Probing long lived particles with SModelS v2

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LPSC Grenoble & LAPTh Annecy

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On behalf of the SModelS collaboration :
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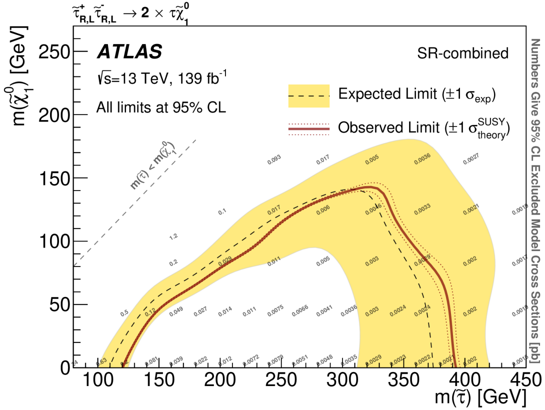
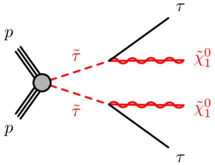
Overview

Results from LHC new physics searches

$2\tau + \not{E}_T$ (ATLAS-SUSY-2018-04)

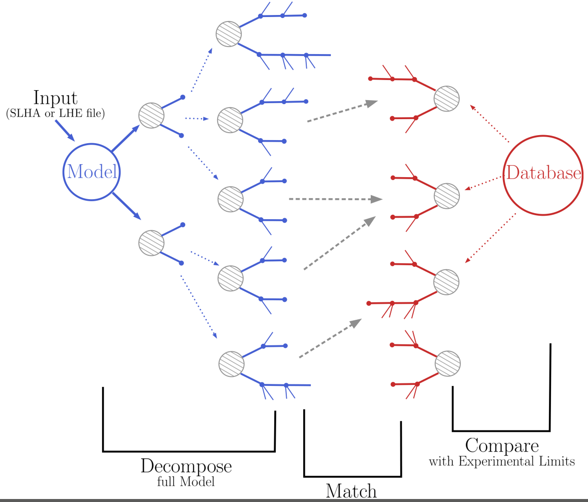


- Usage of simplified models
- Only 2 or 3 new particles and simple decays
- $\approx$ 100 papers for different final states
- How to constrain a full model with many particles and parameters ?



SModelS working principle

- Based on a general procedure to decompose BSM collider signatures featuring a $\mathbb{Z}_2$-like symmetry into simplified-model topologies
- Large database of simplified-model results (currently 46 ATLAS & 50 CMS searches)
- Generally applicable, also beyond SUSY, provided signal selection acceptances remain $\pm$ the same
- Very fast b/c no need for MC simulation
- simultaneous treatment of prompt and LLP constraints



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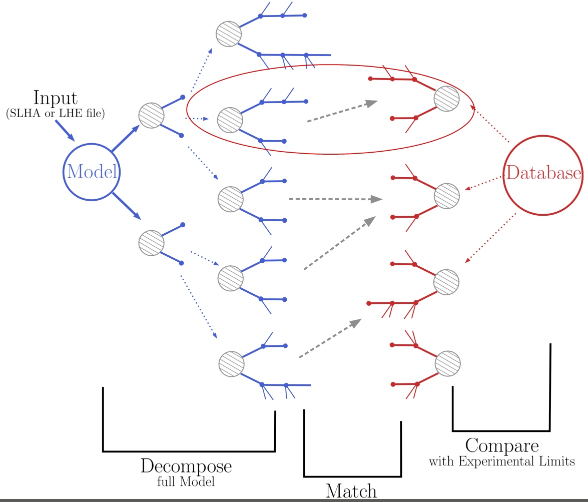
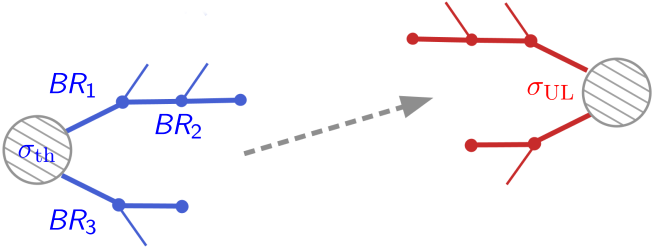
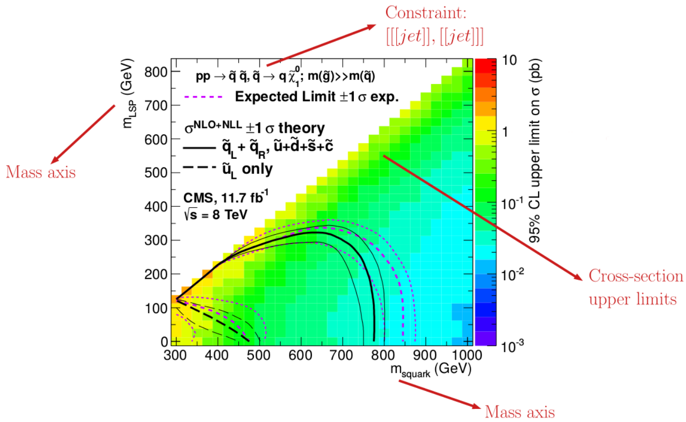


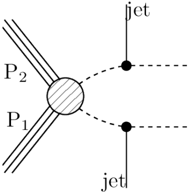
Matching



$\sigma_{\rm th} \times BR_1 \times BR_2 \times BR_3(\times A \times \epsilon)$ to compare with $\sigma_{\rm UL}$

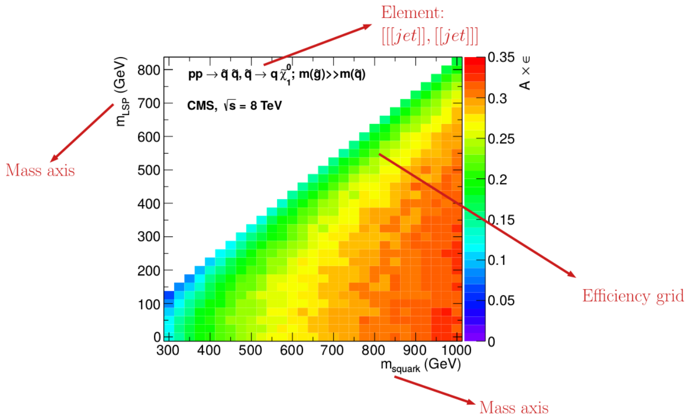
Upper limit map (UL)



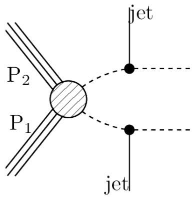


- Constrains $\sigma \times \prod_j BR_j$ per topology
- Only binary decision : excluded or not

Efficiency map (EM)



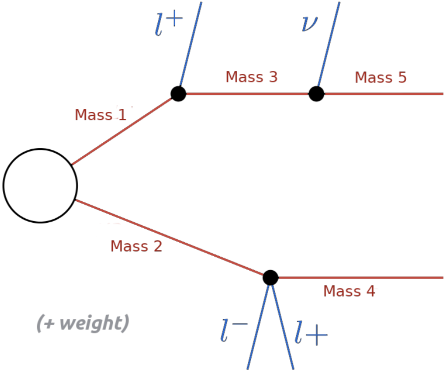
one EM/topology for each signal region



- Constrains $\sum_i A_i \epsilon_i \times \sigma_i \times \prod_j BR_j$ per signal region
- Can sum contributions from several topologies
- Can compute a likelihood (exclusion confidence level)

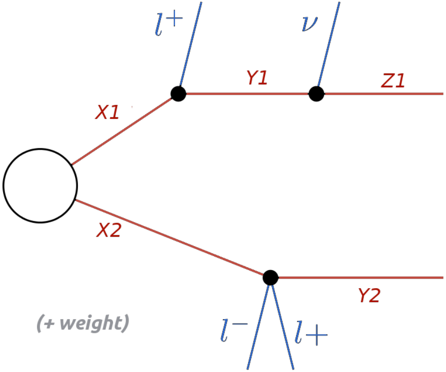
SModelS v1.2.4

- Database
  - 40 ATLAS analyses (5 JSON likelihoods)
  - 46 CMS analyses (1 covariance matrix)
  - of which 3 LLP results
  - 250 ULs and 1700 EMs
- Simplified model description
  - vertices and outgoing particles
  - BSM masses
  - element weight ($\sigma \times$BR)

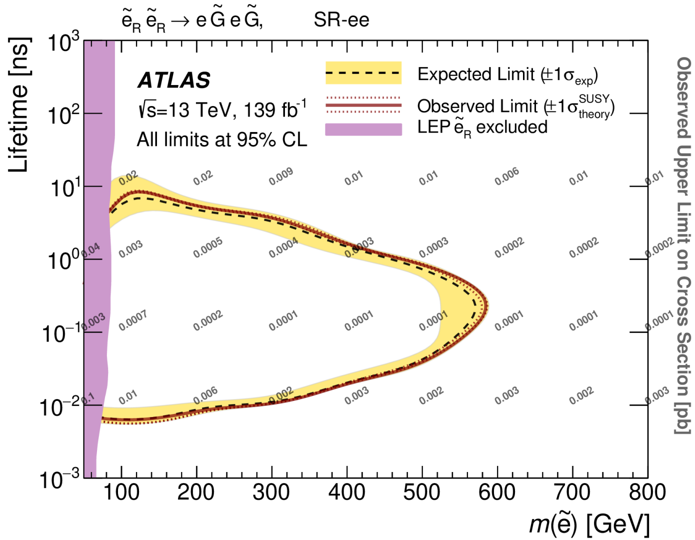


SModelS v2.x

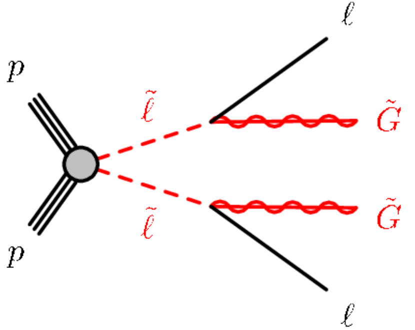
- Major extension of simplified models description
  - vertices and outgoing particles
  - BSM masses + width
  - element weight ($\sigma \times$BR)
  - + particle object (quantum numbers of intermediate BSM states)
    $\Rightarrow$ width and spin-dependent results
    $\Rightarrow$ can treat a larger variety of LLP results (HSCP, disappearing tracks, displaced vertices, ...)



Width-dependent results



ATLAS-SUSY-2018-14



New results in SModelS v2.1.0

- CMS-SUS-19-009 *Analyses at full Run 2 luminosity : 1l + MET
- ATLAS-SUSY-2018-22 * : jets + MET
- ATLAS-SUSY-2016-24 : 2 or 3l
- CMS-EXO-19-001 * : nonprompt jets + MET
- ATLAS-SUSY-2016-08 : displaced vertices + MET
- ATLAS-SUSY-2016-32 : HSCPs, R-hadrons
- CMS-EXO-13-006 : HSPCs (+width dependence)
- ATLAS-SUSY-2016-06 † : disappearing tracks
- CMS-EXO-19-010 * : disappearing tracks
- ATLAS-SUSY-2018-14 * : displaced leptons

∗. Analyses at full Run 2 luminosity

†. Efficiency maps provided by A. Belyaev, F. Rojas-Abbate (2008.08581)

The scotogenic model

Ernest Ma, Phys.Rev.D73 :077301,2006 [arXiv]

- Standard Model extended with
  - an inert Higgs doublet
  - and right-handed neutrinos

$$\begin{pmatrix} H_1^\pm \\ H_1^0 \end{pmatrix}, \begin{pmatrix} H_2^\pm \\ H_2^0 \end{pmatrix}, \begin{pmatrix} N_1 \\ N_2 \\ N_3 \end{pmatrix}$$

  - odd under a $\mathbb{Z}_2$-symmetry

Field	Generations	$\mathrm{SU}(3)_\mathrm{c}$	$\mathrm{SU}(2)_\mathrm{L}$	$\mathrm{U}(1)_\mathrm{Y}$	$\mathbb{Z}_2$
ℓ_L	3	**1**	**2**	$-1/2$	$+$
e_R	3	**1**	**1**	-1	$+$
H_1	1	**1**	**2**	$1/2$	$+$
H_2	1	**1**	**2**	$1/2$	$-$
N	3	**1**	**1**	0	$-$

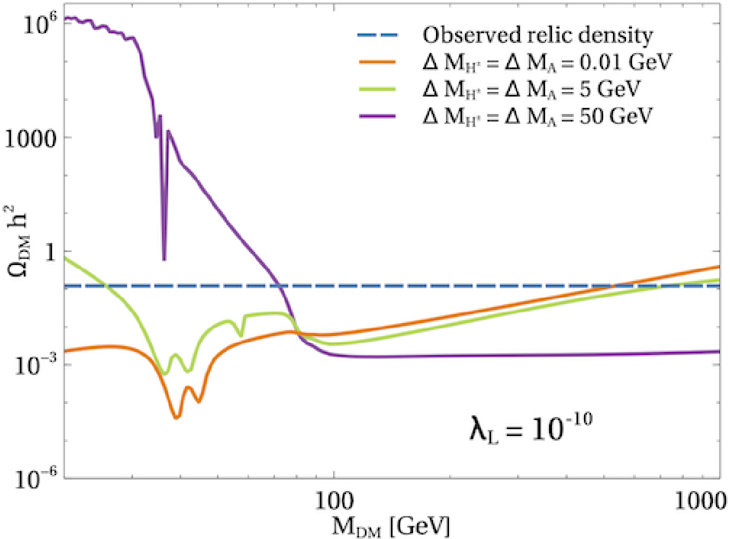
$$H_1 \xrightarrow{\mathbb{Z}_2} H_1$$

$$H_2 \xrightarrow{\mathbb{Z}_2} -H_2$$

- radiative neutrino masses
- provides different DM candidates
  - different production mechanisms (freeze-in, freeze-out, ...)
  - probe with the appropriate LHC signatures (prompt, long-lived, ...)

IDM/scotogenic with scalar DM

D.Bora, A.Gupta [arXiv]

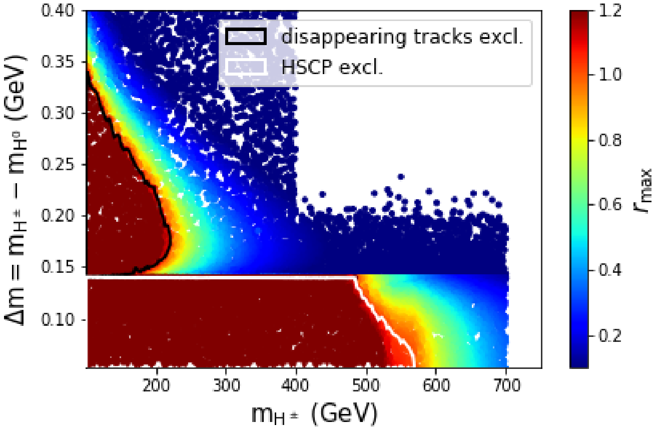


IDM/scotogenic with scalar DM

- random scan over
  $m_{H^\pm}, m_{H^0}, m_{A^0}$
  $\lambda_2 = 0.1, \lambda_L = 10^{-10}$
- cross-sections with micrOMEGAs
- S and T constraints
- DM relic density as upper bound
- direct detection limits rescaled according to relic density
- $H^\pm$ decay into pions

$$\Gamma_{\pi^\pm} = \frac{g^4 f_\pi^2}{64\pi m_W^4} \Delta m^2 \sqrt{\Delta m^2 - m_{\pi^+}^2}$$

A. Belyaev et al [arXiv]



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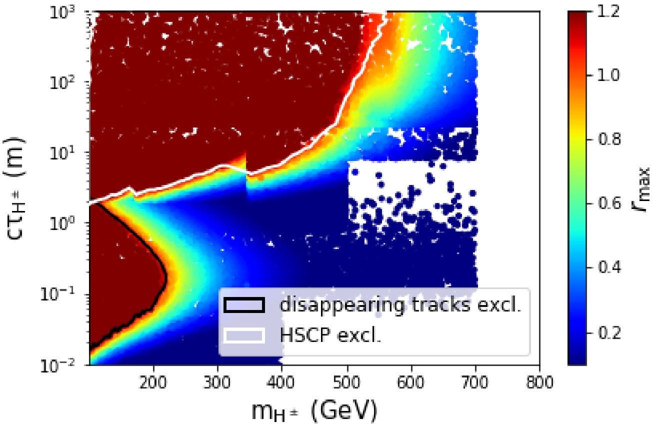


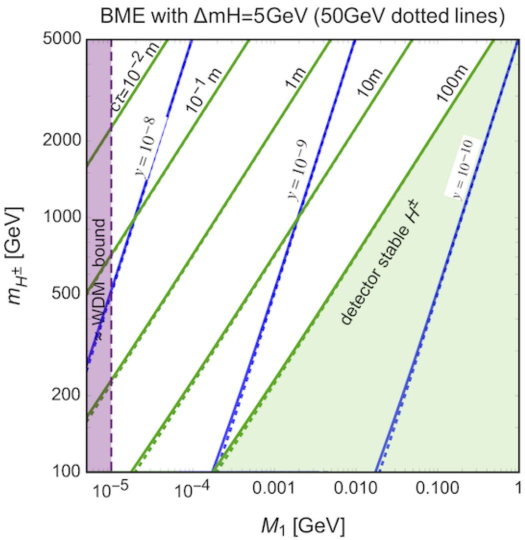
Scotogenic with fermionic DM

- RH neutrino N_1 as DM candidate
- small DM mass and small coupling
- freeze-in production of DM

$$\Omega_{N_1} h^2 \approx 0.12 \left(\frac{M_1}{10\,\mathrm{keV}}\right) \left(\frac{100\,\mathrm{GeV}}{m_{H_2}}\right) \left(\frac{y_1}{2\times 10^{-9}}\right)^2$$

- $m_{A^0/H^0} > m_{H^\pm} > m_{N_1}$
- $H^\pm$ is long-lived and decays to $l^\pm N_1$

A. Hessler et al [arXiv]
E. Molinaro et al [arXiv]



Scotogenic with fermionic DM

- grid IDM scan over m_{H^+} with micrOMEGAs
  $\Delta m = m_{H^0,A^0} - m_{H^\pm}$ fixed
  $\lambda_2 = 10^{-2}, \lambda_L = 10^{-2}$
- then scan over m_{N_1}

$$\Gamma_{H^\pm \to N_1 e^\pm} = \frac{m_{H^\pm}|Y^\nu_{e1}|^2}{16\pi}\left(1 - \frac{m^2_{N_1}}{m^2_{H^\pm}}\right)^2$$

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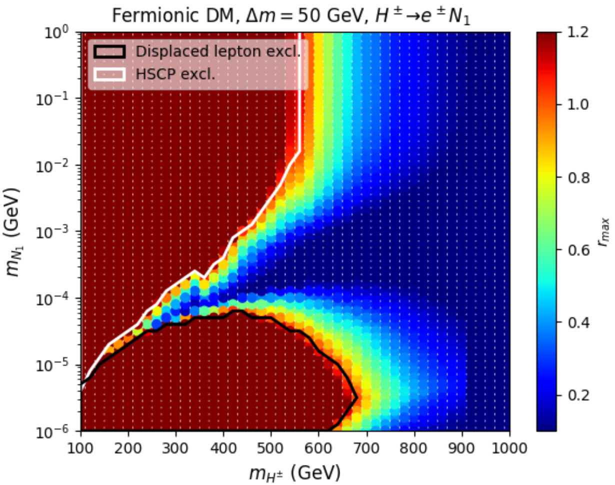

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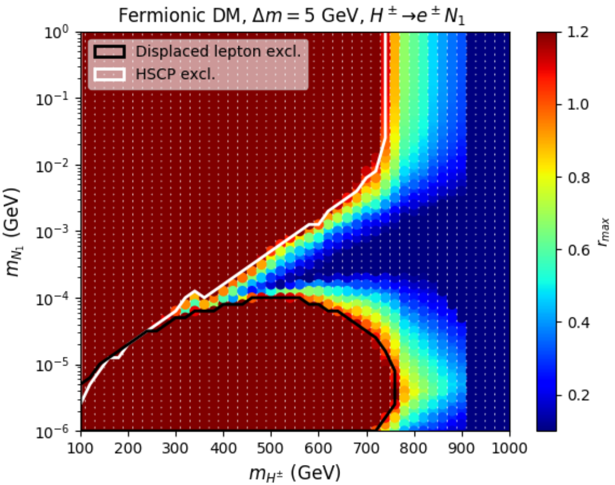
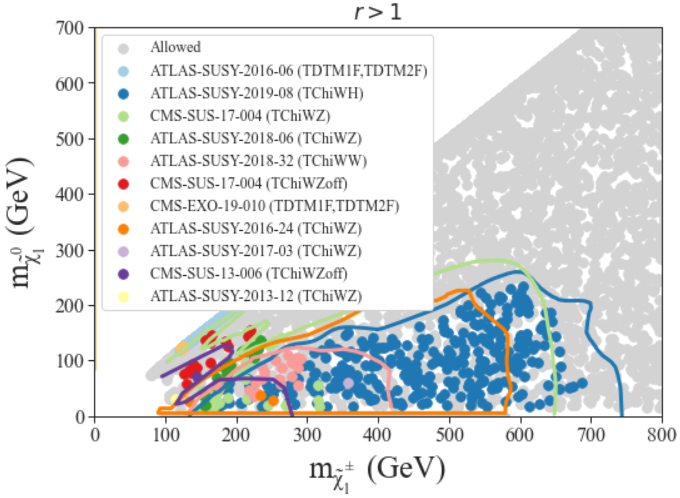


Electroweakinos in the MSSM

- random scan over $M_1, M_2, \mu, \tan\beta = 10$
- generated with SOFTSUSY
- cross-sections with PROSPINO
- simultaneously prompt and LLP constraints



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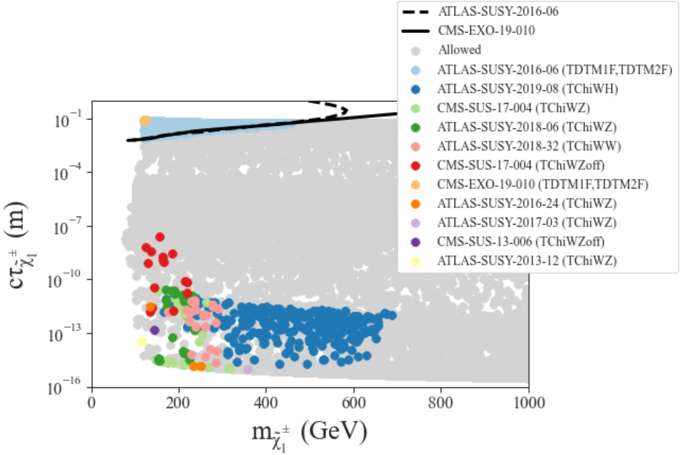


Conclusions

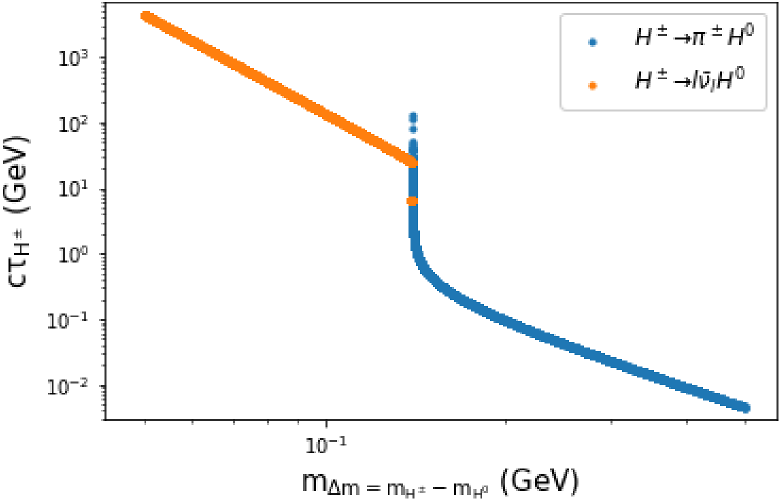
- What's new in SModelS v2.1.0
  - extended description of simplified models (quantum numbers and widths)
  - 7 new LLP results (3 displaced, 2 DT, 2 HSCPs)
- Physics examples
  - scotogenic scalar DM
    $\Rightarrow$ disappearing tracks and HSCPs
  - scotogenic fermionic DM
    $\Rightarrow$ displaced leptons and HSCPs
  - MSSM electroweakinos
    $\Rightarrow$ disappearing tracks and prompt

Thanks for your attention !

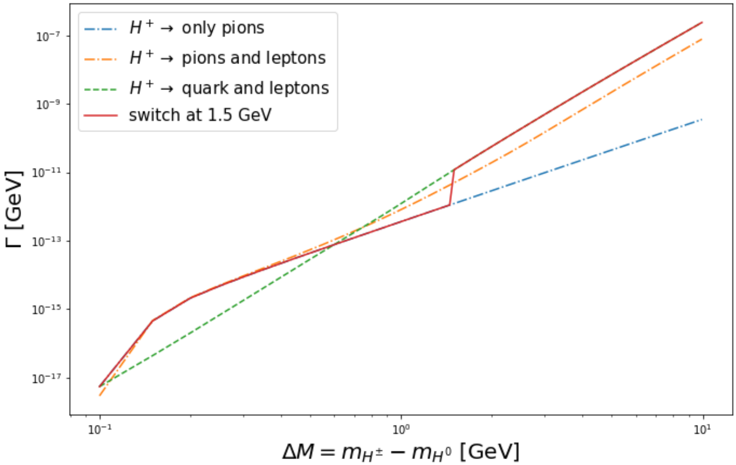
Backup : scotogenic scalar potential

$$\begin{aligned} V &= m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 + \frac{1}{2}\lambda_1 (H_1^\dagger H_1)^2 + \frac{1}{2}\lambda_2 (H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) \\ &+ \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \frac{1}{2}\lambda_5 [(H_1^\dagger H_2)^2 + H.c.], \end{aligned} \tag{1}$$

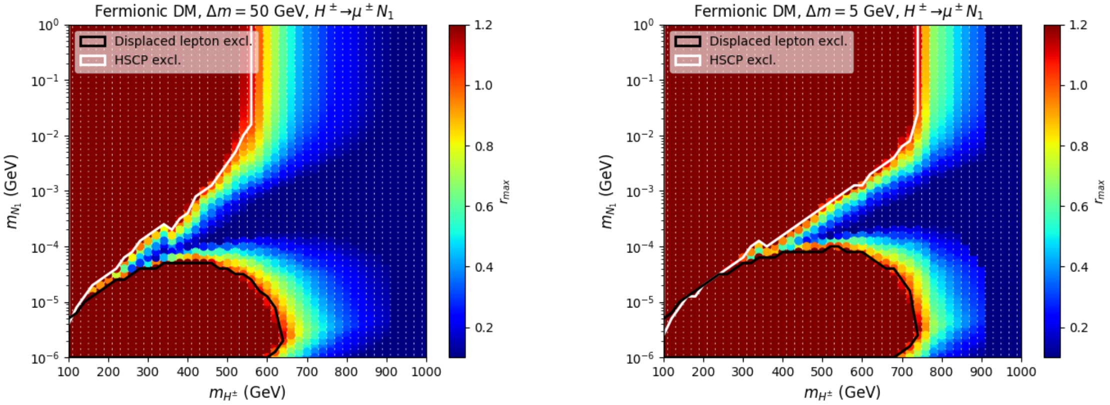
$H^{\pm}$ width


$H^{\pm} \to \pi^{\pm} H^0$
$H^{\pm} \to l \bar{\nu}_l H^0$
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
$c\tau_{H^{\pm}}$ (GeV)
10^{-1}
$m_{\Delta m} = m_{H^{\pm}} - m_{H^0}$ (GeV)

$H^{\pm}$ decay into pions

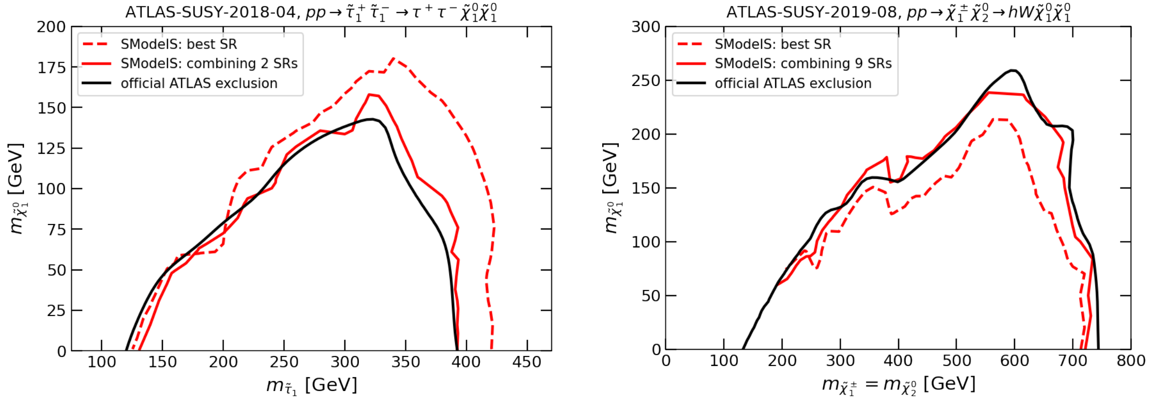


Backup : $H^{\pm} \to \mu^{\pm} N_1$



Backup : SModelS-pyhf interface

arXiv:2009.01809 (pyhf interface)



Backup : ATLAS likelihoods

$$p(n, a|\eta, \chi) = \underbrace{\prod_{c \in channels} \prod_{b \in bins} \text{Pois}\Big(n_{cb}|\nu_{cb}(\eta, \chi)\Big)}_{\text{Measurements}} \underbrace{\prod_{\chi} c_\chi(a_\chi|\chi)}_{\text{Constraints}} \qquad (2)$$

relates the observed events and auxiliary data (n, a)
to the free and constrained parameters (η, χ)

$$\nu_{cb}(\eta, \chi) = \sum_{s \in samples} \nu_{scb}(\eta, \chi) = \sum_{s \in samples} \underbrace{\prod_{\kappa} \kappa_{scb}(\eta, \chi)}_{\text{Mujtiplicative modifiers}} \left(\nu^0_{scb}(\eta, \chi) + \underbrace{\sum_{\Delta} \Delta_{scb}(\eta, \chi)}_{\text{Additive modifiers}}\right) \qquad (3)$$

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