Flavour Anomalies

Neutrinos

@LHC & beyond

N. Leonardo nuno@cern.ch

8th mini-school
on Particle and Astroparticle Physics

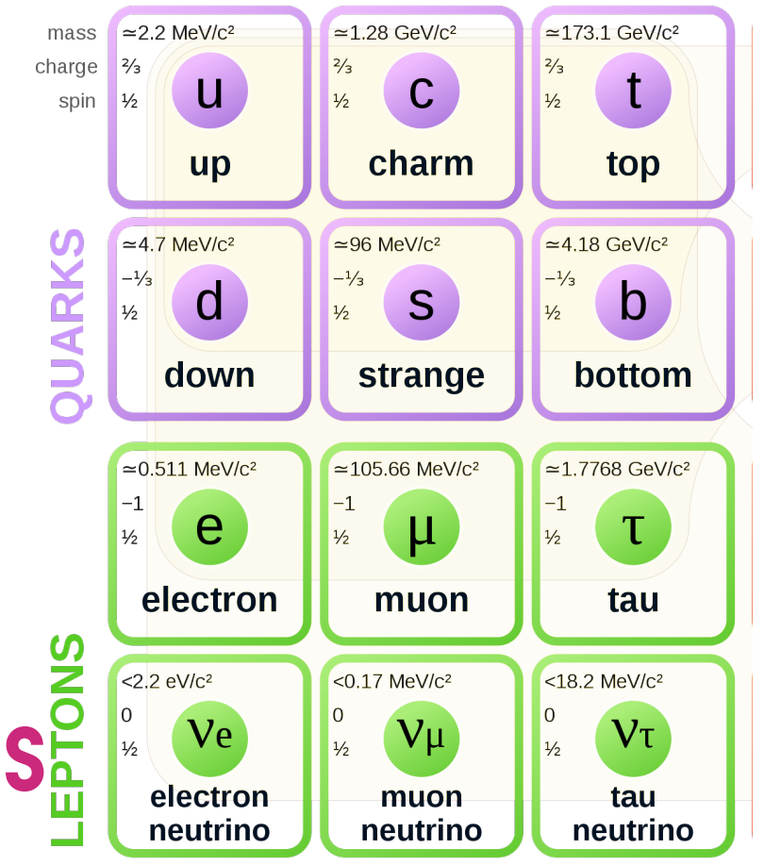
Oeiras 15 – 20 . MAY . 2023

Fundação para a Ciência e a Tecnologia

Flavour

quarks & leptons

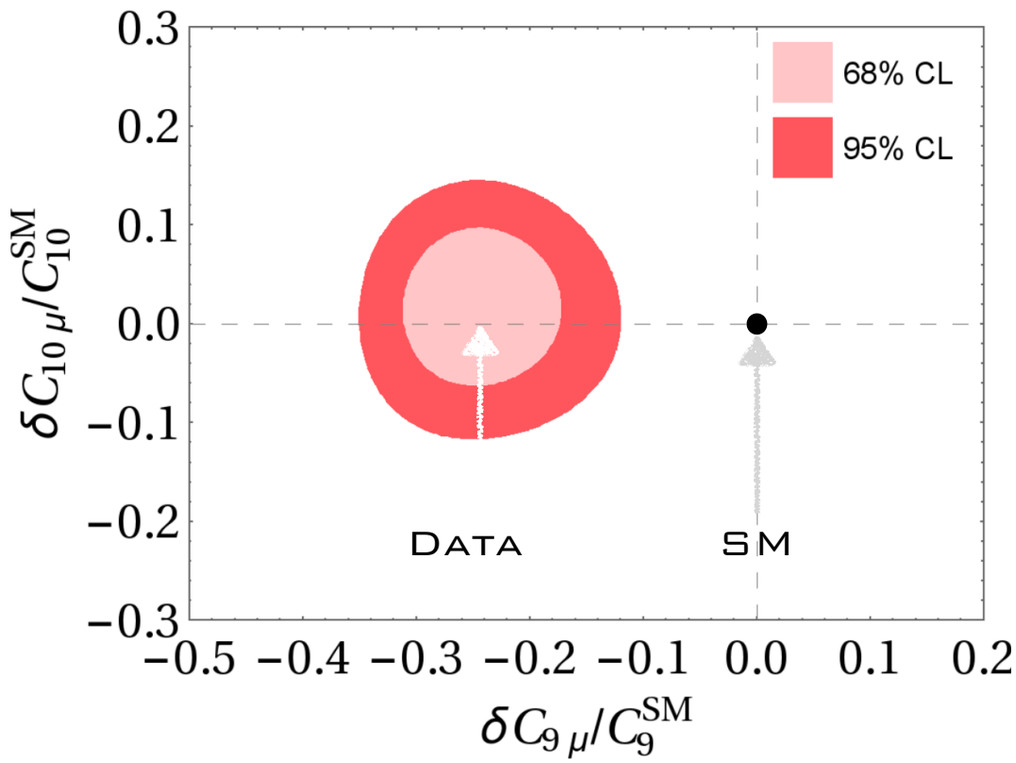
Just as ice cream has both color and flavour, so do quarks



Neutrinos

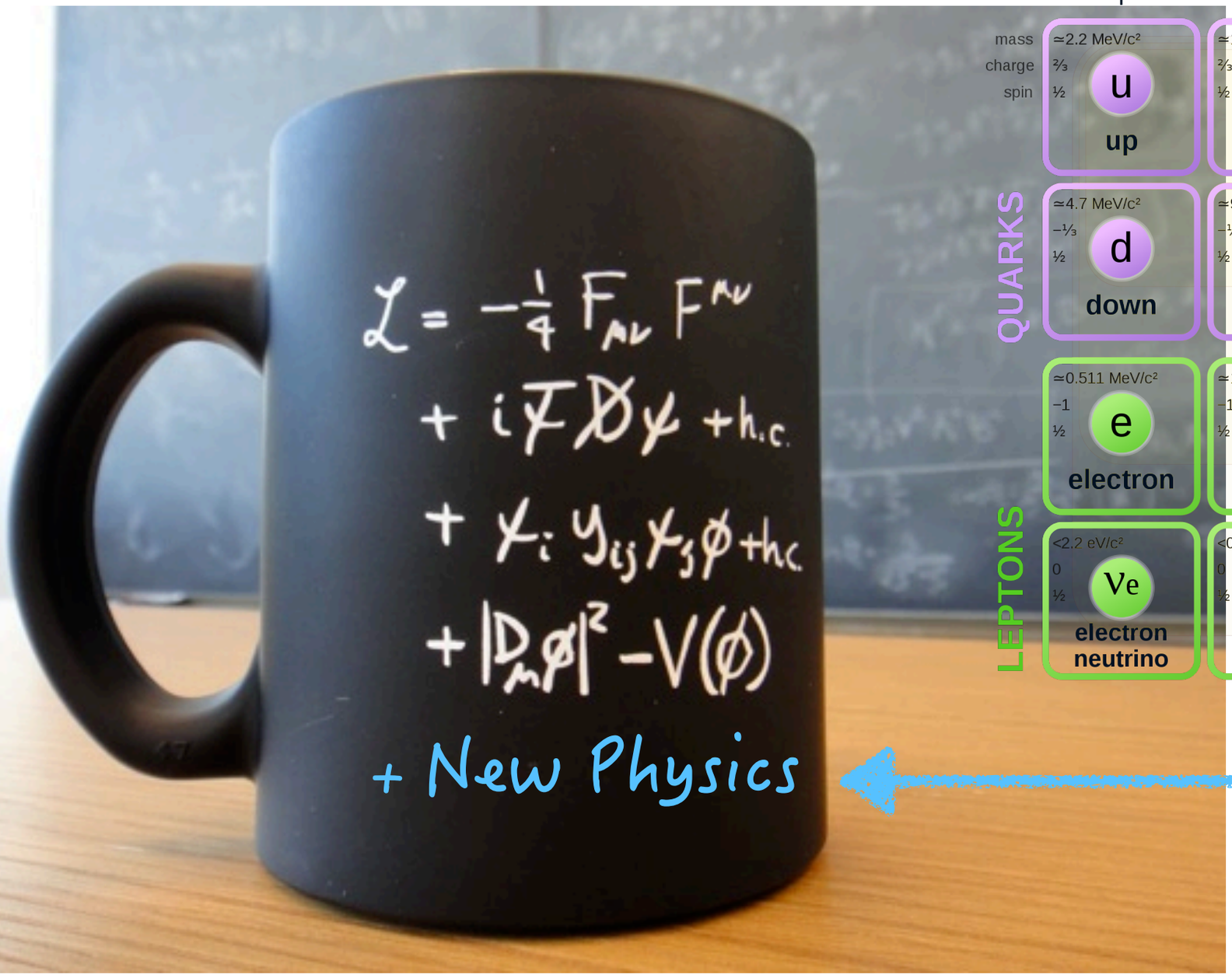
Anomalies

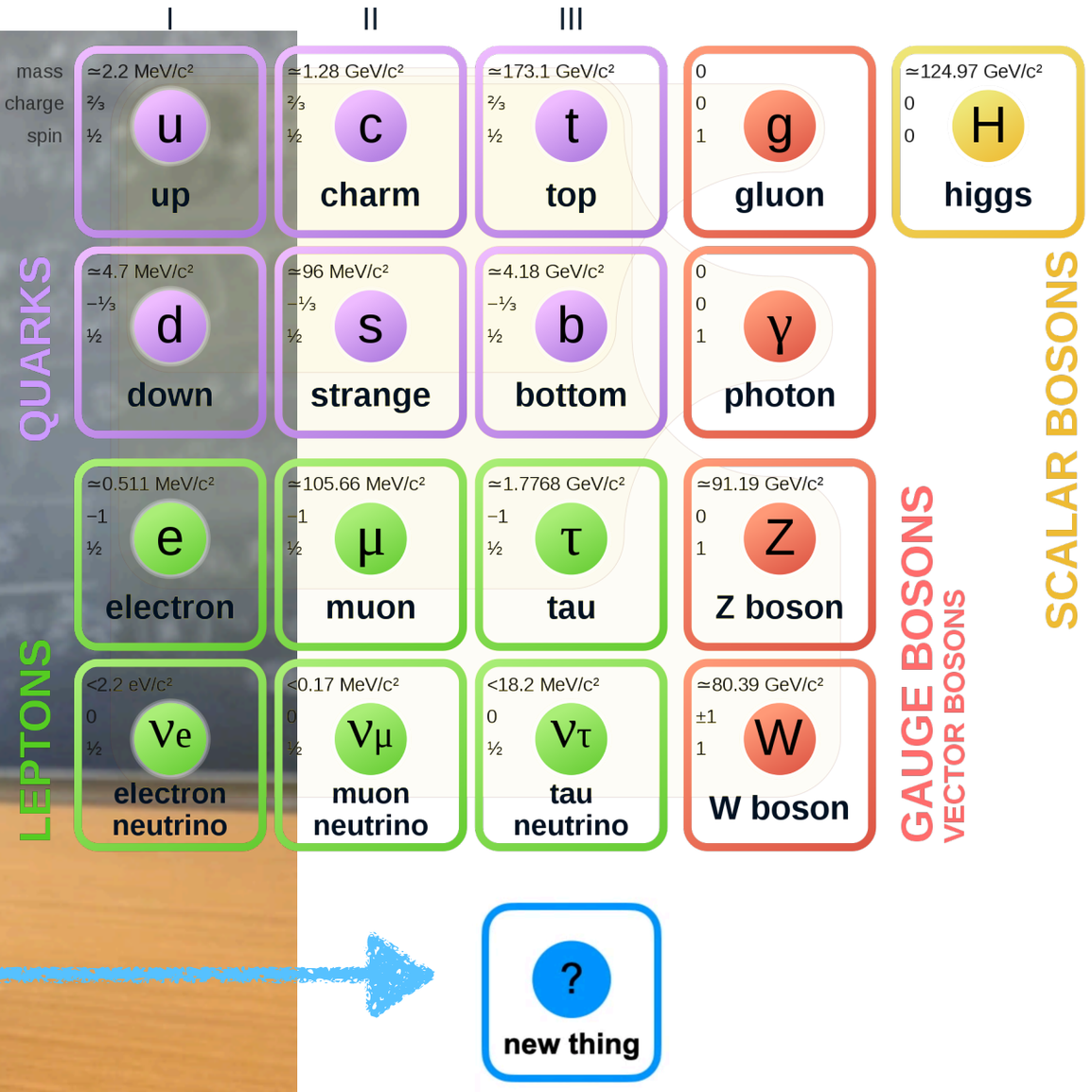
experiment ≠ theory



beyond SM

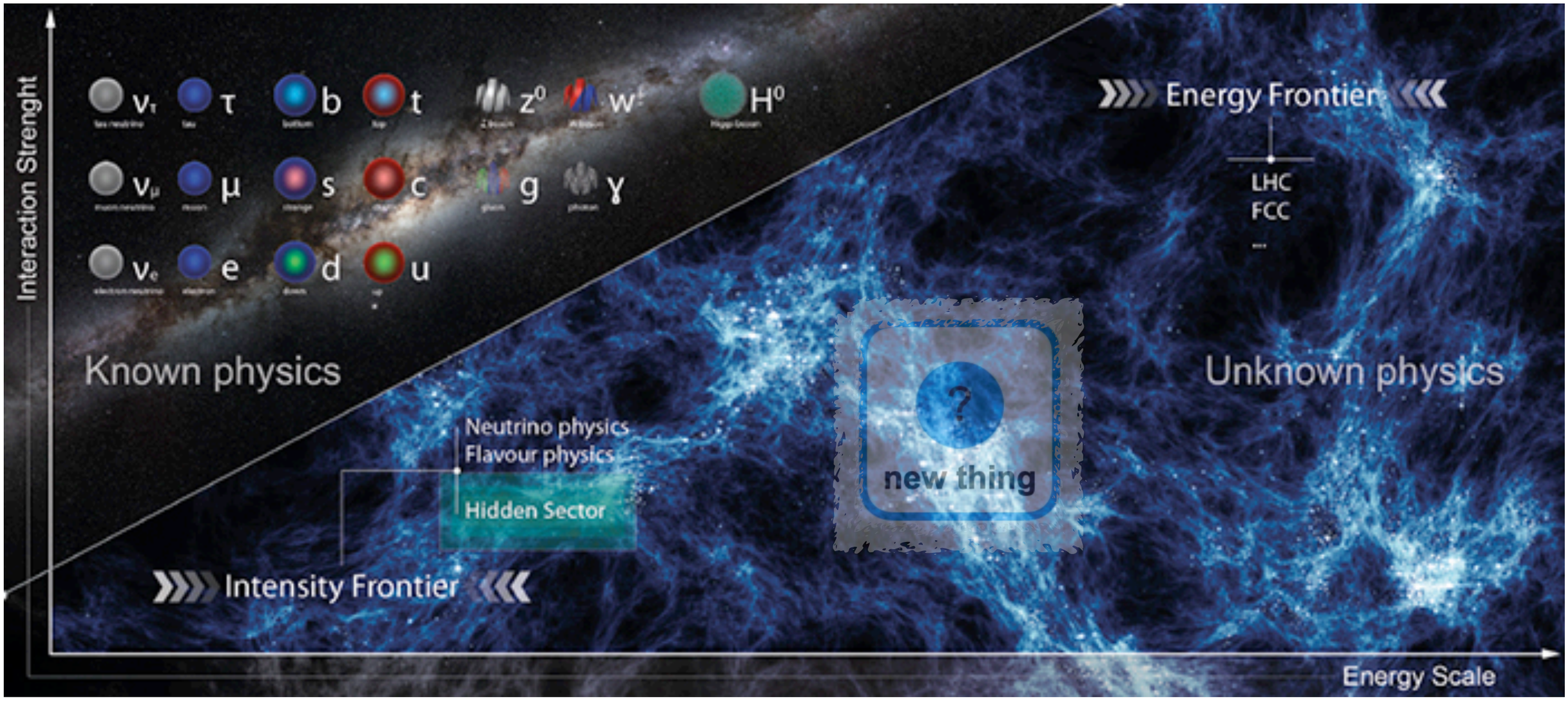
Goal: go beyond the Standard Model





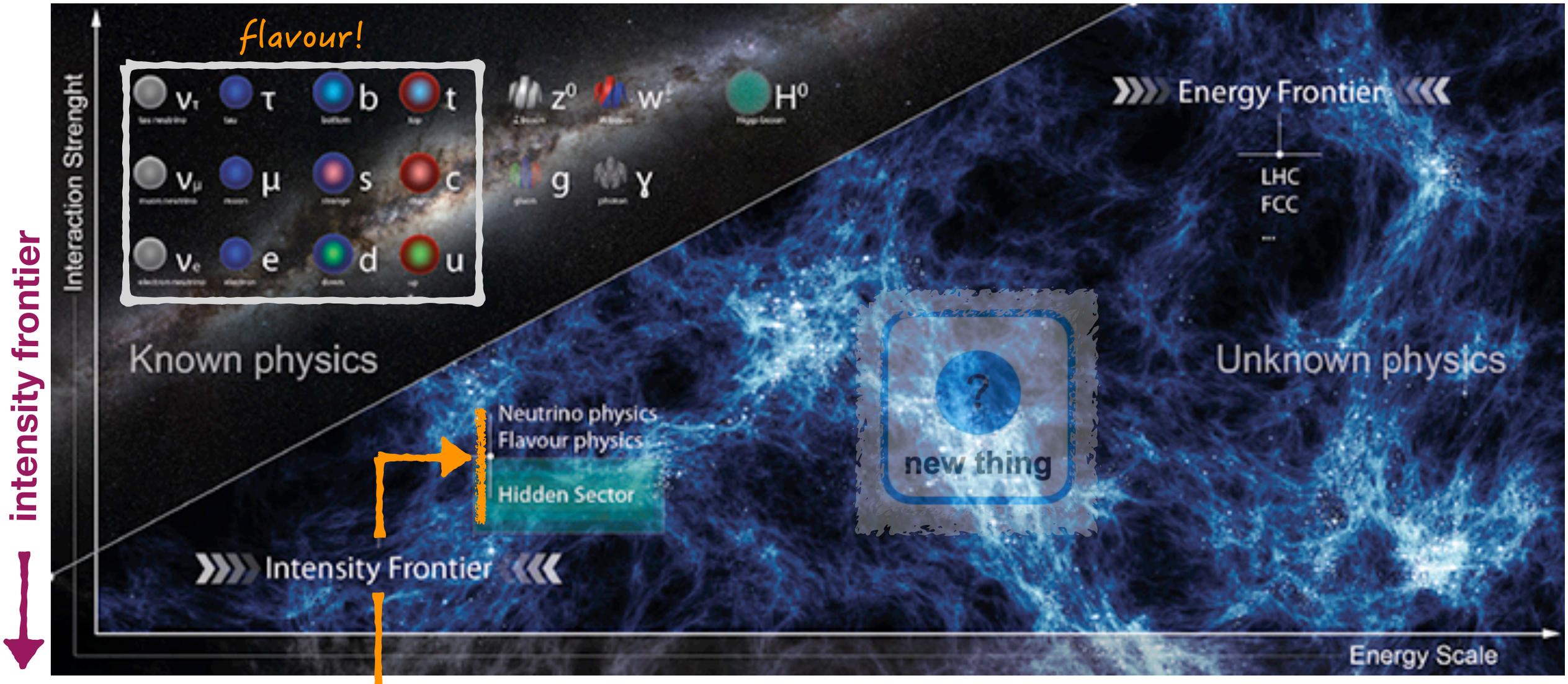
Goal: go beyond the Standard Model

energy frontier →



Goal: go beyond the Standard Model

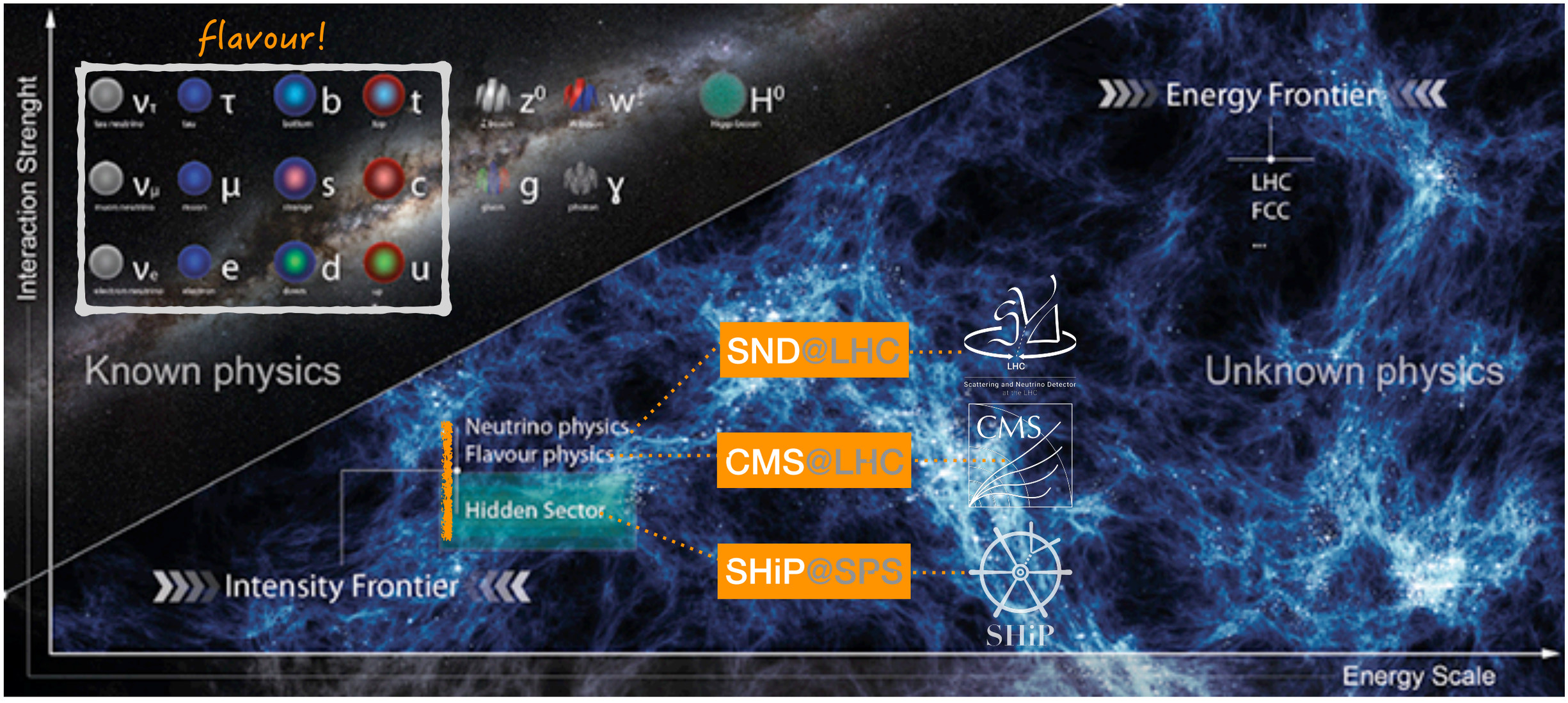
energy frontier →



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

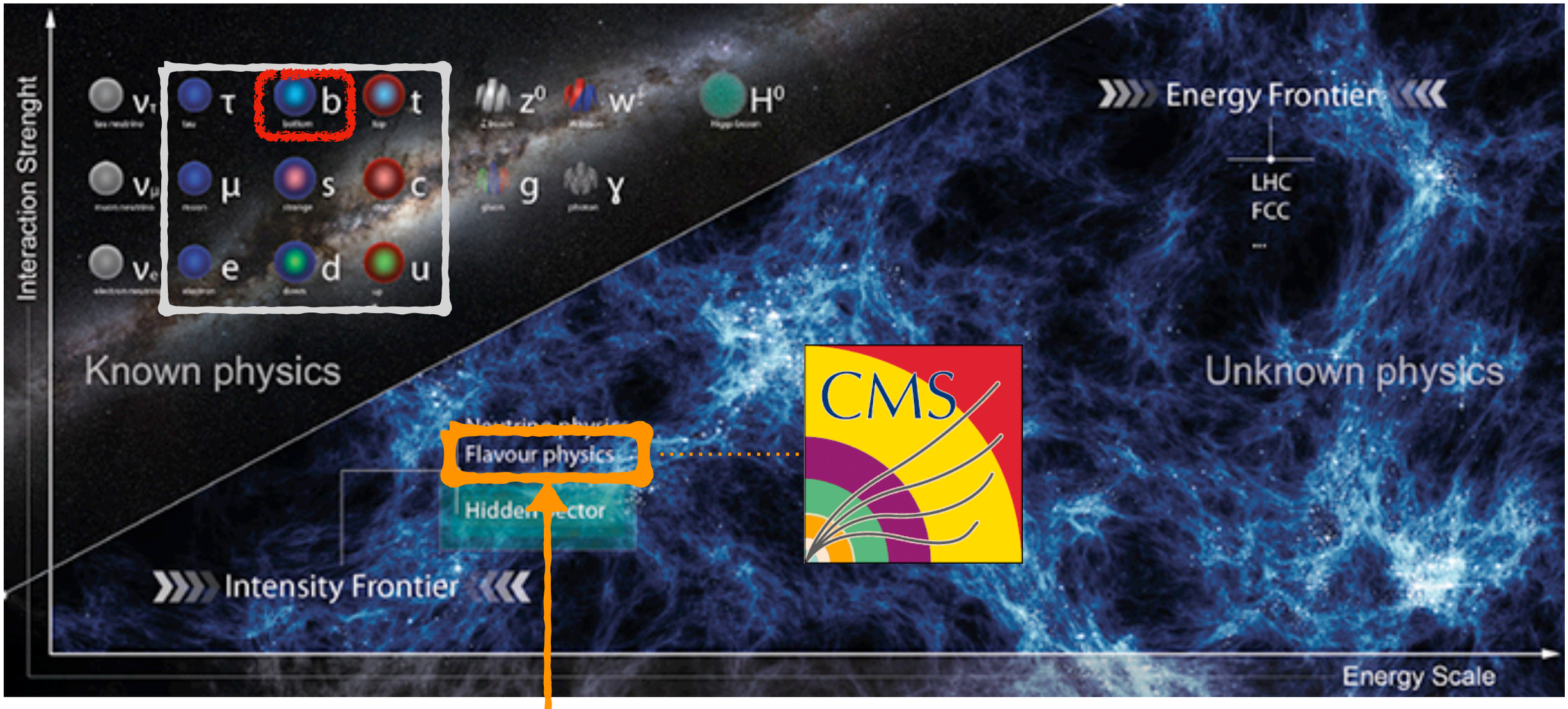
Goal: go beyond the Standard Model

energy frontier →



Goal: go beyond the Standard Model

energy frontier →

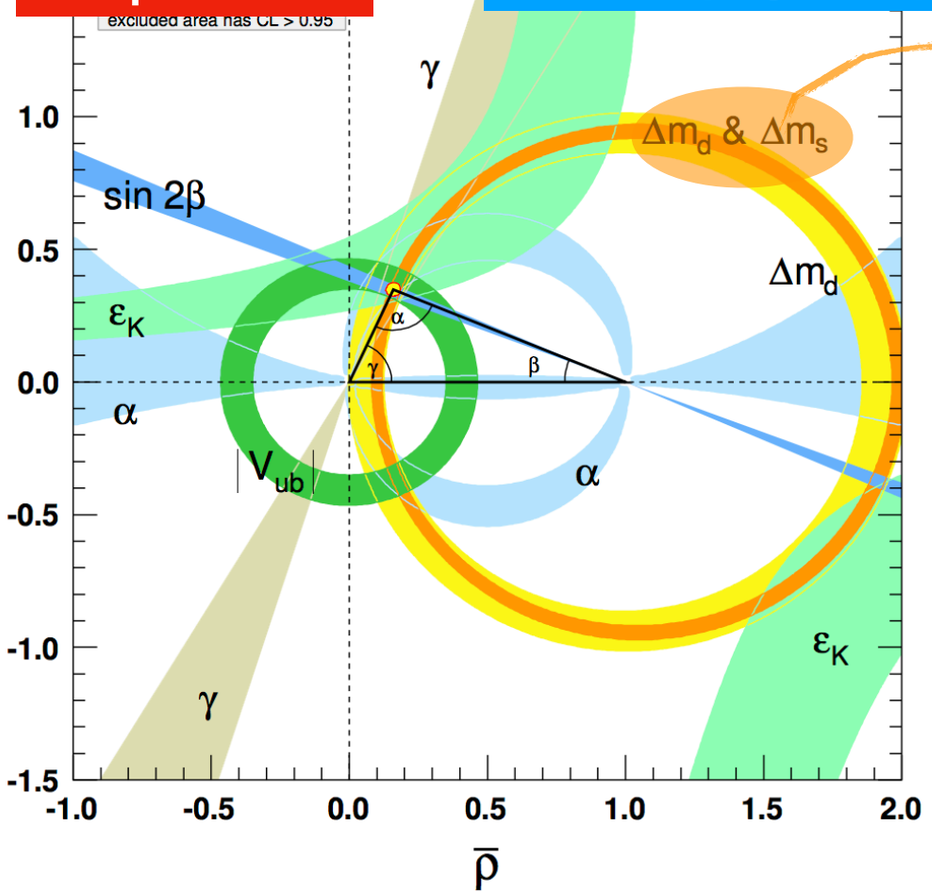


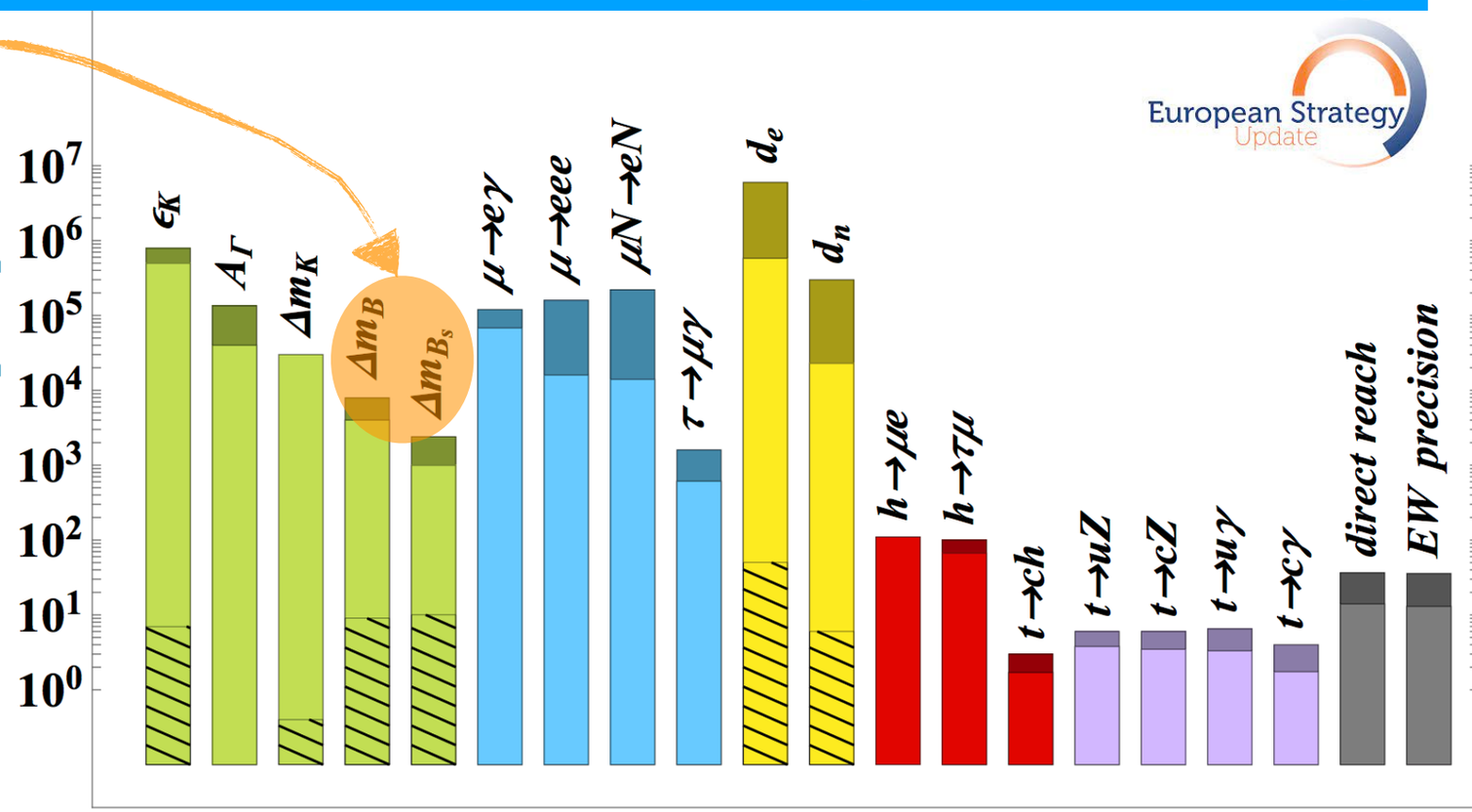
the LHC as a heavy-flavour factory

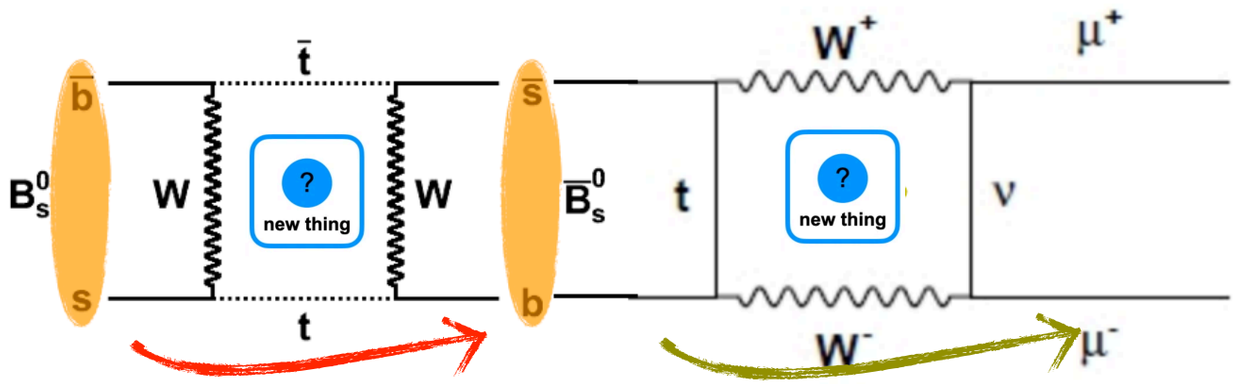
Flavor ➡ (indirect) access heavy BSM

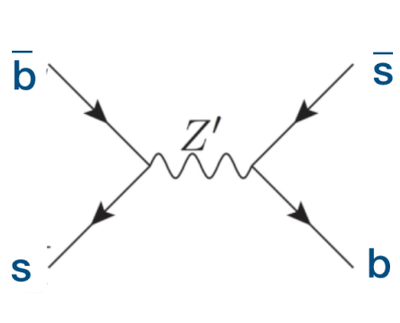
SM precision

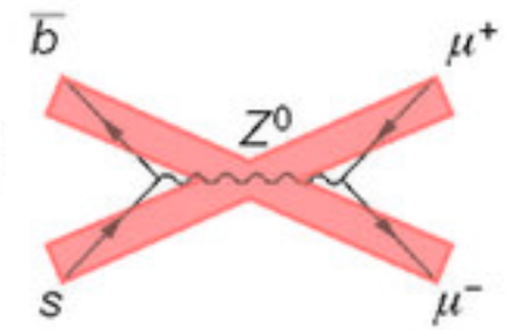
Flavour physics provides access to NP scales well beyond collision energy !





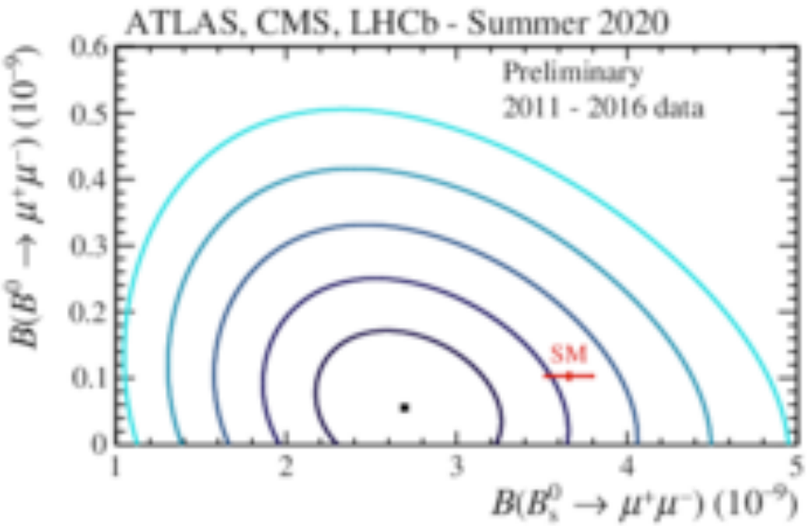




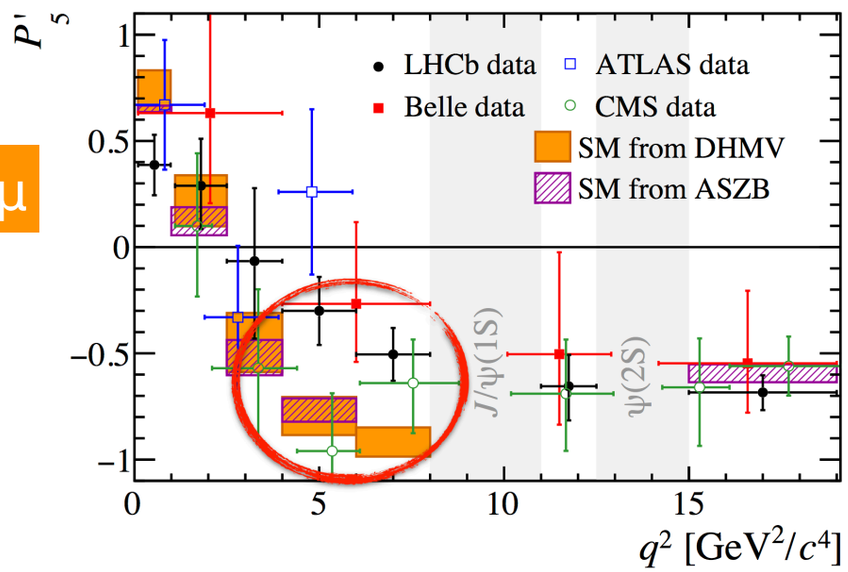


b→sμμ → the Flavour Anomalies!

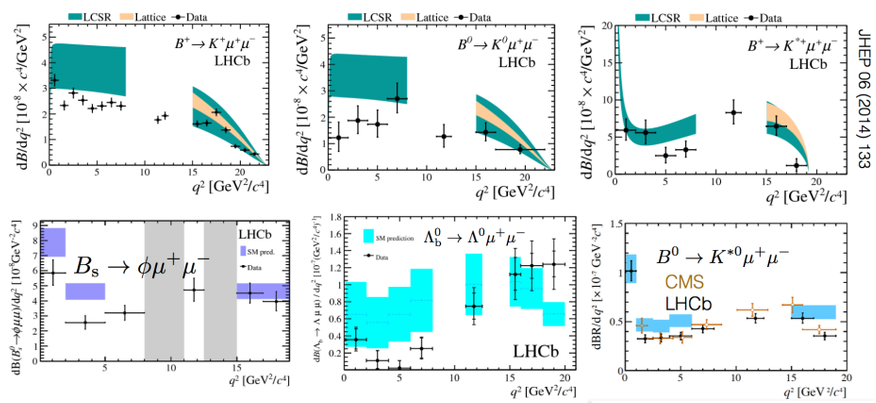
B→μμ



B→K*μμ

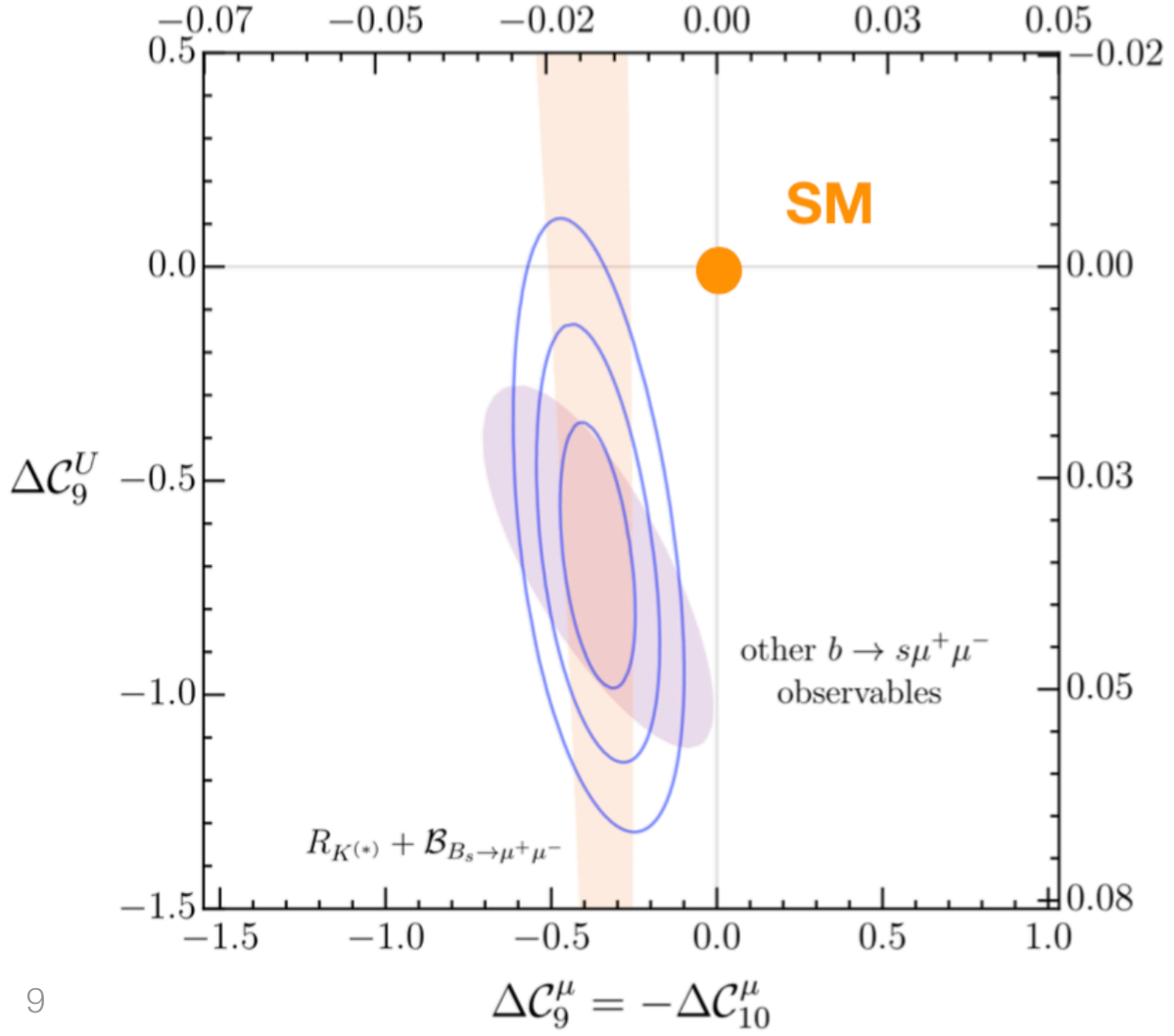


B→Xμμ



SM - Effective Field Theory

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



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

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Bruno now PhD @ Polytechnique, France

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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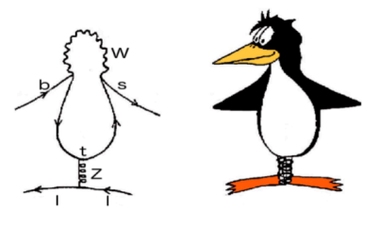
Maria now PhD @ EPFL, Switzerland



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

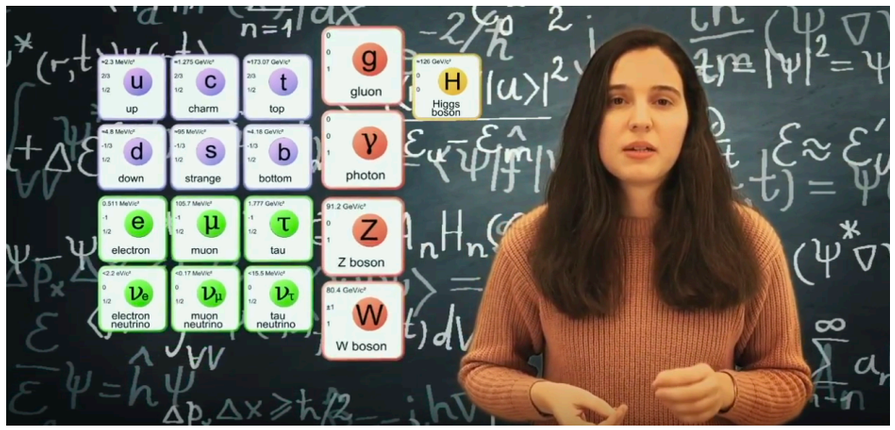
Engineering Physics

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

B→K*μμ

LFU

(probing B mesons in hot QCD medium)



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Julia now PhD @ Birmingham, UK

Probing the quark gluon plasma medium through B meson production measurements in PbPb collisions at the LHC

Júlia Manuela Cardoso Silva

Thesis to obtain the Master of Science Degree in

Engineering Physics

CERN-THESIS-2019-256
https://cds.cern.ch/record/2705630
Defense: October 2019

Bs observation in PbPb

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just defended yesterday !

Probing the Quark-Gluon Plasma with B_s^0 and B^+ Mesons

Cross Sections in pp and Nuclear Modification Factors in PbPb

Henrique Miguel Marques Luís Legoinha

Thesis to obtain the Master of Science Degree in

Engineering Physics

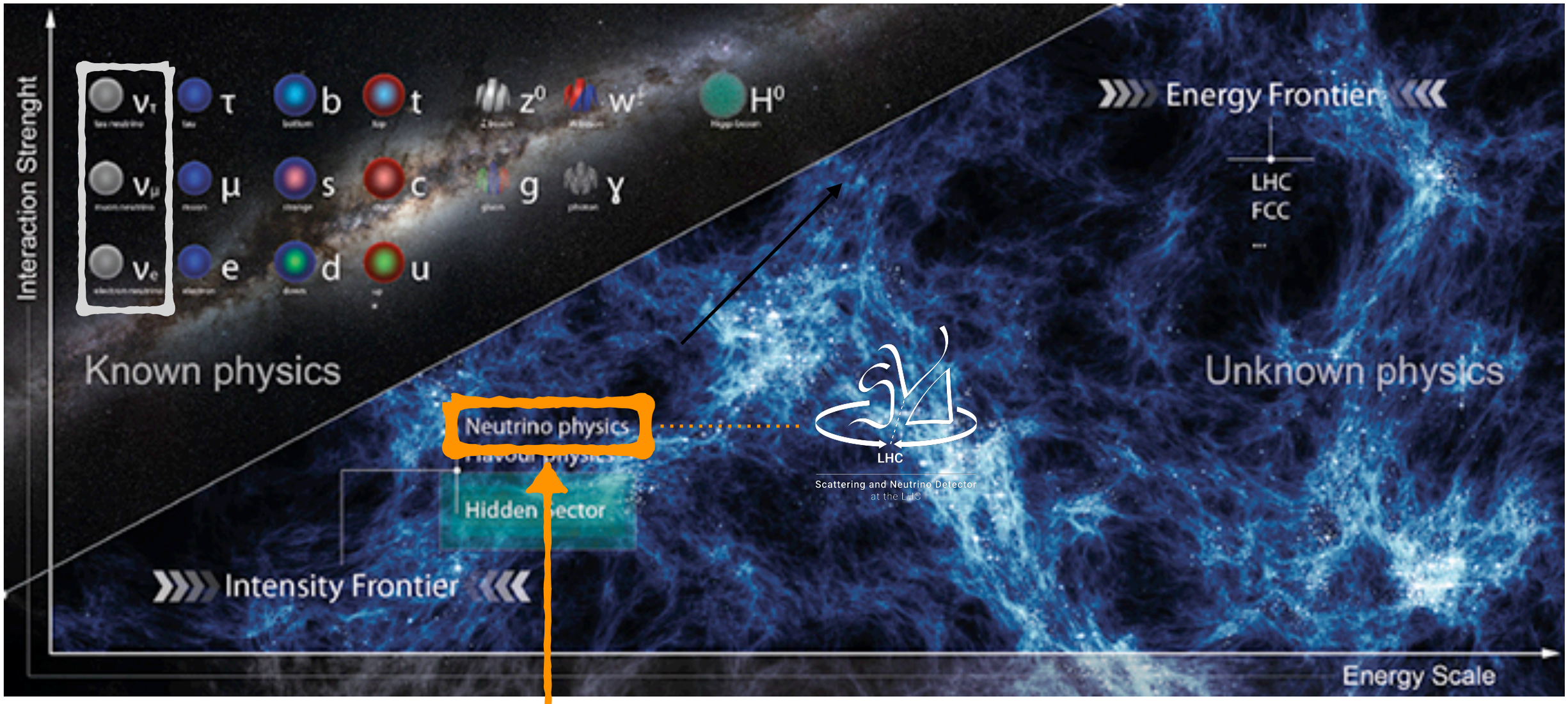
B mesons R_{AA}

thesis opportunity

- New PbPb data — being collected in October 2023
- Study b hadrons as novel probes of QGP
- Reach low p_T region with machine learning
- Search for b baryons
- Explore **exotic** hadrons e.g. X(3872)

Goal: go beyond the Standard Model

energy frontier →



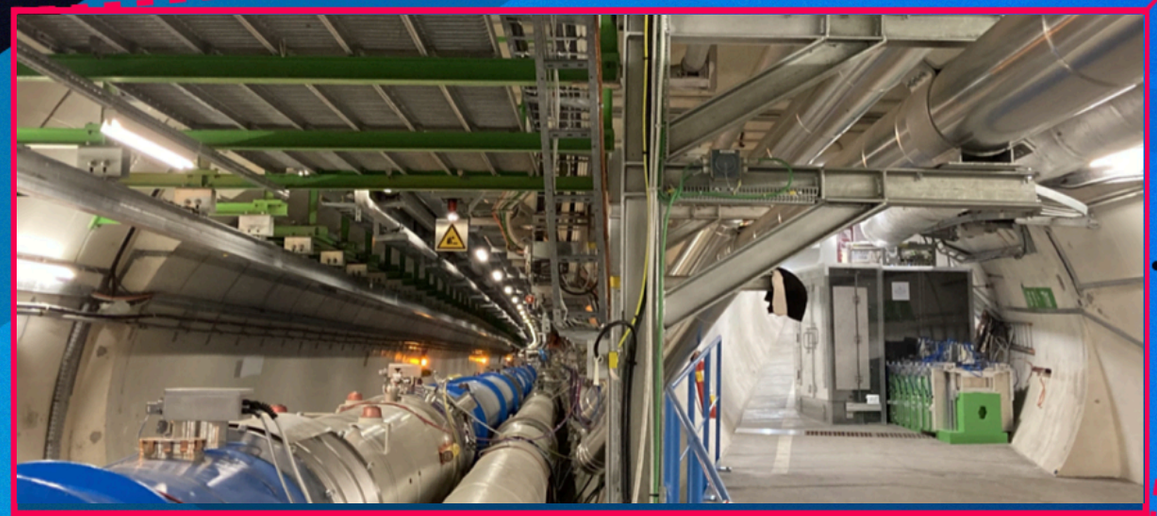
the LHC as a neutrino factory

The most recent LHC experiment

➡ see also C.Vilela's Lecture on Monday

SND@LHC: Scattering and Neutrino Detector at the LHC

Neutrinos at LHC !

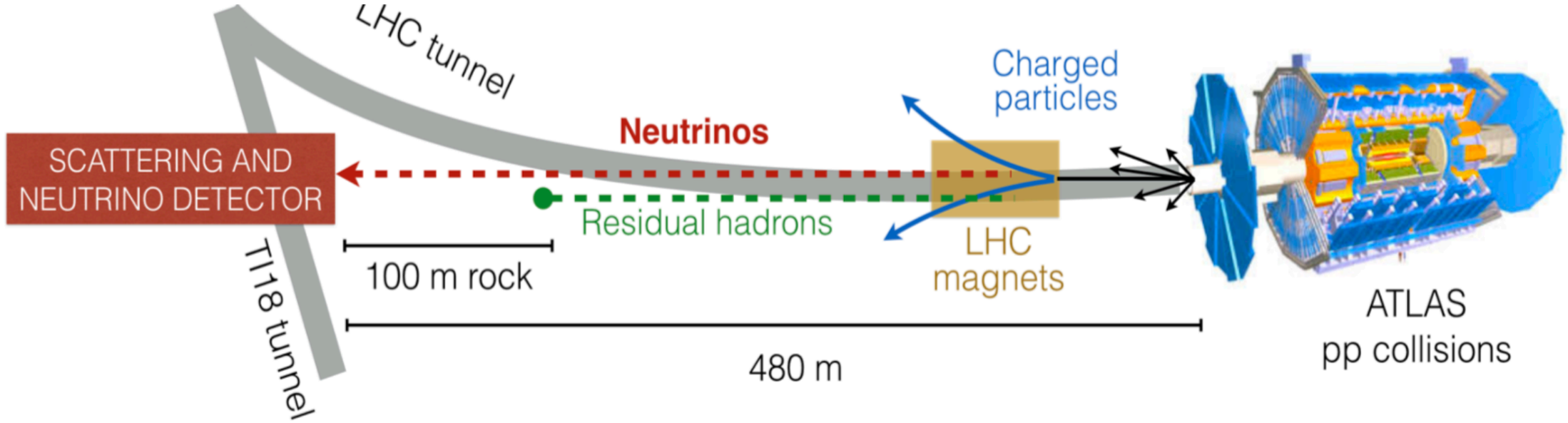


SND@LHC

TI18

ATLAS

SPS



just posted this week !

Observation of collider muon neutrinos with the SND@LHC experiment

Observation of collider muon neutrinos with the SND@LHC experiment

R. Albanese,[1,2] A. Alexandrov,[1] F. Alicante,[1,2] A. Anokhina,[3] T. Asada,[1,2] C. Battilana,[4,5] A. Bay,[6] C. Betancourt,[7] A. Blanco Castro,[8] M. Bogomilov,[9] D. Bonacorsi,[4,5] W.M. Bonivento,[10] P. Bordalo,[8] A. Boyarsky,[11,12] S. Buontempo,[1] M. Campanelli,[13] T. Camporesi,[14] V. Canale,[1,2] A. Castro,[4,5] D. Centanni,[1,15] F. Cerutti,[14] M. Chernyavskiy,[3] K.-Y. Choi,[16] S. Cholak,[6] F. Cindolo,[4] M. Climescu,[17] A.P. Conaboy,[18] G.M. Dallavalle,[4] D. Davino,[1,19] P.T. de Bryas,[6] G. De Lellis,[1,2] M. De Magistris,[1,15] A. De Roeck,[14] A. De Rújula,[14] M. De Serio,[20,21] D. De Simone,[7] A. Di Crescenzo,[1,2] R. Donà,[4,5] O. Durhan,[22] F. Fabbri,[4] F. Fedotovs,[13] M. Ferrillo,[7] M. Ferro-Luzzi,[14] R.A. Fini,[20] A. Fiorillo,[1,2] R. Fresa,[1,23] W. Funk,[14] A. Golovatiuk,[1,2] A. Golutvin,[24] E. Graverini,[6] A.M. Guler,[22] V. Guliaeva,[3] G.J. Haefeli,[6] J.C. Helo Herrera,[25,26] E. van Herwijnen,[24] P. Iengo,[1] S. Ilieva,[1,2,9] A. Infantino,[14] A. Iuliano,[1,2] R. Jacobsson,[14] C. Kamiscioglu,[22,27] A.M. Kauniskangas,[6] E. Khalikov,[3] S.H. Kim,[28] Y.G. Kim,[29] G. Klioutchnikov,[14] M. Komatsu,[30] N. Konovalova,[3] S. Kovalenko,[25,31] S. Kuleshov,[25,31] H.M. Lacker,[18] O. Lantwin,[3] F. Lasagni Manghi,[4] A. Lauria,[1,2] K.Y. Lee,[28] K.S. Lee,[32] S. Lo Meo,[4] V.P. Loschiavo,[1,19] S. Marcellini,[4] A. Margiotta,[4,5] A. Mascellani,[6] A. Miano,[1,2] A. Mikulenko,[11] M.C. Montesi,[1,2] F.L. Navarria,[4,5] S. Ogawa,[33] N. Okateva,[3] M. Ovchynnikov,[11] G. Paggi,[4,5] B.D. Park,[28] A. Pastore,[20] A. Perrotta,[4] D. Podgrudkov,[3] N. Polukhina,[3] A. Prota,[1,2] A. Quercia,[1,2] S. Ramos,[8] A. Reghunath,[18] T. Roganova,[3] F. Ronchetti,[6] T. Rovelli,[4,5] O. Ruchayskiy,[34] T. Ruf,[14] M. Sabate Gilarte,[14] M. Samoilov,[3] V. Scalera,[1,15] O. Schneider,[6] G. Sekhniaidze,[1] N. Serra,[7] M. Shaposhnikov,[6] V. Shevchenko,[3] T. Shchedrina,[3] L. Shchutska,[6] H. Shibuya,[33,35] S. Simone,[20,21] G.P. Siroli,[4,5] G. Sirri,[4] G. Soares,[8] O.J. Soto Sandoval,[25,26] M. Spurio,[4,5] N. Starkov,[3] I. Timiryasov,[34] V. Tioukov,[1] C. Trippl,[6] E. Ursov,[3] A. Ustyuzhanin,[1,36] G. Vankova-Kirilova,[9] V. Verguilov,[9] N. Viegas Guerreiro Leonardo,[8] C. Vilela,[8,*] C. Visone,[1,2] R. Wanke,[17] E. Yaman,[22] C. Yazici,[22] C.S. Yoon,[28] E. Zaffaroni,[6] and J. Zamora Saa[25,26]

(SND@LHC Collaboration)

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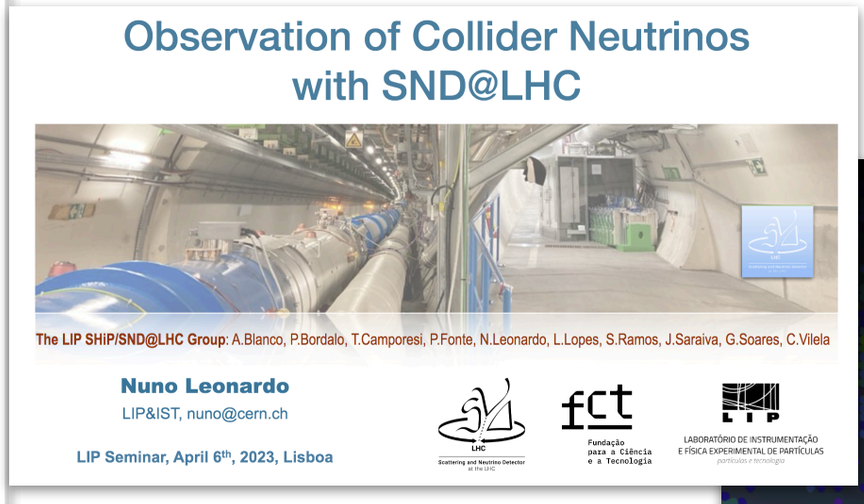
[9] *Faculty of Physics, Sofia University, Sofia, Bulgaria*
[10] *Università degli Studi di Cagliari, Cagliari, Italy*
[11] *University of Leiden, Leiden, The Netherlands*
[12] *Taras Shevchenko National University of Kyiv, Kyiv, Ukraine*
[13] *University College London, London, United Kingdom*
[14] *European Organization for Nuclear Research (CERN), Geneva, Switzerland*
[15] *Università di Napoli Parthenope, Napoli, Italy*
[16] *Sungkyunkwan University, Suwon-si, Gyeong Gi-do, Korea*
[17] *Institut für Physik and PRISMA Cluster of Excellence, Johannes Gutenberg Universität Mainz, Mainz, Germany*
[18] *Humboldt-Universität zu Berlin, Berlin, Germany*
[19] *Università del Sannio, Benevento, Italy*
[20] *Sezione INFN di Bari, Bari, Italy*
[21] *Università di Bari, Bari, Italy*
[22] *Middle East Technical University (METU), Ankara, Turkey*
[23] *Università della Basilicata, Potenza, Italy*
[24] *Imperial College London, London, United Kingdom*
[25] *Millennium Institute for Subatomic physics at high energy frontier-SAPHIR, Fernandez Concha 700, Santiago, Chile*
[26] *Departamento de Física, Facultad de Ciencias, Universidad de La Serena, Avenida Cisternas 1200, La Serena, Chile*
[27] *Ankara University, Ankara, Turkey*
[28] *Department of Physics Education and RINS, Gyeongsang National University, Jinju, Korea*
[29] *Gwangju National University of Education, Gwangju, Korea*
[30] *Nagoya University, Nagoya, Japan*

We report the direct observation of muon neutrino interactions with the SND@LHC detector at the Large Hadron Collider. A data set of proton-proton collisions at $\sqrt{s} = 13.6\,\text{TeV}$ collected by SND@LHC in 2022 is used, corresponding to an integrated luminosity of $36.8\,\text{fb}^{-1}$. The search is based on information from the active electronic components of the SND@LHC detector, which covers the pseudo-rapidity region of $7.2 < \eta < 8.4$, inaccessible to the other experiments at the collider. Muon neutrino candidates are identified through their charged-current interaction topology, with a track propagating through the entire length of the muon detector. After selection cuts, 8 ν_μ interaction candidate events remain with an estimated background of 0.076 events, yielding a significance of seven standard deviations for the observed ν_μ signal.



Observation seminar @LIP last month
https://indico.lip.pt/event/1425/

https://arxiv.org/abs/2305.09383

LHC

Scattering and Neutrino Detector
at the LHC

SND@LHC extends physics potential of LHC

⬅ Mesure first collider neutrinos

⬅ Probe **LFU anomalies** in neutrino sector

SND@LHC physics goals

Observe collider neutrinos for first time ✓

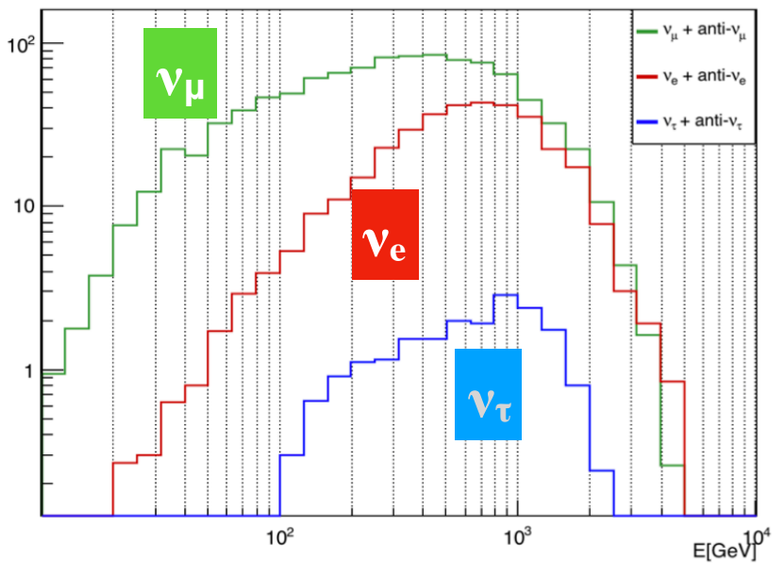
Unexplored energy range (up to 10 TeV)

Measure flavour production in unprobed region

Search for FIPs and Light Dark Matter

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

Lepton Flavour Universality (LFU) tests



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

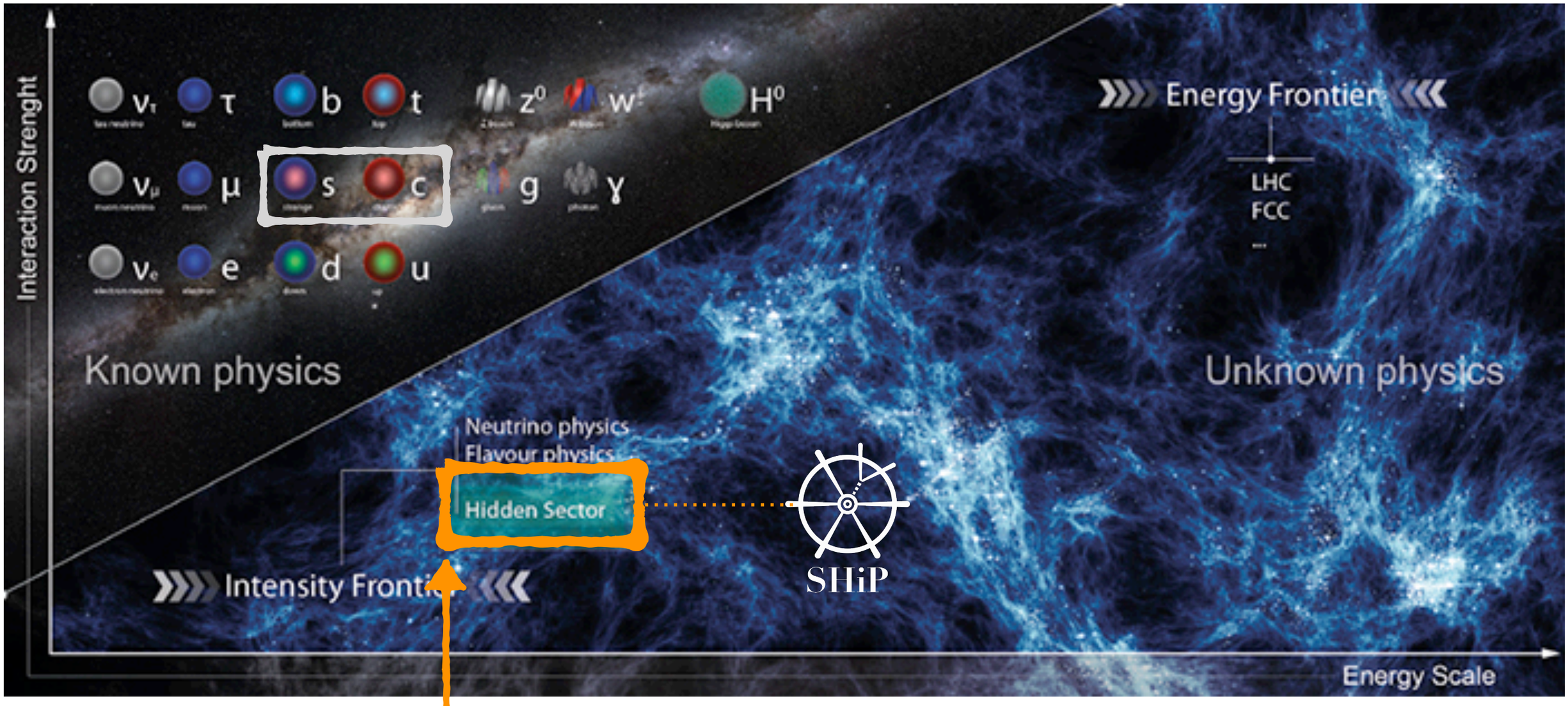
$$R_{13} = \frac{\nu_e}{\nu_\tau}$$

thesis opportunities

- Explore the unique dataset by the new LHC experiment → including 1st observations
- Take part in installation of a novel (sRPC) detector in LHC and analysis of its data
- Drive studies for HL-LHC upgrades (RPC, Si detectors)
- Get integrated in a smaller collaboration operating in the exciting LHC environment

Goal: go beyond the Standard Model

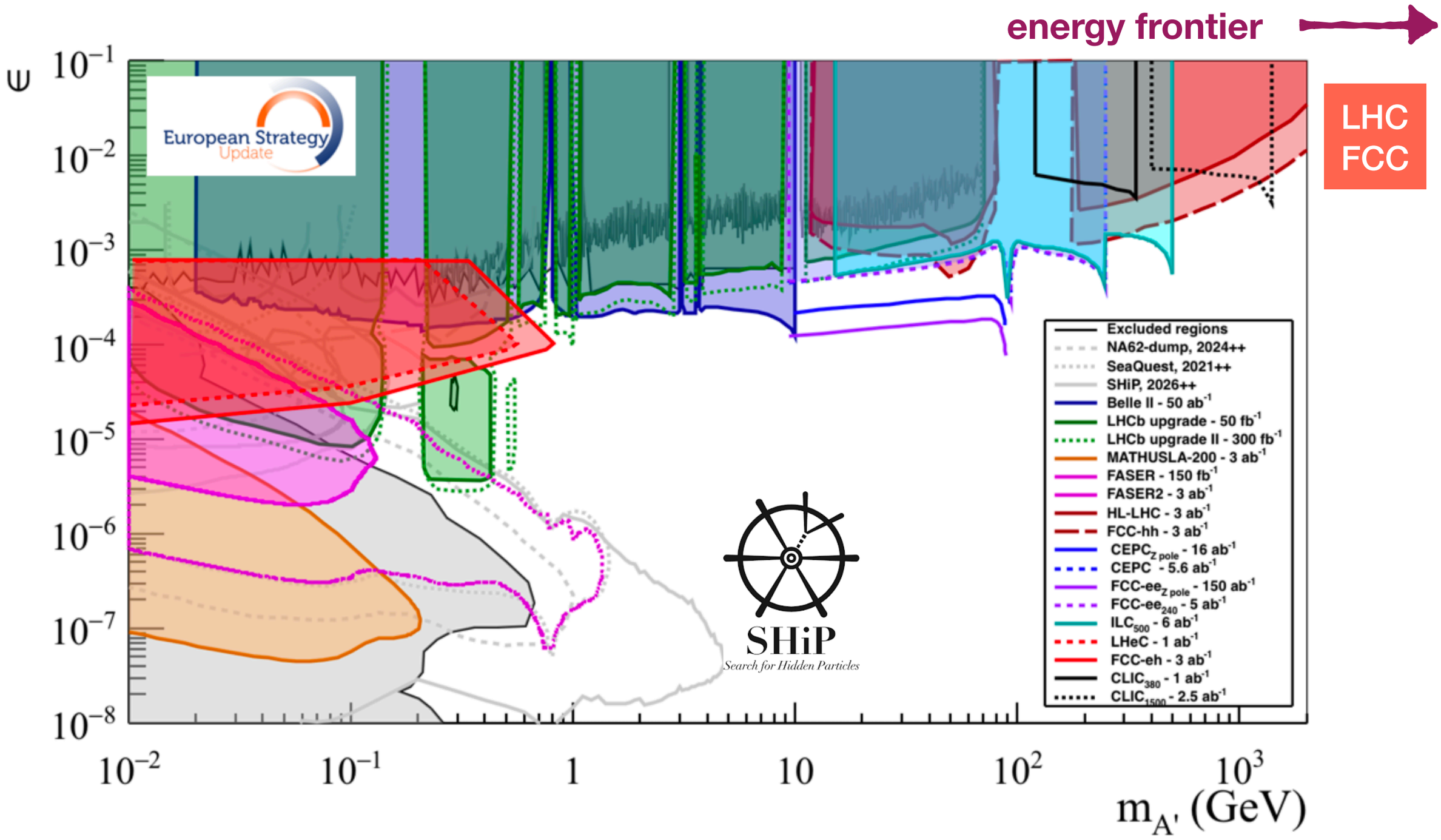
energy frontier →



search for FIPs, Feebly Interacting Particles

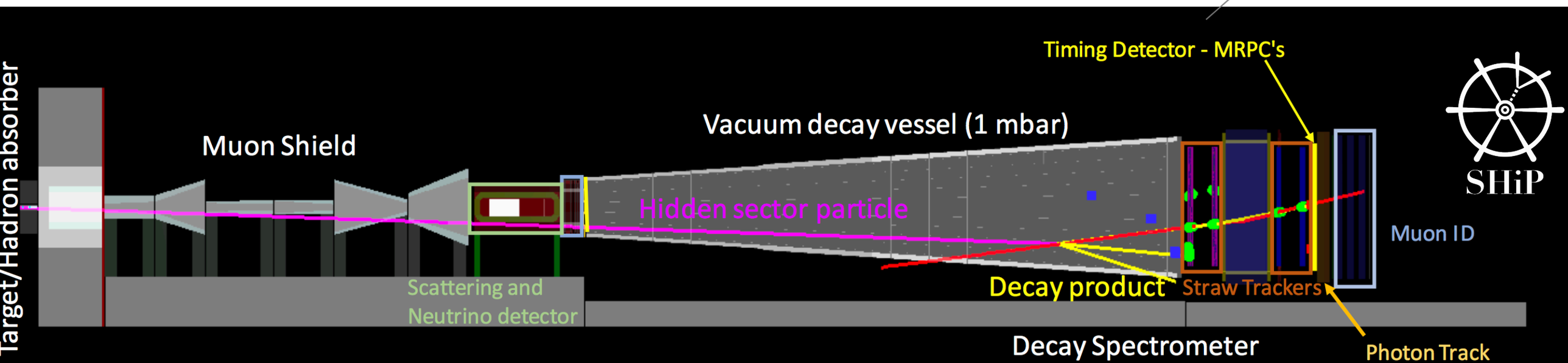
(from decay of flavour hadrons produced in collision)

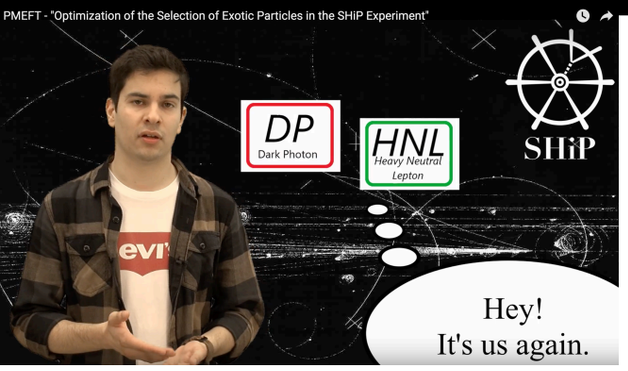
Goal: go beyond the Standard Model



SHiP — Search for Hidden Particles

by LIP





TÉCNICO LISBOA

LIP-STUDENTS-20-17

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

Optimization of the Selection of Hidden Particles in the SHiP Experiment

CERN-THESIS-2021-038

Guilherme Machado Santos Soares

CERN-THESIS-2021-038
https://cds.cern.ch/record/2765979?ln=en
Defsense: January 2021

LIP-STUDENTS-21-06

Distinguishing Hidden Sector Particles with Machine Learning at SHiP

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

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

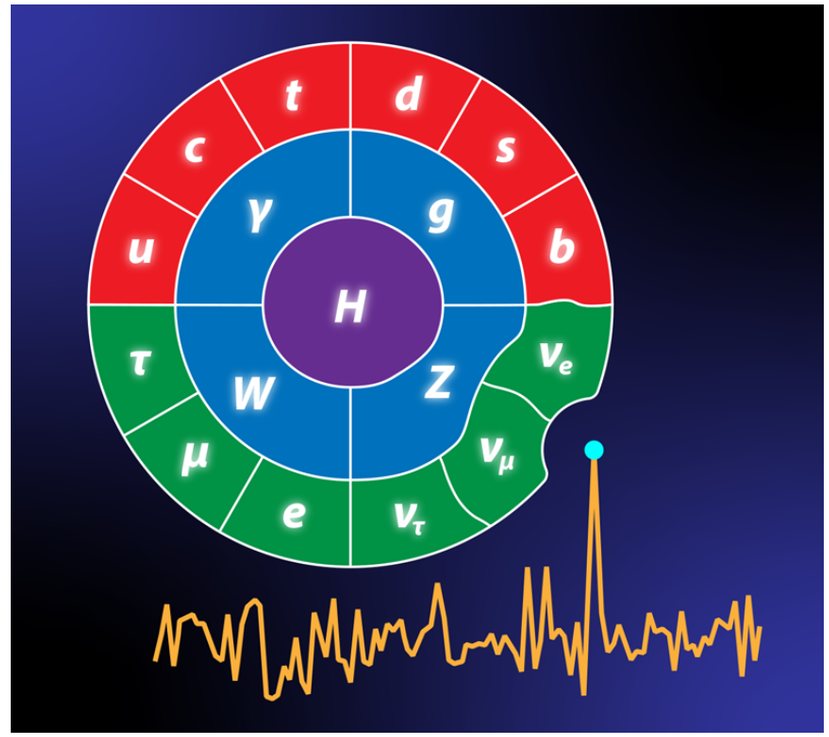
Project supervisors: N. Leonardo, G. Soares — *October 2021*

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, Inten-

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, hinting contributions from New Physics



- **LHC** is entering a high intensity phase
  - new era of precision and rare processes

LHC Run3 just started !

- great **research** opportunities for students
  - anomalies & LFU, Neutrinos & other FIPs
  - in large or smaller, well-established or novel experiments in the exciting LHC environment

Join the adventure!