University of Pittsburgh

The Case of Light Neutralino Dark Matter

Zhen Liu

with Tao Han and Shufang Su, to appear

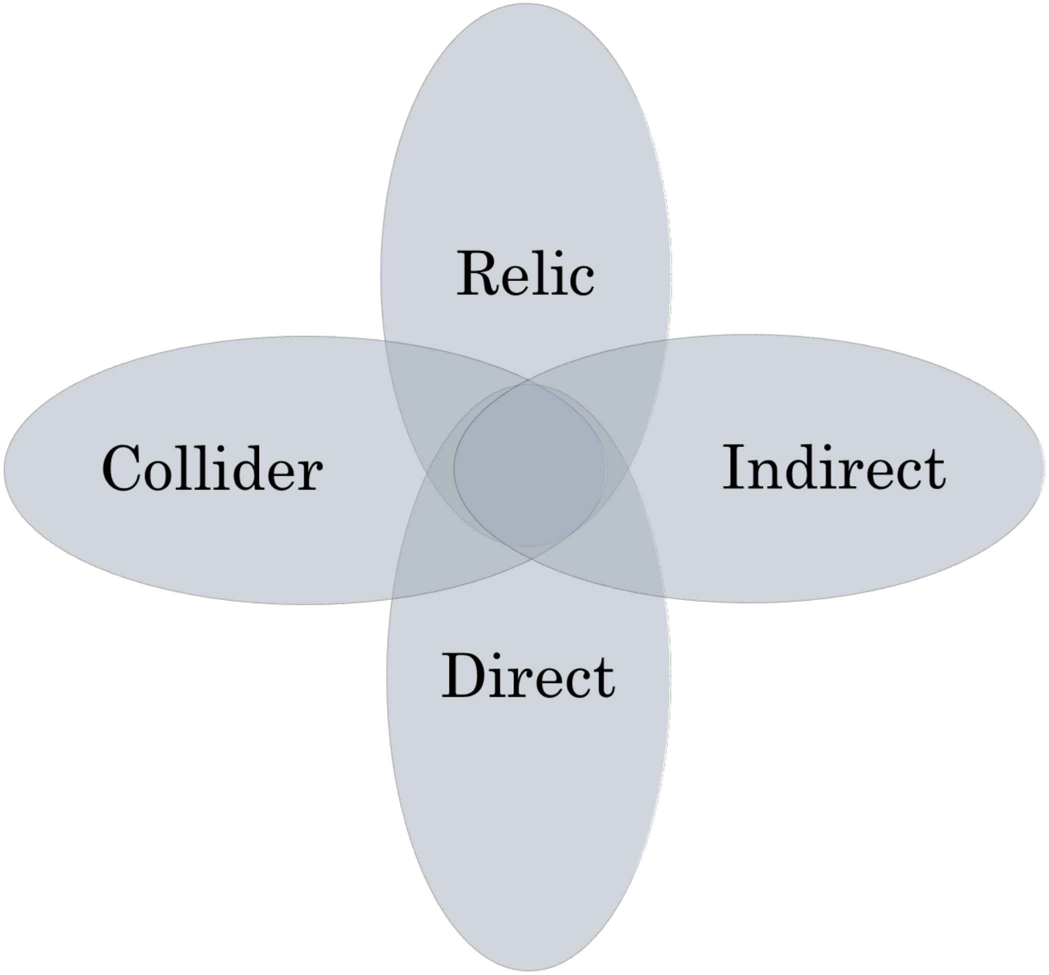
PITTPACC

PITTSBURGH PARTICLE PHYSICS ASTROPHYSICS COSMOLOGY CENTER

Motivation

Particle DM is well-motivated!

We explore DM from **ALL DIRECTIONS** with unprecedented (and growing) precision!



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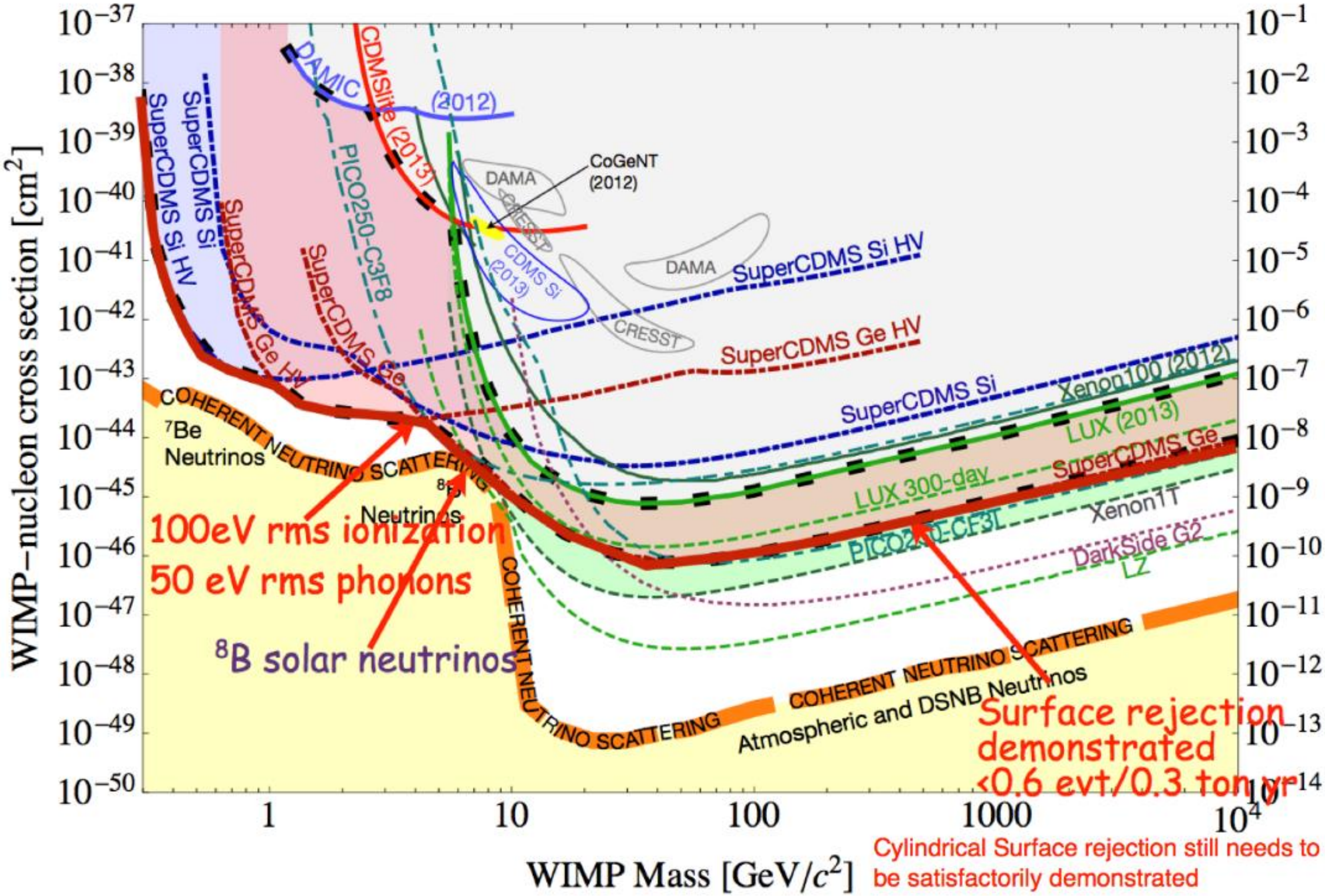
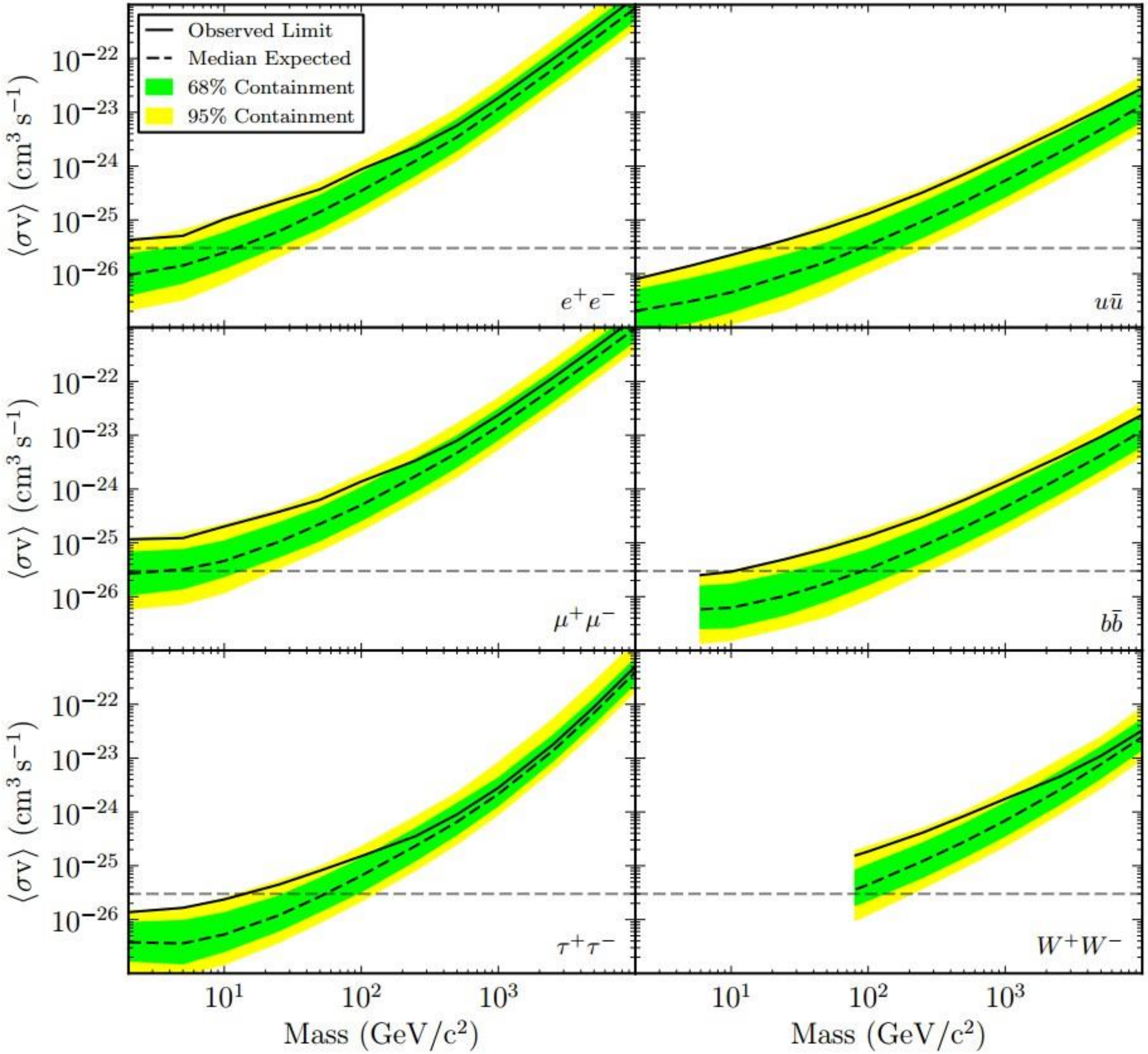


Cylindrical Surface rejection still needs to be satisfactorily demonstrated

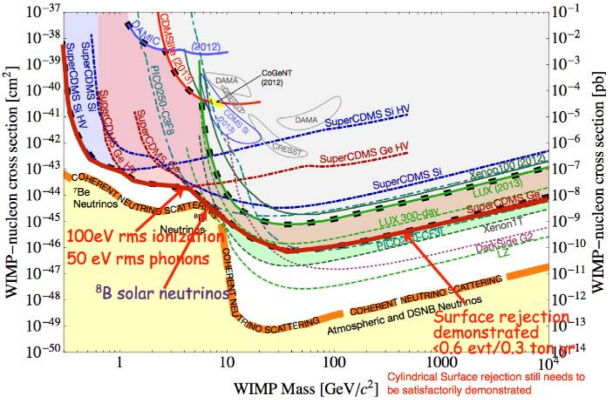
Recent results and plans of CDMS, talk by Bernard Sadoulet

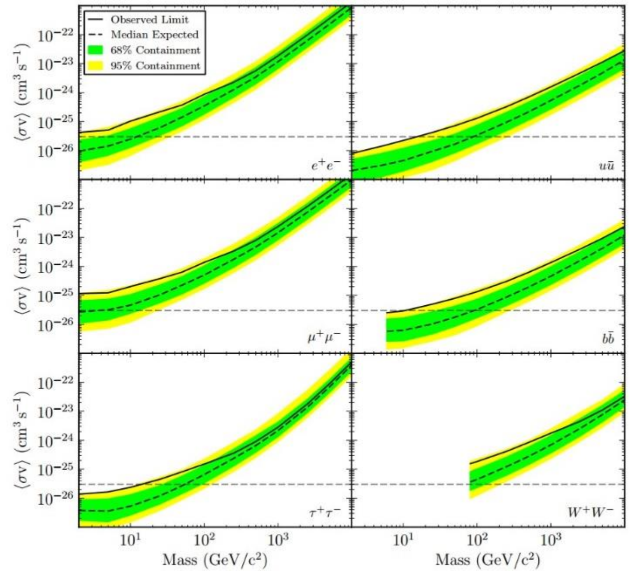
Motivation

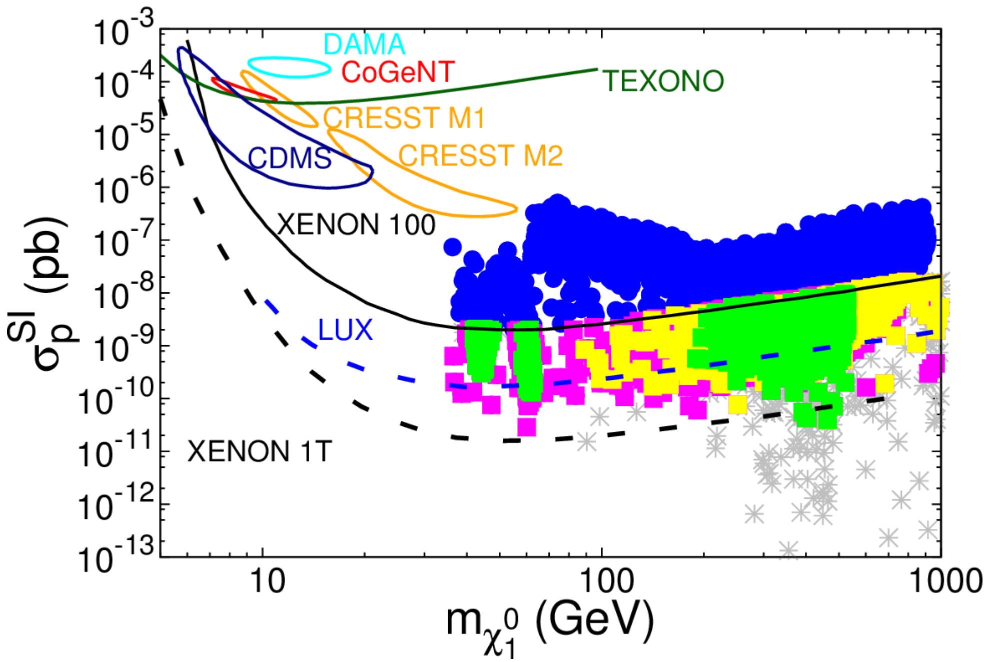


Observed Limit
Median Expected
68% Containment
95% Containment
e^+e^-
$u\bar{u}$
$\mu^+\mu^-$
$b\bar{b}$
$\tau^+\tau^-$
W^+W^-
$\langle\sigma v\rangle$ ($cm^3 s^{-1}$)
Mass (GeV/c^2)
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^1
10^2
10^3

Motivation







T.Han, ZL, A. Natarajan 1303.3040

Collider Searches from Mono-jet, photon, Z, b… mono-everything!

Collider indirect probes with model assumed, Higgs precision/Higgcision.

.

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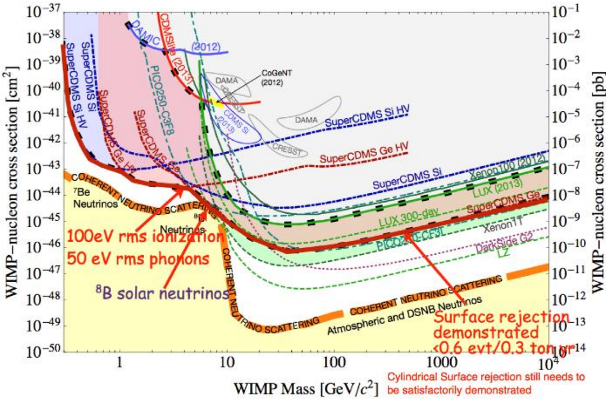

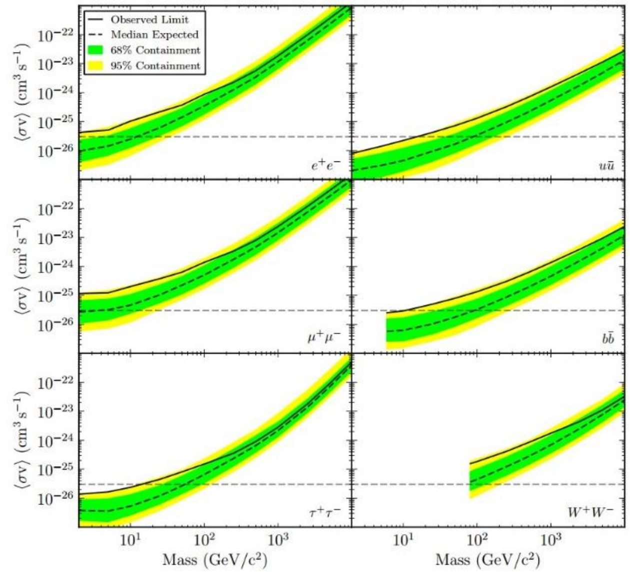

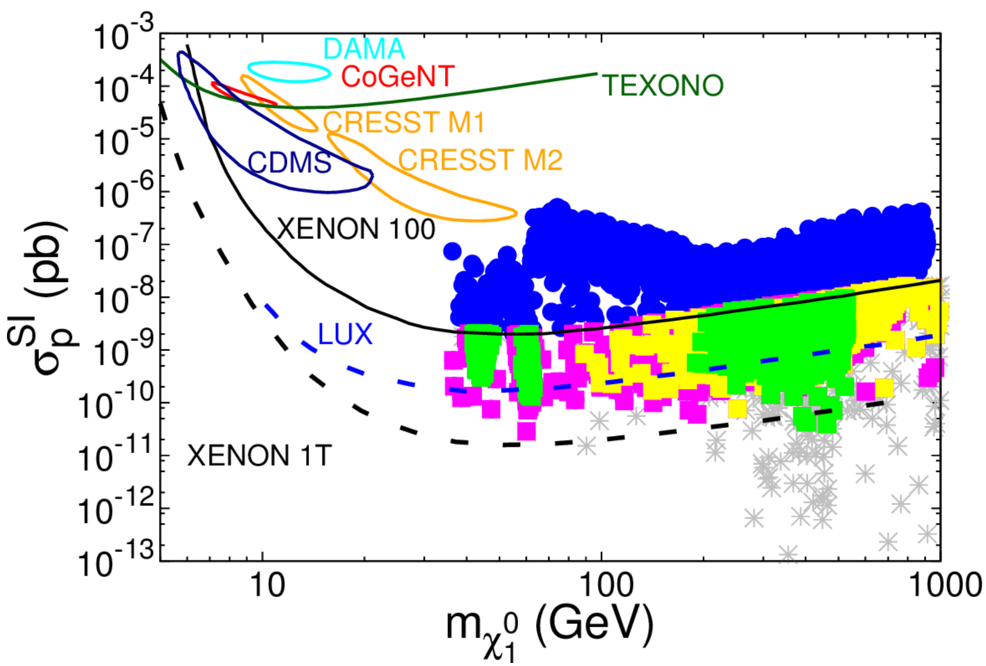

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"the most beloved" SUSY models.
highly constrained⇔ highly predictable.

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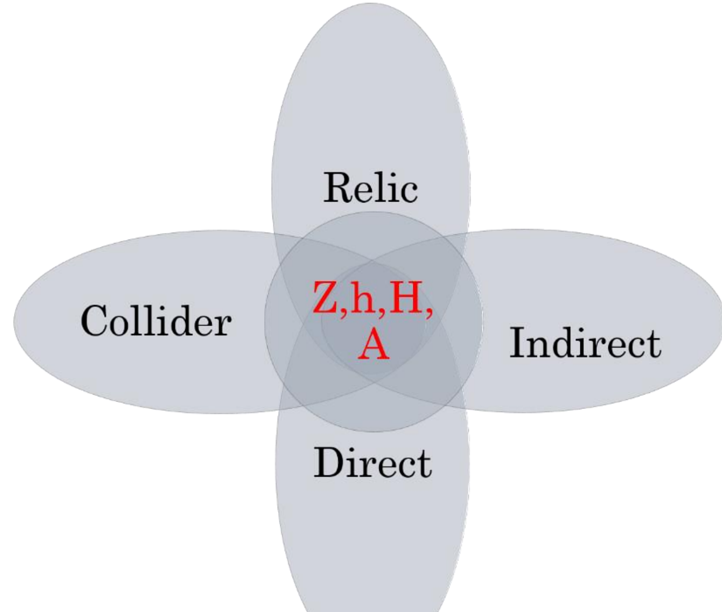

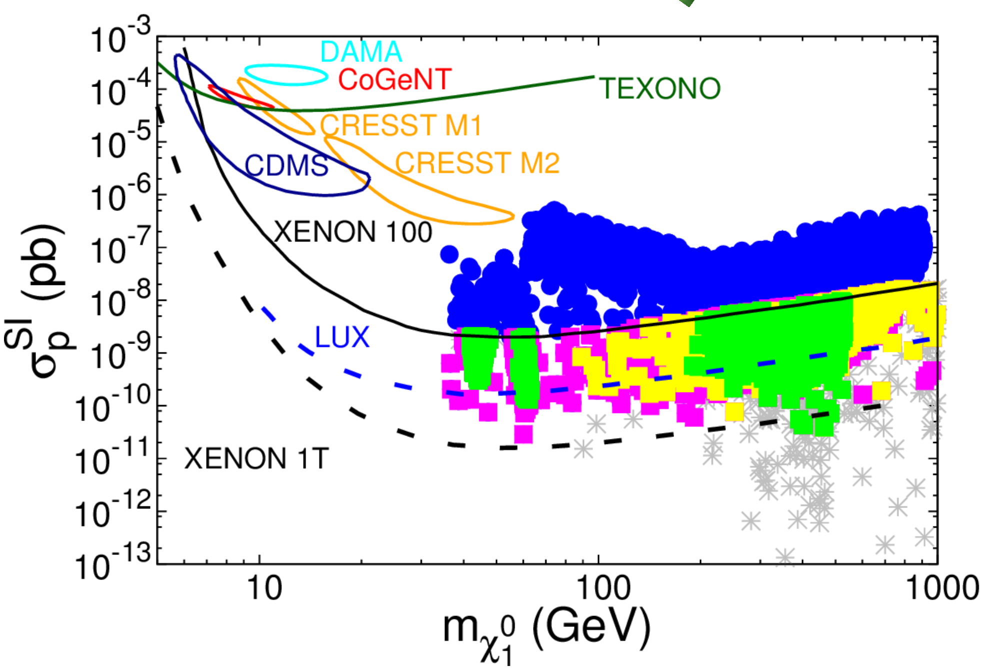

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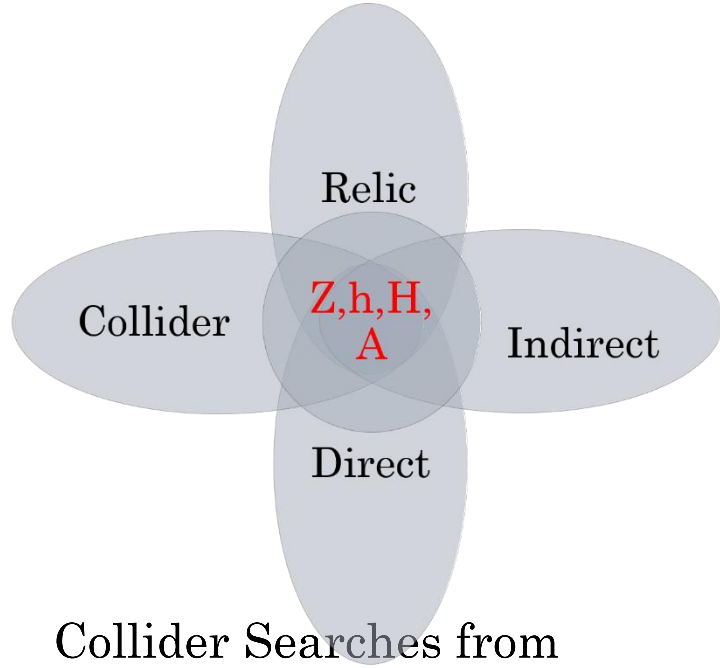

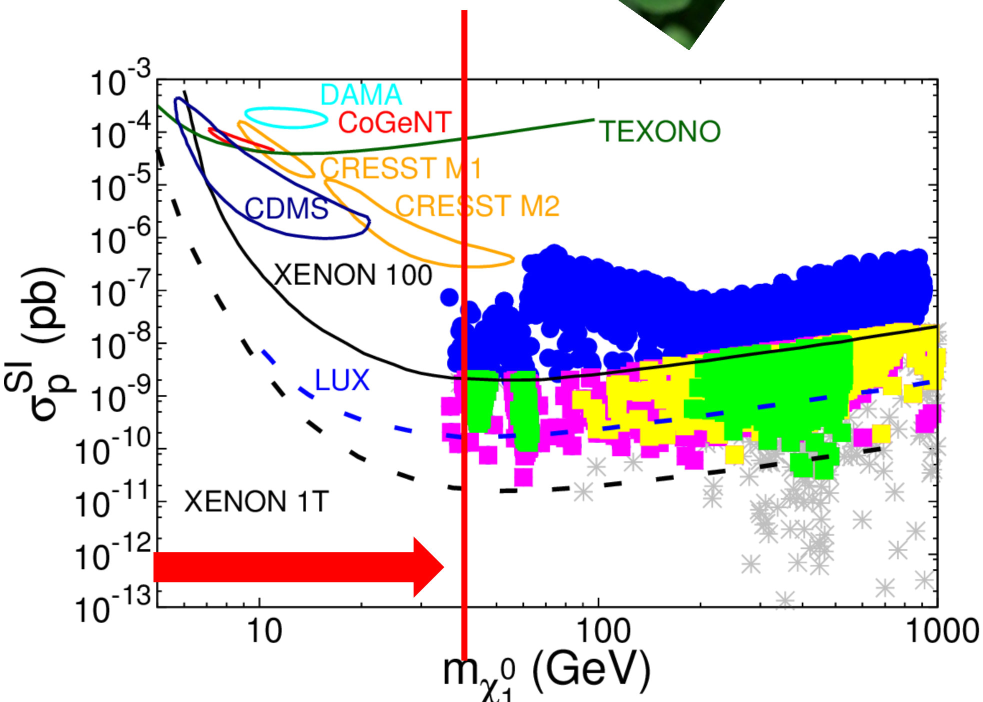

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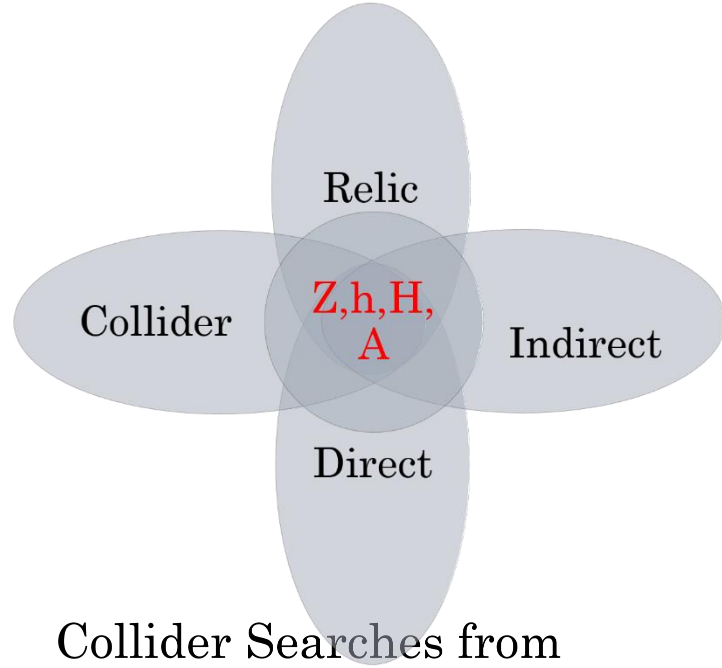

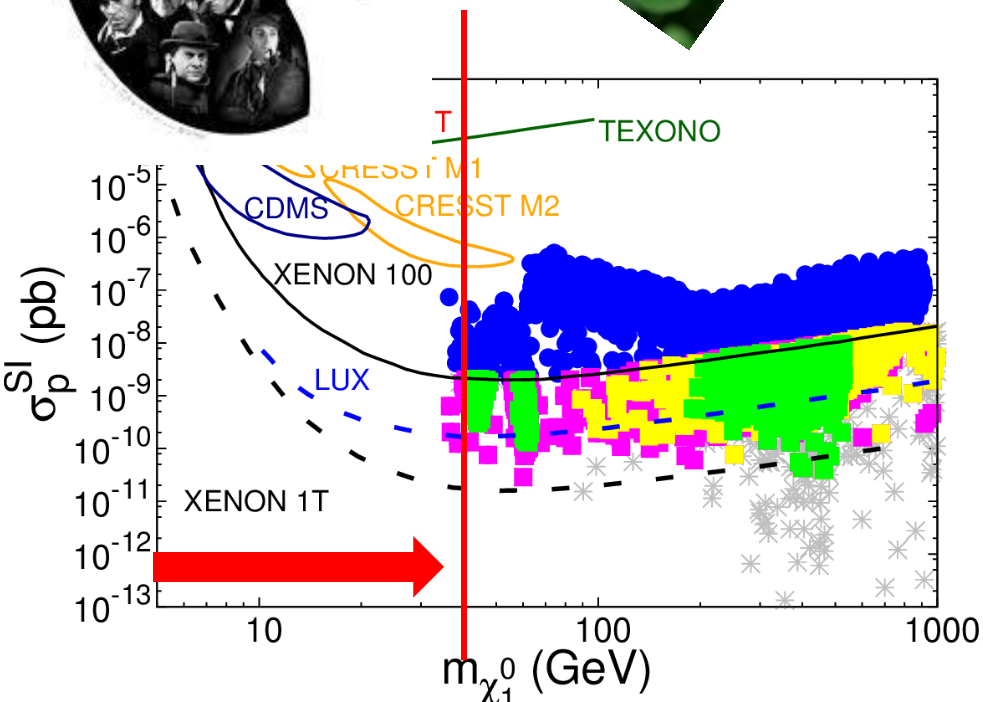

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Neutralino LSP in the NMSSM

Neutralino LSP serves as good DM candidate in R-parity conserving SUSY models

A mixture of Bino, Wino, Higgsino and Singlino

$$\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{w}^3 + N_{13}\tilde{h}_d + N_{14}\tilde{h}_u + N_{15}\tilde{S}$$

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -g_1\frac{v_d}{\sqrt{2}} & g_1\frac{v_u}{\sqrt{2}} & 0 \\ & M_2 & g_2\frac{v_d}{\sqrt{2}} & -g_2\frac{v_u}{\sqrt{2}} & 0 \\ & & 0 & -\mu & -\lambda v_u \\ & & & 0 & -\lambda v_d \\ & & & & 2\frac{\kappa}{\lambda}\mu \end{pmatrix}$$

Higgs Sector in the NMSSM

- Type II Two Higgs Doublet Model plus singlet S

$$W_{\rm NMSSM} = Y_u \bar{u} H_u Q + Y_d \bar{d} H_d Q + Y_e \bar{e} H_d L + \lambda S H_u H_d + \frac{1}{3}\kappa S^3$$

$$V_{H,Soft} = m_{H_u}^2 H_u^\dagger H_u + m_{H_d}^2 H_d^\dagger H_d + M_S^2 |S|^2 + (\lambda A_\lambda (H_t^T \epsilon H_d) S + \frac{1}{3}\kappa A_\kappa S^3 + c.c.)$$

- SSB

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \quad H_u^0 \to v_u/\sqrt{2} \qquad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}, \quad H_d^0 \to v_d/\sqrt{2} \qquad S \to v_s/\sqrt{2} \quad (\mu = \lambda v_s/\sqrt{2})$$

$$v_u^2 + v_d^2 = v^2 = (246\mathrm{GeV})^2$$

$$\tan\beta = v_u/v_d$$

after EWSB, 7 physical Higgses

CP-even Higgses: H_1, H_2, H_3

CP-odd Higgs: A_1, A_2

Charged Higgses: $H^\pm$

For discussion about Low-mass Higgs states, see our work N.Christensen, T. Han, ZL and S. Su, 1303.2113

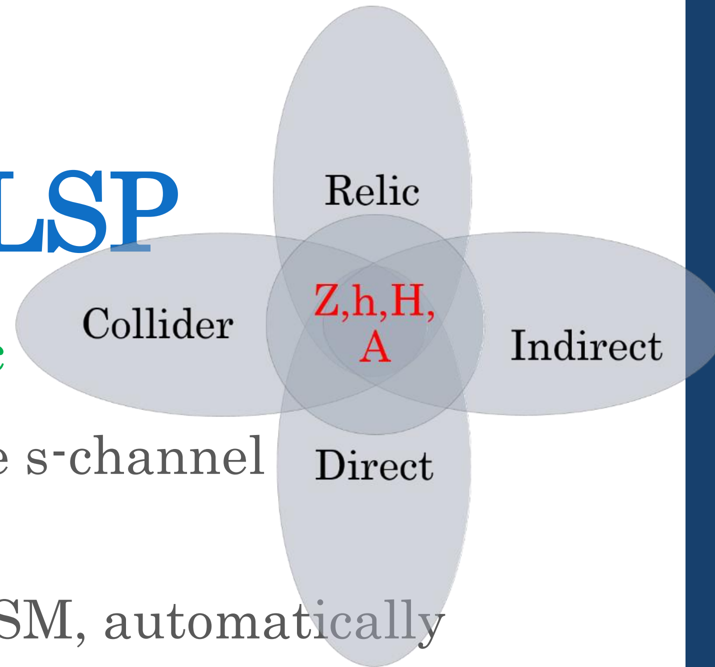
Light Neutralino LSP

Light Wino/Higgsino unlikely due to

Underabundant/No light Chargino/Direct Detection Rate High

Bino and Singlino are **pretty inert**

Light Neutralino LSP



Ways out if assuming thermal relic

Famous "Funnel" regions to hit the s-channel resonance for the mediator.

Especially near the PQ-limit NMSSM, automatically light CP-odd singlet like Higgs.

Dark Light Higgs, P.Drapper, T.Liu, C.Wagner, L-T. Wang and H.Zhang

Famous "Co-annihilation" regions to have sfermions in thermal equilibrium help LSP annihilate efficiently.

A.Arbey, M.Battaglia and F.Mahmoudi, 1205.2557

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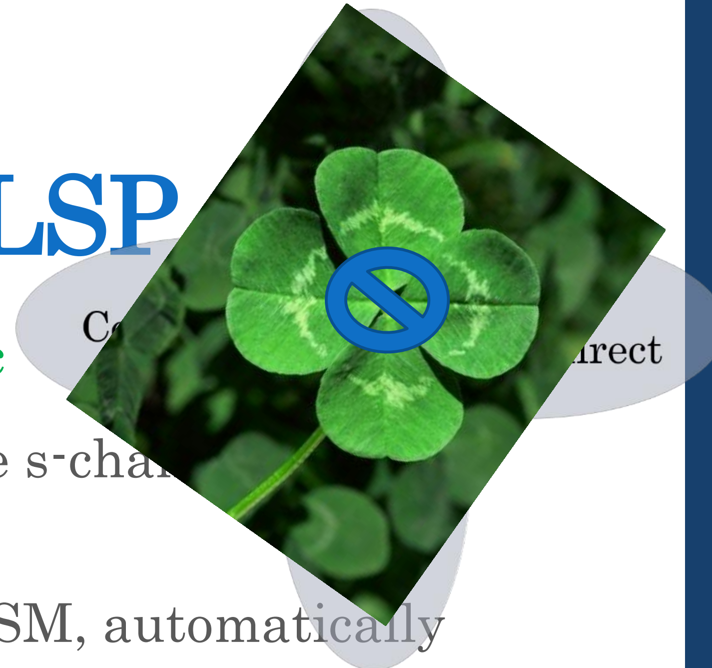

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Finding the Solutions

Using modified NMSSMTools4

Multiple way of scanning:

General

Dedicated

Seeded

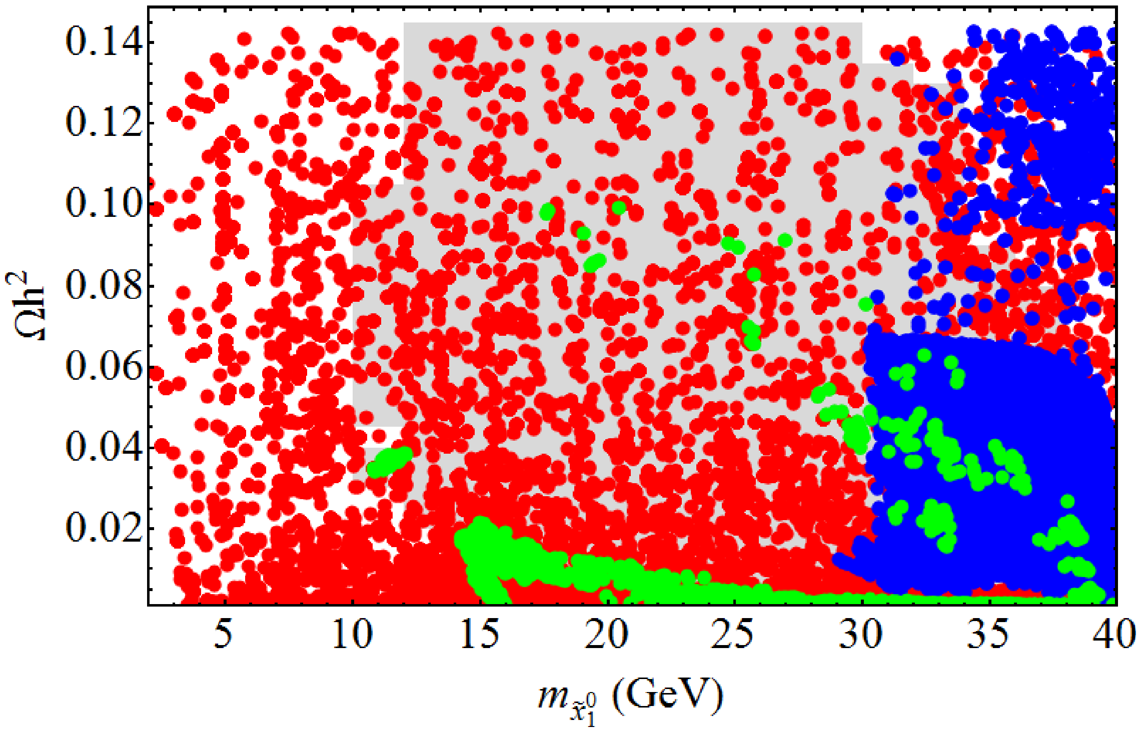
	General	Sbottom	Stau	$H_1,\ A_1$-funnel
$m_{A_{\text{tree}}}$	[0,3000]	—	—	—
$\tan\beta$	[1,55]	—	—	—
μ	[100,500]	—	—	—
$\lvert A_\kappa \rvert$	[0,1000]	—	—	—
λ	[0,1]	—	—	[0.01,0.6]
κ	[0,1]	either $\kappa \in [2,30]\lambda/(2\mu)$ or $M_1 \in [2,30]$, or both		
$\lvert M_1 \rvert$	[0,500]			
$M_{Q3},\ M_{U3}$	[0,3000]	—	—	—
$\lvert A_t \rvert$	[0,4000]	—	—	—
M_{D3}	[0,3000]	[0,80]	3000	
$\lvert A_b \rvert$	[0,4000]	—	0	
M_{L3}, M_{E3}	[0,3000]	3000	[0,500]	3000
$\lvert A_\tau \rvert$	[0,4000]	0	[0,2000]	0

Log prior used for several dedicated scans

Finding the Solutions

- Theoretical constraints such as Vacuum stability.
- Collider Higgs search limits from the LEP, the Tevatron and the LHC.
- LEP, Tevatron and LHC constrains on searches of supersymmetric particles, such as charignos, leptons and squarks;
- 2-σ window of the SM-like Higgs boson mass: $122.7 - 128.7$ GeV (including linearly added estimated theoretical uncertainties of ± 2 GeV).
- 2-σ window of the SM-like Higgs bosons cross sections for $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$ and $b\bar{b}$ different production modes.
- Z boson invisible width and hadronic width
- B-physics constrains, including $b \to s\gamma$, $B_s \to \mu^+\mu^-$, $B \to \chi_s\mu^+\mu^-$ and $B^+ \to \tau^+\nu_\tau$, as well as Δm_s, Δm_d, $m_{\eta_b(1S)}$ and $\Upsilon(1S) \to a\gamma, h\gamma$.

Relic Abundance:



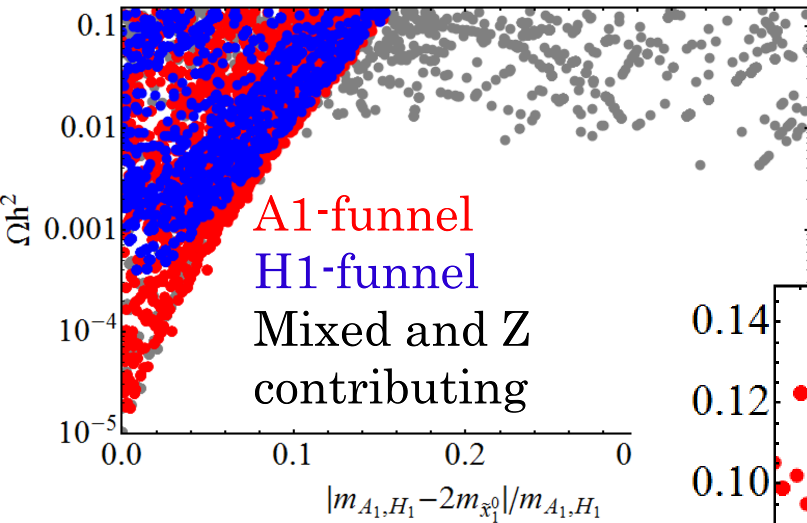
Red A1/H1-funnel

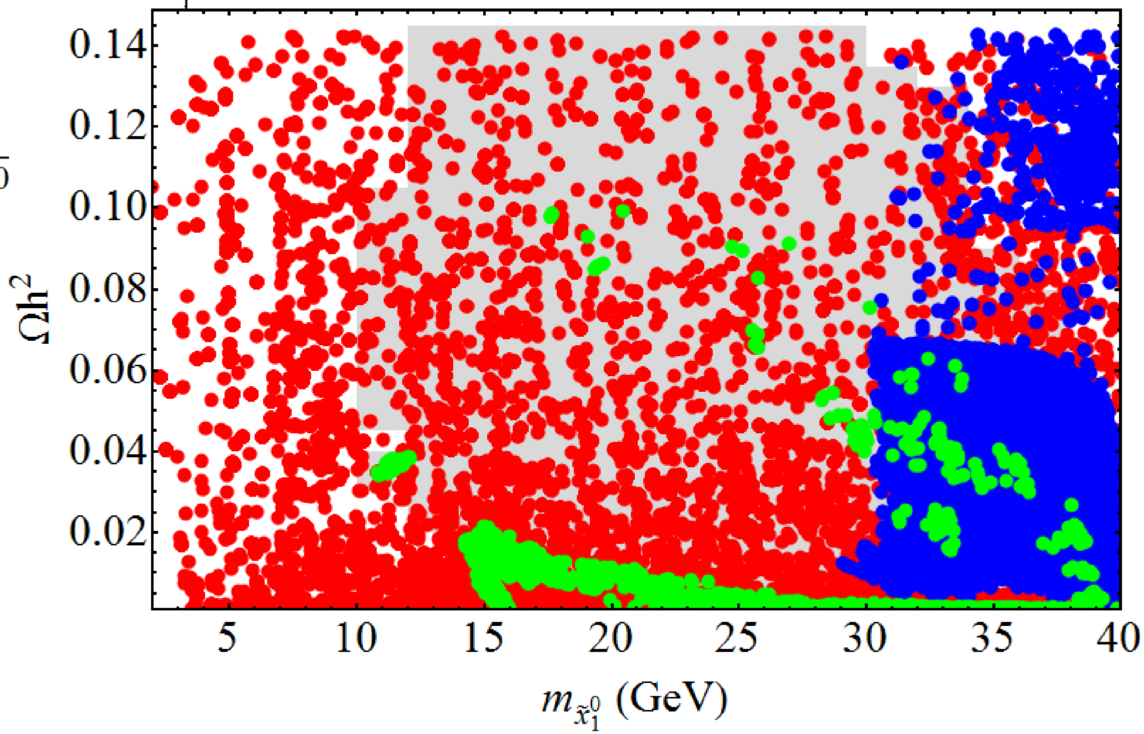
Blue Stau coannhilation

Green Sbottom coannihilation

Shaded Sbottom excluded by direct detection

Relic Abundance:





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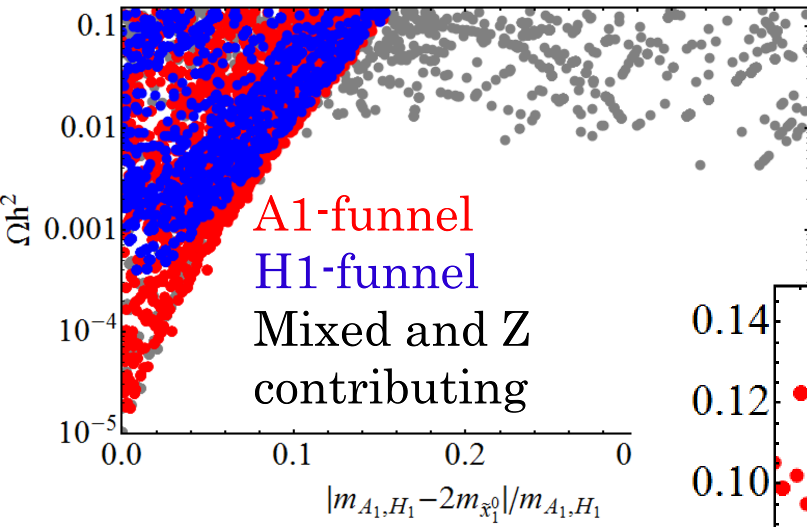
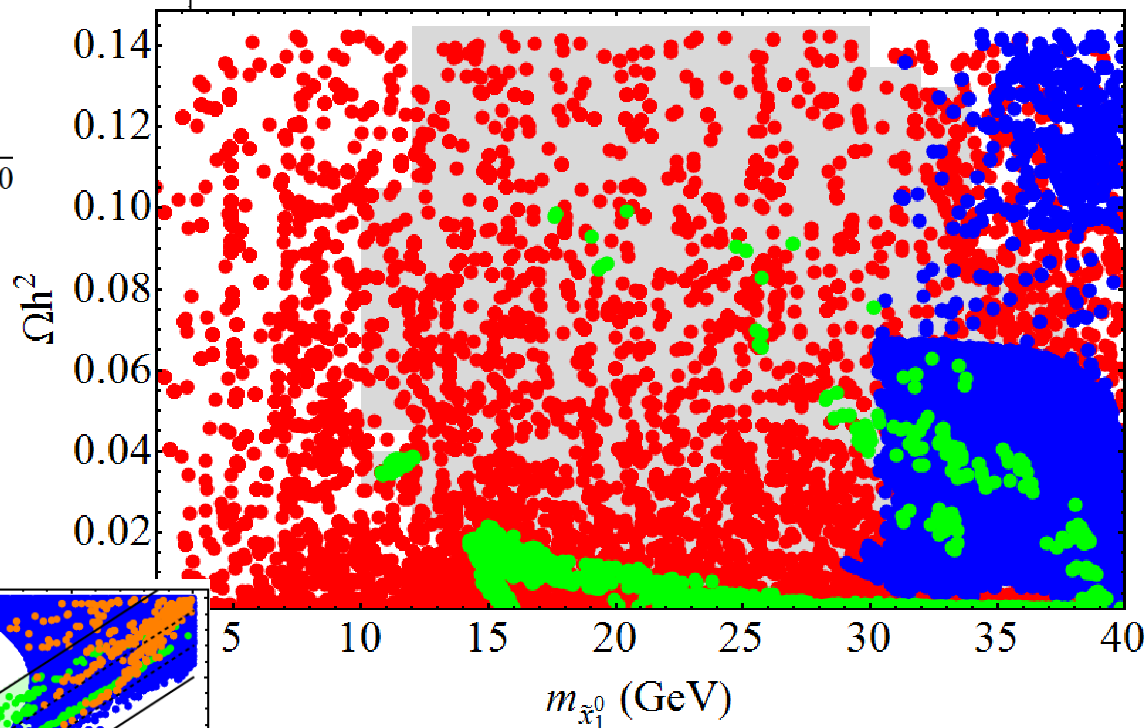
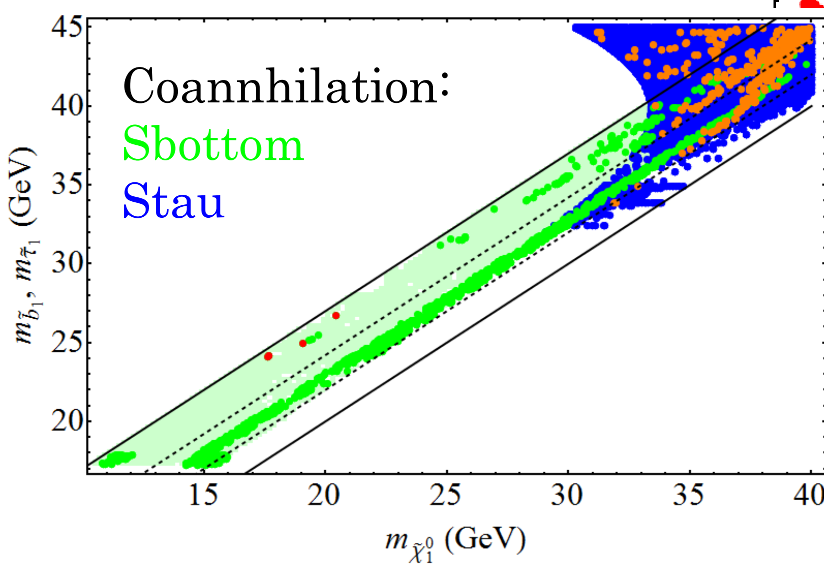
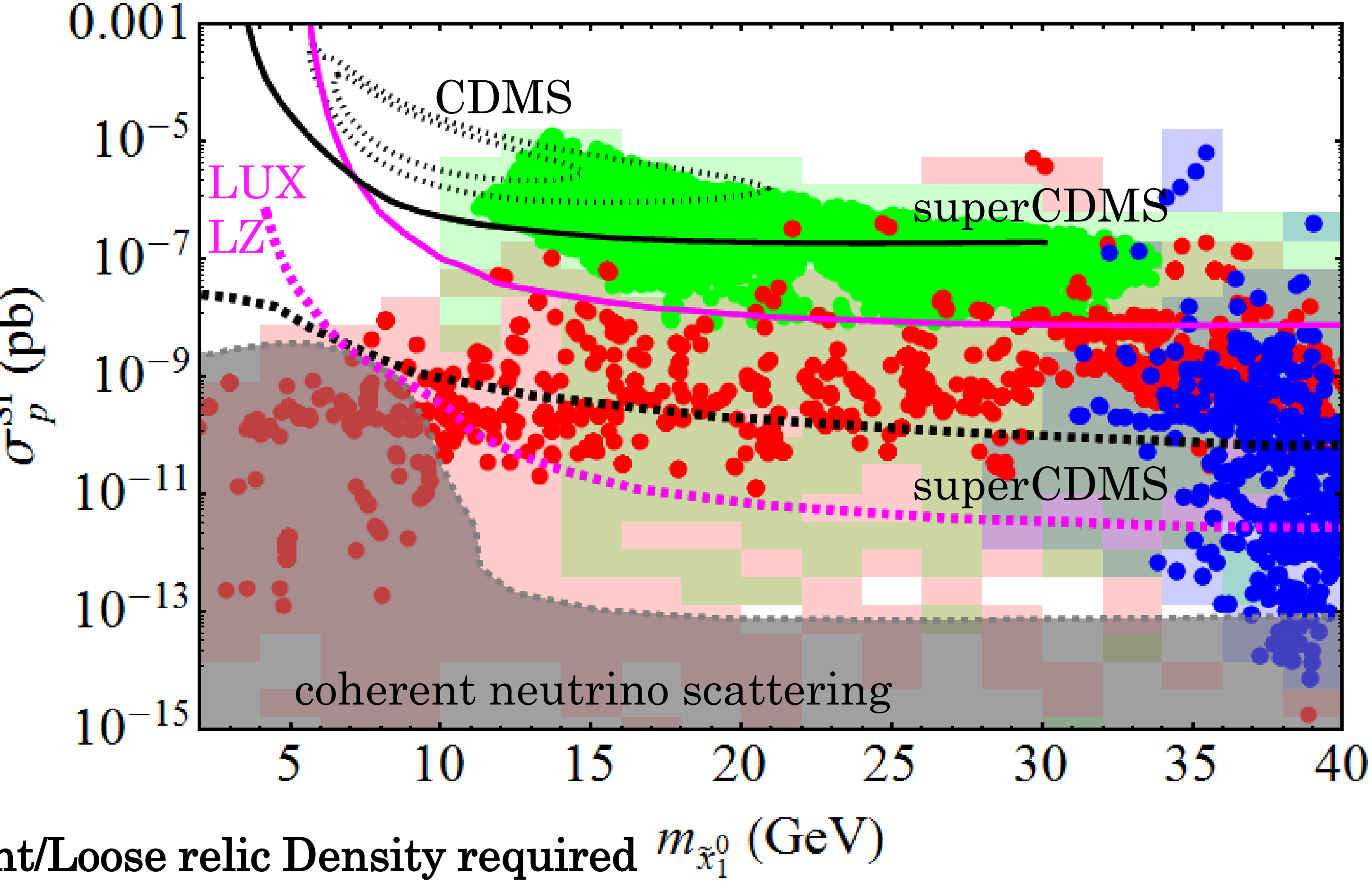






LUX/SuperCDMS imposed:
Red A1/H1-funnel
Blue Stau coannhilation
Green Sbottom coannihilation
Shaded Sbottom excluded by direct detection

Direct Detection



Tight/Loose relic Density required For Solid/Shaded

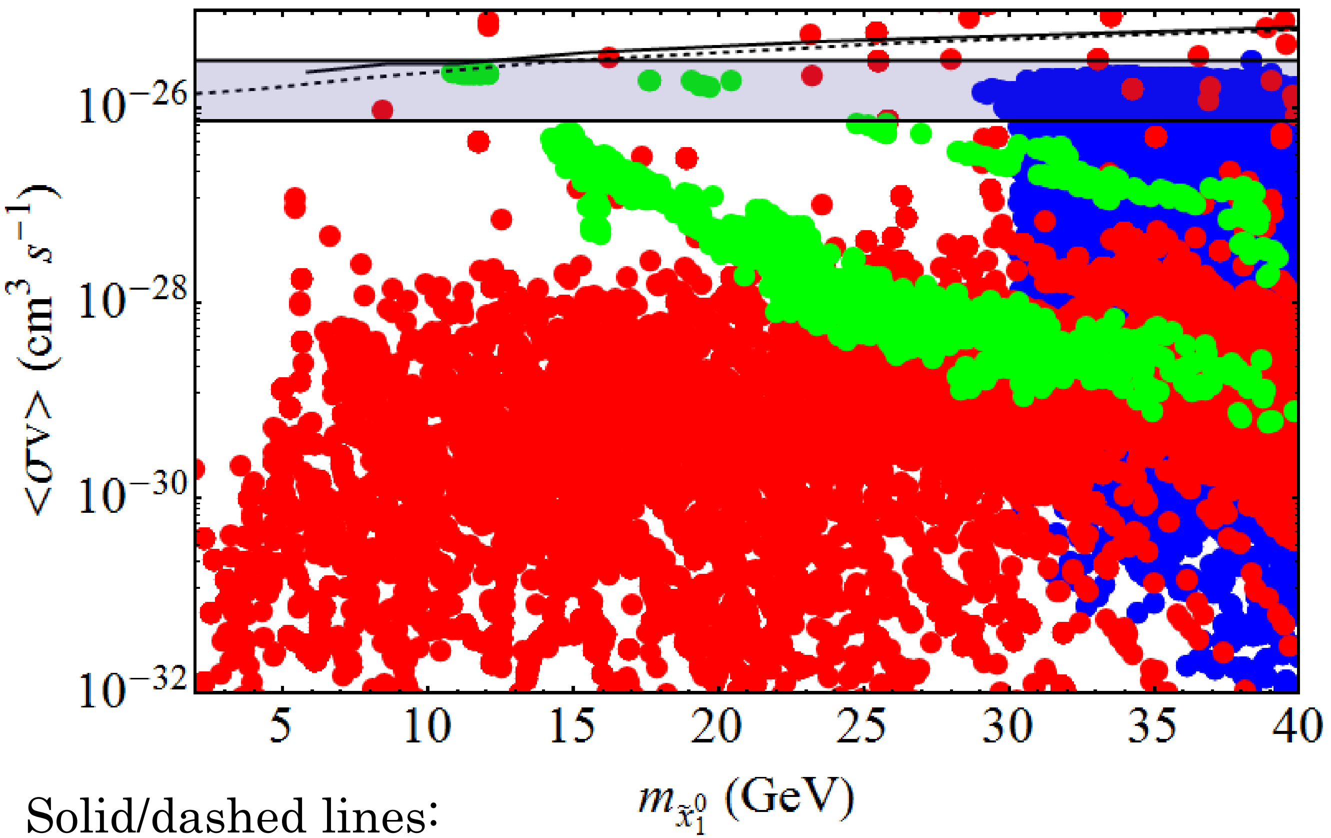
$0.0947\ (0.001) < \Omega_{\tilde{\chi}_1^0} h^2 < 0.142$

Red A1/H1-funnel

Blue Stau coannhilation

Green Sbottom coannihilation

Indirect Detection



Solid/dashed lines:

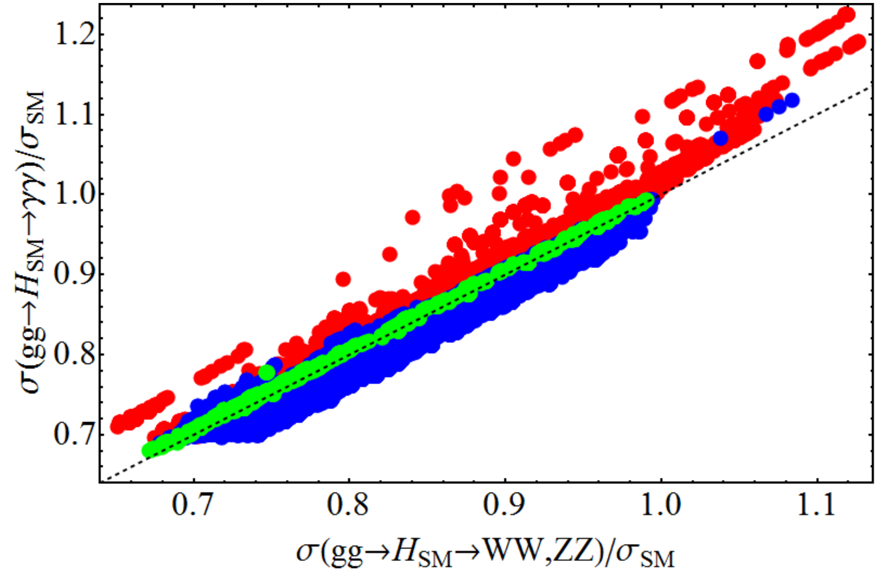
Combined Exclusion from Fermi-LAT from inner galaxy and dwarf galaxies assuming DM annihilate to bottom pair/ tau pair assuming NFW profile

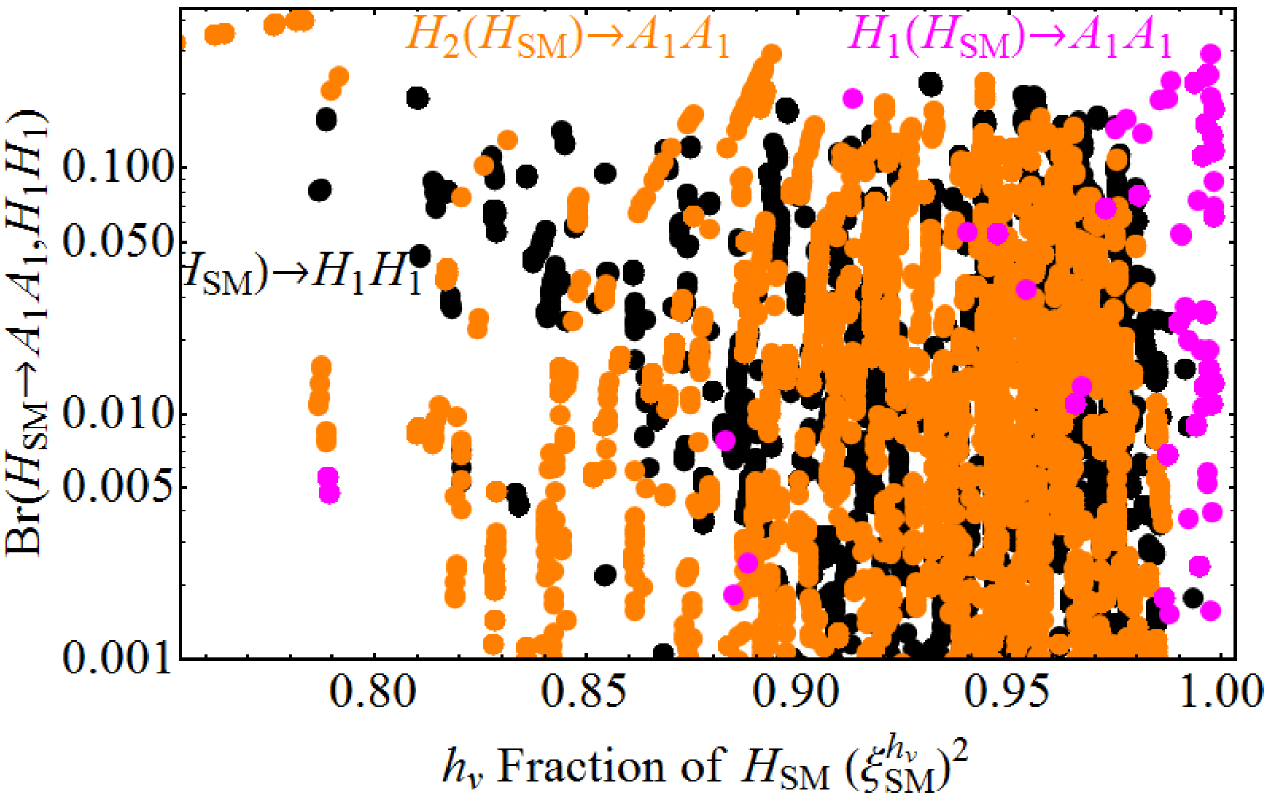
Shaded:

Best fit for GeV Gamma Ray Excess for 35 GeV DM into bb.

126 GeV Higgs Boson!

Not much Enhanced Diphoton
Stau, sbottom loop does not contribute much in our case as one expected from limits of Br of Higgs.





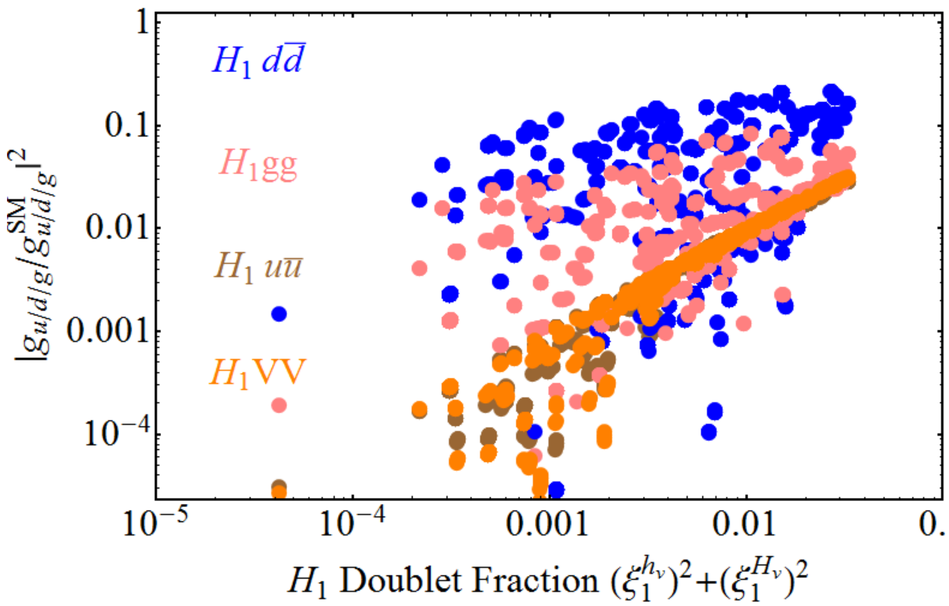
Exotic decays
Up to 30%

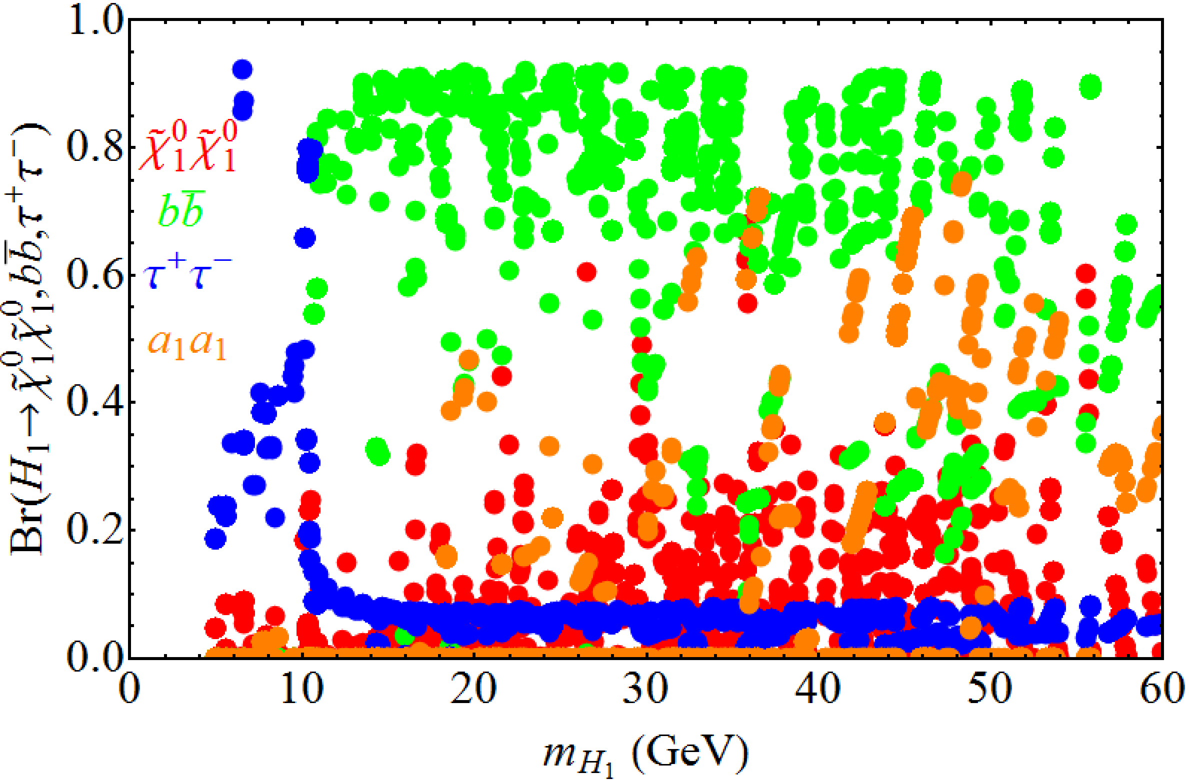
May have triggering issue.
See discussions by the Exotic Higgs Decay Working Group, 1312.4992

Example: Light h1 properties

Generally singlet-Higgs-like

<10% SM Higgs production rate for most modes for a given mass





Mainly bottom pairs tau pairs.

Decay to LSP pairs kinematically suppressed as well as required by efficient annihilation.

a1 pairs possible

Summary

We discuss

- <40 GeV neutralino DM in the NMSSM (sfermion coannihilation also viable in the MSSM)
- (Speculated) Viable Solutions found for
- a1,h1-funnel
- Stau coannhilation
- Sbottom coannhilation
- Discuss the complementarity of different DM searches; (spin-independent, spin-dependent) direct searches, indirect searches (including Gamma-ray excess)
- Relevant collider signatures discussed/proposed; see more in the paper to come

Thank You!

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Hope you enjoy Pheno 14

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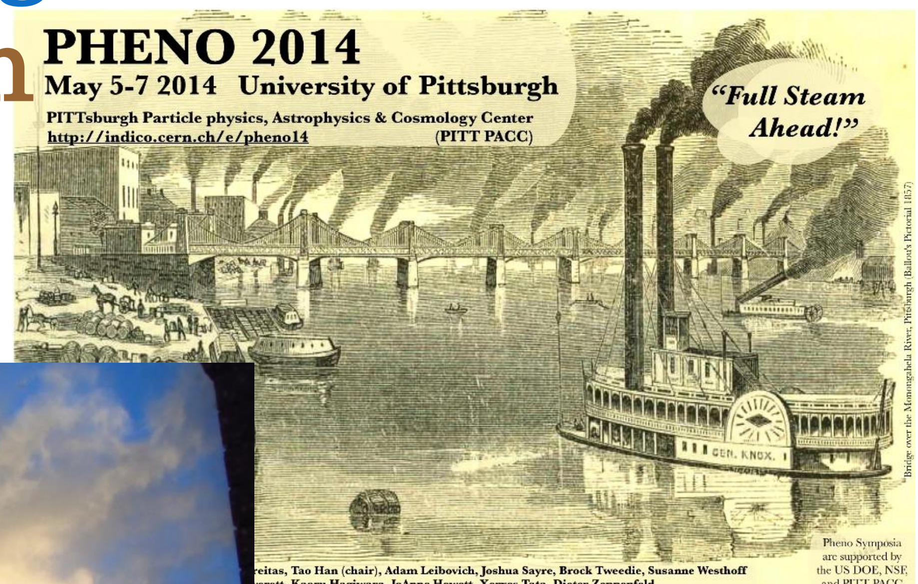


Tuning?

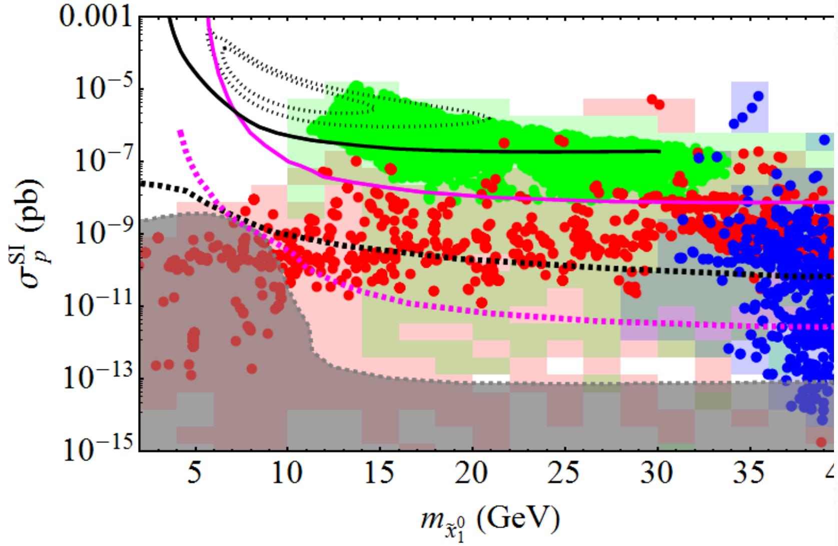
Showed up in many places

1) Resonance
2) Co-annihilation ⇔ small mass splitting
3) Z decoupling

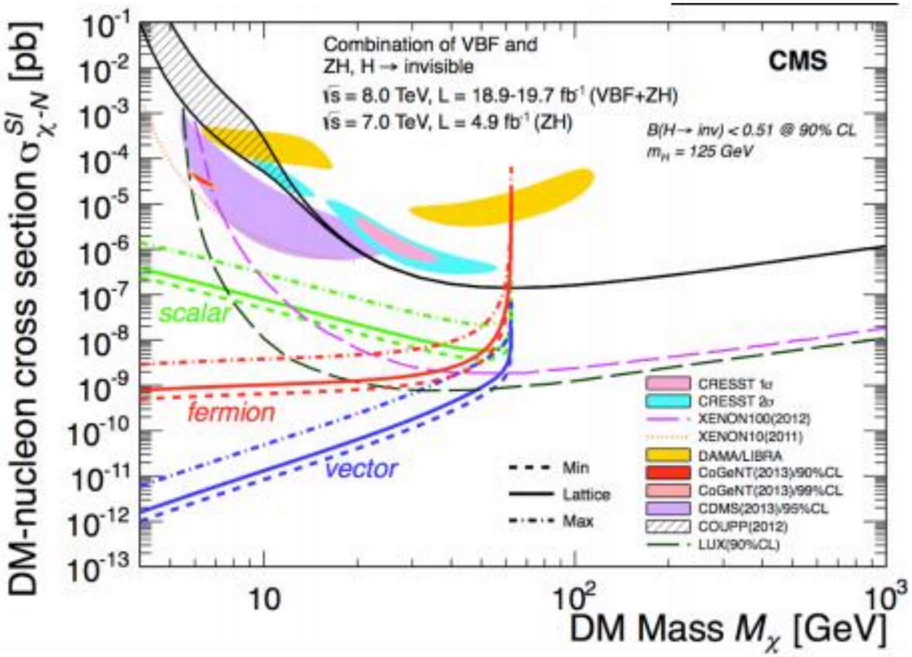
LEP Constrians from mono-photon

>81.9		95	[3]	ABDALLAH	03M	DLPH	$\Delta m > 15$ GeV, all θ_{τ}
none $m_{\tau} -$ 26.3		95	[3]	ABDALLAH	03M	DLPH	$\Delta m > m_{\tau}$, all θ_{τ}

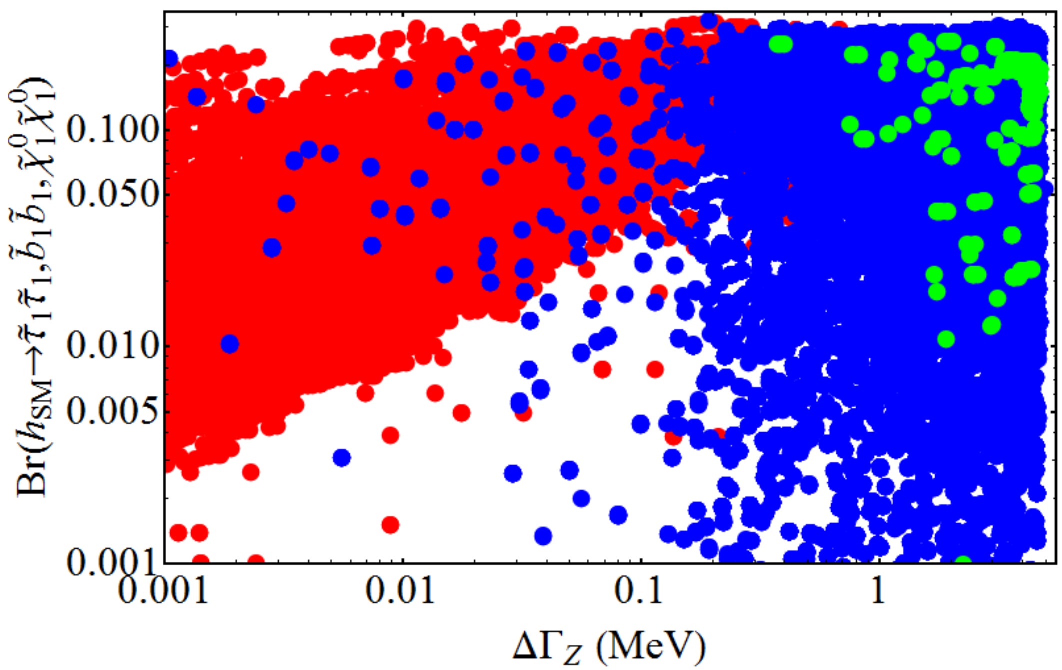
Cut		Selection: low ΔM	very low ΔM	ultra low ΔM
hadronic calorimeter energy	<	12 GeV	10 GeV	10 GeV
$E_{BGO} - E_{\gamma}$	<	10 GeV	6 GeV	1 GeV
remaining calorimetric energy	<	12 GeV	8 GeV	6 GeV
muon momentum	<	8 GeV	No muon	No muon
P_t track	<	10 GeV	4 GeV	none
transverse energy imbalance	>	0.1	0.2	0.3
longitudinal energy imbalance	<	0.85	none	none
number of tracks	<	10	7	5
number of BGO energy clusters	<	15	10	6
isolation angle of the photon	<	160°	none	none



0.001
10−5
10−7
10−9
10−11
10−13
10−15
5
10
15
20
25
30
35
σ_p^SI (pb)
m_χ̃1^0 (GeV)



Combination of VBF and
ZH, H → invisible
√s = 8.0 TeV, L = 18.9-19.7 fb−1 (VBF+ZH)
√s = 7.0 TeV, L = 4.9 fb−1 (ZH)
CMS
B(H → inv) < 0.51 @ 90% CL
m_H = 125 GeV
scalar
fermion
vector
Min
Lattice
Max
CRESST 1σ
CRESST 2σ
XENON100(2012)
XENON10(2011)
DAMA/LIBRA
CoGeNT(2013)/90%CL
CoGeNT(2013)/99%CL
CDMS(2013)/95%CL
COUPP(2012)
LUX(90%CL)
DM-nucleon cross section σ^SI_χ-N [pb]
DM Mass M_χ [GeV]
10
10^2
10^3



0.100
0.050
0.010
0.005
0.001
0.001
0.01
0.1
1
Br(h_SM → τ̃1τ̃1, b̃1b̃1, χ̃1^0χ̃1^0)
ΔΓ_Z (MeV)