Sensitivity to BSM fermions from Higgs precision studies

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A. Freitas and Q. Song,
JHEP 01 (2024) 137 [arXiv:2308.13030]

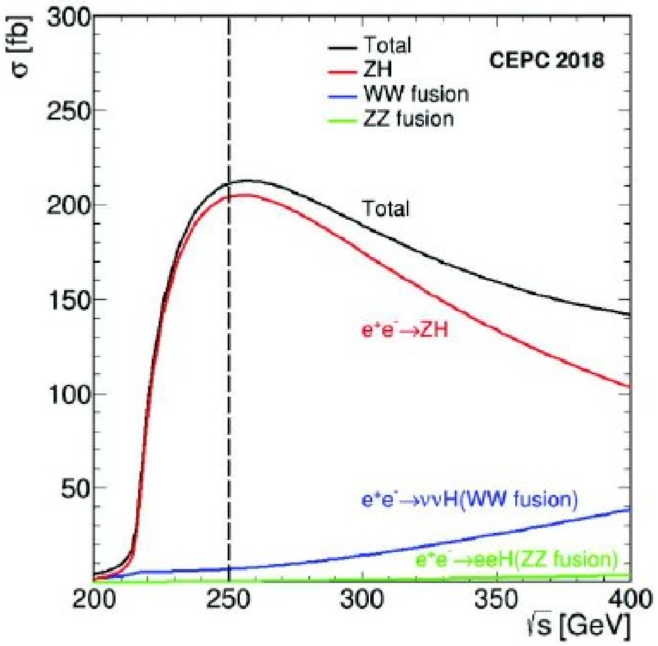
Symmetry magazine (Sandbox studio, Ana Kova)

Introduction

- Precision Higgs studies are sensitive to BSM physics

- Expected precision for ee→HZ:

ILC	1.2%	[1903.01629]
CEPC	0.5%	[1811.10545]
FCC-ee	0.4%	[EPJ ST 228, 261]



- Sensitivity to BSM mass scales:

LO: $\delta \sim (E_{CM}/m_{BSM})^2$

$\delta \sim 1\% \Rightarrow m_{BSM} \sim 2.5$ TeV

NLO: $\delta \sim g^2/(4\pi)\,(E_{CM}/m_{BSM})^2$

$\delta \sim 1\% \Rightarrow m_{BSM} \sim 700$ GeV

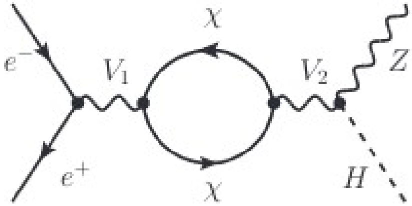
→ **within reach of LHC!**

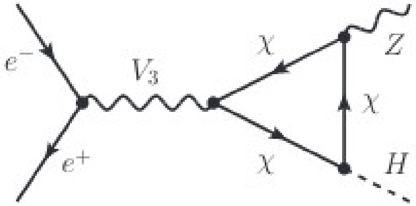
Introduction

- Existing studies of Higgs Factory—LHC complementarity:
  - Singlet scalar model [Ellis et al., 1910.11775]
  - Two-Higgs doublet models [Chen, Han, Su, Su, Wu, 1808.02037] [+ Li, 1912.01431]
  - Composite Higgs models [Thamm, Torre, Wulzer, 1502.01701]
  - SUSY [Bahl, Bechtle, Heinemeyer, Liebler, Stefaniak, Weiglein, 2005.14536]
  - Fermionic DM models [Bi, Xiang, Yin, Yu, 1707.03094] [+ Wang, 1711.05622]
- **This work:** broad class of fermionic dark sector models
  - Lightest fermion can (but need not) be DM
  - Larger parameter region and wider set of (HL-)LHC constraints than prev. work

Observables and constraints

- Cross section for *ee→HZ*





- Oblique S/T parameters from LEP

- Recast (HL-)LHC chargino/neutralino searches

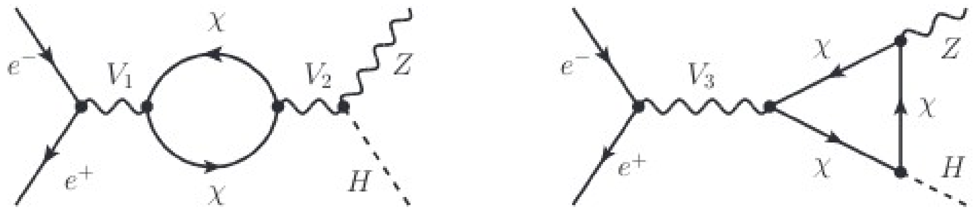
$$q\bar{q}' \to W^{*\pm} \to \chi^{\pm}(\to \chi_l^0 W^{*\pm}) + \chi^0(\to \chi_l^0 + Z^*/H),$$
$$q\bar{q}' \to Z^* \to \chi^0(\to \chi_l^0 + Z^*/H) + \chi^0(\to \chi_l^0 + Z^*/H)$$
$$q\bar{q}' \to Z^* \to \chi^{\pm}(\to \chi_l^0 W^{\pm *}) + \chi^{\mp}(\to \chi_l^0 W^{\mp *}),$$

For stable (unstable) lightest *χ*:
LHC searches assuming R-parity conservation (violation)

- R_γ = BR[H→γγ] (where applicable)

Models

- Two fermion multiplets for Yukawa coupling with Higgs



- Dirac singlet-doublet model (DSDM):

Dirac singlet χ_S + Dirac doublet $\chi_D = (\chi_D^+, \chi_D^0)$

$$\mathcal{L}_{\text{DSDM}} \supset -m_D \overline{\chi}_D \chi_D - m_S \overline{\chi}_S \chi_S - (y \overline{\chi}_D \chi_S H + \text{h.c})$$

χ_S and χ_D^0 mix ⇒ mass eigenstates $\chi_{l,h}^0$

- Majorana singlet-doublet model (MSDM): Majorana singlet χ_S

$$\mathcal{L}_{\text{MSDM}} \supset -m_D \overline{\chi}_D \chi_D - \frac{1}{2} m_S \overline{\chi}_S \chi_S - (y \overline{\chi}_D \chi_S H + \text{h.c}).$$

χ_S and χ_D^0 mix ⇒ Majorana mass eigenstates $\chi_{l,m,h}^0$:

Models

- Dirac doublet-triplet models:

a) triplet hypercharge −1 (DDTM1)

$$\chi_D = \begin{pmatrix} \chi_D^0 \\ \chi_D^- \end{pmatrix}, \qquad \chi_T = \begin{pmatrix} \chi_T^-/\sqrt{2} & \chi_T^0 \\ \chi_T^{--} & -\chi_T^-/\sqrt{2} \end{pmatrix}$$

mass eigenstates $\chi^0_{l,h}$; $\chi^{\pm}_{l,h}$; $\chi_T^{\pm\pm}$

b) triplet hypercharge 0 (DDTM0)

$$\chi_D = \begin{pmatrix} \chi_D^+ \\ \chi_D^0 \end{pmatrix}, \qquad \chi_T = \begin{pmatrix} \chi_T^0/\sqrt{2} & \chi_T^+ \\ \chi_T^{\prime -} & -\chi_T^0/\sqrt{2} \end{pmatrix}$$

mass eigenstates $\chi^0_{l,h}$; $\chi^{\pm}_{l,m,h}$

- Majorana doublet-triplet model (MDTM):

Similar to DDTM0, but χ_T is a Majorana field

mass eigenstates $\chi^{\pm}_{l,h}$; $\chi^0_{l,m,h}$ (Majorana)

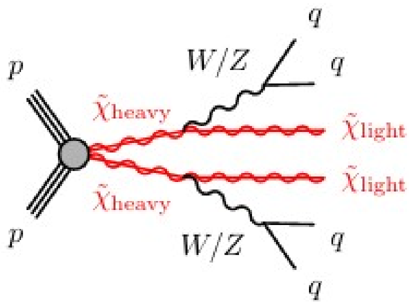
Most sensitive LHC studies

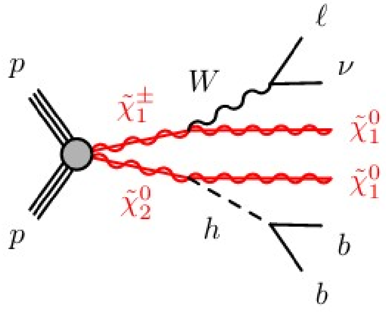
Stable lightest fermion:

- Large mass difference (Bino+Wino-like):

  Current: ATLAS [2108.07586]
  (139 fb^{-1}, fully hadronic W/Z decays)

  HL-LHC: ATLAS [ATL-PHYS-PUB-2018-048]
  (2 b-jets + 1 lepton)





- Small mass difference (Higgsino-like):

  Diffractive chargino prod. with soft-lepton final states
  $pp \rightarrow p(\gamma\gamma \rightarrow \chi^+\chi^-)p$ [Zhou, Liu, 2208.10406]

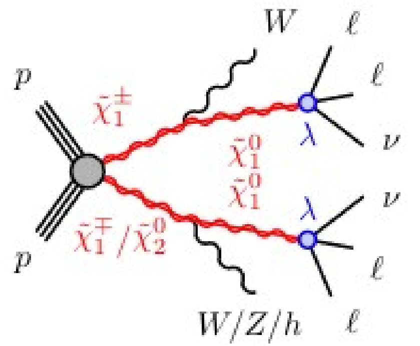
Most sensitive LHC studies

Unstable lightest fermion:

→ consider two scenarios

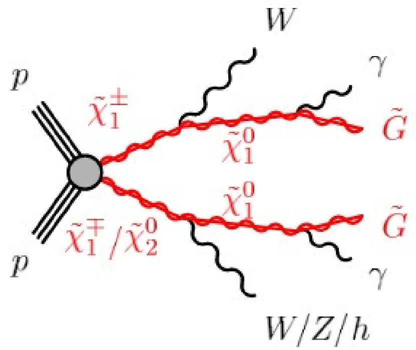
- Leptonic χ_l^0 decays

  SUSY search with LLE R-parity violation [ATLAS, 2103.11684] (139 fb^{-1})



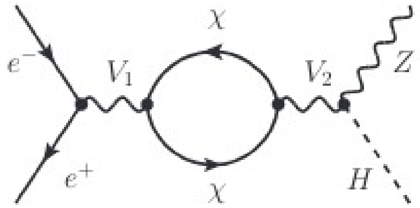
- χ_l^0 decays with photons

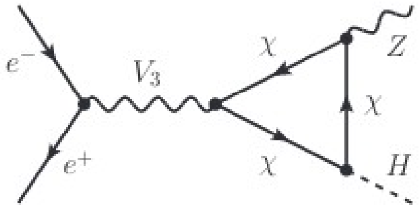
  Search for gauge-mediated SUSY [ATLAS, 1802.03158] (36 fb^{-1})



Calculational methods

- Amplitude generation with
  `FeynArts 3.11` [Hahn., hep-ph/0012260]
  (in-house BSM model files)





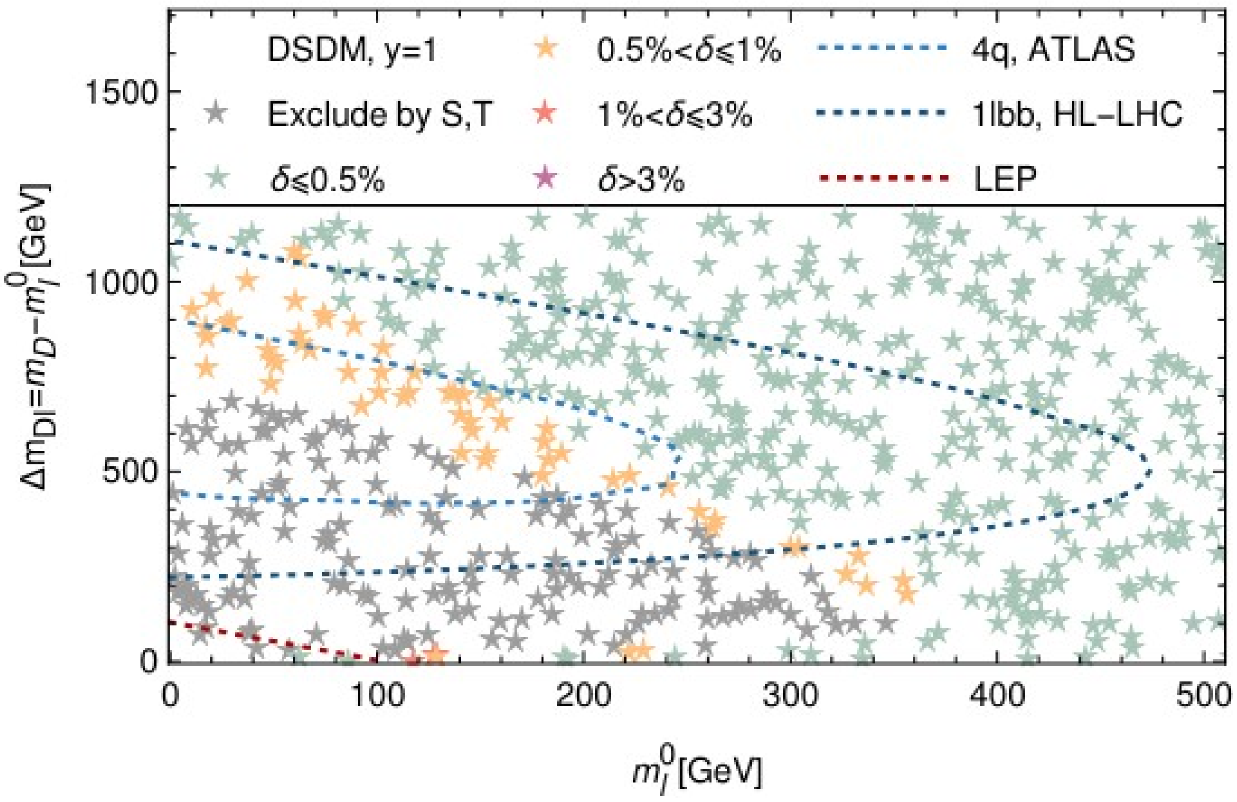
- Computation of "observables" (σ_{HZ}, S/T, R_γ) with
  `FeynCalc 9` [Shtabovenko, Mertig, Orellana. 2001.04407]
  and in-house Mathematica code

- Recast of (HL-)LHC bounds by inter-/extrapolation of published exclusion contours or cross-section limits, compared to model cross-sections

  [limited accuracy, but sufficient for sufficient for present purposes]

Results: stable Dirac singlet-doublet model

Plot for $m_D > m_S$ $\Rightarrow$ $m_h{}^0 \sim m^{\pm} \gg m_l{}^0$ (similar to bino-Higgsino system)



$$\delta = \left| \frac{\sigma_{\rm ZH}^{\rm FDS} - \sigma_{\rm ZH}^{\rm SM}}{\sigma_{\rm ZH}^{\rm SM}} \right|$$

ILC	1.2%
CEPC	0.5%
FCC-ee	0.4%

- strong bounds from oblique parameters
- significant deviations in *ee*→*HZ* unlikely

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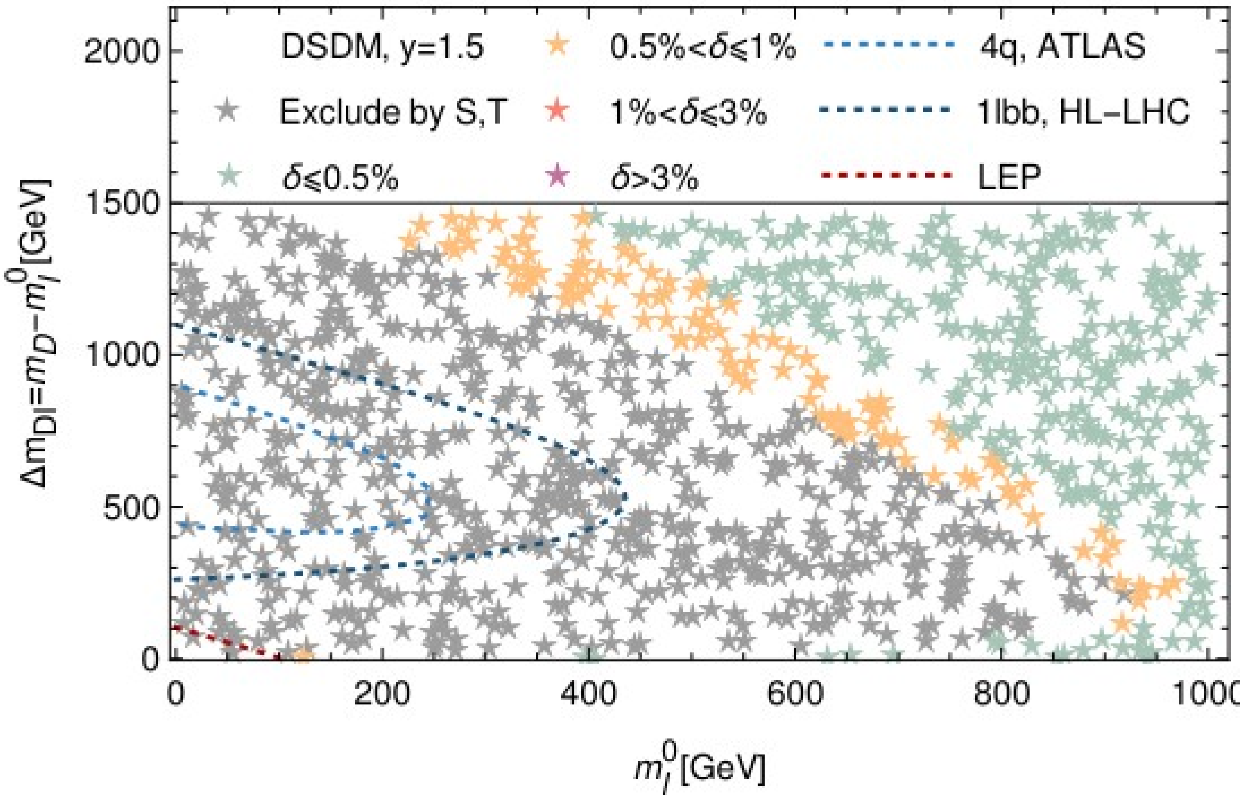

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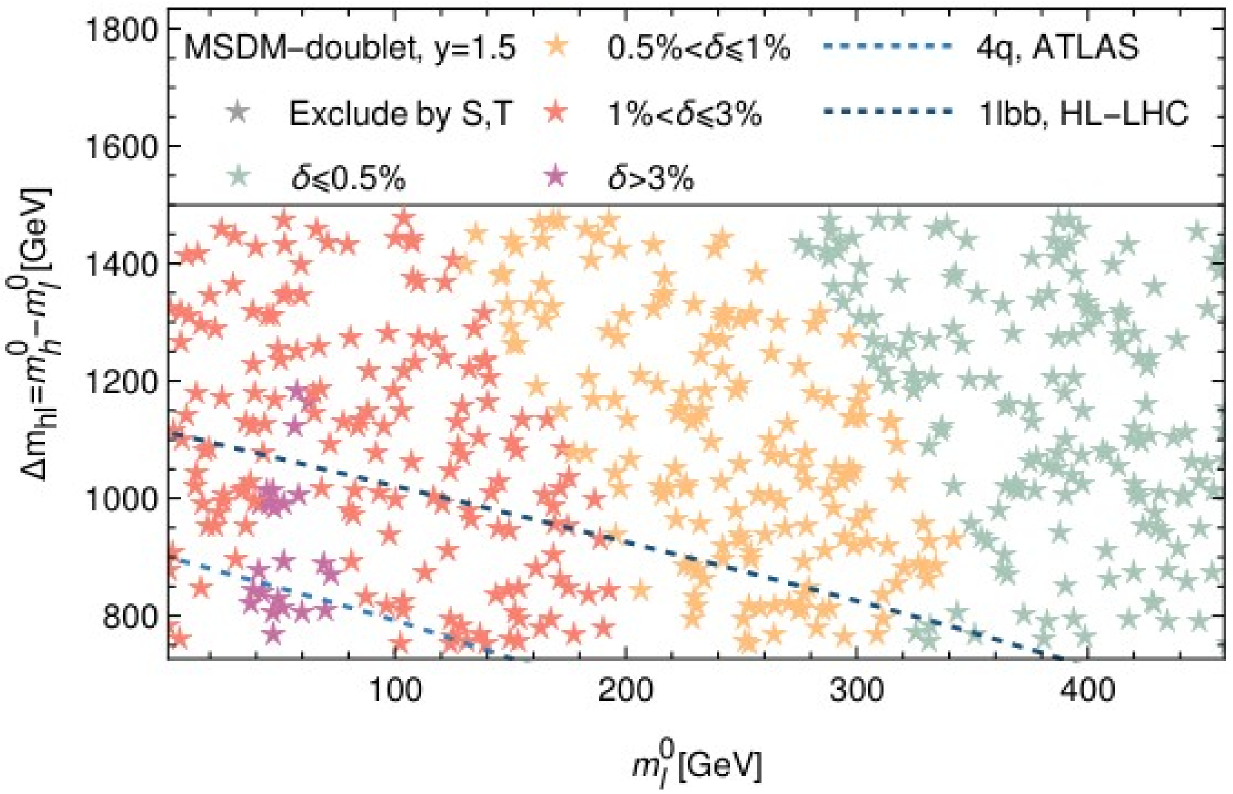


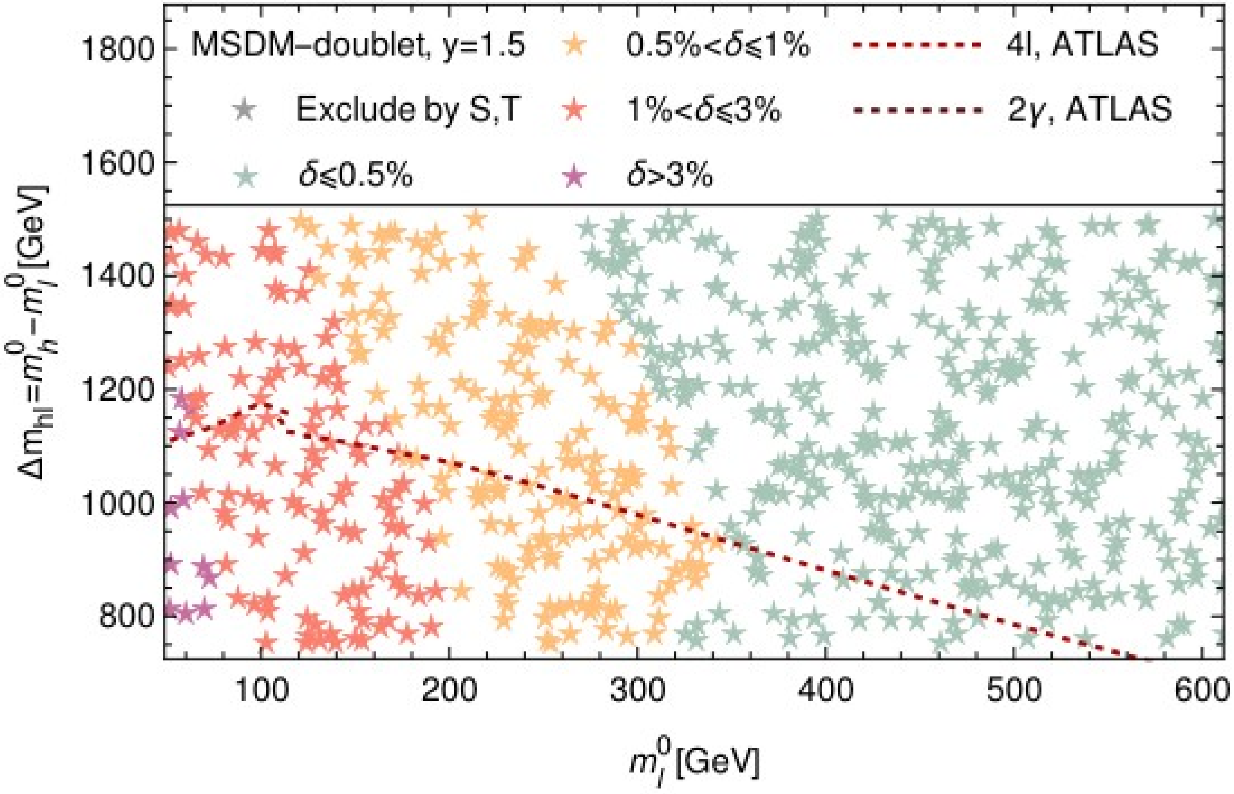
$$\delta = \left| \frac{\sigma_{ZH}^{FDS} - \sigma_{ZH}^{SM}}{\sigma_{ZH}^{SM}} \right|$$

ILC	1.2%
CEPC	0.5%
FCC-ee	0.4%

- no relevant bounds from oblique parameters
- significant deviations in *ee→HZ* beyond (HL-)LHC constraints

Results: decaying Majorana singlet-doublet model

Plot for $m_D > m_S \quad \Rightarrow \; m_h{}^0 \sim m^{\pm} \gg m_l{}^0$ (similar to bino-Higgsino system)



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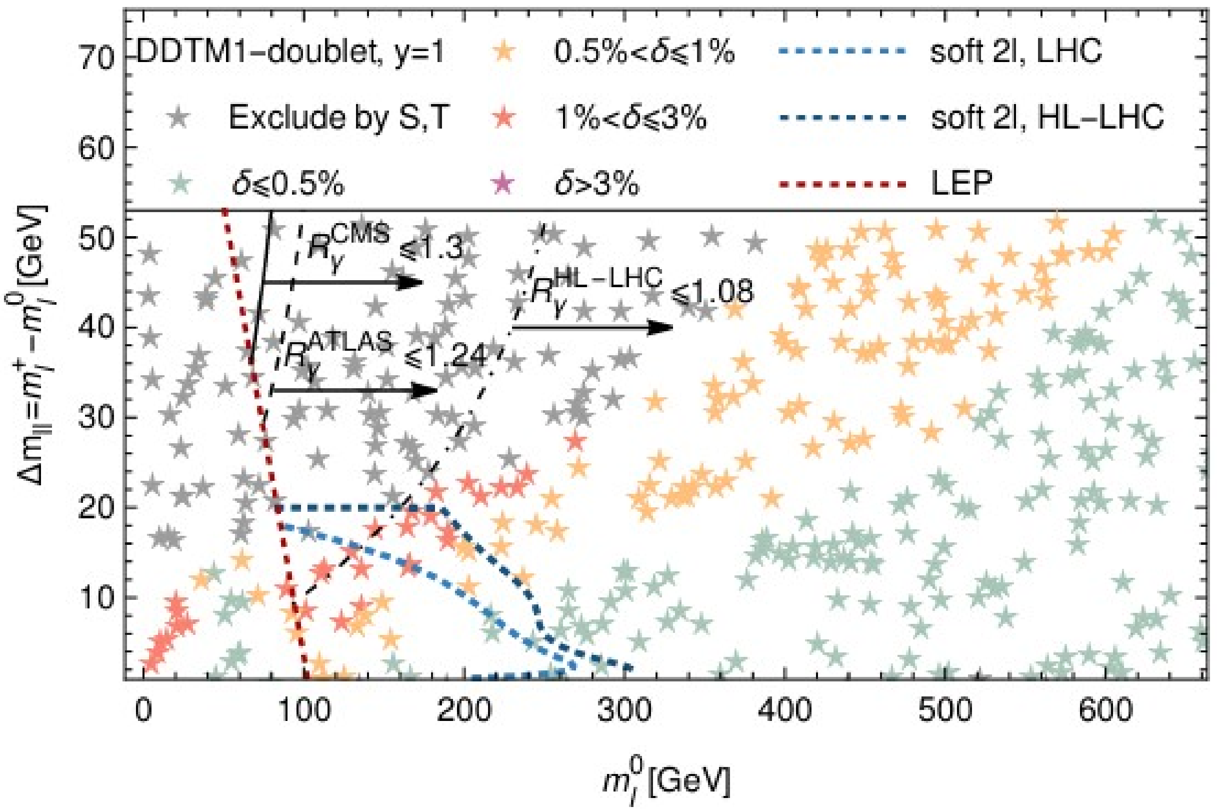
ILC	1.2%
CEPC	0.5%
FCC-ee	0.4%

- stronger (HL-)LHC bounds for leptonic decays
- photonic decay study has small statistics (36 fb^{-1})

Results: stable Dirac doublet-triplet model with *Y*=-1

Plot for $m_D > m_T \quad \Rightarrow \; {m_h}^{0,\pm,\pm\pm} \gg {m_l}^{0,\pm}$ (similar Higgsino with decoupl. wino)



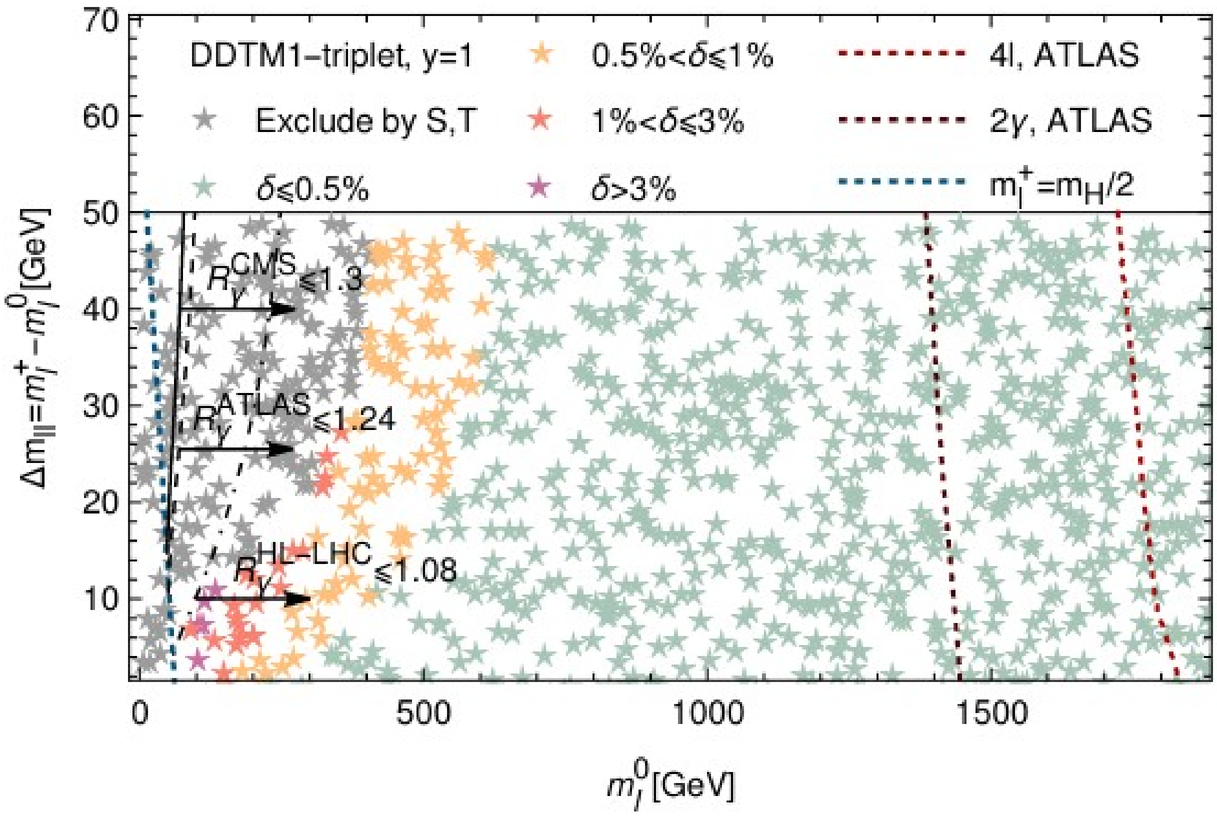
$$\delta = \left| \frac{\sigma_{ZH}^{FDS} - \sigma_{ZH}^{SM}}{\sigma_{ZH}^{SM}} \right|$$

ILC	1.2%
CEPC	0.5%
FCC-ee	0.4%

- significant bounds from oblique parameters
- direct (HL-)LHC searches for soft final states

Results: decaying Dirac doublet-triplet model (*Y*=-1)

Plot for $m_D > m_T \quad \Rightarrow \quad m_h^{0,\pm,\pm\pm} \gg m_l^{0,\pm}$ (similar Higgsino with decoupl. wino)



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ILC	1.2%
CEPC	0.5%
FCC-ee	0.4%

- direct (HL-)LHC searches much stronger, using harder leptons from m_l^0 decay

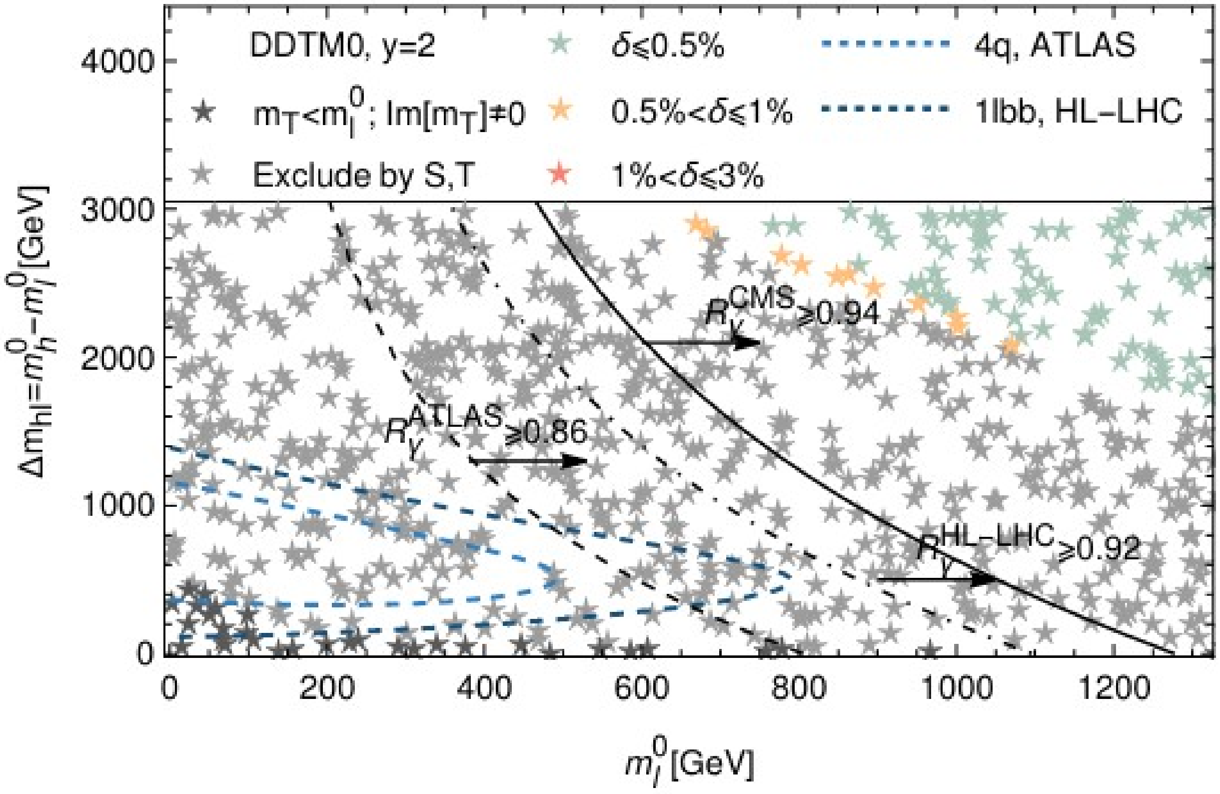
Conclusions

- Minimal dark-sector fermion models modify Higgs physics at NLO
  - Consider SU(2) singlets/doublet/triplets and Dirac/Majorana fields
- Complementary probes at LHC (direct) and Higgs factories (indirect, 1-loop)
  - %-level corrections for σ_{HZ} in large parameter regions; $\mathcal{O}$(TeV) masses
  - Strong constraints from oblique parameters for most Dirac models
- New parameter space probed by Higgs factories (beyond current and projected HL-LHC bounds)
  - in particular for Majorana models
  - also in regions of small Δm
- Oblique parameter measurements at FCC-ee could provide stronger bounds for some models, help with model discrimination (tbd)

Backup

Results: stable Dirac doublet-triplet model with *Y*=0

Plot for $m_T > m_D$ $\Rightarrow$ $m_h^{0,\pm} \gg m_l^{0,\pm}$ (similar to wino-Higgsino system)



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Results: stable Majorana doublet-triplet model

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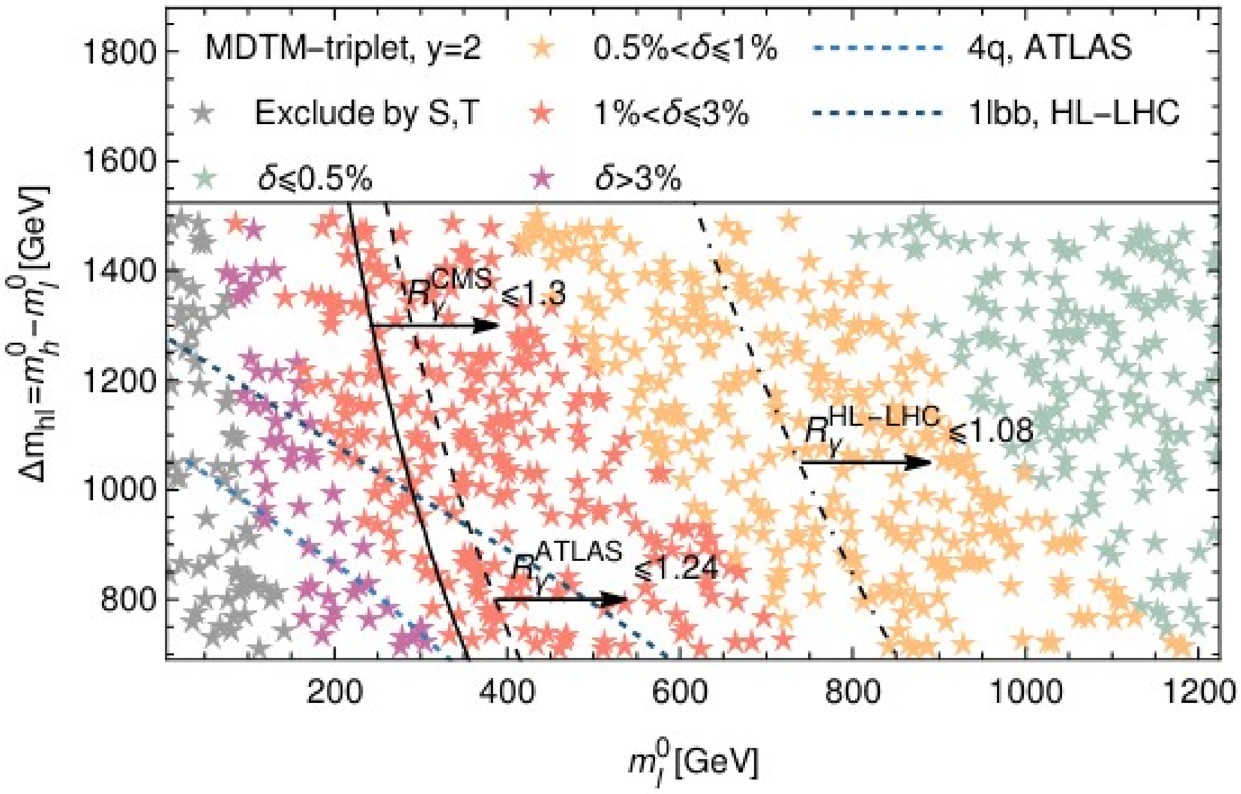

$$\delta = \left| \frac{\sigma_{ZH}^{FDS} - \sigma_{ZH}^{SM}}{\sigma_{ZH}^{SM}} \right|$$

ILC	1.2%
CEPC	0.5%
FCC-ee	0.4%

- most important LHC constraints from R_γ
- significant deviations in $ee \to HZ$ strongly bounded