The search for Leptophilic DM and muon g-2 at future lepton colliders

Taisuke Katayose (Osaka University)

Collaboration with: Shigeki Matsumoto, Ipsita Saha,
Shunichi Horigome, (Kavli IPMU)

based on *Phys.Rev.D* 104 (2021) 5, 055001

Contents

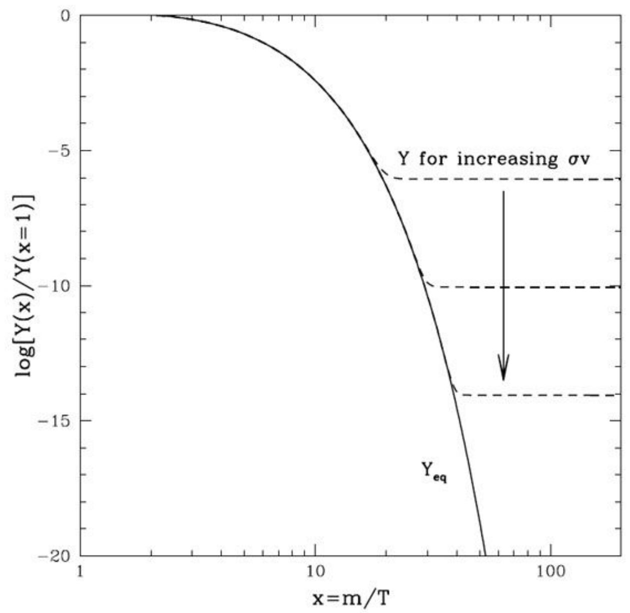
- Introduction of WIMP
- Our model and motivation
- Current constraints on the model
- Future prospect for the model
- Contribution to muon g-2
- Summary

WIMP

- Weakly Interacting Massive Particle (WIMP)
- Well motivated DM candidate
  (by many BSM models like SUSY)
- Thermally created in the early universe
- The abundance is determined by freeze-out mechanism
- Number density follows Boltzmann-eq

$$\frac{dn}{dt} + 3Hn = \langle \sigma v \rangle (n_{\rm eq}^2 - n^2)$$

[E.W.Kolb, M.S.Turner]



WIMP model

- Classifying WIMP by the representation of SM gauge group

Lorentz	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
scalar		$\mathbf{1}$	0
or		$\mathbf{2}$	$-1/2, +1/2$
fermion	$\mathbf{1}$	$\mathbf{3}$	$-1, 0, +1$
or		$\mathbf{4}$	$-3/2, -1/2, +1/2, +3/2$
vector		$\mathbf{5}$	$-2, -1, 0, +1, +2$
		$\vdots$	$\vdots$

- U(1) is quantized because WIMP must be electrically neutral

WIMP model

- Classifying WIMP by the representation of gauge group

Lorentz	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
scalar		$\mathbf{1}$	0
or		$\mathbf{2}$	$-1/2, +1/2$
fermion	$\mathbf{1}$	$\mathbf{3}$	$-1, 0, +1$
or		$\mathbf{4}$	$-3/2, -1/2, +1/2, +3/2$
vector		$\mathbf{5}$	$-2, -1, 0, +1, +2$
		$\vdots$	$\vdots$

Interaction is determined by the SM gauge theory

WIMP model

- Classifying WIMP by the representation of gauge group

Lorentz	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
scalar		$\mathbf{1}$	0
or		$\mathbf{2}$	$-1/2, +1/2$
fermion	$\mathbf{1}$	$\mathbf{3}$	$-1, 0, +1$
or		$\mathbf{4}$	$3/2, -1/2, +1/2, +3/2$
vector		$\mathbf{5}$	$-2, -1, 0, +1, +2$
		$\vdots$	$\vdots$

How about here?

WIMP does not have gauge interaction

We have to study each model case-by-case

WIMP model

- Classifying WIMP by the representation of gauge group

Lorentz	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
scalar		$\mathbf{1}$	0
or		$\mathbf{2}$	$-1/2, +1/2$
fermion	$\mathbf{1}$	$\mathbf{3}$	$-1, 0, +1$
or		$\mathbf{4}$	$3/2, -1/2, +1/2, +3/2$
vector		$\mathbf{5}$	$-2, -1, 0, +1, +2$
		$\vdots$	$\vdots$

How about here?

We focus on fermionic gauge singlet WIMP

Fermionic singlet WIMP

- We impose Z_2 symmetry to make WIMP stable

χ : odd   SM particles : even

- Fermionic gauge singlet WIMP cannot have renormalizable interaction with SM particles.

Mass dimension	Operator
4	None
5	$\bar{\chi}\chi\|H\|^2$ $\bar{\chi}i\gamma_5\chi\|H\|^2$
6	$\bar{\chi}\gamma_\mu\gamma_5\chi\bar{Q}\gamma^\mu Q$ $\bar{\chi}\gamma_\mu\gamma_5\chi\partial_\nu F^{\mu\nu}$ etc.

- For UV completion, we need mediator particles which connect DM and SM particles
- There are many choices of mediator particles

Our model

- We consider Z_2-odd scalar leptophilic mediator
- Correspond to bino (WIMP) and slepton (mediator) in SUSY
- Possibility to explain muon g-2 anomaly
- Direct detection experiment does not work effectively
- The search at collider experiments become more important
- Two scenarios for the mediator choice
  (left-handed slepton, right-handed slepton)

Lagrangian (left-handed slepton)

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

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

interaction term

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

scalar potential term

- Most important parameters are $m_\chi, m_{\tilde{L}}, y_L$
- Assuming flavor blindness for the analysis (slepton mass and interactions are universal for each flavor)

Lagrangian (right-handed slepton)

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

$$\mathcal{L}_{{\rm DM}\,R} = -y_R \bar{E}_i \tilde{R}_i \chi + h.c,$$ interaction term

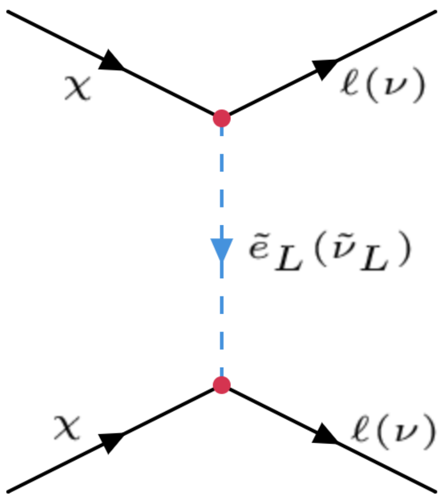
$$V_R = m_{\tilde{R}}^2 |\tilde{R}_i|^2 + \frac{\lambda_R}{4}|\tilde{R}_i|^4 + \lambda_{RH}|\tilde{R}_i|^2|H|^2,$$ scalar potential term

- Most important parameters are $m_\chi, m_{\tilde{R}}, y_R$
- Assuming flavor blindness for the analysis (slepton mass and interaction are universal for each flavor)

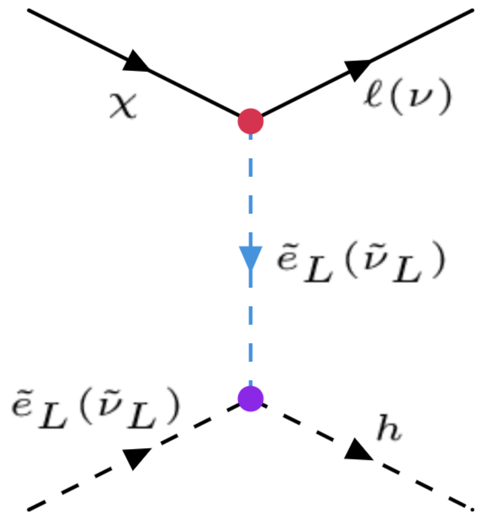
Constraints on the model

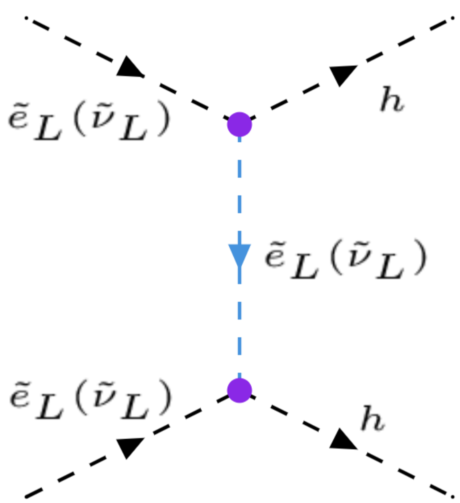
- Vacuum stability condition
- Constraint from $h \to \gamma\gamma$ or $h \to$ inv. decay
- Electroweak precision measurement
- Relic abundance condition
- Direct production of mediators at colliders

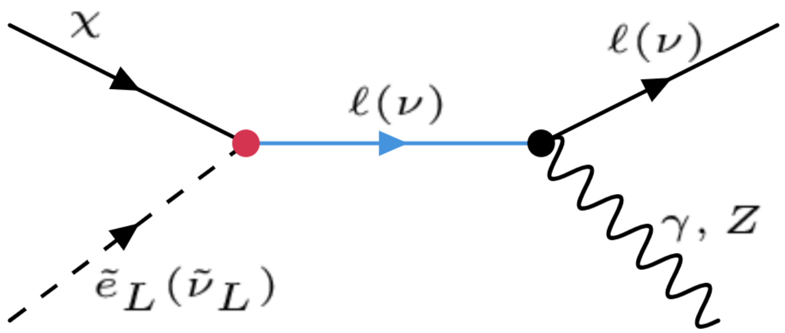
Relic abundance condition
(e.g. left-handed case)



- $\chi\chi \to \bar{l}l$ is dominant annihilation mode
- The abundance is determined by $m_\chi, m_{\tilde{L}}, y_L$
- If WIMP mass and mediator mass are degenerate, other processes also become important (co-annihilation)







and so on

We used MadGraph5_aMC@NLO for the calculation

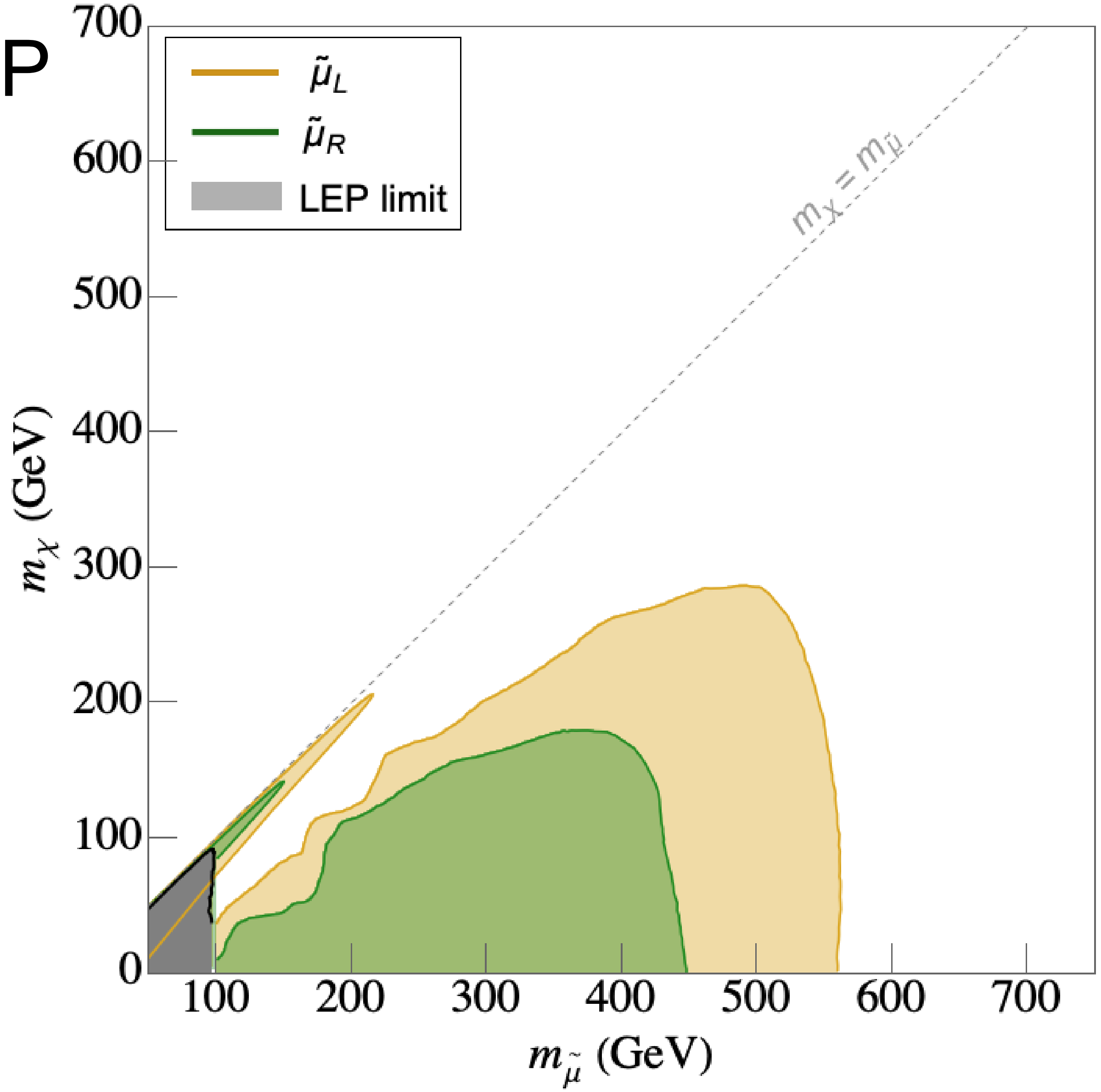
Collider constraints

- Slepton pair can be created via Drell-Yan process at LHC or LEP

- Created slepton decays into WIMP and lepton

- Constraint on slepton mass and WIMP mass

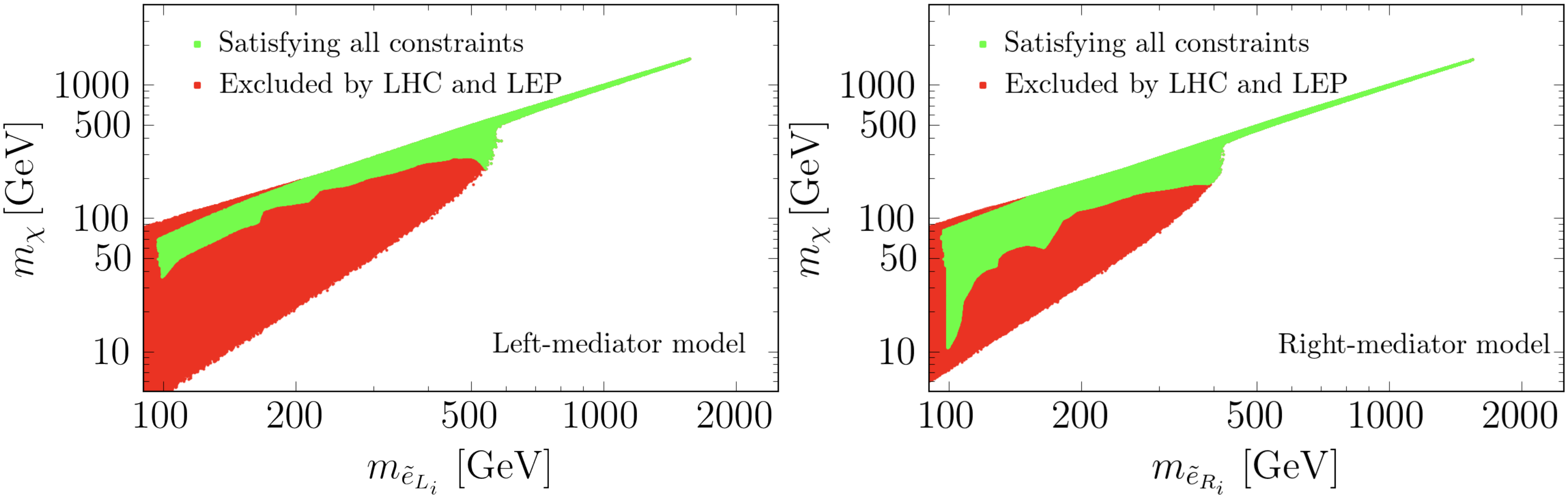
- LEP constrain slepton below 94 GeV
  (under flavor blindness)



[Georges Aad et al. Phys. Rev. D, 101(5):052005,2020]

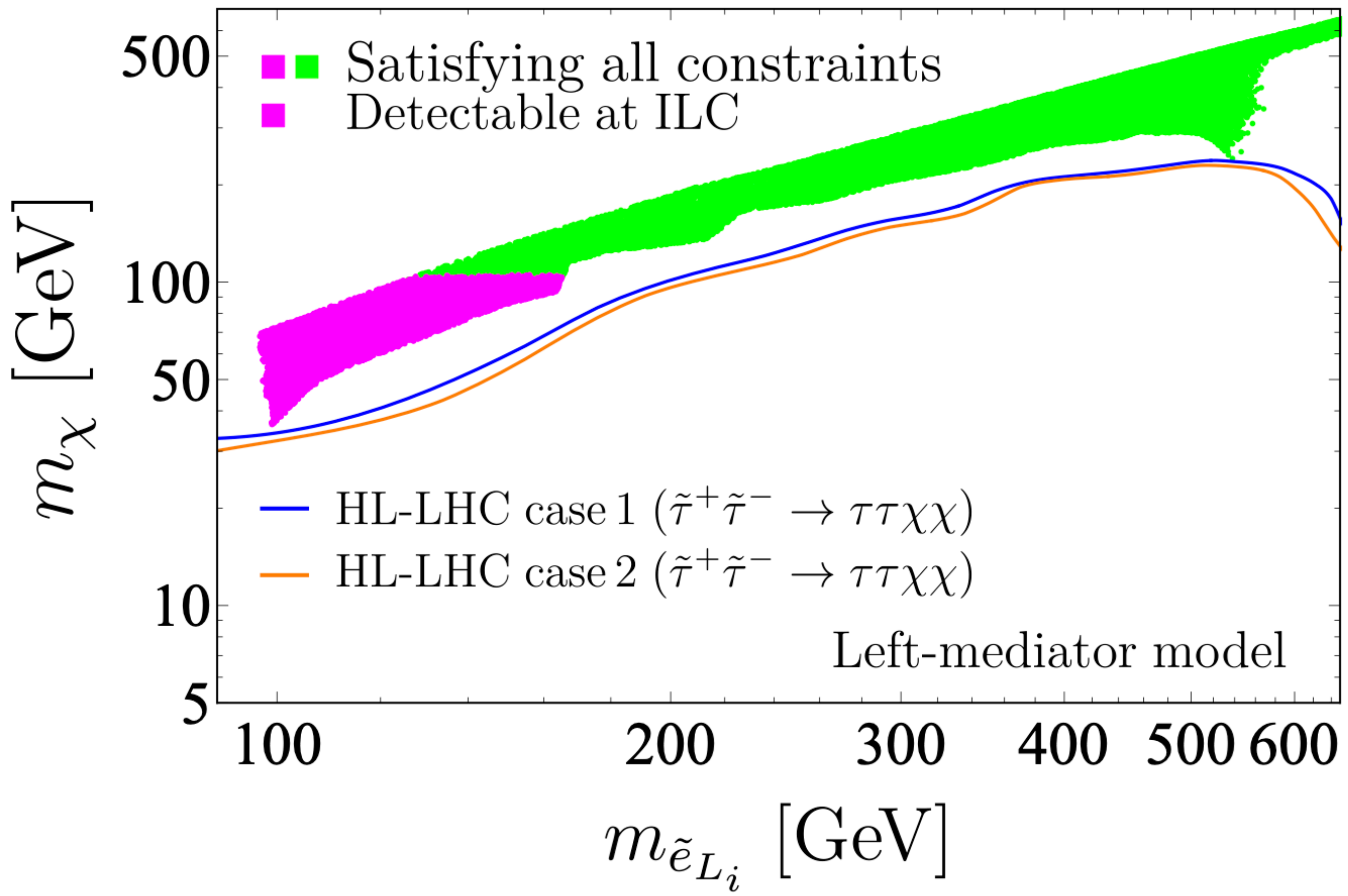
[Georges Aad et al. Phys. J. C, 80(2):123,2020]

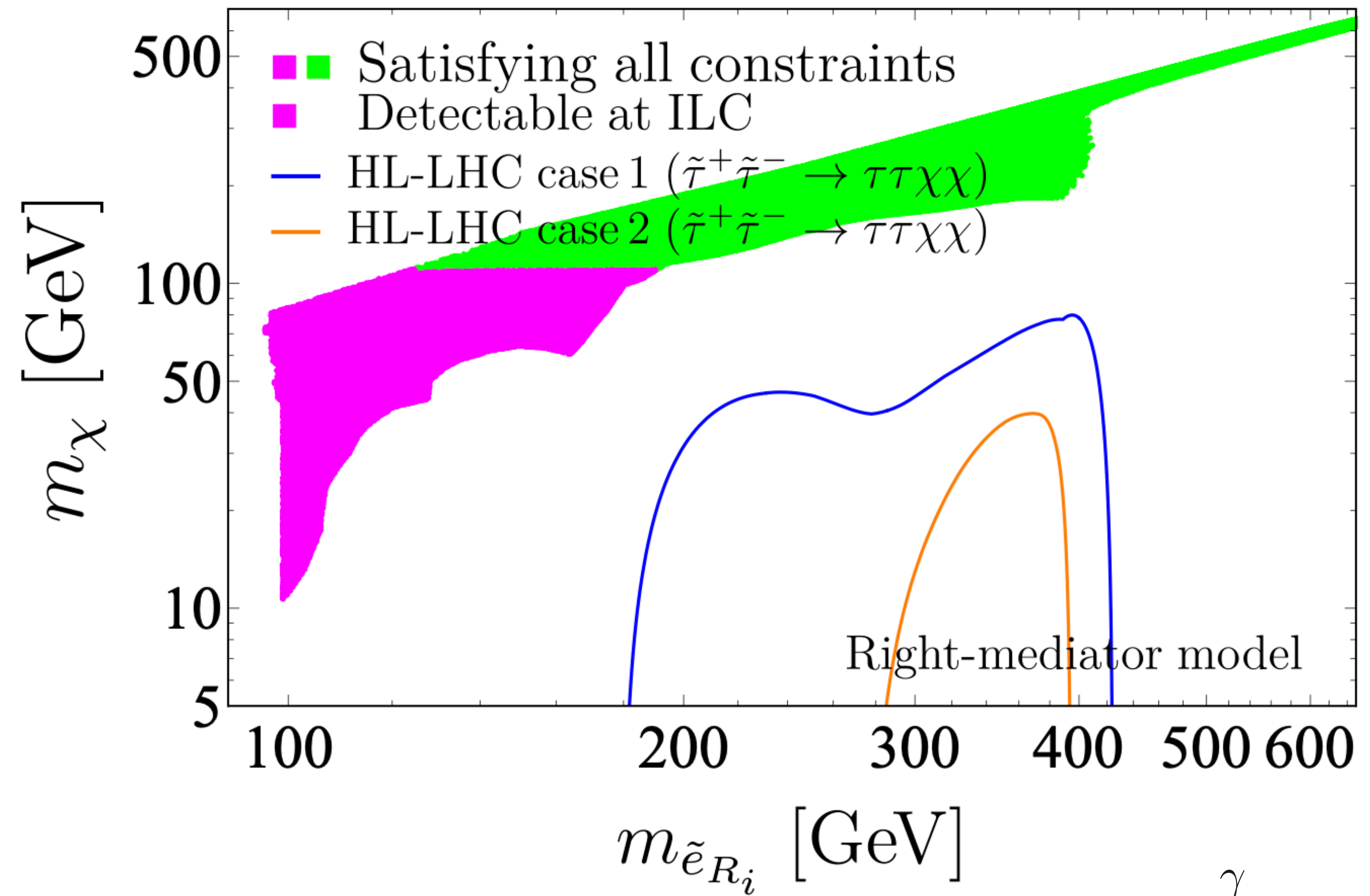
Present status



- Here we also consider other constraints (vacuum stability, electroweak precision, higgs decay)
- Green region is surviving region

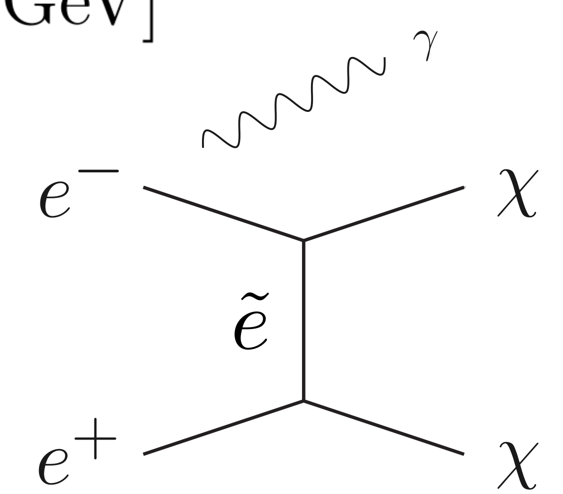
Future prospect





- We consider mono-photon search at 250 GeV ILC

(For HL-LHC, only tau channel analysis is shown)



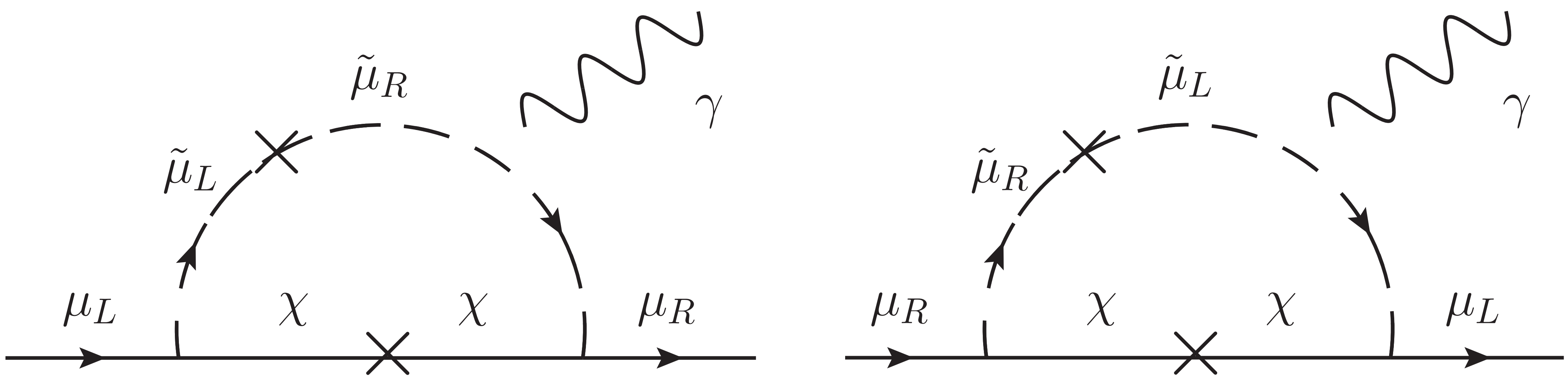
Combined scenario of left and right mediators and muon g-2

Muon g-2

- If we consider left and right mediators simultaneously, there emerge new scalar potential terms

$$\lambda_{LR}(\tilde{L}_i^\dagger \tilde{L}_i)(\tilde{E}_i^\dagger \tilde{E}_i) \qquad A m_i \tilde{E}_i \tilde{L}_i^\dagger H + h.c.$$

- New ‘A’ term induce muon g-2



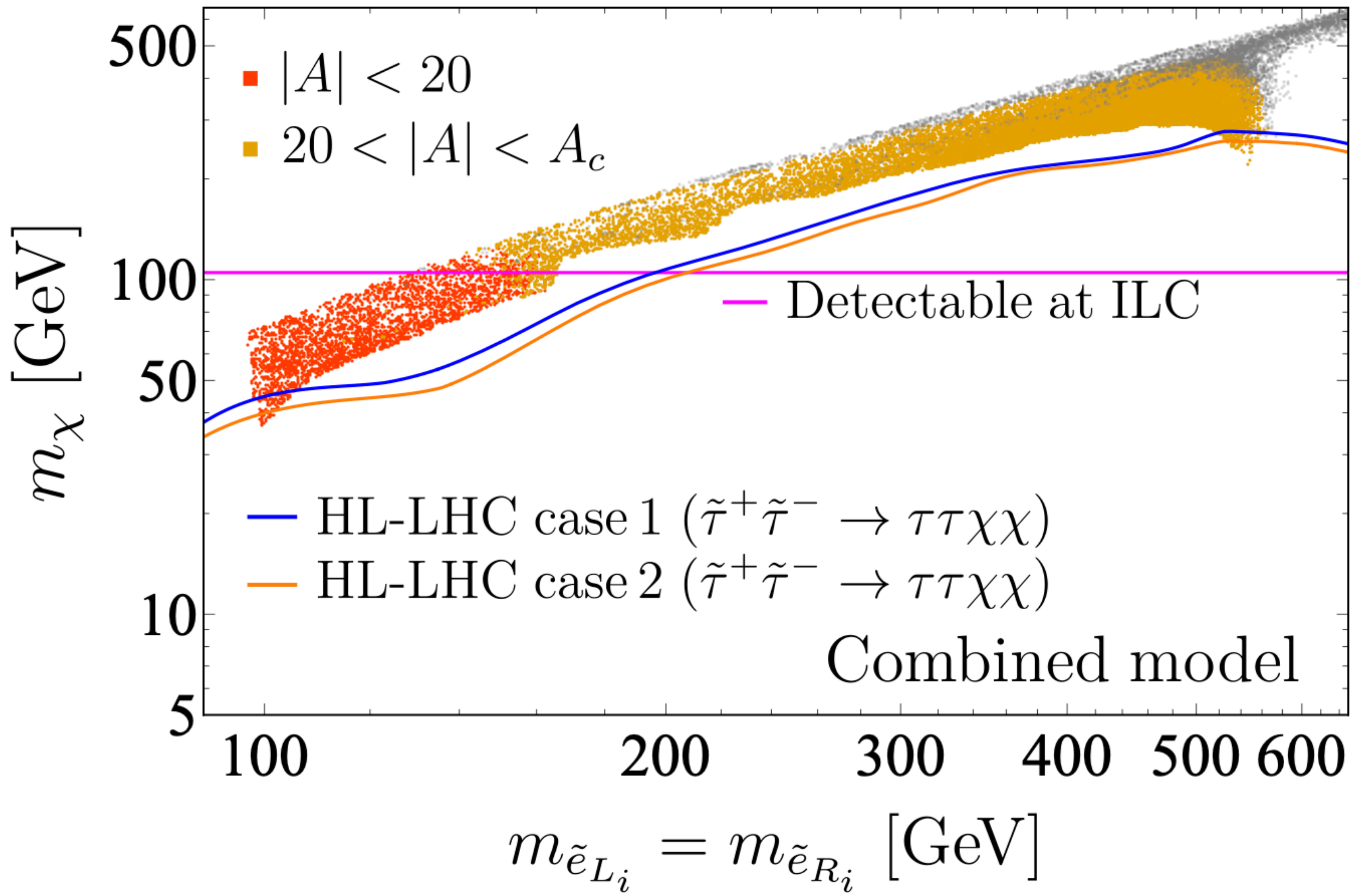
- Muon g-2 anomaly can be explained by combined model

$$\Delta a_\mu \equiv a_\mu^{\rm exp} - a_\mu^{\rm SM} = 251(59) \times 10^{-11}$$ [Fermilab (2021)]

Muon g-2

- This plot shows the value of ‘A’ to explain muon g-2 anomaly
- Yellow and red region have stable vacuum at least SUSY case

[G. H. Duan, C. Han, B. Peng, L. Wu and J. M. Yang, 2019]



Summary

- We studied the phenomenology of fermionic gauge singlet WIMP with leptophilic mediator
- ILC experiment has important role to search such models
- Left and right combined model can be a solution of muon g-2 anomaly
- There are some region which can explain muon g-2 anomaly and also detectable at ILC