$\mathcal{N}$MSSM and 2$\mathcal{H}$DM $\mathcal{A}$ctivities within $\mathcal{WG}$3/$\mathcal{BSM}$

$\mathcal{I}$. $\mathcal{L}$ow, $\mathcal{M}$. $\mathcal{M}$ühlleitner, $\mathcal{M}$. Pelliccioni, $\mathcal{N}$. $\mathcal{R}$ompotis

WG3 BSM

LHCHXSWG

8th General Assembly Meeting

24 January 2015

$\mathcal{S}$mall $\mathcal{I}$ntroduction to the $\mathcal{NMSSM}$ $\mathcal{H}$iggs $\mathcal{S}$ector

- **Supersymmetric Higgs Sector:**

  ◇ MSSM: 2 complex Higgs doublets H_u and H_d ($\leftarrow$ SUSY & anomaly-free theory)

  ◇ NMSSM: additional complex singlet field S

- **Motivation for NMSSM:**

  ▷ **Solution of the μ-problem:** μ must be of $\mathcal{O}$(EWSB scale)

  μ generated dynamically through the VEV of scalar component of an
  additional chiral superfield $\hat{S}$: $\mu_{\text{eff}} = \lambda \langle S \rangle$ from: $\lambda \hat{S} \hat{H}_u \hat{H}_d$

  ▷ **Additional benefit:**

  ⋆ Upper mass bounds + corrections to the MSSM, NMSSM Higgs boson mass:

  $$\text{MSSM:} \quad m_h^2 \approx M_Z^2 \cos^2 2\beta + \Delta m_h^2$$

  $$\text{NMSSM:} \ m_h^2 \approx M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \Delta m_h^2$$

  $\Rightarrow m_h \approx 126$ GeV requires less radiative corrections Δm_h^2 $\Rightarrow$ NMSSM requires less fine-tuning

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The $\mathcal{NMSSM}$ $\mathcal{H}$iggs $\mathcal{S}$ector

- **Most investigations within Z_3 invariant NMSSM:**

$$
\begin{aligned}
V_{\mathsf{Higgs}} \;=\;\; & |\lambda(H_u^+ H_d^- - H_u^0 H_d^0) + \kappa S^2|^2 \\
& + (m_{H_u}^2 + |\lambda S|^2)(|H_u^0|^2 + |H_u^+|^2) + (m_{H_d}^2 + |\lambda S|^2)(|H_d^0|^2 + |H_d^-|^2) \\
& + \frac{g_1^2 + g_2^2}{8}(|H_u^0|^2 + |H_u^+|^2 - |H_d^0|^2 - |H_d^-|^2)^2 + \frac{g_2^2}{2}|H_u^+ H_d^{0*} + H_u^0 H_d^{-*}|^2 \\
& + m_S^2|S|^2 + (\lambda A_\lambda(H_u^+ H_d^- - H_u^0 H_d^0)S + \frac{1}{3}\kappa A_\kappa S^3 + h.c.)
\end{aligned}
$$

The $\mathcal{NMSSM}$ $\mathcal{H}$iggs $\mathcal{S}$ector

- **Most investigations within Z_3 invariant NMSSM**

- **Parameters at tree level:**

$$e, M_W^2, M_Z^2, \lambda, \kappa, A_\lambda, A_\kappa, \tan\beta, \mu_{\text{eff}}$$

- **Enlarged Higgs and neutralino sector:** 2 complex Higgs doublets H_u, H_d, 1 complex singlet S

7 Higgs bosons:	$H_1, H_2, H_3, A_1, A_2, H^+, H^-$
5 neutralinos:	$\tilde{\chi}_i^0 \ (i = 1, ..., 5)$

- **Higgs mass eigenstates:**

  superpositions of doublet and singlet components $\rightsquigarrow$

  the more singlet-like the smaller couplings to SM particles

The $\mathcal{NMSSM}$ $\mathcal{H}$iggs $\mathcal{P}$henomenology

- **NMSSM Phenomenology:**

  ◇ enlarged Higgs sector, singlet-like Higgs states; additional neutralino

  ◇ tree-level CP violation in Higgs sector possible

- **Significant changes of (Higgs boson) phenomenology**

  ∗ light Higgs states not excluded ⤳ Higgs-to-Higgs decays

  ∗ degenerate Higgs bosons around 125 GeV possible

  ∗ very light singlino-like lightest SUSY particle (LSP) ⤳ NLSP long lifetime

  ∗ invisible Higgs decays

  ∗ new CP-violating effects   ...

- **Calls for:**

  ◇ study phenomenological consequences ← not miss or misinterpret Higgs (and sparticle) signals, distinguish from MSSM, ...

  ◇ precise predictions for parameters and observables including higher order corrections

# $\mathcal{S}$ome $\mathcal{E}$xperimental $\mathcal{R}$esults for the $\mathcal{NMSSM}$

- **Experimental Results:** Currently few results directly related to the NMSSM;
  a few more to come; some examples of previous results:

  ◇ $H \to aa \to 4\mu$ (CMS-PAS-HIG-13-010)
     Interpretation within NMSSM for 3 different m_{a_1} and for simplified scenario

  ◇ $a \to \mu\mu$ (CMS arXiv:1206.6326)
     Attempt of 2-dimensional limit vs. the mixing angle between the 2 pseudoscalars of the model.
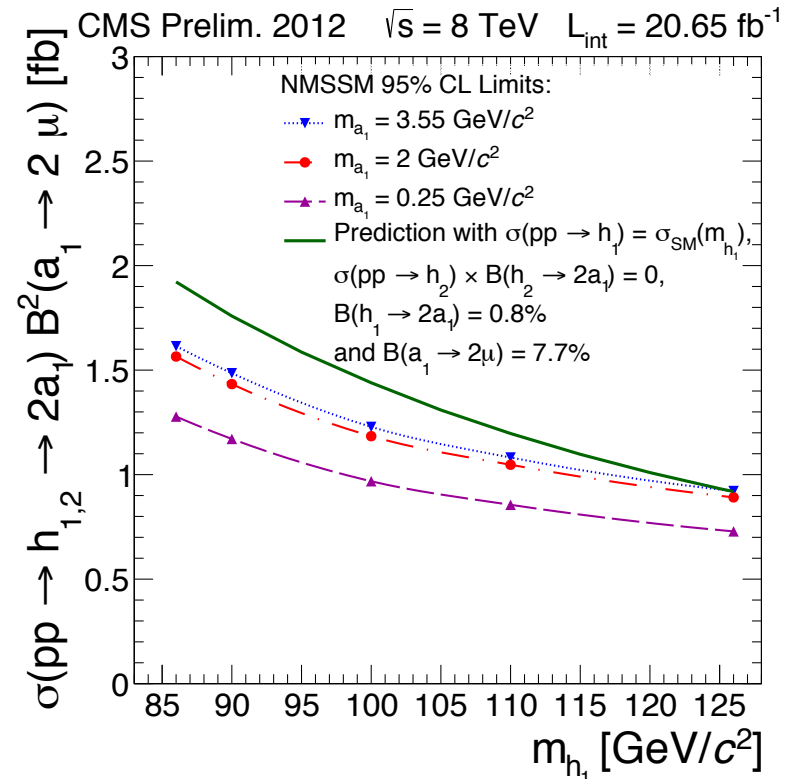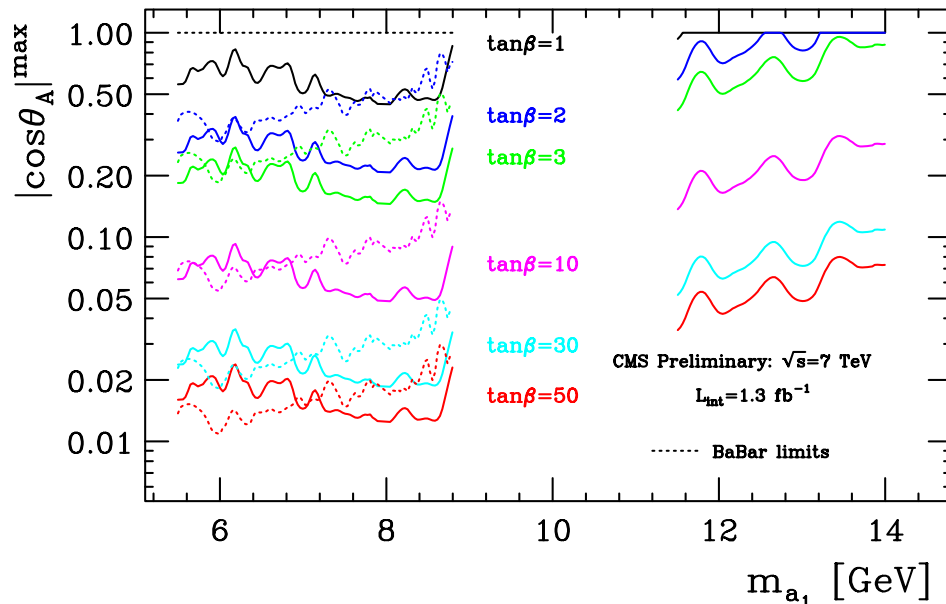
$\mathcal{T}$opics for $\mathcal{N}$MSSM-$\mathcal{WG}$3

- **Topics/Goals:**

  ∗ Provide NMSSM Benchmark Points/Scenarios/Parameter Subspaces:

    − test or exclude subspaces of the NMSSM parameter space

    − distinguish NMSSM from other BSM models

    − unique/exotic signatures (specific) of the NMSSM

    − make sure all relevant mass regions are tested   …

  ∗ Relation with other measurements ($\rightarrow$ Dark Matter) – implications for NMSSM

  ∗ How exchange efficiently information between experiment and theory?

  ∗ Reinterpretation of previous non-NMSSM analyses in the NMSSM?!

  ∗ Common signatures to NMSSM and exotics subgroup?

  ∗ Cross talk with other subgroups: Higgs XS&BR, HH, Exotics, off-shell $\rightsquigarrow$ common meetings

  ∗ Provide tools for the computation of Higgs masses, couplings, cross sections, BRs, …

  ∗ Push towards higher orders in the calculations   …

$\mathcal{T}$opics for $\mathcal{N}$MSSM-$\mathcal{WG}$3

- **Obstacles:**

    ◇ large amount of possible signatures

    ◇ large number of parameters

⤳ What would be a typical signature? Expect the unexpected! Which scenarios testable at LHC13? How make sure not to miss anything? How present results/exclusions as function of parameters?

$\mathcal{N}$MSSM $\mathcal{A}$ctivities

- **Kick-off Meeting:** 8 December 2014

  - ∗ Several talks:

    - ◇ Benchmarks: Higgs-to-Higgs decays, (un-)natural NMSSM

    - ◇ NMSSM w/ singlino LSP

    - ◇ NMSSM with light pseudoscalars

  - ∗ 1st Conclusions:

    - ◇ Theory: collection of signatures → experimentalists check for feasibility ⤳ easy benchmarks, at least some restricted set of numbers

    - ◇ dedicated meeting to review status of NMSSM tools (spectrum, decay, production, relic density, ...)

$\mathcal{T}$ools for the $\mathcal{N}$MSSM

•**Tools for the NMSSM:** Ongoing comparison of spectrum generators for singlet extensions

⬦ FlexibleSUSY (C++)

$$\text{http://flexiblesusy.hepforge.org/}$$

⬦ NMSSMCALC (Fortran)

$$\text{http://www.itp.kit.edu/}{\sim}\text{maggie/NMSSMCALC/}$$

⬦ NMSSMTools (Fortran77)

$$\text{http://www.www.th.u-psud..fr/NMHDECAY/nmssmtools.html}$$

⬦ SoftSUSY (C++)

$$\text{http://softsusy.hepforge.org/}$$

⬦ SPheno (Fortran 90)

$$\text{http://spheno.hepforge.org/}$$

◇ **FlexibleSUSY** (C++)

full 2-loop RGEs; full 1-loop corrections to all SUSY masses; 2-loop Higgs corrections $O(\alpha_t\alpha_s + \alpha_b\alpha_s + \alpha_\tau^2 + \alpha_t^2 + \alpha_t\alpha_b + \alpha_b^2)$; Z_3-invariant and Z_3-violating NMSSM; boundary conditions and EWSB output can be customized via a model file

◇ **NMSSMCALC** (Fortran)

Real and complex NMSSM: Higgs boson masses up to $\mathcal{O}(\alpha_t\alpha_s)$, branching ratios including the state-of-the-art HO (QCD, SUSY-QCD&EW-$\Delta_{b,s,\tau}$, SUSY-QCD to $\tilde{q}$ decays) corrections and off-shell decays.

◇ **NMSSMTools** (Fortran77)

2-loop RGEs; computation of the Higgs (up to $\mathcal{O}(\alpha_s(\alpha_b + \alpha_t))$) and sparticle masses and decay ratios, and the dark matter relic density via MicrOmegas. Possible variants are the general NMSSM, the Z_3-invariant NMSSM, constraints at the GUT scale and GMSB. Present experimental constraints are implemented.

◇ **SoftSUSY** (C++)

full 2-loop RGEs; full 1-loop corrections to all SUSY masses; 2-loop Higgs corrections $O(\alpha_t\alpha_s + \alpha_b\alpha_s + \alpha_\tau^2 + \alpha_t^2 + \alpha_t\alpha_b + \alpha_b^2)$; Z_3-invariant and Z_3-violating NMSSM; a number of boundary conditions (mSUGRA, non-universal trilinears, general, ...)

◇ **SPheno** (Fortran 90)

2-loop RGEs with flavour and CP effects; 1-loop corrections to all SUSY masses; 2-loop Higgs corrections beyond $\mathcal{O}(\alpha_s(\alpha_b + \alpha_t))$; independent calculation of decays as well as flavour and precision observables.

$\mathcal{T}$ools for the $\mathcal{N}$MSSM

- **Comments:**

  ⋆ Implementations of new models in `FlexibleSUSY` and `SPheno` based on `SARAH`

  <div align="center">

  `http://sarah.hepforge.org/`

  </div>

  ⋆ All codes: computation of the Higgs and sparticle masses in the Z_3 invariant NMSSM
  Differences: calculations of the DM relic density, possible variants of the NMSSM,
  implementations of experimental constraints
  (LEP, B-physics, g_μ, Higgs data, electroweak precision tests)

  ⋆ Future releases:

  ◇ SUSHI: neutral Higgs production of real NMSSM in gluon fusion (NLO (S)QCD w/ NNLO
  top contrs in top-quark effective theory and EW contrs by light quarks) and b-quark
  annihilation (NNLO QCD in 5F scheme), SLHA input ⇝ linkable to any spectrum generator

  <div align="center">

  `http://sushi.hepforge.org/`

  </div>

  ◇ FeynHiggs: NMSSM version in preparation

  <div align="center">

  `http://feynhiggs.de`

  </div>

$\mathcal{N}$MSSM $\mathcal{S}$ubgroup

- **Creation of NMSSM Subgroup:** no contact persons appointed yet

  `https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGNMSSM`

  ◇ Information on tools & comparison of tools

  ◇ Information on benchmarks

  ◇ Experimental studies

2$\mathcal{HDM}$ $\mathcal{A}$ctivities

- **Two-Higgs Doublet Model in WG3:** not too much progress since last LHCHXSWG meeting

- **Ongoing bechmark study**

Benchmarks for the 2HDM

- **Benchmarks:** H. Haber and O. Stål work on new benchmark approach for
  CP-conserving 2HDM (types),
  parameters defined in "hybrid" basis (mixture of the physical and the Higgs basis).

- **"General scenarios".** defined based on properties of the 125 GeV Higgs boson,
  different mass hierarchies and phenomenology for the remaining 2HDM states.

- **Actual benchmarks:** chosen from parameter space of the general scenarios;
  for these sample cross sections and branching ratios will be provided.

- **Input welcome** from users of benchmarks (mainly experimentalists):
  What is the preferred (maximum) benchmark dimensionality (point, line, plane, ...) etc.?

- **Common meetings with WG1 offshell, HH subgroup:** to provide benchmarks of BSM,
 applies of course to all BSM activities
  also cross-talk with Higgs XS&BR

2$\mathcal{HDM}$ Activities

- **Two-Higgs Doublet Model in WG3:** not too much progress since last LHCHXSWG meeting

- **Planned future activities:** Dedicated 2HDM meetings with the aim to

  ◇ Review tools for 2HDM (production, decay, check for constraints), check/compare tools

  ◇ Identify and provide necessary higher order corrections (and tools)

  ◇ Provide status of allowed parameter regions based on new data and exp&theory constraints

  ◇ Provide scenarios/signatures to be tested at LHC13

  ◇ Provide observables to distinguish 2HDM from other BSM extensions

  ◇ Investigations of 2HDM extensions (CP violation, inert model); what features are common to all versions, what are specific to CP-conserving non-inert version   ....

- **Existing subgroups:**

  ⋆ Neutral Electroweak singlet/2HDM/triplet:
  > ATLAS: Xiaohu Sun, CMS: Raffaele Gerosa

  ⋆ MSSM/2HDM charged Higgs:
  > ATLAS: Steve Sekula, CMS: Martin Flechl

  Theory conveners will be appointed in future

Some Experimental Results for the 2HDM

- **Experimental Results:** There are some experimental results relevant to the 2HDM
  Not all of them include interpretations in the 2HDM parameter space

  ◇ `SusHi,HIGLU,2HDMC,HDECAY` calculations become more and more used in ATLAS/CMS papers

  ◇ $H \to hh \to bb\gamma\gamma$ (ATLAS arXiv:1406.5053)
  Comparison with 2HDM predictions for a choice of parameters in the parameter space.
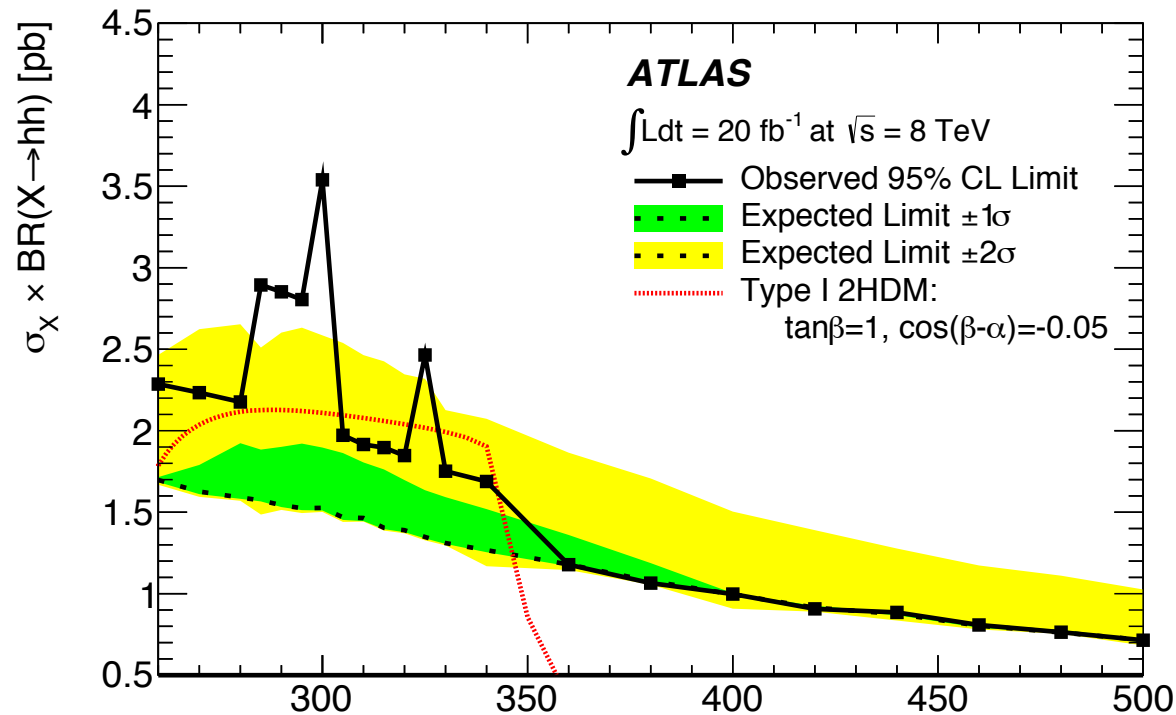
Some Experimental Results for the 2HDM

- **No explicit reference to 2HDM:**

  $H \to hh \to bbbb$ (ATLAS-CONF-2014-005, CMS-PAS-HIG-14-013),

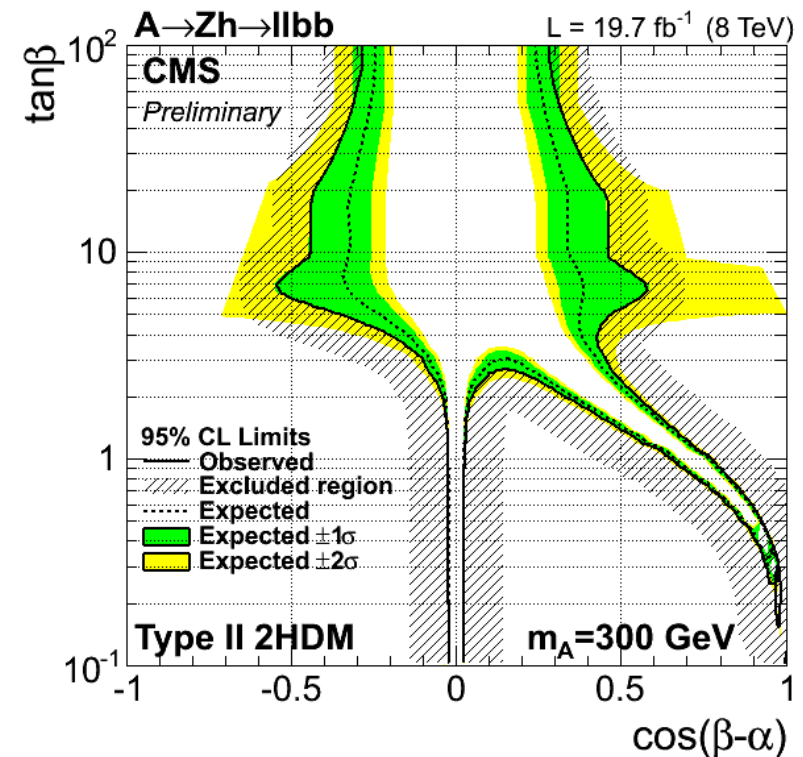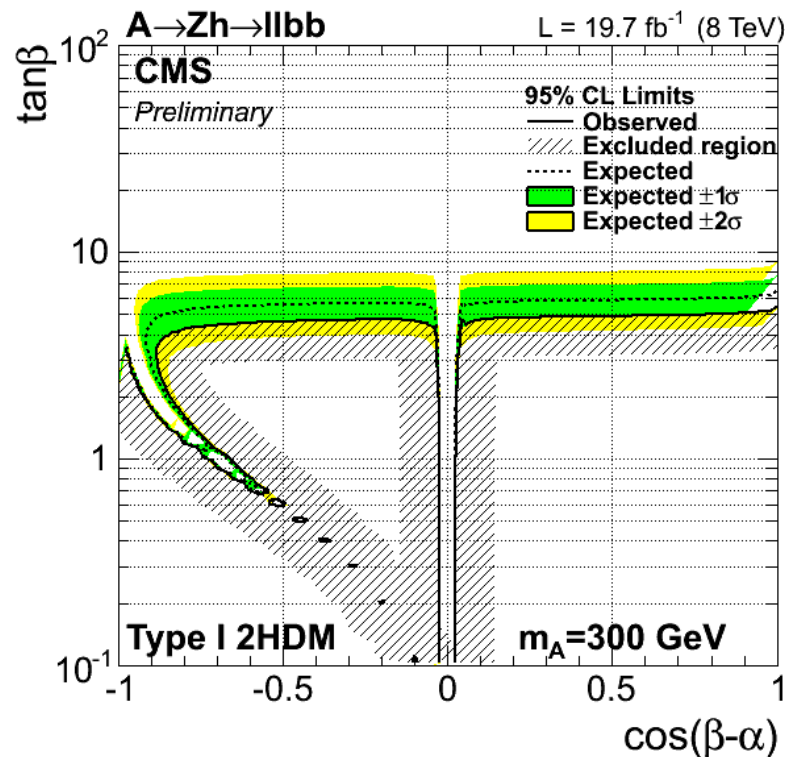 $H/A \to \gamma\gamma$ (ATLAS arXiv:1407.6583, CMS-PAG-HIG-14-006),

  $H^{\pm} \to cs$ (ATLAS arXiv:1302.3694, CMS-PAS-HIG-13-035),

  Higgs cascade: $H \to WH^+ \to WWh \to WWbb$ (ATLAS arXiv:1312.1956)

  ◇ $A \to Zh$ (CMS-PAS-HIG-14-011)

  Interpretation in the 2HDM $\tan\beta - \cos(\beta - \alpha)$ plane

Invitation to give a summary talk on susy2015

Eilam Gross [eilam.work@gmail.com]

Sent: Friday, January 23, 2015 8:41 PM

To: Muehlleitner, Milada Margarete

Dear Prof Muehlleitner
It is my pleasure to invite you to give the summary talk in Susy2015 to be held on planet Mars if you are still alive. Please try to answer within 200 years.
On behalf of the organizing committee
Prof Einstein the third

SUSY 2215

SUSY: THE NEW HOPE

- QUANTUM MECHANICS AND QFT STILL HOLD
- THE ORBITAL COLLIDER STILL SEES NOTHING

THREE CENTURIES OF TRIUMPH FOR SUSY AND STRINGS!

The seasonal trends

Extremely-weeny constrained SUSY

NSFWMSSM

FF3C10ACBA9-MSSM

MSSM retrograde

Anthropic landscaping and trimming it down

The problem of condensed matter: They still don't get it

Strings - The Perpetual Revolution

Number of free parameters: P or NP complete?

Invited seminar

How to ensure your model remains predictability-free

Forum

Is choice moral?

"Every time you choose a path of action, a multiverse is killed"

Special topic

If the universe is not supersymmetric is it necessarily existing?

The perpetual conference

5 Jan - 5 Mar: Chamonix

15 Mar - 30 June: Hainan Island

1 July - 15 Sep: Wailea, Maui

15 Sep - 20 Nov: Jumeirah 1

21 Nov - 24 Dec: Hainan Island

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