Dark Matter and the Higgs in Natural SUSY

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Outline

1. The model
2. Higgs mass and fine tuning
3. Direct detection
4. Thermal relic density
5. Putting it all together

The model

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	Z_2^{DM}	Z_2^M
L	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	-1	1
$\bar{L}$	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	-1	1
S	$\mathbf{1}$	$\mathbf{1}$	0	-1	1

Z_2 symmetry keeps lightest state stable -- WIMP DM candidate!

Majorana mass term for S, otherwise immediately killed by Z-mediated SI DD. (Key diff with previous works on vector-like MSSM extensions!)

$$W = \frac{1}{2} M_S S^2 + M_L L \bar{L} + k_u H_u \bar{L} S - k_d H_d L S$$

$$\delta \mathcal{L}_{\text{soft}} = -m^2 (|\bar{\ell}|^2 + |\ell|^2 + |s|^2)$$

Take $m^2 > 0$ to lift the Higgs mass => DM is fermionic

Fermion mass matrix:

$$\mathcal{M} = \begin{pmatrix} M_S & k_u v \sin\beta & k_d v \cos\beta \\ k_u v \sin\beta & 0 & M_L \\ k_d v \cos\beta & M_L & 0 \end{pmatrix}$$

The Model

After diagonalizing, get couplings of mass eigenstates to h and Z (and W):

$$\delta\mathcal{L} = c_h h \bar{\psi}_\chi \psi_\chi + c_Z Z_\mu \bar{\psi}_\chi \gamma^\mu \gamma^5 \psi_\chi$$

Focus on mostly singlet DM: $m_\chi \sim M_S < M_L$ and $v << M_L$, M_L-M_S

$$c_h = -\frac{m_\chi + \frac{2k_d M_L}{k_u \tan\beta}}{\sqrt{2}v}\frac{k_u^2 v^2}{M_L^2} + \ldots \qquad c_Z = \frac{g}{4c_W}\frac{k_u^2 v^2}{M_L^2} + \ldots$$

Part of a broader framework of Higgs and Z-portal dark matter

(cf e.g. Giudice, de Simone and Strumia '14, Cheung & Sanford '13; Calibbi et al '15)

Higgs mass and fine-tuning

One-loop Higgs mass in the mostly singlet DM regime: ($\tan\beta \to \infty$)

$$\delta m_h^2 = \frac{k_u^4 v^2}{4\pi^2} \log\left(1 + \frac{m^2}{M_L^2}\right) + \mathcal{O}(M_S^2/M_L^2)$$

Assume MSSM stops get you to m_h ~ 110 GeV (~10% FT).
Need δm_h^2 ~ 3500 GeV^2 .

Fine tuning measure:

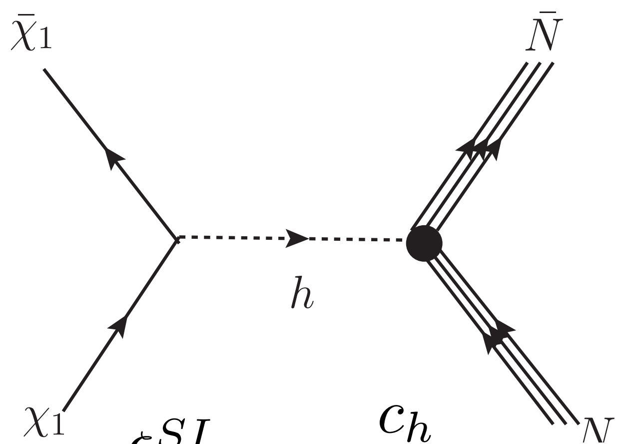
$$\Delta = \frac{2\delta m_{H_u}^2}{m_h^2} = \frac{\frac{k_u^2 m^2 \log 10}{4\pi^2}}{(125\ \mathrm{GeV})^2} \sim k_u^2 e^{\frac{4\pi^2 \delta m_h^2}{k_u^4 v^2}}$$

FT exponentially worse as k_u decreases. This requires $k_u \gtrsim 1.2$ (Different from Bino-Higgsino system where $k_u = g'/\sqrt{2}$)

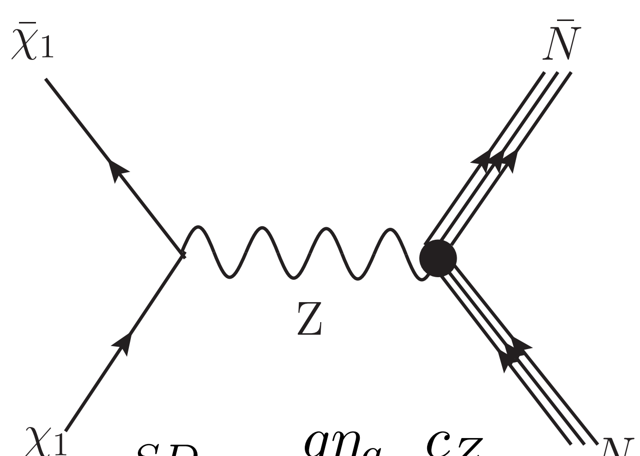
Direct Detection

DM direct detection experiments are probing couplings of DM to nucleons

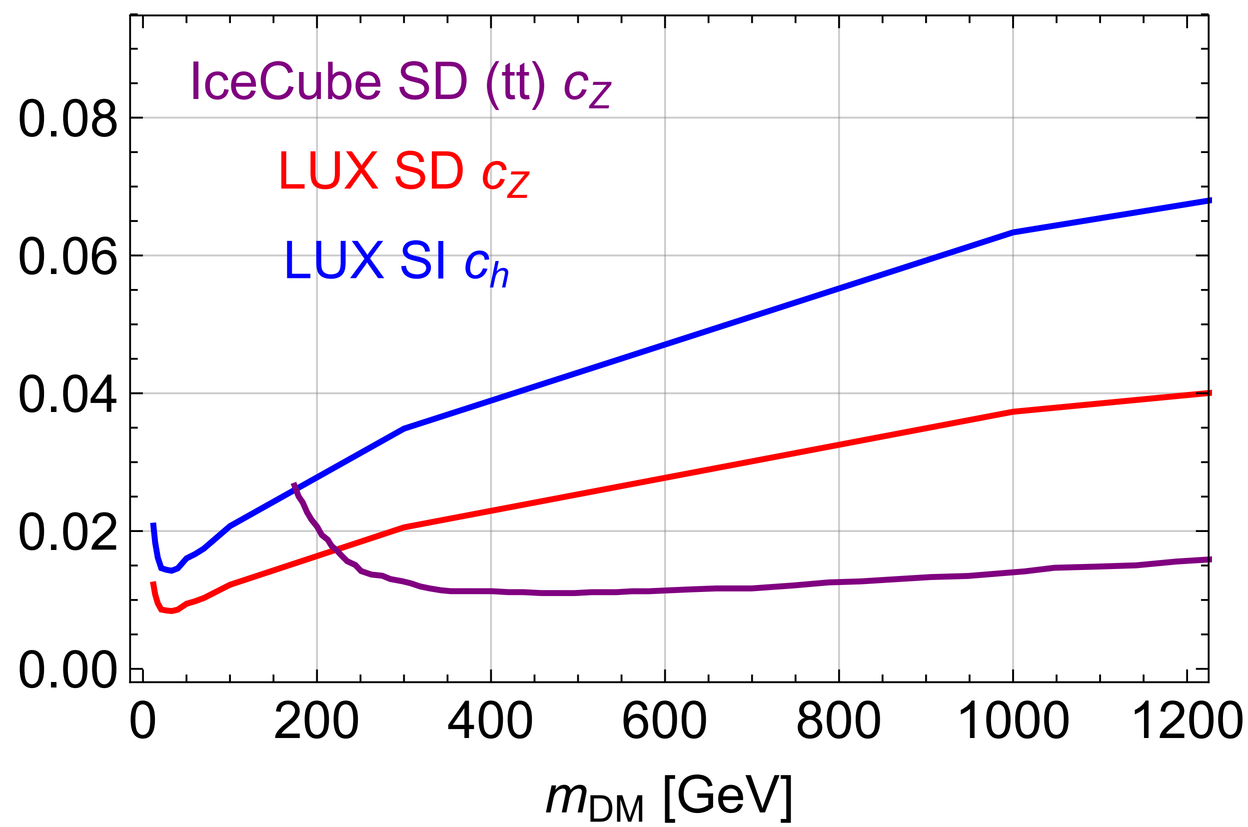
$$\xi_q^{SI}(\bar{\chi}\chi)(\bar{q}q) + \xi_q^{SD}(\bar{\chi}\gamma^5\gamma^\mu\chi)(\bar{q}\gamma^5\gamma_\mu q)$$



$$\xi_q^{SI} = y_q \frac{c_h}{m_h^2}$$



$$\xi_q^{SD} = \frac{g\eta_q}{4c_W}\frac{c_Z}{m_Z^2}$$



SI controlled by c_h and SD controlled by c_Z.

Thermal relic density

$$\Omega_{DM} h^2 \approx 9.2 \times 10^{-12}\ \mathrm{GeV}^{-2} \times \left(\int_{x_f}^{\infty} dx\, \frac{\langle \sigma v_\chi \rangle}{x^2} \right)^{-1}$$

$$\sigma_{xy}\, v_\chi = r_{xy}(a_{xy} + b_{xy}\, v_\chi^2 + \mathcal{O}(v_\chi^4)) \qquad r_{xy} \equiv \sqrt{1 - (m_x + m_y)^2/4m_\chi^2}$$

DM slowly moving at freeze out (v^2~0.1), so all else being equal, annihilation rate dominated by s-wave.

Initial state (pair of identical Majorana fermions) is CP odd, so no s-wave through s-channel Higgs. This leaves s-channel Z and t-channel.

Additional simplifications in large M_L limit...

Thermal relic density

$$a_{f\bar{f}} = \frac{3k_u^4}{32\pi M_L^2}\frac{m_f^2}{M_L^2(1-(M_S/M_L)^2)^2}$$

s-channel Z

$$a_{\psi_H\psi_H} = \frac{(k_d^2+k_u^2)^2}{16\pi M_L^2}\frac{\mu^2}{M_L^2(1+(M_S/M_L)^2+(m/M_L)^2)^2}$$

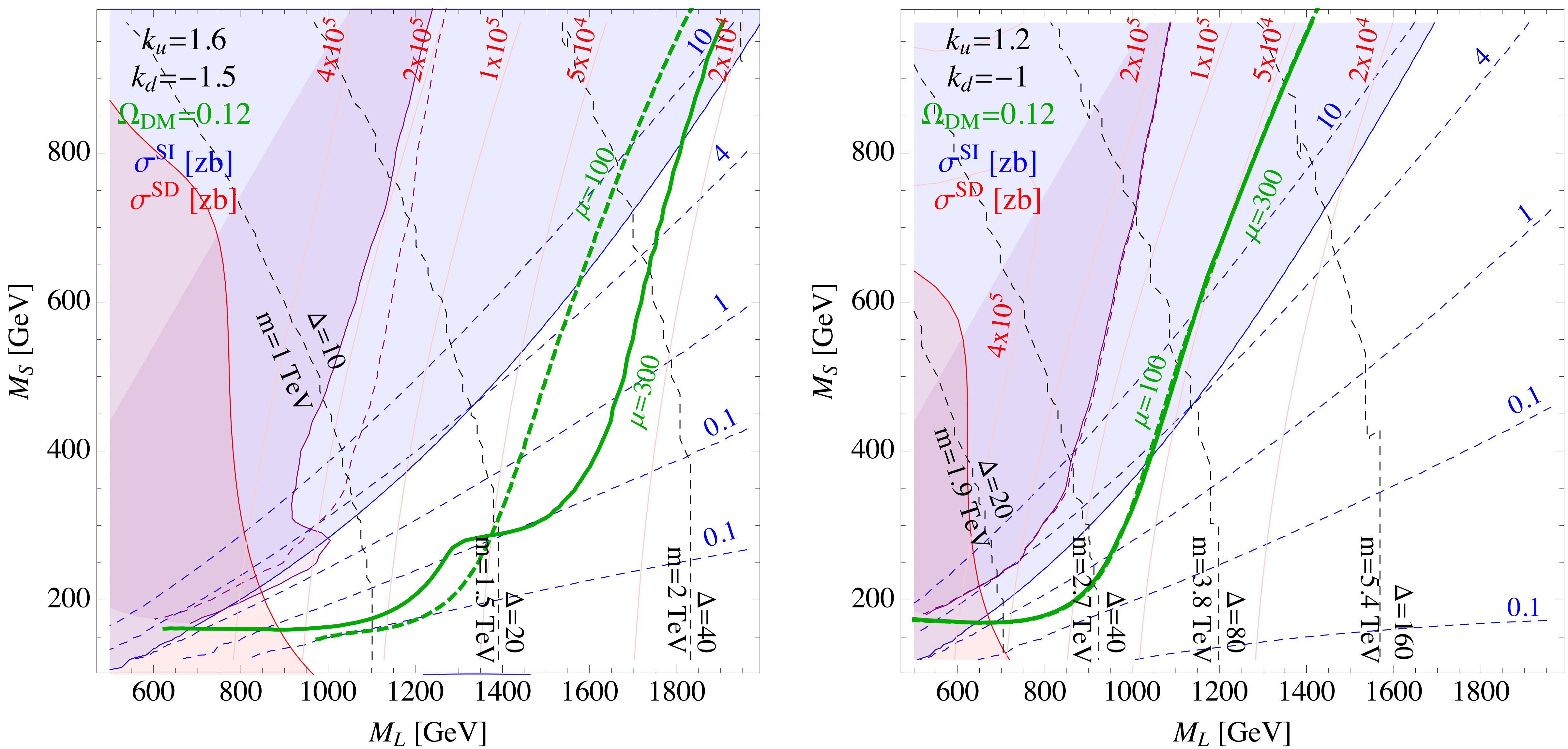
t-channel

Comments:

- s-wave annihilation is to tt and Higgsinos to leading order in v^2/M_L^2.
- Annihilation to dibosons is always subdominant for the parameter space that we study.
- c_Z controls both the SD DD cross section and the annihilation to tt.

Putting it all together

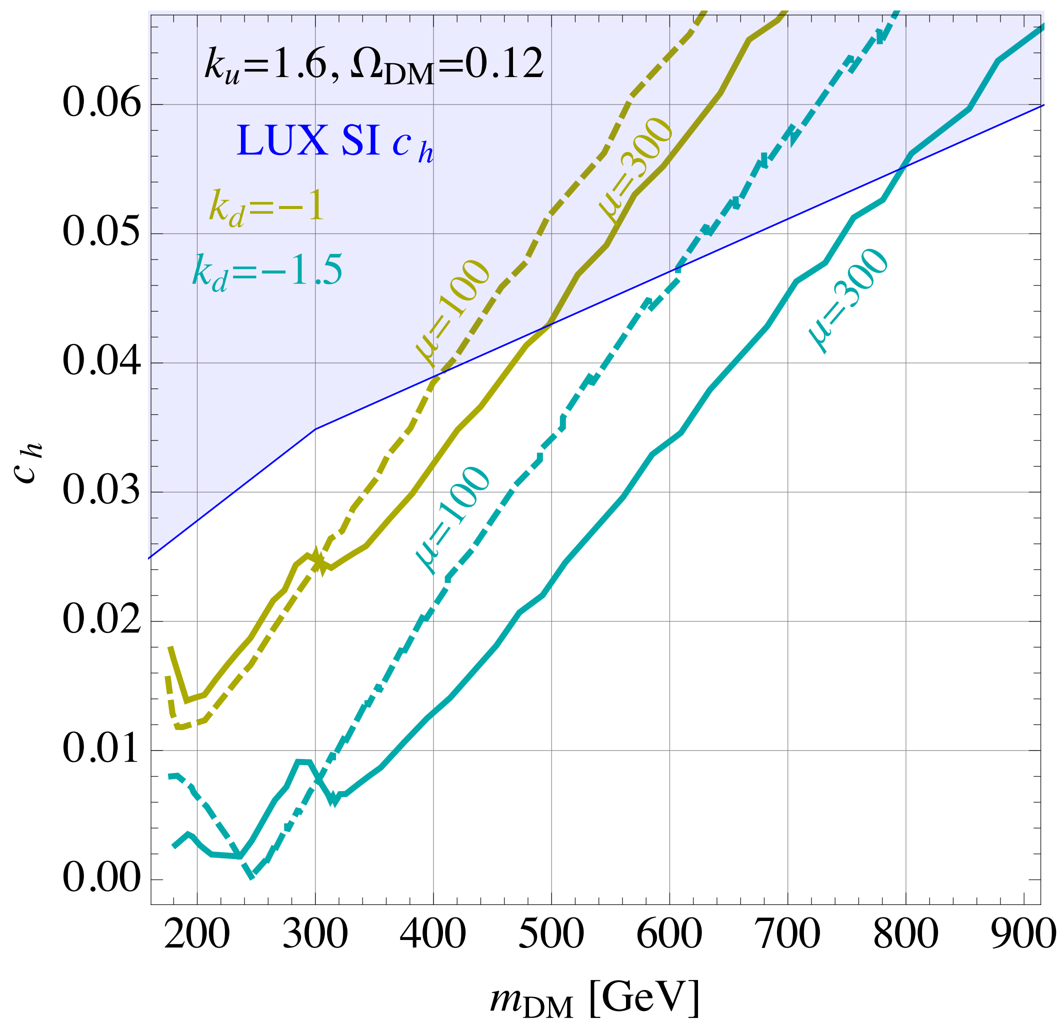
- Confirms analytics of DD bounds.
- Confirms estimates of FT via one-loop Higgs mass.



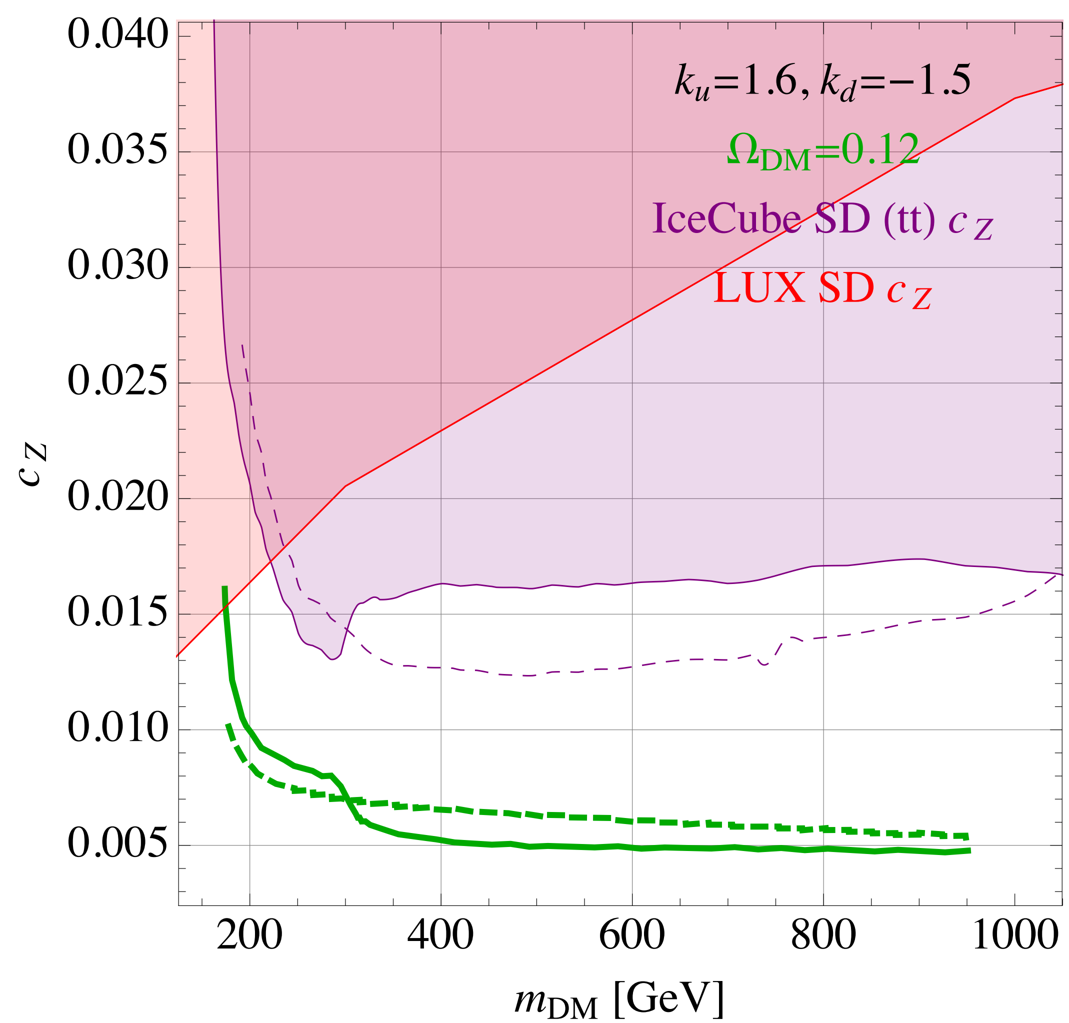
Numerical pipeline: SARAH-SPheno-Micromegas. Confirmed using analytics.

Thermal relic contour plots

We can move toward the blind spot by varying k_d.



Within a factor of a few of being ruled out by SD DD!



Confirms the direct relation between Ω_{DM} and c_Z!

Conclusions

We studied an economic extension of the MSSM that gives a 125 GeV Higgs mass with a fine-tuning as low as 10% and provides a natural thermal WIMP DM candidate.

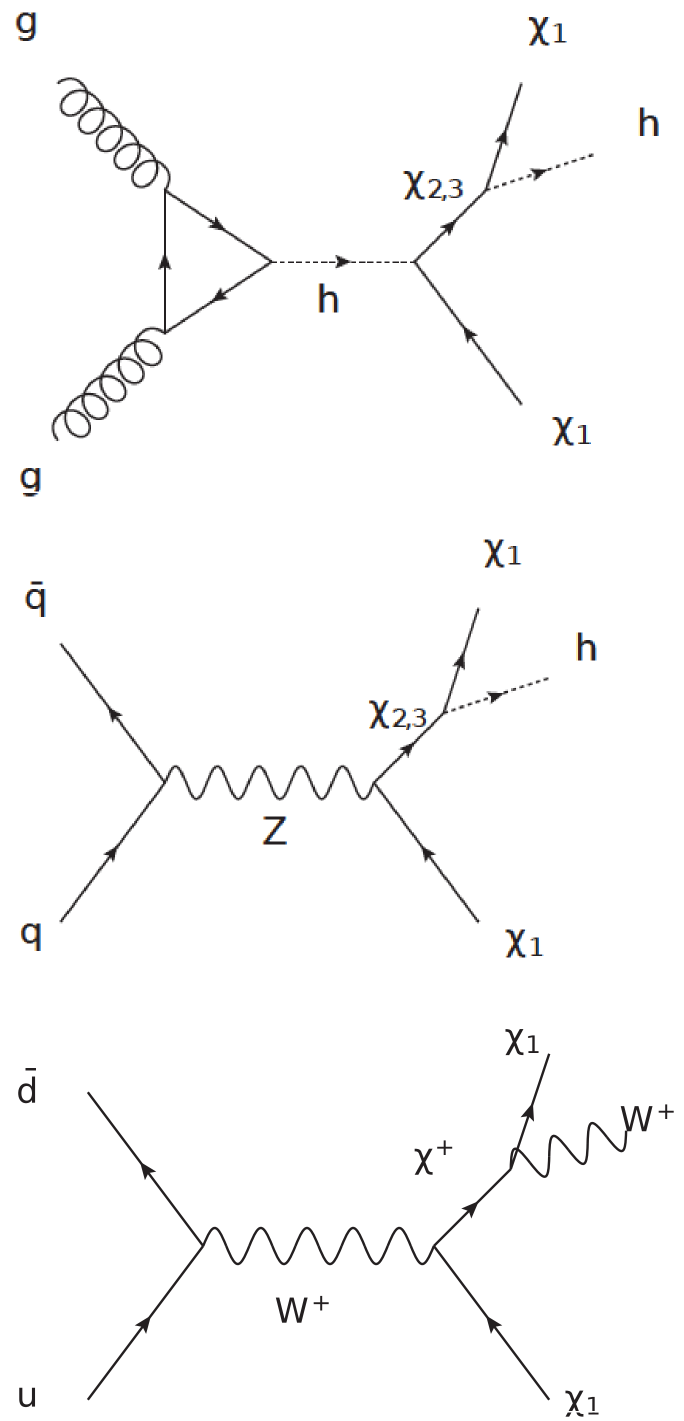
The main annihilation channels in our model are s-wave annihilation to tt and Higgsinos.

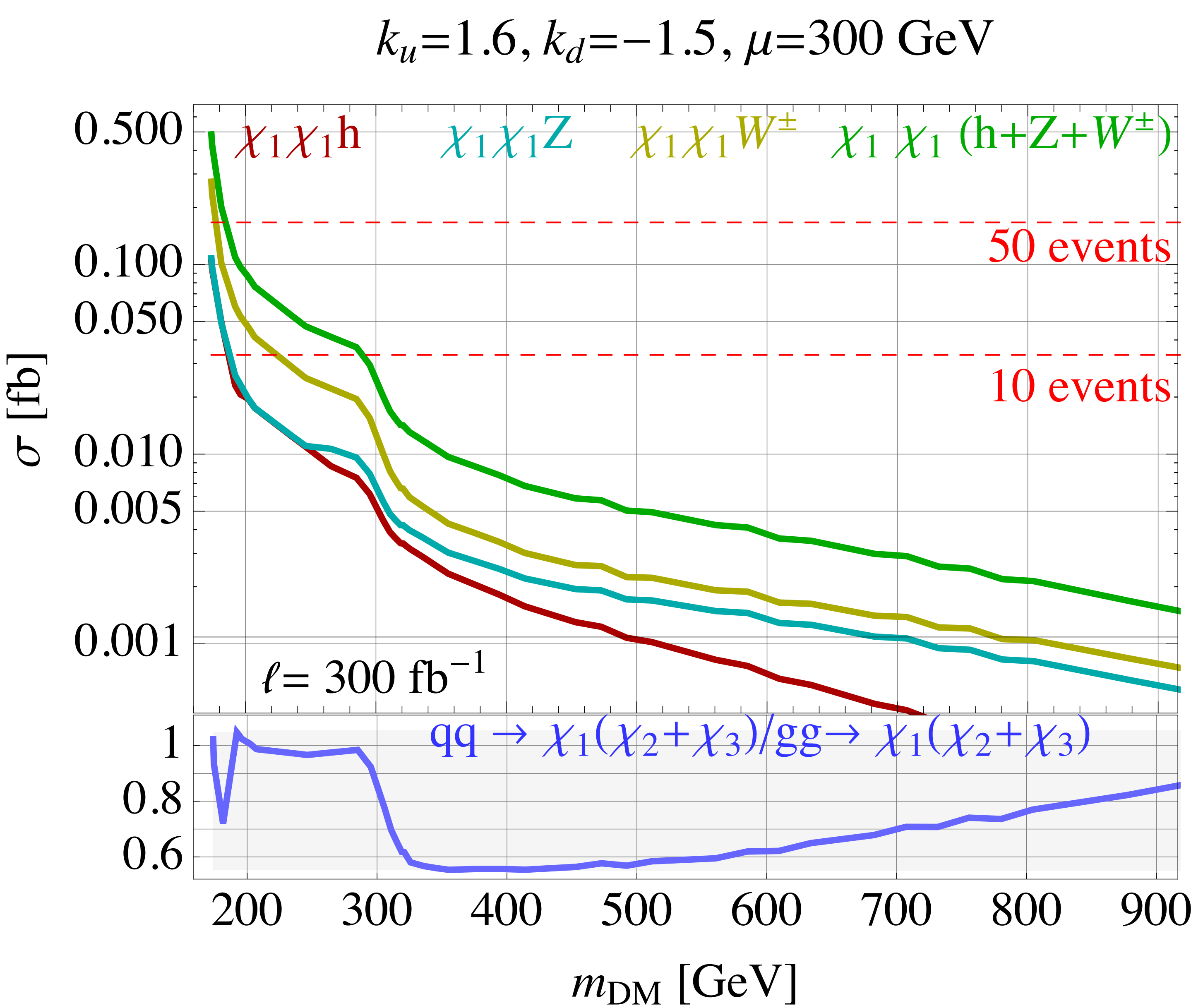
Imposing the relic density constraint immediately implies a particular value for the SD cross-section. This value is not ruled out yet, but the next generation of DM experiments (e.g.\ Xenon1T , LZ) should completely rule out or discover this model.

Thanks for your attention!

LHC prospects

Mono(H,Z,W) through $\chi_1 + (\chi_{2,3},\chi^{\pm})$ production:





Outlook

Xenon1T should probe the entire parameter space of our model in a few years.
More generally true for Higgs and Z-portal DM!

Other models for Higgs and DM beyond the MSSM:

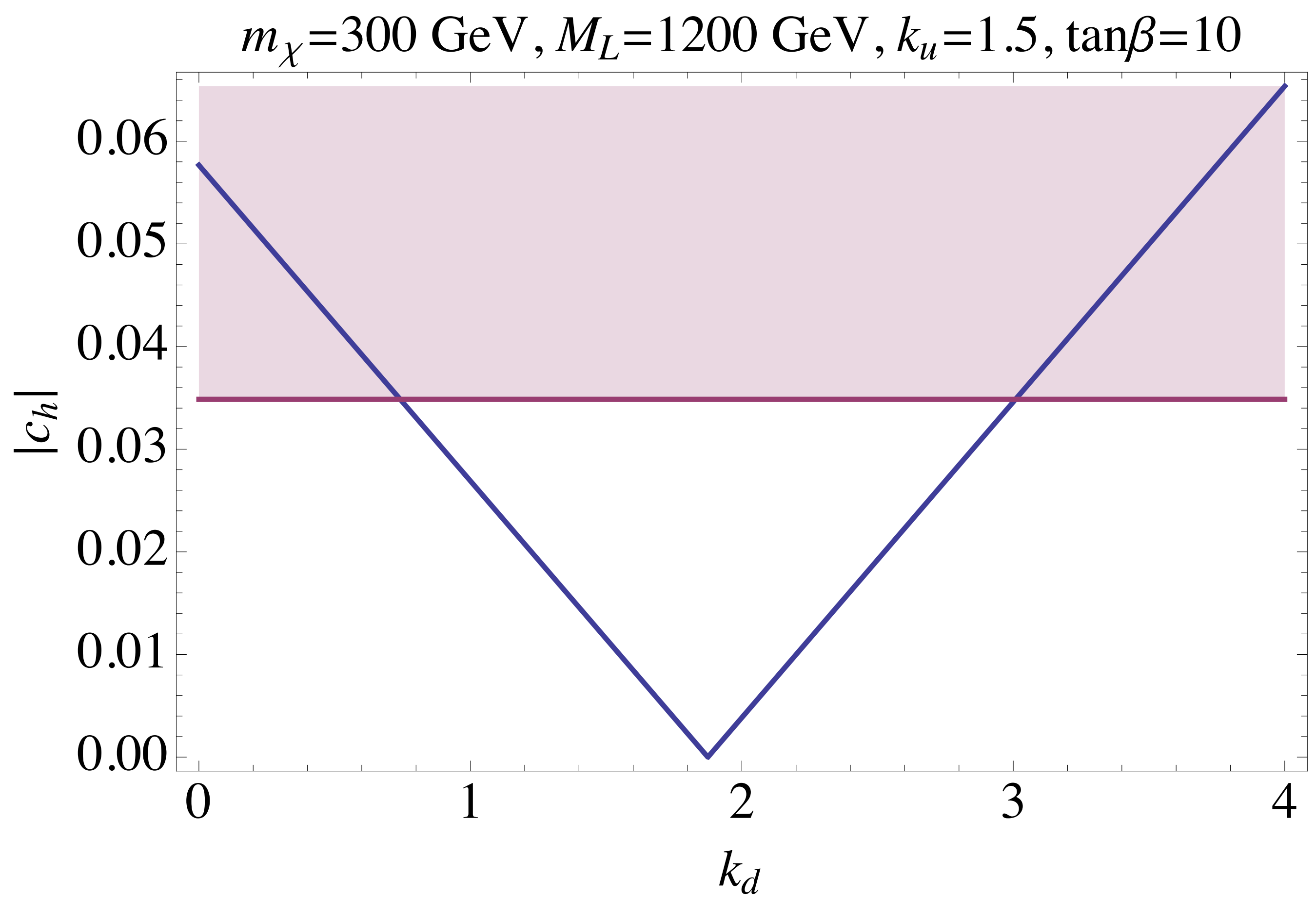
- Other SU(2) representations?
- NMSSM?
- Non-decoupling D-terms?
- ...

Extra particles expected for unification...explore their phenomenology?

Further explorations of the more general effective operator story...

Landau pole problem...

Blind Spot

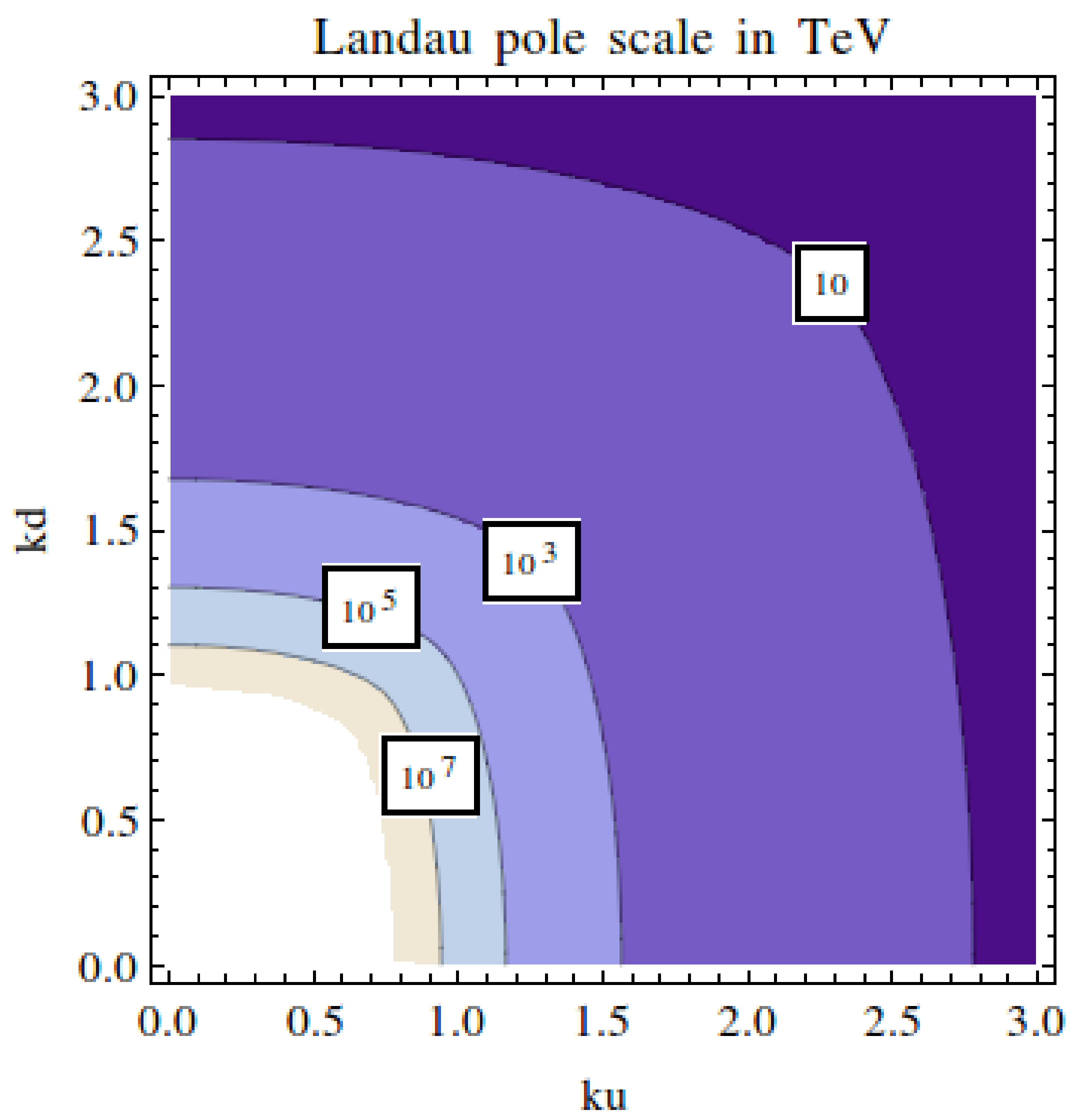


$$c_h = \left(\frac{M_S - \frac{2k_d M_L}{k_u \tan\beta}}{\sqrt{2}v} \right) \frac{k_u^2 v^2}{M_L^2} + \ldots$$

To satisfy LUX SI bounds, need a mild blind spot cancellation (factor of ≲ 2)

Landau Pole Problem

Generally there is a Landau pole well before the GUT scale. Theory needs to be UV completed -- or extended with gauge interactions to deflect the Yukawas...



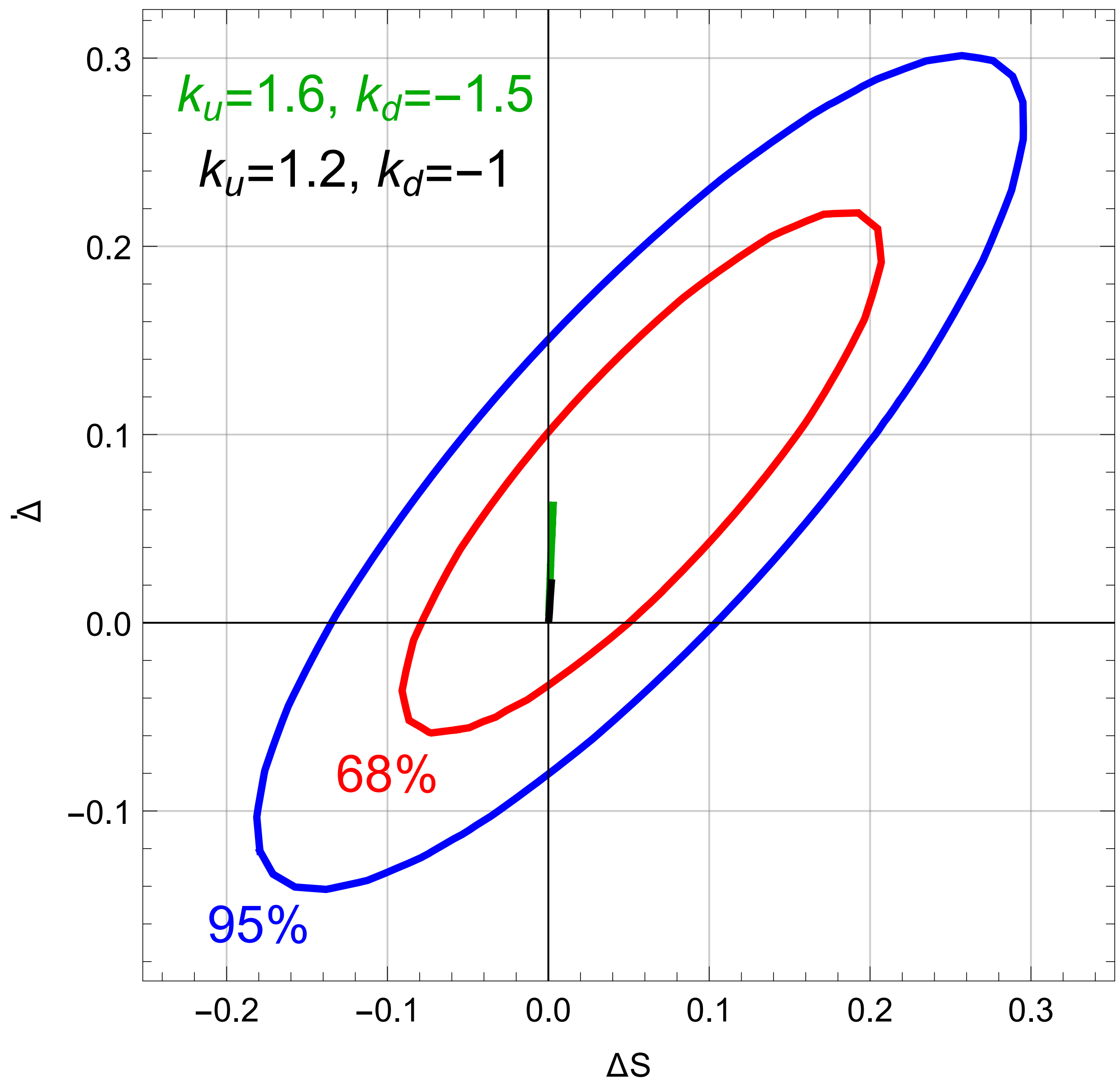
$$\beta_{g_3} = -\frac{3}{16\pi^2} g_3^3$$

$$\beta_{k_u} = \frac{k_u}{16\pi^2}(2k_d^2 + 4k_u^2 + 3y_t^2)$$

$$\beta_{k_d} = \frac{k_d}{16\pi^2}(4k_d^2 + 2k_u^2)$$

$$\beta_{y_t} = \frac{y_t}{16\pi^2}(6y_t^2 + k_u^2 - \frac{16g_3^2}{3})$$

Electroweak Precision Tests



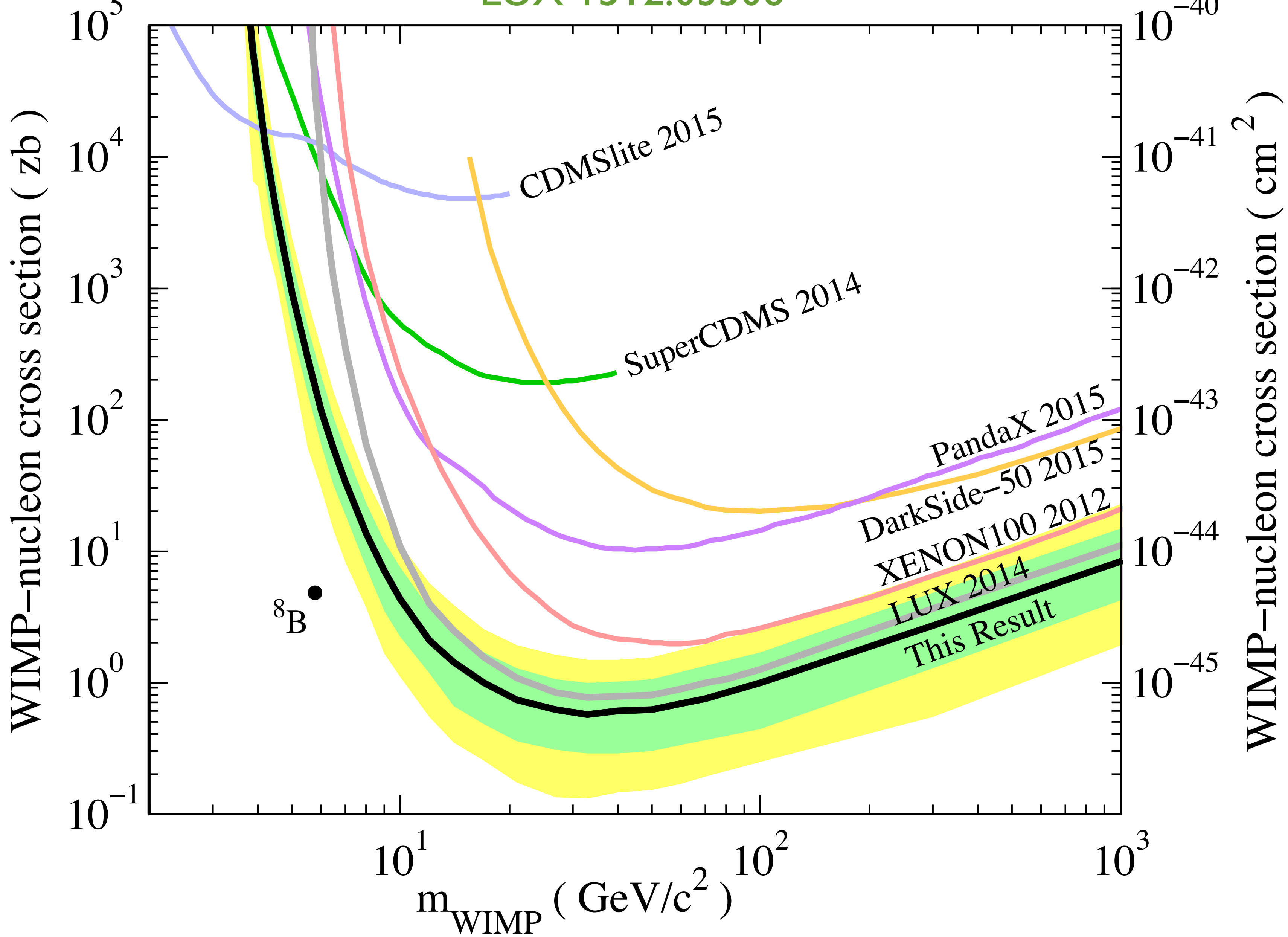
Calculated using formulas in Abe, Kitano & Sato '14.

Agrees qualitatively with results there and in Martin '09.

Model is totally safe from EWPT -- in mostly singlet regime, thermal relic constraint requires doublet mass ≳ 1 TeV...

Direct detection: SI

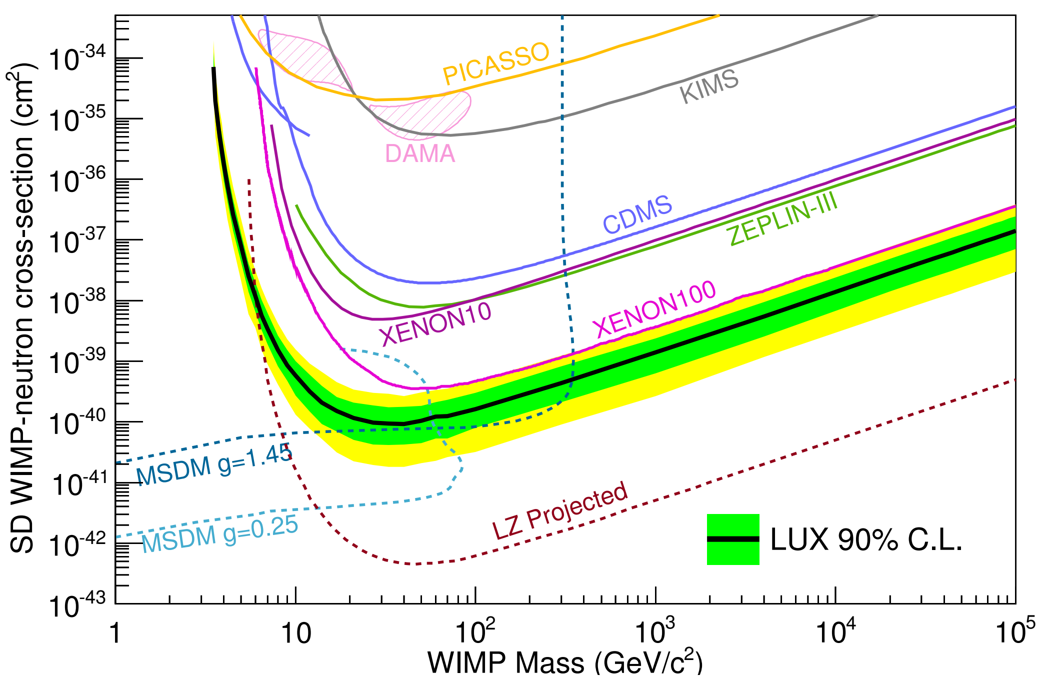
LUX 1512.03506

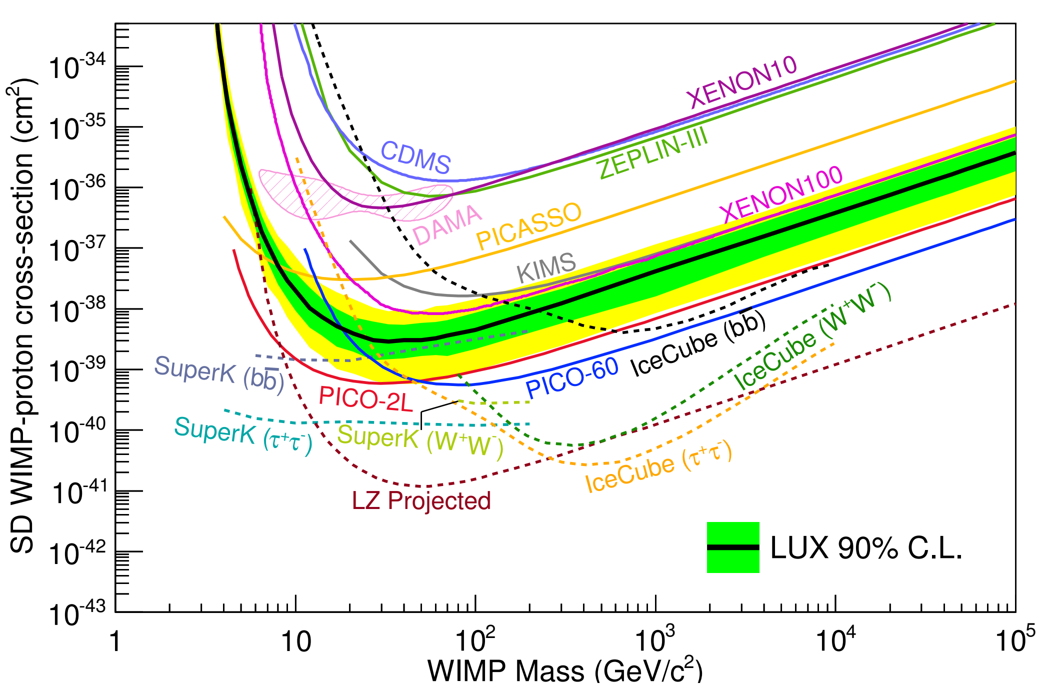


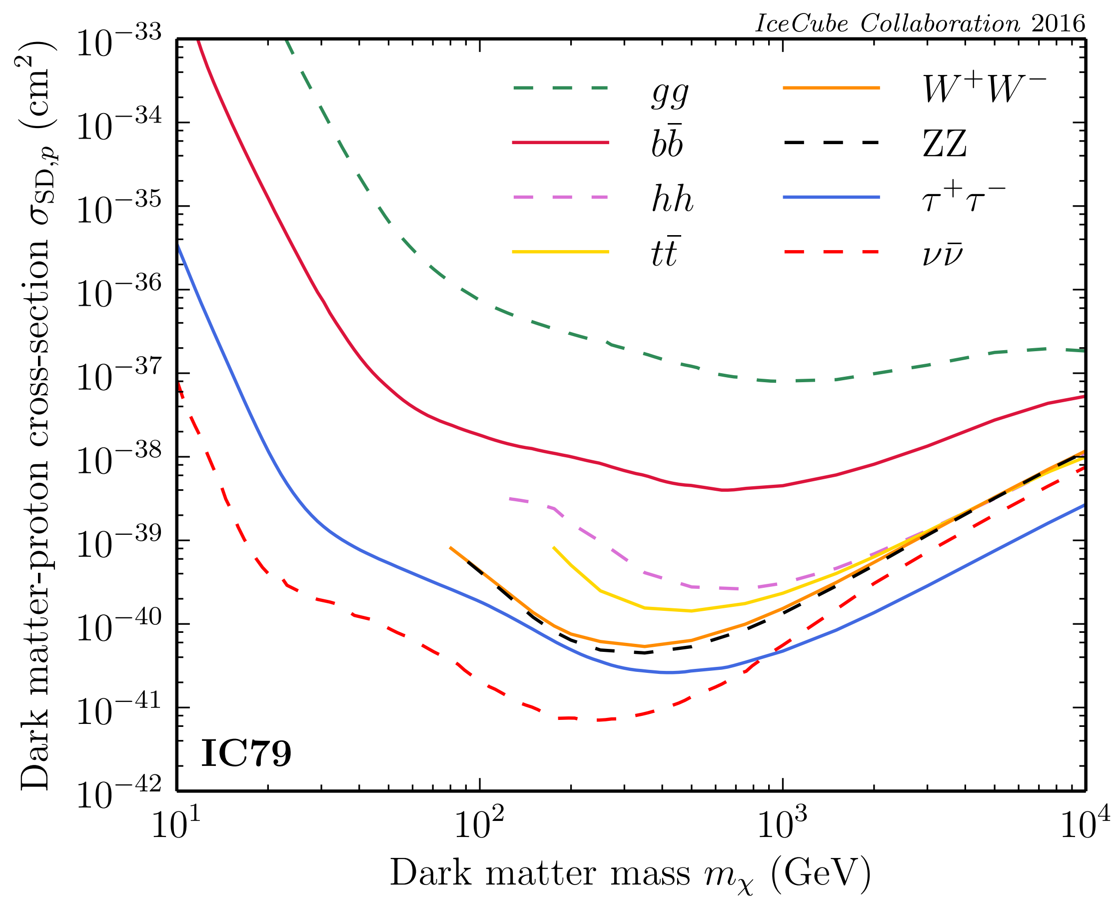
LUX currently sets strongest SI constraints.

Direct Detection: SD

LUX 1602.03489







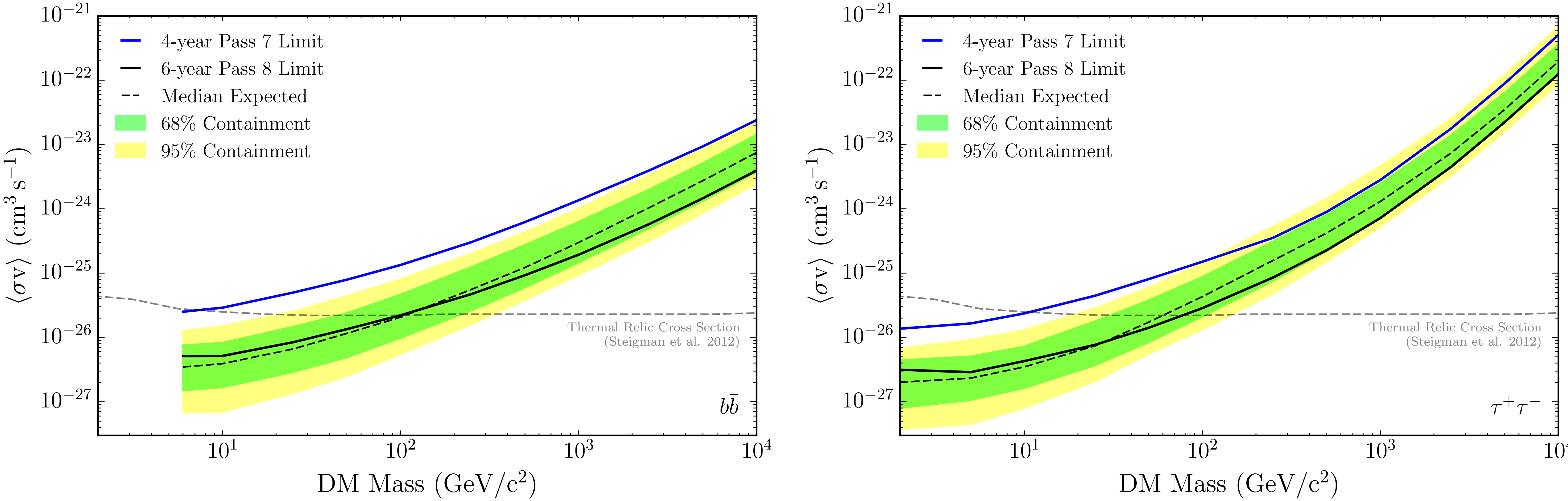
Official ttbar limit is new; previously had to be recasted (see e.g. Cheung, Hall & Ruderman '12).

Factor of a few weaker ttbar vs WW makes a big difference for our model!

LUX neutron (IceCube proton) strongest below (above) ~250 GeV.

Indirect detection

Fermi 1503.02641



No official ttbar limits, but probably ineffective above 100 GeV...

Conclusions

We studied an economic extension of the MSSM that gives a 125 GeV Higgs mass with a fine-tuning as low as 10% and provides a natural thermal WIMP DM candidate. The constraints on the parameter space are:

$\Delta \simeq 10$ requires $k_u \gtrsim 1.2$

Also $k_u \lesssim 2$ from UV considerations

Ω_{DM} and SD DD are determined by $k_u^2/M_L^2 \propto c_Z$ for each μ

Once M_L is given, then the contribution to $\delta m_h^2 \simeq 3500 GeV^2$ fixes $m \sim M_L$

To satisfy SI DD we need $|k_d| \gtrsim 1$

Thanks for your attention!

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Once M_L is given, then the contribution to $\delta m_h^2 \simeq 3500 GeV^2$ fixes $m \sim M_L$

To satisfy SI DD we need $|k_d| \gtrsim 1$

For each μ only M_S is free.

Thanks for your attention!

Introduction: two questions

Why is the Higgs at 125 GeV?

Is it compatible with naturalness?

What is the dark matter?

Does it have anything to do with the theory of the weak scale?

In minimal SUSY, the answer to both questions is basically NO.

- Higgs at 125 GeV in the MSSM requires multi-TeV A-terms or 10 TeV stops. Either way it is fine tuned at the sub-percent level or worse.
- WIMP dark matter in the MSSM requires either a heavy SUSY scale or contrived numerical coincidences (blind spots, funnels, co-annihilation).

So if SUSY solves the hierarchy problem, the source of both DM and the Higgs mass likely lies beyond the MSSM.

Introduction

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	Z_2^{DM}
L	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	-1
$\tilde{L}$	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	-1
S	$\mathbf{1}$	$\mathbf{1}$	0	-1

In this talk, we will study a simple, economical extension of the MSSM that includes both DM and the source of the Higgs mass.

We will see that it is possible to achieve ~10% fine-tuning, a 125 GeV Higgs, and thermal relic DM consistent with all experimental constraints, by just adding a singlet and pair of vector-like doublets to the MSSM.

Introduction

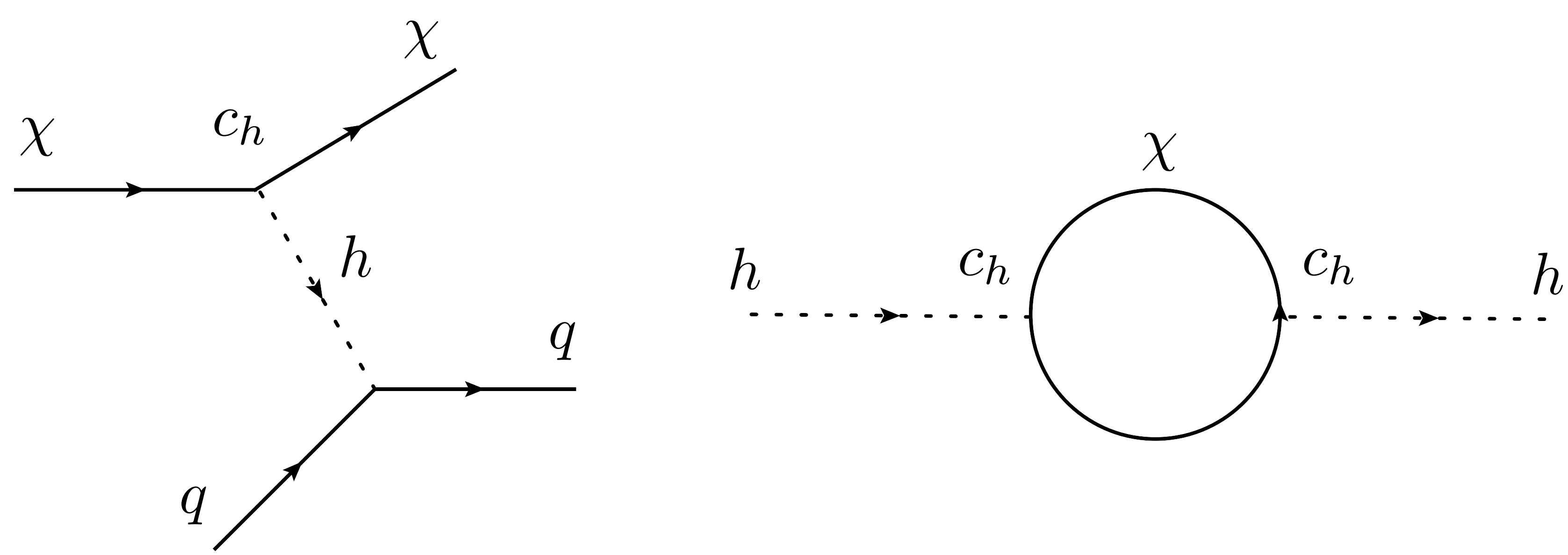
Previous work:

- Singlet-doublet DM extension of SM [Mahbubani & Senatore '05, Cohen et al '11, Cheung & Sanford '13, Calibbi et al '15]

- Lifting the Higgs mass with vector-like extensions of the MSSM [Moroi & Okada '92...Martin '09 '10, Graham et al '09...Evans et al '11, Li et al '11, Moroi et al '11, Martin & Wells '12, Endo et al '11 '12, Ishikawa et al '12,...]

But as far as I know, nobody has combined the two ideas before.

Introduction



Perhaps it didn't look promising, because direct-detection bounds on the Higgs portal are quite stringent?

Key points:

- Blind spot: since it's a 2HDM, effective DM-DM-Higgs coupling c_h can be tuned to zero by balancing up-type and down-type couplings against each other in a particular way.

- DM is lightest mass eigenstate out of a singlet+doublet+anti-doublet, so there is more than one c_h coupling. DD only probes about c_h for DM, while Higgs mass is sensitive to all of them.

The Model

Z₂ symmetry keeps lightest state stable -- WIMP DM candidate!

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	Z_2^{DM}
L	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	-1
$\tilde{L}$	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	-1
S	$\mathbf{1}$	$\mathbf{1}$	0	-1

Majorana mass term for S, otherwise immediately killed by Z-mediated SI DD. (Key diff with previous works on vector-like MSSM extensions!)

Take $k_u > 1$ to help lift the Higgs mass and improve fine tuning.

$$\delta W = k_u \tilde{L} H_u S + k_d L H_d S + \frac{1}{2} M_S S^2 + M_L L \tilde{L}$$

$$\delta \mathcal{L}_{soft} = m_S^2 |S|^2 + m_L^2 |L|^2 + m_{\tilde{L}}^2 |\tilde{L}|^2 + (A - terms) + (B - terms)$$

$$\text{Assume} \quad m_S^2 = m_L^2 = m_{\tilde{L}}^2 = m^2, \quad A = B = 0 \quad \text{for simplicity}$$

Take $m^2 > 0$ to lift the Higgs mass => DM is fermionic

The Model

Assume large tanβ otherwise MSSM contribution to Higgs mass too small

Fermion mass matrix: $$\mathcal{M} = \begin{pmatrix} M_S & k_u v s_\beta & k_d v c_\beta \\ k_u v s_\beta & 0 & M_L \\ k_d v c_\beta & M_L & 0 \end{pmatrix} = U^\dagger \mathcal{M}_{diag} U^*$$

After diagonalizing, get couplings of mass eigenstates to h and Z (and W):

$$\delta\mathcal{L} \supset m_i \bar{\chi}_i \chi_i + c_{hij} h \bar{\chi}_i \chi_j + c_{Zij} Z_\mu \bar{\chi}_i \gamma^\mu \gamma^5 \chi_j$$

<u>The DM talks to the SM through these couplings.</u>

Focus on mostly singlet DM: $m_\chi \sim M_S << M_L$.

- Mostly doublet regime is not promising for fine-tuning (cf pure Higgsino DM), direct detection
- Well-tempered regime ruled out by DD

The Model

$$\delta\mathcal{L} \supset m_\chi \bar{\chi}\chi + c_h h\bar{\chi}\chi + c_Z Z_\mu \bar{\chi}\gamma^\mu\gamma^5\chi$$

Then much of the physics (thermal relic density, direct detection, LHC signatures, ...) controlled by DM-DM-Higgs and DM-DM-Z couplings.
(Cheung & Sanford '13; Calibbi et al '15)

In our model, these are given by: blind spot

σ_{SI}

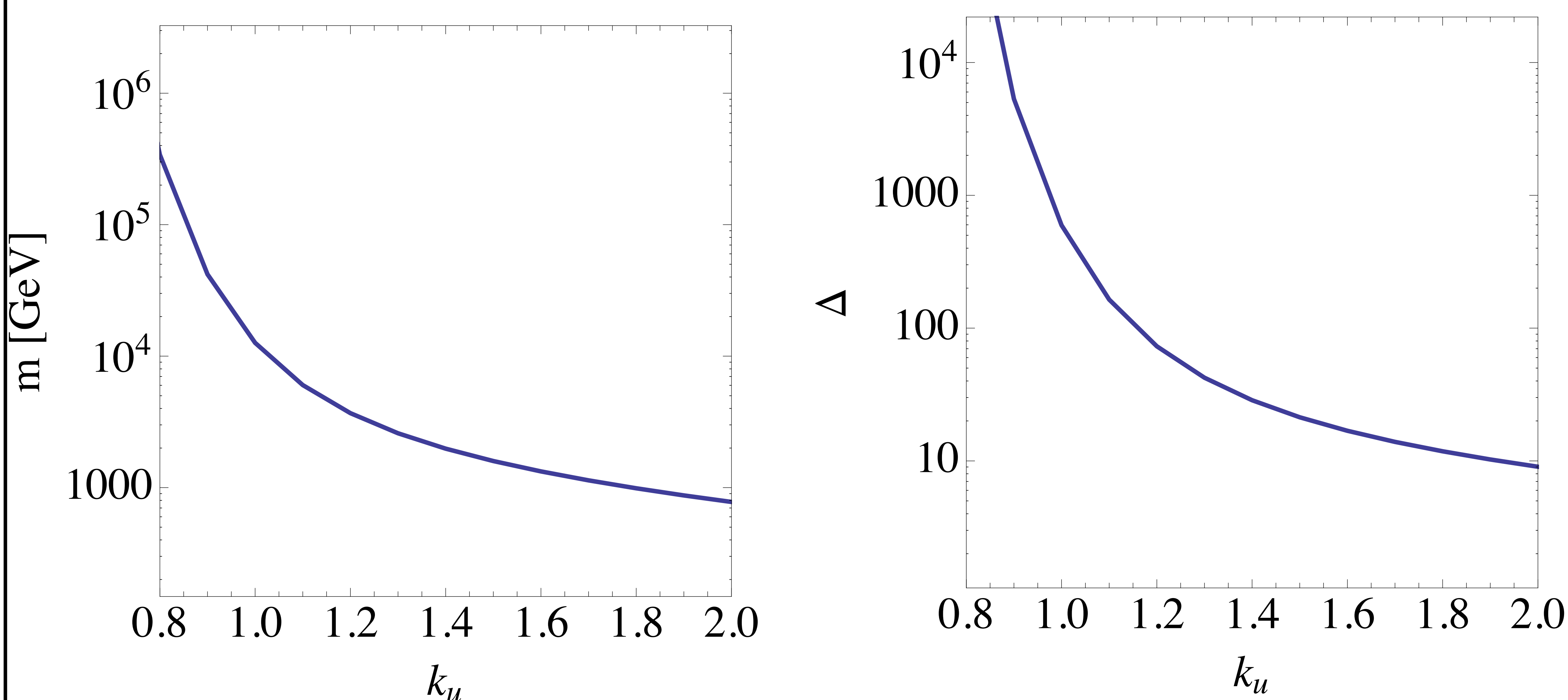
$$c_h = \frac{1}{\sqrt{2}}(k_u s_\beta U_{11}^* U_{12}^* + k_d c_\beta U_{11}^* U_{13}^*) = \left(\frac{M_S - \frac{2k_d M_L}{k_u \tan\beta}}{\sqrt{2}v}\right)\frac{k_u^2 v^2}{M_L^2} + \ldots$$

σ_{SD}, $\langle\sigma v\rangle$

$$c_Z = \frac{g_2}{4c_W}(|U_{12}|^2 - |U_{13}|^2) = \frac{g_2}{4c_W}\frac{k_u^2 v^2}{M_L^2} + \ldots$$

Part of a broader framework of Higgs and Z-portal dark matter
(cf e.g. Giudice, de Simone and Strumia '14)

Higgs mass and fine-tuning



(M_L=1200 GeV, M_S=300 GeV)

Need $k_u>1$ to avoid same fate as MSSM stops. For $k_u \sim 1.5$, can achieve $\Delta \sim 10$.

Thermal relic density

$$\Omega_{DM} \approx \frac{3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle}$$

Thermal relic density determined by 2→2 annihilation of DM to SM particles.

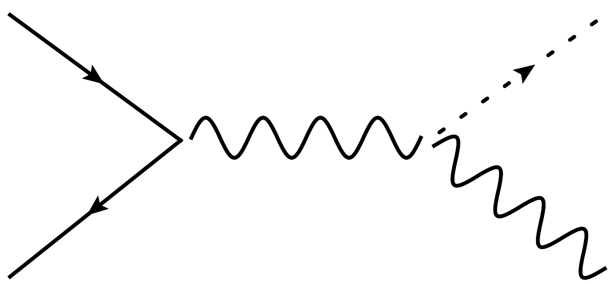
DM slowly moving at freeze out (v^2~0.2), so all else being equal, annihilation rate dominated by s-wave.

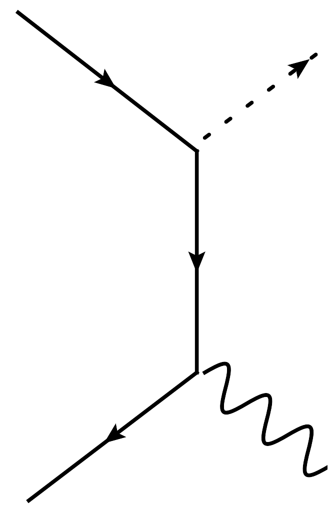
Initial state (pair of identical Majorana fermions) is CP odd, so no s-wave through s-channel Higgs. This leaves s-channel Z and t-channel.

Additional simplifications in large M_L limit...

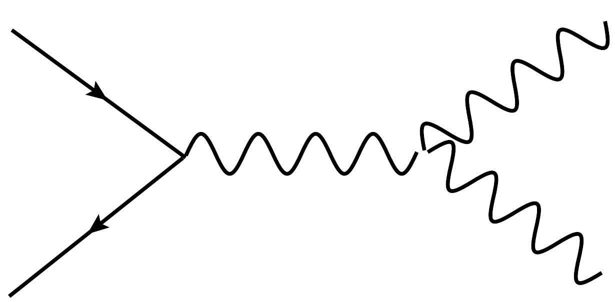
Thermal relic density

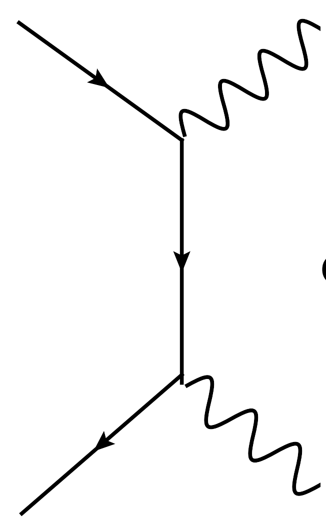
s-wave helicity suppressed





s-wave cancels at leading order in $1/M_L$





extra $1/M_L$ suppressed

no s-wave due to CP and angular momentum conservation

At leading order in 1/ML, only s-wave annihilation is to ttbar, and it's controlled by c_Z!

Thermal relic density

$$\langle\sigma v\rangle_{tt} = \frac{3}{8\pi}\frac{\hat{g}^2 m_t^2}{m_Z^4}c_Z^2 = \frac{3k_u^4 m_t^2}{32\pi M_L^4}$$

$$\Omega_{DM} \approx \frac{3\times 10^{-27}\ \mathrm{cm}^3/\mathrm{s}}{\langle\sigma v\rangle} \approx 0.12\left(\frac{0.008}{c_Z}\right)^2 \approx 0.12\left(\frac{M_L/k_u}{800\ \mathrm{GeV}}\right)^4$$

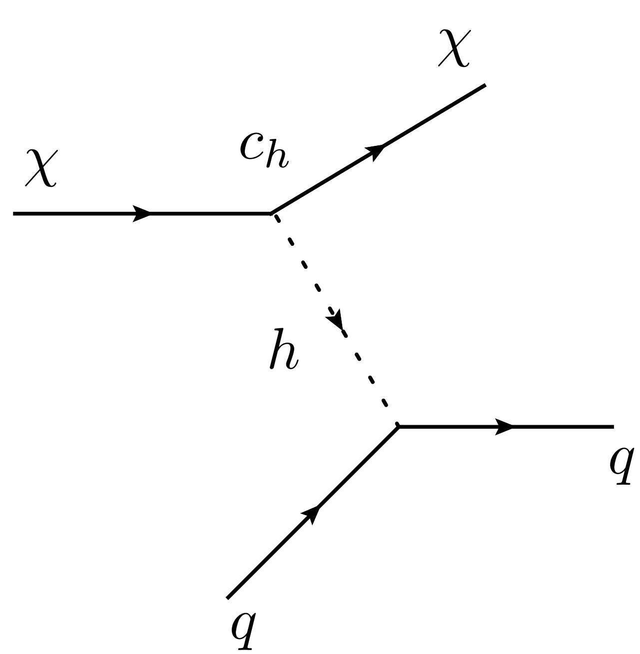
Comments:

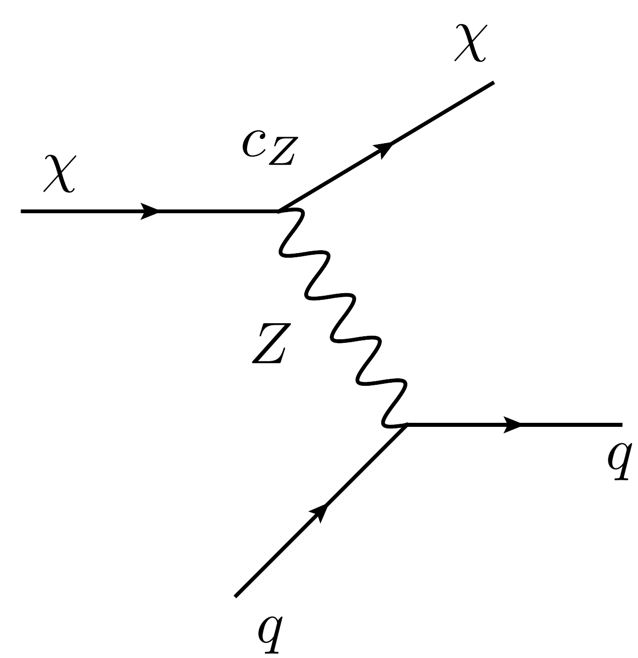
- To leading order, c_Z is fixed to 0.008 by the relic density constraint! Compatible with DD? No escape!
- In our model, M_L/k_u is fixed to 800 GeV. For k_u~1.5 this is M_L~1200-1300 GeV.
- Dependence on DM mass drops out at leading order -- WIMP miracle in terms of mediator scale!
- Higgsinos should be light for naturalness. So if DM heavier than Higgsino, should include DM annihilation to Higgsinos as well. Parametrically similar to ttbar.

Direct Detection

DM direct detection experiments are probing couplings of DM to nucleons

$$\xi_q^{SI}(\bar{\chi}\chi)(\bar{q}q) + \xi_q^{SD}(\bar{\chi}\gamma^5\gamma^\mu\chi)(\bar{q}\gamma^5\gamma_\mu q)$$

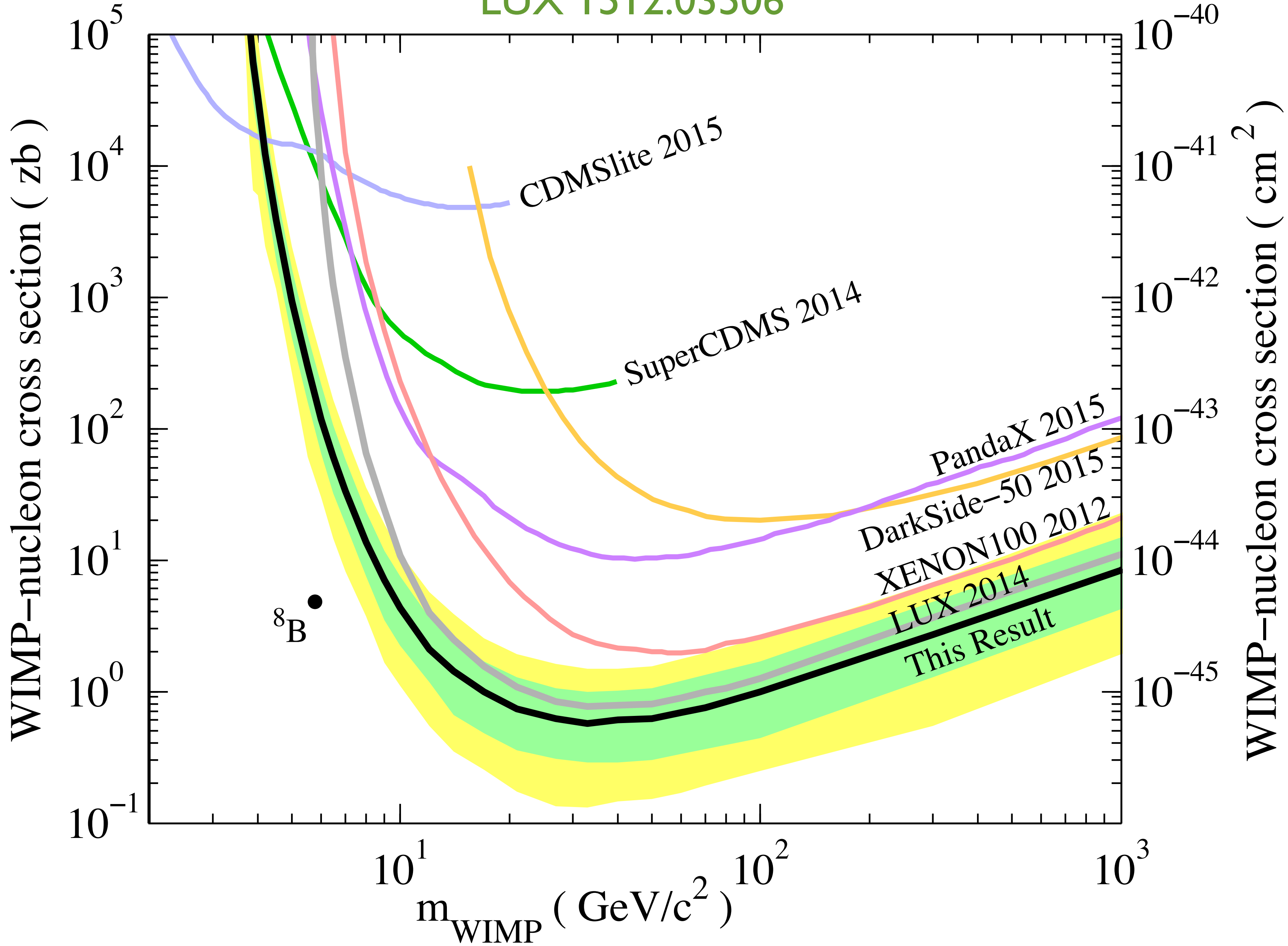




SI controlled by c_h and SD controlled by c_Z.

Direct detection: SI

LUX 1512.03506



LUX currently sets strongest SI constraints.

Direct Detection: SD

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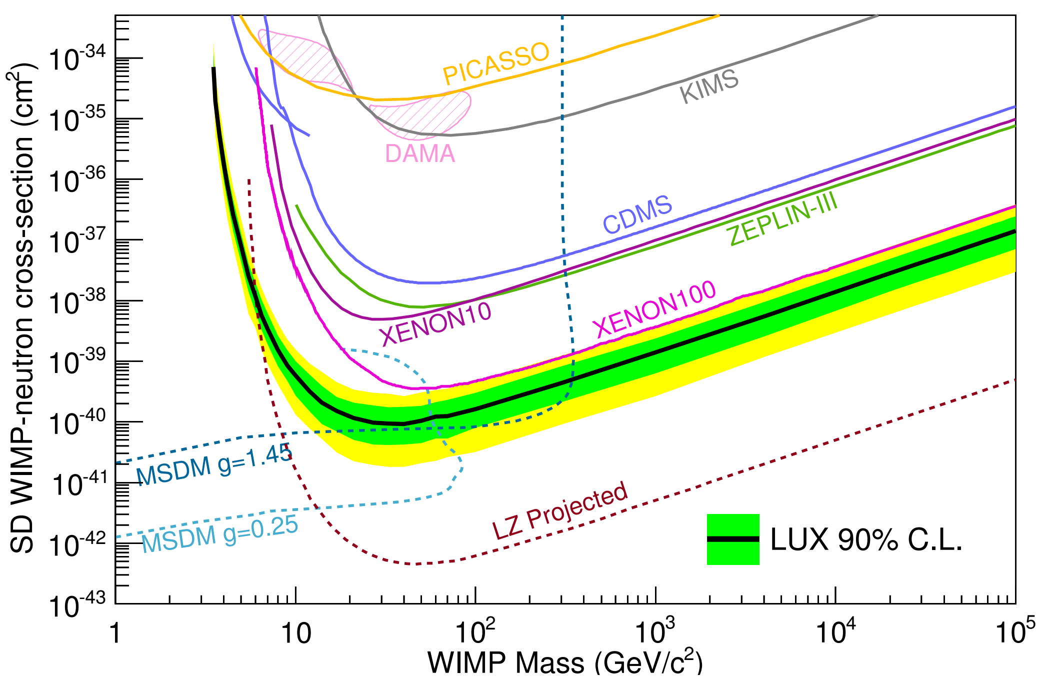

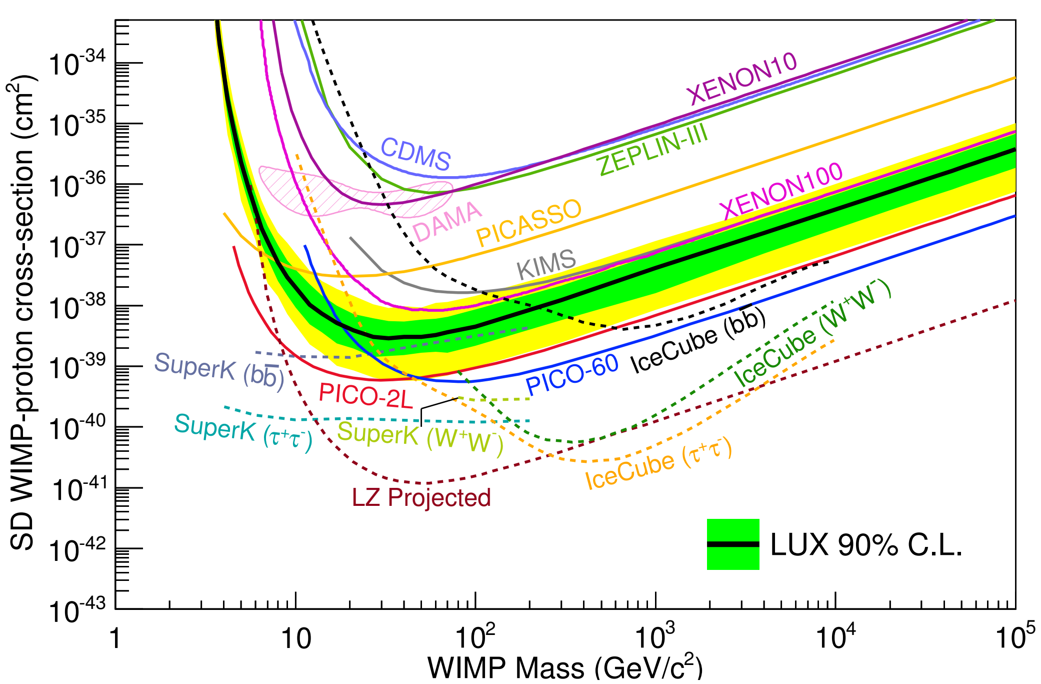

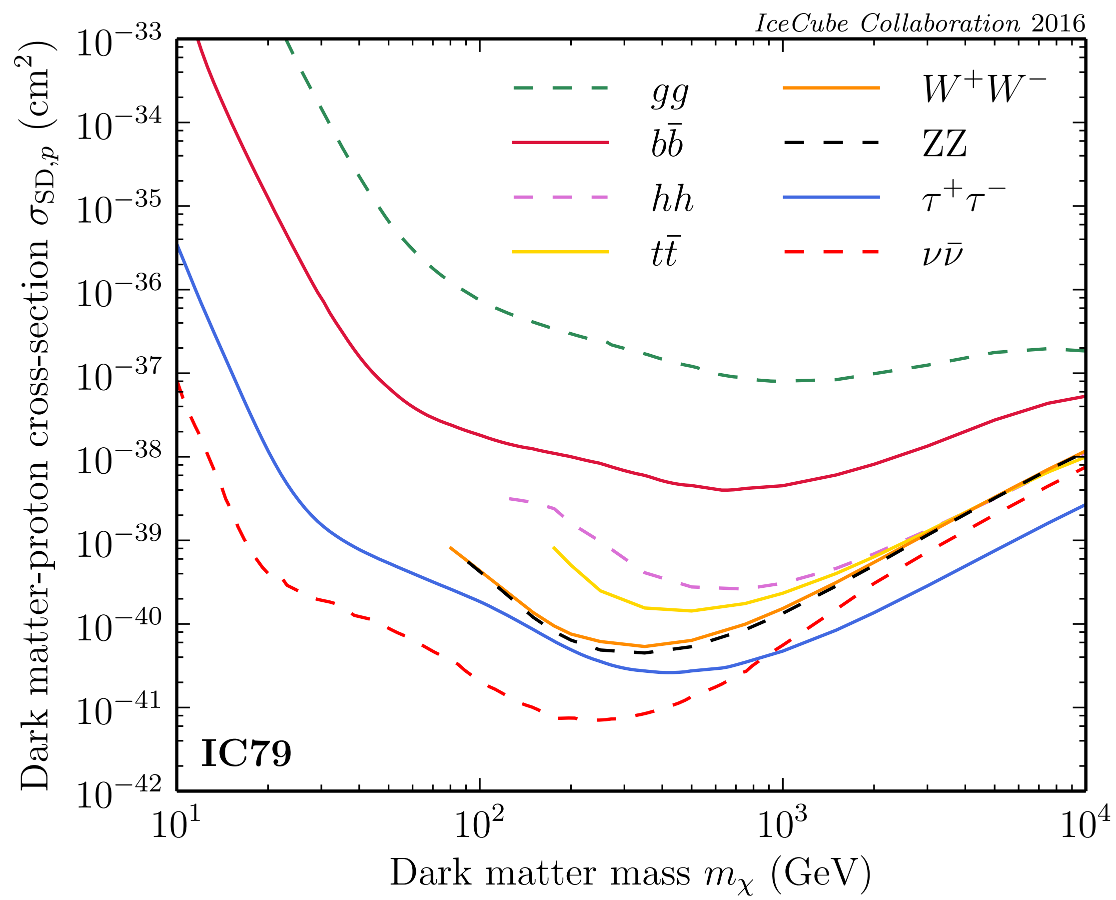

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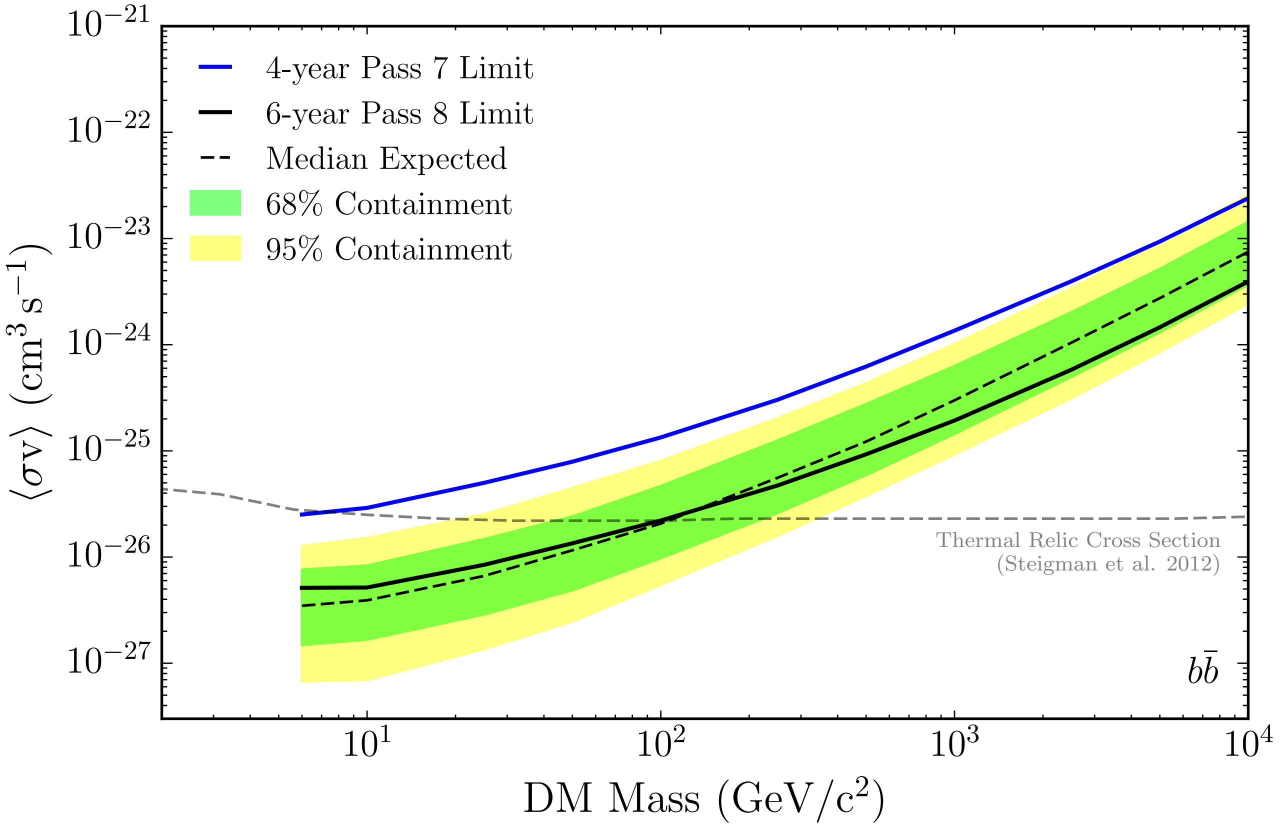
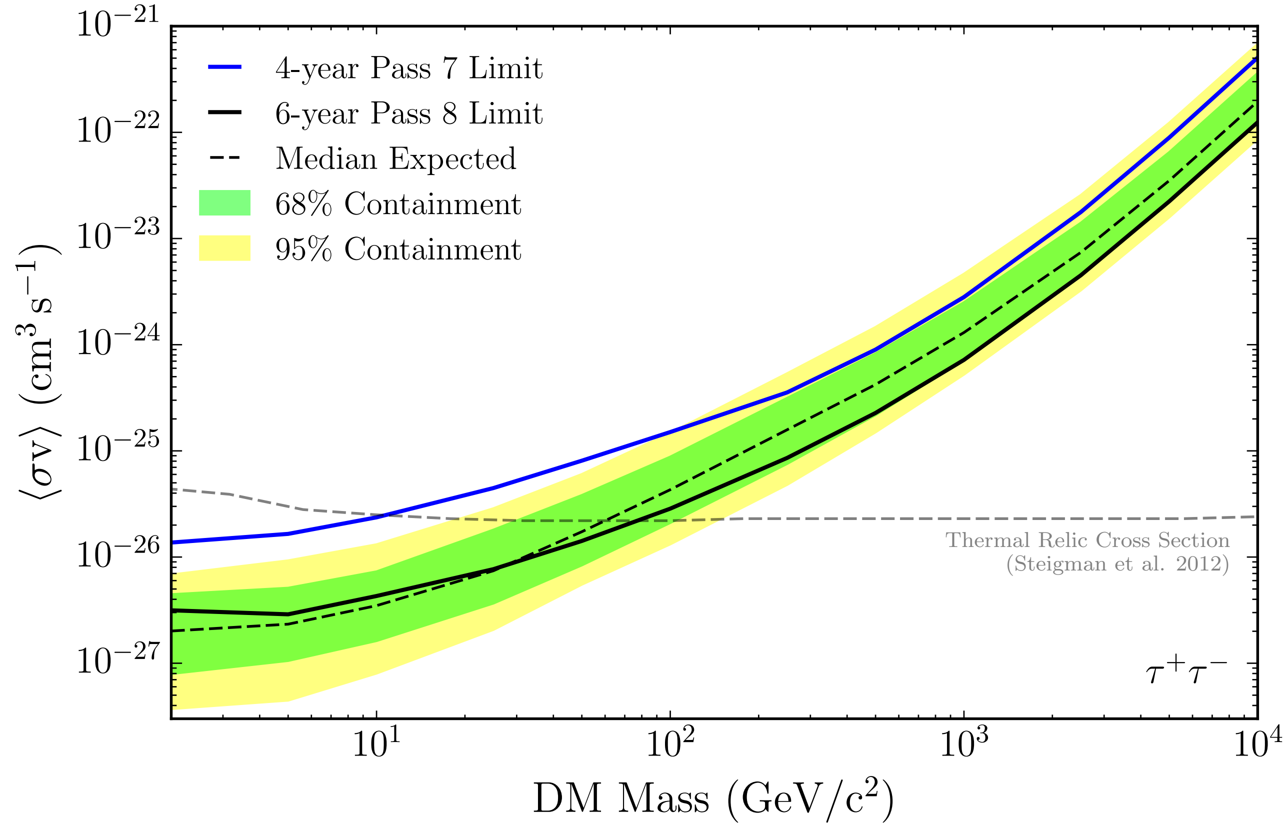
Indirect detection

Fermi 1503.02641

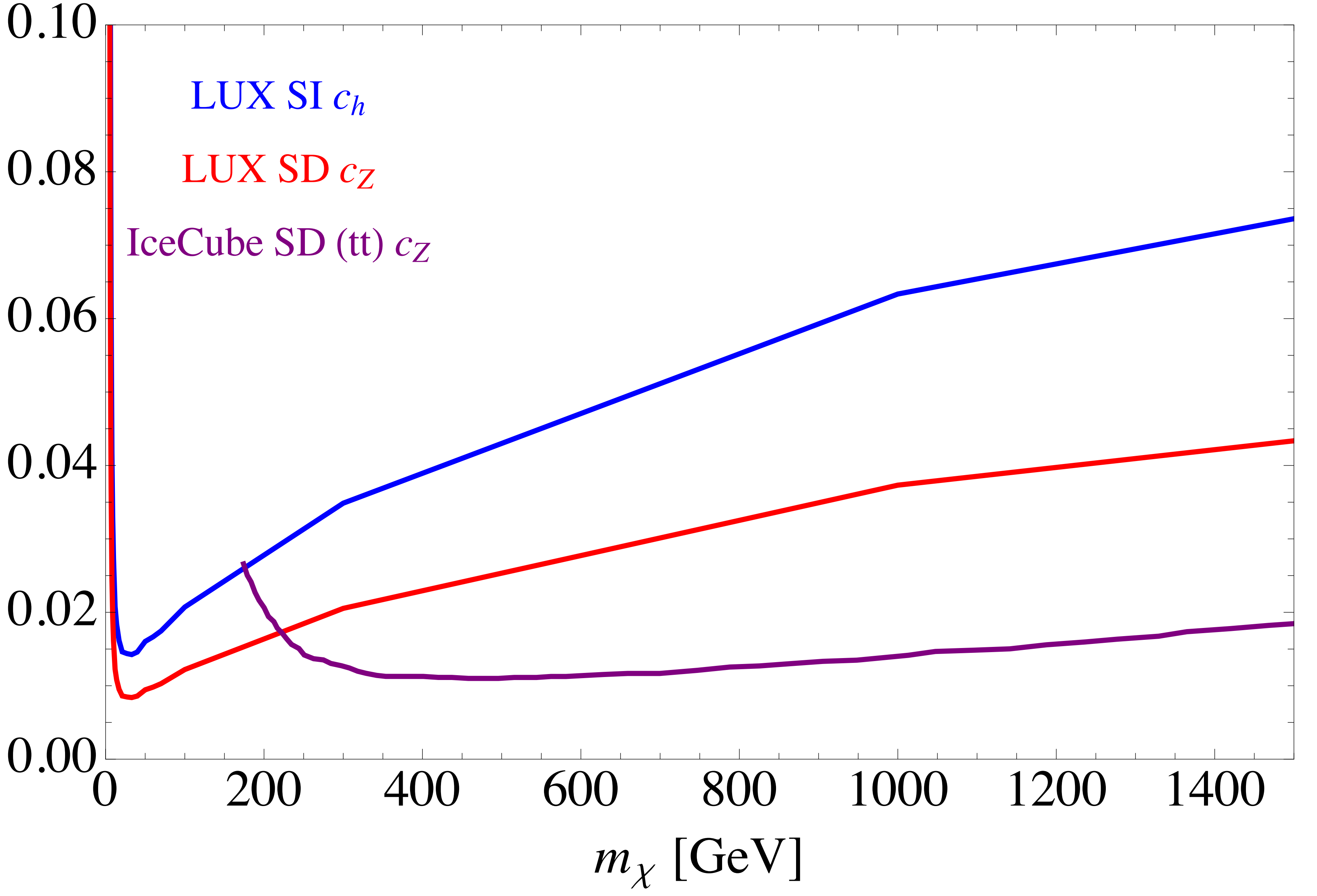




No official ttbar limits, but probably ineffective above 100 GeV...

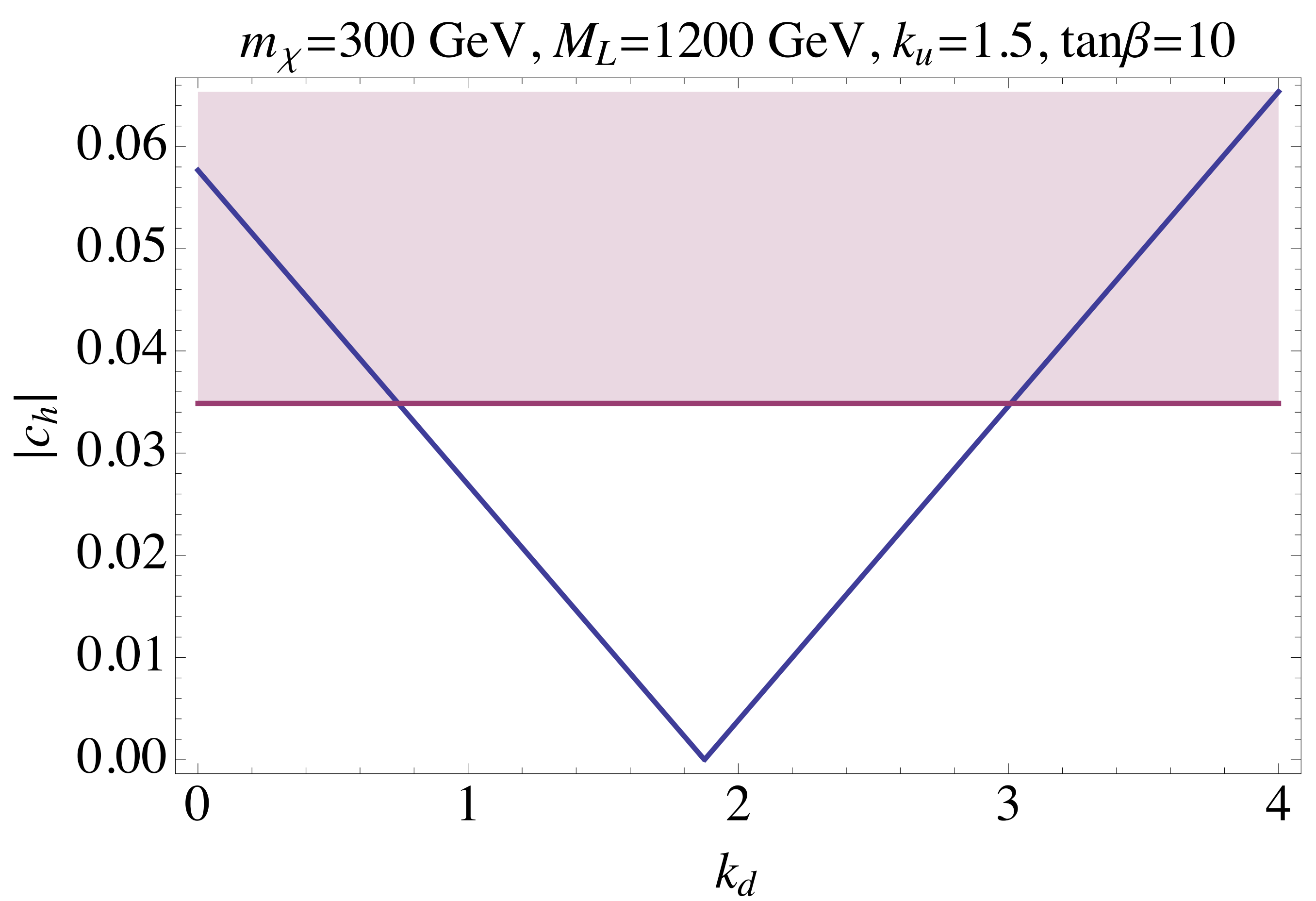
Direct Detection

Reinterpretation in terms of c_h and c_Z



Note: although SD bounds are 5 orders of magnitude weaker than SI bounds in terms of cross section, SD is slightly stronger than SI in terms of c_Z and c_h!

Blind Spot



$$c_h = \left(\frac{M_S - \frac{2 k_d M_L}{k_u \tan\beta}}{\sqrt{2} v} \right) \frac{k_u^2 v^2}{M_L^2} + \ldots$$

To satisfy LUX SI bounds, need a mild blind spot cancellation (factor of ~ 2)

Conclusions

We studied an economic extension of the MSSM that gives a 125 GeV Higgs mass with a fine-tuning as low as 10% and provides a natural thermal WIMP DM candidate.

We interpret the latest constraints from LUX and IceCube on dark matter couplings to Higgs and Z in the Standard Model.

The main annihilation channels in our model are s-wave annihilation to tt and Higgsinos.

Imposing the relic density constraint immediately implies a particular value for the SD cross-section. This value is not ruled out yet, but the next generation of DM experiments (e.g.\ Xenon1T , LZ) should completely rule out or discover this model.

Thanks for your attention!