



# SUSY, Higgs and dark matter : a tribute to Prof. Rohini Godbole

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LAPTh, Annecy, France

IOP Golden Jubilee Young  
Women Scientists' Meet  
Nov. 13th 2024

Many collaborations with scientists in Europe and in particular France  
Involved or leading 4 CEFIPRA project (indo-french collaboration) and  
Laboratoire International LIA-THEP

Received 'Ordre National du mérite' in 2021

Author of 2 books - on physics

*Theory and phenomenology of sparticles*, M. Drees, R. Godbole, P. Roy, World  
Scientific (2005)

And on Women in Science

*Lilivati's daughters : the women scientists in India*

- SUSY, light gauginos
- Invisible Higgs
- SUSY at LHC
- Dark matter and long-lived particles
- Physics at colliders



# Supersymmetry

- Before the Higgs: will LHC discover the Higgs in all SUSY scenarios?
- SUSY Higgs at the LHC : Effects of light charginos and neutralinos, GB, F. Boudjema, F. Donato, R. Godbole, S. Rosier-Lees, NPB 581 (2000) 3
- After LEP : limits on supersymmetric particles around 100 GeV but such light supersymmetric particles could impact the discovery potential of the Higgs at LHC

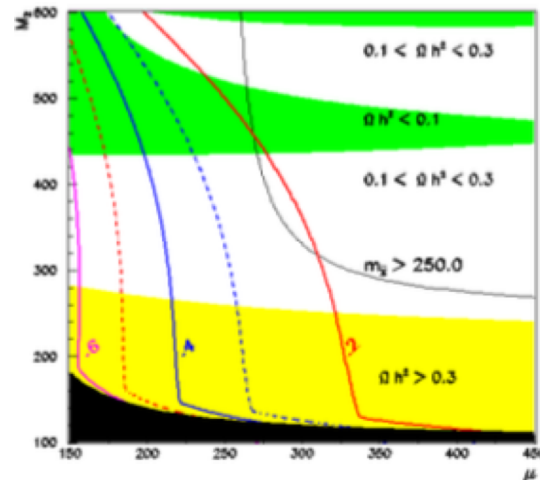


- Charginos/neutralinos have no impact on Higgs production and mild impact on  $h \rightarrow \gamma\gamma$  but invisible decays into neutralinos can make the Higgs disappear in conventional channels— can it be recovered or lead to other signatures?
- If the sparticles are light and suppress the Higgs signal, they could be directly produced at LHC  $\rightarrow$  new physics discovered

- Our original worry was not justified – the Higgs was found – still this paper was important for many reasons
  - Non-unification of gaugino mass
    - Early lower limits on the neutralino mass were quoted assuming SUGRA-type scenario leading to relations amongst gaugino masses at EW scale  $M_1 = M_2 / 2$
    - LEP did not find charginos  $\rightarrow M_2, \mu > \sim 100 \text{ GeV} \rightarrow M_1 > \sim 50 \text{ GeV} \rightarrow M_{\chi_1} > 50 \text{ GeV}$  only if assume gaugino unification
    - Relaxing this common assumption has strong impact on SUSY phenomenology also extends possibilities for Higgs  $\rightarrow$  invisible
  - Higgs invisible (more later)
  - Importance of dark matter
    - Light neutralinos can overclose the universe unless sfermions are light and/or neutralinos annihilate through a resonance
    - *This paper lead to the development of micrOMEGAs, a code to compute dark matter properties in extensions of the standard model*
  - 4 to 1

# Higgs invisible

- If the light neutralino (dark matter) is light enough so that the Higgs can decay invisibly – impact on the Higgs signal (not yet discovered at the time) and importance of measurement of invisible width e.g in Wh
  - *Search for invisible Higgs signals at LHC via associated production with gauge bosons*, R. Godbole, M. Guchait, K. Mazumdar, S. Moretti, DP Roy, PLB 571 (2003) 184
- Large invisible width can be found even after relic density constraint, moreover when sleptons are light, models can be compatible with muon g-2 (anomaly)
  - *The MSSM invisible Higgs in the light of dark matter and g-2*, GB, F. Boudjema, A. Cottrant, R. Godbole, A.Semenov, hep-ph/0106275
  - *Invisible decays of the supersymmetric Higgs and dark matter*, GB, F. Boudjema, R. Godbole, hep-ph/0206311

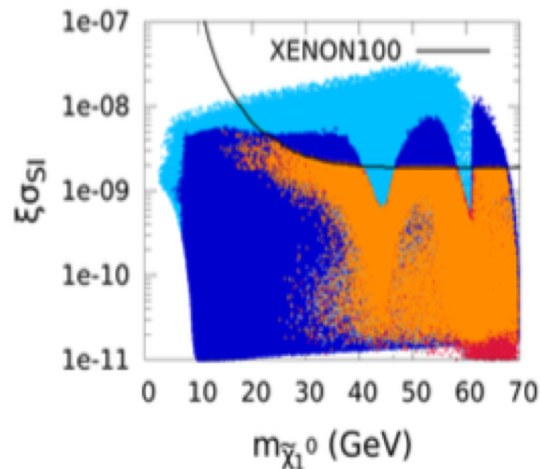


# Higgs invisible

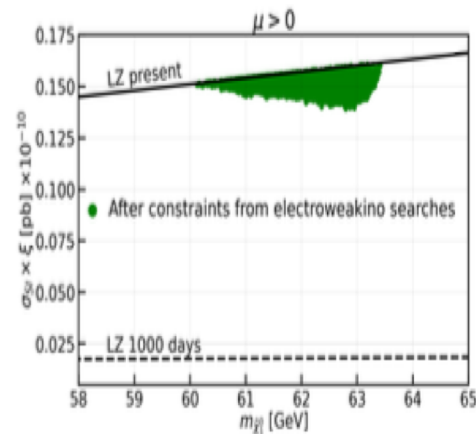
- In 2012 Higgs was found – branching ratios close to predictions of the SM
- Still possible to have  $H \rightarrow$  invisible?
  - *LHC constraints on light neutralino dark matter in the MSSM*, GB, G. Drieu La Rochelle, B. Dumont, R. Godbole, S. Kraml, S. Kulkarni, PLB726 (2013) 773
  - *Invisible decay of the Higgs boson in the context of a thermal and non-thermal relic in the MSSM*, R. Barman, GB, B. Bhattacharjee, R. Godbole, G. Mendiratta, D. Sengupta, PRD95 (2017) 9, 095018
  - *Current bounds and future prospects of light neutralino dark matter in NMSSM*, R. Barman, GB, B. Bhattacharjee, R. Godbole, D. Sengupta, X. Tata, PRD103 (2021) 1, 015029
  - *Status of low mass LSP in SUSY*, R. Barman, GB, R. Godbole, Eur. Phys. JST 229 (2020) 21, 3159.
  - *Is light neutralino dark matter in the phenomenological supersymmetric standard model ruled out?* R Barman, GB, B. Bhattacharjee, R. Godbole, R. Sengupta, PRL 131 (2023) 1, 011802.
  - *Current status of the light neutralino dark matter in the phenomenological MSSM*, R. Barman, GB, B. Bhattacharjee, R. Godbole, R. Sengupta, 2402.07991

# 'Light' neutralino DM

- Has to be dominantly bino and lightest LSP found when relax unification of gaugino mass at high scale (otherwise  $M_{\chi} > 50\text{GeV}$  from LEP)
- Need coupling to Z or Higgs for efficient enough annihilation in early universe (some higgsino component)
  - After first constraints from LHC - SUSY and Higgs invisible,  $h \rightarrow \gamma\gamma$  (loop contribution) - AND direct detection



GB et al, 1308.3735

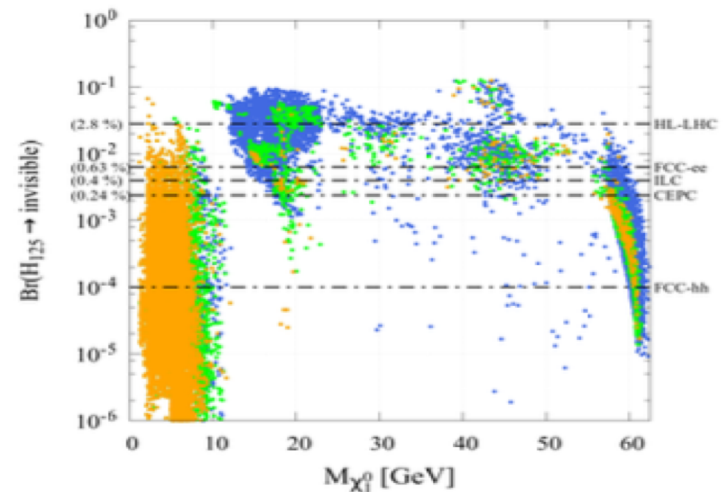
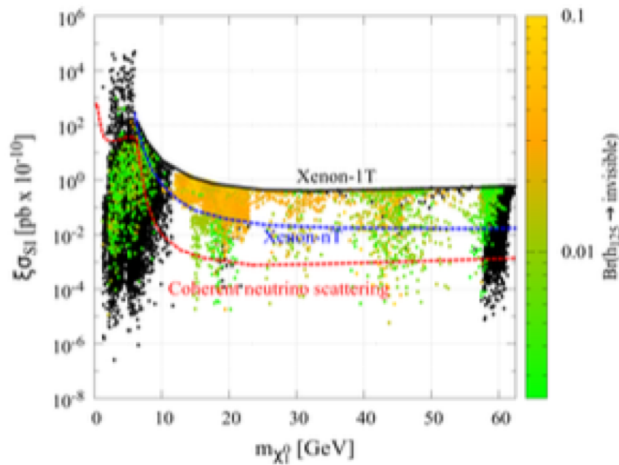


Barman et al, 2402.07991



# Light neutralinos in NMSSM

- Singlet extension of the MSSM (NMSSM) – motivation :  $\mu$  parameter is related to the vev of the singlet, natural to be at EW scale
- Possibility of efficient DM annihilation in the early Universe near resonance of a light scalar/pseudoscalar - DM near GeV allowed
- Hard to probe in direct detection – can be in part probed via invisible Higgs



Barman et al, 2006.07854

# Supersymmetry at LHC



- The LHC found the Higgs – and nothing else
- Still SUSY well motivated – hierarchy problem required not too heavy stop quarks -> hope to be discovered at LHC
- Suggest new searches and new observables to measure stop properties
  - *Probing the flavor violating scalar top quark signal at the LHC*, GB, D. Ghosh, R. Godbole, M. Guchait, D. Sengupta, PRD89 (2014) 015003

$$pp \rightarrow \tilde{t}_1 \tilde{t}_1^* \rightarrow c\bar{c} + 2\chi_1^0 \rightarrow 2\text{jets} + \cancel{p}_T,$$

- A challenge for small mass differences
  - Important since preferred decay when stop relevant for DM co-annihilation
- *Top polarization in Stop production at the LHC*, GB, R. Godbole, L. Hartgring, I. Niessen, JHEP 05 (2013) 167; *Top polarization in sbottom decays at the LHC*, GB, R. Godbole, S. Kraml, S. Kulkarni, 1304.2987
  - Top polarization sensitive to mixing stop-neutralino and mass difference
- What's left of SUSY after LHC Run 1
  - *Light stop in the MSSM after Run 1*, GB, D. Ghosh, R. Godbole, S. Kulkarni, JHEP 09 (2015) 214
    - Identify parameter space and suggest complementary searches (associated production with Higgs, heavy stop production, heavy Higgs)

# Dark Matter and LLP

- Proposing a valid DM candidate is one of the main motivation for physics beyond the SM
- Model motivated by neutrino masses:
  - *WIMP and FIMP dark matter in singlet-triplet fermionic model*, GB, S. Choubey, R. Godbole, S. Khan, M. Mitra, A. Roy, JHEP 11(2022) 133.
  - When singlet is DM – triplet can be long-lived – possibilities to discover in MATHUSLA also disappearing tracks
- Dark matter in the extended Georgi Machacek model with a singlet
  - *Revisiting the decoupling limit of the Georgi-Machacek model with a scalar singlet*, GB, J. Dutta, R. Godbole, S. Kraml, M. Mitra, R. Padhan, A. Roy, JHEP 2410 (2024) 058
  - New neutral charged and doubly charged scalars – several new particles around 100 GeV – collider probe at HL-LHC
- *A novel signatures for long-lived particles at the LHC*, S. Banerjee, GB, B. Bhattacharjee, F. Boudjema, R. Godbole , S. Mukerjee– PRD98 (2018) 11, 115026

# Collider physics and WG: Exp/TH



Les Houches 2013

CERN Cafeteria 2024



# Collider physics and WG: Exp/TH

- Strong involvement in physics at colliders at international level
  - *Physics with  $e^+e^-$  linear colliders* , E. Accomando et al, Phys. Rept 299 (1998) 1
  - *ILC Linear Collider Design Report* (2007)
  - *Physics Interplay of the LHC and the ILC*, G. Weiglein et al (2004)
  - *From the LHC to future Colliders*, A. De Roeck et al (R. Godbole); EPJC 66 (2010) 52
- Interactions Theory/experiments
  - *Les Houches Physics at TeV colliders Workshop* (all reports from 1999 to 2013)
  - *SUSY Les Houches Accord: Interfacing SUSY spectrum calculators, decay packages, and event generators*, P. Skands et al, JHEP07 (2004) 036; *SUSY Les Houches Accord 2*, B. Allanach et al, Comp. Phys. Comm. 180 (2009) 8.
  - *Supersymmetry Parameter analysis: SPA convention and project*, J. Aguilar-Saavedra (2005) et al, EPJC 46 (2006) 43.
  - *CP studies and non-standard physics* : CERN Yellow Report (2006)
  - *On the presentation of the LHC Higgs results*, Workshop on the Likelihoods for the LHC searches, F. Boudjema et al, 1307.5865

Thanks for your major contributions to particle physics and your commitment to support women in science - We will miss you



Les Houches, 2013