

# **Scalars 2015**

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## **Book of abstracts**

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1

## New results on CP violation in multi-Higgs models

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I will discuss several new aspects of CP violation coming from the scalar sector in multi-Higgs-doublet models.

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## New Physics in Lepton Flavor Violating Higgs Decays

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We investigate possible New Physics interpretations of the recently observed excess in the  $h \rightarrow \tau \mu$  decay. We derive a lower bound on the Higgs boson coupling strength to a tau and a muon, even in presence of the most general new physics affecting other Higgs properties. Then we reevaluate complementary indirect constraints coming from low energy observables as well as from theoretical considerations. In particular, the tentative signal should lead to  $\tau \rightarrow \mu \gamma$  at rates which could be observed at Belle II. In turn we show that, barring fine-tuned cancellations, the effect can only be accommodated within models with an extended scalar sector. These general conclusions are demonstrated using a number of explicit new physics models. Finally we show how, given the  $h \rightarrow \tau \mu$  signal, the current and future searches for  $\mu \rightarrow e \gamma$  and  $\mu \rightarrow e$  nuclear conversions unambiguously constrain the allowed rates for  $h \rightarrow \tau e$ .

3

## Asymptotically free scaling solutions in nonabelian Higgs models

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We construct asymptotically free renormalization group trajectories for the generic nonabelian Higgs model in four-dimensional spacetime. These ultraviolet-complete trajectories become visible by generalizing the renormalization/boundary conditions in the definition of the correlation functions of the theory. Though they are accessible in a controlled weak-coupling analysis, these trajectories originate from threshold phenomena which are missed in a conventional perturbative analysis relying on the deep Euclidean region. We identify a candidate three-parameter family of renormalization group trajectories interconnecting the asymptotically free ultraviolet regime with a Higgs phase in the low-energy limit. We provide estimates of their low-energy properties in the light of a possible application to the standard model Higgs sector.

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## What 126 GeV Higgs mass means?

Prof. HABA, Naoyuki Haba <sup>1</sup>

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126 GeV Higgs mass indicates a vanishing Higgs potential at the high energy scale (around  $10^{10}$  GeV) in the framework of the standard model (SM). It seems to indicate a hint of new physics beyond the SM. I will suggest various possibilities of the SM extensions from the view point of vacuum stability, naturalness, gauge coupling unification and so on.

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## Electroweak and Dark matter scalegenesis from a bilinear scalar condensate

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We discuss an extension of the standard model based on the classically scale invariance. We introduce scalar fields coupled to strongly interacting gauge fields in hidden sector and the Higgs field in the standard model sector. In the model, the electroweak symmetry is broken through a condensation of the scalar fields by non-perturbative effects in the hidden sector. We formulate an effective model to quantitatively evaluate physical values such as the condensation of scalar bilinear. We show that the excitation of condensate can be the candidates of dark matter. Furthermore, we discuss the possibility of the strong first order electroweak phase transition in the model.

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## Fate of false vacua at one loop

Dr. ENDO, Motoi <sup>1</sup>; Prof. MOROI, Takeo <sup>1</sup>; Prof. NOJIRI, Mihoko <sup>2</sup>; Mr. SHOJI, Yutaro <sup>3</sup>

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It can be the case that we are in a meta-stable vacuum and its decay time is longer than the age of universe. In most papers, the decay rate is estimated without calculating the pre-exponential factor because they believe that it is much less significant than the exponential suppression factor. What we point out is that this estimate can involve a large error owing to the uncertainty in the renormalization scale. Since the potential itself is scale dependent, it modifies the bounce solution and thus the decay rate. The uncertainty can be comparable to the exponential factor and it should be controlled to get a consistent result. We explicitly calculate the pre-exponential factor and show that it is greatly reduced.



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## Leptogenesis during the reheating era

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We propose a novel leptogenesis scenario at the reheating era.

Our setup is minimal in the sense that, in addition to the standard model Lagrangian, we only consider an inflaton and higher dimensional operators. After the decay of an inflaton, the model is described within the standard model with higher dimensional operators which induce the violation of the lepton number and the CP violation. It is found that the successful baryogenesis is realized for the wide range of parameters, the inflaton mass and reheating temperature, depending on the cutoff scale.

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## SMEFT at NLO

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Standard Model effective field theory at NLO. Higgs Physics and EWPD

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## Pseudoscalar fields in the Universe, novel ways of Majorana neutrino mass generation and Leptogenesis

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I first discuss the role of pseudoscalar fields in potentially inducing Majorana neutrino mass in a way alternative to seesaw and then I proceed to study the role of cosmic backgrounds of such fields in the early Universe in inducing Leptogenesis. A particularly interesting realization of the above ideas, motivated from string theory, which I will concentrate upon in the talk, is that of an antisymmetric Kalb-Ramond (KR) tensor field arising in the gravitational multiplet of the string. In four space-time dimensions, the field strength of the KR field is dual to a pseudoscalar field, whose mixing with ordinary axions in the Universe can lead to the above mentioned Majorana mass generation via Yukawa couplings of the axions to neutrinos. On the other hand, a constant in time background of the KR field strength in the early Universe, playing the role of a torsion field, can lead to Leptogenesis via CP violating tree level decays of right-handed Majorana neutrinos. Phenomenological challenges and open issues in such scenarios are discussed.

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## Bosonic seesaw mechanism in a classically scale invariant model

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In the standard model, electroweak symmetry breaking is caused by a negative mass term of the Higgs doublet, while it seems to be ad hoc. We suggest the so-called bosonic seesaw mechanism in a two Higgs doublet model with a classically conformal  $U(1)_{B-L}$  extension. After the  $U(1)_{B-L}$  breaking, mass terms for the two Higgs doublets are generated through scalar quartic couplings. Their masses are all positive but, nevertheless, the electroweak symmetry breaking is realized by the bosonic seesaw mechanism. The bosonic seesaw is naturally realized by the renormalization group evolutions, although a large hierarchy among the quartic couplings is required. In our model, the heavy Higgs boson masses should be less than 2 TeV, in order to satisfy the perturbativity and the electroweak vacuum stability as well as the naturalness of the electroweak scale.

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## Searches for low-mass scalar particles with the BABAR detector

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We present results from the BaBar experiment on searches for low-mass new physics. This includes a search for a light CP-odd Higgs boson ( $A_0$ ) in  $Upsilon(1S) \rightarrow \gamma A_0$ ,  $A_0 \rightarrow c\bar{c}$  decays, providing limits on the product branching fraction  $B(Upsilon(1S) \rightarrow \gamma A_0) \times B(A_0 \rightarrow c\bar{c})$  at the level of  $7 \times 10^{-5} - 2 \times 10^{-3}$  for  $A_0$  masses between 4.0 GeV and 9.25 GeV; and a search for neutral, long-lived particles produced in  $e^+e^-$  collisions or neutral B meson decays obtaining limits on the product of the production cross-section, branching fraction, and reconstruction efficiency are set for each final state.

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## Heavy Higgs decays in models with vectorlike fermions

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I will discuss several aspects of Higgs phenomenology that can be significantly altered in models with vectorlike families with focus on new decay modes of Heavy Higgs bosons.

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## Gauge-Higgs unification: from EW to GUT

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The  $SO(5) \times U(1)$  gauge-Higgs EW unification is successful at low energies. The 4D Higgs boson appears as a part of the extra-dimensional component of gauge fields. It gives definitive predictions for  $H \rightarrow \gamma\gamma$ ,  $Z\gamma$  etc, consistent with 8 TeV LHC, and for  $Z', W'$  events to be explored at 14 TeV LHC. The model is extended to the  $SO(11)$  gauge-Higgs grand unification with fermion multiplets in 32 and 11 representations.

Although GUT multiplets show up at the KK scale much smaller than  $10^{15}$  GeV, the proton decay is naturally suppressed by the new fermion number conservation.

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## Recasting LHC searches: the case of the Inert Doublet Model and other examples

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ATLAS and CMS have been searching for new physics in many different channels. While the experimental analyses are often optimised for specific signatures of specific models, the number of observed events in the various signal regions can also be used to constrain other models, which were not considered by the experimental collaborations. As a concrete example I will discuss how the dilepton + missing energy searches performed in the context of Higgs and SUSY analyses at Run 1 currently constrain the Inert Doublet Model. I will also elaborate on the difficulties met in using the experimental results and explain why more information is needed from the experimental collaborations in order to establish reliable tools for interpretation studies.

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## Fitting the two-loop renormalized Two-Higgs-Doublet model

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We present the latest status of global fits to the softly broken  $Z_2$  symmetric Two-Higgs-Doublet models of type I and II with CP conservation in the scalar potential.

We show how much the parameter space is constrained by the combination of the relevant theoretical and experimental inputs, including the LHC data after the first run and interpreting the 125 GeV boson as the light CP even Higgs. Using the next-to-leading order renormalization group equations, we address the questions of vacuum stability and the hierarchy problem in the context of the mentioned Two-Higgs-Doublet models.

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## The Higgs and cosmology

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I will discuss possible connections between the Higgs and dark matter as well as inflation.

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## Inflation and higher order corrections to Higgs/Starobinsky models

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In my talk I will analyse the influence of higher order corrections to the Jordan frame potentials or  $\mathcal{S}f(R)$  function to Higgs and Starobinsky inflationary models. I will present inflationary scenarios which emerge from modified potentials and compare results with experimental data. In principle I will focus on possibility of obtaining saddle point inflation generate by higher order corrections.

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## An extended scalar sector for the known physics beyond the SM

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We propose a minimal scalar extension of the Standard Model that addresses in a structural and natural way a number of its observational and theoretical open issues: neutrino masses, dark matter and the strong CP problem. The technical naturalness of the model implies new scalar states well within the LHC reach, while the very low-energy dynamics is governed by the axion-dilaton interplay.

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## Enhancement of the HWZ vertex in the three scalar doublet model

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We compute one-loop induced trilinear vertices with physical charged Higgs bosons  $H^\pm$  and ordinary neutral gauge bosons,

i.e.,  $H^\pm W^\pm Z$  and  $H^\pm W^\pm \gamma$ , in the model with two active plus one inert scalar doublet fields under a  $Z_2(\text{unbroken}) \times \tilde{Z}_2(\text{softly-broken})$  symmetry. The  $Z_2$  and  $\tilde{Z}_2$  symmetries are introduced to guarantee the stability of a dark matter candidate and to forbid the flavour changing neutral current at the tree level, respectively.

The dominant form factor  $F_Z$  of the  $H^\pm W^\pm Z$  vertex can be enhanced by non-decoupling effects of extra scalar boson loop contributions. We find that, in such a model,  $|F_Z|^2$  can be one order of magnitude larger than that predicted in two Higgs doublet models under the constraints from vacuum stability, perturbative unitarity and the electroweak precision observables.

In addition, the branching fraction of the  $H^\pm \rightarrow W^\pm Z$  ( $H^\pm \rightarrow W^\pm \gamma$ ) mode can be of order 10~(1)% level when the mass of the  $H^\pm$  is below the top quark mass.

Such a light  $H^\pm$  is allowed by the so-called Type-I and Type-X Yukawa interactions which appear under the classification of

the  $\tilde{Z}$  charge assignment of the quarks and leptons.

We also calculate the cross sections for the processes  $H^\pm \rightarrow W^\pm Z$  and  $H^\pm \rightarrow W^\pm \gamma$  onset by the top quark decay  $t \rightarrow H^\pm b$  and electroweak  $H^\pm$  production at the LHC.

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## Connection between a mass of the 2nd Higgs boson and a deviation in the 125 GeV Higgs boson couplings

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Although there is no report for the discovery of additional Higgs bosons at the LHC Run-I, there still remain possibilities that the Higgs sector is extended from the minimal form as in the SM.

One of the most important parameters in non-minimal Higgs sectors is a mass of the second Higgs boson.

In general, such a parameter is taken to be free, but

this can be constrained by taking into account the theoretical consistency.

In this talk, we would like to show that we can obtain an upper limit on the mass of the second Higgs boson by using the constraint from perturbative unitarity and vacuum stability.

As a well motivated example, we consider two Higgs doublet models.

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## NLO SQCD corrections to the decay of top-squarks to charm and neutralino

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In order to solve the hierarchy problem, the stop quark should be rather light and its mass can be close to the one of the LSP. If the mass difference of the stop to the neutralino LSP is smaller than the top mass it can only decay flavour violating (mainly to charm and neutralino). The decay is not allowed in naive MFV at tree-level and is suppressed by small CKM angles in symmetry based MFV giving a sizable lifetime to the stop. We calculate the SQCD corrections to this decay in the MSSM with generic sources of flavour-violation. Assuming that the SUSY breaking mechanism is flavour-blind the stop-neutralino-charm vertex is RGE-induced. Our new corrections allow us to use the 2-loop running and we study the numerical impact of our QCD correction.

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## Unitarity bound in the composite two Higgs doublet model.

Ms. YILDIRIM, Emine <sup>1</sup>; Dr. YAGYU, Kei <sup>2</sup>; Prof. MORETTI, Stefano <sup>1</sup>; Dr. DE CURTIS, Stefania <sup>3</sup><sup>1</sup> *University of Southampton*<sup>2</sup> *University Of Southampton*<sup>3</sup> *INFN***Corresponding Author:** ey1g13@soton.ac.uk

We discuss a composite two Higgs doublet model based on a symmetry breaking  $SO(6) \times U(1)_X \rightarrow SO(4) \times SO(2) \times U(1)_X$  at a scale  $f$ , and explain how the effective kinetic terms and Yukawa interactions are obtained.

The coupling of the Higgs boson as a pseudo Nambu-Goldstone boson to the standard model fields can deviate from that of the standard model Higgs boson due to the non-linear feature.

These deviations cause

to unitarity violation at high energies because the cancellation of the quadratic energy terms does not happen.

We will examine the constraints on parameter space

from perturbative unitarity with a fixed energy scale in the composite two Higgs doublet model.

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## New Physics Effectes in Higgs couplings through Effective Lagrangian Method

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The discovery of the Higgs boson by the LHC has initiated an era of Higgs precision studies. In the absence of any new particles in the spectrum, and no indication of it at the electroweak scale, suggest that the new physics effects are better explored through precision studies of the interactions of the SM particle spectrum. Related the Higgs sector, this could be investigated efficiently through an effective Lagrangian framework in which the new physics effects are coded through the higher dimensional operators involving Higgs bosons. In the talk, we shall give a brief overview of the studies in the context of LHC as well as future electron collider like ILC/FCC, and present results of our own work in the study of the Higgs self-couplings and Higgs-gauge boson couplings.

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## Scrutinizing the Alignment Limit in Two-Higgs-Doublet Models

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In the alignment limit of a multi-doublet Higgs sector, one of the Higgs mass eigenstates aligns with the direction of the vacuum expectation value, and its couplings approach those of the Standard Model (SM). Considering the CP-conserving Two-Higgs-Doublet Models of Type I and Type II near the alignment limit, we focus on the case in which the heavier of the two CP-even state, H, is the 125 GeV SM-like state observed at the LHC. A decoupling regime thus cannot be attained in these scenarios since the lighter CP-even state, h, has a mass below 125 GeV by definition.

After a short review of the theoretical structure, the phenomenological consequences of this realization of the alignment regime are presented. Implications for the coming 13 TeV LHC run, including expectations regarding the observation of the extra scalar states, are discussed.

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## Conditions of positivity and unitarity in the most general 2HDM via measurable quantities

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The well known conditions of positivity and unitarity in the 2HDM are written usually via parameters of potential  $\lambda_a$  which values cannot be obtained from measurements unambiguously. We express these very conditions in terms of measurable quantities. These conditions cannot be checked soon since they include values of some triple and quartic Higgs couplings (with charged Higgs bosons).

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## Production of Inert Scalars at the $e^+e^-$ Linear Colliders

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In this talk I will present the signatures of Inert Doublet Model scalars at the Linear Colliders with the center of mass energies 500-GeV and 1000-GeV at the integrated luminosity of 500  $\text{fb}^{-1}$ . Several benchmark points are studied with focus on  $H^\pm \rightarrow W^\pm H$  and  $A \rightarrow Z H$  decays and the signal statistical significance is calculated in different final states. The result shows that the signals are well observable in different final states for all chosen benchmark points.

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## Dark Matter at the LHC: Bringing scalar portals into play

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We discuss how mono-X searches at the LHC (with  $X = h, W, Z$ ) could shed light on the nature of Dark Matter (DM) and its interactions with the Standard Model (SM), focusing on two well-motivated scenarios: (i) The scalar Higgs portal DM scenario, where such signatures could allow to distinguish between a linear and a non-linear realization of electroweak symmetry breaking. (ii) The pseudo-scalar portal to DM, possible to realize within extensions of the SM Higgs sector, and yielding novel DM signatures at the LHC.



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## GUT-inspired SUSY and the muon $g-2$ anomaly: prospects for LHC 14 TeV

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We consider the possibility that the muon  $g-2$  anomaly,  $\Delta(g-2)_\mu$ , finds its origins in low energy supersymmetry (SUSY). In the general MSSM the parameter space consistent with  $\Delta(g-2)_\mu$  and correct dark matter relic density of the lightest neutralino easily evades the present direct LHC limits on sparticle masses and also lies to a large extent beyond future LHC sensitivity. The situation is quite different in GUT-defined scenarios where input SUSY parameters are no longer independent. We analyze to what extent the LHC can probe a broad class of GUT-inspired SUSY models with gaugino non-universality that are currently in agreement with the bounds from  $\Delta(g-2)_\mu$ , as well as with the relic density and the Higgs mass measurement. To this end we perform a detailed numerical simulation of several searches for electroweakino and slepton production at the LHC and derive projections for the LHC 14 TeV run. We show that, within GUT-scale SUSY there is still plenty of room for the explanation of the muon anomaly, although the current LHC data already imply strong limits on the parameter space consistent with  $\Delta(g-2)_\mu$ . On the other hand, we demonstrate that the parameter space will be basically fully explored within the sensitivity of the 14 TeV run with 300 inverse fb. This opens up the interesting possibility that, if the  $(g-2)_\mu$  anomaly is real then some positive signals must be detected at the LHC, or else these models will be essentially ruled out. Finally, we identify the few surviving spectra that will provide a challenge for detection at the LHC 14 TeV run and we characterize their properties.

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## Higgs-Radion unification in warped extra dimensions

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I will talk about "Higgs-Radion unification" scenario, where an  $SU(2)$  Higgs doublet plays the role of a stabilizing field in the Randall-Sundrum model-I (RSI). In the 4D effective theory the zero-mode of the Higgs-radion field mimics the scalar particle observed at the LHC with mass 125 GeV. I will discuss some of the phenomenological implications of this scenario.

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## Radiatively Induced Fermi Scale in Grand Unified Theories

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We propose a Grand-Unified-Theory framework [arXiv:1511.01910], where the hierarchy between the unification and the Fermi scale emerges radiatively. As a concrete example, we study a Pati-Salam-type unification scenario, where the SM scalar sector is replaced by an SU(4)-symmetric one. In this scenario, the observed Higgs particle is an elementary pseudo-Goldstone boson.

We show that it is possible to construct a viable model where the unification scale is taken to be above the experimental

bound, while the Fermi scale is generated radiatively. This scenario opens up interesting prospects for exploring a wide variety of open problems in particle physics, ranging from neutrinos to cosmic inflation.

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## The Higgs, the top and the singlet scalar -- gravity and the stability of the effective potential

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We set out to investigate the stability of the Higgs effective potential in curved spacetime. To this end, we considered the gauge-less top-Higgs sector with an additional scalar field. Using the heat kernel method we derived the one-loop effective action for the model at hand. We found that the lowest order nontrivial gravity induced terms are proportional to the square of the Riemann and the Ricci tensors. Next, we analyzed the changes induced by these terms on the behavior of the effective potential in the small field region (electrovacuum minimum) and on the effective Higgs quartic coupling in the large field region.

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## An elementary Goldstone Higgs

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We show, via a careful analytical and numerical analysis, that a pseudo Goldstone nature of the Higgs is naturally embodied by an elementary realization that also serves as ultraviolet completion. Renormalizability married to perturbation theory allows to precisely determine the quantum corrections of the theory while permitting to explore the underlying parameter space. By characterising the available parameter space of the extended Higgs sector we discover that the preferred electroweak alignment angle is centred around  $\theta \approx 0.02$ , corresponding to the Higgs chiral symmetry breaking scale  $f \approx 14$  TeV. The latter is almost 60 times higher than the Standard Model electroweak scale. However, due to the perturbative nature of the theory, the spectrum of the enlarged Higgs sector remains in the few TeV energy range. We also analyse precision constraints and the relevant phenomenological aspects of the theory.

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## FIMP/SWIMP Dark Matter at LHC

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We will present a simple model of decaying DM, where the DM population is generated from the decay of an exotic scalar particle, charged under the Standard Model gauge group and in equilibrium in the early universe. The phenomenology of the model at the LHC and the connection to DM indirect detection will be discussed, especially for the region of parameter space compatible with FIMP/SWIMP production.

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## The study of multi-Higgs-doublet model potentials

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In an explicit example of a three-Higgs-doublet model we study the potential with respect to stability, electroweak-symmetry breaking, CP symmetry and the mass matrices of the physical Higgs bosons. As we show, this can be done easily in the bilinear formalism.

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## Probing extended Higgs sectors by precision measurements of the Higgs boson couplings

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We discuss how we are able to discriminate extended Higgs sectors by using future precision measurements of the couplings of the discovered Higgs boson  $h(125)$  with the mass of 125 GeV. To this end, we construct a full set of numerical codes for evaluating all the couplings of  $h(125)$  at the one-loop level in various general extended Higgs sectors, such as the Higgs model with an isospin singlet scalar field, the two Higgs doublet models with four types of Yukawa interaction under the softly-broken discrete symmetry, the inert doublet model and the Higgs model with triplets.

In these extended Higgs models, characteristic patterns of deviations in the couplings for  $h(125)$  appear not only at the tree level but also at the one-loop level. We numerically evaluate the patterns at the one-loop level, and examine how we can separate and identify extended Higgs model by detecting the patterns of the coupling deviations using the future precision data for these couplings at ILC.

This talk is based on the papers;

1. S. Kanemura, M. Kikuchi, K. Yagyu, Nucl. Phys. B 896, 80 (2015).

2. S. Kanemura, M. Kikuchi, K. Yagyu, in preparation.

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## Scalar particle production at the STAR experiment in the Double Pomeron Exchange process

**Dr. GURYN, Wlodek** <sup>1</sup>

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We shall describe the physics program with tagged forward protons, focusing on scalar particle production in the Central Exclusive Production (CEP) Process in polarized proton-proton collisions at the Relativistic Heavy Ion Collider, with the STAR detector at  $\sqrt{s} = 200$  GeV. Preliminary results in CEP of two oppositely charged pions and kaons produced in the processes  $pp \rightarrow pp \pi^+ \pi^-$  and  $pp \rightarrow pp K^+ K^-$  shall be presented. Because of the quantum numbers of the Pomeron exchange these Double Pomeron Exchange processes favour scalar  $0^{++}$  particle production. Hence the final states are dominated by gluonic exchanges. Silicon strip detectors placed in Roman Pots were used for measuring forward protons. The preliminary results are based on the measurement of the recoil system of charged particles in the STAR experiment's Time Projection Chamber. Ionization energy loss of charged particles was used for particle identification. In addition to those preliminary results, the present status and future plans of diffractive physics at STAR shall be described.

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## Benchmark scenarios and resonant decays in singlet models at the LHC run 2

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Singlet models are an interesting and simple framework to address several beyond the standard model issues which can also provide interesting new phenomenology at colliders. They can provide dark matter candidates, improve the stability of the standard model (SM) at high energies, make electroweak baryogenesis viable and provide Higgs to two-Higgs decay signatures at colliders. In this talk I will discuss the real and complex singlet extensions of the SM with emphasis on resonant decays of heavy Higgs bosons with an SM-like Higgs boson in the decay. I will also present a comparison between a singlet model with two new Higgs bosons (visible at the LHC run 2) and the NMSSM, as well as with two singlet models with only one new Higgs boson at the LHC run 2.

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## Light singlet scenario in R-symmetric SUSY

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R-symmetry is an additional symmetry which might be preserved after SUSY breaking. This leads to interesting phenomenological consequences like the existence of Dirac gauginos. A model with a minimal implementation of this symmetry, the MRSSM, also includes a gauge singlet Higgs state which could be lighter than the observed 125 GeV SM-like Higgs, while still not conflicting LEP or LHC bounds. In this talk I will discuss positive effects of mixing between SM-like and singlet Higgses as well as phenomenology of Dirac bino-singlino dark matter.

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## Muon $g-2$ in MSSM and B-L-SSM

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The Higgs boson discovery in the ATLAS and CMS experiments has led to strict constraints for the supersymmetric models. The experimental analyses have approved that the Standard Model predictions are highly consistent with the experimental results. The highest discrepancy between the experiment and the Standard Model happens in the measurements of the muon anomalous magnetic moment (muon  $g-2$ ). The calculations within the Standard Model have been achieved in a high sensitivity, and hence the new physics beyond the Standard Model can solve or ameliorate the discrepancy in muon  $g-2$  measurements. If supersymmetry is a solution to muon  $g-2$  problem, the smuons and weak gauginos need not to be heavier than a few hundred GeV. However, the Higgs boson of mass about 125 GeV requires rather a heavy sparticle mass spectrum, and so it leads to a tension in resolution of the muon  $g-2$  problem. In this talk, the status of muon  $g-2$  results in supersymmetry will be discussed and some supersymmetric models such as flavour symmetry-based minimal supersymmetric standard model, non-universal gauginos and MSSM extended by  $U(1)_{B-L}$  will be discussed. The work represented is supported in part by Technological Research Council of Turkey (TUBITAK) Grant no. MFAG-114F461 and grant H2020-MSCA-RISE-2014 no. 645722 (NonMinimalHiggs).

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## Exact $SU(5)$ Yukawa matrix unification in the General Flavour Violating MSSM

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The simplest Grand Unified Theory (GUT) embedding the Standard Model (SM) is based on the  $SU(5)$  symmetry. The unification of gauge couplings, failing in the SM, takes place in the R-parity conserving Minimal Supersymmetric Standard Model (MSSM).

We investigated the possibility of satisfying the minimal  $SU(5)$  boundary conditions also for Yukawa matrices at the GUT scale within the MSSM. We found a new region in the model's parameter space consistent with this requirement.

In this talk, we consider non-vanishing flavour off-diagonal entries in the soft SUSY-breaking mass matrices. The diagonal A-terms are assumed to be proportional to the respective Yukawa couplings. We show that a precise bottom-tau and strange-muon Yukawa coupling unification is possible, while the phenomenological constraints are satisfied. These include the flavour and electroweak observables, Higgs physics and the LHC bounds as well as the dark matter relic density and the stability of vacuum.

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## Particle production in time-dependent backgrounds

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It is known that time-dependent vacuum expectation value of the background field causes the production of particles. Talk would present the general mechanism of particle production in time-varying backgrounds with the impact of rescattering emphasised, also in models with more than one coupling constant. Cosmological applications of this general method shall be presented.

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## Improved analysis of the CLFV process: $\mu e \rightarrow e e$ in muonic atom

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We proposed a new charged lepton flavor violation (CLFV) process,  $\mu^- e^- \rightarrow e^- e^-$  in a muonic atom, as one of the promising processes to search for new physics beyond the standard model [1]. It was found that the attractive interaction of leptons with the nucleus in the muonic atom enhances the transition rate of the  $\mu^- e^- \rightarrow e^- e^-$  process. We report on our improved the analysis of this process by taking account the distortion of the out-going electrons in the nuclear Coulomb potential and the relativistic treatment of the muon and the electrons. As results, we found significant enhancement of the transition rate. The transition rate for  $^{208}\text{Pb}$  becomes about 7 times larger than the previous calculation, which enhances the sensitivity of this process to discover the CLFV process.

[1] M. Koike, Y. Kuno, J. Sato and M. Yamanaka, Phys. Rev. Lett. 105, 121601 (2010)

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## Dark Matter in the Three Higgs Doublet Model

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Multi-scalar extensions of the Standard Model can accommodate a viable Dark Matter candidate and modification of Higgs decay rates. One of the simplest choices for the extended scalar sector is the Inert Doublet Model, i.e. the Standard Model with an additional inert scalar doublet. The IDM can be further extended by extra doublets or singlets, which may modify both DM- and collider phenomenology.

Dark Matter (DM), arising from an Inert Higgs Doublet, may either be light, below the  $W$  mass, or heavy, above about 525 GeV. While the light region may soon be excluded, the heavy region is known to be very difficult to probe with either DM direct detection experiments or the Large Hadron Collider (LHC). We show that adding a second Inert Higgs Doublet helps to make the heavy DM region accessible to both direct detection and the LHC, by either increasing its couplings to the observed Higgs boson, or lowering its mass to 360 GeV, or both.

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## SIMP model at NNLO in chiral perturbation theory

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We investigate the phenomenological viability of a recently proposed class of composite dark matter models where the relic density is determined by  $3 \rightarrow 2$  number-changing processes in the dark sector. Here the pions of the strongly interacting field theory constitute the dark matter particles. By performing a consistent next-to-leading- and next-to-next-to-leading-order chiral perturbative investigation we demonstrate that the leading-order analysis cannot be used to draw conclusions about the viability of the model. We further show that higher-order corrections substantially increase the tension with phenomenological constraints challenging the viability of the simplest realization of the strongly interacting massive particle paradigm.

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## SCALAR WIMPS 2015

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In this talk, I will briefly put in context scalar WIMPs as dark matter candidates. I will then go on discussing two recent simple scalar DM models and their possible signatures (some striking) for direct and indirect detection experiments and at the LHC.

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## Stability of the inert vacuum state beyond tree level

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In this talk I will discuss the issue of the stability of the inert vacuum state. It is the ground state of the inert doublet model (IDM), with one scalar doublet having SM-like vacuum expectation value and the other not participating in spontaneous symmetry breaking. Two approaches to this problem will be presented. First, the influence of heavy inert scalars on the SM-like vacuum will be studied. Secondly, I will discuss coexistence of different minima in the IDM at one-loop level, and compare it with the tree-level picture.



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## Coincidence of Higgs Mass with one giving Corrected Barely Stability of Vacuum

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Assuming that a resonance of mass 300 GeV decaying into two Higgs bosons with two standard deviation observed by LHC is indeed our long speculated bound state of 6 top + 6 anti top quarks we include corrections leading to that in pure Standard Model there could be just barely stability of the vacuum! This is a coincidence improving the accuracy of our earlier on the basis of our Multiple Point Principle PREDICTED Higgs mass.

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## The most bizarre two-Higgs doublet model ever

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The Lee-Wick Standard Model is a highly constrained two-Higgs model, with one parameter determining all additional masses and mixing angles. It also solves the gauge hierarchy problem. However, it contains states with negative norm, i.e. negative widths, i.e. they decay before they are produced. Nonetheless, the model appears to be unitary and macroscopically causal. The model will be reviewed, and an extension to the Lee-Wick two-Higgs doublet model will be presented.

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## CP violation in the extended Standard Model with a complex singlet

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We construct the scalar potential of the Standard Model with an additional singlet scalar field (SMS), assuming an exact  $Z_2$  symmetry, where the singlet is  $Z_2$ -even. To simplify the model we use a softly broken  $U(1)$  symmetry, which allows a reduction of the number of free parameters in the potential. Additional CP violating phase can appear if a complex singlet with a non-zero vacuum expectation value is added to the scalar sector of the SM. We study the masses of scalar particles, gauge couplings and fermionic sector.

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## Higgscision and Higgs Boson Pair Production

Prof. CHEUNG, Kingman<sup>1</sup><sup>1</sup> *National Tsing Hua University***Corresponding Author:** kingman.cheung@cern.ch

A brief review on the Higgs-gauge and Yukawa couplings will be given. The most important is to determine the size and the sign of the top Yukawa coupling. The current Higgs data cannot completely ruled out the opposite sign of the top Yukawa. We propose single-top plus Higgs production to determine the sign of the top Yukawa. The second part is the study of Higgs-pair production, which can probe the trilinear coupling of the Higgs boson, which can in turn reveal the inside structure of the EWSB sector. We show how we can disentangle the triangle diagram from the box diagram, such that the trilinear coupling can be probed.

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## The Inert Doublet Model in the light of LHC and astrophysical data

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We discuss the parameter space of the Inert Doublet model, a two Higgs doublet model with a dark matter candidate. An extensive set of theoretical and experimental constraints on this model is considered, where both collider as well as astroparticle data limits are taken into account. We discuss the effects of these constraints on the models parameter space. The combination of all constraints leads to relatively strong mass hierarchy in the dark scalar sector, and to a minimal scale for the dark scalar masses. We propose benchmark points and benchmark planes for dark scalar pair-production for the current LHC run.

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## Naturalness. A user's manual

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After reviewing the use (and misuse) of naturalness in model building, I discuss a possible application: a natural model of minimal dark matter

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## All about the triplet

Prof. DELGADO, Antonio <sup>1</sup>

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In this talk I will introduce the Supersymmetric Custodial Triplet Model (SCTM), the supersymmetric version of the Georgi-Machacek model where three triplets of SU(2) are added to the MSSM in a custodial invariant way. I will embed it into a predictive theory of supersymmetry breaking and I will also study its implication for Dark Matter.

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## Effect of interaction terms on parametric resonance

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It is known that non-perturbative particle production are induced if the particles couple to a time-varying background field, such as the preheating theory. Especially, bosonic particles can grow exponentially due to parametric resonance. We have investigated this mechanism with a interacted system, in which there are fields without direct coupling to the background but with coupling to other fields. As our conclusion, it is possible to induce particle production even if particles do not couple to the background directly. Such particles are produced through the interactions with other fields, which couple to a varying background. In this talk, we will demonstrate with a simple model and show the results of parametric resonance.

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## Does Quantum Gravity constrain Large-Field Inflation?

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I will briefly recall the interest in and status of large-field models of inflation. I will then discuss general no-go arguments against this version of inflation which are based on gravitational instantons and the so-called weak-gravity conjecture. Then I will turn to possible loopholes in those arguments and explain how certain string-theoretic constructions might, nevertheless, be able to realize large-field inflation.

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## Vacuum stability from vector dark matter

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We study a model of a vector dark matter coming from the complex scalar Higgs portal with an additional U(1) gauge symmetry. Renormalisation group equations at the 2-loop level are used to analyse perturbativity and influence of the dark gauge coupling on the vacuum stability. We discuss LHC and LEP constraints on the additional Higgs-like scalar present in the model and bounds coming from the Planck data and direct detection experiments.

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## 2HDM: CP violation in the ZZZ and ZWW couplings

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In the Two-Higgs-Doublet model, CP-violation in the Higgs sector can be described using three weak-basis invariants. At one-loop level, CP violating effects arise in the effective ZZZ and ZWW vertices. These vertices provide a direct measure of one of the CP-violating invariants in the 2HDM.

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## CP Violation in the scalar sector

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I will discuss CP violation in the scalar (Higgs) sector, with emphasis on possible complex vacua and spontaneous CP violation in a theory with an S<sub>3</sub>-symmetric potential.

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## Radiative Neutrino Masses

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We discuss the motivations and perspectives of radiative neutrino mass models with special emphasis on those which only contain new scalars.

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## Beyond the Coleman--Weinberg Effective Potential

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The Two-Particle-Irreducible (2PI) formalism as introduced by Cornwall, Jackiw and Tomboulis provides a systematic analytic approach to consistently describing non-perturbative phenomena in Quantum Field Theory. In spite of its great success, one major problem of the 2PI approach is that its loopwise expansion gives rise to residual violations of symmetries and hence to massive Goldstone bosons in the spontaneously broken phase of the theory. In my talk I will present a novel Symmetry-Improved 2PI formalism which consistently encodes global symmetries in a loopwise expansion, leading to massless Goldstone bosons within quantum loops and to a second order phase transition in  $O(N)$  theories. In particular, I will outline the derivation of a Symmetry-Improved 2PI effective potential, in which new topologies of infinite series of graphs can be systematically resummed that allow to successfully address the Goldstone-boson IR problem of the fixed-order Coleman--Weinberg effective potential.

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## NLO SMEFT for Higgs and EW precision data

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After the LHC Run 1, the standard model (SM) of particle physics has been completed. Yet, despite its successes, the SM has shortcomings vis-à-vis cosmological and other observations. At the same time, while the LHC restarts for Run 2 at 13 TeV, there is presently a lack of direct evidence for new physics phenomena at the accelerator energy frontier. From this state of affairs arises the need for a consistent theoretical framework in which deviations from the SM predictions can be calculated and compared to precision measurements.

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## Low-energy signals of strongly-coupled electroweak symmetry-breaking scenarios

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The non-observation of new particles at the LHC suggests the existence of a mass gap above the electroweak scale. This situation is adequately described through a general electroweak effective theory with the established fields and Standard Model symmetries. Its couplings contain all information about the unknown short-distance dynamics which is accessible at low energies. We consider a generic strongly-coupled scenario of electroweak symmetry breaking, with heavy states above the gap, and analyze the imprints that its lightest bosonic excitations leave on the effective Lagrangian couplings. Different quantum numbers of the heavy states imply different patterns of low-energy couplings, with characteristic correlations which could be identified in future data samples. The predictions can be sharpened with mild assumptions about the ultraviolet behaviour of the underlying fundamental theory.

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## FLAVOUR CHANGING YUKAWA COUPLING IN TWO HIGGS DOUBLET MODELS

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We consider a special case of 2HDM type III known as BGL. These models have tree level flavour changing neutral couplings in the Higgs sector. As a result of a flavour symmetry these couplings are suppressed by the CKM and the PMNS matrices and /or by light masses. In fact these models can be considered as implementing the MFV hypothesis. After imposing the diagonal or flavour blind constraints from LHC, we present the predictions on several flavour changing processes like  $t \rightarrow hu$ ,  $hc$ , leptonic Higgs decays as  $h \rightarrow \mu\tau$  as well as hadronic decays  $h \rightarrow bs$ ,  $bd$ . We also comment on the low energy constraints.

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## Relaxing the Higgs with cosmology

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Recently, a new mechanism to generate a naturally small electroweak scale has been proposed. It exploits the coupling of the Higgs to an axion-like field and a long era in the early universe where the axion unchains a dynamical screening of the Higgs mass. We present a new realization of this idea with the new feature that leaves no signs of new physics up to a rather large scale,  $10^9$  GeV, except for two very light and weakly coupled axion-like states.

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### **Asymptotically free scaling solutions in nonabelian Higgs models**

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### **An extended scalar sector for the known physics beyond the SM**

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### **An elementary Goldstone Higgs**

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### **GUT-inspired SUSY and the muon $g-2$ anomaly: prospects for LHC 14 TeV**

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### **Searches for low-mass scalar particles with the BABAR detector**

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### **Scalar particle production at the STAR experiment in the Double Pomeron Exchange process**

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### **Fate of false vacua at one loop**

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### **The Higgs, the top and the singlet scalar -- gravity and the stability of the effective potential**

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### **Leptogenesis during the reheating era**

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### **Scrutinizing the Alignment Limit in Two-Higgs-Doublet Models**

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### **2HDM: CP violation in the ZZZ and ZWW couplings**

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### **Radiatively Induced Fermi Scale in Grand Unified Theories**

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### **Improved analysis of the CLFV process: $\mu e \rightarrow e e$ in muonic atom**

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### **Muon $g-2$ in MSSM and B-L-SSM**

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## **Benchmark scenarios and resonant decays in singlet models at the LHC run 2**

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## **The Inert Doublet Model in the light of LHC and astrophysical data**

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## **Fitting the two-loop renormalized Two-Higgs-Doublet model**

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## **Connection between a mass of the 2nd Higgs boson and a deviation in the 125 GeV Higgs boson couplings**

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## **New Physics Effectes in Higgs couplings through Effective Lagrangian Method**

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## **Production of Inert Scalars at the $e^+ + e^-$ Linear Colliders**

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## **Inflation and higher order corrections to Higgs/Starobinsky models**

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## **Dark Matter in the Three Higgs Doublet Model**

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## **Dark Matter at the LHC: Bringing scalar portals into play**

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## **Effect of interaction terms on parametric resonance**

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## **What tell us LHC data about Higgs boson parity**

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## **Electroweak and Dark matter scalegenesis from a bilinear scalar**

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## **SIMP model at NNLO in chiral perturbation theory**

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**Enhancement of the HWZ vertex in the three scalar doublet model**

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**Unitarity bound in the composite two Higgs doublet model.**

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**Stability of the inert vacuum state beyond tree level**

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**CP violation in the extended Standard Model with a complex singlet**

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**Probing extended Higgs sectors by precision measurements of the Higgs boson couplings**

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**Light singlet scenario in R-symmetric SUSY**

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**Exact SU(5) Yukawa matrix unification in the General Flavour Violating MSSM**

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**NLO SQCD corrections to the decay of top-squarks to charm and neutralino**

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**Particle production in time-dependent backgrounds**

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**Bosonic seesaw mechanism in a classically scale invariant model**

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**Vacuum stability from vector dark matter**

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**MLRSM Higgs bosons at the LHC and beyond**

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## **Recent Highlights from CMS**

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## **Non-linear Higgs Portal to Dark Matter**

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## **On the quantum structure of indirect BSM effects**

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## **Relaxing the Higgs with cosmology**

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## **General extensions of the Standard Model with new scalars**

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## **The most bizarre two-Higgs doublet model ever**

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## **Extended Higgs sector phenomenology and interference effects**

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## **Conformal Electro-Weak Symmetry Breaking and Implications for Neutrinos and Dark Matter**

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## **What 126 GeV Higgs mass means?**

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## **Coincidence of Higgs Mass with one giving Corrected Barely Stability of Vacuum**

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### **Naturalness. A user's manual**

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### **Heavy Higgs decays in models with vectorlike fermions**

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### **New Physics in Lepton Flavor Violating Higgs Decays**

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### **Does Quantum Gravity constrain Large-Field Inflation?**

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### **FIMP/SWIMP Dark Matter at LHC**

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## **The Higgs and cosmology**

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## **Radiative Neutrino Masses**

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## **Higgs, Supersymmetry and Dark Matter: Relations and Perspectives**

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## **Relaxing the Higgs with cosmology**

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## **New results on CP violation in multi-Higgs models**

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## **The study of multi-Higgs-doublet model potentials**

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## **CP Violation in the scalar sector**

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## **Collider Phenomenology of 3HDMs**

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## **Invariants in Two Higgs Doublet Models**

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## **Minimal Flavour Violation in BGL Models**

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## **Flavour changing Yukawa coupling in two Higgs doublet models**

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## **Higgs potential, future colliders and future gravitational wave interferometers**

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## **2HDMs as benchmark models at run 2**

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## **Beyond the Coleman--Weinberg Effective Potential**

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## **Gauge-Higgs unification: from EW to GUT**

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## **Supersymmetry and Higgs Physics**

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## Light Higgs bosons, constraints and prospects

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## All about the triplet

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## Flavon-induced Higgs lepton flavour violations

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The current experimental limit on Charge Lepton Flavour Violating (CLFV) processes allows the branching ratios of  $h \rightarrow \tau \mu$  and  $h \rightarrow \tau e$  processes to be of order 10%. Since such CLFV processes are forbidden in the Standard Model (SM), we aim to explain these processes by employing the Froggatt-Nielsen mechanism. This mechanism requires the addition of a scalar field called the flavon, singlet under SM gauge group which breaks spontaneously due to the flavon field acquiring a Vacuum Expectation Value (VEV). We show that the observed CLFV branching ratios can be explained due to the flavon field mixing with the Higgs boson passing all experimental bounds.

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## Higgs-Radion unification in warped extra dimensions

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## Higgs-Radion unification in warped extra dimensions

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## Exact SU(5) Yukawa matrix unification in the General Flavour Violating MSSM

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## Rethinking Fundamental Interactions: From Asymptotic Freedom to Asymptotic Safety

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I will discuss new exact results in four-dimensional quantum field theory that led us to the discovery of asymptotically safe theories in four dimensions without supersymmetry. I will then move to supersymmetric cousins of the theories above, and present exact results that make use of a number of non-perturbative tools ranging from the unitarity of the conformal operators to the a-theorem and a-maximisation. In addition, the supersymmetric results also complete Seiberg' phase diagram once asymptotic freedom is lost. The results allow to rethink about fundamental interactions and pave the way for the construction of novel extensions of the standard model of particle interactions.

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## Flavon-induced Higgs lepton flavour violations

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## CP violation in the extended Standard Model with a complex singlet

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