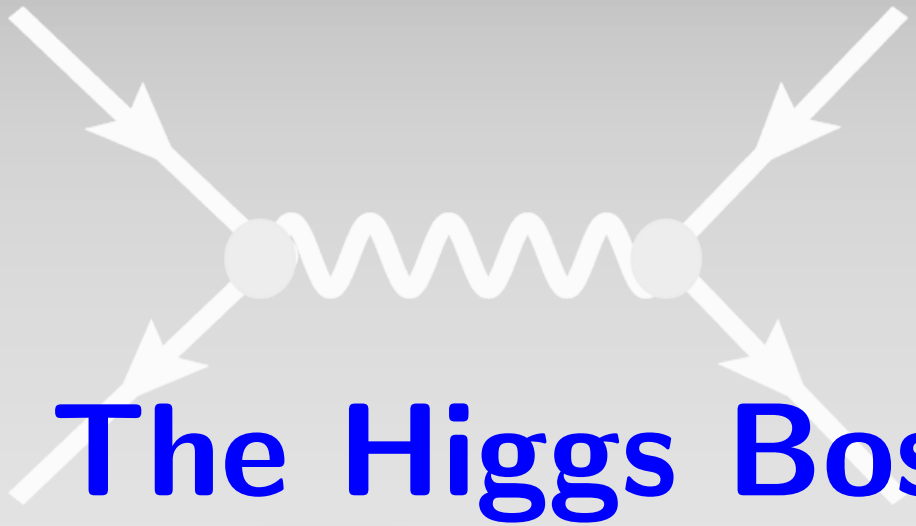

The Higgs Boson as a Window into "New Physics"

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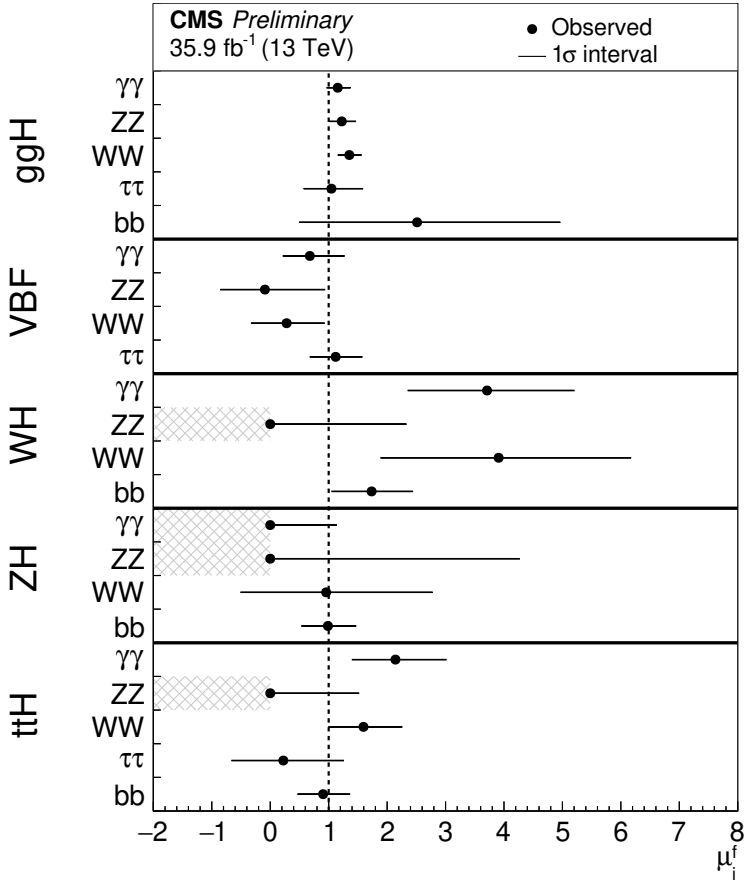
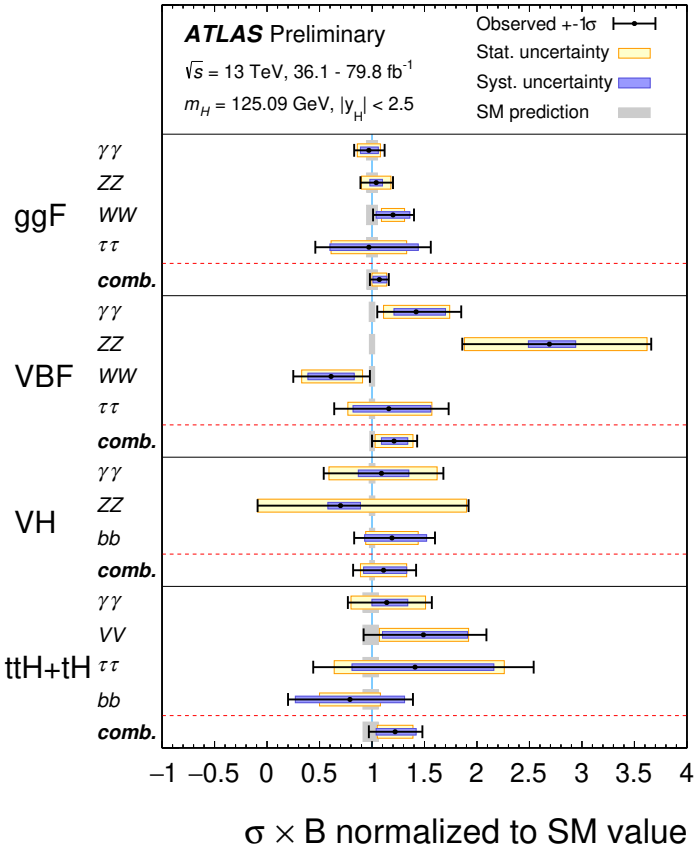
2024

The LHC Higgs boson and the SM: What freedom do we have?

- *Signal Strengths*: For a given final state f,

$$\mu_f = \frac{\sigma(pp \to H)^{\rm NP} \times {\rm BR}(H \to f)^{\rm NP}}{\sigma(pp \to H)^{\rm SM} \times {\rm BR}(H \to f)^{\rm SM}}$$





At this moment we have an agreement with the SM at the 10-15% level

Why only 1 Higgs Boson?

❒ Number of particles with Spin 1

Fixed by the choice of Symmetry Group $\mathbf{SU(3)} \times \mathbf{SU(2)} \times \mathbf{U(1)}$

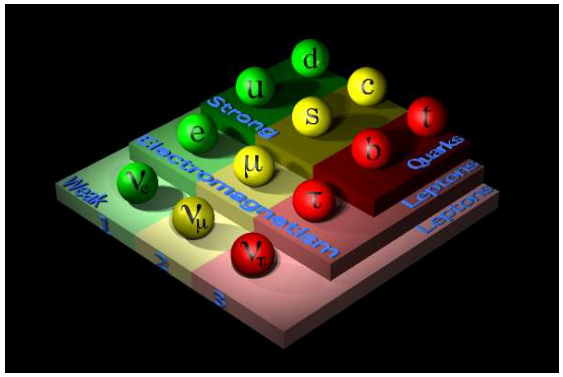
Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

❒ Number of Particles with Spin $\frac{1}{2}$

There is no principle. Fixed by experiment



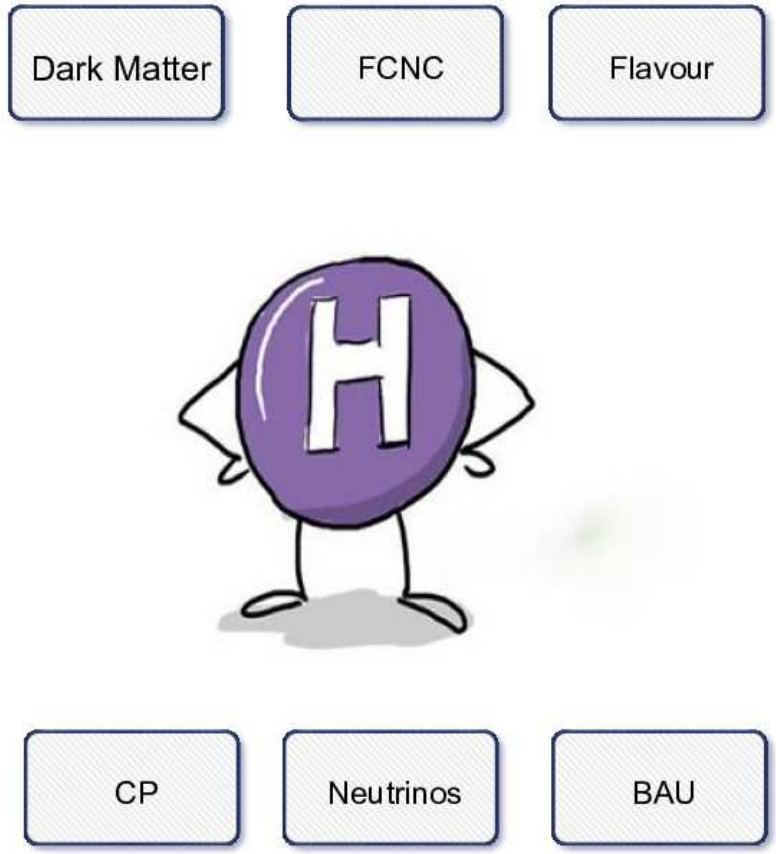
❒ Number of particles with Spin 0

There is no principle. Therefore should be fixed by experiment!

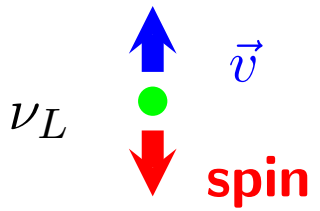
The Higgs Boson as a Window into "New Physics"

- Although it has been discovered already in 2012 the Higgs boson continues to have an high impact in the research in Particle Physics
- This is due to the fact that an extended Higgs sector leads to many topics that we still do not know:
  - Higgs and "FCNC" (Flavour Changing Neutral Currents)
  - Higgs and Flavour
  - Higgs and Neutrinos
  - Higgs and CP Violation
  - Higgs, Baryogenesis and Leptogenesis
  - Higgs and Dark Matter

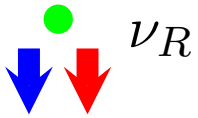
The Higgs Boson: A Window of Opportunities!



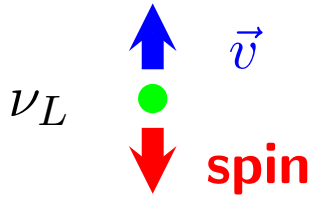
CP Violation



P →



Does not take part Weak Interaction



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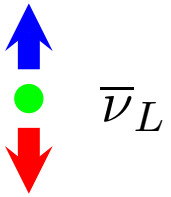
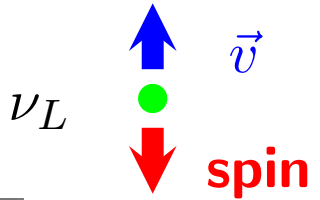
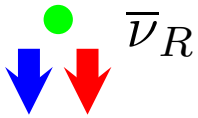


Does not take part Weak Interaction



CP →

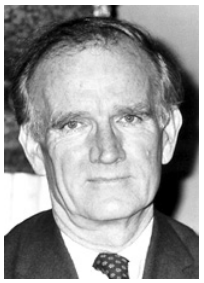


Takes part in Weak Interaction

CP ok

Cronin

But in 1964 Cronin & Fitch (Nobel Prize 1980)



Fitch

K_L^0**(CP=-1)** → $\pi\pi\pi$**(CP=-1)**

K_L^0**(CP=-1)** → $\pi\pi$**(CP=+1)** **(0.23% das vezes)**

CP

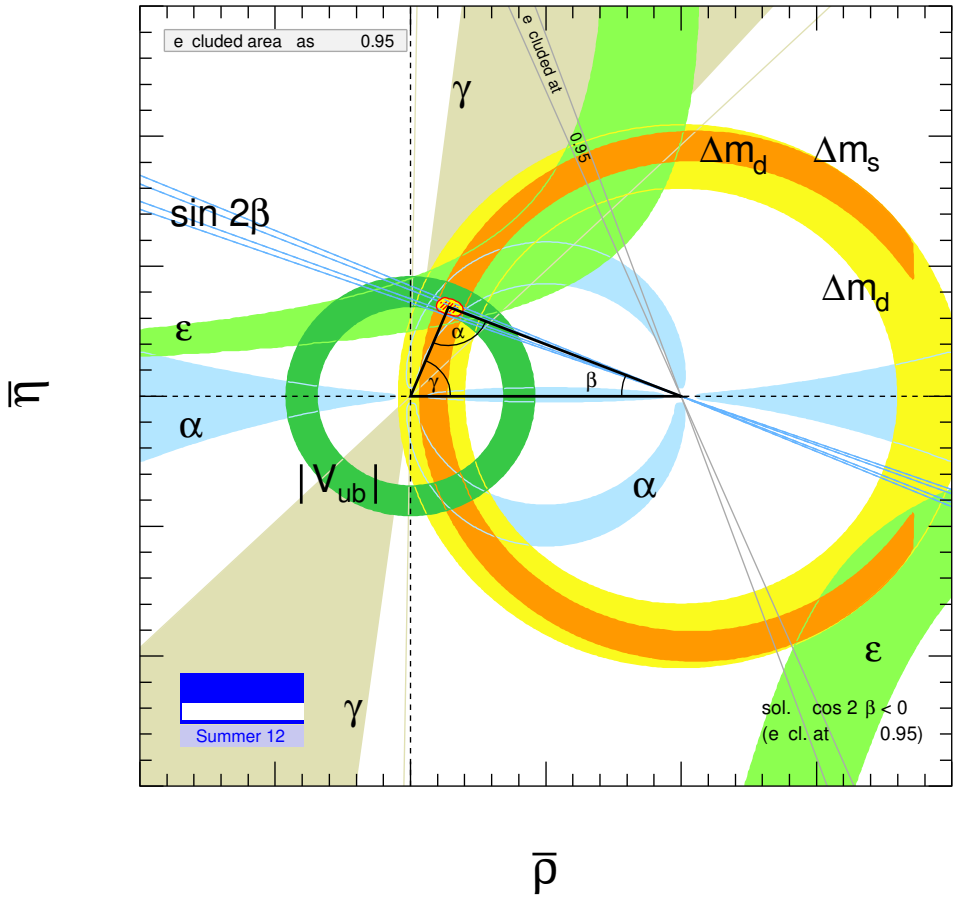
CP Violation and the Higgs Sector

- CP violation has only being observed in the quark sector. The explanation uses the CKM matrix (Cabibbo-Kobayashi-Maskawa), Nobel Prize in 2008. It fits the current data (except BAU) but the question arises, can we also have CP violation in the Higgs sector?


Nicola Cabibbo


Makoto Kobayashi


Toshihide Maskawa



Baryonic Asymmetry of the Universe

- In the beginning of the Universe there was an equal amount of matter and anti-matter
- Why it did no annihilate completely producing only photons?
- How to explain the number $\frac{n_B}{n_\gamma} \simeq 10^{-10}$?

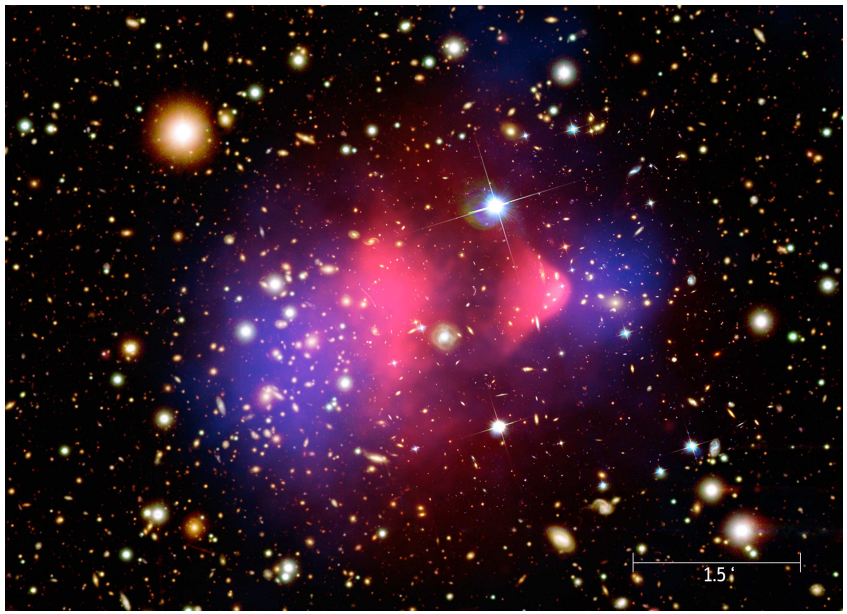
Conditions for Baryogenesis ⟵ Sakharov

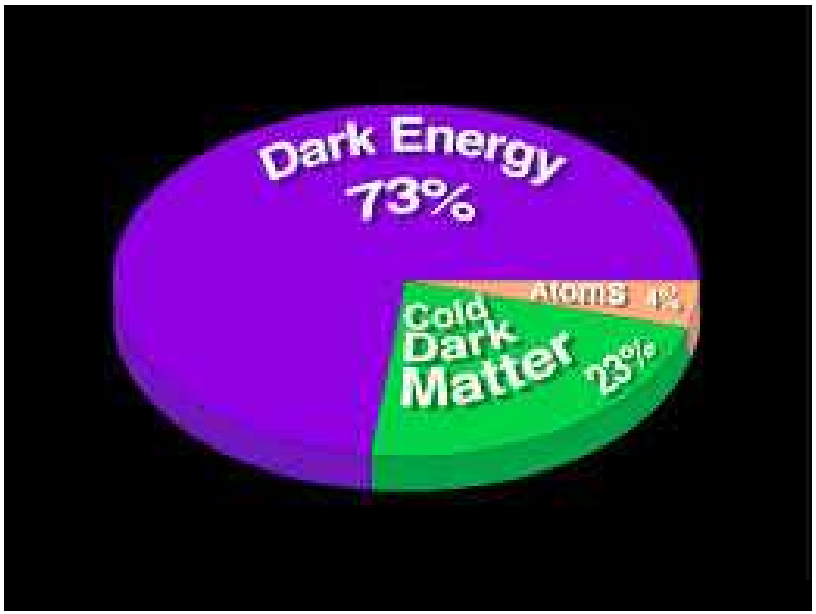
- Non-conservation of Baryon Number
- Non-equilibrium
- CP Violation

SM is not enough. Extended Higgs sector is needed! CP in Higgs sector?

Higgs and Dark Matter

- Experimental evidence for Dark Matter





- How can the Higgs boson explain Dark Matter?
  - Suppose that exists a symmetry with some conserved charge $Q_{\rm DM}$
  - Suppose that all SM particles have $Q_{\rm DM} = +1$
  - We can have theories with extended Higgs sectors where some of the Higgs have $Q_{\rm DM} = -1$.
  - The lightest of these is stable. If it is neutral it can be DM

Minimal Extension: 2HDM. Many Novelties

- Several particles with Spin 0
  - Neutral:
    - Scalars: h e H
    - Pseudoscalar: A
    - Or mixed: h_1, h_2, h_3 like in the C2HDM
  - Charged: $H^{\pm}$
- Properties of the minimum of the potential changed
  - Minima with charge breaking (to avoid!)
  - More than one minimum. What is the absolute minimum?

Models with N Higgs doublets: Ongoing work

- In collaboration with Prof. João P. Silva
- We are interested in Models with $N \geq 3$ Higgs doublets
- We will have many more particles, including several charged Higgs, but the structure can be described in very simple terms.
- We want to study:
  - Compatible Symmetries
  - CP Violation
  - Dark Matter
  - New interactions in the fermionic sector
- We want candidates the finish the Master Thesis in 2026, but we can start at any time
- We offer good results: all students that have done Master degree with us finished publishing at least one paper and were integrated in international collaborations with world experts in the field

Our Students in Multi-Higgs

- Duarte Fontes
  - Master 2014
  - 13 published papers while with us
  - Finished PhD with us in 2021. Now at Brookhaven
  - The new software `FeynMaster`
- Miguel Bento
  - Master 2017
  - 7 published papers
  - Finished PhD with us in 2023
- Francisco Faro
  - Master 2019
  - 2 published papers

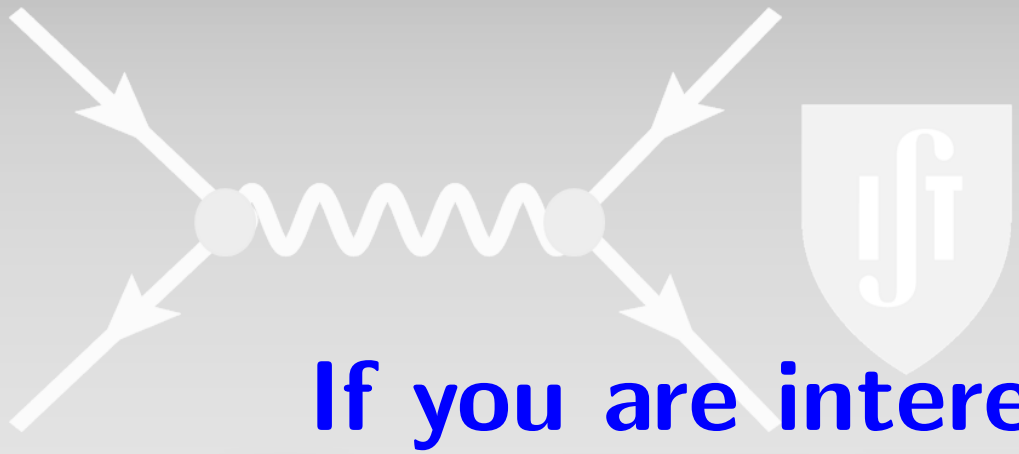
Our Students in Multi-Higgs

- Rafael Boto
  - Master 2020
  - 6 published papers
  - Now our PhD student
- Francisco Vazão
  - Master 2021, now doing Ph.D. in Munich, Germany
  - 2 published papers while with us
- Ricardo Florentino
  - Master 2021, now doing Ph.D. in Osaka, Japan
  - 1 published paper
- Sérgio Carrôlo
  - Master 2022, now doing Ph.D. Munich, Germany
  - 3 published papers

Our Students in Multi-Higgs

- Íris Brée
  - Finished Master in 2023
  - One published paper
- Luís Lourenço
  - Finished Master in 2023
  - One published paper
- Pedro Figueiredo
  - Will finish Master in 2025
- PIC 1
  - 2023: Pedro Figueiredo, Francisco Ferreira
  - 2024: João Belas, João Matos e Duarte Correia

Multi-Higgs@CFTP



If you are interested we encourage you to come and talk with us at CFTP