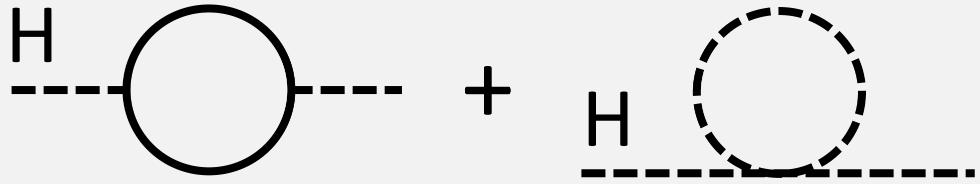
SUSY Higgs Mass and Collider Signals with a Hidden Valley

Yuichiro Nakai (Harvard)

YN, M. Reece and R. Sato, In preparation

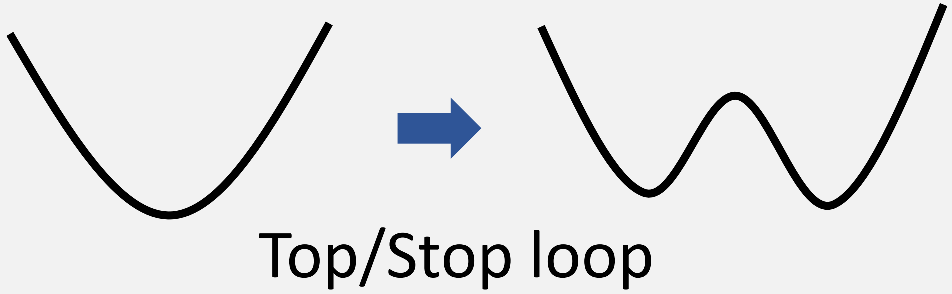
Supersymmetry (SUSY)

Naturalness



Quadratic divergence is cancelled.

Dynamics of EWSB



EWSB is driven radiatively.

However, LHC poses two significant obstacles …

SUSY Higgs mass problem

125 GeV Higgs is light, but not so light …

A significant radiative correction is needed in MSSM.

$$\Delta\lambda_{H_u} \approx \frac{y_t^4 N_c}{16\pi^2} \ln \frac{m_{\tilde{t}}}{m_t} \qquad N_c = 3$$

A large quadratic term is also generated.

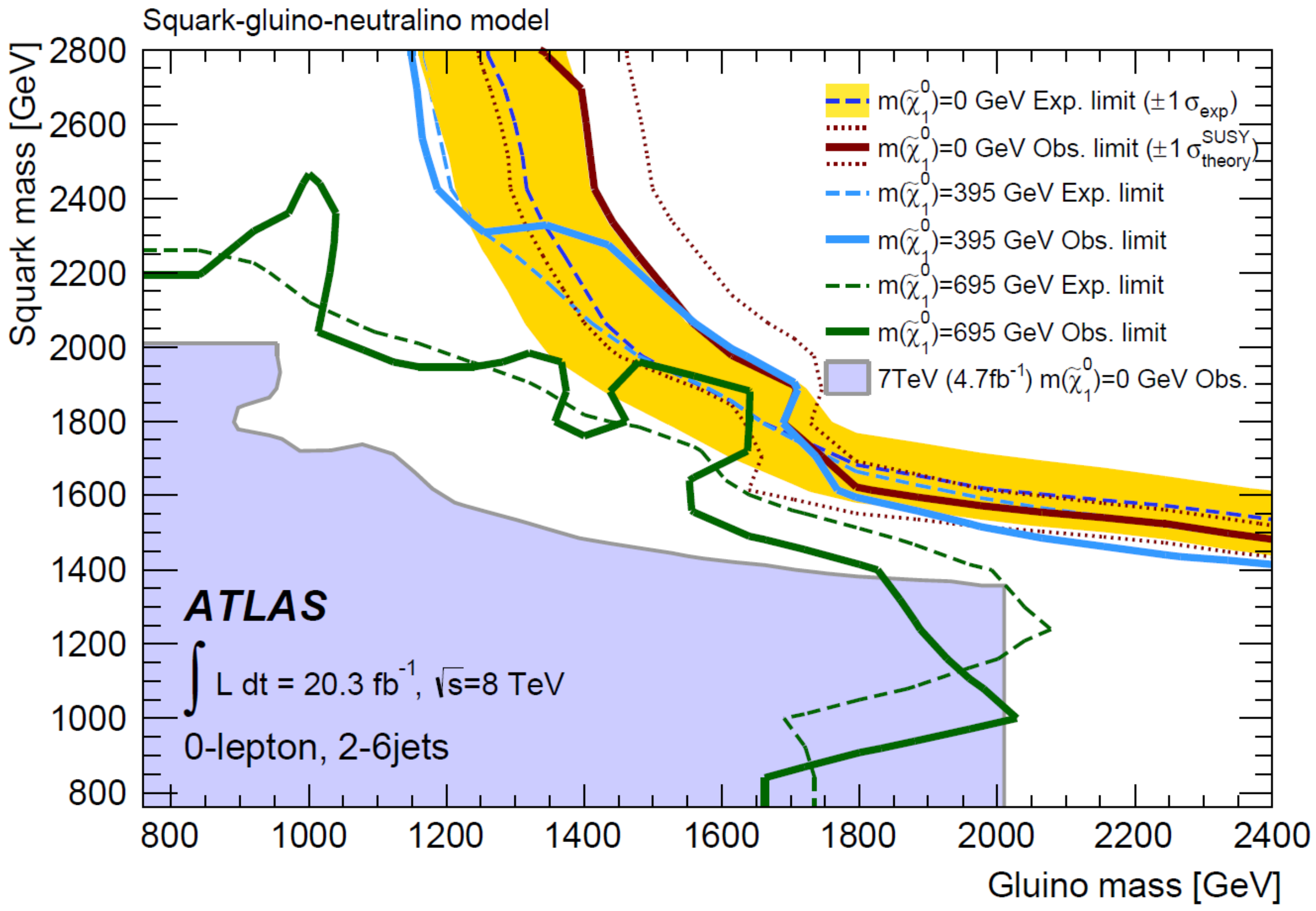
$$\Delta m_{H_u}^2 \approx -\frac{y_t^2 N_c}{4\pi^2} m_{\tilde{t}}^2 \ln \frac{M_{\mathrm{m}}^2}{m_{\tilde{t}}^2}$$

M_{m} : Mediation scale

Fine tuning is required in MSSM.

Missing superpartner problem

Superpartners have not been observed yet.



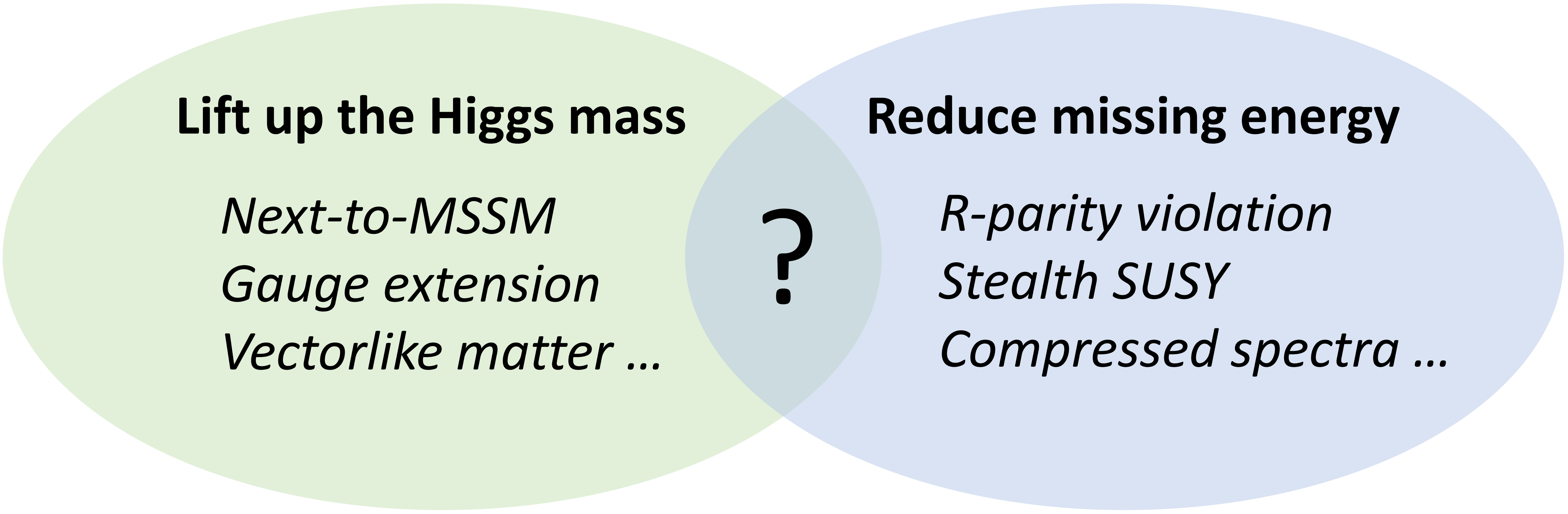
Jets and missing P_T search

(Gluino mass) > 1.4 TeV

(Squark mass) > 1.6 TeV

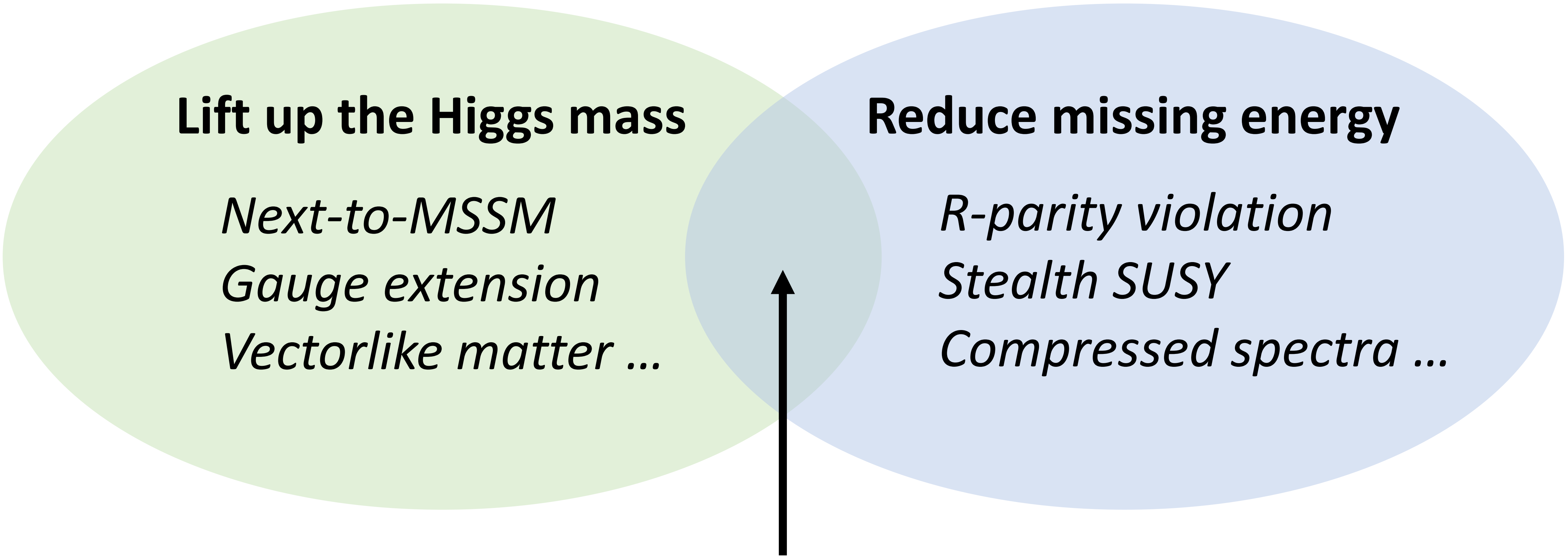
➡ **Fine tuning**

Two modules for two problems



Two problems are usually treated as independent.

One module for two problems



Explore a scenario that can ameliorate both problems !

Our framework : New loop contributions

Let's look at SUSY Higgs mass problem again.

$$\Delta\lambda_{H_u} \approx \frac{y_t^4 N_c}{16\pi^2} \ln \frac{m_{\tilde{t}}}{m_t} \qquad \Delta m^2_{H_u} \approx -\frac{y_t^2 N_c}{4\pi^2} m^2_{\tilde{t}} \ln \frac{M^2_{\mathrm{m}}}{m^2_{\tilde{t}}}$$

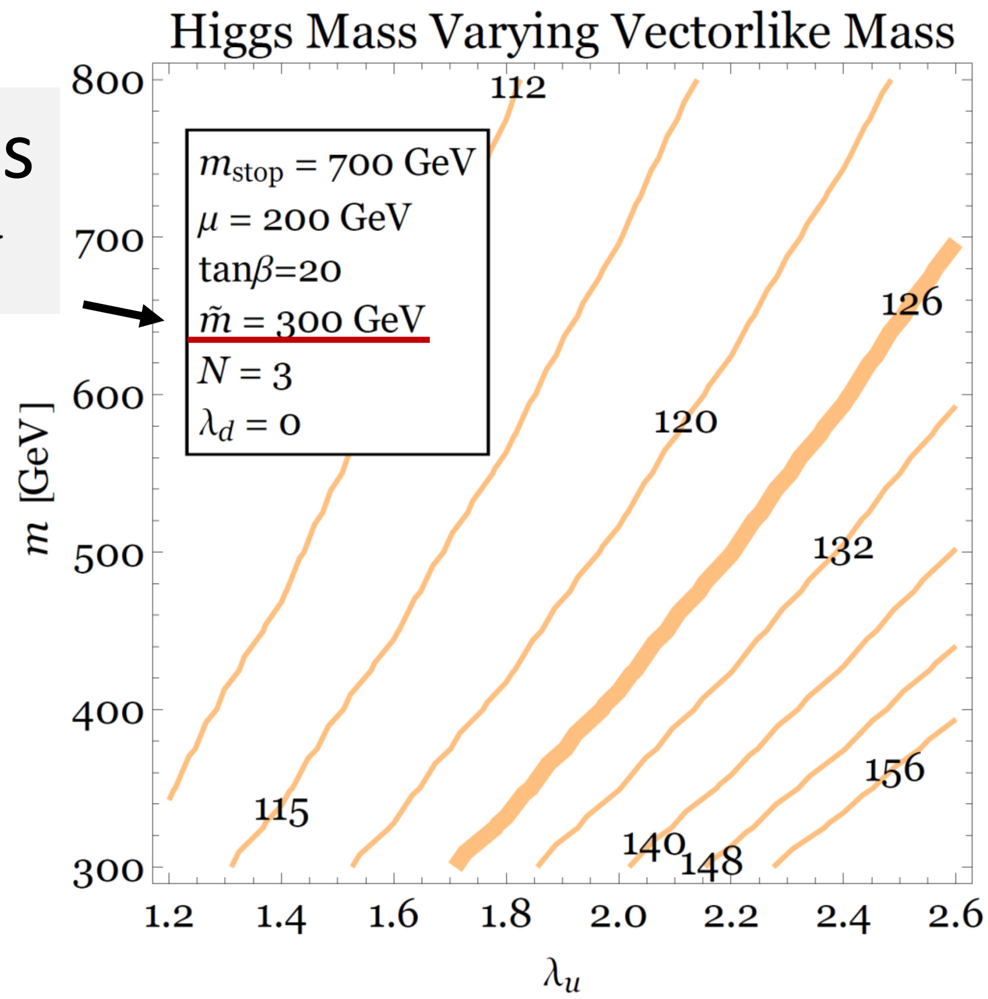
If we have new Higgs interactions larger than the top Yukawa, large SUSY breaking is not needed and fine tuning is relaxed.

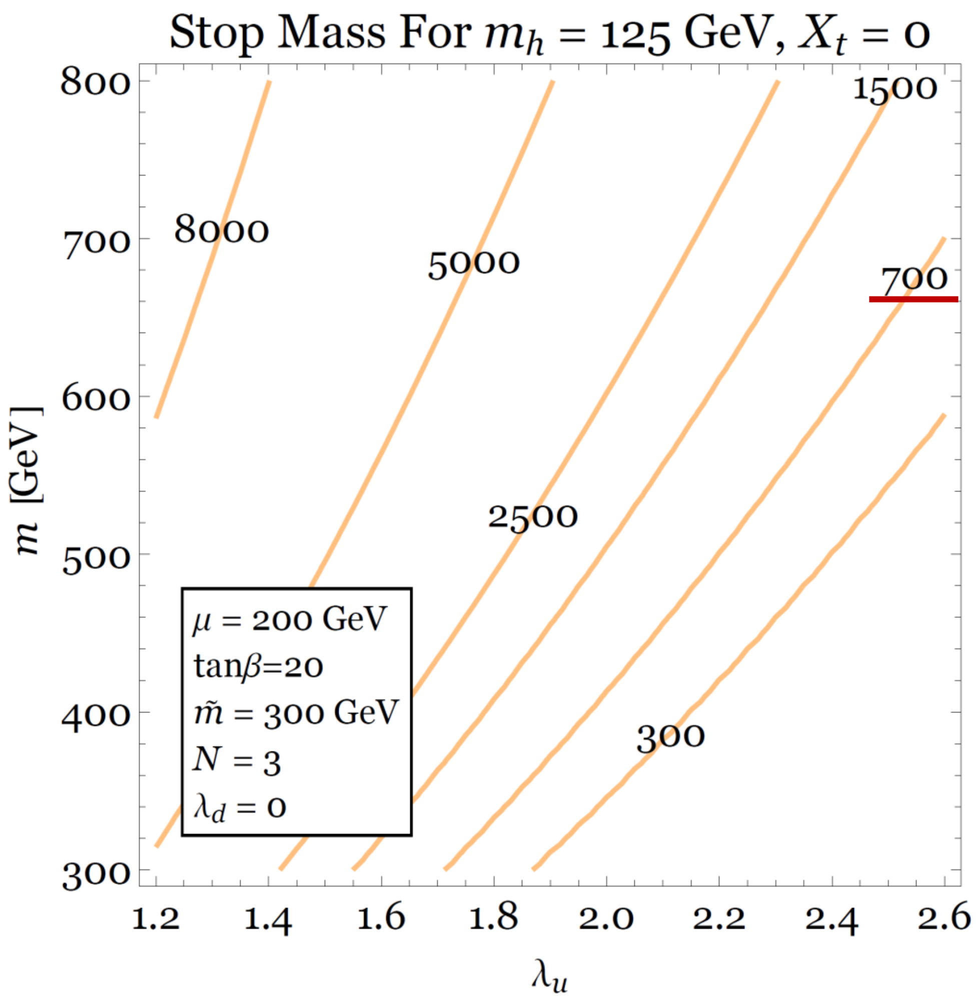
$$\Delta W = \lambda_u H_u \bar{\Psi}_d \Psi + \lambda_d H_d \Psi_u \bar{\Psi} + m \Psi_u \bar{\Psi}_d + m' \Psi \bar{\Psi}$$

$\Psi_u,\ \bar{\Psi}_d$: $SU(2)_L$ doublets , $\Psi,\ \bar{\Psi}$: singlets

Our framework : New loop contributions

Soft mass of Ψ, $\bar{\Psi}$





Large λ_u ➡ **Small SUSY breaking is enough for 125 GeV Higgs.**

Our framework : Avoiding Landau poles

Running of the new large Yukawa hits a Landau pole immediately …

cf. running of top Yukawa coupling

$$\frac{dy_t}{d\ln\mu} \simeq \frac{y_t}{16\pi^2}\left(6y_t^* y_t - \frac{16}{3}g_3^2\right)$$

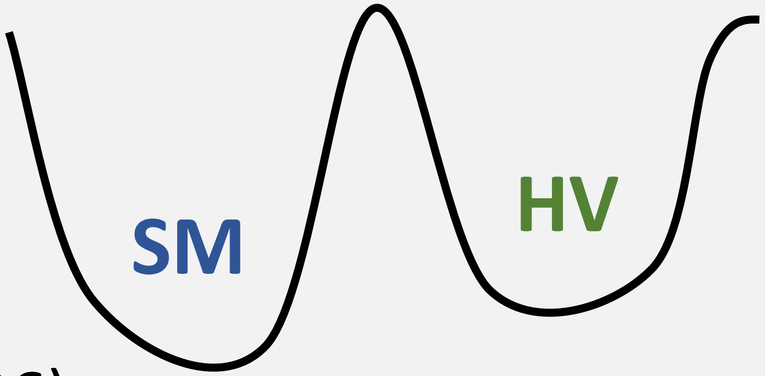
If we introduce a new gauge interaction to new particles, Landau poles can be avoided.

Ψ_u, Ψ : $SU(N)_H$ fundamentals , $\bar{\Psi}_d, \bar{\Psi}$: anti-fundamentals

Our framework : Avoiding Landau poles

The new gauge theory finally confines.

Confinement scale : $\Lambda = \mathcal{O}(10)\,\mathrm{GeV}$



➡ **Hidden Valley** M. Strassler, K. Zurek (2006)

*G*augino mediation with a vanishing hidden gaugino mass

➡
- Small SUSY breaking for new vectorlike fields
- **(Almost) supersymmetric Hidden Valley sector**

Benchmark points

2-loop RGEs calculated by SARAH

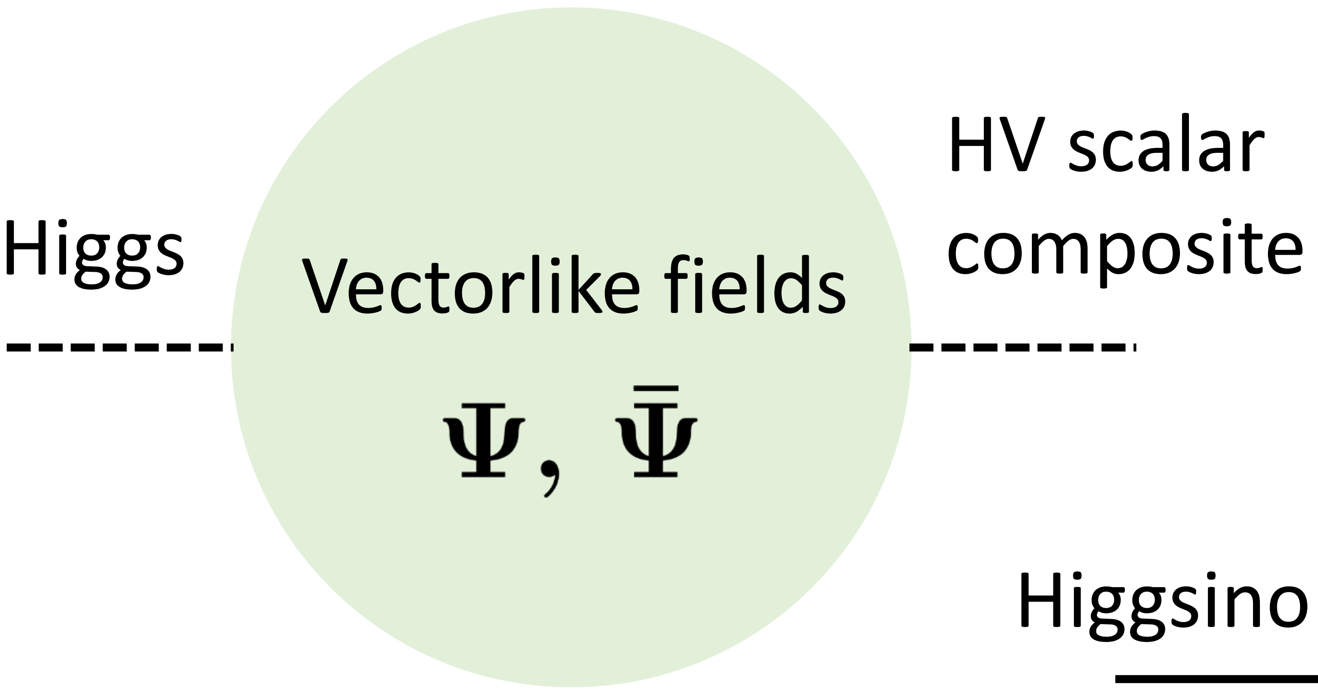
Small hidden gaugino mass

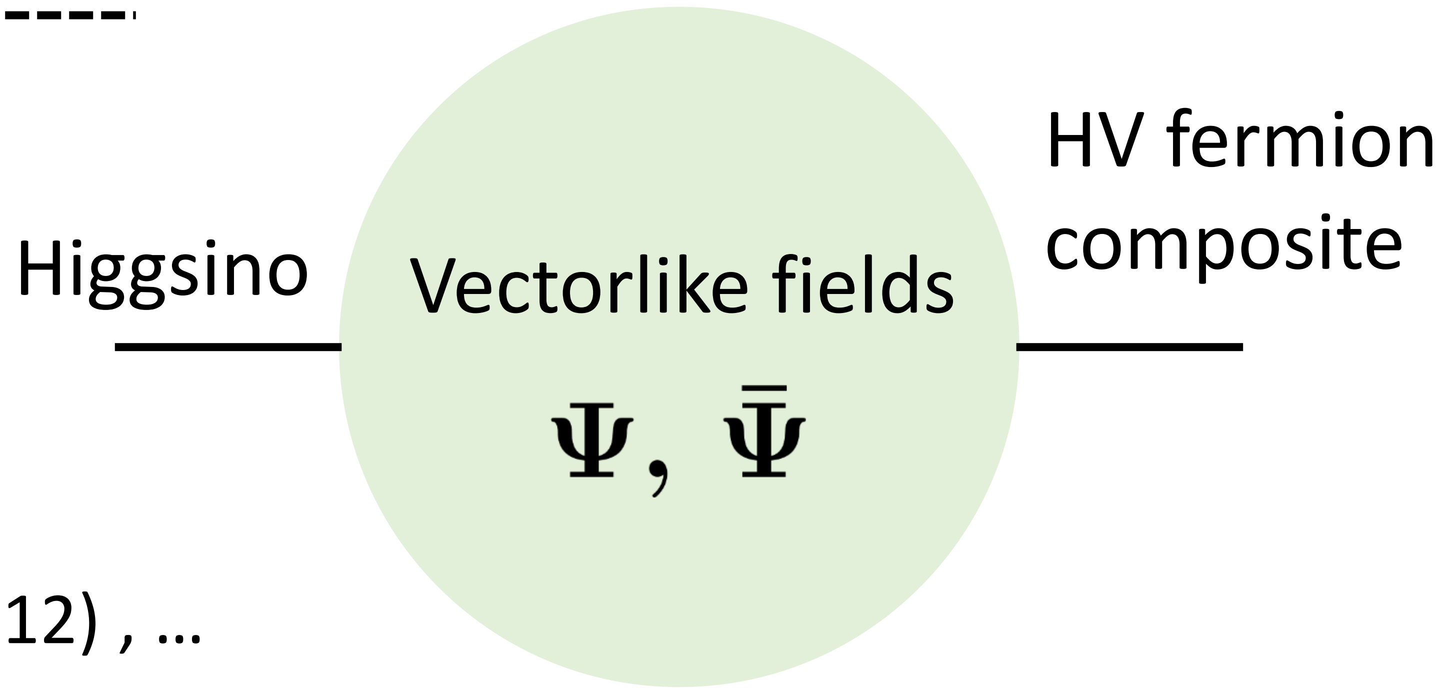
	(A)	(B)	(C)	(D)
M_1 [GeV]	1865	1823	1867	1825
M_2 [GeV]	1893	1856	1897	1860
M_3 [GeV]	1971	1949	1980	1958
$-\sqrt{\lvert m_{H_u}^2\rvert}$ [GeV]	-158	-268	-179	-277
m_{H_d} [GeV]	517	556	516	555
m_{q_1} [GeV]	1227	1325	1228	1325
m_{u_1} [GeV]	1152	1244	1153	1244
m_{d_1} [GeV]	1139	1230	1140	1230
m_{q_3} [GeV]	1202	1292	1202	1293
m_{u_3} [GeV]	1094	1169	1094	1170
m_{d_3} [GeV]	1139	1230	1140	1230
m_l [GeV]	524	565	524	565
m_e [GeV]	323	348	323	348

	(A)	(B)	(C)	(D)
M_λ [GeV]	38.2	44.7	26.3	30.8
$\tilde{m}_u$ [GeV]	476	510	493	529
$\tilde{m}_d$ [GeV]	470	504	485	522
$\tilde{m}_f$ [GeV]	1079	1164	1097	1184
$\tilde{\bar{m}}_f$ [GeV]	1079	1164	1097	1184
$-\sqrt{\lvert\tilde{m}_0^2\rvert}$ [GeV]	-235	-256	-226	-240
$-\sqrt{\lvert\tilde{\bar{m}}_0^2\rvert}$ [GeV]	-166	-191	-135	-156
$-\sqrt{\lvert\tilde{m}^2\rvert}$ [GeV]	-147	-171	-108	-126
$-\sqrt{\lvert\tilde{\bar{m}}^2\rvert}$ [GeV]	-147	-171	-108	-126
m_h [GeV]	125.3	125.7	125.9	125.5
$\Lambda^{\overline{MS}}$ [GeV]	10	10	10	10
λ_u	1.45	1.40	1.45	1.37
$M_{\rm m}$ [TeV]	50	100	50	100

Higgs interactions with a Hidden Valley

Higgs/Higgsino interacts with HV scalar/fermion via vectorlike fields.



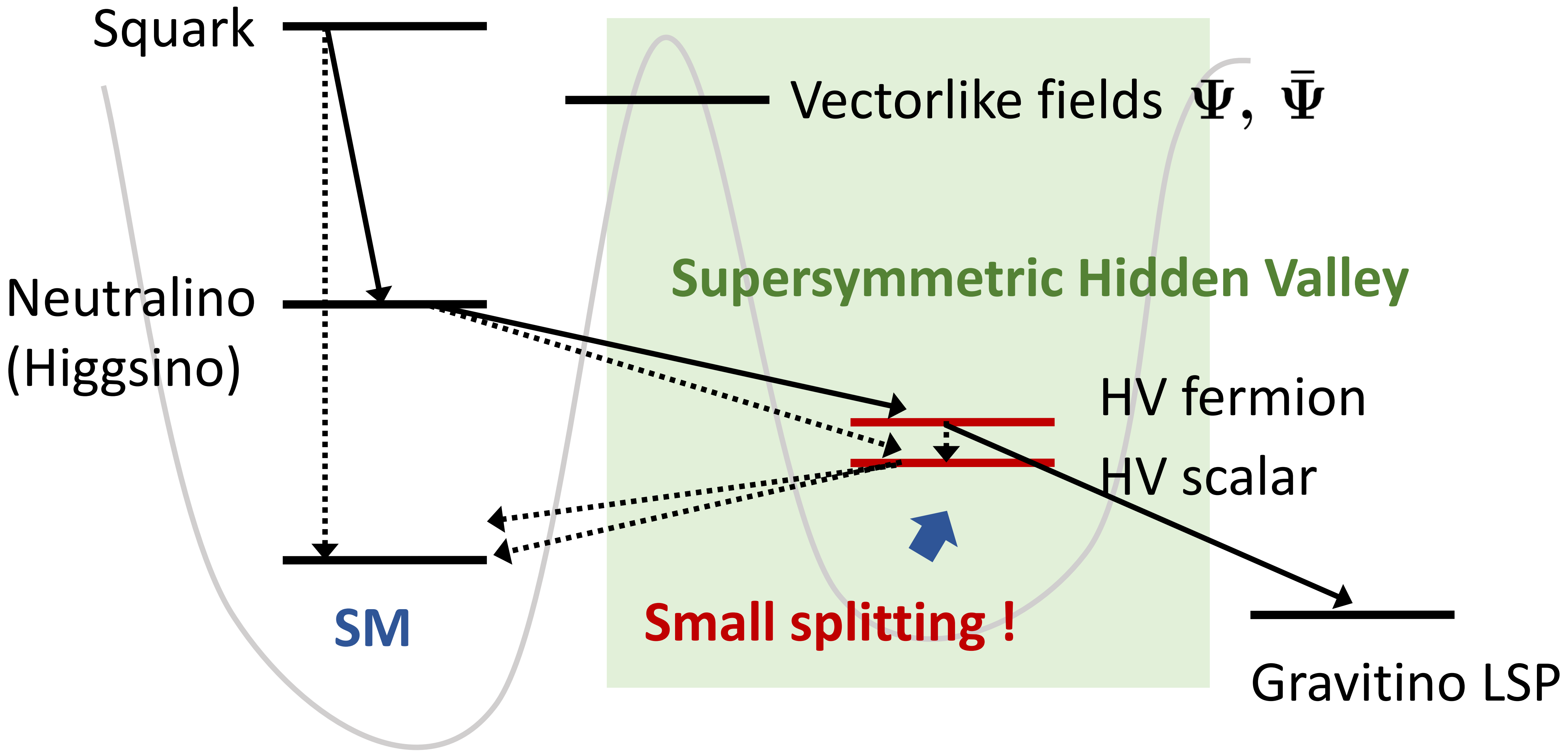


Higgs is partially composite.

R. Kitano, M. Luty, YN (2012) , …

Decay chain with a Hidden Valley

cf. Stealth SUSY, J. Fan, M. Reece, J. Ruderman (2011)



A simplified model

Our HV sector is strongly interacting and difficult to analyze.

➡ **Consider a simplified model for collider phenomenology.**

Include two light supermultiplets (Singlets of SM gauge groups)

$(S, \tilde{S})$: Hidden gluinoball(ino) , $(S', \tilde{S}')$: Hidden glueball(ino)

$$W_{\text{simplified}} = \mu H_u H_d + \lambda_S S H_u H_d + m_{SS'} S S' + \frac{1}{2} m_S S^2 + \frac{1}{2} m_{S'} S'^2$$

$$+ \frac{1}{3} \kappa S^3 + (\text{cubic terms with } S')$$

$$m_S \sim m_{S'} \sim 5\Lambda \qquad \lambda_S \sim 10^{-3} \qquad \kappa \sim 4\pi$$

Decay chain (A simplified model)

- Neutralino decay $\tilde{\chi}_1^0 \to \tilde{S} S$ ➡ Prompt.

- HV fermion decay $\tilde{S} \to S\tilde{G}$ $\tilde{S}' \to S'\tilde{G}$ $\tilde{G}$: Gravitino

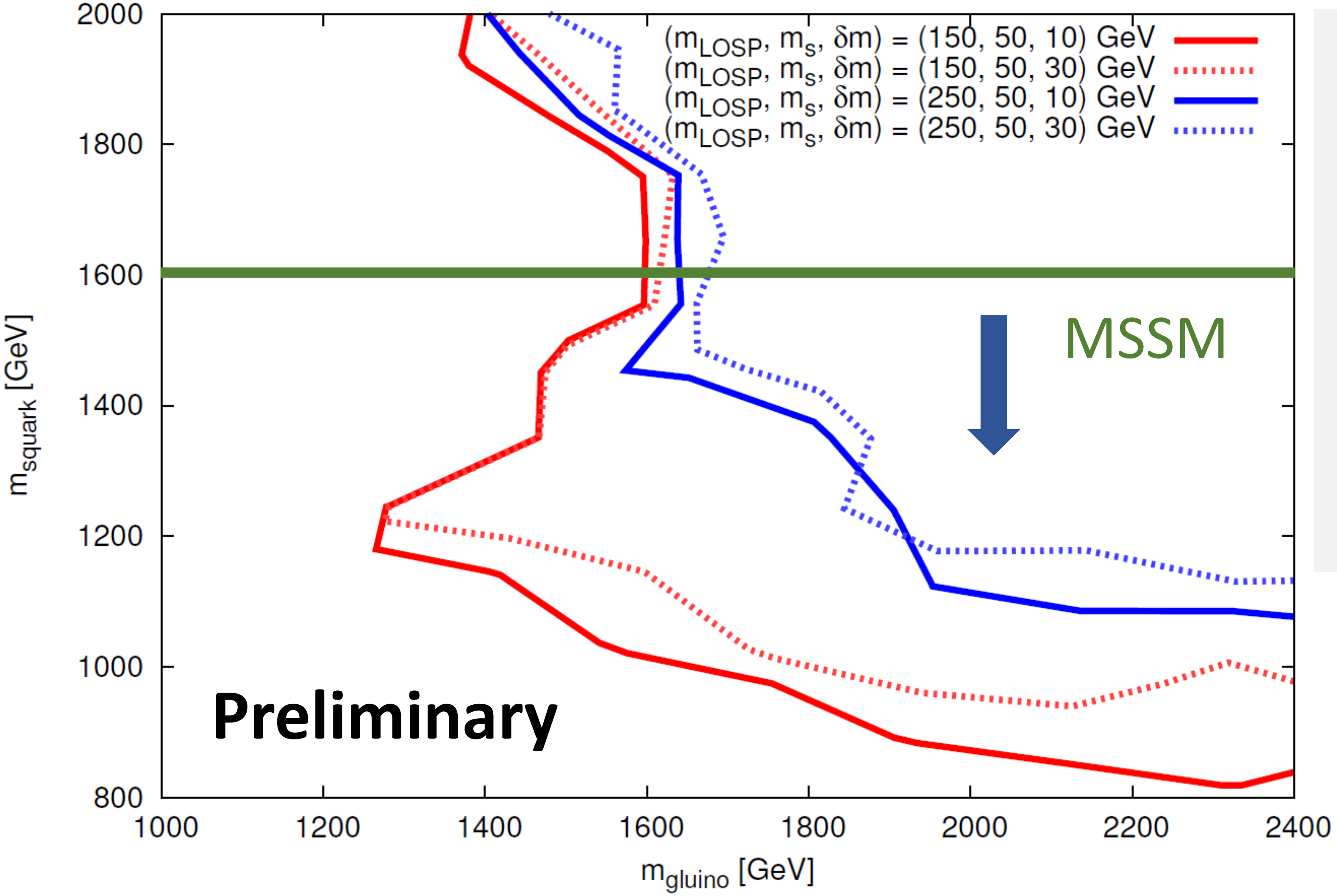
  ➡ Missing $\not{E}_T \sim (m_{\tilde{g},\tilde{q}}/m_{\tilde{S}})\delta m$ $\delta m \equiv m_{\tilde{S}} - m_S$

  Small mass splitting suppresses missing energy.

- HV scalar decay $0^{++} \to h^{(*)} \to b\bar{b}$ $0^{++} \subset S, S'$

The branching fractions are the same with those of the Higgs.

Large jet-multiplicity with missing P_T search



ATLAS, arXiv:1308.1841

Decay table : SUSYHIT

Production cross sections at NLO : Prospino 2.1

Event generation : PYTHIA 8

Squark mass bound is weaker than MSSM !

The effect on Higgs decays

- $h \to \gamma\gamma$: No important contributions from new exotic particles

- $h \to 0^{++}0^{++}$: $\mathrm{Br}(h \to 0^{++}0^{++}) \sim \underline{0.17}$ $(m_{0^{++}} = 50\,\mathrm{GeV})$

  Global fit of signal strength ➡ $\mathrm{Br}(h \to 0^{++}0^{++}) < \underline{0.19}$

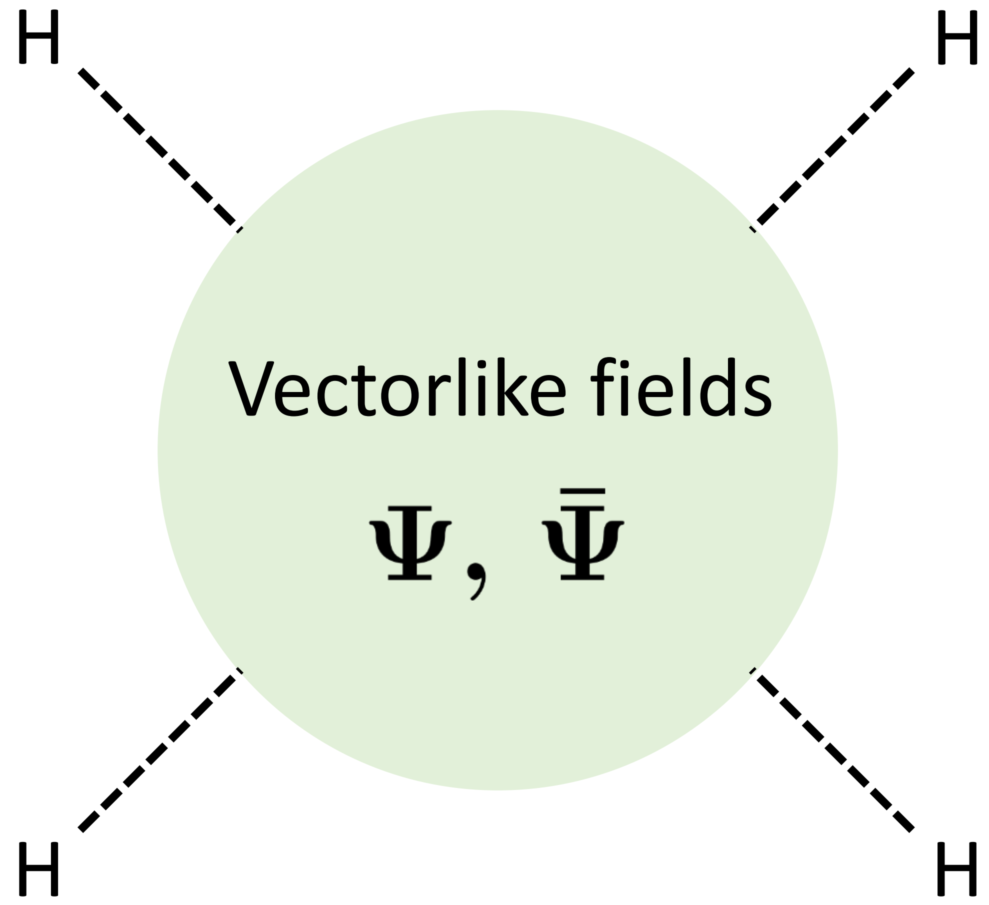
  $h \to 0^{++}0^{++} \to b\bar{b}\mu^+\mu^-$: $\mathrm{Br}(h \to b\bar{b}\mu^+\mu^-) \sim \underline{7 \times 10^{-5}}$

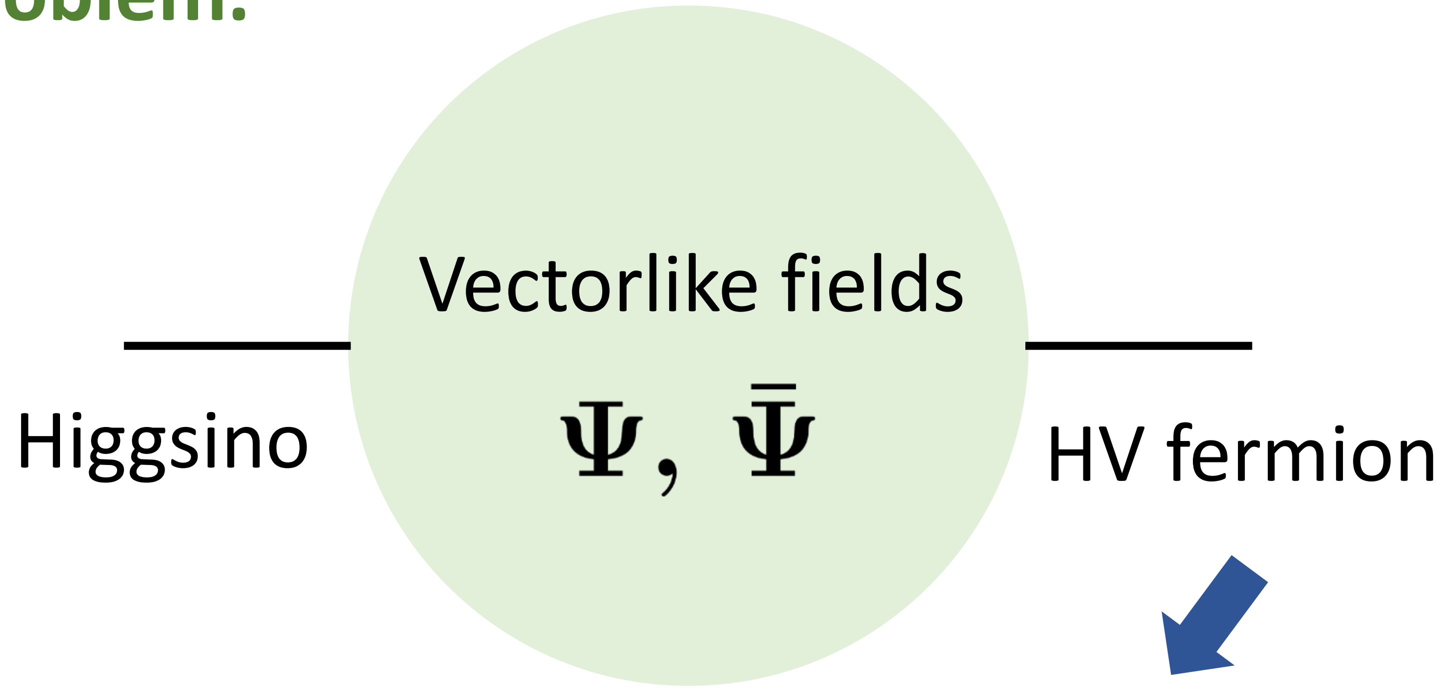
  Expected bound at Run I ➡ $\mathrm{Br}(h \to b\bar{b}\mu^+\mu^-) \lesssim \underline{10^{-4}}$

Deviation may be observed in future observations.

Summary

A scenario that can ameliorate both of SUSY Higgs mass problem and Missing superpartner problem.

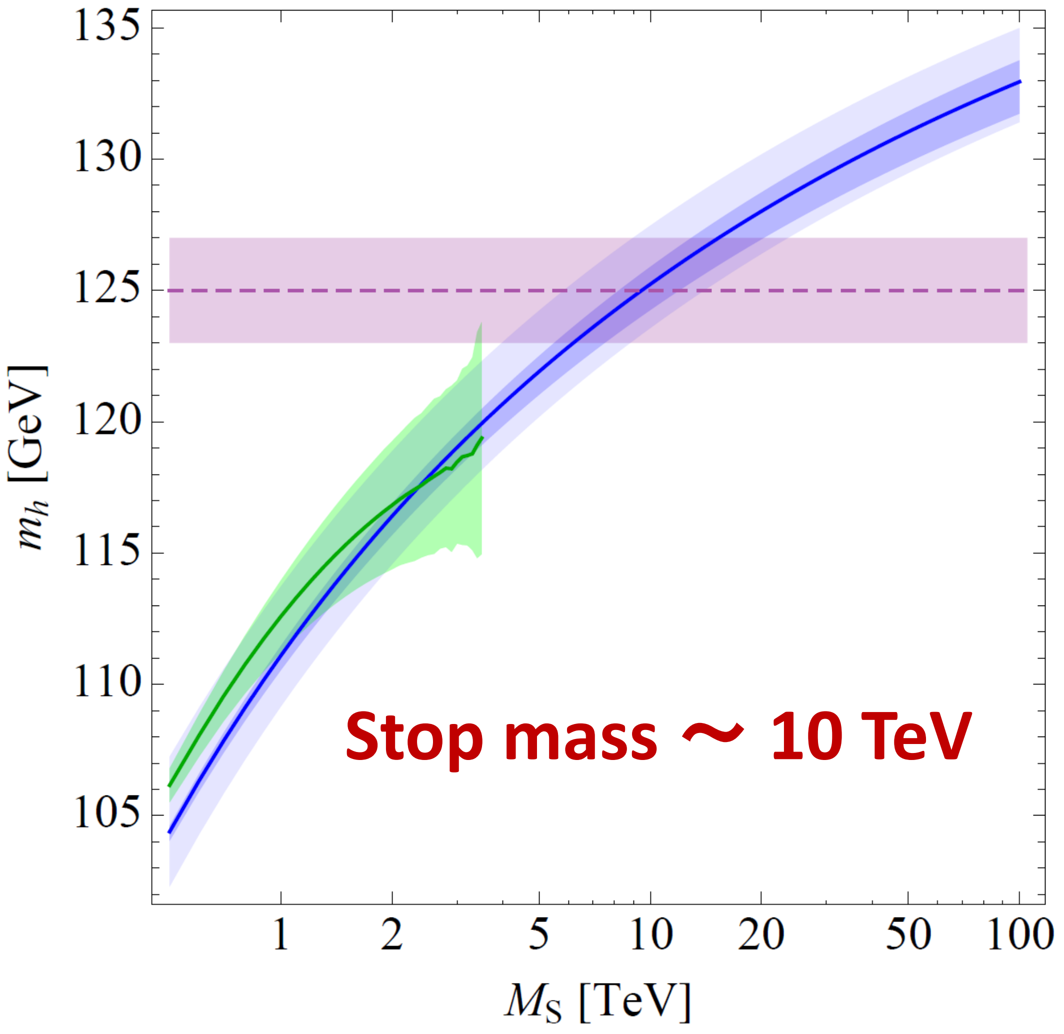




Decay to HV scalar and gravitino with reduced missing energy

Extra slides

SUSY Higgs mass problem



P. Draper, P. Meade, M. Reece, D. Shih (2011)

Two possible directions

- Just accept fine-tuning

- **Provide new interactions to lift the Higgs mass**

  NMSSM, Gauge extension, Vectorlike matter, …

Missing superpartner problem

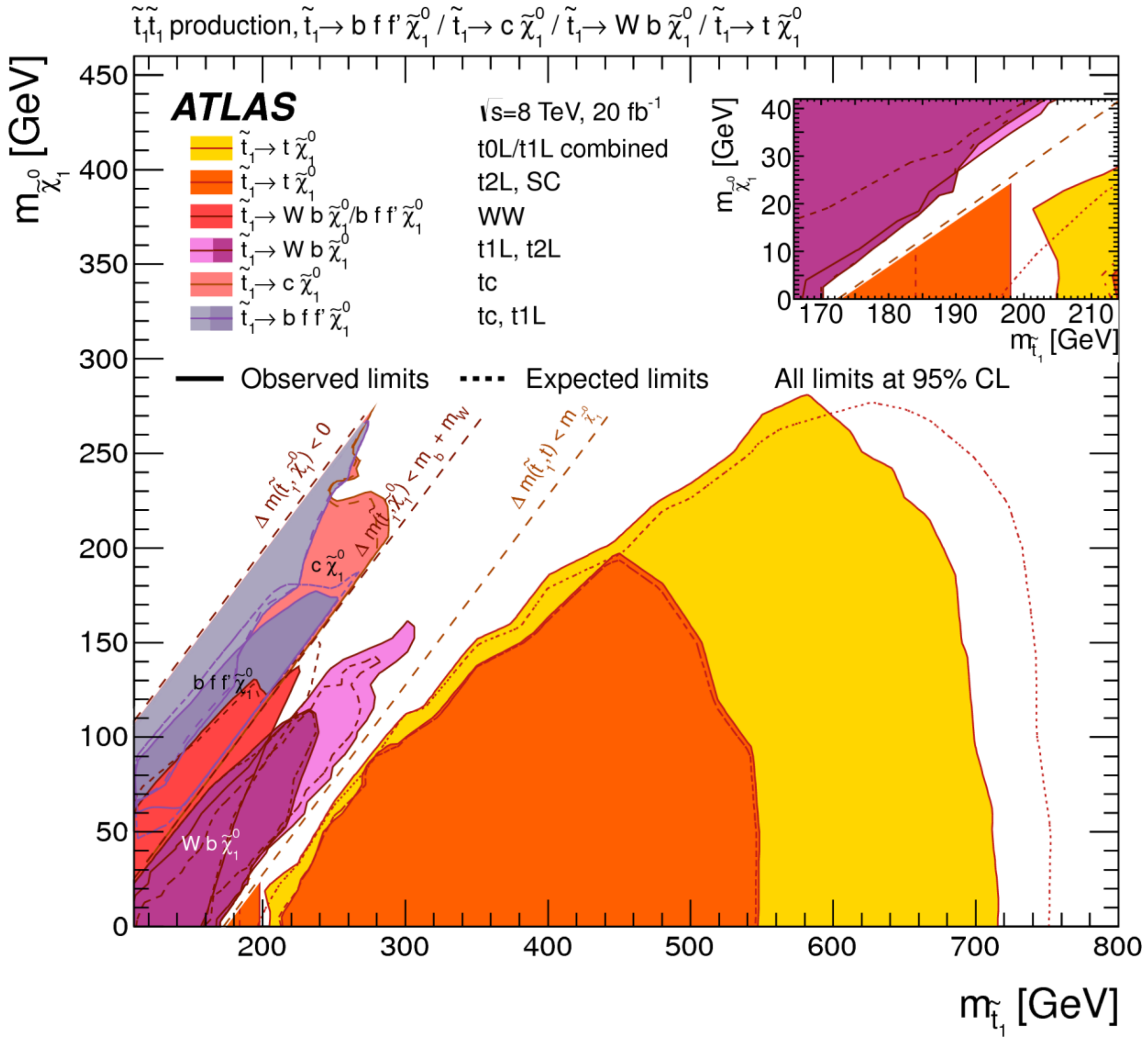
Three possible directions

- Just accept fine-tuning

- Natural SUSY spectrum

$$m_{\tilde{t}} < m_{\tilde{q}_{1,2}}$$

- **Modify usual decay chains of superpartners**



Missing superpartner problem

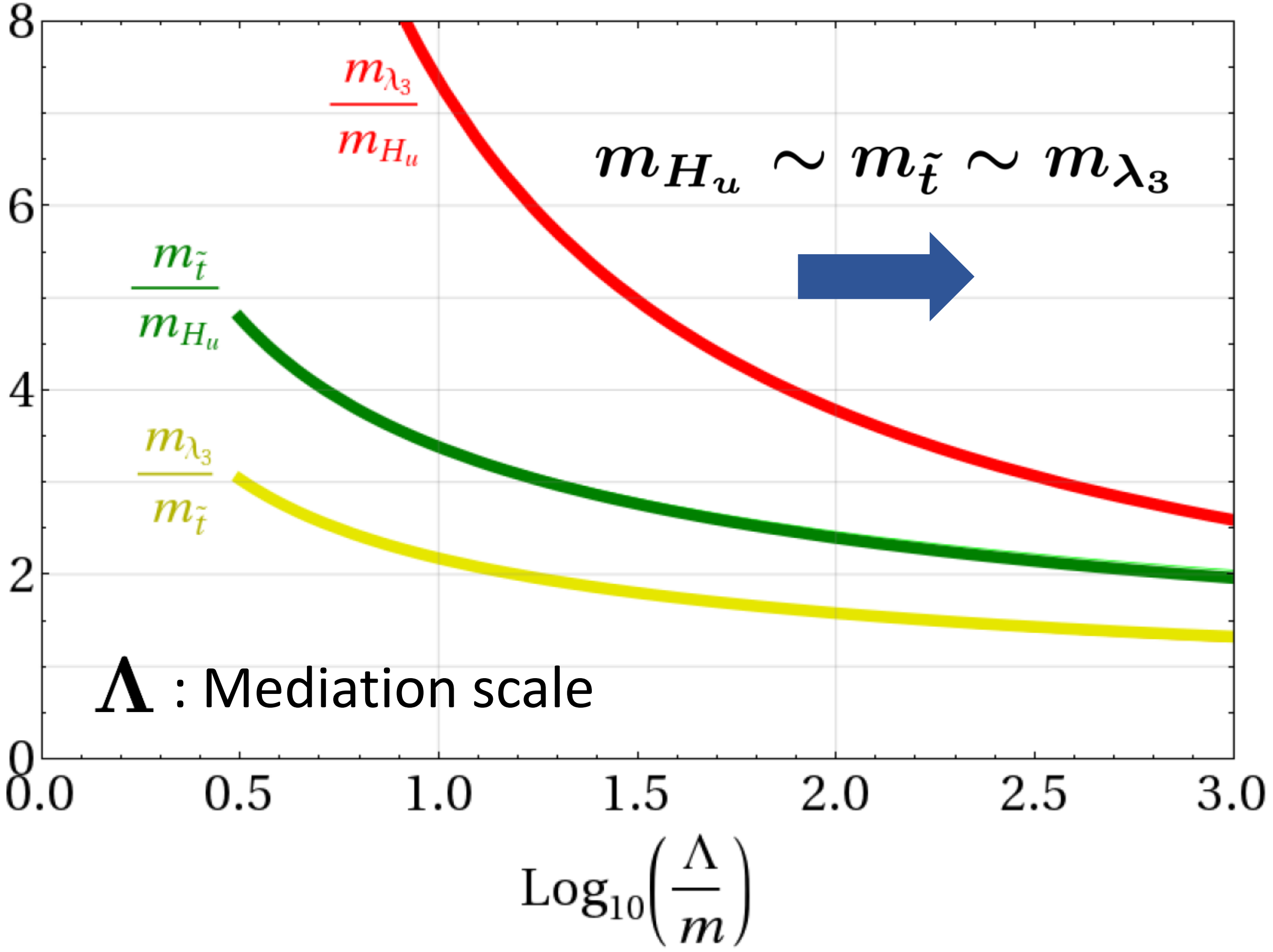
When the gluino mass is large (> 1 TeV) …

Naturalness requires

$$m_{H_u} < m_{\tilde{t}} < m_{\lambda_3}$$

Low mediation scale is needed for naturalness.

(Exception : Supersoft SUSY)



A. Arvanitaki, N. Craig, S. Dimopoulos, G. Villadoro (2012)

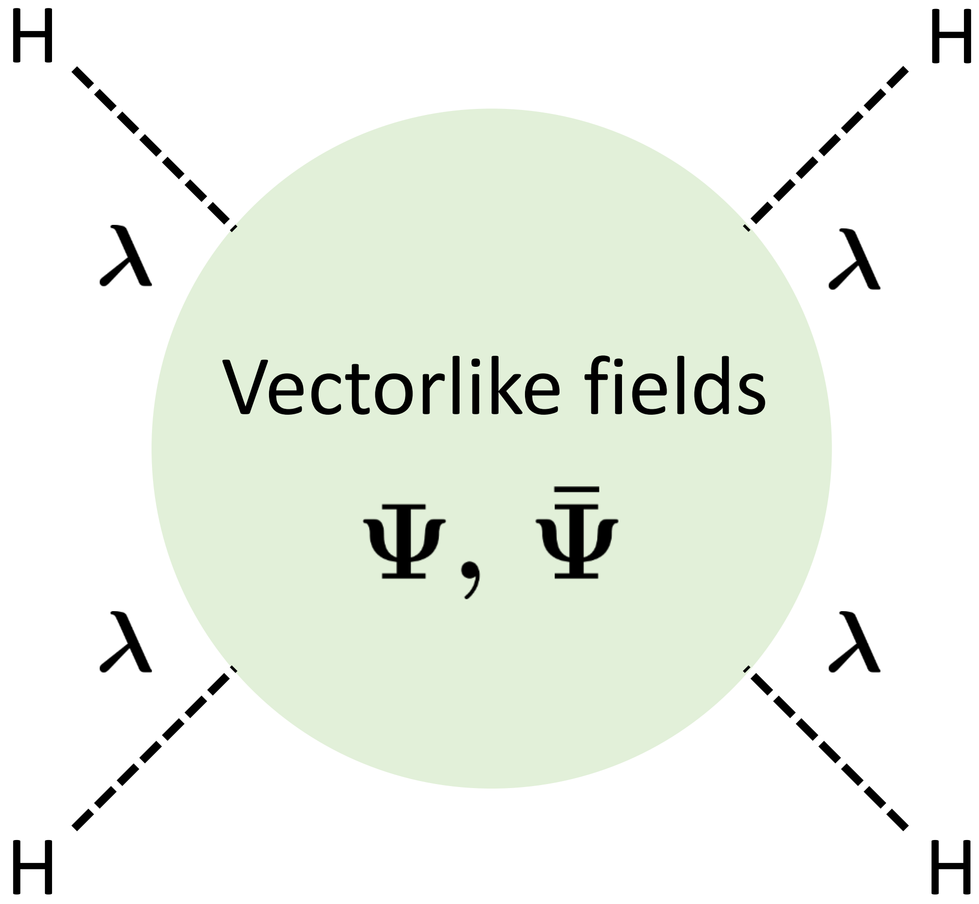
Our framework : Specific models

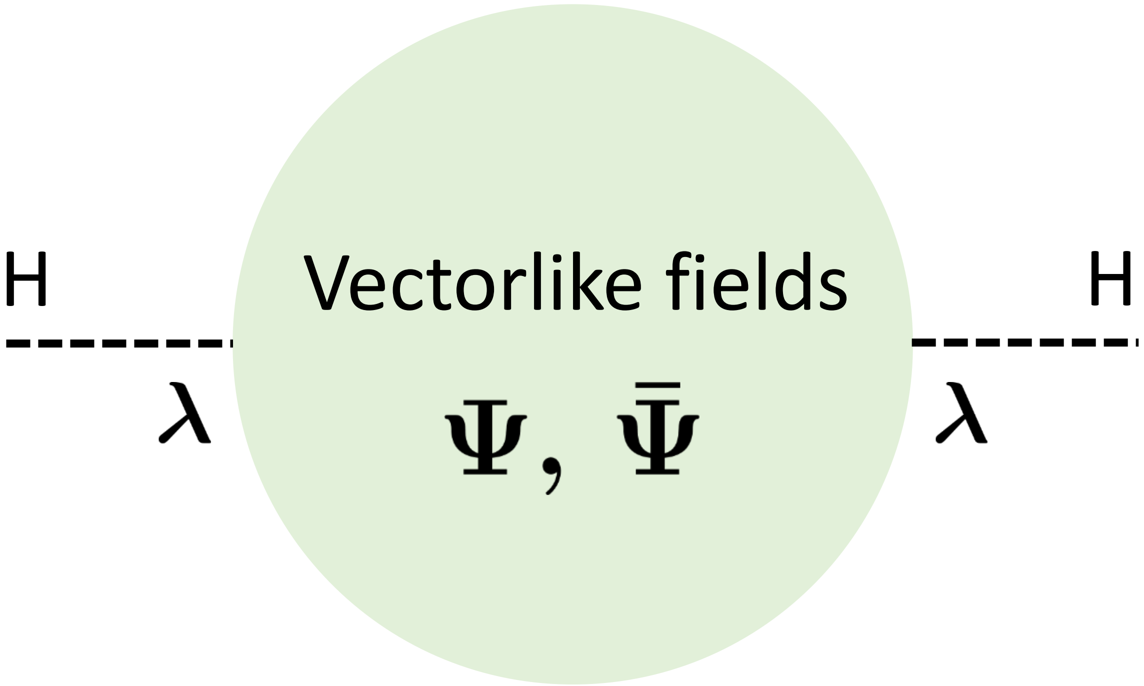
	$SU(N)_H$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	scalar name	fermion name
Ψ_u	$\mathbf{N}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$	ϕ_u	ψ_u
$\bar{\Psi}_d$	$\bar{\mathbf{N}}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$\bar{\phi}_d$	$\bar{\psi}_d$
f	$\mathbf{N}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	ϕ_f	ψ_f
$\bar{f}$	$\bar{\mathbf{N}}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	$\bar{\phi}_f$	$\bar{\psi}_f$
Ψ_i	$\mathbf{N}$	$\mathbf{1}$	$\mathbf{1}$	0	ϕ_i	ψ_i
$\bar{\Psi}_i$	$\bar{\mathbf{N}}$	$\mathbf{1}$	$\mathbf{1}$	0	$\bar{\phi}_i$	$\bar{\psi}_i$

$$W_{\rm VL} = \lambda_{u,i} H_u \bar{\Psi}_d \Psi_i + \lambda_{d,i} H_d \Psi_u \bar{\Psi}_i + m \Psi_u \bar{\Psi}_d + m'_{ij} \Psi_i \bar{\Psi}_j + M f \bar{f}$$

$$i = 0, 1, \ldots F - 1$$

Our framework : New loop contributions





Large λ ➡ **Small SUSY breaking is enough for 125 GeV Higgs.**

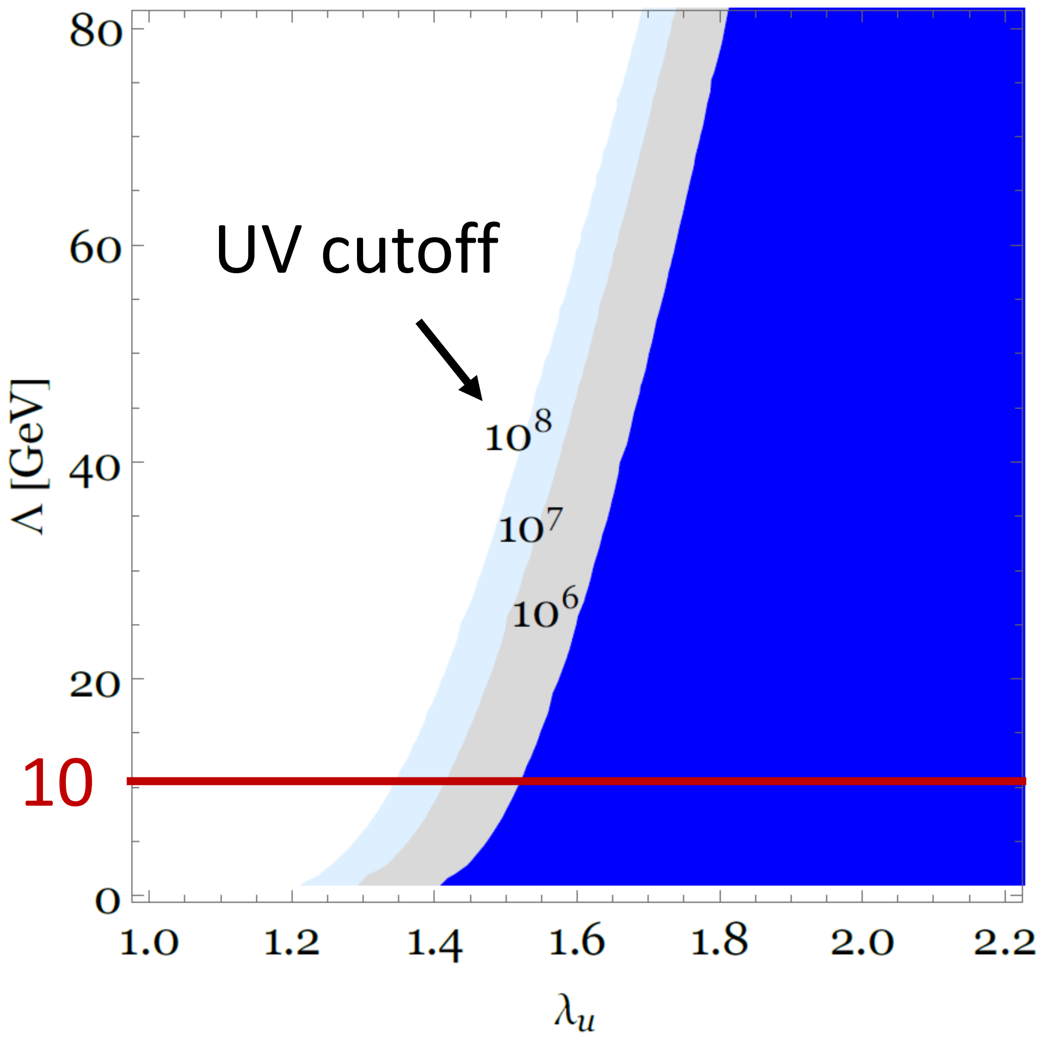
Our framework : Avoiding Landau poles

Allowed (white) region of the new Yukawa and the confinement scale :

2-loop RGEs calculated by SARAH

Supersymmetric masses of vectorlike fields : 500 GeV

$F = 3$

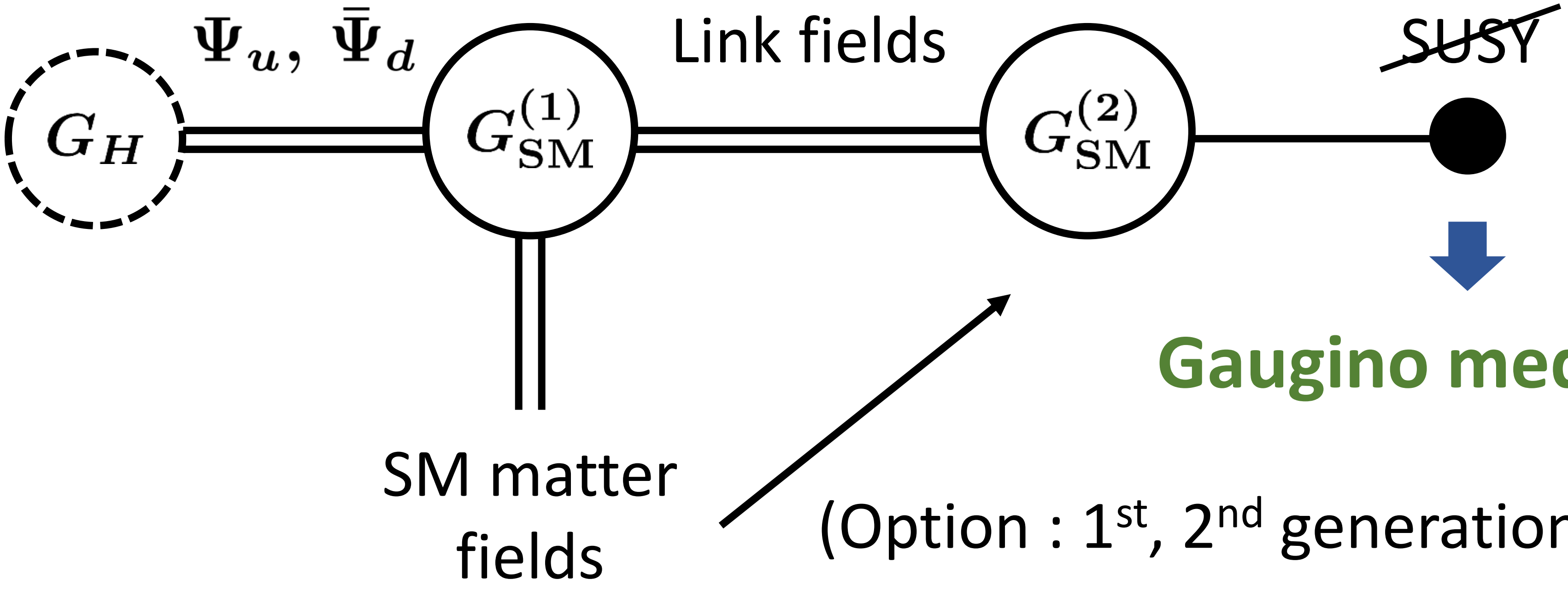


Multi-fold replication of SM

Moose (quiver) of SM gauge groups is spontaneously broken by a link scalar vev.

➡ **Accelerated Unification**

N. Arkani-Hamed, A. Cohen, H. Georgi (2001)

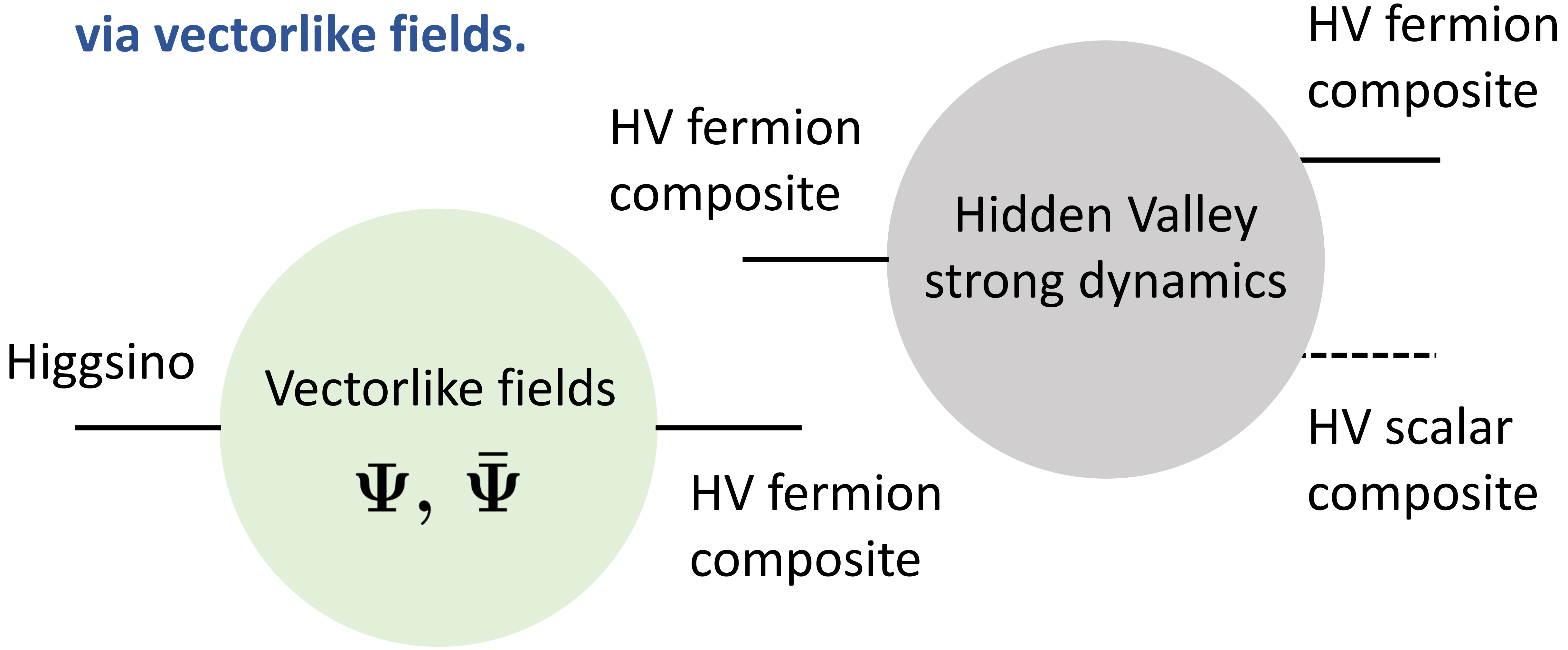


Gaugino mediation

(Option : 1st, 2nd generations → Natural SUSY)

Higgs interactions with a Hidden Valley

Higgs/Higgsino interacts with HV scalar/fermion via vectorlike fields.



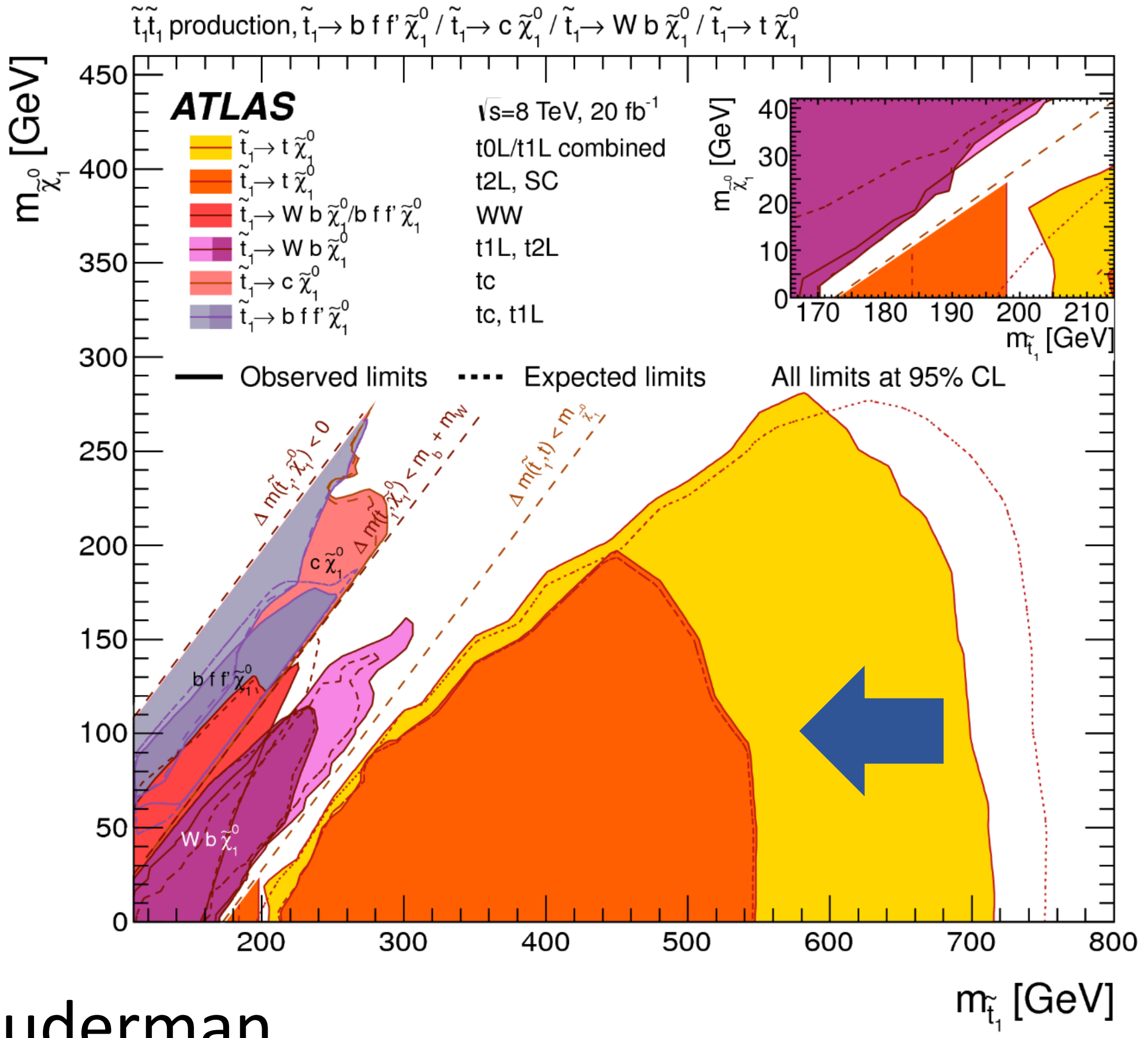
Natural SUSY models

Natural SUSY variations are naturally possible.

$$m_{\tilde{t}} < m_{\tilde{q}_{1,2}}$$

Stealth SUSY from a Hidden Valley

➡ **Stop mass bound is even weaker.**



J. Fan, R. Krall, D. Pinner, M. Reece, J. Ruderman

Discussions : (S)Quirk phenomenology

J. Kang, M. Luty (2008) , …

(S)Quirks : $\boldsymbol{\Psi_u, \bar{\Psi}_d}$ $\boldsymbol{f = (\phi_f, \psi_f), \bar{f}}$ (Colored partners of SU(5))

Quirk direct pair-production

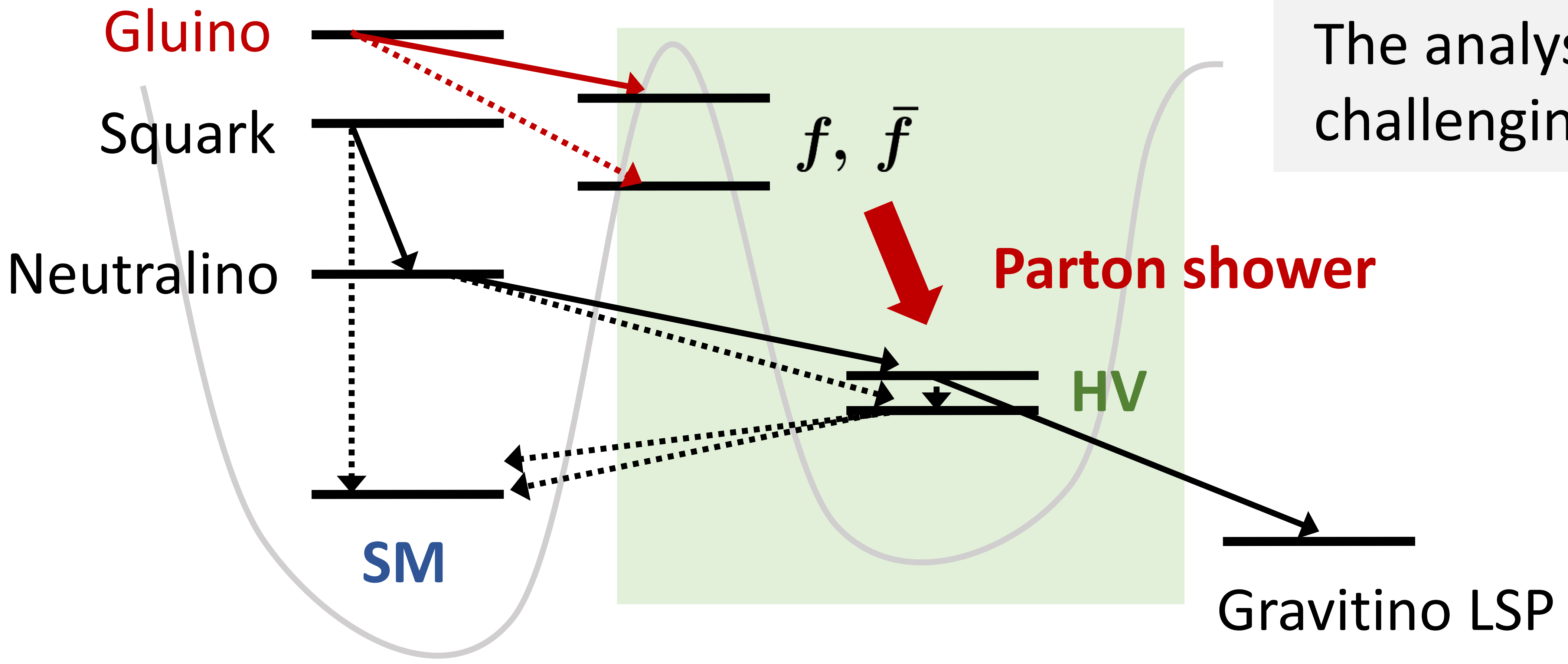
$$\boldsymbol{pp \to \psi_f \bar{\psi}_f \, , \quad pp \to Z^{(*)}, \gamma^{(*)} \to \psi_u^+ \bar{\psi}_d^- \, , \, \psi_u^0 \bar{\psi}_d^0}$$

Quirk-antiquirk pairs form (microscopic) bound states.

➡ They lose energy via HV (and SM) particle emission before pair annihilation.

Discussions : (S)Quirk phenomenology

Colored (s)quirks may be produced by gluino decays at LHC Run II.



The analysis is challenging …