~ Leptophilic WIMP ~ Role of future lepton collider

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Based on 2102.08645.
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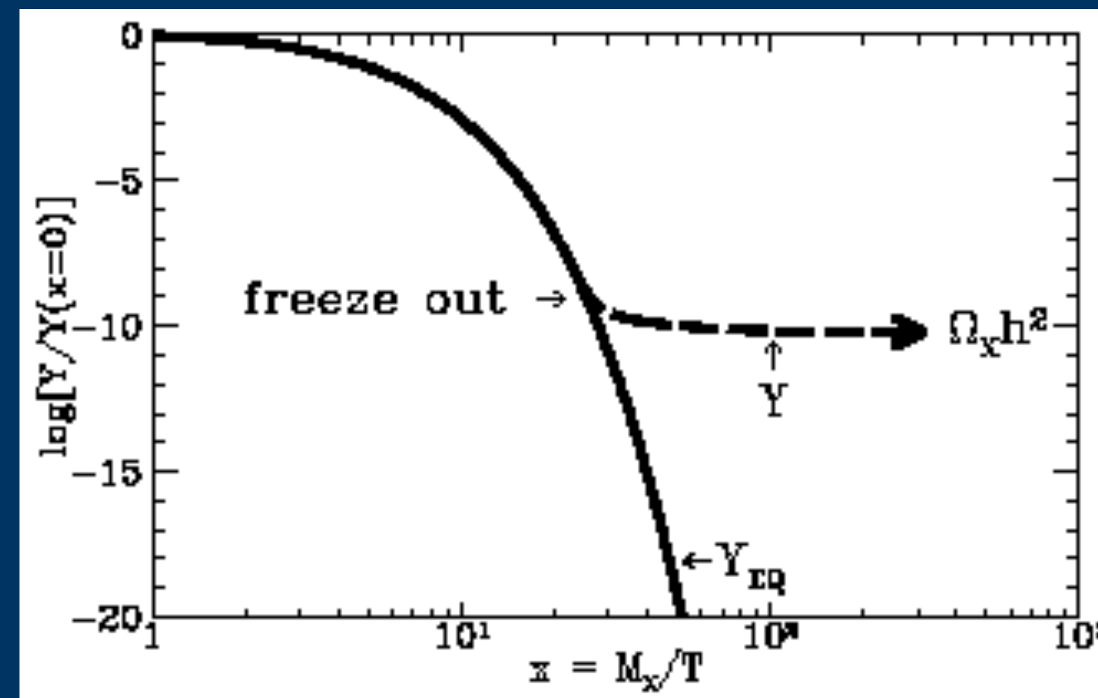
Thermal WIMP

DM abundance is fixed
by Freeze-out mechanism

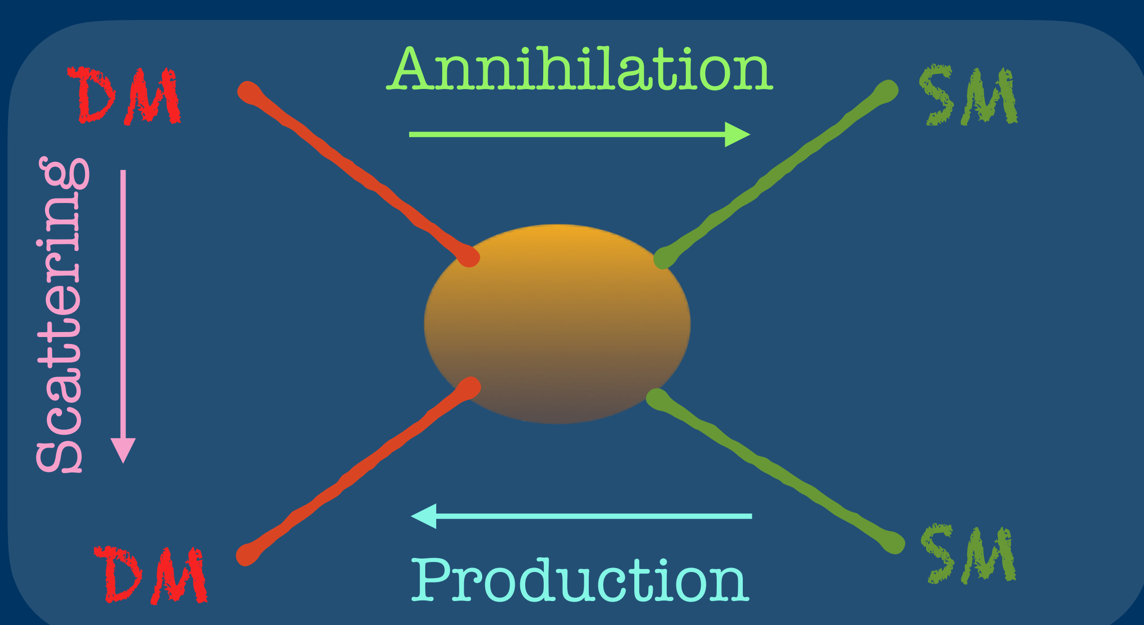
$$\Omega h^2 = \frac{3 \times 10^{-27}\ \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma v^2 \rangle}$$



Thermally averaged cross-section

PLANCK measurement of CMB+BAO : $\Omega h^2 = 0.120 \pm 0.001$

Cosmological measurements constraint particle DM theory

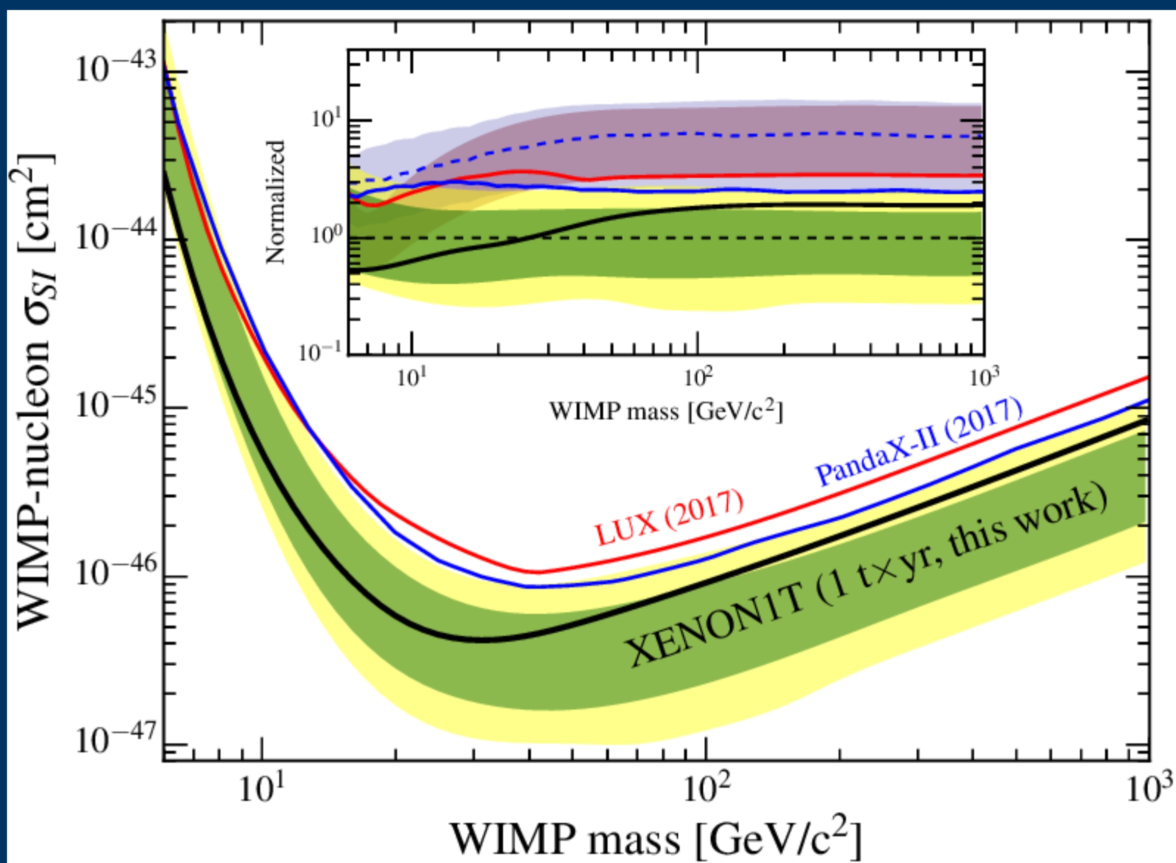


WIMPs are highly promising from experimental point of view.

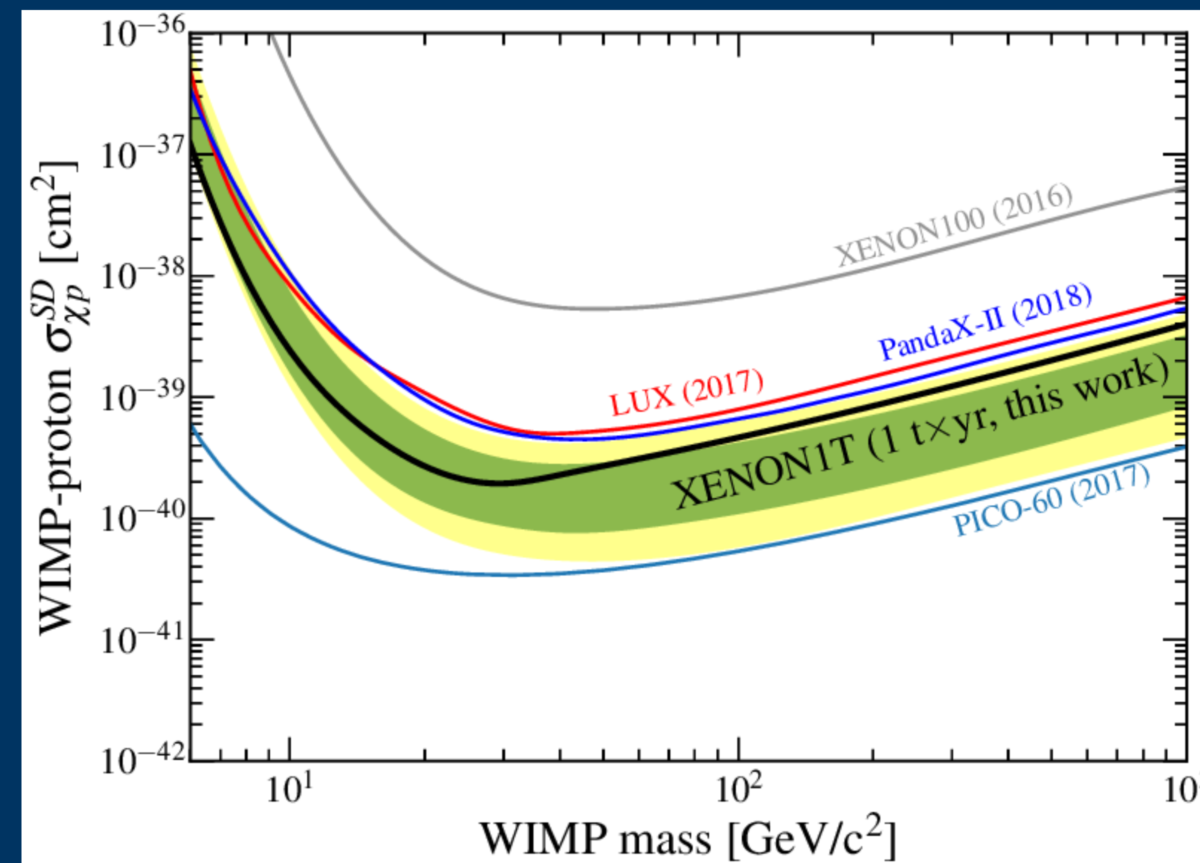
Many ways to test the WIMP paradigm.

Direct Detection

Phys. Rev. Lett. 122 (2019) no.14



Spin-independent cross section



Spin-dependent cross section

Current detector sensitivities. No significant hints yet.

Leptophilic WIMP

Predominantly couples to SM leptons

- SM singlet Majorana DM
- Stabilized by a Z_2 symmetry
- WIMP interaction with the SM leptons can be described by dimension-6 four point interaction $(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{\ell}_i\gamma^\mu\ell_j)$.

Doublet or Singlet

Mediator Type	Spin	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	Z_2
Scalar	0	**1**	**1**	-1	-1
Scalar	0	**1**	**2**	$-1/2$	-1
Vector	1	**1**	**1**	-1	-1
Vector	1	**1**	**2**	$-1/2$	-1
Vector	1	**1**	**1**	0	$+1$

Flavor universal scenario, only one mass parameter for the mediator.

SU(2) Doublet Mediator

$$\mathcal{L}_L = \mathcal{L}_{\rm SM} + \frac{1}{2}\bar{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + (D_L^\mu \tilde{L}_i)^\dagger (D_{L\mu}\tilde{L}_i) + \mathcal{L}_{{\rm DM}\,L} - V_L(H,\tilde{L}_i),$$

$$\mathcal{L}_{{\rm DM}\,L} = -y_L \bar{L}_i \tilde{L}_i \chi + h.c,$$

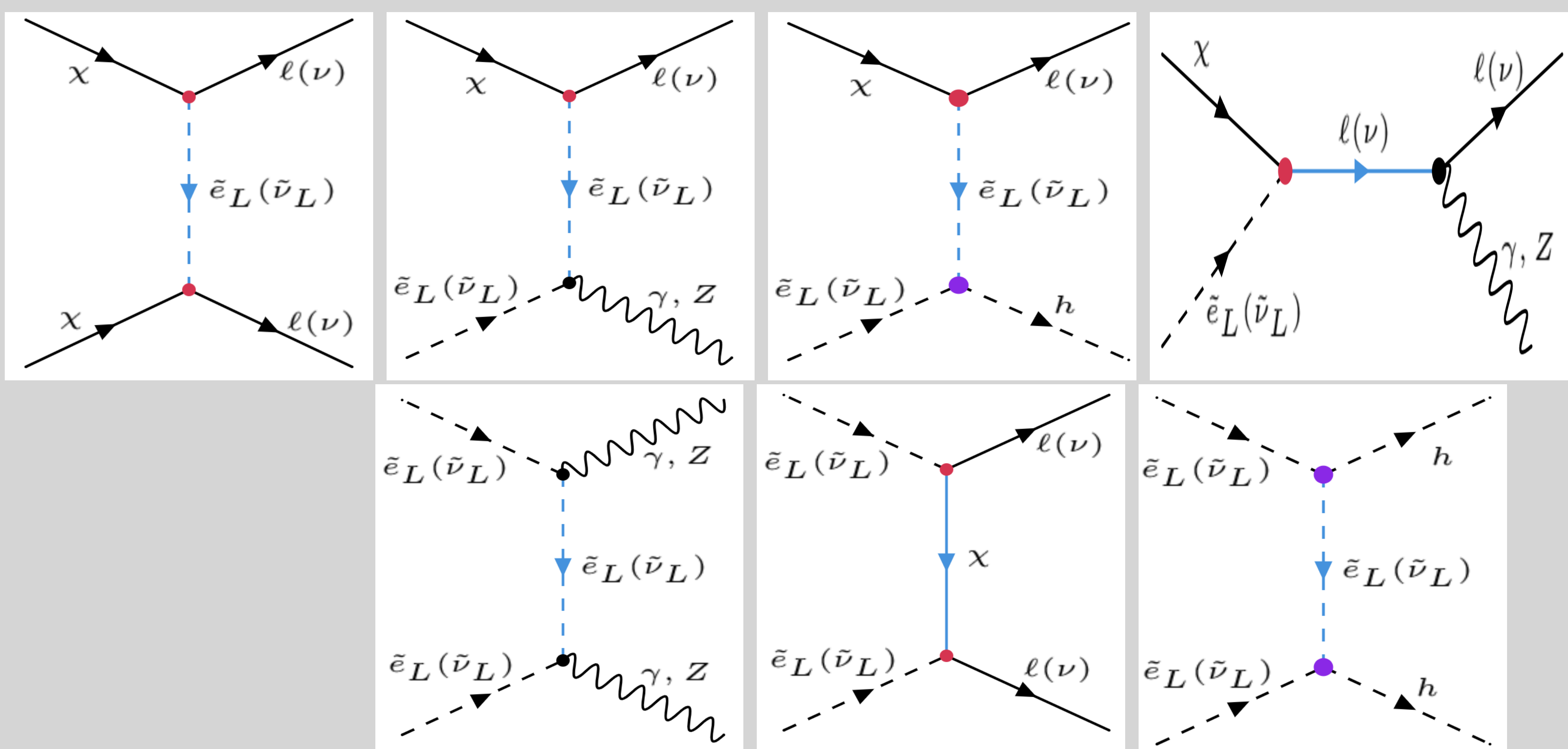
Prohibited by B-L symmetry

$$V_L = m_{\tilde{L}}^2 |\tilde{L}_i|^2 + \frac{\lambda_L}{4!}|\tilde{L}_i|^4 + \lambda_{LH}|\tilde{L}_i|^2|H|^2 + \lambda'_{LH}(\tilde{L}_i^\dagger \tau^a \tilde{L}_i)(H^\dagger \tau^a H) + \cancel{[\frac{\lambda''_{LH}}{4}(\tilde{L}_i^\dagger H^c)^2 + h.c.]}$$

$$\left\{\begin{aligned} m_{\tilde{e}_L}^2 &= (\lambda_{LH} + \lambda'_{LH})\frac{v^2}{2} + m_{\tilde{L}}^2, \\ m_{\tilde{\nu}_L}^2 &= (\lambda_{LH} - \lambda'_{LH})\frac{v^2}{2} + m_{\tilde{L}}^2, \end{aligned}\right.$$

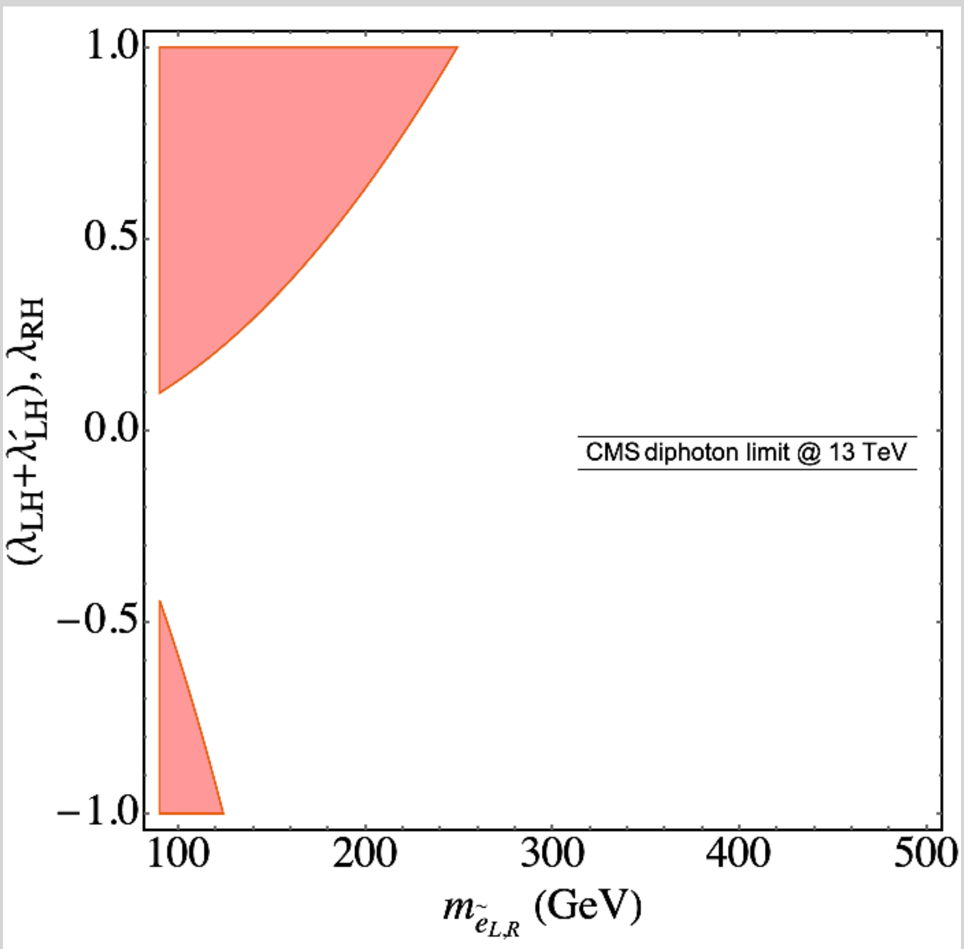
Independent parameters $\lambda_L, \lambda_{LH}, y_L, m_{\tilde{e}_L}, m_{\tilde{\nu}_L}, m_\chi$

Example diagrams of annihilation and co-annihilation



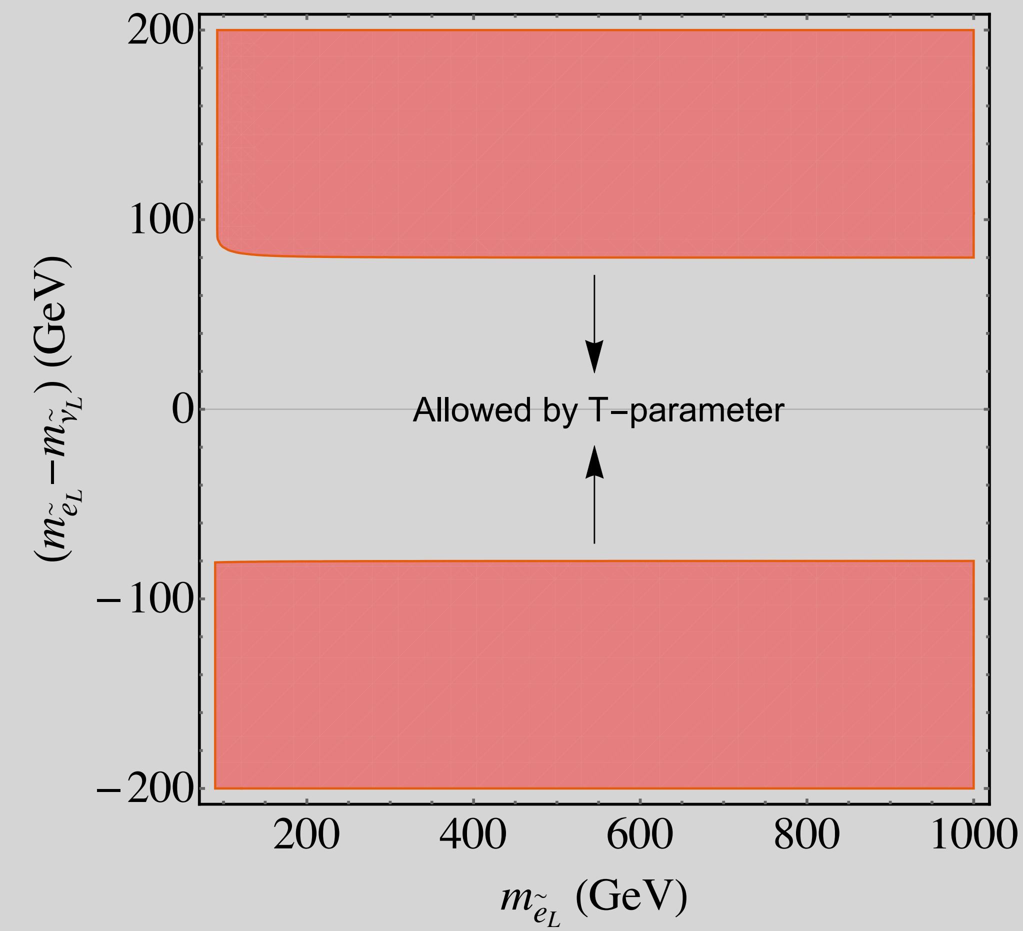
Current Constraints

Higgs to diphoton



Charged scalars contribute to loop-induced Higgs decay to diphoton. Scalar trilinear coupling is $\left(\lambda_{LH} + \lambda'_{LH}\right)$ and λ_{RH} in doublet and singlet case.

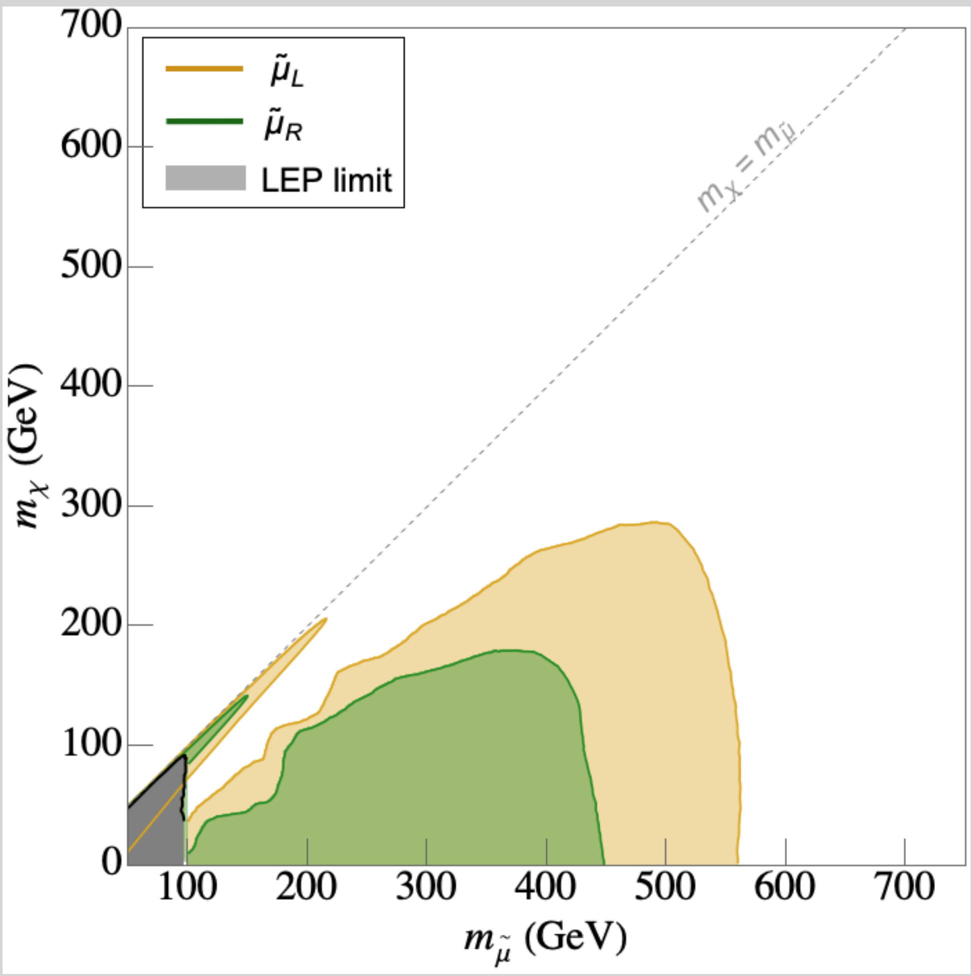
Electroweak Precision



SU(2) Doublet mediator can significantly contribute to electroweak precision measurement. The mass splitting is controlled by T-parameter constraint.

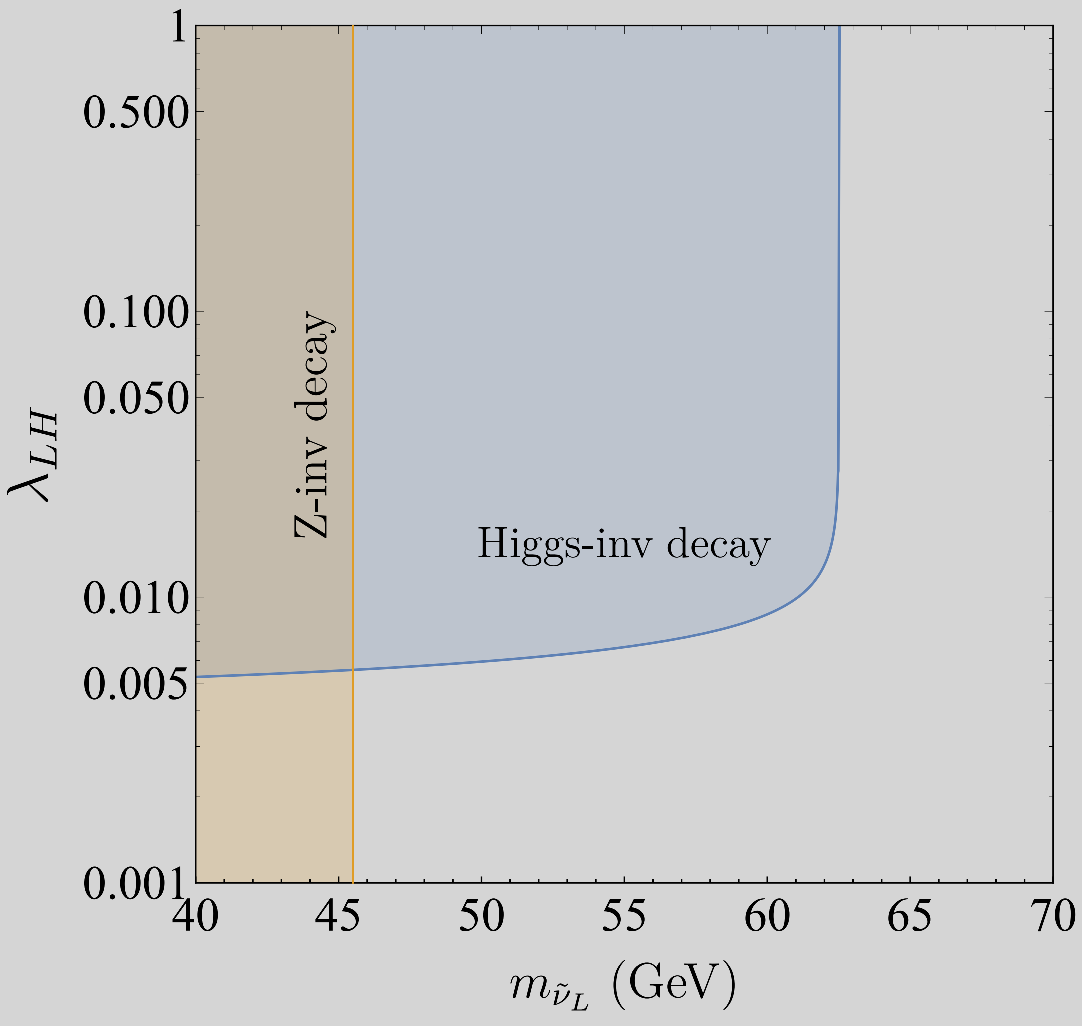
Current Constraints

LHC 13 TeV analysis for sleptons.



Flavor universal scenario, strongest limit comes from smuon searches.

Invisible modes of Z and Higgs.



$$\Gamma(h \to \tilde{\nu}_L \tilde{\nu}_L^*) = \frac{\lambda_{LH}^2 v^2}{16\pi m_h}\sqrt{1 - \frac{4m_{\tilde{\nu}_L}^2}{m_h^2}},$$

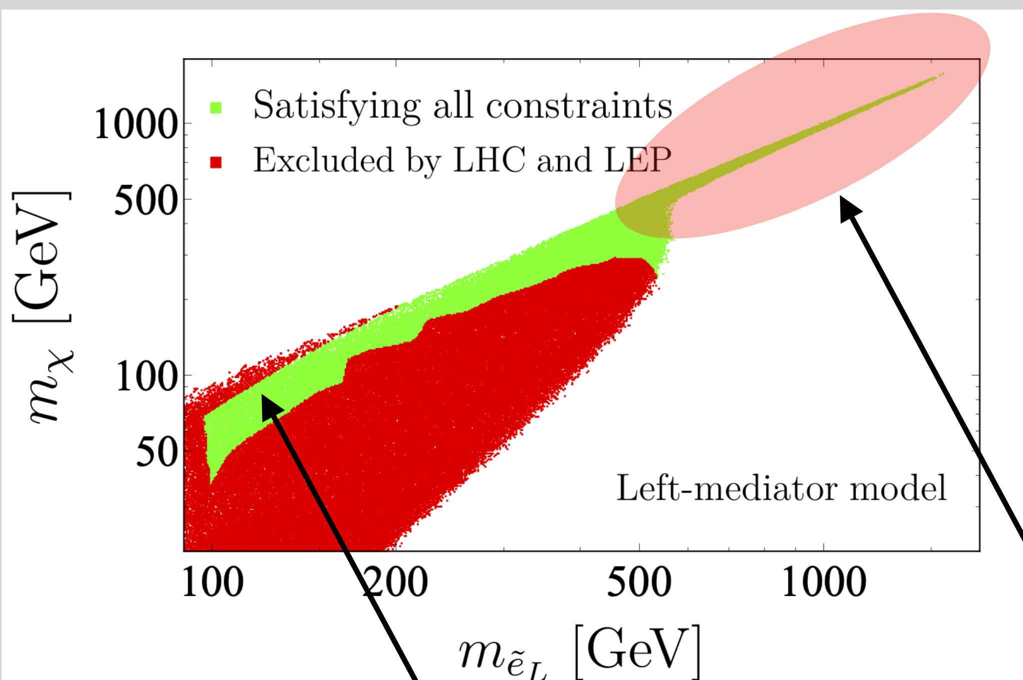
$$\Gamma(Z \to \tilde{\nu}_L \tilde{\nu}_L^*) = \frac{m_Z \alpha}{48 \sin^2\theta_W \cos^2\theta_W}\left(1 - \frac{4m_{\tilde{\nu}_L}^2}{m_Z^2}\right)^{3/2},$$

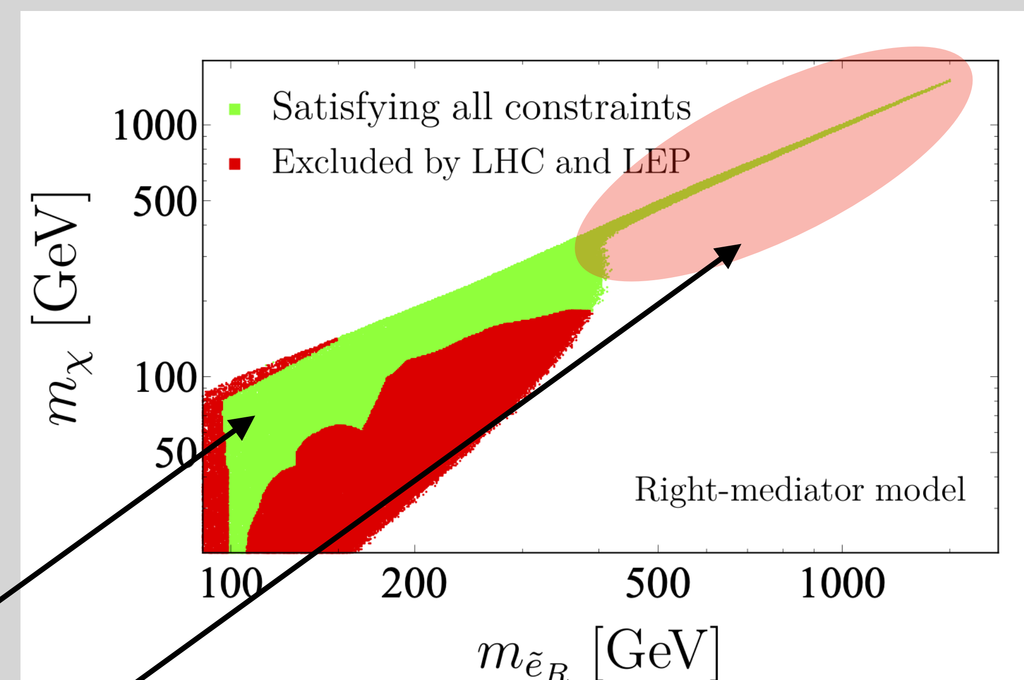
Present Status

$$|\lambda_{LH}| \leq 1, \quad |y_L| \leq 1, \quad 90\,\text{GeV} \leq m_{\tilde{e}_L} \leq 2\,\text{TeV}, \quad |m_{\tilde{e}_L} - m_{\tilde{\nu}_L}| \leq 80\,\text{GeV}, \quad m_{\tilde{\nu}_L} > 45\,\text{GeV},$$

$$|\lambda_{RH}| \leq 1, \quad |y_R| \leq 1, \quad 90\,\text{GeV} \leq m_{\tilde{e}_R} \leq 2\,\text{TeV}, \quad 1\,\text{GeV} \leq m_\chi \leq 2\,\text{TeV}.$$

Allowed region by all previous constraint plus DM relic density and vacuum stability constraints.



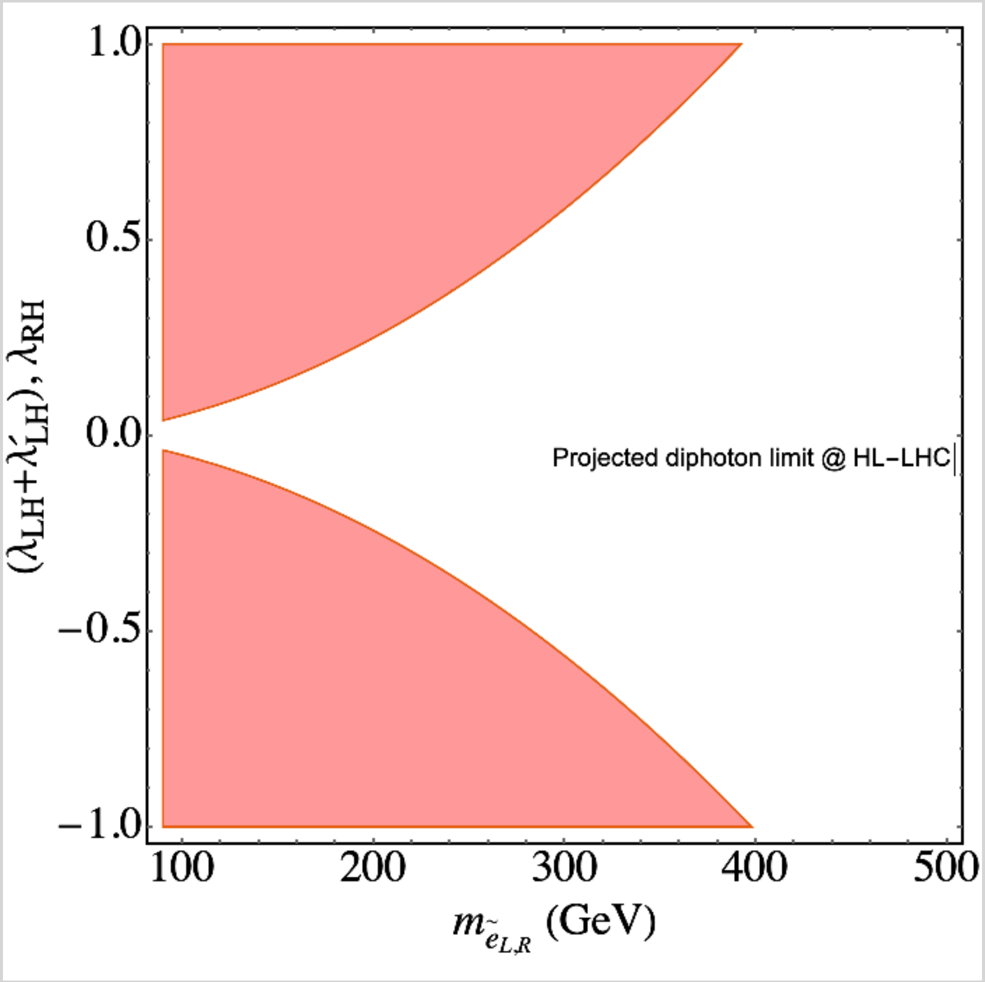


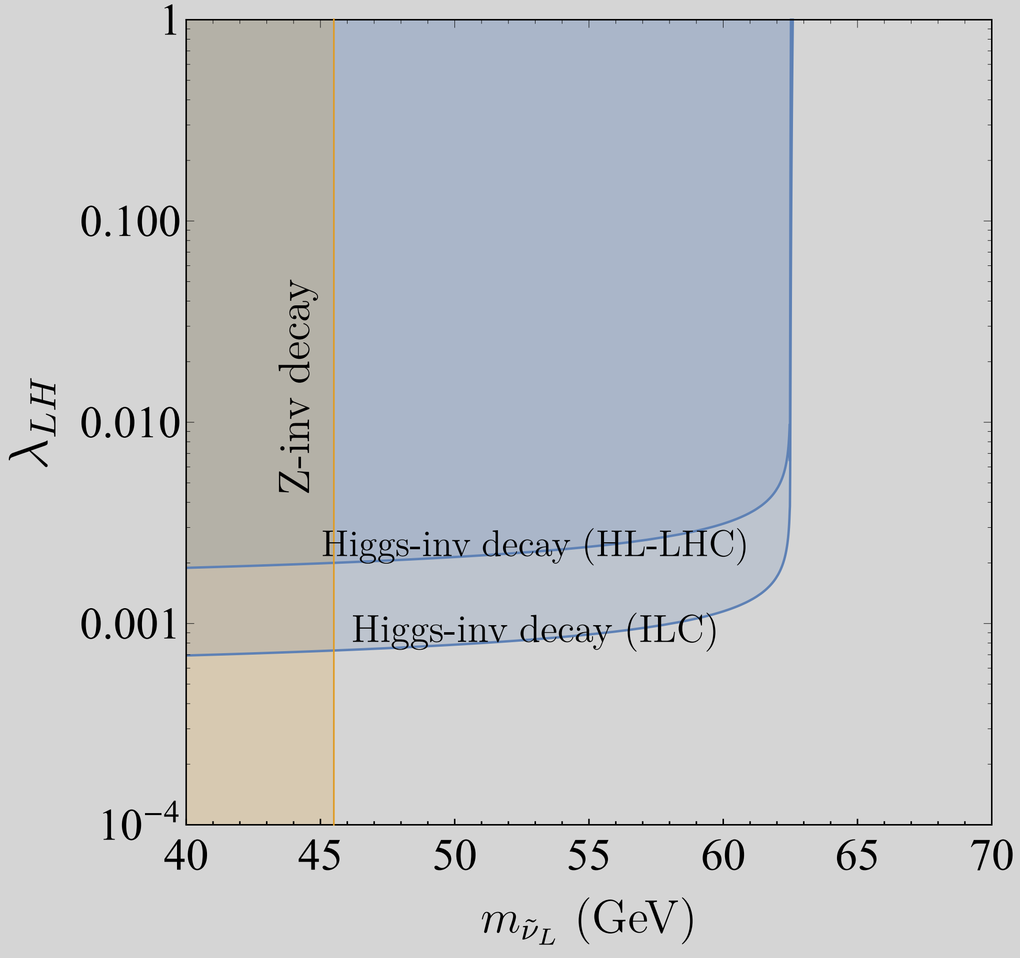
Co-annihilating region. Compressed spectrum.

micrOMEGAs

Interesting region at future ILC.

Future Projection

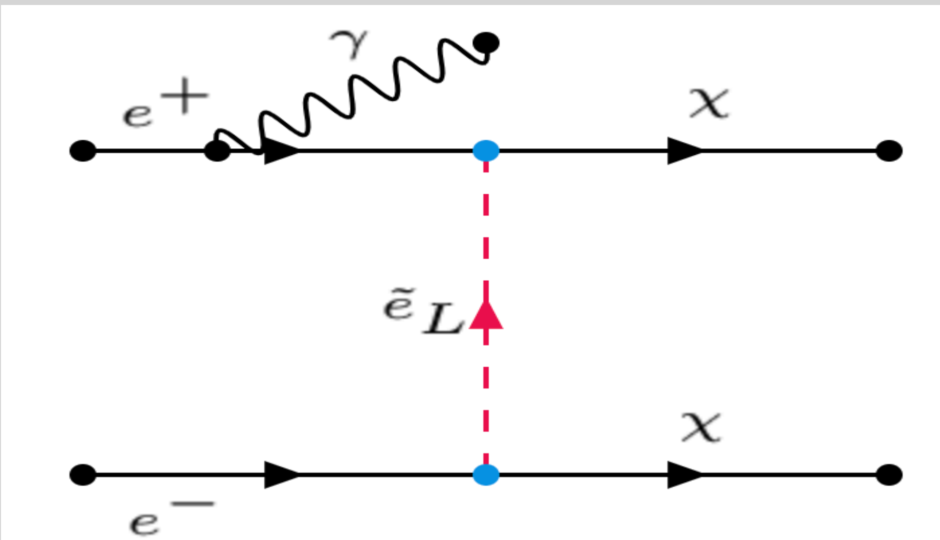


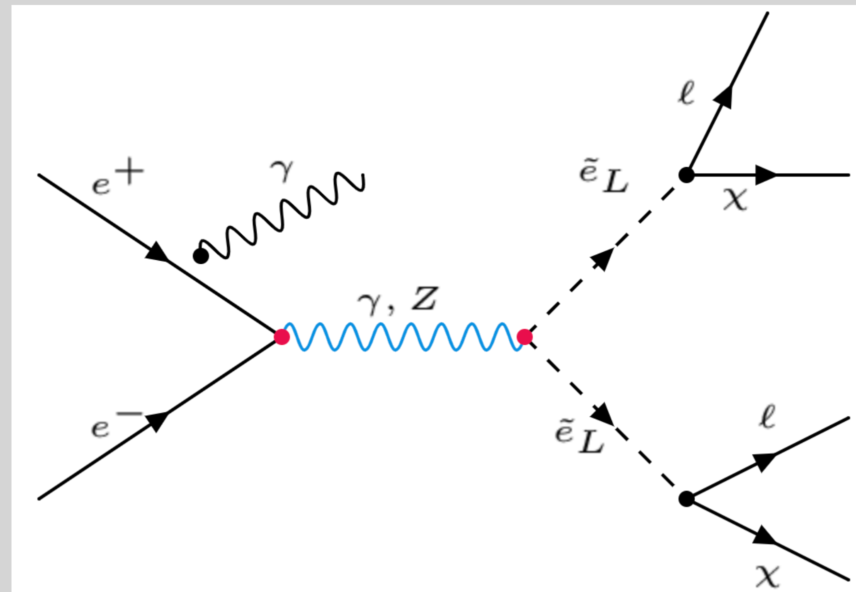


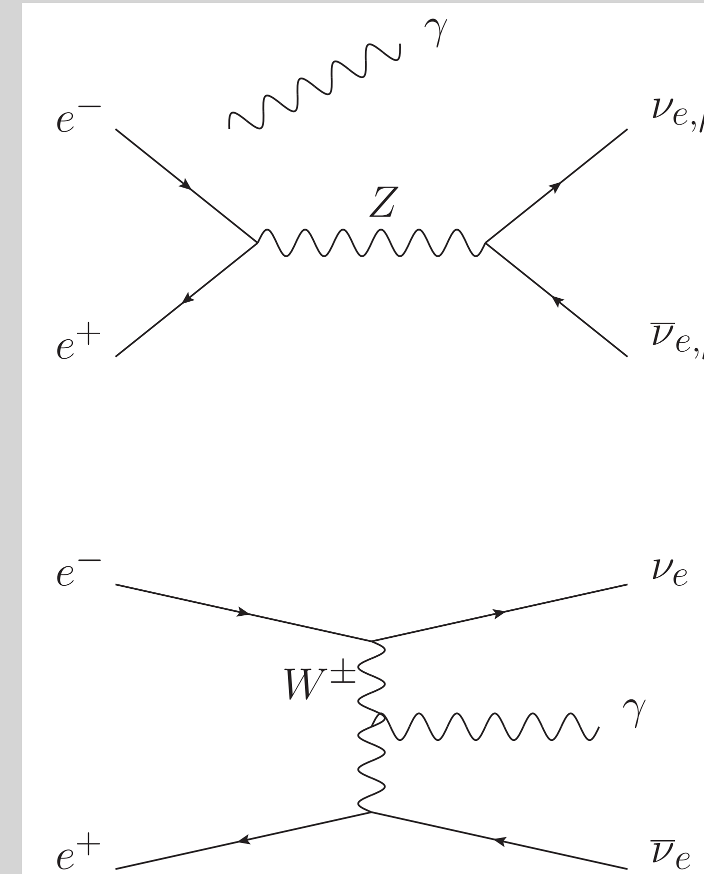
Full run of HL-LHC can measure Higgs to diphoton at around 2% accuracy.

$$\mathscr{B}_{\rm inv} \leq \begin{cases} 0.019 & [\text{HL-LHC}], \\ 0.0026 & [250\,\text{GeV ILC}]. \end{cases}$$

Future Status





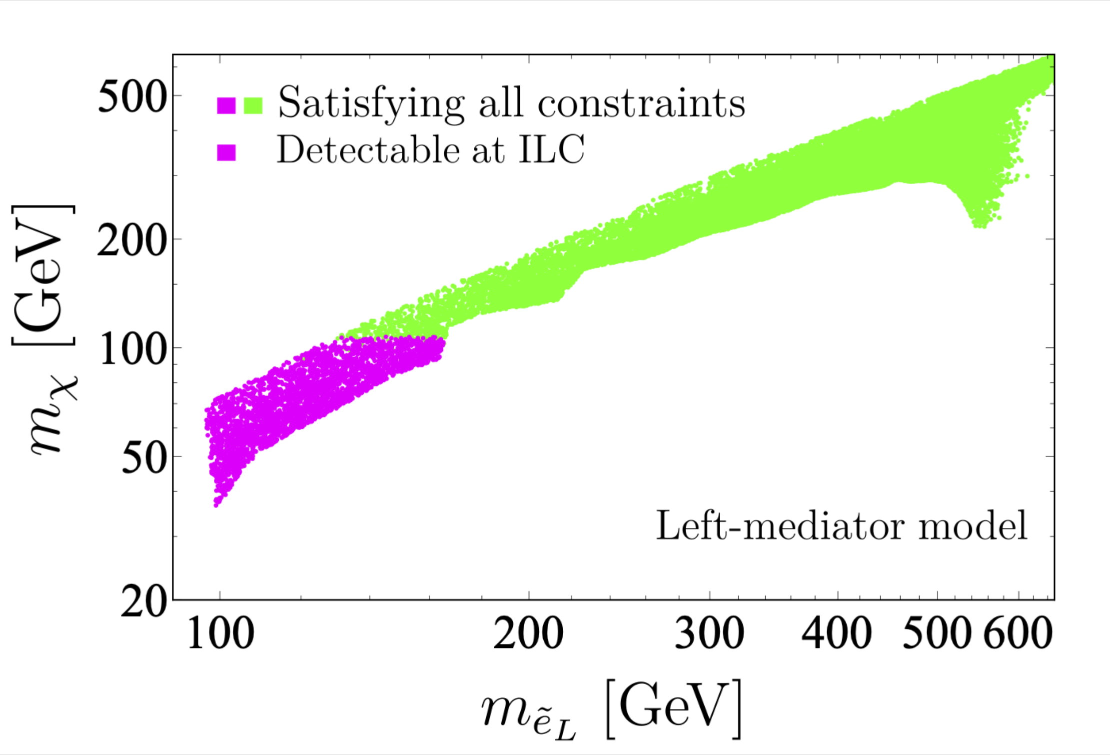


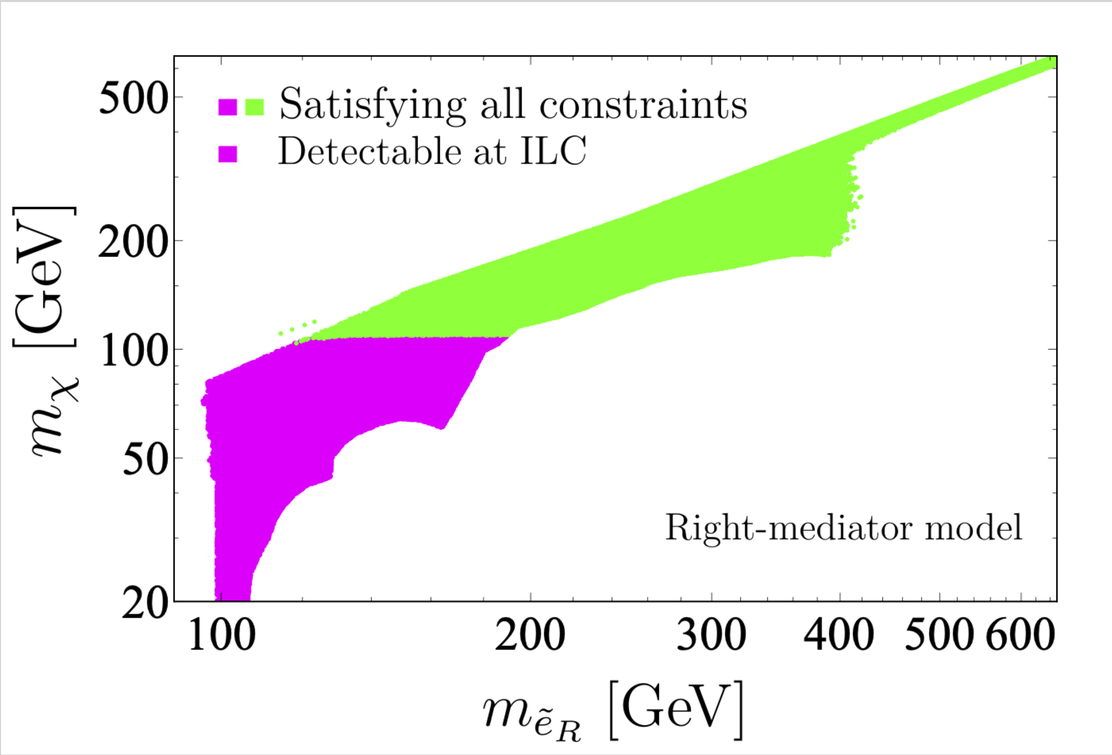
- WIMP mass less than half of the c.o.m energy, mono-photon searches will be effective.
- When WIMP mass and mediator mass is almost degenerate, pair production of mediator is important.
- In the degenerate mass region, the Drell-Yan production of the mediator particles at the ILC with a hard photon emission will contribute to mono-photon signal. Final state leptons will be soft.
- ISR, beam bremstrauhlung and detector effects and 0.1% systematic uncertainty has been taken into account.

Photon isolation requirement: $E_\gamma > 10\ \text{GeV}$, $\cos\theta_\gamma \leq 0.98$

Future Status

95% CL reach at the ILC-250 GeV 500 inv fb luminosity for mono-photon searches.





Combined Model Scenario

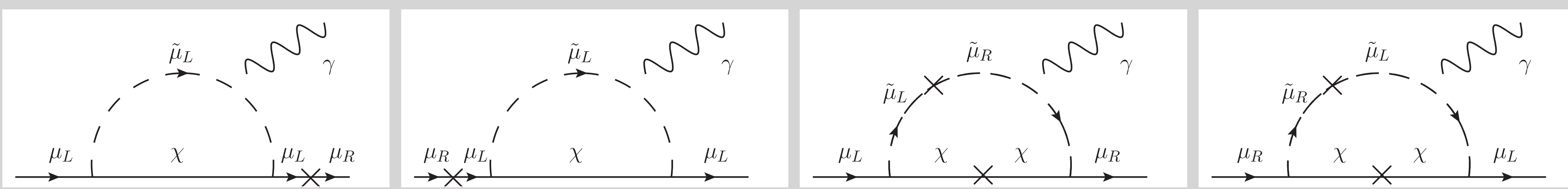
- Both the SU(2) and doublet and singlet mediators are present.
- Motivated by muon anomalous magnetic moment.

$$\mathscr{L}_{LR} = \mathscr{L}_{\rm SM} + \frac{1}{2}\bar{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + (D_L^\mu \tilde{L}_i)^\dagger (D_{L\,\mu}\tilde{L}_i) + (D_R^\mu \tilde{R}_i)^\dagger (D_{R\,\mu}\tilde{R}_i) + \mathscr{L}_{\rm DM} - V_{LR}(H, \tilde{L}_i, \tilde{R}_i),$$

$$\mathscr{L}_{\rm DM} = \mathscr{L}_{{\rm DM}\,L} + \mathscr{L}_{{\rm DM}\,R},$$

$$V_{LR} = V_L(H, \tilde{L}_i) + V_R(H, \tilde{R}_i) + \lambda_{LR}|\tilde{L}_i|^2|\tilde{R}_i|^2 + (A m_i \tilde{L}_i^\dagger H \tilde{R}_i + h.c.).$$

Mixing between two mediator plays important role to satisfy muon (g-2).



Only doublet mediator

Additional contribution in the combined scenario

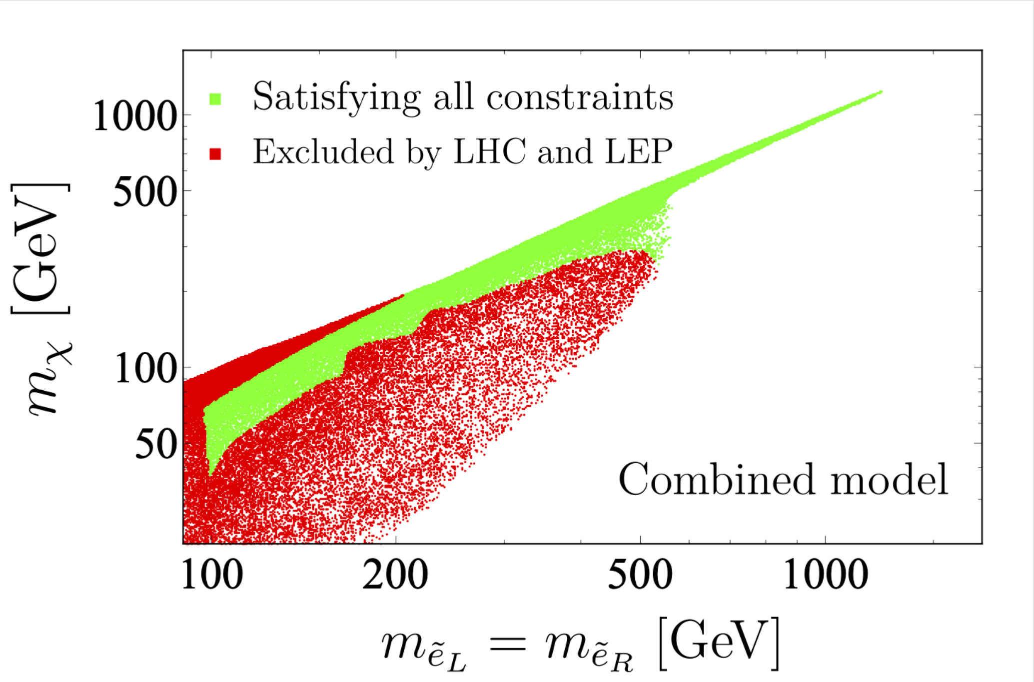
$$\Delta a_\mu^{\rm L+R} = -\frac{y_L y_R}{96\pi^2}\frac{A v\, m_\mu^2}{\sqrt{2} m_\chi^3} f(x,y),$$

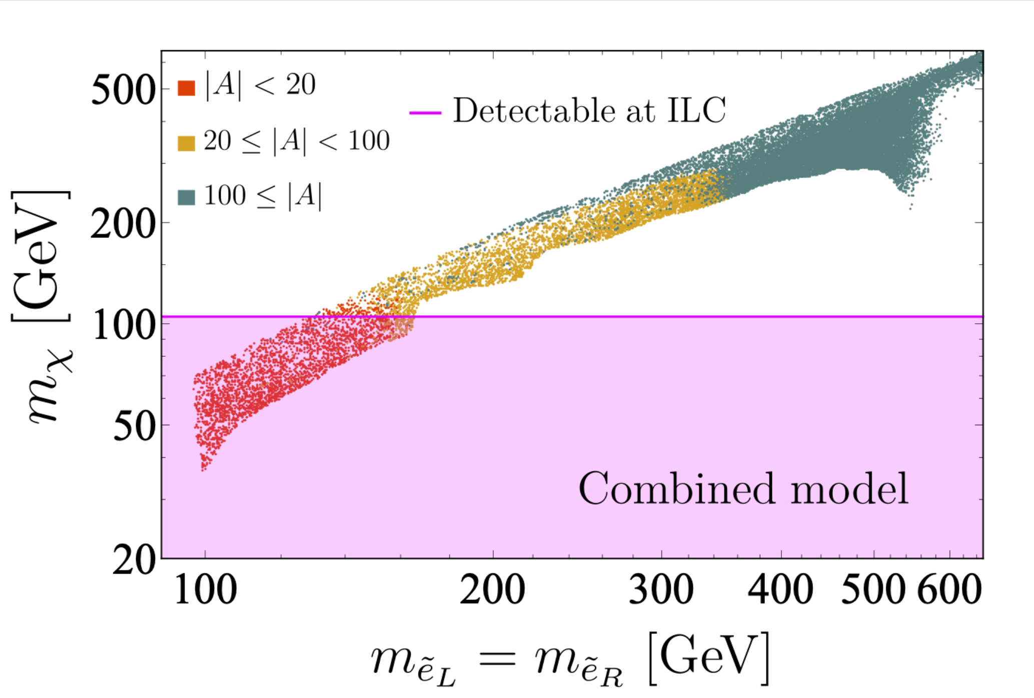
Ref. T. Moroi, hep-ph/9512396

$$f(x,y) = \frac{6}{xy}\left[\frac{-3+x+y+xy}{(x-1)^2(y-1)^2} + \frac{2x\log x}{(x-y)(x-1)^3} + \frac{2y\log y}{(y-x)(y-1)^3}\right],$$

$x \equiv m^2_{\tilde{\mu}_L}/m^2_\chi$ and $y \equiv m^2_{\tilde{\mu}_R}/m^2_\chi$.

Combined Model Detection





- We scan the parameter space for degenerate left and right mediator masses. Sufficient assumption for future collider exploration.
- A term of the order of 1-10 can satisfy the current muon (g-2) anomaly while being detectable at the future ILC.

Conclusions

- We discuss the minimal renormalizable model hypothesis to explain a leptophilic Majorana WIMP nature. A leptophilic WIMP structure can be hidden from the WIMP-nucleon direct detection experiment.

- In the minimal case with either a SU(2) singlet or doublet mediator scenario, the WIMP relic density can be satisfied by following the WIMP self-annihilation as well as co-annihilation mechanism.

- We have found ample parameter space in the WIMP-mediator mass plane that explains the relic abundance and still allowed by other experimental and theoretical constraints, such as LHC direct searches.

- We show that the ILC can play a complementary role to the High-Luminosity future hadron collider to probe such WIMP interaction. Finally, we discussed that a combined model scenario including both the doublet and singlet mediator will have additional advantages which can explain the enhanced anomalous muon magnetic moment.

- We hope one day we will go from constraints to discovery!!

Thank You !

Backup

Vacuum stability constraint

$$\lambda > 0, \quad \lambda_L > 0, \quad \sqrt{\lambda\,\lambda_L} > 2\,(|\lambda'_{LH}| - \lambda_{LH}).$$

$$-\lambda\, m_{\tilde{L}}^2/(2\,\mu^2) > |\lambda'_{LH}| - \lambda_{LH}.$$

$$\lambda > 0, \quad \lambda_R > 0, \quad \sqrt{\lambda\,\lambda_R} > -\lambda_{RH}, \quad -\lambda\, m_{\tilde{R}}^2/(2\,\mu^2) > -\lambda_{RH},$$

Likelihood analysis of photon energy distribution

$$\Delta\chi^2 \equiv \sum_i \frac{(N_i - N_i^{\mathrm{BG}})^2}{N_i^{\mathrm{BG}}},$$

Backgrounds