Phenomenology of modified Higgs sectors

Testing the Singlet Extension in the W^+W^- channel with semi-leptonic final states at the LHC

Under the supervision of Prof. Stefania De Curtis

Premio Nazionale “Milla Baldo Ceolin 2024”
Galileo Galilei Institute, Largo Enrico Fermi 2, Firenze
4 Novembre 2025

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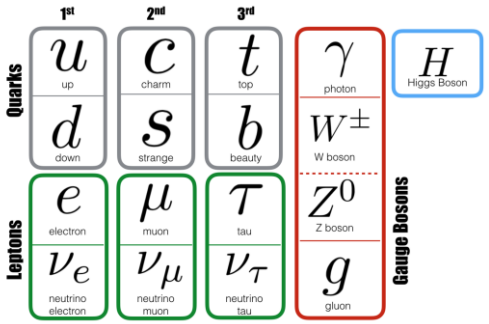
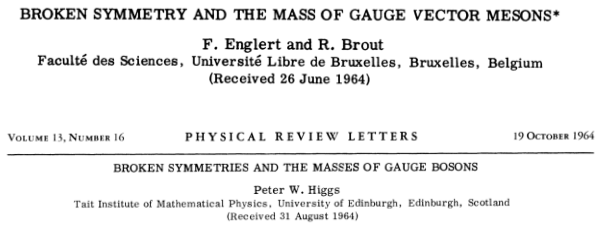
Introduction

Standard Model





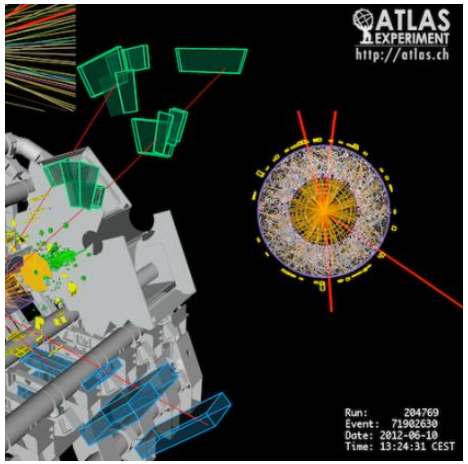
BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

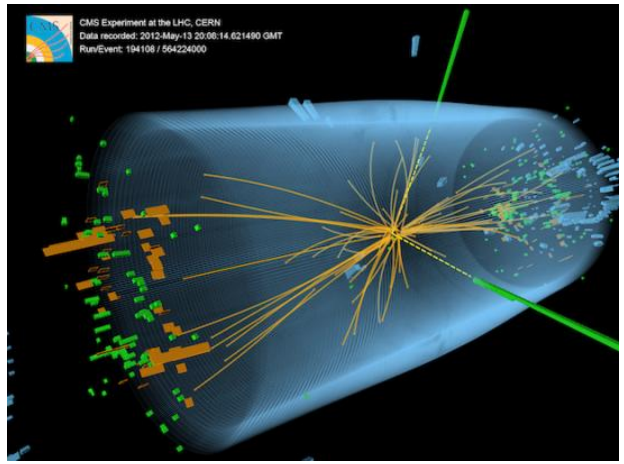
F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)





[CMS/ATLAS/CERN]

Beyond the Standard Model

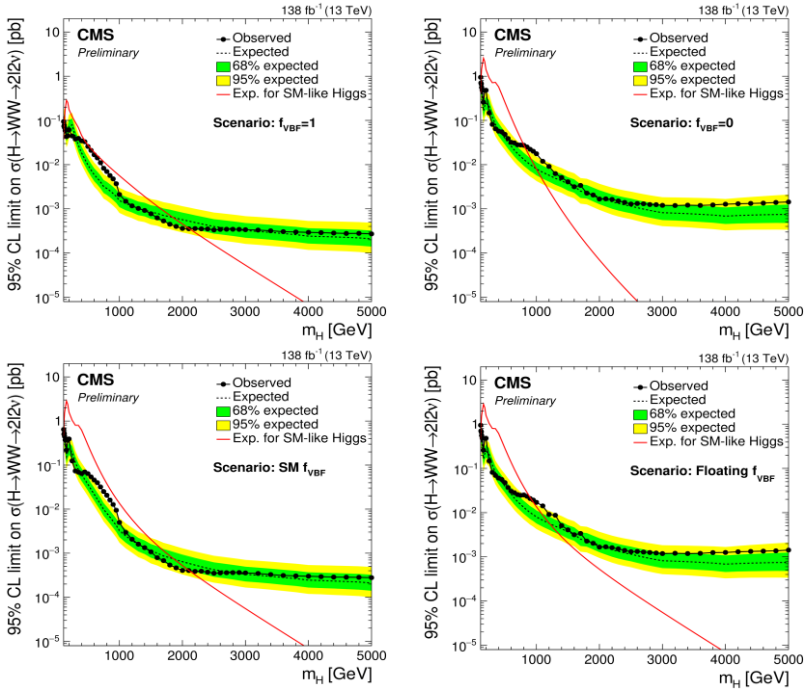
- **Beyond the Higgs Boson discovery:**
  Couplings to light fermions,
  Higgs self-coupling,
  Range of fermion masses,
  …

- **Complete description of Nature:**
  Matter-antimatter asymmetry,
  Dark Matter,
  Neutrino masses,
  …

Search of a heavy scalar at the LHC

Experimental input by CMS analysis

Search for high mass resonances in the W^+W^- channel, fully-leptonic final states [CMS-PAS-HIG-20-016]



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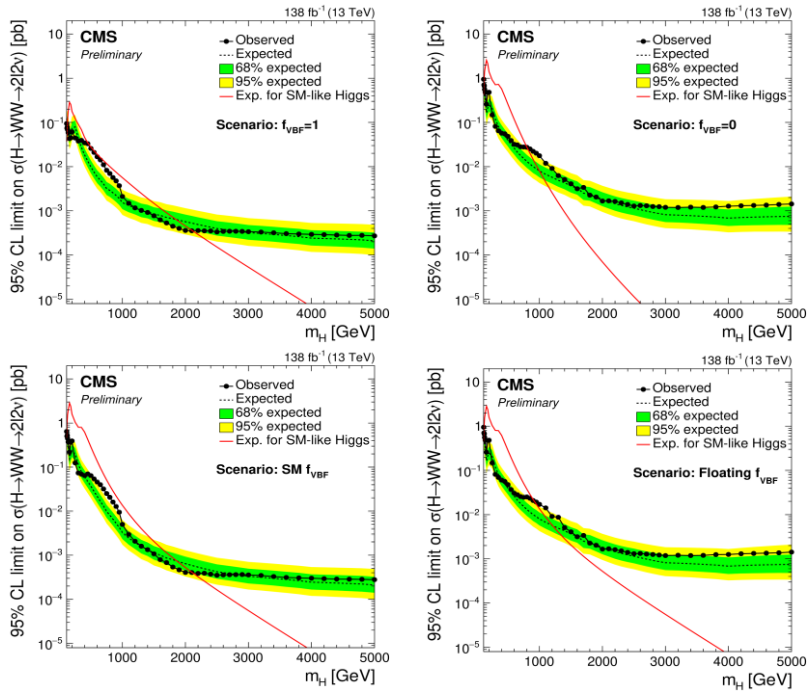
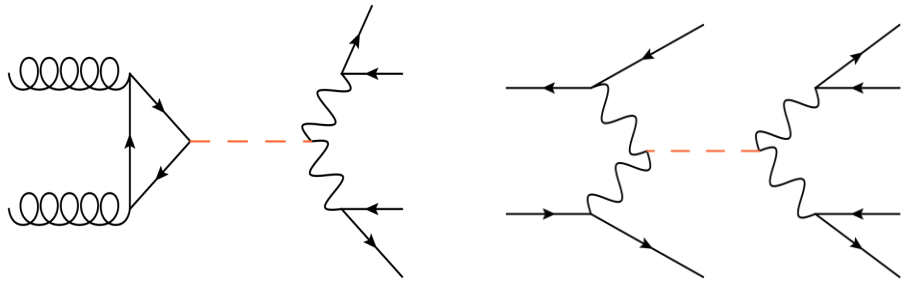


[CMS-PAS-HIG-20-016]

Goal of my master's thesis

Testing the Singlet Extension in the W^+W^- channel with semi-leptonic final states

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{h_{mod}} + \mathcal{L}_S$$



- Simulation of collider events;
- Preliminary and comparative analysis: SM-like.

Singlet Extension

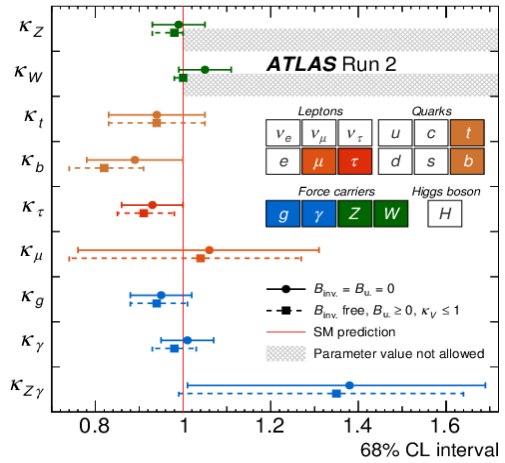
- Minimal extension → real field σ, singlet;
- Interaction only with the Higgs doublet, additional $\mathbb{Z}_2$:

$$V(\Phi,\sigma) = -m^2\Phi^\dagger\Phi - \mu^2\sigma^2 + \lambda_1(\Phi^\dagger\Phi)^2 + \lambda_2\sigma^4 + \lambda_3\Phi^\dagger\Phi\sigma^2$$

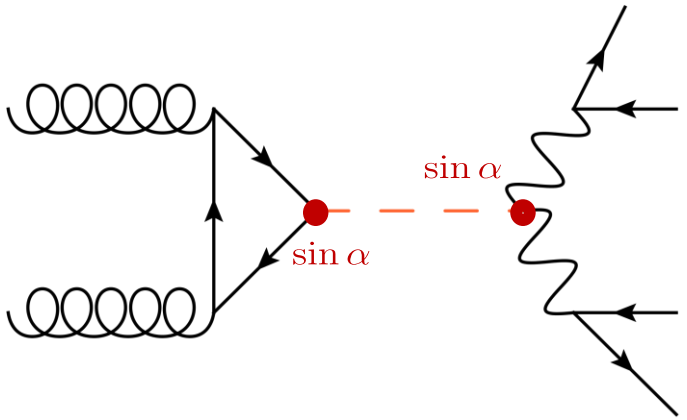
- Non-trivial VEVs (v, v_s) ;
- Two mass eigenstates (h, S) :

$$\phi_0 = \cos\alpha\, h + \sin\alpha\, S$$

[ATLAS, Nature 607, 52–59 (2022)]



LHC $h(125)$ → **Small mixing angle**.



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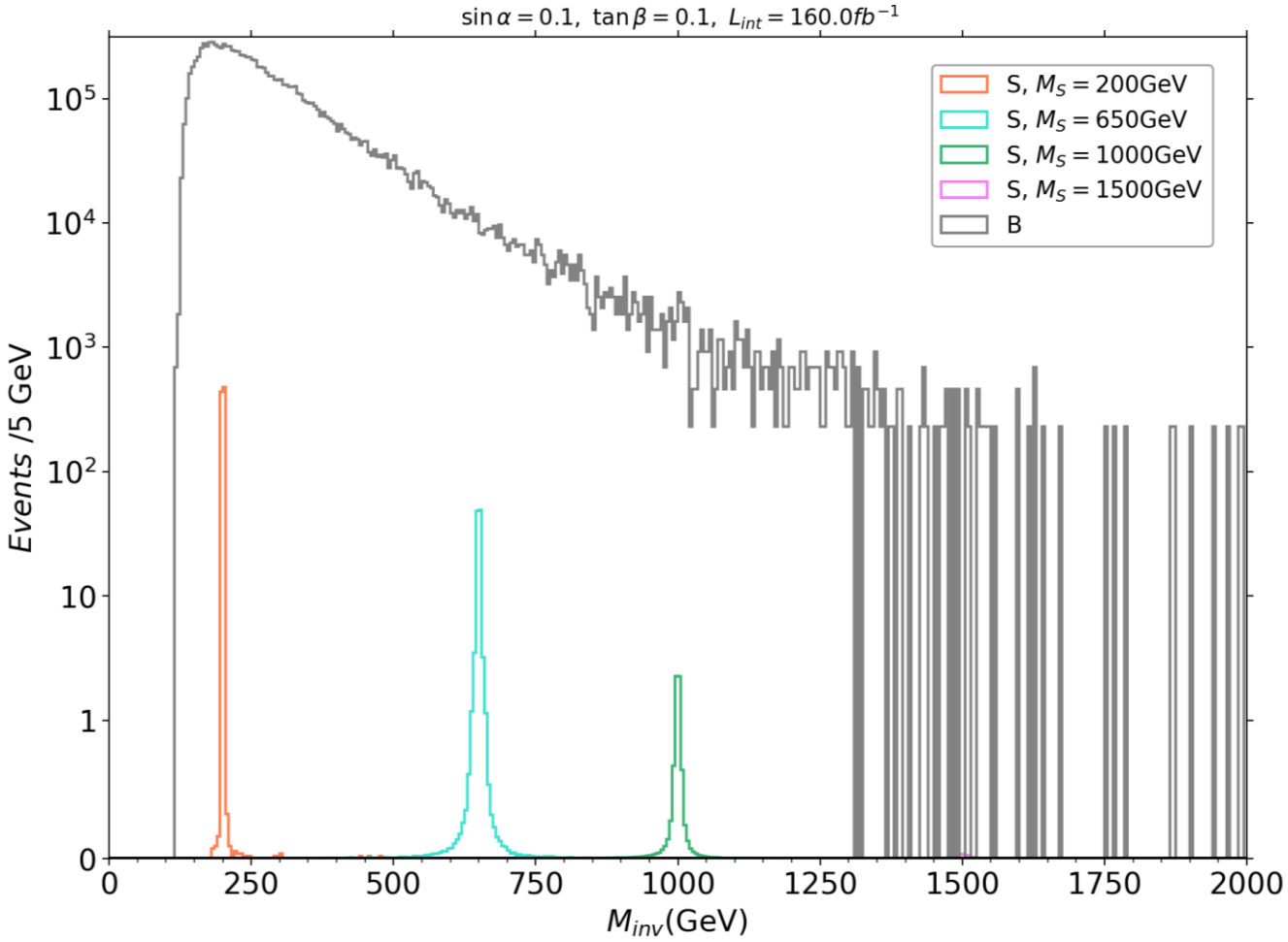
  - Non-trivial VEVs $(v, v_s) \rightarrow \beta$
  - Two mass eigenstates $(h, S) \rightarrow \alpha, M_S$

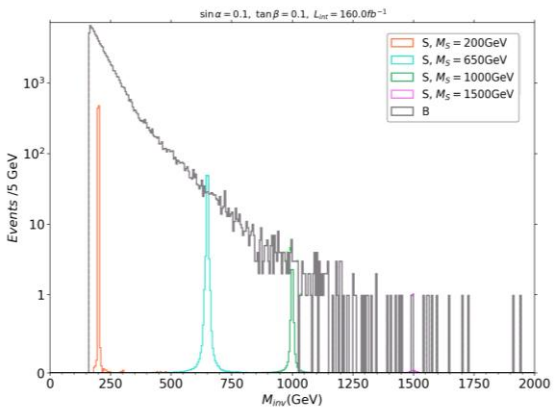
↳ **Three free parameters** α, β, M_S

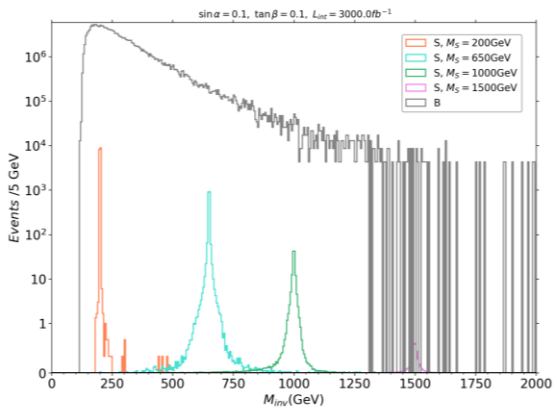
- Parameters scan (benchmark points):
  1) **Theoretical constraints**: vacuum stability, perturbativity, unitarity, …
  2) **Experimental bounds**: exclusion limits from additional scalars searches at colliders, measurements for $h(125)$, EWPO global fit, …

Results for GGF



- Four M_S hypotheses;
- Parton level /Reco level;
- Background: tree-level (dominant without cuts), one-loop;
- Integrated luminosity: Full LHC Run-2, HL-LHC.





Future perspectives

- Additional background simulations + cuts;
- Interference and VBF production;
- Different channels.

- Less constrained BSM scenarios.

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{h_{mod}} + \mathcal{L}_{S}$$

PhD - Quantum observables for collider physics

Under the supervision of Prof. Fabio Maltoni

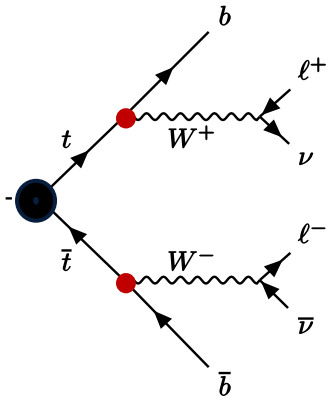
Particles involved in high energy collisions are expected to display quantum properties

- *Observation of quantum entanglement with top quarks at the ATLAS detector* [Nature 633, 542–547 (2024)]
- *Observation of quantum entanglement in top quark pair production in proton-proton collisions at* $\sqrt{s}$*= 13 TeV* [*Rep. Prog. Phys.* **87** 117801].

- Pair of spin ½ particles: $\rho_{(\frac{1}{2},\frac{1}{2})} = \frac{1}{4}\left(\mathbb{I}\otimes\mathbb{I} + B_i\,\tau_i\otimes\mathbb{I} + \bar{B}_i\,\mathbb{I}\otimes\tau_i + C_{ij}\,\tau_i\otimes\tau_j\right)$

- $t\bar{t}$ pairs in collider experiments: $\tau_{decay} < \tau_{hadr.}, \tau_{spin-flip.}$

- Reconstruction of the state: quantum state tomography $d\sigma \sim Tr[\rho_{t\bar{t}}(\rho^{Decay,t}\otimes\rho^{Decay,\bar{t}})^T]$



Are quantum observables sensitive to CP violation in $t\bar{t}$ *pairs?*

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Thank you for your attention!

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