Light Dark Matter and Invisible Quarkonium Decays

Bob McElrath
University of California, Davis

hep-ph/0506151 [B. McElrath]
hep-ph/0507xxx [J. Gunion, D. Hooper, S. Hess, B. McElrath]

TeV Particle Astrophysics, FNAL, Jul 15, 2005

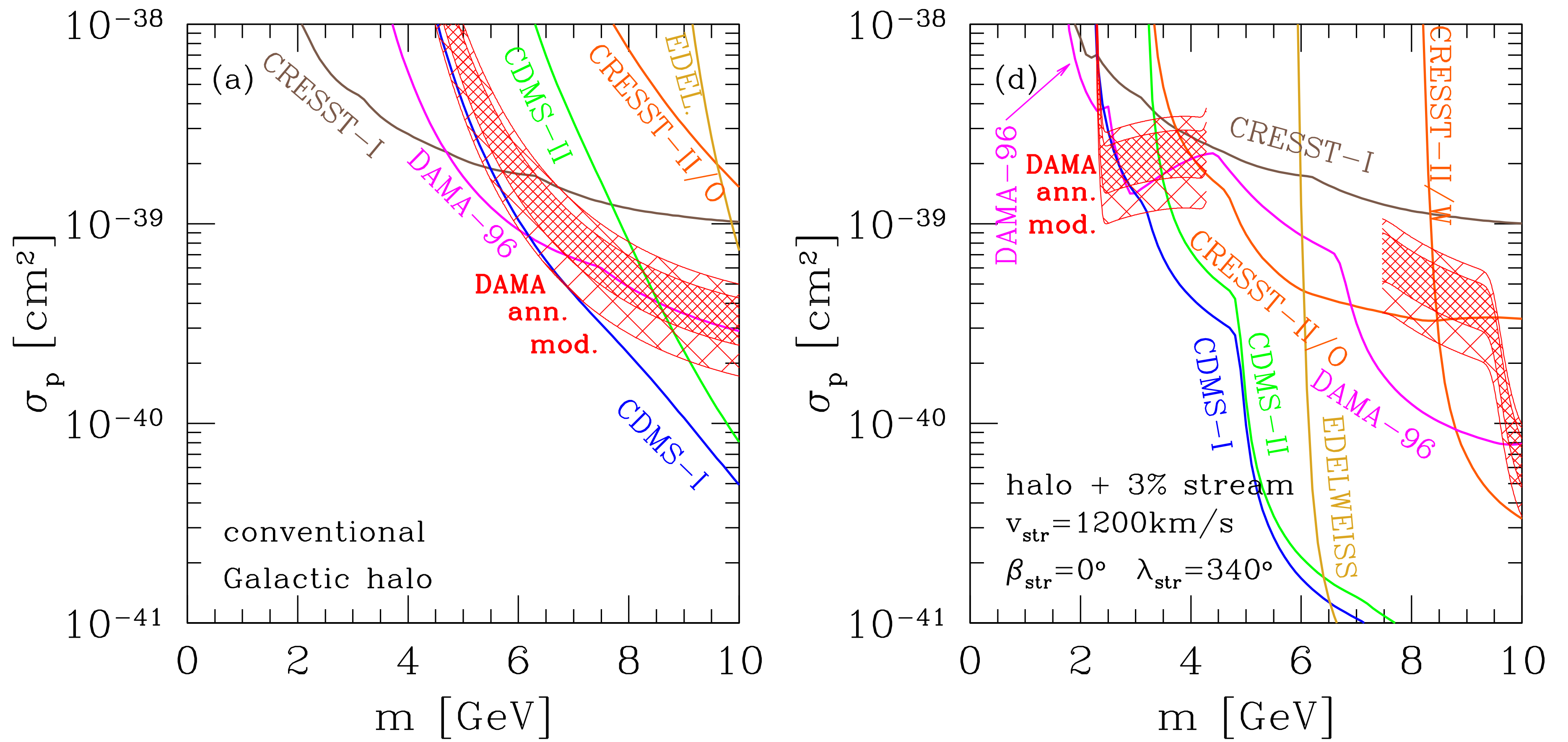
DAMA Evidence

DAMA is a 100kg NaI detector. They observed an annual modulation signal consistent with a WIMP with mass $M_{\chi^0} = 52^{+10}_{-8}$ GeV and a cross section $\sigma = 7.2^{+0.4}_{-0.9} \times 10^{-6}$ pb. [Phys.Lett.B480:23-31,2000]

This is inconsistent with recent CDMS results using Si and Ge. [astro-ph/0405033]

It was pointed out that Na has a lower detection threshold than Si and Ge, making DAMA more sensitive to light dark matter. Furthermore, a "wind" passing through our local region can make DAMA and CDMS compatible. [Gondolo, Gelmini, Savage, Freese]

DAMA/CDMS Compatability



[Gondolo, Gelmini, hep-ph/0504010]

INTEGRAL Evidence

The SPI spectrometer aboard the INTEGRAL satellite observes a gaussian profile of 511 keV γ-rays coming from the inner kiloparsec of our galaxy. Attempt to explain this from astrophysical sources have failed thus far.

If this is coming from dark matter annihilation, the dark matter must be in the range $m_e < m_{\chi^0} < 207$ MeV. This annihilation must not produce any π^0 or high-energy electrons, due to COMPTEL and EGRET limits on gamma rays.

Annihilation through Z^0 and MSSM higgses is not efficent enough to prevent a neutralino this light from over-closing the universe.

$\Rightarrow$ A new SM-DM annihilation mediator is required.

Pseudoscalars make the best mediators since the annihilation cross section is non-zero at zero velocity.

Start from first principles

Forget everything you know. . .

LSP

LKP

Axion

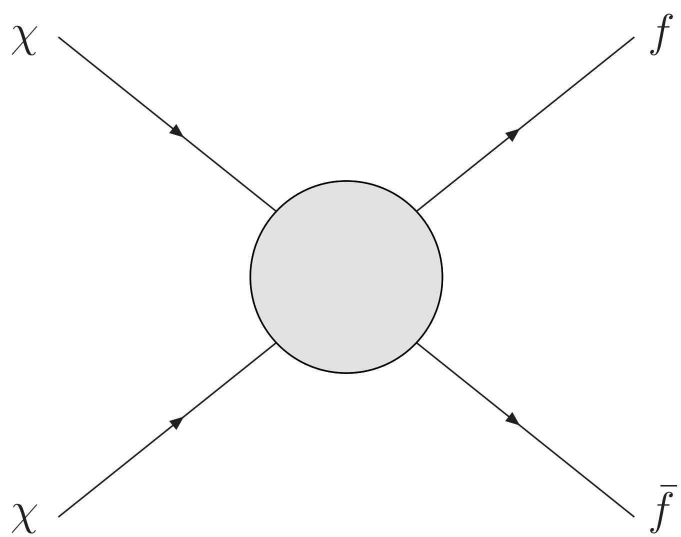
T-Parity

All fell out of theories designed to solve *other* problems!

What happens if we consider particle Dark Matter by itself?

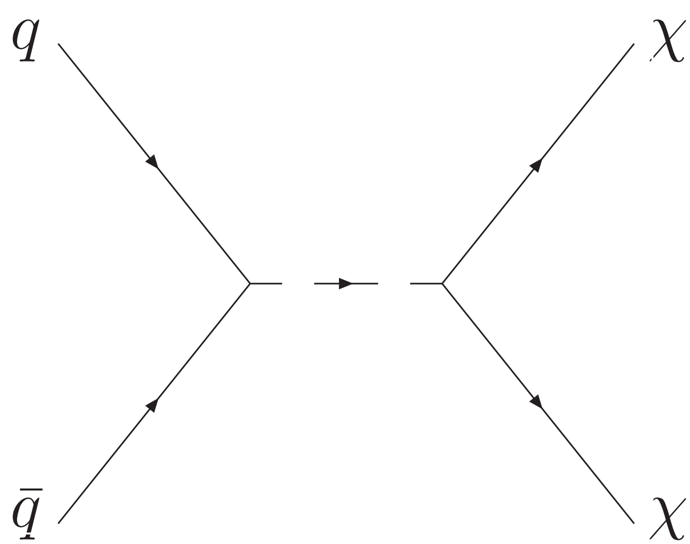
What do we know?

- If Dark Matter is decoupled, we could never discover it.
- If not, it must have been in thermal equilibrium at some point.
- WMAP has measured the relic density, and therefore, the *annihilation cross section*.



$t \to -t$

The time-reversed annihilation diagram corresponds to the *invisible decay of particle -onia*.



Measuring an invisible decay gives direct sensitivity to the J^{CP} of the mediator!

We have many $f\bar{f}$ bound states: π^0, ρ, η, ω, η', J/Ψ, χ_c, χ_b, Υ, η_b, etc.

Only *two* particles have any limit on their invisible width: π^0 and Z.

Model Independence

Assume:

- Dark Matter annihilates in pairs (rather than a single particle with very small coupling like the axion)

Then we are forced to consider:

- Scalar or fermion Dark Matter particle

- Scalar, pseudoscalar, or vector particle mediates the SM-DM interaction

- If it is measured in $f\bar{f}$ -onia decays, it must be light.

Branching Ratio Expectations

Using the WMAP measurement $\Omega h^2 = 0.113$ and

$$\Omega h^2 \simeq \frac{3 \times 10^{-27} cm^3/s}{\langle \sigma v \rangle}$$

Where v is the average velocity at freeze-out, $v = T = m_\chi/20$

The invisible width of a hadron composed dominantly of $q\bar{q}$ is given by:

$$\Gamma(H \to \chi\chi) = f_H^2 M_H \sigma(q\bar{q} \to \chi\chi)$$

and $\sigma(q\bar{q} \to \chi\chi) \simeq \sigma(\chi\chi \to q\bar{q})$.

This gives

$$BR(\Upsilon(1S) \to \chi\chi) \simeq 0.41\% \qquad BR(J/\Psi \to \chi\chi) \simeq 0.023\%$$

$$BR(\eta \to \chi\chi) \simeq 0.033\%$$

Scalars and Pseudoscalars tend to have very small branching ratios because they are wider.

Other low-energy measurements

The measurements at B-factories and lower energy colliders that are sensitive to dark matter are:

$$\begin{aligned} \Upsilon &\to invisible && \text{(new)} \\ J/\Psi &\to invisible && \text{(new)} \\ \eta &\to invisible && \text{(new)} \\ \Upsilon &\to \gamma + invisible && \text{(better precision needed)} \\ B^+ &\to K^+ + invisible && \text{(better precision needed)} \\ K^+ &\to \pi^+ + invisible && \text{(measured)} \end{aligned}$$

The decay $K^+ \to \pi^+ \nu\bar{\nu}$ was recently measured by the E787 and E949 experiments (*Holy Tiny Number Batman!*):

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10} \tag{1}$$

is within error bars of the predicted Standard Model branching ratio

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (0.67^{+0.28}_{-0.27}) \times 10^{-10}. \tag{2}$$

Dark Matter in Particle Decays

In order to see an invisible decay of a hadron H, we must *tag* the state so that we know that H was created.

One way to do this: radiative decays.

Many particles have radiative decays from excited states involving a $\pi^+\pi^-$ pair. e.g. $\Psi(2S) \to J/\Psi\pi^+\pi^-$, $\eta' \to \eta\pi^+\pi^-$.

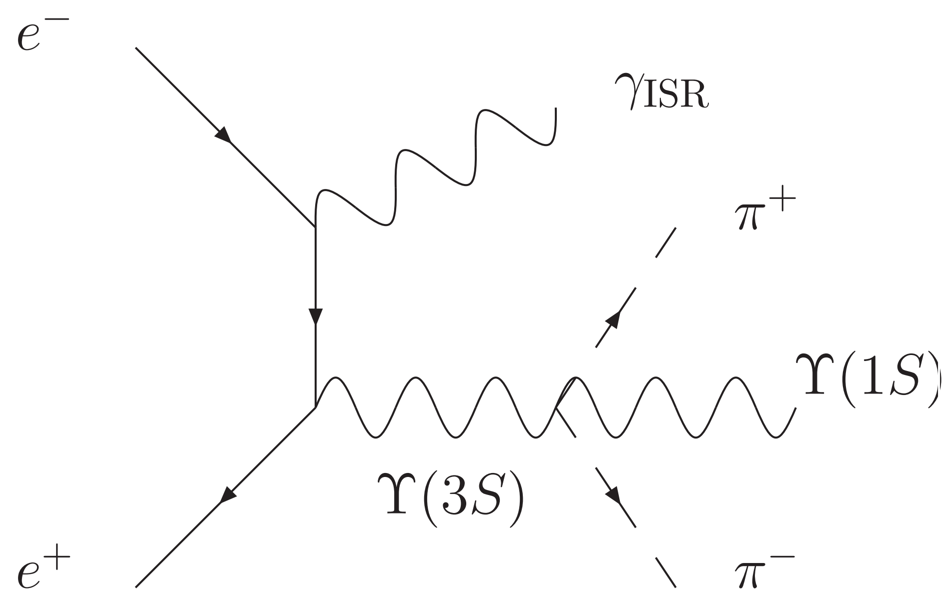
Knowledge that two narrow resonances were formed gives us strong kinematic constraints.

We have B-factories running at the $\Upsilon(4S)$, so let's concentrate on $\Upsilon(nS) \to \Upsilon(1S)\pi^+\pi^-$ for this talk (where $n = 2, 3$).

How to measure invisible branching ratios

Create heavier quarkonia e.g. $\Upsilon(3S)$ or $\Upsilon(2S)$ via ISR

ISR photons are monochromatic in the CM frame, and inside the detector volume about 16% of the time.



Allow quarkonia to decay radiatively to lighter quarkonia (perhaps multiple radiative decays)

Radiative decays are *overconstrained*

Invisible Upsilon Punch Line

With 400 fb^{-1} one can limit at 2σ:

$$BR(\Upsilon(1S) \rightarrow \text{invisible}) < 0.11\% \tag{3}$$

using the $\Upsilon(2S)$ mode and

$$BR(\Upsilon(1S) \rightarrow \text{invisible}) < 0.33\% \tag{4}$$

using the $\Upsilon(3S)$ mode.

(expected branching ratio is $\sim 0.4\%$)

There are *many* more modes and radiative decays that can be used. Also radiative decays from the $\Upsilon(4S)$ give about the same event rate as ISR production.

The NMSSM and μ-solvable models

The NMSSM was originally designed to solve the μ problem in the MSSM by adding a single chiral supermultiplet that is uncharged under SM gauge symmetries. Its superpotential is

$$W = \lambda S H_u H_d + \frac{\kappa}{3} S^3 \tag{5}$$

when the scalar compnent of S gets a vev, $\mu = \lambda \langle S \rangle$ is dynamically generated, solving the μ problem.

The matter spectrum is extended to have one extra neutralino (called the singlino), one extra CP-even higgs, and one extra CP-odd higgs.

After SUSY is broken, trilinears and soft masses are generated for S:

$$V_{\text{soft}} \subset A_\lambda \lambda S H_u H_d + A_\kappa \kappa S^3 + m_S^2 S^2 \tag{6}$$

There are other ways to add a singlet and also solve the μ problem. (e.g. MNSSM, singlets to break extra gauge groups, etc) We take the NMSSM to be a prototype for "μ-solvable" models. The necessary features for light dark matter should be found in any μ-solvable model.

Light Neutralinos in the NMSSM

The MSSM can allow a massless neutralino. Solving $\det M_{\chi^0} = 0$:

$$M_1 = \frac{M_Z^2 \sin^2\theta_W \sin(2\beta) M_2}{M_2\mu - M_W^2 \sin(2\beta)} \tag{7}$$

This gives 80MeV $< M_1 <$ 16GeV for reasonable parameters.

By a similar analysis, the NMSSM can also allow a massless neutralino (with M_1 as large as 55 GeV).

To evade $Z \to invisible$ constraints, a neutralino lighter than $M_Z/2 \simeq$ 45 GeV must be mostly bino or mostly singlino. Given an LSP with an eigenvector:

$$\chi^0 = \epsilon_u \tilde{H}_u^0 + \epsilon_d \tilde{H}_d^0 + \epsilon_W \tilde{W}^0 + \epsilon_B \tilde{B} + \epsilon_s \tilde{S}, \tag{8}$$

the invisible Z decay constraint limits $|\epsilon_u^2 - \epsilon_d^2| \lesssim 6\%$.

The lightest neutralino (LSP) can be any linear combination of bino and singlino, since for a given singlino mass we can tune M_1 to be near it, and therefore get any singlino-bino mixing angle we want.

Light A_1 in the NMSSM

There are two CP-odd A bosons in the NMSSM. After removing the goldstone corresponding to the Z, we can write the lightest as:

$$A_1 = \cos\theta_A A_{\mathrm{MSSM}} + \sin\theta_A A_S. \tag{9}$$

In either the large $\tan\beta$ limit or large $\langle S\rangle$ limits, $M^2_{A_1} \simeq 3\kappa A_\kappa \langle S\rangle$. (Alternatively: $M^2_{A_1} = 3\frac{\kappa}{\lambda} A_\kappa \mu$)

Thus, A_1 will be light and mostly singlet in the small κ and/or small A_κ limits.

The light A_1 can also be MSSM-like if the angle $\cos\theta_A$ is large. This is possible but constrained. For $M_{\chi^0} < 5$ GeV:

$\cos\theta_A \tan\beta < 5$	LEP $Z \to b\bar{b}b\bar{b}$ or $\tau^+\tau^-\tau^+\tau^-$
$\cos\theta_A \tan\beta < 3$	$b \to s\gamma$, $B_s \to \mu\mu$, and $(g-2)_\mu$
$\cos\theta_A \tan\beta < 0.5$	$\Upsilon \to \gamma\chi^0\chi^0$ ($M_{\chi^0} < 1.5$ GeV)

$U(1)$ symmetries give a small M_A

$$W = \lambda S H_u H_d + \kappa S^3 \qquad V_{soft} = \lambda A_\lambda S H_u H_d + \kappa A_\kappa S^3 \tag{10}$$

$$Q_{H_u} = 1 \qquad Q_{H_d} = 1 \qquad Q_S = -2 \tag{11}$$

This is a Peccei-Quinn symmetry. Superpotential λ term is symmetric, soft M_i are symmetric, Yukawa's are symmetric. Broken explicitly by κ and A_κ. Symmetry is approximate in $\kappa \ll 1, A_\kappa \ll M_{SUSY}$ limit. [Miller, Moretti, Nevzorov, `hep-ph/0501139` (among others)]

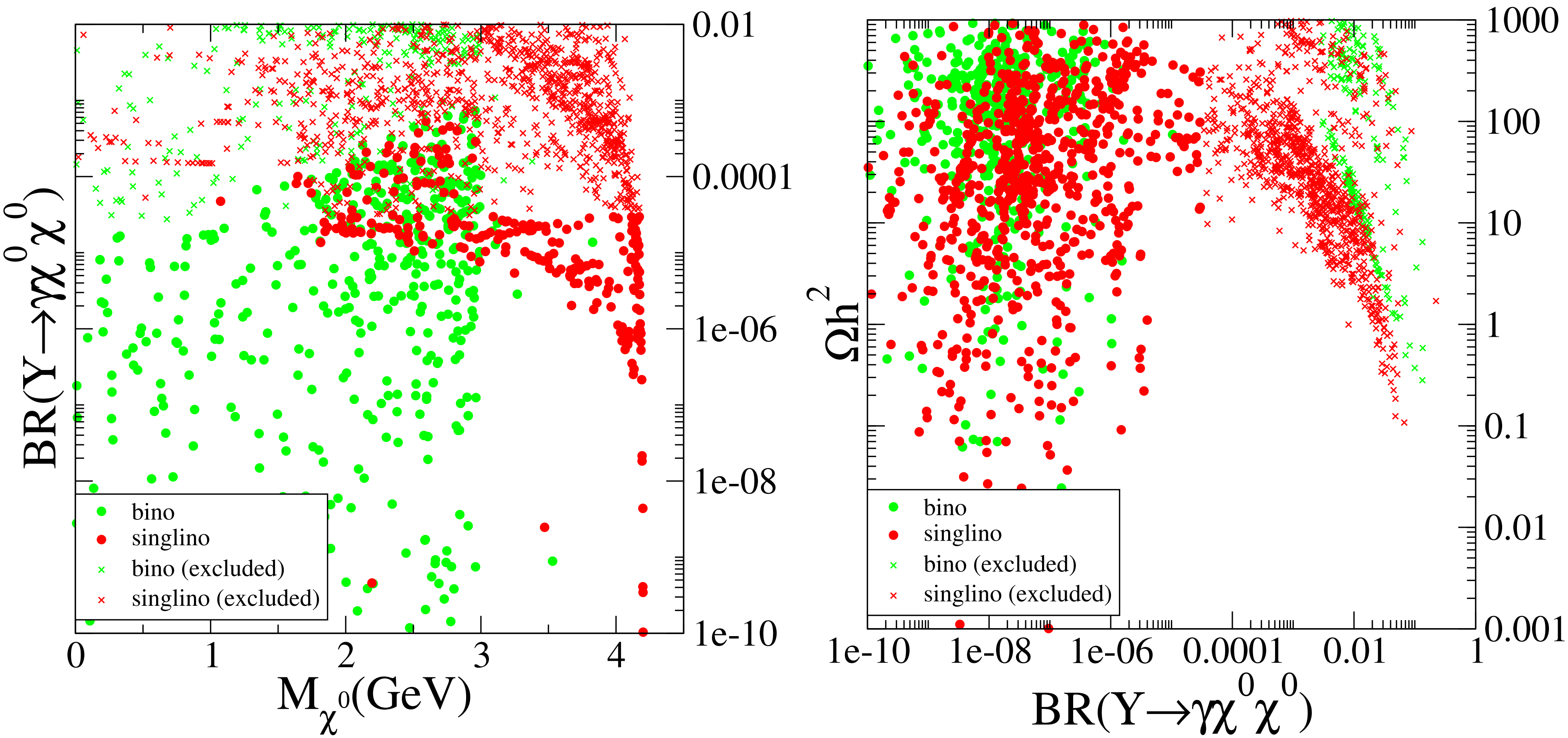
$$Q_{H_u} = 1 \qquad Q_{H_d} = 1 \qquad Q_S = 1 \tag{12}$$

This is an R-symmetry (not respected by supersymmetry). Broken by soft SUSY breaking trilinear terms A_λ, A_κ. Symmetry is approximate in $\kappa A_\kappa, \lambda A_\lambda \ll M_{SUSY}$ limit. [Matchev, Cheng, `hep-ph/0008192`]

In *both* cases, A_1 is the PNGB of the broken symmetry.

R-symmetry also broken by radiative corrections.

Υ decays and relic density

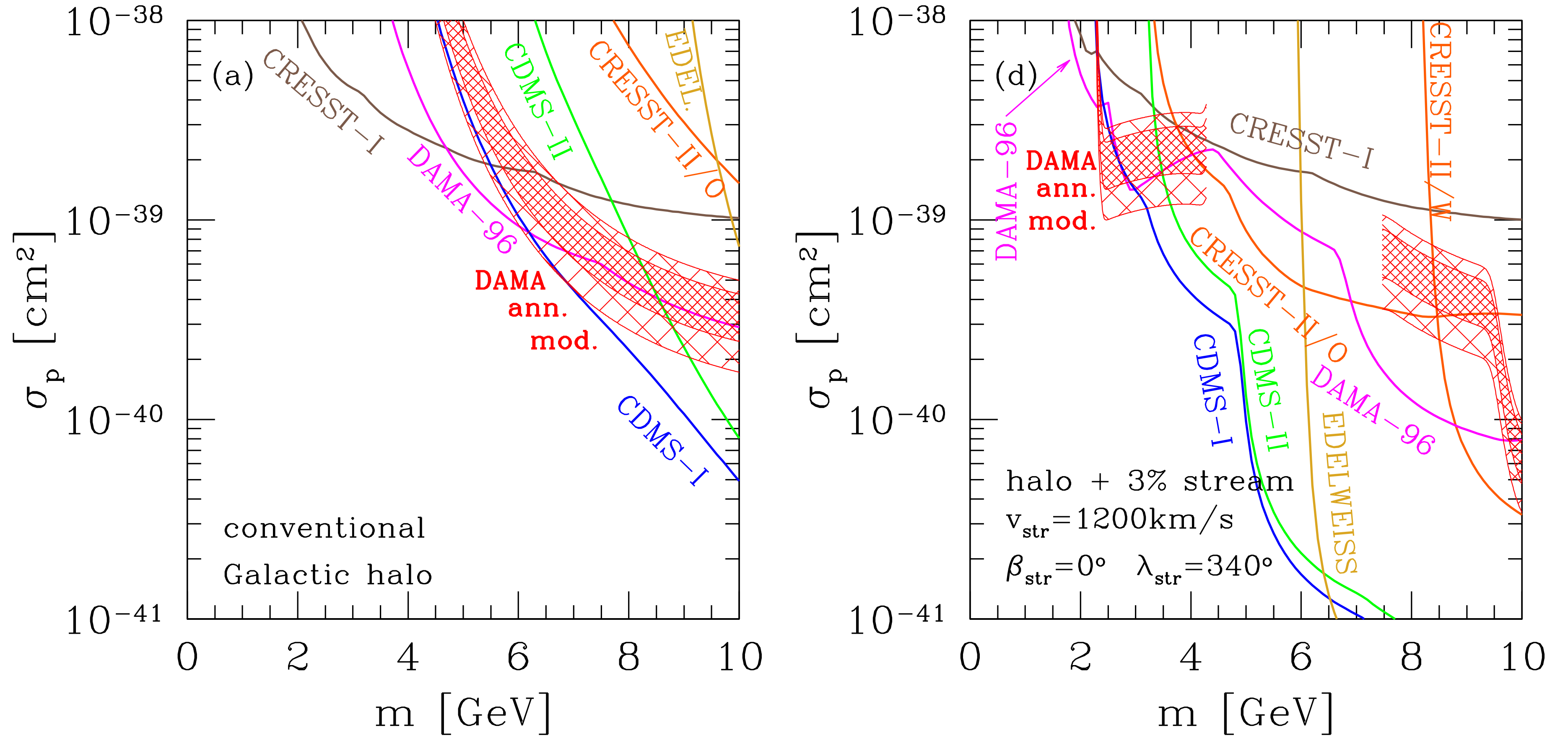


CLEO limits are $BR(\Upsilon \to \gamma\chi^0\chi^0) \simeq 3 \times 10^{-5}$ for $M_{\chi^0} < 1.5$ GeV.
CLEO used only 48 pb^{-1} of data (about 1M $\Upsilon(1S)$). They have 20 times this recorded. BaBar and Belle have produced about 5M $\Upsilon(1S)$ each with ISR.
This measurement can be drastically improved with existing data!

Direct Detection Prospects and DAMA

$$\sigma_{\rm elastic} \sim 4\times 10^{-45}{\rm cm}^2 \left(\frac{120{\rm GeV}}{M_H}\right)^4 \left(\left(\frac{M_H}{120{\rm GeV}}\right)^{3/2} + 0.1\right)^2 \left(\frac{\tan\beta}{10}\right)^2 {\rm F}_\lambda$$

where $F_\lambda = 1$ for a bino-like neutralino and $F_\lambda = 2\lambda^2/g'^2 \simeq 0.67 \times (\lambda/0.2)^2$ for singlino. ϵ_H is the higgsino fraction of the χ^0.



A solution to INTEGRAL?

Anihilation to electrons requires $M_{\chi^0} < 20$ MeV from gamma-ray considerations [Beacom]. Since annihilation mediator is a higgs, annihilation is extremely inefficent due to small electron Yukawa.

Consider instead annihilation to muons, which decay to electrons. Need $M_\mu < M_{\chi^0} < M_{\pi^+} + M_{\pi^0}/2$ or 106MeV $< M_{\chi^0} <$ 207 MeV.

Therefore 212MeV $\lesssim M_A \lesssim$ 414MeV.

Also need $\cos\theta_A \tan\beta < 0.13$ to evade $\Upsilon \to A_1\gamma$.

Correct relic density can be obtained for $M_{A_1} \simeq 2M_{\chi^0} \pm 10$ MeV.

Can be confirmed by improving the $\Upsilon \to A_1\gamma$ measurement with existing data from CLEO, BaBar, Belle!

Conclusions

Model-independence is *the* way to disentagle the zoo of models, at *all* energies. These considerations force us to consider DM that couples preferentially to some particles and not others, and mediators that are scalars, pseudoscalars, or vectors. *NO* region of mediator or DM mass is definitively ruled out.

An arbitrarily light A_1 and χ^0 are allowed in SUSY.

A light bino/singlino in the NMSSM can reconcile DAMA and CDMS-II, especially if there is some "wind" of dark matter through our local area, and the H_1 is also light. (But this is fine-tuned)

A light bino/singlino can explain the INTEGRAL observation.

$\Upsilon \to \gamma A_1$ and invisible decays of quarkonia should be pursued immediately at colliders such as BaBar, Belle, and CLEO to discover such light dark matter.

Direct detection prospects look bleak if the DM couples preferentially to heavy quarks/leptons.

Experimentalist's Conclusion

The measurements at BaBar that are sensitive to dark matter are:

$$\begin{aligned} \Upsilon &\to invisible \\ J/\Psi &\to invisible \\ \eta &\to invisible \\ \Upsilon &\to \gamma + invisible \\ B^{+} \to K^{+} &+ invisible \end{aligned}$$

But there are issues to be worked out for invisible decays:

Triggering is a big issue
Track reconstruction for soft tracks
Measure photon-fusion backgrounds in the range $0 < Q^2 < 1$ GeV.

Can tweaks be made to improve background? (e.g. machine running at higher energy?)

Theorist's Conclusion

If invisible Υ or J/Ψ decays are present, what is the model?

Can $\lambda << 1$ and/or $\kappa << 1$ be natural?
SUSY breaking models which generate small trilinears
Vector-mediated DM annihilation anyone?

A light A_1 and bino or singlino χ^0 is technically natural in μ-solvable models such as the NMSSM.

An arbitrarily light A_1 and χ^0 are allowed.

A light bino/singlino in the NMSSM can reconcile DAMA and CDMS-II, especially if there is some "wind" of dark matter through our local area, and the H_1 is also light.

A light bino/singlino can explain the INTEGRAL observation.

Direct detection prospects look bleak unless H_1 is very light.

Reference Formulae

$$M_{\chi^0} = \begin{bmatrix} M_1 & 0 & -\frac{1}{\sqrt{2}}g'v\cos\beta & \frac{1}{\sqrt{2}}g'v\sin\beta & 0 \\ 0 & M_2 & \frac{1}{\sqrt{2}}gv\cos\beta & -\frac{1}{\sqrt{2}}gv\sin\beta & 0 \\ -\frac{1}{\sqrt{2}}g'v\cos\beta & \frac{1}{\sqrt{2}}gv\cos\beta & 0 & -\lambda x & -\lambda v\sin\beta \\ \frac{1}{\sqrt{2}}g'v\sin\beta & -\frac{1}{\sqrt{2}}gv\sin\beta & -\lambda x & 0 & -\lambda v\cos\beta \\ 0 & 0 & -\lambda v\sin\beta & -\lambda v\cos\beta & 2\kappa x \end{bmatrix}$$

$$M_A^2 = \begin{bmatrix} \frac{2\lambda x(\kappa x + A_\lambda)}{\sin 2\beta} & -2\lambda v\kappa x + \lambda A_\lambda v \\ -2\lambda v\kappa x + \lambda A_\lambda v & \left(2\kappa\lambda v^2 + \lambda A_\lambda \frac{v^2}{2x}\right)\sin 2\beta + 3\kappa A_\kappa x \end{bmatrix}$$

$$\tan 2\theta_A = \frac{4\sin(2\beta)\lambda v x(2\kappa x - A_\lambda)}{2x^2(2\lambda\kappa x - 3\kappa A_\kappa \sin(2\beta) + 2\lambda A_\lambda) - \lambda v^2 \sin^2(2\beta)(4\kappa x + A_\lambda)}$$

Relic Density Calculation

The relic density is given by:

$$\langle \sigma v \rangle = \frac{1}{m_{\chi^0}^2}[1 - \frac{3T}{m_{\chi^0}}]\omega(s)|_{s \to 4m_{\chi^0}^2 + 6m_{\chi^0}T} + \mathcal{O}(T^2),$$

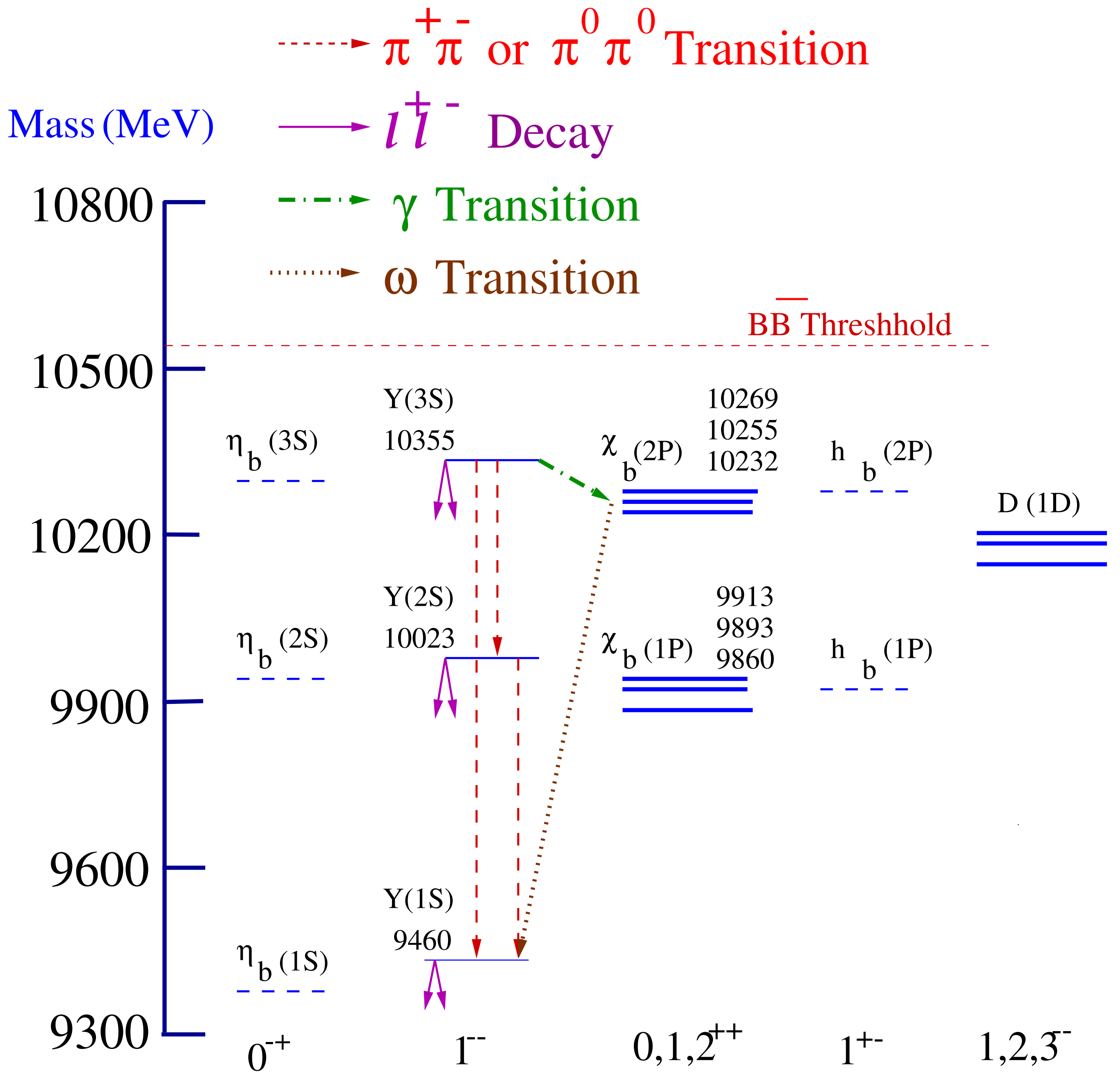
The squared amplitudes for the processes, $\chi^0\chi^0 \to A \to f\bar{f}$ and $\chi^0\chi^0 \to H \to f\bar{f}$, averaged over the final state angle are given by:

$$\omega_{f\bar{f}}^A = \frac{C_{ffA}^2 C_{\chi^0\chi^0 A}^2}{(s - m_A^2)^2 + m_A^2 \Gamma_A^2} \frac{s^2}{16\pi} \sqrt{1 + \frac{4m_f^2}{s}},$$

where

$$\begin{aligned}
C_{\chi^0\chi^0 A} &= \cos\theta_A \left[(g_2\epsilon_W - g_1\epsilon_B)(\epsilon_d \cos\beta - \epsilon_u \sin\beta)\right] \\
&+ \cos\theta_A \left[\sqrt{2}\lambda\epsilon_s(\epsilon_u \sin\beta + \epsilon_d \cos\beta)\right] \\
&+ \sin\theta_A \sqrt{2}\left[\lambda\epsilon_u\epsilon_d - \kappa\epsilon_s^2\right] \\
C_{ffA} &= \frac{m_f}{\sqrt{2}v}\cos\theta_A \tan\beta. \\
A_1 &= \cos\theta_A A_{\mathrm{MSSM}} + \sin\theta_A A_s \\
\chi^0 &= \epsilon_u \tilde{H}_u^0 + \epsilon_d \tilde{H}_d^0 + \epsilon_W \tilde{W}^0 + \epsilon_B \tilde{B} + \epsilon_s \tilde{S}
\end{aligned}$$

Bottomonium Spectra



photon fusion backgrounds to $\Upsilon(nS) \to \Upsilon(1S)\pi^+\pi^-$

In photon fusion, each incoming electron emits a photon and is scattered by a small angle.

l^+l^- photon fusion background can be removed since the leptons are back-to-back.

$e/\mu/\pi/K$ particle ID generally fails at these low momenta. $\pi^+\pi^-\gamma$ is about an order of magnatude smaller.

Backgrounds to $\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$

cut	$\gamma\gamma \to l^+l^-$	$\gamma\gamma \to$ hadrons	$\gamma\gamma \to l^+l^-\gamma$
$\pi^+\pi^-\gamma$ selection	228 fb	866 fb	44.9 pb
$-1.1 < \cos\theta < 1.1$	$<$ 0.1 fb	3.7 fb	1.40 pb
$\lvert\cos\theta - \cos\theta_{\text{meas}}\rvert < 0.15$	$<$ 0.1 fb	0.5 fb	197 fb
$\lvert E_\gamma - E_{\text{ISR}}\rvert <$ 6MeV	$<$ 0.1 fb	$<$ 0.1 fb	5.4 fb
Backgrounds to $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$			
$\pi^+\pi^-\gamma$ selection	228 fb	866 fb	44.9 pb
$-1.1 < \cos\theta < 1.1$	$<$ 0.1 fb	0.8 fb	3.65 pb
$\lvert\cos\theta - \cos\theta_{\text{meas}}\rvert < 0.035$	$<$ 0.1 fb	$<$ 0.1 fb	108 fb
$\lvert E_\gamma - E_{\text{ISR}}\rvert <$ 15MeV	$<$ 0.1 fb	$<$ 0.1 fb	1.6 fb

Di-tau backgrounds to $\Upsilon(nS) \to \Upsilon(1S)\pi^+\pi^-$

Tau's are the only states which have true missing energy (ν).

$BR(\Upsilon \to \nu\bar{\nu}) \simeq 1 \times 10^{-5}$ due to M_Υ / M_Z suppression.

Backgrounds to $\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	
cut	$\tau^+\tau^-$
$\pi^+\pi^-\gamma$ selection	71.8 pb
$-1.1 < \cos\theta < 1.1$	120.8 fb
$\lvert \cos\theta - \cos\theta_{\text{meas}} \rvert < 0.15$	16.2 fb
$\lvert E_\gamma - E_{\text{ISR}} \rvert < 6\text{MeV}$	< 0.1 fb
Backgrounds to $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	
$\pi^+\pi^-\gamma$ selection	71.8 pb
$-1.1 < \cos\theta < 1.1$	60.7 fb
$\lvert \cos\theta - \cos\theta_{\text{meas}} \rvert < 0.035$	2.1 fb
$\lvert E_\gamma - E_{\text{ISR}} \rvert < 15\text{MeV}$	< 0.1 fb

Extra photon must come from π^0 decay, or initial/final state radiation.

If the photon were *unobserved*, this background completely swamps the signal. (Imagine two 1-prong tau decays)

Two-body backgrounds to $\Upsilon(nS) \to \Upsilon(1S)\pi^+\pi^-$

This background is where the $\Upsilon(1S)$ decays into any 2-body state, and those particles disappear outside the detector acceptance.

cut	$\Upsilon(1S) \to l^+l^-$
Backgrounds to $\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	
$\pi^+\pi^-\gamma$ selection	1.41 fb
$-1.1 < \cos\theta < 1.1$	1.39 fb
$\|\cos\theta - \cos\theta_{\text{meas}}\| < 0.15$	1.20 fb
$\|E_\gamma - E_{\text{ISR}}\| < 6\text{MeV}$	1.06 fb
Backgrounds to $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	
$\pi^+\pi^-\gamma$ selection	3.97 fb
$-1.1 < \cos\theta < 1.1$	3.97 fb
$\|\cos\theta - \cos\theta_{\text{meas}}\| < 0.035$	2.80 fb
$\|E_\gamma - E_{\text{ISR}}\| < 15\text{MeV}$	2.52 fb

This background is irreducible, but can be directly measured and background-subtracted. The branching ratio for this background is $f_2\Omega$ with $f_2 = 5\%$ is the fraction of 2-body decays and $\Omega = 91.5\%$ is the fractional detector acceptance.

P_T cuts are not useful

A p_T cut is not useful since the required p_T would be larger than the sum of all the momenta in the event.

$$(p_r)_T > \frac{1}{2}(E_{CM} - E_{ISR} - E_r)\sin\theta_{min} \simeq 2\mathrm{GeV}, \tag{13}$$

For a collider running at $\mathcal{O}(30GeV)$, requiring the ISR photon to be visible provides enough transverse momentum that the decay products of the final state must lie in the detector acceptance. However, the ISR production cross section of Υ's is reduced by a factor ~ 100. This requirement also eliminates most of the two-photon background.

Electroweak Baryogenesis

In MSSM:

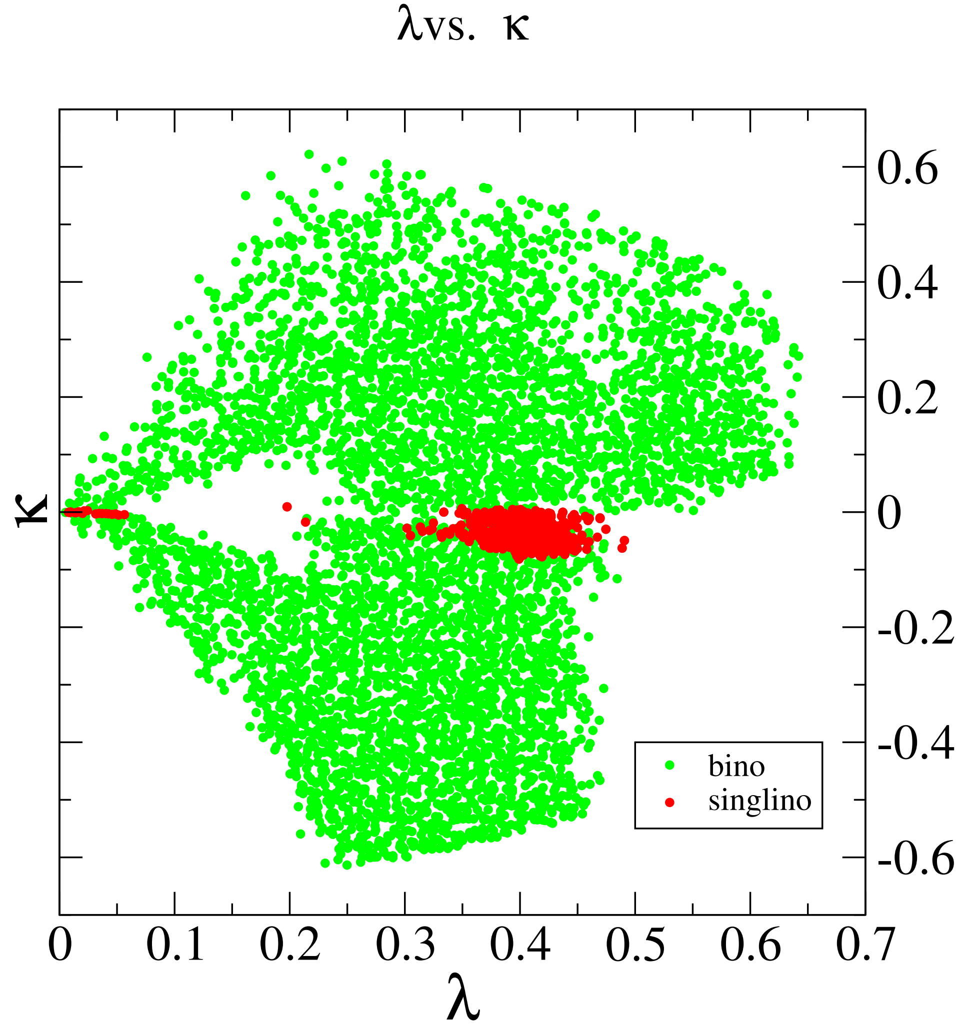
- Two-loop stop effects required to enhance phase transition.

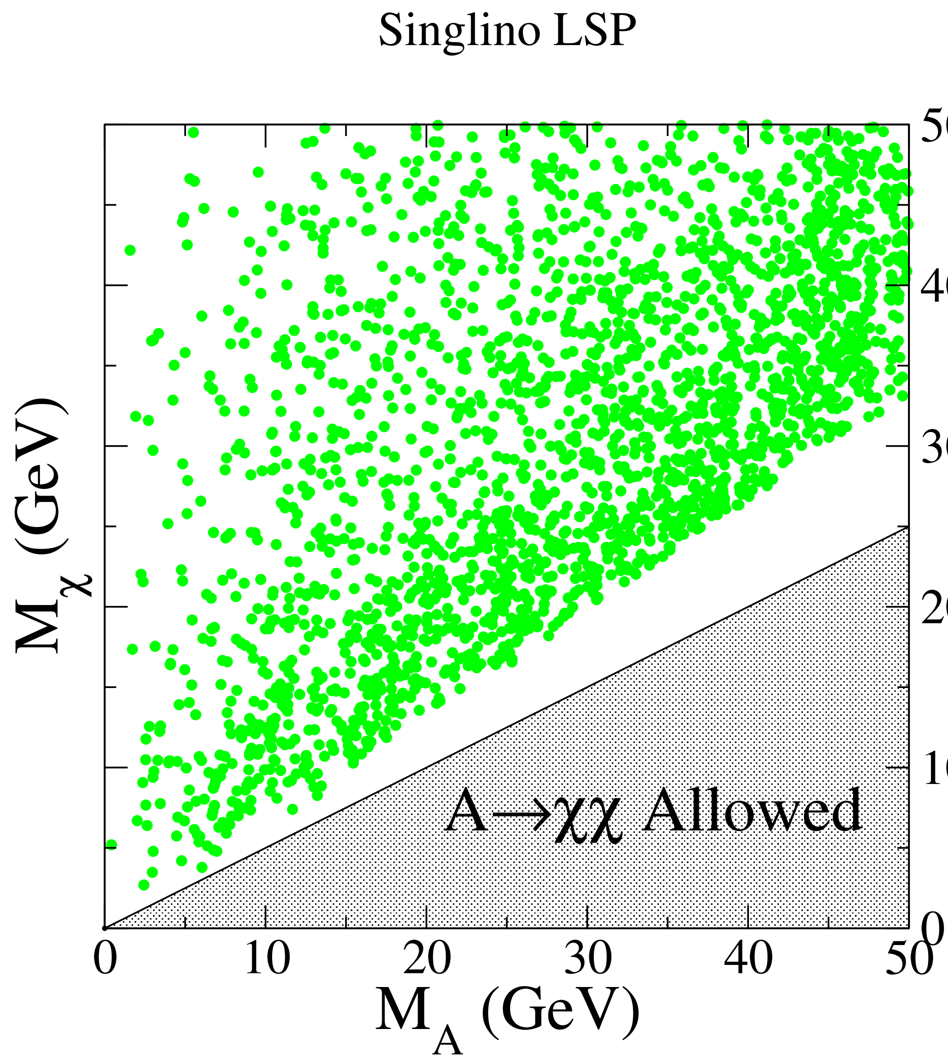
- Requires $105 < M_{\tilde{t}} < 165$ and $110 < M_h < 115$. [Quiros hep-ph/0101230]

NMSSM can easily get strong first-order phase transition without light stop, due to new trilinear soft SUSY terms.

A_1 also tends to be light, especially for large $\tan\beta$
[Menon, Morrissey, Wagner hep-ph/0404184]
[Ham, Oh, Kim, Yoo, Son hep-ph/0406062]

Parameter Space

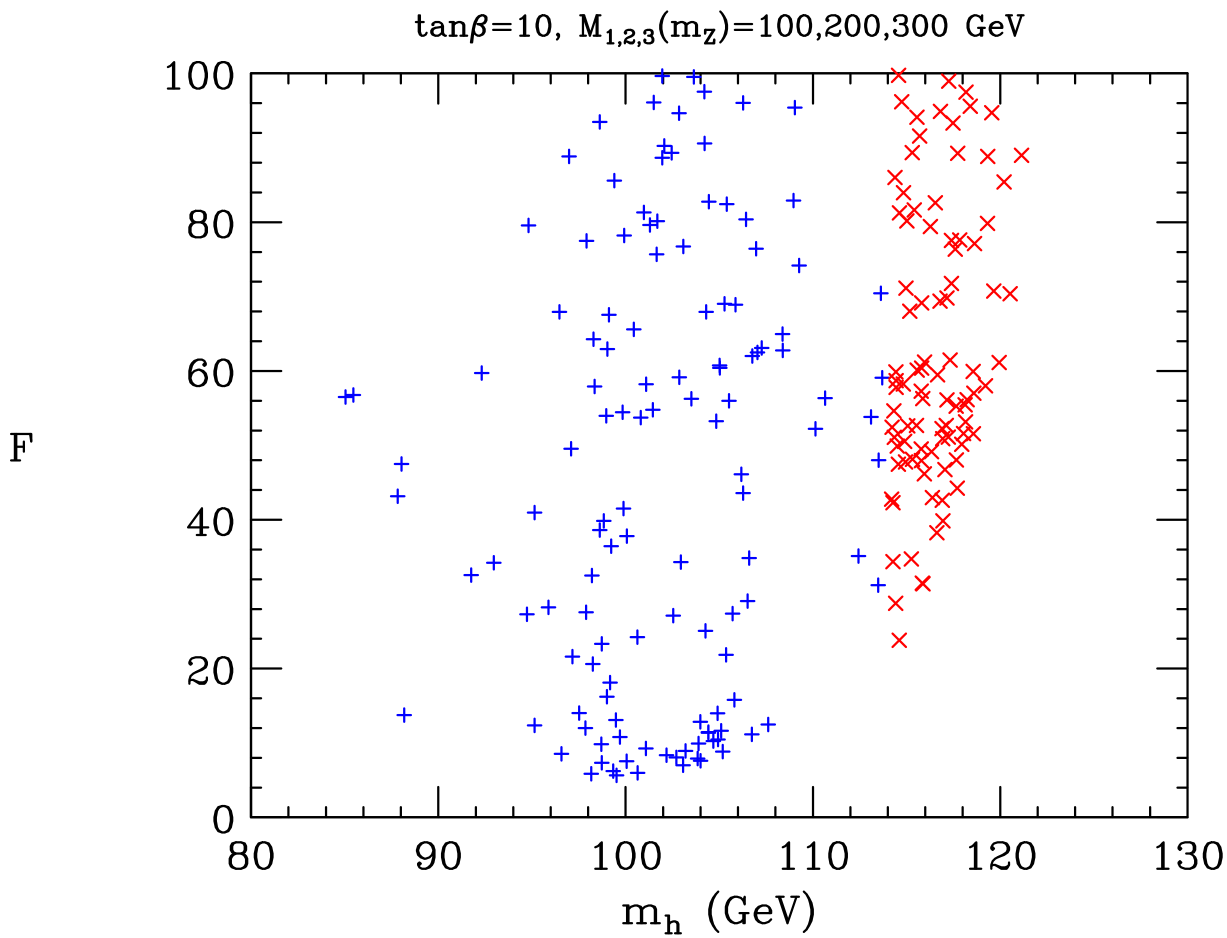




When both singlet A_1 and singlino are light, mass relationships do not allow $A_1 \to \chi^0\chi^0$. ($M_{\chi^0} \simeq 2\kappa x$, $M^2_{A_1} \simeq 3\kappa A_\kappa x$) Up to 80% singlino can be allowed with appropriate relic density.

We *want* a light A_1

A light A_1 can eliminate the fine-tuning problem in the MSSM.



Dermisek, Gunion, `hep-ph/0502105`

Indirect Constraints

Binos, winos and singlinos do not couple to the Z directly. $\Rightarrow Z \to invisible$ only constrains the higgsino component of the LSP. Given an LSP with an eigenvector:

$$\chi^0 = \epsilon_u \tilde{H}_u^0 + \epsilon_d \tilde{H}_d^0 + \epsilon_W \tilde{W}^0 + \epsilon_B \tilde{B} + \epsilon_s \tilde{S}, \tag{14}$$

the invisible Z decay constraint limits $|\epsilon_u^2 - \epsilon_d^2| \lesssim 6\%$.

The wino component of the LSP is limited by direct chargino searches, which force M_2 large. $\Rightarrow$ The LSP must be a linear combination of bino and singlino.

We computed $(g-2)_\mu$, $b \to s\gamma$, $B_s \to \mu\mu$, Z invisible width, all LEP constraints on higgses, and $\Upsilon \to A_1\gamma$ where the A_1 decays visibly or invisibly, in a 2-body or 3-body decay.

Constraints generally limit the product $\cos\theta_A \tan\beta$, but a light A_1 or bino generally have small effects that can be compensated or cancelled by other things in the theory (e.g. squarks, H^+, χ^+, etc).

Trade-off: lighter A_1/χ^0 or improved constraints $\Rightarrow$ must be closer to relation $M_{A_1} \simeq 2M_{\chi^0}$.

Muon anomalous magnetic moment

The one-loop contribution to $(g-2)_\mu$ comes from a triangle diagram with a smuon on two sides, and the neutralino on the third. This leads to:

$$\delta a_\mu^{\chi^0} \sim 2.3 \times 10^{-11} (\frac{m_{\chi^0}}{10\,\mathrm{GeV}})(\frac{200\,\mathrm{GeV}}{m_{\tilde{\mu}}})^4 (\frac{\mu \tan\beta - A_{\tilde{\mu}}}{1000\,\mathrm{GeV}}). \qquad (15)$$

The light A_1 can contribute at 1-loop and 2-loops:

$$\begin{aligned}
\delta a_\mu^{A\,1+2\,\mathrm{loop}} &\approx -7 \times 10^{-11} \times \cos^2\theta_A \tan^2\beta \quad \text{for } \mathrm{m_A} = 1\,\mathrm{GeV}, \\
\delta a_\mu^{A\,1+2\,\mathrm{loop}} &\approx 1.7 \times 10^{-12} \times \cos^2\theta_A \tan^2\beta \quad \text{for } \mathrm{m_A} = 10\,\mathrm{GeV}.
\end{aligned}$$

The experimental limits are:

$$\begin{aligned}
\delta a_\mu(e^+e^-) &= 23.9 \pm 7.2_{\mathrm{had-lo}} \pm 3.5_{\mathrm{lbl}} \pm 6_{\mathrm{exp}} \times 10^{-10} \\
\delta a_\mu(\tau^+\tau^-) &= 7.6 \pm 5.8_{\mathrm{had-lo}} \pm 3.5_{\mathrm{lbl}} \pm 6_{\mathrm{exp}} \times 10^{-10}
\end{aligned}$$

Thus only for a light smuon, or large $\cos\theta_A \tan\beta$ are we in danger of violating $(g-2)_\mu$. Contributions from other SUSY particles can also be arranged to cancel these contributions, if they were too large.

Rare kaon decays

The decay $K^+ \to \pi^+ \nu \bar{\nu}$ was recently measured by the E787 and E949 experiments (*Holy Tiny Number Batman!*):

$$BR(K^+ \to \pi^+ \nu \bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10} \tag{16}$$

is nearly twice the predicted Standard Model branching ratio

$$BR(K^+ \to \pi^+ \nu \bar{\nu}) = (0.67^{+0.28}_{-0.27}) \times 10^{-10}. \tag{17}$$

The leading process involves a loop of W^+ bosons, and *two* A_1's in the final state since there is no $W^+ W^- A_1$ vertex. This means *four* χ^0 in the final state, with a mass less than 88.5 MeV to be kinematically allowed.

$\Rightarrow M_\chi^0 < 88.5$ MeV is ruled out.

However if this is the explanation of the INTEGRAL signal and $\chi^0 \chi^0 \to A_1 \to e^+ e^-$, $M_{\chi^0} \lesssim 20$ MeV by COMPTEL and EGRET gamma ray constraints. [Beacom, Bell, Bertone, `astro-ph/0409403`]

Rare B-Meson Decays

We compute $B_s \to \mu\mu$ and $b \to s\gamma$ directly using MicrOmegas. [Bélanger, Boudjema, Pukhov, Semenov, `hep-ph/0405253`]

CDF places an upper limit $BR(B_s \to \mu^+\mu^-) < 5.8 \times 10^{-7}$.

$b \to s\gamma$ has been measured by BaBar, Belle, CLEO, and ALEPH, giving $BR(B \to X_s\gamma) = (3.25 \pm 0.37) \times 10^{-4}$. SUSY processes that contribute to this must involve either a charged Higgs boson or chargino, which we can take to be heavy to evade all constraints.

These constraints, taken together, generally restrict $|\cos\theta_A \tan\beta| < 12$, and are not very strong.

$B^+ \to K^+ + invisible$ also provides a constraint. In scalar dark matter scenarios, this may be 50 times larger than the SM process. [Bird, Jackson, Kowalewski, Pospelov, `hep-ph/0401195`]

Υ and J/Ψ Decays

If kinematically allowed, vector resonances can decay into a photon and A_1.

$$\frac{\Gamma(V \to \gamma A)}{\Gamma(V \to \mu\mu)} = \frac{G_F m_b^2}{\sqrt{2}\alpha\pi}\left(1 - \frac{M_H^2}{M_V^2}\right)\cos^2\theta_A x^2. \tag{18}$$

where $x = \tan\beta$ for Υ and $x = \cot\beta$ for J/Ψ.

The 3-body decay $\Upsilon \to \chi^0\chi^0\gamma$ is also measured.

It is claimed that by measuring both $\Upsilon \to A_1\gamma$ and $J/\Psi \to A_1\gamma$, the standard axion is ruled out. However

$$BR(\Upsilon \to A_1\gamma) \times BR(J/\Psi \to A_1\gamma) \propto \cos^4\theta_A \tag{19}$$

which is generally quite small. Thus we can evade these limits even for $M_\chi^0 < M_{J/\Psi}/2$.

Direct Detection Prospects

Direct detection occurs dominantly through t-channel exchange of a CP-even higgs.

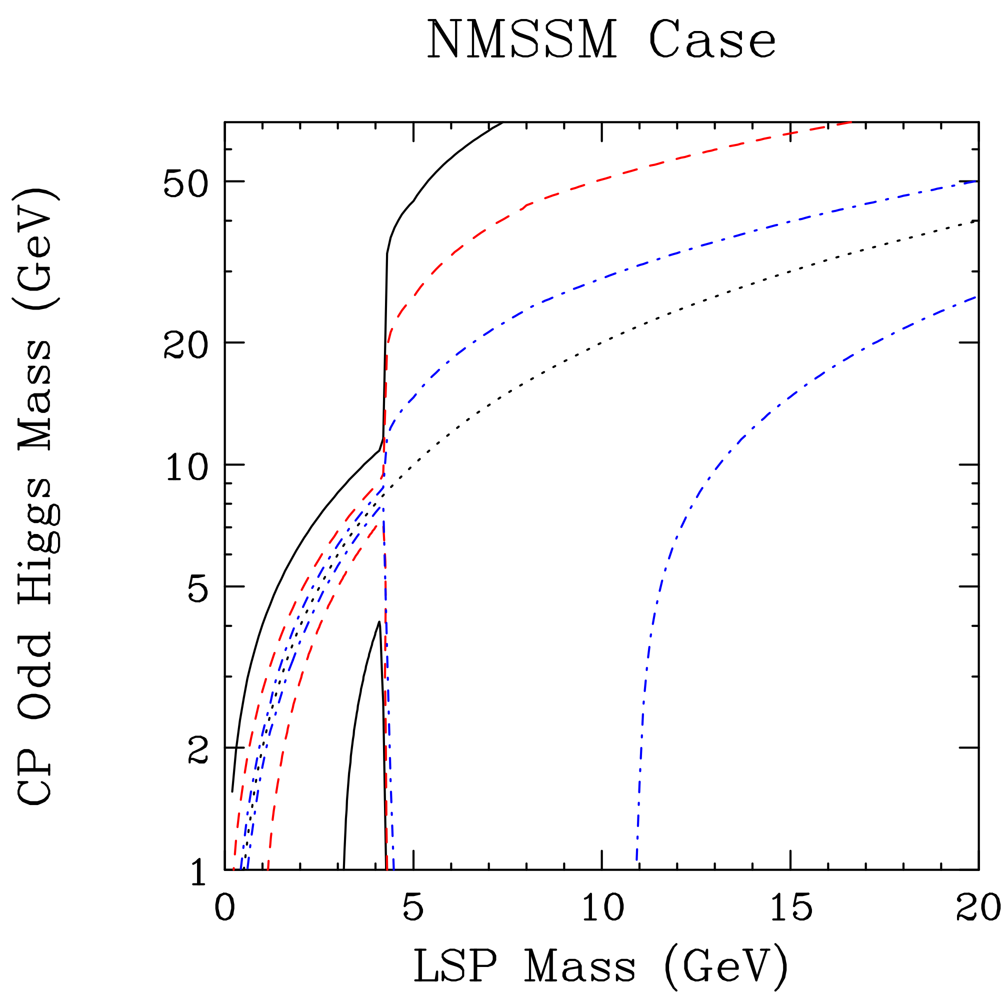
Very light dark matter generally has problems with detection thresholds.

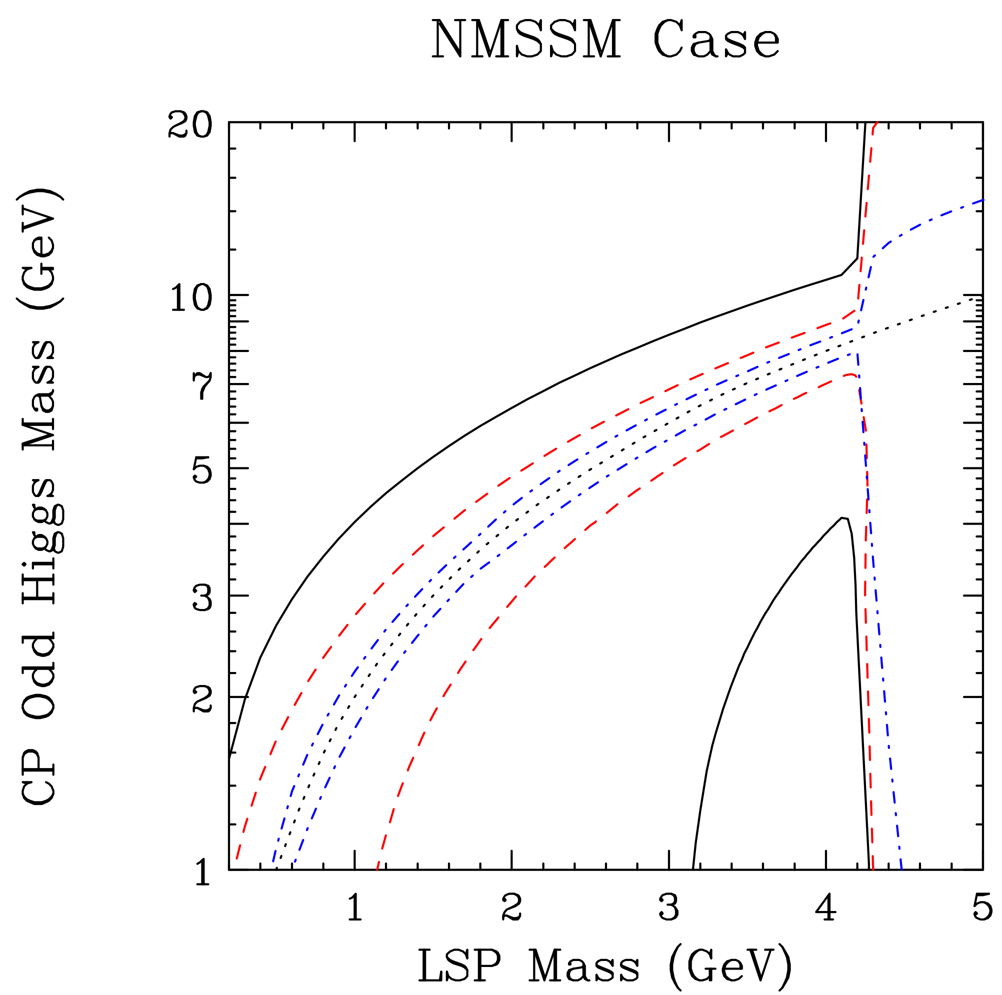
$$\sigma \approx \sum_H \frac{16 G_F^2 m_z^2 v^2 \cos^2\theta_W}{\pi m_H^4 g_2^2 \sin^2\beta} \left(C_{\chi^0\chi^0 H} C_{ffH}\right)^2 \left(\frac{m_p m_{\chi^0}}{m_p + m_{\chi^0}}\right)^2 \left(\sum_q \langle N|q\bar{q}|N\rangle\right)^2$$

Where

$$\begin{aligned} C_{\chi^0\chi^0 H} &= (g_1\epsilon_B - g_2\epsilon_W)(\epsilon_d\xi_u - \epsilon_u\xi_d) \\ &+ \sqrt{2}\lambda\epsilon_s(\epsilon_d\xi_d + \epsilon_u\xi_u) + \sqrt{2}\xi_s(\lambda\epsilon_u\epsilon_d - \kappa\epsilon_s^2) \\ C_{ffH} &= \frac{m_f}{\sqrt{2}v}\frac{\xi_d}{\cos\beta} \end{aligned}$$

Relic Density figures





These results are for ($\epsilon_B^2 = 0.94$, $\epsilon_u^2 = 0.06$). $\tan\beta$=(50, 15 and 3) are shown as solid black, dashed red, and dot-dashed blue lines, respectively. Also shown as a dotted line is the contour corresponding to $2m_{\chi^0} = m_A$. For each set of lines, we have set $\cos^2\theta_A = 0.6$.

Kinematic Constraints

With one intermediate resonance with mass M_2, and the ISR photon *unobserved*, all but one kinematic variable is determined. Using the beam constraint and only the sum of pion momenta, p_r, we can predict the angle between p_r and the ISR photon:

$$E_{\mathrm{ISR}} = \frac{s - M_1^2}{2\sqrt{s}}, \qquad \cos\theta = \frac{\sqrt{s}}{p_r}\frac{M_1^2 - M_2^2 + M_r^2}{s - M_1^2} - \frac{E_r}{p_r}\frac{s + M_1^2}{s - M_1^2} \tag{20}$$

A cut on $\cos\theta$ is equivalent to a cut on $\Delta M^2 = M_1^2 - M_2^2$.

When the ISR photon is observed, the event is *overconstrained*.

With *two* intermediate resonances we can predict all kinematic variables with the ISR photon *unobserved*, and predict the angle between the ISR photon and the *second* radiative decay:

$$\cos\theta' = \frac{\sqrt{s}}{|\vec{r}_2|}\frac{M_2^2 - M_3^2 + r_2^2 + 2r_1 \cdot r_2}{s - M_1^2} - \frac{E_2}{|\vec{r}_2|}\frac{s + M_1^2}{s - M_1^2} \tag{21}$$

The ISR cross section for a particular final state f, with e^+e^- cross section $\sigma_f(s)$ is to first order:

$$\frac{d\sigma(s,x)}{dx} = W(s,x) \cdot \sigma_f(s(1-x)) \tag{22}$$

where $x = \frac{2E_\gamma}{\sqrt{s}}$, E_γ is the energy of the ISR photon in the nominal CM frame, and $\sqrt{s}$ is the nominal CM energy. The function

$$W(s,x) = \beta\left[(1+\delta)x^{(\beta-1)} - 1 + \frac{x}{2}\right] \tag{23}$$

describes the energy spectrum of the ISR photons, where $\beta = \frac{2\alpha}{\pi x}(2\ln\frac{\sqrt{s}}{m_e} - 1)$ and δ takes into account vertex and self-energy corrections. At the $\Upsilon(4S)$ energy, $\beta = 0.088$ and $\delta = 0.067$.

This function (Eq. 23) is strongly peaked in the forward and backward directions, so ISR photons will be close to the beamline. The fractional luminosity delivered to the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances is 1.9×10^{-5}, 3.2×10^{-5} and 5.0×10^{-5} respectively. This results in hundreds of thousands of events per resonance with current recorded luminosities.

The gaugino-mediated connection

In gaugino-mediated SUSY breaking, gauginos get soft masses M_{SUSY} first, and transmit SUSY breaking to the rest of the theory at 1-loop.

H_u and H_d are charged under $SU(2)_L$ and $U(1)_Y$, therefore we expect $A_\lambda \simeq M_{SUSY}/4\pi$.

S is *uncharged* under SM gauge symmetries. Therefore we expect $A_\kappa \simeq M_{SUSY}/16\pi^2$.

Other SUSY breaking scenarios generate small trilinears.