Dark Matter Studies from a Long-Term Perspective

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This is an exciting time in the study of cosmic dark matter.

In direct detection, operating detectors are reaching levels of sensitivity at which we robustly expect to see signals.

GLAST and ground-based telescopes are about to dramatically increase our sensitivity to gamma rays.

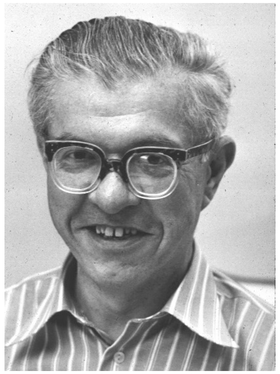
The LHC should reach the energy scale at which dark matter particles are produced at accelerators.

It is tantalizing to try to imagine the coming era of discovery as it unfolds.

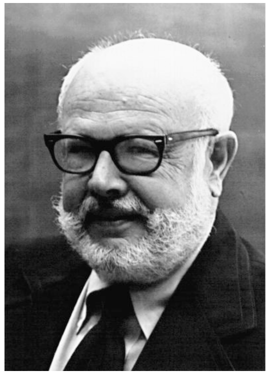
But, we also realize that the early data will fall short of doing ‘dark matter astrophysics’.

Here is my definition of astrophysics:

The interpretation of observations of objects at cosmic distances based on our knowledge of the microscopic physics of particles to deduce the structure and origin of the major components of the universe.

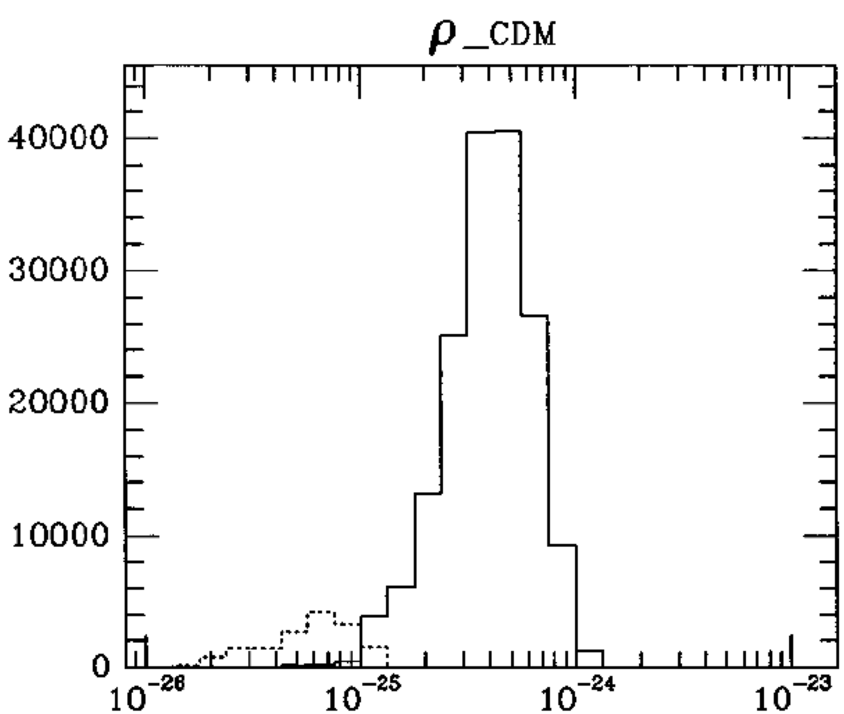


This is quite a purist definition, but nevertheless, this program has taught us an enormous amount about stars, galaxies, and cosmology.   This knowledge rests on laboratory observation of atomic and nuclear processes.



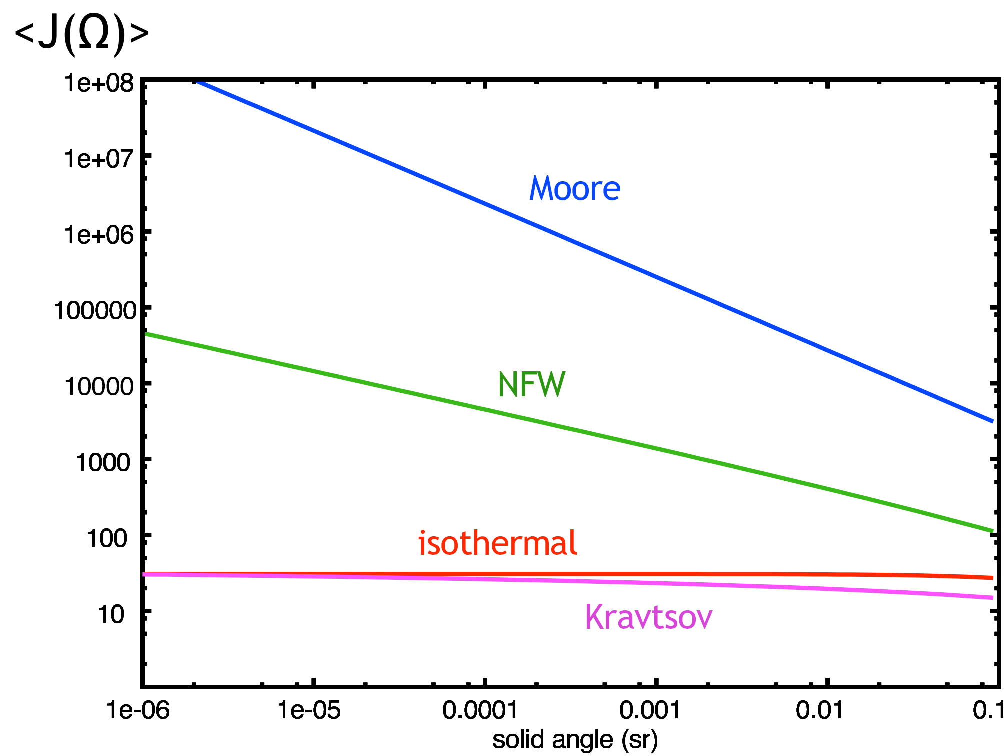
We need this perspective. Interpreting dark matter observations on the basis of unknown microphysics and unknown astrophysics is an ill-posed problem.

Even for models with a smooth distribution of dark matter in the disk, the local density is uncertain to a factor of 2:



Gates, Gyuk, Turner

Viable models of the clustering of dark matter lead to enormously different predictions for annihilation signals:



On the other hand, from the side of microphysics, there are problems that seem insuperable:

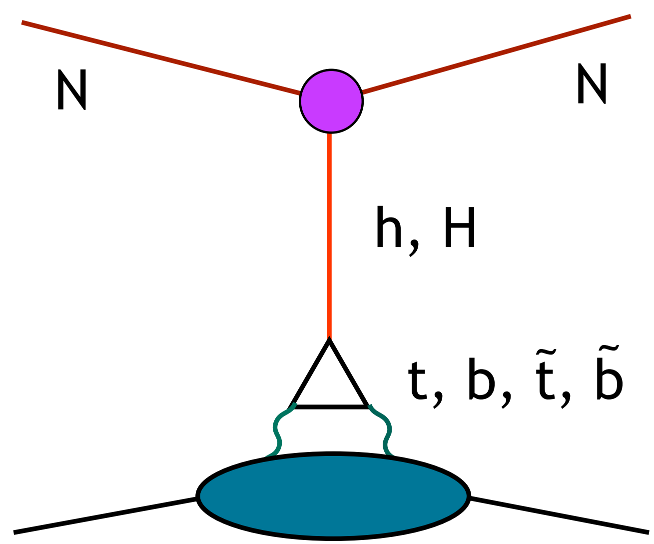
Dark matter particles are not observable in controlled high-energy collider experiments.   It is not feasible to produce dark matter beams. So the cross sections needed for astrophysics must be inferred indirectly.

Fortunately, all we need are cross sections near threshold, obtained in a weak-coupling QFT setting. These are determined by the elementary particles and couplings of the dark matter particle sector.

That is, we need to understand the basic physics of the 100 GeV - 1 TeV energy scale.   This is the basic goal of the LHC + ILC program.

Look at a concrete example:

In supersymmetry, in most of the parameter space with neutralino dark matter and squarks not observable at the Tevatron, the direct detection cross section is dominated by Higgs exchange:



The major issues are:

1. Is supersymmetry (MSSM) the right context ?
2. What are the masses of the relevant Higgs bosons ?
3. What is the neutralino-Higgs coupling ?

The physics of stop, sbottom can also enter significantly.

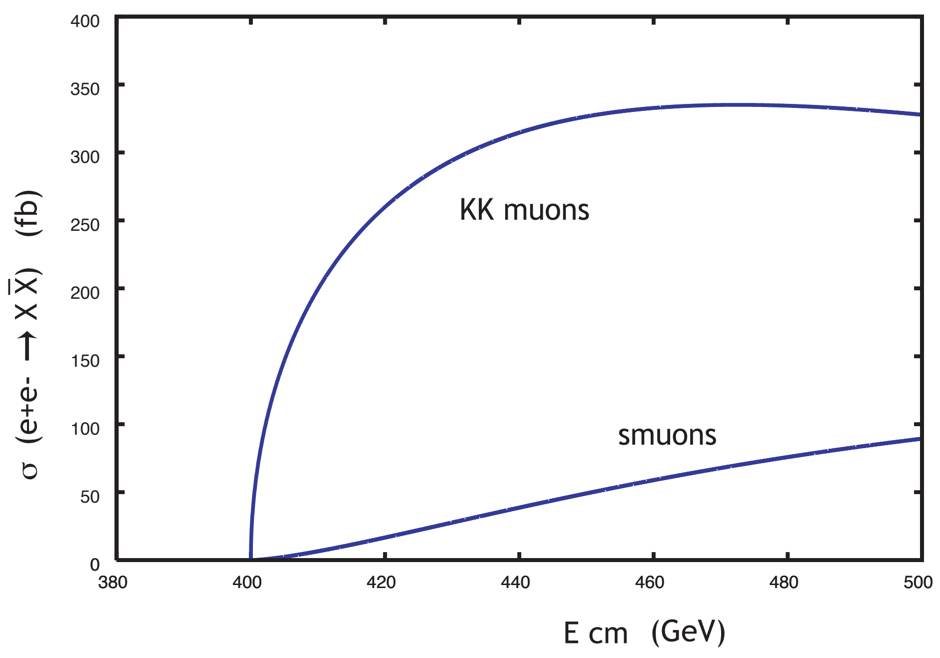
1. Is supersymmetry (MSSM) the right context ?

In the era we are talking about, we should not have to assume mSUGRA, cMSSM, NMMSSM, etc.

LHC will have measured an important part of the mass spectrum of particles that decay to dark matter.

ILC will have definitively established the spins and quantum numbers of at least the lightest of these particles.

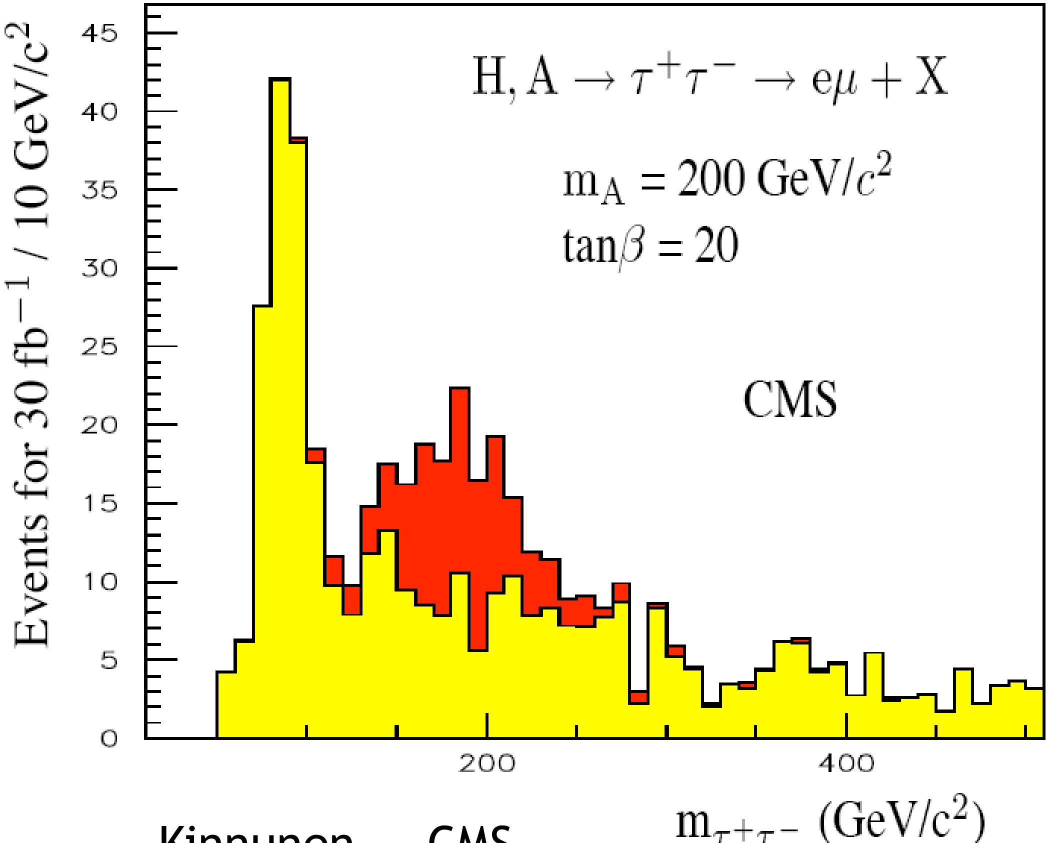
This will give a firm foundation for the next steps.



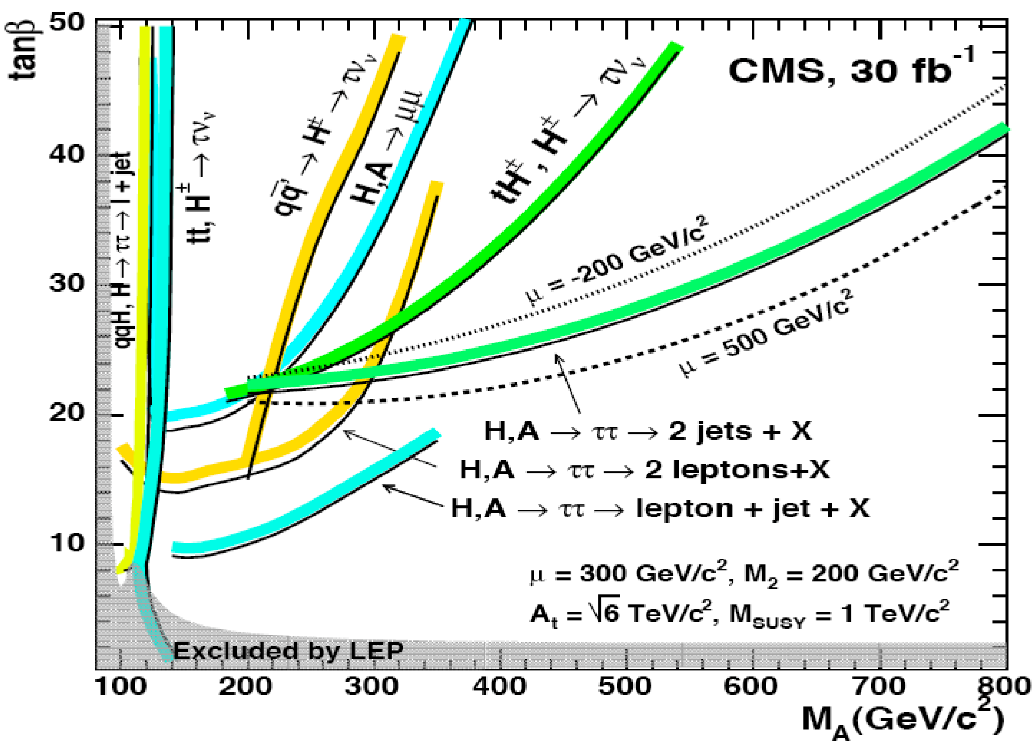
2. What are the masses of the relevant Higgs bosons ?

For large enough $\tan\beta$ the heavy MSSM bosons H and A can be discovered at the LHC through

$$b\bar{b} \to H, A \to \tau^+\tau^-$$



Kinnunen CMS



This gives the mass to a few %, but with a large uncertainty in $\tan\beta$

H will be found at the ILC above the threshold for the processes

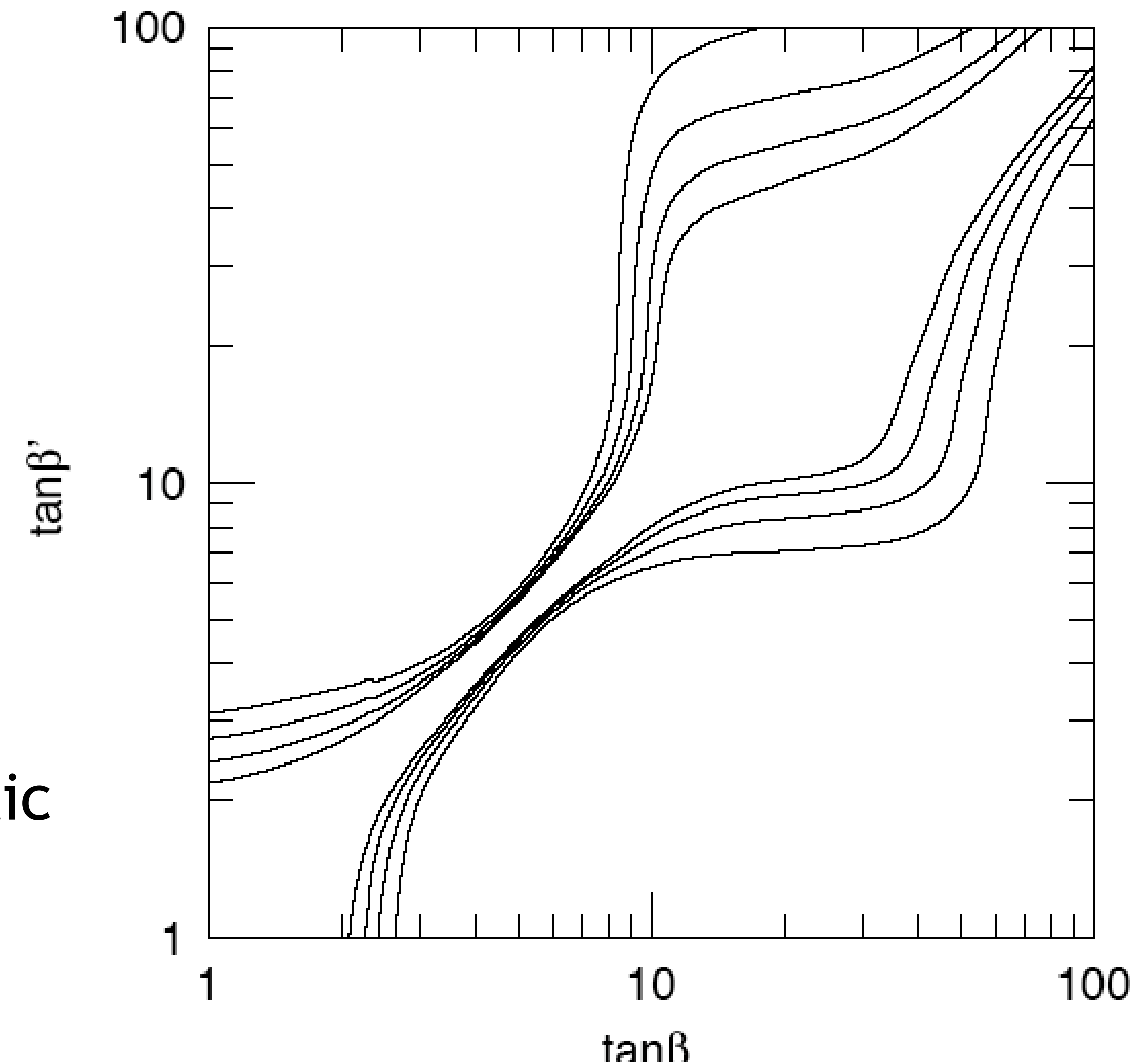
$$e^+e^- \to HA\ ,\ e^+e^- \to H^+H^-$$

$$\Delta m(H) \approx 1\ \mathrm{GeV}$$

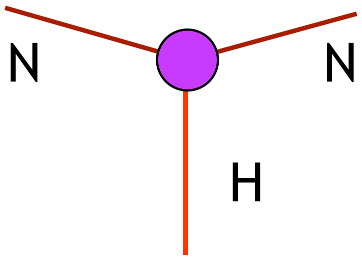
The widths and branching ratios give a more precise determination of $\tan\beta$

Feng-Moroi '96
for m(H) = 200, ILC-500

(assumptions on luminosities and b tagging were pessimistic by current standards)



3. What is the neutralino-Higgs coupling ?



$$= \frac{ie}{2}\left(\frac{V_{11}}{c_w} - \frac{V_{21}}{s_w}\right)(V_{31}\cos\alpha - V_{41}\sin\alpha) + (i \leftrightarrow j)$$

this depends both on $\tan\beta$ and on the neutralino mixing angles.

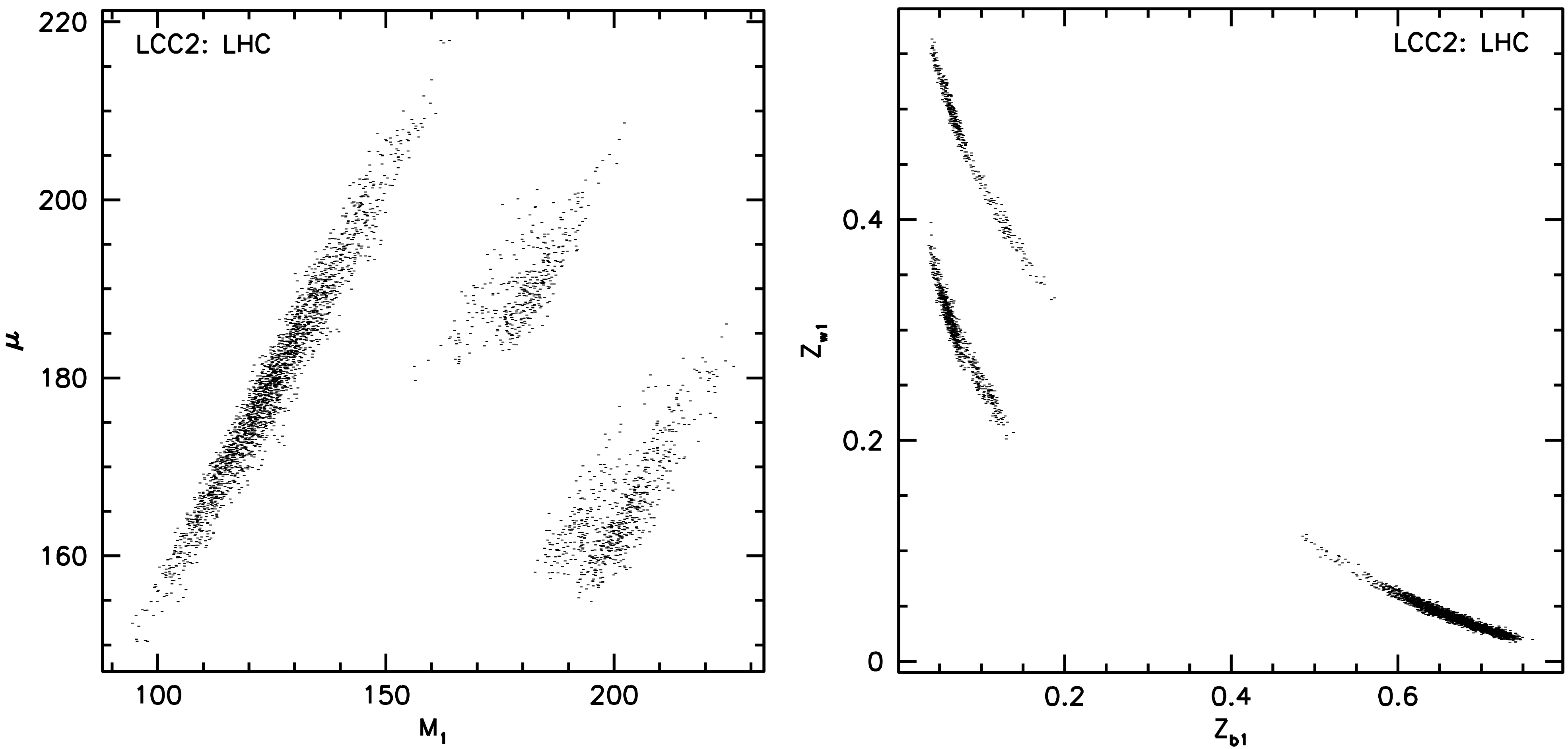
Neutralino mixing can be measured from the spectrum, but it is beautifully measured from polarized e+e- cross section,

e.g. (Feng '95) $e^+e^- \to C_1^+ C_1^-$

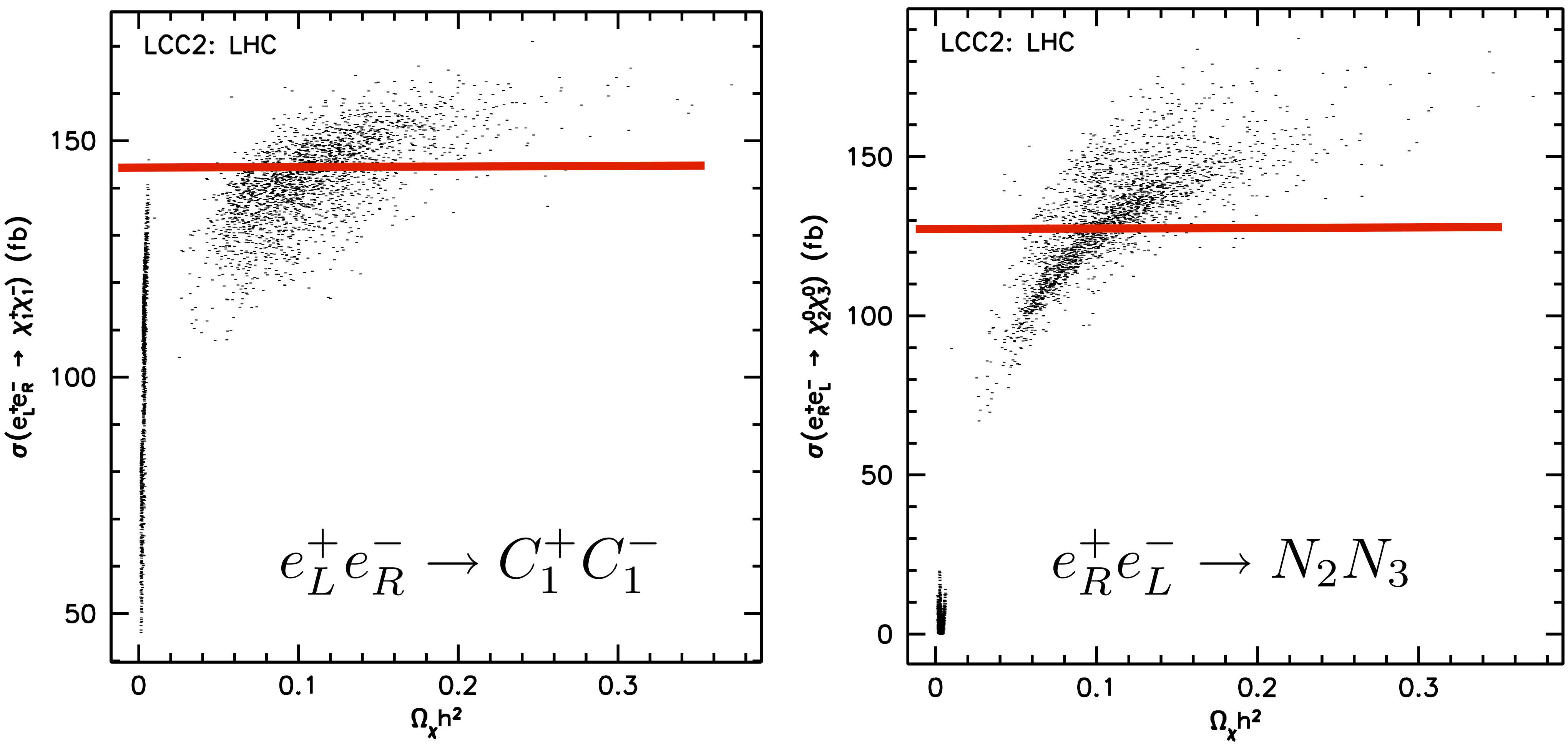
from right-handed polarized e- beams.

ILC will measure this and similar cross-sections at the few-% level.

Here are some SUSY parameters sets consistent with spectrum data from the LHC, at a point (LCC2) in the MCMC study of Baltz et al.



Here are the same points, scattered in the plane of relic density vs. ILC cross sections:



Now put the pieces together and look at the expectations for direct detection cross sections.

The data I will show is from the MCMC study of Baltz, Battaglia, Peskin, and Wizansky, hep-ph/0602187.

Methodology:

Choose 4 representative MSSM points, one in each major region of mSUGRA with neutralino dark matter.

Input the expected experimental measurements of the SUSY spectrum from LHC, ILC-500, ILC-1000. Battaglia will discuss the basis of these estimates in the next talk.

Fit to 24 parameters, the most general MSSM.

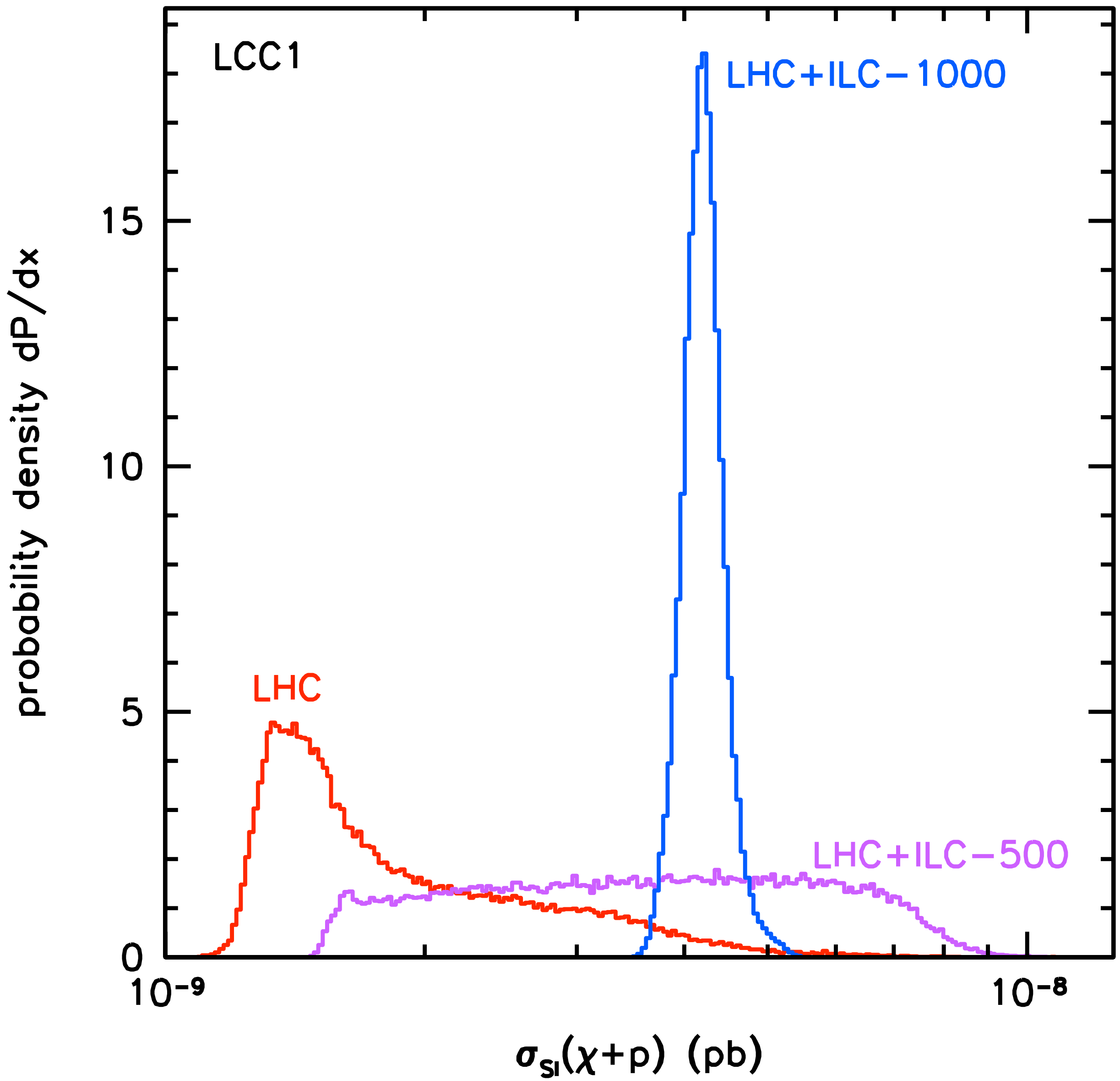
Generate models weighted by likelihood. Histogram the values of the direct detection cross section.

LCC1 = SPS1a

bulk region

In this case, we have no information about the heavy Higgs H mass until ILC-1000.

However, most of the SUSY spectrum is seen already at LHC.

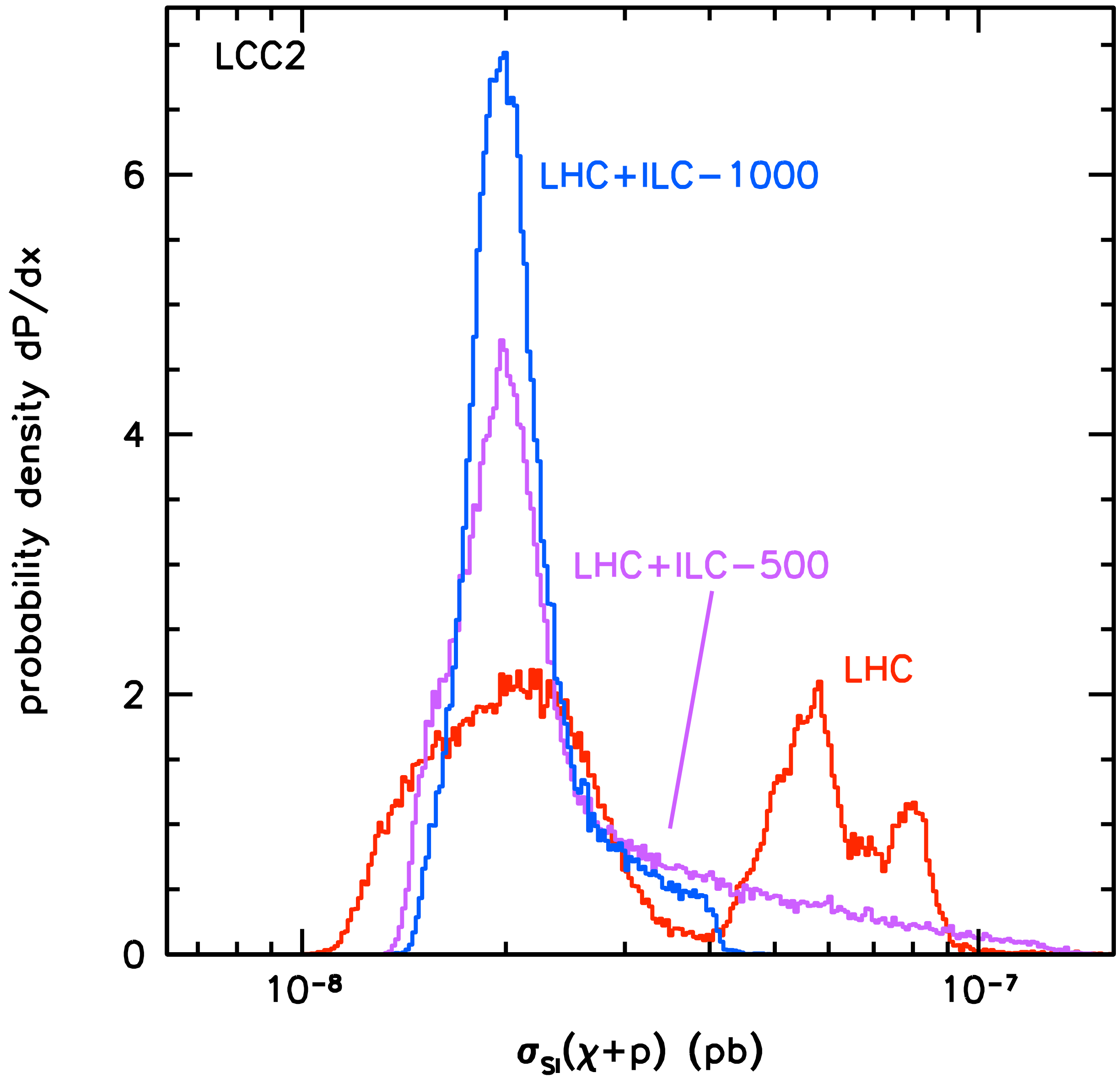


LCC2

focus-point region

In this case, the direct detection cross section is dominated by exchange of the light Higgs h.

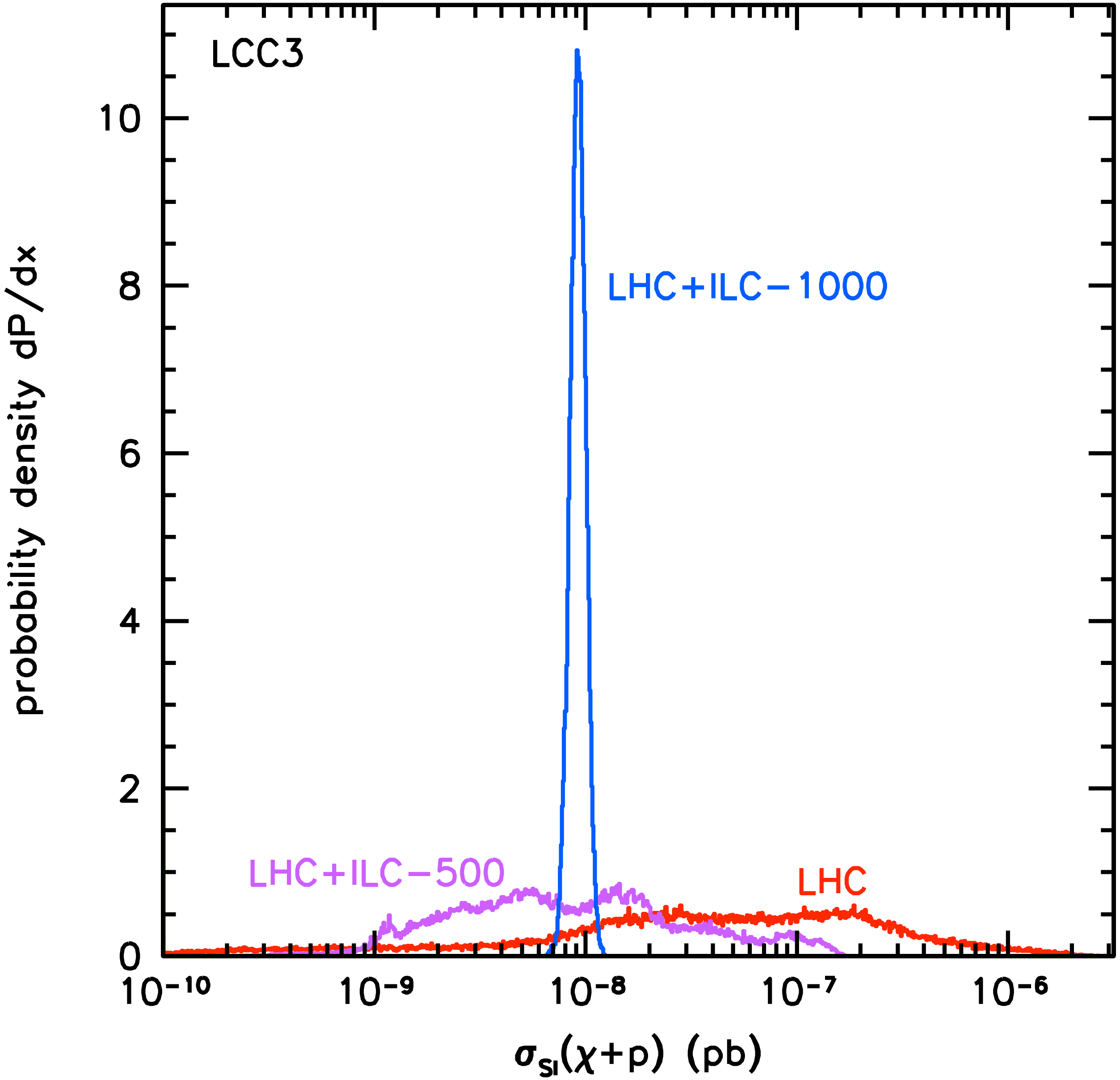
The role of the ILC is to determine the neutralino mixing angles.



LCC3

coannihilation region
 - Dutta-Kamon point

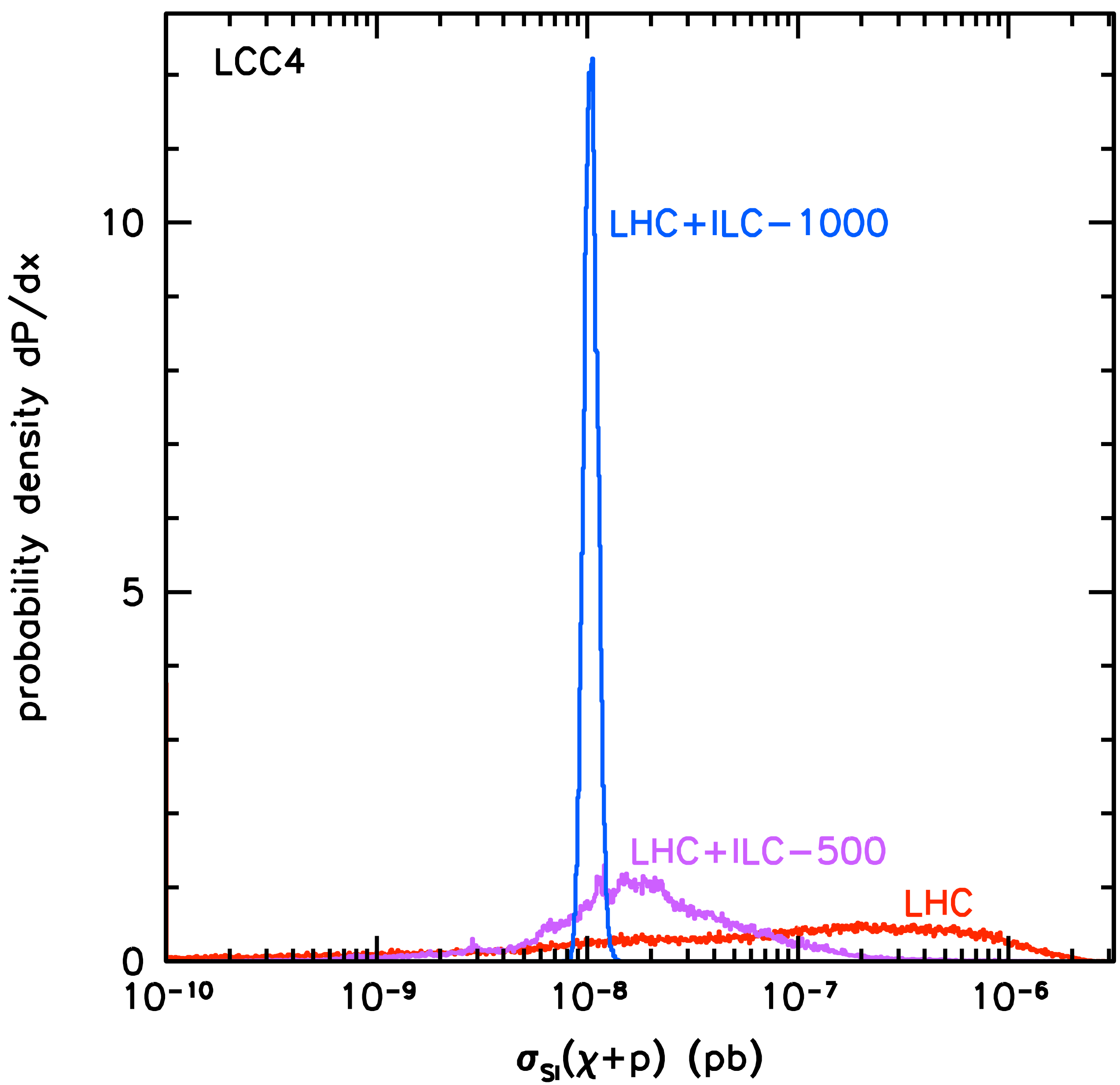
In this case, the H mass is measured at LHC. However, we need ILC-1000 to measure enough sleptons and gauginos to learn the mixing angles and $\tan\beta$



LCC4

A funnel region

As in the previous case, the H mass is measured at LHC. However, we need ILC-1000 to measure enough sleptons and gauginos to learn the mixing angles and $\tan\beta$

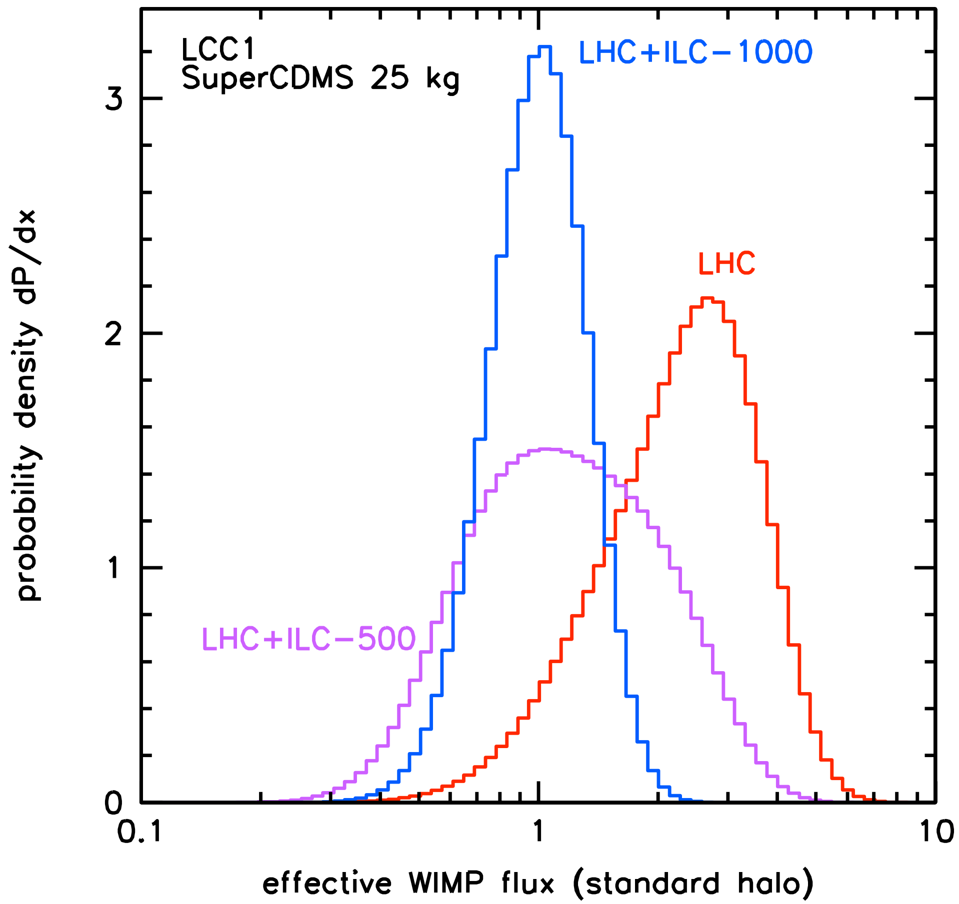


In this situation, we can do astrophysics in the narrow sense given at the beginning of this lecture.

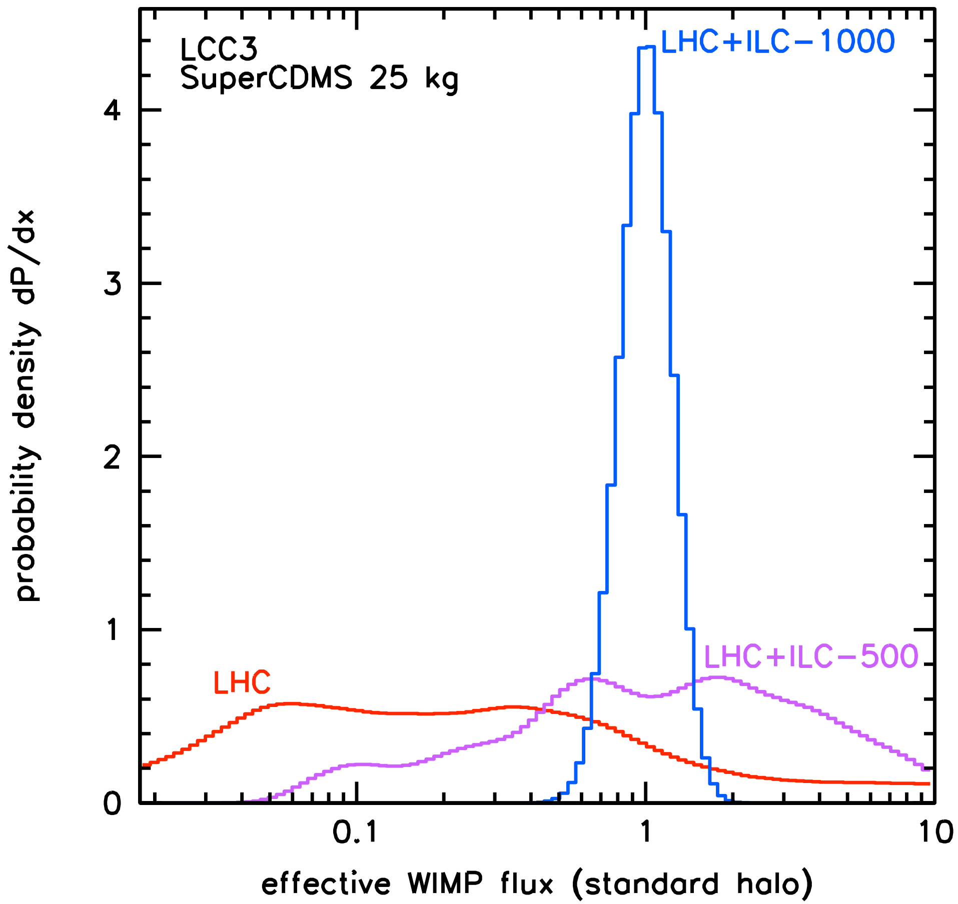
Count events in your detector, divide by the known cross section, obtain the flux of dark matter !

examples with SuperCDMS 25 kg :

LCC1: 16 events



LCC3: 29 events



From these examples, we expect that the accelerators of the next generation, LHC and ILC, will provide a microphysical basis for true dark matter astrophysics. Over the long term, we will use accelerator data to measure the dark matter distribution in the galaxy.

Today, the overall density of dark matter, the velocity distribution of dark matter, and the clustering properties of dark matter are all matters of controversy. The values of these quantities are closely connected to theories of the formation of the galaxy by aggregation of dark matter.

We can learn about these quantities experimentally, with the combined power of accelerators and direct and indirect dark matter searches. This is a program for the long term, but in time we will have the knowledge.