Dark Matter - Neutrino Connection at the LHC

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CP3 Origins
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The particle dark matter paradigm

Strong empirical evidence for the existence of a “dark sector” beyond the Standard Model

1. Very little is known about its matter content and its interactions with the visible sector

2. 85% of the matter content of the Universe is in the form of a new particle which must have a long lifetime (longer than the age of the Universe), as indicated by the non-observation of its decay products in cosmic ray experiments

3. No evidence up to now of dark matter detection from *direct* and *indirect* searches

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Missing information:

1. What are the quantum numbers of particle dark matter?

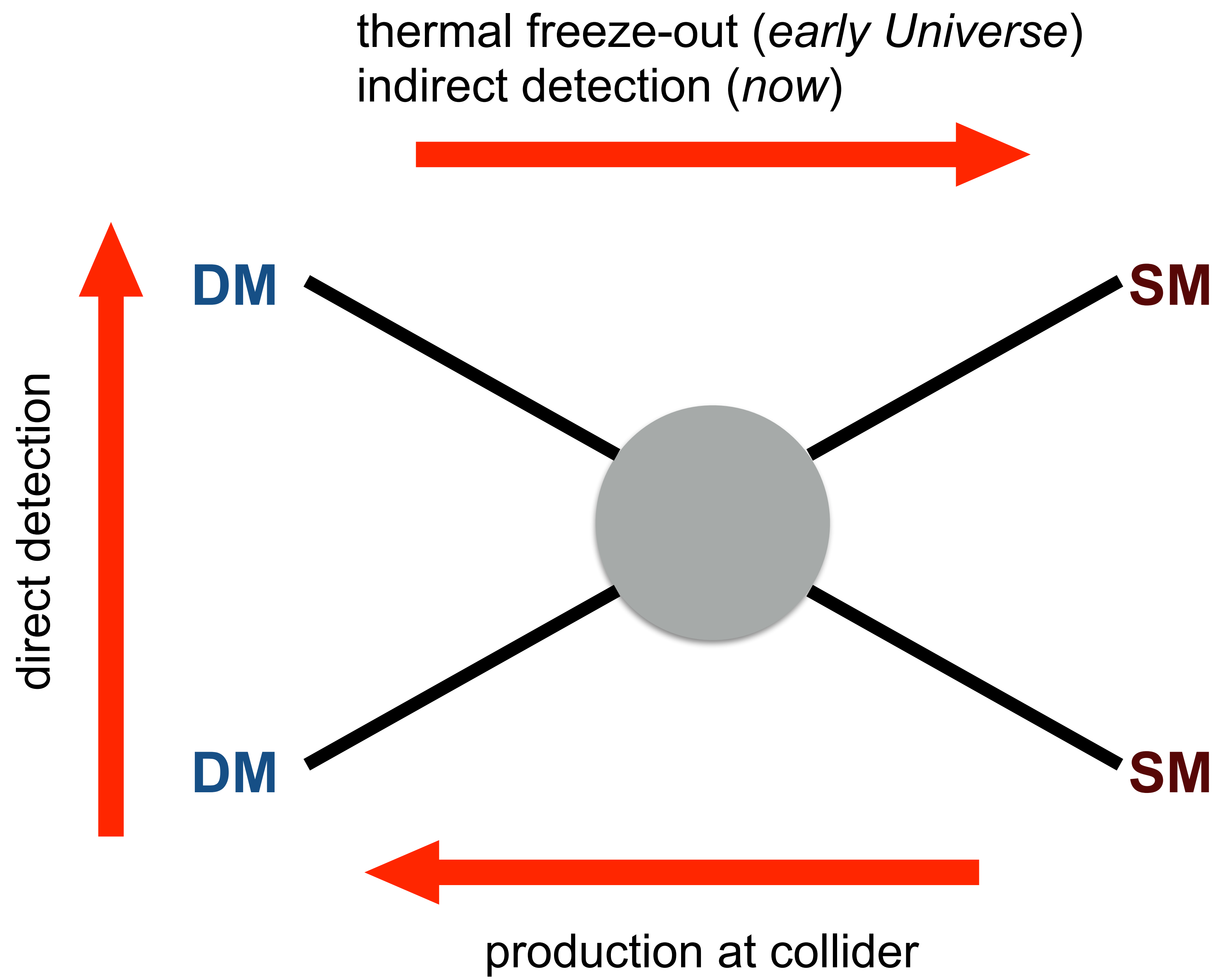
2. How was dark matter produced in the early universe (thermal relic, freeze-in, asymmetry in a conserved quantum number, …)?

3. What is the portal between the “dark sector” and the Standard Model?

4. Is there a new global/gauge symmetry that characterizes the “dark sector”?

The particle dark matter paradigm

Complementarity of dark matter search strategies



SM = $W^{\pm}, Z, H, g, \gamma, q^{\pm}, l^{\pm}$

The particle Dark Matter paradigm

Weakly Interacting Massive Particles (WIMPs) are natural Dark Matter candidates: the typical relic density matches observation (*WIMP miracle*)

$$\Omega h^2 \simeq \frac{3\times 10^{-27}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle\sigma v\rangle_{\mathrm{th}}} \qquad \langle\sigma v\rangle_{\mathrm{th}} \simeq 3\times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1} = 1\,\mathrm{pb}\cdot c$$

The WIMP paradigm is naturally realised in several extensions of the Standard Model

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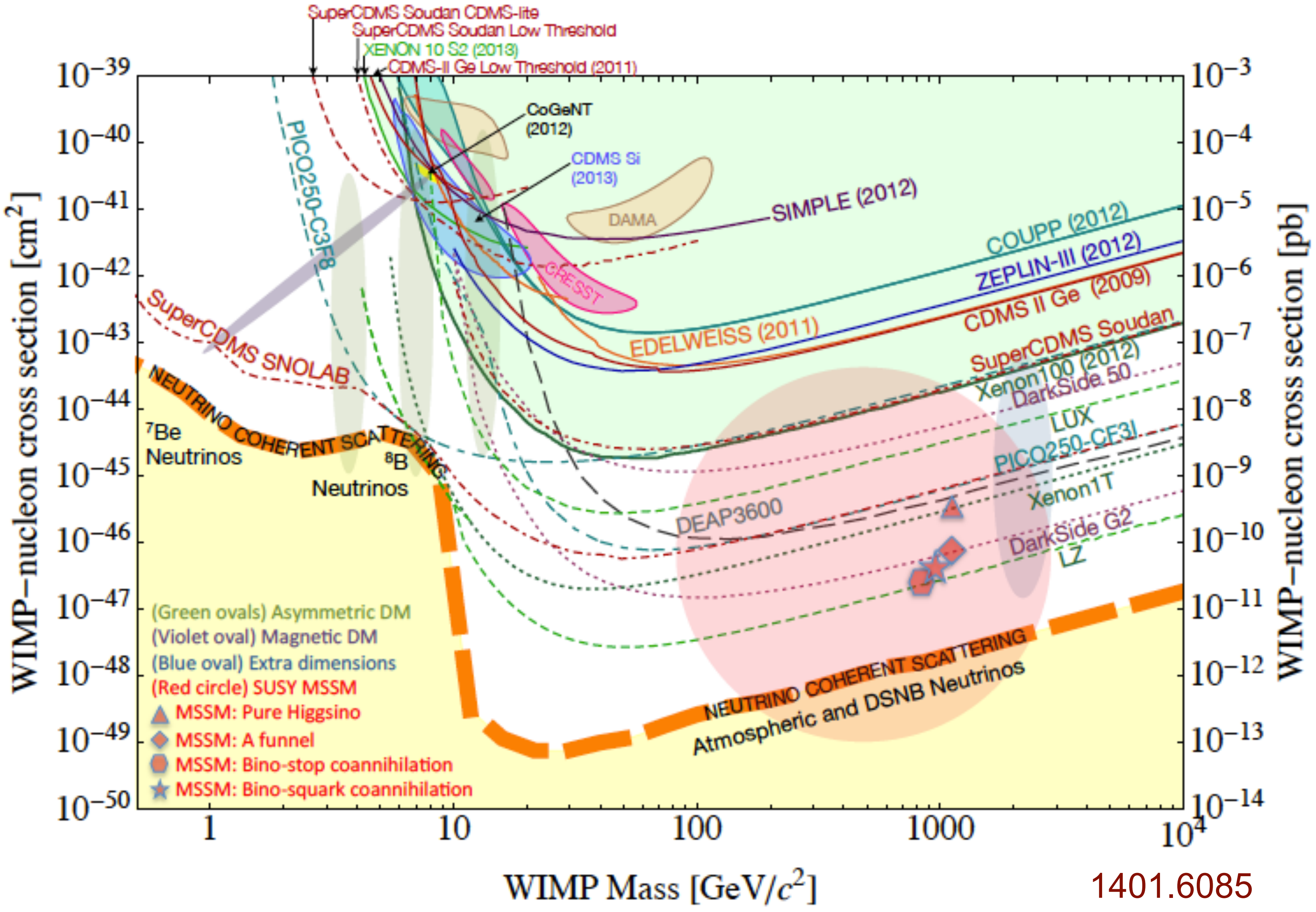

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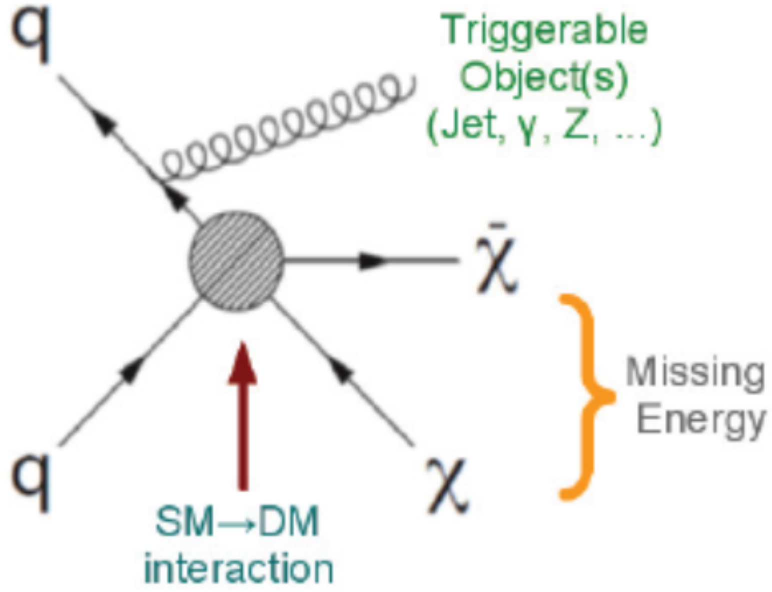
LHC dark matter searches

Missing energy signals: *direct pair-production of dark matter* with SM particles emitted in the initial, intermediate or final state (model independent approach)



Challenges:

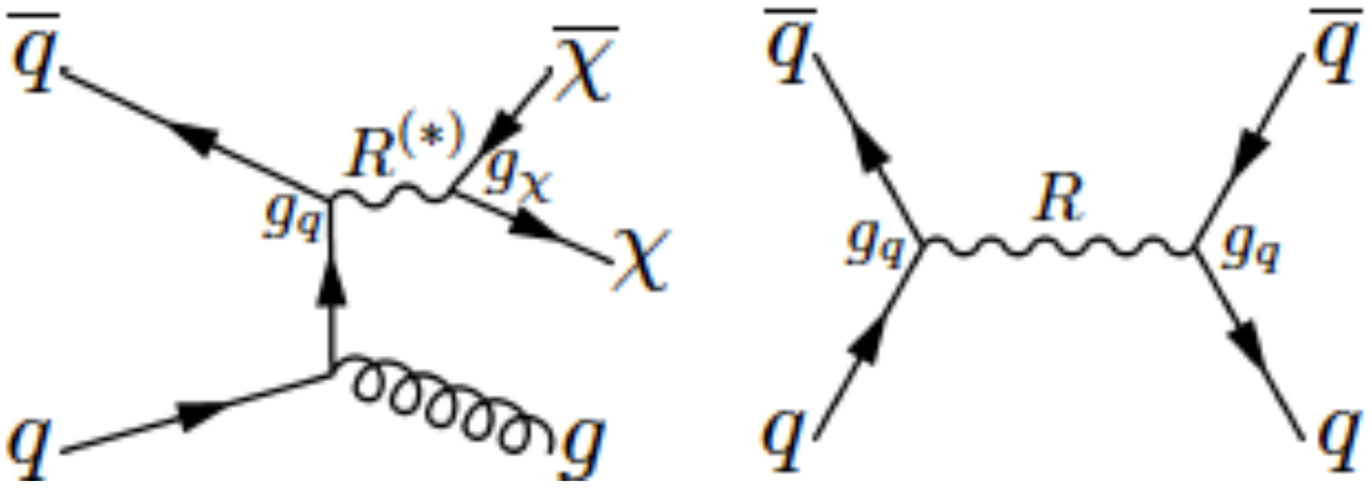
1. Any observation of missing momentum is not directly connected to dark matter: particles with a lifetime ≳ 1 sec cannot be distinguished at LHC

2. Limitations of effective field theory approach: the energy probed at the LHC intrinsically depends on the parton distribution functions

LHC dark matter searches

top-down approach

Searches for mediators: if dark matter is produced at the LHC via s-channel, the mediator can always decay back into quarks and gluons



The shape of the kinematic distributions depends on the mediator mass

Model-dependent analysis which involves a rich phenomenology

The particle Dark Matter paradigm

Strong empirical evidence of the existence of a “Dark Sector” beyond the Standard Model:

1. Very little is known about its matter content or its interactions
2. 85% of the matter content of the Universe is in the form of a new particle which must have a long lifetime (longer than the age of the Universe), as indicated by the non-observation of its decay products in cosmic ray experiments
3. No evidence up to now of Dark Matter detection from *direct* and *indirect* searches

Alternative particle Dark Matter scenarios:

- The Dark Matter particle is not a thermal relic, but it is dynamically produced as an asymmetry between the corresponding particle and antiparticle number densities, in analogy with the *baryogengesis mechanism:* **Asymmetric Dark Matter**

$$\rho_{DM}/\rho_B \approx 5 \qquad\qquad \langle\sigma_{ann} v\rangle > 1\,\mathrm{pb}\cdot c$$

- The Dark Matter is a **Feebly Interacting Massive Particle** (FIMP).

FIMPs have very weak interactions with SM particles and never enter in thermal equilibrium. Their abundance is produced via *thermal freeze-in*. No signatures of these particles in *direct/indirect* searches. FIMPs may induce exotic collider signatures.

Dark matter - neutrino connection

The origin of neutrino masses can be connected with the dark matter

Dark matter - neutrino connection

The origin of neutrino masses can be connected with the dark matter

- Dark matter from minimal realizations of the seesaw mechanism
  - Sterile neutrino dark matter (vMSN and variations)

    Asaka, Shaposhnikov, 2005; Asaka, Blanchet, Shaposhnikov, 2005;
    Canetti, Drewes, Shaposhnikov, 2013; Merle, Niro, Schmidt, 2014,…

  - Majoron dark matter

    Chikashige, Mohapatra, Peccei, 1980; Schecter, Valle, 1982;
    Rothstein, Babu, Seckel, 1993; Berezinsky, Valle, 1993;
    Lattanzi, Valle, 2007; Frigerio, Ha,bye, Masso, 2011;
    EM, Josse-Michaux, 2012; Garcia-Cely, Heeck, 2017, ….

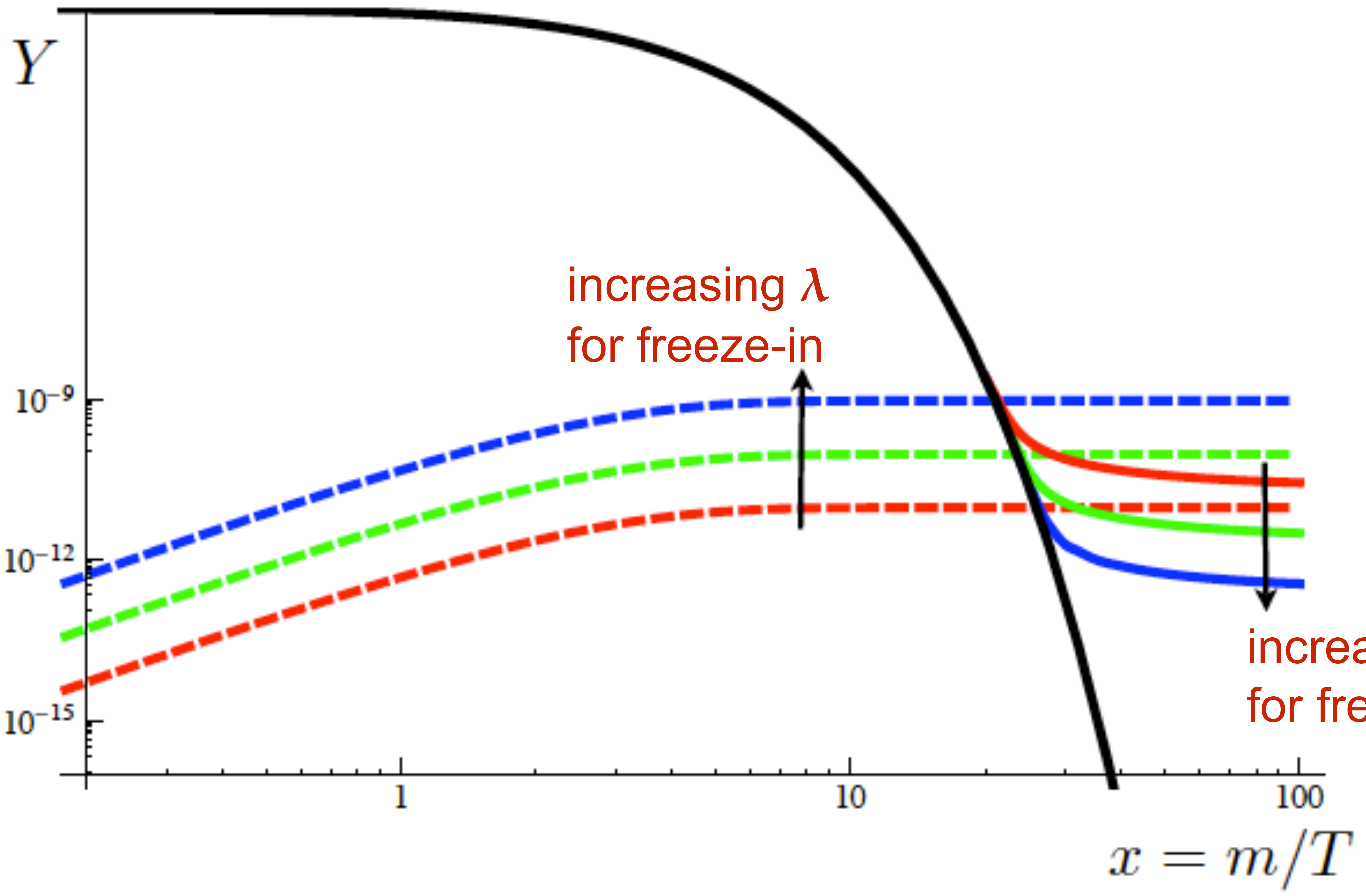
  - Dark matter and discrete flavour symmetries

    Hirsch, Morisi, Peinado, Valle, 2010; Meloni, Morisi, Peinado, 2011;
    Adaulpravitchai, Batell, Pradler, 2011; Kajiyama, Okada, Toma, 2011;
    Kajiyama, Kannike, Raidal, 2012; Boucenna, Morisi, Peinado, Shimizu, Valle, 2012;
    Lavoura, Morisi, Valle, 2013; Peinado, 2015,…

- Dark matter from radiative seesaw models

Ma, 2006; Ma, Suematsu, 2009; Farzan, Pascoli, Schmidt, 2013; Restrepo, Zapata, Yaguna, 2013; EM, Yaguna, Zapata, 2014;
Bonilla, Ma, Peinado, Valle, 2015; Diaz, Rojas, Urrutia-Quiroga, Valle, 2016; Cai, Herrero-Garcia, Schmidt,Vicente, Volkas, 2017,…

Dark matter production: freeze-in vs freeze-out



increasing λ
for freeze-in

increasing λ
for freeze-out

Hall, Jedamzik, March-Russell, West (2010)

Long-lived particles at the LHC

ATLAS and CMS searches for long-lived particles can be recast to test the FIMP dark matter paradigm

- The next-to-lightest odd particle (NLOP) is the portal to the dark sector: its decay width might be directly related to the cosmological dark matter abundance and/or the dark matter mass
- LHC production cross-section of the NLOP might be sizeable
- NLOP lifetime/decay modes/collider signatures depend on the mass spectrum of the model

Interesting phenomenology within radiative neutrino mass models, which can naturally implement the FIMP dark matter paradigm

Radiative neutrino mass model

Lagrangian invariant under a Z₂ symmetry

Ernest Ma (2006)

$$\mathcal{L} \supset \left[Y^{\nu}_{\alpha i}\left(\overline{\nu}_{\alpha L}\, H_2^0 - \overline{\ell}_{\alpha L}\, H^+\right) N_i + \text{H.c.}\right] + \frac{1}{2}\, M_j\, \overline{N}_j\, N_j^C$$

$$\begin{aligned} V(H_1, H_2) \;=\; & -\mu_1^2\left(H_1^\dagger H_1\right) + \lambda_1\left(H_1^\dagger H_1\right)^2 + \mu_2^2\left(H_2^\dagger H_2\right) + \lambda_2\left(H_2^\dagger H_2\right)^2 \\ & + \lambda_3\left(H_1^\dagger H_1\right)\left(H_2^\dagger H_2\right) + \lambda_4\left(H_1^\dagger H_2\right)\left(H_2^\dagger H_1\right) \\ & + \frac{\lambda_5}{2}\left[\left(H_1^\dagger H_2\right)^2 + \text{H.c.}\right] \end{aligned}$$

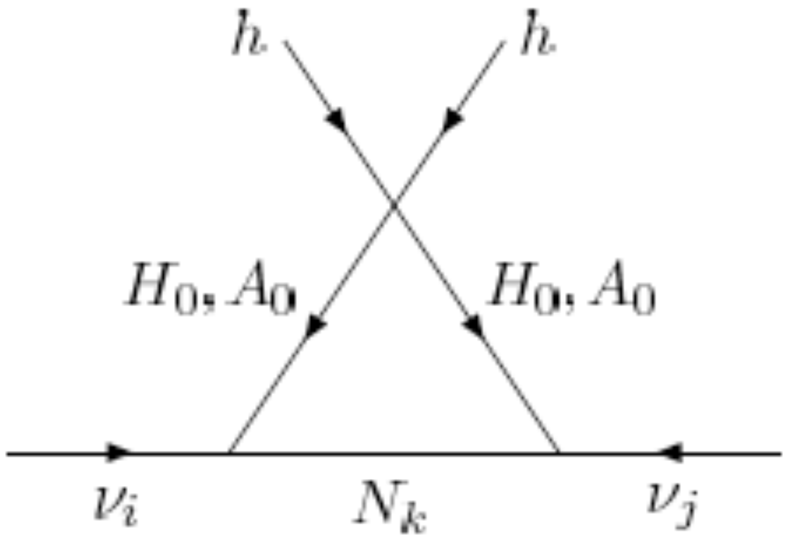
The dark sector mass spectrum:

- 3 Majorana fermions with masses $M_1 < M_2 < M_3$
- 1 CP-even neutral scalar H^0 with mass $m^2_{H^0} = \mu_2^2 + v^2\left(\lambda_3 + \lambda_4 + \lambda_5\right)/2$
- 1 CP-odd neutral scalar A^0 with mass $m^2_{A^0} = \mu_2^2 + v^2\left(\lambda_3 + \lambda_4 - \lambda_5\right)/2$
- 2 charged scalars $H^{\pm}$ with masses $m^2_{H^\pm} = \mu_2^2 + v^2\,\lambda_3/2$

The lightest Z₂-odd particle is stable and provides a dark matter candidate

Radiative neutrino mass model

Majorana mass term for active neutrinos is generated at 1-loop



Case in which only $N_{2,3}$ contribute to neutrino mass generation

$$(\mathcal{M}_\nu)_{\alpha\beta} \simeq \frac{\lambda_5\, v^2}{32\,\pi^2} \sum_k Y^\nu_{\alpha k}\, Y^\nu_{\beta k}\, \frac{M_k}{m_0^2 - M_k^2} \left[1 - \frac{M_k^2}{m_0^2 - M_k^2} \log\left(\frac{m_0^2}{M_k^2}\right)\right]$$

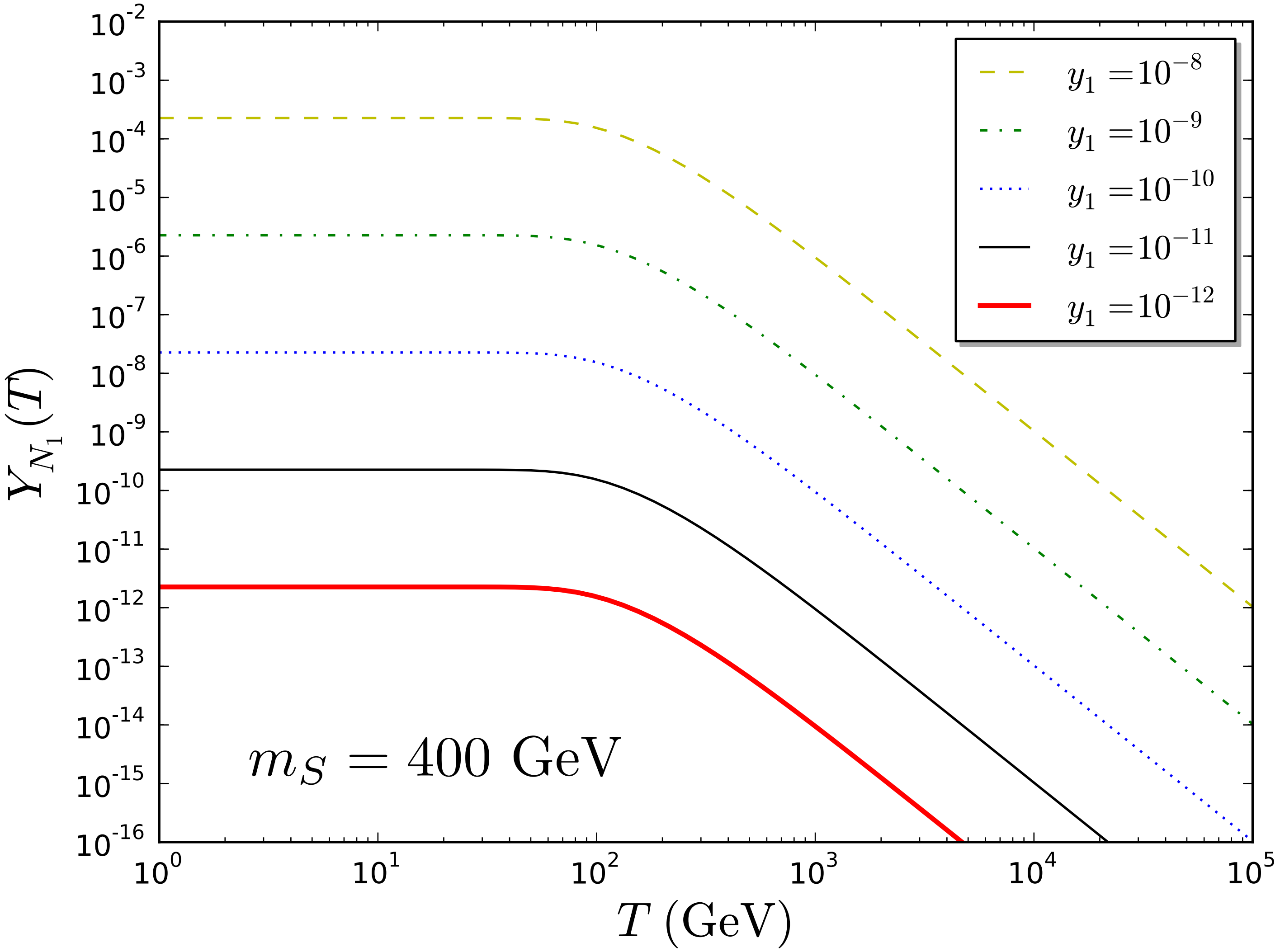
$$\approx 10^{-2}\,\mathrm{eV} \left(\frac{\lambda_5\, y_{2,3}^2}{10^{-11}}\right) \left(\frac{1\,\mathrm{TeV}}{M_{2,3}}\right)$$

2 massive neutrinos $\lambda_5 \lesssim 0.1 \quad \Longrightarrow \quad 10^{-5} \lesssim y_{2,3} \lesssim 10^{-2}$ $\mu \to e\,\gamma$ bound

For $y_1 \ll 10^{-6}$ N_1 gives no contribution to neutrino masses

$$y_1 \lesssim 10^{-8} \quad \Longrightarrow \quad \Gamma(H_2 \to N_1\, L) \lesssim H(T \sim M_{H_2})$$

Fermionic FIMP dark matter



EM, Yaguna, Zapata '14

$$\frac{dY_{N_1}}{dT} \approx -5\times 10^3\,\mathrm{GeV}^3 \left(\frac{m_S}{1\,\mathrm{TeV}}\right)^2 \left(\frac{y_1}{10^{-8}}\right)^2 T^{-4} \qquad \text{at} \quad T \gg m_S$$

$$Y_{N_1}\left(T \lesssim m_S\right) \approx 10^{-4}\left(\frac{1\ \mathrm{TeV}}{m_S}\right)\left(\frac{y_1}{10^{-8}}\right)^2$$

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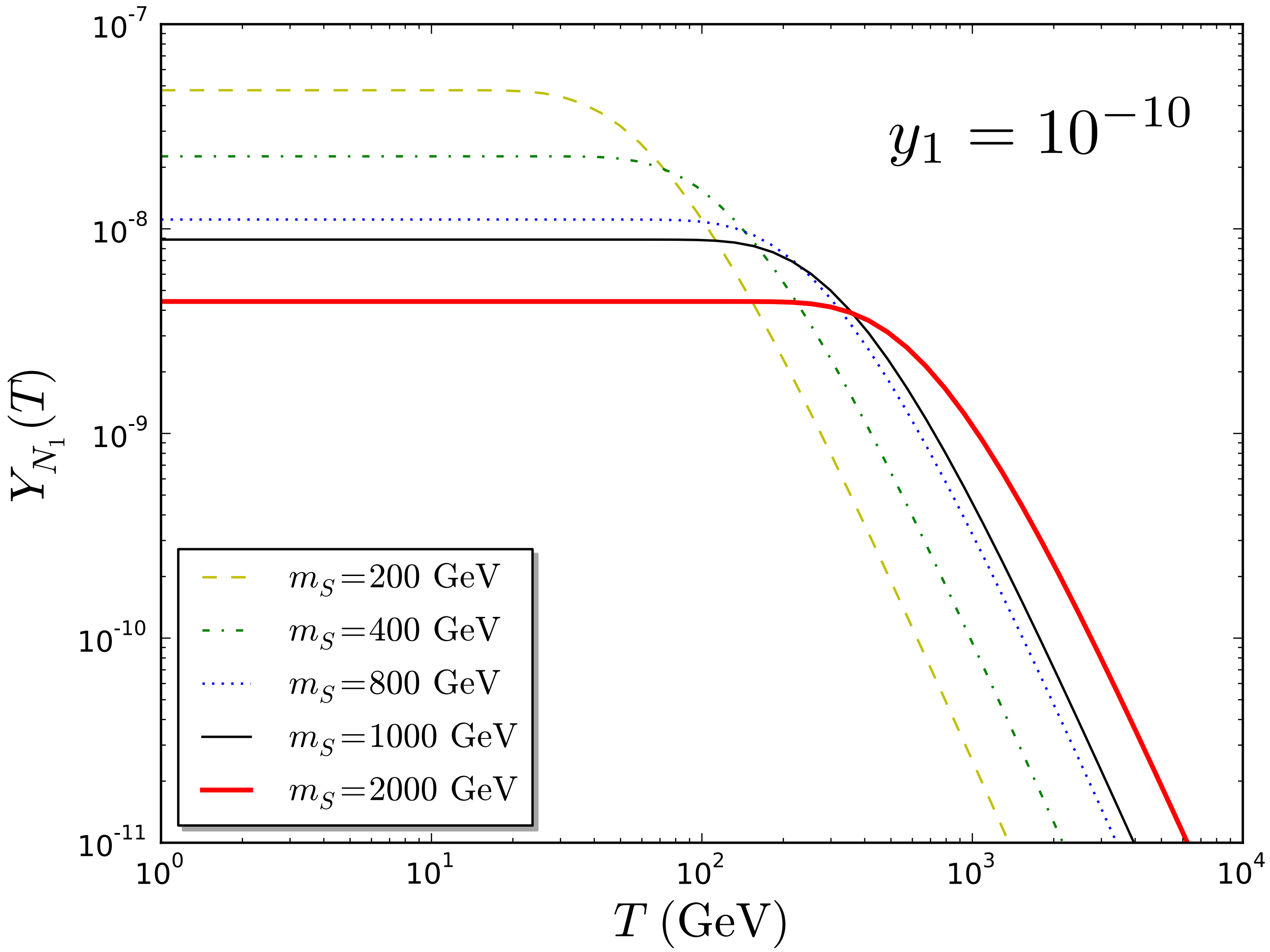

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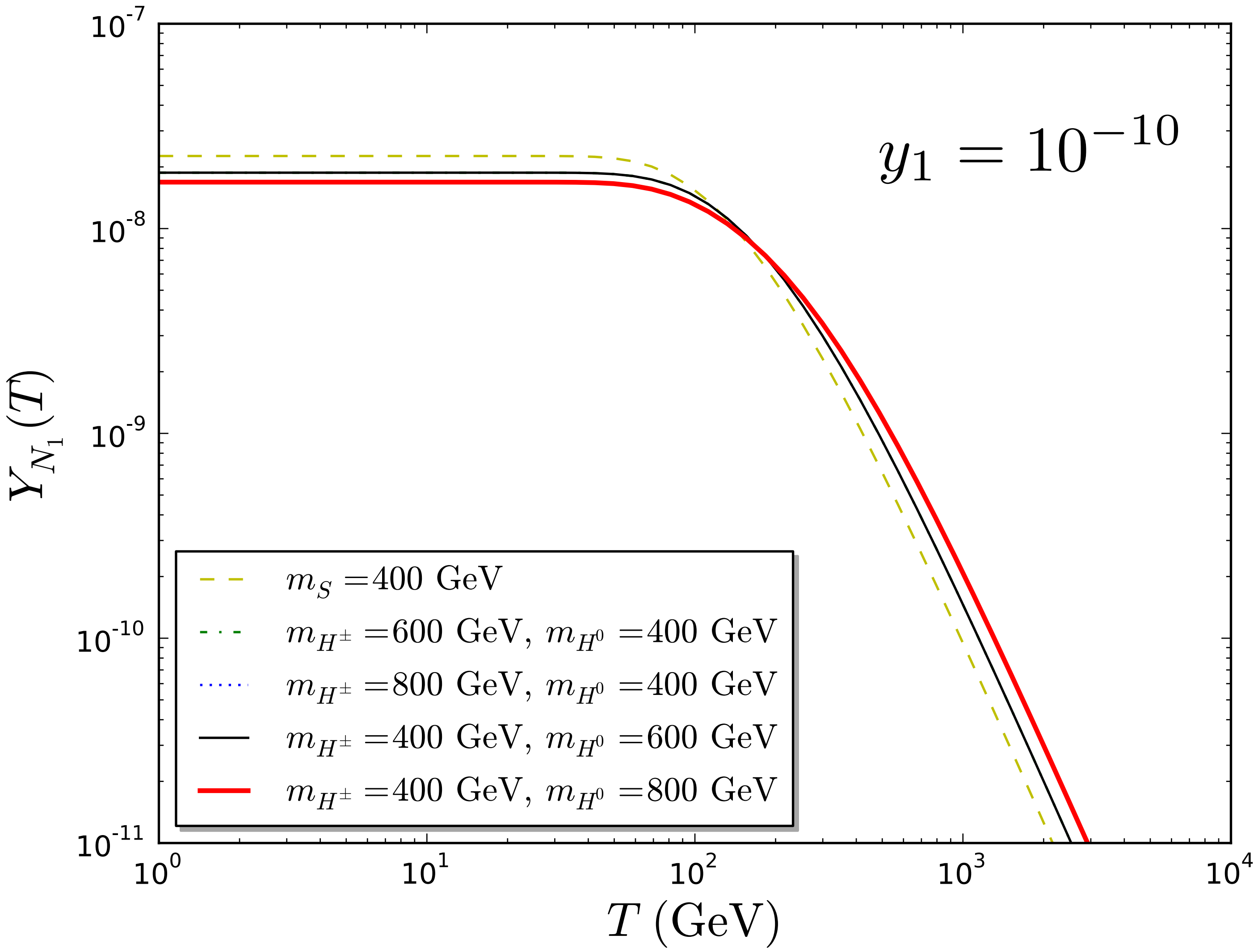

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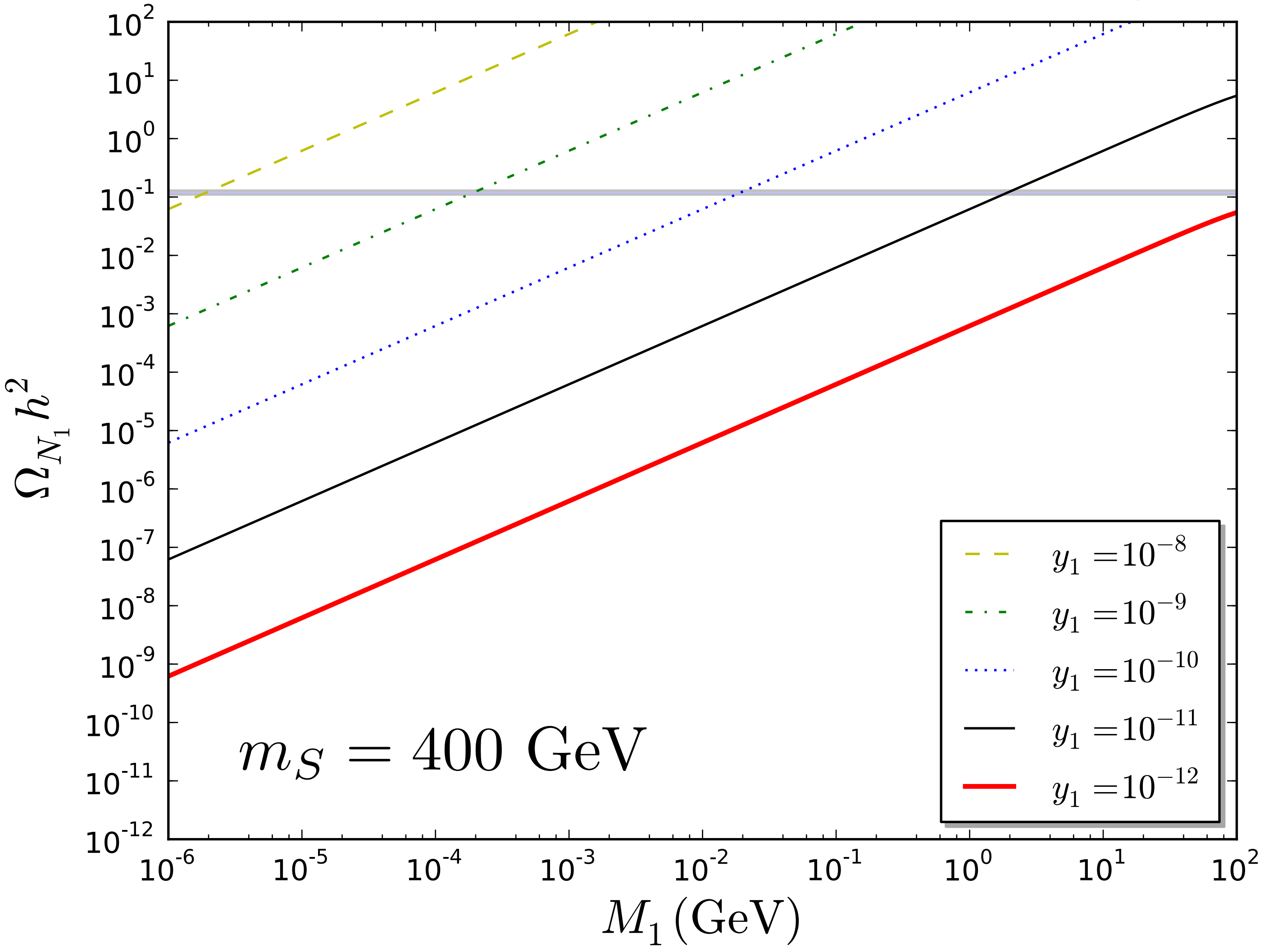
Fermionic FIMP dark matter

Parameter space compatible with the observed relic density



EM, Yaguna, Zapata '14

$$\Omega_{N_1}\, h^2 \quad \approx 0.3 \left(\frac{M_1}{0.1\,\mathrm{GeV}}\right) \left(\frac{1\,\mathrm{TeV}}{m_S}\right) \left(\frac{y_1}{10^{-10}}\right)^2$$

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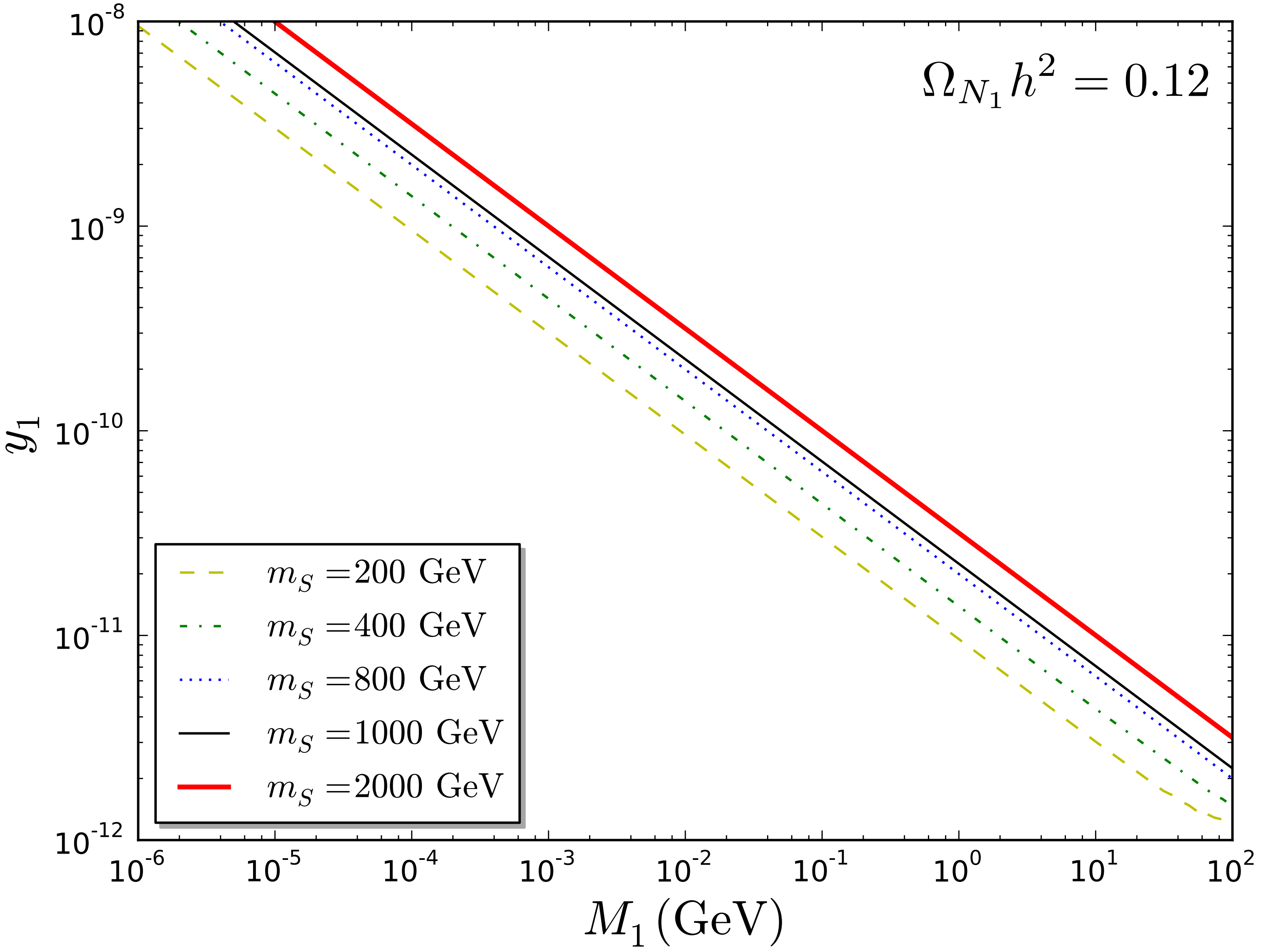

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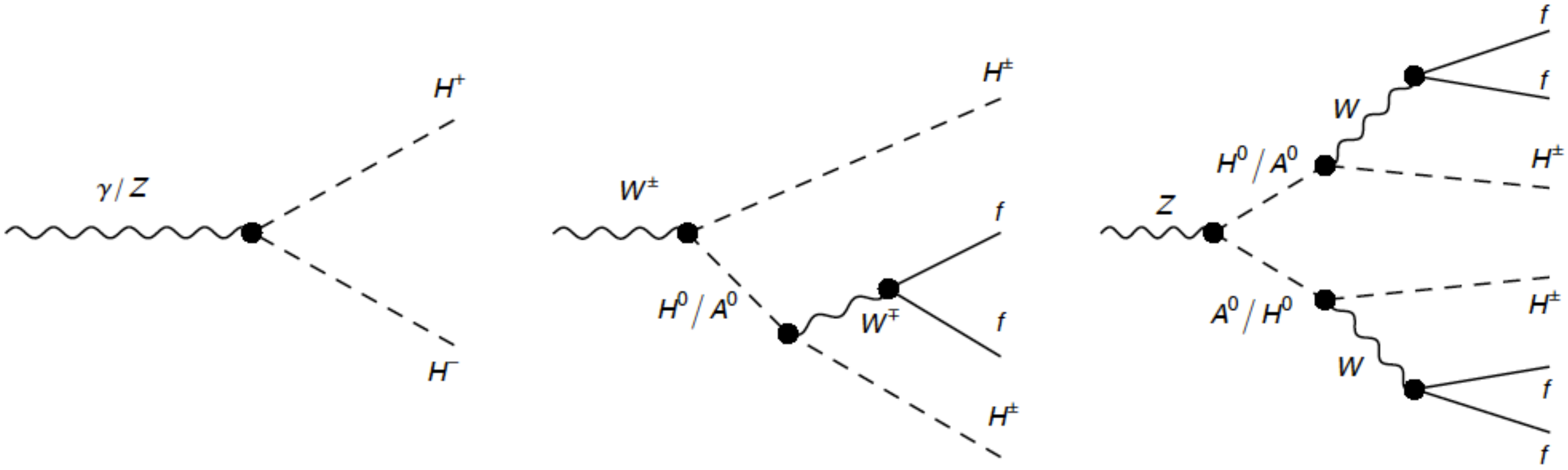
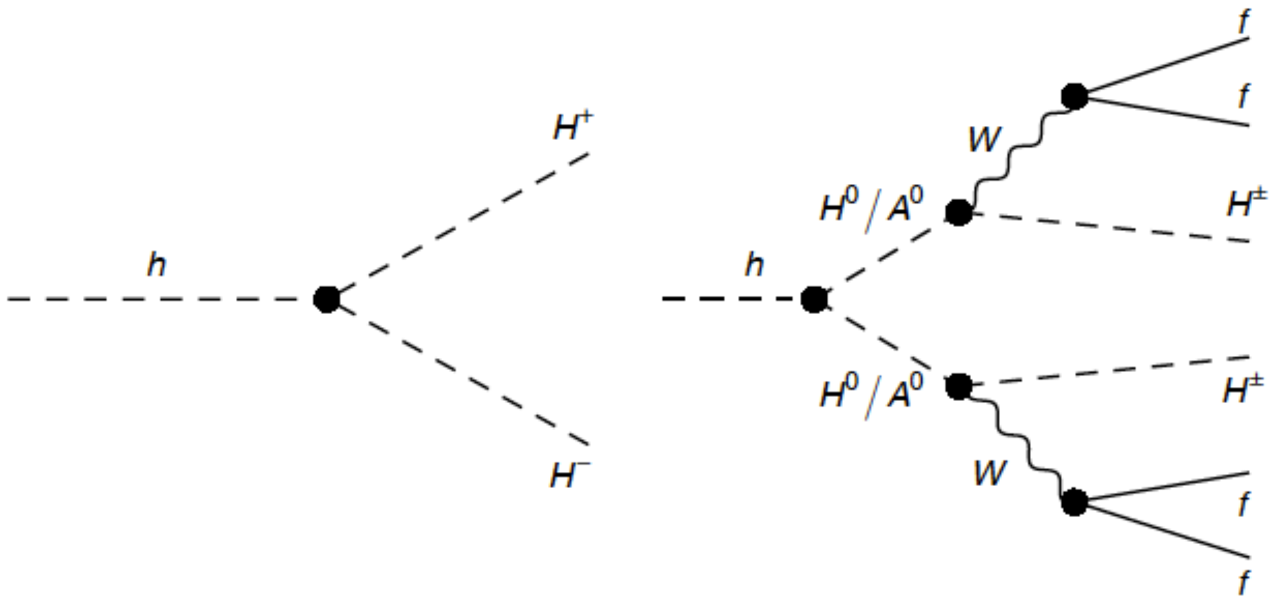
Charged scalar NLOP at the LHC

mass spectrum: $M_1 < m_{H^\pm} < m_{H^0,\,A^0} < M_{2,3}$

Drell-Yan



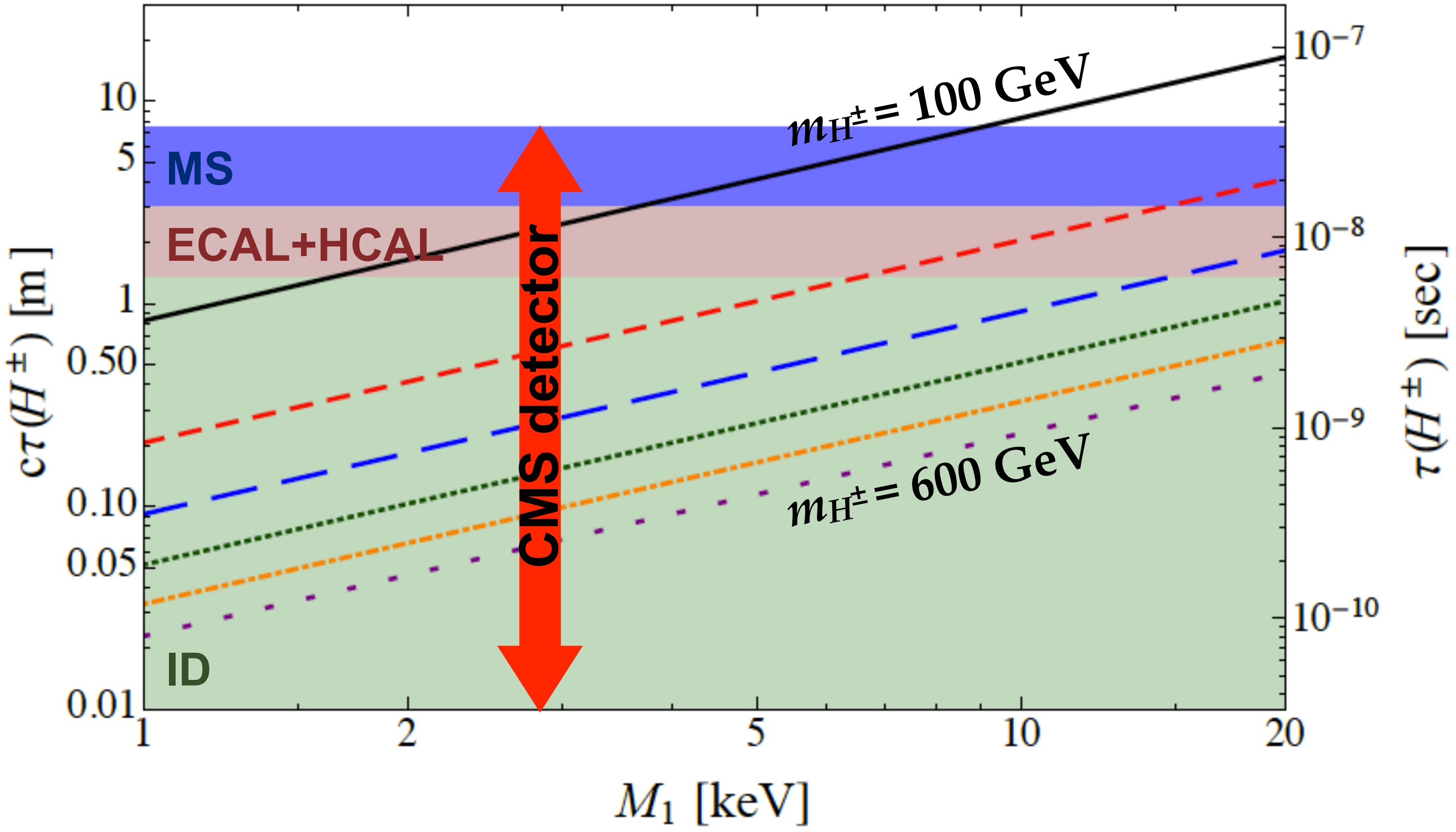
Higgs-portal



Charged scalar NLOP at the LHC

$$\text{mass spectrum:}\ \ M_1 < m_{H^\pm} < m_{H^0,\,A^0} < M_{2,3}$$

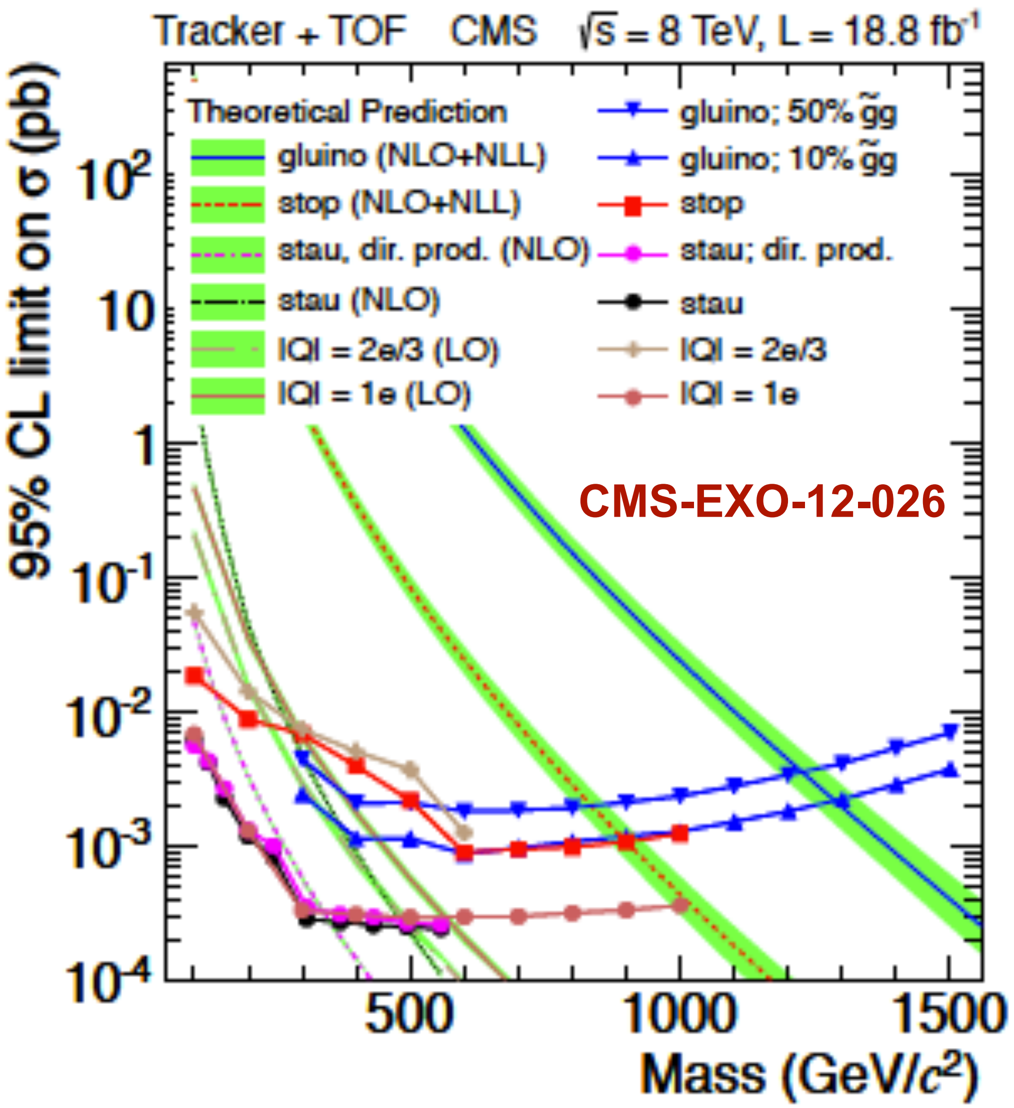
- Dark Matter abundance via *freeze-in*
- for $m_{H^\pm} \gtrsim 100$ GeV the NLOP is either stable or decays within the detector
- the life-time/decay-length of the NLOP depends on the initial velocity and the Dark Matter mass



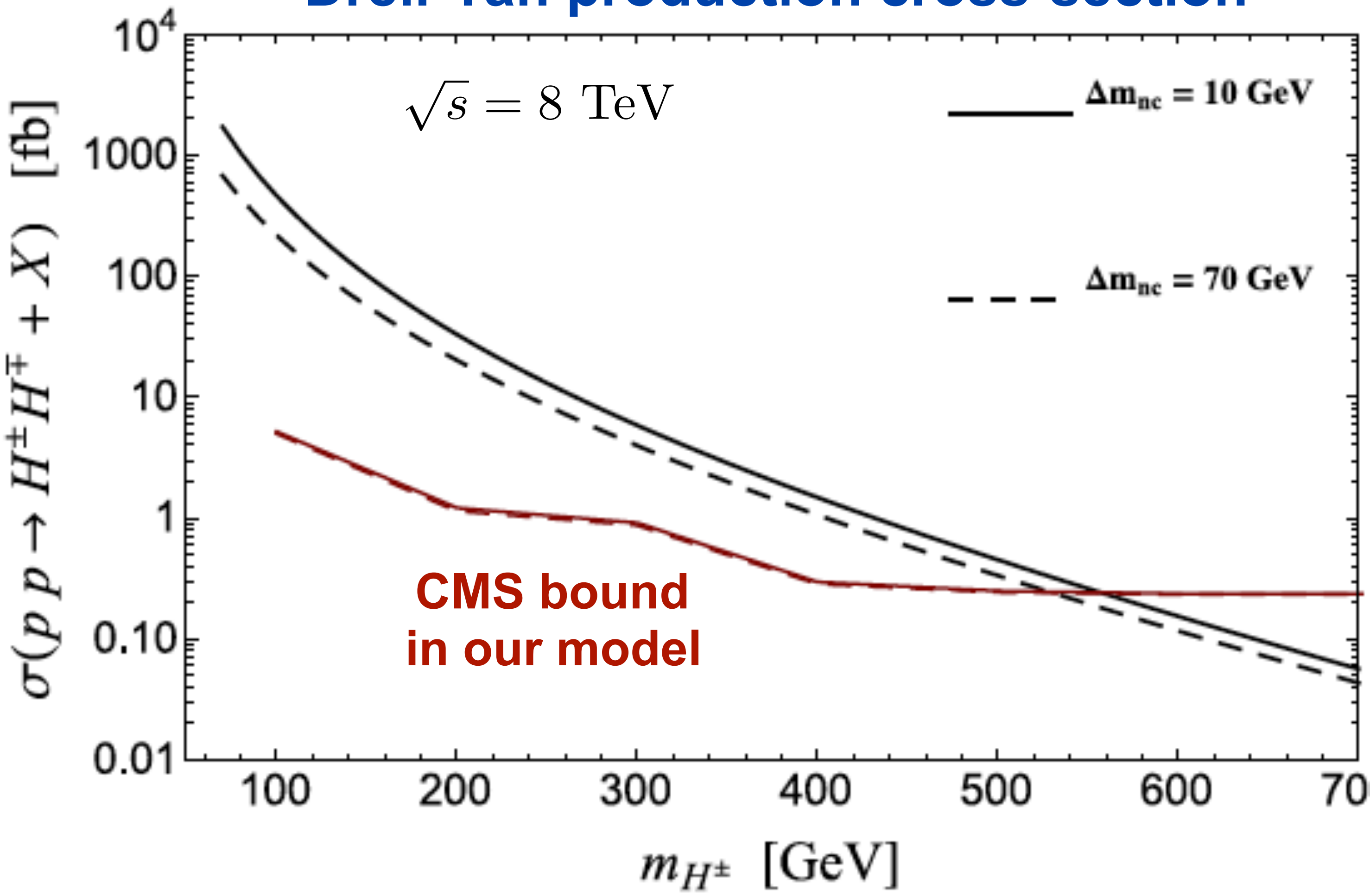
$$c\tau(H^\pm) \approx 8.3\,\text{m}\left(\frac{M_1}{10\ \text{keV}}\right)\left(\frac{100\ \text{GeV}}{m_{H^\pm}}\right)^2$$

$$\tau(H^\pm) \approx 2.8\times 10^{-8}\,\text{sec}\left(\frac{M_1}{10\ \text{keV}}\right)\left(\frac{100\ \text{GeV}}{m_{H^\pm}}\right)^2$$

Charged tracks analysis at the LHC



Drell-Yan production cross-section



We recast Tracker + Time-of-Flight analysis of CMS on metastable singly-charged particles:

$$m_{H^\pm} \gtrsim 560\ (530)\ \text{GeV} \quad \text{for} \quad \Delta m_{\rm nc} = 10\ (70)\ \text{GeV}$$

bound for stable heavy singly-charged particles

Charged tracks analysis at the LHC

in-flight decays of the NLOP

Survival probability of $H^{\pm}$ depends on the distance x:

$$P^{\rm sur}_{H^{\pm}}(x) \;=\; \exp\left(-\,\frac{x}{\beta\gamma\, c\tau(H^{\pm})}\right)$$

Excluded cross-section:

$$\sigma(p\,p \to H^{+}\,H^{-} \;+\; X) \;\lesssim\; \sigma_{ex} \;\equiv\; \frac{N_{ex}}{L\times\mathcal{A}_{\rm scot}}$$

L: integrated luminosity 18.8 fb^{-1}

N_{ex} : # excluded events for stau pair production (CMS-EXO-12-026)
tracker+TOF analysis (tracks reconstructed in the ID and MS)

$\mathcal{A}_{\rm scot}$: signal acceptance computed via a Monte Carlo technique (CMS-EXO-13-006)

$$\mathcal{A}_{\rm scot} = \frac{1}{N}\sum_{i=1}^{N} P^{\rm on}(k_i^1, k_i^2, \Gamma_{H^{\pm}}) \times P^{\rm off}(m_{\rm thr}, k_i^1, k_i^2) \qquad k_i = (\beta_i, \eta_i, p_{Ti})$$

contains information of $H^{\pm}$—lifetime/probability of the track passing through the muon spectrometer

Charged tracks analysis at the LHC

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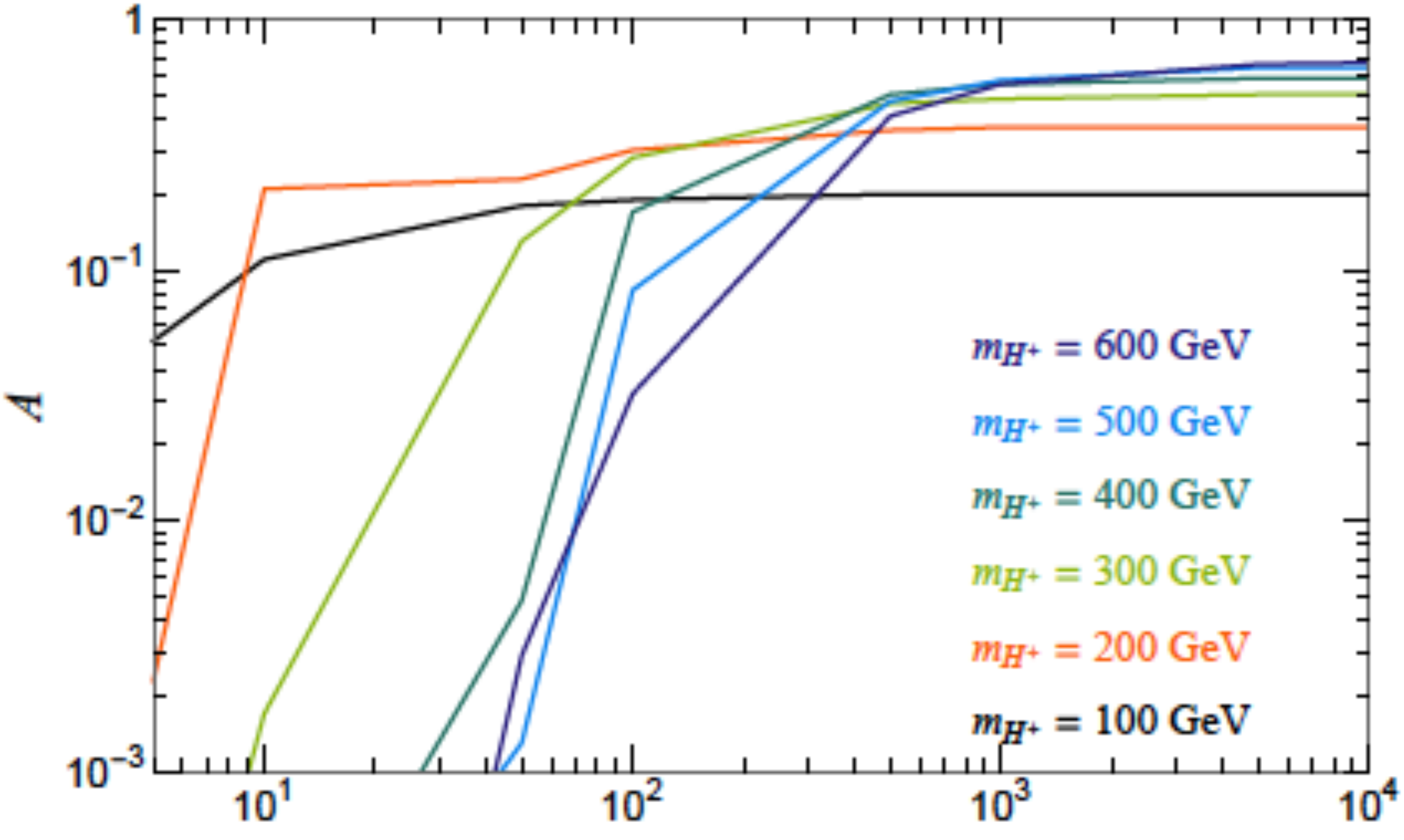
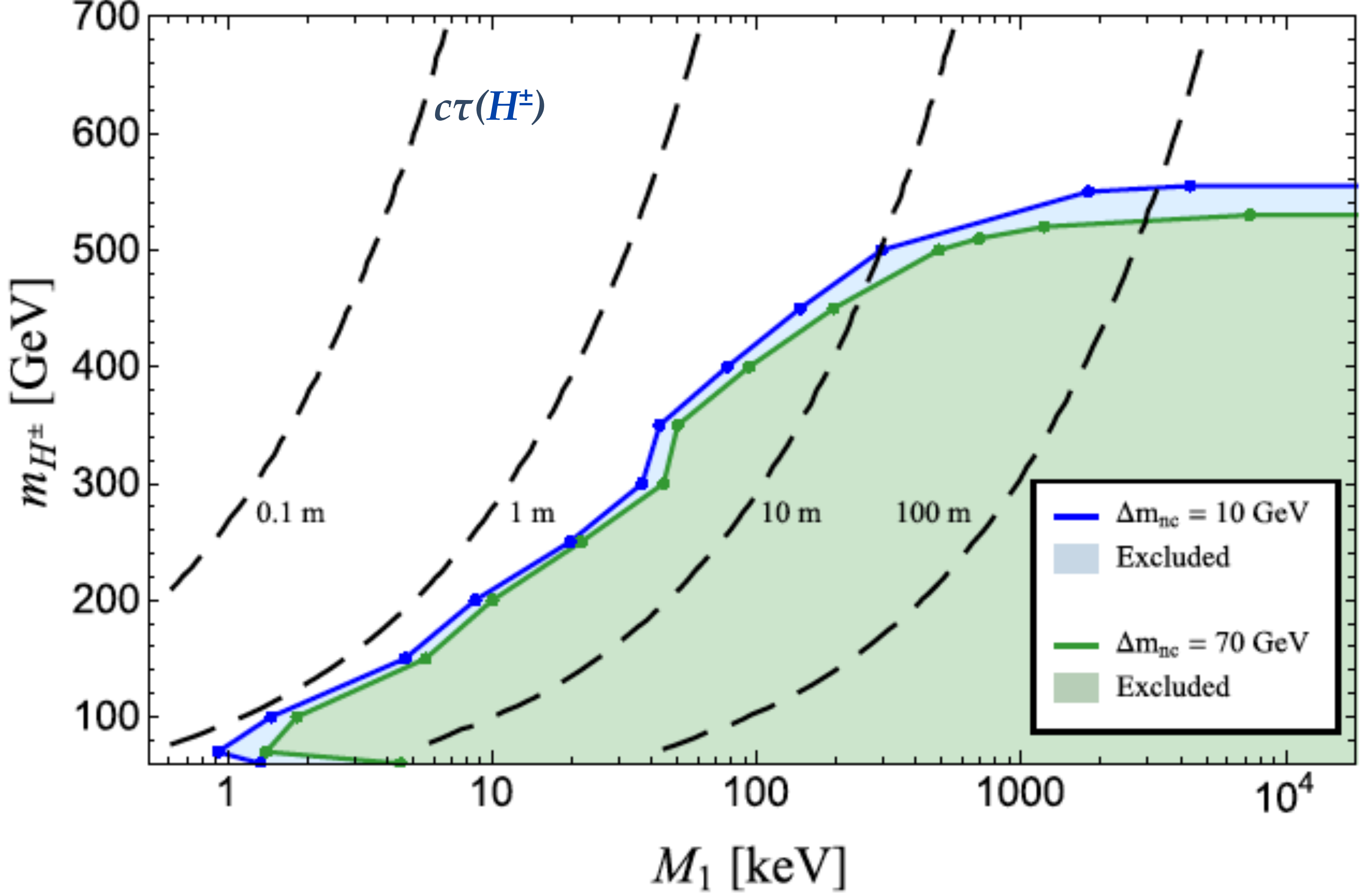


Hessler, Ibarra, EM, Vogl, 2016

Charged scalar NLOP at the LHC

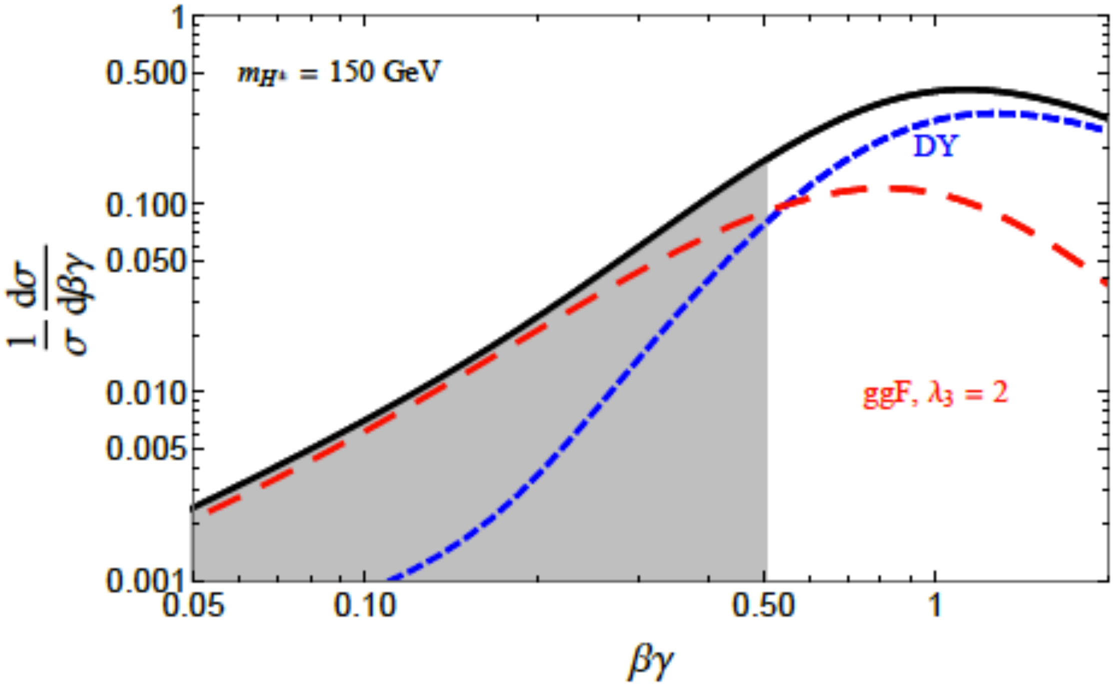
95% CL excluded regions



Hessler, Ibarra, EM, Vogl, 2016

Decays of stopped long-lived $H^{\pm}$

- **Grey region:** $H^{\pm}$ stopped in the barrel of ATLAS detector ($|\eta|<1.2$)
- Higgs portal: $\lambda_3\, v\, h\, H^{\pm} H^{\mp}$, strongly affects the stopping efficiency, ε_{stop}
- ε_{stop} calculated solving Bethe-Bloch equation: $\varepsilon_{stop}=0.085$ (0.013) for $\lambda_3=1$ (2)



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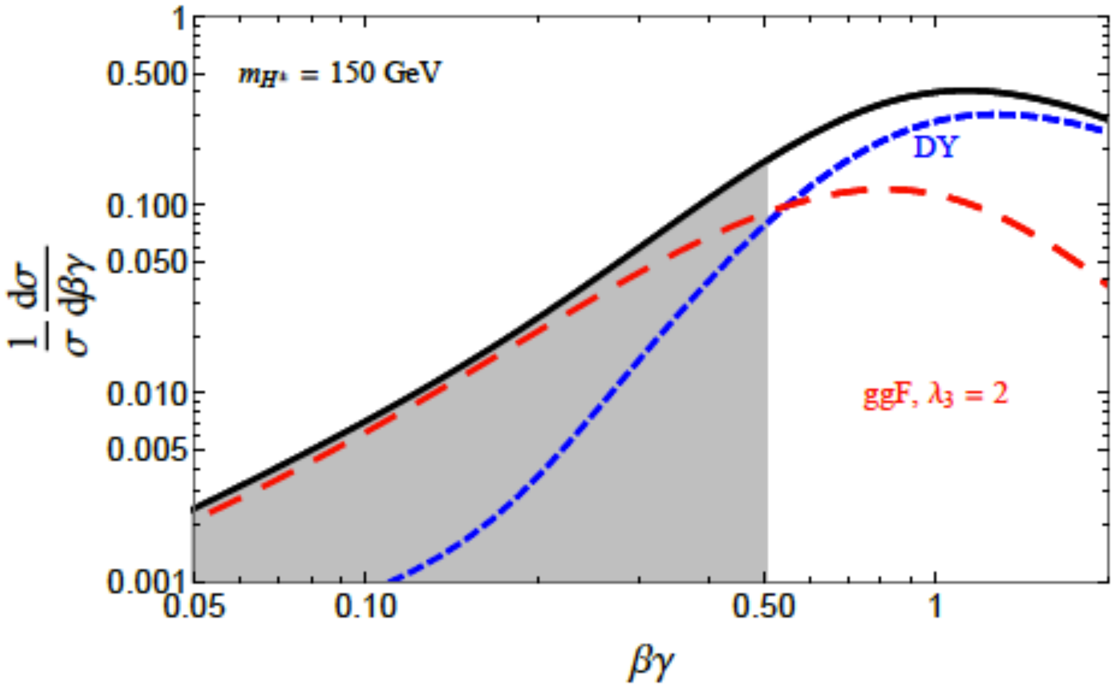
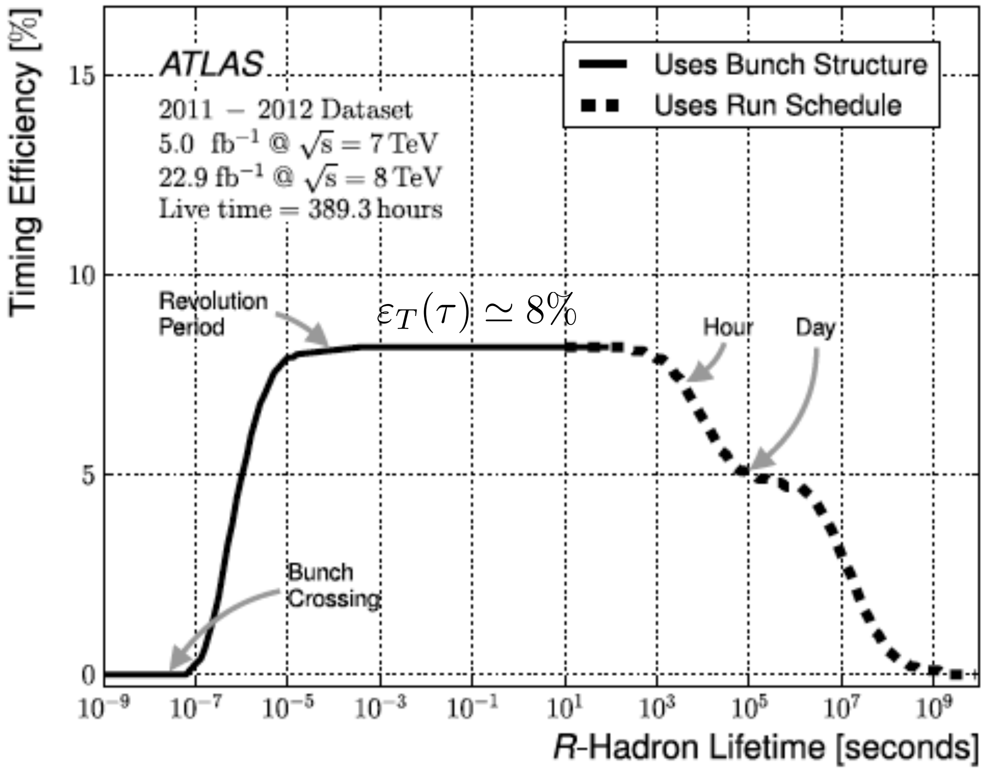


- Recast searches of R-hadrons decaying out-of-time, when there is no bunch crossing
- Signal: $H^\pm \to N_1\,\tau^\pm,\ \tau^\pm \to$jets, with $E_{\rm jet} > 50$ GeV
- $N^{\rm exp} = \sigma\, L\, \varepsilon_{\rm stop}\, \varepsilon_{\rm rec}\, \varepsilon_T(\tau)$
- This search is sensitive to DM masses $M_1 \gtrsim 1$ MeV
- No constraints set by this search at LHC run-1

1310.6584



Fermion NLOP

mass spectrum: $M_1 < M_2 < m_{H^\pm, H^0, A^0} < M_3$

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- Prompt decays (***y*₂>>*y*₁**):

$$H^0/H^\pm \to N_2 \ell/\nu$$

- Three-body decays of the NLOP:

$$N_2 \to \ell_\alpha \bar{\ell}_\beta N_1 \text{ and } N_2 \to \nu_\alpha \bar{\nu}_\beta N_1$$

N_2 decay-length exceeds the detector size (**dilepton signatures in MATHUSLA**)

Constraints from regular searches of final states with large transverse missing energy

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Constraints from regular searches of final states with large transverse missing energy

collider signature: two charged leptons and large missing energy

We apply ATLAS constraints from searches for SUSY simplified models with light sleptons and weakly decaying charginos (1403.5294):

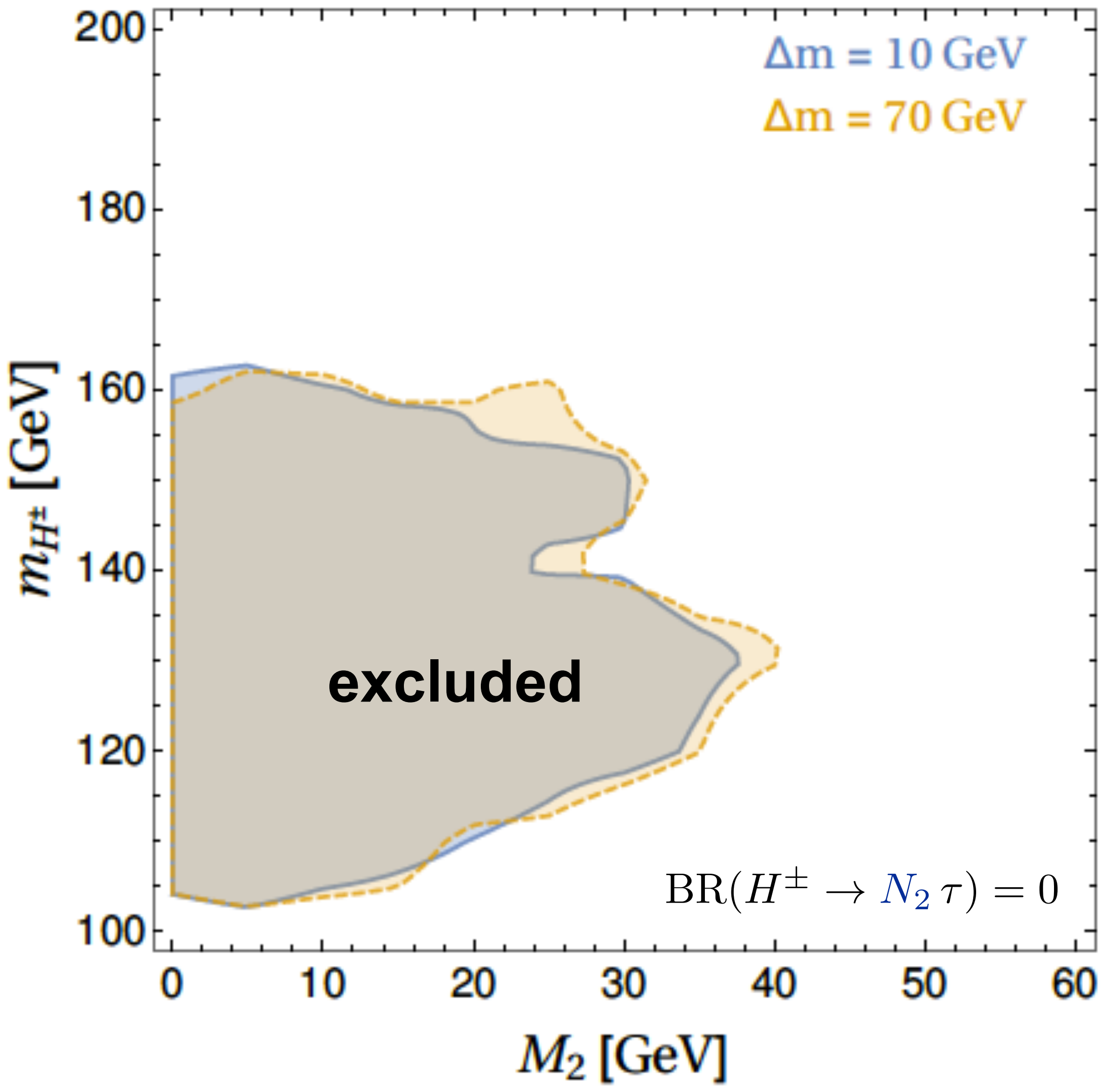
$$\tilde{\chi}_1^\pm \to (\tilde{\ell}^\pm \nu \text{ or } \ell^\pm \tilde{\nu}) \to \ell^\pm \nu \tilde{\chi}_1^0$$

Fermion NLOP

mass spectrum: $M_1 < M_2 < m_{H^\pm,H^0,A^0} < M_3$

- reconstruction of τ's challenging
- only e and μ in the final state
- use CheckMATE to recast analysis of ATLAS 1403.5294
- for BR($H^\pm \to N_2 \tau$) ≳ 0.3 dilepton production cross-section reduced: all the parameter space is allowed

$m_{H^\pm} < m_{H^0,A^0}$



most optimistic scenario

Fermion NLOP: displaced dileptons

mass spectrum: $M_1 < M_2 < M_3 < m_{H^\pm, H^0, A^0}$

Fermion NLOP: displaced dileptons

mass spectrum: $M_1 < M_2 < M_3 < m_{H^\pm, H^0, A^0}$

- Direct connection to the neutrino sector
- N_2 stable on collider scales (**dilepton signatures in MATHUSLA**)
- N_3 decay rate suppressed by neutrino Yukawa couplings: $N_3 \to \ell_\alpha \bar{\ell}_\beta N_2$

$$c\tau(N_3) \approx 0.02\text{cm} \frac{10 \text{ GeV}}{M_3} \frac{(10^{-2})^4}{|Y^\nu_{\alpha 2}|^2 |Y^\nu_{\beta 3}|^2} \frac{m^4_{H^\pm}}{M^4_3}$$

Fermion NLOP: displaced dileptons

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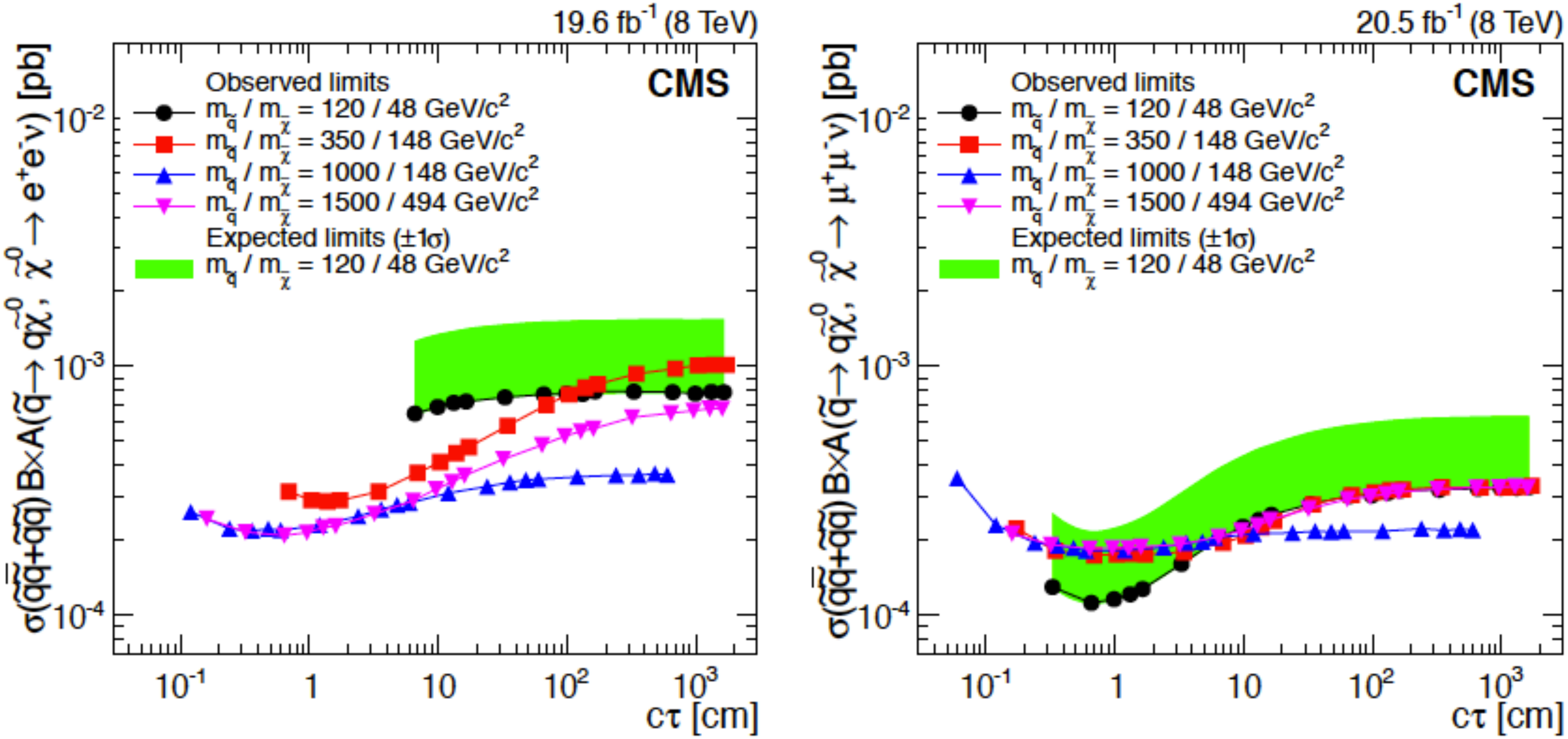
collider signature: displaced dileptons

Displaced dilepton pairs can be searched for very efficiently at the LHC. We focus on the search of displaced muon pairs in CMS-EXO-12-037

CMS displaced dilepton searches

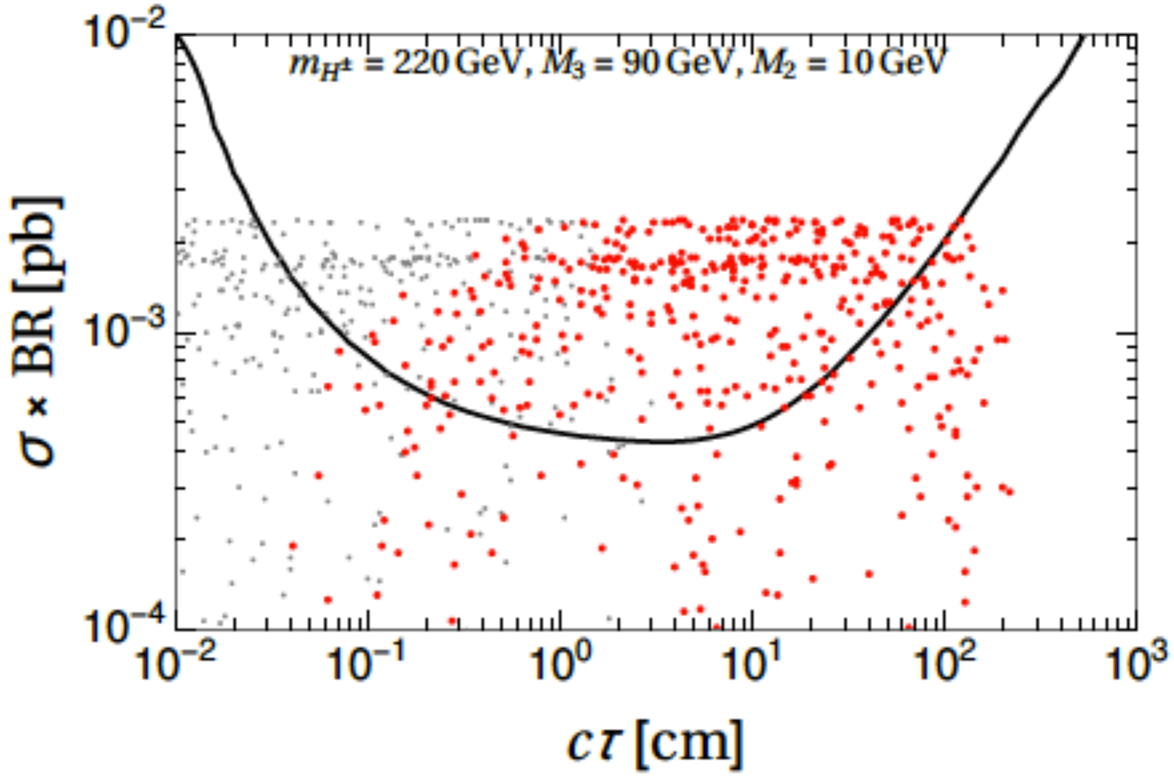
CMS-EXO-12-037



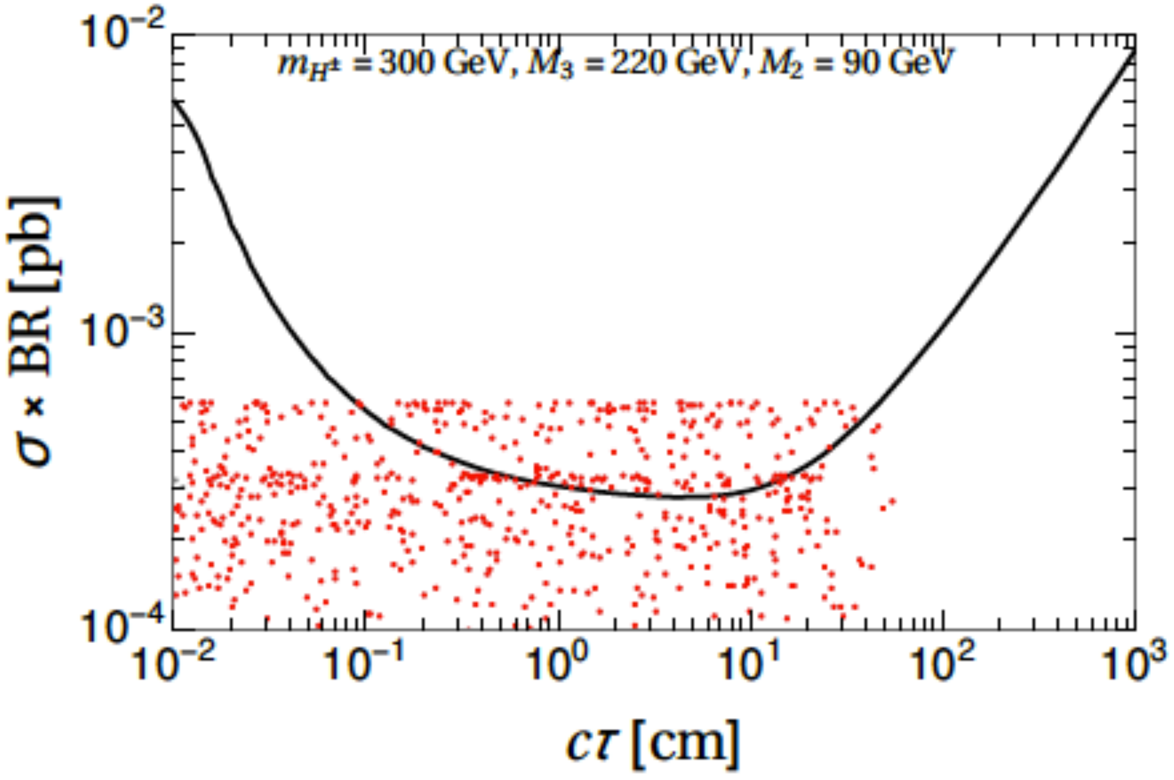
$$\tilde q \to q\,\tilde\chi^0, \quad \tilde\chi^0 \to \ell^+\ell^-\nu$$ in RPV-SUSY

Fermion NLOP: displaced dileptons

mass spectrum: $M_1 < M_2 < M_3 < m_{H^\pm, H^0, A^0}$



95% CL exclusion on displaced $\mu^+ \mu^-$ pair production

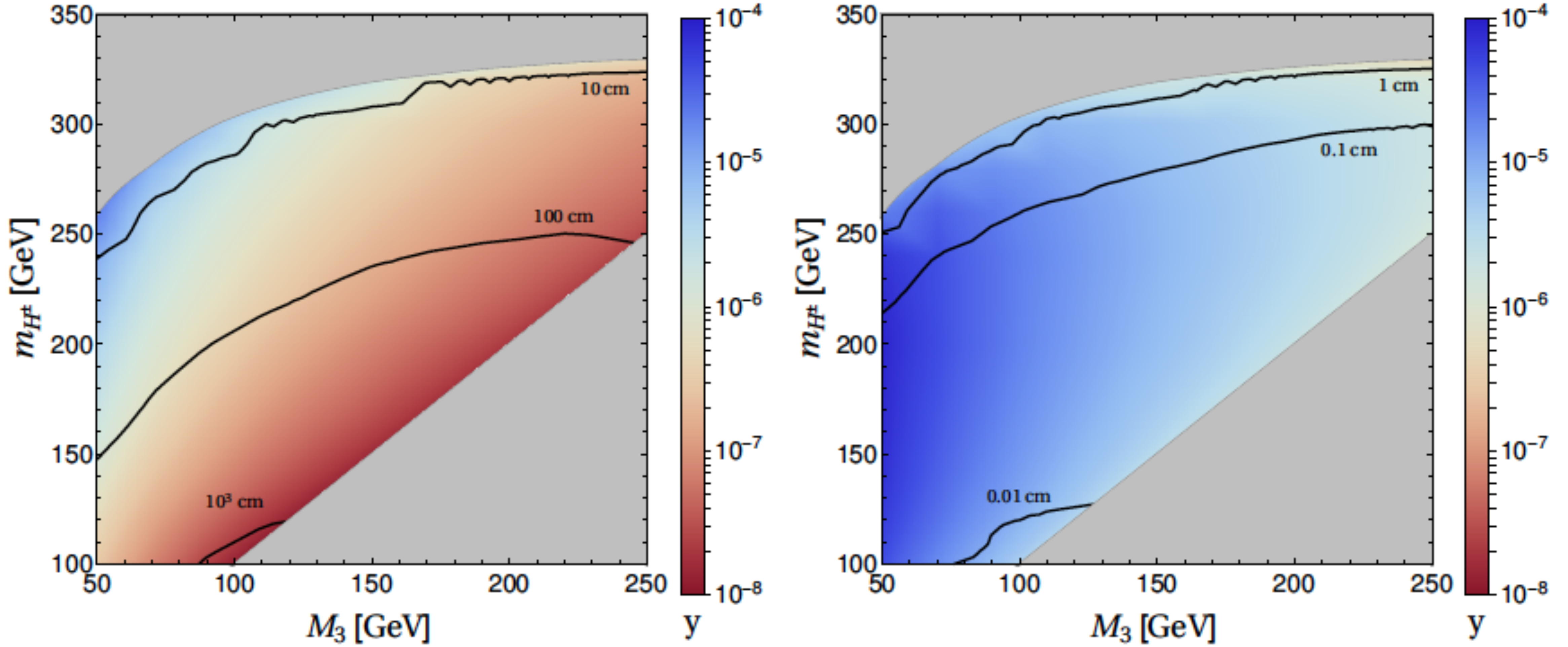


- All the points reproduce light neutrino masses and mixing
- Grey points are excluded by upper limit on $\mu \to e \gamma$

Fermion NLOP: displaced dileptons

mass spectrum: $M_1 < M_2 < M_3 < m_{H^\pm, H^0, A^0}$

smallest and largest combination of Yukawa couplings excluded



$$y \equiv \sqrt{|Y^\nu_{\mu 2} Y^\nu_{\mu 3}|}$$

$$\mathrm{BR}(N_3 \to \mu^+ \mu^- N_2) = 1/18$$

Summary

The nature of dark matter can be connected with the origin of neutrino masses in several extensions of the Standard Model. Possible tests: *direct detection* (scattering off nuclei), *indirect detection* (searching for annihilations into gamma-rays, neutrinos, charged cosmic-rays), *production at LHC*

In radiative neutrino mass models dark matter production can be linked to a feebly interacting massive particles

✤ Search program for long-lived particles at the LHC provides powerful tests of the FIMP dark matter paradigm (the NLOP is the portal between the visible and dark sectors)

✤ In the radiative neutrino mass model different collider topologies are possible according to the mass spectrum:

- heavy long-lived charged particles
- out-of-time decays of stopped long-lived charges particles
- displaced dileptons
- prompt decays to leptons $+ \not{E}_T$

BACKUP SLIDES

Stopped particles at the LHC

The mean energy loss of a particle in a material is described by the Bethe-Block equation

$$\langle -dE/dx\rangle = \kappa z^2 \langle Z/A\rangle \rho \frac{1}{\beta^2}\left[\ln\left(\frac{2\,m_e}{I}\frac{E^2-M^2}{M\sqrt{M^2+2\,m_e\,E+m_e^2}}\right)-\beta^2\right]$$

Layer	Δ [cm]	$[\lvert\eta\rvert_{\rm min},\, \lvert\eta\rvert_{\rm max}]$	Material	$\langle\rho\rangle$ [g/cm^3]	$\langle I\rangle$ [eV]	$\langle Z/A\rangle$
ID+Sol.	150.0	[0, 1.4]	Vacuum	-	-	-
EMB R1	47.6	[0, 0.8]	LAr+Pb	4.01	487	0.406
EMB R2	47.6	[0.8, 1.4]	LAr+Pb	3.67	447	0.408
HLB+HEB	197.0	[0, 1.4]	Fe+PS	6.40	286	0.466
MS+Tor.	∞	[0, 1]	Vacuum	-	-	-

Specs of our simplified ATLAS barrel.

Displaced dilepton analysis

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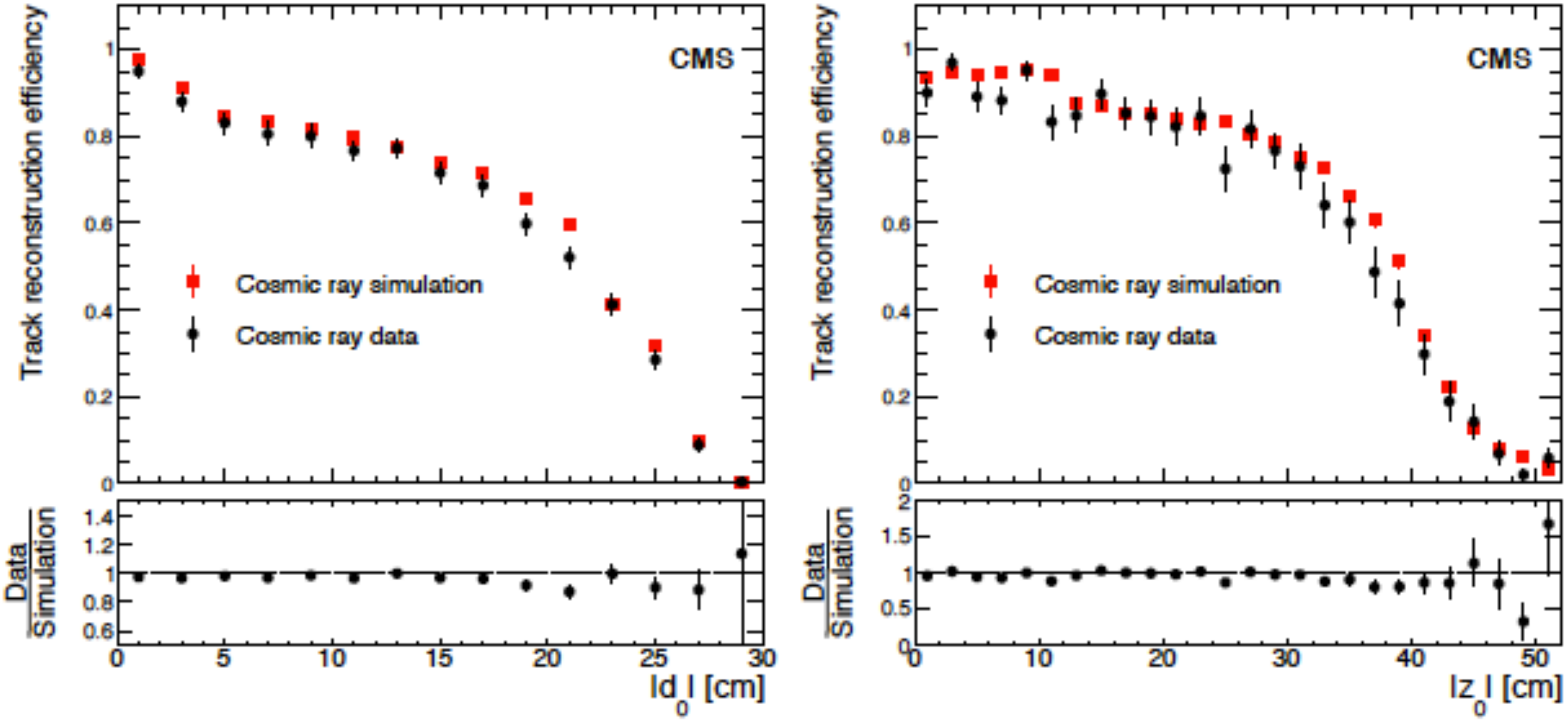


Figure 3: Efficiency to find a track in the tracker, measured using cosmic ray muons reconstructed in the muon detectors, as a function of the transverse (left) and longitudinal (right) impact parameters (relative to the nominal interaction point of CMS). The efficiency is plotted in bins of 2 cm width. For the left plot, the longitudinal impact parameter $|z_0|$ is required to be less than 10 cm, and for the right plot, the transverse impact parameter $|d_0|$ must be less than 4 cm. The bottom panels show the ratio of the efficiency in data to that in simulation. The uncertainties in the simulation are smaller than the size of the markers and are not visible.

Dark matter production via FIMP decays

1. In this case the FIMP ***N*₁** is not the lightest Z₂-odd particle

2. ***N*₁** decays modify the regions where the dark matter constraint is satisfied

$$\boxed{\begin{aligned} \Omega_{H^0}\, h^2 &= \Omega_{H^0}^{freeze-out}\, h^2 + \Omega_{H^0}^{N_1-decay}\, h^2 \\ \Omega_{H^0}^{N_1-decay}\, h^2 &= \frac{m_{H^0}}{M_1}\, \Omega_{N_1}^{freeze-in}\, h^2 \end{aligned}}$$

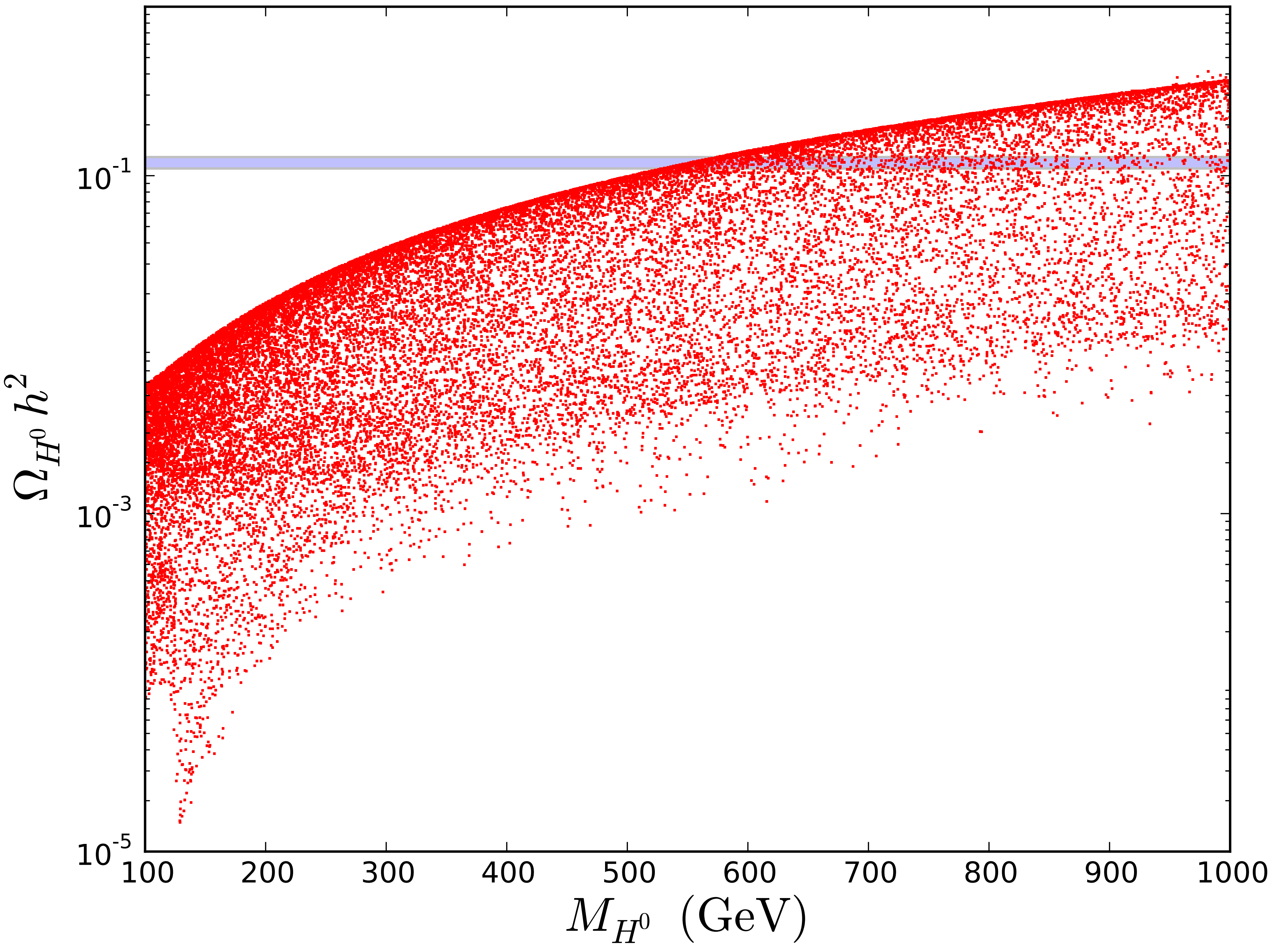
N_1 is produced via *freeze-in* $(H_2\, \ell \to N_1)$ and decays after DM *freeze-out*

$$\gamma_{N_1}(T) \;=\; \sum_X \frac{g_{N_1}\, m_{N_1}^2\, T}{2\,\pi^2}\, K_1\,(M_1/T)\; \Gamma\,(N_1 \to X\,\ell)\,,$$

$$\Omega_{H^0}^{N_1-decay} h^2 \quad \approx 0.1 \left(\tfrac{m_S}{100\,\mathrm{GeV}}\right) \left(\frac{1\,\mathrm{TeV}}{M_1}\right) \left(\frac{y_1}{2\times 10^{-12}}\right)^2 .$$

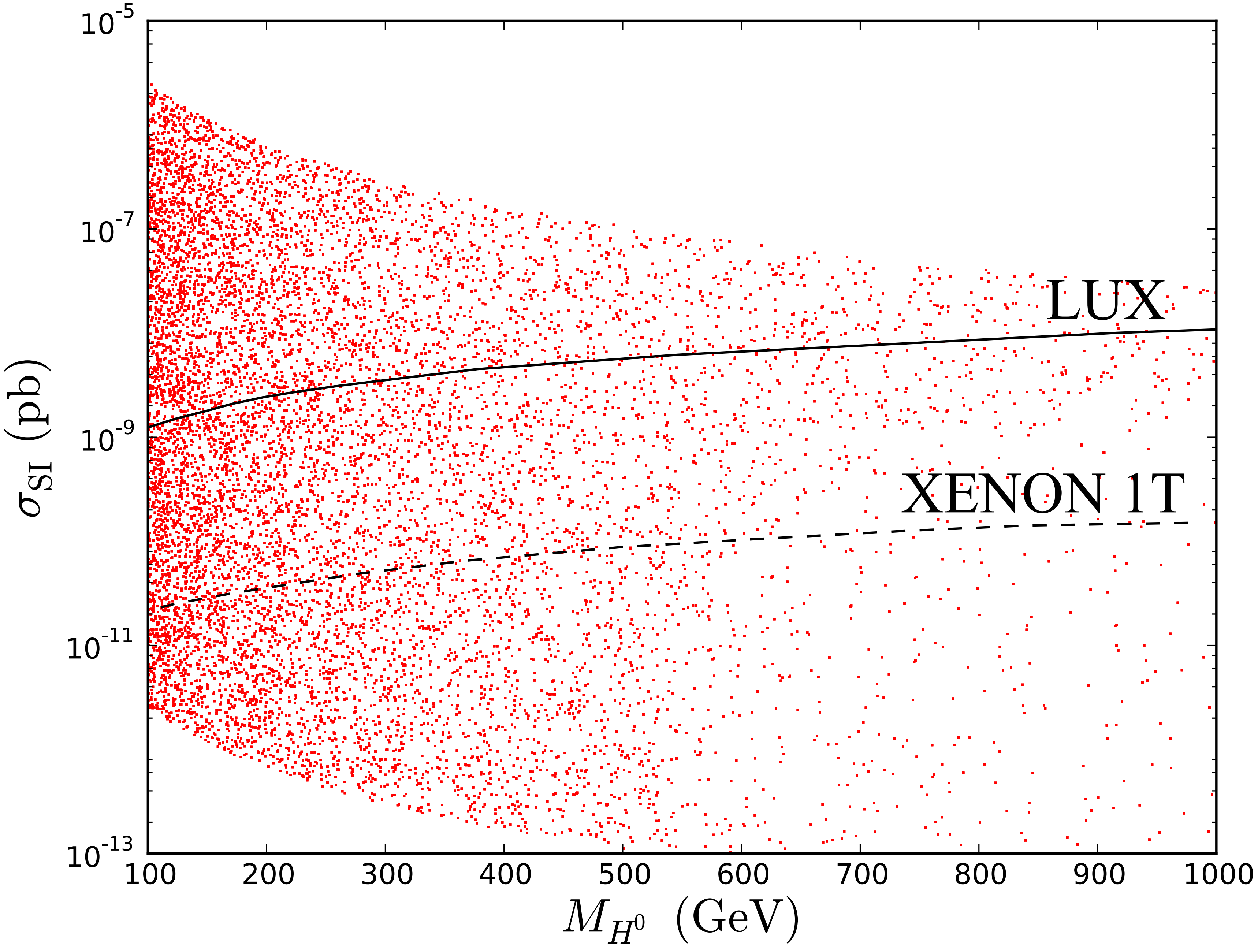
Dark matter production via FIMP decays

Expected dark matter relic density if $\boldsymbol{H^0}$ is a thermal relic



Dark matter production via FIMP decays

Direct detection cross-section mediated by the Higgs exchange



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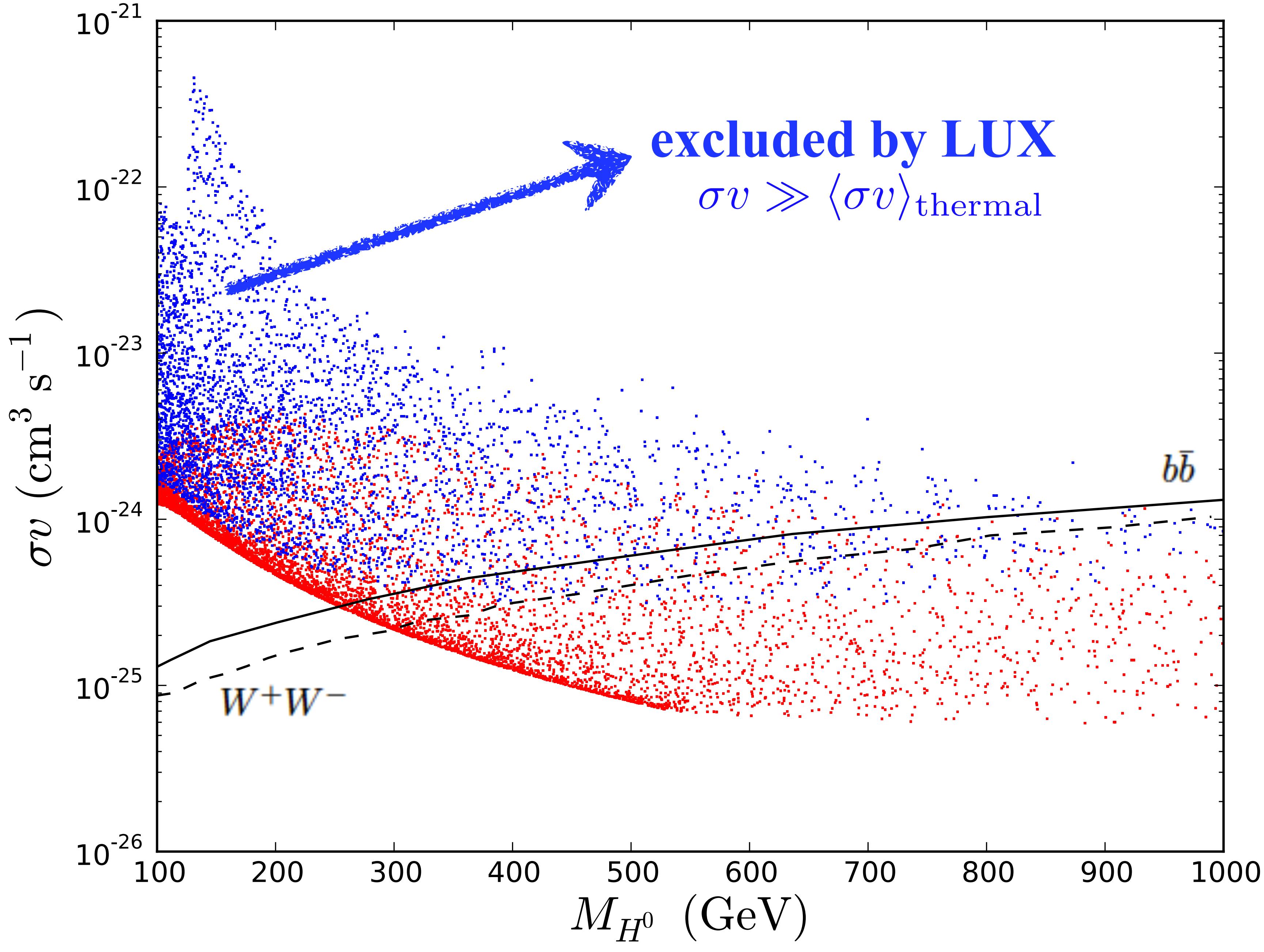
Dark matter production via FIMP decays

Indirect detection constraints from Fermi-LAT



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