Dark matter, MFV and RPV SUSY

Lian-Tao Wang
University of Chicago

Work in collaboration with Brian Batell and Tongyan Lin

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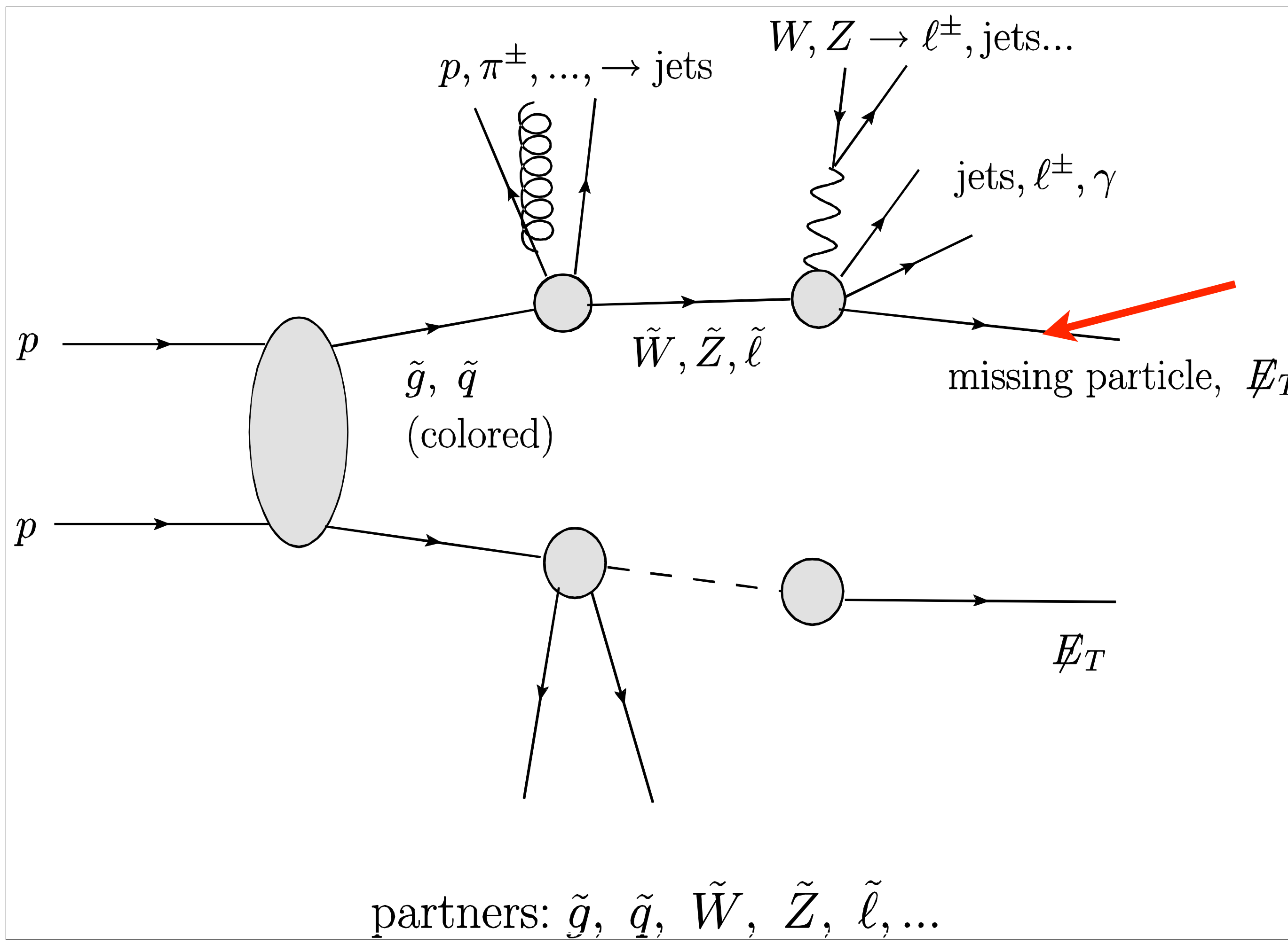
SUSY and SUSY dark matter under some stress.

In SUSY like scenario

- DM candidate embedded in an extended TeV new physics scenario

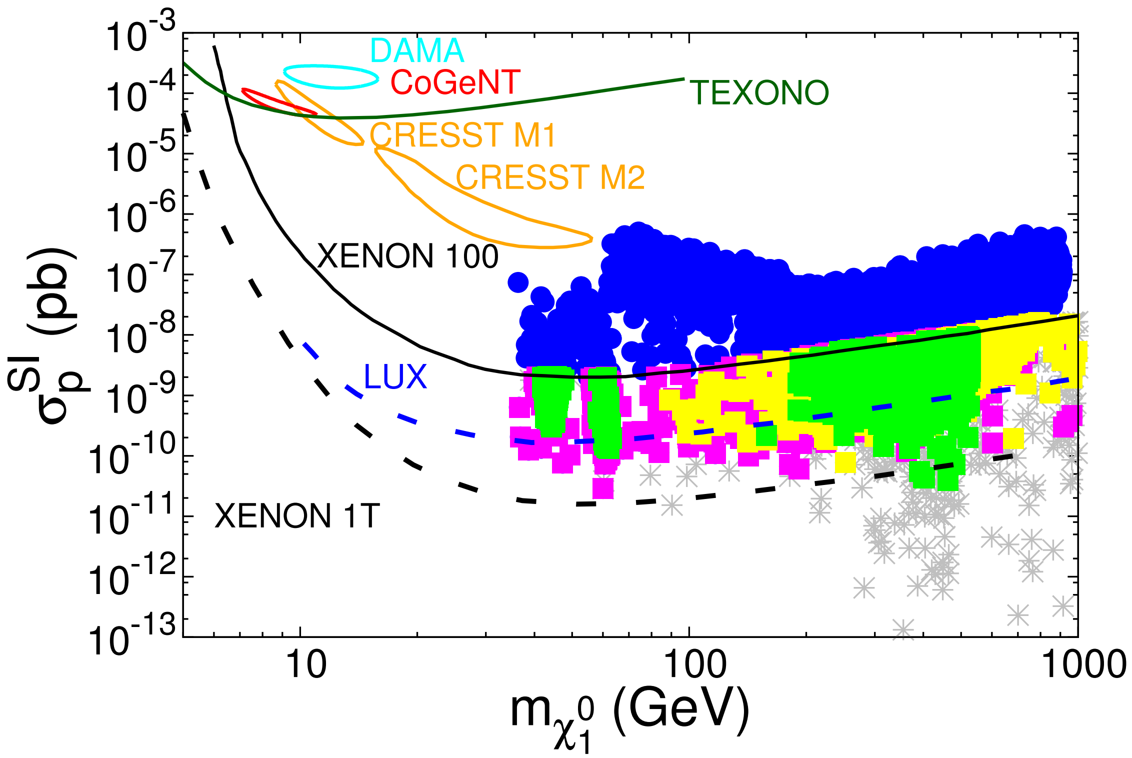


DM candidate

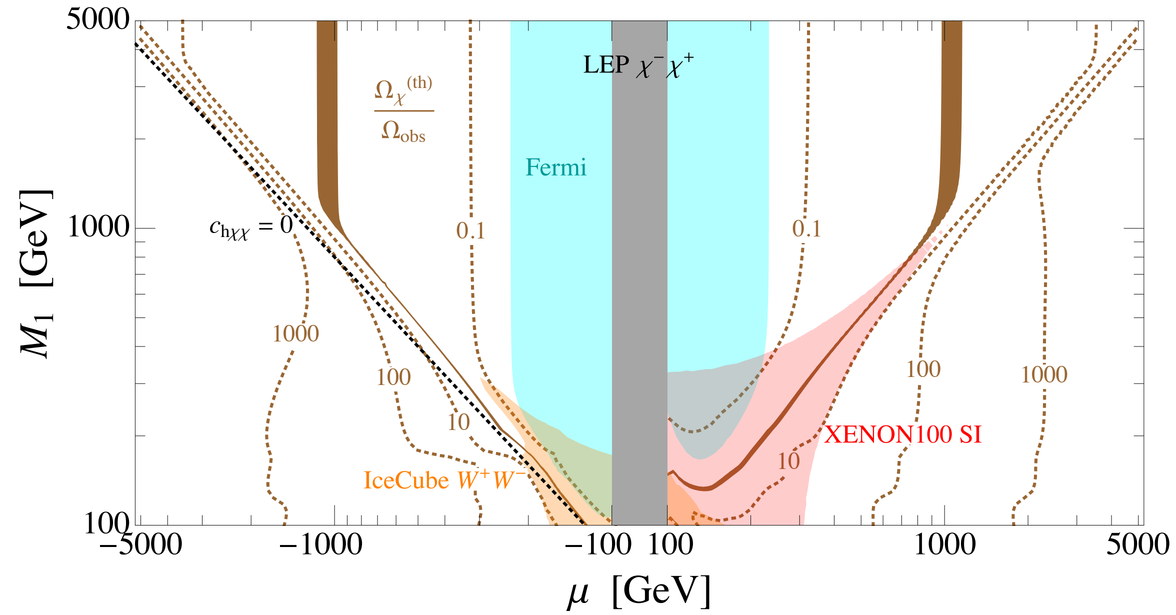
Lightest superpartner (LSP)
Neutral and stable.

- Discovery should be ``straightforward". Not yet.

Narrow parameter space, could still work.



Han, Liu, Natarayan, 2013.3040



Cheung, Hall, Pinner, Ruderman, 1211.4873

Arkani-Hamed, Delgado, Giudice, hep-ph/0601041

- The so called "well tempered" scenario.
- Also, A-funnel, stau/stop/squark co-ann.

Cahill-Rowley, Hewett, Ismail, Peskin, Rizzo, 1305.2419
Cohen, Wacker, 1305.2914

- Challenging to see at the LHC.

Giudice, Han, Wang and LTW, 1004.4902

dark matter in RPV SUSY

"Hiding SUSY" with R-parity violation:

$$P_R = (-1)^{3(\mathrm{B-L})+2s}$$

RPV: $$W' = \lambda LL\bar{e} + \lambda' QL\bar{d} + \lambda'' \bar{u}\bar{d}\bar{d} + \bar{\mu} LH_u$$

- R-parity ⇒ stable LSP ⇒ MET.
- One can get rid of R-parity, and "turn on" some couplings without violating low energy constraints.
  - However, this looks ad hoc.
- Many progresses on implementing RPV with symmetry principles.

Minimal flavor violation (MFV) + RPV

C. Csaki, Y. Grossman, B. Heidenreich, 1111.1239

- MFV, all flavor violation coming from SM yukawa couplings.
  - A good framework to address the SUSY flavor problem.
- Imposing MFV on R-parity breaking couplings?
  - MFV+RPV can satisfy all the constraints on RPV!
- For example, the often studied udd coupling would be

$$W_{\rm BNV} = \frac{1}{2} w''(Y_u\,\bar{u})(Y_d\,\bar{d})(Y_d\,\bar{d})$$

But, what about dark matter?

- Need to add new states to MSSM.

- New symmetries to make sure the dark matter candidate is stable.

- However, MFV can be the new symmetry
  - If dark matter candidate is in a flavor multiplet
    - MFV itself could stabilize the dark matter.

Batell, Pradler, Spannowsky, 1105.1781

MFV and DM stability

$$\begin{aligned} G &= G_{\rm SM} \times G_q, \\ G_{\rm SM} &= SU(3)_c \times SU(2)_L \times U(1)_Y, \\ G_q &= SU(3)_Q \times SU(3)_{u_R} \times SU(3)_{d_R} \end{aligned}$$

$$\begin{aligned} Q &\sim (\mathbf{3},\mathbf{2},\tfrac{1}{6})_{\rm SM} \times (\mathbf{3},\mathbf{1},\mathbf{1})_{G_q}, \\ u_R &\sim (\mathbf{3},\mathbf{1},\tfrac{2}{3})_{\rm SM} \times (\mathbf{1},\mathbf{3},\mathbf{1})_{G_q}, \\ d_R &\sim (\mathbf{3},\mathbf{1},-\tfrac{1}{3})_{\rm SM} \times (\mathbf{1},\mathbf{1},\mathbf{3})_{G_q}, \\ Y_u &\sim (\mathbf{1},\mathbf{1},0)_{\rm SM} \times (\mathbf{3},\bar{\mathbf{3}},\mathbf{1})_{G_q}, \\ Y_d &\sim (\mathbf{1},\mathbf{1},0)_{\rm SM} \times (\mathbf{3},\bar{\mathbf{1}},\bar{\mathbf{3}})_{G_q}, \\ \chi &\sim (\mathbf{1},\mathbf{R}_L,Y)_{\rm SM} \times ((n_Q,m_Q),(n_u,m_u),(n_d,m_d))_{G_q} \end{aligned}$$

χ in flavor rep $n_Q \times m_Q$ (tensorial), ...

MFV and DM stability

$$G = G_{\rm SM} \times G_q,$$
$$G_{\rm SM} = SU(3)_c \times SU(2)_L \times U(1)_Y,$$
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$$Q \sim (\mathbf{3}, \mathbf{2}, \tfrac{1}{6})_{\rm SM} \times (\mathbf{3}, \mathbf{1}, \mathbf{1})_{G_q},$$
$$u_R \sim (\mathbf{3}, \mathbf{1}, \tfrac{2}{3})_{\rm SM} \times (\mathbf{1}, \mathbf{3}, \mathbf{1})_{G_q},$$
$$d_R \sim (\mathbf{3}, \mathbf{1}, -\tfrac{1}{3})_{\rm SM} \times (\mathbf{1}, \mathbf{1}, \mathbf{3})_{G_q},$$
$$Y_u \sim (\mathbf{1}, \mathbf{1}, 0)_{\rm SM} \times (\mathbf{3}, \bar{\mathbf{3}}, \mathbf{1})_{G_q},$$
$$Y_d \sim (\mathbf{1}, \mathbf{1}, 0)_{\rm SM} \times (\mathbf{3}, \bar{\mathbf{1}}, \bar{\mathbf{3}})_{G_q},$$
$$\chi \sim (\mathbf{1}, \mathbf{R}_L, Y)_{\rm SM} \times ((n_Q, m_Q), (n_u, m_u), (n_d, m_d))_{G_q}$$

$\boldsymbol{\chi}$ in flavor rep $n_Q \times m_Q$ (tensorial), ...

discrete Z_3 sub-group

$$U = \left(e^{2\pi i k_c/3}\right)_{SU(3)_c} \left(e^{2\pi i k_Q/3}\right)_{SU(3)_Q} \left(e^{2\pi i k_u/3}\right)_{SU(3)_{u_R}} \left(e^{2\pi i k_d/3}\right)_{SU(3)_{d_R}}$$

	$SU(3)_c$	$SU(3)_Q$	$SU(3)_{u_R}$	$SU(3)_{d_R}$
Q	k_c	k_Q	0	0
u_R	k_c	0	k_u	0
d_R	k_c	0	0	k_d
Y_u	0	k_Q	$-k_u$	0
Y_d	0	k_Q	0	$-k_d$
χ	0	$(n_Q - m_Q)k_Q$	$(n_u - m_u)k_u$	$(n_d - m_d)k_d$

$$U = \left(e^{2\pi i k_c/3}\right)_{SU(3)_c} \left(e^{2\pi i k_Q/3}\right)_{SU(3)_Q} \left(e^{2\pi i k_u/3}\right)_{SU(3)_{u_R}} \left(e^{2\pi i k_d/3}\right)_{SU(3)_{d_R}}$$

	$SU(3)_c$	$SU(3)_Q$	$SU(3)_{u_R}$	$SU(3)_{d_R}$
Q	k_c	k_Q	0	0
u_R	k_c	0	k_u	0
d_R	k_c	0	0	k_d
Y_u	0	k_Q	$-k_u$	0
Y_d	0	k_Q	0	$-k_d$
χ	0	$(n_Q - m_Q)k_Q$	$(n_u - m_u)k_u$	$(n_d - m_d)k_d$

U is a symmetry of Yukawa couplings if

$$\begin{aligned} (k_c + k_Q) \bmod 3 &= 0 \\ (k_c + k_u) \bmod 3 &= 0 \\ (k_c + k_d) \bmod 3 &= 0 \\ (k_Q - k_u) \bmod 3 &= 0 \\ (k_Q - k_d) \bmod 3 &= 0 \end{aligned}$$

e.g.: $k_c = 2$, $k_Q = k_u = k_d = 1$

χ stable if $\left((n_Q - m_Q)k_Q + (n_u - m_u)k_u + (n_d - m_d)k_d \right) \bmod 3 \neq 0$

Stable reps under $SU(3)_Q \times SU(3)_u \times SU(3)_d$: (3,1,1), (1,3,1), (6,1,1), ...

A simple model with (1,3,1)

Batell, T. Lin, LTW, in progress

$$W = \overline{\Phi}_X M_X \Phi_X + M_Y \overline{\Phi}_Y \Phi_Y + \overline{u}\,\lambda\,\Phi_X\,\Phi_Y$$

$$\Phi_X \supset (\phi_X, \psi_X) \sim (\mathbf{1},\mathbf{1})_0 \times (\mathbf{1},\mathbf{3},\mathbf{1})_{G_q}$$ ← Dark matter multiplet

$$\Phi_Y \supset (\phi_Y, \psi_Y) \sim (\mathbf{3},\mathbf{1})_{2/3} \times (\mathbf{1},\mathbf{1},\mathbf{1})_{G_q}$$ ← colored

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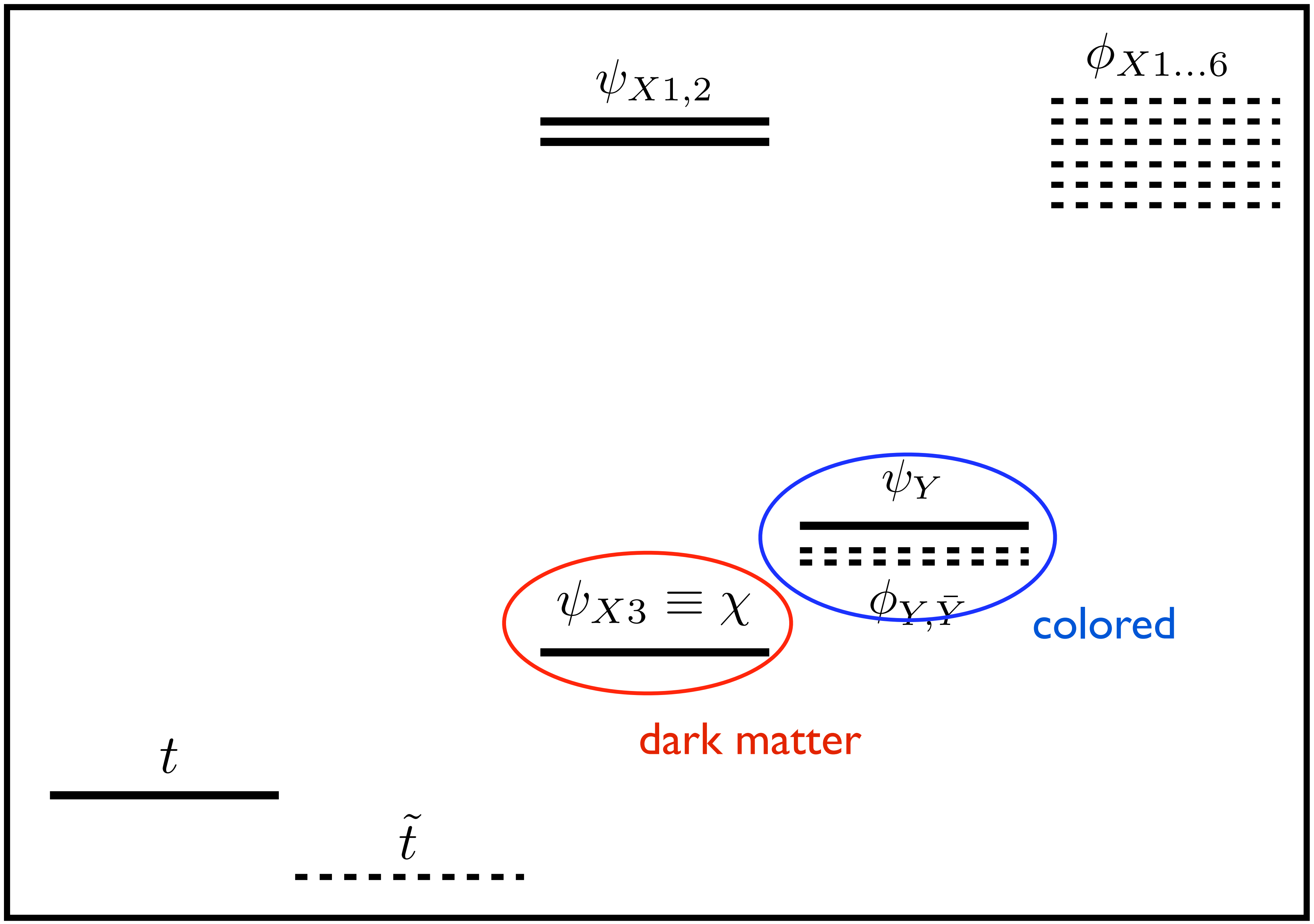
$$\begin{aligned} K_X &= \hat{\Phi}_X^\dagger \hat{k}_X \hat{\Phi}_X + \hat{\overline{\Phi}}_X \hat{\overline{k}}_X \hat{\overline{\Phi}}_X^\dagger \\ &+ \left[\frac{X^\dagger}{M} \hat{\overline{\Phi}}_X \hat{\mu}_X \hat{\Phi}_X + \frac{X}{M} \hat{\Phi}_X^\dagger \hat{\kappa}_X \hat{\Phi}_X + \frac{X}{M} \hat{\overline{\Phi}}_X \hat{\overline{\kappa}}_X \hat{\overline{\Phi}}_X^\dagger - \frac{X^\dagger X}{M^2} \hat{\overline{\Phi}}_X \hat{B}_X \hat{\Phi}_X + \text{h.c.} \right] \\ &- \frac{X^\dagger X}{M^2} \hat{\Phi}_X^\dagger \hat{m}_X \hat{\Phi}_X - \frac{X^\dagger X}{M^2} \hat{\overline{\Phi}}_X \hat{\overline{m}}_X \hat{\overline{\Phi}}_X^\dagger + \ldots, \end{aligned}$$

$$\begin{aligned} \hat{k}_X &= 1 + k\, Y_u^\dagger Y_u + \ldots, \\ \hat{\overline{k}}_X &= 1 + \overline{k}\, Y_u^\dagger Y_u + \ldots, \\ \hat{\mu}_X &= \mu_0 + \mu_1\, Y_u^\dagger Y_u + \ldots, \\ \hat{\kappa}_X &= \kappa_0 + \kappa_1\, Y_u^\dagger Y_u + \ldots, \\ \hat{\overline{\kappa}}_X &= \overline{\kappa}_0 + \overline{\kappa}_1\, Y_u^\dagger Y_u + \ldots, \\ \hat{B}_X &= B_0 + B_1\, Y_u^\dagger Y_u + \ldots, \end{aligned}$$

⇒ mass splittings within DM multiplet

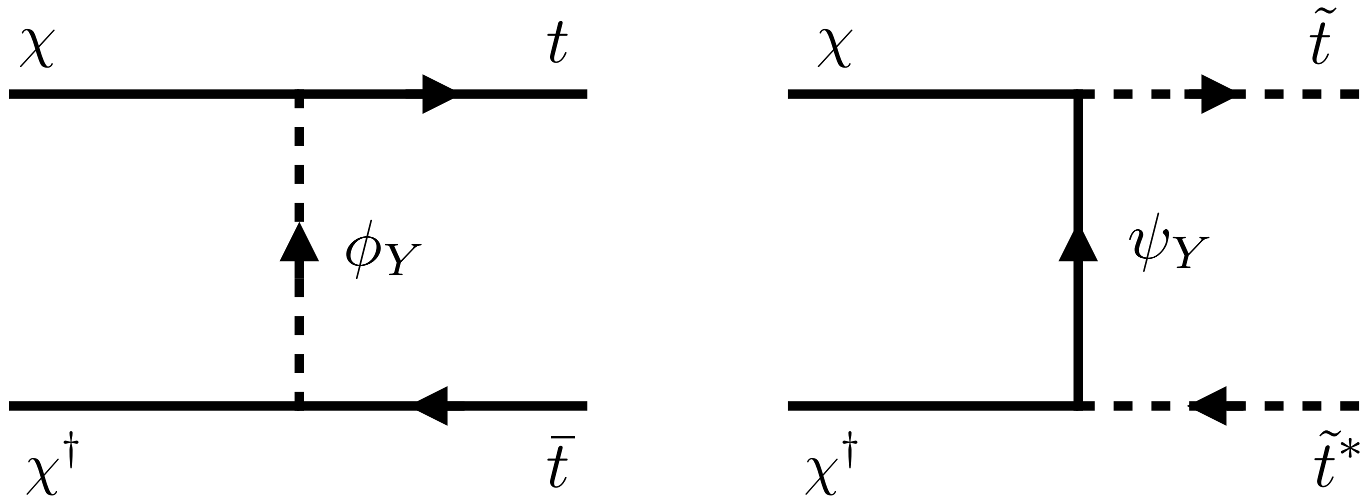
An example of spectrum



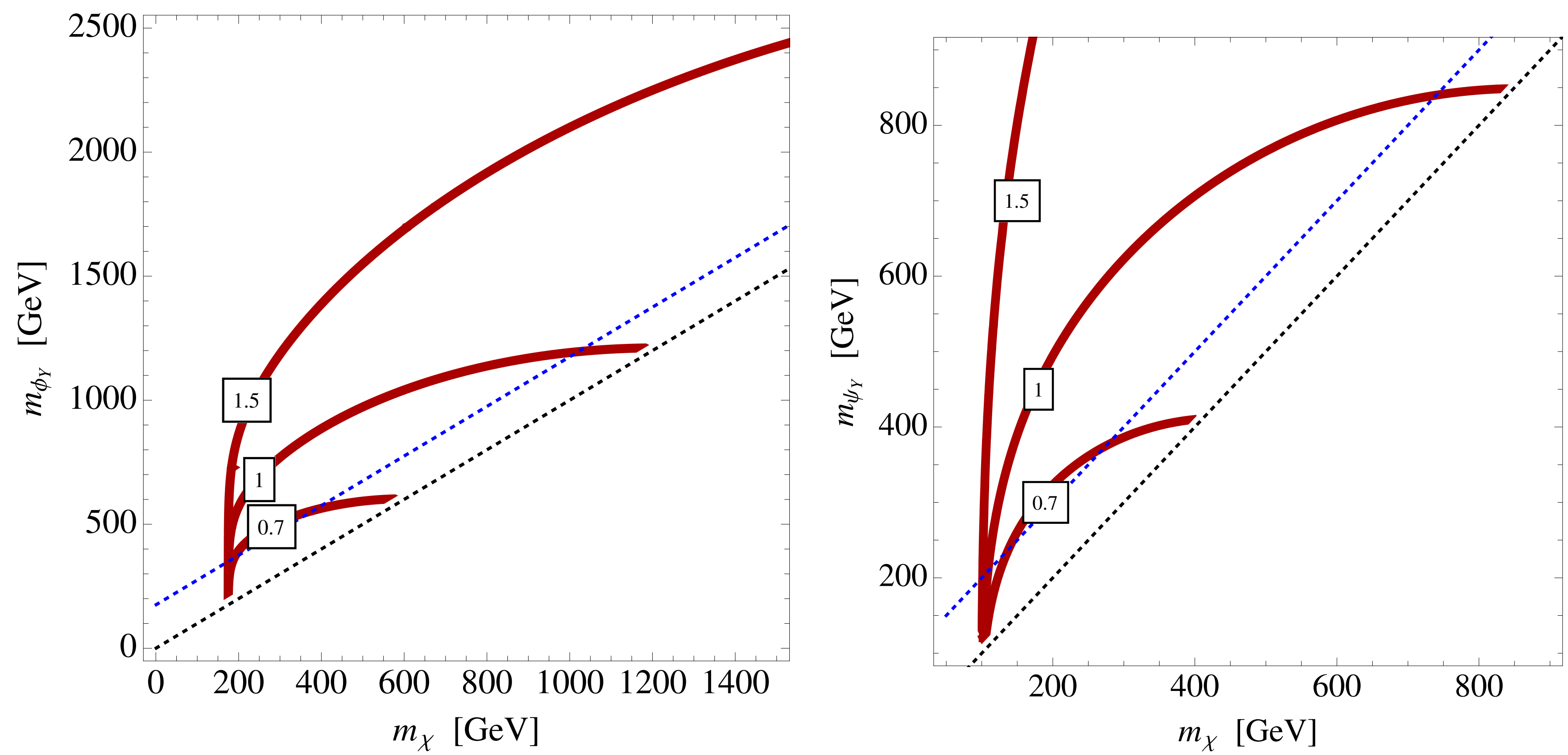
"top-philic", with $W = \lambda_t \phi_X \phi_Y t_R$

Relic abundance

$$W = \lambda_t \phi_X \phi_Y t_R$$

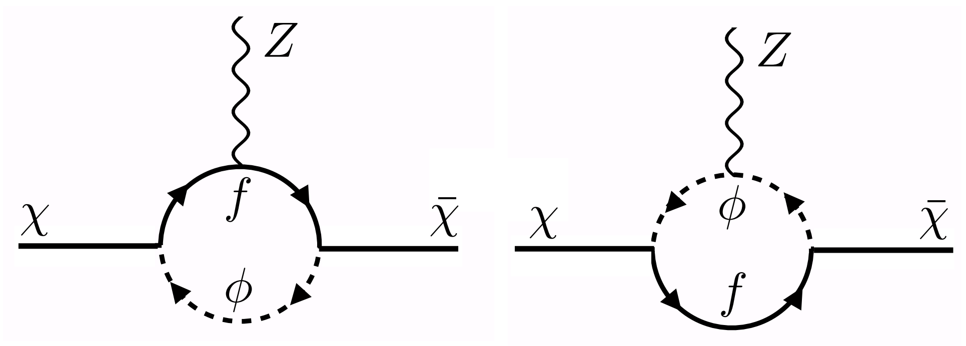


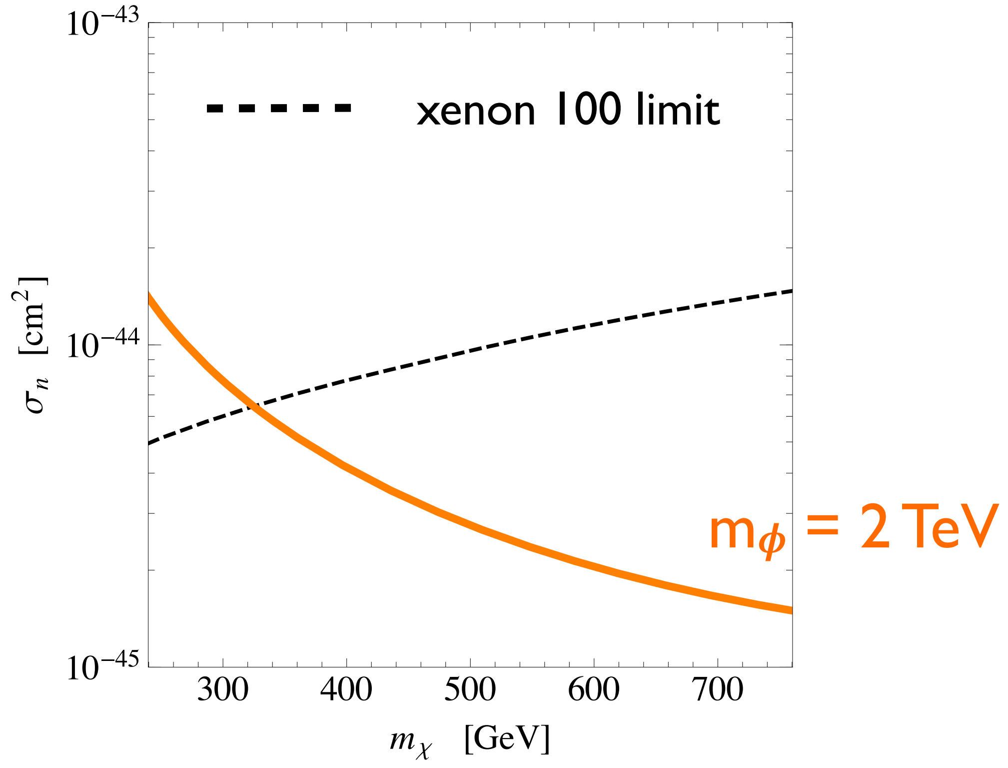
$$\sigma_{\text{ann}} \propto \lambda_t^4 \frac{m_\chi^2}{m_{\phi_Y,\psi_Y}^4}$$



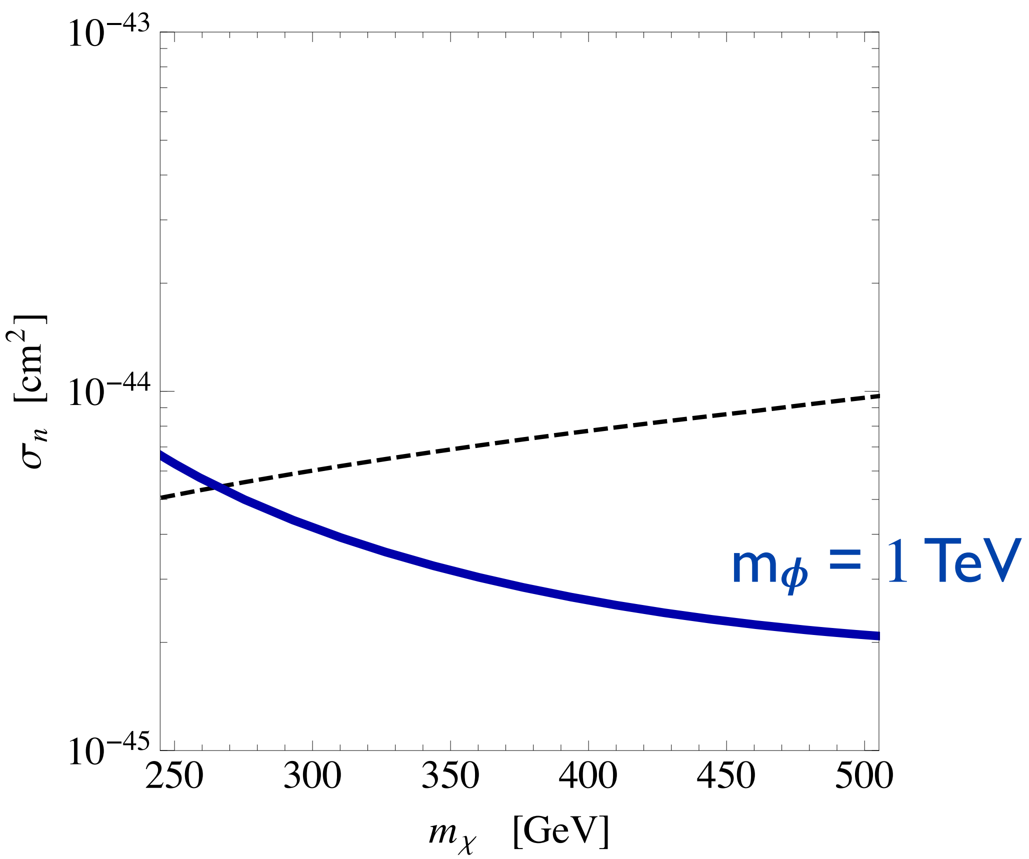
contour of λ_t with correct relic abundance

Direct detection vs relic abundance

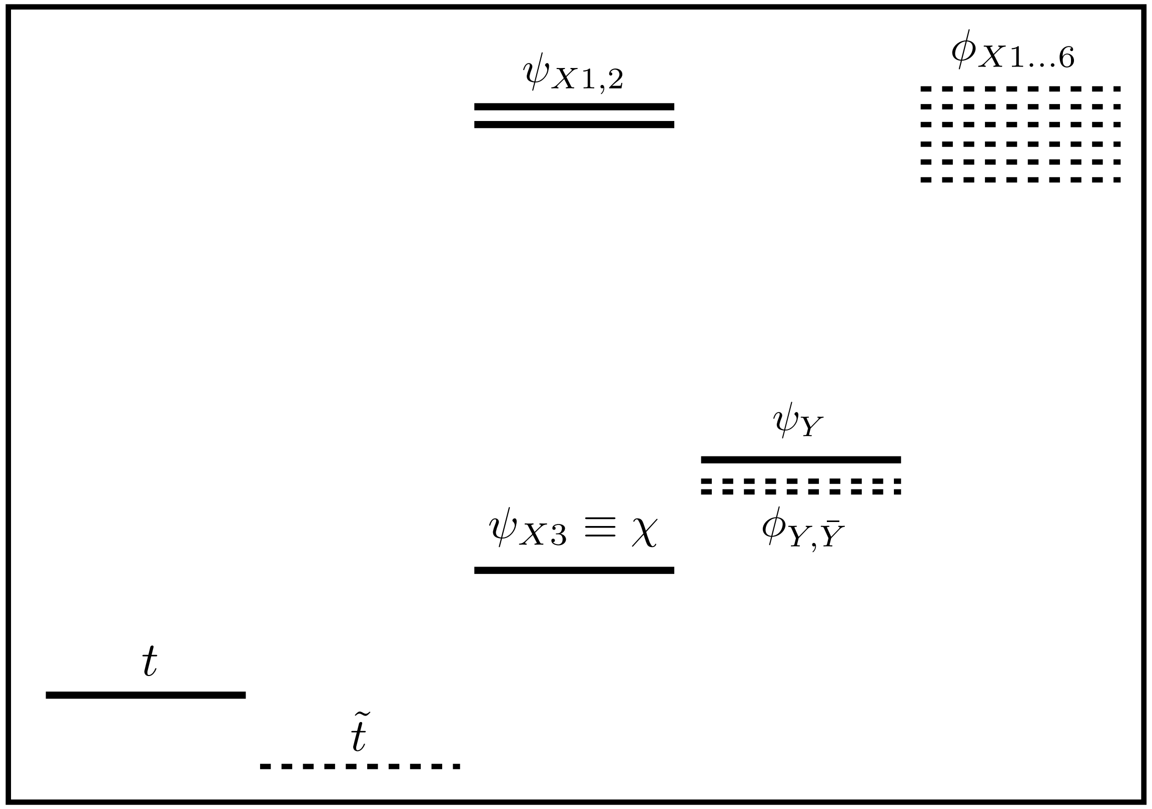




f=top
Direct detection dominated
by Z exchange



LHC



$$pp \to \phi_Y \phi_Y^*, \ \phi_Y \to t + \chi$$

But not the stop.

$$pp \to \psi_Y \bar{\phi}_Y, \ \psi_Y \to \tilde{t} + \chi$$

$$\tilde{t} \to jj \ (udd \ \mathrm{RPV})$$

"hidden" stop

- May find "heavy stop", but theory is natural.

Conclusions.

- SUSY and SUSY LSP dark matter could still be the answer, e.g. benchmarks in the pMSSM, etc.
- Another route: Dark matter in RPV+MFV SUSY.
  - Interesting collider signals.