Flavour & Anomalies @LHC & beyond

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07th mini-school

09-14 MAY 2022

on particles and astroparticles physics

CFTP Centro de Física Teórica de Partículas

TÉCNICO LISBOA

LIP LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTÍCULAS

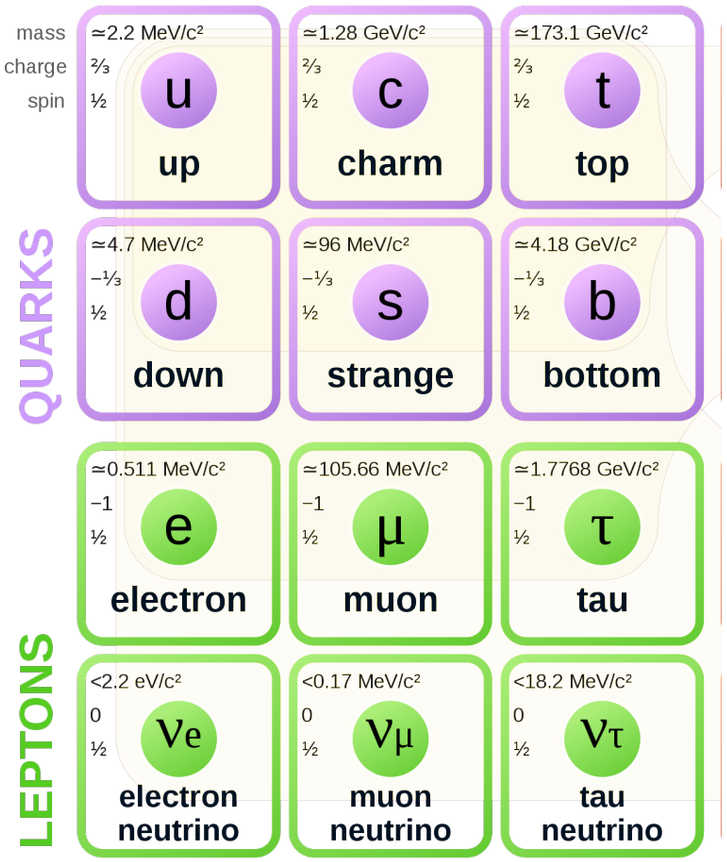
partículas e tecnologia

FCT Fundação para a Ciência e a Tecnologia

Flavour

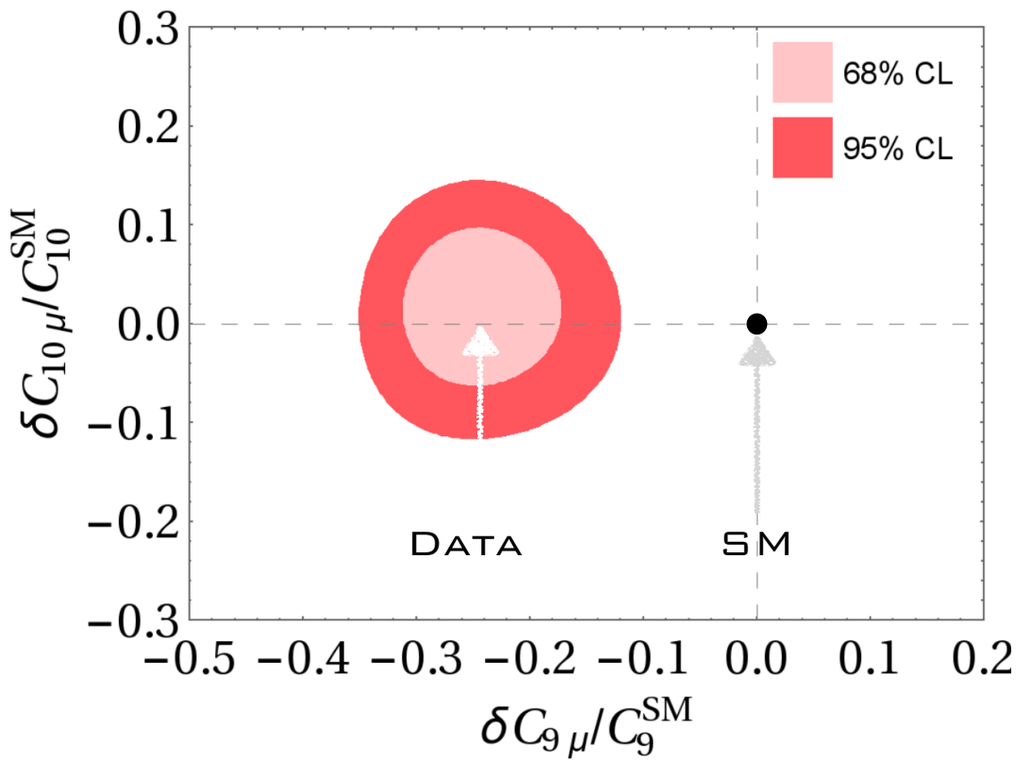
quarks & leptons

Just as ice cream has both color and flavour, so do quarks



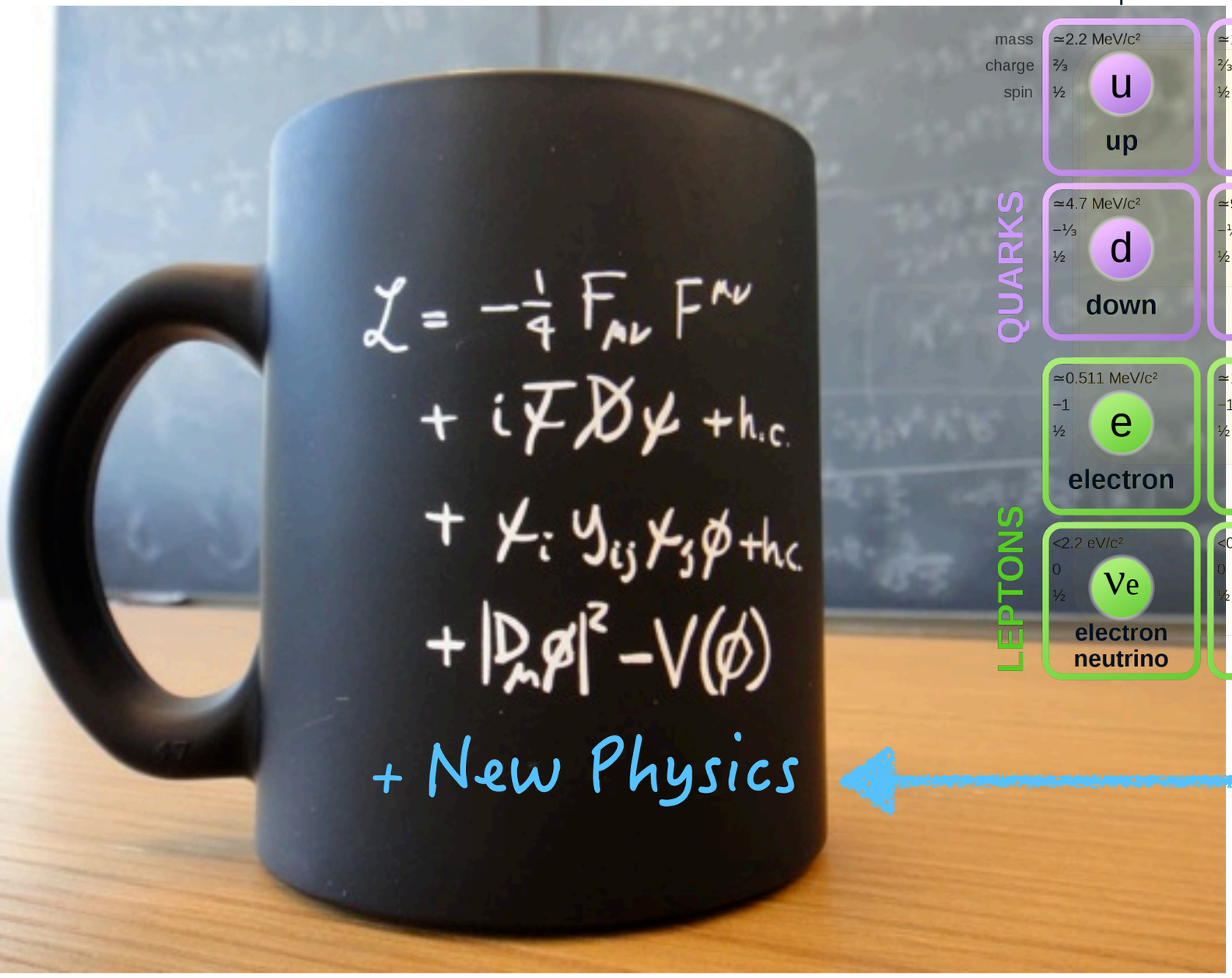
Anomalies

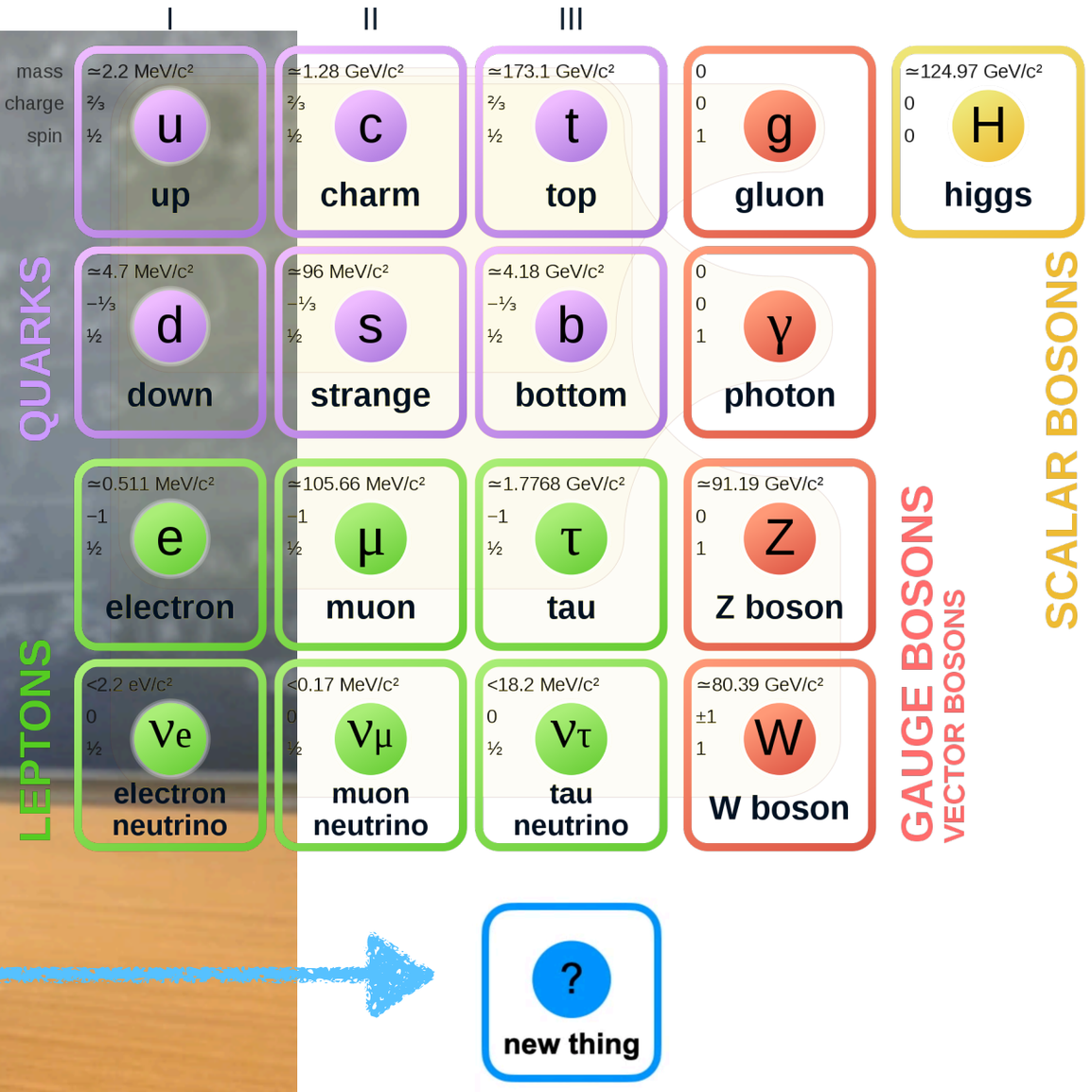
experiment ≠ theory



beyond SM

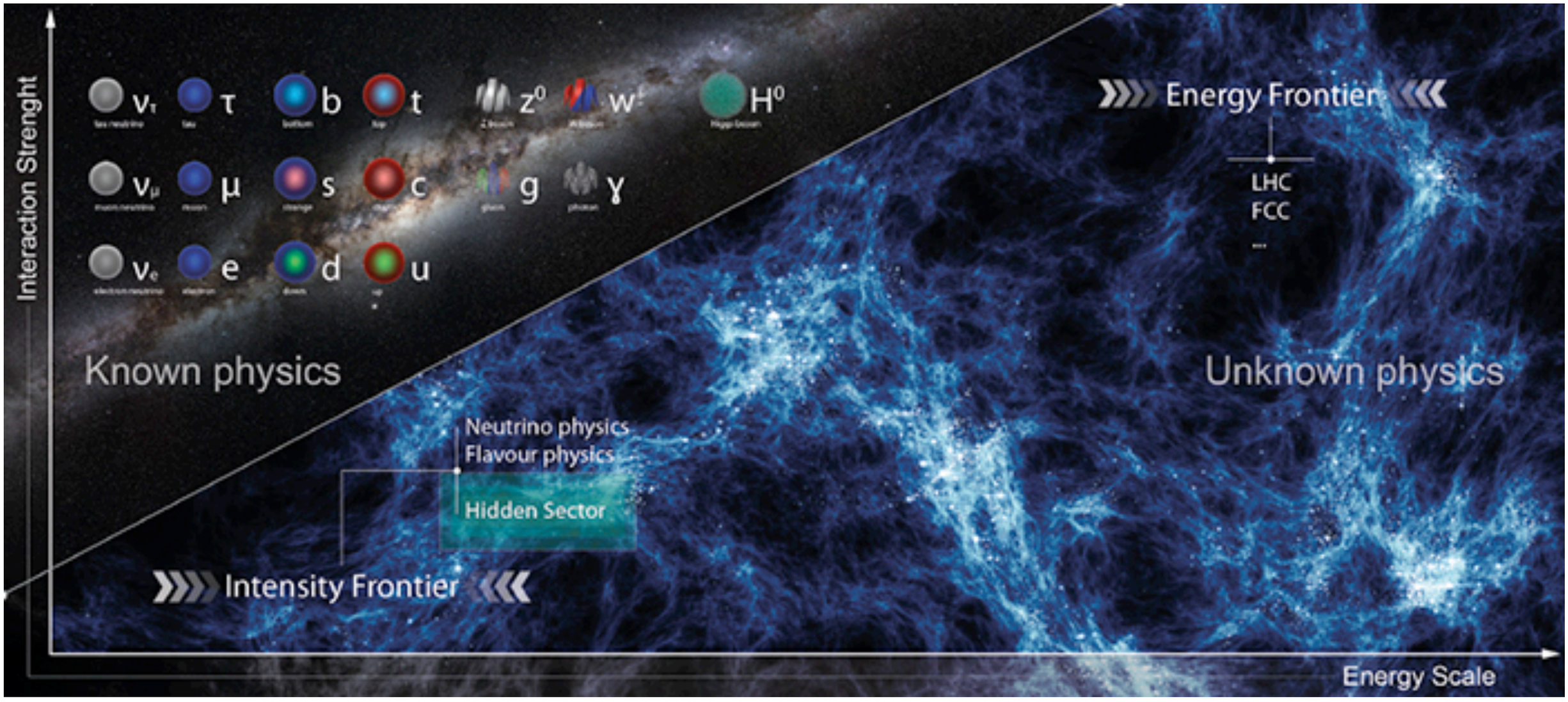
Goal: go beyond the Standard Model





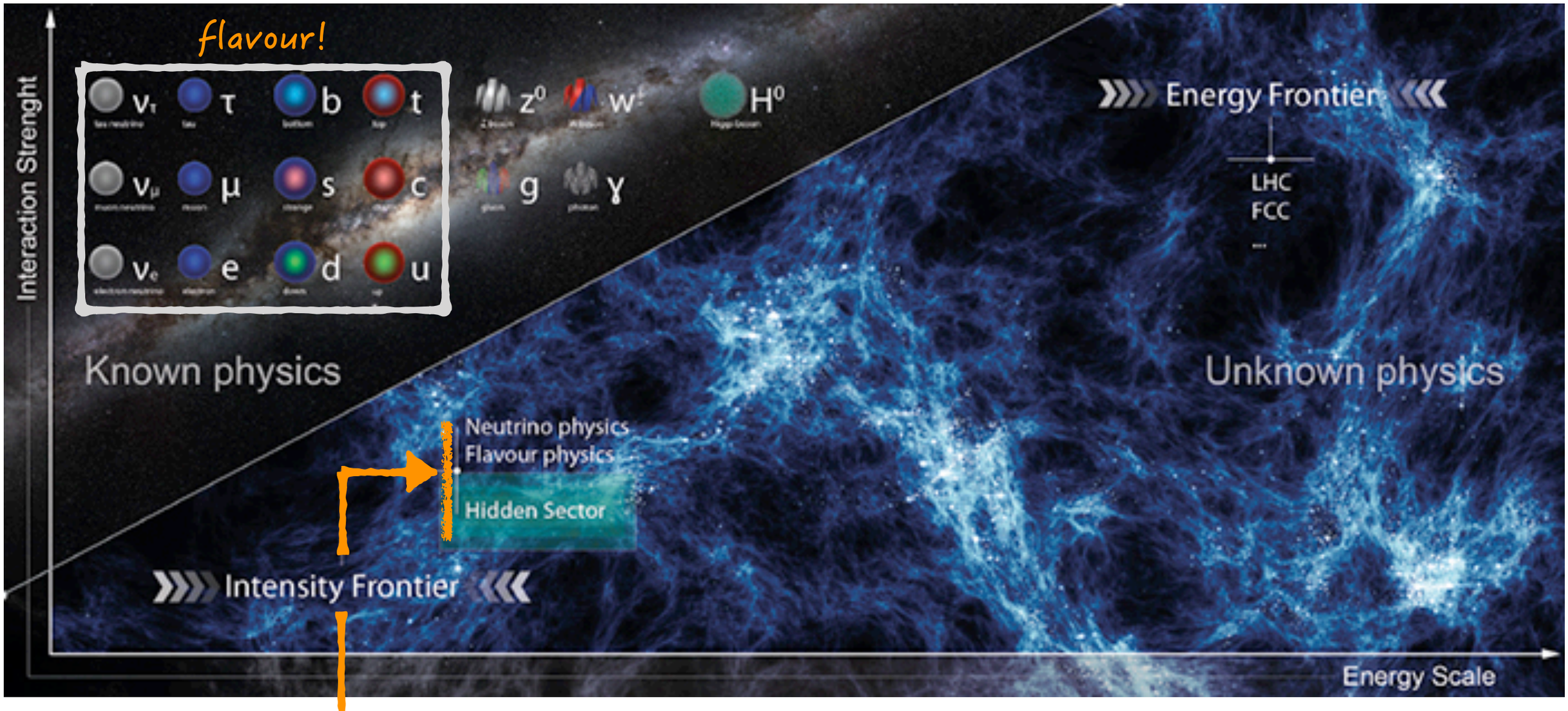
Goal: go beyond the Standard Model

energy frontier →



Goal: go beyond the Standard Model

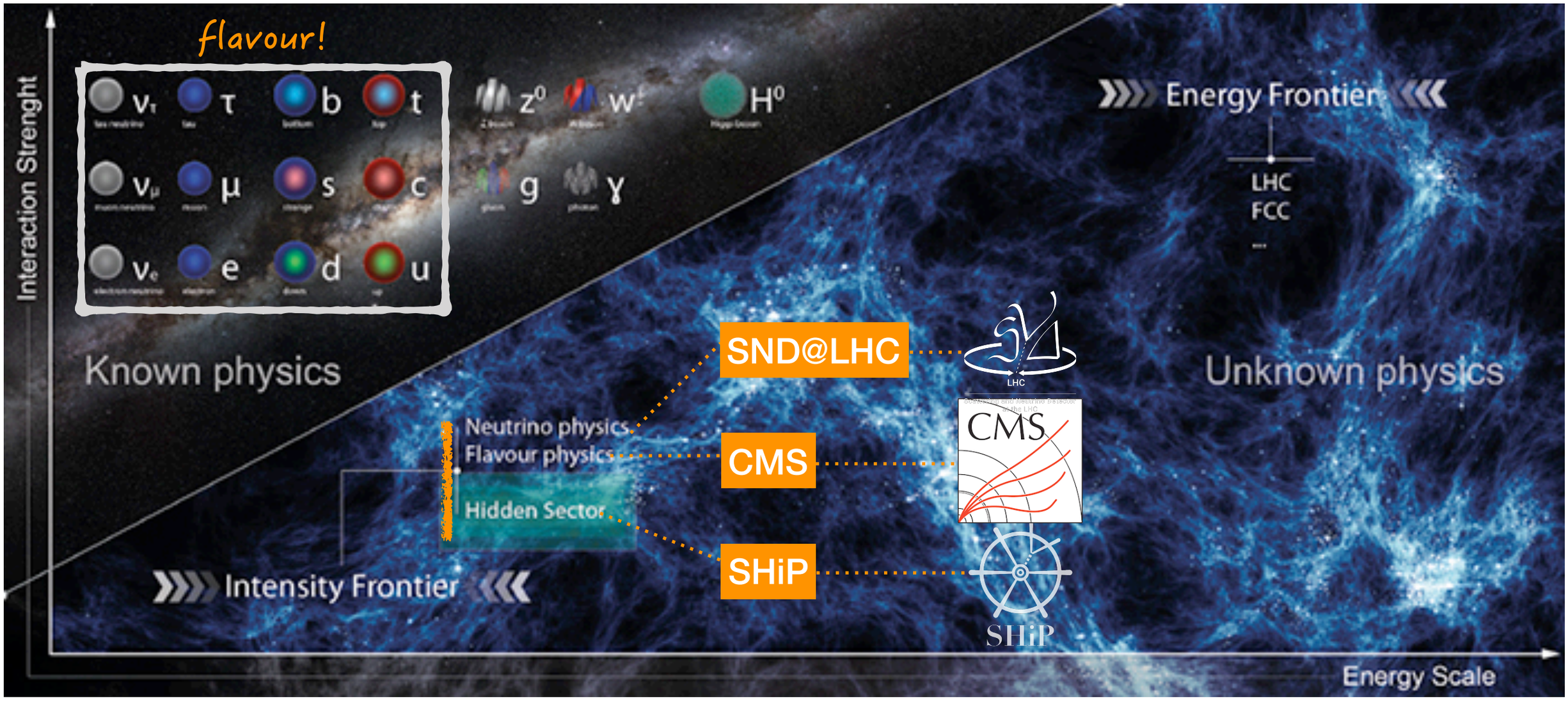
energy frontier →



LHC (and esp. HL-LHC) as an *intensity frontier* machine

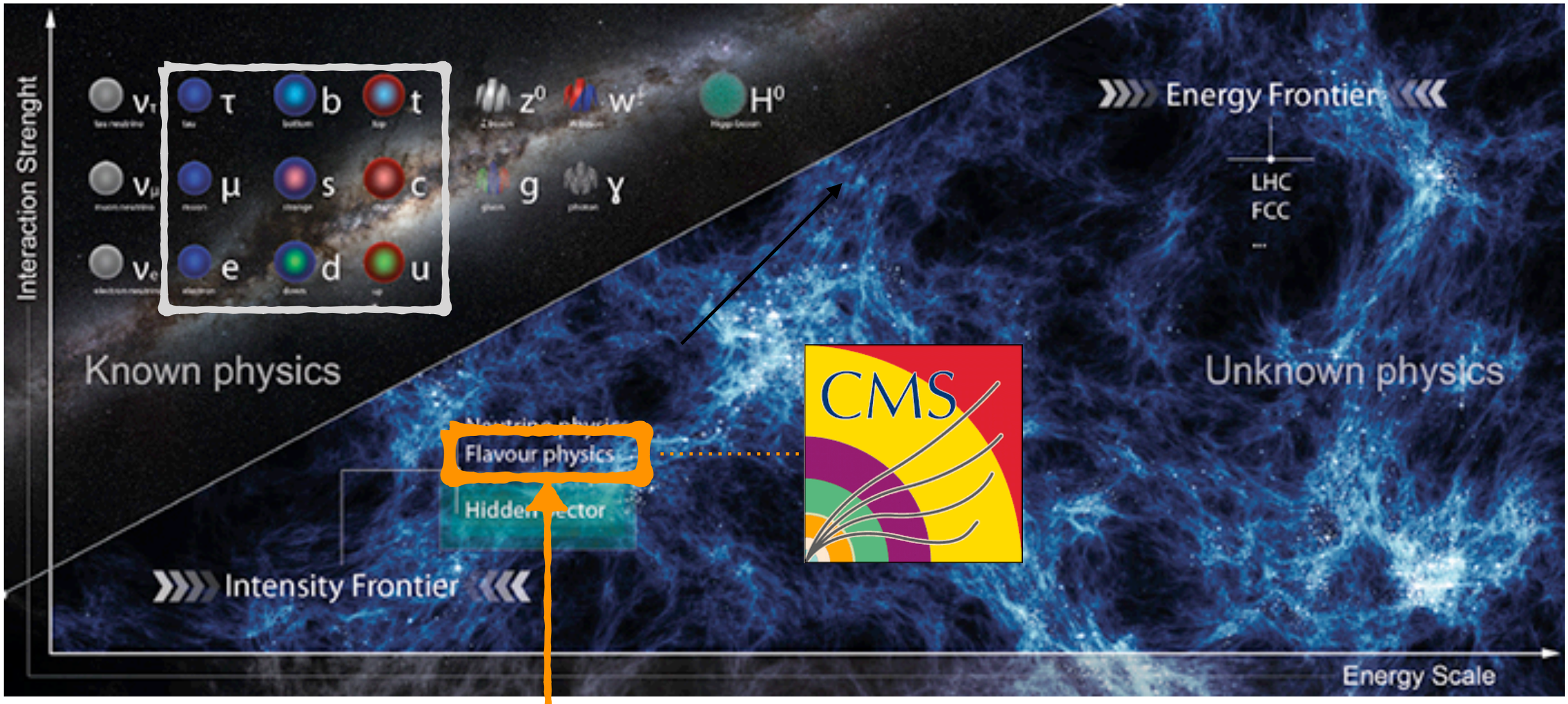
Goal: go beyond the Standard Model

energy frontier →



Goal: go beyond the Standard Model

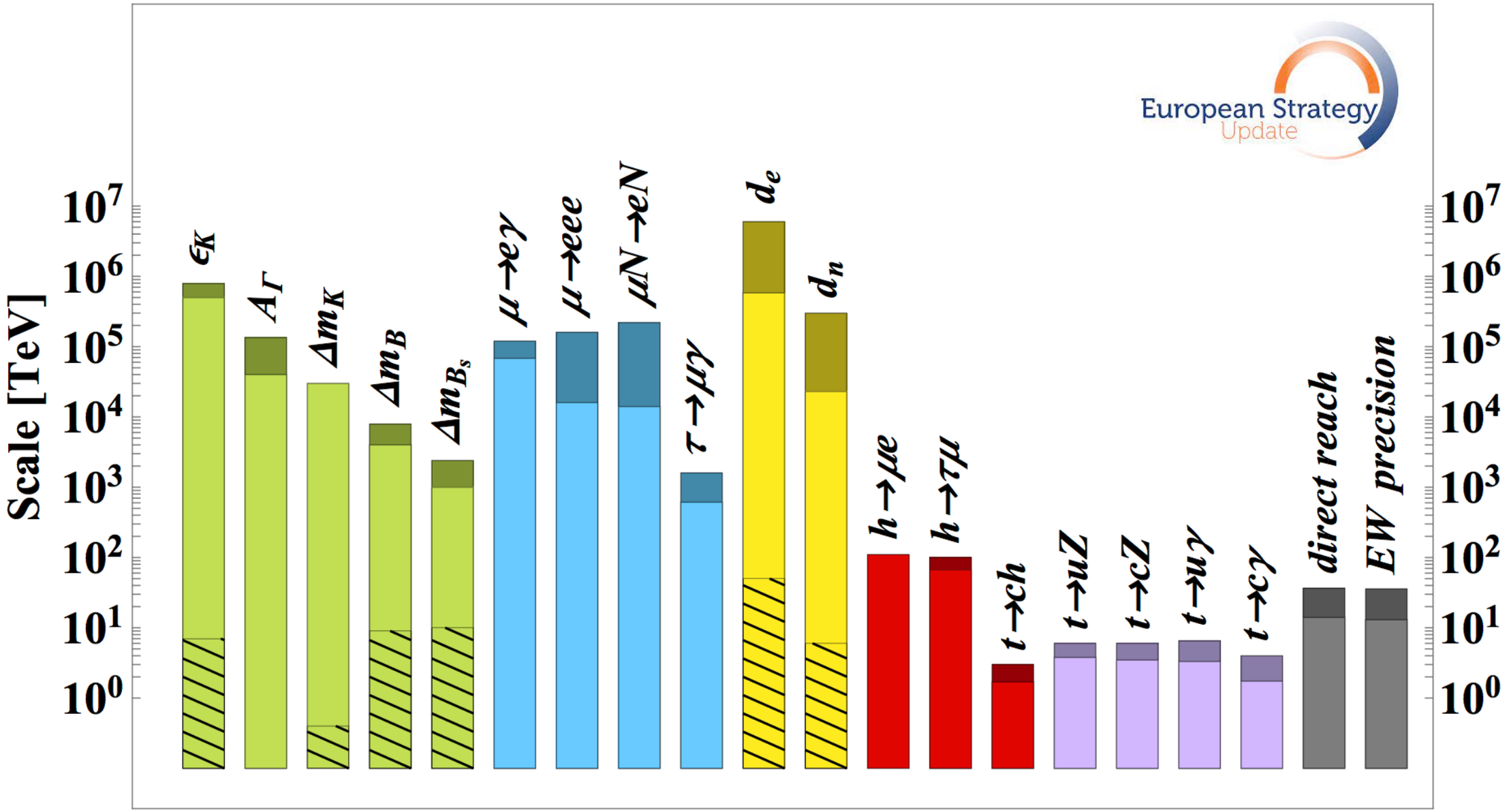
energy frontier →



the LHC as a flavour factory

Goal: go beyond the Standard Model

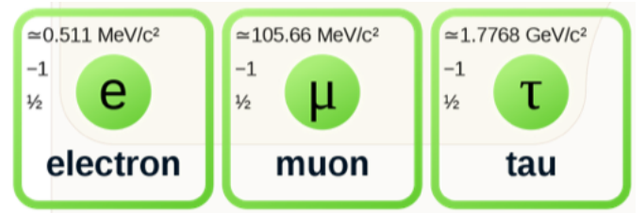
Indirect searches: fuelled by Quantum Mechanics



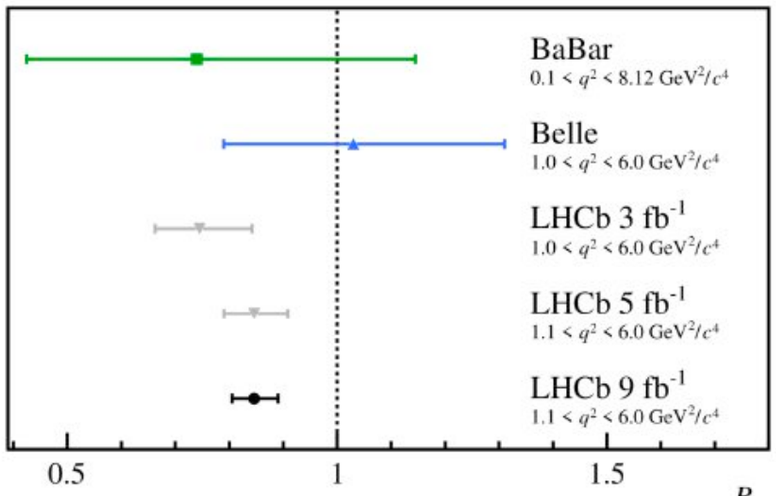
Flavour physics provides access to NP scales well beyond collision energy !

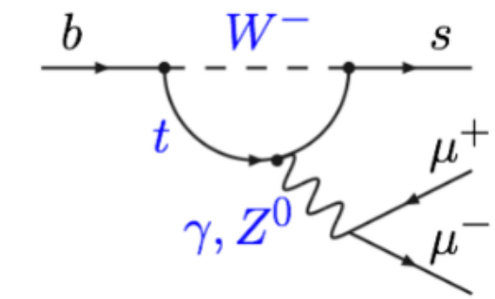
Lepton Flavour Universality

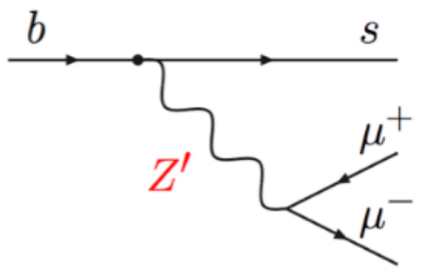
SM (gauge) interactions do not distinguish lepton flavours

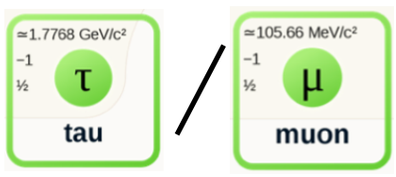


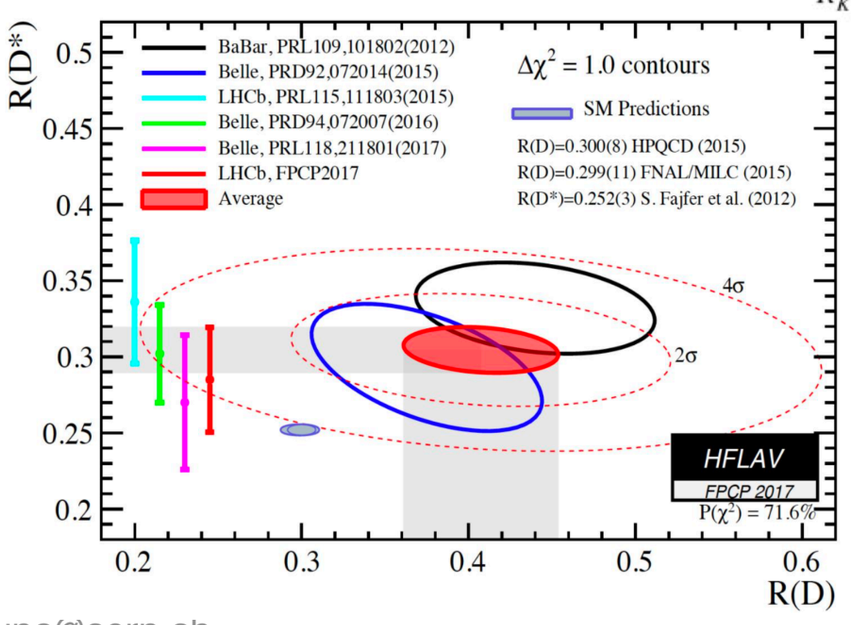
$$R_K = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)} \overset{\text{SM}}{\cong} 1$$

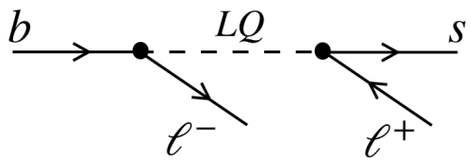






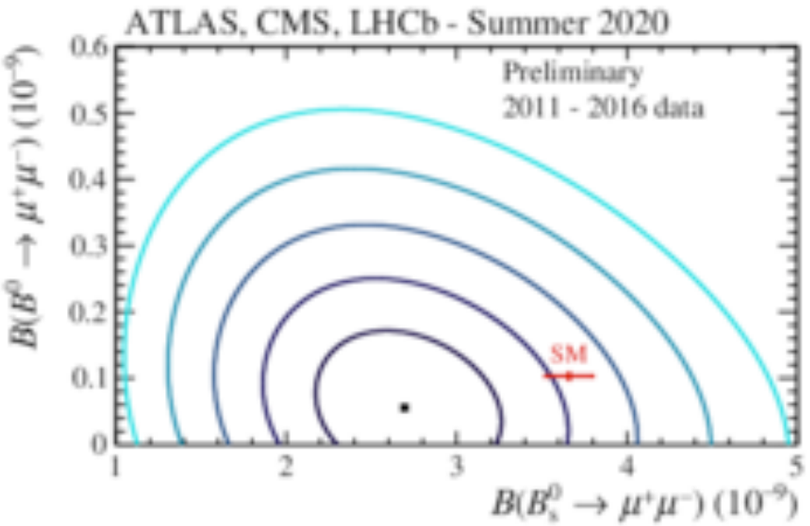




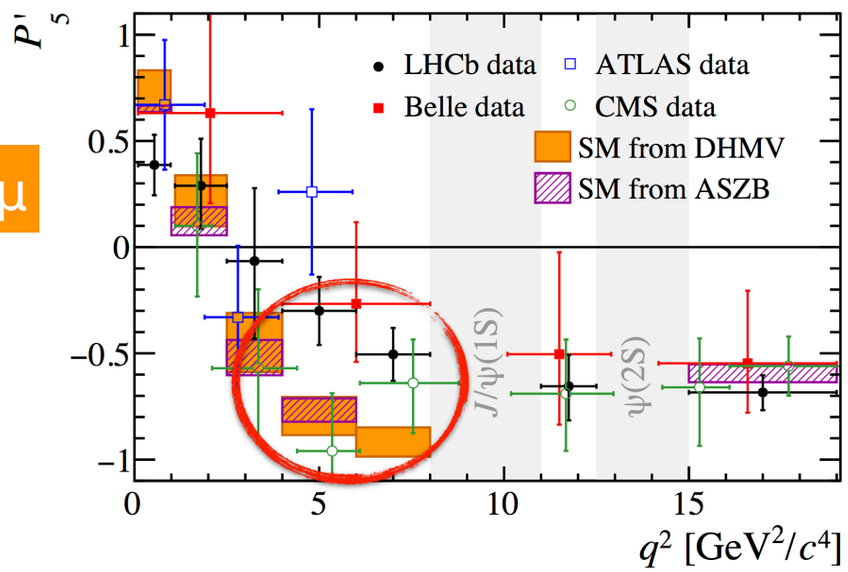


b→sμμ (flavour anomalies!)

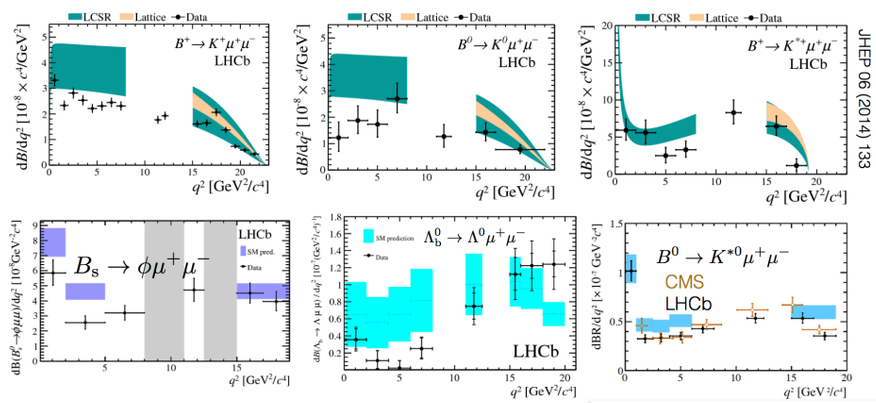
B→μμ



B→K*μμ

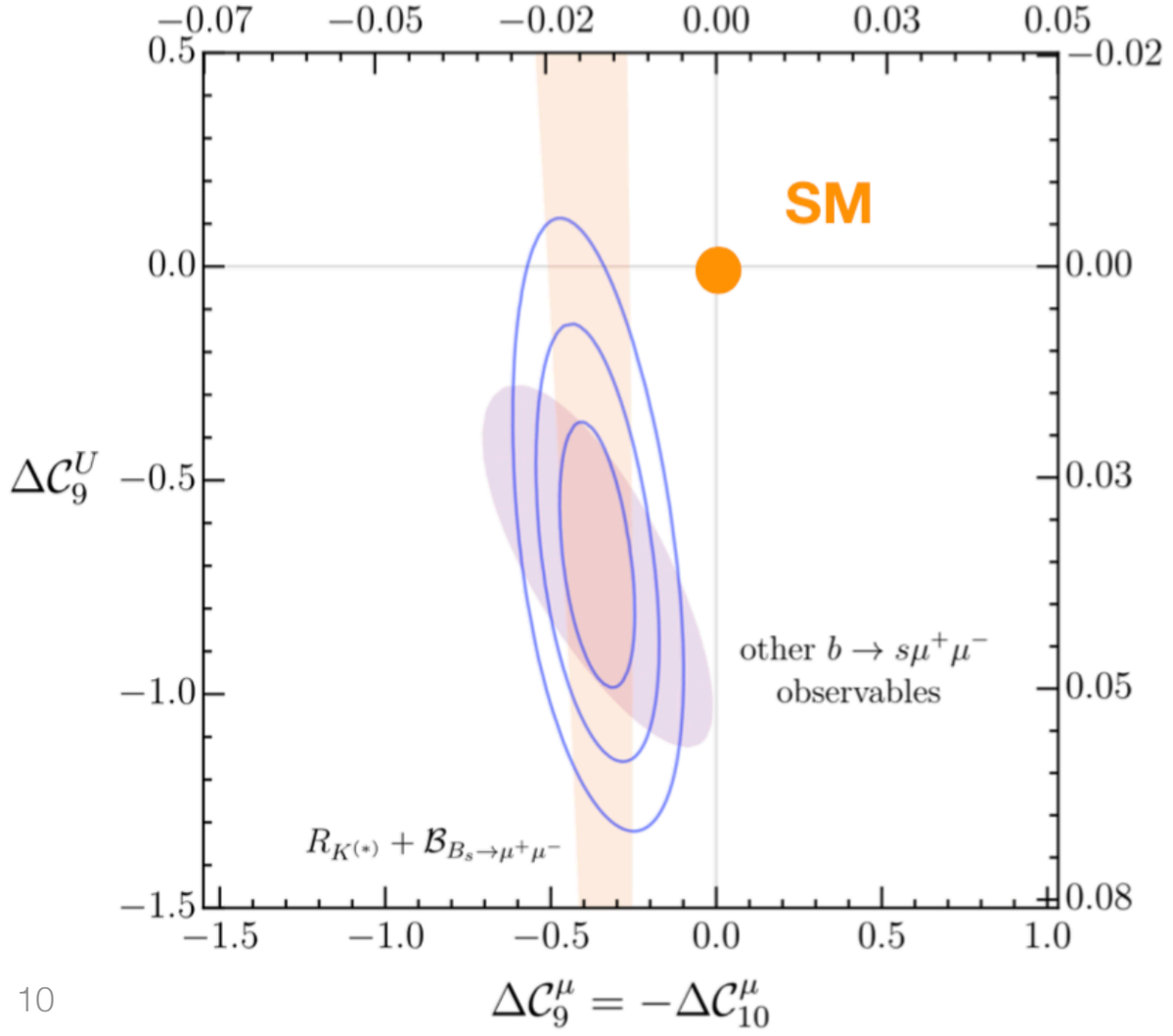


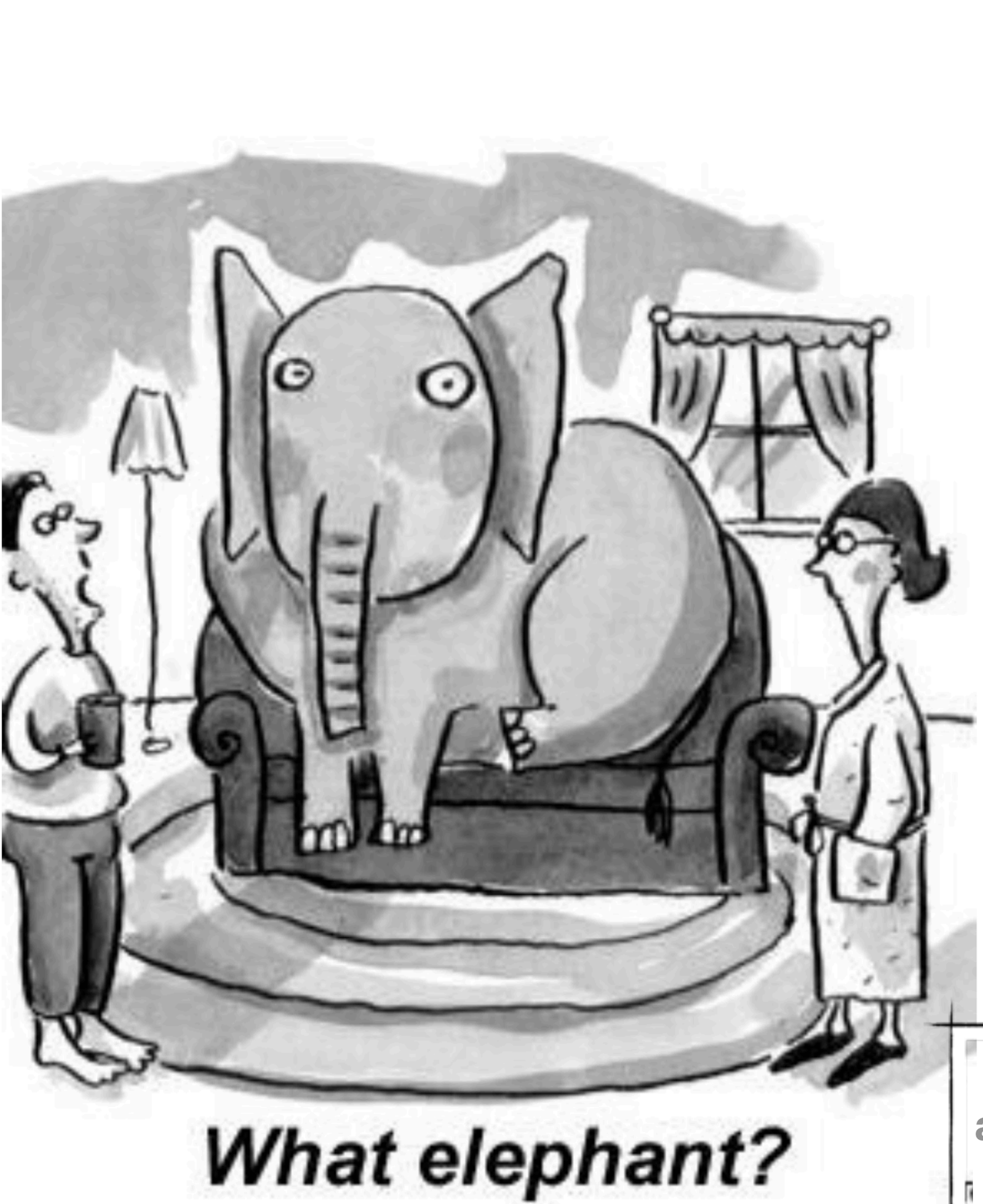
B→Xμμ

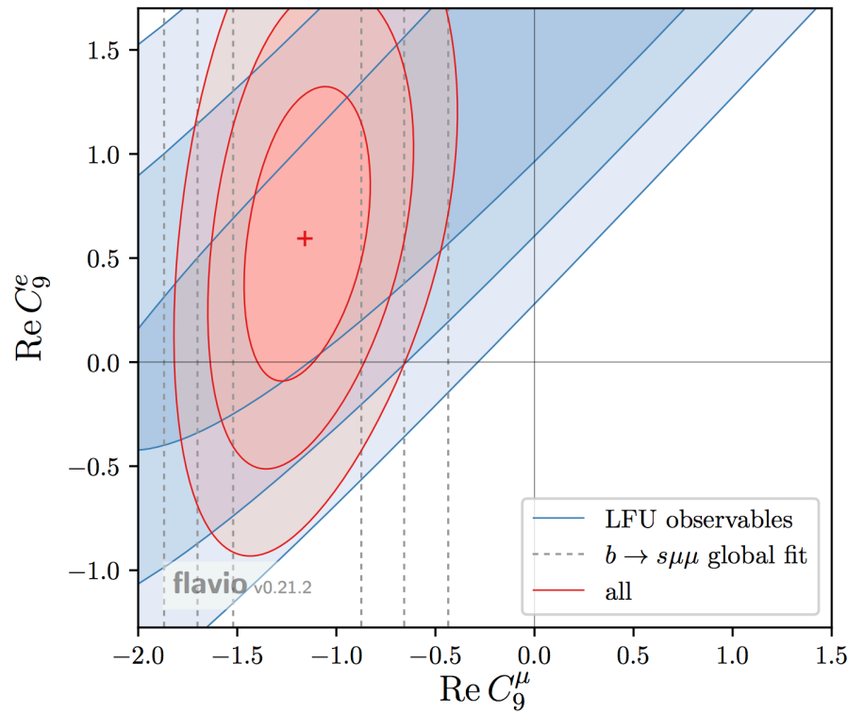


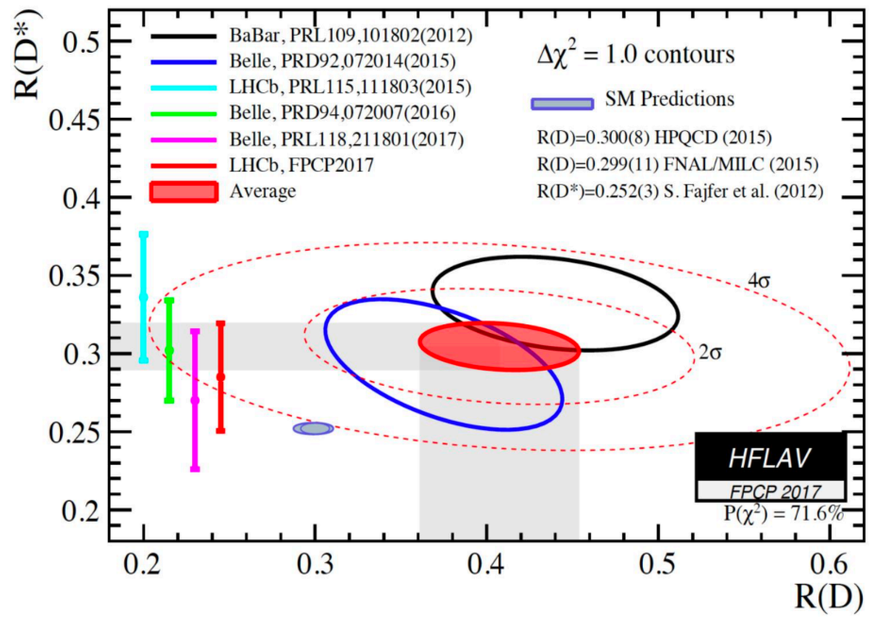
SM - Effective Field Theory

$$\mathcal{L}_{SM\text{-}EFT} = \mathcal{L}_{SM} + \Sigma_i C_i O_i$$









Taken together, the flavor anomalies are most significant deviation from SM, and the strongest indication of NP in current collider data !

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Measurement of b-quark fragmentation fraction ratios at the CMS experiment: a key ingredient for the $B_s^0 \to \mu^+\mu^-$ rare decay analysis

Bruno Afonso Fontana Santos Alves

CERN-THESIS-2018-274
https://cds.cern.ch/record/2649927
Defense: May 2018
youtube

B→μμ

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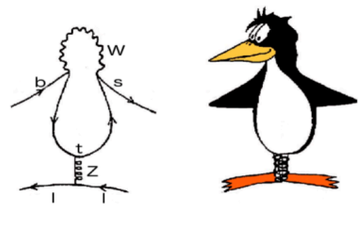


Investigating the flavour anomalies through the rare beauty decay $B^0 \to K^{*0}\mu^+\mu^-$

Maria Carolina Feliciano Faria

Thesis to obtain the Master of Science Degree in

Engineering Physics

CERN-THESIS-2021-220
https://cds.cern.ch/record/2791778
youtube

B→K*μμ

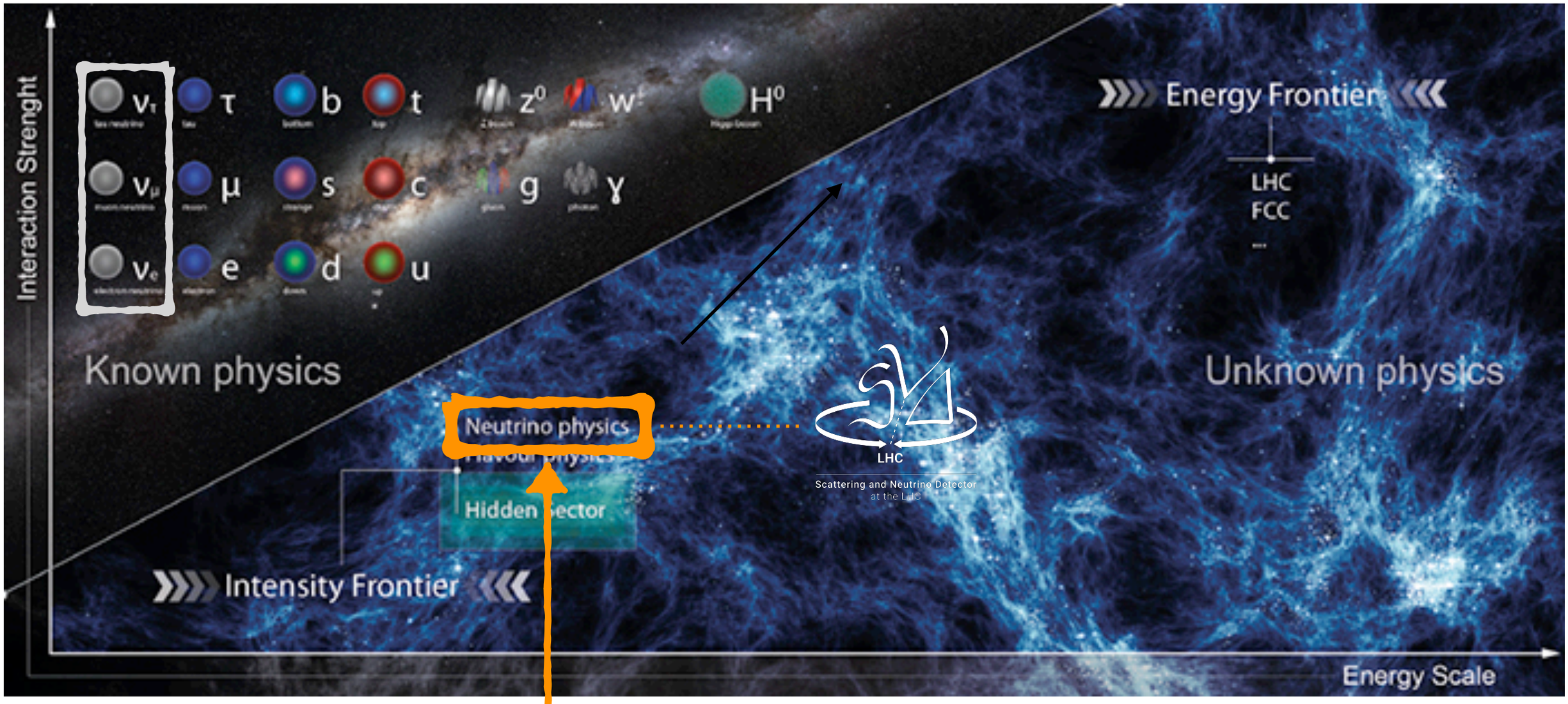
PhD thesis opportunity!

- **LFU** analysis
- b→sττ / b→sμμ
- anomaly-dedicated CMS dataset
- machine learning for τ reconstruction and B signal selection
- potential to clarify flavour anomalies and establish new physics

LFU

Goal: go beyond the Standard Model

energy frontier →



the LHC as a neutrino factory

Neutrinos at LHC !

SND@LHC is the most recent LHC experiment.

Approved, built and installed last year (2021).

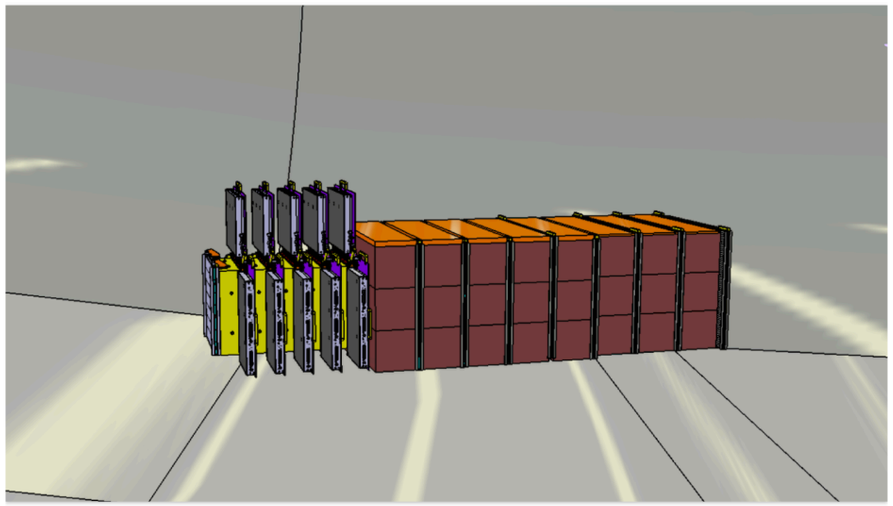
LIP is a founding member, built part of muon system.

A neutrino detector at the LHC!

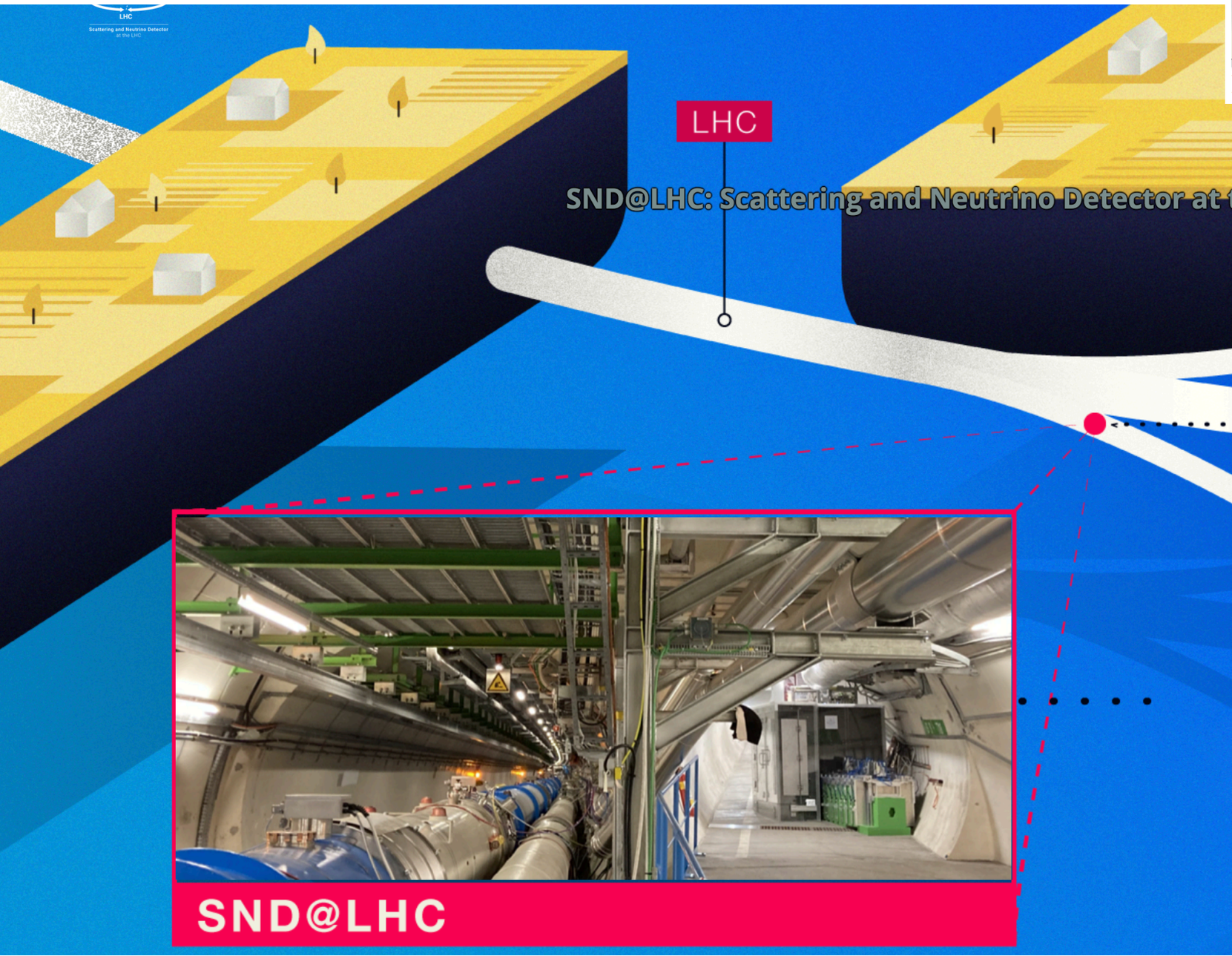
CERN approves new LHC experiment

SND@LHC, or Scattering and Neutrino Detector at the LHC, will be the facility's ninth experiment

27 AVRIL, 2021 | Par Ana Lopes



The SND@LHC experiment consists of an emulsion/tungsten target for neutrinos (yellow) interleaved with electronic tracking devices (grey), followed downstream by a detector (brown) to identify muons and measure the energy of the neutrinos. (Image: Antonio Crupano/SND@LHC)



LHC

Scattering and Neutrino Detector
at the LHC

SND@LHC extends physics potential of LHC

← **Probe LFU anomalies in neutrino sector!**

SND@LHC physics goals

Observe collider neutrinos for first time

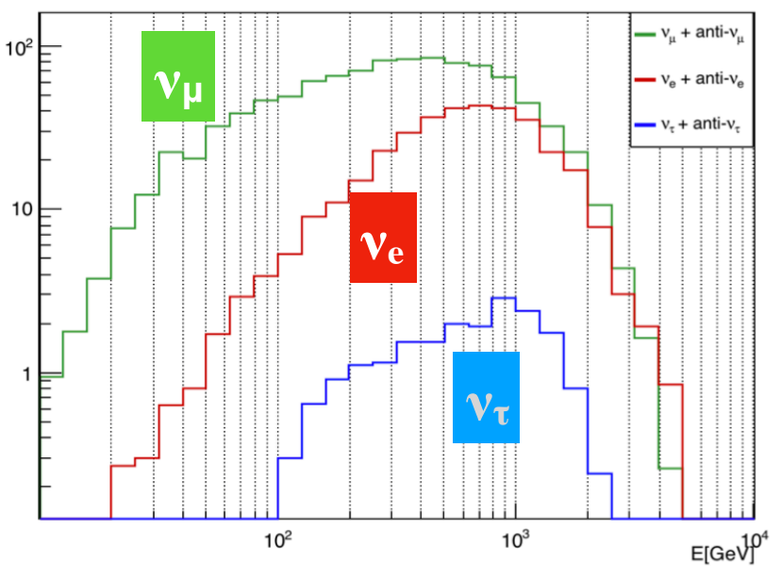
Unexplored energy range (up to 10 TeV)

Measure flavour production

Search for FIPs and Light Dark Matter

Detect and study all 3 flavours: ν_e, ν_μ, ν_τ

Lepton Flavour Universality (LFU) tests



$$R_{12} = \frac{\nu_e}{\nu_\mu}$$

$$R_{13} = \frac{\nu_e}{\nu_\tau}$$

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Measurement of Collider Neutrinos with the SND@LHC Experiment

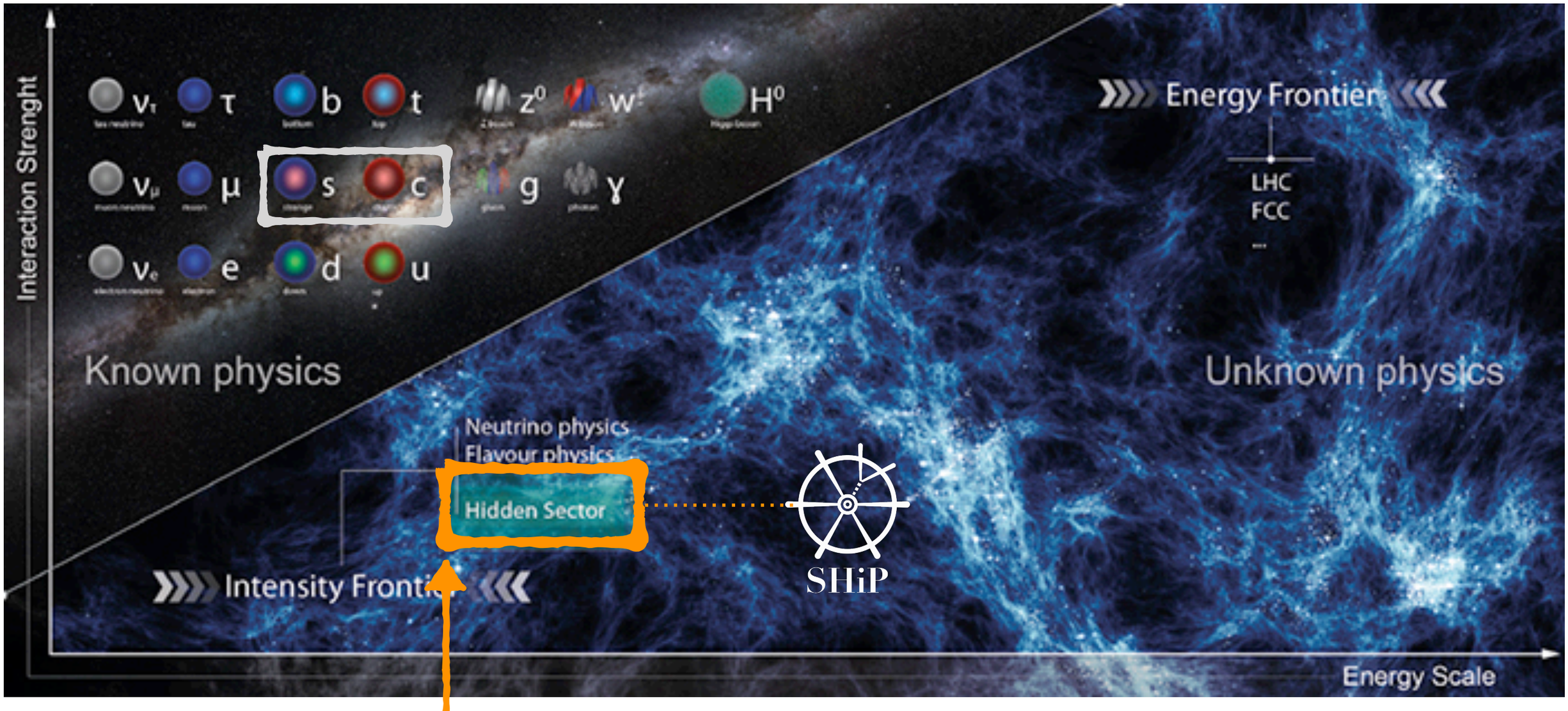
PhD thesis ongoing, by G.Soares

Masters thesis opportunity

- explore first data by the new LHC experiment
- Get integrated in a smaller collaboration in the exciting LHC environment
- first LHC collisions very soon!

Goal: go beyond the Standard Model

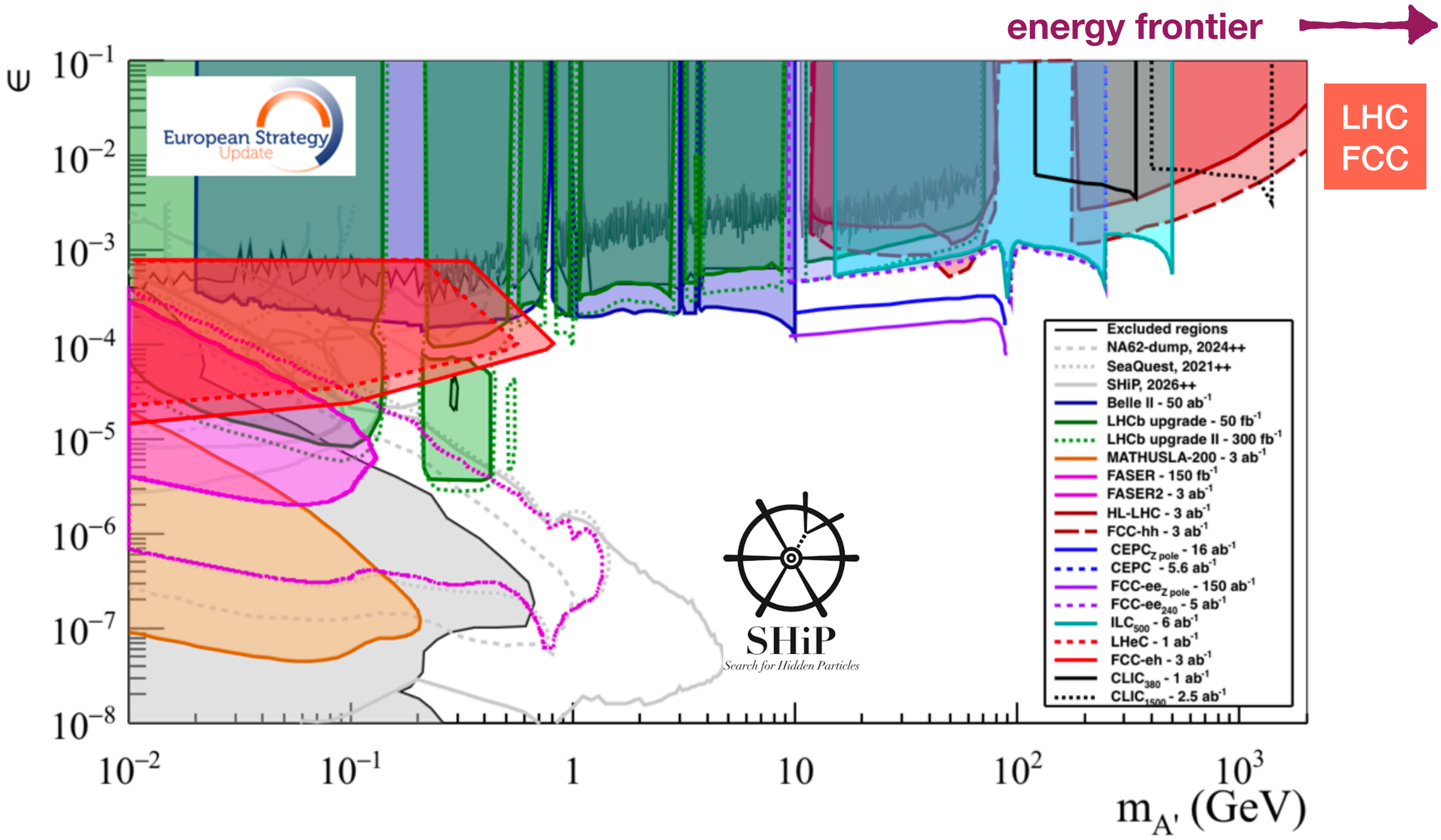
energy frontier →



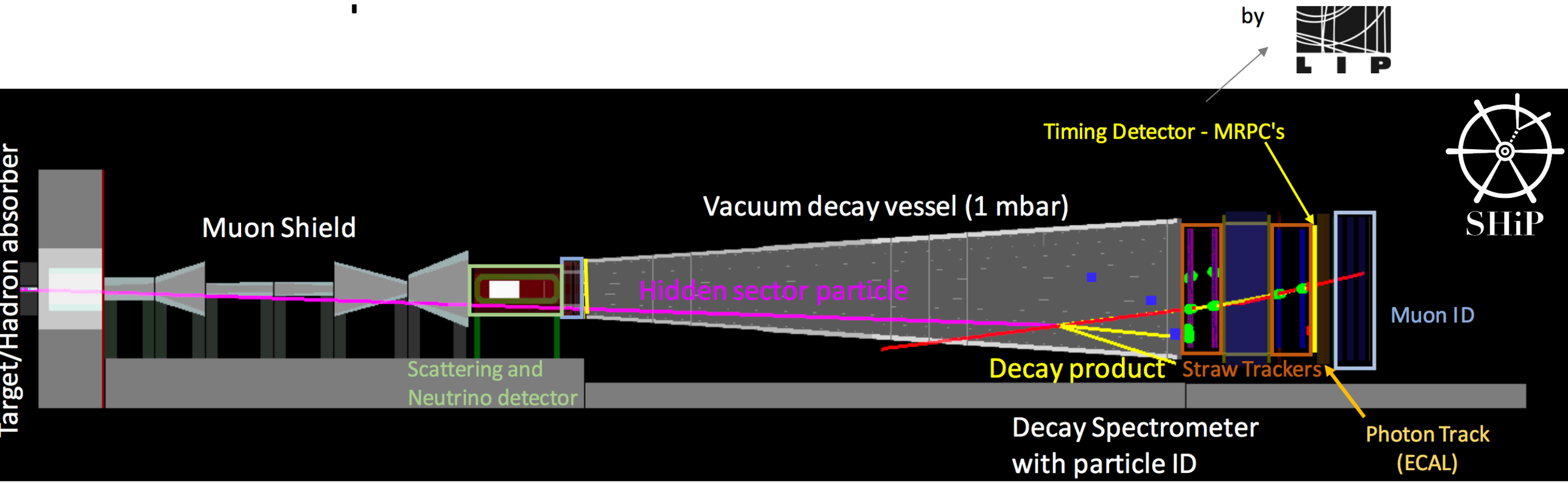
search for FIPs, Feebly Interacting Particles

(from decay of flavour hadrons produces in collision)

Goal: go beyond the Standard Model



SHiP — Search for Hidden Particles



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Optimization of the Selection of Hidden Particles in the SHiP Experiment

Guilherme Machado Santos Soares

CERN-THESIS-2021-038

Search for dark matter and supersymmetry using machine learning at SHiP

Francisco Safara[1,a] and Raúl Santos[2,b]

[1] *Faculdade de Ciências da Universidade de Lisboa, Lisboa, Portugal*
[2] *Instituto Superior Técnico, Lisboa, Portugal*

Project supervisors: N. Leonardo, G. Soares — *October 2020*

LIP-STUDENTS-20-17

Abstract. SHiP is an In
actions, low masses and
of the *hidden sector* of p
particles, specifically da
and tested several mach
taining a high signal effi
regression and classifica

Keywords: Hidden Sec

Distinguishing Hidden Sector Particles with Machine Learning at SHiP

Henrique Santos[1,a] and André Branco[1,b]

[1] *Instituto Superior Técnico, Lisboa, Portugal*

Project supervisors: N. Leonardo, G. Soares — *October 2021*

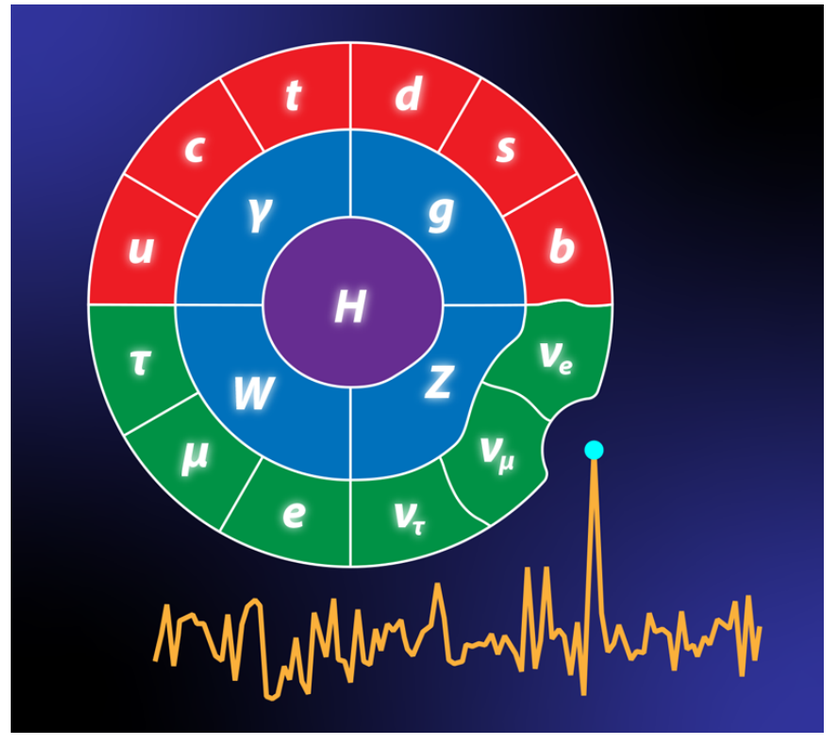
Abstract.
Given the plausible existence of new physics particles and interactions, the SHiP experiment at CERN aims to explore the Intensity Frontier in search for the so called Hidden Sector particles with exceedingly feeble couplings and thus distinctively rare decays. Three theoretical particles are studied consisting of Dark Photons(DP), Heavy Neutral Leptons(HNL) and Neutralinos. Using previously Monte Carlo simulated data sets in conjunction with sundry machine learning methods it is possible to classify those three different hypothetical particles from several decays (into Pion-muon and Muon-muon pairs) yielded from the input information culminating in efficiencies over 74% for all results and over 99% for the foremost ones.

Keywords: Hidden Sector, Dark Photons, Heavy Neutral Leptons, Neutralinos, Deep Neural Networks, Intensity Frontier

LIP-STUDENTS-21-06

Summary

- **flavour** provides a promising portal into new-physics beyond the SM
  - sensitive to new heavy particles beyond the collision energy
- a pattern of **anomalies** revealed in data, indicating contribution of new-physics
  - their clarification is current field priority
- **LHC** is entering a high intensity phase
  - new era of precision and rare processes
- great **research** opportunities for students
  - anomalies & LFU, neutrinos & other FIPs

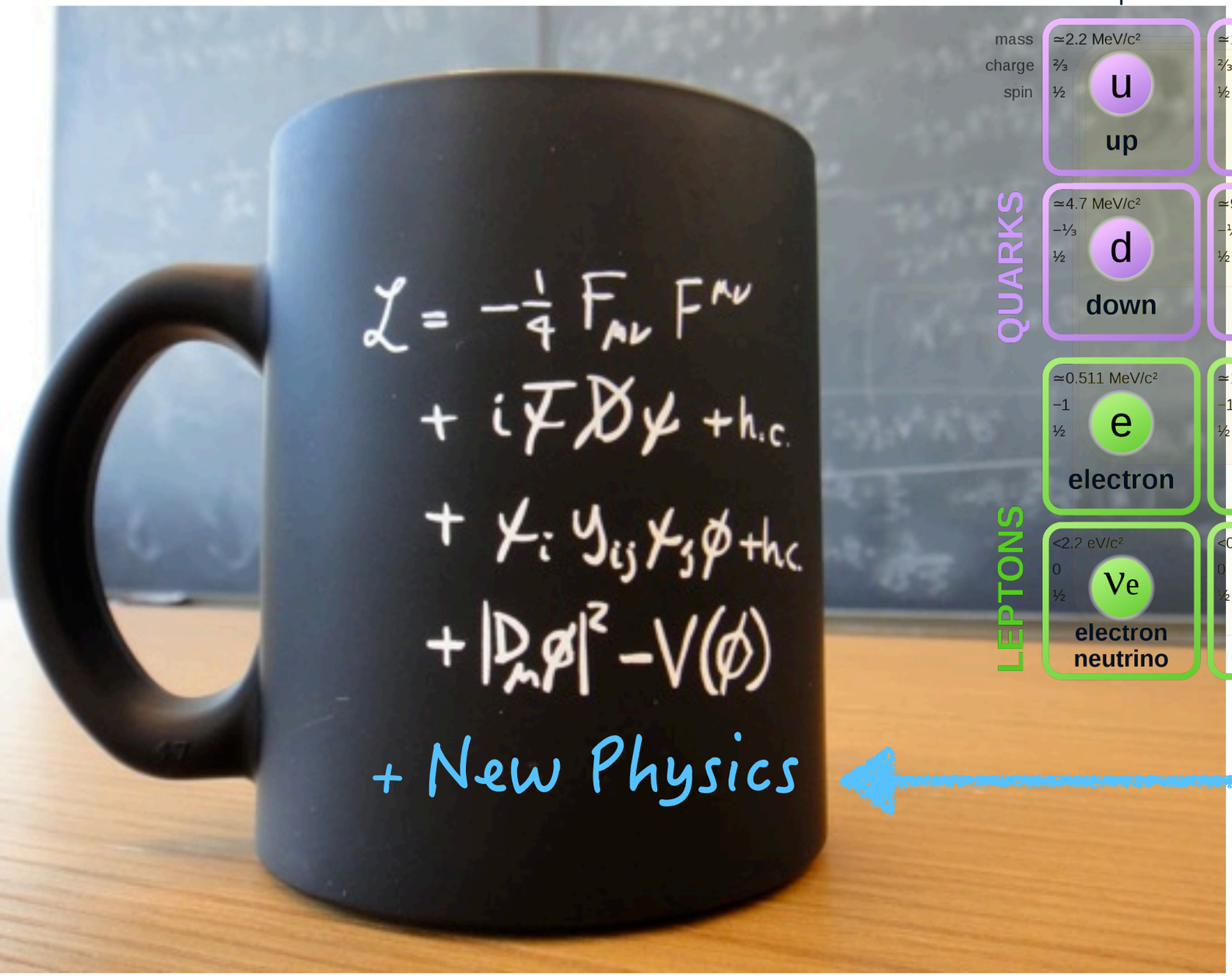


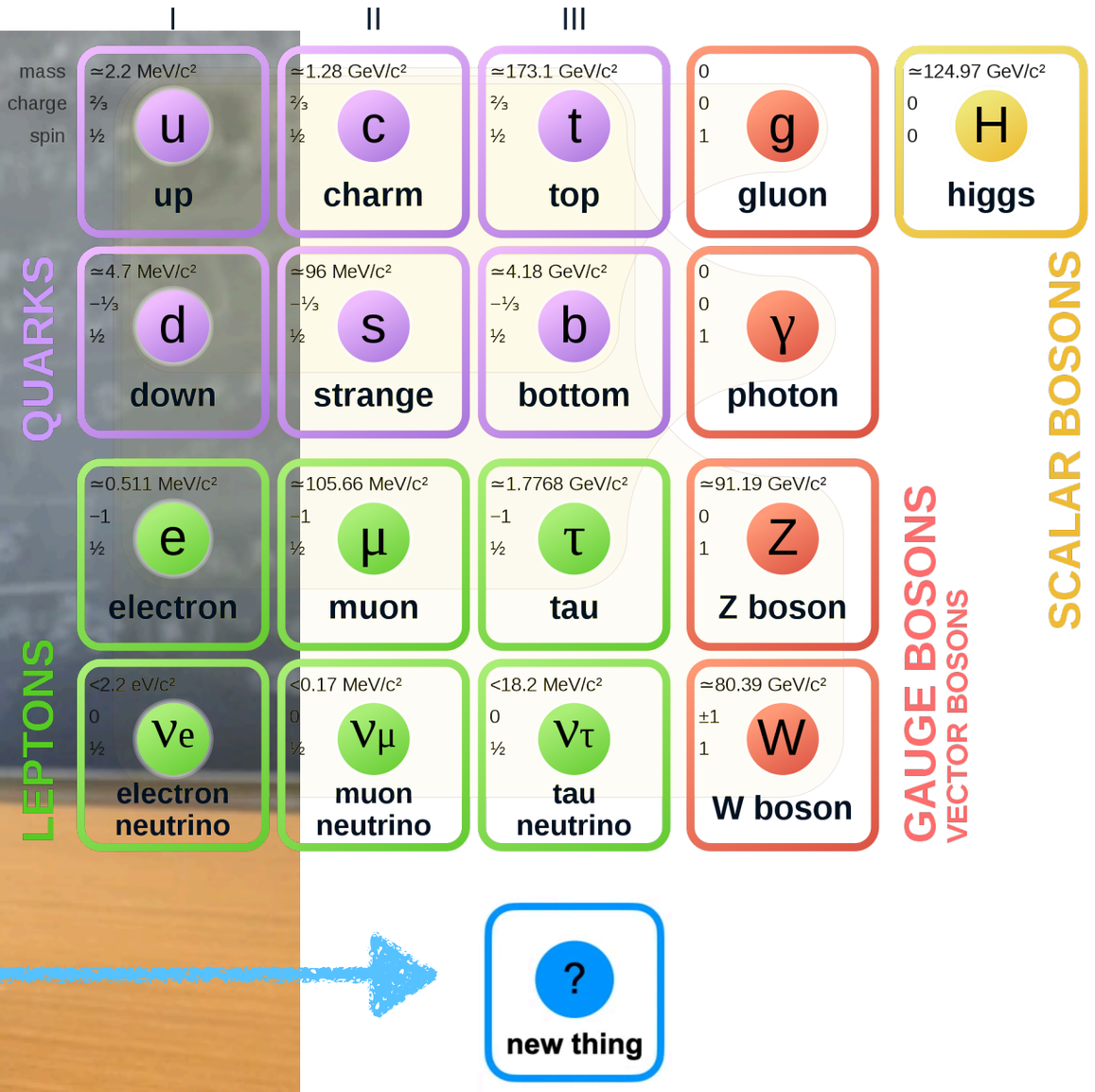
LHC Run3 starting now!

Join the adventure!

thank you

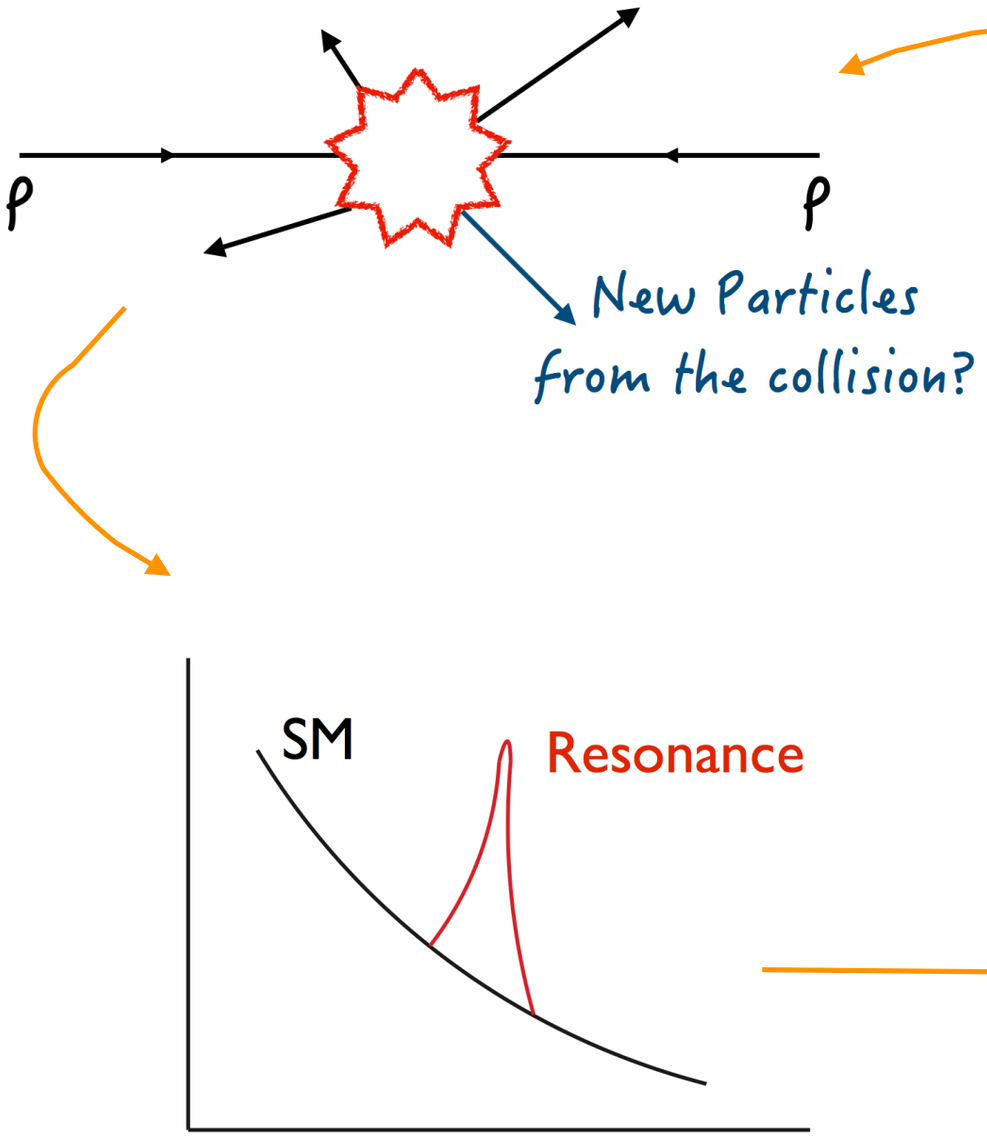
Goal: go beyond the Standard Model

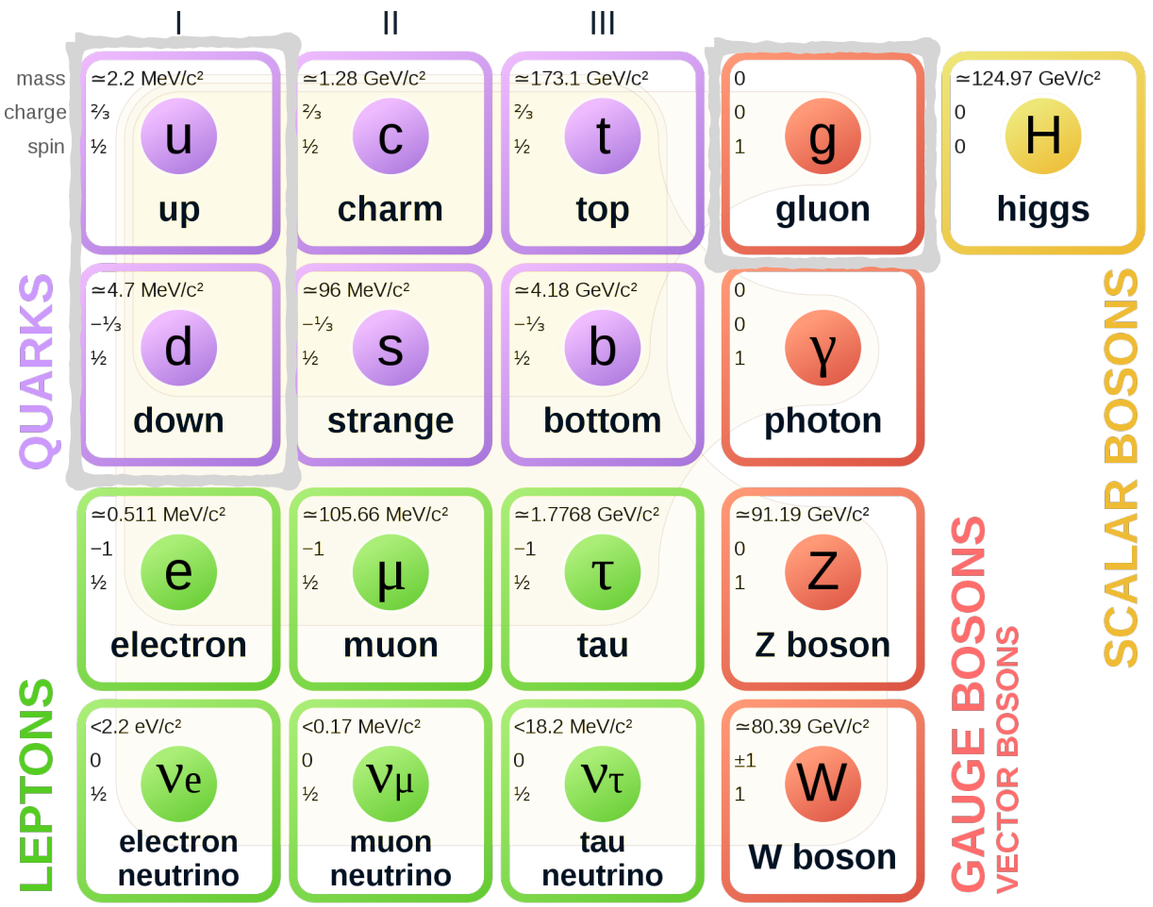




Goal: go beyond the Standard Model

1) the easy way: direct discovery

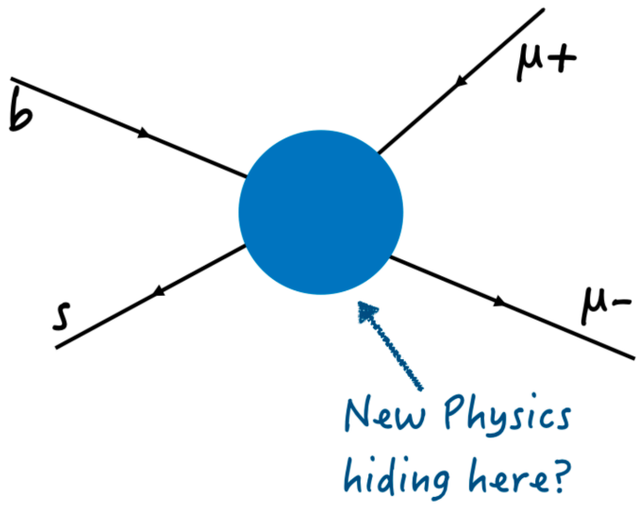


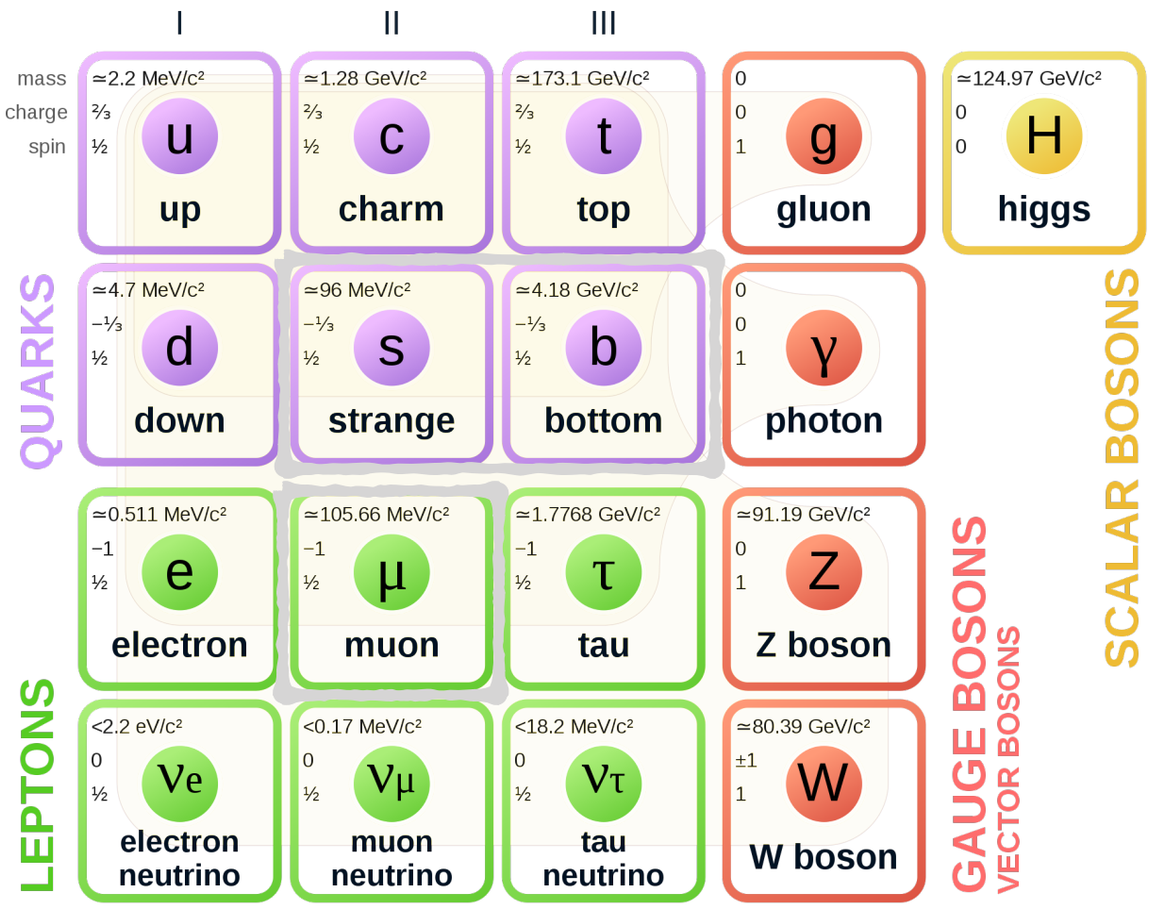


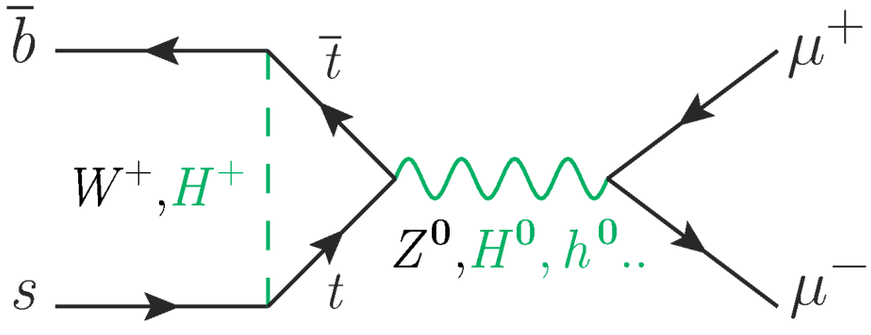
Energy frontier

Goal: go beyond the Standard Model

2) the not-so-easy way: *in*direct discovery



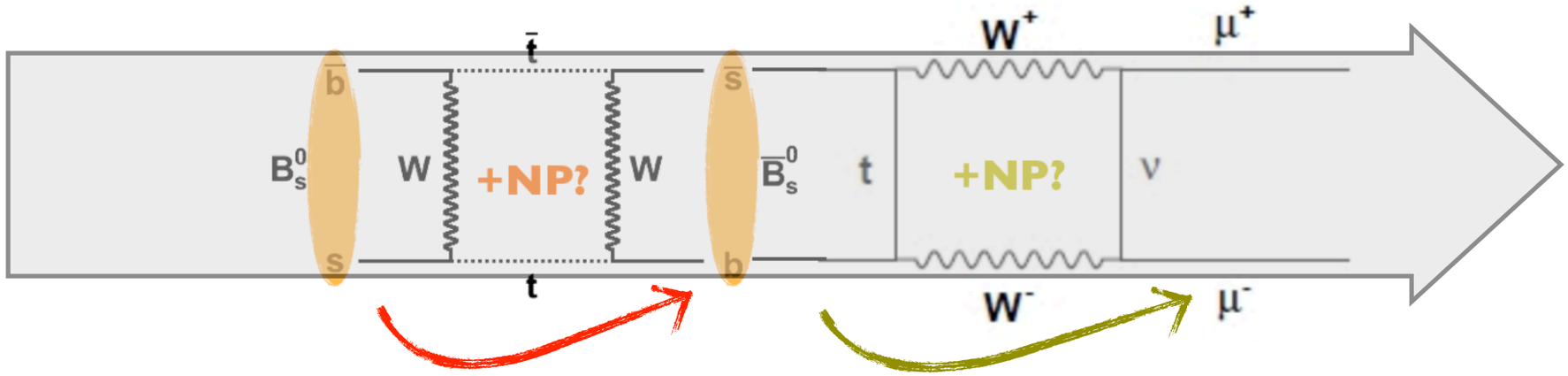




fuelled by **Quantum Mechanics**

Intensity frontier

B



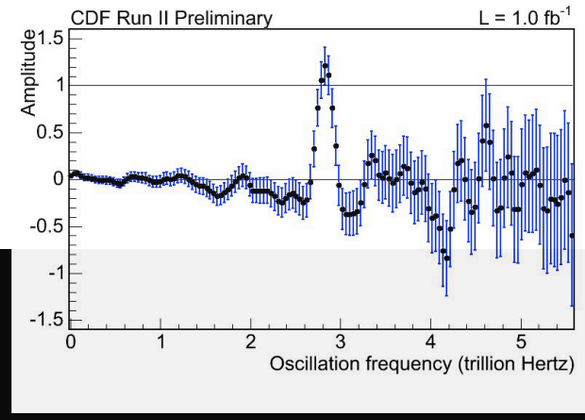
μμ

"fast and rare"

PARTICLE MIXING

RARE DECAY

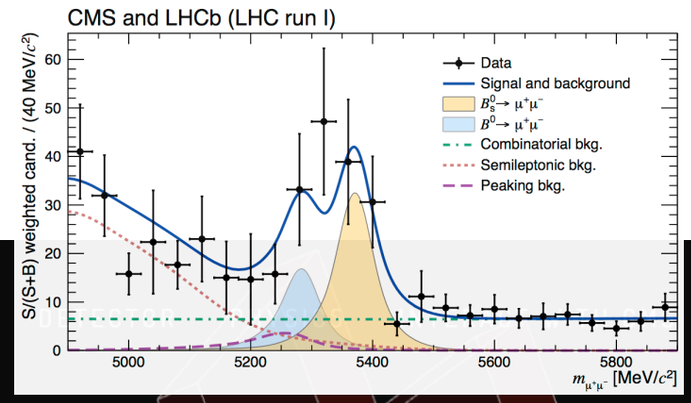
"doubly sensitive to NP"



PRL 97 (2006) 242003, NL thesis

flavour oscillations

Tevatron flagship (2006)



Nature 522 (2015) 68

Flavour-Changing Neutral Currents

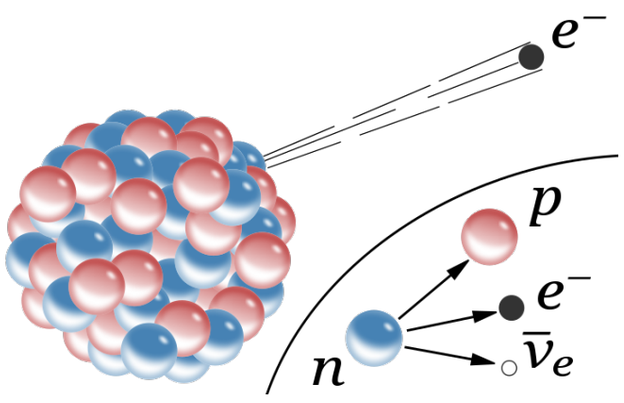
LHC flagship (2015)

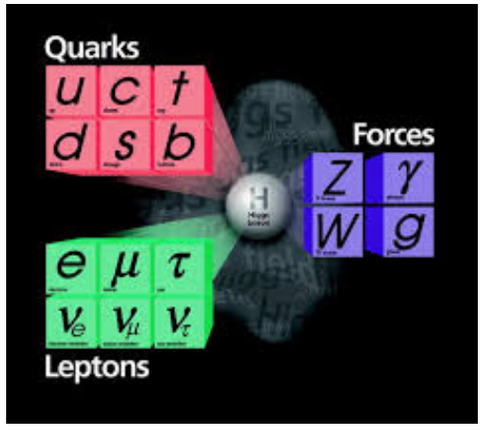
AUGUST 2019

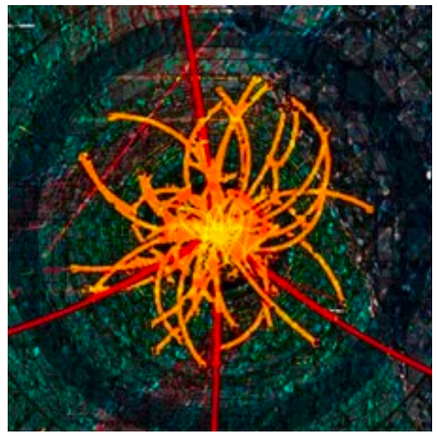
ULTRA-RARE DECAY OF A BEAUTIFUL STRANGE MESON

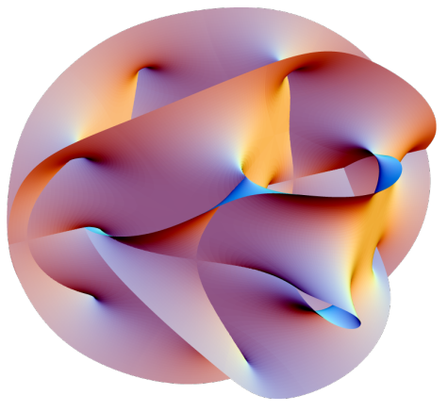
energy scale $m_{Z,W}$ m_H m_t Λ_{NP}

1930 ... 1970 2012 2020 ... future

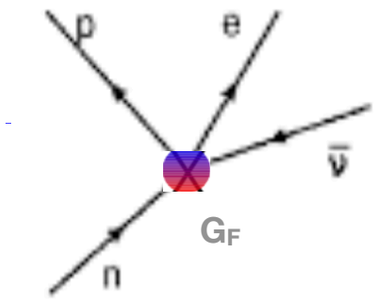


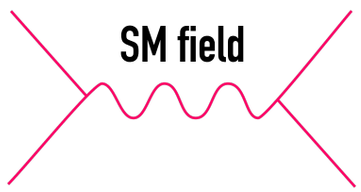


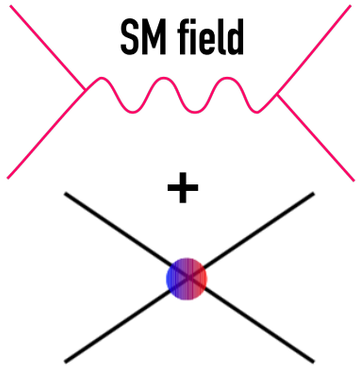


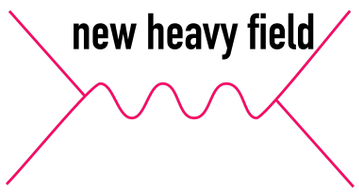


Fermi model | **Standard Model** | **SM-EFT** | **UV theory**









$\mathcal{L}_{\text{Fermi}} = -\frac{G_F}{\sqrt{2}}\,\bar{p}\gamma_\mu n\,\bar{e}\gamma^\mu\nu + \text{h.c.}$

$\mathcal{L}_{SM} = \mathcal{L}_{gauge} + \mathcal{L}_{higgs}$

$\mathcal{L}_{SM\text{-}EFT} = \mathcal{L}_{SM} + \Sigma_i C_i O_i$

a predecessor of EWK theory

simple and elegant theory describing *almost* all microscopic phenomena

we're here!

a more fundamental theory with new degrees of freedom

an analogy: machine learning