Part 4/3: SUSY Dark Matter and LHC

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Dark Matter

Existence of Dark Matter in the universe by now well established

Studies of clusters of galaxies suggest $\Omega_{DM} \simeq 0.2$ to 0.3 where $\Omega_X = \rho_X/\rho_{crit}$

From anisotropies in Cosmic Microwave Background (WMAP): $\Omega_{DM} = 0.23 \pm 0.04$

From nucleosynthesis, only 4% of total matter density baryonic

From analyses of structure formation in the universe: most DM must be "cold", non-relativistic at onset of galaxy formation.

DM candidates must be stable on cosmological time scales, interact very weakly with EM radiation, and give the right relic density. Main particle candidates:

- Axions
- Weakly Interacting Massive Particles (WIMP)

  Mass: 10 GeV – few TeV, and cross section of $\sim$ weak strength

R-parity conserving SUSY provides candidate WIMP: Lightest SUSY Particle (LSP)

Concentrate on LHC contribution to understanding of SUSY LSP Dark Matter

Experimental approaches to Dark Matter

Information on Dark matter from large variety of experimental sources. In all cases expect stringent tests in the next decade

- WIMP searches
  1. Direct WIMP searches: look for elastic scattering of WIMP on nuclei
  2. Indirect WIMP searches: look for annihilation products of WIMPS in the galactic halo
- Cosmological measurements
- Production of WIMPS in accelerator experiments

Explore what kind of information the LHC can produce on Dark Matter candidates

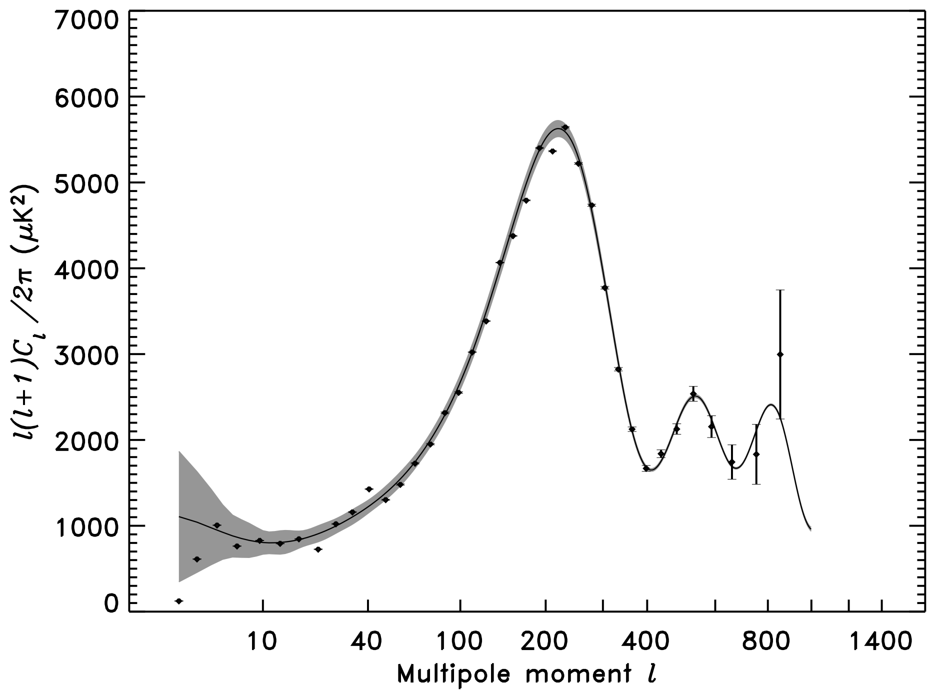
Study how to combine LHC information with direct searches and cosmology measurements

Cosmological measurements of DM relic density

Anisotropies in Cosmic Microwave Background carry information about the conditions at the time of decoupling

- Accurate measurement of the spectrum of CMB fluctuations from WMAP
- Galaxy power spectrum measured by the 2-degree Field (2dF) Galaxy Redshift Survey

These measurements can be fitted to a standard cosmological model (ΛCDM) defined in terms of 7 parameters (RPP 2004). Relevant ones for this talk:



Hubble parameter $h = 0.73 \pm 0.03$

Total matter density $\Omega_M h^2 = 0.134 \pm 0.006$

Baryon density $\Omega_b h^2 = 0.023 \pm 0.001$

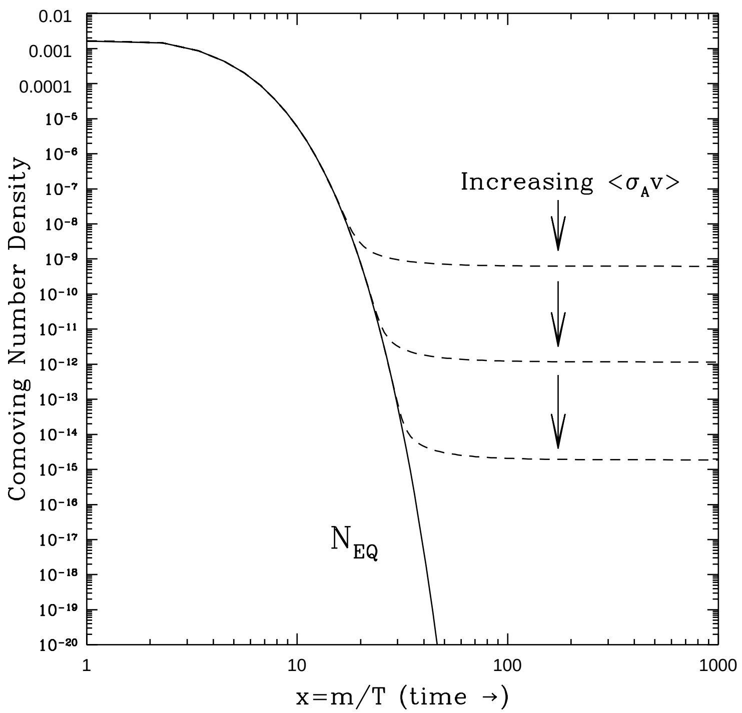
Neutrino density $\Omega_\nu h^2 < 0.0067$ (95% CL)

Derivation of Relic Density

At first, when $T \gg m_\chi$ all particles in thermal equilibrium

Universe cools down and expands:

- When $T < m_\chi$ is reached only annihilation: density becomes exponentially suppressed
- As expansion goes on, particles can not find each other: freeze out and leave a relic density



Master equation is:

$$\frac{dn}{dt} = -3Hn - <\sigma v> (n^2 - n_{eq}^2) \quad (1)$$

The relic density is:

$$\Omega_{\tilde{\chi}_1^0} = m_{\tilde{\chi}_1^0} n_{\tilde{\chi}_1^0} / \rho_{cri}, \quad \rho_{cri} = h^2 \times 1.91 \times 10^{-29} \mathrm{gcm}^{-3} \quad (2)$$

From solving Boltzmann equation:

$$\Omega_{\tilde{\chi}_1^0} \propto 1/\sigma_{\tilde{\chi}_1^0} \quad (3)$$

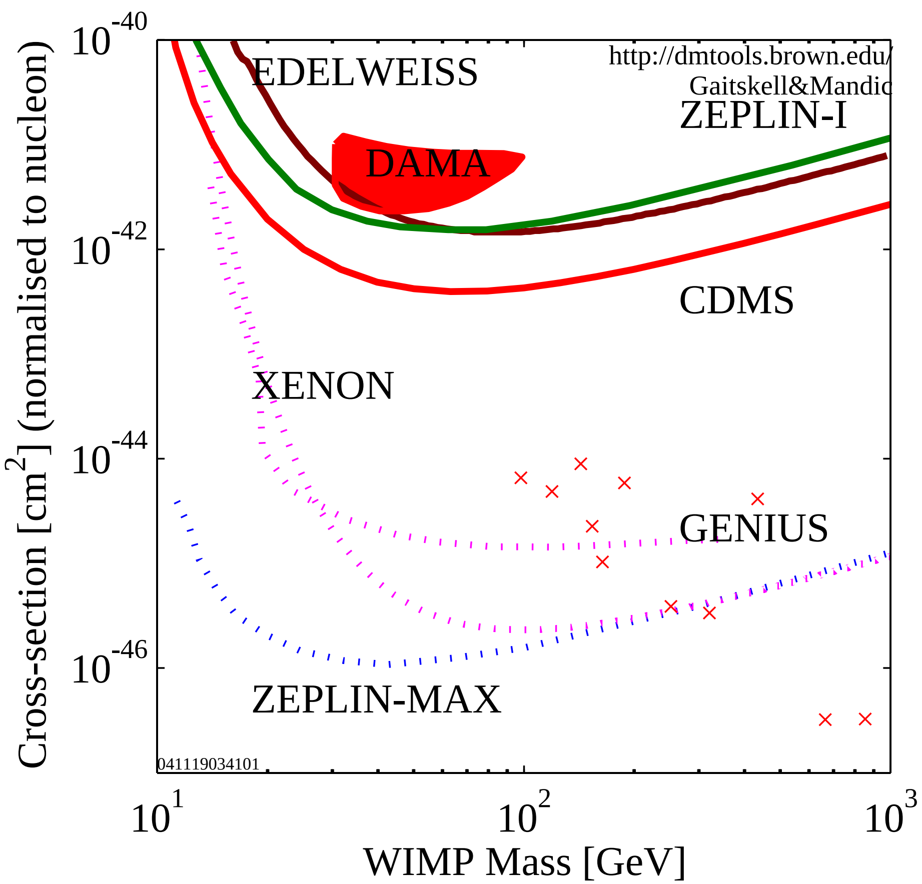
By measuring LSP annihilation X-section at the LHC we can predict relic density and verify agreement with cosmological measurements

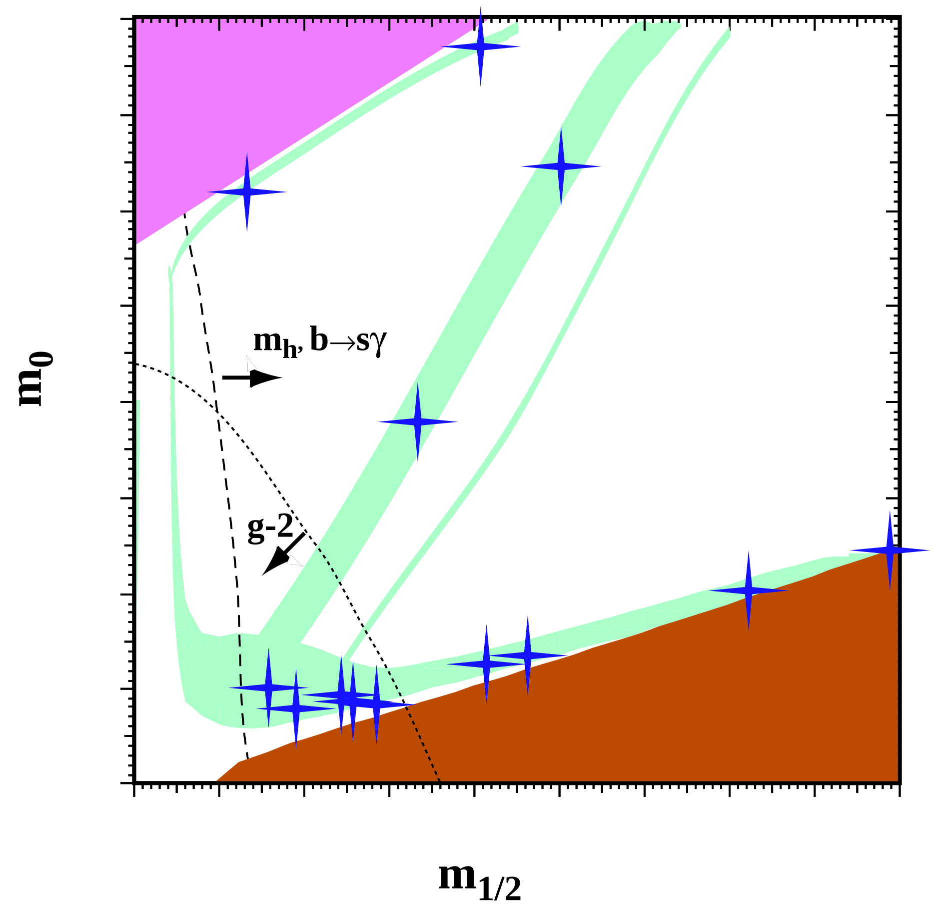
Direct DM Searches

Within next 10 year next generation of tonne scale direct detection experiments should have acquired several years of data

Will give sensitivity to scalar WIMP-nucleon cross section $\sim 10^{-10}$ pb

Region of interest for LHC SUSY studies covered





Dark Matter Strategy

SUSY studies at the LHC will proceed in 4 steps:

- SUSY discovery phase (inclusive searches). Success assumed.
- Inclusive studies (comparison of significance in inclusive channels etc.)

  Relevance to DM: verify if discovered signal provides a possible DM candidate

- Exclusive studies (calculation of model-independent SUSY masses using kinematics)

  Relevance to DM: Model-independent calculation of LSP mass, compare with direct searches

- Interpretation of results in terms of SUSY breaking
  - Fit measured quantities to constrained model (e.g. mSUGRA)

    Relevance to DM: model-dependent calculation of relic density, $\sigma(\chi p)$, etc.

  - Perform additional more complex measurements, such as BR's and rare decays, and reconstruct MSSM parameters

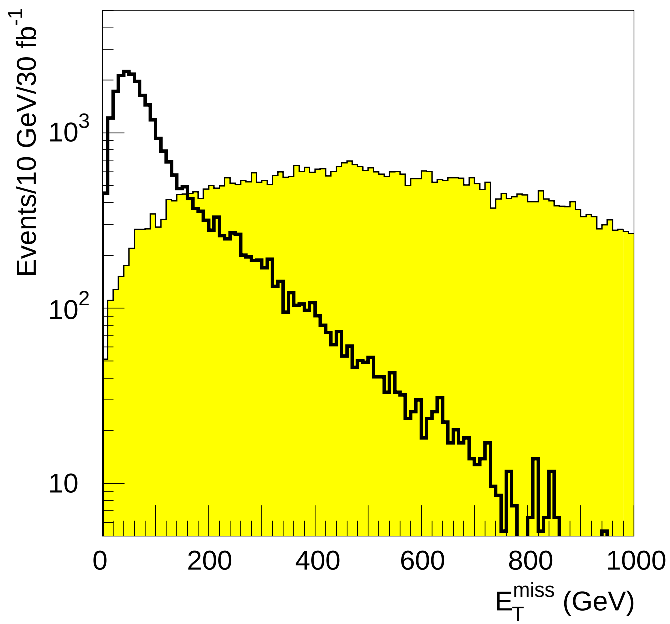
    Relevance to DM: model-independent calculation of relic density $\sigma(\chi p)$, etc.

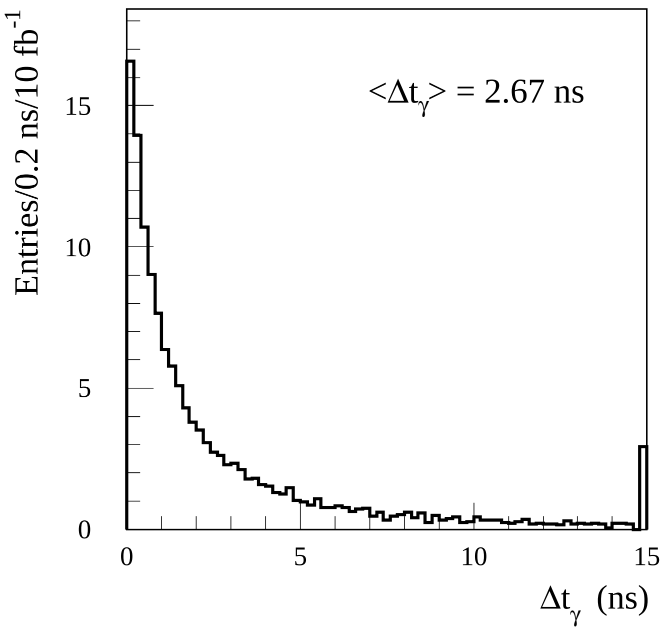
Inclusive Studies

Following any discovery of SUSY next task will be to test broad features of potential Dark Matter candidate

Question 1: Is R-parity conserved?

- If YES possible DM candidate
- Loophole: LHC experiments sensitive only to lifetimes $\lesssim 1$ ms ($\ll t_U \sim 13.7$ Gyr) $\Rightarrow$ need confirmation from direct DM detection





Question 2: Is the LSP the lightest neutralino?

- Natural in many MSSM models
- If YES then test for consistency with astrophysics
- If NO, then what is it?
- e.g. Light gravitino DM from GMSB models (not considered here)

Neutralino relic density prediction from SUSY parameter measurement

Need to calculate rate for all possible neutralino annihilation processes

In order to do this all the masses and couplings of sparticles contributing to neutralino annihilation needed

Question is whether the measurements which LHC can perform for a given MSSM point allow to fully perform this calculation

Answer possible only by going to a specific model point and performing full analysis of available constraints

Perform the exercise for our usual SPS1a Point

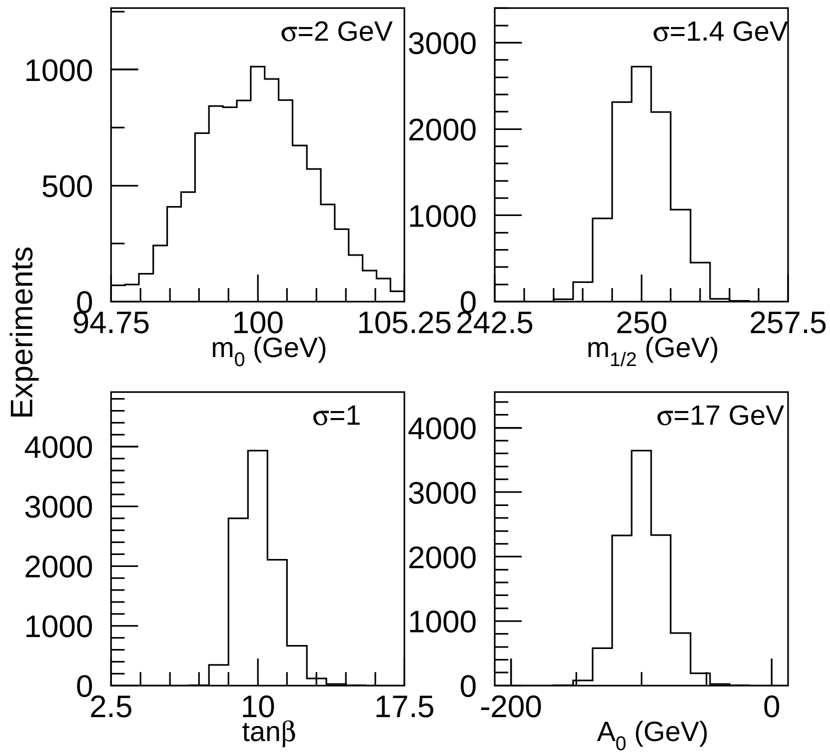
First attempt: put ourselves in well constrained mSUGRA model and evaluate if at least on easy case prediction possible

Available measurements for SPS1a (300 fb^{-1}):

		Errors		
Variable	Value (GeV)	Stat. (GeV)	Scale (GeV)	Total
$m_{\ell\ell}^{max}$	77.07	0.03	0.08	0.08
$m_{\ell\ell q}^{max}$	428.5	1.4	4.3	4.5
$m_{\ell q}^{low}$	300.3	0.9	3.0	3.1
$m_{\ell q}^{high}$	378.0	1.0	3.8	3.9
$m_{\ell\ell q}^{min}$	201.9	1.6	2.0	2.6
$m_{\ell\ell b}^{min}$	183.1	3.6	1.8	4.1
$m(\ell_L) - m(\tilde{\chi}_1^0)$	106.1	1.6	0.1	1.6
$m_{\ell\ell}^{max}(\tilde{\chi}_4^0)$	280.9	2.3	0.3	2.3
$m_{\tau\tau}^{max}$	80.6	5.0	0.8	5.1
$m(\tilde{g}) - 0.99 \times m(\tilde{\chi}_1^0)$	500.0	2.3	6.0	6.4
$m(\tilde{q}_R) - m(\tilde{\chi}_1^0)$	424.2	10.0	4.2	10.9
$m(\tilde{g}) - m(\tilde{b}_1)$	103.3	1.5	1.0	1.8
$m(\tilde{g}) - m(\tilde{b}_2)$	70.6	2.5	0.7	2.6

Reconstructing mSUGRA paramters

Simplest approach: postulate SUSY breaking model, and verify if any set of the model parameters fits measured quantities. Exercise performed for SPS1a postulating mSUGRA



- m_0 dominated by sleptons ($\Delta m_0 \sim 2\%$)
- $m_{1/2}$ " by light gauginos ($\Delta m_{1/2} \sim 0.6\%$)
- Need $\tilde{b}_1$ and $\tilde{b}_2$ for $\tan\beta$, otherwise long tails
- Trilinear couplings A_0 related to μ, fixed by $\tilde{\chi}_4^0$
- Wrong μ sign ruled out by bad fit

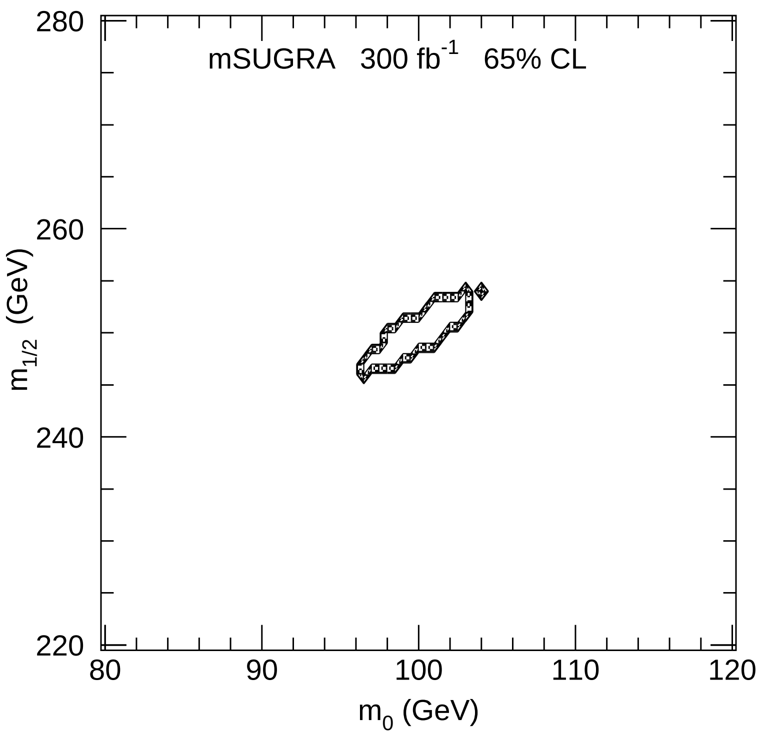
Good constraints $\Rightarrow$ verify how this translates on relic density prediction

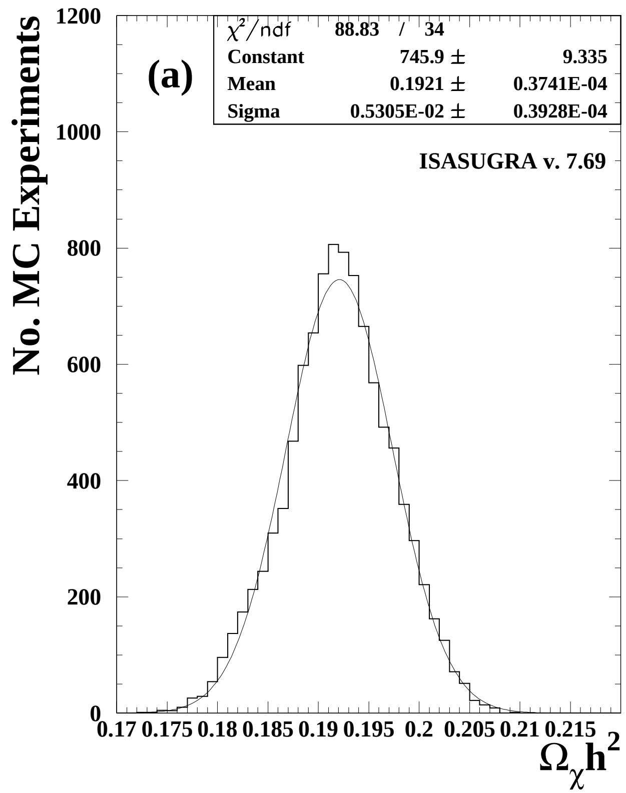
Model Dependent Relic density prediction

Assume mSUGRA model, and find point in (m_0, $m_{1/2}$, $\tan\beta$, A_0) space with best fit to measured quantities

Calculate confidence region in parameter space with n MonteCarlo experiments

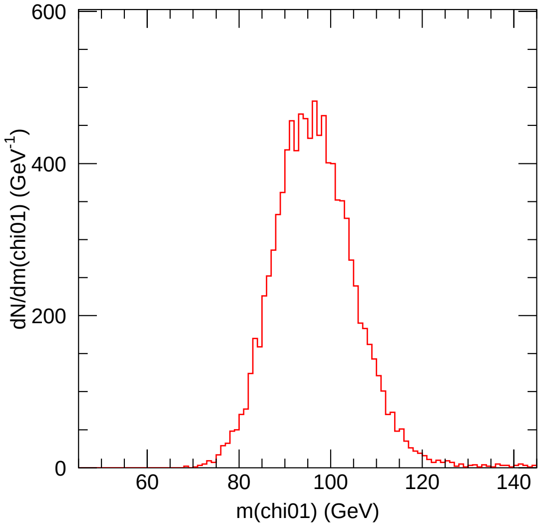
Translate into confidence interval for Dark matter density





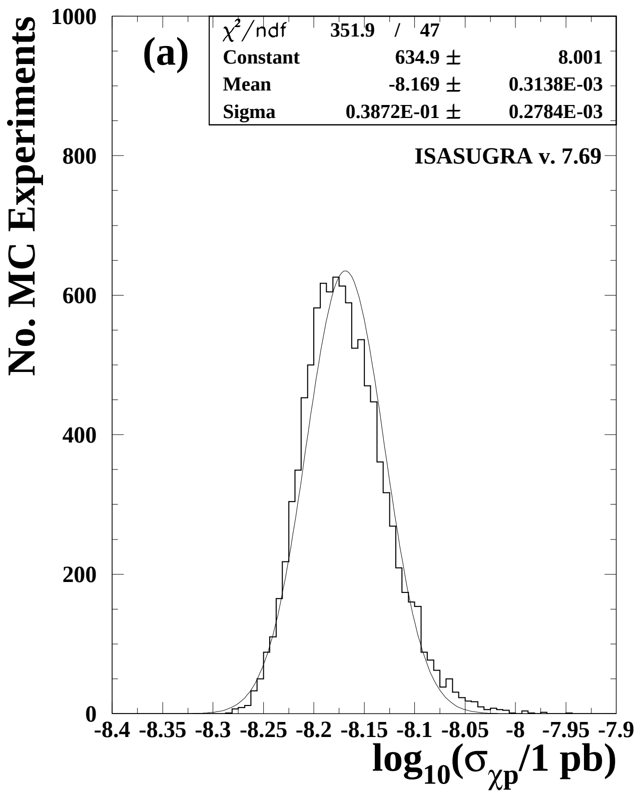
Result: $\Omega_{\tilde{\chi}_1^0} h^2 = 0.192 \pm 0.005$

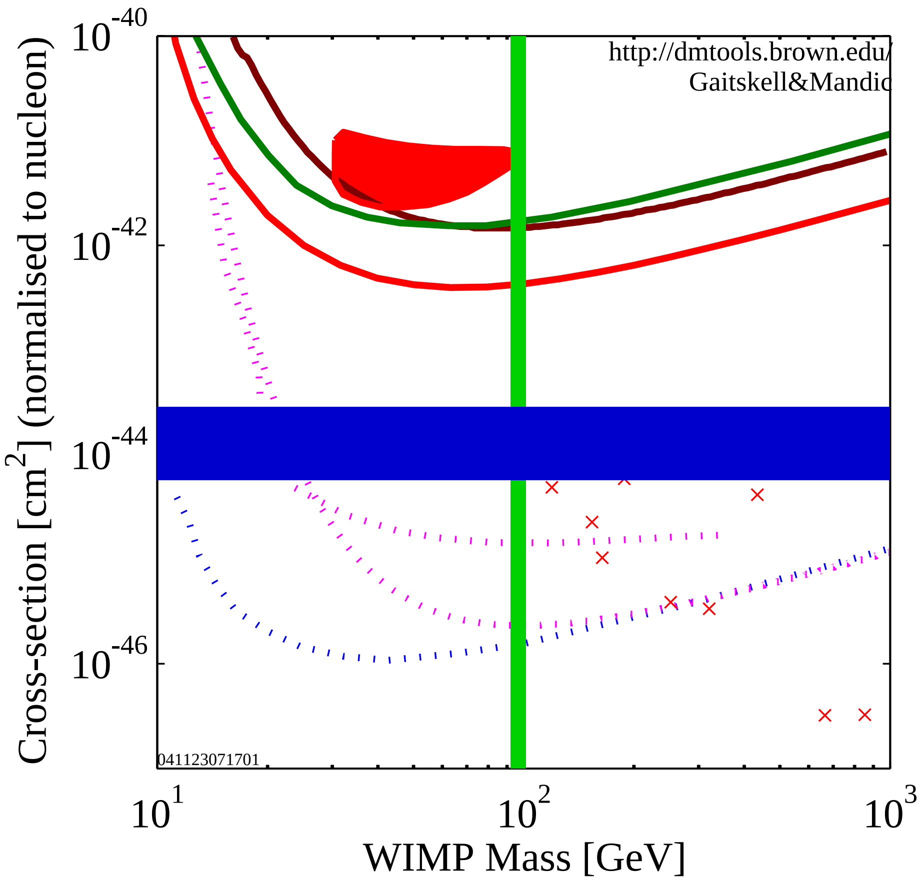
Connection to direct DM detection experiments



$$m_{\tilde{\chi}_1^0} = 96.05 \pm 4.7 \text{ GeV } (300 \text{ fb}^{-}1)$$

$$log_{10}(\sigma_{\chi p}/1\text{pb}) = -8.17 \pm 0.39$$



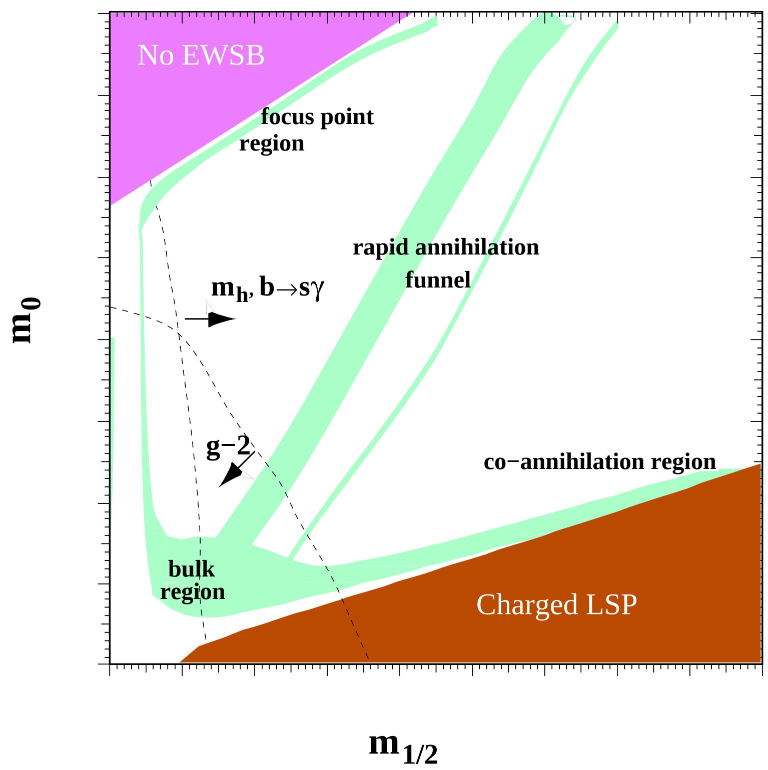


Are these this result general enough in mSUGRA?

Favourable region "bulk" region studied, now badly shrunk by WMAP measurement.

Boost annihilation via degeneration of a sparticle with $\tilde{\chi}_1^0$, or large higgsino content of $\tilde{\chi}_1^0$

Regions in mSUGRA $(m_{1/2}, m_0)$ plane with acceptable $\tilde{\chi}_1^0$ relic density (e.g. Ellis et al.):



- Coannihilation region: small $m(\tilde{\chi}_1^0) - m(\tilde{\tau})$ (1-10 Gev).

  Dominant processes $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \tau\tau$, $\tilde{\chi}_1^0\tilde{\tau} \to \tau\gamma$

  Similar to bulk, but softer leptons!

- Funnel region: $m(\tilde{\chi}_1^0) \simeq m(H/A)/2$ at high $\tan\beta$

  Annihilation through resonant heavy Higgs exchange.

  Heavy higgs at the LHC observable up to ~800 GeV

- Focus Point: high m_0, significant higgsino content.

  $\Rightarrow$ enhanced annihilation through coupling to W/Z

  Sfermions outside LHC reach, study gluino decays.

  Signatures depend on gaugino masses

Both ATLAS and CMS are performing detailed studies on selected models with the above signatures.

Strategy in MSSM

- Identify which of the annihilation processes are likely to give a significant contribution

  For this step main ingredient is knowing the composition of the neutralino, if it is a Bino, Wino, Higgsino or a mix

  One has therefore to reconstruct as well as possible the neutralino matrix

- It is also to be checked that there are no resonance situations which would enhance a specific channel

  Example $m(H/A) = 2m(\tilde{\chi}_1^0)$

- Finally for relevant processes the couplings and masses of involved sparticles need to be fixed

  In particular, if the annihilation $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \tilde{\tau}_1\tilde{\tau}_1$ and co-annihilation $\tau_1\tilde{\chi}_1^0 \to \tau Z(A)$ important, need to understnd the mixing in the stau sector

Ingredients of MSSM study

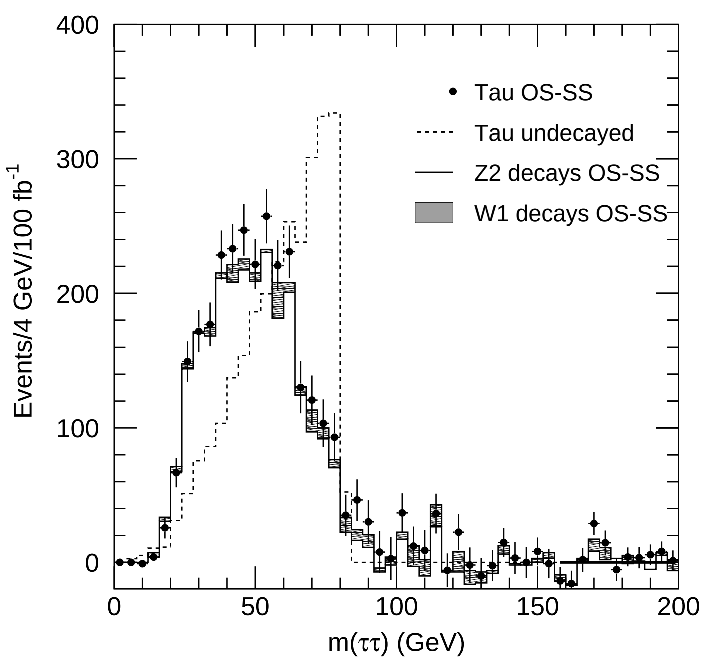
Start with explicit calculation of sparticle masses from edges

In MSSM SUSY partners of the neutral gauge and higgs bosons: $(\tilde{B}, \tilde{W}^3, \tilde{H}_1^0, \tilde{H}_2^0)$ mix to form the mass eigenstates χ_i^0 (i=1,2,3,4) through a matrix depending on M_1, M_2, μ, $\tan\beta$

In SPS1a measure mass of three neutralinos (1,2 and 4): constrain all parameters in matrix except $\tan\beta$

Need additional information for relic density determination. e.g:

1. (non) observation of H/A into $\tau\tau$, $\tilde{\chi}_2^0\tilde{\chi}_2^0$;



2. Detect and measure $\tilde{\chi}_2^0 \to \tilde{\tau}_1\tau$

Exploit excellent ATLAS tagging capability for τ jets

Position of $\tau\tau$ end point: sensitive to $\tilde{\tau}_1$ mass

Detailed study on achievable precision in progress.

Assume here variation between 0.5 and 5 GeV

Number of events in edge can be used to measure:

$BR(\tilde{\chi}_2^0 \to \tilde{\ell}_R\ell)/BR(\tilde{\chi}_2^0 \to \tilde{\tau}_1\tau)$

No detailed experimental study available: assume 10% systematic uncertainty

Step 1: solving neutralino matrix

Use measured masses for $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_4^0$

Input fixed value for $\tan\beta$, and get numerically the values of M_1, M_2, μ.

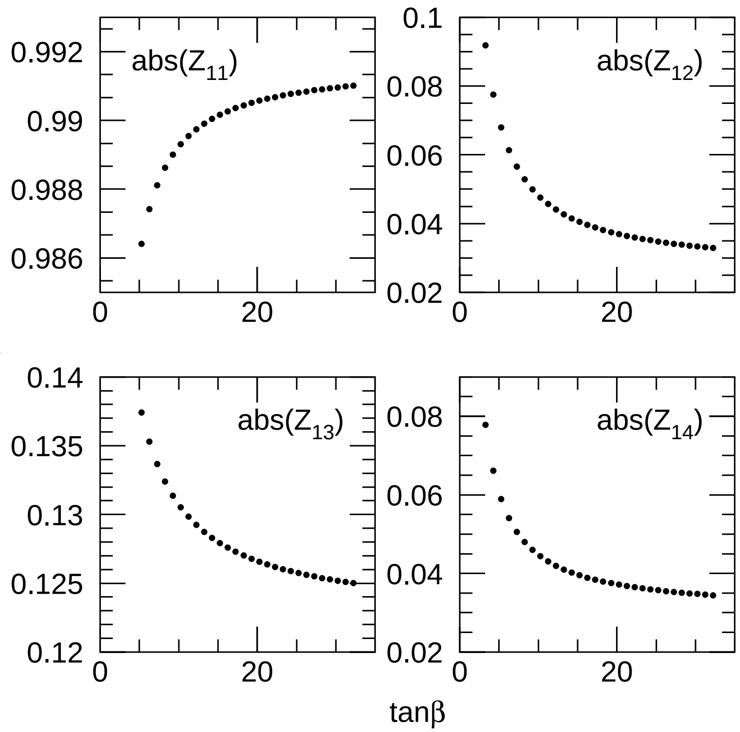
Annihilation X-section determined by components of the lightest neutralino:

$$\tilde{\chi}_1^0 = Z_{11}\tilde{B} + Z_{12}\tilde{W}^3 + Z_{13}\tilde{H}_1^0 + Z_{14}\tilde{H}_2^0$$

Experimental spread is 0.03% for bino component and 1-2% for other components

Study the dependence of the values of the neutralino components from the assumed value of $\tan\beta$

Little dependence for the bino component, larger variation for subdominant component



Step 2: stau sector

$\tilde{\tau}_1$ and $\tilde{\tau}_2$ produced from the mixing of $\tilde{\tau}_L$ and $\tilde{\tau}_R$ through a mixing angle θ_τ

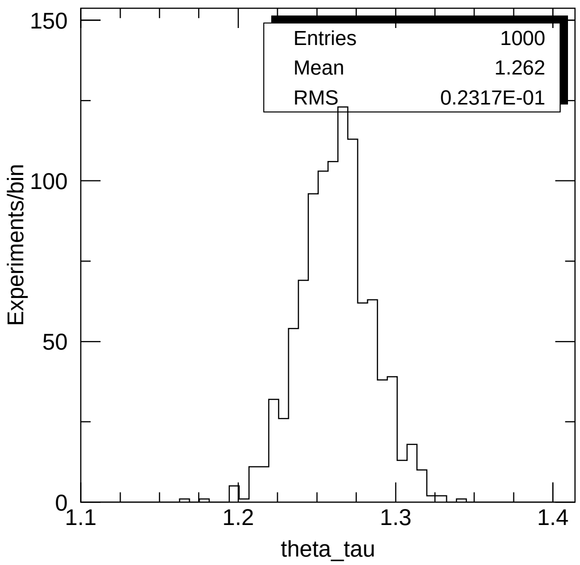
Assume no mixing in the sleptons sector for the first two generations

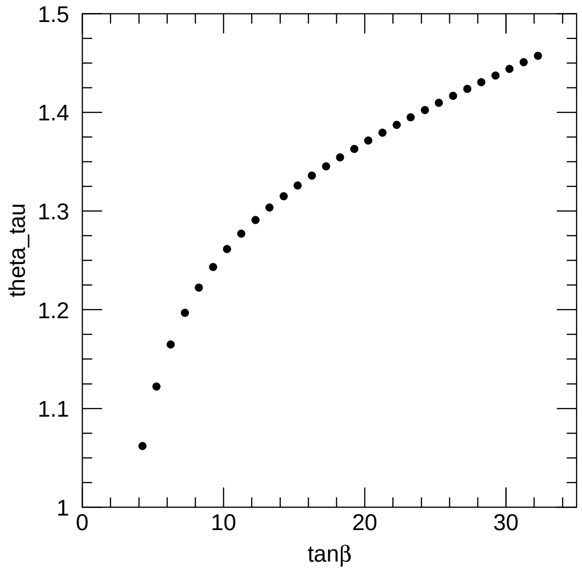
From the knowledge of the neutralino mixing matrix, $m(\tilde{\tau}_1)$, and $BR(\tilde{\chi}_2^0 \to \tilde{\ell}_R \ell)/BR(\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau)$ can extract the value of θ_τ

Show distribution of calculated θ_τ for the MonteCarlo experiments

Uncertainty from experimental error is $\sim 2\%$

Large uncertainty (25-30%) from $\tan\beta$ spread





$\tilde{\tau}$ sector not fully solved, need one more parameter, $m(\tilde{\tau}_2)$ or $m(\tilde{\tau}_R)$

$m(\tilde{\tau}_2) > m(\tilde{\chi}_2^0)$, otherwise it would be seen in $\tilde{\chi}_2^0$ decay

For $\tan\beta = 10$, if require $|A_\tau| < 5$ TeV, $m(\tilde{\tau}_2) < 250$ GeV

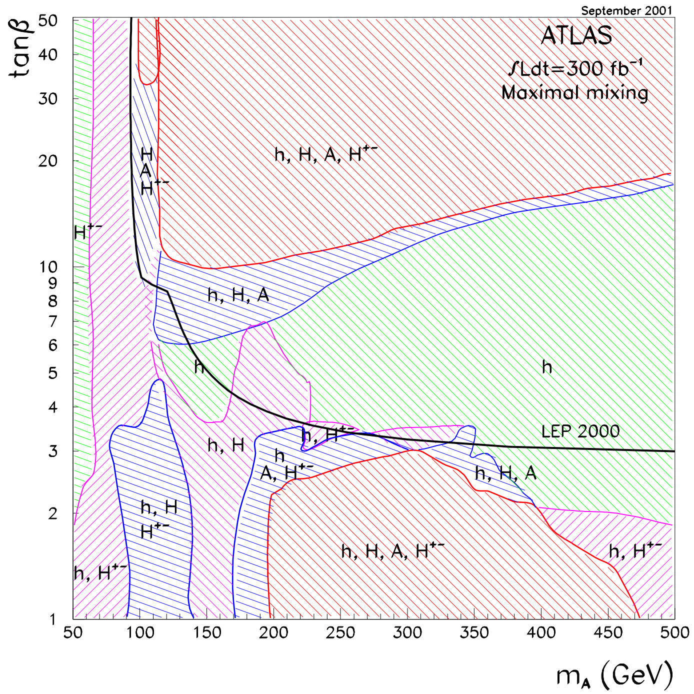
Constraints from higgs sector

h can be discovered over the whole parameter space

For high $\tan\beta$ little info on $\tan\beta$ from $m(h)$

Can assume approx $\tan\beta > 5$, need detailed study of stop sector

Heavy higgses can not be discovered at the LHC in their SM decay modes for the selected model: m(A)∼425 GeV, $\tan\beta = 10 \Rightarrow$ try with SUSY sector



- Detection of $A/H \rightarrow$bb in chargino/neutralino decays

Kinematically closed: can probably put a limit $m(A/H) < m(\tilde{\chi}^0_4) - m(\tilde{\chi}^0_1) \sim 300$ GeV from non-observation of $H/A \rightarrow bb$ peak in cascade decays. Detailed analysis needed

- Detection of $A/H \rightarrow \tilde{\chi}^0_2\tilde{\chi}^0_2 \rightarrow 4\ell\ell$

Very small rate: ~ 40 events/experiment for 300 fb^{-1}. Need detailed background study to verify observability.

Calculation of relic matter density

Use the soft parameters as extracted from the mass and BR measurements.

The stop can be observed in this point in the gluino decay, and $m(\tilde{t}_1) > m(\tilde{\chi}_1^\pm) \rightarrow$ no impact of light stop on relic density prediction

$\tan\beta$, $m(A)$, $m(\tilde{\tau}_2)$ affect the relic density measurement and are badly constrained

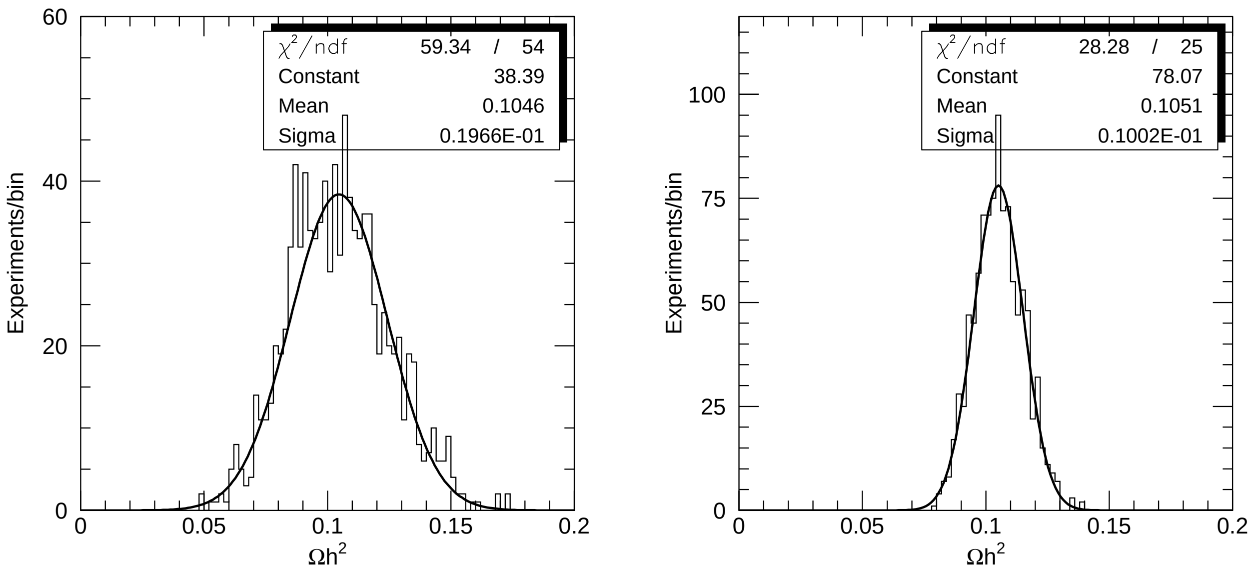
Fix them at nominal value, calculate relic density for each MonteCarlo experiment with Micromegas 1.36

Uncertainty dominated by error on on $\tau\tau$ edge position

Show distribution of calculated $\Omega_\chi h^2$ for:

$\Delta(m_{\tau\tau}) = 5$ GeV (left)

$\Delta(m_{\tau\tau}) = 0.5$ GeV (right)

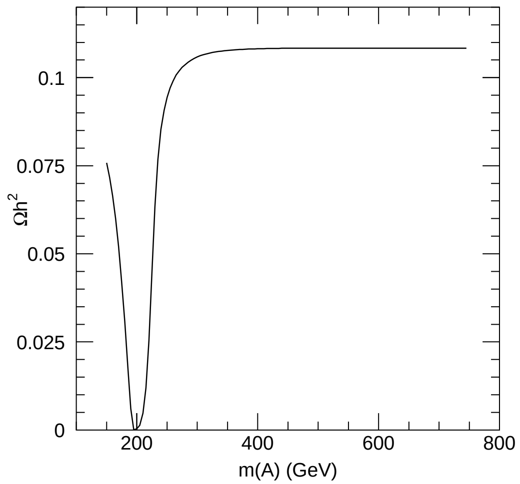


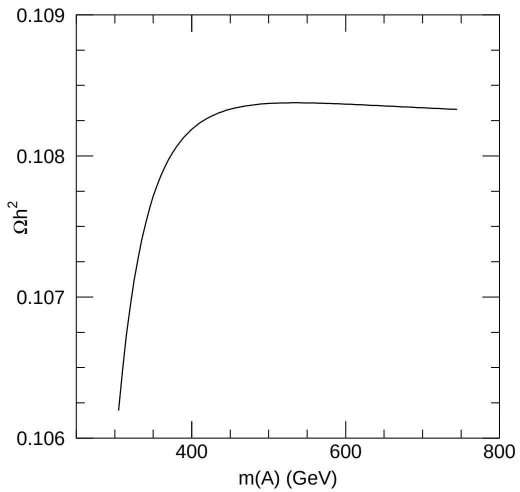
If the error on $m_{\tau\tau}$, better than 1 GeV measurement error of 10% on $\Omega_\chi h^2$

Need to considered contribution from badly known $\tan\beta$, $m(A)$, $m(\tilde{\tau}_2)$

Uncertainty from badly constrained parameters

Method: vary concerned parameter in relevant range, and recalculate all other soft SUSY breaking parameters such that measurable masses and BR are kept at measured value



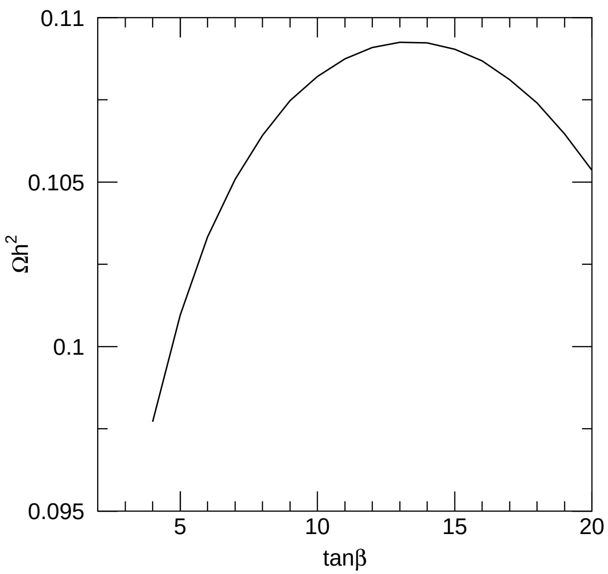


$m(A)$ dependency. Three scenarios:

- No handle on $m(A/H)$ Resonant annihilation of neutralino possible: can only give upper limit on $\Omega_\chi h^2$
- Lower limit of approximately 300 GeV on the H/A mass from non-observation in SUSY cascade decays.
  Spread on $\Omega_\chi h^2$ of ∼1%
- H/A is discovered in its $\tilde\chi_2^0\tilde\chi_2^0$ decay mode.
  No contribution from $m(A)$ to the spread on $\Omega_\chi h^2$

It might be necessary to go to upgraded LHC to be able to detect H/A in SUSY decay modes

Uncertainties (continued)



$\tan\beta$ dependency

All dependency coming from $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \tau\tau$

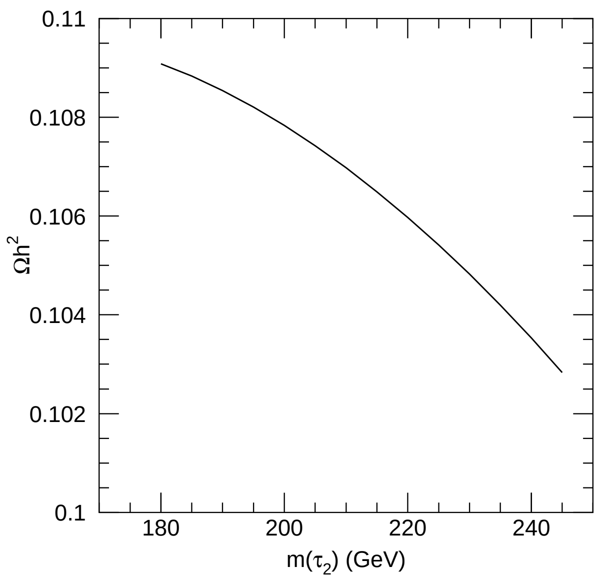
Caused by dependency of θ_τ on $\tan\beta$

The relic density estimate varies by $\sim 11\%$, depending on the lower limit one can assume on $\tan\beta$ from the higgs sector.

$m(\tilde{\tau}_2)$ dependency

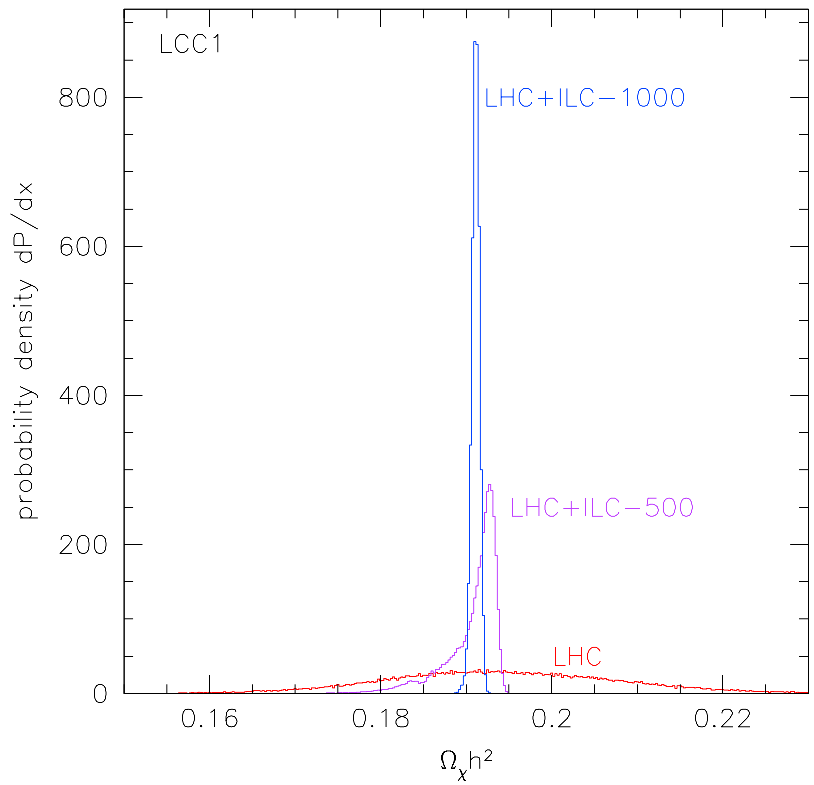
The variation with $m(\tilde{\tau}_2)$ is $\sim 7\%$, for the assumed range of $\tilde{\tau}_2$ mass, i.e. $m(\tilde{\tau}_2) > m(\tilde{\chi}_2^0)$ and $A_\tau < 5$ TeV

Work in progress to understand exactly origin of dependence



Alternative approach: scan of MSSM parameter space

Similar work by M. Peskin and collaborators, based on a scan of the MSSM parameter space on similar space point.



Results compatible with detailed analysis, improvement in precision from e^+e^- linear collider

Conclusions

SUSY parameter measurement at the LHC can be used to predict the LSP Dark Matter density

When neutralino annihilation is dominated by slepton exchange it is possible to predict the neutralino relic density from slepton/stau exchange

Dominant factors: precision on $\tau\tau$ edge position, ignorance of $m(\tilde{\tau}_2)$

Detection of heavy higgs boson necessary to exclude the possibility of resonant annihilation into them, and to help constraining $\tan\beta$

Preliminary result for SPA point, assuming $m(H/A) < 300$ GeV can be excluded and 1 GeV systematic uncertainty on $m(\tau\tau)$:

$$\Omega_\chi h^2 = 0.108 \pm 0.01(stat + sys)^{+0.00}_{-0.002}(M(A))^{+0.001}_{-0.011}(\tan\beta)^{+0.002}_{-0.005}(m(\tilde{\tau}_2))$$

SUSY signals observed at the LHC can be confirmed as Dark Matter only with input (observations) from Dark Matter searches

Ultimate goal: observations of SUSY neutralinos at the LHC together with observation of e.g. signal in direct detection Dark Matter experiment at calculated masses and cross-section.

Results only valid for slepton-exchange region, situation much more difficult for other parameter choices!

Studies in progress

Backup

Masses SPA ISAJET 7.71, tree level

Sparticle	mass (GeV)	Sparticle	mass (GeV)
$\tilde{\chi}_1^0$	97.2	$\tilde{\chi}_2^0$	180.1
$\tilde{\chi}_3^0$	398.4	$\tilde{\chi}_4^0$	413.8
$\tilde{\ell}_L$	189.4	$\tilde{\ell}_R$	124.1
$\tilde{\tau}_1$	107.7	$\tilde{\tau}_2$	194.2
$\tilde{u}_L$	533.3	$\tilde{g}$	607.0
h	116.8	A	424.6

Contributions to relic density SPA Micromegas 1.36

Process	Fraction
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \ell^+\ell^-$	40%
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \tau^+\tau^-$	28%
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \nu\bar{\nu}$	3%
$\tilde{\chi}_1^0\tilde{\tau}_1 \to Z\tau$	4%
$\tilde{\chi}_1^0\tilde{\tau}_1 \to A\tau$	18%
$\tilde{\tau}_1\tilde{\tau}_1 \to \tau\tau$	2%