Lepton portal dark matter at future electron-positron and muon colliders

기초과학연구원
Institute for Basic Science

Adil Jueid

Workshop on Higgs and Cosmology connection:
Yonsei-APCTP-France-Korea Star collaboration project
12-17/12/2022

Based on work in collaboration:

- S. Nasri, R. Soualah (JHEP2021, 2006.01348)
- S. Nasri (arXiv: 23XX.ABCDE)

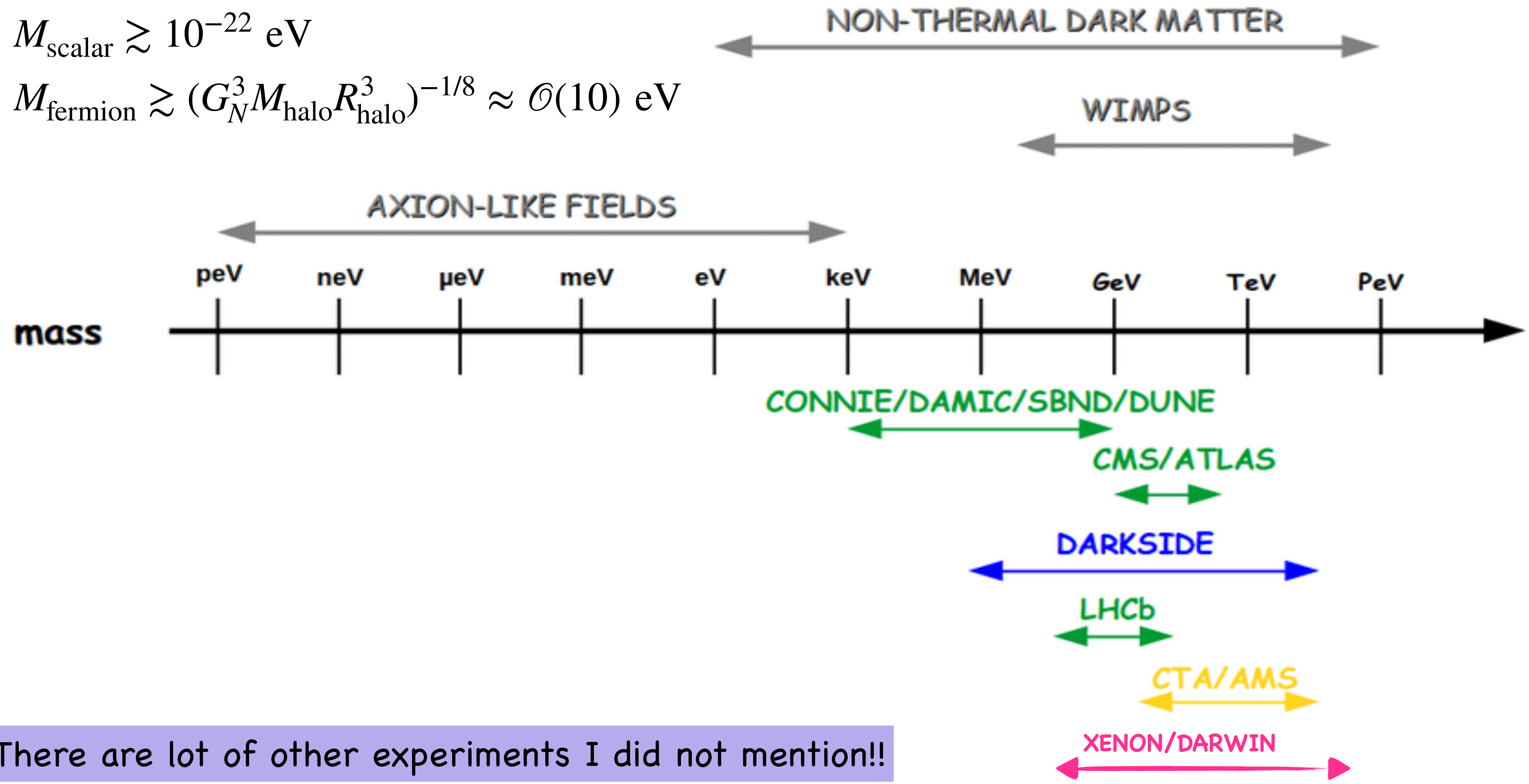
Is dark matter the aether of the twenty-first century?

- The existence of dark matter in the universe is supported by various data at astronomical and cosmological scales.
- The measurement of anisotropies in the Cosmic Microwave Background (CMB) implies that about 80% of the matter budget in the universe is formed by dark-matter (Planck Experiment; 2015).
- Dark matter is required to be (mostly) non-relativistic when the gravitational clustering started at the matter-radiation equality.
- The freeze-out mechanism can be straightforwardly realized by extending the Standard Model with Weakly Interacting Massive Particles (WIMPs).
- This scenario has driven multiple searches of dark matter through direct detection (Xenon, DAMA, LUX, PandaX), indirect detection (Fermi-LAT, IceCube, AMS) and collider experiments (LHC).
- No signals above the expected backgrounds have been observed (besides some mild excesses…)

The dark matter landscape

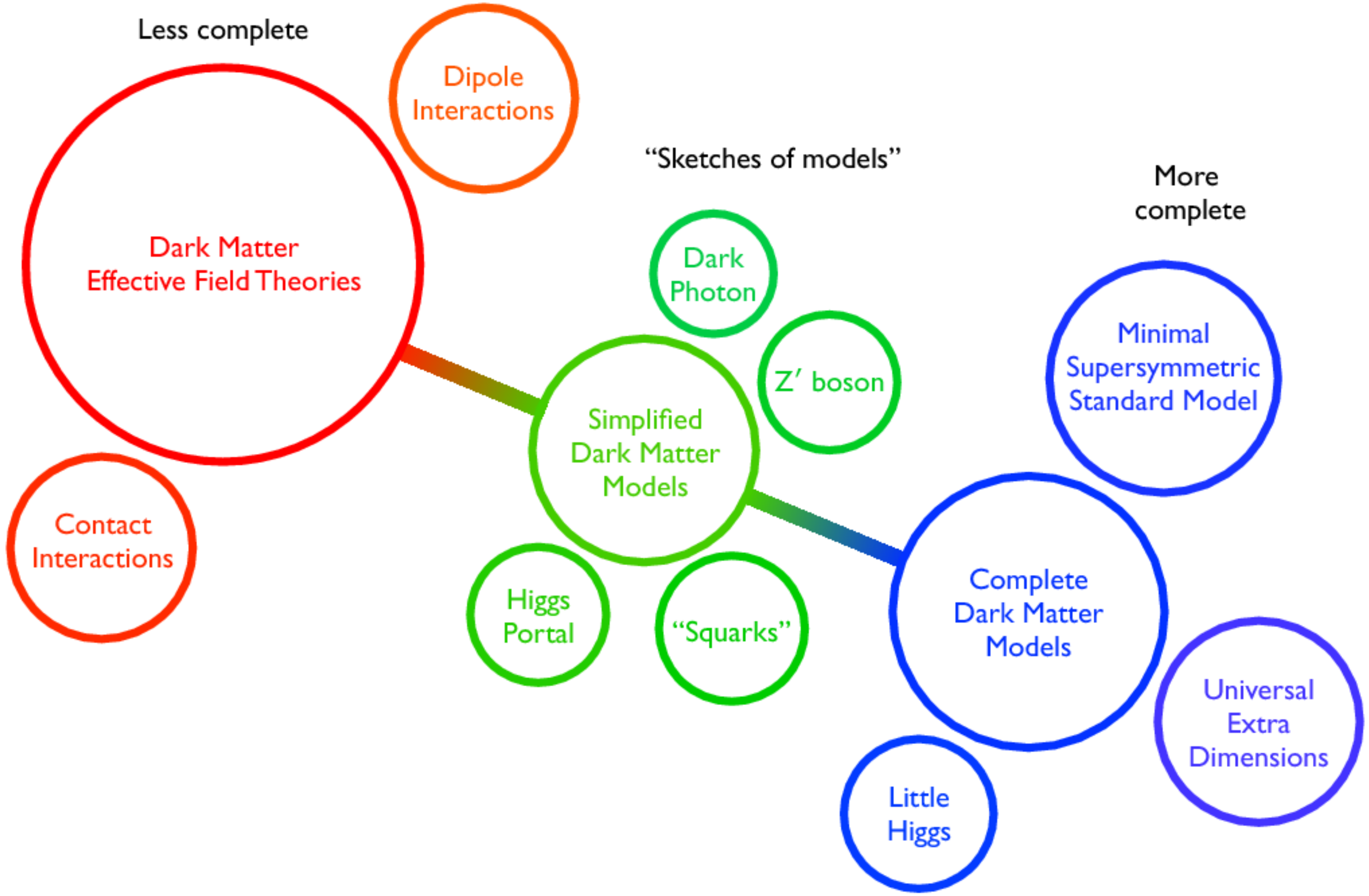
Halo stability implies lower on dark matter mass:

- $M_{\rm scalar} \gtrsim 10^{-22}$ eV
- $M_{\rm fermion} \gtrsim (G_N^3 M_{\rm halo} R_{\rm halo}^3)^{-1/8} \approx \mathcal{O}(10)$ eV



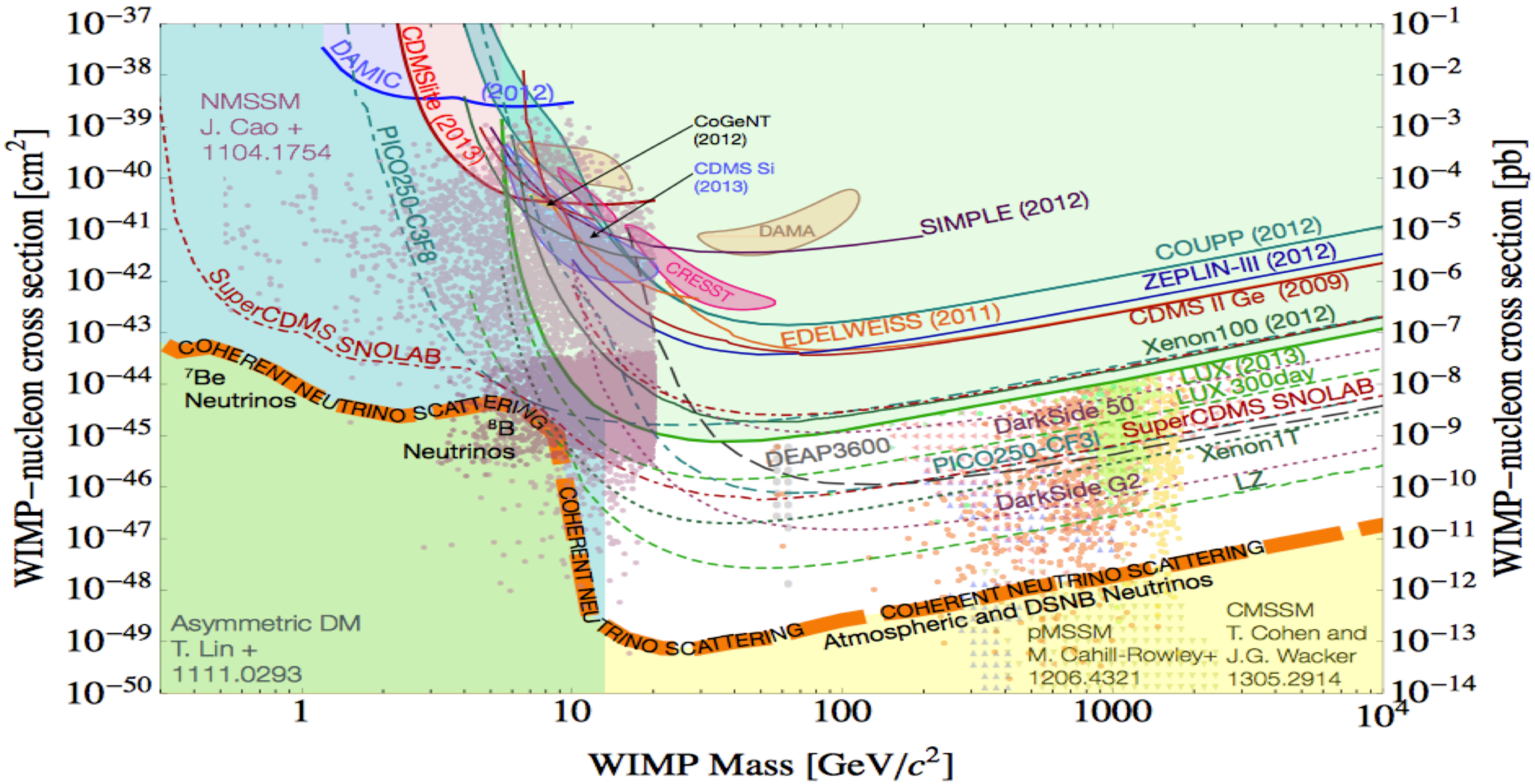
There are lot of other experiments I did not mention!!

The dark matter landscape



Credit: T. Tait

Direct detection is more harsh for WIMP: Close to the neutrino floor



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

→ Strong bounds imply expected weak signals at colliders; (excluding simple models)

- The strong bounds from direct-detection experiments tend to exclude the simplest dark-matter model; e.g. **the singlet model**.

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

- Usually, these simple dark-matter models lead to s-wave annihilation channels; Models with s-wave annihilations are almost excluded (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 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 dark-matter candidates:

  i. 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 $\mathcal{O}(1)$.

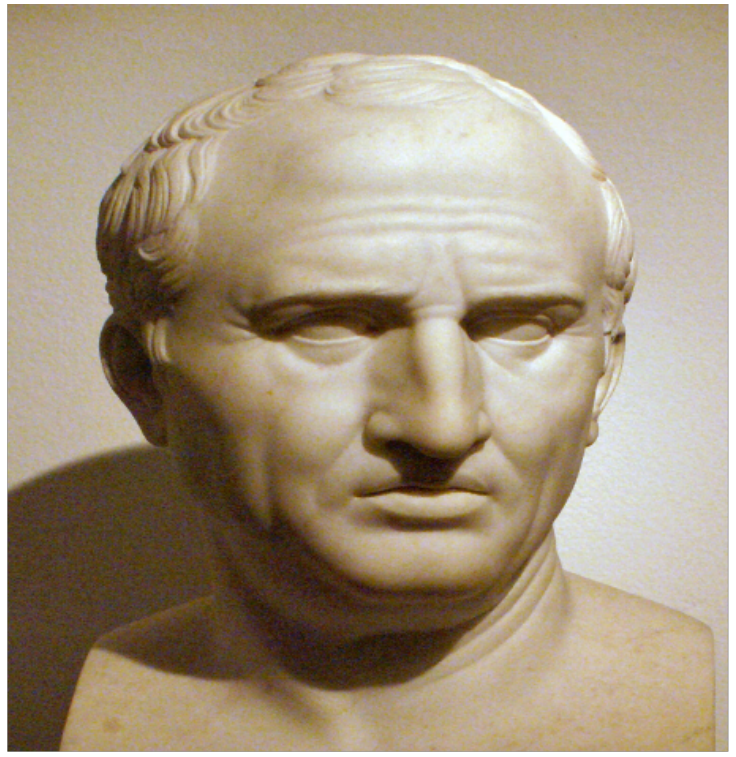
  ii. Hard to produce at hadron colliders for a wide class models ⟶ Explain why it is not observed so far?

  iii. Annihilation cross section occurs through p-wave amplitudes; no signal, no problem.

  iv. Lepton colliders may play the role of discovery machines for these models.

Guiding principle: History

By what other voice, too, than that of the orator, is history, the witness of time, the light of truth, the life of memory, the directress of life, the herald of antiquity, committed to immortality?



Cicero, De Oratore II, 36

The only lesson we can take from history in what concerns dark matter except minimality.

Important: Minimal is not Simplified

- Take a simplified $s-$channel model with spin-0 mediator and Dirac dark matter

$$\mathscr{L}^{Y_0} \supset \sum_i \left(\frac{y_i^q}{\sqrt{2}} g_{q_i}^S \bar{q}_i q_i + g_\chi^S \bar{\chi}\chi \right) Y_0$$

(Assuming flavour-diagonal couplings)

Couplings DM Mediator

- In principle, you cannot get this interaction unless: (i) Y_0 is a member of a Higgs multiplet (doublet for example) or (ii) Y_0 is a singlet that mixes with the SM Higgs boson after EWSB $\Longrightarrow$ models get more complicated with many additional parameters and smaller rates due to constraints from e.g. Higgs boson data.

- Minimal dark matter, on the other hand, do not rely on any extra assumption except (may be) unification at some higher scales…

Models with Majorana dark matter: directions

- Singlet Majorana fermions can be accommodated in many extensions of the SM; Mainly for 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 (taken from Stephen King)

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

A Minimal dark-matter model

We suggest a new minimal model where 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

$$S: \ (\mathbf{1}, \mathbf{1})_{+2} \text{ and } N_R: \ (\mathbf{1}, \mathbf{1})_0$$

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

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

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

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

UV realizations

- If you would like neutrinos to be massive, add two extra right handed neutrinos (N_2, N_3) and an inert scalar isodoublet Φ_2.

  $\Longleftrightarrow$ decouple the two other right-neutrinos and make the other couplings small and you will get Leptogenesis as a bonus.

- We can embed this into e.g. a $SU(5)$ theory: the matter fields in the $\mathbf{10}_F$ and $\bar{\mathbf{5}}_F$ representations and the charged singlet belongs to the $\mathbf{10}_H$ representation, while N_R belongs to the singlet representation $\mathbf{1}_N$

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

- You can also have it in a flipped-$SU(5) \otimes U(1)_X$ grand-unified theory: The lepton field is a singlet of $SU(5)$, and N_R is a member of the $\mathbf{10}_F$ representation

$$\mathscr{L} = \frac{h_{\alpha\beta}}{\Lambda}\overline{\mathbf{10}}_{F_\alpha} \otimes \bar{\mathbf{1}}_{F_\beta} \otimes \mathbf{10}_H \otimes \mathbf{1}_S \supset \frac{h_{\alpha\beta}\langle \mathbf{10}_H \rangle}{\Lambda} N^T C \ell_R S^-$$

What about the various constraints?

After electroweak symmetry breaking; one lefts 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

- General case: $\{M_{H^\pm}, M_{N_R}, \lambda_2, \lambda_3, Y_{eN}, Y_{\mu N}, Y_{\tau N}\}$
- Relevant for DM: $\{M_{H^\pm}, M_{N_R}, \lambda_2, \lambda_3, Y_{\ell N}\}$

Good approximation for massless leptons;

$Y_{\ell N} = \sqrt{Y_{eN}^2 + Y_{\mu N}^2 + Y_{\tau N}^2}$

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) $H \to \gamma\gamma$

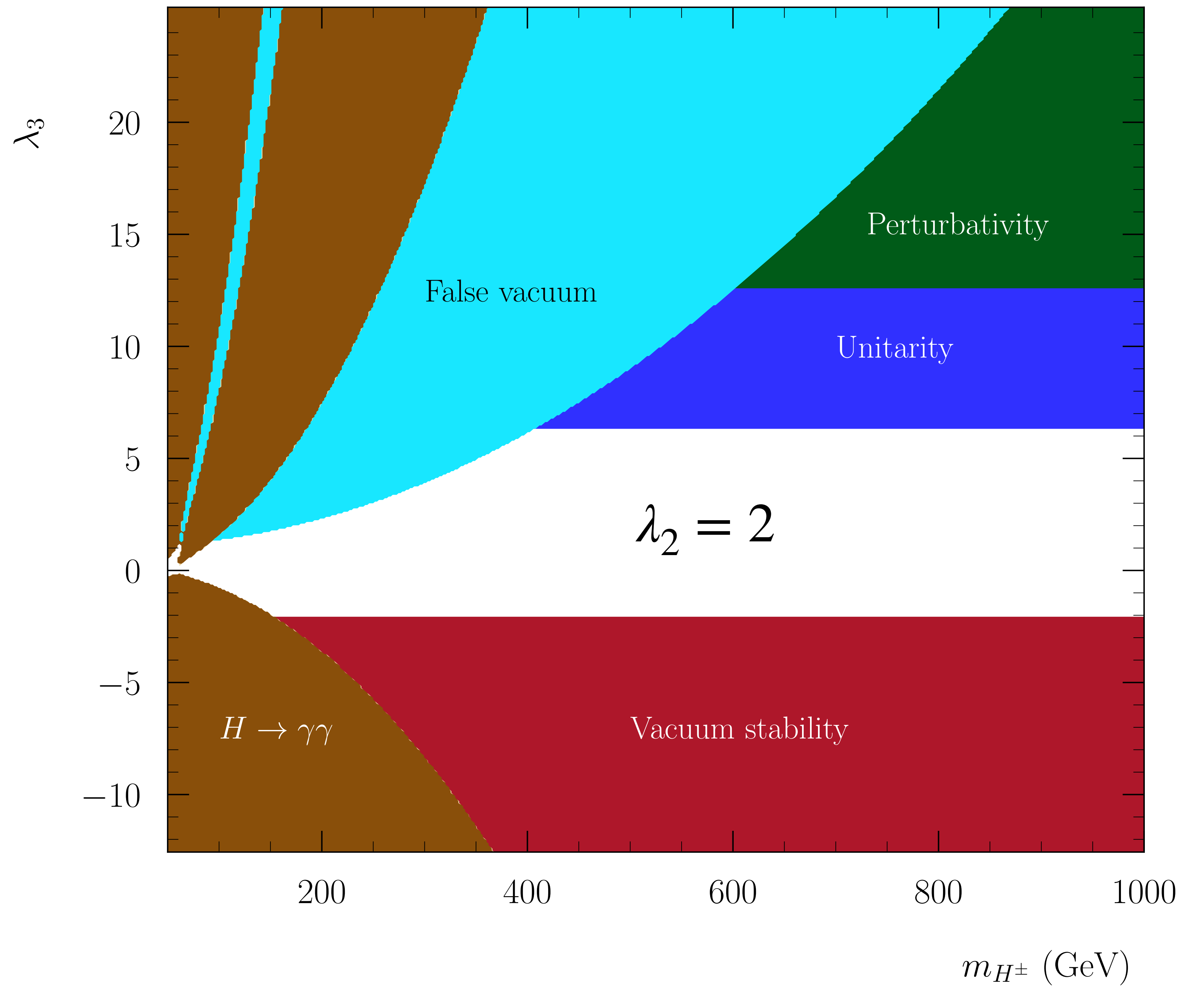
(ii) Higgs invisible decay ($H \to NN$): relevant for $m_H > 2m_N$

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

(iv) Searches of charginos at LEP-II.

Summary of theoretical and experimental constraints

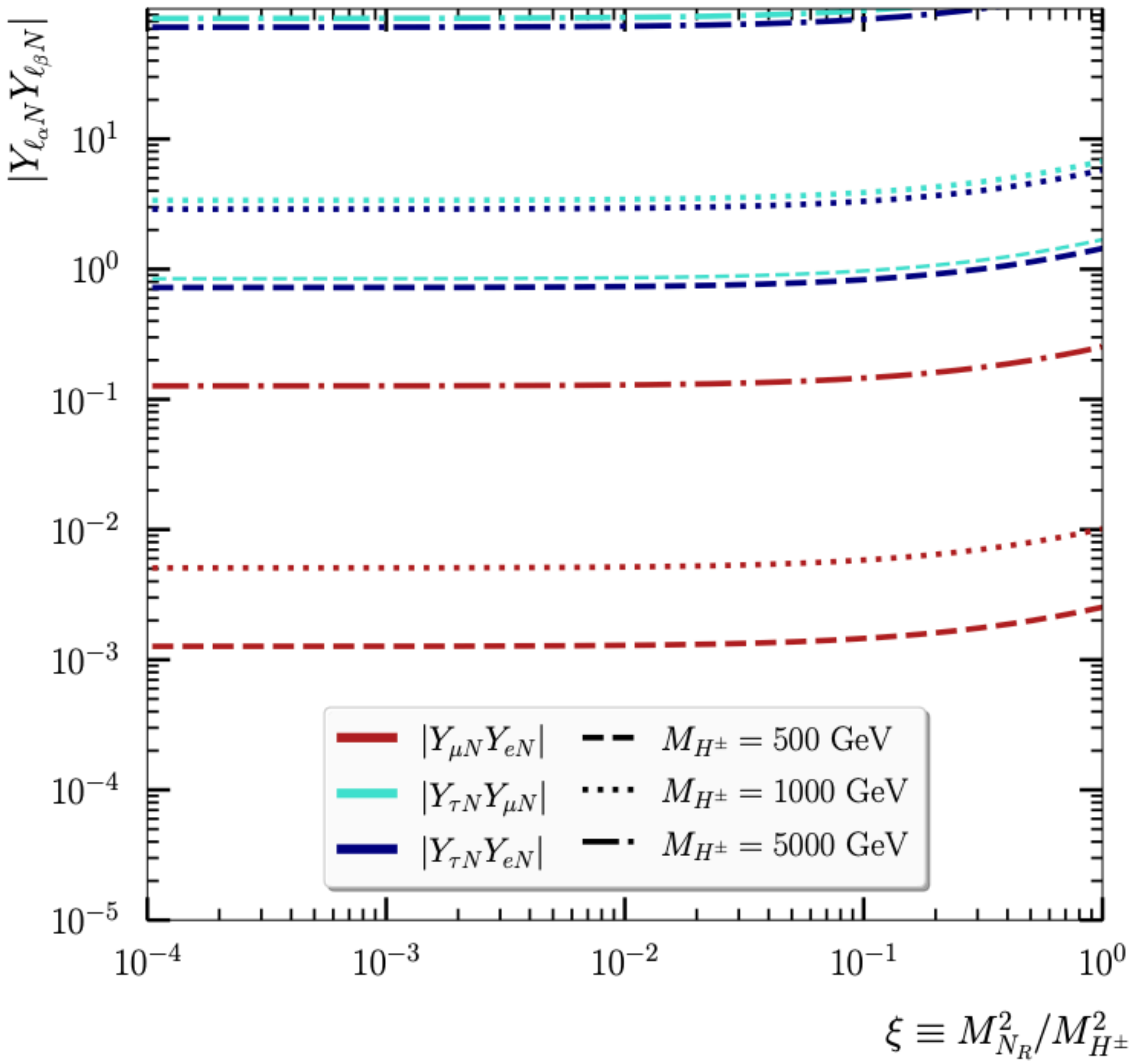
- Perturbativity and unitarity constraints exclude large values of λ_3.
- The bounds on the charged Higgs mass do not depend on λ_3 for $\lambda_3 \approx \mathcal{O}(1)$.
- If λ_3 is large, false vacuum constraints exclude light charged scalar masses; i.e. one has $m_{H^\pm} \geq 350$ GeV for $\lambda_3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



Charged lepton flavor violation

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

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



The constraints on $|Y_{iN}Y_{jN}|$ are very severe if $H^\pm$ is light and become weak for $m_{H^\pm} \simeq \mathcal{O}(10^3)$ GeV.

- $Y_{eN} \simeq \mathcal{O}(1) \gg Y_{\tau N} \geq Y_{\mu N}$: Interesting for e^+e^- colliders.
- $Y_{eN} \simeq Y_{\mu N} \simeq Y_{\tau N} \simeq \mathcal{O}(10^{-2})$: can be tested in hadronic collisions (very hard to achieve the correct relic density).
- $Y_{\mu N} \simeq \mathcal{O}(1) \gg \ (\geq) Y_{\tau N} \gg Y_{eN}$: Interesting for $\mu^+\mu^-$ colliders.

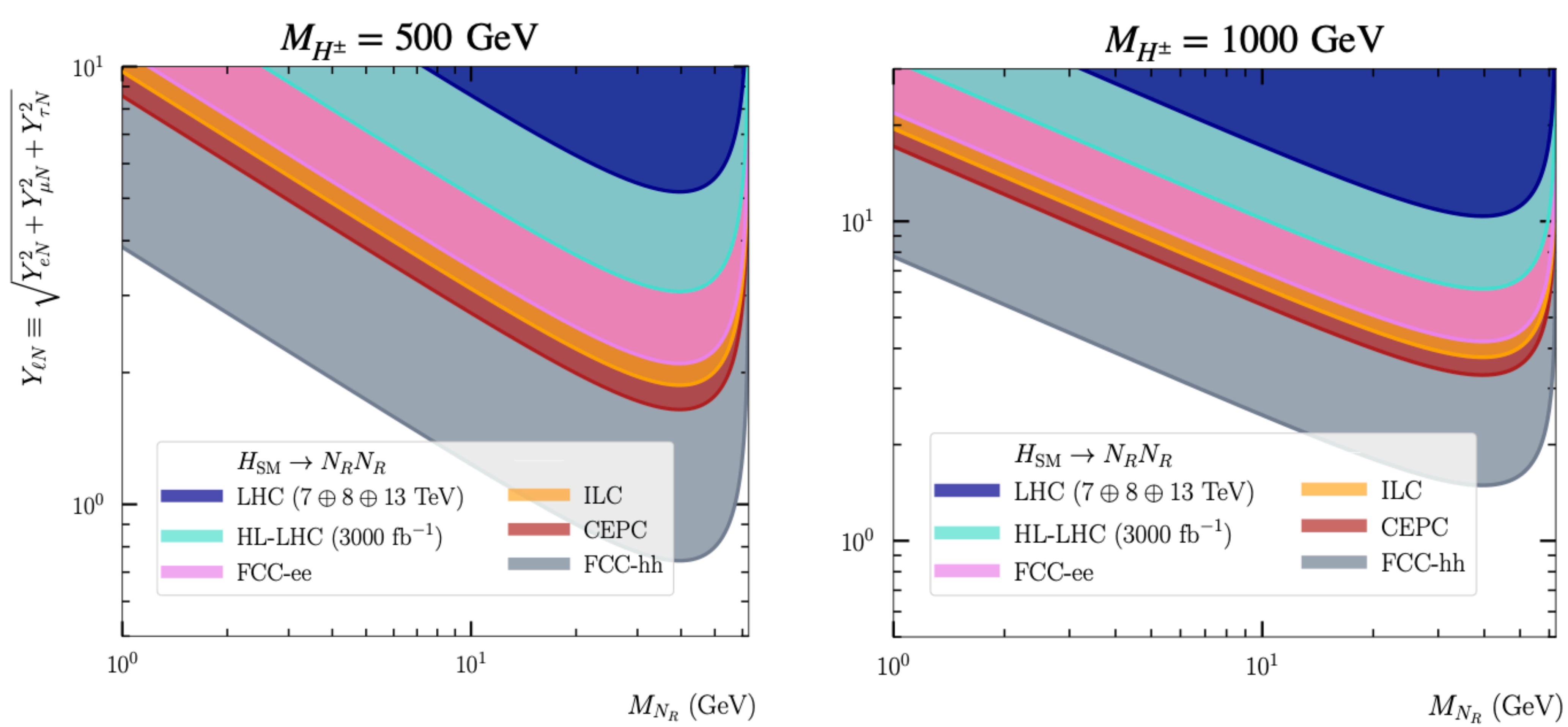
Higgs invisible decay

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

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

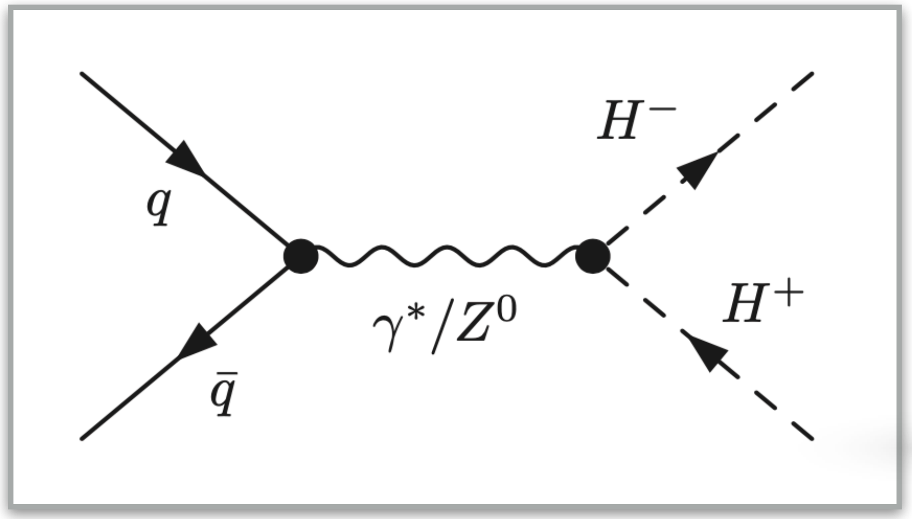
Passarino-Veltman functions

- The future constraints on $Y_{\ell N}$ are expected to be very important for light charged Higgs boson.
- Still some room for future studies to be focused on light dark-matter masses.
- Note that it's very hard to produce the correct relic density for $M_{N_R} < 10$ GeV (assuming freeze-out mechanism); freeze-in needed?



Status at the Large Hadron Collider

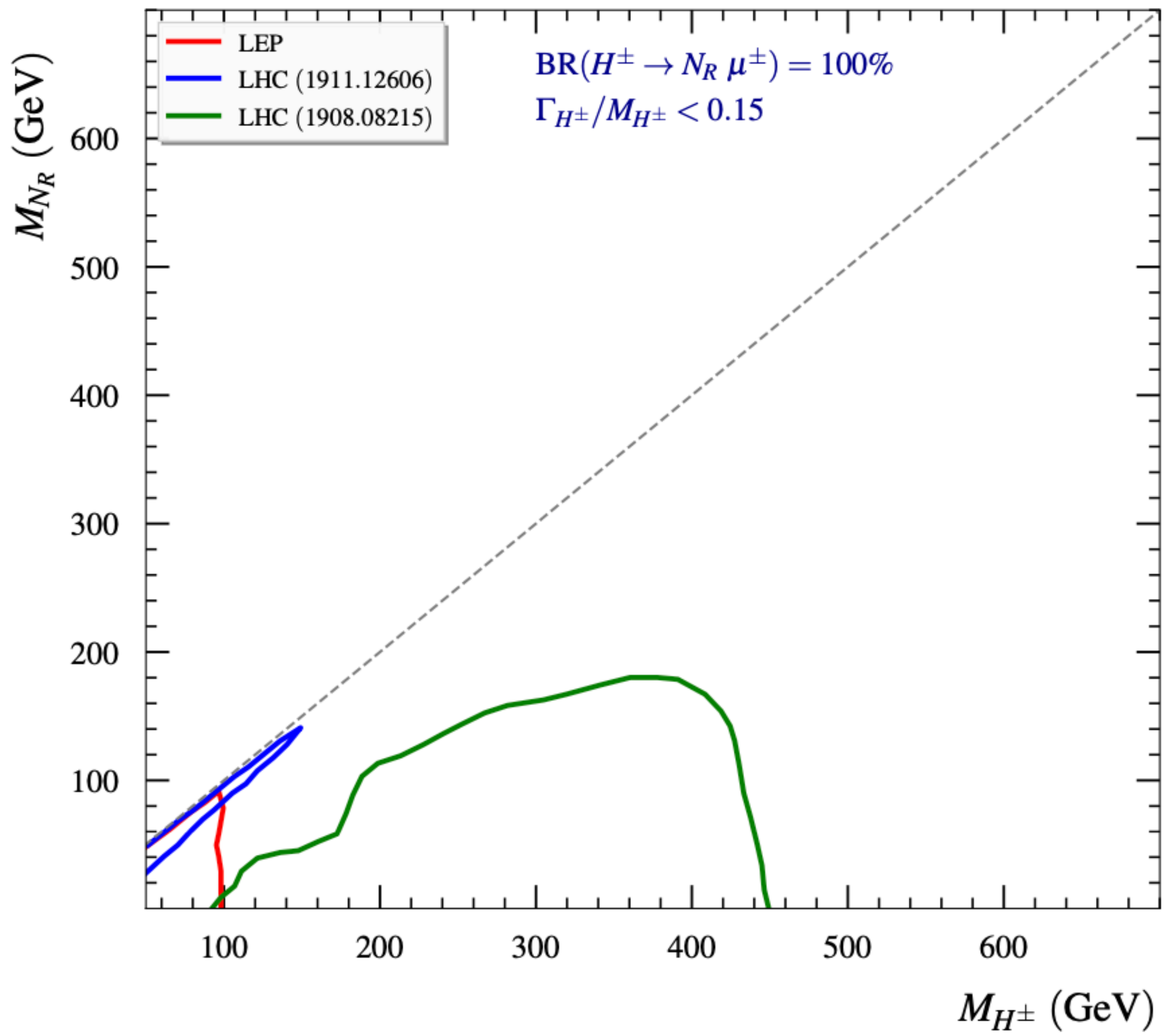
- The model can be constrained from re-interpretation of the results of sleptons/charginos (using MadAnalysis 5).
- In our model, we can pair produce the charged Higgs boson through $q\bar{q}$ annihilation and then decay them to charged leptons plus large MET.
- ATLAS has searched for sleptons/charginos defining eight signal regions — depend on the jet multiplicity $n_{\text{jet}} = 0,1$ 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



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 $Y_{\ell N} = \sqrt{Y_{eN}^2 + Y_{\mu N}^2 + Y_{\tau N}^2} \approx \mathcal{O}(1)$

$$N_R N_R \to \ell_\alpha^\pm \ell_\beta^\mp$$

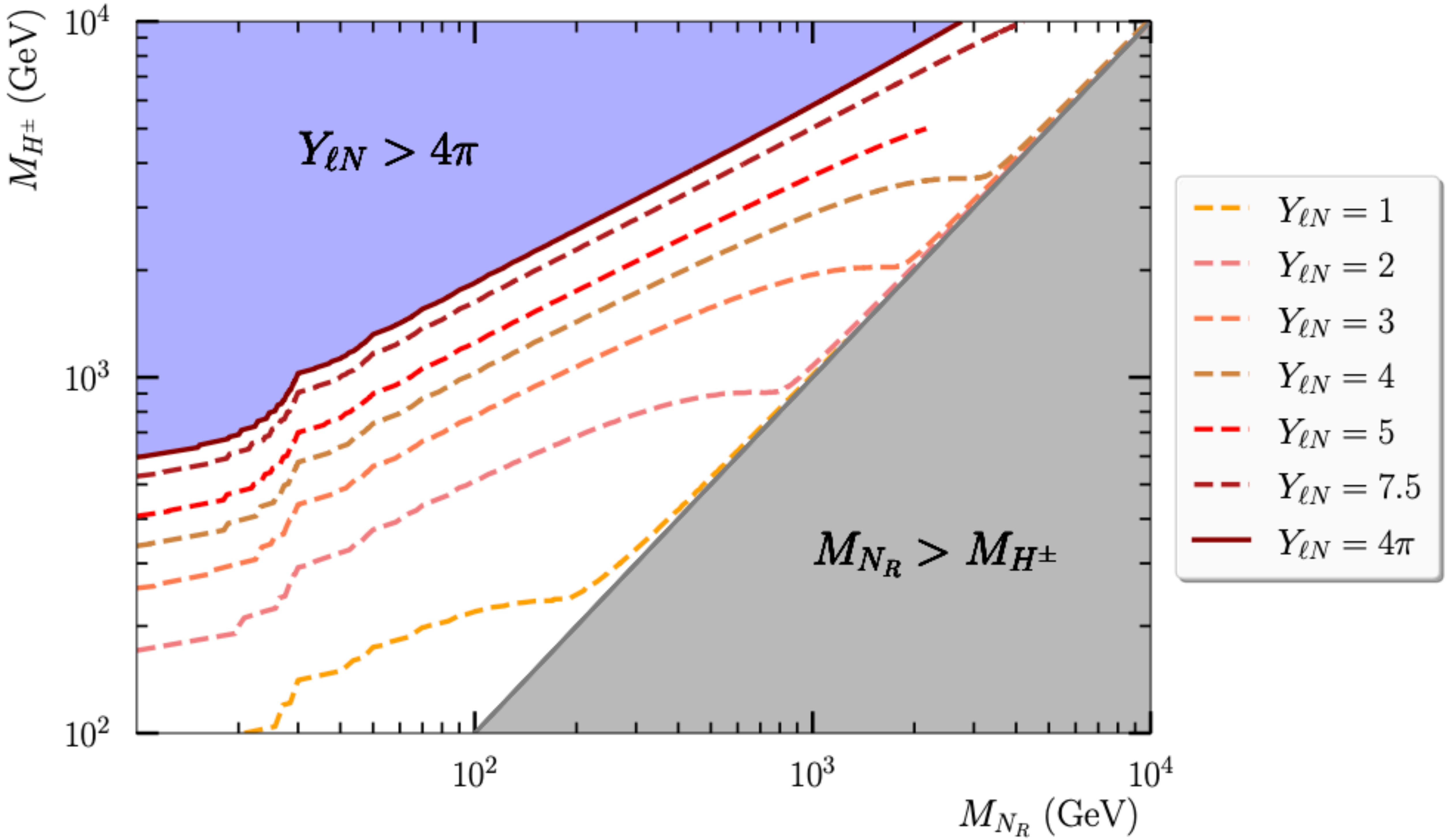
$$N_R N_R \to H^* \to \tau\tau, b\bar{b}, t\bar{t}, Z^0 Z^0, W^+ W^-, HH$$

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

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

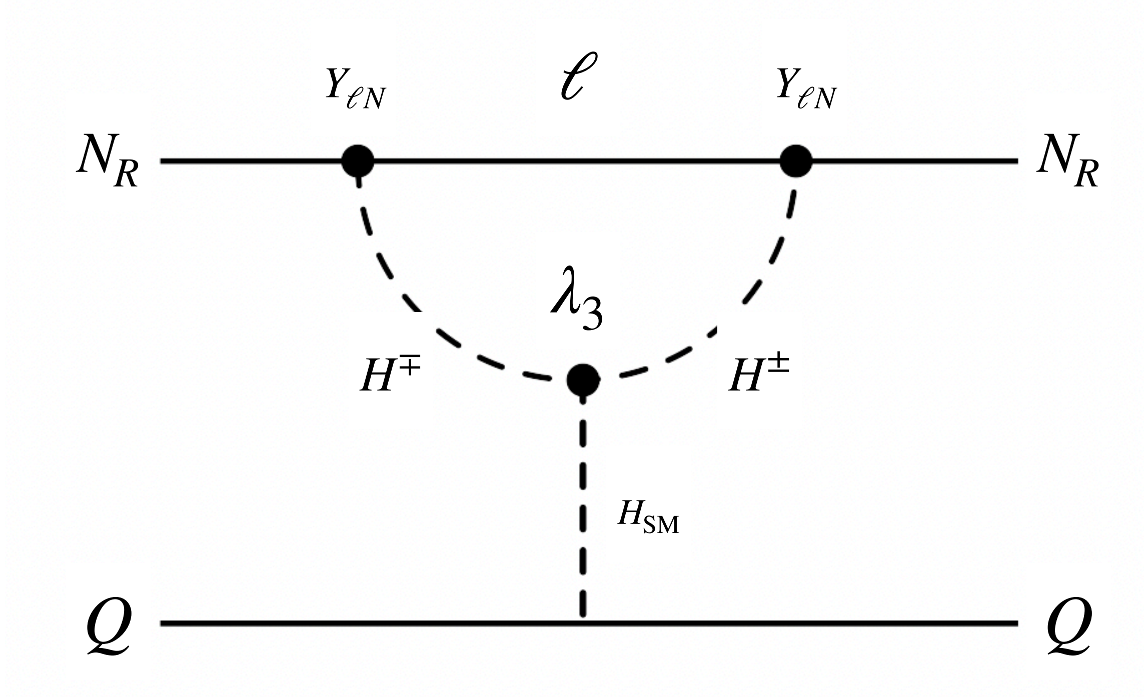
$$H^\pm H^\mp \to \ell^\pm \ell^\mp, q\bar{q}, HH, ZZ, W^\pm W^\mp, ZH, t\bar{t}$$

Dark matter relic abundance



Direct detection constraints

The spin-independent nucleus-N_R elastic cross section occurs at the one(two)-loop order



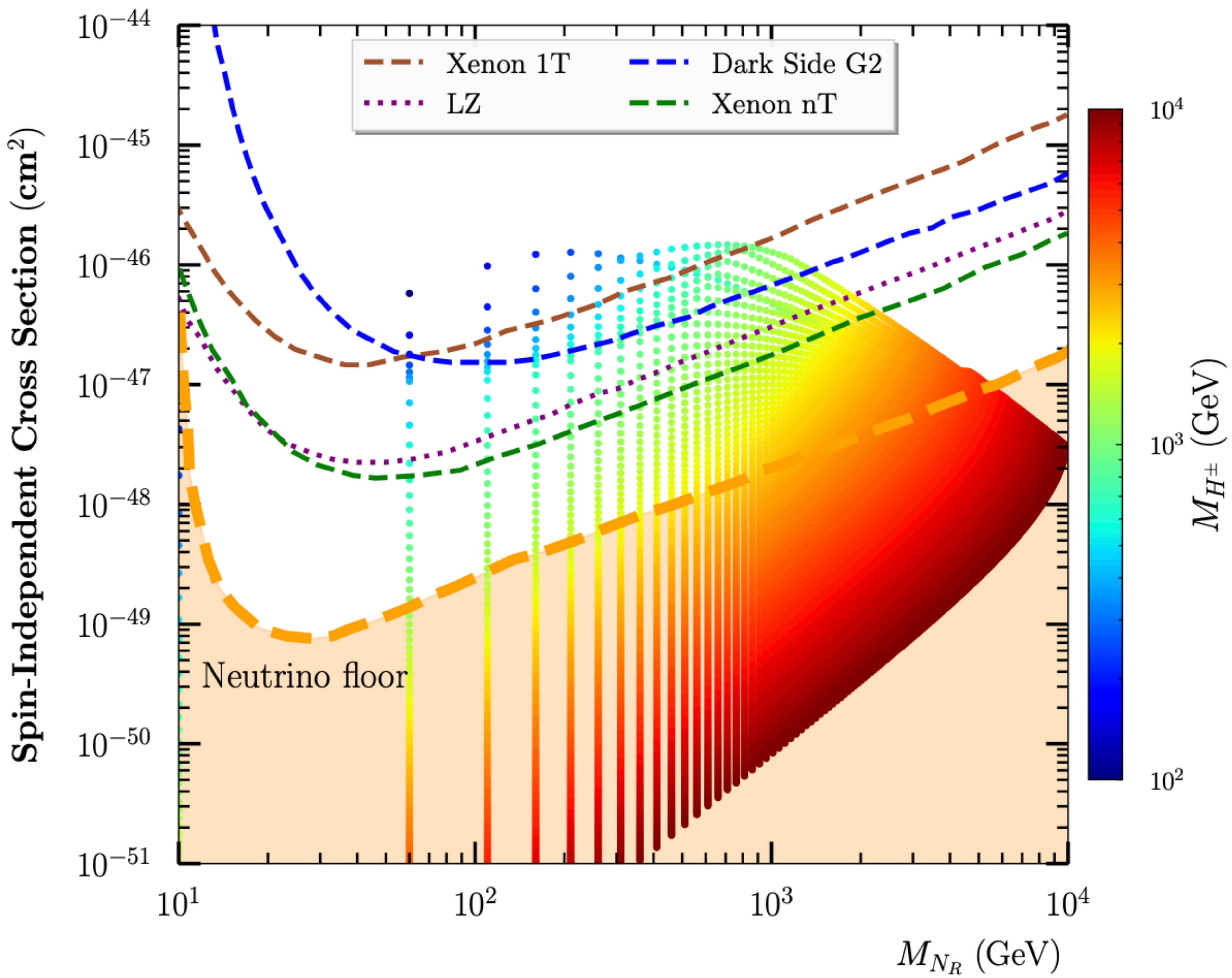
We get something like

$$\sigma_{\rm SI} \propto \left(\text{Nuclear matrix elements}\right)^2 \times \left|\frac{\tilde{y}(Q^2 \approx 0)}{M_{H^\pm}^2}\right|^2 \times \text{phase space}$$

Effective Higgs-N_R coupling

$$\tilde{y}(Q^2 \approx 0) = -\frac{\lambda_3 v\,|Y_{\ell N}^2|}{16\pi M_{H^\pm}}\varrho_N \times \left[1 - (1-\varrho_N^{-2})\log(1-\varrho_N^2)\right] \quad (\varrho_N = M_{N_R}/M_{H^\pm})$$

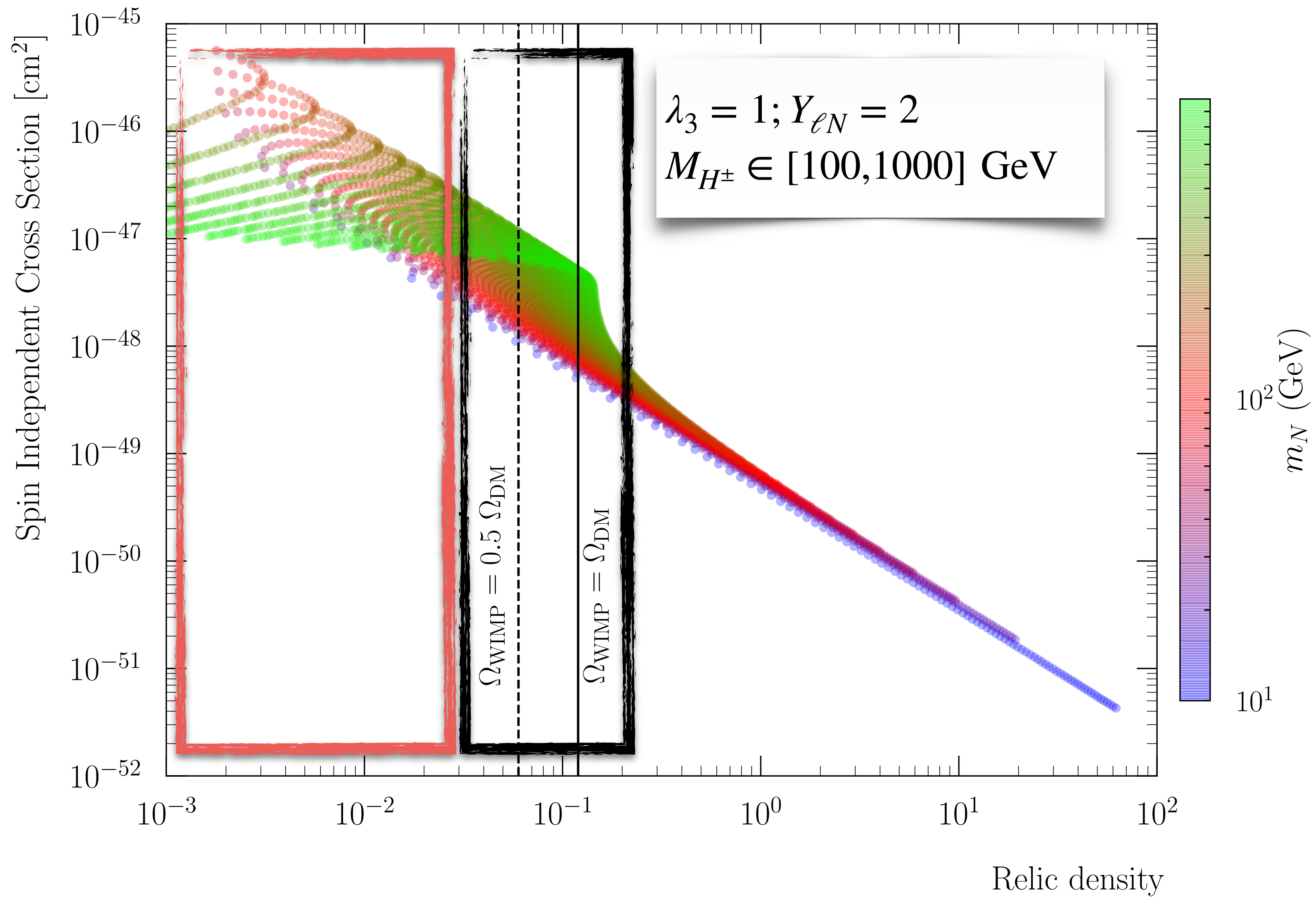
Direct detection constraints



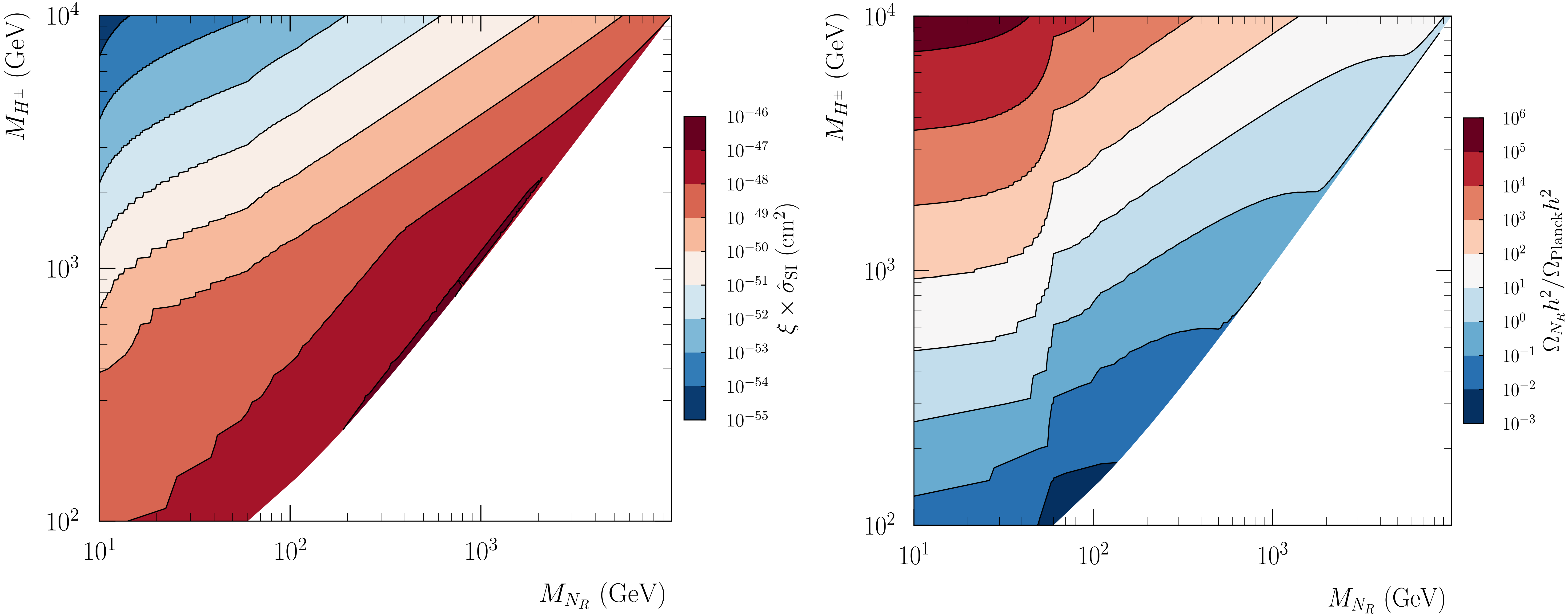
Correlations: Ωh^2 vs $\sigma_{\rm SI}$

- 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 $\xi \equiv \Omega_N h^2/\Omega_{\rm Planck} h^2 \ll 1$



Correlations: Ωh^2 vs $\sigma_{\rm SI}$

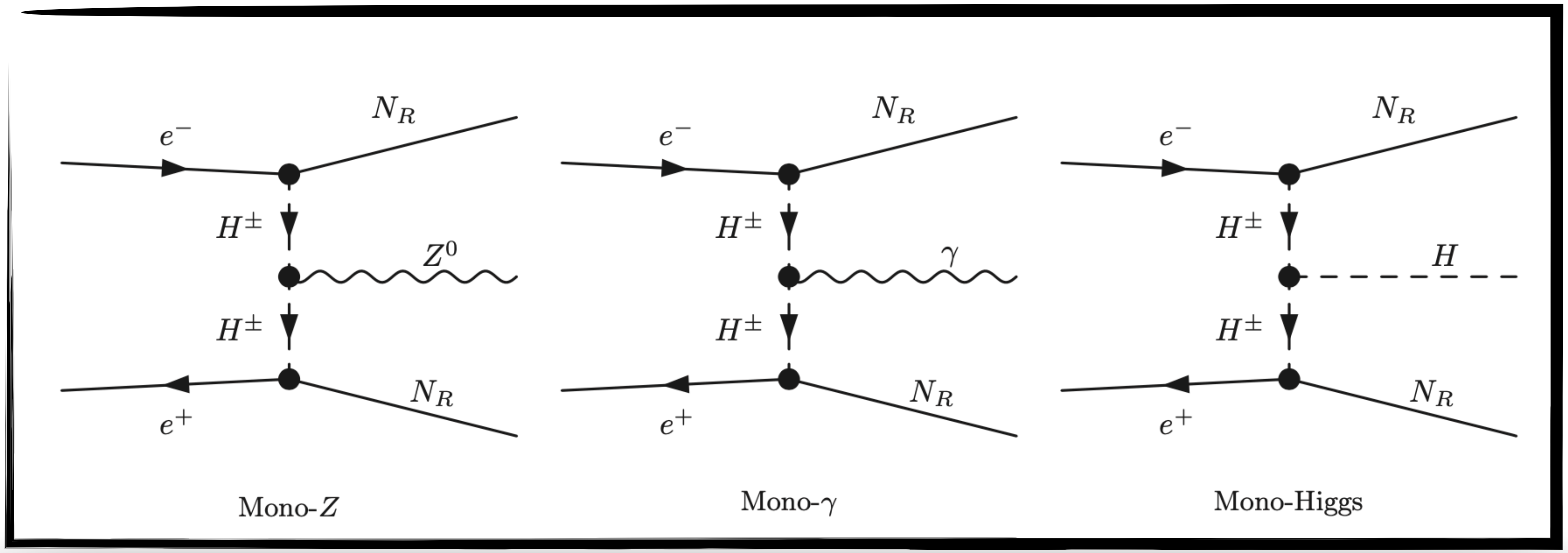


$$Y_{\ell N} \equiv \sqrt{Y_{eN}^2 + Y_{\mu N}^2 + Y_{\tau N}^2} = 2$$

Phenomenology at e^+e^- colliders

Collider Phenomenology: e^+e^- colliders

(i) Mono-X processes



$\sigma_{N_R N_R Z} \propto e^2 \tan^2\theta_W Y_{eN}^4$

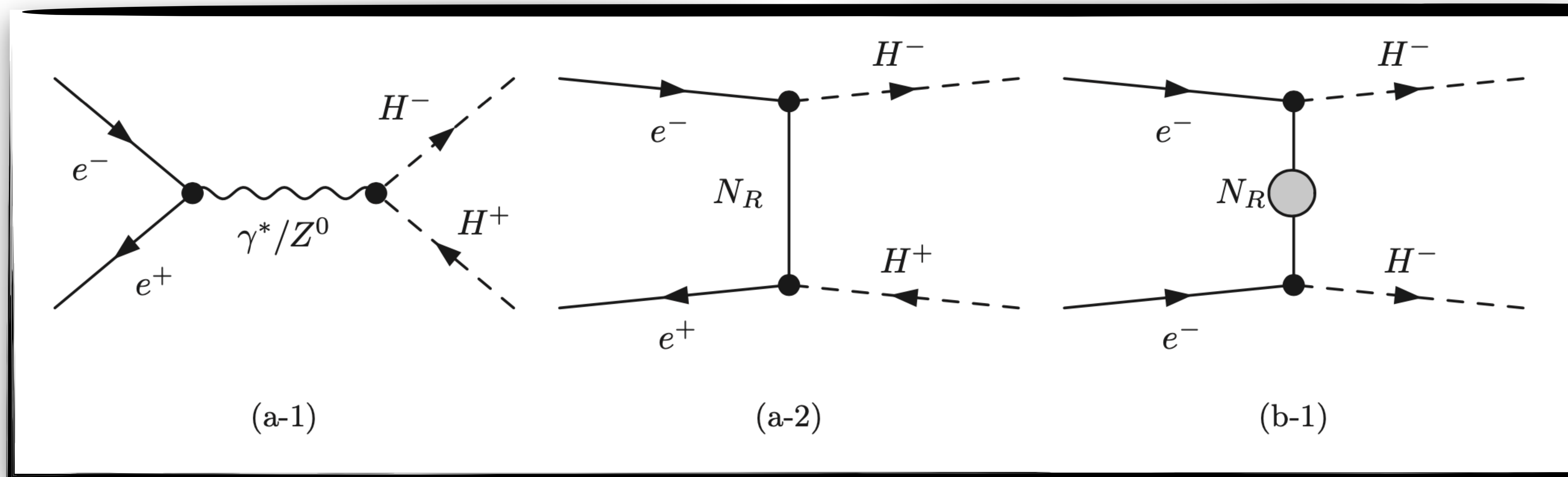
$\sigma_{N_R N_R \gamma} \propto e^2 Y_{eN}^4$

$\sigma_{N_R N_R H} \propto \lambda_3^2 Y_{eN}^4$

We study the mono-Higgs channel.

Collider Phenomenology: e^+e^- colliders

(ii) Charged scalar pair production



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

Much more interesting:

- Very small backgrounds in e^-e^- collisions
- $\sigma(H^-H^-) \propto Y^4_{eN} M^2_{N_R}$ (grows quadratically with the DM mass)

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

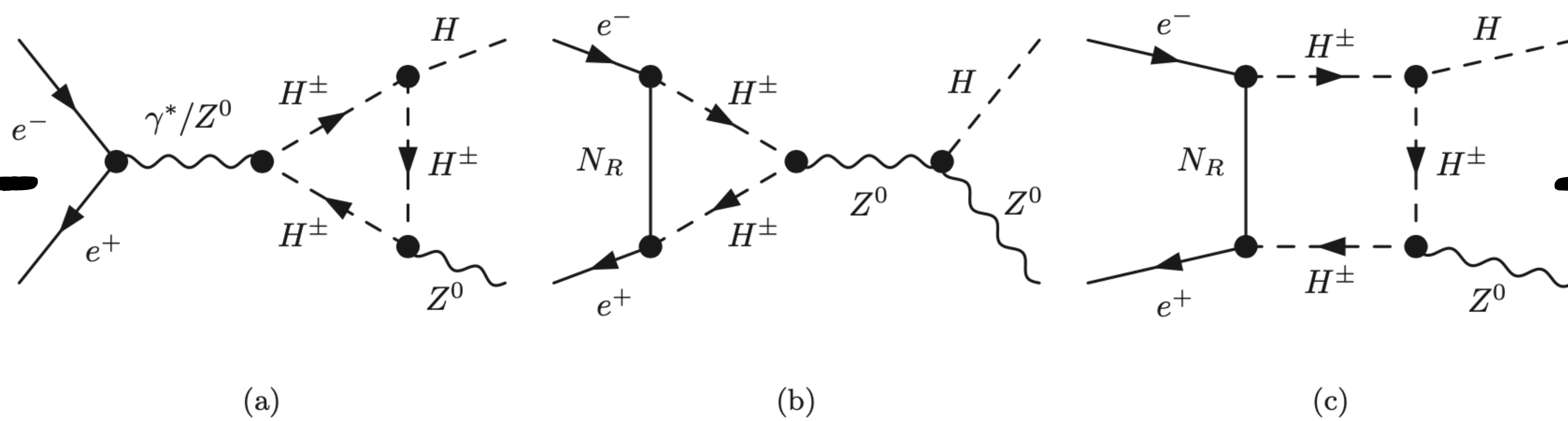
$$e^-e^- \to H^-H^- \to \ell^-_\alpha N_R,\ \ell^-_\beta N_R$$

$$\sigma_{e^-e^- \to \ell^-_\alpha \ell^-_\beta + 2kN_R} \propto M^2_{N_R} Y^4_{eN} Y^2_{\ell_\alpha N} Y^2_{\ell_\beta N}$$ (High-energy probe of CLFV!!)

(iii) Indirect effects

Never estimated before.

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



Never estimated before: interesting threshold effects are expected.

$$\sigma_{e^+e^-\to HZ} \propto \sigma^{\rm SM}_{\rm tree} \times (1 + \Delta\sigma) + \mathcal{O}(\alpha^4)$$

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

There are also effects on Higgs and Z-bosons couplings (AJ, in progress)

Mono-Higgs at the ILC

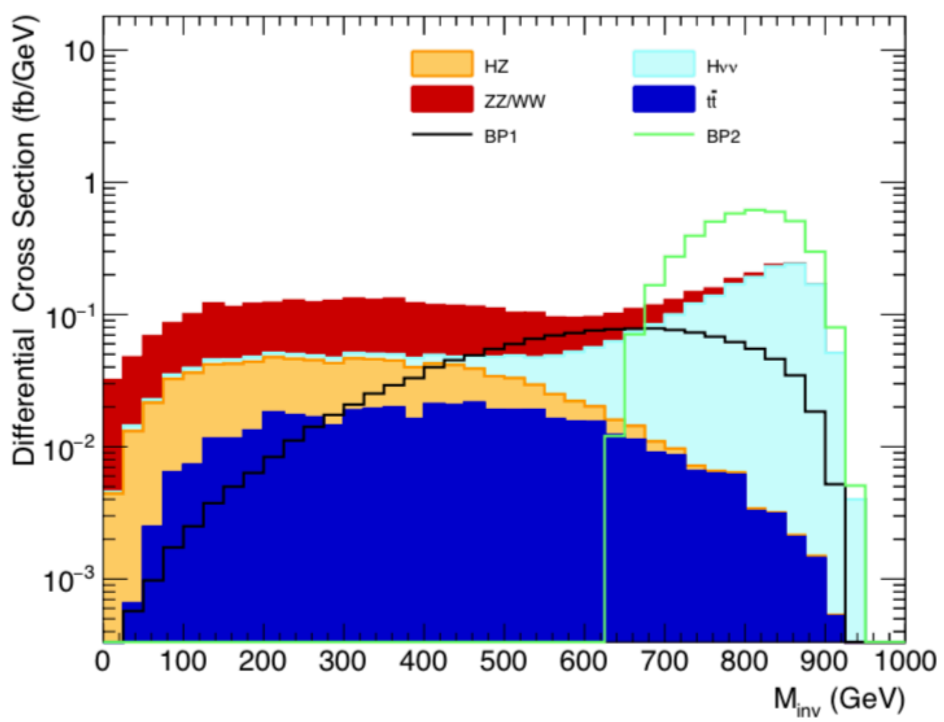
We consider $e^+e^- \to H\,(\to b\bar{b})\,N_R N_R$ at $\sqrt{s_{ee}} = 500,\ 1000$ GeV

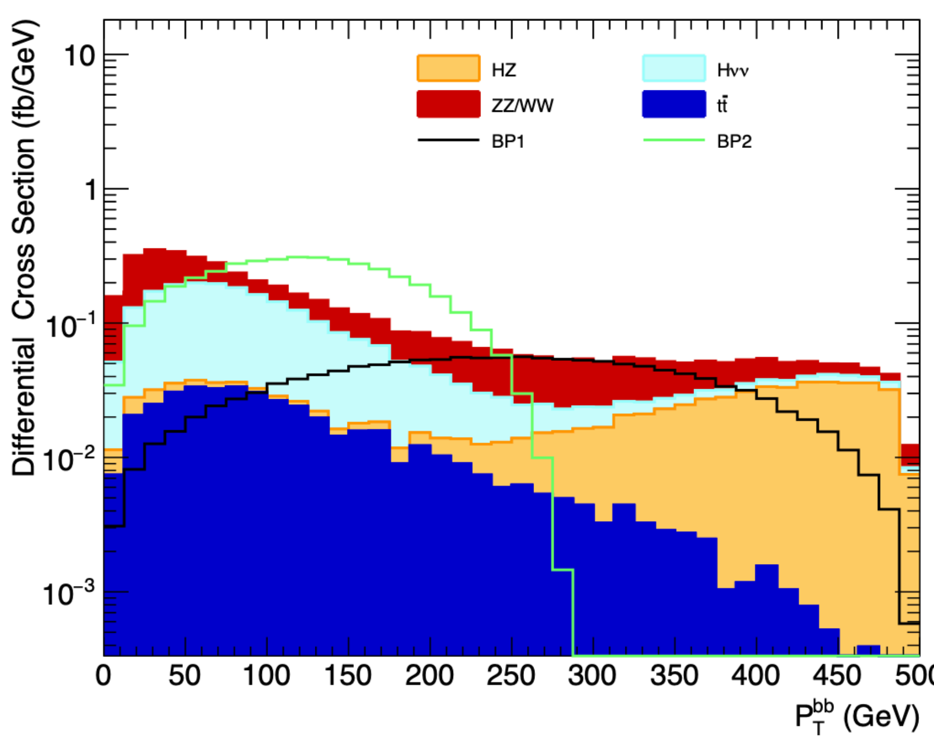
Major backgrounds are $HZ, H\nu_e\bar{\nu}_e$, W^+W^-, ZZ and $t\bar{t}$

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

- 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.

$\sqrt{s}$ [GeV]	500			1000		
$[P_{e^-}, P_{e^+}]$	$[0,0]$	$[+0.8,-0.3]$	$[-0.8,+0.3]$	$[0,0]$	$[+0.8,-0.2]$	$[-0.8,+0.2]$
W^+W^-	7.19	1.06	16.77	2.68	0.44	5.79
ZZ	0.42	0.32	0.71	0.15	0.11	0.24
$t\bar{t}$	0.55	0.44	0.92	0.16	0.13	0.25
$H\nu\bar{\nu}_e$	7.76×10^{-2}	1.14×10^{-2}	0.18	0.21	3.44×10^{-2}	0.45
HZ	5.72×10^{-2}	5.72×10^{-2}	8.47×10^{-2}	1.28×10^{-2}	1.21×10^{-2}	1.77×10^{-2}





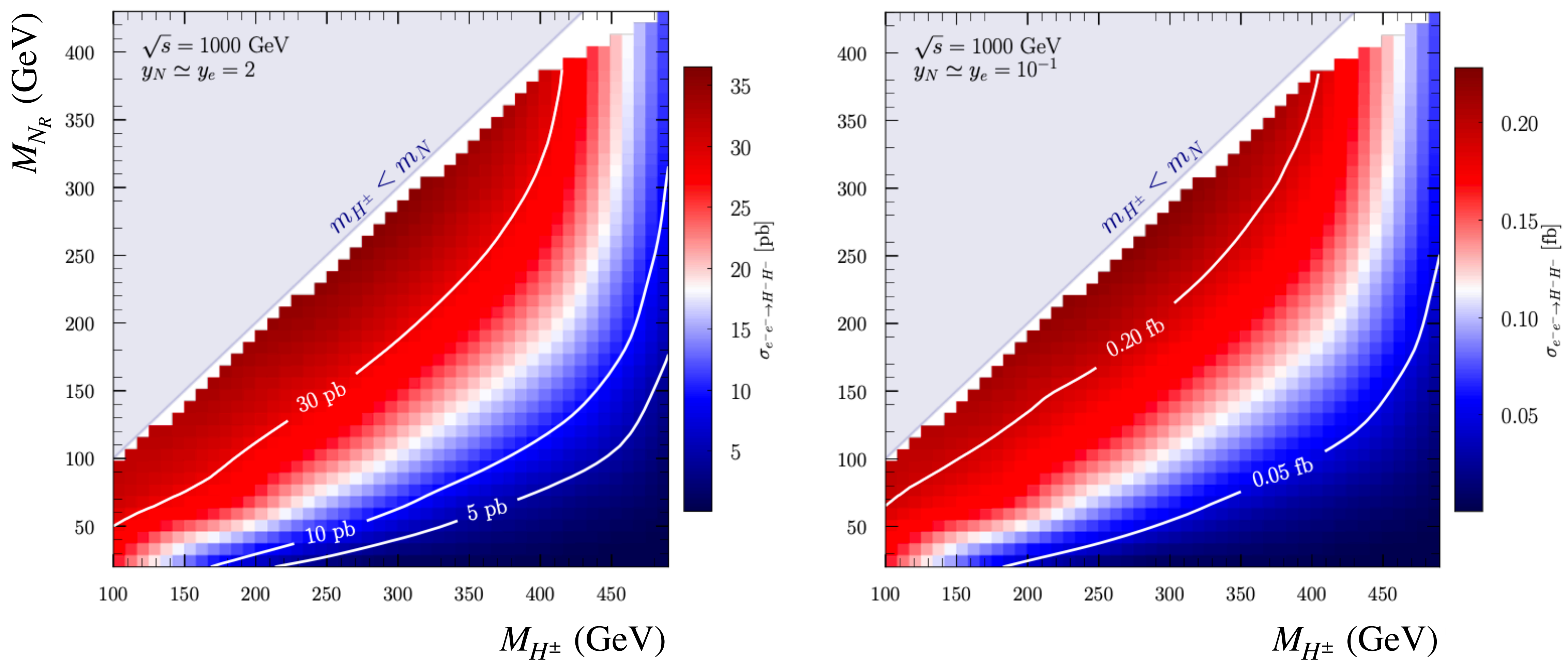
BP1: $M_{H^\pm} = 1000$ GeV and $M_{N_R} = 20$ GeV

BP2: $M_{H^\pm} = 460$ GeV and $M_{N_R} = 320$ GeV

Same-sign charged Higgs pair production

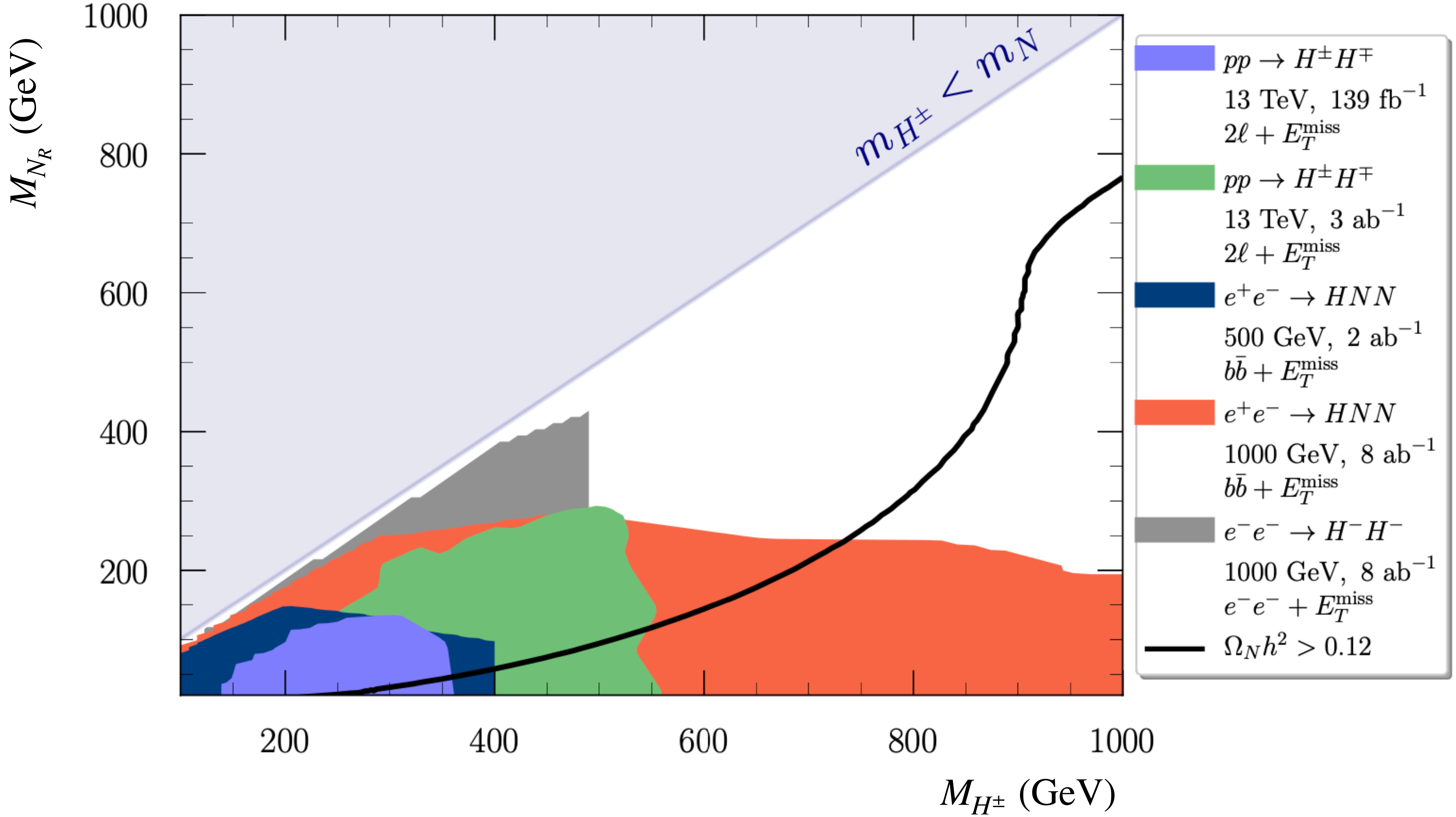
For same-sign charged Higgs pair production, we consider $e^-e^- \to H^- \, (\to e^- N_R) H^- \, (\to e^- N_R)$

Very small backgrounds: $e^-e^- \to Z \, (\to \nu\bar{\nu}) \, e^-e^-$ and $e^-e^- \to W^- \, (\to e^-\bar{\nu}_e) \, W^-(\to e^-\bar{\nu}_e)\nu\bar{\nu}$



Just pick up events with two SS electrons with $p_T^e > 15$ GeV and $|\eta^e| < 2.5$ $\Longrightarrow$ Large significance

Results for the ILC



Phenomenology at muon colliders

Phenomenology at muon colliders: BPs

For the case of muon colliders, we need to choose the following scenario

$$Y_{\mu N} \geq \ (\approx) Y_{\tau N} \gg Y_{eN}$$

Benchmark scenario	BP1	BP2	BP3	BP4
Parameters				
M_{N_R} (GeV)	50	200	598	1000
$M_{H^\pm}$ (GeV)	500	500	600	1500
Y_{Ne}	10^{-4}	5×10^{-4}	10^{-3}	5×10^{-3}
$Y_{N\mu}$	2.8	1.6	1	2
$Y_{N\tau}$	5×10^{-2}	5×10^{-1}	5×10^{-1}	2
λ_3	4	5	5	6

DM production at muon colliders

At muon colliders, one can assess the discovery potential of DM within this model through a variety of production mechanisms.

(i) DM production plus X ($N_R N_R + X$)

- $N_R N_R + \gamma \Longrightarrow$ High-energetic photon plus MET.
- $N_R N_R + Z \Longrightarrow$ 2 leptons or two jets plus MET.
- $N_R N_R + H_{\rm SM} \Longrightarrow$ variety of final-state particles depending on the Higgs boson decays.

(ii) DM production plus XY ($N_R N_R + XY$)

- $N_R N_R + \gamma\gamma \Longrightarrow$ 2photons plus MET.
- $N_R N_R + \gamma Z \Longrightarrow$ one photon + 2 leptons or two jets plus MET.
- $N_R N_R + ZZ/HZ/W^+W^-/HH/t\bar{t} \Longrightarrow$ variety of final-state particles depending on the decay products of the heavy resonances.

(iii) DM production plus XYZ ($N_R N_R + XYZ$)

About 16 processes with more complicated event topologies and final-state signatures.
Smaller rates but backgrounds are more suppressed

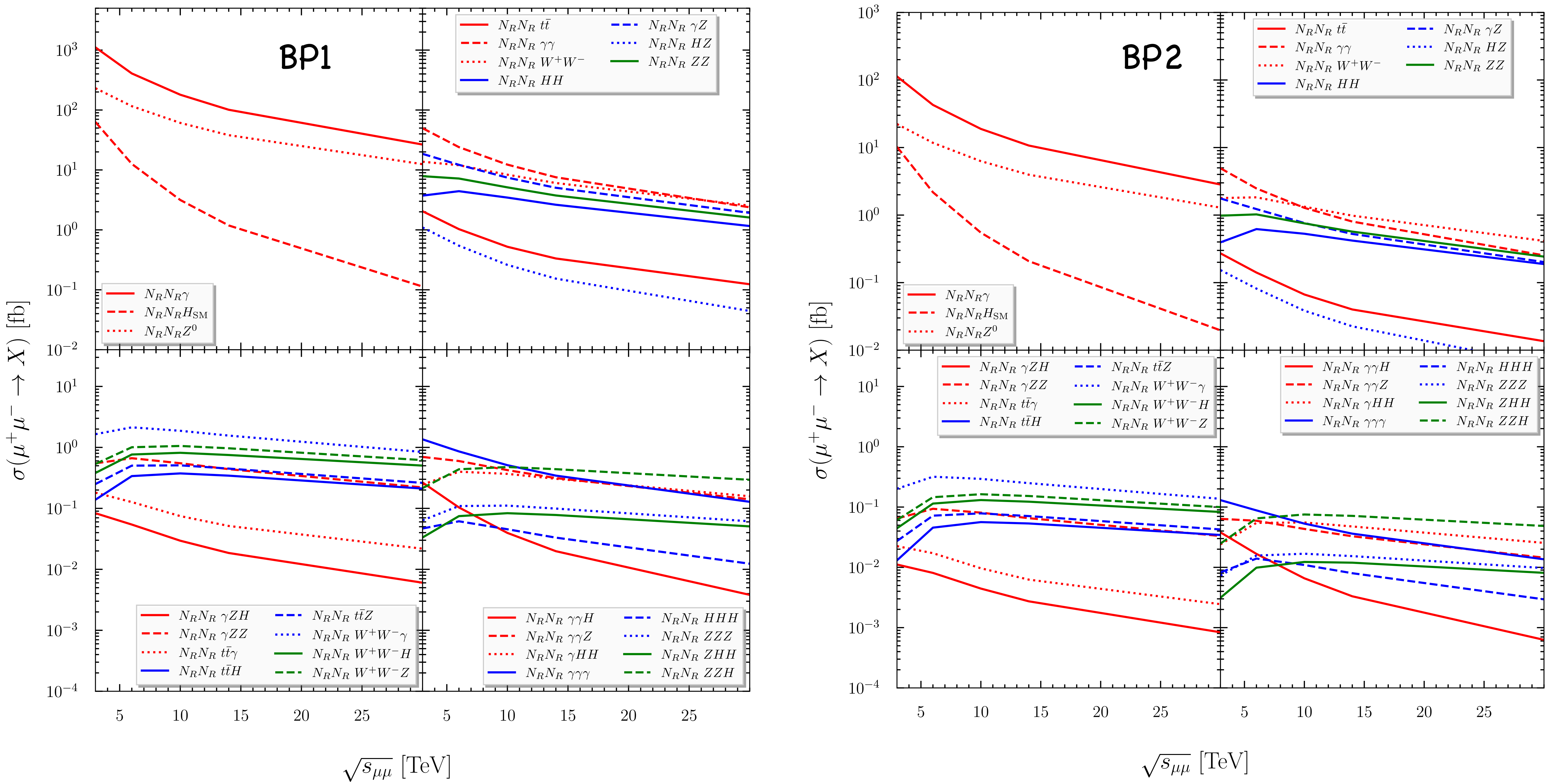
Work is ongoing for $N_R N_R + \gamma/Z/H$ and $N_R N_R HH/t\bar{t}/\gamma\gamma/\gamma Z/VV$ for the following center-of-mass energies

$$\sqrt{s_{\mu\mu}} = 3{,}14, \text{ and } 30 \text{ TeV}$$

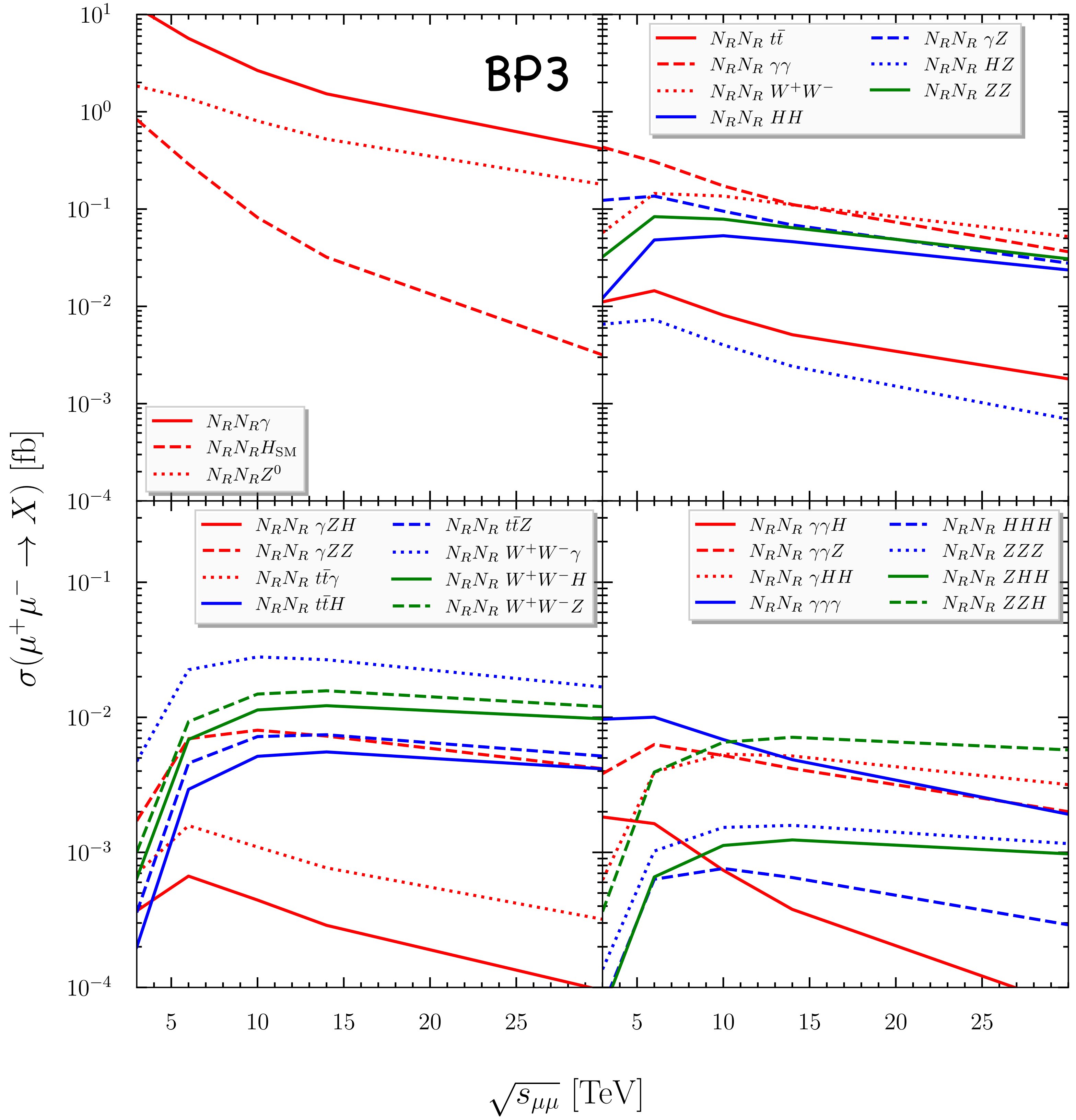
$$\int \mathscr{L} = 1{,}20, \text{ and } 90 \text{ ab}^{-1}$$

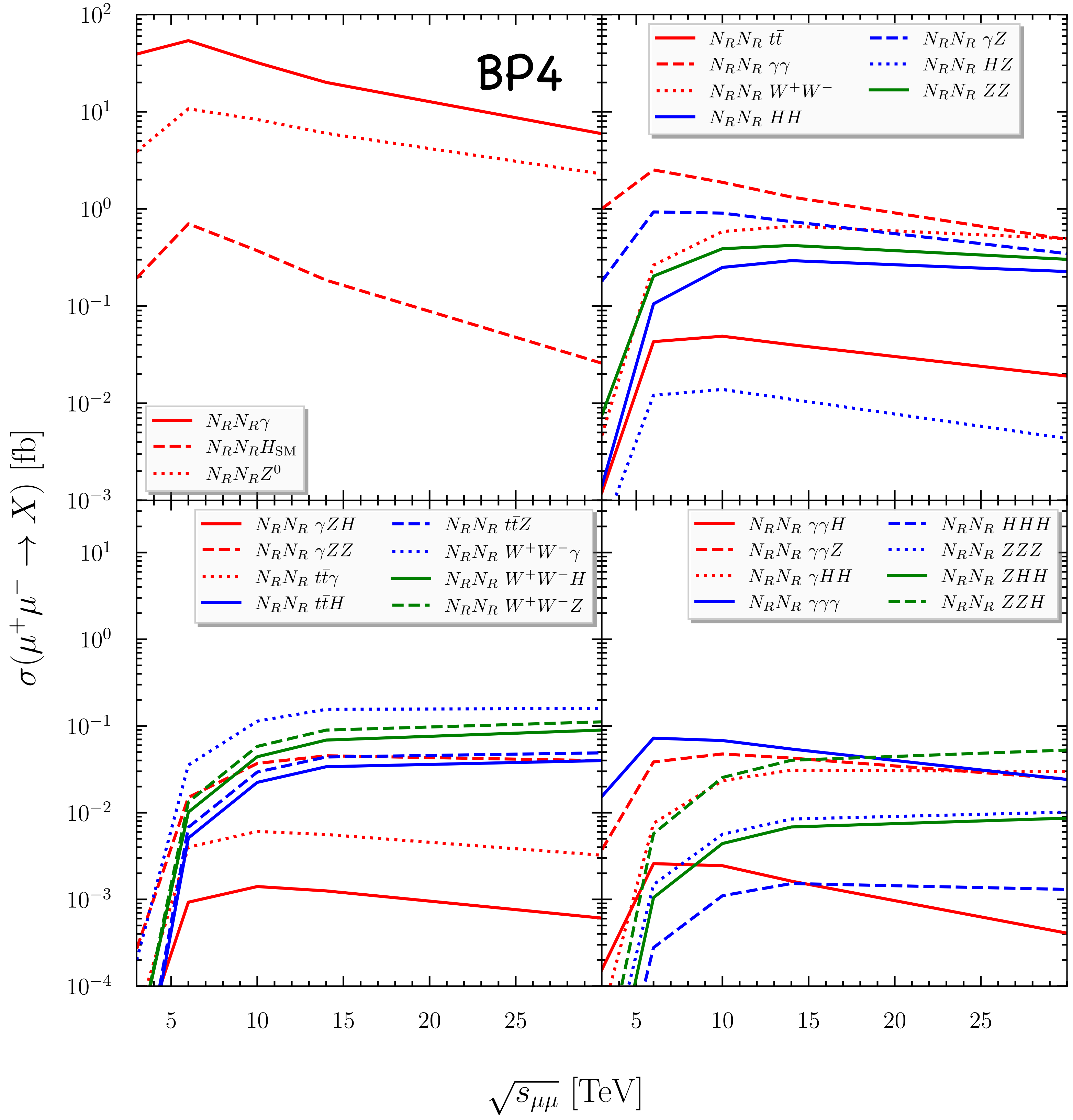
$\Longrightarrow$ Decent statistics for signal events!

DM production at muon colliders: results



DM production at muon colliders: results





Conclusions and Outlook

- We suggested a minimal model for dark matter interacting primarily with charged leptons via a charged Higgs singlet.
- Strong anti-correlations between the relic abundance and the spin-independent cross section.
- 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 scalar bosons CLFV processes.
- The model can be embedded into a grand-unified theory.
- The potential discovery at muon colliders is very promising (work in progress)