The Role of the ILC in the Study of Dark Matter

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The following talks in this session will present ILC analyses of precision SUSY parameter determination and their implications for predicting the cosmic density of dark matter.

In this talk, I would like to put these talks in context by explaining more generally how the ILC is relevant to the problem of dark matter.

I will discuss:

Why the WIMP model deserves special attention

Why the LHC should see huge new physics signals

Why--despite this--the LHC is insufficient,
and what ILC can do about it.

Scenarios for fixing the dark matter density in SUSY

Implications of these scenarios for astrophysical detection
of dark matter

Among the many models of dark matter, there is a generic class in which the dark matter particle is a ‘thermal relic’ (WIMP).

A WIMP is a heavy, neutral stable particle that was in thermal equilibrium in the early universe.

Due to the expansion of the universe, such particles eventually cannot find partners to annihilate.

Thus, a WIMP has a calculable density today.

Basic formulae for WIMP dark matter

(Turner-Scherrer approximation)

freeze-out: $\xi = T_f / m_N \sim 1/25$

then
$$\Omega h^2 = \frac{s_0}{\rho_c / h^2} \left(\frac{45}{\pi g_*} \right)^{1/2} \frac{1}{m_{\rm Pl}} \frac{1}{\langle \sigma v \rangle}$$

putting in numbers:
$$\Omega h^2 = 0.1 \to \langle \sigma v \rangle = 1 \ {\rm pb}$$

setting $\langle \sigma v \rangle = \dfrac{\pi \alpha^2}{8 m^2}$ we find m = 100 GeV,

so models of electroweak symmetry breaking with conserved quantum numbers lead to WIMPs !

With this guidance, it is easy to generate WIMP dark matter candidates:

SUSY: use R-parity

neutralino, R-sneutrino, and gravitino super-WIMP

Extra dimensions: use P_5 , R-parity, Z_3

KK photon, KK neutrino, KK graviton super-WIMP

B = 1/3 neutrino in ‘warped dark matter

branon

Little Higgs: use T-parity

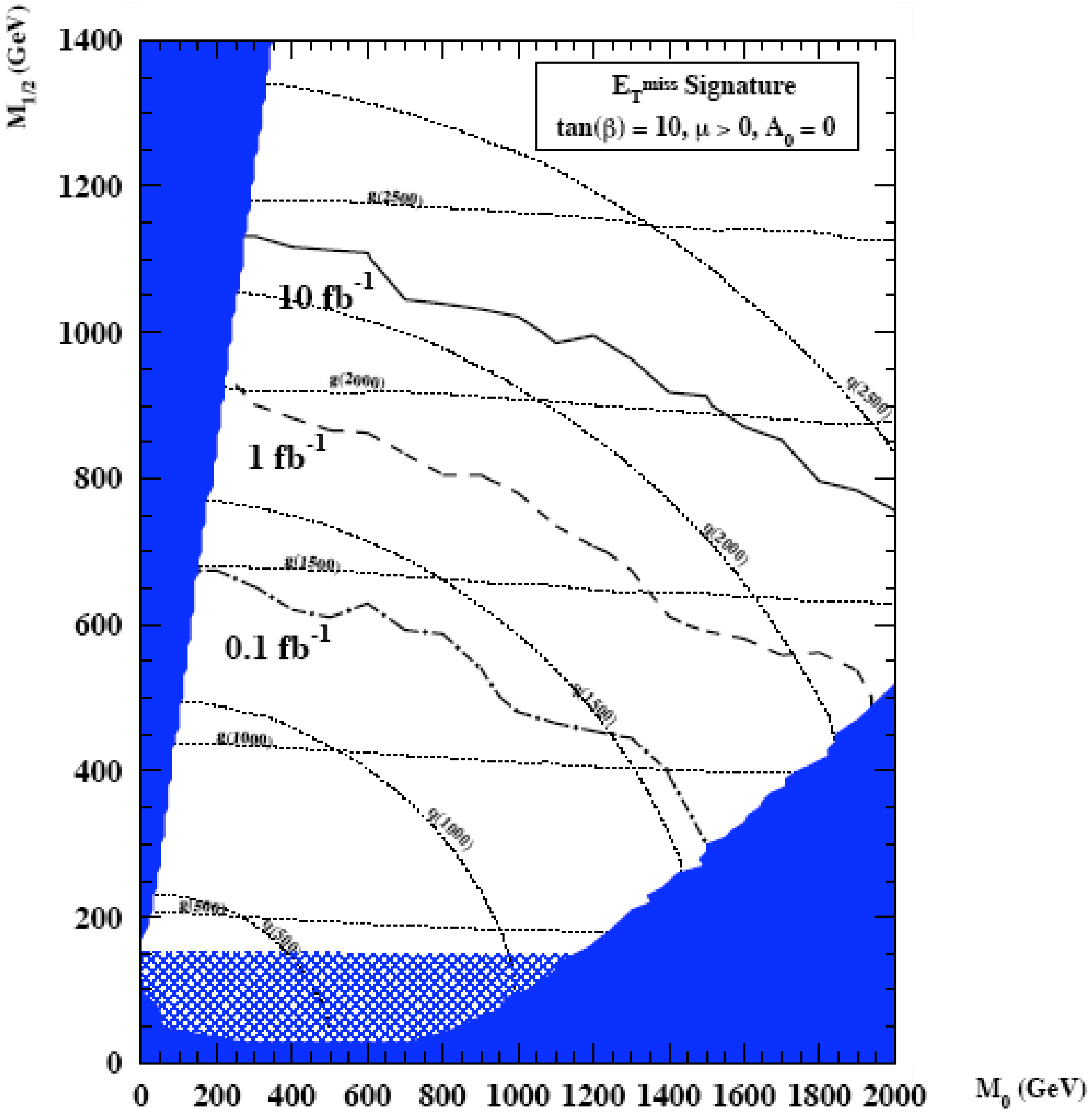
etc.

A common feature in these models is the presence of fermions or bosons with QCD color that decay to the WIMP.

This leads, at LHC, to jets + missing energy.

The cross section depends mainly on the mass of the colored particle

$\sigma \sim 100\ \mathrm{pb}$ for m < 1 TeV.


E_T^{miss} Signature
$\tan(\beta) = 10, \mu > 0, A_0 = 0$
10 fb^{-1}
1 fb^{-1}
0.1 fb^{-1}
g(2500)
g(2000)
g(1500)
g(1000)
g(500)
q(2500)
q(2000)
q(1500)
q(1000)
q(500)
$M_{1/2}$ (GeV)
1400
1200
1000
800
600
400
200
0
M_0 (GeV)
0
200
400
600
800
1000
1200
1400
1600
1800
2000

ATLAS

If this logic is correct, the LHC must discover the new physics signal of jets + missing energy very early in its program.

We should anticipate this and be ready to follow up this discovery.

What is needed as the next step?

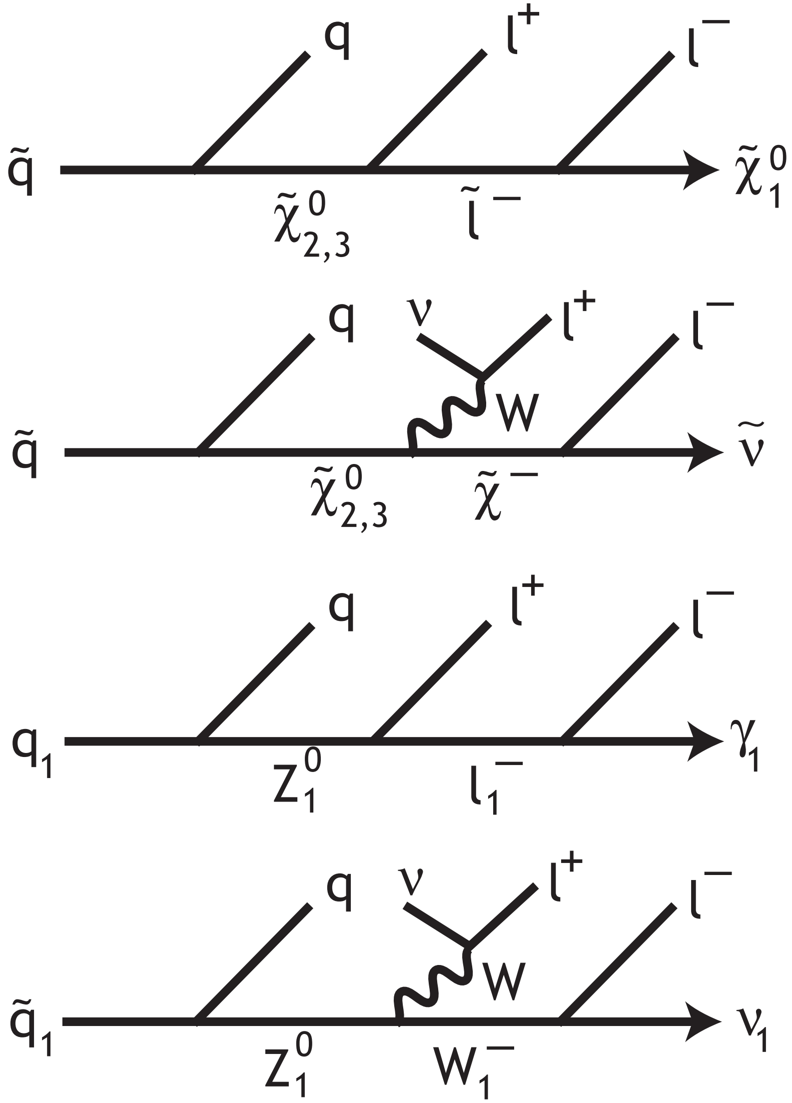
Because the jet + missing energy signature is generic in WIMP models, the discovery of this type of event is not a proof of supersymmetry.

In fact, this discovery would open many possibilities for new physics.

The connection to dark matter would make it very important to find out which option is correct.

These diagrams illustrate the difficulty of resolving this question at the LHC.

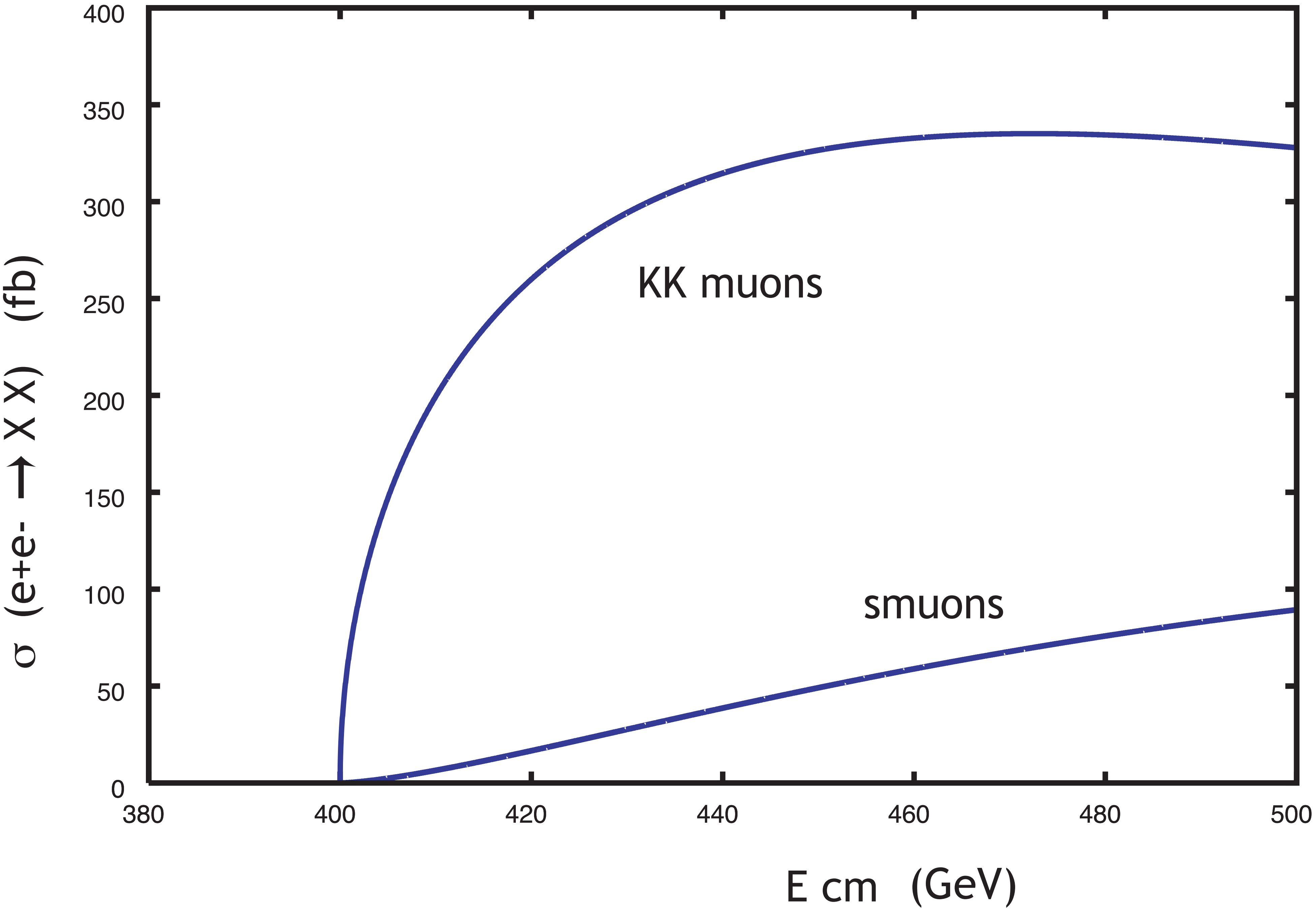
Remember: every WIMP event contains at least 2 unobserved neutral particles !



The key is to measure the spin and EW quantum numbers of particles that carry the conserved quantum number of the WIMP.

Often, it is sufficient to measure the properties of the lightest charged particle in this sector.

That is very straightforward at the ILC.


400
350
300
250
200
150
100
50
0
380
400
420
440
460
480
500
σ (e+e- → X $\bar{X}$) (fb)
E cm (GeV)
KK muons
smuons

Once we have qualitatively identified the dark matter particle, the next step is to see whether we can quantitatively account for the relic density.

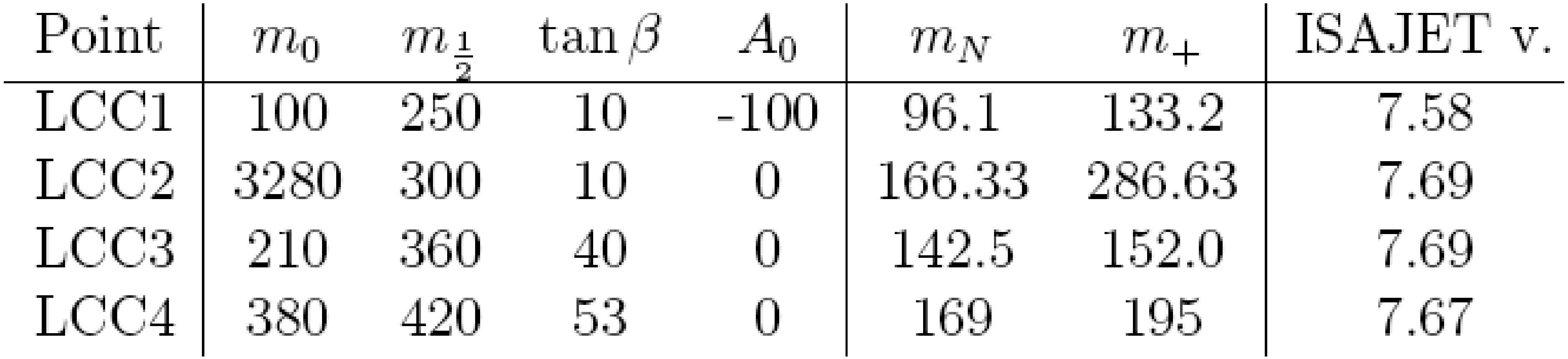
This is nontrivial. The relic density depends on the annihilation cross section σ_{NN}, but that is typically very model-dependent.

Fortunately, σ_{NN} depends mainly on the masses and couplings of the lightest states of the new sector.

The determination of these quantitites is the forte of the ILC.

To explore this, look in great detail into supersymmetry models with neutralino dark matter. Here are some sample parameters.

For definiteness, we choose points in mSUGRA. However, the evaluation of the relic density should not rely on such a model. For this, we assume only the general MSSM.



Point	m_0	$m_{\frac{1}{2}}$	$\tan\beta$	A_0	m_N	m_+	ISAJET v.
LCC1	100	250	10	-100	96.1	133.2	7.58
LCC2	3280	300	10	0	166.33	286.63	7.69
LCC3	210	360	40	0	142.5	152.0	7.69
LCC4	380	420	53	0	169	195	7.67

(LCC1 is the well-studied point SPS1a)

The physics of the WIMP annihilation cross section is different at each point:

LCC1: ‘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 $m(\widetilde{\chi}^0_1), m(\widetilde{\tau}), \theta_\tau$

LCC4: ‘A funnel region’
annihilation through A resonance
σ_{NN} depends on $m(\widetilde{\chi}^0_1), m(A), \Gamma(A), \tan\beta$

Whereas the LHC is well-positioned to go after other parameters, e.g., squark and gluino masses,

the ILC is well-suited to make precise measurements of these parameters.

The next three talks will illustrate that.

Finally, once we are certain of the particle physics origin of the dark matter particle, we will bring new information to the astrophysical questions about dark matter.

It is a controversial question in astrophysics whether the dark matter density in our galaxy is smooth or very irregular.

To address this question, look for dark matter annihilation products in cosmic rays. For illustration, I will consider the case of gamma rays.

The flux of gamma rays is given by

$$\frac{d\Phi}{dE_\gamma} = \int d^3r \frac{c}{|r|^2} n^2(r) \frac{d\sigma}{dE_\gamma}$$

The question is, what is $n(r)$? To make progress, we had better know σ

Now, from the relic density, $\sigma v = 1 \ \ \mathrm{pb}$?

It depends on the scenario:

LCC1: annihilation at T/m = 1/25 is in the P-wave. Today, the annihilation cross section is fb.

LCC2: $\sigma v = 1 \ \ \mathrm{pb}$ dominant products are WW, ZZ

LCC3: σv = fb for $\widetilde{\chi}^0_1$ pb for $\widetilde{\tau}$. But today, no $\widetilde{\tau}$ are left !

LCC4: $\sigma v = 1 \ \ \mathrm{pb}$ dominant products are $b\bar{b}, \tau^+\tau^-$

direct detection cross sections have a similar model-dependence

There are good reasons to give special attention to WIMP models of dark matter.

For these models, we must

1. Observe dark matter as missing energy at a collider.
2. Determine qualitatively which model is correct.
3. Determine whether that model quantitatively explains the relic density.
4. Determine the cross sections relevant to astrophysical dark matter observations.

LHC is crucial for #1. After that, the tasks are beyond the reach of LHC and call for the ILC experiments.