Determination of Dark Matter Properties at High-Energy Colliders

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This talk describes work that I have done in collaboration with Ted Baltz, Marco Battaglia, and Tommer Wizansky.
You can find it written up in great detail in hep-ph/0602187 .

I am sorry that I cannot be in Bangalore to present this talk.
I thank JoAnne Hewett for giving the presentation.

Over the past few years, many of us have been interested in the implications of the ILC experiments for cosmology. A particularly focus of this work has been on the ability of the ILC to identify the particle that is responsible for cosmic dark matter.

The ability of high-energy colliders to analyze the qualitative nature of dark matter has been discussed by many people at the previous LCWS. In short:

1. Particle physics models lead to the expectation that dark matter is composed of a heavy neutral stable particle with a mass of the order of 100 GeV.

2. This particle should be produced at the LHC, leading to a huge rate for missing energy + multijets events

3. It is difficult to distinguish models of this general class from one another at the LHC. To do this, we need spin and quantum number measurements. This is difficult at the LHC, but it is a strength of the ILC.

Ultimately, we would like to predict the annihilation and scattering cross sections of dark matter particles from collider experiments. We cannot observe dark matter particles directly in a collider setting. So we must infer these properties from particle spectrum and cross section measurements at colliders.

Can we estimate how well this can be done ?

We have done studies of this question in models of supersymmetry in which the dark matter particle is a neutralino. To answer the question, we have summarized the data on the supersymmetry spectrum that we expect to be measured at the LHC and the ILC and then translated these summaries into estimates of the dark matter abundance and cross sections.

This procedure implies an underlying model. What model should we use ? How many free parameters ? This space should have enough degrees of freedom that one can claim some measure of "model-independence" in its context.

mSUGRA is not appropriate. Four precision measurements (of any SUSY or Higgs masses) fix the model.

The general MSSM with flavor, CP, R-parity conservation has 24 parameters: 3 gaugino masses, 15 sfermion masses, μ, $\tan\beta$, m_A, 3 A parameters.

This parameter space encodes most of the important alternatives for SUSY phenomenology.

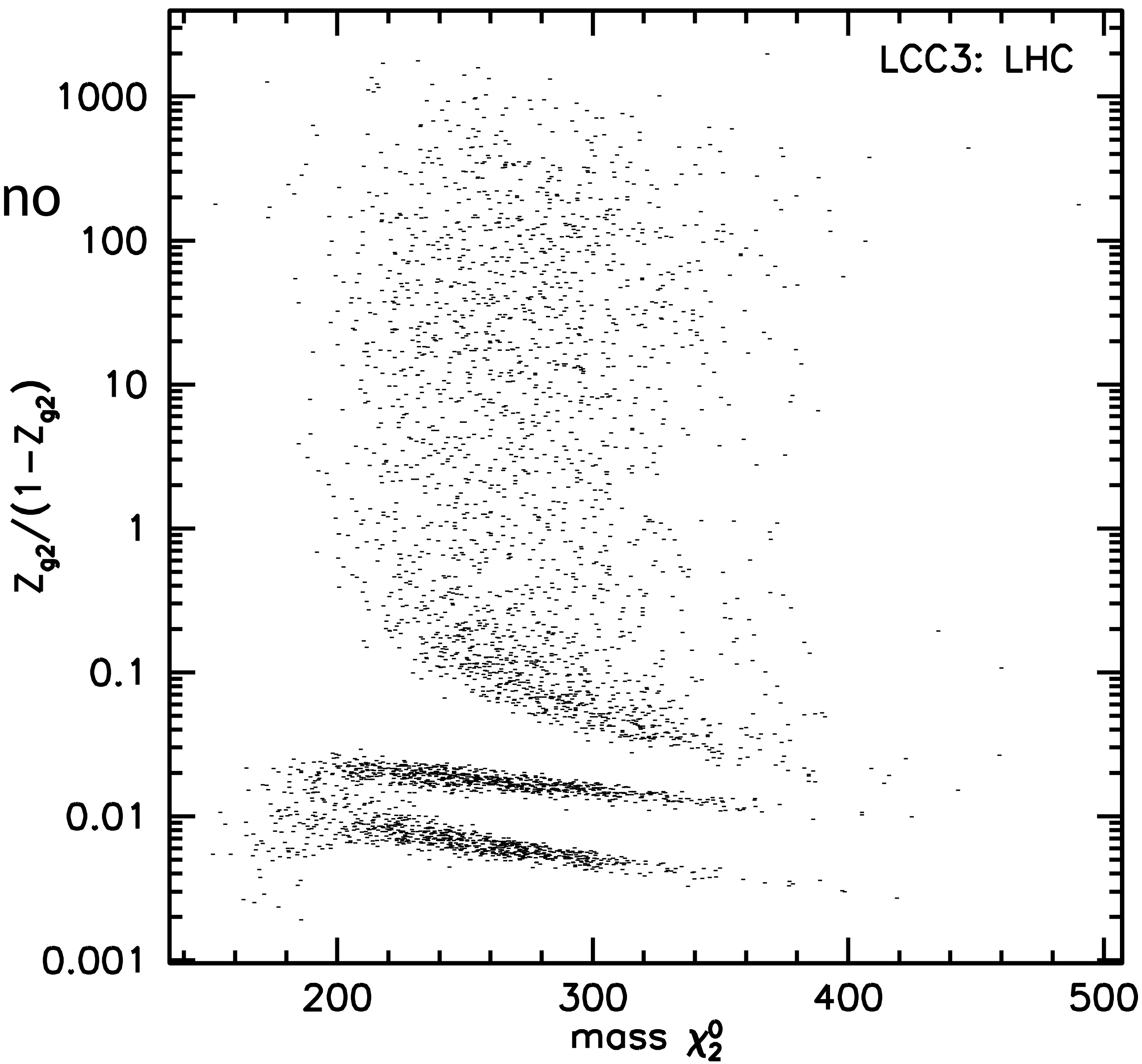
To derive our conclusions, we scan this whole 24-dimensional space using the Markov Chain Monte Carlo (MCMC) method.

We set up a process in the 24-d space for which detailed balance corresponds to an ensemble of points appearing with probabilities equal to the likelihood function corresponding to the given set of supersymmetry spectrum measurements.

Using 40,000 points per chain, we check that the process does come to thermal equilibrium. The final results average 25 chains.

MCMC has the interesting property that, if there are multiple solutions that explain the measurements, the chains tunnel between them and find these possibilities.

gaugino/Higgsino fraction



For our study, we analyzed the SUSY points chosen in the American LC/Cosmology study:

LCC1 = SPS1a 'bulk region'

annihilation through slepton exchange

σ_{NN} depends on the light slepton masses and couplings

LCC2 'focus point region'

annihilation to WW, ZZ

σ_{NN} depends on $m_1, m_2, \mu, \tan\beta$

LCC3 'coannihilation region'

annihilation of $\widetilde{\tau}$ is actually dominant

σ_{NN} depends on $m(\widetilde{\chi}_1^0), m(\widetilde{\tau}), \theta_\tau$

LCC4 'A funnel region'

annihilation through A resonance

σ_{NN} depends on $m(\widetilde{\chi}_1^0), m(A), \Gamma(A), \tan\beta$

Begin with a detailed discussion of LCC2:

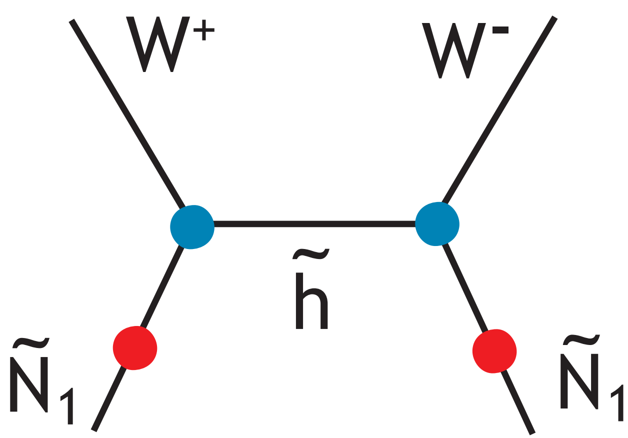
Squarks and sleptons are heavy, so the dynamics depends on the four supersymmetry parameters

$$m_1, \ m_2, \ \mu, \ \tan\beta$$

NN annihilation is dominated by

$$NN \to W^+W^- \ , \ Z^0Z^0$$

which in turn depends on the mixing of gauge and Higgs supersymmetry partners:

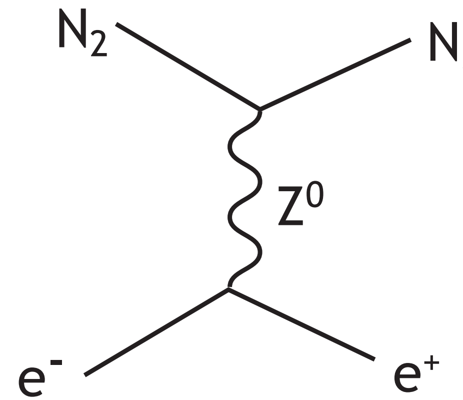


To measure this mixing, determine the mass spectrum and the polarized cross sections.

A particularly important reaction at this point is

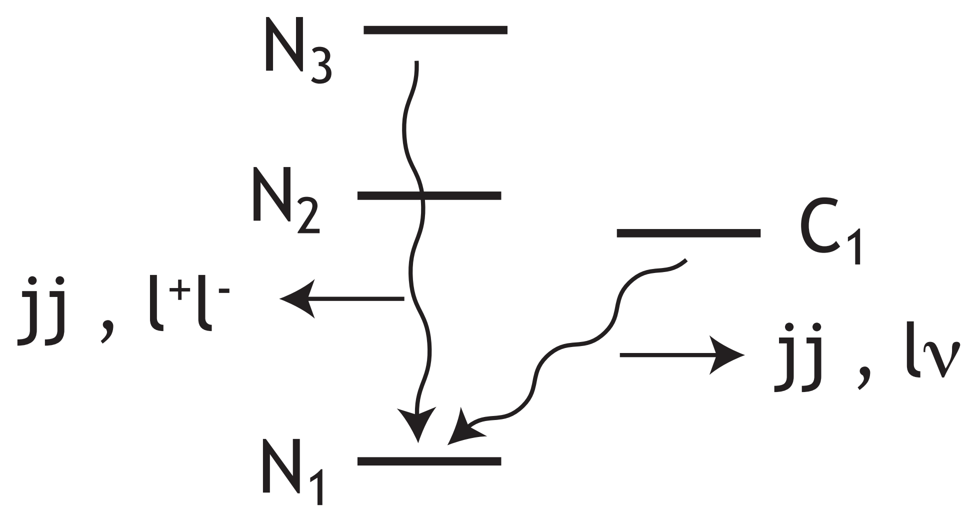
$$e^+e^- \rightarrow N_2 N_3$$

The cross section from e^-_R depends specifically on $\widetilde{w}^0 - \widetilde{h}^0$ mixing.



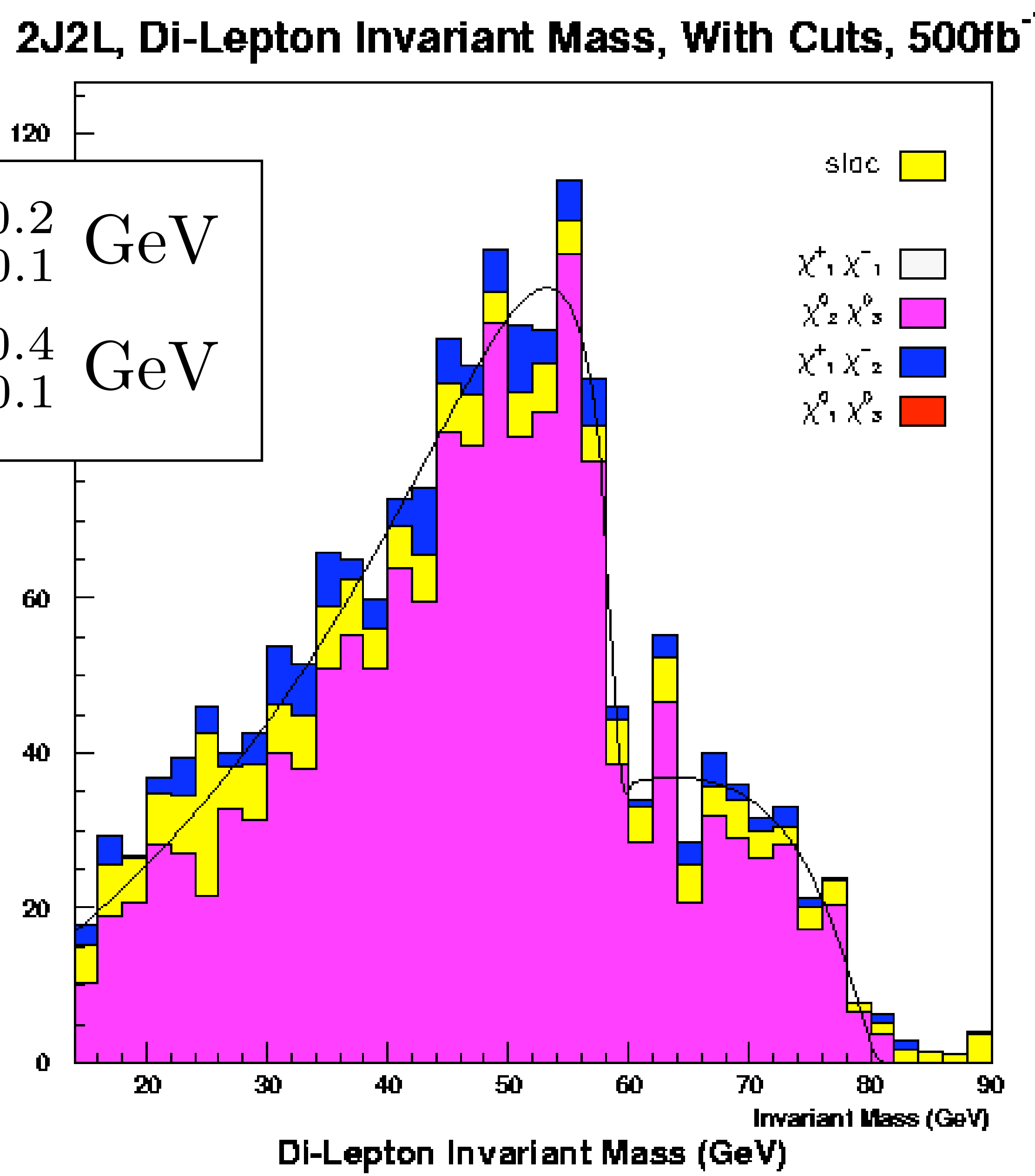
Observe the final particles through the transitions to the lightest neutralino

The l+l- transitions can be observed, and measured precisely, at the LHC.



$$m(\widetilde{N}_2) - m(\widetilde{N}_1) = 58.7^{+0.2}_{-0.1}\ \text{GeV}$$
$$m(\widetilde{N}_3) - m(\widetilde{N}_1) = 82.0^{+0.4}_{-0.1}\ \text{GeV}$$

The Cornell group (J. Alexander et al.) has studied SUSY spectroscopy at LCC2 with detailed simulations



J. Alexander, et al.

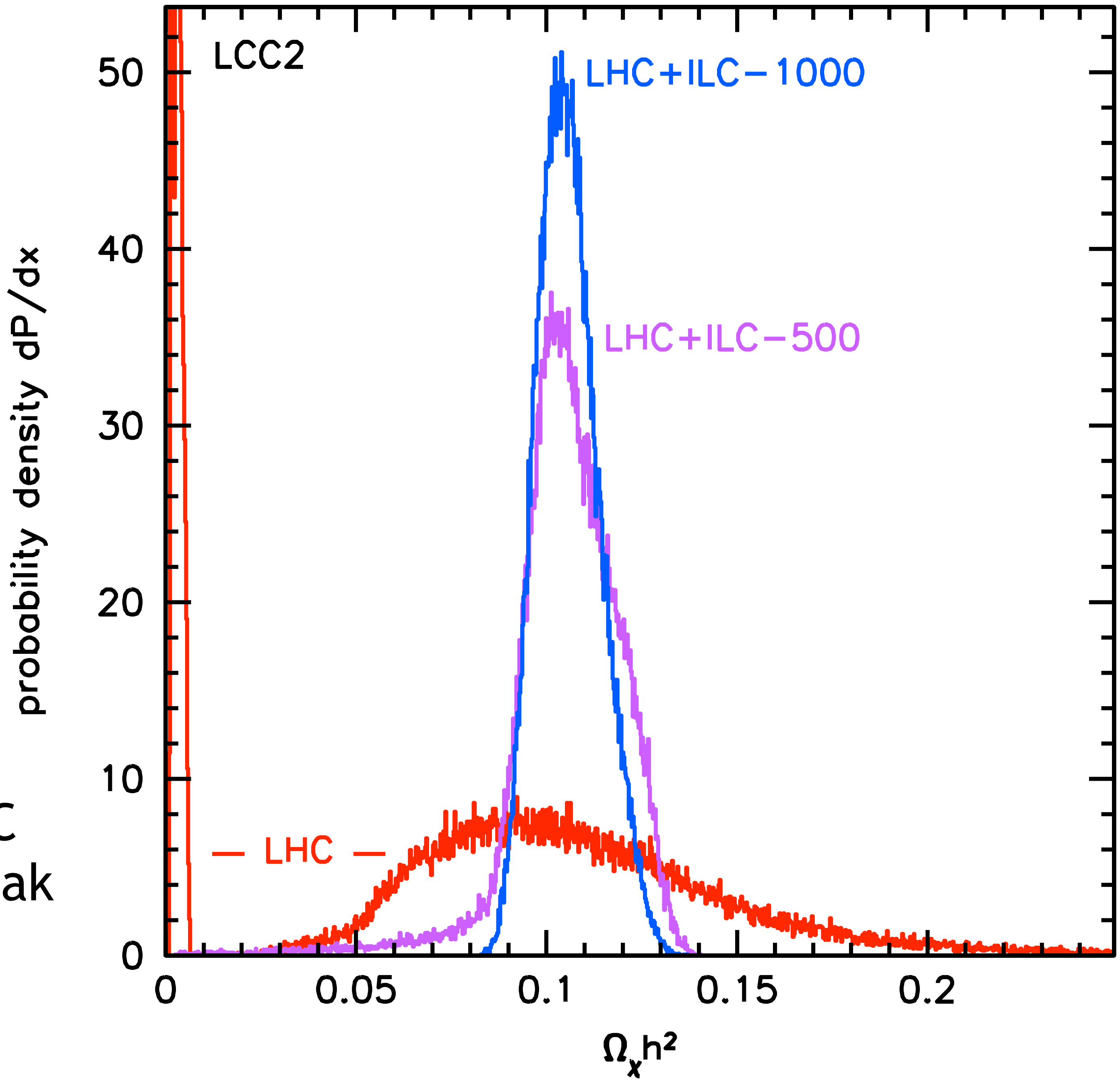
mass/mass splitting	LCC2 value		LHC	ILC 500	ILC 1000
$m(\widetilde{\chi}_1^0)$	107.9	$\pm$	10	1.0	
$m(\widetilde{\chi}_2^0) - m(\widetilde{\chi}_1^0)$	58.5	$\pm$	1.0	0.3	
$m(\widetilde{\chi}_3^0) - m(\widetilde{\chi}_1^0)$	82.3	$\pm$	1.0	0.2	
$m(\widetilde{\chi}_4^0) - m(\widetilde{\chi}_1^0)$	186.3	$\pm$	-	-	3.0
$m(\widetilde{\chi}_1^+)$	159.7	$\pm$	-	0.55	
$m(\widetilde{\chi}_1^+) - m(\widetilde{\chi}_1^0)$	51.8	$\pm$	-	0.25	
$m(\widetilde{\chi}_2^+)$	286.7	$\pm$	-	-	1.0
$m(\widetilde{e}_R)$	3277.	$\pm$	(> 350)		(> 480)
$m(\widetilde{\mu}_R)$	3277.	$\pm$	(> 350)		(> 480)
$m(\widetilde{\tau}_1)$	3252.	$\pm$	$(> m(\chi_2^0))$		(> 480)
$m(\widetilde{e}_L)$	3280.	$\pm$	(> 350)		(> 480)
$m(\widetilde{\mu}_L)$	3280.	$\pm$	(> 350)		(> 480)
$m(\widetilde{\tau}_2)$	3268.	$\pm$			(> 480)
$m(h)$	118.68	$\pm$	0.25	0.05	
$m(A)$	3242.	$\pm$	*	(> 240)	(> 480)
$m(\widetilde{u}_R)$, $m(\widetilde{d}_R)$	3312.	$\pm$	(> 2000)		
$m(\widetilde{s}_R)$, $m(\widetilde{c}_R)$	3312.	$\pm$	(> 1500)		
$m(\widetilde{u}_L)$, $m(\widetilde{d}_L)$	3301.	$\pm$	(> 2000)		
$m(\widetilde{s}_L)$, $m(\widetilde{c}_L)$	3301.	$\pm$	(> 1500)		
$m(\widetilde{b}_1)$	2710.	$\pm$	(> 1500)		
$m(\widetilde{b}_2)$	3241.	$\pm$	(> 1500)		
$m(\widetilde{t}_1)$	1976.	$\pm$	(> 1500)		
$m(\widetilde{g})$	850.	$\pm$	85.		

$m_A > 200(\tan\beta/7)$

cross section		LCC2 value		ILC 500	ILC 1000
$\sigma(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-)$	LR	1364. (0.479)	$\pm$	1%*	
	RL	145.6 (0.438)	$\pm$	4%*	
$\sigma(e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_3^0)$	LR	127.6	$\pm$	4%*	
	RL	105.8	$\pm$	5%*	

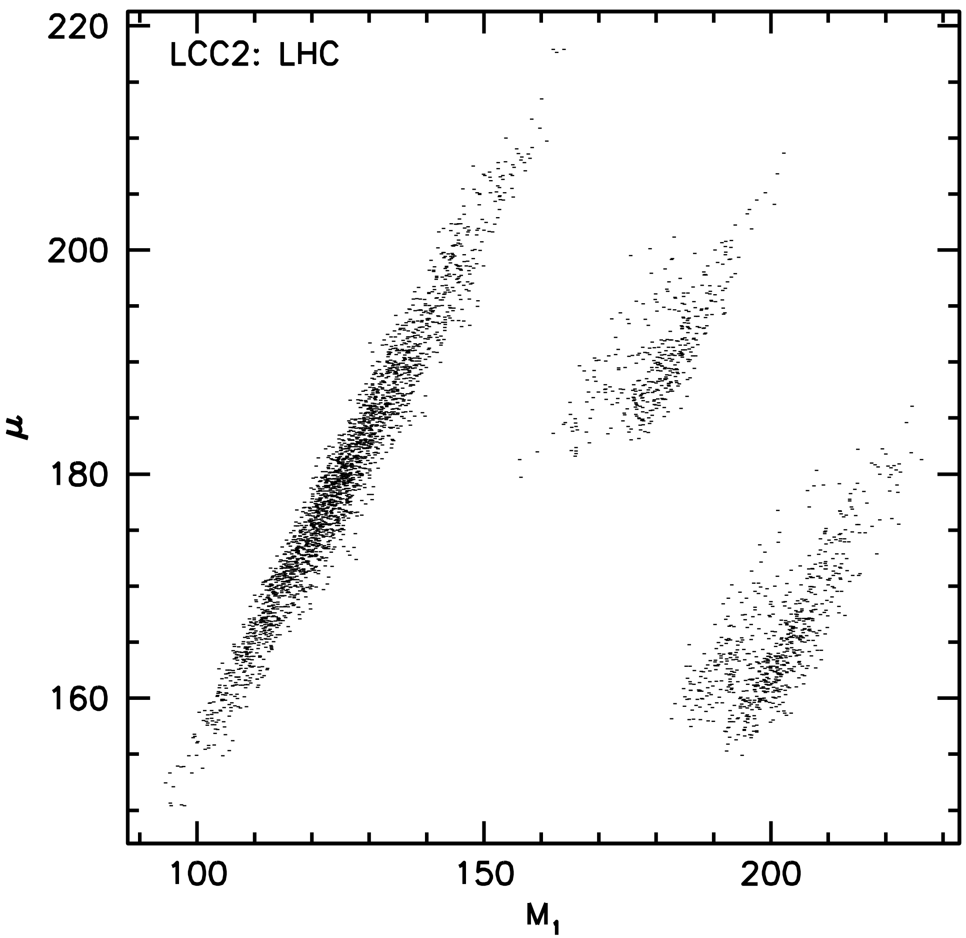
Write these values as a likelihood function over the 24-d space. Generate the MCMC chains. Project down onto the neutralino abundance and cross sections. What do we find ?

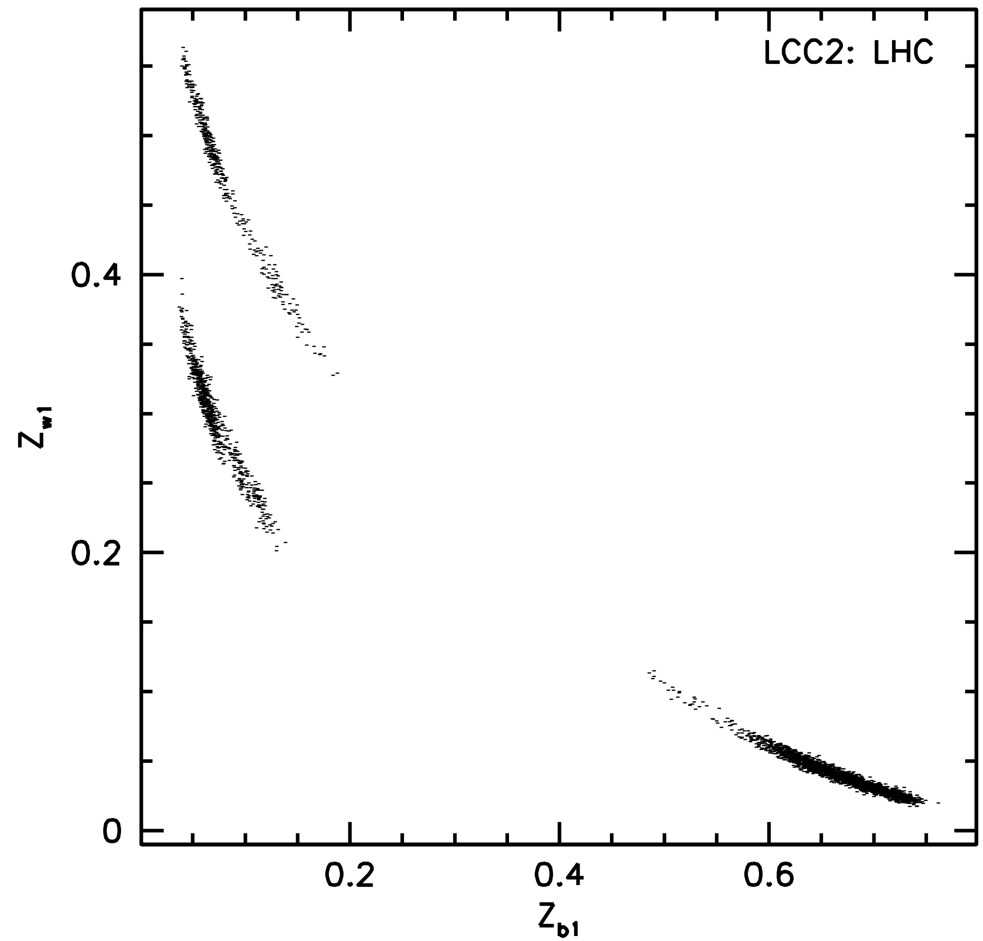
Prediction of the neutralino relic abundance:



Note for LHC the large peak near Ω = 0.

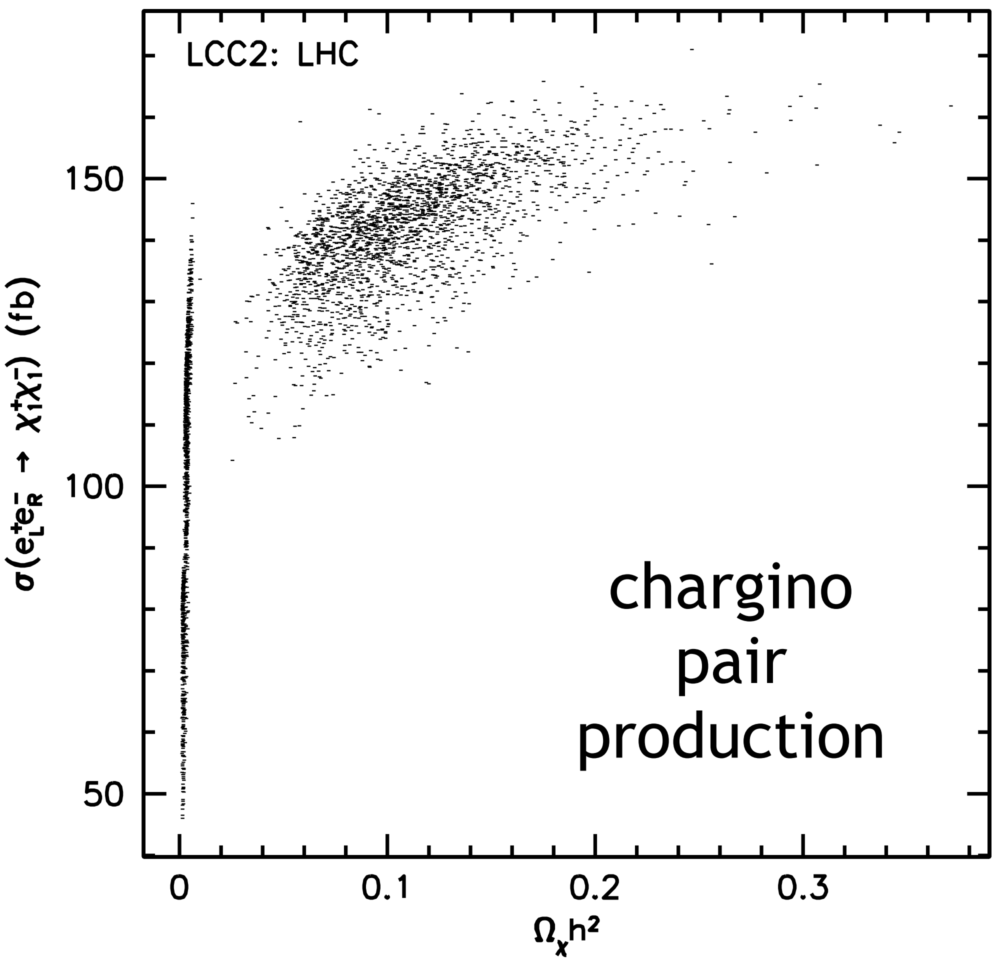
LHC data set shows multiple solutions, corresponding to bino, wino, and Higgsino-like LSP.

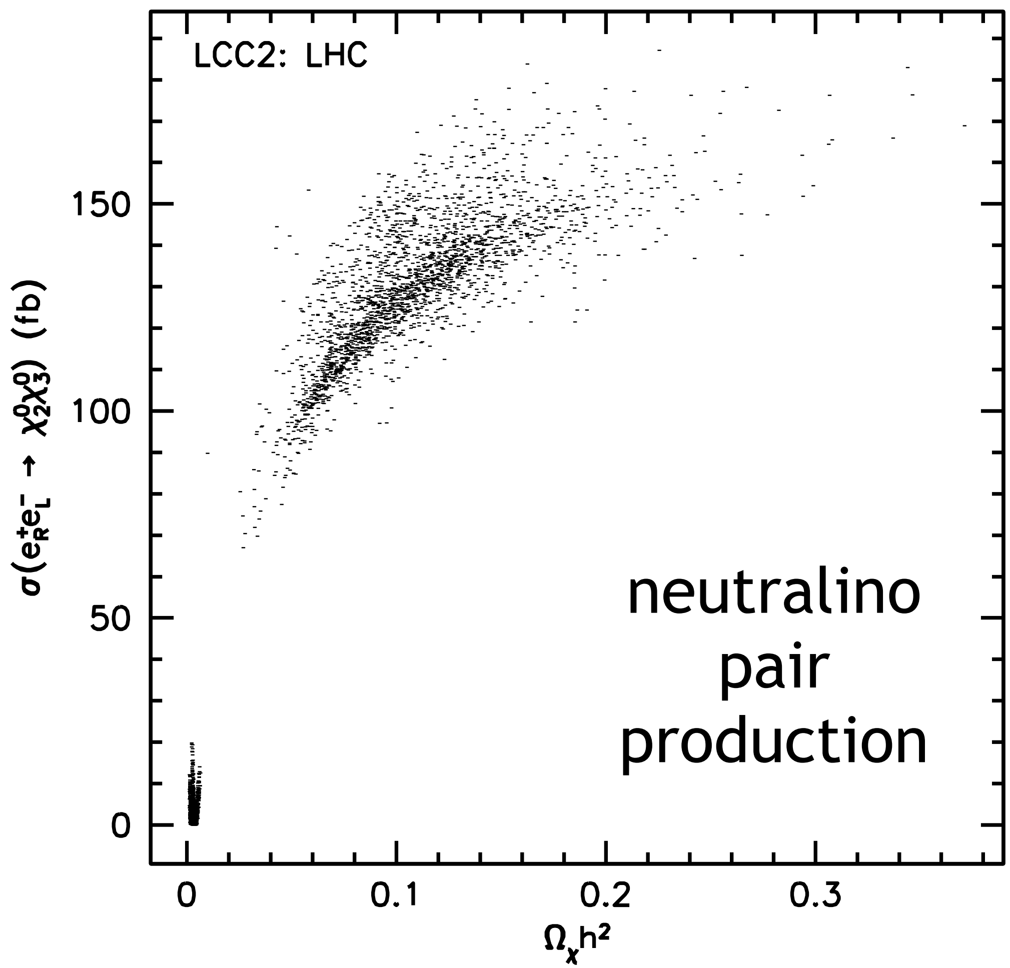




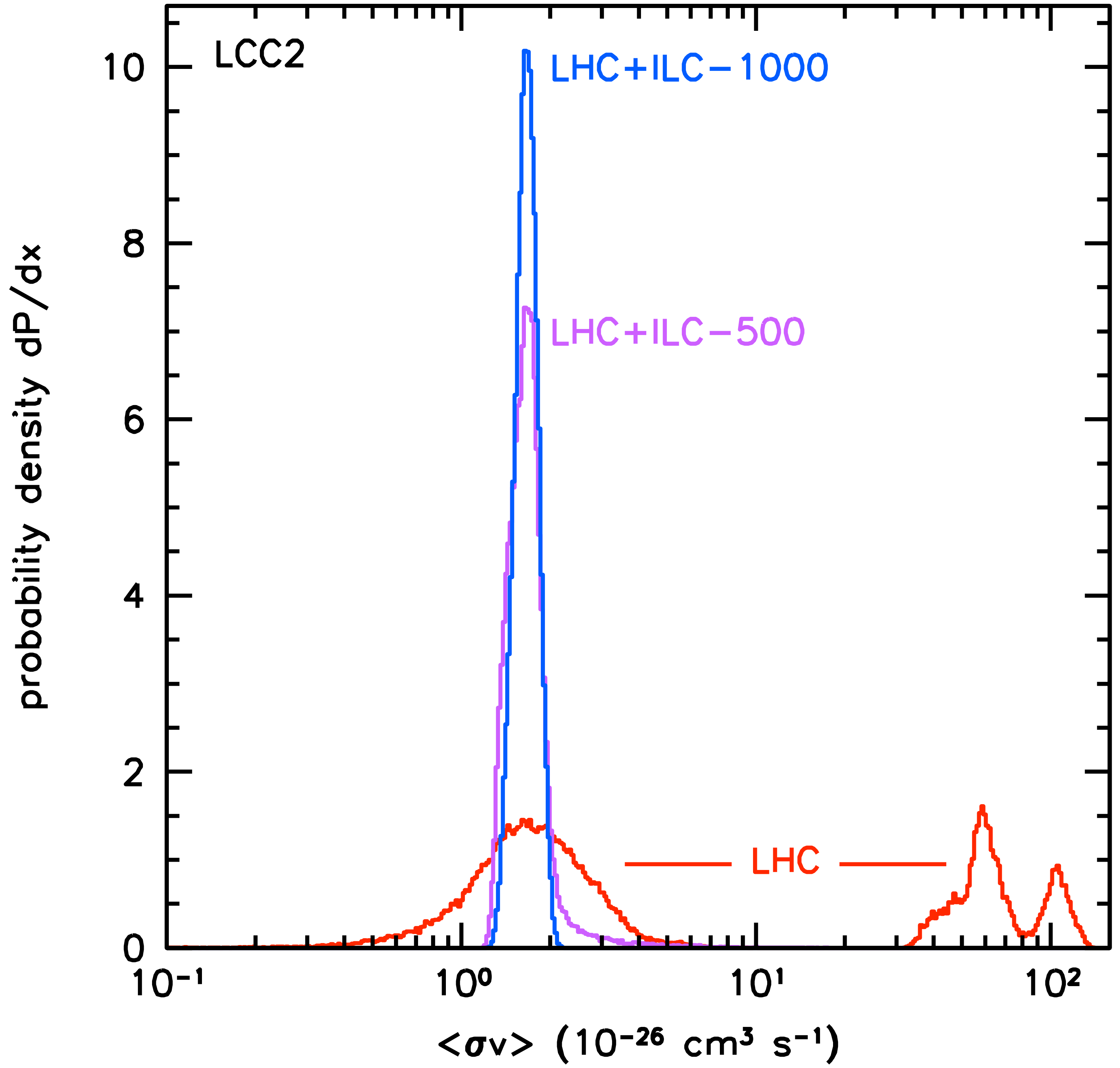
Polarized cross section measurements at the ILC resolve the ambiguities

LHC data set





neutralino annihilation cross section at threshold



The rate of production of gamma rays from dark matter annihilation in the galactic halo is proportional to this cross section. By dividing the luminosity in gammas by this cross setion, we can measure the dark matter density in a model-independent way.

Here are some objects that we might wish to observe in gammas:

The galactic center:

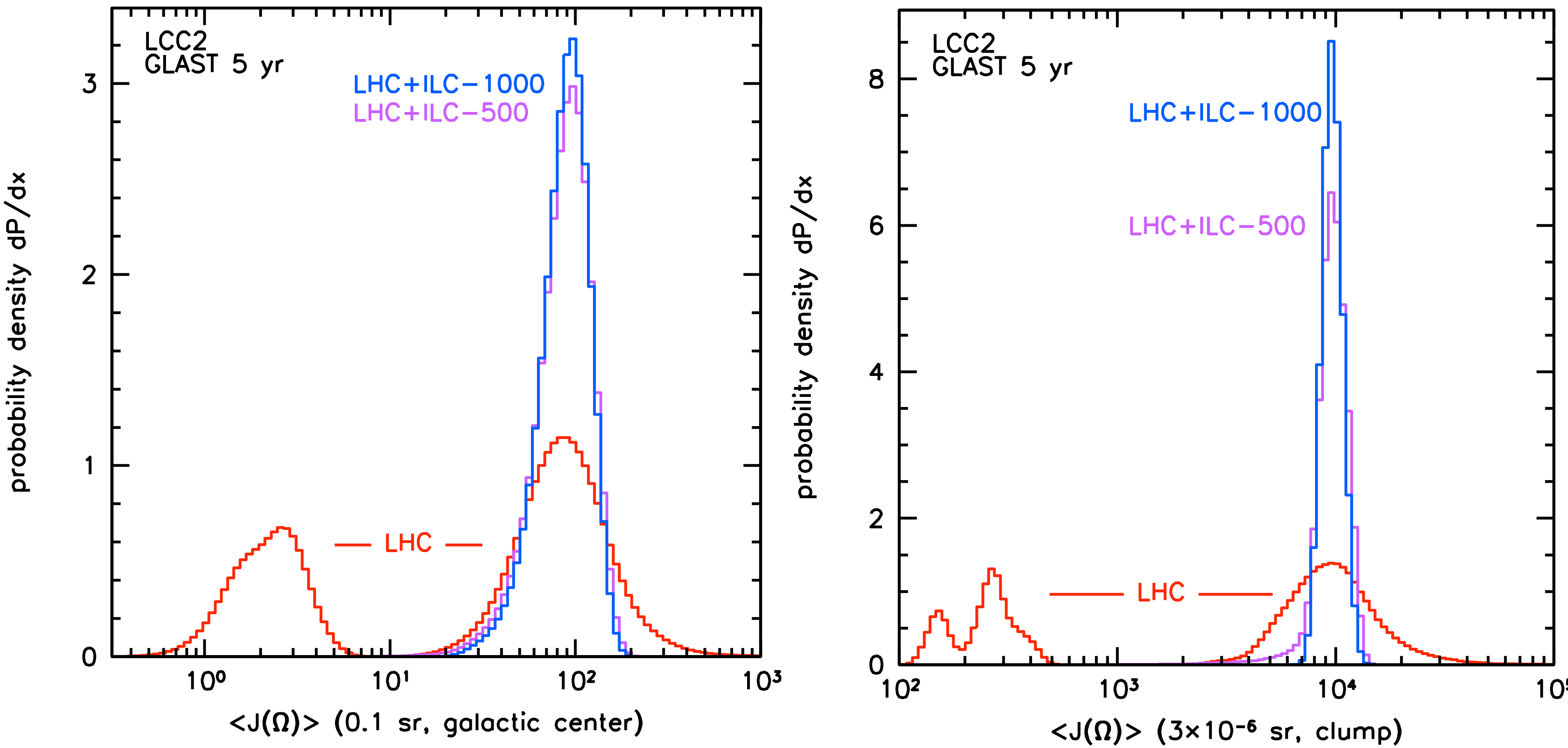
For definiteness, assume the NFW profile. Astrophysical estimates vary by 6 orders of magnitude. Add background consistent with EGRET measurements.

A subhalo dark matter clump:

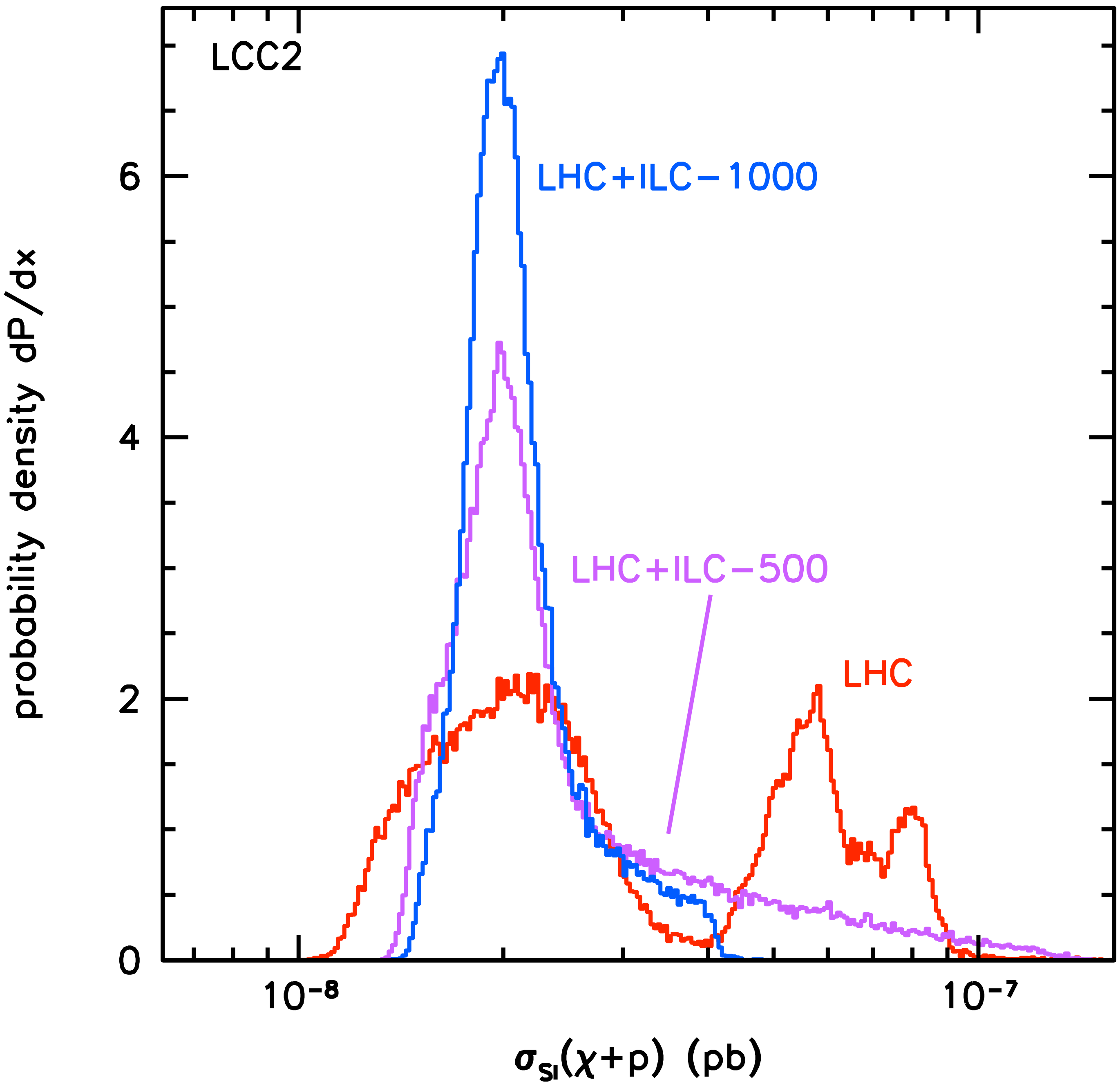
Pick a typical object from the simulation data of Taylor and Babul:
M = $10^6 M_\odot$ scale size = 500 pc distance = 6 kpc
NFW profile. Observe in a circle of $10^{-5} sr$.

Here is the accuracy with which we can determine $J \sim \int dz \rho^2$
by combining GLAST gamma observations with collider data

galactic center LCC2 sub-halo clump

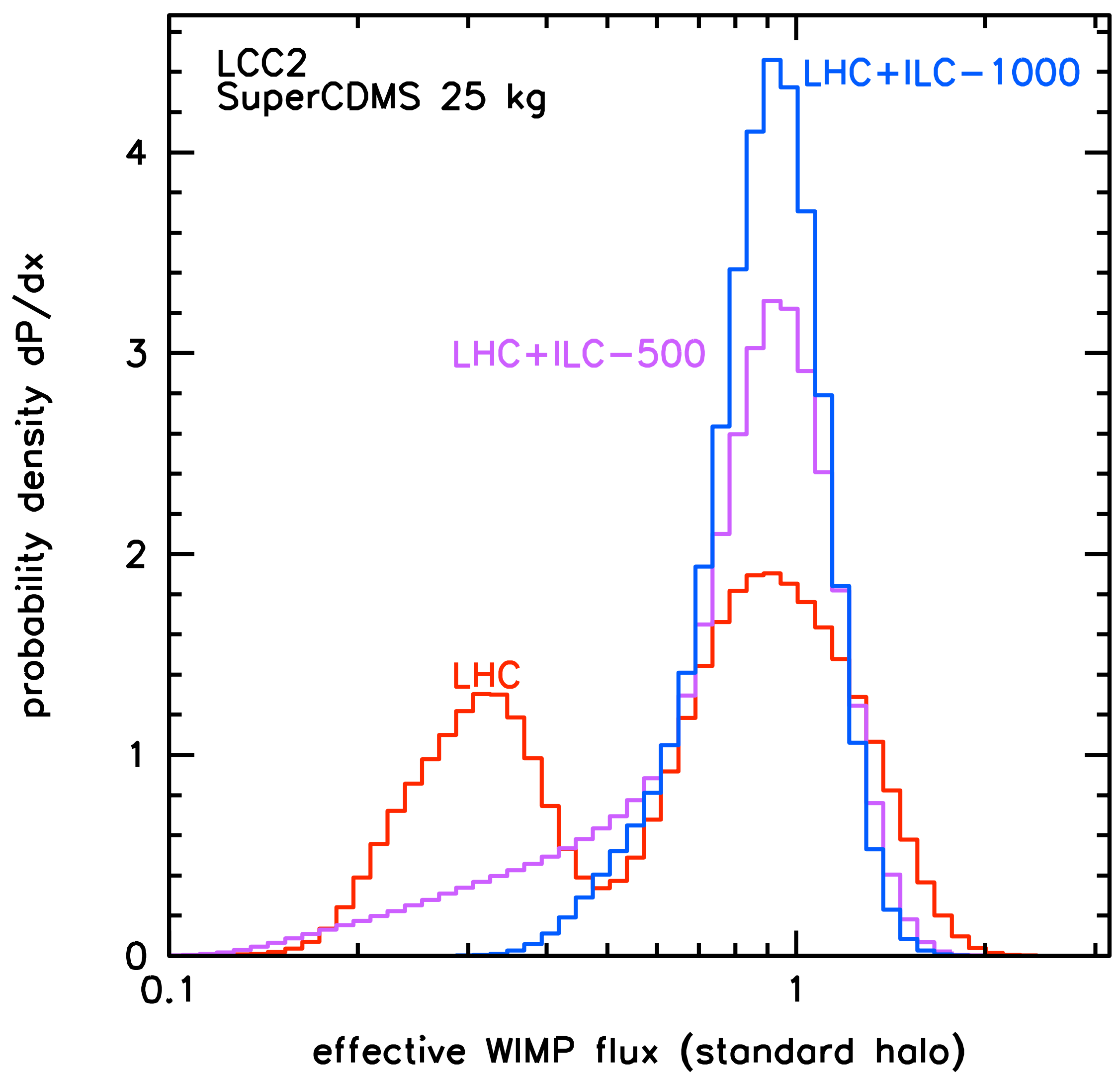


direct detection cross section



dominated by t-channel h exchange

Super-CDMS should see 67 events. Using this number and the cross section just determined, we can directly evaluate the flux of dark matter impinging on the CDMS detector.



We carried out similar analyses at the four LCC points. Here are the results for the dark matter abundance

		fractional errors (variance/mean)		
point	Ωh^2	LHC	ILC 500	ILC 1000
LCC1	0.192	7.2%	1.8%	0.24%
LCC2	0.109	82%	14%	7.6%
LCC3	0.101	167%	50%	18%
LCC4	0.114	405%	85%	19%

Our results for SPS1a' + LHC agree with those of Nojiri, Polesello, and Tovey.

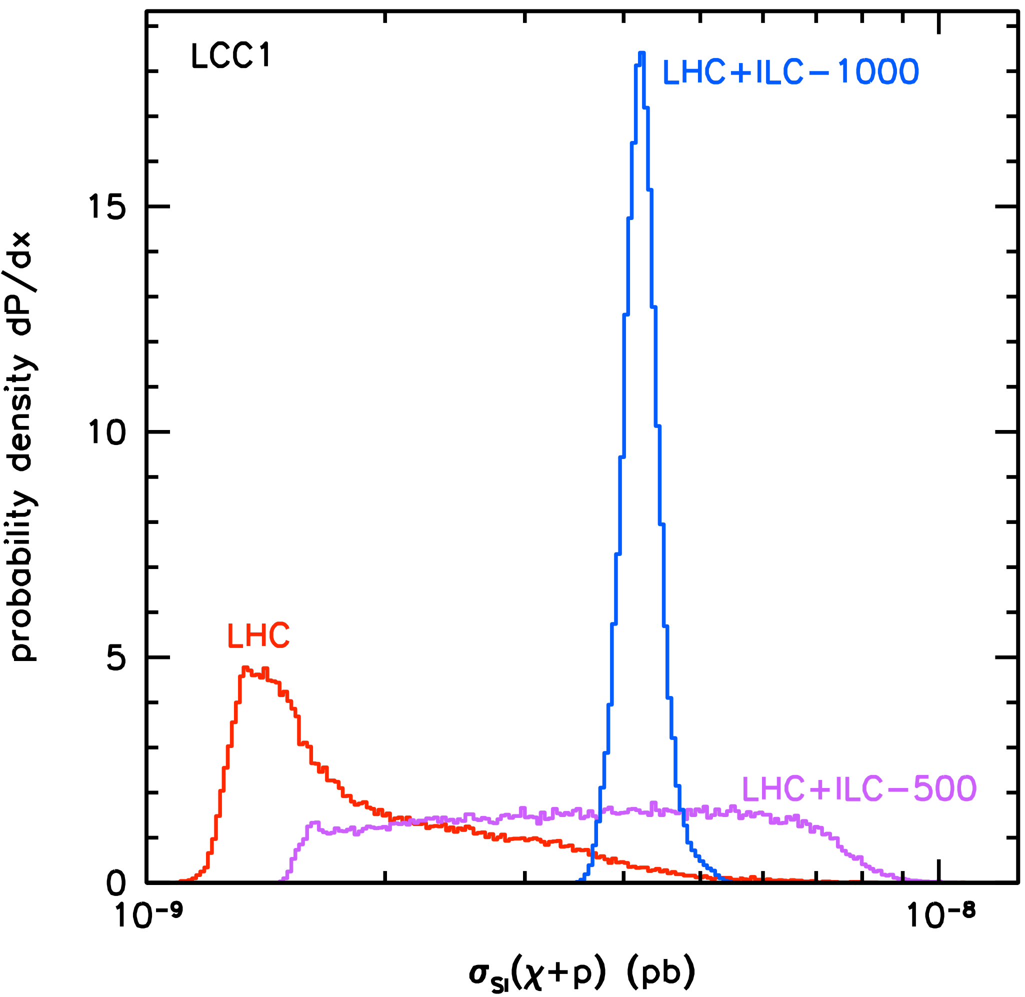
Our error estimates for Ω are larger than those presented by Richard, Belanger, and others. We believe that this results from our more extensive exploration of parameter space. We do not believe that Ω can be determined to few-percent accuracy at generic points in SUSY parameter space.

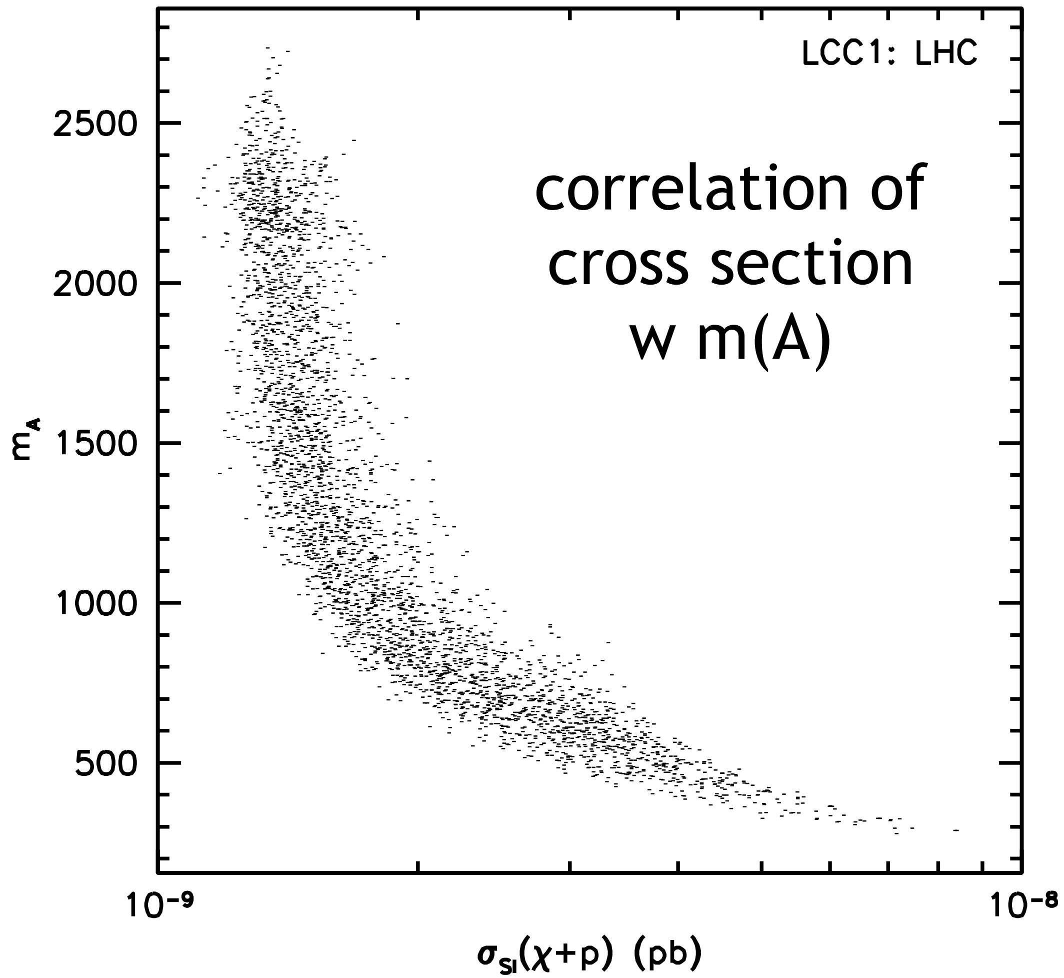
However, the ILC can do quite well enough for a nontrivial comparison with microwave background data.

The four LCC points are chosen so that some SUSY particles can be studied at the 500 GeV ILC. However, it all cases, it is necessary to go to 1 TeV to get the whole story.

In particular, the heavy Higgs bosons H and A often play an important role in the neutralino dark matter properties. It is often important to determine $\tan\beta$ from H and A decays. But sometimes H, A play a more direct role:

direct detection cross section at LCC1





correlation of cross section w m(A)

dominated by t-channel H exchange

Finally, let me call attention again to the direct determination of dark matter densities and fluxes by interpreting the results of dark matter search experiments using cross sections based on collider measurements.

We know that the ILC will be an important tool for particle physicists. Now we see that it will also be important for astrophysicists. The ILC will help us learn about the distribution of dark matter in the galaxy and the role of dark matter in galaxy formation.