Dark Matter in the Singlet Extension of MSSM: Explanation of Pamela and Implication on Higgs Phenomenology

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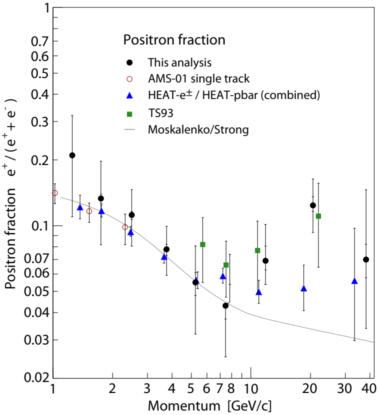
Outline:

- Important discovery in 2008
- New theory of dark matter
- A possible model
- The phenomenology in collider physics
- Summary

Important discovery in 2008



The positron fraction $e^+/(e^+ + e^-)$ measured in this analysis (filled circles), compared with earlier results from AMS-01 (open circles), TS93 (squares), the combined results from HEAT-$e^\pm$ and HEAT-pbar (triangles), together with a model calculation for purely secondary positron production from (solid line).(From astro-ph/0703154)

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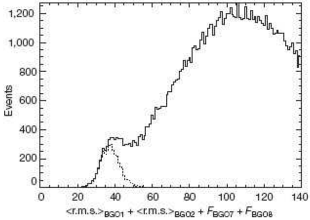


Figure 1 | Separation of electrons from protons in the ATIC instrument. Candidate electron events (162,000) with energy over 50 GeV are plotted as a histogram with the horizontal axis showing the sum of the 'weighted energy fraction' (F values as defined below) in the last two BGO layers and the shower width (root mean squared, r.m.s.) in the first two layers. The shower width is calculated as

$$\langle \text{r.m.s.} \rangle^2 = \sum_{i=1}^{n} E_i (X_i - X_c)^2 / \sum_{i=1}^{n} E_i$$

where X_c is the coordinate of the energy centre, X_i is the coordinate of the centre of the ith crystal and E_i is the energy deposited in the ith crystal. The F value is calculated as $F_n = (E_n/\text{Sum})\ \langle \text{r.m.s.} \rangle^2$ where E_n is the energy deposit in BGO layer n, Sum is the total energy deposit in all BGO layers and ⟨r.m.s.⟩ refers to layer n (ref. 12). Each event is also fitted to an electromagnetic cascade profile to estimate the starting point and the depth of the cascade maximum. An event is accepted if the cascade starts above the first BGO layer, which eliminates many protons (~75%) but passes most electrons (~90%). Next a diagonal cut in r.m.s. and F is determined for each energy bin and used to isolate the electrons. This removes most of the protons (2 in 10^4 remain) and retains 84% of the electrons[12]. The selected electrons are

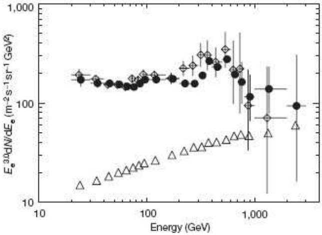


Figure 2 | ATIC-1 and ATIC-2 spectra at balloon altitude, showing good agreement with each other. The measured primary electron flux (scaled by E^3) at flight altitude is shown for ATIC-1 (open squares) and ATIC-2 (filled circles). The errors are one standard deviation. Both balloon flights were from McMurdo, Antarctica, and circumnavigated that continent. ATIC-1 was a test flight in 2000–01 and the usable data correspond to an exposure of 0.61 m^2 sr days. ATIC-2 was a science flight in 2002–03 with an exposure of 2.47 m^2 sr days. To eliminate edge effects, we restrict the incident zenith angle to be less than ~37° ($\cos\theta \geq 0.8$), use only the central 80% of the SiM and eliminate events in the outer crystals in each BGO layer. Within these limits, the electron detection efficiency above 60 GeV is 84% essentially independent of energy. The effective acceptance was determined as a function of particle energy considering the trigger efficiency, trajectory reconstruction efficiency and the geometrical restrictions. The effective acceptance of the instrument increases from 0.075 m^2 sr at 20 GeV to 0.15 m^2 sr for $E > 60$ GeV. Above 100 GeV, a total of 1,724 electron events were observed, with the highest energy event at 2.3 TeV. The total background is also shown in the figure as the open triangles and is a combination of unresolved protons, unidentified γ-rays and atmospheric secondary electrons produced in the material (~4.5 g cm^{-2}) above the

Possible explanations:

The astrophysical explanations:

- Supernovae for WMAP haze
- Pulsar wind nebulae for PAMELA and ATIC
- A micro qusar near the sun for ATIC

Particle physics explanation

- Annihalation of Dark matter particle

Solve all the problem!

There is also problems in particle explanation

(1) Initially, DM is in thermal equilibrium:

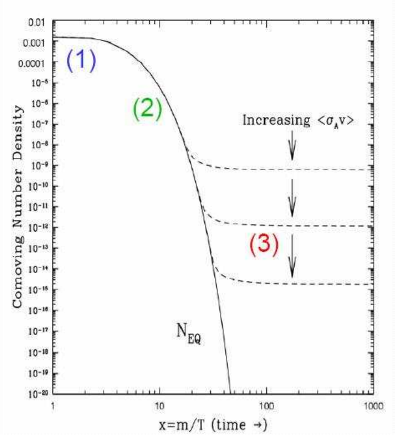
$\chi\chi \leftrightarrow \bar{f} f$

(2) Universe cools:

$N = N_{EQ} \sim e^{-m/T}$

(3) χs "freeze out":

$N \sim \text{const}$



$$\Omega_X h^2 \approx \frac{1.07 \times 10^{-9} GeV^{-1}}{M_{pl}} \frac{x_F}{\sqrt{g_*}} \frac{1}{a + 3b/x_F}$$

The observed relic density is

$$\Omega_X h^2 \approx 0.1$$

which implies that the annihilation rate of dark matter is too small the explain the observed positron and electrons. We need a boost factor at about 100 The new model of the dark matter must have these features:

- A large cross section
- A large cross section into leptons
- A low cross section into hadrons

A new theory is proposed

New force is proposed in the dark sector. When the dark matter annihilate at present times via Sommerfield enhancement. The decays to hadron are kinematically forbbiden.

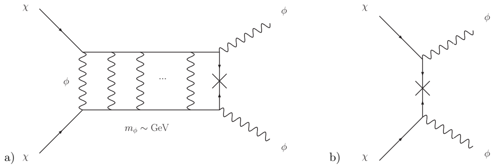


Figure: The annihilation diagrams $\chi\chi \to \phi\phi$ both with (a) and without (b) the Sommerfeld enhancements.

$$S \sim \frac{m_{\chi_0}}{v^2 m_b}$$

v is the velocity of the particle

What is sommerfield enhancement ?

schrödinger equation

$$-\frac{1}{2M}\nabla^2\psi + V(r)\psi = \frac{k^2}{2M}\psi \quad \text{with} \quad V(r) = -\frac{\kappa^2}{2\pi}\frac{e^{-m_{h_1}r}}{r}$$

In spherical coordinate

$$\psi = \sum_l A_l P_l(\cos\theta) R_l(r)$$

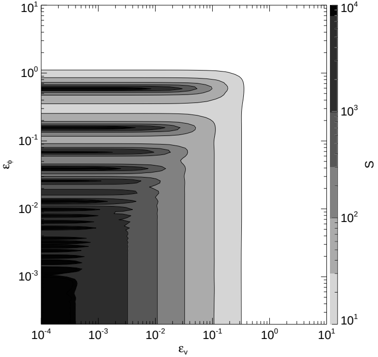
with the boundary condition ($r \to \infty$)

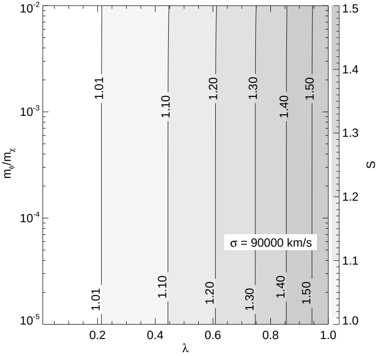
$$-\frac{1}{2M}\frac{d^2}{dr^2}\chi + V(r)\chi = \frac{k^2}{2M}\chi$$

The boost factor is:

$$S = \left|\frac{\frac{d\chi}{dr}(0)}{k}\right|^2$$

The boost factor at different era





Now the average velocity of the particle in the halo of our galaxy is 150km/s.

In the early universe the velocity of the dark matter is about c.

A possible model in supersymmetric models

SM particle and their super partner

Names	spin 1/2	spin 1	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\mathbf{8},\ \mathbf{1}\ ,\ 0)$
winos, W bosons	$\widetilde{W}^{\pm}\quad \widetilde{W}^{0}$	$W^{\pm}\quad W^{0}$	$(\mathbf{1},\ \mathbf{3}\ ,\ 0)$
bino, B boson	$\widetilde{B}^{0}$	B^{0}	$(\mathbf{1},\ \mathbf{1}\ ,\ 0)$

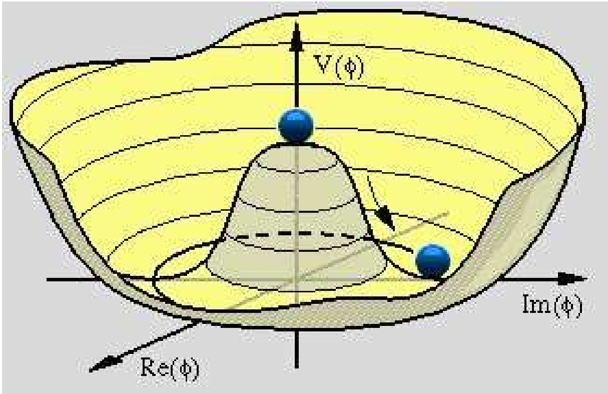
Names		spin 0	spin 1/2	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L\quad \widetilde{d}_L)$	$(u_L\quad d_L)$	$(\mathbf{3},\ \mathbf{2}\ ,\ \frac{1}{6})$
(×3 families)	$\overline{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$	$(\overline{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$	$(\overline{\mathbf{3}},\ \mathbf{1},\ \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu}\quad \widetilde{e}_L)$	$(\nu\quad e_L)$	$(\mathbf{1},\ \mathbf{2}\ ,\ -\frac{1}{2})$
(×3 families)	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(\mathbf{1},\ \mathbf{1},\ 1)$
Higgs, higgsinos	H_u	$(H^+_u\quad H^0_u)$	$(\widetilde{H}^+_u\quad \widetilde{H}^0_u)$	$(\mathbf{1},\ \mathbf{2}\ ,\ +\frac{1}{2})$
	H_d	$(H^0_d\quad H^-_d)$	$(\widetilde{H}^0_d\quad \widetilde{H}^-_d)$	$(\mathbf{1},\ \mathbf{2}\ ,\ -\frac{1}{2})$

Superpotential

$$W_{\rm MSSM} = \overline{u}\mathbf{y_u}QH_u - \overline{d}\mathbf{y_d}QH_d - \overline{e}\mathbf{y_e}LH_d + \mu H_u H_d\ .$$

μ is the SUSY preserving parameter, why EW scale?

How to solve μ problem



$$\mu_{eff} = \lambda < S >$$

$SH_u \cdot H_d$ $\Longrightarrow$ $\mu_{eff} H_u \cdot H_d$

Table: MSSM and several of its extensions.

Model	Symmetry	Superpotential	CP-even	CP-odd	Charged
MSSM	–	$\mu \hat{H}_u \cdot \hat{H}_d$	H_1^0, H_2^0	A_2^0	$H^\pm$
NMSSM	$\mathbb{Z}_3$	$h_s \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3$	H_1^0, H_2^0, H_3^0	A_1^0, A_2^0	$H^\pm$
nMSSM	$\mathbb{Z}_5^R, \mathbb{Z}_7^R$	$h_s \hat{S} \hat{H}_u \cdot \hat{H}_d + \xi_F M_n^2 \hat{S}$	H_1^0, H_2^0, H_3^0	A_1^0, A_2^0	$H^\pm$
UMSSM	$U(1)'$	$h_s \hat{S} \hat{H}_u \cdot \hat{H}_d$	H_1^0, H_2^0, H_3^0	A_2^0	$H^\pm$
sMSSM	$U(1)'$	$h_s \hat{S} \hat{H}_u \cdot \hat{H}_d + \lambda_s \hat{S}_1 \hat{S}_2 \hat{S}_3$	$H_{1,2,3,4,5,6}^0$	$A_{1,2,3,4}^0$	$H^\pm$

- Unfortunately non of these models can satisfy the requirement.
- Fortunately the more general extention of MSSM with a singlet can work!

$$W = \mu \widehat{H}_u \cdot \widehat{H}_d + \lambda \widehat{S} \widehat{H}_u \cdot \widehat{H}_d + \eta \widehat{S} + \frac{1}{2}\mu_s \widehat{S}^2 + \frac{1}{3}\kappa \widehat{S}^3$$

The soft SUSY-breaking terms are given by

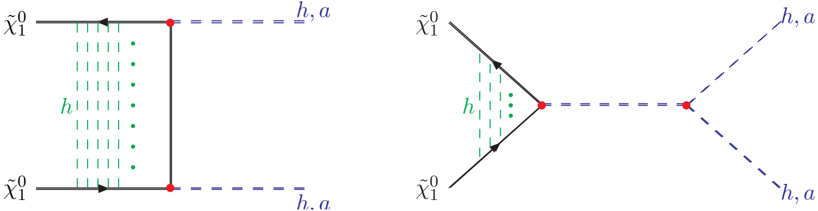
$$\begin{aligned} V_{\rm soft} &= m_{\rm H_u}^2 |H_u|^2 + m_{\rm H_d}^2 |H_d|^2 + m_{\rm S}^2 |S|^2 \\ &+ (B\mu H_u \cdot H_d + \lambda A_\lambda\ H_u \cdot H_d S \\ &+ C\eta S + \frac{1}{2} B_s \mu_s S^2 + \frac{1}{3}\kappa A_\kappa\ S^3 + {\rm h.c.}) \end{aligned}$$

Note that in this model we donot solve the μ problem.

When λ is much smaller than κ

$$\begin{aligned} A_\kappa &\sim \left(-4\kappa s - 3\mu_s + \frac{C\eta}{\kappa s^2} \right) \\ 2B_s\mu_s &\sim \left(-3A_\kappa \kappa s - \mu_s \kappa s - \frac{C\eta}{s} \right) \end{aligned}$$

can give a very light h and a



- χ_0 is singlino dominent thus mainly decay into singlet higgs;
- h can give the sommerfield enhancement;
- $h \to aa \to$ leptons.

Satisfy all the requirements !!

We modified the package NMSSMTools to scan the parameter space

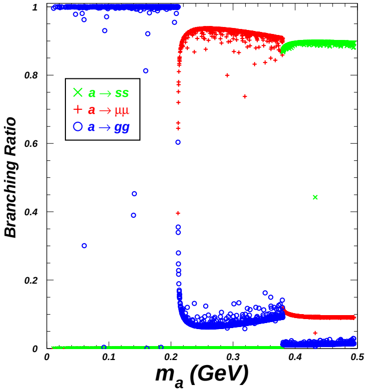
$$-500 \text{ GeV} < C,\ \mu,\ \mu_s,\ B,\ A_\lambda,\ M_1,\ M_2 < 500 \text{ GeV}$$
$$-(500 \text{ GeV})^2 < \eta < (500 \text{ GeV})^2, \quad s < 500 \text{ GeV}, \quad 2 < \tan\beta < 40.$$

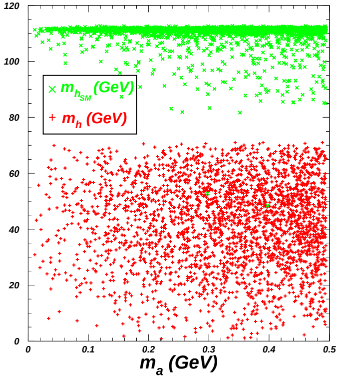
and

$$A_\kappa \in \left(-4\kappa s - 3\mu_s + \frac{C\eta}{\kappa s^2}\right) \pm 20\text{GeV},$$
$$2B_s\mu_s \in \left(-3A_\kappa \kappa s - \mu_s \kappa s - \frac{C\eta}{s}\right) \pm (3\text{GeV})^2$$

We also require all the scanned points satisfy the LEP experiments, B physics and dark matter constraints.

Higgs phonmenology

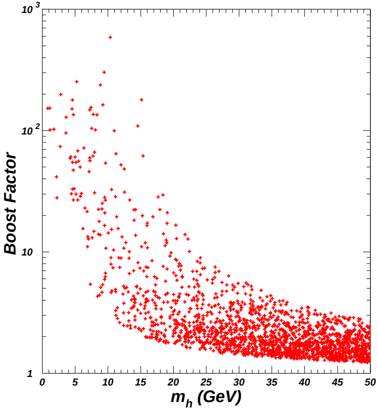




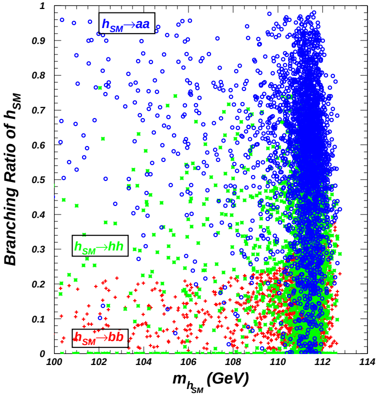
there exits a region for a decay into leptons, $(2m_\mu < m_a < 2m_\pi)$

mass of SM like higgs h_{SM} can be light than 100GeV.

The boost factor and h_{SM} decay



There is parameter space for h to give enough sommerfield enhancement



h_{SM} mainly decay into aa ?

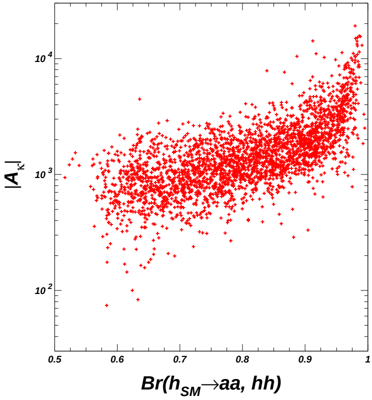
- In MSSM h_{SM} mainly decay in $b\bar{b}$
- In our calculation we chose the unified parameterization of MSSM like input

$$A_0,\ M_0 = 500GeV$$

thus LEP experiments strictly contrain process such as $h \rightarrow b\bar{b}$.

- In our model mixing between $H_{u,d}$ and S is controled by
  - $\lambda S H_u \cdot H_d$ from superpotential
  - $\lambda A_\lambda S H_u \cdot H_d$ from soft term
- h_{SM} can decay into the dark sector

other discussions



- D0 search for $h \to aa \to 4\mu$ or $2\mu 2\tau$ constrained a in range of 3.6-9.5 GeV;
- Squark sector are fixed to be 500 GeV thus not heavy enough to push the mass of h_{SM} up to 135 GeV;

Summary:

- Signal of Dark matter may be detected;
- There may be a fifth forth;
- Supersymmetry maybe right;
- We may find that in the colliders.

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Thank you !