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Cornering GeV-scale Majorana dark matter using Higgs bosons

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Based on the work in collaboration with S. Nasri & R.Soualah
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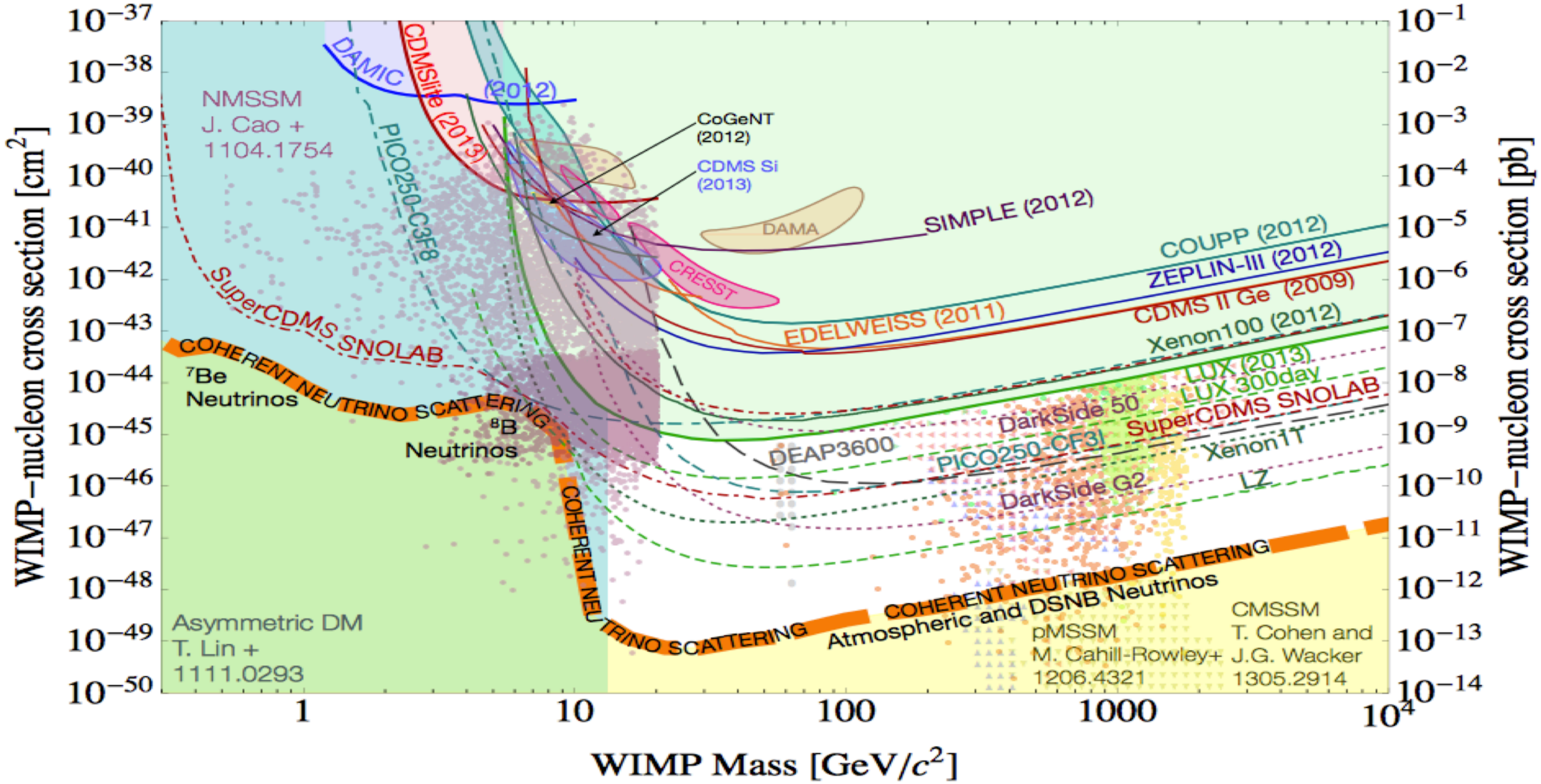
Is dark matter the aether of the twenty-first century?



PROBLEM: dark-matter direct searches are strongly correlated with collider searches.

→ Strong bounds from direct searches imply expected weak signals at colliders.

→ It tends to exclude the simplest dark-matter model; *i.e.* the singlet model.

What if the dark matter candidate is a singlet Majorana fermion?

- Simple dark-matter models lead to *s*-wave annihilation channels; Models with *s*-wave annihilations are almost excluded from indirect-detection searches (model-independent analysis by **Leane, Slatyer, Beacom and Ng; 2018**).
- Collider searches at the Large Hadron Collider tend to exclude couplings of order $\mathcal{O}(1)$ and light dark-matter masses (see e.g. the summary plots in **ATL-PHYS-PUB-2020-021**)
- An alternative solution is to consider (or reconsider) Majorana singlet fermions as a dark-matter candidate:
  1. The elastic scattering of dark-matter off the nucleus is induced at the one-loop order → The corresponding cross-section is always suppressed even for couplings of order $\mathcal{O}(1)$.
  2. Hard to produce at hadron colliders for a wide class models → Explain why it is not observed so far?
  3. Annihilation cross section occurs through p-wave amplitudes; no signal, no problem.
  4. Lepton colliders may play the role of discovery machines for these models.

Models with Majorana dark matter: directions

- Singlet Majorana fermions can be accommodated in many extensions of the SM in e.g. models neutrino mass generation through loops

Examples: One-loop **(E. Ma; 2006)**, Three-loops **(Krauss-Nasri-Trodden; 2003)** and Three-loops with multi-Doublets **(Aoki-Kanemura-Seto; 2009)**

What if follows a bottom-up approach?

Any model of this kind should fulfill these four pillars **(Stephen King: 1701.04413)**

Minimality
It must be simple/elegant to have a chance of being correct

Predictivity
It must be possible to exclude such models by experiments

Robustness
It must be firmly based on some theoretical symmetry and/or dynamics

Unification
It must be capable of being embedded into a grand-unified theory

Can be studied for a wide class of models

A Minimal Leptophilic dark-matter model

We suggest a new minimal model where we extend the Standard Model with two gauge-singlets: a charged scalar S and a right-handed singlet Majorana fermion N_R.

They transform under $SU(3)_c \times SU(2)_L \times U(1)_Y$ as

$$S: \ (1,1,2) \text{ and } N_R: \ (1,1,0)$$

These extra states are odd under an extra Z_2 symmetry (called matter parity) while all the SM particles are even, *i.e.* $\{S, N_R\} \to \{-S, -N_R\}$ and $\{V^\mu, f, \Phi\} \to \{V^\mu, f, \Phi\}$

The most general interaction Lagrangian can be written as

$$\mathscr{L}_{\rm int} \supset \sum_{\ell=e,\mu,\tau} y_\ell \bar{\ell}^c_R S N_R + \lambda_2 |S^\dagger S|^2 + \lambda_3 |\Phi^\dagger \Phi||S^\dagger S|$$

The scalar singlet (S) is electrically-charged and plays the role of a mediator between dark matter and the SM sectors:

$$\mathscr{L}_{\rm gauge} \supset -i\left(eA^\mu - e\tan\theta_W Z^\mu\right) S^\dagger \overleftrightarrow{\partial}_\mu S$$

$$A\overleftrightarrow{\partial}B = A(\partial B) - (\partial A)B$$

What about the various constraints?

After electroweak symmetry breaking; one is left with two extra states (N_R and $H^\pm$) and seven extra parameters (three are interconnected via lepton-flavor violation and one is irrelevant in phenomenological studies). The parameters are

$$\{m_{H^\pm}, m_N, \lambda_2, \lambda_3, y_e, y_\mu, y_\tau\} \longrightarrow \{m_{H^\pm}, m_N, \lambda_2, \lambda_3, y_N\}$$

Good approximation for massless leptons; $y_N = \sqrt{y_e^2 + y_\mu^2 + y_\tau^2}$

The model is subject to various constraints:

Theoretical constraints

(i) Vacuum stability: the scalar potential should bounded from below **(Branco et al.; 2012)**

(ii) Perturbativity & Perturbative unitarity

(iii) False vacuum

Experimental constraints

(i) $H \to \gamma\gamma$

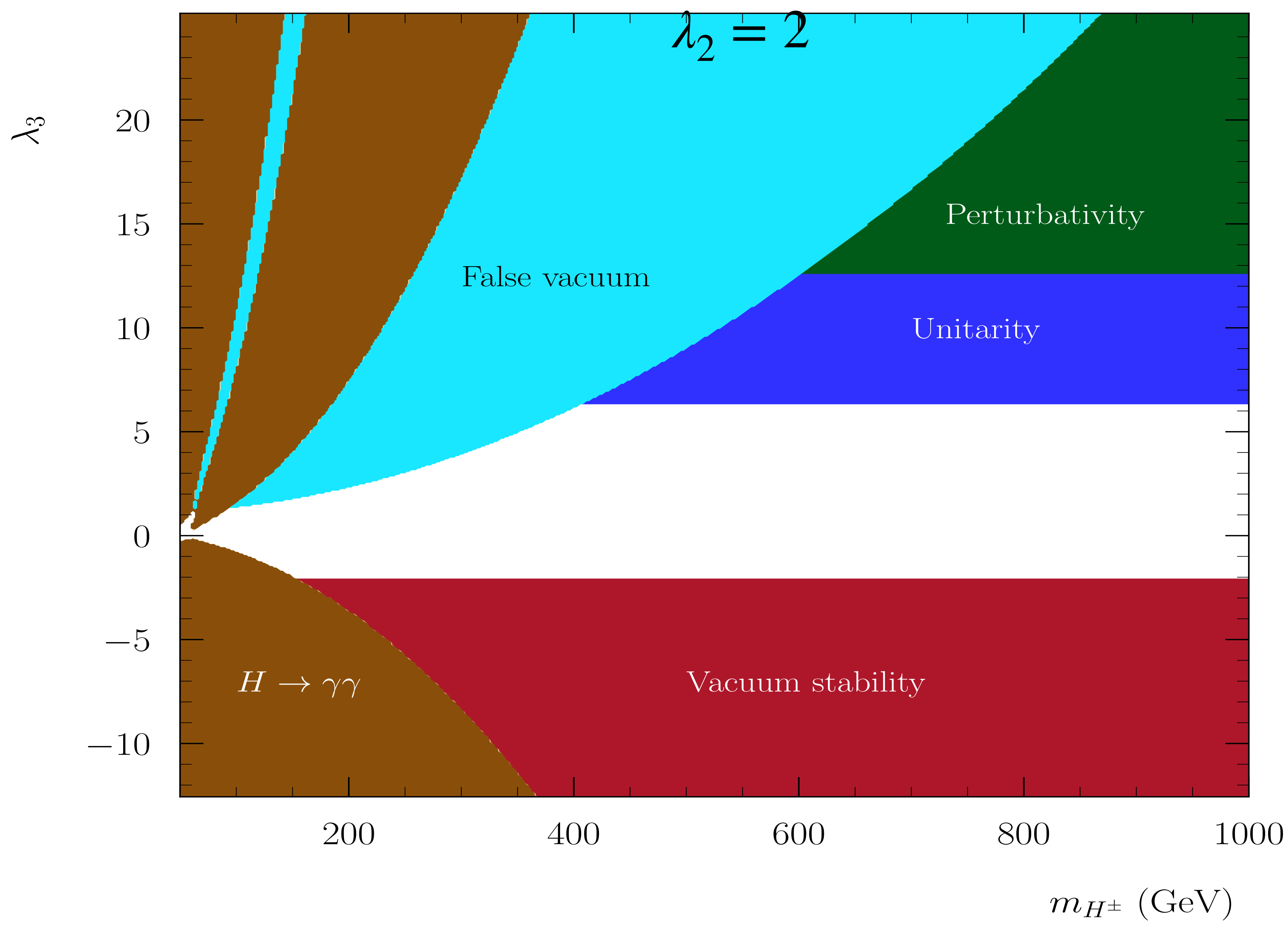
(ii) Higgs invisible decay ($H \to N_R N_R$): relevant for $m_H > 2m_N$

(iii) Charged lepton flavor violating decays; $\ell_\alpha \to \ell_\beta \gamma$ and $\ell_\alpha \to \ell_\beta \ell_\gamma \bar{\ell}_\gamma$

(iv) Searches of charginos at LEP-II.

Summary of theoretical and experimental constraints

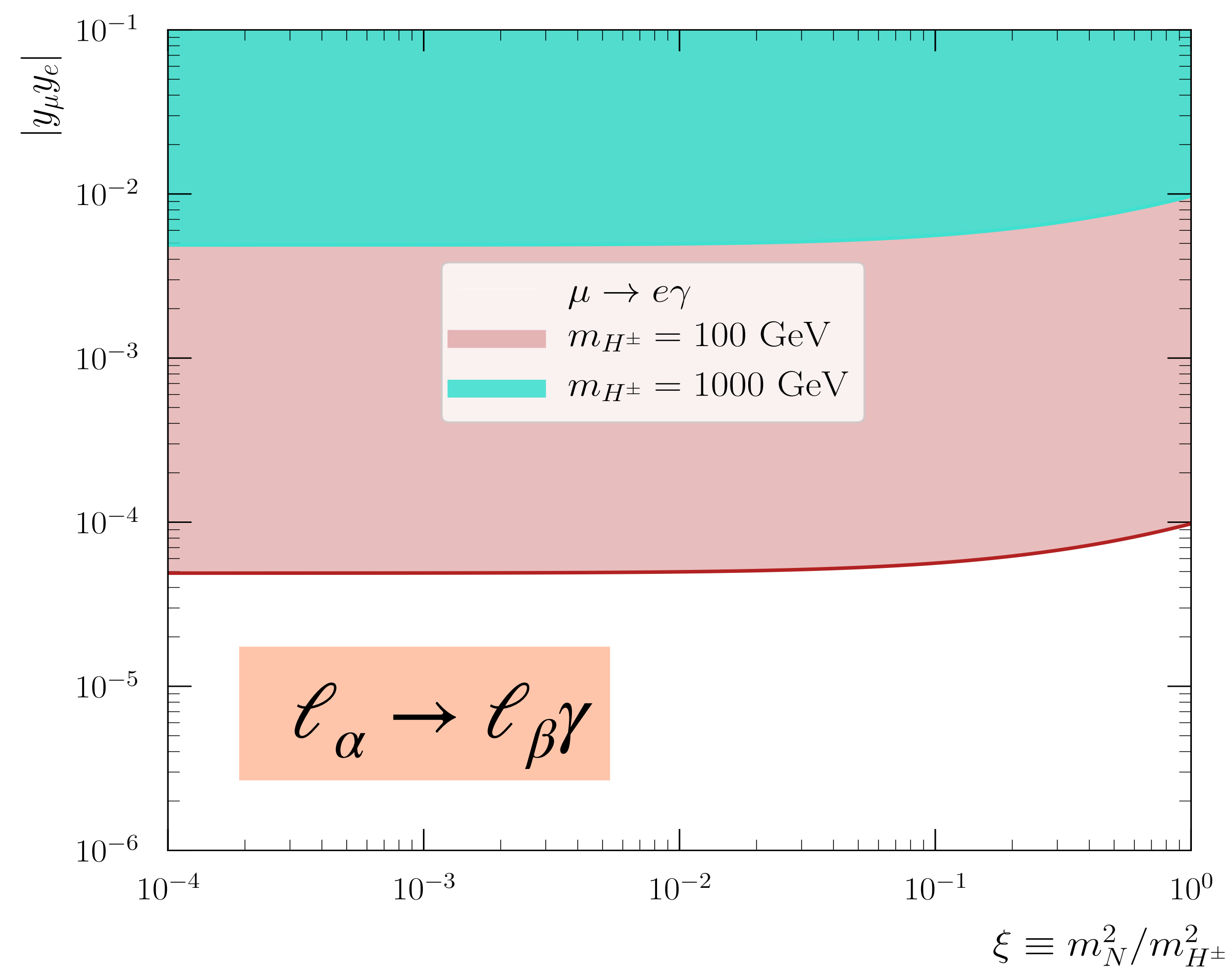
- Perturbativity and unitarity constraints exclude large values of λ_3.
- The bounds on the charged Higgs mass do not depend on λ_3 for $\lambda_3 \approx \mathcal{O}(1)$.
- If λ_3 is large, false vacuum constraints exclude light charged Higgs masses; i.e. one has $m_{H^\pm} \geq 350$ GeV for $\lambda_3 = 5$.
- For $\lambda_3 > 0$, there is a region where the constraints from $H \to \gamma\gamma$ completely vanish.



CLFV and Higgs invisible decays

Bounds on $\mathrm{BR}(\ell_\alpha \to \ell_\beta \gamma)$ from MEG and BABAR

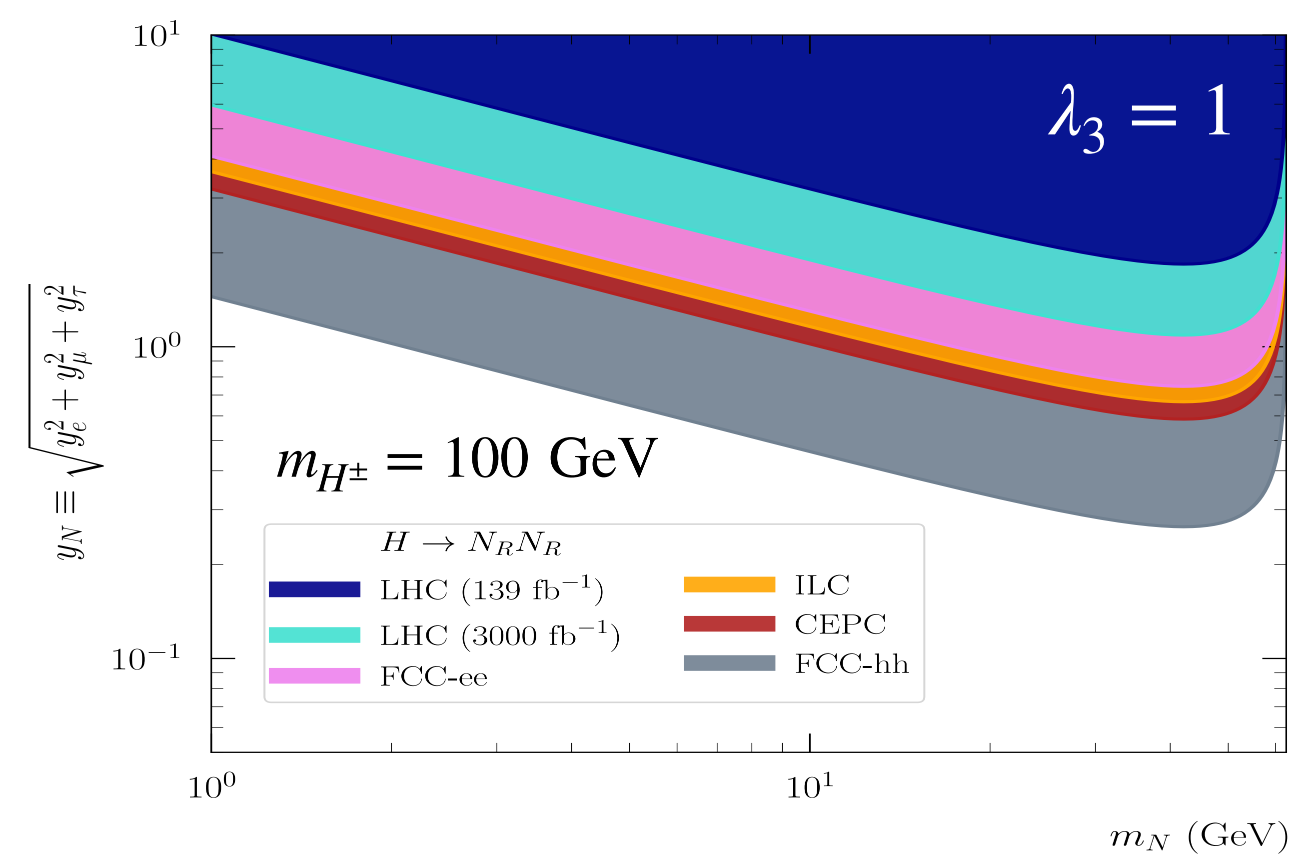
$$\{|y_e y_\mu|, |y_\mu y_\tau|, |y_\tau y_e|\} < \left\{ \left(\frac{2.85\times 10^{-5}}{\mathrm{GeV}}\right)^2, \left(\frac{3.07\times 10^{-4}}{\mathrm{GeV}}\right)^2, \left(\frac{2.87\times 10^{-4}}{\mathrm{GeV}}\right)^2 \right\} \times \frac{m_{H^\pm}^2}{|F(\xi)|}$$



$$y_N < \left(\frac{2^{11}\pi^5 \Gamma_H^{\mathrm{SM}}}{\beta_N^3 m_H \lambda_3^2 v^2 m_N^2 |C_0 + C_2|^2 \mathscr{R}_{\mathrm{exp}}} \right)^{1/4}$$

$$\mathscr{R}_{\mathrm{exp}} = \frac{1}{B_{H\to\mathrm{invisible}}^{\mathrm{up.bound}}} - 1 \qquad C_{0,2} \equiv C_{0,2}(m_N^2, m_H^2, m_N^2, m_\ell^2, m_{H^\pm}^2, m_{H^\pm}^2)$$

Passarino-Veltman functions

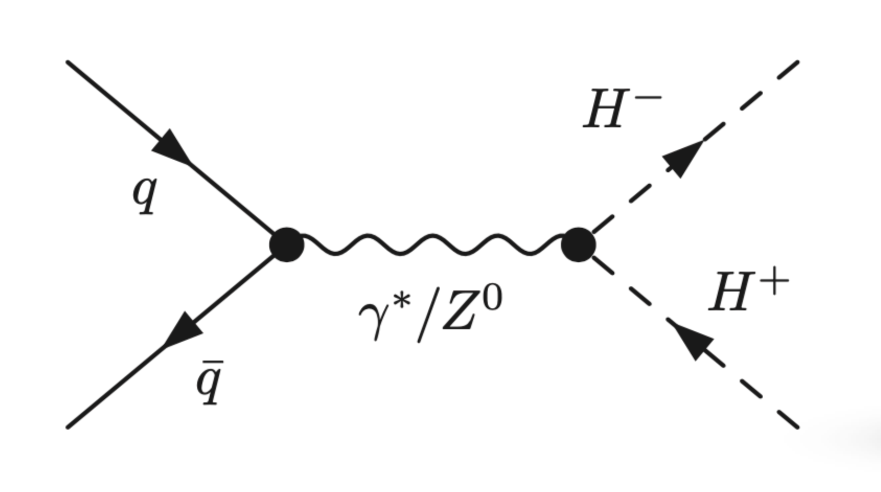


- $y_e \simeq \mathcal{O}(1) \gg y_\tau \gg y_\mu$: Interesting for e^+e^- colliders (will be used in this study).
- $y_e \simeq y_\mu \simeq y_\tau \simeq \mathcal{O}(10^{-2})$: can be tested in hadronic collisions.
- $y_\mu \simeq \mathcal{O}(1) \gg y_\tau \gg y_e$: Interesting for $\mu^+\mu^-$ colliders.

- The future constraints on y_N are expected to be very important for light charged Higgs boson.
- Note that it's very hard to produce the correct relic density for $m_N < 10$ GeV; *freeze-in needed?*

Status at the Large Hadron Collider

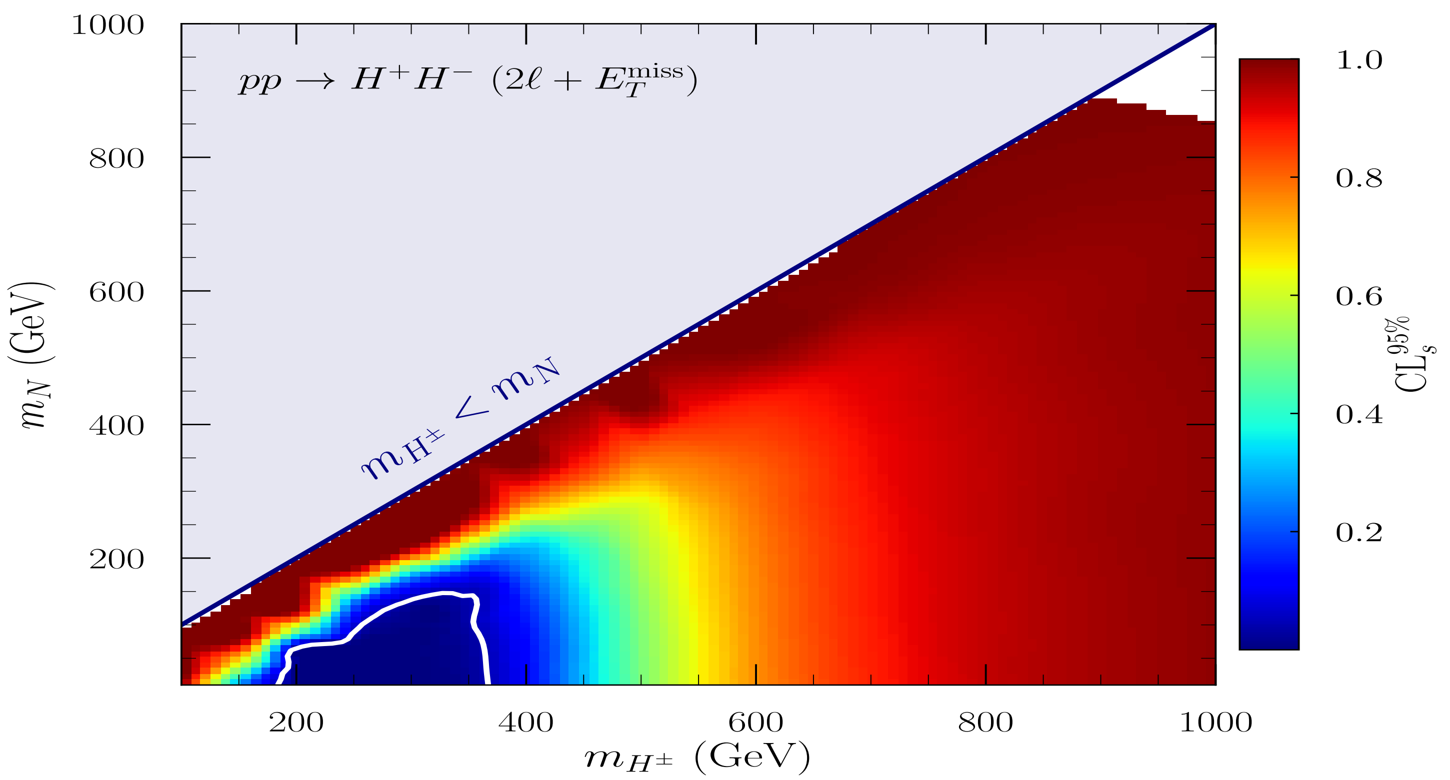
- The model can be constrained from re-interpretation of the results of sleptons/charginos; In our model, we can pair produce the charged Higgs boson through $q\bar{q}$ annihilation and then decay them to charged leptons plus N_R.
- ATLAS has searched for sleptons/charginos defining eight signal regions — depend on the jet multiplicity $n_{\rm jet} = 0{,}1$ and the bins for the stranverse mass M_{T2} —.
- Masses of the charged Higgs boson up to 400 GeV can be excluded.
- No sensitivity at all for small mass splitting $(m_{H^\pm} - m_N)$.



+ ≤ 2 partons

+ Merging

Destructive interference between γ^* and Z^0



Strongest bound comes from the same-flavor (SF) region with $n_{\rm jets} = 0$ and $M_{T2} \in [160, \infty)$

(Electron-enriched because of our choice of y_ℓ)

Dark matter relic abundance

The relic abundance of N_R gets contributions that can be categorized into sets (assuming freeze-out mechanism):

(i) Annihilation into SM particles (important for $y_N = \sqrt{y_e^2 + y_\mu^2 + y_\tau^2} \approx \mathcal{O}(1)$

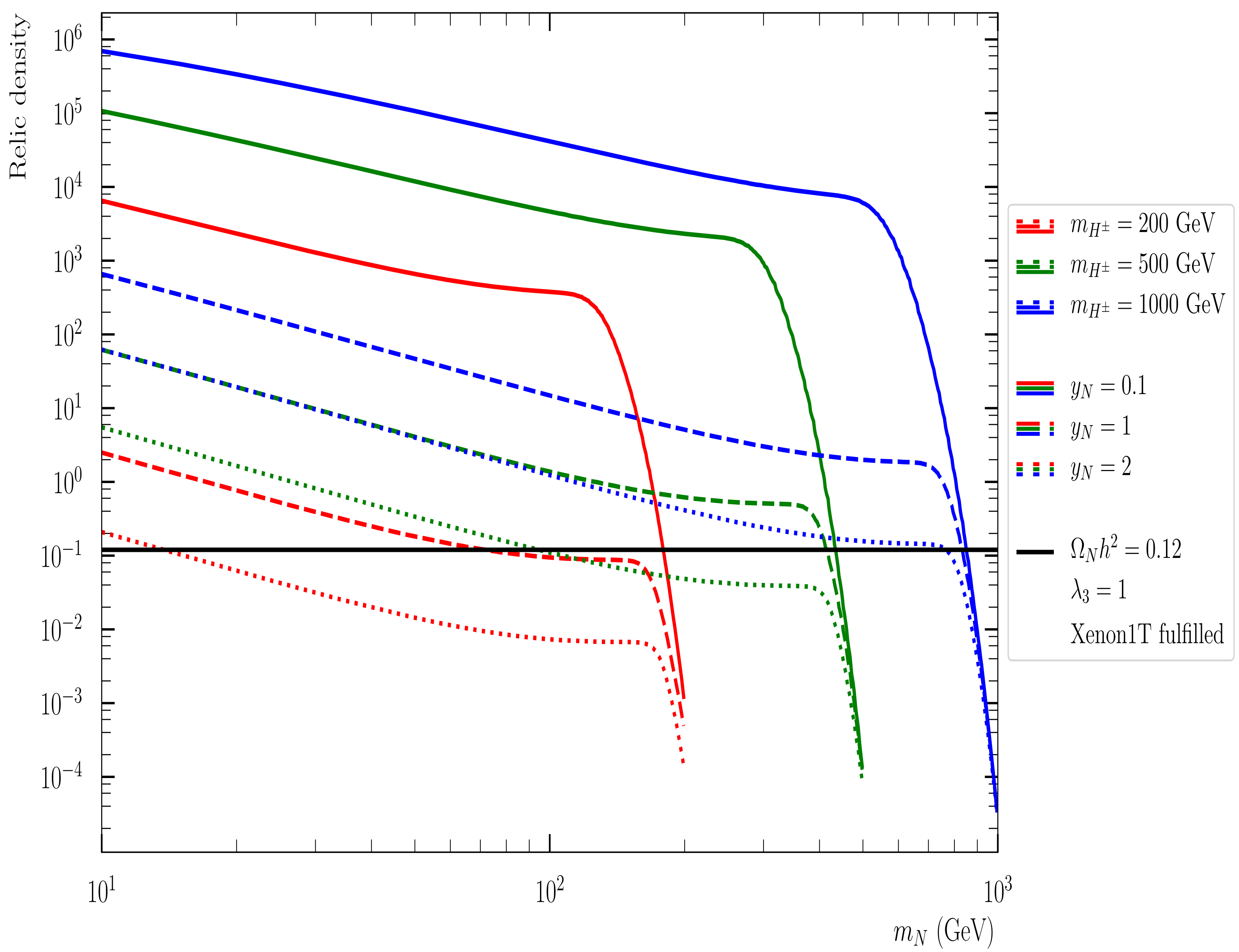
$$N_R N_R \to \ell^\pm \ell^\mp$$

$$N_R N_R \to H^* \to \tau\tau, b\bar{b}, t\bar{t}, Z^0 Z^0, W^+ W^-, HH$$

(ii) Co-annihilation channels; dominates for tiny mass-splitting; $\Delta < m_N/10$:

$$N_R H^\pm \to \ell^\pm H, W^\pm \nu_\ell, \ell^\pm Z, \ell^\pm \gamma$$

$$H^\pm H^\mp \to \ell^\pm \ell^\mp, q\bar{q}, HH, ZZ, W^\pm W^\mp, ZH, t\bar{t}$$



Dark matter direct detection & its correlation to $\Omega_N h^2$

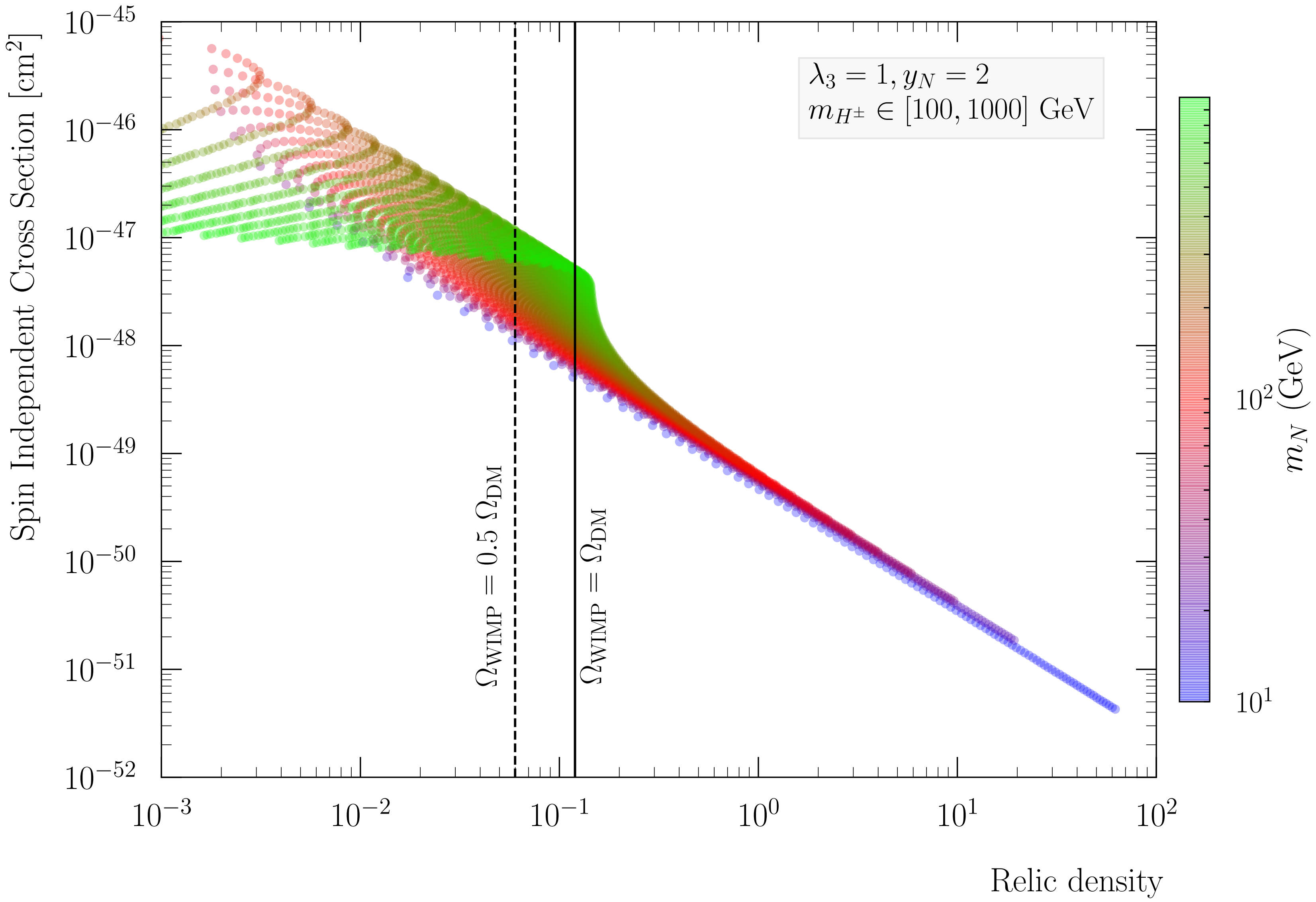
The spin-independent nucleus-N_R elastic cross section occurs at the multi-loop level

Always suppressed even for couplings of order one

An overall factor of

$$+ \frac{y_N^4 \lambda_3^2}{m_N^2}\left(1 + \frac{m_{H^\pm}^2 - m_N^2}{m_N^2}\log(\mathcal{O}(1))\right)^2$$

- Strong anti-correlation is observed between the spin-independent cross section ($\sigma_{\rm SI}$) and the relic abundance of N_R.
- Regions where the predicted $\sigma_{\rm SI}$ is enhanced are hard to exclude as they correspond to $\xi \equiv \Omega_N h^2/\Omega_{\rm Planck} h^2 \ll 1$

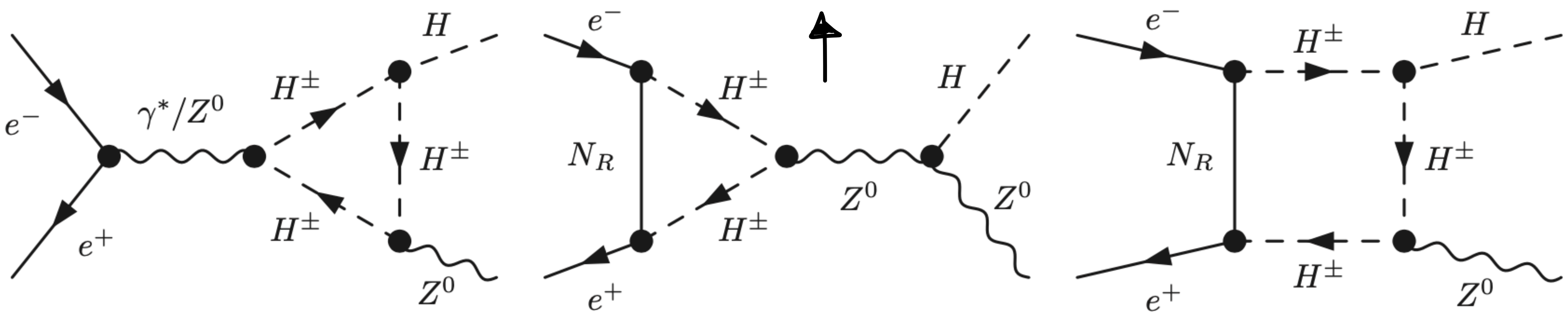


Prospects at the International Linear Collider

(Indirect effects)

Known to be of order 4-10% of the tree-level cross section (within e.g. the IHDM)

Never estimated before.



(a) (b) (c)

Never estimated before: interesting threshold effects are expected.

$$\sigma_{e^+e^-\to HZ} \propto \sigma_{\rm tree}^{\rm SM} \times (1 + \Delta\sigma) + \mathcal{O}(\alpha^2)$$

$$\Delta\sigma \propto {\rm RE}(\mathcal{M}_{\rm SM}^{\rm tree}\mathcal{M}_{\rm loop}^\dagger); \quad \mathcal{M}_{\rm loop} = \lambda_3 g^2_{H^\pm H^\mp\gamma/Z}\mathcal{M}^{(a)} + y_e^2 g_{H^\pm H^\mp Z}\mathcal{M}^{(b)} + y_e^2\lambda_3 g_{H^\pm H^\mp Z}\mathcal{M}^{(c)}$$

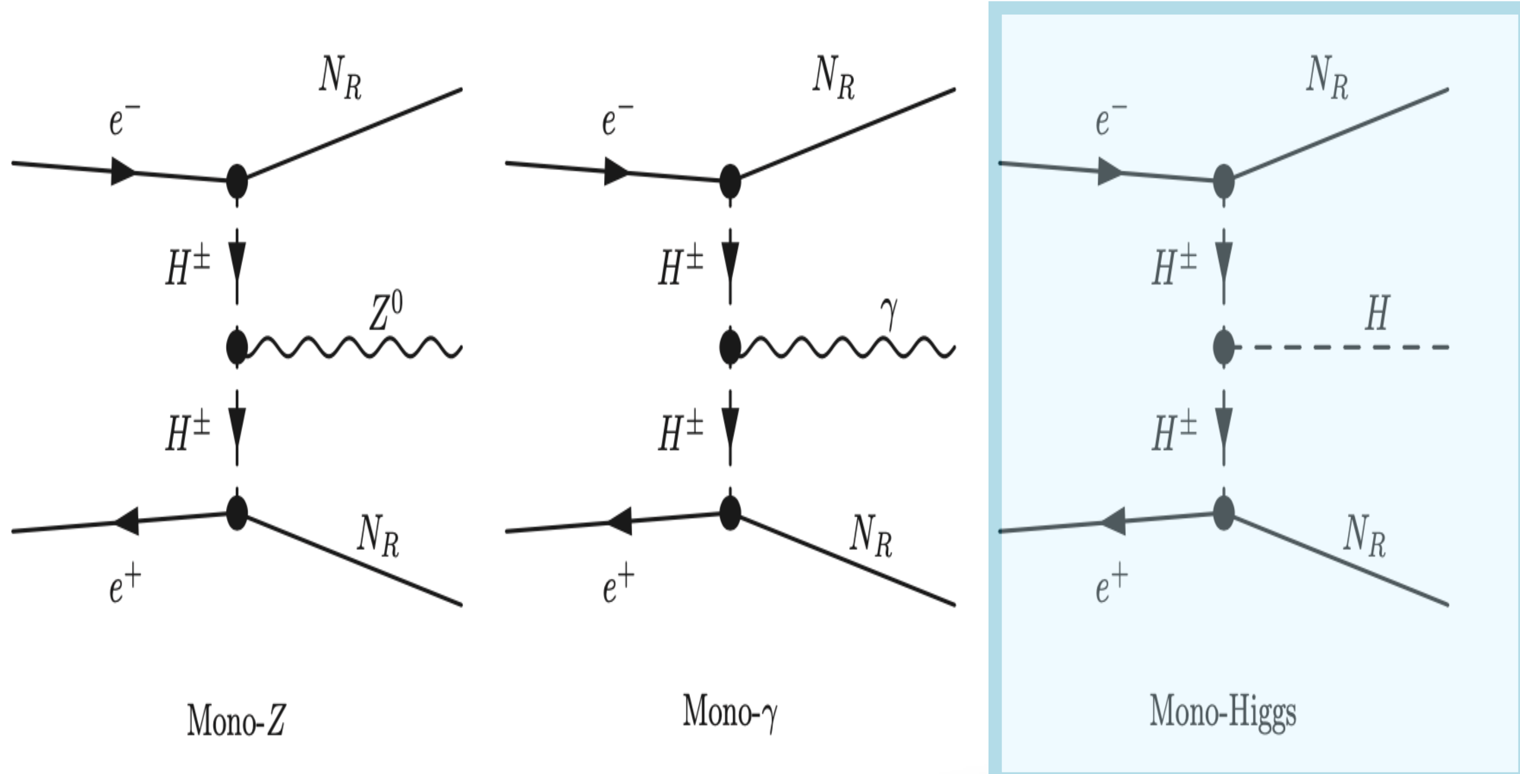
At linear colliders, $\sigma(HZ)$ is going to be measured with high precision ***(ILC white paper; 2013)***:

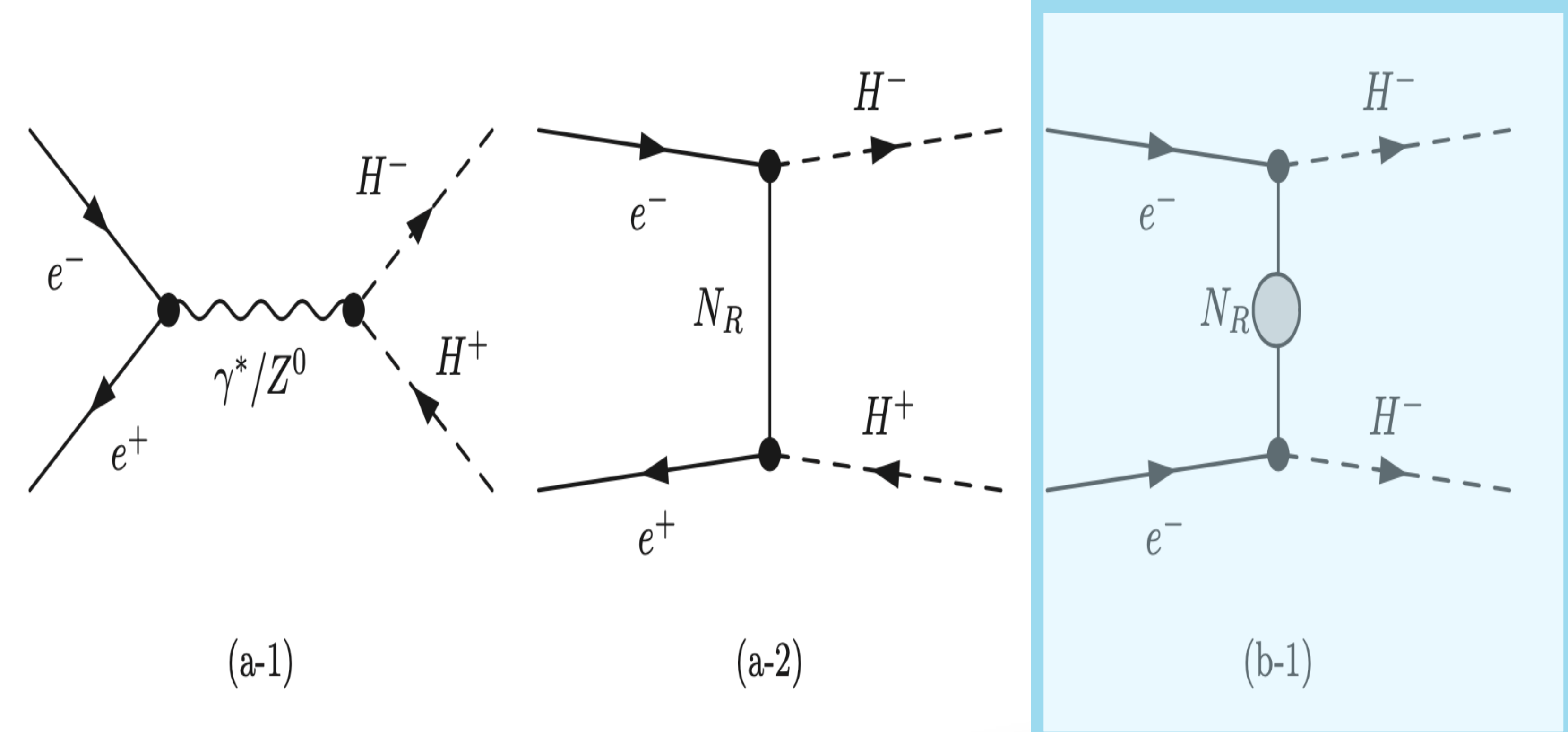
- $\delta\sigma = 1.2\,\%$ at $\sqrt{s} = 250$ GeV (recoil mass technique $\ell^+\ell^-H$).
- $\delta\sigma = 3.9\,\%$ at $\sqrt{s} = 500$ GeV (fat k_T jet associated with $Z \to q\bar{q}$).

- These corrections can be a part of an important study to constrain this class of models (could include more processes e.g. $e^+e^- \to HH + X$).
- Expect threshold effects (bump-like structures) in the tails of the M_{ZH} and p_T^H distributions.
- Dedicated search strategy (orthogonal to the recoil-mass techniques?).

Prospects at the International Linear Collider

(Direct probes)





Sensitive to y_e; $\sigma_{NNZ} \propto e^2 \tan^2\theta_W y_e^4$

Sensitive to y_e; $\sigma_{NN\gamma} \propto e^2 y_e^4$

Sensitive to y_e and λ_3; $\sigma_{NNH} \propto \lambda_3^2 y_e^4$

Sensitive to y_e:

$$\sigma_{H^+H^-} \propto |e^2\mathcal{M}^{\gamma^*}_{(a1)} + e^2\tan^2\theta_W \mathcal{M}^{Z}_{(a1)} + y_e^2 \mathcal{M}_{(a2)}|^2$$

Expects destructive interference between the different diagrams

Much more interesting:

- Very small backgrounds in e^-e^- collisions
- $\sigma(H^-H^-) \propto y_e^4 m_N^2$ (grows with the dark-matter mass)

Processes of class (b-1) can be used to probe CLFV

$$e^-e^- \to H^-H^- \to \ell_i^- N_R, \quad \ell_k^- N_R$$

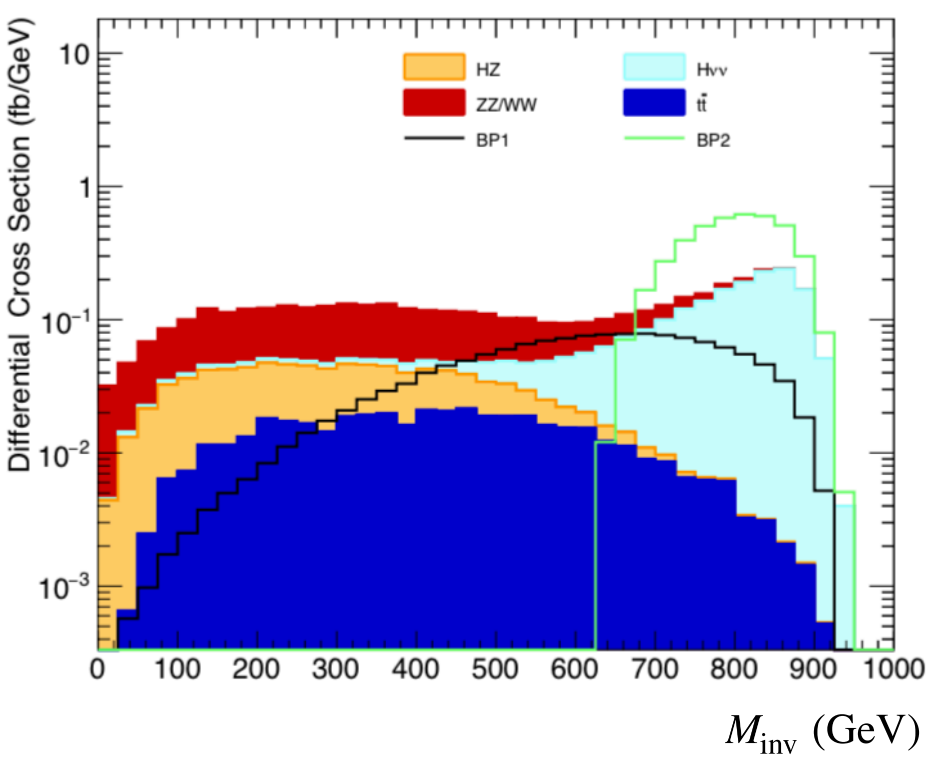
$$\sigma_{e^-e^-\to\ell_i^-\ell_k^-} \propto m_N^2 y_e^4 y_i^2 y_k^2$$

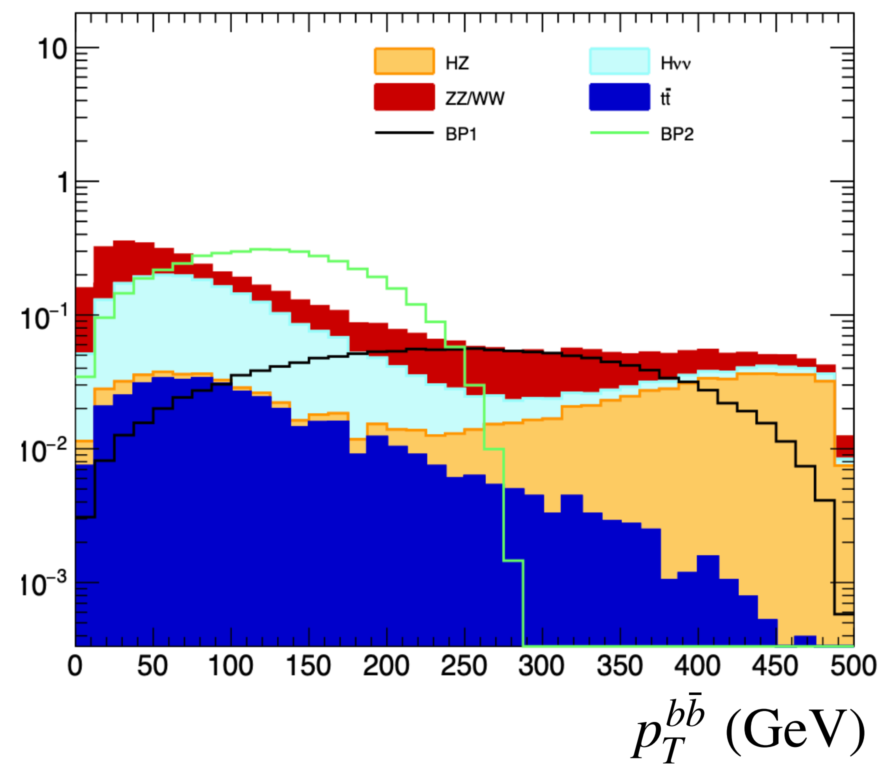
Strongly correlated to CLFV decays: High energy probe of CLFV? ***(Needs a dedicated study)***

Prospects at the International Linear Collider

In this study, we focus on two processes:

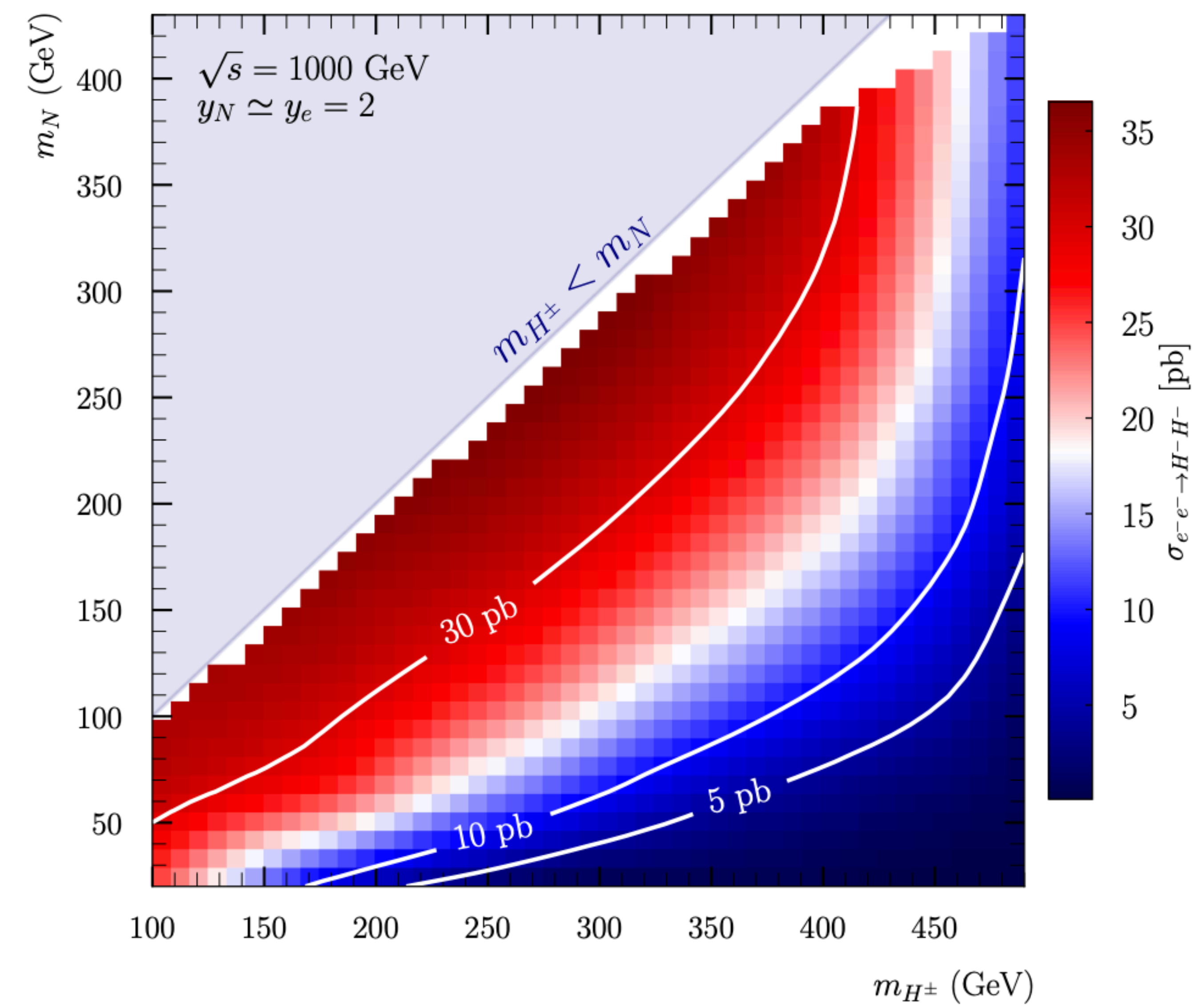
- Mono-Higgs process at $\sqrt{s} = 500,\ 1000$ GeV
- Same-sign charged Higgs pair production at $\sqrt{s} = 1000$ GeV





For mono-Higgs search, a dedicated analysis has been designed:

- Assuming $H \to b\bar{b}$; there are five main backgrounds, i.e. $HZ, H\nu_e\bar{\nu}_e, t\bar{t}, ZZ, W^+W^-$
- Selecting events which consist of exactly two b-tagged jets, and large missing energy.
- To reconstruct the invisible mass, we veto events which comprise of isolated leptons, photons or taus.
- Signal region is based on the invariant mass of $b\bar{b}$ and invisible systems.



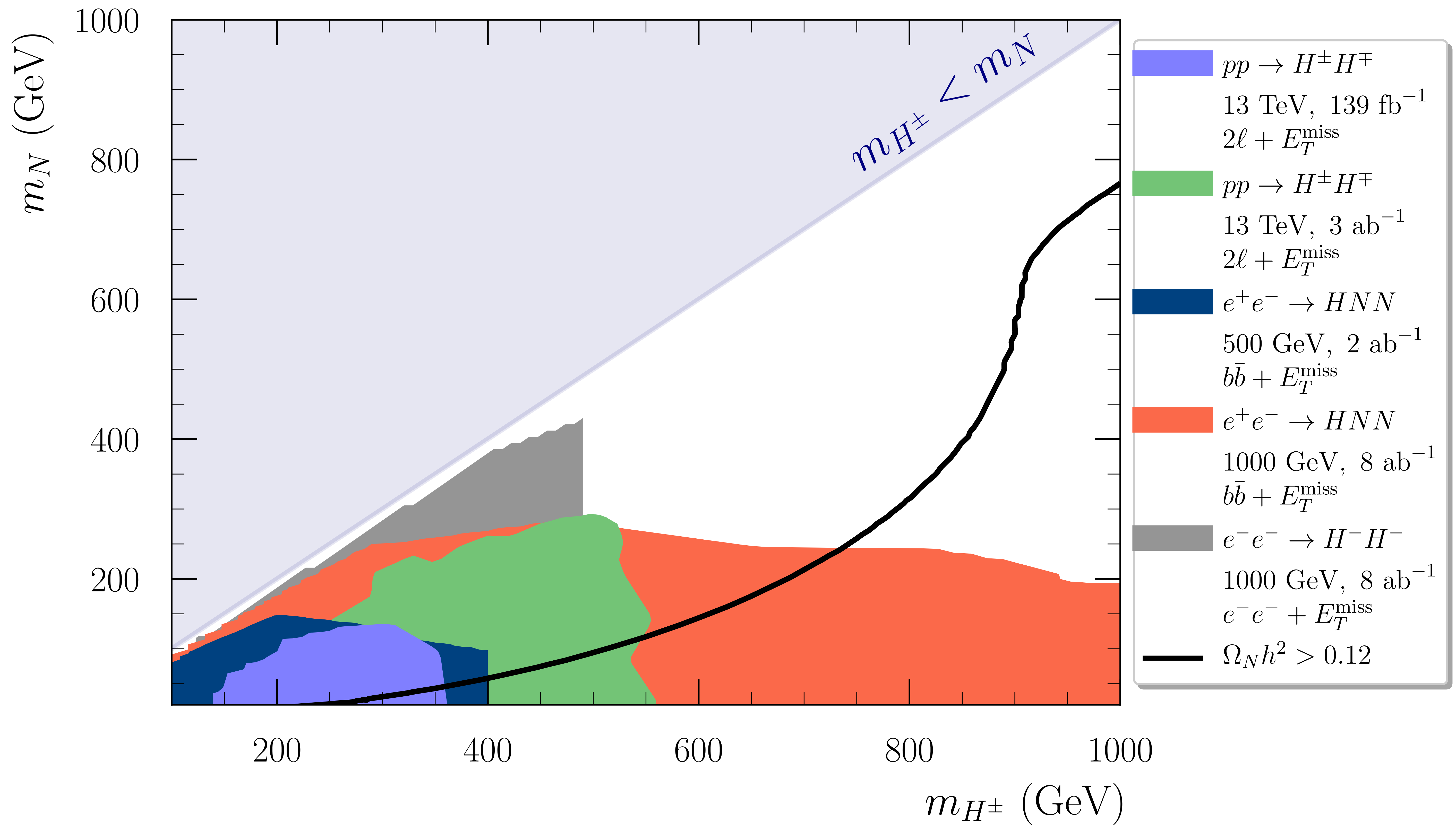
to be compared with the backgrounds:

$\sigma_{Ze^-e^-} = 98.1$ fb $\qquad \sigma_{W^-W^-\nu\bar{\nu}} = 21.53$ fb

just pick up events with two SS electrons with

$p_T^e > 15$ GeV and $|\eta^e| < 2.5$

Summary Plot



Conclusions

- We suggested a minimal model for dark matter interacting primarily with charged leptons via a charged Higgs singlet.
- The model is simple and give interconnected predictions (can be used to either exclude or confirm this model in the near future).
- Spin-independent nucleus-dark matter elastic scattering cross section is always suppressed.
- Strong anti-correlations between the relic abundance and the spin-independent cross section are found.
- The International Linear Collider would provide a unique avenue to test the model.
- Future hadron colliders would provide a complementary cross-check via multi-charged Higgs bosons production with CLFV.
- The model can be embedded into a grand-unified theory: SU(5) with fermions in the $\mathbf{10}$ and $\overline{\mathbf{5}}$ representations, charged singlet belongs to the $\mathbf{10}_H$ and the right hand fermion to $\mathbf{1}_N$:

$$\mathscr{L}_{\text{int}} = g_{\alpha\beta}\overline{\mathbf{10}}_\alpha \otimes \mathbf{10}_H \otimes \mathbf{1}_{N_\beta} \supset g_{\alpha\beta}\ell^T_{R\alpha} C N_\beta S + h.c.$$

- Certainly possible for other class of grand-unified theories; e.g. flipped-SU(5), SO(10) ***(A. Jueid, S. Nasri; in progress)***.


Thank you for your attention