Super-B Considerations for Higgses and Dark Matter

Bob McElrath
CERN

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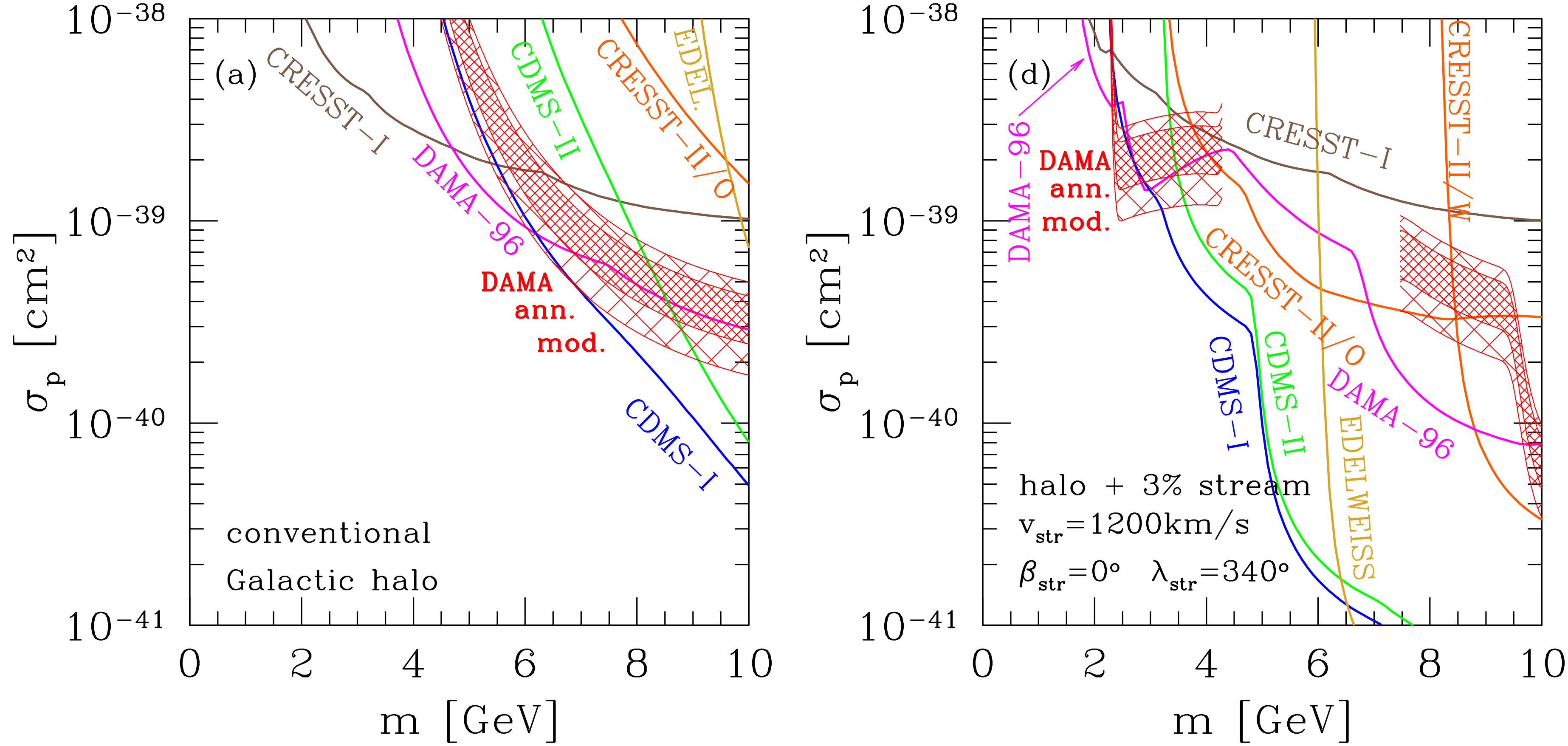
DAMA Evidence

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

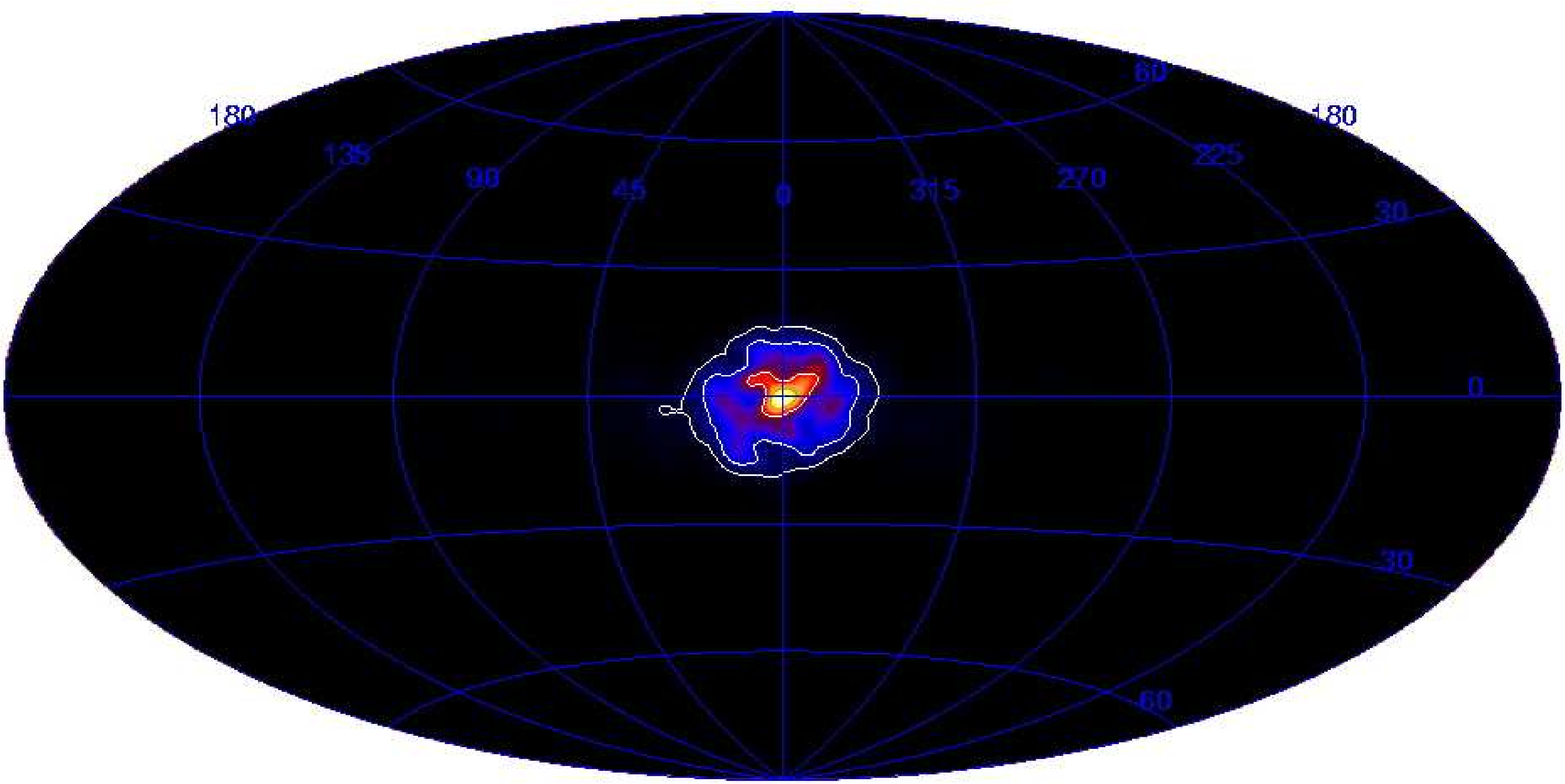
The SPI spectrometer aboard the INTEGRAL satellite observes a gaussian profile of 511 keV γ-rays coming from the inner kiloparsec of our galaxy. Attempt to explain this from astrophysical sources have failed thus far.

If this is coming from dark matter annihilation, the dark matter must be in the range $m_e < m_{\chi^0} < 20$ MeV (and possibly as low as 3 MeV: Yuksel [astro-ph/0609139]). This annihilation must not produce any π^0 or high-energy photons from $e^+e^-\gamma$ final state, 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.

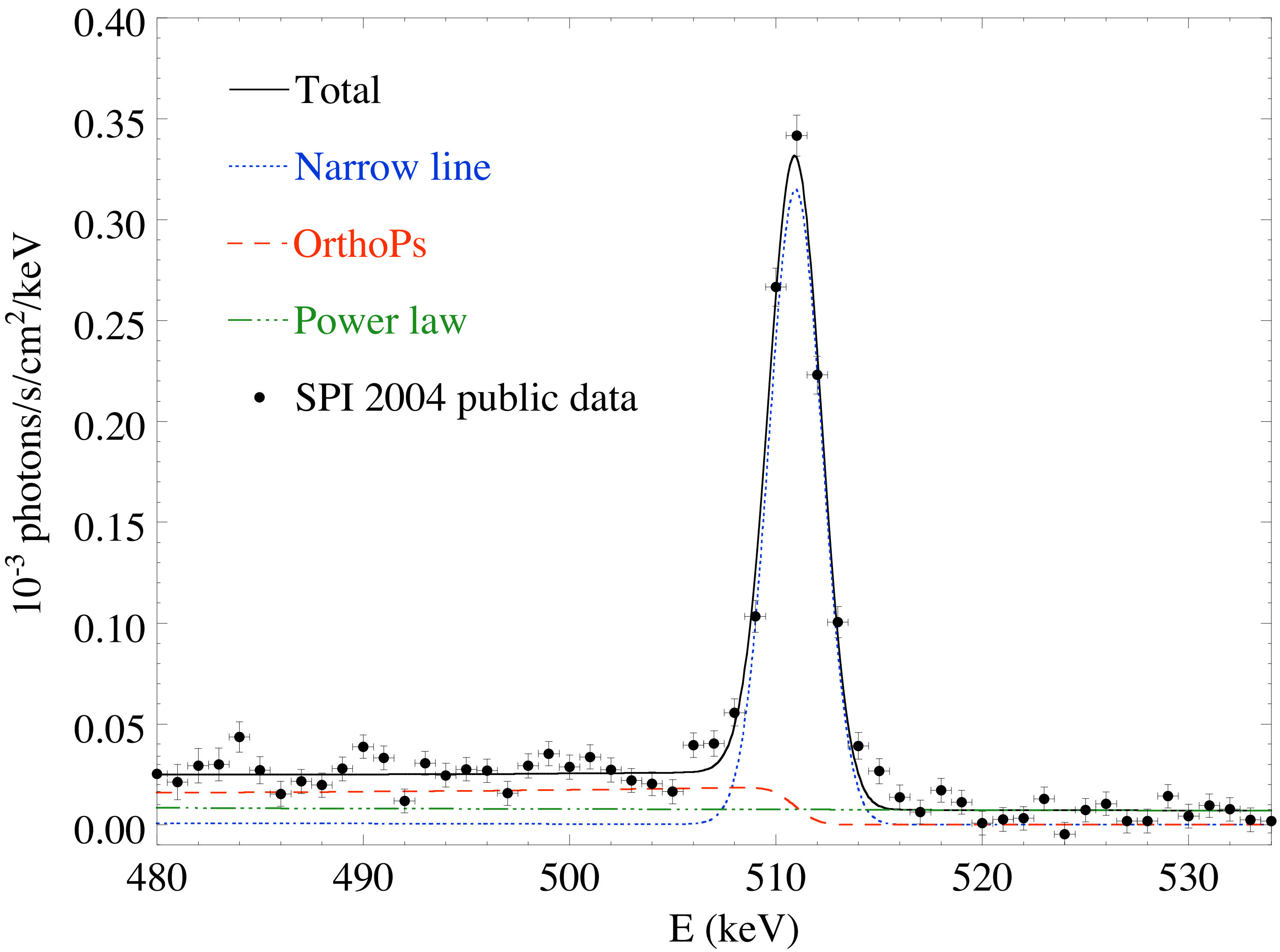
$\Rightarrow$ A new SM-DM annihilation mediator is required.

INTEGRAL Spectrum



[Knödlseder et. al. astro-ph/0506026]

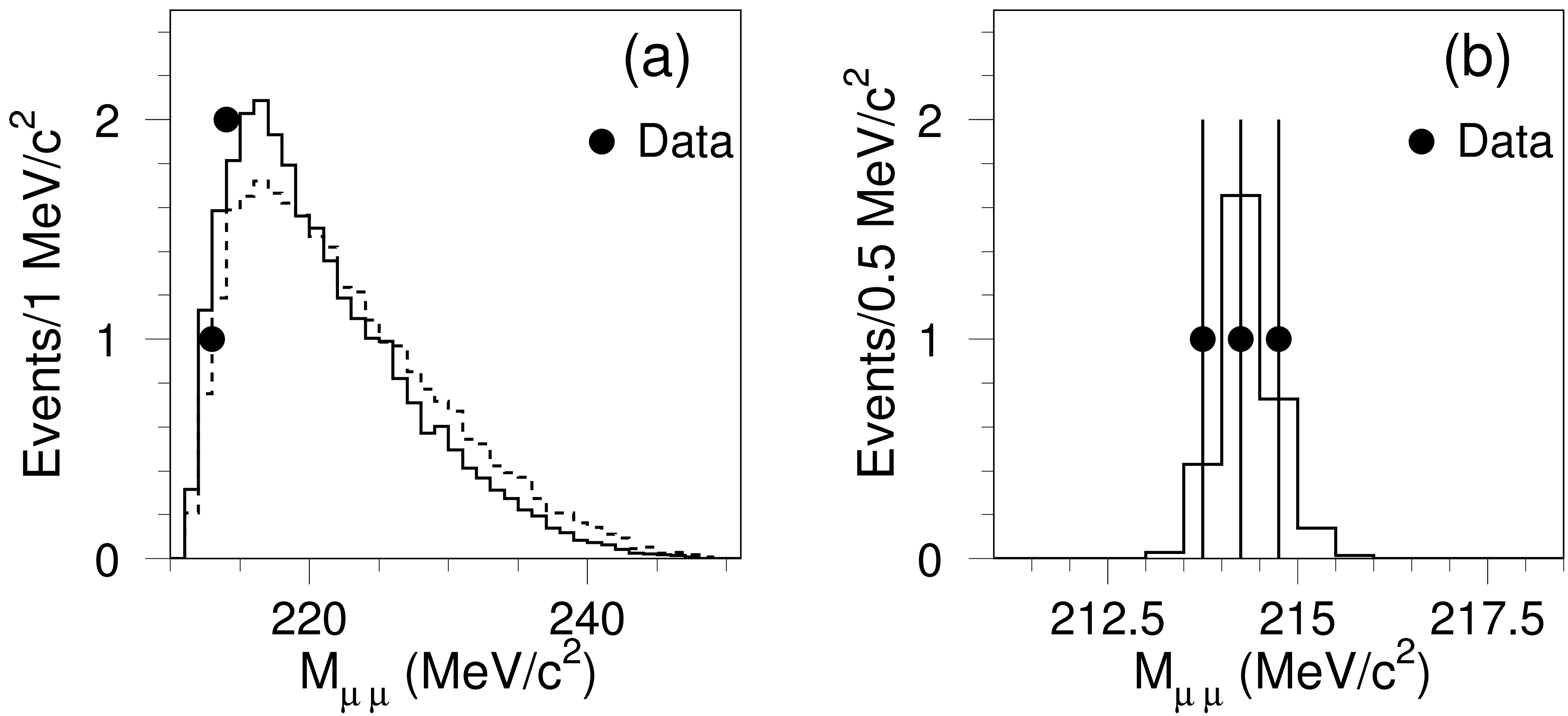
INTEGRAL Spectrum



[Jean et. al. astro-ph/0509298]

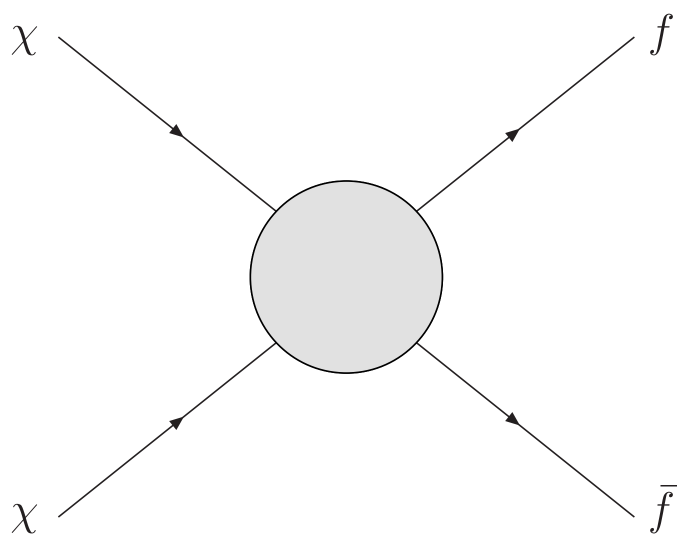
The HyperCP Events

The HyperCP experiment has detected $\Sigma^+ \to p^+\mu^+\mu^-$ at a rate consistent with the Standard Model (a virtual γ decaying to $\mu^+\mu^-$). But their events all lie in a narrow bin. They claim this could be a new narrow pseudoscalar particle decaying to $\mu\mu$. [Park et. al. `hep-ex/0501014`]



What do we know?

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



How light can Dark Matter be?

Let us concentrate on the region that can be tested by BaBar, Belle, BESIII, CLEO, and similar experiments: $M_\chi < 5$ GeV.

Such light Dark Matter *must not couple significantly to the Z boson*. For SUSY theories this means the Higgsino component of the lightest neutralino $\epsilon_u^2 - \epsilon_d^2 < 6\%$. Binos and neutral Winos do not couple to the Z. Here:

$$\chi_1^0 = \epsilon_u \widetilde{H}_u + \epsilon_d \widetilde{H}_d + \epsilon_B \widetilde{B} + \epsilon_W \widetilde{W}^0 + \ldots$$

$BR(Z \to \text{invisible}) = 20.00 \pm 0.06\%$ is well measured, and consistent with SM expectation of $N_\nu = 3$.

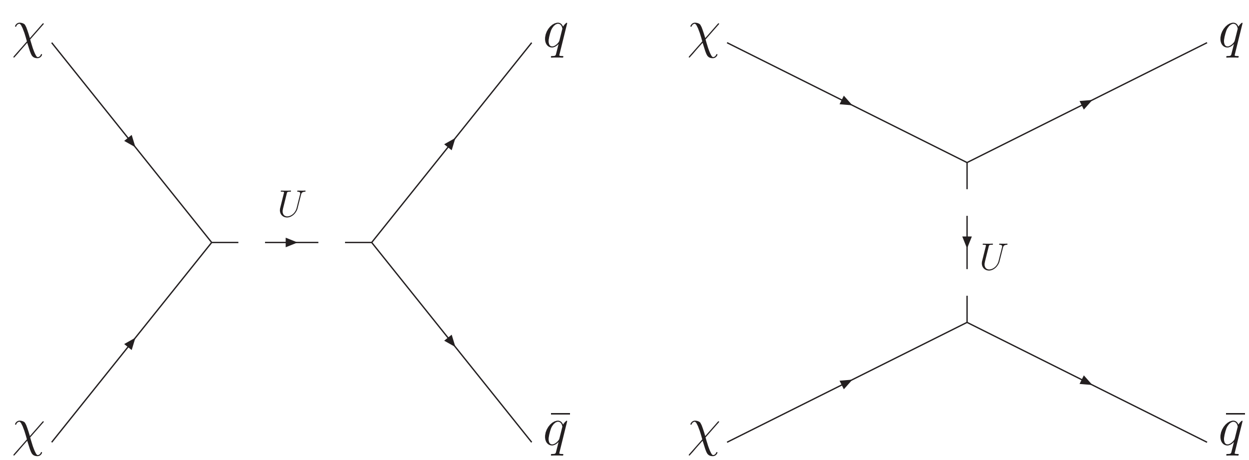
The Z and MSSM Higgses do not generally provide a strong enough annihilation to get the correct relic density if $M_\chi < 20$ GeV.

The only *model-independent* limit on dark matter is $M_\chi \gtrsim 2$ eV (because we don't want it to be relativistic at present times).

Dreiner et. al. [`arXiv:0707.1425`], Gunion, Hooper, BM [`hep-ph/0509024`]

Annihilation Mediators

Light dark matter requires a new *annihilation mediator* U in addition to the Dark Matter itself.



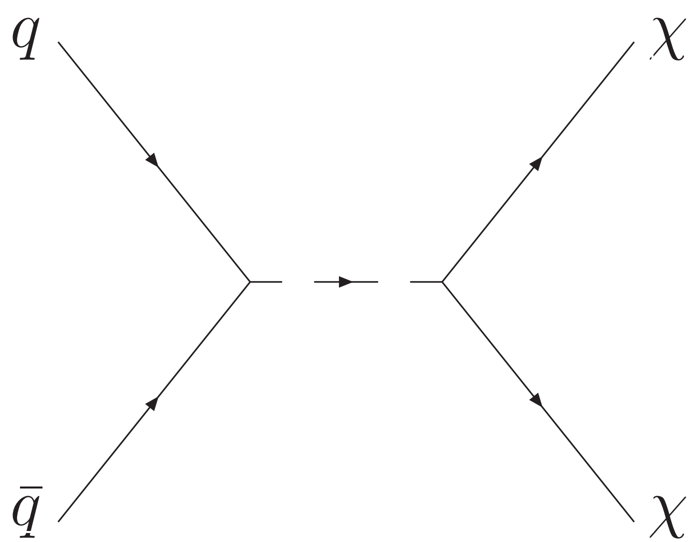
If the annihilation mediator appears in the t-channel (right), *must carry Standard Model quantum numbers*. Such as, squarks, sleptons, charginos, etc.

Let's assume we have not missed any charged or colored states with $M \lesssim 100$ GeV.

In the s-channel, the parameter space consists of the couplings $g_{U\chi\chi}$ and $g_{Uf\bar{f}}$, and masses M_χ and M_U.

$t \rightarrow -t$

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.

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.

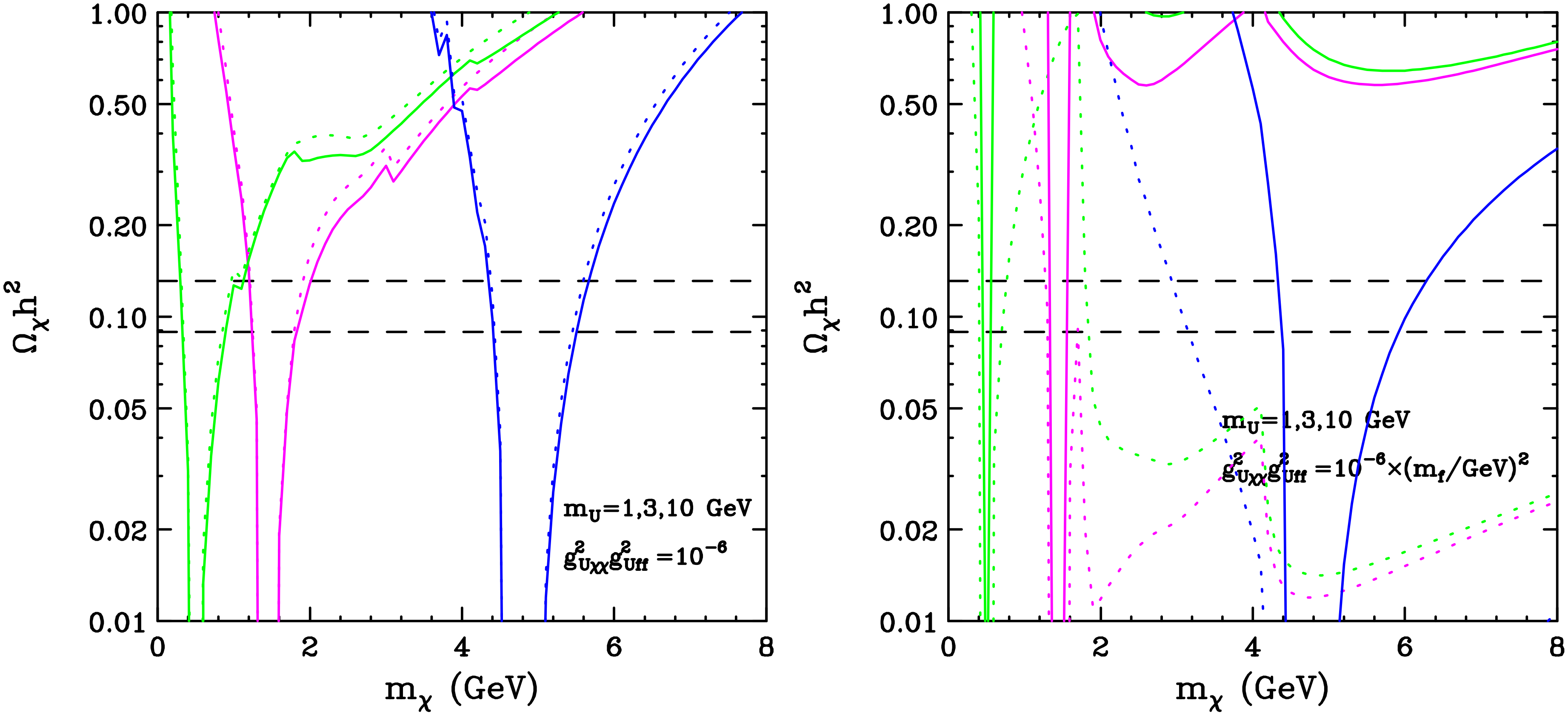
Many particles have radiative decays from excited states involving a $\pi^+\pi^-$ pair. e.g. $\Psi(2S) \to J/\Psi\pi^+\pi^-$, $\eta' \to \eta\pi^+\pi^-$.

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

We have B-factories running at the $\Upsilon(4S)$, so I studied $\Upsilon(nS) \to \Upsilon(1S)\pi^+\pi^-$ (where $n = 2, 3$).

Belle had a better idea: run on the $\Upsilon(3S)$. Almost the same analysis, but signal is enhanced by $\mathcal{O}(10^4)$.

Relic Density Calculation



(left solid) scalar DM, vector mediator
(left dotted) scalar DM, axial vector mediator
(right solid) fermion DM, scalar mediator
(right dotted) fermion DM, pseudoscalar mediator

[D. Hooper, B. McElrath, to appear]

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

$$W = \lambda S H_u H_d + \frac{\kappa}{3} S^3 \tag{1}$$

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:

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

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 $\det M_{\chi^0} = 0$:

$$M_1 = \frac{M_Z^2 \sin^2\theta_W \sin(2\beta) M_2}{M_2\mu - M_W^2 \sin(2\beta)} \tag{3}$$

This gives $80\text{MeV} < M_1 < 16\text{GeV}$ 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.

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:

$$A_1 = \cos\theta_A A_{\mathrm{MSSM}} + \sin\theta_A A_S. \tag{4}$$

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

$$W = \lambda S H_u H_d + \kappa S^3 \qquad V_{soft} = \lambda A_\lambda S H_u H_d + \kappa A_\kappa S^3 \tag{5}$$

Peccei-Quinn symmetry is approximate in $\kappa \ll 1, A_\kappa \ll M_{SUSY}$ limit. [Miller, Moretti, Nevzorov, `hep-ph/0501139` (among others)]

R-symmetry (not respected by supersymmetry): is approximate in $\kappa A_\kappa, \lambda A_\lambda \ll M_{SUSY}$ limit. [Dobrescu, Matchev, `hep-ph/0008192`]

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

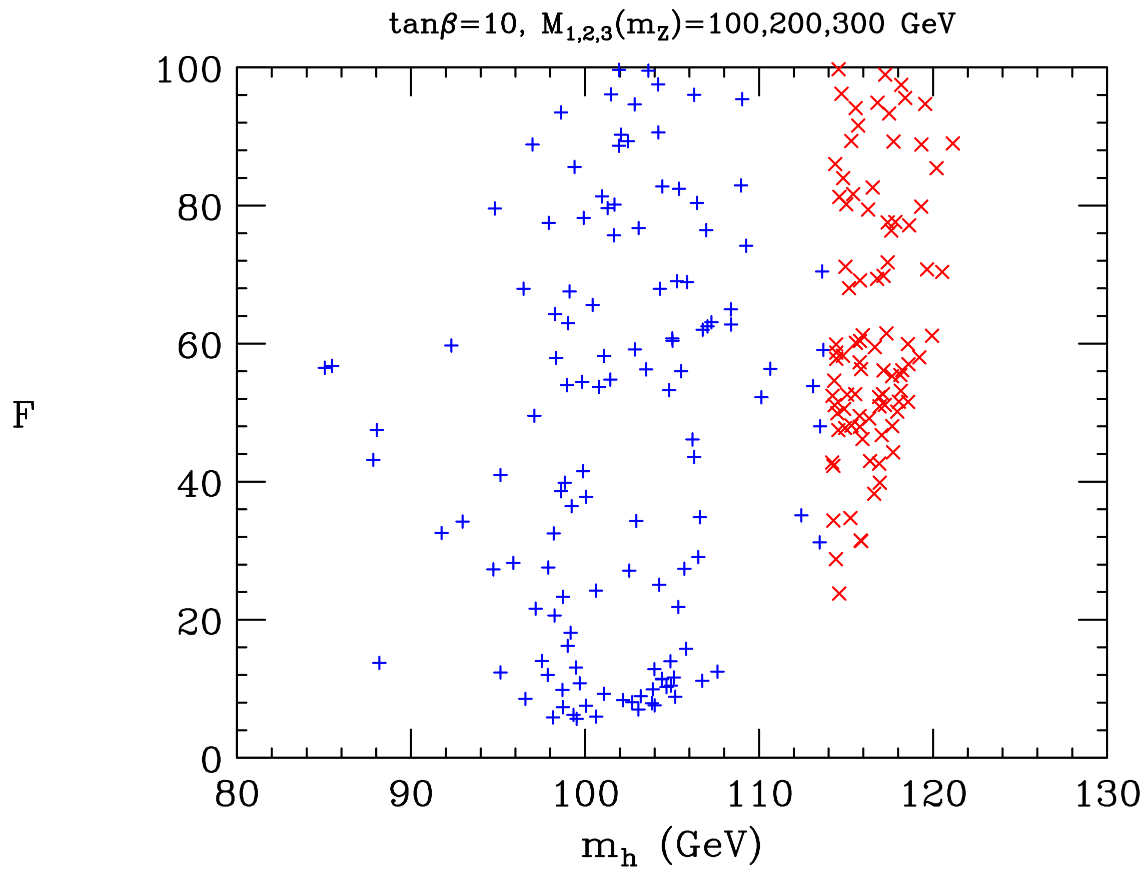
In "Secluded Sector" models with a gauged $U(1)'$, the $Z - Z'$ mass hierarchy can also generate a small M_A:

$$m^2_{A_1} \simeq m^2_{SS_i} \frac{v_s v_{si}}{v^2_{si} + v^2_{s3}} \tag{6}$$

[Erler, Langacker, Li, `hep-ph/0205001`; Han, Langacker, McElrath `hep-ph/0405244`; Barger, Langacker, Lee, Shaughnessy `hep-ph/0603247`]

We *want* a light A_1

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



Dermisek, Gunion, `hep-ph/0502105`, `hep-ph/0510322`, `hep-ph/0611142`, `arXiv:0705.4387`

Υ and J/Ψ Decays

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

$$\frac{\Gamma(V \to \gamma A)}{\Gamma(V \to \mu\mu)} = \frac{G_F m_b^2}{\sqrt{2}\alpha\pi}\left(1 - \frac{M_H^2}{M_V^2}\right)\cos^2\theta_A x^2. \quad (7)$$

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

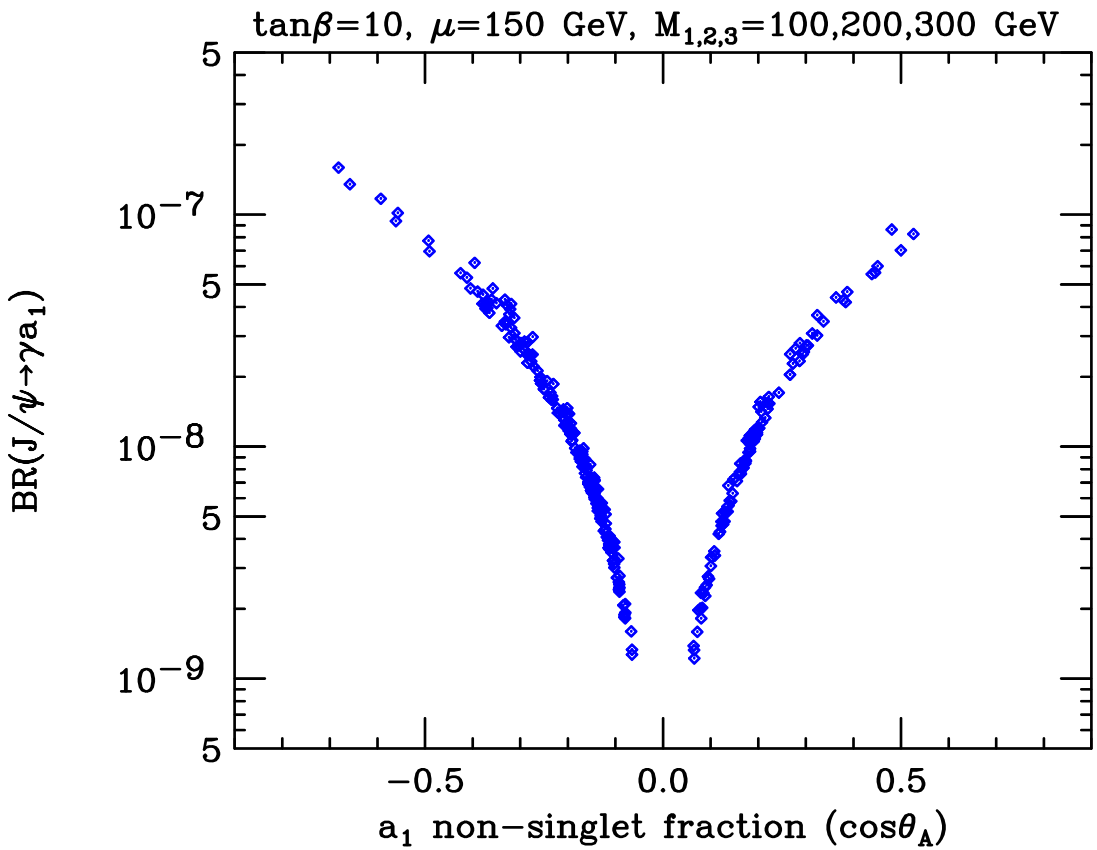
The 3-body decay $\Upsilon \to \chi^0\chi^0\gamma$ is also measured.

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

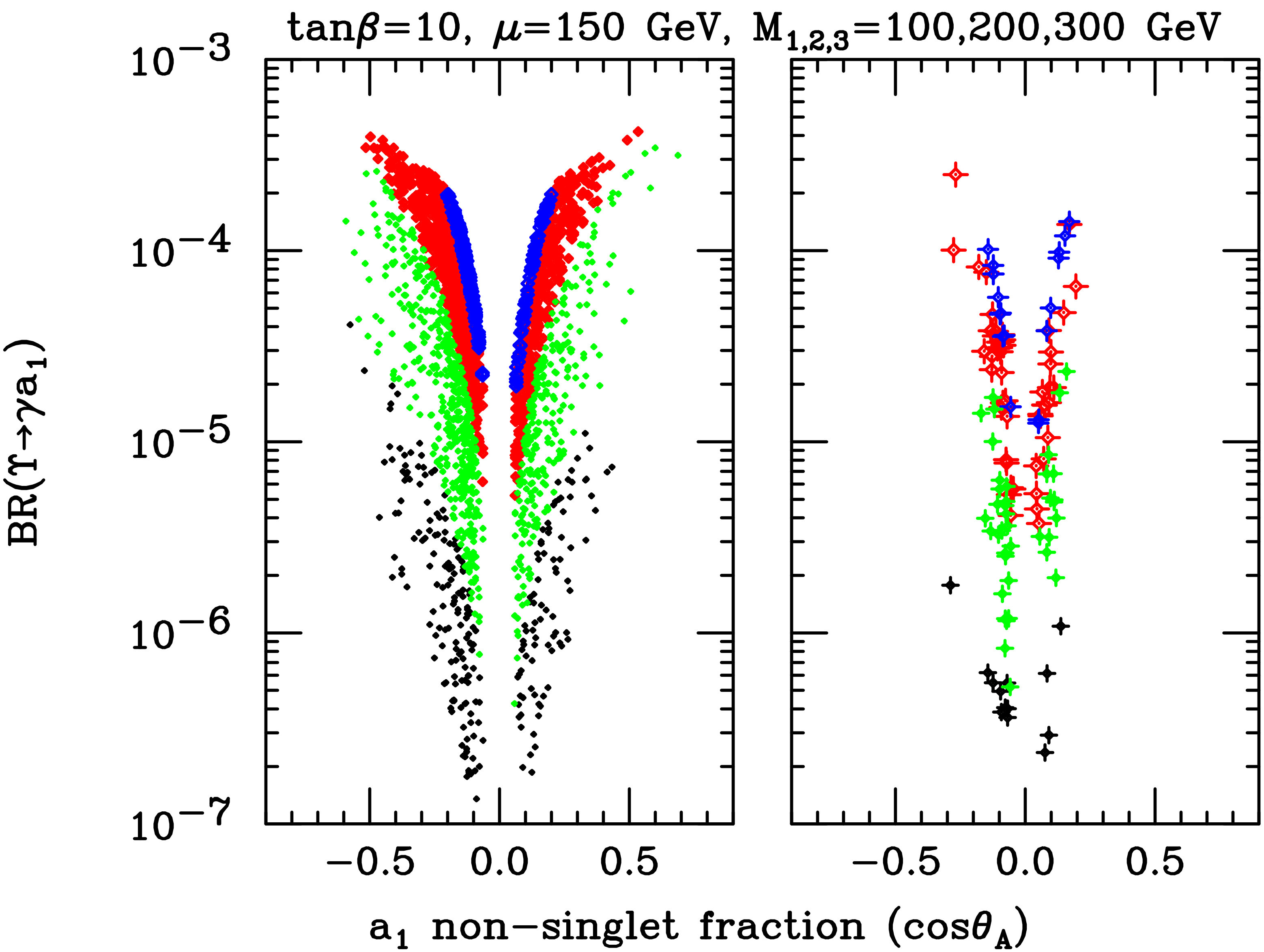
$$BR(\Upsilon \to A_1\gamma) \times BR(J/\Psi \to A_1\gamma) \propto \cos^4\theta_A \quad (8)$$

which is generally quite small. Thus we can evade these limits even for $M_\chi^0 < M_{J/\Psi}/2$ (or $M_{A_1} < M_{J/\Psi}$).

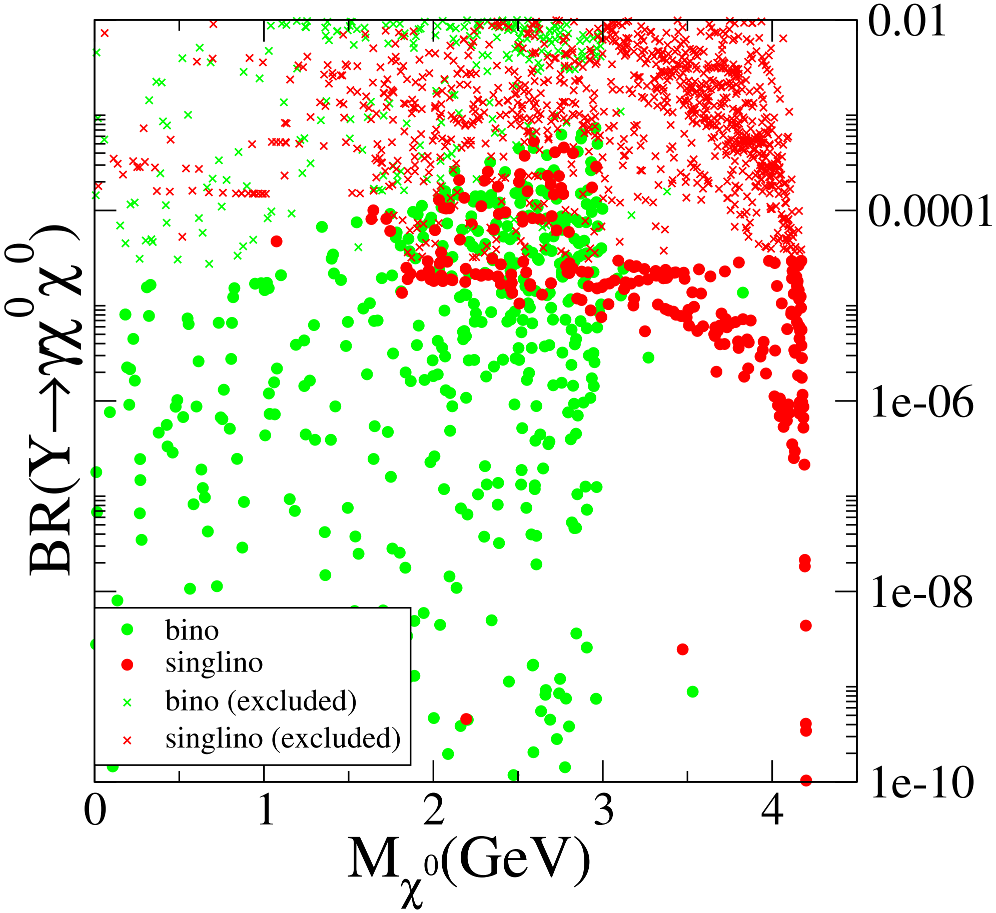
Υ and J/Ψ decays

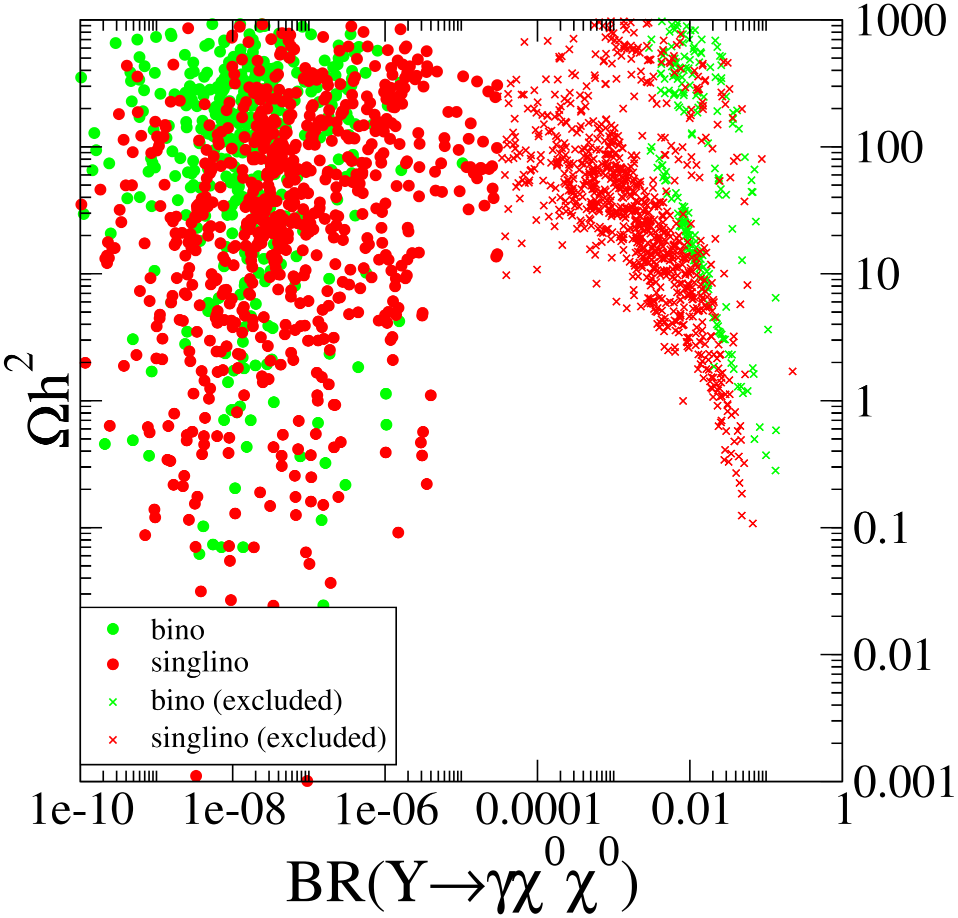


Υ and J/Ψ decays



Υ decays and relic density



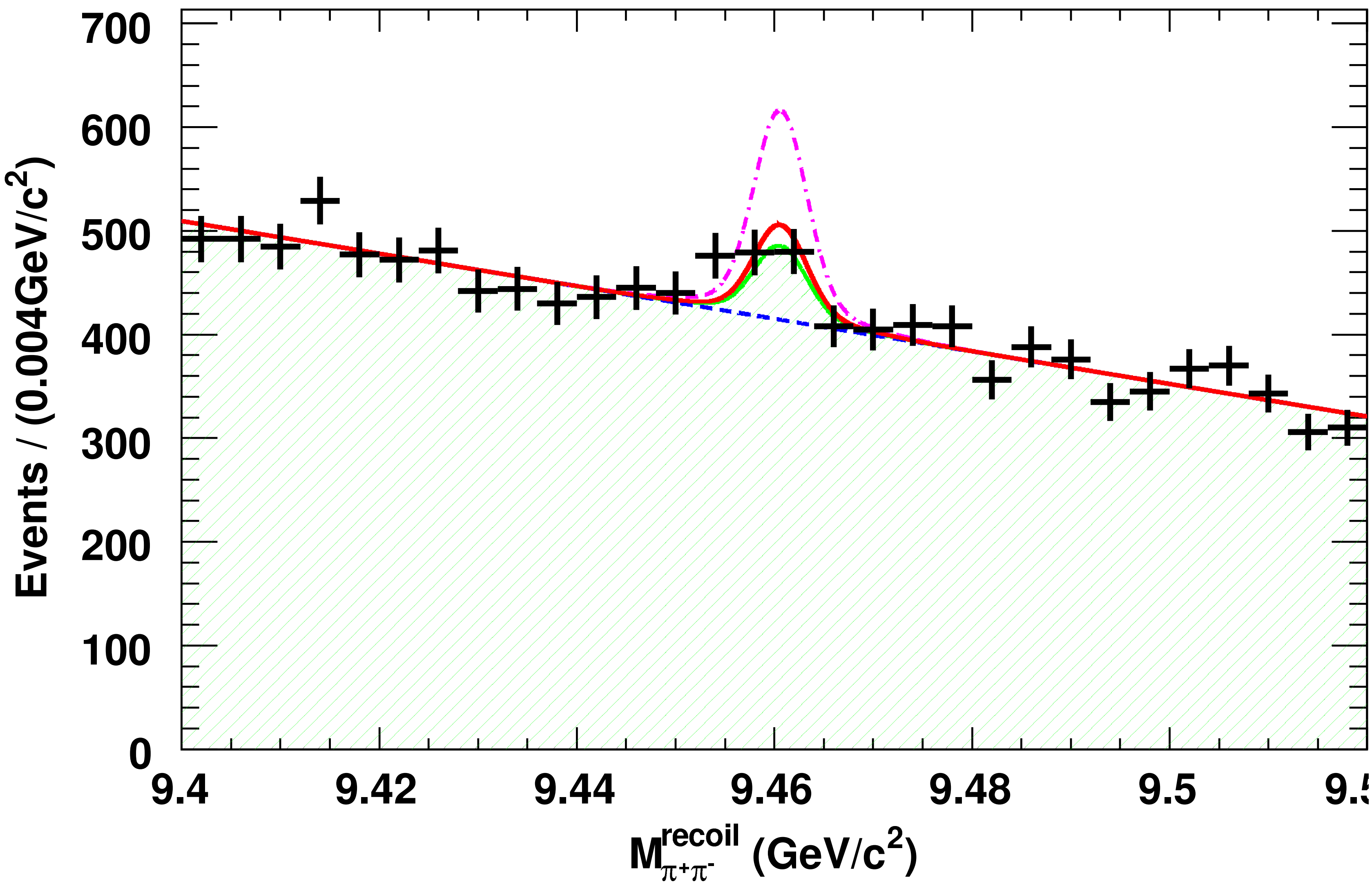


CLEO limits are $BR(\Upsilon \to \gamma\chi^0\chi^0) \simeq 3 \times 10^{-5}$ for $M_{\chi^0} < 1.5$ GeV.

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!

Belle Invisible Upsilon Search



Irreducible background is from $\Upsilon \to e^+e^-, \mu^+\mu^-$ where the leptons go down the beam pipe.

Super-B Invisible Upsilon Search

One can do better by inserting detector material to veto these events than by increasing luminosity

With Belle nominal coverage, it would require 59 ab^{-1} to discover $\Upsilon \rightarrow \nu\overline{\nu}$ at 5σ. This has $S : B = 3 : 1000$.

Let us assume that the detector coverage can be improved by a factor 10 (e.g. 99% coverage of 4π, or $5 < \theta < 170$). This would only require 6 ab^{-1}. With $2 < \theta < 178$, we would need only 400 fb^{-1}.

The required detector subsystem need only *veto* on 4.7 GeV tracks in the far-forward regions to reject this background.

Can a thin layer of scintillator be placed forward to veto these tracks?

Super-B Higgs Search

In the $\Upsilon \to \gamma\tau\tau$ search presented earlier, the coincidence of $h \to aa$ explaining the LEP Higgs excess causes the a to be not entirely singlet. If we allow the a to be singlet, the BR($\Upsilon \to \gamma a$)$\propto \cos\theta_A$. From that analysis, we expect this branching ratio to be larger than 10^{-7}.

Using $\Upsilon(3S) \to \gamma\tau\tau$, this would require 1.7 ab^{-1}, where I have simply assumed the direct $e^+e^- \to \gamma\tau\tau$ background.

Conclusion(s)

A Super-B factory can significantly constrain and discover higgses or dark matter at low masses. During the workshop I will contribute (better) estimates for invisible Upsilon, $\Upsilon \to \gamma + invisible$, and $\Upsilon \to \gamma\tau\tau$.

(Some of the) Interesting new physics measurements sensitive to dark matter or singlet higgses are:

$\Upsilon \to invisible$	$J/\Psi \to invisible$
$\eta \to invisible$	$\Upsilon \to \gamma + invisible$
$B^+ \to K^+ + invisible$	$\Upsilon \to \gamma A_1, A_1 \to \tau^+\tau^-$
$K^+ \to \pi^+ + invisible$	$J/\Psi \to \gamma A_1$
$e^+e^- \to \tau\tau A_1$	$J/\Psi \to \gamma A_1, A_1 \to \mu^+\mu^-$
$D^+ \to X(\not{l}^+) + invisible$	$B^+ \to X(\not{l}^+) + invisible$