa_u (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 - \\
& \gamma^5) u^\kappa_j] - \tfrac{g}{2} \tfrac{m^\lambda_u}{M} H (\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2} \tfrac{m^2_\lambda}{M} H (\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2} \tfrac{m^\lambda_u}{M} \phi^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \\
& \tfrac{ig}{2} \tfrac{m^2_\lambda}{M} \phi^0 (\bar{d}^\lambda_j \gamma^5 d^\lambda_j) + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \\
& \tfrac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + igc_w W^+_\mu (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + igs_w W^+_\mu (\partial_\mu \bar{Y} X^- - \\
& \partial_\mu \bar{X}^+ Y) + igc_w W^-_\mu (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + igs_w W^-_\mu (\partial_\mu \bar{X}^- Y - \\
& \partial_\mu \bar{Y} X^+) + igc_w Z^0_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + igs_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
& \partial_\mu \bar{X}^- X^-) - \tfrac{1}{2} gM [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2} \bar{X}^0 X^0 H] + \\
& \tfrac{1 - 2c_w^2}{2c_w} igM [\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \tfrac{1}{2c_w} igM [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \\
& igMs_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \tfrac{1}{2} igM [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
\end{aligned}$$

The Large Hadron Collider (LHC) at CERN

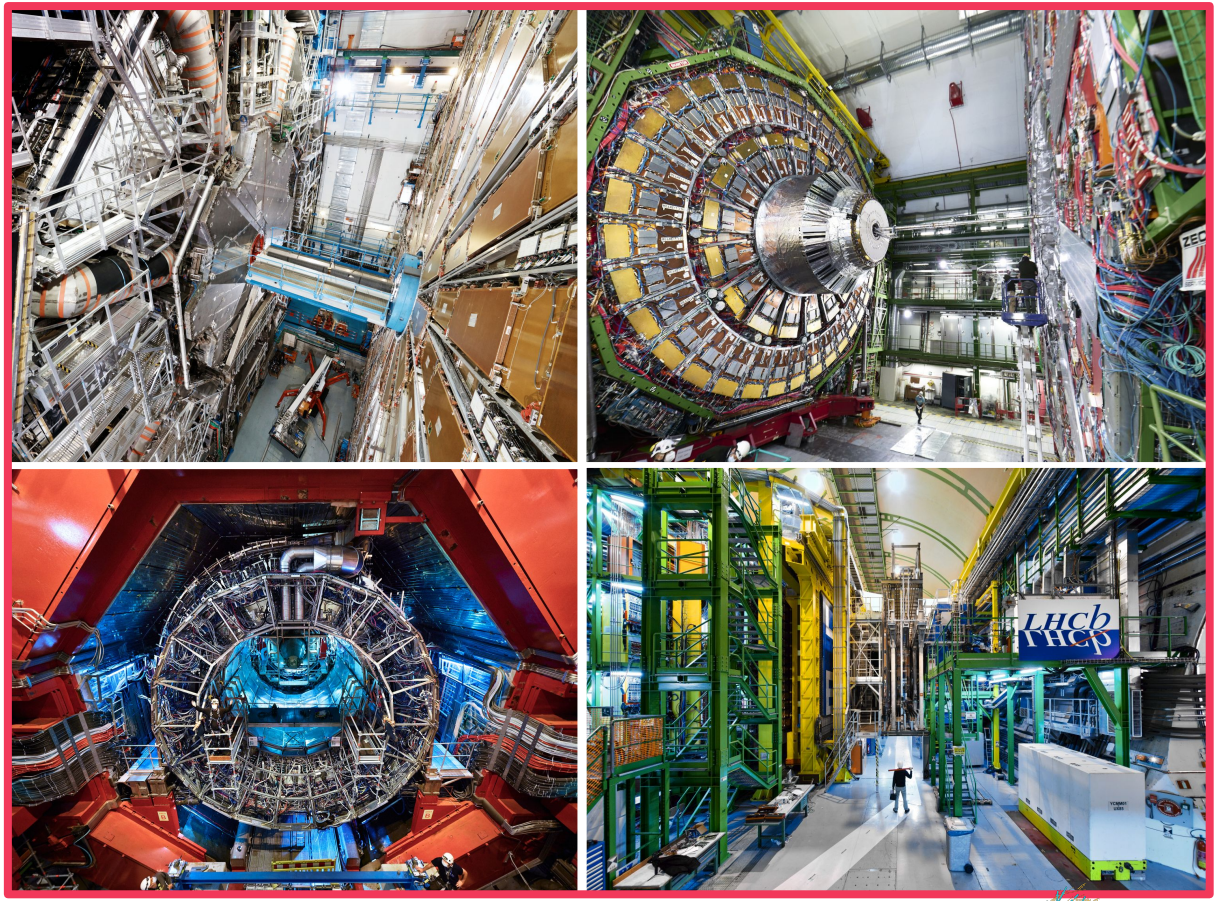
- LHC is a 27 kilometer ring situated ~100 m below ground on the border between France and Switzerland.
- LHC is the coldest, hottest and the emptiest place in the Universe!*
- It is the most powerful particle accelerator ever built,
  with proton beam energies of up to 7 TeV.
- This energy, equivalent to a car driving at 2'300 km/h,
  is focused in an cross-sectional area the size of the tip of a pin !
- Thousands of bunches of protons, containing ~10^{11} protons each,
  circulate in opposite directions separated by 25 ns or ~7.5 metres.
- These beams are made to collide at 4 locations around the LHC, where
  colossal underground caverns house the large LHC experiments:
  ATLAS, **CMS**, **ALICE** and **LHCb**.



* unless some aliens have a better particle accelerator somewhere else in the Universe !

The LHC experiments

- These huge (ATLAS is 25 metres tall) and heavy (CMS weights 14’000 tonnes) machines collect the data from the proton-proton collisions.
- The collisions take place every 25 ns (@ 40 MHz).
- When LHC is running, the experiments are collecting data 24/7; it is not possible to store so much data !
- Complex algorithms are used to select only the most interesting collision events.
- Ingenious software tools, including Machine Learning tools, are used to analyse the data.
- More than 12’000 physicists and engineers work on these particle physics experiments !



- **CO**mprehensive **M**ultiboson **E**xperiment-**T**heory **A**ction, is a **COST Action**, bringing together the theoretical and experimental particle physics communities in order to tackle some of the most challenging questions in particle physics !

- The Standard Model is extremely powerful, but it is incomplete …

  … can we expand and improve it to explain more of our Universe ?

- The Electroweak unification is a triumph …

  … can we understand further and more precisely the mechanisms behind it ?

- The physics community uses advanced software algorithms for their research …

  … could Machine Learning tools facilitate the next triumph in the field of particle physics ?

- For the common goal of all physics, to truly understanding our Universe, collaborative actions, such as COMETA, are invaluable !

- We are here, in İzmir, this week to work towards this goal, and hopefully to inspire some of the listeners here to pursue their career in scientific research !

Today's event

- We are very happy to be here to talk physics with you !
- Today's panel includes both theoretical and experimental physicists !

Ilaria Brivio

Flavia de Almeida Dias

Pietro Govoni

Kadri Özdemir

Richard Ruiz

Kārlis Dreimanis

Arnaud Ferrari

Claudius Krause

- Do not hesitate to ask us anything that interests you about CERN, the LHC, particle physics or the laws of physics of our Universe !

Thank you

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