Supersymmetry explanation of the Fermi Galactic Center Excess and its test at LHC Run-II

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Exploring the Dark Sector

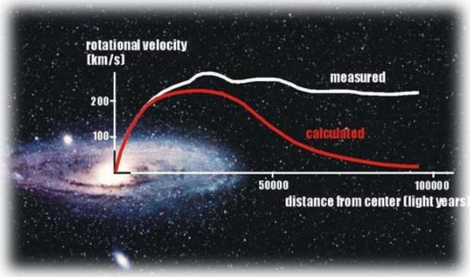
March 16-20, 2015, KIAS

based on

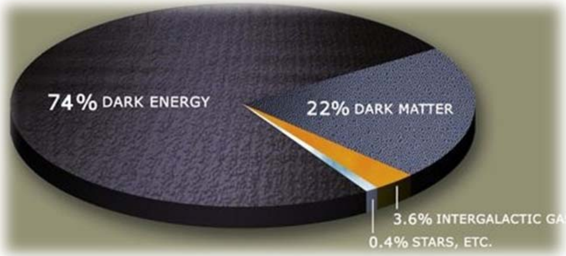
PRD 91 (2015) 5, 055005 (arXiv: 1410.3239)

Highly motivated DM studies

- evidence of DM



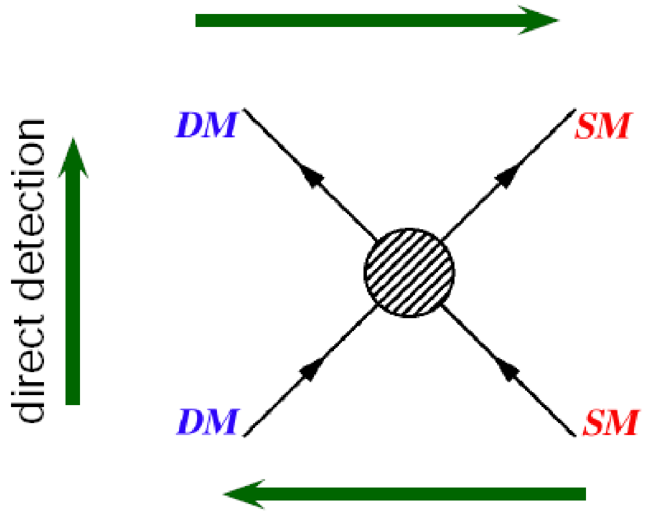
- composition of the Universe



Fermi, PAMELA, AMS…

thermal freeze-out (early Univ.)
indirect detection (now)

DAMA
CDMS
CRESST
CoGeNT
XENON
LUX

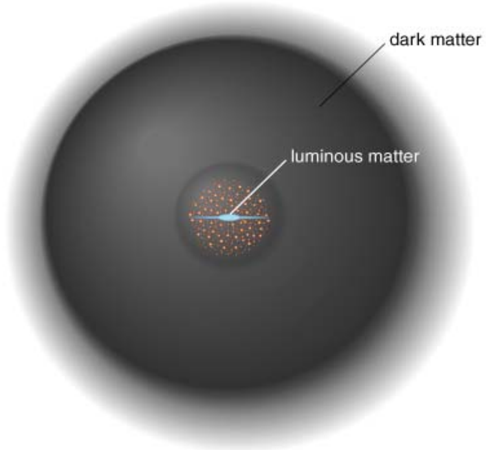


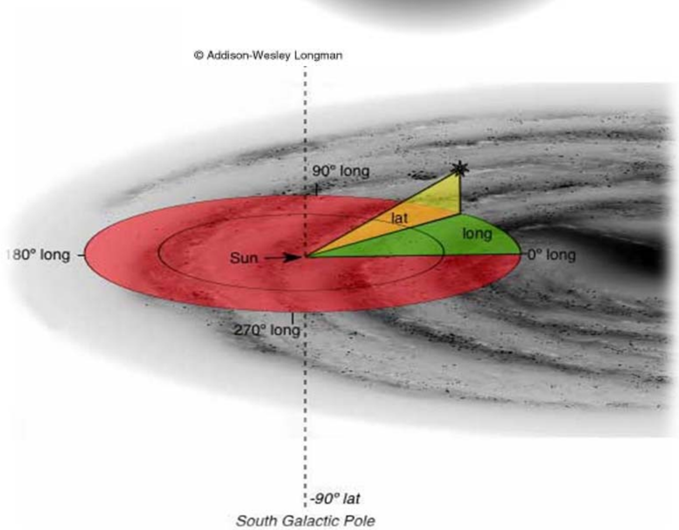
production at colliders

LEP, Tevatron, LHC…

DM indirect detections

- products of DM annihilation/decay
  - anti-proton ($\bar{p}$), positron (e^+)
  - photon (γ), neutrino (ν)…
- DM halo: spherically symmetric
  - line of sight (l.o.s)
  - half-cone angle: θ
- Galactic Disk: (b, l) coordinate system

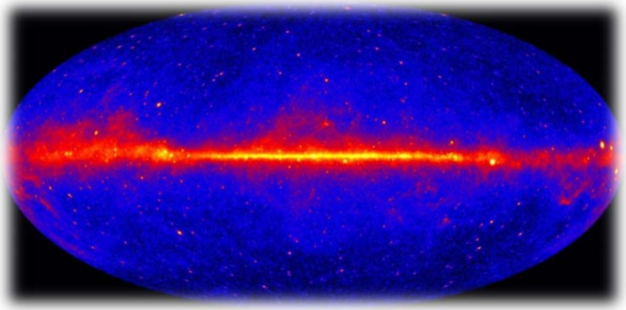




Fermi Gamma-ray Space Telescope

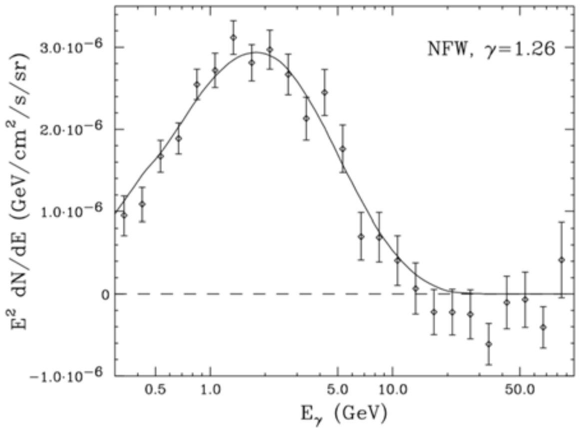
- launched in 2008
- two main instruments
  - Large Area Telescope (LAT)
  - Gamma-ray Burst Monitor (GBM)

Fermi 5 years, from Fermi website

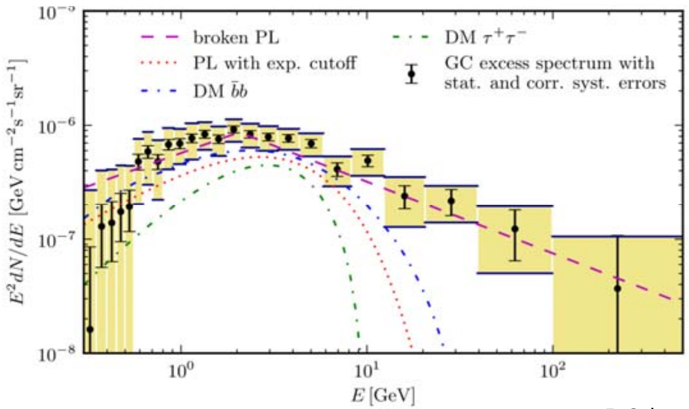


Galactic Center gamma-ray Excess (GCE)

- background subtraction:
  - point sources
  - diffuse emission
  - …
- systematic uncertainties
  - background/foreground light
  - interstellar environment
  - …



D. Hooper, 1402.6703

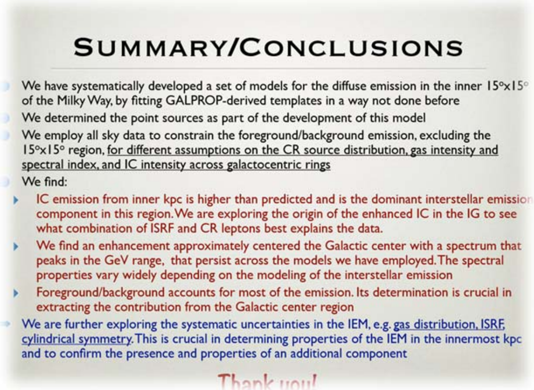


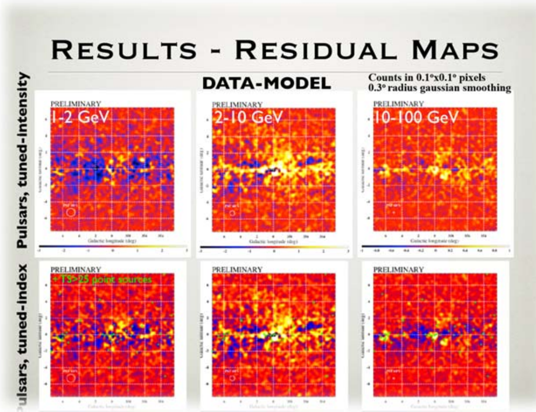
F. Calore 1409.0042

Galactic Center gamma-ray Excess (GCE)

- analysis from Fermi Group (preliminary)
  - fifth Fermi Symposium
    Nagoya, 20-24 October 2014

  - …an enhancement approximately centered the Galactic Center…
  - …depending on the modeling of the interstellar emission…





S. Murgia, *Fermi* Collaboration

Categories of Interpretation

- astrophysical
  - unresolved point sources (millisecond pulsars…)
  - (transient injected) cosmic-ray collision with interstellar gases
  - …

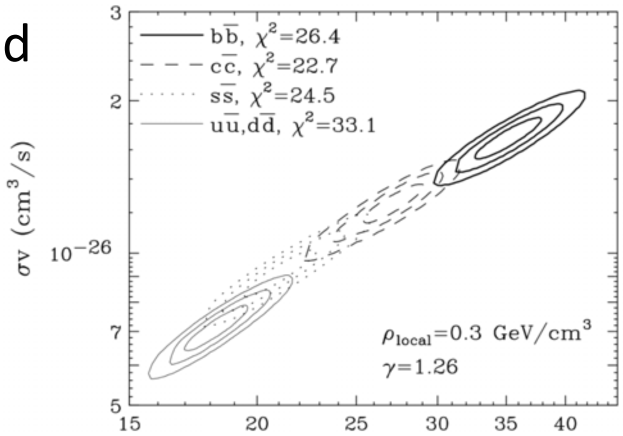
- DM annihilation
  - many DM candidates in extensions of SM
  - a variety of channels/final states

DM annihilation (Simplified model)

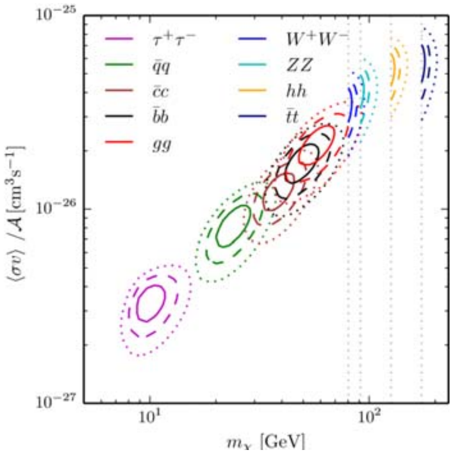
- systematic uncertainties included
  more channels available

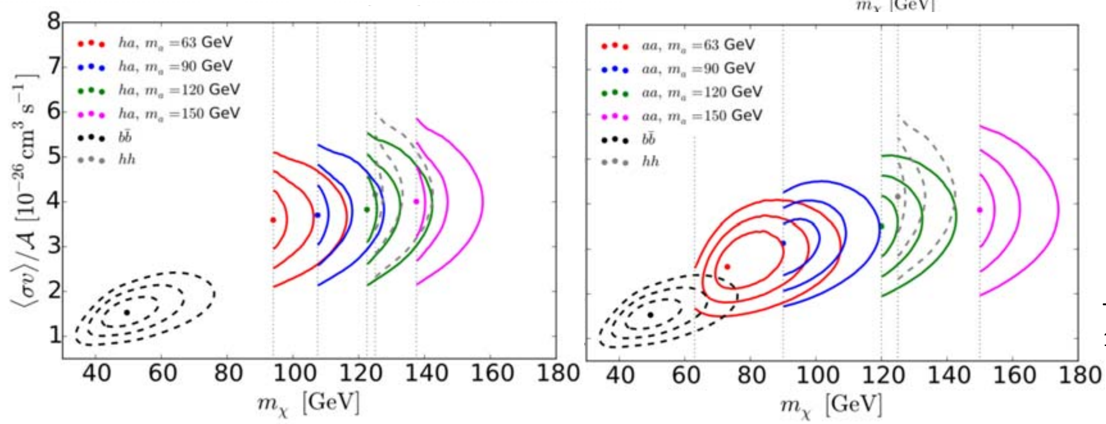
- $\mathrm{DM} + \mathrm{DM} \to$
  - $b\bar{b}, c\bar{c}, s\bar{s}, \tau^+\tau^-$, light quarks
  - W^+W^-, ZZ, hh, tt
  - ha, aa

D. Hooper, 1402.6703



F. Calore, 1411.4647





T. Gherghetta
1502.07173

DM annihilation (Simplified model)

- an example: fit to $b\bar{b}$ final states

	$m_{\rm DM}$ [GeV]	$\langle\sigma_{b\bar{b}}v\rangle_0$ $[10^{-26}\,\frac{\rm cm^3}{\rm s}]$	γ	$\rho_\odot$ $[\frac{\rm GeV}{\rm cm^3}]$	R_s [kpc]
Hooper+[5]	$\sim 40-50$	~ 0.8	1.2	0.4	20
Huang+[6]	$61.8^{+6.9}_{-4.9}$	$3.30^{+0.69}_{-0.49}$	1.2	0.4	20
Gordon+[7]	$34.1^{+4.0}_{-3.5}$	$2.47^{+0.28}_{-0.25}$	1.2	0.36	23.1
Abazajian+[8]	$39.4^{+3.7}_{-2.9} \pm 7.9$ (sys)	5.1 ± 2.4	1.1	0.3	23.1
Daylan+[9][2]	$31-40$	$0.7-3.9$	1.26	0.3	20
Calore+[10]	$49^{+6.4}_{-5.4}$	$1.76^{+0.28}_{-0.27}$	1.2	0.4	20

T. Gherghetta, 1502.07173

- obtained with *different* (background subtraction, DM halo profiles…)

An “coincidence”

- $\langle \sigma v \rangle_{FO} \sim 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$
  - required by $\Omega_{\mathrm{DM}} h^2 \sim 0.11$
- $\langle \sigma v \rangle_{GCE} \sim O(1) \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$
- $\langle \sigma v \rangle_{GCE} \sim \langle \sigma v \rangle_{FO}$
  - hint of DM existence

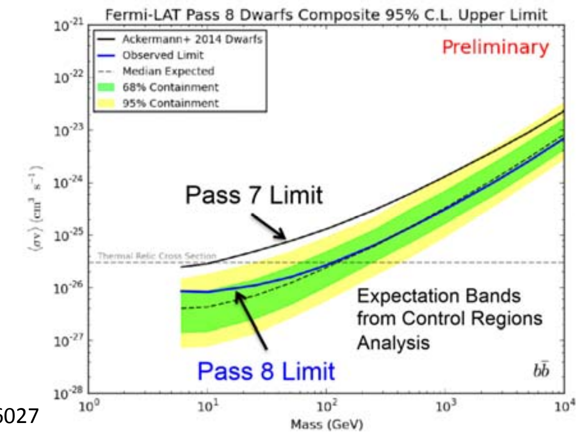
Channel	$\langle \sigma v \rangle$ (10^{-26} cm^3 s^{-1})	m_χ (GeV)	$\chi^2_{\min}$	p-value
$\bar{q}q$	$0.83^{+0.15}_{-0.13}$	$23.8^{+3.2}_{-2.6}$	26.7	0.22
$\bar{c}c$	$1.24^{+0.15}_{-0.15}$	$38.2^{+4.7}_{-3.9}$	23.6	0.37
$\bar{b}b$	$1.75^{+0.28}_{-0.26}$	$48.7^{+6.4}_{-5.2}$	23.9	0.35
$\bar{t}t$	$5.8^{+0.8}_{-0.8}$	$173.3^{+2.8}_{-0}$	43.9	0.003
gg	$2.16^{+0.35}_{-0.32}$	$57.5^{+7.5}_{-6.3}$	24.5	0.32
W^+W^-	$3.52^{+0.48}_{-0.48}$	$80.4^{+1.3}_{-0}$	36.7	0.026
ZZ	$4.12^{+0.55}_{-0.55}$	$91.2^{+1.53}_{-0}$	35.3	0.036
hh	$5.33^{+0.68}_{-0.68}$	$125.7^{+3.1}_{-0}$	29.5	0.13
$\tau^+\tau^-$	$0.337^{+0.047}_{-0.048}$	$9.96^{+1.05}_{-0.91}$	33.5	0.055
$[\mu^+\mu^-$	$1.57^{+0.23}_{-0.23}$	$5.23^{+0.22}_{-0.27}$	43.9	$0.0036]_{\text{ICS}}$

F. Calore, 1411.4647

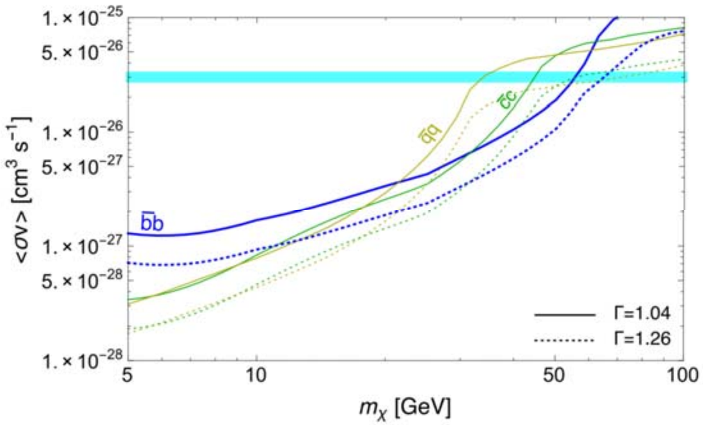
Tension with DM interpretations

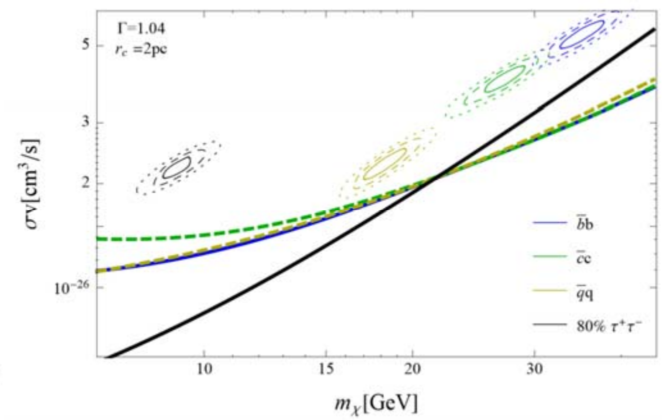
- constraints from other cosmic ray observations
  - dwarf spheroidal galaxies (γ)
  - anti-proton flux ($\bar{p}$)
  - positron flux (e^+)
  - radio signals
- relaxed by systematic uncertainties

M. Wood, Fermi Collaboration



T. Bringmann, 1406.6027





Supersymmetry framework

- solution to hierarchy problem
- unification of gauge couplings
- a suitable DM candidate

Minimal Supersymmetric SM (MSSM)

- $W_{\mathrm{MSSM}} = W_F + \mu \widehat{H}_u \cdot \widehat{H}_d$
- Higgs sector
  - CP-even: h, H
  - CP-odd: A
  - charged: $H^{\pm}$

$$H_u = \begin{pmatrix} H_u^+ \\ v_u + \frac{1}{\sqrt{2}}(H_{u,R}^0 + iH_{u,I}^0) \end{pmatrix}$$

$$H_d = \begin{pmatrix} v_d + \frac{1}{\sqrt{2}}(H_{d,R}^0 + iH_{d,I}^0) \\ H_d^- \end{pmatrix}$$

$$tan\beta = \frac{v_u}{v_d}, v = \sqrt{v_u^2 + v_d^2} \simeq 174\ \mathrm{GeV}$$

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} C_\alpha & -S_\alpha \\ S_\alpha & C_\alpha \end{pmatrix} \begin{pmatrix} H_{u,R}^0 \\ H_{d,R}^0 \end{pmatrix}$$

$$\begin{pmatrix} A \\ G \end{pmatrix} = \begin{pmatrix} C_\beta & S_\beta \\ -S_\beta & C_\beta \end{pmatrix} \begin{pmatrix} H_{u,I}^0 \\ H_{d,I}^0 \end{pmatrix}$$

$$\begin{pmatrix} H^\pm \\ G^\pm \end{pmatrix} = \begin{pmatrix} C_\beta & S_\beta \\ -S_\beta & C_\beta \end{pmatrix} \begin{pmatrix} H_u^\pm \\ H_d^\pm \end{pmatrix}$$

Minimal Supersymmetric SM (MSSM)

- neutralino sector
  - mixture among
    (bino, wino, higgsinos)
  - mass eigenstates: $\tilde{\chi}_i^0, i = 1\sim4$
  - $\tilde{\chi}_1^0$: DM candidate (χ)

$$\psi_N^T = (\tilde{B}, \widetilde{W}, \widetilde{H}_d^0, \widetilde{H}_u^0)$$

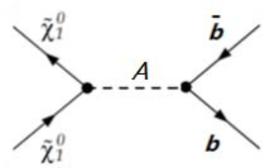
$$L_N \ni -\frac{1}{2}\psi_N^T M_N \psi_N + h.c.$$

$$\begin{pmatrix} \tilde{\chi}_1^0 \\ \tilde{\chi}_2^0 \\ \tilde{\chi}_3^0 \\ \tilde{\chi}_4^0 \end{pmatrix} = N_{4\times4} \begin{pmatrix} \tilde{B} \\ \widetilde{W} \\ \widetilde{H}_d^0 \\ \widetilde{H}_u^0 \end{pmatrix}$$

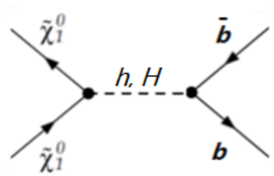
$$M_N = \begin{pmatrix} M_1 & 0 & -g_1 v_d/\sqrt{2} & g_1 v_u/\sqrt{2} \\ & M_2 & g_2 v_d/\sqrt{2} & -g_2 v_u/\sqrt{2} \\ & & 0 & -\mu \\ & & & 0 \end{pmatrix}$$

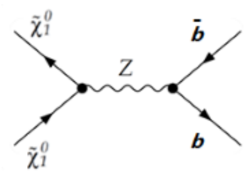
$\chi\chi \to b\bar{b}$ in MSSM

- small-$v_{\mathrm{DM,rel}}$ expansion: $\langle \sigma v \rangle \simeq a + bv^2$
  - a: s-wave
  - bv^2: p-wave ($\to 0$ when $v_{\mathrm{DM,rel}} \to 0$)

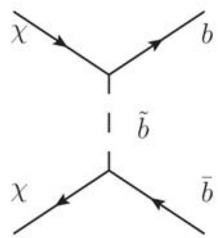


- s-channel
  - s-wave: A
  - p-wave: $h/H/Z$ ($\to 0$ when $v_{\mathrm{DM,rel}} \to 0$)



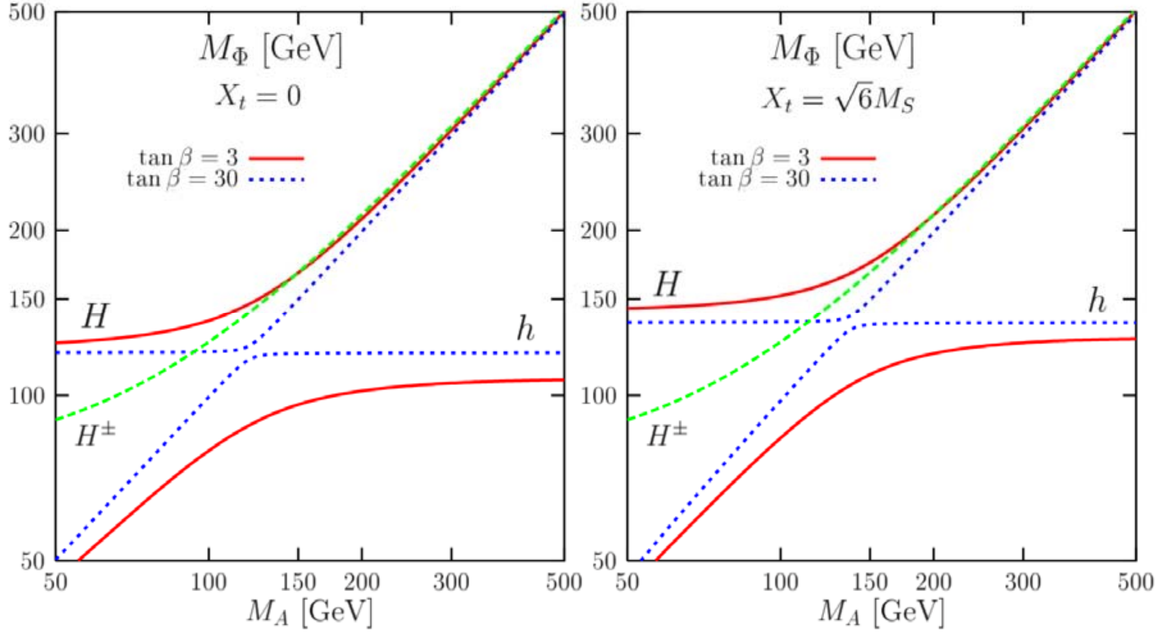


- t/u-channel
  - negligible with LHC constraints on light sbottom



Minimal Supersymmetric SM (MSSM)

- mass correlation
  - $M_A \simeq M_H \simeq M_{H^\pm}$
    for $M_A > \sim 150$ GeV
  - $M_A \sim 2m_\chi \sim 140$ GeV
    constrained by $H/A \to \mu^+\mu^-$
  - $M_H \sim 140$ GeV
    constrained by h/H mixing
  - $M_{H^\pm} \sim 140$ GeV
    constrained by $B_s \to \mu^+\mu^-$



A. Djouadi, 0503173

Next-to-MSSM (NMSSM)

- $W_{\mathrm{NMSSM}} = W_F + \lambda\, \widehat{H}_u \cdot \widehat{H}_d \hat{S} + \frac{\kappa}{3}\, \hat{S}^3$
- Higgs sector
  - CP-even: h_1, h_2, h_3
  - CP-odd: a_1, a_2
  - charged: $H^{\pm}$

$$H_u = \begin{pmatrix} H_u^+ \\ v_u + \frac{1}{\sqrt{2}}(H_{u,R}^0 + iH_{u,I}^0) \end{pmatrix}$$

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = S_{3\times 3} \begin{pmatrix} H_{u,R}^0 \\ H_{d,R}^0 \\ S_R \end{pmatrix}$$

$$H_d = \begin{pmatrix} v_d + \frac{1}{\sqrt{2}}(H_{d,R}^0 + iH_{d,I}^0) \\ H_d^- \end{pmatrix}$$

$$\begin{pmatrix} a_1 \\ a_2 \end{pmatrix} = P_{2\times 2} \begin{pmatrix} A_{\mathrm{MSSM}} \\ S_I \end{pmatrix}$$

- μ dynamically generated
  - $\mu_{eff} = \lambda\, v_s$

$$S = v_s + \frac{1}{\sqrt{2}}(S_R + iS_I)$$

$$\begin{pmatrix} H^{\pm} \\ G^{\pm} \end{pmatrix} = \begin{pmatrix} C_\beta & S_\beta \\ -S_\beta & C_\beta \end{pmatrix} \begin{pmatrix} H_u^{\pm} \\ H_d^{\pm} \end{pmatrix}$$

Next-to-MSSM (NMSSM)

- neutralino sector
  - mixture among
    (bino, wino, higgsinos, singlino)
  - mass eigenstates: $\tilde{\chi}_i^0, i = 1\sim5$
  - $\tilde{\chi}_1^0$: DM candidate (χ)

$$\begin{pmatrix} \tilde{\chi}_1^0 \\ \tilde{\chi}_2^0 \\ \tilde{\chi}_3^0 \\ \tilde{\chi}_4^0 \\ \tilde{\chi}_5^0 \end{pmatrix} = N_{5\times5} \begin{pmatrix} \tilde{B} \\ \widetilde{W} \\ \widetilde{H}_d^0 \\ \widetilde{H}_u^0 \\ \tilde{S} \end{pmatrix}$$

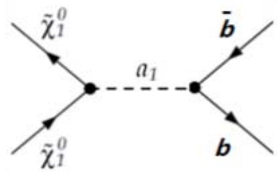
$$\psi_N^T = (\tilde{B}, \widetilde{W}, \widetilde{H}_d^0, \widetilde{H}_u^0, \tilde{S})$$

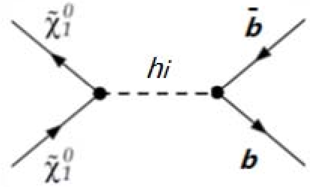
$$L_N \ni -\frac{1}{2}\psi_N^T M_N \psi_N + h.c.$$

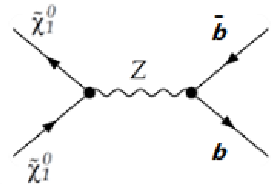
$$M_N = \begin{pmatrix} M_1 & 0 & -\frac{g_1 v_d}{\sqrt{2}} & \frac{g_1 v_u}{\sqrt{2}} & 0 \\ & M_2 & \frac{g_2 v_d}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} & 0 \\ & & 0 & -\mu & -\lambda v_u \\ & & & 0 & -\lambda v_d \\ & & & & \frac{2\kappa}{\lambda}\mu \end{pmatrix}$$

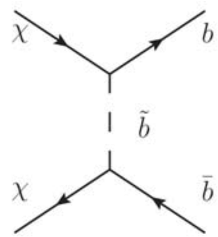
$\chi\chi \to b\bar{b}$ in NMSSM

- with singlet component, $a_1 \simeq 2m_\chi$ can exist to explain GCE
- s-channel
  - s-wave: a_i-mediated
  - p-wave: h_i/Z-mediated ($\to$ when $v_{\mathrm{DM,rel}} \to 0$)
- t/u-channel
  - negligible with LHC constraints on light squark



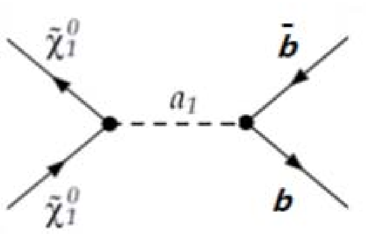






Simplified picture

- early:



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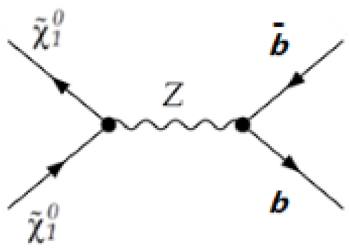
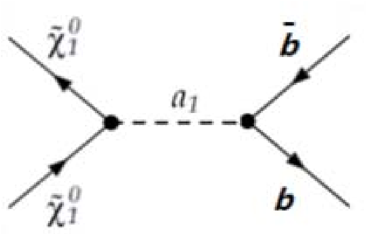


(in unit of $10^{-26}\mathrm{cm}^3/\mathrm{s}$)

$= \langle \sigma v \rangle_{\mathrm{FO}} \simeq 3.0$

- today:



(resonance enhancement)

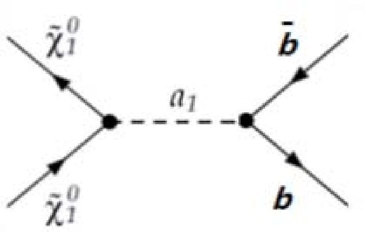
+ ($\rightarrow 0$ when $v_{\mathrm{DM,rel}} \rightarrow 0$)

$= \langle \sigma v \rangle_{\mathrm{GCE}} \simeq (0.4\sim1.3)$

(dwarf constraints considered)

Simplified picture

- early:



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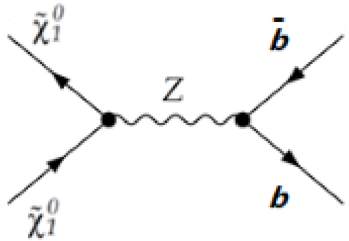
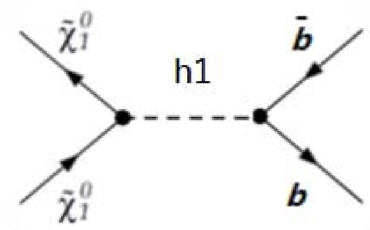
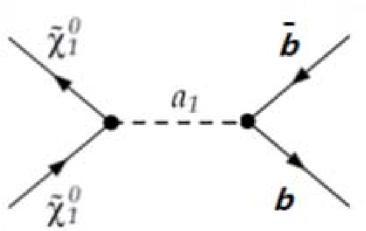


?+



(off-resonance, negligible)

- today:

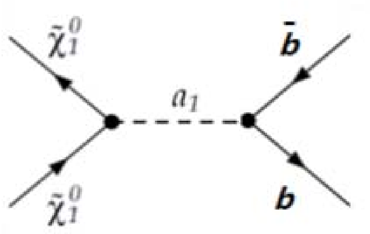


(resonance enhancement)

+ ($\rightarrow 0$ when $v_{\mathrm{DM,rel}} \rightarrow 0$)

Thermal broadening ($2m_\chi > m_{a_1}$ or $2m_\chi < m_{a_1}$?)

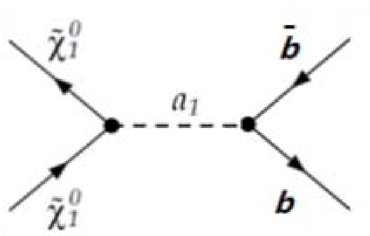
- early:



$\langle \sigma v \rangle_{\mathrm{a_1,FO}}$

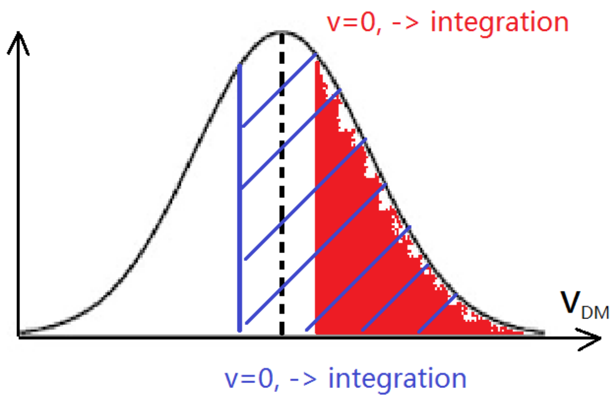
$\langle \sigma v \rangle_{\mathrm{a_1,GCE}}$

- today:



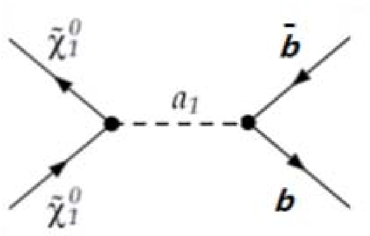
- to reach $\langle \sigma v \rangle_{\mathrm{GCE}} \simeq (0.4 \sim 1.3) \times 10^{-26}\ \mathrm{cm^3/s}$

  Breit-Wigner resonance needed: $2m_\chi \simeq m_{a_1}$



Thermal broadening ($2m_\chi > m_{a_1}$ or $2m_\chi < m_{a_1}$?)

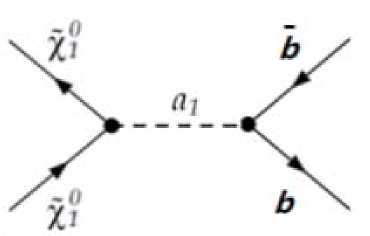
- early:



$\langle\sigma v\rangle_{\mathrm{a_1,FO}}$

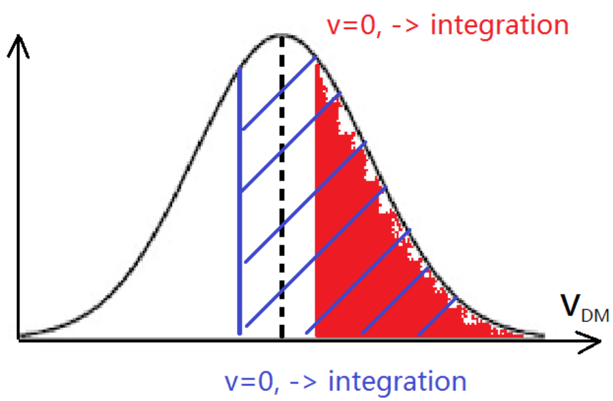
$\langle\sigma v\rangle_{\mathrm{a_1,GCE}}$

- today:



- $\langle\sigma v\rangle_{\mathrm{a_1,FO}} \propto \int dv_1 dv_2\, f(v_1, T_{\mathrm{FO}}) f(v_2, T_{\mathrm{FO}}) \times \frac{1}{\left(4E_{\mathrm{DM}}^2(v_1,v_2) - m_{a_1}^2\right)^2 + m_{a_1}^2 \Gamma_{a_1}^2}$

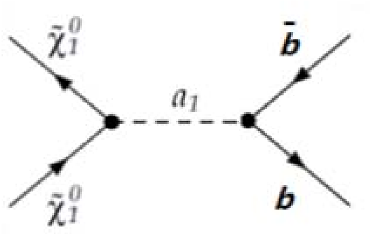
- $\langle\sigma v\rangle_{\mathrm{a_1,GCE}} \propto \frac{1}{\left(4m_\chi^2 - m_{a_1}^2\right)^2 + m_{a_1}^2 \Gamma_{a_1}^2}$, Γ_{a_1} is small

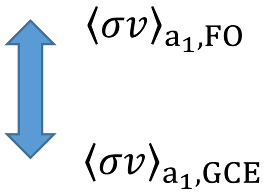


$f(v, T) \sim e^{-E_{\mathrm{DM}}(v)/T}$

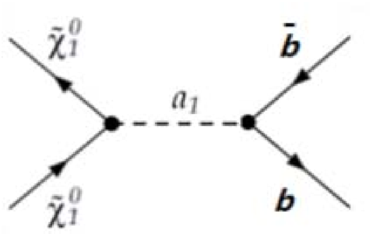
Thermal broadening ($2m_\chi > m_{a_1}$ or $2m_\chi < m_{a_1}$?)

- early:

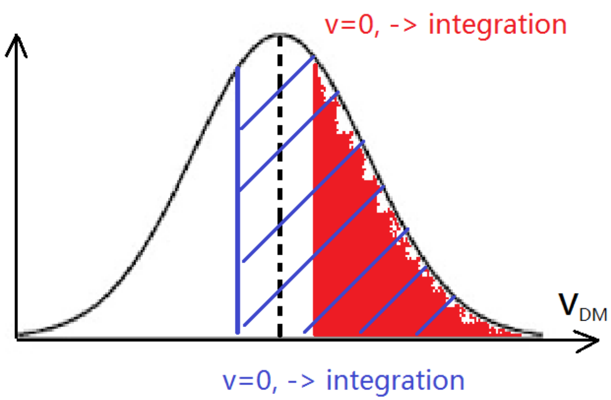




- today:

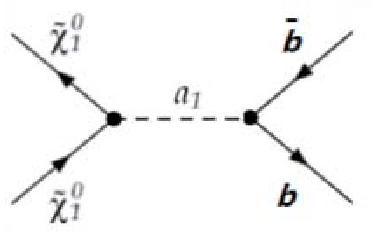


- $2m_\chi > m_{a_1}$, $\langle\sigma v\rangle_{\mathrm{a_1,FO}} < \langle\sigma v\rangle_{\mathrm{a_1,GCE}}$
  - Z-contribution can help
- $2m_\chi < m_{a_1}$, $\langle\sigma v\rangle_{\mathrm{a_1,FO}} \gg \langle\sigma v\rangle_{\mathrm{a_1,GCE}}$
  - too small $\Omega_{\mathrm{DM}}h^2$



Thermal broadening ($2m_\chi > m_{a_1}$ or $2m_\chi < m_{a_1}$?)

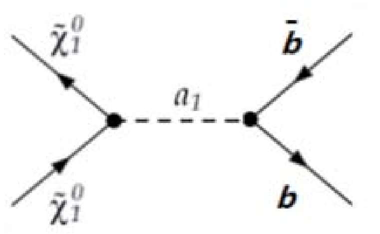
- early:



$\langle\sigma v\rangle_{\mathrm{a_1,FO}}$

$\langle\sigma v\rangle_{\mathrm{a_1,GCE}}$

- today:



- $2m_\chi > m_{a_1}$, $\langle\sigma v\rangle_{\mathrm{a_1,FO}} < \langle\sigma v\rangle_{\mathrm{a_1,GCE}}$
  - Z-contribution can help
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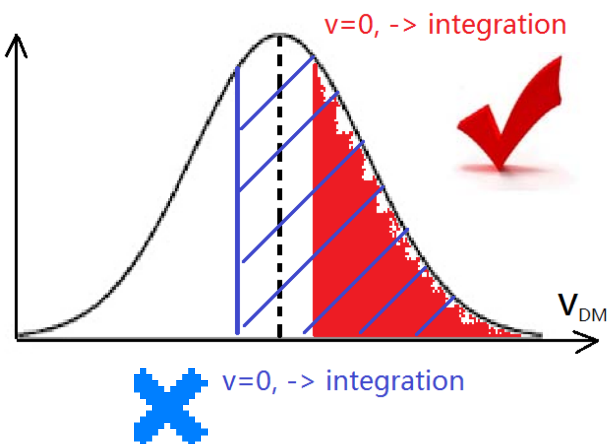
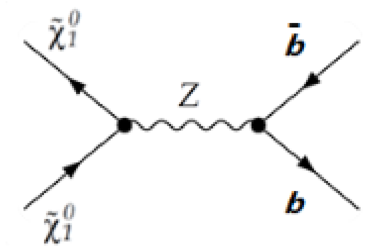


Z-contribution needed

- $m_\chi \sim 40$ GeV, not far from $m_Z/2$
- $c_{Z\chi\chi} \propto (N_{13}^2 - N_{14}^2)$
  - higgsino component in DM should be sizable
  - μ should be moderate/small
- higgsino-like neutralinos/chargino are light
  - $\sigma(pp \to \chi_i^\pm \chi_j^0)$ can be large
  - 3-lepton signal: $\chi_i^\pm \chi_j^0 \to W^\pm \chi_1^0 Z \chi_1^0 \to E_{miss}^T + 3l$



$$\begin{pmatrix} \tilde{\chi}_1^0 \\ \tilde{\chi}_2^0 \\ \tilde{\chi}_3^0 \\ \tilde{\chi}_4^0 \\ \tilde{\chi}_5^0 \end{pmatrix} = N_{5\times 5} \begin{pmatrix} \tilde{B} \\ \widetilde{W} \\ \widetilde{H}_d^0 \\ \widetilde{H}_u^0 \\ \tilde{S} \end{pmatrix}$$

Four scenarios

- which one is h_{SM}: h_1 or h_2?
- what component dominates DM: Bino ($\tilde{B}$) or singlino ($\tilde{S}$)?

	$\boldsymbol{h_1}$	$\boldsymbol{h_2}$
$\tilde{B}$	I-B	II-B
$\tilde{S}$	I-S	II-S

SM-like Higgs: h_1 or h_2?

- see-saw mechanism
- $h_3 \sim H_{\mathrm{MSSM}}$ is decoupled
- $h_{\mathrm{MSSM}} \sim h_{\mathrm{SM}}$
  - $m_{h_{\mathrm{MSSM}}} > m_{S_R}$, h_2 is h_{SM}
  - $m_{h_{\mathrm{MSSM}}} < m_{S_R}$, h_1 is h_{SM}

$$\begin{pmatrix} h_1 \\ h_2 \\ \cancel{h_3} \end{pmatrix} = S_{3\times 3} \begin{pmatrix} H_{u,R}^0 \\ H_{d,R}^0 \\ S_R \end{pmatrix} \sim S'_{3\times 3} \begin{pmatrix} h_{\mathrm{MSSM}} \\ \cancel{H_{\mathrm{MSSM}}} \\ S_R \end{pmatrix}$$

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} \sim S_{2\times 2} \begin{pmatrix} h_{\mathrm{MSSM}} \\ S_R \end{pmatrix}$$

- $a_2 \sim A_{\mathrm{MSSM}}$ is decoupled
  - a_1 can be singlet-like and light

$$\begin{pmatrix} a_1 \\ a_2 \end{pmatrix} = P_{2\times 2} \begin{pmatrix} A_{\mathrm{MSSM}} \\ S_I \end{pmatrix}$$

DM is bino ($\tilde{B}$)-like or singlino ($\tilde{S}$)-like?

- simplification: wino ($\widetilde{W}$) decoupled, large M_2
- moderate μ: necessary higgsino component

- $\tilde{B}$-like: small $|M_1|$, moderate/large κ/λ
- $\tilde{S}$-like: small κ/λ, moderate/large $|M_1|$

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

$$\begin{pmatrix} \tilde{\chi}_1^0 \\ \tilde{\chi}_2^0 \\ \tilde{\chi}_3^0 \\ \tilde{\chi}_4^0 \\ \tilde{\chi}_5^0 \end{pmatrix} = N_{5\times5} \begin{pmatrix} \tilde{B} \\ \widetilde{W} \\ \widetilde{H}_d^0 \\ \widetilde{H}_u^0 \\ \tilde{S} \end{pmatrix}$$

I-S is hard to realize

	$\boldsymbol{h_1}$	$\boldsymbol{h_2}$
$\tilde{B}$	I-B	II-B
$\tilde{S}$	I-S, hard to realize	II-S

- $(M_{\mathrm{DM}} \sim M_{\tilde{S}}) \sim 40\ \mathrm{GeV}$
- $(M_{a_1} \sim M_{S_I}) \sim 2M_{\mathrm{DM}} \sim 80\ \mathrm{GeV}$

then

- M_{S_R} is generally small (with $\kappa A_\kappa < 0$)

- $h_{\mathrm{MSSM}} \sim h_{\mathrm{SM}}$
  - $m_{h_{\mathrm{MSSM}}} > m_{S_R}$, h_2 is h_{SM}
  - $m_{h_{\mathrm{MSSM}}} < m_{S_R}$, h_1 is h_{SM}

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} \sim S_{2\times 2} \begin{pmatrix} h_{\mathrm{MSSM}} \\ S_R \end{pmatrix}$$

I/II-B need fine-tuning

	h_1	h_2
$\tilde{B}$	I-B, fine-tuned	II-B, fine-tuned
$\tilde{S}$	I-S, hard to realize	II-S

- $y_{a_1\chi\chi}$ is small (a_1 is singlet-like)
- experimental constraints
  - $B_s \to \mu^+\mu^-, e^+e^- \to ha$
- limited A_{MSSM} component in a_1
  - y_{a_1bb} is suppressed

$$\langle\sigma v\rangle_{b\bar{b}}|_{v\to 0} \propto \frac{y_{a_1\chi\chi}^2 y_{a_1 b\bar{b}}^2 m_\chi^2}{(4m_\chi^2 - m_{a_1}^2)^2 + m_{a_1}^2 \Gamma_{a_1}^2}$$

Consequently
$\langle\sigma v\rangle_{\mathrm{a_1,GCE}}$ is not large enough

II-S is promising

	$\boldsymbol{h_1}$	$\boldsymbol{h_2}$
$\tilde{B}$	I-B	II-B
$\tilde{S}$	I-S	II-S, promising

- more freedom to explain $\Omega_{\mathrm{DM}}h^2$ and GCE simultaneously

Numerical Scan

- simplifications
  - $\tilde{q}$ = 2 TeV
    - $A_t = A_b$ to tune $m_{h_{\rm SM}}$
  - $\tilde{l}$ = 300 GeV
    - muon g-2
  - $\tilde{g}$ = 2 TeV
  - $\widetilde{W}$ = 1 TeV

- parameter ranges ([mass] in TeV) :
  - $1 < tan\beta < 40,\ 0 < \lambda < 0.7,\ 0 < |\kappa| < 0.7,$
  - $0 < |A_\kappa| < 2,\ 0 < A_\lambda < 5,\ |A_t| < 5,$
  - $0 < |M_1| < 0.6,\ 0.1 < \mu < 0.6$
- spectrum calculator:
  - NMSSMTools-4.3.0

Numerical Scan

- Higgs sector:
  - $m_{h_{\rm SM}} \sim 125$ GeV
- implement Higgs constraints/data
  - HiggsBounds-4.2.0/HiggsSignals-1.2.0
- $B_s \to \mu^+\mu^-, b \to s\gamma$
- neutralino sector:
  - $m_{\tilde{\chi}_1^0} \in (30,40)$ GeV, singlino-like
- $\Omega_{\rm DM} h^2$ at 3σ level: $(0.107, 0.131)$
- LUX exclusion at 90% C.L
- GCE with dwarf constraints
  - $\langle \sigma v \rangle|_{v \to 0} \in (0.4, 1.3) \times 10^{-26} {\rm cm}^3/{\rm s}$

Simulation of 3-lepton signal

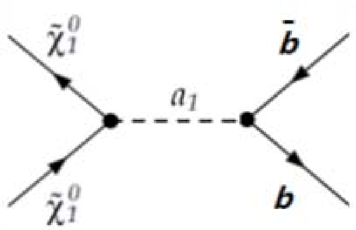
- spectrum calculator: NMSSMTools
- event generator: MadGraph5
- parton shower: Pythia
- cut efficiencies: Delphes encoded in CheckMATE
  - six SRs in ATLAS-CONF-2013-035
  - SRZd added (more efficient for large μ)
- $\sigma\left(pp \rightarrow \tilde{\chi}_i^{\pm}\tilde{\chi}_j^0\right)$ at NLO: Prospino2

Resonance and cross section

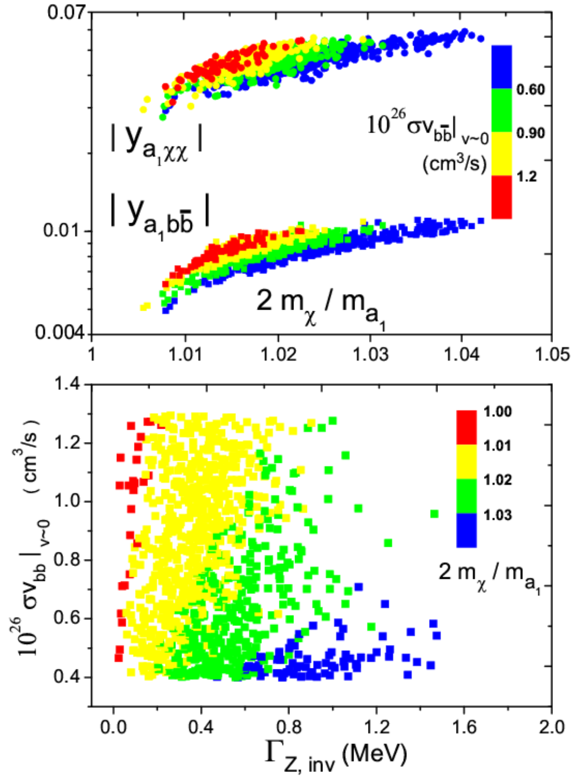
- a_1 off-resonance, a_1 contribution decreases

$$-L_{int} = iy_{a_1\chi\chi} a_1 \bar{\chi}\gamma^5\chi + iy_{a_1 b\bar{b}} a_1 \bar{b}\gamma^5 b$$

$$< \sigma v >_{b\bar{b}} \Big|_{v\to 0} \propto \frac{y_{a_1\chi\chi}^2 \, y_{a_1 b\bar{b}}^2 \; m_\chi^2}{\left(4m_\chi^2 - m_{a_1}^2\right)^2 + m_{a_1}^2 \Gamma_{a_1}^2}$$



- fixed $2m_\chi/m_{a_1}$
    - $\langle \sigma v \rangle|_{v\to 0}$ increases with larger $|y_{a_1\chi\chi}|$, $|y_{a_1 b\bar{b}}|$

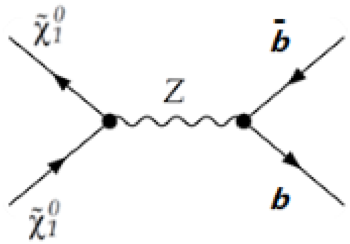


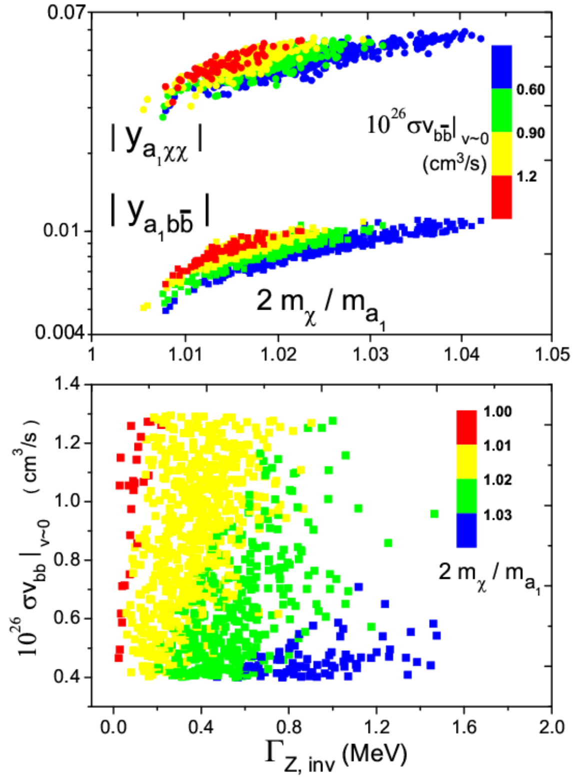
Z-contribution illustration

- larger $2m_\chi/m_{a_1}$>1
  - $\langle\sigma v\rangle|_{v\to 0}$, $\langle\sigma v\rangle_{a_1,\mathrm{FO}}$ decreases
  - $\Gamma_{Z,inv}$ generally increases

$$\Gamma_{Z,inv} = \frac{G_F m_Z^3}{12\sqrt{2}\pi}(N_{13}^2 - N_{14}^2)^2\left(1-\frac{4m_\chi^2}{m_Z^2}\right)^{3/2}$$

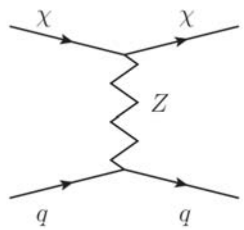
  - kinematic β-factor also plays a role

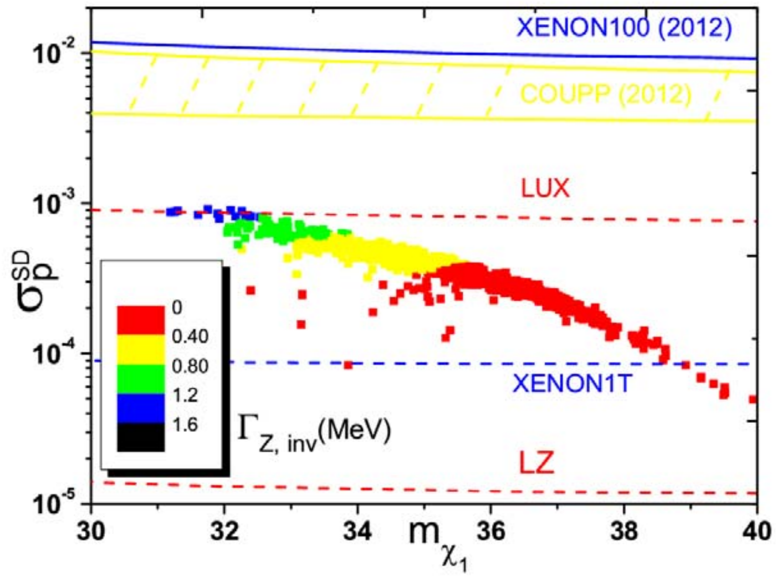




DM Spin-Dependent scattering

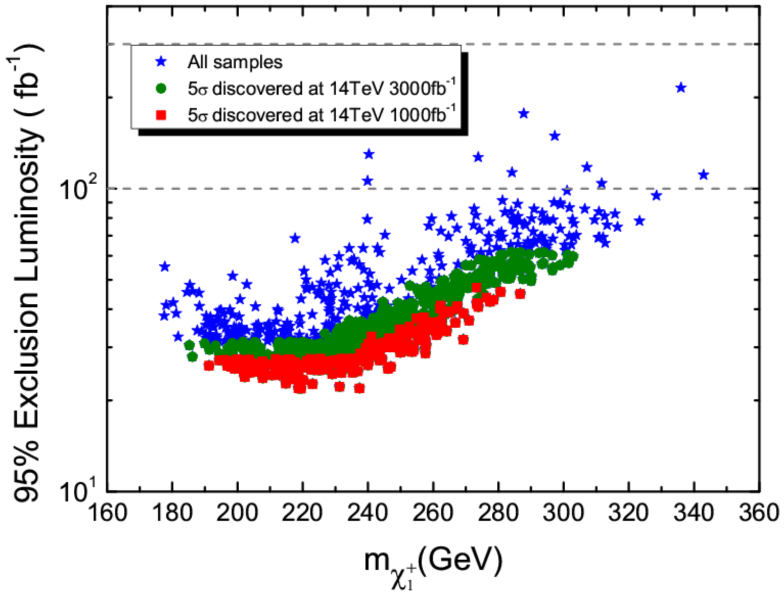
- σ_p^{SI} already satisfied (LUX)
- σ_p^{SD} bounds, weaker than σ_p^{SI}
- larger m_χ → smaller $\Gamma_{Z,inv}$, σ_p^{SD}
  - $m_\chi \propto 2\left(\frac{\lambda}{\mu}\right)^{-1}\kappa$, $g_{Z\chi\chi} \propto \left(\frac{\lambda}{\mu}\right)^{2} v^2$
  - suppressed kinematic β-factor
- beyond current LUX capability
- testable at future XENON-1T/LZ





3-lepton signal at 14 TeV LHC

- most sensitive SR chosen for each sample
  - SRZc for $m_\chi < 230\ \mathrm{GeV}$
  - SRZd for $m_\chi > 280\ \mathrm{GeV}$
- 100 (200) fb^{-1}exclude most (all) II-S samples
- partially discoverable at 14-TeV LHC



Conclusions

- NMSSM can explain $\Omega_{\mathrm{DM}}h^2$ and GCE simultaneously
- a_1 resonance is usually needed, singlino-like DM is favored
- Z-contribution is needed when a_1 is off-resonant
  - Higgsino mass μ is upper bounded
- future SD experiment may cover the GCE-favored region
- 3-lepton signals at 14-TeV LHC can test this GCE scenario

Thank you